END OF TERM REPORT

FOR

IMPLEMENTING AGREEMENT FOR CO-OPERATION IN DEVELOPMENT OF THE STELLARATOR CONCEPT

TIME PERIOD 2005-2010

INTERNATIONAL ENERGY AGENCY

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EXECUTIVE SUMMARY

The IEA Implementing Agreement for **Co-operation in Development of the Stellarator Concept** has been operational since 1985 and, after the incorporation of Ukraine in 2002, it presently involves the participation of six parties, namely: Australia, European Union (mainly Germany and Spain), Japan, Russia, Ukraine, and the United States. A number of successful and important results from international collaborations for the period of 2005-2009 under the auspices of the Implementing Agreement fully justify the extension of the Agreement. At this extension of the Agreement, all participating countries have unanimously agreed to the change of the title to **Co-operation in Development of the Stellarator/Heliotron Concept** in order to be suited to a frequent and prevailed use in the last period.

Stellarator/heliotron's potentially unique feature, inherent favourable characteristics for steady-state operation, makes this concept an invaluable alternative to tokamaks in the development of future Fusion Power Plants. Contrary to tokamaks, stellarators/heliotrons can create the magnetic field without requiring a net toroidal plasma current, which makes unnecessary an auxiliary current drive and brings remarkable advantages for plasma stability, in particular the absence of disruptions, instabilities due to currents and significant reduction of circulating power in a power plant. In this way, steady-state operation would be intrinsically and safely achieved in a stellarator/heliotron reactor. Also enhancement of the understanding of 3-dimensional physics in stellarators/heliotrons is now beginning to make a great contribution to advanced physics in tokamaks.

The Implementing Agreement has pursued the advancement and coordination of the promising Stellarator/Helotron Concept towards a fusion reactor, which will provide environmentally friendly, safe and abundant energy. The Stellarator/Helotron Concept has allowed exploration of a wide range of physics and technological issues in the variety of topological configurations available in the Parties. The exchange of knowledge and views, including joint participation in experiments and compilation of database, as well as coordinated strategy definition and planning, have greatly strengthened Stellarator/Helotron Concept research over the past five years.

Collaborations within the IEA framework were very active and successful for the period of 2005-2009, evidenced by the much fruitful collaboration in this document. All participating countries have greatly benefited from the collaborations. Exploiting a leading large-scale experiment in the Large Helical Device and other experiments constructs a broader and firmer basis for the development of a stellarator concept than before. Construction of another large-scale device, Wendelstein 7-X, is expected to be completed in 2014. These results and promising prospects justify the extension of the Agreement. A large number of scientific collaborations planned in 2010 and beyond make the extension of the Agreement highly desirable.

1 MISSION OF THE IMPLEMENTING AGREEMENT

The Implementing Agreement for co-operation in development of the Stellarator Concept signed in 1985 states the purpose of the Agreement.

"Recent advances in the Stellarator area have considerably enhanced the viability of this toroidal confinement concept. The advances include experiments with high plasma parameters and favourable confinement results, theoretical prospects for high beta operation, and more attractive reactor designs. Steady state operation is an inherent property of this concept. The United States and EURATOM *(and the other parties)* have major Stellarator experimental programmes underway which are complementary to and supportive of each other."

"The objective of the co-operation is to improve the physics base of the Stellarator concept and to enhance the effectiveness and productivity of research and development efforts related to the stellarator concept by strengthening co-operation among Agency member countries."

"The co-operative programme to be carried out by the contracting parties within the framework of this Agreement shall consist of the following activities:

- exchanges of information;
- assignment of specialists to the facilities or research groups of the contracting parties;
- joint planning and co-ordination of experimental programmes in selected areas;
- workshops, seminars and symposia;
- joint theoretical, design and system studies;
- exchanges of computer codes; and
- joint experiments."

The Stellarator concept has been an alternative confinement approach to the Tokamak concept. Significant progress of this concept has been made for the period of 2005-2009. In particular, the Large Helical Device (LHD) in Japan has demonstrated a 1-hour long discharge with the temperature in the keV range and the high beta of 5 % for longer than 100 times the energy confinement time. These achievements are certainly beyond tokamaks and have established the use of *Stellartor/Heliotron* to show this concept in the community in these years.

Stellarator/Heliotron research ranges from small-size experiments to large-scale experiments like LHD and Wendelstein 7-X. Net-current-free plasmas have a great advantage in both basic physics research in small devices and high-performance stable plasma experiment in large devices. Clarification of the underlying physics has matured and experimental verification of the theoretical predications has been advanced. Different approaches to the Stellarator/Heliotron Concept are pursued in different countries.

The original dedication of the Implementing Agreement from 1985 has to be updated now in important aspects: Euratom and Japan have major experimental programmes, complementary to each other and comprehensive understanding of 3 physics specific to the 3-dimensional geometry is requested to application to advanced tokamak operation such as resonant helical perturbation for ELM suppression.

The Implementing Agreement provides mechanisms to jointly investigate the properties of different Stellarator/Heliotron approaches and to compare them with the tokamak concept. The Implementing Agreement co-ordinates all the ongoing Stellarator/Heliotron activities around the world in one co-ordinated programme. For example, a joint international Stellarator/Heliotron database including experimental results from participating facilities is a representative activity under the Implementing Agreement.

The collaboration programme includes jointly planned experiments for comparison purposes, mutual participation in experiments and theoretical activities, joint evaluation of results, and information sharing. Exploiting a larger number of devices provides a broader basis of experimental results, better progress on confinement configurations, and increases the reliability of the results from the various facilities, thus contributing to improve the design of next-step devices and the demo reactor. Reducing uncertainties will reduce construction costs.

The planned start-up of the optimized stellarator Wendelstein 7-X in 2014 will provide new insight not only to the Stellarator/Heliotron Concept but also to overall fusion science, thus having a potential impact on the ITER project.

The Implementing Agreement will be extremely relevant to Stellarator/Heliotron research in the period 2010-2015.

2 CURRENT FOCUS AND OBJECTIVES

The long-term, strategic objective of the Stellarator/Heliotron programme is making this concept a suitable candidate technology for future fusion power reactors. For this purpose the different conceptual approaches being explored by the Parties have been coordinated using the IEA Implementing Agreement through theoretical studies and a wide range of experimental devices:

- **WENDELSTEIN 7-X** aims at proving the power plant relevance of advanced stellarators, testing an optimised magnetic field that will allow a quality of plasma equilibrium and confinement comparable to that of a tokamak. Energy and particle confinement will be investigated in an optimized magnetic configuration and the stationary operation of a power plant relevant divertor system will be demonstrated.
- **LHD** (Large Helical Device, National Institute for Fusion Science) in Japan is the world's largest superconducting helical device that employs a heliotron magnetic field. Other experiments such as **CHS** (Compact Helical System, shut-down in 2006) and **Heliotron J** have contributed both to physics studies (transport, plasma turbulence) and to the development of new concepts such as the heliotron line with helical magnetic field configuration.
- The highly flexible **TJ-II** heliac in Spain permits the exploration of a large number of magnetic configurations in a device with helical magnetic axis. The results achieved in the TJ-II during 2005-2009 were obtained in plasmas created and heated by Electron Cyclotron Resonance Heating (ECRH) (2 x 300 kW gyrotrons, at 53.2 GHz, 2nd harmonic, X-mode polarisation) and Neutral Beam Injection (NBI). Two beams of 400 kW port-through (H0) power at 30 kV, were injected on TJ-II. The inherently strong plasma wall interaction of TJ-II has been successfully reduced after Lithium coating by vacuum evaporation.
- The United States is developing the Compact Stellarator approach through three operating experiments. **HSX** (Helically Symmetric Experiment, University of Wisconsin) explores a helical quasi-symmetric magnetic configuration and high effective transform. **CTH** (Compact Toroidal Hybrid, Auburn University) is a low-aspect-ratio stellarator in which a substantial fraction of the rotational transform will be provided by ohmic plasma current. **CNT** (Columbia Non-Neutral Torus, Columbia University) studies the confinement of non-neutral and electron-positron plasmas.
- The **H-1NF** flexible heliac in Australia is used for fundamental experiments in magnetic configuration topology, instabilities, turbulence, flows and confinement transitions at moderate heating power, and the development of imaging spectroscopy and microwave diagnostics for broader use in the fusion programme.

These and other devices involved in the programme, either operating or under construction, are shown in the following table together with their main parameters.

	LHD	TJ-II	H-1NF	HSX	Heliotron J	CHS	L-2M
Type	Heliotron	Flexible Heliac	Heliac	Quasi-helical Stellarator	Heliotron	Heliotron	Planar axis classical St.
Number of periods	10	4	3	4	8	8	14
Major Radius (Ro)	3.9 m	1.5 m	1 m	1.2 m	1.2 m	1 m	1 m
Minor Radius (a)	0.5-0.65 m	0.10-0.25 m	0.2 m	0.15 m	0.1-0.2 m	0.2 m	0.115 m
Magnetic Field (Bo)	3/6.6T	1 T	0.2 - 1 T	1.2 T	1-1.5 T	2 T	1.34 T
Plasma Volume (V)	20-30 m^3	1.2 m^3	0.91 m3	0.44 m^3	0.95 m^3	0.8 m^3	0.26 m^3
Additional heating							
ECRH	10 MW	0.6 MW	0.2 MW	0.4 MW	0.4 MW	1 MW	0.4 MW
ICRH	3-9 MW	-	-	-	-	0.2 MW	-
NBI	15-20 MW	2(+2) MW	-	-	-	1.8 MW	-
Discharge time	> 10 s	0.5 s	1 s	0.1 s	10-12ms		10-12ms
Status	Operating	Operating	Operating	Operating	Operating	Operating	Operating
Country	Japan	Spain	Australia	USA	Japan	Japan	Russia

	WEGA	URAGAN-3M	CTH	CNT	URAGAN-2M	W7X
Type	Classical Stellarator	Torsatron	Compact Stellarator	Compact Stellarator	Torsatron	Helias
Number of periods	5	9	6	2	4	5
Major Radius (Ro)	0.72 m	1 m	0.75 m	~0.3 m	1.7 m	5.5 m
Minor Radius (a)	0.19 m	0.125 m	0.18 m	0.14-0.19 m	0.22 m	0.53 m
Magnetic Field (Bo)	0.04 – 0.1 T	1.5 T	0.5 T	0.26-0.31 T	2.4 T	3 T
Plasma Volume (V)	0.5 m^3	0.3 m^3	0.48 m^3	0.13-0.23 m^3	1.6 m^3	30 m^3
Additional heating						
ECRH	35 kW	-	0.02 MW		-	10 MW
ICRH	-	0.5 MW	0.2 MW		3-5 MW	3 (9) MW
NBI	-	-	-		-	10 (20) MW
Discharge time	Up to steady state	0.1s			0.3-0.5s	< 30 minutes, steady state with microwave heating
Status	Operating	Operating	Operating	Operating	Operating	Under construction
Country	Germany	Ukraine	USA	USA	Ukraine	Germany

As part of the programme, differences with other concepts, mainly tokamaks, are also systematically studied.

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In Europe, the construction of Wendelstein 7-X is making good progress. After a re-alignment of the project schedule and the scope of the initial period of operation, the completion of the assembly is foreseen in 2014. Followed by a commissioning period of about one year, two years of scientific exploitation are planned with a test divertor and mostly uncooled in-vessel components, limiting the pulse duration to 5 to 10 sec at 8 MW of electron cyclotron heating (ECRH) power or 11 MW of combined ECRH and neutral beam injection. This first operational period will focus on the assessment of the basic capabilities of W7-X, including divertor operation and improved neoclassical confinement. In a subsequent shut-down the actively cooled divertor, designed for a stationary heat load of up to 10 MW/m^2 will be installed, all other in-vessel components will be connected to water cooling and the heating systems will be upgraded. This will bring W7-X to its full high power steady state capability. Activities with a specific role in the frame of the Implementing Agreement are the project diagnostics for W7-X, the working group electron-cyclotron-resonance-heating (within the project microwaves for W7-X), the WEGA stellarator and stellarator theory division. At present under discussion between IPP Greifswald and Poland is collaboration on the construction of a neutral beam injection (NBI) system for W7-X. The activities of the stellarator system studies (development of stellarator power plant concepts) have been strongly reduced. However, it is foreseen to increase this work again as soon as resources from the W7-X construction become available. Future stellarator system studies will focus on a combination of physics and engineering questions.

The present focus of research in the various fields of research can be summarised as follows:

- Advanced Stellarators

The three dimensionality of the stellarator field offers - together with the use of modular field coils - the possibility to produce specific 3-D magnetic field configurations where the third (geometrical) degree of freedom is used for system optimization. Thus the optimized stellarator concept was developed to overcome the deficiencies of the classical stellarator. Whereas the diamagnetic current meets the equilibrium condition, the force-free Pfirsch-Schlüter current, which affects the shape of the constant-pressure surfaces, can be minimised by stellarator optimisation. This was one of the design criteria of W7-AS. For a specific class of optimised stellarators, also the bootstrap current can be nullified. This is one of the design criteria of the fully optimised W7-X.

The purpose of W7-X is to demonstrate the principle of reactor suitability for the optimised concept. The period between 2005 and 2010 was characterized by completion of the essential device components and the transition into the full assembly phase: All 70 superconducting coils have been manufactured and successfully tested. Coil support structure, vacuum vessel, outer cryostat vessel and ports for heating, cooling, pumping and diagnostic access are completed. By now the assembly comprises all five magnet modules. The first module is already in its final position on the machine base, encased by the cryostat vessel.

- Heliotron devices

The goals of the LHD programme are: 1) to realize high-temperature plasmas with high performance that can be extrapolated to fusion plasmas, 2) to deepen physics understanding of helical plasmas and to study systematically differences with other concepts, leading to a comprehensive understanding of toroidal plasmas, and 3) to find the requirements for the design and construction of a helical fusion reactor.

The current objectives are: 1) to make extensive efforts to enhance confinement and hence to achieve a high fusion triple product ($nT\tau_E$), 2) to explore the relevant physics for high-beta (~5%) regime, 3) to demonstrate a stable long-pulse discharge with a heatinf power exceeding 1 MW, 4) to integrate the high-cnfiement scenario achieved in a separate parameter regime so far, 5) to control edge plasmas by divertor for simultaneous achievement of confinement improvement and a stable long-pulse discharge, and 6) to investigate the behaviour of energetic particles and to execute experiments simulating behaviours of alpha particles. Steady increase of heating power and the launch of the installataion of divertor function (partially) as well as consolidation of diagnostics, has been programmatically progressed.

Heliotron J was constructed with the aim of obtaining the experimental basis for the physics design principles in the "helical-axis heliotron" approach in order to prepare the next generation of the heliotron line based on a helical magnetic field configuration. The main characteristics of Heliotron J are the strongly modulated helical variation of its magnetic axis (providing the controllable bumpy field), the resultant reduction of the neoclassical collisionless transport, the favourable MHD characteristics with its edge magnetic well and the operational capability of studying the island divertor as well as the helical divertor.

- Torsatron devices

URAGAN-3M (IPP KIPT, Kharkov, Ukraine) is a l=3 torsatron with open helical divertor, where open magnetic field lines cross the material surfaces out of direct view of the plasma confinement volume with the exception of small parts of RF antennae surfaces. This is the only stellarator/heliotro-type fusion device where plasma is produced and heated with RF power in the range of frequency $\omega \lesssim \omega_{ci}(0)$. Two different kind RF antennae are in use for plasma production, plasma heating, and for conditioning of the plasma facing stainless steel surfaces. The main program is connected (i) with optimization of operation of both RF antennae and (ii) with detail measurements of plasma characteristics (plasma flows, ion and electron energy distributions, poloidal and toroidal asymmetry, etc.) in the divertor area during different phases of discharge.

URAGN-2M (IPP KIPT Ukraine) is is a medium size torsatron (large radius is R = 1.7 m, medium radius $a \leq 0.24$ m) with reduced helical ripple value, moderate shear value and magnetic well ($\delta V'/V' \approx -4.3\%$). The main parameters of the magnetic system: l = 2, m = 4 torsatron with additional toroidal magnetic field coils; maximum toroidal magnetic field value $B_{max} < 2.4$ T. Presence of the toroidal magnetic coils and auxiliary coils of the vertical magnetic coils provides high flexibility of this device in experiment. In regimes of Uragan-2M operation the most attractive for investigations of plasma confinement, in the law frequency regimes, the helical ripple at the confinement volume boundary can be reduced down $\varepsilon_h(a)$ = 0.06. The main scenarious of plasma production and heating will be provided with several RF generators of up to 5 MW total-power. RF discharge wall conditioning is in focus at the machine also. The strategic goal of these studies is to improve RF wall conditioning for superconducting stellarators in which the magnetic will be stationary.

- Compact Stellarators

The U.S. compact stellarator programme complements the larger world stellarator/heliotron programme by extending research to lower aspect ratio and by incorporating magnetic quasi-symmetry into optimization. HSX is verifying the physics basis for the compact stellarator programme in addition to exploring some basic stellarator physics issues. The primary goals of HSX are to: (1) test reduction of direct loss orbits and neoclassical electron thermal conductivity, (2) demonstrate lower parallel viscous damping of plasma flows, (3) explore possible radial electric field (Er) control through plasma flow and/or ambipolarity constraint, and (4) investigate turbulence and anomalous transport in quasi-symmetric configurations without plasma current.

The NCSX project based on the quasi-axisymmetric concept, combining stellarator/heliotron and tokamak feature, was unfortunately terminated in May 2008 by the decision of the DOE. The main reason was the increasing construction cost beyond the initial estimate and the delayed schedule. Special modular and toroidal field coils as well as other machine components had been fablicated in FY 2008. Engineering efforts and R&D achievements have been documented so that the world fusion program will utilize them in the future developments.

The CTH is a low-aspect ratio helical device with the distinguishing capability of operating with significant toroidal. The experiment focuses on a greater understanding of current-driven disruptions in stellarators/heliotrons. While disruptions are typically not observed in helical systems, it is nonetheless of interest to investigate the MHD stability of stellarators/heliotrons with finite plasma current because disruption avoidance is relevant to helical configurations with tokamak-like levels of bootstrap current, e.g. quasi-axisymmetric devices, and stellarator-tokamak hybrids. In close collaboration with the V3FIT equilibrium reconstruction code effort, experiments on current-carrying CTH plasmas also test new methods of three-dimensional plasma reconstruction of stellarator/heliotron. Furthermore, field-mapping studies have been used to experimentally determine subtle adjustments to the placement of the actual coils for an improved model of the as-built coil set.

