stellarator news

Published by Fusion Energy Division, Oak Ridge National Laboratory
Building 9201-2; P.O. Box 2009; Oak Ridge, TN 37831-8071, USA

Editor: James A. Rome
Issue #10
July 1990

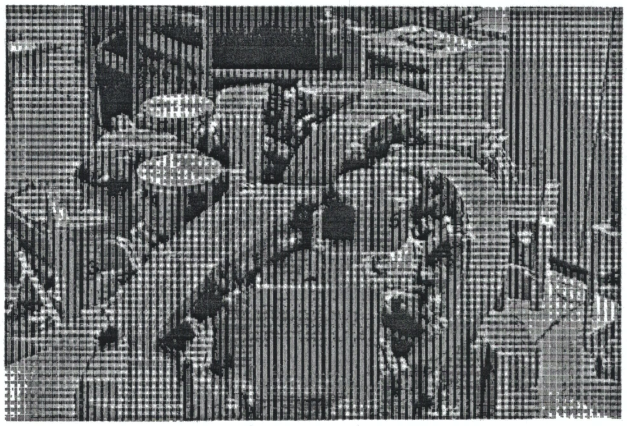
Auburn CAT to be Dedicated

The Compact Auburn Torsatron (CAT) is an $l = 2$, $m = 5$ and $l = 1$, $m = 5$ torsatron with a plasma aspect ratio of 5. The major radius is 53 cm and the magnetic field is 1 kG.

A major milestone has been reached in the construction of CAT. The winding of the helical coils was completed on May 30, 1990. Machine assembly occupied the month of June. Magnetic surface mapping and initial plasma operation will commence in July. During the first year of operation the focus of the research effort will be on magnetic island studies. These studies will include studies of various field errors and their "repair" using trim coils. A helical $l = 2$, $m = 5 \sin(\theta)$ trim coil is already in place.

A machine dedication ceremony for CAT will be held on Friday, July 20, 1990. All interested members of the fusion community are invited. Contact Rex Gandy at (205)844-4126 for more information.

Rex Gandy
Auburn University Physics Department
206 Allison Lab
Auburn, Alabama 36849, USA



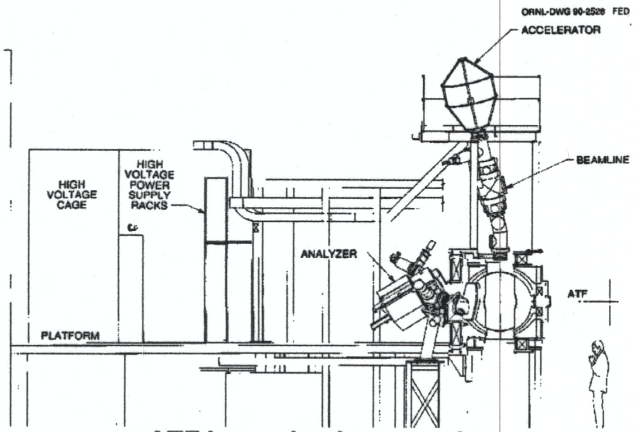
Compact Auburn Torsatron

Initial Results From the ATF Heavy Ion Beam Probe

Secondary ions (Cs^{2+}) were successfully detected for the first time by the ATF HIBP energy analyzer in May. This analyzer was designed and built by the Rensselaer Polytechnic Institute. The total current measured by the four analyzer detectors was as high as several hundred nanoamperes during these initial tests. These results were obtained in ECH-sustained plasmas at 0.95 T. Secondary ions produced by the interaction of the primary beam with neutral gas puffed into ATF at the end of each shot were also detected. This may offer the possibility of an in-situ calibration of the analyzer on every shot. The primary beam (Cs^{+}) has also been detected on two primary beam detectors installed inside the ATF vacuum vessel. These signals provide information that will be used to verify particle trajectories.

