stellarator news

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Ninth International Workshop on Stellarators

The Ninth International Workshop on Stellarators was held as an International Atomic Energy Agency (IAEA) Technical Committee Meeting at the Max-Planck-Institut für Plasmaphysik (IPP), in Garching, Germany, from 10 to 14 May 1993. Other recent Workshops were held in Kharkov, Ukraine, in 1991 and at Oak Ridge, USA, in 1989. The approximately 110 participants and guests at the Ninth Stellarator Workshop came from Austria, Australia, France, Germany, Greece, Italy, Japan, Russia, Spain, Ukraine, United Kingdom, and the United States of America. Forty-eight papers were presented orally, and an additional 47 papers were presented in two poster sessions. The proceedings of the workshop will be published as a technical document by the IAEA.

The workshop was opened by K. Pinkau, IPP Garching. He pointed out that stellarators, when extrapolated to steady-state fusion reactors, promise many advantages compared to tokamaks. Whereas ITER is the right step for the tokamak line, a sufficiently broad stellarator program requires new devices of an adequate size to study reactor-relevant plasmas. This task, to be performed by taking advantage of international cooperation. It can contribute to the data base for a future decision on the optimum scheme of toroidal confinement and for the long-term development of fusion towards producing electric power in an environmentally acceptable and economic way.

This summary concentrates on the overviews given for the operating stellarators. The summary is followed by a list the titles and main authors of the contributions. One of the key issues of the workshop was new results of edge plasma studies. In this field, stellarator results are complemented by a number of contributions from tokamaks.

Overviews of operating stellarator experiments

Experimental results from 11 operating stellarators were reported at the workshop. Their machine parameters are listed in the table on the next page. Also given are the machine parameters of the three stellarators which are under development or construction at the present time.

In the following, the term "stellarator" is used as a generic term for the various kinds of toroidal systems that produce confining magnetic fields by currents in external coils. All stellarators operate with the axis position controlled by vertical fields. Many of them also use net current-free discharges with stationary plasma parameters for pulse lengths up to seconds. Torsatrons often apply quadrupole fields for further optimization, e.g., of the bootstrap current. Heliacs enlarge their field parameters by superposing the field of an $l = 1$ helical coil to that of the center conductor. W7-AS, IMS, and W7-X use modular coils. The two large future systems, LHD and W7-X, will be equipped with superconducting coils.

In CHS (NIFS, Nagoya) the magnetic field was increased to a value $B = 2$ T, and a second neutral beam injection (NBI) system was used. This allowed the study of energy transport over a broader range of parameters: T_i up to 450 ± 50 eV was obtained with 0.8 MW co-NBI and 0.6 MW counter-NBI at 1.8 T. The results support gyro-reduced Bohm scaling. The increased magnetic field also led to larger values of plasma-stored energy, W_{dia} up to 1.2 kJ, when approaching cut-off densities with O-mode electron cyclotron resonant heating (ECRH) at the fundamental resonance and optimum major radius position. High-beta plasmas (diamagnetic $\langle\beta\rangle$ up to 1.6 %) were obtained at low fields, $B = 0.6$ T, using both NBI systems. The effects of a radial electric field were studied in combined ECRH/NBI discharges. Boronization has almost the same effect as Ti gettering in reducing the radiation losses; however, it allows many more reproducible shots. H-mode-like transitions occur in certain NBI plasmas with the introduction of a small ohmic current. The line-averaged electron density rises while the H_α signal drops and the n_e profile steepens near the edge. A different plasma reheat mode is characterized by an increase in W_{dia} after the gas feed is switched off. Study of these schemes for improved confinement is in progress. Plans for the near-future include

an increase in ICRH power, including a new antenna as a prototype development for LHD, and a new 53-GHz gyrotron with higher power. New diagnostics to be used are a heavy-ion beam probe (HIBP) and multiple Thomson scattering.