The CNT can contribute to stellarator/heliotron fusion research in several ways. The role of the electric field in confining plasma in stellarators/heliotrons is a very active area of research, and the CNT is exploring the extreme case where the electrostatic potential energy of the particles completely dominates their kinetic energy. The ultrahigh vacuum and very low plasma densities make the mean free path of particles extremely long, allowing detailed studies of collisionless orbit confinement. The simplicity of the CNT coils; the extremely low aspect ratio; the large, high-quality magnetic surfaces; and the relative resilience to magnetic field errors are all attractive features for a future fusion device.

- Heliac devices

The TJ-II heliac offers unique features that make it a very suitable tool to investigate the complex phenomenology that inter-relates electric field, instabilities, magnetic topology and transport in fusion plasmas. It possesses a large range of achievable magnetic configurations and low magnetic shear that allow for accurate control of the low-order rationals present in the rotational transform profile.

The flexible magnetic topology of H-1NF allows fundamental studies in plasma confinement and stability, turbulence and flows, and confinement transitions at moderate heating power with rapid turnaround. Its coil-in-tank construction makes it an ideal testbed for the development of advanced active and passive imaging diagnostic technologies from microwave through to optical frequencies.

- Classical Stellarators

In the L-2M stellarator, the programme focus on measurements of the plasma parameters in the edge and their dependence on the conditions of ECR heating (microwave power, plasma radius, shift of the magnetic axis), as well as theoretical and experimental studies of plasma turbulence and anomalous transport, and theoretical studies of the ambipolar electric field and its influence on transport.

The WEGA, operating at the IPP Greifswald, is used for training and educational purposes, the development of diagnostics and a prototype control system for W7-X, and for basic plasma physics research. Major topics are wave physics and turbulent transport.

- Diagnostics

LHD, W7-X and a the rising number superconducting tokamaks from Tores Supra, EAST, KSTAR, SST1 to ITER make it necessary to develop diagnostics for plasma characterisation, control and machine protection which are compatible with high power quasi-continuous operation. It is the strategy of the W7-X project to ensure that all diagnostics are right from the start of operation compatible with 10 MW of quasi-continuous ECR heating, because stepwise hardening of diagnostics is much more difficult. Close ties exist with LHD, Tore Supra and ITER. An extensive exchange of knowledge is also ensured by active participation of the stellarator/heliotron community in the bi-annual ITPA-Diagnostics Topical Group Meetings which also provides an official stellarator/heliotron representative, who is presently coming from W7-X. At W7-X the diagnostic groups have been re-organised into three groups: (1) core spectroscopy, (2) microwave & laser based diagnostics and (3) divertor & magnetic diagnostics. The development of diagnostic component shielding techniques for high levels of ECRH stray radiation, being a particularly critical issue at high plasma density operation, has become an area of intensive. A special large ECRH stray radiation test chamber, allowing for full scale component testing at quasi-continuous power loads of up to 100 kW/m^2, has been set up for testing using one of the W7-X gyrotrons.

- Heating

The need for steady state heating and current drive of LHD and next generation superconducting devices such as W7-X and ITER drives new and challenging developments. ECR heating with 10 MW at 140 GHz provides the basic heating system for W7-X and is a key player at ITER with 24 MW at 170 GHz. Both systems are designed for continuous wave (CW) operation supporting 1800 s for W7-X and 1000s operation for ITER, respectively. The gyrotron R&D at both frequencies was successfully completed and gyrotrons with 1 MW output power and high efficiency are available. The know-how transfer from prototype manufacture to industrial series production with high quality has not yet arrived at a fully satisfying state. The success of the gyrotron development, however, has triggered even more ambitious R&D towards 2 MW units for future ECRH-systems. CW-tests of the W7-X transmission line, which is based on optical free-space transmission under atmospheric pressure, have demonstrated full power capability at low losses, which are close to the theoretical minimum losses. The development, installation and tests of the ECRH system including all required subsystems are handled by FZK, IPP, IPF-Stuttgart and the Euratom Association EPFL Lausanne.

The initial setup of W7-X foresees also neutral beam injection (NBI). Based on the ASDEX Upgrade design, four beam sources will deliver either 10 MW of deuterium or 7 MW of hydrogen injection. At present Poland is considering making contributions to the construction of this heating system.

The low-energy (40 keV) NBI was installed in LHD (2005), aiming to increase the ion- heating power and to measure the ion temperature profile. It has provided the extension of the ion-temperature in LHD, and to enhance the physics investigation of the ion heat transport. Additional perpendicular NBI is now in the instllation, which will be utilized in experiments in 2010. The ECH power has also been steadily increased to reach 3.5 MW in the current status.

- Theory and data analysis

Stellarator/heliotron theory research is carried out as an important part of the world stellarator/heliotron programme. Its roles are: advancing the fundamental understanding of 3-D plasma physics phenomena; developing numerical analysis tools, such as equilibrium, MHD stability, turbulence simulation, and boundary modelling codes, for experiment design and data analysis; and providing integrated simulations that enable knowledge gained in stellarator/heliotron research to be applied to other configurations such as tokamaks, and vice versa.

There are numerous examples of collaborative theory activities. The international collaboration on neoclassical transport code benchmarking has been advanced for benchmarking work for the parallel current properties and the momentum correction technique in several codes. Experimental application of these neoclassical transport codes has been intensively advanced based on the close relationships with experimentalists. Collaborations, related to MHD equilibrium and stability, have been progressed in order to perform a comparative study between LHD and W7-AS, especially on the stochastization of magnetic filed lines at high-beta regimes and its prediction for W7-X.

The predictive/experimental analysis code package for helical systems, extensively developed in NIFS (TASK/3D) and in IPP Greifswald (Predictive code), are employing the extensive joint collaboration activity. The existing and up-coming experiments have provided valuable experimental results for code validation/upgrading.

International collaboration on the confinement database activity will be maintained covering both a global database and a profile database. The database is jointly hosted by IPP-Greifswald (www.ipp.mpg.de/ISS) and NIFS (ishpdb.nifs.ac.jp). The Coordinated Working Group Meeting (CWGM) has been initiated as the forum to facilitate the international collaboration, which was based on discussions between H. Yamada (NIFS) and A. Dinklage (IPP). Data administration responsible officer has been A. Kus (IPP) and H. Funaba (NIFS). The activity will continue to have a task force structure covering physics oriented topics (scaling, high-beta physics, H-mode physics, neoclassical effects etc.). Contributions from major experimental devices will be continuously submitted. Contact persons are E. Ascasibar (CIEMAT), J. Talmadge (Univ. Wisconsin), F. Sano (Kyoto Univ.) and M. Yokoyama (NIFS) and many more, reflecting the activity being open to the community. The meetings are publicly announced by e-mail list. The progress and the significant outcome from the the CWGM collaboration was introduced in the Stellarator News (Oct. 2009) to facilitate the activity with more envolvement from the community. This activity interacts with the international collaboration on neoclassical transport to assess theoretical approaches.

- Stellarator/Heliotron System Studies

Stellarators/heliotrons have significant advantages as reactors: inherent steady-state capability with no disruptions, fully ignited operation with no power input to the plasma, and no need for rotation drive or feedback control of instabilities. Stellarator/heliotron reactor studies are pursued in Germany, the U.S., and Japan, each focusing on the complementary approach followed in that country. The Helias reactor (HSR) developed at IPP is an upgraded version of W7-X that takes into account the design criteria of a power reactor. A straightforward extrapolation of the W7-X experiment towards a power reactor leads to a 5-field period magnetic configuration with the same optimized properties as in W7-X. The dimensions of the HSR5/22 reactor are determined by the need to accommodate a blanket and a shield between coils and plasma, and to have a sufficient confinement time to ensure ignition. Magnetic islands at the plasma edge can be utilized for divertor action. Thermal fusion power should be about 3 GW. The main data for HSR5/22 are: major radius 22 m and average plasma radius 1.8 m. In order to allow for NbTi superconducting coils, in the first versions the magnetic field on axis was limited to 5 T for keeping the maximum field on the coils $\leq$10 T. Recently the upgraded version HSR50a, based on Nb_3Sn or Nb_3Al superconductors, with $\approx$5.5 T on axis and 12 T at the coil conductor was investigated. It was found that the magnet system including mechanical structure is feasible with ITER-technology and existing superconductor characteristics.

In Japan, reactor studies are based on the LHD achievements and engineering concept. The basic approach is the requirement for sufficient experimental data, sufficient space for a closed helical divertor, and simplified continuous-coil systems. Force-Free Helical Reactor (FFHR) is one of such concepts. Several candidates have been investigated to secure such as the blanket space, α-heating efficiency and the cost effectiveness. The detailed physics investigation was initiated based on the 3D equilibrium (VMEC), by putting the physics and engineering constraints such as 1) the energy confinement time less than 1.4 times improvement of confinement compared to the LHD, 2) density less than 1.5 times the Sudo-limit, 3) stored magnetic energy less than 160 GJ (4 times that of the ITER), 4) space of the blanket > 98 cm, 5) the averaged neutral particle load at the first-wall less than 1.5 MW/m^2.

Stellarator power plant studies are carried out in the U.S. as part of the advanced design (ARIES) programme. It is developing an evolving vision for compact stellarator power plant designs based on current knowledge and highlighting high-leverage R&D issues for compact stellarator physics research. The objective is to combine the advantages of stellarators such as an inherent steady-state without a large plasma current with the compactness of tokamaks. Reducing the plasma aspect ratio should lead to significant cost reductions through reducing the mass of the most expensive parts of the fusion reactor core. The ARIES-CS study is beinig conducted in parallel to examine critical issues of compact stellarators as power producing reactors and to find configurations which are optimized with respect to componenets critical to a reactor performance. Such key elements include plasma aspect ratio (compacteness) in relation to the attaractive quasi-axisymmetry, alpha–particle loss and its minimization, equilibrium and MHD beta limits and the quality of flux surfaces.

The current status of several stellarator/heliotron reactor concepts was discussed at the 4th CWGM (Oct. 2008) to launch the comparative study along with the efforts to form the international collaboration on the enginnering aspects.

3 PAST ACHIEVEMENTS AND ACCOMPLISHMENTS

- Advanced Stellarators

Regarding the W7-X project, all major components of the basic device have been manufactured in industry. This holds for the superconducting non-planar and planar coils, the coil support structure, the ports, the plasma vessel, the outer vessel, the thermal insulation. Design and fabrication of the in-vessel components is continuing. In addition, the power supplies for the superconducting coils and for the control coils and the high voltage DC supplies for the heating systems (ECRH, ICRH and NBI) have been delivered and commissioned. The helium refrigeration system has been installed and is being commissioned.

Design and construction of the components for W7-X represented a major challenge for all companies involved and required innovative solutions, a close co-operation of the project engineers of W7-X with industry and intensive monitoring by specialists in the field. Several components had to be developed by the contractors. A major task has been the fabrication of the 50 superconducting non-planar coils which required the casting of the large and complicated shaped casings, winding of the superconductor to the 3-dimensional shape with an accuracy of 1 millimetre, and very careful insulation of the winding pack and especially of the header area where the different superconductors (6 layers per coil) are led through the winding pack and connected with each other. The insulation of this header area has proven very difficult and required the development of Paschen tests as a testing and diagnostics tool. Meanwhile, all these coils have been manufactured and, prior to assembly, have been tested successfully at nominal conditions at a test facility of CEA at Saclay.

Assembly has been thoroughly assessed and all the tools for the assembly of half-modules, modules, the ports and the torus have been made available. Due to delays in the delivery of the superconducting coils, assembly of the first two magnet half-modules (out of 10) has been finished only early in 2008. Since then, however, assembly progress has been steady and mostly according to the planning. The first magnet module (out of 5) has now been equipped with the bus-bars, the superconducting connections between the bus-bars and the coils conductors and the cryo-piping and it has been installed in the outer vessel module recently. Space in the outer vessel with the thermal insulation on its inside is very much constrained, resulting in a rather closed packing of the components. This results in the necessity for a very detailed collision control of bus-bars, cryo-piping and thermal insulation with respect to each other and to the coils and the support ring. These checks have to be performed with as-built CAD models and have to take all relevant operation modes into account. Special CAD- and IT-tools and control schemes had to be developed for this task. This work is now progressing routinely in a specialised department within the project.

Meanwhile, work on all five modules of Wendelstein 7-X is progressing with 83% of the superconducting coils assembled by the end of 2009. According to the assembly schedule, assembly will be finished late in 2014. To minimise risks, Wendelstein 7-X will then start operation with a temporary divertor unit (TDU) with inertially cooled target plates and with only very limited water-cooling of in-vessel components. In a first operational period of two years, basic stellarator characteristics will be investigated and a consistent high-density scenario needs to be developed. This will then form the basis of developing stead-state operation in Wendelstein after a break in which the steady-state water-cooled High Heat Flux divertor (HHF) and the cryo-pump are installed and also heating and diagnostic systems will be completed and extended.

- Heliotron devices

Significant progress in many areas of the toroidal confinement research has been achieved on LHD. The major achievements are the following.

1) Demonstration of compatibility between MHD stability and transport: A potential conflict between the plasma stability and confinement was the major concern. Theoretically, an inward-shifted configuration has good neoclassical transport, but poor MHD stability. But LHD exhibits low amplitudes of the MHD modes, which do not appear to affect the confinement. Rather, transport dominated by anomalous loss is optimal in inward-shifted configurations.

2) The central density has exceeded 1×10^{21} m^{-3} with the formation of the Internal Diffusion Barrier (IDB). Such values of the density are far beyond the “equivalent” Greenwald limit in tokamaks, and have opened up the innovative helical fusion reactor concept based on the high deninty plasmas. Such high-density plasmas was firstly realized in the LID configuration, but has been also demonstrated in the helical-divertor configuration. The repetitive pellet injection has played a significant role as the particle-fuelling source. It was upgraded to make the 20-repetitive injection possible in 2009.

3) Achievement of high β plasma: Progress in NBI heating capability and the extensive optimization experiment of the magnetic configuration in LHD enables exploration of MHD studies in the β range up to ~ 5.1 %. High β ranging 5 % is demonstrated to be maintained in the steady state for longer the 100 times the energy confinemet time. A clear limitation of the achieved β value due to MHD activities has not been observed. Real-time control of the vertical field to shift-back the magnetic axis inward has been examined to recover the heating efficiency in higher β range.

4) The ion-temperature has been increased after the installation of the low-energy (40 keV) NBI (primarily for the ion-heating) in 2005. A hydrogen plasma with the ion temperature of 5.6 keV at $n = 1.6\times10^{19}$ m^{-3} has been achieved. It was also found that the impurity is expelled out from the core region in such high ion-temperature plasmas to form the “imputiy hole”. This is favourable feature for reactor scenario, and the detailed investigation has been undertaken.

5) Steady-state operation: A long-pulse discharge (54 min 28 sec) has been successfully demonstrated, achieving the world record value of the total input energy of 1.6 GJ beyond that of the Tore-Supra. . The average input power was 490 kW (ICRF 380 kW, ECH 110 kW). The central temperature was around 1 keV and the averaged density was around 0.4×10^{19} m^{-3}. A swing technique for the magnetic axis position between 3.65 m and 3.67 m was also used for spreading the heat load. With these improvements, the long-pulse operation was realized. The discharge was terminated just because the loss of the heating power due to an engineering control accident, not because the sudden impurity flux which had been the case previously.The long-pulse discharge with higher heating power has been pursued, and the 525 sec with the heating power of 1 MW has been achieved. The upgrade of the ICRF system are now in consideration.

6) The core electron-temperature has been increased far beyond 10 keV with the Core Electron-Root Confinement (CERC) along with the increase of the ECH power in a low density ($n \sim O(10^{18})$ m^{-3}) regime. The measuremet of the radial electric field in the core region has been also performed with the heavy ion beam probe (HIBP) measurement.

7) The above-mentioned parameters have been achieved in separate discharges with different conditions. However, the integration os the high-performance confinement has been pursued to reach the fusion triple product, $nT\tau_E$, of up to 5×10^{19} m^{-3} s keV. This achievement has elucidated the potential of heliotron concept for the fusion reactor.

8) Toroidal-plasma-confinement physics research have progressed utilizing the controlling, diagnostics, simulation and theory capavbility in these extended parameter regimes. The edge transport, island dynamics, radial electric field, turbulence are such examples.

The Heliotron J have clarified the impact of the bumpy field (that is a critical knob on the quasi-isodynamic configuraration) on several physics propweties such as the global confinement, energetic particle confinement and bootstrap current. The Alfven Eigenmode study also has been progressing.

The CHS was shut down in 2006. The physics research has been continued using those data, such as H mode, CERC, bifurcation nature of confinement. It has also played a role in the international collaboration such as in CWGM

- Torsatron devices

It was shown in experiments on torsatron Uragan-3M that the formation of high radial electric field shear region during the transition to the improved confinement regime takes place in the vicinity of stochastic magnetic field line layers near rational surfaces. According to estimates, the energy confinement time increases noticeably (≥ 20%) and the effect varies with plasma parameters. The regime of low collision frequency is realized with an absolute energy confinement time up to ~ 4 ms.
The reconstruction of plasma pressure profile takes place during transition to the regime of better confinement. The time of reconstruction is rather short, ~130 μs, what indicates that the heat flux providing the reconstruction of pressure profile, is probably connected with the electron plasma component.

The method of plasma production and heating in the U-3M (Alfven resonance in the $\omega \lesssim \omega_{ci}(0)$ range of frequencies) was shown to result in a two-temperature ion energy distribution (T_{i1}~50-80 eV, T_{i2} ~250-400 eV with $T_e(0)$ ~500-700 eV at $\bar{n}_e \sim 10^{12}$ cm^{-3}) with a minor (<1%) group of suprathermal ions with energies up to several keV. An extremely important aspect of the effect of fast ions (FI) generation in U-3M is its influence on H-like mode formation. It was experimentally observed that the H-transition is always synchronized with a short-time increase of FI loss, which is a primary effect. This indicates that the edge E_r bifurcation toward a more negative value and occurrence of the layer with a strong E×B velocity shear at the plasma boundary where the anomalous transport is suppressed, are triggered by the FI loss (ion orbit loss and/or radial flow of drift orbits of helically trapped ions).