The ATF HIBP system consists of a Cs^{+} source, a 160kV accelerator, a 2-m beam line, three primary beam detectors, and a 40-kV parallel plate electrostatic energy analyzer.

John J. Zielinski (RPI)
Oak Ridge National Laboratory
P.O. Box 2009
Oak Ridge, TN 37831-8072, USA



ATF heavy ion beam probe

Oak Ridge National Laboratory is operated by Martin Marietta Energy Systems, Inc. for the U.S. Department of Energy

Around the Labs

New Heating and Diagnostic Systems for Heliotron-E

The inside launch systems to produce a linearly polarized HE$_{11}$ mode from two gyrotron tubes (2 × 200 kW) are almost completed. Thus, well focused 53.2-GHz microwave beams will be applied to future experiments, where central electron heating is stressed for studying both the low-collisionality regime and high-density plasma heating. Furthermore, with inside launching, heating efficiency is expected to be improved, owing to more favorable drift orbits of RF-heated high energy electrons.

The beam diameter on the magnetic axis, as measured under the conditions of the constructed waveguide system, was 8.2 cm (1/e-folding diameter). The Gaussian-like beam pattern was also good.

The installation of the heavy neutral beam probe (HNBP) is almost complete after improvement of the particle analyzer and other parts, which had some problems in the previous experimental phase. The HNBP is especially important in the next experiments for measuring electric potential and fluctuations, which are extremely significant for transport.

Particle transport will be also intensively studied with two-photon excited laser fluorescence spectroscopy (LFS), Balmer α LFS, H$_\alpha$ array measurement, Fraunhofer diffraction method, and so on. These studies will be made by changing the configuration using the toroidal and vertical coils.

Heliotron E was evacuated in the middle of June, and the vacuum chamber is now being baked. Experiments will start again in the middle of July after discharge cleaning of vacuum chamber. Machine maintenance is planned for October–November. Afterwards, a 106-GHz, 500-kW gyrotron tube will be added in the following experimental phase which will run from November to the next year. The tube is now also being conditioned, and power of more than 450 kW has already been achieved.

Yuji Nakamura for the Heliotron-E Group
Plasma Physics Laboratory
Kyoto University
Uji, Kyoto, Japan

News from ATF

ATF recently began its Phase IV operating campaign with the completion of several maintenance and repair projects. Initial experiments focused on cross-calibration of electron density measurements made by Thomson scattering, 2-mm interferometry, and FIR interferometry. With the understanding of the interferometry measurements gained during the shutdown, the equivalence of the line density measurements made by the two interferometers was verified.

The cross-calibrations provided the ability to make systematic and accurate pressure profile measurements during ECH-only bootstrap current studies. Self-consistent predictions of bootstrap current behavior based on neoclassical theory compare well with experiment over a wide range of experimental conditions. In these latest experiments, the line density was held constant, and the dipole and quadrupole field components were varied.

In ECH-only experiments, the density profile was changed from flat to peaked at the center by injecting small pellets. In these discharges, the central density doubled, yet the plasma remained collapse-free. The stored energy recovered or increased beyond the pre-pellet level in about 50 ms; the peaked density profile was maintained for times of order 100 ms.

Preliminary indications of bulk plasma heating from ICRH were obtained in quasi-stationary, high-density plasmas [n_e around 5–8 × 10^{13} cm^{-3}] sustained with about 1 MW of neutral helium beam injection into deuterium target plasmas at 0.95 T. The beams provided the path to high density and to good RF coupling of about 1 Ω. The ICRH studies used hydrogen minority (5–10%) and deuterium majority. Before ICRH, the plasma stored energy content was 5–10 kJ. With about 100 kW to the antenna, the stored energy rose about 0.75 kJ. There were accompanying indications of heating from Thomson scattering and from spectroscopy.

John C. Glowienka for the ATF Group
Oak Ridge National Laboratory
P.O. Box 2009
Oak Ridge, TN 37831-8072, USA

Correction...