In W7-AS (IPP Garching) electron energy transport is analyzed from a stationary power balance as well as from heat-wave propagation techniques. Results agree to within an average factor of 1.5 between the two methods. Electron heat conduction usually is dominated by anomalous losses. Several empirical scaling laws can be applied to describe the experimental data, e.g., LHD scaling, Lackner-Gottardi-scaling, or W7-AS-scaling. In low-density ECRH discharges with central power deposition, neoclassical losses are found in DKES code calculations to dominate electron heat transport for the long mean-free-path regime if only small radial electric fields are permitted. Ion heat conduction is roughly neoclassical. Particle and impurity transport are studied using laser blow-off techniques, H_α measurements near the limiters and at various other positions, and probe measurements of the edge plasma. Results are compared with impurity transport calculations (SITAR code) and the DEGAS code. A smooth transition is seen from the plasma core towards the edge. Edge-plasma studies were intensified with emphasis placed on separatrix-dominated configurations. Maximum beta values achieved so far are limited by the heating power. Average beta values up to 1.2% are reached at $B = 1.25$ T at full NBI power with only small fluctuation levels.

A new 140-GHz gyrotron (0.4 MW for up to 1.1 s) provided a larger density range in ECRH discharges at 2.5 T. This improvement allowed H-mode operation to be obtained, so far near $\iota = 1/2$. Experiments with differ-

Stellarators in Operation

Device	Location	Type	l	m	R (m)	a (m)	B (T)	ι_{axis}	ι_{edge}
CHS	Nagoya, Japan	Heliotron*	2	8	1.0	0.2	0.6–2.0	0.3	0.8
W7-AS	Garching, Germany	Advanced Stellarator	NA	5	2.0	0.2	1.25, 2.5	0.3–0.7	
Heliotron–E	Kyoto, Japan	Heliotron*	2	19	2.2	0.2	0.9–1.9	0.5	2.5
H–1	Canberra, Australia	Heliac	1	3	1.0	0.2	1.0	0.6–1.9	
ATF	Oak Ridge, USA	Torsatron	2	12	2.1	0.3	0.6–2.0	0.3	1.0
U-3M	Kharkov, Ukraine	Torsatron	3	9	1.0	0.1	0.4–1.2	0.0	0.3
U-2M	Kharkov, Ukraine	Torsatron	2, 4	4	1.7	0.2	2.4	0.6	0.7
L-2	Moscow, Russia	Stellarator	2	14	1.0	0.1	1.5	0.2	0.8
CAT	Auburn, USA	Torsatron	1, 2	5	.53	0.11	0.1	0.25	0.5
IMS	Madison, USA	Modular Stellarator	3	7	0.4	0.04	0.3	0.0	0.6
TJ-IU	Madrid, Spain	Torsatron	1	6	0.6	0.1	0.5	0.14–0.4	

Stellarators Under Development or Construction

Device	Location	Type	l	m	R (m)	a (m)	B (T)	ι_{axis}	ι_{edge}
LHD	Nagoya, Japan	Heliotron*	2	10	3.9	0.65	3.0 (4.0)	0.5	1.0
W7-X	Garching, Germany	Advanced Stellarator	NA	5	5.5	0.5	2.5 (3.0)	0.84–1.2	
TJ-II	Madrid, Spain	Heliac	1	4	1.5	0.2	1.0	0.9–2.5	

NA = Not Applicable
*Torsatrons are called heliotrons in Japan.

ent spatial modulation of the magnetic field (mirror ratio) were initiated with an emphasis on studying the effects on the bootstrap current and the electron cyclotron current drive (ECCD) efficiency.

Various new diagnostics for stationary and fluctuating plasma parameters are used or are under development. Recently, the W7-AS diagnostics were upgraded to allow one-shot Thomson scattering (20 radial points) and full-profile ECE temperature measurement at 1.25 T. A new ICRH antenna is under investigation. After the present experimental campaign, one of the 70-GHz gyrotrons will be replaced by a long-pulse (3-s) 140-GHz gyrotron. In the coming years other 140-GHz gyrotrons will be installed, and the NBI power available at W7-AS will be raised to 3 MW.