By means of electrostatic probes the comparative behaviour of fluctuations of plasma density above and below central plane of the torus was for the first time studied in two poloidal cross sections of the U-3M before and after transition to the H-like mode. It was found out a new type of the vertical asymmetry of the divertor plasma flows (DPF), namely, the lack of coincidence of power spectra and coherency of fluctuations in symmetrically disposed divertor channels. Also, for the first time it was shown a significant FI contribution into a vertical (up-down) asymmetry of divertor plasma flows in the helical divertor of torsatron/heliotron.

Some nonlinear effects, realizing when the RF electric field excited by the power applied to RF antennae does interact with plasma, were studied theoretically and experimentally. It was shown that not only the main RF component is excited but its second harmonic and the time-independent term denoting the rectification of alternating voltage occurs. Thus, some part of energy of the original RF mode can be transformed into higher harmonics and constant component. During the experimental investigations on U-3M the number of disturbed harmonics of RF-field was up to eleven.

The investigations of the structure of magnetic surfaces were carried out in the U-2-M by the use of the luminescent rod method. The measurements were done for wide range of the K_φ values (K_φ =0.295 ÷ 0.4) and the vertical magnetic field amplitude. The magnetic configurations was found to have magnetic surfaces with the cross-sections mean radius $a \approx 20.5$ cm for $K_\varphi = 0.31$,

$\langle B \rangle / B0 \approx 1.14\%$, 1.85%, 2.55%. Configurations with no magnetic islands, with K_φ =0.31 и K_φ =0.32, are recommended for plasma confinement investigations.

U-2M torsatron is equipped with two compact RF antennas of frame type. The first antenna has a broad $k_{||}$ spectrum and is used for plasma production. The second one with narrower $k_{||}$ spectrum heats plasma in the Alfven range of frequencies. Two generators with RF power 0.5 MW and frequency in the range of 10 MHz can be used. The antenna with the broad $k_{||}$ spectrum provides reliable gas break-down in the pressure range of (3.10^{-6} - 8.10^{-5}) torr and produces plasma with density (1-2).10^{12} cm^{-3}. Combined usage of two antennas with RF power P_{RF}~100 kW (after preliminary short time wall conditioning) results in increase of the plasma density up to 6×10^{12} cm$^{-3.}$ The increase of the carbon line intensity in time indicated that for improving the plasma parameters there is a need to perform a more careful wall conditioning.

Continuous RF discharges in U-2M are sustained by the 1 kW RF oscillator in the frequency range of 4.5-8.8 MHz. This power is launched to plasma by a frame antenna. The discharge parameters are measured in wide range of confining magnetic field and pressures. The dependence on launched power is also investigated. Evolution of the impurities in the discharge signified by the optical measurements, the residual gas composition and partial pressures measured with the mass-spectrometer indicate the wall conditioning. Their development is analyzed during days of operation. The continuous discharge is combined with a pulse discharge with power 50-100 kW, frequency 5.6 MHz, pulse duration 10-20 ms and the frequency 2-5 pulses per minute. This improves the rate of wall conditioning. A self-consistent numerical model for wall conditioning discharges was developed. First calculation results are compared with the experimental data.

A compact four-strap antenna is proposed and developed for Alfvén resonance heating in U-2M. For this antenna periphery plasma heating has to be suppressed and both low and high-density plasma heating are possible according to calculations. There is no sensitive dependence on the plasma parameters.

Development of the HIBP diagnostics for the U-2M has been fulfilled in the frame of STCU-Ukrainian Academy of Sciences assignment. The numerical calculations of the heavy ion (Cs^+ and Tl^+) beams with different energies and different values of torsatron magnetic fields were carried out for optimization of the HIBP experiment: the choice of the relevant ports and particle energy to prove measurements in the main part of a plasma column from the edge to the center of the plasma confinement volume. The most appropriate positions of the heavy ions accelerator and the secondary particles analyzer to use the minimum energy of the primary beam particles were found. It was shown that the use of thallium ion beam with the energy 100-150 keV will provide adequate measurements of the plasma potential in U-2M plasma confined in toroidal magnetic field up to 0.8 T. For the second stage of experiments with magnetic field $\leq$ 2.4 T the primary thallium beams with energy 500-900 keV will provide measurements of potential and other plasma parameters in the main part of the plasma cross-section. On the base of the calculations for optimized HIBP installation at U-2M the general form of diagnostic hardware have been designed, which includes primary beam injector of Cs^+ and Tl^+ ions with energy ranging between 100 and 950 keV, and the ion energy analyzing units.

Compact Stellarators

NCSX

The NCSX project was, unfortunately, terminzted by the decision made by the DoE (Department of Energy), USA on May 23, 2008. The main reason was the budjet increases and the delay of the device construction. However, wide range of theoretical/computational/technological studies progressed for NCSX projects has produced a lot of fruitful results, which have strong impacts not only to the stellarator/heliotron plasmas, but also to the tokamak plasmas. In this sense, NCSX project has been one of particular examples bridging between the stellarator/heliotron community and the tokamak community, with which critical issues on both communities has been discussed systematically. All completed device components, specialized tooling, and documentations will be secured and stored, so that it would be possible to complete construction in the future should circumstances warrant.

HSX

1-Tesla operation has been performed which highlight the unique features of the bootstrap and Pfirsch-Schlueter currents. Large parallel flows, usually neglected in stellarator/heliotron calculations, have been observed by CXRS in qualitative agreement with results first predicted by the PENTA code. Electron temperatures in the core during ECRH are up to 2.5 keV with 100 kW input power and drop to 1.5 keV when the symmetry is intentionally degraded. The steep temperature gradient in the core is indicative of a core electron root confinement (CERC) mode. PENTA calculations support the conclusion that even with small symmetry breaking, it is possible to achieve a neoclassical ITB based on the proximity of an electron root near an ion root. A Weiland ITG/TEM tokamak model for anomalous transport supports the conclusion that E x B suppression of turbulence is responsible for the improved confinement in the plasma core. At a lower field of 0.5 Tesla, instability due to fast electrons is observed, which disappears when the symmetry is broken. Experimental measurements indicate that the mode is acoustic.

CTH

Test and validation of the new V3FIT 3D magnetic equilibrium reconstruction code are underway on the CTH. The present suite of magnetic diagnostics includes internal and external 8-part and full Rogowski coils; four flux loops, and a diamagnetic loop. The measured signals from these diagnostics include contributions from the plasma current, externally applied currents, vacuum vessel current, and various sources of pickup and drift. The induced toroidal vacuum vessel current (<15kA) significantly contributes to the magnetic diagnostic signals. In order to include this current contribution in the reconstruction process, the VALEN code was used to model the time varying vacuum vessel current distribution. For reconstructions, the plasma contribution is extracted from the total signal to provide the experimental input to V3FIT, which utilizes least squares fitting and the VMEC equilibrium code to reconstruct 3D plasma equilibria.

CNT

Pure electron plasmas and electron plasmas with a finite ion fraction have been studied in the CNT. Stable, small Debye length pure electron plasmas are routinely created, and have confinement times up to 20 msec. The confinement is limited by radial transport caused by internal rods, as well as electron-neutral collisions. The neutral driven transport rate is indicative of poor particle orbits in CNT, despite the strong radial electric field. Numerical simulations shed light on this issue, demonstrating the detrimental effects of variations in the electrostatic potential on a magnetic surface. With the installation of a magnetic surface conforming electrostatic boundary and the transition to external diagnostics, significantly longer confinement time has been achieved. Also a sudden confinement jumps have been observed with a hysteretic behavior. An ion driven instability is also observed.

- Heliac devices

Significant improvements in characterising the confinement and stability properties have been achieved in the TJ-II during 2005 - 2009. The main conclusions can be summarized as follows.

Improvement of plasma particle control has been observed in the TJ-II after Li-coating, in comparison with the operation under Boron coated walls. The beneficial Li properties for plasma-wall interaction have a strong effect on this device that presents a helical limiter very close to the magnetic axis, which receives the strongest particle and heat fluxes. The outstanding results are the density control due to very low recycling conditions in formerly collapsing NBI discharges and the access to improved confinement regimes. A key ingredient for understanding the operational improvement is the change of profile radiation under Li coated wall. The edge radiation is observed to fall, which avoids the local power unbalance that produces the low radiation collapse.

Confinement studies in ECH plasmas show that the lowest values for the effective electron heat diffusivity are found in regions where the lowest order magnetic resonances are located, while Alfven eigenmodes destabilized in NBI plasmas, also related to low order resonances, can degrade fast ion confinement. A transition from kinetic effect-dominated to a more collisional regime is found in ECH plasmas. The electric field, positive all over the plasma in the low ECH plasma regime, starts developing negative values at the maximum density gradient region when the collisionality reaches a threshold value. For given heating power and magnetic configuration, this translates into a line-density threshold to restore particle confinement. Further increments in the density extend the region with negative electric fields towards the centre of the plasma.

During the high density NBI operation, a transition to an improved confinement regime (H-mode) is observed, characterised by the increase of diamagnetic energy, the decrease of Hα emission, the drastic reduction of turbulence, and the development of steep density gradients. High temporal and spatial resolution measurements indicate that turbulence reduction precedes the increase in the mean sheared flow, but is simultaneous with the increase in the low frequency oscillating sheared flow. So far, the H-mode has been obtained in a transient way and the estimated NBI absorbed power is comparable to the power threshold calculated using the empirical scaling obtained for tokamaks. This type of spontaneous transitions is added to the ones that happen at lower densities, which correspond to the shear flow development and can be also provoked by biasing. Regression analysis of the energy confinement time (up to 14 ms in NBI discharges) indicates stronger degradation with power (power exponent – 0.8) and weaker density dependence (power exponent 0.4) than ISS04.

During both low and high-density plasma bifurcations, the correlation length of the plasma potential becomes of the order of the machine size during the edge bifurcation itself, quite unlike the density fluctuations. These results show that the increase in the degree of long-range correlation is strongly coupled to the presence of radial electric fields.

The measurements of the radial plasma potential and electron density as well as their fluctuations by HIBP diagnostics and study of their influence on the plasma confinement in TJ-II with ECR and NBI heating were continued in the frame of the collaboration between KIPT Kharkov and RNC “Kurchatov institute”, Moscow.

HIBP diagnostics in TJ-II has been upgraded to study directly the plasma electric potential and plasma density, as well as poloidal component of electric field E_p with good spatial (up to 1cm) and temporal (up to 10 μs) resolution, and thus there appeared the chance for the first time for stellarator-type fusion devices to estimate the radial turbulent flux of particles $\Gamma r=\Gamma(E_{pol}xB_{tor})=\Gamma_{ExB}$. The experiments with NBI heating showed the existence of spontaneous L-H transition. The observations demonstrate that the L-H transition is not only the peripheral event, but that the changes in plasma gradients, the level of oscillations and Γ_{ExB} fluxes in the core plasma occur simultaneously. Suppression of Γ_{ExB} in the core (measured by HIBP) and in the edge (by Langmuir probes) is associated with increasing negative E_r, which may allow suggesting that shearing stabilization mechanism plays dominant role in the transition to better plasma confinement.

Alfven modes were observed by HIBP. Correlation studies with reflectrometry; magnetic probes and Langmuir probes can give an insight to spatial structure and properties of the Alfven modes.

MHD modes in H-1NF have been investigated by a combination of probes, interferometry, and innovative spectral imaging and data mining techniques. The low shear and precise magnetic geometry have allowed highly accurate mapping of Alfvénic dispersion over a wide range of rotational transform and mode numbers, and demonstrated the accuracy of “Alfvén

Spectroscopy” in measuring rotational transform. Initial data from synchronous spectral imaging has allowed radial mode structure to be determined to very high resolution and promises to resolve toroidal mode structure.

Studies of the relationship between turbulent particle transport, the development of sheared ExB flows, and transitions to improved confinement modes have provided rich data on self-organisation of turbulence, the development of zonal flows and the role of the GAM. Magnetic configuration studies include novel techniques for the detection of magnetic islands and have shown a possible link between island formation and local improvement in confinement in low temperature plasmas.

Innovative coherence-imaging diagnostics for neutral and ion spectroscopy have revealed 2-D flow and temperature data in the H-1 and WEGA and many other international toroidal confinement experiments. The first imaging measurement of internal magnetic fields was achieved using a development of this technique on TEXTOR tokamak.

In collaboration between ANU, the University of Sydney, Hiroshima University and Kyoto University a pulsed supersonic helium beam has been developed and installed on H-1NF. With the aid of a collisional radiative model, the radial electron temperature profile can be deduced from measurements of spectral line emission from the beam due to excitation by the plasma.

- Classical Stellarators

WEGA plasmas are heated using 2.45-GHz and 28 GHz ECRH sources with a total power of 26 kW and 10 kW, respectively. In this context experiments on O2 and X2 and X3-mode ECR heating have been performed at 0.5T and 0.3T, respectively. Furthermore, plasmas could be sustained by electrostatic Bernstein waves (EBW) at low magnetic field of about 60mT, using the 2.45GHz ECRH, and at 0.5T using the 28 GHz ECRH. These EBWs which have been excited by a two step mode conversion process from O- to X-mode polarized electromagnetic waves and in second step from X-mode into Bernstein waves, resulting in over-dense plasmas with central power deposition. Studies on turbulence and transport have been performed with different Langmuir probes. Special interest has been paid to the influence of the magnetic field configuration on the dynamics of turbulent structures, including details on their parallel dynamics inside the scrape off layer (SOL). A 2D probe array was used to study turbulence in the region of magnetic islands, which has been carefully characterized before by means of flux surface measurements. In general, the magnetic flux surface measurements with different electron beam techniques have been refined for their later application in W7-X. A prototype control system for W7-X has been developed and implemented on WEGA, including segmented plasma control, a newly developed timing system and special hardware components.

- Diagnostics

A number of workshops and design reviews with respect to the start-up set of diagnostics for W7-X were organised with international experts’ participation. Also, following the decision to reduce the number of ports on W7-X and to start plasma operation with an uncooled divertor, some W7-X diagnostics had to be rearranged and adapted to the new situation. A topical review article on “Diagnostics for steady state plasmas” has been written, summarising the issues to be tackled in the development of diagnostics suitable for quasi-steady state operation. Examples demonstrating the good level of collaborations are e.g. the development of diagnostic neutral beam at the Budger Institute in Novosibirsk, a phase meter detection system together with CIEMAT and IST, Lisbon, or of a long pulse integrated electronic board for magnetic diagnostics developed for W7-X, now being installed on KSTAR. A new flux surface measurement technique developed on W7-AS and WEGA, based on field line visualisation, is now being tested on LHD in preparation for W7-X. A new diagnostic technique, Coherence Imaging Spectroscopy, has been developed on WEGA in close collaboration with the H-1NF team in recent years.

An example that illustrates the good level of co-operation on diagnostics development among labs is the HIBP diagnostic installed by KIPT in the TJ-II at the beginning of 2000 and in full operation during 2005-2009. The HIBP diagnostic was used for measurement of the plasma potential and density, as well as their fluctuations, with high spatial (0.5-1 cm) and time (10 μs) resolution. A set of experiments was devoted to the study of the behaviour of the plasma potential during the develoment of core and edge transport bifurcations and to characterize the radial structure of Alfven instabilities. Further development of the HIBP system is in progress including the construction of a second HIBP for zonal flow studies.

The solid-state ion sources for Beam probing plasma diagnostics elaborated in IPP NSC KIPT covers a wide range of beam species (Li, Na, K, Cs, Tl), beam intensities (4 mA/cm^2 in steady and a few A/cm^2 in pulse operational modes), and ion capacities (up to 6 mA*hour). These ion sources are successfully used in injectors of HIBP and Li^0 diagnostics.

The HIBP group of KIPT (Kharkov, Ukraine) have developed, installed and successfully used of the HIBP diagnostics at several fusion devices: T-10, Tuman - 3M and TM-4 tokamaks in Russia, TJ-II, and WEGA.

Significant improvements in the HIBP facility and measurement procedure on TJ-II (two-slits detection, signal/spurious noise suppression; increasing the primary probing beam Cs+ intensity up to 200 μA) resulted in an increase of the possibilities of the diagnostics. The most crucial one is the extension of the signal dynamic range, which allows getting the reliable profiles from the plasma center to the edge.

Two new HIBP sets have been developed for Uragan -2M (energy interval 100-900 keV) and for TJ-II (the second set at this fusion device) with havy ion beam energy up to 150 keV.

- Heating

All supporting systems for ECRH such as the HV-power supplies, the water cooling plant, the cryo-plant, the superconducting magnets, the transmission line, the supporting ECRH-towers, and the 4 plug-in front steering launchers are completed. The in-vessel components such as reflecting first wall tiles and the ECRH-related diagnostics are presently being fabricated. A point of concern is still the series production of gyrotrons with the specified performance. After successful test-operation and taking over of the first series gyrotron, the following gyrotrons showed output power degradation by typically 20-30 %. Parasitic oscillations, which are excited in the electron beam tunnel, were identified as the origin of the power degradation. A 6-month R&D programme was launched at Karlsruhe Institute of Technology (KIT) in collaboration with IPF Stuttgart and Thales to solve the problem. The R&D was successfully terminated in June 2009, an improved beam tunnel is presently being incorporated into the series gyrotrons and first results are expected soon.

- Theory and data analysis

Stellarator/heliotron theory has made important progress on a number of fronts in the last five years. This progress ranges from increased understanding of basic physics issues to the development of numerical tools for quantitatively simulating stellarator/heliotron plasma behaviour.

A basic understanding of plasma rotation has emerged by the establishment of fundamental results as to how the magnetic configuration affects intrinsic ambipolarity and the toroidal plasma flow velocity. For instance, it has become clear that momentum transport is far less important than in tokamaks and that the plasma rotation can thus largely be calculated without having to simulate plasma turbulence. On short radial scales, so-called zonal flows are however possible, and are seen to affect the turbulence level in gyrokinetic calculations.

In the field of turbulence, it has become possible to make nonlinear gyrokinetic simulations using flux-tube codes in realistic geometry. This is a major new development, which has led to a strong collaborative effort involving the groups at IPP, NIFS and PPPL, and which is beginning to shed light on the old question of how details in the magnetic geometry affects plasma turbulence. The long-term goal is to use this information for optimising stellarators/heliotrons to reduce the anomalous transport. Particle-in-cell codes are also being developed with the view of performing global gyrokinetic simulations.