The article about whistler waves in SHEILA which appeared in the last issue was actually written by Peter Loewenhardt of the Australian National University.

Confinement Studies on the Wendelstein VII-AS Stellarator

Summary and Conclusion of Invited Paper, given at the 17th European Conference on Controlled Fusion and Plasma Heating.

W VII-AS with its modular field system has operated routinely since January 1990 with full field parameters. From this experience one can also draw the conclusion that a large modular system can be realized, especially since the mechanical forces will not exceed values known from W VII-AS. In the first and second experimental campaigns most of the investigations were devoted to ECR-heated plasmas (70 GHz) at magnetic fields of 1.25 T and 2.5 T with second harmonic X-mode and fundamental O-mode launching. Maximum plasma parameters of $T_e(0) \sim 2.5$ keV, $T_i(0) \approx 0.4$ keV, $n_e(0) \sim 5 \times 10^{13}$ cm^{-3}, and $\tau_E \sim 10$–20 ms have been achieved with this technique. The expected reduction of the Shafranov shift by reducing the Pfirsch-Schlüter currents by a factor of two has been confirmed by the experiment.

The control of the rotational transform at the plasma edge, $\iota\!\!\!-(a)$, works for all possible scenarios under consideration. For low internal shear operation, degraded confinement is found to be related to low-order rational values of $\iota\!\!\!-$, which indicates island formation and ergodization in the magnetic configuration. Even local flattening of the electron temperature profile has been resolved for these conditions. Internal shear is generated by internal currents. In most discharges, the pressure-driven bootstrap current, which is experimentally confirmed, is feedback-compensated by an Ohmic current. This scenario results in a positive shear depending on the magnitude of the bootstrap current and consequently on the energy content. The positive effect of internal shear on the energy confinement has been shown to be significant. Finally, a future task will be the study of confinement optimization by means of an appropriate shaping of the whole rotational transform profile using local electron cyclotron current drive.

Electron energy balance analysis based on measured T_e and n_e profiles yields the electron heat conductivity, $\chi_e(r)$. The best χ_e values achieved are well below 10^4 cm^2/s, which is in the range of the optimum χ_e values found in tokamaks. For all analyzed discharges, the neoclassical transport coefficients were calculated by using the DKES code and compared with the experimental values. Due to the strong T_e dependence, the neoclassical χ_e values decrease rapidly with radius and are typically about one order of magnitude smaller than the experimental value at half the plasma radius. The experimental χ_e values, however, are roughly constant in the bulk part of the plasma and increase close to the plasma edge. The neoclassical χ_e values reach the experimental values only for high central ECR power deposition with peaked temperatures where the neoclassical ripple losses dominate. For discharges with $n_e > 3 \times 10^{13}$ cm^{-3} at full field, optimum confinement properties were achieved; these discharges were characterized by $T'_e \sim$ constant as well as $n_e\chi_e \sim$ constant in nearly the whole confinement region. For these discharges, the global energy confinement time scales with a^2. With the present database a regression analysis of both τ_E and local χ_e has been performed. No significant T_e dependence was found in the local χ_e regression. χ_e scales with ECR heating power and inversely with n_e, B, and $\iota\!\!\!-(a)$.

From the DEGAS code, particle fluxes and diffusivities have been derived using measured T and n_e profiles and absolute H_α intensities at relevant positions around the machine. The radial range of the diffusivities includes the density gradient region up to the limiter. Here, D is found to range between 500 and 10^4 cm^2/s for the discharges analyzed, exceeding neoclassical predictions by more than one order of magnitude. D scales with ECR heating power and inversely with n_e, B, and $\iota\!\!\!-$(a). The ratio D/χ_e was between 1/10 and 1/3.

Density profiles were found to become hollow in the plasma center with increasing ECRH power (200 to 800 kW). For the hollow profiles at high power level, the central particle fluxes from DEGAS simulations agree fairly well with the neoclassical fluxes, which are dominated by thermodiffusion. Consequently, the ECRH density pump-out in the central region is consistent with neoclassical transport in W VII-AS.