The Heliotron-E group (Kyoto University) continued detailed experiments studying the magnetic field structure near the edge. Various rational iota values were identified and compared with field calculations. The "whisker" structure and effects of external symmetry breaking fields could be identified. The magnetic field structure in the scrape-off layer (SOL) region was investigated under finite-beta conditions from the analysis of the cloud of an ablating pellet. Radial electric fields can be controlled by biasing a small probe or the limiter, distinguishing between limiter and separatrix configurations. Future plans are upgrades in NBI up to 4 MW, and ECRH up to 0.5 MW at 106 GHz.

The H-1 Heliac (Canberra) recently went into operation. Plasma was produced by a helicon-type antenna at 7 MHz, or by ECH at 2.45 GHz. The first results of field mapping demonstrate the absence of gross field errors, and show nested magnetic surfaces up to the temporary limiter at $\langle a \rangle \sim 0.16$ m. For a particular helical core current, influence of rational iota values is seen near $\iota = 3/2$ in reasonable agreement with field-line tracing. Various field parameters (iota, magnetic well to hill) are accessible. From LHD scaling, a value of $\langle \beta \rangle = 1\%$ is expected for $n_e = 1 \times 10^{19}$ m^{-3} at a low steady-state field of 0.2 T and full heating power using 0.2 MW ECRH (if a suitable source is obtained) and 0.25 MW ICRF.

ATF (ORNL, Oak Ridge) stopped operation in November 1991 to replace to damaged helical winding segments with spare segments utilizing improved insulation. The experimental data base has been analyzed regarding transport and the effect of fluctuations. Microwave scattering measurements of electron density fluctuations in the core of low-collisionality ECRH plasmas showed features that might be evidence of trapped-electron instabilities. Fast-ion behavior, limiter biasing, and magnetic field perturbations also influence transport. There are indications of an improvement of the energy confinement time compared with gyro-reduced Bohm scaling at elevated beta and reduced collisionality. Therefore ATF aims at a substantial increase of the available heating power within the coming years: for ECRH (35 GHz for longer than 1 hour operation at 100 kW, and at the higher power of 1.4 MW for 10 s using a 1-MW gyrotron at 84 GHz or 110 GHz), for NBI (two existing 1-MW systems plus a third beam line with 1.5 MW perpendicular injection), and for ICRH (two antennas for outside and inside launch, 3.5 MW up to 30 s). The target is an integrated test of stellarator confinement demonstrating $\langle \beta \rangle$ of about 4%, low collisionality, and improved confinement regimes in long-pulse operation.

The torsatrons U-3M and U-2M (Kharkov) differ in their magnetic topology pure $l = 3$, $m = 9$, and combined $l = 2$ and 4, with $m = 4$, respectively. An additional toroidal field is provided to reduce the neoclassical ripple losses. U-3M operates with ICRF plasmas and in investigating two antenna types in an enlarged range of density, as well as studying particle transport for bulk, edge, and divertor plasmas. The new system, U-2M, is presently being prepared for magnetic field measurements. Various topologies are accessible. Rf plasma production and heating is foreseen for 1994, using a rather large antenna (1.7-m^2 surface) for ion Bernstein waves. NBI plasmas are planned for 1995, with two systems for co- and counter injection.

The L-2 stellarator (Moscow) has been fully reconstructed and uses a new bakeable vacuum chamber. The ECRH power supply was upgraded to reach a 20-ms pulse length. Magnetic field measurements verify the iota profile with $\iota_{axis} = 0.2$ and $\iota_{sep} = 0.8$ for a separatrix radius of 11.5 cm. The width of the $\iota = 1/2$ island is about 1 cm. Plasma parameters of initial ohmic discharges are an average density of 1–2 10^{13} cm^{-3} and $T_e(0) = 0.3$–0.4 keV for $B = 1.35$ T and $I_p = 15$ to 20 kA. More than 50% of the ohmic power is radiated. ECRH plasmas with beta up to 1% are planned. The ECRH power (75 GHz, 0.5 MW) will be increased to 1 MW by a second gyrotron in 1994.