In the field of edge transport, the EMC3-EIRENE code, which was developed in Jülich and Greifswald, has become the standard tool for simulating fully three-dimensional edge transport. Comparative studies of W7-AS, LHD and W7-X have been carried out, and valuable insights have been gained about how different geometries affect divertor functionality. For instance, it has been established why a high-recycling regime was absent in W7-AS, why impurity screening occurs in W7-AS and LHD, and what parameters and operating regimes may be expected in W7-X. The code has also been "exported" to tokamak groups doing modelling of axisymmetry-breaking effects, e.g., for the mitigation of edge-localised modes.

In the field of neoclassical transport, an international benchmarking activity has been completed and is being documented. Momentum correction techniques have been developed, benchmarked and applied to bootstrap current calculations as well as to current drive modelling.

The confinement time scaling activity ISS04 within the IEA-IA framework is continued to maintain and systematically extend the energy confinement time dataset of stellarators/heliotrons. Density scans of high-density H-mode discharges indicate ISS04 being not valid at highest densities. High beta confinement data from LHD and W7-AS reveal differences between low- and high-beta confinement and collisionality dependence.

The profile database has documented the Core Electron-Root Confinement (CERC) regime to be a generic neoclassical effect for 3D devices differing from tokamak ITB regimes. High beta 1D analysis is being addressed. H-mode phenomena are documented from CHS, LHD, TJ-II, URAGAN and W7-AS. Comparative assessments of MHD activity are performed. An extension to edge profile experimental data is underway also including edge turbulence data from tokamaks.

An international collaboration on MHD and configuration studies has grown to the point where ANU datamining techniques have now been implemented on five large stellarators/heliotrons, including the largest, LHD. Using a new version of the data mining technique recently developed by D. Pretty (ANU/CIEMAT), collaboration between ANU, Kyoto University, NIFS, CIEMAT and MPIPP has successfully classified data from thousands of shots data into a small number of clusters of similar modes.

A new formulation of the 3-D MHD equilibrium and stability problem (with possible applications to electron transport barrier and heat flow studies) is being developed in a joint ANU/PPPL collaboration. A multi-region (stepped pressure profile) variational code is being developed and progress has been made on an alternative Hamilton–Jacobi method. A new construction of almost invariant tori (imperfect magnetic surfaces) based on a unification of the quadratic-flux-minimizing (QFMIN) surface method has been formulated.

- Stellarator/Heliotron System Studies

The studies undertaken by IPP have culminated in the following Helias reactor configurations: HSR5/22, HSR4/18/i,HSR3/15i, and the recent HSR50a, the main data of which are shown in the following table:

	HSR5/22	HSR4/18i	HSR 3/15i	HSR50a
Major radius [m]	22	18	15	22
Av. minor radius [m]	1.8	2.1	2.5	21.8
Plasma volume [m^3]	1410	1560	1600	1410
Av. field on axis [T]	4.75	4.4	4.4	5.6
Max. field on coils [T]	10	8.5	8.3	12.3
Number of coils	50	40	30	50
Magnetic energy [GJ]	100	76	72	152

Various coil systems of the HSR3/15-type were investigated in order to improve the alpha-particle confinement.

Impurity transport studies were carried out in collaboration with the National Institute for Fusion Science and Kyoto University (Japan). The influence of the radial electric field on impurity behaviour was analyzed, and impurity accumulation within the externally induced islands was simulated by means of the Impurity Transport code SIT STRAHL.

Neutronic computations for W7-X and Helias Reactors were carried out by using the MCNP code. An axisymmetric shell model was used consisting of a toroidal plasma region surrounded by a Lithium breeding zone (Li-6, Li-7), a stainless steel shell of variable thickness, blanket and shielding zones, and the coil winding packs. A tritium breeding ratio of about 1.15 was obtained for a breeding zone thickness of 40 cm together with a steel zone thickness of 5 cm.

Superconducting coil power supply options for a Helias Fusion Reactor were investigated and optimized using the SIMPLORER code. The goal was to achieve low losses in the components, a small negative impact to the power grid, and to reduce the network loadings in the power plant start-up phase during plasma heating. The entire coil system and passive structures were included.

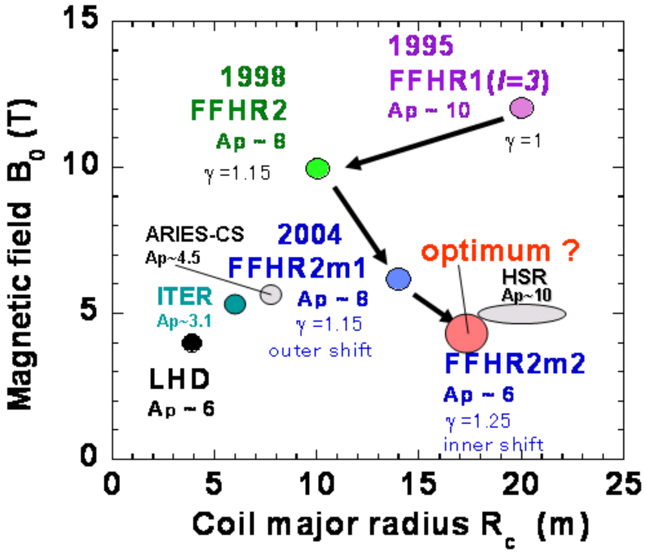
A new code “MODUCO” (MODUlar COils) was developed for interactive magnetic field optimization, parameter studies, and coil layout. Based on the representation of the central coil current filament by control points and Bézier interpolation, it is an easy-to-handle analytic description of the coils which allows modifying them within wide limits. It reproduces well the magnetic field of W 7-X and can be used for other stellarator/heliotron-types and tokamaks too. Magnetic surfaces and particle orbits, forces, as well as magnetic fields inside the coil cross sections can be computed, and the code is well-suited to model stellarator/heliotron experiments and reactors.

The HSR50a-study was performed which showed that the magnet system of a 5-periodic HElias reactor with 12.3 T maximal induction at the superconductor is feasible. Since the coils of such a machine are very similar in size to the ITER toroidal field coils and also the electromagnetic loads are comparable, one can take advantage of the ITER developments as well as prototype works. This means that the ≈12 T magnet of such a stellarator reactor would not require basic new developments but just an adaption and upgrade of existing technologies. HSR50a is like HSR5/22 a straightforward extrapolation from W7-X; therefore, its physics is basically the same.

Extensive studies have also been carried out in Japan.
After concept definition of the initial FFHR1 (l=3) design, optimization studies have been needed on the reactor size, based on the LHD-type (l=2, m=10) compact design FFHR2 (γ=1.15, R_c=10 m) and modified FFHR2m1 (γ=1.15 and outward shifted plasma axis, R_c=14 m) and FFHR2m2 (γ=1.20 and inward shifted plasma axis, R_c~17 m) with the ISS95 enhancement factor ~ 1.8 as shown in the following figure and the table.

In those studies from 2005, it is found that, with increasing the reactor size, the capital cost does not drastically increase, because the total magnetic energy, which provides the mass of coils supporting structure under the Virial theorem, increases only in proportion to $R^{0.4}$ due to the decrease of B_0.

From the requirement of α-heating efficiency over 0.9, the importance of the ergodic layers surrounding the last closed flux surface has been found by collision-less orbits simulation of 3.52MeV alpha particles. Therefore, to avoid the interference between the first walls and the ergodic layers at the inboard side in particular, the reactor size is increased with alternative options, and the design is improved as FFHR2m2, in which γ=1.20 is selected with inward shifted magnetic axis. In this case, it is found that there is the optimum major radius of plasma around 16 m with B_0 of about 5 T by taking into account the neutron wall loading below $2MW/m^2$, cost analyses based on the ITER (2003) design and engineering feasibility on large scaled magnets. The magnetic stored energy is reduced less than 150GJ by selecting the location of poloidal coils, then it is about three times as large as ITER but the maximum magnetic field of 13T and mechanical stress can be comparable.



Design parameters			LHD	FFHR2	FFHR2m1	FFHR2m2	SDC
Polarity	l		2	2	2	2	
Field periods	m		10	10	10	10	
Coil pitch parameter	γ		1.25	1.15	1.15	1.20	
Coil major Radius	R_c	m	3.9	10	14.0	17.3	
Coil minor radius	a_c	m	0.98	2.3	3.22	4.16	
Plasma major radius	R_p	m	3.75	10	14.0	16.0	
Plasma radius	$\langle a_p \rangle$	m	0.61	1.24	1.73	2.35	
Plasma volume	Vp	m^3	30	303	827	1744	
Blanket space	Δ	m	0.12	0.7	1.1	1.05	
Magnetic field	B_0	T	4	10	6.18	4.84	
Max. field on coils	B_{max}	T	9.2	14.8	13.3	11.9	
Coil current density	j	MA/m^2	53	25	26.6	26	
Magnetic energy		GJ	1.64	147	133		
Fusion power	P_F	GW		1	1.9	3	
Neutron wall load	Γ_n	MW/m^2		1.5	1.5	1.5	
External heating power	P_{ext}	MW		70	80	43	100
α heating efficiency	η_α			0.7	0.9	0.9	0.9
Density lim.improvement				1	1.5	1.5	7.5
H factor of ISS95				2.40	1.92	1.92	1.60
Effective ion charge	Z_{eff}			1.40	1.34	1.48	1.55
Electron density	$n_e(0)$	$10^{19} m^{-3}$		27.4	26.7	17.9	83.0
Temperature	$T_i(0)$	keV		21	15.8	18	6.33
Plasma beta	$\langle\beta\rangle$	%		1.6	3.0	4.40	3.35
Plasma conduction loss	P_L	MW			290	453	115
Diverter heat load	Γ_{div}	MW/m^2			1.6	2.3	0.6
Total capital cost		G$(2003)		4.6	5.6	7.0	
COE		mill/kWh		155	106	93	

Minimization of the external heating power to access self-ignition is advantageous to increase the reactor design flexibility. Because any fusion power rise-up time can be employed in a helical reactor, it has been recently found in a zero-dimensional simulation that a lower density limit margin reduces the external heating power, and over 300 s of the fusion power rise-up time can reduce the heating power from 100 MW to a minimized 30 MW in the FFHR2m1.

Recent discovery of the super dense core (SDC) plasma up to $1.1x10^{21}m^{-3}$ in LHD has led the new ignition scenario, in which the control of thermally unstable operation is crucial and a new and simple feedback method is proposed in FFHR2m1 using proportional-integration-derivative (PID) control of the fueling. Such high density and low temperature operation is generally advantageous to reduce the divertor heat flux due to an enhanced radiation loss rate.

For continuously wound large superconducting magnet systems under the maximum nuclear heating of 200W/m^3, cable-in conduit conductor (CICC) of 90 kA with Nb_3Al are proposed with react and wind method and quench protection candidates and with the maximum cooling path of about 500 m and a robust design of LHD-type cryogenic support posts (~16,000 ton/30 posts).

Long-life blanket concept is first proposed, using carbon armor tiles that soften the neutron energy spectrum incident on the self-cooled Flibe-RAF blanket. In this adaptation of the Spectral-shifter and Tritium breeder Blanket (STB) concept a local tritium breeding ratio TBR over 1.2 is feasible by optimized arrangement of the neutron multiplier Be in the carbon tiles, and the radiation shielding of the super-conducting magnet coils is also significantly improved. Using the constant cross sections of helically winding shape, the “screw coaster” concept is proposed to replace in-vessel components such as the STB armor tiles. The blanket designs have been improved to obtain the total TBR over 1.05 for the standard design of Flibe + Be/JLF-1 and the STB blanket with the blanket cover rate over 90%, which is effectively possible by a new proposal of Discrete Pumping with Semi-closed Shield (DPSS) concept and is very important not only to increase the total TBR over 1.2 but also to reduce the radiation effects on magnets.

In the U.S., it has been identified and developed new classes of quasi-axisymmetric configurations with attractive properties from the viewpoints of power producing reactors for ARIES-CS. Taking advantage of recent experimental results which generally showed that the stellarator plasmas are more resilient to MHD perturbations than predicted by the linear theories, rotational transform-aspect ratio space for configurations have been widely searched to be compatible with better quasi-axisymmetry, lower alpha-particle loss and better integrity of flux surfaces at high beta regime. The configurations have been fonud with rotational transform having small but positive shear even with a large amount of bootstrap current, in which low order rational surfaces can be avoided. The configurations in two field periods having very low aspect ratio also have been found, which can make reactors of higher power density and smaller sizes likely. In addition, NCSX-like configurations with better quality of flux surfaces and alpha-particles confinement have also been developed. The most attractive configurations will ultimately be determined by results of systems optimization and constraints arising from engineering designs in addition to the physics and configuration considerations.

- Achievements relating to technology developments/spin-offs, and efficiency of use of R&D resources

Large R&D progress has been made on low activation V-alloy and ferritic steel for miniature test, welding, irradiation, corrosion and coating, on long-life liquid Flibe and Li blanket based on the reactor design.

New R&Ds have been initiated for a quick-feed back 3D code system and 14 MeV irradiation mockup tests on neutronics for reactor design,

Wide R&D progress has been made on neutron irradiation effects and low activation SC materials.

Investigation of microwave sintering techniques for novel ceramics has been significantly progressed so that it has been applied to the construction of the mirror of the next-generation extra-large Telescope.

Research on non-equilibrium plasma by using LHD and the Solar-obserbing satellite “HINODE” has been advance. To examine non-equilibrium plasmas by spectroscopy, a collisional-radiative (CR) mode has been developed for Fe ions, progressing for evaluation of atomic data of Fe ions, observervation of the solar plasma by HINODE satellite, measurement of LHD plasma.

Applications of microwave technology in wide range of industry have been tried. On such example would be the steel production by utilizing the microwave heating, so that the innovatively significant reduction of the CO_2 emission will be possible.

The U.S. stellarator R&D program has the following milestone: “Issue report on engineering metrics for stellarator complexity, for use in targeting simpler designs, September, 2009.” In fiscal year 2009, the first year of the study, the goal was to make progress in documenting metrics that could be tested in design studies the following year. The report was posted at http://nsdr.pppl.gov/meetings/aug20PeerRev/Stel_MetricsRev.pdf

A novel method has been investigated to simplify the magnetic field coils, by the use of monolithic high-temperature superconductor (HTS) for field shaping in stellarators and tokamaks. The basic concept is to use a relatively simple coil set that generates a background magnetic field, and to use HTS monoliths to shield/shape the magnetic field to the desired configuration. Yttrium barium copper oxide (YBCO) has excellent properties, operating at elevated temperatures (> 10 K). High-field, cryostable, highly complex magnetic field topologies can be generated using this material. The diamagnetic properties of the bulk HTS material can be used to provide simple mechanisms for field shaping.

- Some examples of co-operative projects

Many projects have been developed by the parties of the Agreement in support of foreign fusion devices sited in other parties’ laboratories, as well as for benchmarking results and theories among devices, stellarator/heliotron classes, and also with tokamaks. This is not only an essential contribution to physics understanding and fusion progress, but also leads to a very positive specialization among the laboratories in the various fields, which improves the efficiency of the overall effort. Some examples are:

– Integrated studies of the unified data sets have confirmed earlier confinement scaling studies for stellarators/heliotrons, but also indicate validity limits with respect to reactor relevant operational regimes. They lend support to the configuration optimization schemes now being implemented in the next generation of stellarator/heliotron experiments. Accompanying 1D transport studies are focusing on topical issues such as neoclassical radial electric field formation, H-mode confinement and high-beta physics. The documentation is accompanied by systematic studies of MHD activities and edge turbulence. This community exercise benefits from regular meetings (CWGM: Coordinated Working Group Meetings) for topical discussions, work break down and coordination and common publication activities. It has been organized as the forum to facilitate the international collaboration, which was initiated based on discussions between H. Yamada (NIFS) and A. Dinklage (IPP). This activity interacts with another international collaboration on neoclassical transport to explore theoretical approaches.

– The global gyrokinetic particle-in-cell code EUTERPE has been given from IPP to CIEMAT, where it has been benchmarked with the TORB code in linear and nonlinear simulations, and is being further optimised by the Barcelona Supercomputing Centre.

– A particle-in-cell based method has been developed for calculating the growth or damping rates of fast-ion-driven instabilities in stellarators/heliotrons in collaboration between IPP and ORNL.

– In a collaboration between NIFS, IPP and PPPL, three gyrokinetic flux-tube codes (GKV, GENE and GS2) have been benchmarked extensively against each other, and a geometry interface (GIST) has been written that enables equilibrium data to be read in a consistent way. These codes are used to calculate turbulent transport in LHD, W7-X and NCSX, and details in the geometry have been varied and identified as important for regulating the transport.

- The benchmarking of numerical methods used within the stellarator/heliotron community to calculate the three mono-energetic neoclassical transport coefficients (needed to describe the radial and parallel transport along with the bootstrap current) has been continued and is nearing its conclusion. Results obtained within the International Collaboration on Neoclassical Transport Codes are now being documented and their publication is expected during 2010. As a natural extension of this work, methods which have been developed to correct the neoclassical fluxes so as to conserve parallel momentum (violated when assuming only pitch-angle scattering by the linearized collision operator) are currently undergoing benchmarking as well and it is hoped that this task will be concluded during the coming year and results published by 2011 at the latest.

- The Australian heliac programme at the ANU has produced several technological spin-offs that are now attracting support independent of the fusion programme. These include technology for long distance, non-line-of-sight VHF digital wireless communications in rural Australia (the BushLAN project), microwave imaging for early detection of breast cancer, and a coherence imaging spectroscopy system for blast furnaces which promises to provide accurate steel surface-temperature estimates without the need for emissivity corrections.

- Recent studies emphasize the importance of the statistical description of transport process in fusion plasmas as an alternative approach to the traditional way to characterize transport based on the computation of effective transport coefficients and the important role of long-range correlations. These studies, carried out close collaboration between TJ-II and ORNL scientists, have led to a reconsideration of diffusive transport, based on the Continuous Time Random Walk. In addition, TJ-II results have shown the important role of long distance correlation as a first step in the transition to improved confinement regimes and the key role of electric fields to amplify them, in consistency with a model based on zonal flows.

- During 2008 LHD experimental campaign, a TJ-II fast camera system was installed on the LHD as part of the CIEMAT/NIFS bilateral agreement; LHD high beta regime discharges have been investigated showing both radial and parallel transport dynamics.