Future work will concentrate on NBI discharges. First, there are two ways to avoid radiation collapse. Combined ECRH and NBI discharges have already been shown to reach a stationary state. However, the understanding of the density control by ECRH in NBI discharges is of dominant importance. Future experiments with 140-GHz ECRH will concentrate on this topic. Furthermore, ECRH may also be used to avoid impurity accumulation. Second, the machine is now being carbonized and will be boronized later in the year. So far, only glow discharges have been used for the conditioning of the machine. From the experience of other machines it is expected that these measures will reduce the radiation problem connected with the good particle confinement in pure NBI discharges.

H. Ringler, G. Kühner, H. Maaβberg, H. Renner, F. Sarde,
W VII-AS Team, NBI Team, and ECRH-Group
Max-Planck Institut für Plasmaphysik, Association EURATOM-IPP
D-8046 Garching, FRG

Status of CHS

NBI long-pulse operation

During the last shutdown, armor plates were installed to protect the inner wall from NBI shinethrough so that we can try long-pulse NBI. The CHS armor plates are made of the same graphite which used for the armor plates in Heliotron-E. They were placed on the vacuum chamber at the inside wall and limit the plasma radius, because the inside wall has been the limiter during the usual experimental conditions where the magnetic axis is shifted inward. The measured positions of the plates correspond to a reduction of average plasma radius by about 2 cm. This was confirmed experimentally by Thomson scattering measurement of the electron density and temperature profiles. In the second week, we achieved 830-ms neutral beam injection without radiation collapse with the help of strong titanium gettering. In this discharge, the average electron density is kept constant around 3×10^{13} cm^{-3} without additional gas feed at the latter half of the discharge, and no impurity buildup was observed, which indicates that the recycling rate is unity in spite of the titanium-gettered wall.

Comparison of co- and counter-injection

We are planning to install a second neutral beam injector in the next fiscal year. To decide the arrangement of the second injector, the heating efficiencies of co- and counter-injection of the neutral beam have been compared. To do this, the toroidal field direction was reversed while maintaining the same injection angle into the torus. In the case of counter-injection, the drift orbits for the toroidally circulating fast ions shift inward and cross the inner wall; thus, a reduction of heating efficiency has been presumed. However, the plasma stored energy was 70 to 100% of that in the standard co-injection case, although the maximum density in this series of experiments is lower than that we had achieved in previous NBI experiments. This limited maximum density is considered to result from insufficient wall conditioning, especially of the armor plates. From the measurements of VUV line radiation, more carbon impurity was observed, possibly due to the new armor plates, but the dominant impurity species that causes the radiation collapse is still oxygen. A clear difference is a reduced Shafranov shift in the counter-injection case, and thus the observed Pfirsch-Schlüter current is also smaller. The results indicate that the parallel pressure of the beam component is smaller, which is reasonable from drift orbit considerations for the fast ions. A more detailed comparison of heating efficiency, especially in the higher density regime, is necessary.

Transport analysis improvements

Transport analysis using the ORNL PROCTR-MOD code has used equilibrium magnetic surfaces calculated using the fixed-boundary 3-D equilibrium code VMEC. However, experimental observations such as electron or ion temperature profiles are not necessarily consistent with this model. We have thus started to use calculations with free boundaries. We acknowledge with appreciation the help of Drs. S. P. Hirshman, H. C. Howe, and D. K. Lee (ORNL) on this matter. Now the temperature profiles fit well to the finite-beta equilibrium configuration. The free-boundary equilibria improve reliability in the profile of the electron thermal conductivity. On the other hand, the profile of the ion thermal conductivity is still ambiguous, because it requires a very accurate electron and ion temperature difference, which is very small in the present experiment.