The CAT torsatron (Auburn) with $R = 0.53$ m, aspect ratio $A = 5$, $l = 1$ and 2, $m = 5$, is used for magnetic island studies at low field strength ($B = 0.1$ T). Two pairs of Helmholtz coils produce mutually perpendicular horizontal fields, and two helical coils are designed for resonance at $\iota = 1/2$. Different currents in either set match the phase of the perturbation. At $B = 0.024$ T the unperturbed system shows a width of 3 cm for the $\iota = 1/2$ island. It could be reduced by a factor of 3 with either set of correction coils. The helical coils need less current, due to their proximity.

In IMS (Madison) experimental measurements of plasma flows and radial electric fields are made with biased probes and compared with a new neoclassical model. The plasma flows and the electrical conductivity are dominated by collisions with neutrals for the interior. Effects of viscosity are important near the edge. The measured Pfirsch-Schlüter currents agree with numerical calculations.

The TJ-1 U torsatron (Madrid) is almost completed. It uses an $l = 1$, $m = 6$ helical winding with pitch modulation, $R = 0.6$ m and $B = 0.5$ T. The minor plasma radius is about 0.1 m. Vertical fields allow the axis to shift by about 5 cm with an associated change of ι_{axis} between 0.14 and 0.4. An inward axis shift changes the magnetic well towards a hill. After field mapping, ECRH experiments are foreseen for 1994, using 0.2 MW at 28 GHz, to be followed by ICF experiments.

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Stellarator Workshop Program

The following list contains the names of the lead authors and the titles of the Ninth Stellarator Workshop contributions, in the sequence of the workshop program. For more information, please contact the respective author directly.

Overviews

Matsuoka, K.	Nagoya	Overview of CHS Experiments
Jaenicke, R.	Garching	Overview of W7-AS Results
Obiki, T.	Kyoto	Recent Heliotron-E Experiments
Hamberger, S. M.	Canberra	First Operation of the H-1 Heliac
Lyon, J. F.	Oak Ridge	Overview of the ATF Stellarator Program
Motojima, O.	Nagoya	Status of LHD Project and Construction
Nakajima, N.	Nagoya	Theoretical Consideration for LHD Plasma
Alejaldre, C.	Madrid	TJ-II Flexible Heliac
Pavlichenko, O.	Kharkov	Status of Uragan-3M and Uragan-2M Experiments
Knowlton, S.	Auburn	Magnetic Island Studies on the Compact Auburn Torsatron
Rau, F.	Garching	Wendelstein 7-AS Configurations at Various Mirror Ratios and Iota-Values
Colchin, R. J.	Oak Ridge	Effects of Magnetic Field Perturbations on ATF Torsatron

Equilibrium

Hayashi, T.	Nagoya	3D MHD Equilibria of Helical Systems
Schwenn, U.	Garching	Application of the Hint Code to W7-X
Monticello, D. C.	Princeton	The PIES Code: Three-dimensional Equilibria with Pressure, Islands and Stochastic Regions
Johnson, J. L.	Princeton	Applications of the PIES Code to the ATF Stellarator
Salas, A.	Madrid	Equilibrium Studies with Islands in Stellarators
Merkel, P.	Garching	Equilibrium Studies with PIES Code

Transport

Maassberg, H.	Garching	Transport in the Stellarators
Beidler, C. D.	Garching	Neoclassical Transport Scalings Determined from A General Solution of the Ripple-averaged Kinetic Equation (GSRAKE)
Talmadge, J. N	Madison	Comparison of Radial Conductivity and Plasma Flows in IMS to Neoclassical Theory

Overviews (poster)

Ascasibar, E.	Madrid	Status of TJ-I U Torsatron
Grekov, D. L.	Kharkov	Quadrupole Magnetic Configuration Studies for Uragan-2M
Grekov, D. L.	Kharkov	Progress in Physics Studies of Uragan-2M Torsatron
Schauer, F.	Garching	Status of W7-X Technical Developments