4 FUTURE STRATEGY AND PLANS

- Advanced Stellarators

The major goal is the completion of the assembly of W7-X and the preparation of the scientific programme. With W7-X, a scientifically attractive experiment with high relevance for the development of the stellarator line will be available and will be used in the frame of the EURATOM programme and in collaboration with the international stellarator/heliotron community. For this purpose an international programme committee will be set up. Following the completion of the assembly in 2014 and a one year commissioning phase the first two years of operation will focus on the assessment of the basic optimization and design criteria. In a subsequent shut down W7-X will the full steady state capability of W7-X will be established by installing amongst others the high heat flux divertor. As recognized by the European Facilities Review in 2008, the task of W7-X is to investigate steady-state operation with relevance also to ITER and to demonstrate the reactor potential of the stellarator concept.

- Heliotron devices

The Large Helical Device (LHD) is a heliotron type device employing large-scale superconducting magnets to enable advanced study on net current free plasmas. Since the initial operation in 1998, the LHD has been producing high-performance plasmas comparable to large tokamaks and the achievements in the LHD have led to the establishment of a helical system as an alternative and complementary approach to tokamaks. The LHD project is aimed at two goals, one is to formulate a systematic scenario to an attractive helical reactor and one is a comprehensive understanding of toroidal plasmas including tokamaks. Consequently, the following five priority subjects are defined; (1) to produce plasmas with high temperature, high density and long energy confinement time, and execute a wide range of studies on transport which can be extrapolated to reactor plasmas; (2) to achieve high β plasmas with β of more than 5% and study the related physics; (3) to obtain the basic data required for steady state operation by long pulse experiment of net current free plasmas with the installation of a divertor; (4) to study the behaviour of highly energetic particles in the helical magnetic field and execute a simulation experiment of α particles in reactor plasmas; and (5) to execute studies complementary to tokamak plasmas to deepen the comprehensive understanding of toroidal plasmas.

These major elements have been demonstrated to significant extent separately. For example, a central ion temperature has reached 5.6 keV at the density of $1.6\times10^{19}m^{-3}$ compared with the ultimate goal of 10 keV at $2\times10^{19}m^{-3}$. A reactor relevant high β of 5 % has been achieved at the magnetic field of 0.425T. Although this stable high β plasma is encouraging, a high β study in more collisionless regime at a higher magnetic field is requested to fulfil the objective. A steady state one-hour long discharge with the temperature beyond 1 keV has been demonstrated by 0.5 MW of heating power compared with the final goal of the steady state operation with 3 MW. Also, unexpected findings such as an Internal Diffusion Barrier which leads to the super dense core exceeding $1\times10^{21}m^{-3}$ and Impurity Hole should be highlighted to prospect a future strategy. Efforts towards the integration of high-performance confinement achieved so far in separate regimes are essential to meet ultimate goals.

The upgrade of the LHD towards goals is launched in 2010. The upgrading plan is a package of heating capability, closed divertor and the use of deuterium gas. It should be noted that the present LHD has open divertor and working gas is limited to hydrogen and helium. The new 5th NBI with perpendicular injection and a power of 7MW will be available in 2010. The total heating power by NBI will reach 30 MW. Also the vacuum vessel will be modified in order to incorporate a baffle structure to form a closed divertor. The closed divertor has an extremely important role in particle control for steady-state operation, confinement improvement and density limit. As the first step, the closed divertor will be installed at the inboard side of 2 of 10 toroidal sections. This is a proto-type without cryo-pumps. The capability of neutral compression will be evaluated and it will be applied to the final design. Together with this closed divertor, an upgrade of the steady state heating capability of ICH as well as ECH will enable us to attempt steady state operation with 3MW for 1 hour in a couple of years. The deuterium experiment is also a very important next step to assess the isotope effect and confinement of highly energetic particle produced by a fusion reaction. In parallel with this upgrade of infrastructures, improvement of highly accurate and multi-dimensional diagnostics and development of numerical codes to simulate the high performance plasmas will be advanced.

Deep understanding and insight into the physical mechanisms attributed to a 3-D magnetic configuration will be emphasized by thorough study in the LHD. The 3-D effect is now recognized as a critical element in tokamaks as well. For example, resonant helical perturbation is seriously considered in order to suppress ELMs in ITER. The LHD provided a unique and complementary basis for fusion power development and shares its role with tokamaks.

Combined effects of three elements: a joint experiment, compilation of database and physics modelling should greatly promote the Stellarator/Heliotron Concept. The LHD is a leading platform of an international joint experiment and a good test bed for application of new tools and ideas. It should be mentioned that revision of the LHD experiment Technical Guide was made in 2009 to facilitate the participation to the LHD experiment internationally as well as domestically. Thus international collaborations are certainly needed and should be extended for the next five years.

The Heliotron-J will further extend the study of the confinement improvement through the configuration scan, mainly focusing such as on the energetic particles, density control in a higher density regime (achived by the supersonic molecular beam injection, SMBI). Flow observation/measurements by fast-camera and probes will the big topic for the international collaboration such as with TJ-II. Study on the structural formation and its impact on the confinement improvement will be conducted in a big effors, which certainly serves for increasing physics understandings.

- Torsatron devices

The U-3M installation with *l*=3 belongs to the family of heliotron/torsatron fusion devices. The peculiarity of this device is a natural helical divertor with open magnetic field lines crossing the surfaces of stainless steel casings of helical coils out of the direct view of the plasma confinement volume. Investigation of the role of divertor in screening of plasma from impurities, and physics of anomaly particle and energy losses in different confinement modes (L- and H-like modes) will be the main objectives for nearest years.

The U-2M installation with *l*=2 will be used for investigation of behavior of plasma produced and heated with RF power only. The device has a quite low helical inhomogeneites in the plasma confinement volume; the value of inhomogeneites can be varied by changing separately the currents in toroidal and helical coils. The study of plasma confinement depending on the state of wall and details of magnetic configuration will be provided.

Comparative results from both devices will allow making the conclusion on the role of helical inhomogeneity of the plasma confinement in stellarator/heliotron-type fusion devices.

In the framework of our next 5-year plans:
- new HIBP diagnostics set for stellarator U 2-M will be manufactured and installed;
- new Li^0 beam diagnostic set for U-2M will be developed and tested.

- Compact Stellarators

<u>HSX</u>

Impacts of the hquasi-helical symmetry on the confinement will further investigated in improved confibement regime. The international collaboration such as on the edge fluctuations/long-range correlations/zonal flow dynamics, biasing experiments, active participation in profile and confinement DB, wall-conditioning technique and its impact, ICRF heating, have been launched.
The HSX is also the good testbed for momentum correction techniques, being benchmarked in the international collaboration on theory side, and the relevant information will be provided for its verification/validation.

CTH

At present, CTH is only helical device testing new V3FIT reconstruction code. The issues to be explored are accuracy of reconstruction from magnetic diagnostics, what are the most effective magnetic diagnostics, incorporation of non-flux surface codes (HINT, PIES, SIESTA) as equilibrium solver, and the means of validation, inclusion of other diagnostics to provide constraints. Especially, the international collaboration for incooperation of non-flux surface code has been launched and extensively incoperated.

CNT

One near term goal of CNT is to develop the ability to create and diagnose plasmas without internal objects. This is a necessary step before operation with positrons can commence. This will provide another great contribution of stellarator/heliotrons on general physics. The non-neutral plasma confinement has been also investigated in Heliotron-J, for which the international collaboration will play a significant role

- Heliac devices

The TJ-II heliac research activities will be focussed in the investigation of physic mechanisms that interrelates electric field, magnetic configuration and transport in fusion plasmas. In addition, physics studies in different magnetic confinement concepts will continue and extend (stellarator/ /heliotron/tokamaks), looking for common clues as a fundamental way to investigate basic properties of confinement in fusion plasmas, with the following areas of activity:

- Stellarator/heliotron physics: confinement database, neoclassical transport and magnetic configuration effects. These activities are carried out within the framework of the international stellarator/heliotron implementing agreement.
- Plasma diagnostic development and engineering: Diagnostic developments for TJ-II will continue and in a wider context for JET, ITER and W7-X.
- Plasma heating (NBI, ECRH and studying the efficiency of Electron Bernstein Waves). The upgrade of the heating power capabilities including ECRH, NBI and EBW is a key element for the TJ-II high beta research programme.
- Physics of advanced confinement scenarios: transport barrier physics (L-H physics) and stability in high beta regimes.
- Theory and modelling of plasma transport, stability and equilibrium.
- Plasma – wall studies, exploring plasma-wall interaction scenarios with Li coating and divertor concepts based on flux expansion.
- Data acquisition, control and advanced data analysis techniques.

The hardware upgrades and diagnostics needed to achieve these goals will continue in the TJ-II, including :

1) **Ion temperature diagnostic** diagnostics based on atomic beam measurements and comparative studies with RFA.
2) **Electric fields diagnostics:** Construction of a second HIBP for zonal flow studies in TJ-II.

3) **Probe diagnostics:** a) Test of multi-probe arrays to characterize the radial structure of long-range correlations b) Development of electromagnetic probes to characterize the electromagnetic nature of plasma filaments.
4) **Pellet injector in TJ-II:** Work continuing at ORNL on pellet formation and propulsion systems plus microwave cavity.
5) **Soft x-ray based** Te diagnostic for high density plasmas. Prototypes construction and testing.
6) **DNBI diagnostic:** Testing of toroidal lines-of-sight and Upgrade of spectral calibration system to enable continuous in-situ instrument calibration.
7) **Doppler system:** Design and construction of a new Doppler reflectometer
8) **Infrared interferometer:** Trials of new phase-meter with TJ-II real pulses. Real time control signal ready to synchronize heating and diagnostics. Trials with expanded beam multichannel interferometer. Inverse reconstruction of spatial shape of plasma section.

In 2009, the Australian Government awarded ~US$6M for upgrade of the H-1 facility, now known as the Australian Plasma Fusion Research Facility. The funding, which is earmarked for infrastructure upgrades, will be spent over the period 2010-2013. Enhancements to the Facility will enable future growth of Australian capability in fusion science and engineering, and as a focus for collaboration within the Australian community, will support the development of world-class diagnostic systems for application to international facilities in preparation for ITER. The upgrade will include new heating and diagnostic systems with provision for vacuum and data system enhancements. Improved configurational flexibility will deliver access to magnetic configurations suitable for development of divertor plasma diagnostics for future devices.
As part of a longer term strategy that aims for an Australian involvement with ITER, some of the funding will support the development of a small linear, high power-density satellite device that utilizes the H-1 heating and power systems, which will facilitate development of diagnostics for plasma wall interactions and for characterizing advanced high temperature materials.

Future configuration studies will focus on the characterisation and effects of Alfvén-driven instabilities and turbulence that can be moderated through fine control of the H-1NF magnetic configuration. Plasma density and polarimetry interferometers, and multi-channel/imaging spectroscopic detectors will provide profile information for configuration studies and mode structure of Alfvénic instabilities. Combined with fast, gated CCD cameras, newly developed passive spatial heterodyne CI systems will be deployed for synchronous detection of velocity distribution function perturbations associated with magnetic fluctuations in the H-1 heliac.

- Classical Stellarators

After the completion of the prototype control system for W7-X on WEGA some time practical tests is foreseen. In addition, some diagnostics for W7-X will be tested on WEGA. Fundamental plasma physics research topics are the interaction of the microwaves with the plasma, the transport at the last closed flux surface and inside magnetic islands and possibly reconnection phenomena.

- Diagnostics

The preparation of new, state-of-the-art diagnostics for experiments such as W7-X will continue over the next years. Several partners from inside and outside the EU are significantly contributing and have completely taken on the development of diagnostics for W7-X and do have a strong interest in later participation in the physics program. Discussions with potentially new collaboration partners, like PPPL and Tore Supra are presently ongoing.

There are plans to deploy ANU-developed coherence imaging systems for edge physics studies in the W7-X. The recent success of Doppler imaging on the DIII-D tokamak divertor is a valuable guide in planning, and future 2D MSE snapshot imaging experiments to synchronously image magnetic perturbations associated with MHD activity such as sawteeth will further develop techniques.

- Heating

Encouraged by the achievements obtained with ECRH-systems so far and driven by new demands, mainly from MHD-stabilization physics, new developments were started to improve the flexibility of ECRH-systems. Within the frame of international collaboration, fast directional switches (FADIS) and beam combiners for high power microwave beams were investigated, which are based on optical diplexers rather than on mechanical switches. Two prototypes, a quasi-optical as well as a waveguide-based system was fabricated and tested successfully under low- and high power conditions at IPF-Stuttgart and IPP-Greifswald using the ECRH-installation for W7-X. Such diplexers allow a more efficient use of existing ECRH-systems. The beam combination capability of diplexers allows reducing the required port-space for power launching as well as number of transmission lines and in future systems. The developments will continue over the next years, aiming at the demonstration of the diplexer-features in plasma experiments.
Poland has already provided significant contributions to the assembly of W7-X. At present discussion are ongoing to extend this collaboration to other components of W7-X. In particular it is being considered to provide essential parts of the neutral beam injection system.

Ongoing developments include plasma heating by Bernstein waves in the TJ-II (using the OXB mode conversion scenario).

- Theory and data analysis

Stellarator/heliotron theory will be developed on a broad front, involving improvement in theoretical tools to handle all relevant aspects of the theory and increasingly using (gyro)kinetics where fluid models have been employed previously.

In MHD, it has long been possible to calculate equilibria both with and without nested flux surfaces, but stability calculations have only been possible when such surfaces exist throughout the plasma. An attempt will be made to find techniques to determine how the growth rate is affected by islands and ergodic regions in the magnetic configuration.

A major effort will be made to advance the field of gyrokinetic stability and turbulence calculations. As described above, this is a highly internationalised and rapidly developing field, where a large step is going to be taken in the direction of global simulations. A dual strategy is followed to achieve this goal: flux-tube codes such as GENE and GKV will be made global, first in the poloidal and later in the radial direction, and global particle-in-cell codes are developed from first principles. The latter codes are in the process of taking the step from linear stability calculations to nonlinear turbulence simulations.

It is expected that advances in the field of gyrokinetics will spill over to equilibrium calculations. Until now, these have been based entirely on the MHD equations, but the amount of reconnection that magnetic field experiences on rational flux surfaces is known to be sensitive to kinetic effects, which is a topic that will be explored as a collaboration between several groups.

Gyrokinetics is also going to affect the study of fast-ion-driven MHD modes in a decisive way. It has just become possible to simulate such modes linearly in tokamak geometry proceeding entirely from gyrokinetics. The next step is to do nonlinear and fully three-dimensional simulations, which requires electromagnetic effects to be incorporated into global gyrokinetics. An intermediate step, which being taken in a collaboration between IPP and ORNL, is the construction of "hybrid" codes, where the fast ions are treated fully kinetically but the mode structure is fixed (but with a varying amplitude) from a fluid analysis.

International collaboration on confinement database activity has been extended from global database to profile database. The database will be jointly hosted by NIFS and IPP Greifswald. A. Dinklage (IPP) and M. Yokoyama (NIFS) are in charge for physics coordination. Contributions from experimental devices and support will be provided by all involved laboratories (ANU, CIEMAT IPP, IPP-Charkov, NIFS, PPPL, U-Auburn, U-Kyoto, U-Stuttgart, U-Wisconsin). Contact persons are by E. Ascasibar (CIEMAT), J. Talmadge (Univ. Wisconsin), F. Sano (Kyoto Univ.) and H. Funaba (NIFS) and more. This activity will interact with another international collaboration on neoclassical transport to explore theoretical approaches.

The international confinement time scaling activity will be continued. In addition to the confinement time database of global confinement parameters, a database of (validated) profiles for the most important discharge scenarios and confinement modes has been established. W7-AS contributes to this international profile data activity. IPP and NIFS provide resources for data base management and maintenance.

The international collaboration on neoclassical transport and kinetic theory will be extended to the treatment of the bootstrap current, momentum correction technique, and density variations on flux surfaces (quasi-neutrality). This collaboration will have official status within the IEA framework.

In collaboration with activities at JET, at MAST and in Australia an integrated data validation concept is being prepared for W7-X. Contacts with ITER on this work are being established at present.

Further development of the ANU/PPPL stepped pressure 3D MHD equilibrium formulation will be carried out. A working version of the 3D MHD equilibrium solver will be produced in 2010. Alternative variational principles for equilibria to replace the Kruskal–Kulsrud energy minimization principle will be investigated to allow transport through imperfect magnetic surfaces and thus improve the flexibility of the stepped-pressure equilibrium code.

Building on pioneering development of Bayesian inference for current tomography in W7-AS, a compact torus/stellarator collaboration between ANU, MPIPP and the UKAEA will apply this technique (using the MINERVA code) to analysis of current tomography, radial profiles and force balance in the MAST compact torus, and radial profiles and MHD mode structure in H-1NF.

- Stellarator/Heliotron System Studies

Further work shall put more emphasis on engineering issues of a Helias reactor. The existing HSR50a conceptual magnet system needs to be more detailed in order to reveal any potential design problem. It shall be demonstrated that also the individual structural components and interfaces can be built with current technology. A similar study is needed to show that existing tokamak and/or stellarator blanket and shield concepts can be adapted to Helias reactors without excessively increasing costs and effort, and that maintenance can be performed economically within appropriate time windows. Also the other main components like cryostat (plasma vessel, outer vessel, ports, thermal insulation, and cryo-piping), bus system, current leads, coil protection, refrigeration system, etc. have to be brought to a comparable conceptual design level. Since the coils of the three- and four-periodic Helias types are of practically the same size, all these findings apply also to them so that the final decision about the periodicity can be left open without loss of time until W7-X experimental results are available.

In order to achieve all or at least a significant part of these aims an engineering team needs to be set up which ideally emerges from the W7-X technical team in order to use the wealth of the W7-X design and construction experience.

As soon as W7-X will provide first experimental results, a new assessment of the assumptions on confinement, stability and plasma exhaust for the Helias reactor concept will have to start.

Further study will be continued for the LHD-type helical reactor, FFHR, in Japan. Detailed analyses on the design window including physics and cost evaluation will be ursued. Ensuring the blanket spacing along divertor field lines is the big issue. For the new design regime based on the high-density ignition scenario, 3D numerical analyses (not the 0D) are crucial. Further exploitation of the progress of LHD experiments will assure the design study of FFHR.