Another improvement is the first results from a Monte Carlo simulation using the HELIOS code for the slowing down process of the injected neutral beam. This code was developed by Dr. K. Hanatani of Kyoto University. The estimates of the power deposition profile and the orbit loss are now more accurate, and this should improve the accuracy of transport coefficients calculated with the ORNL PROCTR-MOD code.

Data acquisition system improvements

CHS data acquisition and analysis systems have been upgraded to VAX 6310 systems from two PDP11/73 systems. It is expected that the amount of data will be increased from 2 Mb to 4–5 Mb per shot at the end of this year. It is planned to introduce the DMG system developed at ORNL as one of the basic software programs used for data management of the CHS experiments. Mr. C. Takahashi spent last March in Oak Ridge and started this work with lots of help from ORNL staff. The system is now ready for use and we hope that it will make cooperation easier and more effective.

Harukazu Iguchi
National Institute for Fusion Science
464-01 Nagoya, Japan

Nonexistence of Quasi-Helically Symmetric Equilibria

The neoclassical transport properties of toroidal plasmas depend only on the variation of the magnetic field strength within the magnetic surfaces.[1] If the field strength depends on only one angular coordinate within the magnetic surfaces, then the guiding center drift trajectories are strictly confined.[2] Such stellarator equilibria are said to be quasi-helically symmetric. The field strength of quasi-helically symmetric equilibria takes the form $B(\psi, \theta - N\varphi)$, with ψ the toroidal flux within a magnetic surface, θ and φ poloidal and toroidal angles, respectively, and N an integer. Nührenberg and Zille[3] computationally found large-aspect-ratio stellarator configurations that are quasi-helically symmetric to a high approximation. Unlike conventional stellarators, the drift orbits of stellarators with approximate quasi-helical symmetry never stray more than a few gyroradii from their home flux surfaces.

We have analytically shown that although quasi-helical symmetry can be approximated rather well, it can never be made exact. Our method involves Taylor expanding the field strength $B(\psi, \theta, \varphi)$ and the three components of the spatial position $\boldsymbol{x}(\psi, \theta, \varphi)$ as analytic functions about a magnetic axis. Our expansion parameter ε is the plasma radius over the minimum radius of curvature of the magnetic axis. The two forms of the magnetic field in Boozer coordinates give constraints that must be obeyed in order that $B(\psi, \theta, \varphi)$ and $\boldsymbol{x}(\psi, \theta, \varphi)$ represent an equilibrium. We attempt to constrain the field strength to have the quasi-helically symmetric form, $B(\psi, \theta - N\varphi)$, order by order in ε. If $f(\varphi)$ is a measure of the fractional toroidal variation of the magnetic surfaces, then quasi- helical symmetry is broken by terms of order $f(\varphi)\,\varepsilon^2$ for circular axis configurations, and it is broken by terms of order $f(\varphi)\,\varepsilon^3$ for configurations in which the magnetic axes have the appropriate helical distortions from a circle. These symmetry-breaking results apply for equilibria with arbitrary pressure and current profiles. Our method can also be used to investigate the continuous spectrum of possible three-dimensional equilibria with magnetic surfaces.

We will be developing a related perturbative method for studying three-dimensional equilibria. One assumes that a given $\boldsymbol{x}_0(\psi, \theta, \varphi)$ is consistent with an equilibrium. One then adds a perturbation $\delta\boldsymbol{x}(\psi, \theta, \varphi)$ that is consistent with an equilibrium that has the same profiles of current $G(\psi)$ and pressure $p(\psi)$. This procedure yields a change in the field strength $\delta B(\psi, \theta, \varphi)$. Perturbations of this type can be produced by changes in the external field coils. An application of this perturbative analysis is the determination of which terms in the Fourier expansion of $B(\psi, \theta, \varphi)$ can be removed by a change in the coil configuration. This analysis can also be used to determine the effect of plasma pressure on the toroidal ripple of a tokamak.

We acknowledge support from the U.S. Department of Energy under grant DE-FG05-84ER53176.