Equilibrium & Stability (poster)

Burdo, O. S.	Kiev	Criterion of Stability with Anisotropic Pressure in Stellarators
Cheremnykh, O. E.	Kiev	The Influence of Fast Particles on Flute Mode in Stellarators
Cheremnykh, O. E.	Kiev	A Structure of Flute Perturbations in Stellarators
Kalyuzhnyj, V. N.	Kiev	Calculations of the Mercier Stability Criterion for the Uragan-2M Torsatron with Enhanced Longitudinal Magnetic Field
Geiger, J.	Garching	W7-AS Equilibria with Toroidal Current
Schwab, C.	Garching	Computation of Stable MHD TAE Modes with CAS3D
Zheng, L.-J.	Garching	Ideal-MHD and Kinetic Ballooning Mode Equations in Low-Shear Configurations

Transport (poster)

Chechkin, V. V.	Kharkov	Particle Transport During rf Plasma Heating in the Torsatron with Divertor "Uragan-3M"
Chechkin, V. V.	Kharkov	Diverted Plasma Characteristics in the Uragan-3M Torsatron Under rf Heating Conditions
Danilkin, I. S.	Moscow	A Possible Evolution of the *l*-2/4 concept (Flexible Compact Torsatron)
Danilkin, I. S.	Moscow	"Neoclassical" and "Anomalous" Scaling Laws in Stellarators
Kraemer-Flecken, A.	Jülich	Investigation of Various Plasma Parameters as Function of the Injected Beam Power at TEXTOR
Liniers, M.	Madrid	NBI Physics Studies in TJ-II
Pankratov, I. M.	Kharkov	Numerical Simulation of Particle and Energy Transport in Uragan-3M Torsatron
Pankratov, I. M.	Kharkov	The Molecular and Atomic Hydrogen Behaviour in the Uragan 3-M Torsatron

Fluctuations (poster)

Giannone, L.	Garching	Temperature, Density and Potential Fluctuations by a Swept Langmuir Probe in W7-AS
Sanchez, J.	Madrid	Fluctuation Studies in W7-AS by Reflectometry
Sattler, S.	Garching	Temperature Fluctuations in the Core of W7-AS

Kick, M.	Garching	Ion Energy Confinement in W7-AS

Transport

Isler, R. C.	Oak Ridge	Fluctuations and Confinement in ATF
Yamada, H.	Nagoya	Confinement Studies in CHS Plasmas
Stroth, U.	Garching	On the Diffusive Nature of W7-AS Transport
Dory, R. A.	Oak Ridge	Distinguishing Gyro-Bohm and Bohm Scaling in Stellarators
Wagner, F.	Garching	The H-Mode of W7-AS
Hartfuss, H.	Garching	Heat Wave Studies on W7-AS

Edge Fluctuations

Laviron, C.	Cadarache	Edge Turbulence with the Ergodic Divertor on Tore Supra
Hidalgo, C.	Madrid	On the Role of Atomic Physics Mechanisms on Edge Turbulence in Tokamaks and Stellarators
Niedermeyer, H.	Garching	Edge Turbulence in ASDEX and W7-AS

Plasma Edge & Impurities (poster)

Alladio, F.	Frascati	Alpha Particle Behaviour in Boundary Layer of Stellarators
Brakel, R.	Garching	Recycling Studies in the W7-AS Stellarator
Herre, G.	Garching	Connection Length Studies and SOL Parameters for the Limiter and Separatrix Dominated Configurations in W7-AS
Hildebrandt, D.	Garching	Studies on Impurity Production and Transport in W7-AS
Kisslinger, J.	Garching	Island Divertor Concept for the Stellarators W7-X and W7-AS
Kuznetsov, Yu. K.	Kharkov	Magnetic Divertor in the $l = 3$ U-3M Torsatron
Mizuuchi, T.	Kyoto	Limiter Bias Experiments in Heliotron-E
Ochando, M.	Madrid	Impurity Radiation and Edge Turbulence in the TJ-I Tokamak
Uckan, T.	Oak Ridge	Limiter Biasing Experiments on the Advanced Toroidal Facility (ATF)