The ARIES Compact Stellarator Reactor Study will continue exploration of configuration design space with respect to physics (beta, aspect ratio, number of periods, rotational transform, shear, etc.) and engineering (configuration optimization, management of space between plasma and coils, etc.), and pursue configuration for detailed physics based on 3D computational codes and engineering design and optimization

5 ITER RELEVANCE OF THE STELLARATOR/HELIOTRON CONCEPT

The Stellarator/Heliotron Concept is largely related to other magnetic fusion fields of utmost relevance such as the Tokamak concept. Whereas both lines of research differ in an important number of features they also share a great deal of technology and physics challenges, which make both fields highly complementary. The role of the Stellarator/Heliotron Concept can be revealed by recalling the definition of the Broader Approach. The basic activities and functions in a broader approach are categorized into three frameworks which are primarily ITER oriented, ITER/DEMO oriented and primarily DEMO oriented. This second category, ITER and DEMO oriented, is attributed to exploration of operational regimes and issues complementary to those addressed in ITER. Here three major subjects have been extracted; steady state operation, the advanced plasma regime that is high β, and control of power fluxes to walls. Although these are identified in the roadmap towards a tokamak DEMO reactor, it should be pointed out that these are indeed fully shared with the Stellarator/Heliotron Concept and that the Stellarator/Heliotron Concept has a significant advantage in these issues. Additionally the existence of such similarities and differences between tokamaks and stellarators make possible the testing of the fundamental underlying physics, thus becoming an important asset for basic plasma research.

It must be noted that even if the tokamak concept is more advanced than the Stellarator/Heliotron Concept in terms of proximity to the final goal of constructing a fusion reactor, the particular, stringiest characteristics of the Stellarator/Heliotron Concept (for instance the higher requirements for accuracy in magnetic field generation) have led to a higher development of the Stellarator/Heliotron line in a large number of areas which the tokamak line will benefit from.

On the other hand the Stellarator/Heliotron relevance is not limited to tokamaks and ITER but embraces the whole magnetic fusion research, including alternative confinement approaches and, in the long term, future Fusion Power Plants (i.e. DEMO and beyond).

In order to illustrate all this, a description of some areas where the Stellarator/Heliotron Concept contributes to ITER objectives is shown below:

1. SUPERCONDUCTING COILS

It should be also pointed out that the poloidal coils of LHD are the first demonstration of coils employing cable-in-conduit (CIC) conductors with a forced-flow cooling which have been used for a real plasma experiment

The latest developments in superconducting coils, such as W7-X's, have pushed forward this technology that ITER requires. W7-X is the last large superconducting device built in the EU before ITER. Although its coils are much smaller than the ITER coils and use exclusively NbTi conductors, the W7-X and ITER coils share the same basic design and manufacturing concept: the winding pack uses a cable-in-conduit conductor with internal forced flow helium cooling, the winding pack is vacuum impregnated with epoxy resin and embedded in a steel casing. The W7-X coil manufacturing contracts are, therefore, helping industry to qualify and demonstrate their readiness for ITER coil construction. The Quality Assurance, inspection and testing procedures of the W7-X and ITER coils share many common features and the knowledge acquired by industry with W7-X is directly applicable to ITER. In the area of coil instrumentation, the W7-X development and experience, including in particular quench detection, are relevant to ITER.The initial quality problems with the W7-X coils have led to considerations to change the testing scheme of the ITER coils.

2. IN-VESSEL & HIGH HEAT-FLUX COMPONENTS

In-vessel components, such as protection tiles and actively cooled first wall components have been developed for Tore-Supra and also in the framework of the ITER R&D programme. The production of these components for the stellarators/heliotrons presently under construction will add to the body of industrial manufacturing and Quality Assurance know-how in preparation for ITER construction.

The W7-X steady state high heat flux divertor, which is based on the Tore-Supra design, has advanced the performance and reliability of this plasma target design significantly.

Unlike the present large tokamaks, ITER will not have walls dominated by carbon. LHD is operated in the metal wall and partial introduction of tungsten divertor plates have been started. Assessment of interaction between plasma, and a metal wall and divertor plates in steady state operation will be a unique study among existing toroidal devices.

3. STEADY-STATE OPERATION ISSUES

Whereas the physics basis for ITER is well developed there is a need on steady-state operational experience, plasma control and diagnostics, and on long-pulse technology, specifically heating and exhaust. The long-pulse superconducting stellarators/heliotrons (LHD and W7-X) will produce knowledge in this field applicable to ITER.

The target of steady state operation of LHD is the heating power of 3 MW for 1 hour which corresponds to an input energy of 10 GJ. This is close to the operational regime of ITER in terms of handled auxiliary heating power.

In December 2009 a workshop on plasma control took place in Cadarache, where the ITER CODAC team showed strong interest in the W7-X developments of new concepts on plasma control, data acquisition and integrated data analysis.

4. OPERATING EXPERIENCE

As regards the operation experience acquired in stellarator/heliotron devices, it is not only contributing with novel science to fusion research but it is also extremely valuable for the education and training of physicists for the scientific exploitation of ITER and other future devices.

Since the initial operation of LHD, several-month-long operation has been executed 12 times. The operational time of the helium compressor has amounted to 57,000 hours with the average duty of 99.4%. The cryogenic system has a capability of 10 kW and works for 5000 hours in a year with this high duty. The experience of cryogenic operation of a fusion device has been accumulated in LHD and also operational simulator developed for LHD is applicable to operation of the superconducting system in ITER.

5. PLASMA HEATING

The series production of the W7-X gyrotrons revealed problems with the design of the so-called beam tunnel, recognizable by reduced power output and lower efficiency. The solution to the problem was also applied to the European development of the ITER co-axial gyrotron, bringing it for the first time to the specified power of 2 MW.

6. PHYSICS

Some bullet points:

3D physics

- Scrape-off layer physics (ergodic divertor)

- 3D edge transport
- ambipolar electric fields (generation of momentum and sheared flows)

- ELMs
  - ELM control with edge ergodisation (meanwhile part of the ITER design)
  - plasma edge in W7-X / LHD already (partially) ergodized
  - study of ELMs without current driven instabilities (if bootstrap current is not too strong) may contribute to the clarification of their mechanism
- Resistive wall modes
  - design and modelling of 3D wall components, based on codes originally developed for stellarators/heliotrons

High-density operation beyond Greenwald limit

- W7-AS and LHD have achieved high-density exceeding the „equivalent“ Greenwald limit
- Plasma wall interaction and divertor physics under DEMO relevant conditions

In Ukraine, a version of fusion driven system (FDS), a sub-critical fast fission assembly with the fusion plasma neutron source, theoretically investigated is based on a stellarator with a small mirror part. In the magnetic well of the mirror part, fusion reactions occur from collision of an RF heated hot ion component (tritium), with high perpendicular energy with cold background plasma ions. The hot ions are assumed to be trapped in the magnetic mirror part. The stellarator part which connects to the mirror part provides confinement for the bulk (deuterium) plasma. Calculations based on a power balance analysis indicate the possibility to achieve a net electric power output with a compact FDS device. For representative thermal power output of a power plant ($P_{th} \approx P_{fis} = 0.5 - 2\,GW$), the computed electric Q-factor is in the range $Q_{el} = 8 - 14$ that indicates high efficiency of the FDS scheme.

6 COLLABORATIONS

Coordinated Working Group Meeting (CWGM) for Stellarator/Heliotron Studies

The Coordinated Working Group Meeting (CWGM) for Stellarator/Heliotron Studies has been continuously held since its 1st meeting in Kyoto in Sep. 2006. The main long-term goals of CWGM activity were specified as to identify critical issues for helical systems, to perform thorough and critical assessment of data, and to define a data base for system/reactor studies. These goals can be achieved through obtaining the comprehensive, complementary and deductive perspectives to provide highly reliable extrapolations. The helical system research by exploiting the diversity of the three-dimensional nature of magnetic configurations provides the best opportunity to achieve this through joint comparative studies. The CWGM has offered the appropriate forum to accomplish this, and has been held typically in between the major international conferences, such as the IAEA fusion energy conference (IAEA-FEC) and the international stellarator/heliotron workshop (ISHW), to facilitate collaborative research documented in joint papers.

Helical system research has a long history of programmatic international collaborations. One of the formalisms supporting such collaborations is the IEA Implementing Agreement for Cooperation in the development of the Stellarator Concept, concluded by the Stellarator Executive Committee (SEC) on 2nd Oct., 1992.

Extensive collaborations based on the database provided from multi-devices have led to, so to say, the landmark achievement, the International Stellarator Scaling 1995 (ISS95). Such confinement database [International Stellarator/Heliotron Confinement DataBase: ISH-CDB] activity acquired the “official” auspices of the above agreement in 2002. Since new helical devices such as Heliotron J, HSX, LHD and TJ-II (alphabetic order) came into operation after the derivation of the ISS95, the 2nd phase of ISH-CDB activity was launched, to be able to explore a wider range of configuration and plasma parameter space. The effective helicity, as the configuration-dependent quantity, was introduced to produce the ISS04. The trend, of better energy confinement in the case of smaller effective helicity, is recognized through inter-machine comparison and even in the configuration-scan experiments in one device.

As the detailed profile information of plasma parameters had become routinely available, qualitative upgrade of the database activity to include profile information is possible and expected. More physics-based discussions can be anticipated with this upgrade. One particular example was selected as its prototype project, that is, plasmas having a peculiarly steep electron-temperature gradient in the core region commonly obtained in CHS, LHD, TJ-II and W7-AS (alphabetic order) with centrally-focused ECH. The significance of the electron-root in the core region was recognized through the comparative studies. Based on this clarification, those plasmas were denoted, reflecting its physics background, as Core Electron-Root Confinement (CERC). After its presentation at the 15th International Stellarator Workshop (Madrid, 2005), discussions among volunteers with interest (coordinated mainly by Prof. H.Yamada (NIFS) and Dr. A.Dinklage (IPP-Greifswald)) led to the agreement to launch the programmatic collaboration on profile database activity [International Stellarator/Heliotron Profile DataBase: ISH-PDB]. Meanwhile it was agreed to initiate the “working-basis” meetings as the supporting body of ISH-C/P DB activities and to facilitate joint collaborations. This is the origin of the CWGM.

The CWGMs have been held 6 times so far. In Table 1, some facts along with the topics discussed are summarized. Although the detailed discussion of each topic is not described here, presentation materials can be collectively obtained through the NIFS web site, http://www.nifs.ac.jp/en/index_cat04.html (DATABASE →International Stellarator/Heliotron Confinement/Profile Database [ISH-C/P DB]). The CWGM has evolved by identifying a person in charge from each device/institution on each possible topic, to support the steady progress.

Along with the progress of individual topics related to critical issues in helical systems, issues on reactor scenarios and collaborations in technology fields were also discussed in the 4th meeting, to draw concrete action plans towards system/reactor studies. In the 5th meeting held in Stuttgart University, sessions dealing with H mode and island dynamics were kicked-off.

One of the advanced capabilities of the stellarator/heliotron community, the computational tools rigorously dealing with the 3D nature of magnetic configurations, can be also extensively applied to critical issues in the tokamak community. One example would be the quantitative understanding of the impacts of induced ergodization of the edge field structure on ELM behaviour. The CWGM has provided suitable opportunities to discuss the strategic ways to outreach to the tokamak community and to make the understanding of helical systems to be a more comprehensive one of toroidal confinement.

The collection of profile data has been extended to construct the profile database (PDB). The PDB has been jointly hosted by IPP and NIFS, in a similar manner as the confinement database (CDB). The web site is http://xanthippe.ipp-hgw.mpg.de/ISS/public/index.html (IPP) and http://ishpdb.nifs.ac.jp/index.html (NIFS). The time trace of the shot, profile information and some key profiles are stored. In principle, published data are stored for the public use. Currently, the number of profile data has been gradually increased to make it more comprehensive.

Meanwhile, associated configuration (equilibrium) data are now intended to be stored, so that people who are interested in applying their computational codes to experimental profiles can do so. The registered profiles on ISH-PDB can also be utilized as a test bed, with the equilibrium information commonly used by a number of different computational codes.

The 5 tentative abstracts for possible joint papers to be presented at the major international conferences (such as EPS and IAEA-FEC) are now in circulation among CWGM collaborators, so that wide range of collaborations is promoted. The next (7th) CWGM has been agreed to be held in Greifswald from 30 Jun. to 2 Jul. 2010. The details of contents of the joint papers for the IAEA-FEC will be discussed along with the promotion of the collaborative research in each topic.

Joint papers from CWGM collaboration

[20th IAEA Fusion Energy Conference (2004)]

- H.Yamada et al., Nucl. Fusion 45 (2005) 1684.

[15th International Stellarator Workshop (2005)]

- M.Yokoyama et al., Fusion Science and Technology, 50 (2006) 327.
- A.Dinklage et al., Fusion Science and Technology, 51 (2006) 1

[21st IAEA-FEC (2006)]

- M.Yokoyama et al., Nucl. Fusion 47 (2007) 1213.
- A.Dinklage et al., Nucl. Fusion 47 (2007) 1265.

[16th International Stellarator/Heliotron Workshop/17th International Toki Conference (2007)]

- E.Ascasibar et al., J.Plasma and Fusion Research, Vol.3 Special Issue (2009) S1004.
- K.McCarthy et al., "Comparison of Impurity Transport in Different Magnetic Configurations"
- Y.Feng et al., "Comparative Divertor-Transport Study for W7-AS and LHD (EMC3/EIRENE)"
- M.Kobayashi et al., J.Plasma and Fusion Research, Vol.3 Special Issue (2009) S1005.
- A.Weller et al., "Extensions of the International Stellarator Database by High-β Data from W7-AS and LHD"
- A.Dinklage et al., "Status of the International Stellarator/Heliotron Profile Database"
- H.Funaba et al., "Data Structure for LHD Plasmas in the International Stellarator/Heliotron Profile Database"
- K.Nagasaki et al., J.Plasma and Fusion Research, Vol.3 Special Issue (2009) S1008.

[22nd IAEA-FEC (2008)]

- Y.Feng et al., Nucl. Fusion 49 (2009) 095002.
- R.Burhenn et al., Nucl. Fusion 49 (2009) 065005.
- A.Weller et al., Nucl. Fusion 49 (2009) 065016.

[17th International Stellarator/Heliotron Workshop (2009)]

- M.Hirsch et al., "Overview of LH-transition experiments in helical devices"
- T.Akiyama et al., "Status of a stellarator/heliotron H-mode database"
- H.Funaba et al., "Data Servers for the International Stellarator/Heliotron Profile Database (ISHPDB)"
- S.Sakakibara et al., "Remarks on Finite Beta Effects in International Stellarator/Heliotron Scaling"
- Y.Narushima et al., "Experimental study of effect of poloidal flow on stability of magnetic island in LHD"
- D.Pretty et al., "Results from an international MHD data mining collaboration"
- B.Nold et al., "Inter-machine edge turbulence data base"

Some records on 1st to 6th CWGM.

	Place	Date	# attendants (on record) [1]	Remarks: topics discussed *etc*. (alphabetic order unless marked)
1st	Kyoto Univ.,	19-22, Sep. 2006	41	ISS04(CDB)→PDB, possible topics on collaborations, Joint meeting with Kinetic Theory in Stellarators
2nd	IPP-Greifswald	4-6, Jun. 2007	26	edge/3D divertor, high-beta, impurity, iota/shear, momentum transport, neoclassical (NC) transport
3rd	NIFS	23-24, Oct. 2007	34	current drive (CD), edge/3D divertor, flow/momentum transport, high-beta, high performance, impurity, iota/shear, NC, technical issues of DB, transport codes
4th	CIEMAT	20-22, Oct. 2008	29	reactor, collaboration on technology, 3D effects, CD, data access, edge/3D divertor, high-beta, impurity, iota/shear, transport codes, turbulent transport codes (→ passed to discussions in expert group)
5th	Stuttgart Univ.	6-8, Jul. 2009	29	H mode & ELM, turbulence studies (experiment), usage of PDB, data access, high-beta, iota/shear, 3D effects
6th	PPPL	16, Oct. 2009	27	database, US experiments, turbulence studies, H mode & ELM, high-beta, iota/shear/island

1: On-site/video participants may not be counted

Collaborations: Australia

2005: Multilateral International Stellarator/Heliotron Database activity

2005-6: with R. Koenig, Otte (IPP-Greifswald) on coherence imaging spectrometer on WEGA (also Consorzio RFX, Alcator/MIT)

2005-6: with Takiyama (Hiroshima Univ.), and Sydney University on n_e, T_e via spectroscopy of pulsed supersonic He beam

2005: with Nagasaki (Kyoto Univ.) on Comparative study of Alfven-range fluctuations in H-1 and Heliotron-J

2005: Multilateral collaboration on control of edge localised mode (ELM) instabilities using stochastic magnetic fields

2005: with MPIPP Greifswald and University of Tokyo on quantum chaos in MHD

2005-2009: with S. Hudson (PPPL) – Theory and development of improved MHD codes, initially using a stepped pressure profile code

2006: with M. Yokoyama (NIFS) – numerical study of GAM, bumpiness in H-1

2006-2007: with E. Solano (CIEMAT) - singularity theory applied to toroidal equilibria

2006-2009: with MP IPP Greifswald, comparison of MHD Modes in H-1 with CAS-3D predictions

2006-2009: with K. Nagasaki, (Kyoto Univ.), S. Yamamoto (Kyoto Univ, Univ. Osaka), Application of Datamining techniques to Heliotron J

2007-2009: with JAEA on imaging birefringent interferometers for Thomson scattering

2007-2008: with ORNL on Magnetic configuration modelling and island studies

2008-2009: Extension of the coherence imaging collaboration to include DIIID and Textor, and imaging of divertor flows and internal magnetic fields

2008-2009: with S. Yamamoto, K. Nagasaki (Kyoto Univ.), E. Ascasibar, R. Jimenez-Gomez (CIEMAT), S. Sakakibara (NIFS): International collaboration on datamining of MHD data

2008: with K. Nagasaki on Collaboration on ECH heating

2008: Prof. Dewar, 3 month sabbatical at Univ. Tokyo, on entropy production principles, adiabatic wave-particle interaction

2009: with MPP-Greifswald, UKAEA Bayesian inference of profile and mode structure data

2009: A/Prof. Blackwell, 3 month sabbatical at Kyoto Univ., on the application of datamining including a comparative study of MHD activity in Heliotron-J and H-1NF

Collaborations in 2005-2010 in EU

W7-X; WEGA; experiment

- Australian National University (Canberra/Australia)
  A new kind of spectrometer was adapted for plasma properties typical for WEGA plasmas.