[1] A. H. Boozer, Phys. Fluids **27**, 2441 (1984).
[2] A. H. Boozer, Phys. Fluids **26**, 496 (1983).
[3] J. Nührenberg and R. Zille, Phys. Lett. **A129**, 113 (1988).

David A. Garren and Allen H. Boozer
Department of Physics
College of William and Mary
Williamsburg, VA 23185, USA

Proposals

Proposal for the Wendelstein VII-X Stellarator Submitted

IPP Garching has initiated the procedure to obtain EURATOM Preferential Support for the new Stellarator Wendelstein VII-X, by submitting the *Overview* and *Part 4* of the Proposal for Wendelstein VII-X to the CCFP by the end of May 1990.

The *Overview* summarizes the theoretical and experimental basis for the Wendelstein VII-X Project, and lists its objectives and experimental parameters, as well as the performance targets and principle of the technical realization. It also contains some fusion reactor considerations, comments on the relation to other projects inside and outside the European Fusion Program, and gives estimates of the time scale, cost, and manpower involved with the project.

Superconducting modular coils are key elements of the Wendelstein VII-X experiment. They require a prototye development program as described in *Part 4* of the Proposal.

Definition of Wendelstein VII-X

The Helical Advanced Stellarator configuration selected for Wendelstein VII-X satisfies the following set of essential criteria simultaneously:

- high quality of vacuum-field magnetic surfaces (regular boundary, avoidance of major resonances on the torus, adjustment of the shear, sufficiently small thickness of islands).
- good finite-beta equlibrium properties (small shift of the magnetic axis and small change of iota with beta).
- good MHD stability properties (stability with respect to local resistive interchanges and ideal ballooning at an average beta of about 5%).
- small neoclassical transport in the $1/\nu$ regime (equivalent ripple δ_e less than 2%).
- small bootstrap current in the *lmfp* regime (ratio of bootstrap current in a stellarator to the bootstrap current in a tokamak with same aspect ratio and rotational transform less than 10%).
- good collisionless alpha-particle containment (fractional prompt loss less than 10%).
- good modular coil feasibility (sufficiently large distance between coils and plasma, and a sufficiently small coil curvature).

While the optimization takes into consideration only the classical physics goals, it also results in interesting and desirable perspectives as far as anomalous transport is concerned; several candidate mechanisms for exciting anomalous transport (stochasticity in vacuum and finite-beta fields; trapped orbits, instabilities such as ballooning, tearing; and trapped-particle drift modes) are influenced in a beneficial way.

Results from Wendelstein VII-AS

Experimental results obtained from W VII-AS already support the following conclusions, which are of basic importance for the physics and technology picture underlying Wendelstein VII-X:

- A high-accuracy modular coil system is technically feasible and cost-effective in construction.
- It leads to excellent agreement between the measured magnetic surfaces and the designed ones.
- The importance of configurational effects is confirmed: major resonances have to be avoided in the confinement region. Shear has to be maximized within these constraints. These effects are less drastic in a separatrix-bound configuration than in a limiter-bound one.
- The reduction by a factor of about 2 of the axis shift occurring with increasing beta could be demonstrated and so verifies the equilibrium concept of the Advanced Stellarator.
- The measured bootstrap current agrees rather well (within a factor of 2) with the calculated one, and ECR current drive was verified.
- Plasma operation of up to 1.5 s has been established, exhibiting internal plasma time constants (e.g., time variations of internal currents) of about this duration.
- Using ECRH (0.2–0.8 MW), plasmas could be generated at $B = 1.25$ and 2.5 T and maintained up to 1.5 s with densities up to close to the cut-off density and energy confinement times of up to 20 ms.