Heating (poster)

Ballico, M.	Garching	First Experimental Results Using a Toroidally-Broad ICRH Antenna in the W7-AS Modular Stellarator
Fedyanin, O. I.	Moscow	Status of the L-2 Stellarator Experimental Program
Karulin, N.	Garching	Alpha Particle Confinement in Helias Reactor Under the Influence of GAEs
Marushchenko, N. B.	Kharkov	IBW Plasma Heating Dynamic Studies by Solution of the Fokker-Planck Equation
Marushchenko, N. B.	Kharkov	Ray Tracing Studies of IBW for Production and Heating Plasma in U-2M Device
Okada, H.	Kyoto	ICRF Experiment in Heliotron-E
Plyusnin, V. V.	Kharkov	Performance of Three-Half-Turn and Frame Antennas for ICRF Plasma Heating in Uragan-3M Torsatron
Plyusnin, V. V.	Kharkov	Confinement of rf Plasma in the Uragan-3M Torsatron
Wade, M. R.	Oak Ridge	Fast Ion Behaviour During Neutral Beam Injection in ATF

Diagnostics, Technical Developments (poster)

Drakakis, E.	Iraklion	The Modified Betatron Accelerator: New "Twist" in Stellarators
Harmeyer, E.	Garching	The Modular Coil System of a Helias Reactor
Mccormick, K.	Garching	High-Energy-Lithium-Beam Diagnostics on W7-AS
Pankratov, I. M.	Kharkov	Helical Winding Detachable Joint and Current Feed Influence on the Uragan-4 Magnetic Configuration at Rotational Transform Less Than 0.5
Georgievskij, A.	Kharkov	The Conception of a Tokamak Magnetic System with Magnetic Surfaces (post-deadline paper)
Mank, G.	Jülich	Thermographic Observations of Toroidal Limiter Blades

Edge

Todd, T. N.	Culham	Divertor Configurations in the Compass-D Tokamak
Schaffer, M.	San Diego	Results from the DIII-D Advanced Divertor Program
Schneider, R.	Garching	On the Feasibility of Gas Targets
Capes, H.	Cadarache	Particle Flux Across a Stochastic Magnetic Layer
Wobig, H.	Garching	Electron Temperature Bifurcation in the High Recycling Regime
Grigull, P.	Garching	Boundary Layer Studies on W7-AS
Sardei, F.	Garching	Open Magnetic Surfaces and Resonant Topology for Modeling Plasma Edge Transport in W7-AS
Strumberger, E.	Garching	Topology of Field Line Mapping in the Ergodic Region of Optimized Stellarators and Divertor Design
Morita, S.	Nagoya	Topological Edge Layer Studies of ECH and NBI Plasmas in CHS

MHD

Nakamura, Y.	Kyoto	New Stellarator Configuration and Ballooning Modes in Stellarator
Weller, A.	Garching	Global, Toroidal and Helical-Induced Shear Alfvén Instabilities in Stellarators
Fredrickson, E.	Princeton	Experimental Observations of Toroidal Alfvén Modes
Wootton, A.	Austin	Is Magnetic Turbulence Important in Tokamaks? (Is It Responsible for Electron Thermal Transport?)

Impurities

Lotz, W.	Garching	Neoclassical Transport of Impurities in Stellarators
Monier-Garbet, P.	Cadarache	Impurity Screening During Ergodic Divertor Experiments on Tore Supra

Reactor

Horiike, H.	Naka	Comparative Study of Steady-State and Pulsed Reactors
Lyon, J. F.	Oak Ridge	Assessment of Stellarators as Reactors
Erckmann, V.	Garching	Status and Prospects of 140-GHz ECRH

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