- CIEMAT (Madrid / Spain)
  Loan of a 28GHz microwave heating source at WEGA and joint use
  Development and construction of a multichannel CO2-Interferometer for W7-X
  Scientific exploitation of a neutral particle analyser ACORD 24-2 at TJ-II
  Heating and current drive with electron Bernstein waves (EBW). Exchange of equipment and experiments at WEGA and TJ-II
  International Stellarator/Heliotron Profile Database

- FZJ
  Development, providing and test of VUV-spectrometers for W7-X

- INP Krakow
  MCNP calculations for W7-X

- IPF Stuttgart
  International Stellarator/Heliotron Profile Database

- IPJ Swierk
  Construction of NBI at W7-X: Mechanical Components for NBI at W7-X

- IPPLM Warsaw
  MCNP calculations for W7-X
  Development of neutron activation diagnostics for W7-X
  Spectrometry of soft X-ray emission from the W7-X (pulse height analysis – PHA, and multi-foil spectrometry - MFS

- IPP Prague
  Heating and current drive with electron Bernstein waves (EBW) at WEGA. Comparison of experiment and modelling.

- KFKI-Research Institute for Particle and Nuclear Physics (KFKI-RMKI)
  Development and construction of Soft- and Hardware for a fast video survey camera diagnostic for W7-X

- Maritime University Szczecin (MUS)

- Szczecin University of Technology (SUT)
  Analysis of Microwave Propagation in the Frame of the Quasi Optical Approximation aiming at Plasma Diagnostics

- PTB Braunschweig
  Fluence measurements of neutrons at W7-X for neutron energies in the MeV range

- RFX Padova
  Neutral Particle Diagnostics

- UKAEA
  Charge Exchange Experiments

- University of Opole
  C-, O- Monitor System for W7-X

Collaborations in 2009 with Australia

- Australian National University
  International Stellarator/Heliotron Profile Database

Collaborations in 2009 with Japan

- Kyoto University, NIFS
  International Stellarator/Heliotron Profile Database (IEA) and Coordinated Working Group Meeting
  Magnetic Field Line Visualization

Collaborations in 2009 with Russia

- IOFFE Institute
  Neutral particle analysis

Collaborations in 2009 with Ukraine

- INR Kiev (STCU)
  Theory and modelling of Alfvén instabilities and energetic ion effects in Wendelstein Stellarators

Collaborations in 2009 with USA

- Princeton Plasma Physics Laboratory
- University of Wisconsin
- Oak Ridge National Laboratory
  International Stellarator/Heliotron Profile Database

Diagnostics for W7-X

Collaborations have been established with

- Forschungszentrum Jülich (FZJ)

- PTB-Braunschweig
- Budker-Institute of Plasma Physics (BINP), Novosibirsk, Russia
- IOFFE-Insitute St. Petersburg, Russia
- EURATOM HAS, Budapest, Hungary
- IPPLM, Warshaw, Poland
- University of Opole, Poland
- Akademia Morska, Szczecin
- Szczecin University of Technology, Szczecin
- IST/CFN, Lisbon
- Culham Science Centre (UKEA), Culham, U.K.
- CIEMAT, Fusion National Laboratory, Madrid, Spain

Stellarator Theory

The Stellarator Theory Division at IPP Greifswald has collaborated, and still does, with the following institutions. These collaborations typically involve several exchanges of scientific personnel each year.

- ANU, Australia:
- CIEMAT, Spain
- Columbia University, USA
- CRPP, Switzerland
- General Atomics, USA
- TU Graz, Austria
- INFN, Milan, Italy
- Kyoto University, Japan
- NIFS, Japan
- Kurchatov Institute, Russia
- MIT, USA
- ORNL, USA
- PPPL, USA
- UKAEA, UK
- University of Wisconsin, USA
- Warwick University, UK

<u>In the field of neoclassical transport and kinetic theory with:</u>

- KIPT, Kharkov, Ukraine
- TU-Graz, Austria
- PPPL, USA
- ORNL, USA
- CIEMAT, Spain
- Kyoto University, Japan

Database Activities

In the field of tau_E scaling ISS04 (within IEA framework) with:

- NIFS, Japan
- Kyoto University, Japan
- ANU, Australia
- Stuttgart University, Germany
- CIEMAT, Spain
- University of Wisconsin, USA
- PPPL, USA
- U-Auburn, USA

– KIPT, Charkov, Ukraine

Collaborations in 2005-2010 of the experimental divisions of the IPP NSC KIPT.

- Development and manufacturing of HIBP diagnostic for WEGA was started in 2004 (L.I.Krupnik and HIBP team in collaboration with Wega team, IPP, Greifswald, Germany).

Collaborations of Japan in 2005-2009

Australia

- Australian National University
- Sydney University
- Flinders University

Germany

- Max-Planck Institut fur Plasmaphysik
- Forschungszentrum Juelich GmbH
- Forschungszentrum Karlsruhe GmbH
- EFDA-Garching
- Consorzio RFX, EURATOM ENEA Association
- Stuttgart University

Spain

- CIEMAT
  Scientific Agreement was concluded and newly established between NIFS and CIEMAT in Feb. 2009
- Carlos III University

Other European countries

- Meryland University (Burgalia)
- Charmers Institute of Technology (Sweden)
- FOM (Fundamenteel Onderzoek der Materie) (Holland)
- CEA-Cadarache (France)
- CEA-Sacley (France)
- Dipartimento di energetica, Pol (Italy)
- Culham Science Center (UK)
- CRPP (Switzerland)
- Laboratorie d'Optique Applique (France)
- Institut Elie Carten de Nancy (France)
- CETP-UVSQ-IPSC (France)
- Kocaeli University (Greece)
- Innsbruck University (Austria)
- Utrecht Univeristy (Holland)
- Technische Universitat Graz (Austria)
- Ecole Normal-Superior Uiversity (France)
- University of Provence (France)
- Helsinki Institute of Technology (Finland)
- Queens University (UK)
- Warwick Univeristy (UK)
- Royal Institute of Technology (Sweden)
- Dublin University (Ireland)
- University of Strathclyde (UK)
- Plasma Physics Center (Italy)

- Beograd University (Serbia)
- Gent University (Bergium)
- ITER organization (France)

Russia
- Kurchatov institute
- General Physics Institutre
- St. Petersburg University
- Budkar nuclear physics institute
- VNIKP Cable Institute
- VNIIFTRI data center
- Moscow State University
- Lebedev Physics Institute
- Tomsk Institute of Technology

Ukraine
- Kharikov Institute of Physics and Technology
- NSC

USA
- Princeton Plasma Physics Laboratory
- University of Wisconsin
- Oak Ridge National Laboratory
- Univeristy of California
- Massachusetts Institute of Technology
- General Atomics
- University of Texas
- Los Alamos National Laboratory
- Lawrence Livermore National Laboratory
- Laerence Berkley National Laboratory
- Science Applications International
- Univeristy of Nevada
- Delta Search Laboratory
- DoE
- Auburn University
- NASA
- Harvard Univerity
- Pacific-Northwest Laboratory
- Idaho National Laboratory
- Argonne National Laboratory
- New York University
- University of Montanna
- Columbia University

Collaborations of Spain in 2005-2009

- IOFAN team (Russia)
  ECRH system in TJ-II.
  Bernstein Waves heating project, theoretical calculations and design of the system.
  Development of TJ-II diagnostics (2 mm scattering)

- IOFFE (Russia)
  Development and operation of new neutral particle analyzer in TJ-II.

- Kurchatov Institute (Russia)
  Characterization of radial electric fields in the TJ-II.
  Development of plasma diagnostics (HIBP)

- IPP-Germany:
  Transport in stellarator devices
  Plasma Diagnostics (reflectometry)
  Bernstein wave heating experiments.

- IPF – Stuttgart (Germany):
  ECRH system

- IST – Lisbon (Portugal):
  Plasma diagnostics: Reflectometry and HIBP
  Edge physics

- ORNL (USA):
  NBI heating
  Electron Bernstein Waves heating.
  Pellet injection in TJ-II
  Alfvén instabilities and NBI heating in TJ-II
  Statistical description of turbulent transport in fusion plasmas.

- PPPL (USA):
  Code development
  Edge physics: 2-D visualization of transport in the TJ-II

- ANU (Australia):
  Data mining techniques

- University of Wisconsin (USA)
  Stellarator physics
  Impurity transport
  Plasma-wall studies (Li coating)

- Kharkov Institute of Physics and Technology (Ukraine)
  Development of HIBP diagnostic and characterization of radial electric fields in stellarators/heliotrons.

- NIFS - JAPAN
  Stellarator/heliotron operation and physics of transport barrier formation.
  Development of ray tracing calculation code.
  Edge physics
  Fast particle physics

- International collaborations: Stellarator Implementing agreement
  Participation in the on-going activities of the International stellarator confinement and profile data: Coordinated Working Group Meetings

International collaborations of the plasma theory division of IPP NSC KIPT in 2005-2009

Collaboration with Technische universität Graz, Austria

- Optimization of stored energy for URAGAN-2M was carried out in the 1/ν regime with applying the fast field line tracing NEO code. The data base for the coils of the U-2M magnetic system, which was used earlier for computations of magnetic surfaces taking into account the influence of current-feeds and detachable joints of the helical winding, is transformed to a new form which is suitable for the already existing Biot-Sawart code for computations of the magnetic field strength and its spatial derivatives and study of the 1/ν neoclassical transport for U-2M with taking into account the influence of the current-feeds and detachable joints of the helical winding has been performed in collaboration with Kursk State Technical University, Russia. The magnetic surface function gradient and associated quantities were calculated for stellarators with broken stellarator symmetry.

- Study of the velocity of the poloidal motion of trapped particle orbits was performed for stellarators in real-space coordinates.
- New target functions which are related to collision-less α–particle confinement are introduced. They are based on specific averages of the bounce averaged ∇B drift velocity of trapped particles across magnetic surfaces. Using this target functions which allow to save computer resources, a number of optimized stellarator configurations has been analyzed with respect to trapped particle confinement.
- A numerical method for fast evaluation with the help of integration along the magnetic field lines of the bootstrap current and current drive efficiency in stellarators with arbitrary collisionality has been developed. As well as the coefficients of diffusion and heat conductivity in the long-mean-free-pass regimes for the Uragan-2M torsatron have been computed. Kinetic equation solver NEO-2 with solves the drift kinetic equation in arbitrary collisionality regime and general toroidal geometry has been applied for the computations of generalized Spitzer function in a tokamak with intermediate collisionality regime. New features of this function have been revealed which are of special importance for ECCD in stellarators. This work has been performed in cooperation with Max-Planck-Institute of Plasma Physics at Greifswald. Germany.
- The electron cyclotron heating in a stellarator has been modeled using the Monte Carlo method and taking into account the nonlinear wave-particle interaction effects and non-Maxwellian distribution function of electrons. These effects are shown to cause broadening of radial power deposition profiles at low plasma densities in the heating scenario using the second harmonic resonance for the extraordinary wave.
- The delta-f Monte Carlo method for the computation of bootstrap current with improved convergence in the low collisionality regime has been developed.
- The effective ripple was calculated for a stellarator magnetic field computed by the HINT2 code. For the magnetic configuration CNT (Columbia University, USA) the diffusion coefficients in 1/ν regime were calculated.
- Fully relativistic code SYNCH for computations of the generalized Spitzer function in the long mean free path regime has been extended for general toroidal geometry with permits its use for stellarators. For calculations of the electron cyclotron current drive in tokamaks and stellarators, SYNCH has been coupled with ray tracing code TRAVIS. This work has been performed in cooperation with Max-Planck-Institute of Plasma Physics at Greifswald. Germany.

Collaboration with PPPL, USA

- E-beam mapping simulation program on the NCSX stellarator (Princeton Plasma Physics Laboratory, USA).was studied.

Collaboration with CIEMAT

- The influence of weakly relativistic effects on the Electron Bernstein Wave heating of plasma confined in the TJ-II near the fundamental electron cyclotron harmonic using TRUBA beam/ray tracing code has been studied and the TRUBA beam/ray tracing code for the exact fully relativistic calculations was developed in collaboration with General Physics Institute, Moscow, Russia.
- The influence of relativistic effects on the Electron Cyclotron plasma heating in conditions of stellarator has been analyzed in collaboration with of Plasmaphysics, Stuttgart University,

Germany

- An overview of the main Electron Bernstein Wave plasma heating theoretical results obtained for conditions of the TJ-II was presented at 15th Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonanse Heating, March 2008, California, USA
- The general method to evaluate the fully relativistic plasma dispersion functions on the base the theory of Cauchy-type integrals, related to the Reactor plasma conditions and the method of fast calculations of the weakly relativistic and fully relativistic plasma dispersion functions on the base of Jacobi continued fractions were presented.

Collaboration with NIFS, Japan

- Neoclassical transport for LHD in the 1/ν regime was analyzed by the NEO code (mainly for inward shifted configurations) in collaboration with Institut für Theoretische Physik, Technische universität Graz, Austria. The results are benchmarked with the corresponding results obtained recently with the GIOTA code as well as with Monte-Carlo calculations from the DCOM code.
- New methods of selective cold alpha-particles removal from the fusion helical plasma have been developed:

  1. Use of Drift Resonances of Removed Particle. The moving drift island of the helium ash (W=35 keV) can be arranged in LHD by the change of poloidal field coil currents. The main ion orbits are not deteriorated.

  2. Small magnetic island structure at the plasma periphery leads to the resonance structure of particle orbits. The penetration of the W=350 keV alpha-particles through the magnetic islands takes place in the Force Free Helical Reactor.

Collaboration with Uppsala University, Sweden

- The study of fundamental properties of the charged particle motion in stationary magnetic and electric fields is carried out. The study relates both for open-ended and toroidal magnetic traps.
- The version of fusion driven system (FDS), a sub-critical fast fission assembly with the fusion plasma neutron source based on a stellarator with a small mirror part, was theoretically investigated. The combination of a stellarator and mirror is beneficial to localize the fusion neutron flux to the mirror part of the device which is surrounded by a fission mantle. In the magnetic well of the mirror part, fusion reactions occur from collision of an RF heated hot ion component (tritium), with high perpendicular energy, with cold background plasma ions. The hot ions are assumed to be trapped in the magnetic mirror part. The stellarator part which connects to the mirror part provides confinement for the bulk (deuterium) plasma. Calculations based on a power balance analysis indicate the possibility to achieve a net electric power output with a compact FDS device.

International collaborations of the plasma experimental divisions o f IPP NSC KIPT in 2005-2009

Collaboratin with IPP (Greifswald, Germany)

- Installation of HIBP diagnostic on WEGA

  The work on development and manufacturing of the system of HIBP diagnostic for WEGA was started in 2004 **(L.I.Krupnik** and HIBP team in collaboration **with Wega team**, IPP, Greifswald, Germany).

  During last five years a noticeable improvement of the HIBP facility and measurement procedure on WEGA was provided and the following results were obtained:

  - Verification of the calculated trajectories of the probing beams was done by special detector of the primary beam. Good agreement between calculated and experimental data was found.

  - In the experiments, helium plasma was heated non-resonantly with microwaves at 28 GHz, and both plasma potential and plasma density were measured. The results obtained with HIBP are consistent with Langmuir probe potential measurements.

Collaborations in with Spain (TJ-II experiment):

- **L.Krupnik** and HIBP team was collaborated with C.Hidalgo **and TJ-II team** (CIEMAT, Madrid, Spain) and A.Melnikov and HIBP team (RNC "Kurchatov Institute", Moscow, Russia).
  - The measurements of the radial plasma potential and electron density as well as their fluctuations by HIBP diagnostic and study of their influence on the plasma confinement in TJ-II with ECR, NBI and Bernstein wave heating were continued in the frame of the collaboration with KIPT Kharkov and RNC "Kurchatov institute"
  - The direct measurements of an electric potential and its fluctuations in core plasma are of a primary importance for the understanding of the mechanisms of the confinement improvement in toroidal plasmas and the role of the electric field in plasma confinement.
  - Low density ($n = 0.3\text{-}0.5\times10^{19}$ m^{-3}) ECRH plasma in TJ-II is characterized by positive plasma potential ($\varphi(0)$ = 600 - 400 V). At higher densities a small part of plasma volume near the edge of plasma confinment volume becomes to have a negative electric potential. This area increases with the density, finally makes potential fully negative. The NBI plasmas are characterized by negative electric potential in the whole plasma column from the center to the edge, ($\varphi(0) = 300 \div 600$ V). These results show the clear link between plasma potential, temperature, density and particle confinement.
  - Density rise (particle confinement, energy confinement) is associated with the rise of the negative E_r suppression of the turbulence. These observation lies inside the paradigm of the turbulence suppression by E_r as a mechanism of confinement improvement.
  - Recent experiments with Li-coating of walls and NBI heating have shown evidence of spontaneous L-H transition in the TJ-II occurring at a threshold value of the plasma density. NBI plasmas in L mode are characterized by negative electric potential in the whole plasma column from the center to the edge. The absolute value of the central potential is negative of < -1000 V, These observations are independent on the magnetic configuration. At the back H-L transition the plasma potential recovers to its L value.
  - HIBP becomes a new tool to study Alfven Eigen modes with the high spatial and frequency resolution. HIBP in the TJ-II observed the locally (~1 cm) resolved AE at radii $-0.8 < \rho < 0.9$. The set of low **m** (**m**<8) branches, detected with the high frequency resolution (<5 kHz) is supposed to be Toroidicity Induced Alfvén Eigen modes (TAE). TAE are pronounced in the local density, electric potential and poloidal magnetic field oscillations, detected simultaneously by HIBP in the frequency range 50 kHz<ω_{AE}<300 kHz. AE are visible in the NBI-heated plasma. The high coherency between Mirnov coil and HIBP data was found for specific branches of AE.

Collaborations with Russia (Kurchatov Institute)

- **L.Krupnik** and HIBP group are collaborated with **RNC "Kurchatov Institute**", Moscow, Russia
  - Comparative study of the plasma electric fields behavior in the T-10 tokamak and TJ-II during ECR heating.
  - The evolution of the electric potential in a wide range of regimes of ECR heated plasma using upgraded HIBP diagnostics on T-10 and TJ-II was investigated. On both devices the potential in SOL plasma was measured by multipin Langmuir probes. Comparison of the plasma potential behavior in both devices demonstrated the clear link between the core plasma potential and ECRH power: The stronger power leads to the higher (more positive) absolute potential.