Two consistent sets of parameters for ECRH plasmas with an average minor radius $a = 0.17$ m are:

(1) $P_{rf} = 700$ kW, $n_e(0) = 3.5 \times 10^{19}\ \mathrm{m}^{-3}$,
$T_e(0) = 2.4$ keV, $T_i(0) = 0.38$ keV, $\tau_E = 8.5$ ms,
$\chi_e(2a/3) = 0.7\ \mathrm{m}^2/\mathrm{s}$;

(2) $P_{rf} = 350$ kW, $n_e(0) = 4.2 \times 10^{19}$ m^{-3},
$T_e(0) = 1.7$ keV, $T_i(0) = 0.4$ keV, $\tau_E = 17$ ms,
$\chi_e(2/3\ a) = 0.35$ m^2/s.

The low ion temperature is in accordance with the low power transfer from the electrons to the ions at the densities of the ECRH experiment.

The confinement quality plays the same crucial role in a stellarator as in a tokamak. Transport analysis on WVII-AS indicates that the electron heat diffusivity χ_e approaches the neoclassical limit in the plasma core; χ_e in the periphery, however, is governed by anomalous processes.

Objectives of Wendelstein VII-X

The overall goal of Wendelstein VII-X is progress in the understanding of physics and engineering relevant to stellarator reactor-grade fusion plasmas, in particular relevant to Advanced Stellarators, continuing and augmenting W VII-AS experience and knowledge.

In particular, the programmatic objectives of Wendelstein VII-X are:

- Achievement of adequate confinement and investigation of plasma transport under reactor relevant conditions, including the confinement properties of fast particles, but avoiding the use of deuterium-tritium mixtures.
- Application of effective non-Ohmic heating methods to generate the plasma and to reach plasma temperatures of several kilo electron volts.
- Investigation of impurity transport and development of means for impurity control.
- Achievement of beta values of 4–5% and analysis of the beta limit.
- Long-term and quasi-stationary operation.
- Study of plasma refueling, exhaust, and plasma-wall interaction under steady state conditions.
- Development of means for proper control of the plasma edge conditions.

Planning activities and theoretical studies over several years have now resulted in the completion of the conceptual design of Wendelstein VII-X. Its dimensions will be considerably larger than those of W VII-AS to provide access to plasma parameter regimes adequate to allow conclusions about the reactor properties of Advanced Stellarators. These considerations have led to the following technical objectives:

- A steady-state magnetic field of 3 T on axis.
- Powerful heating systems for plasma generation and heating (ECRH) and for further heating by NBI and ICRH.
- Optimum access for neutral beam injection.
- Maximum distance between plasma and first wall.
- Flexibility in the magnetic field structure (variation of rotational transform and mirror ratio, position control).

Wendelstein VII-X is a modular Advanced Stellarator realizing a five-period Helias system. In the standard configuration the rotational transform is 0.84 on axis and 1.0 on the boundary, thus providing shear larger than that in W VII-AS but still small enough to avoid major resonances in the confinement region. The equilibrium properties are characterized by strongly reduced Pfirsch-Schlüter currents with the parallel currents less than 75% of the diamagnetic currents. MHD stability with respect to ideal ballooning modes is achieved at an average beta up to 4.3% by providing a vacuum field magnetic well and small Pfirsch-Schlüter currents rather than by magnetic shear. Neoclassical transport is strongly reduced and characterized by an equivalent ripple δ_e less than about 1.5%. The residual bootstrap current is less than 5% of that in an equivalent axisymmetric system with the same rotational transform and aspect ratio.

In the boundary region a separatrix bounded by magnetic islands of corresponding topology could be arranged so that the desired divertor action of this region can be investigated. Experimental flexibility with respect to resonance as well as trapped-particle physics manifests itself in the possibility for variation of the rotational transform by ±20%, of the shear by ±10%, and of the amplitude of the mirror field along the magnetic field up to 10%.

Characteristic Dimensional Data of Wendelstein VII-X

Quantity	Symbol	Value
Average major radius	R_0	5.5 m
Average plasma radius	r_a	0.53 m
Average coil radius	r_c	1.14 m
Min. distance plasma – coils	δ_{pc}	0.29 m
Min. distance plasma – wall	δ_{pw}	0.12 m
Induction on axis	B_0	3.0 T
Max. induction at coils	B_m	6.1 T
Total magnetic energy	W_m	600 MJ
Max. net force (one coil)	Fm	3.6 MN

Performance targets and plasma heating

The objectives of the experiment as stated above require the achievable plasma parameters to be in the following ranges:

Central temperatures: $T_i(0), T_e(0) = 2\text{–}5$ keV
Central electron density: $n_e(0) = (0.1\text{–}2.0) \times 10^{20}$ m^{-3}
Energy confinement time: $\tau_E = 0.1\text{–}0.5$ s
Average beta value: $\langle\beta\rangle \leq 0.05$

These parameters are calculated assuming neoclassical transport and anomalous transport, applying heating powers in two stages as described below.

Heating, stage I:

For determining the confinement capability of the device, about 10 MW of ECRH is required. In order to have the cut-off density not too far below the highest operating density, a frequency of 140 GHz has been selected. This frequency is compatible with a magnetic field strength of 2.5 T.

To increase the experimental flexibility available during this operation stage, it is further planned to start with two NBI systems, which add 3.0–4.5 MW of NBI to the available heating power. Their injection energy of around 50 keV is adequate for perpendicular injection of hydrogen. Furthermore, the 4-MW ICRH installed for W VII-AS and ASDEX will also be made available for Wendelstein VII-X.

Heating, stage II:

For exploring the beta limit of the configuration the heating power has to be increased to 20–25 MW. This upgrading of the available heating power by 10–15 MW will be applied for in a later proposal. ICRH and NBI are the candidates, probably in a combined fashion. The corresponding decisions will and can be made later when more information is available on the influence of these heating systems on the detailed behavior of stellarator plasmas. Production of impurities, additional fueling by NBI, and influence of the heating scheme on the conditions at the plasma edge will be decisive criteria for making the selection. Upgrading the power of ECRH is considered desirable but too expensive in the present stage of ECRH development.

Exhaust experimentation

The development of a proper exhaust technology is one of the tasks for Wendelstein VII-X. The separatrix region of the configuration selected for the experiment has basic properties favorable for this purpose. The geometry of the separatrix region is reasonably insensitive to variations of beta because of the small parallel current density and will favor the diverting of field lines from the plasma boundary. As far as possible, basic properties of this concept will be tested in Wendelstein VII-AS, which has already shown that a concentration of particle and energy fluxes in half-helix-like stripes exists.

Engineering design

Two study contracts on superconducting coil systems have been performed with industry and were evaluated by IPP Garching and KfK Karlsruhe, the latter contributing special experience on superconducting coils for fusion devices, e.g., from the Large Coil Task (LCT).

The following guidelines have been worked out for an optimized engineering design of Wendelstein VII-X:

- The superconducting material for the windings will be arranged as cable-in-conduit, using NbTi at 4 K with forced-flow He cooling.
- The winding technique will be the same as for W VII-AS. A cable jacket in an annealed status during the winding procedure that can be hardened at moderate temperatures combines the two requirements of good workability during construction and sufficient mechanical rigidity for assembly and operation.
- All modular coils and their housings are integrated into a toroidal vault support. The whole unit will be at a temperature of about 4.5 K and represents the cold mass of the machine of about 350 tons, a value similar to that of LCT.
- The cold mass will be isolated in a double-walled modular cryostat; the inner vessel is the plasma chamber, the outer wall envelops the whole magnet system.

On the basis of these guidelines the necessary prototype work was defined: One of the nonplanar coils with housing has to be tested under combined loads simulating the operational ones in magnitude and spatial complexity; a test segment for the cryostat has to serve for optimum detailed design for the complete machine.

F. Rau for the W VII-X Team
Max-Planck Institut für Plasmaphysik
Association EURATOM-IPP
D-8046 Garching, FRG