- In tokamak the electric potential follows the electron temperature similarly to its behaviour in stellarator. Potentials in the plasma core and edge depend on plasma density. The negative plasma potential was observed when n_e exceeded some threshold value.
- It is possible to modify global confinement and plasma parameters with biasing, illustrating the direct impact of the radial electric fields on stellarator and tokamak confinement properties.

Collaborations with Russia (Ioffe Institute)

- **L.Krupnik** and HIBP group are collaborated **with Ioffe Institute of Physics and Technology, St. Petersburg, Russia**
  - Spatial structure and temporal dynamics of the radial electric field in TUMAN-3M was studied in different modes of plasma heating and confinement, namely, in the ohmic L- and H-modes and NBI, with and without low frequency MHD oscillations. Central plasma potential was measured by HIBP, which gives a rare possibility of direct measurement of hot dense plasma potential. Due to the geometrical limitations, only a region of $0<r<16$ cm (i.e. $0<r/a<0.73$) is typically covered by the HIBP. Peripheral radial electric field was measured using Langmuir probes.
  - Strong positive perturbation of the core plasma potential was registered by the HIBP during the burst of peripheral MHDs with low *m*, *n*. If such a burst takes place in the H-mode (both ohmic and counter-NBI heated), the positive potential perturbation leads to H-mode termination. The most probable mechanism of the positive field building-up during MHD burst is thought to be connected with a loss of fast electrons along partly disturbed magnetic field lines near the island's separatrix.
  - In a scenario with Counter-NBI it was found using HIBP that, due to the NBI effect (most probably, orbit loss with some heating and momentum impact), core plasma potential plasma gradually became more negative (by ~200V).
  - The GAM with $\delta\phi/\phi\sim0.3$ and $\delta\phi/\phi>>\delta n/n\sim0.05$, were observed with HIBP in a core region of the TUMAN-3M, $r/a\sim0.33$, during the current ramp up phase. Further studies are planned to reveal a possible connection between the GAM properties (localization, plasma condition dependence) and plasma confinement in the TUMAN-3M.

Collaborations with Japan (NIFS)

- V.Voitsenya collaborated with S.Masuzaki and A.Sagara (NIFS) in grounding a suggestion to use the plasma of H_2+N_2 mixture for wall conditioning instead of usually used H_2+He mixture.

Collaborations with Japan (Institute of Advanced Energy, Kyoto University)

- The investigation of influence of plasma rotation on the shift of diverted plasma flux position (in like of magnetic island divertor magnetic configuration) during the biasing experiment in Heliotron J is started in collaboration with Tohoku University (Dr. I.M. Pankratov, Prof. T. Mizuuchi, Prof. S. Kitajima). The more detail experiments are planed. These investigations are important for LHD (local island divertor regime) and W-7X (magnetic island divertor).

Kharkov V.N. Karazin National University (KhNU)

- Regular Project of Science and Technology Center in Ukraine (STCU) # 2313 “The Impurity transport and electromagnetic waves in the plasma periphery of a HELIAS reactor configuration and WENDELSTEIN 7-X” has been successfully accomplished in 2005 in collaboration with Prof. Dr. F. Wagner, Dr. H. Wobig, Dr. R. Schneider, Dr. Yu. Igitkhanov and Dr. C. Beidler from MPIPP. 12 papers were published as a result of its accomplishment, including 4 - in co-authorship with foreign collaborators. 18 reports were made on the Conferences, including 7 - in co-authorship with foreign collaborators.
- Regular STCU Project # 3685 “Impurity transport in 3D magnetic field for the stellarator

W7-X and tokamaks" has been successfully finished in 2009 in collaboration with Prof. Dr. F. Wagner, Dr. Th. Klinger, Dr. R. Schneider, Dr. J.-M. Noterdaeme and Dr. C. Beidler from MPIPP. 22 papers were published as a result of its accomplishment, including 8 - in co-authorship with foreign collaborators. 25 reports were made on the Conferences, including 7 - in co-authorship with foreign collaborators.

- The first PhD thesis "Stochasticity of impurity ion trajectories and particles' flows in high temperature plasma of stellarators" was defended in the framework of Sandwich promotion by O. Shyshkin (KhNU) on December, 2005 (supervisor from MPIPP side was Dr. R. Schneider).
- **T**he second PhD thesis "Experimental study of tungsten sputtering by simultaneous carbon and deuterium bombardment at Dual-Beam Experiment facility" was defended in the framework of Sandwich promotion by I. Bizyukov (KhNU) in 2007 (supervisor from MPIPP side was Dr. K. Krieger).
- The third PhD thesis "Testing the ICRF antenna of new geometry" was prepared in the framework of Sandwich promotion by A. Onyshchenko (KhNU) in collaboration with Dr. J.-M. Noterdaeme (supervisor), Dr. Vl. Bobkov, W.Becker (MPIPP).
- For simulating the processes of plasma-wall interaction in stellarators at MPIPP, high-current stationary ion source of Hall type with ballistic and reversible magnetic focusing was developed at KhNU. The coefficient of beam compression in the respect of current reaches 40 if diameter of the beam in the plane of the crossover is of 1 mm. If the current of the ion beam is equal to 200 *mA* and average energy of ions is 2 *KeV* then it corresponds to power density of nearly *20 Mw/m2* that is close to parameters of ion flows on a wall in modern stellarators.
- Several KhNU graduates defended their PhD thesis at MPIPP.
- Dynamics of D+D fusion products in LHD geometry was studied by Prof. Dr. A. Shishkin, A. Eremin, A. Moskvitin and Yu. Moskvitina (KhNU) in collaboration with Prof. Dr. O. Motojima and Prof. Dr. S. Sudo (NIFS)). The conditions when 42He ions can escape from the confinement volume due to the drift of the drift island, while 21D and 31T ions are confined are found by Prof. Dr. A. Shishkin, O. Antufyev (KhNU), and Prof. Dr. O. Motojima, Prof. Dr. A. Sagara (NIFS).
- A new concept for the selective removal of cold alpha-particles is developed by Alexander A.Shishkin (KIPhT and KhNU) in collaboration with Akio Sagara, Osamu Motojima, Osamu Mitarai, Tomohiro Morisaki, and Nobuyoshi Ohyabu (NIFS), which is specific to the helical devices (heliotron/ torsatron system). It includes escape of trapped cold alpha-particles due to enhanced drift in the helical magnetic field under finite β and resonant removal of passing cold alpha-particles trough the island structure created by drift resonance. For both mechanisms, control of the perturbation field coil current is the key issue. There is proposed to include the *perturbation* poloidal field coils in the design of the Force Free Helical Reactor 2m1 /FFHR 2m1/. There is developed the new scenario of the plasma heating in Force Free Helical Reactor 2m1 /FFHR 2m1/ to minimize the external heating power and prolong the fusion power rise-up time over 300 seconds.
- Evolution in time of the plasma density, temperature and thermal alpha-particle density is considered under modeling of the helium ash removal. It was shown that slow changing in time of the helium ash density can be used for the operation path changing in fusion plasma. There is considered also the effect of different scenarios of fueling rates on the plasma operation path and steady state parameters. The temporal evolutions of the operating point during the ignition access and ignited operation phases were analyzed analytically and numerically. The main target of the study is the optimization of the plasma operation scenario in LHD. Here the effect of the removal of the helium ash on the achieving of the steady state and plasma parameters in steady state is considered. The removal of helium ash was modeled with taking into account the rule of the helium ash confinement time changing during plasma discharge. It was supposed that τ_E is not constant but is a harmonic function of the time. With this it was obtained that operation paths with and without helium ash removal reach ignition region in different ways. While the operating point approaches the final point slowly with the increase of the plasma density from the higher temperature side after

switching off the heating power, the ignition boundary also shifts up with the increase in the helium ash density. The effect of the removal of helium ash on the plasma parameters is demonstrated. Some reduction of the bremsstrahlung losses was seen and in the steady state the plasma parameters are more stable in time under the removal of the helium ash. The fusion power does not change in time so rapidly. The effect of the change of the fuel source S_{DT} in time on the plasma parameters in the steady state was found. In the case of the smaller fuel rate, the steady state is established on the level of the lower value of the helium ash (approximately 12% instead of 15%). The fusion power is smaller too, namely $P_{fusion} \approx 1$GW in the case of the smaller fuel rate in comparison with the $P_{fusion} \approx 1.5$GW in the other fueling case. It is expected that plasma operation paths on the background of POPCON can distinguish noticeably under the different scenarios of fueling. The plasma operation path leads to lower value of temperature and plasma density for the desired value of the output fusion power P_{fusion}. It means that we can operate at lower densities, so can use simpler fuel and power injection system, magnetic confinement system, and have easier plasma operation. Some work was devoted to finding optimal operation windows for plasma burning. It allows using simpler and faster methods of diagnostic and feedback control.

- As a part of collaborative research between the University and Los Alamos National Laboratory, USA (Dr. K. Sickafus) and Colorado School of Mines (CSM), USA (Dr. I. Reimanis) the STCU Project #2058 "Development and investigation of magnesium aluminate spinel crystals for devices of energy transformation" was successfully finished in 2005. The origin of high resistance of magnesium aluminate spinel to irradiation inducing the radiation-induced defect formation was explained by the existence of spatially correlated anti-site defects in this type of material, which influence on the efficiency of formation of stable radiation induced defects. Results of collaborative investigations were published in 4 papers in international journals and presented at two International Conferences.
- The investigation of mechanisms of optical emission and optical absorption of complex oxides prospective for devices of plasma diagnostics subjected to ionizing irradiation. Research was carried out by KhNU group (V. Gritsyna, V. Bobkov, Yu. Kazarinov, A. Moskvitin) in collaboration with the group from CSM (I. Reimanis). There were provided investigations of processes of optical emission from complex oxides under ion bombardment. As complex oxides there were chosen magnesium aluminate spinel crystals and ceramics which is highly radiation resistant material. Photon emission was stimulated by bombardment with mass-separated Ar^+-ion beam at an energy of 20 keV and density current of 10 $\mu A/cm^2$. The lay-out of equipment allowed to measure emission of photons from sputtered exited atoms and ions. The yield of particles in different exited states was defined as the flux of excited particles divided by the flux of incident ions. There were observed in excited states Mg and Al atoms, Mg^+, Al^+ and Al^{2+} ions spontaneous decay of which leads to optical emission. No emission from oxygen atoms or ions was registered. The dependences of yield of all particles in different excited states on the composition of spinel crystals quantitatively do not reflect the variation of the calculated bulk concentration of constituent ions in the targets. In general, there were found two types of particles excited in definite states, the yield of which depends on the dose of ion bombardment and composition of targets and these could be used as *in-situ* indicators for modification of surface properties of complex oxides during ion bombardment.
- There were investigated the radiation induced optical centers in magnesium aluminate spinel ceramics doped with LiF at different types of irradiation: (1) UV-light, which provides only charge exchange between nearest neighbour defects or defects and impurities; (2) X-rays, which provides also generation of free charge carriers in conduction band of this insulator and subsequent capture them by different defects or impurities; and (3) gamma-rays (maximal energy $E\gamma \sim 7$ MeV) which ensure also formation of new lattice defects. The differential absorption bands demonstrate that gamma-rays generate some additional lattice defects, which could be activated into optical centers by subsequent irradiation with UV-light or X-rays. Because UV-irradiation causes charge transfer between near neighbour defects the appearance of low intensity bands at 3.8 eV and 4.2 eV indicate the formation of additional concentration of closely located anti-site defects in spinel lattice. Much more anti-

site defects become apparent at X-irradiation, which were formed at spatially separated defects capturing free charge carriers generated by X-rays. These centers give contribution to optical absorption in the spectral range of 2.2÷4.2 eV. These data can be used for choice of optimal materials of specific transparency and photon emission to avoid the interference of emission radiation induced from materials and signal from plasma.

- Research into interaction of ions of carbon and deuterium with a surface of tungsten was carried out by Dr. I. Bizyukov (KhNU) in collaboration with Dr. K. Krieger and Dr. J. Roth (MPIPP) and the group of studying the materials of fusion reactor of Institute of Space Research of University of Toronto, headed by Professor Haas. Application of carbon (C) and tungsten (W) as divertor materials in fusion devices results in exposure of W surface to the particle flux containing fuel and C ions. Physical sputtering is considered as a basic phenomenon responsible for erosion of W surface, but chemical sputtering of C from mixed W-C surface may be a factor increasing the erosion rate. Experimental identification of this phenomenon has been carried out using dual beam accelerator setup. W surface was simultaneously bombarded by 6 keV C ions and D ions with energy in the range of 0.1÷0.4 keV/D. The chemical sputtering was detected initially as release of CD_4 (mass 20) molecules from the surface under ion bombardment. Experimental results show that chemical sputtering of C peaks at RT and decreases below the measurement error at surface temperature of 400 Celsius. The absolute values of chemical sputter yield are estimated by comparison to similar QMS measurements of leak-bottle containing D.
- In the framework of particle transport problem study for the toroidal plasma configurations related to Stellarator devices the Test Particle Transport Code (TransPar), created by Dr. Oleg A. Shyshkin (KhNU) in collaboration with Dr. R. Schneider and Dr. C. Beidler (MPIPP), was extended to trace particles in the real geometry in cylindrical and toroidal coordinates. This research was carried out in collaboration with colleagues from Universite Libre de Bruxelles (ULB), Brussels, Belgium, in particular, with Prof. Dr. Boris Weyssow. This code simulates the particle transport in terms of test particle fraction transport. In was used to analyse tungsten transport for the HELIAS reactor with five periods of the magnetic field. In order to upgrade the transport model reproduced by TransPar Code, a comprehensive picture of particle motion in plasmas is under study. The model is extended by including the Monte Carlo equivalent of collision operator extended for the non Maxwellian plasmas often observed in fusion devices due to magnetic resonant structures, particle injection or plasma heating.

7 INFORMATION DISSEMINATION ACTIONS

International Stellarator/Heliotron Workshops

The largest scientific meetings devoted specifically to stellarators are the biannual International Stellarator/Hliotron Workshops (ISHW). During the time frame of this report, the 15th ISW was held in 2005 in Madrid (Spain), the 16th ISHW was held (jointly with the 17th International Toki Conference) in 2007 in Toki, Japan, and 17th ISHW was held in 2009 in Princeton, NJ, USA. Selected papers from these workshops were peer-reviewed and published in special issues of Fusion Sceicne and Technology (15th ISW) and Plasma and Fusion Research (16th ISHW), and currently being peer-reviewed in Contributions to Plasma Physics (17th ISHW). The 18th ISHW has been agreed to be held in 2011 in Canberra, Australia.
The information on the history of ISW and ISHW is accumulated at FusionWiki web-page, http://www-fusion.ciemat.es/fusionwiki/index.php/International_Stellarator_and_Heliotron_Workshop

Conferences, workshops, topical meeting, seminars

- 6 Coordinated Working Group Meeting [CWGM] (Kyoto, Greifswald, Toki, Madrid, Stuttgart, Princeton), the next meeting is scheduled for Jun. 30- Jul. 2, 2010 in Greifswald.

- International Toki conference (ITC) (15th to 19th) was annually hosted by NIFS from 2005 to 2009.

- 19th Internatinal Conference on Numerical Simulation of Plasmas (ICNSP), in joint with 7th Asia-pacific Theory Conference (APPTC) was organized by NIFS in 2005.

- 9th IAEA-Tenhnical Meeting on Energetic Particles in Magnetic Confinement Systems was organized by NIFS in 2005.

- 11th International International Workshop on Plasma Edge Theory in Fusion Devices was organized by NIFS in 2007.

- 6th IAEA Technical Meeting on Control, Data Acquisition, and Remote Participation for Fusion Research was organized by NIFS in 2007.

- 13th International Symposium on Laser-Aided Plasma Diagnostics (LAPD-13) was organized by NIFS in 2007.

- 3 Workshops on Magnetic Fusion Data Processing, Validation and Analysis (Jülich, Germany; Culham, UK; Madrid, Spain).

- IPP NSC KIPT provided two International Conferences and School on Plasma Physics and Controlled Fusion (with essential number of reports dealing with the stellarator problems) in 2006 and 2008.

- Simultaneously with these Conferences, the 2nd and 3rd Alushta International Workshops on the Role of Electric Fields in Plasma Confinement in Stellarators and Tokamaks were organized.

- In parallel with the last Conference and School, the 18th IAEA Technical Meeting on Research Using Small Fusion Devices (25-27 September 2008) was held in Alushta.

- IPP NSC KIPT is planning to organize International Conferences on Plasma Physics and Controlled Fusion (with essential number of reports dealing with the stellarator problems) in 2010, 2012 and 2014.

- IPP NSC KIPT also plans to organize in 2010 and 2012 the International Workshops on the Role of Electric Fields in Plasma Confinement in Stellarators and Tokamaks.

Websites

FusionWiki web (http://www-fusion.ciemat.es/fusionwiki/) has been developed.

The confinement and profile database has been hosted by two websites (IPP and NIFS) and an open database of the magnetic configurations and the neoclassical transport results is installed at IPP (www.ipp.mpg.de/ISS and ishpdb.nifs.ac.jp). ORNL publishes a bi-monthly technical newsletter (Stellarator News) on the world stellarator/heliotron research and maintains a web site for stellarator articles, announcements and workshop papers. Each of the major experimental stellarator/heliotron programmes also maintains a web site; a listing of these can be found on the ORNL stellarator page at http://www.ornl.gov/sci/fed/stelnews/stelnews.html.

8 PUBLICATION RECORD

The publications based on the this Implementing Agreement (2005-2009)
(Based on the collected information, as of Jan. 25, 2010)

Area of research	# of papers
Turbulence phenomena	59
Edge physics/three-dimensional divertor	40
Wave physics/current drive	39
Diagnostics	34
MHD phenomena/hige beta plasmas	31
Transport (particle, energy, momentum)	31
Database/data handling	21
Atomic/molecule issues	21
Neoclassical transport	12
Radial electric field on confinement	9
Impurity in plasmas	7
Energetic particles	6
Iota/shear/island, magnetic configuration	4
Reactor concepts	9
Engineering	43
Overview	6
Total	**372**

CWGM collaboration 23(also counted above)

Tokamaks (including ITER) 73