stellarator news

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TJ-II assembly completed

The TJ-II team is very happy to announce to *Stellarator News* that on Friday, 5 October, the last coil of TJ-II was installed, finalizing TJ-II coil assembly. At this point the central coil system (called the hard core), the poloidal field coils, the toroidal field coils, the vacuum vessel, and the general support structure are in their final position.

The intense assembly phase began in the summer of last year with the positioning of the hard core and the four lower octants of the vacuum vessel. From September 1995 until April 1996, the upper octants were assembled and welded together. After the vacuum vessel had passed vacuum tests, the toroidal field coils were assembled in July and August 1996. At the beginning of October, the outer rings of the general support structure, which carry the outer poloidal field coils, were installed.

During the months ahead, the peripheral systems will be installed. The installation of the four vacuum pumping systems will be done in November 1996. Each of the four pumping units consists of a turbopump and a forepump. The vacuum tests of the vacuum vessel done in June 1996 showed very good vacuum properties and a very low leak

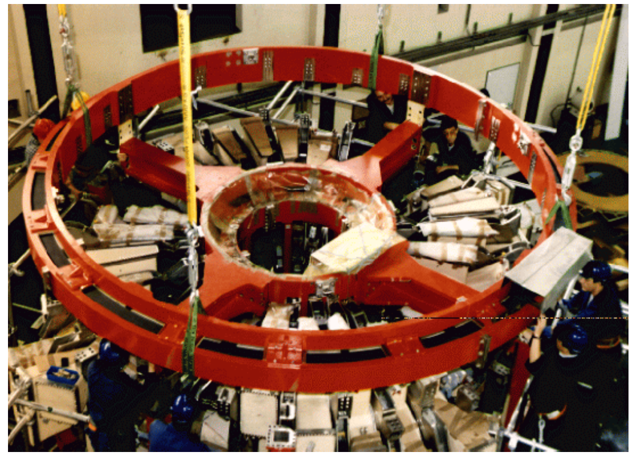

Fig. 2. The picture shows the moment when the outer ring of the support structure holding the vertical field coil was placed in position, completing the coil assembly.

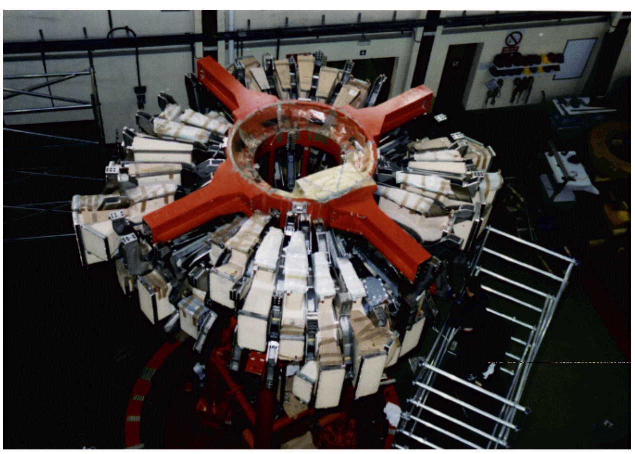

Fig. 1. The helical structure of the TJ-II vacuum chamber can be appreciated in the distribution of the 96 experimental ports

In this issue . . .

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rate (a global leak rate as low as 1×10^{-9} mbar·L/s was measured with just one pump). The connection of the coil systems to the cooling system will be finished in December 1996. The cooling plant itself was commissioned last year. The assembly of the high-power lines in the torus hall is planned for January and February 1997.

The installation of the power supply system commenced only in August of this year because of the delayed availability of the building for this system. Meanwhile all the thyristor converters and the transformers have been put in their position. The no-load breakers and the high-current cables from the experimental site and the site of the power supply have been mounted. In January 1997, the assembly of all the main components, including the motor generator, will be finished. First tests of the power supply system with a DC dummy load are planned for February 1997.

The magnetic field mapping for TJ-II will be performed in January 1997. As the direct currents required for this measurement are rather low, we will supply the magnetic field coils of TJ-II by DC converters fed directly from the grid. The first half of 1997 will be used for the commissioning of the power supply system and the entire experimental device. The first plasma can be expected in summer 1997.

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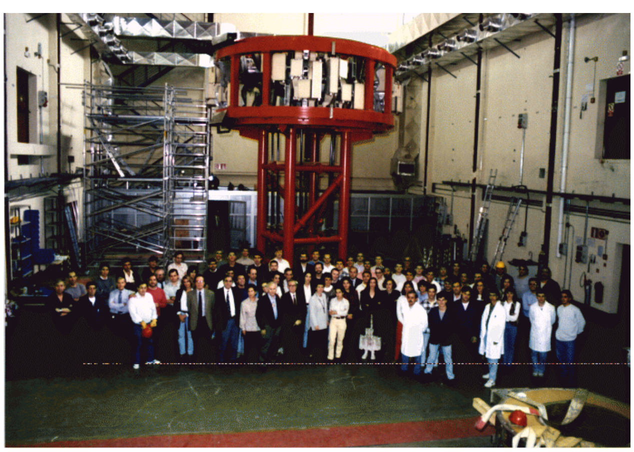

Fig. 3. The TJ-II team standing below TJ-II. An experimental platform beneath TJ-II is presently being installed.

Spherical Stellarator concept

The Spherical Stellarator (SS) concept, proposed in Ref. [1] and further analyzed in Refs. [2–5], represents a novel and promising approach in stellarator research. The three principal characteristics of the SS approach are (a) ultra-low aspect ratio, in the range of $A \sim 1.2–3.5$, (b) relatively simple modular coils, and (c) significant plasma current (i.e., its contribution to the total rotational transform is significant). Our research indicates that the SS concept features many attractive properties of importance to a future fusion reactor. Among these are the following:

- Compact design, making it inexpensive to construct and operate
- Easy access to the plasma
- Simple, toroidally symmetric divertor
- Strong bootstrap current enhancing the vacuum rotational transform
- Good control over the horizontal plasma position and magnetic axis location
- High-beta regimes of operation
- Good particle and energy transport at high beta
- Enough space to install a blanket and to protect the coils (including their central parts) from intense fluxes of particles, heat, and neutrons
- Easy plasma start-up
- No need, in principle, for the ohmic current transformer or for an auxiliary current drive (CD) system

The three principal characteristics of the SS concept are rather unusual for a standard stellarator approach, which normally features a large aspect ratio, $A \sim 10$, complicated three-dimensional (3-D) coils, and an almost currentless plasma.

The SS concept can be viewed as a synthesis of the two leading concepts for magnetic plasma confinement: stellarators and tokamaks. Tokamaks normally feature much lower aspect ratios than stellarators, much simpler planar coils, and a strong plasma current. This is especially true for the relatively recently proposed concept of the Spherical Tokamak (ST), which promises to be more compact, less expensive, less disruptive, capable of achieving higher β, etc., than a standard tokamak. The SS concept appeared partially to overcome some severe problems of ST such as: problems of plasma startup (for an ST-ractor, the central ohmic current transformer cannot be used), problems of long-pulse or steady-state operation, problems of the central post, and danger of a large plasma current.

The plasma current can be supplied in an SS by the bootstrap effect alone [3,4] in a relatively large device with high beta. However, in relatively small initial experiments, the bootstrap current will be small and other

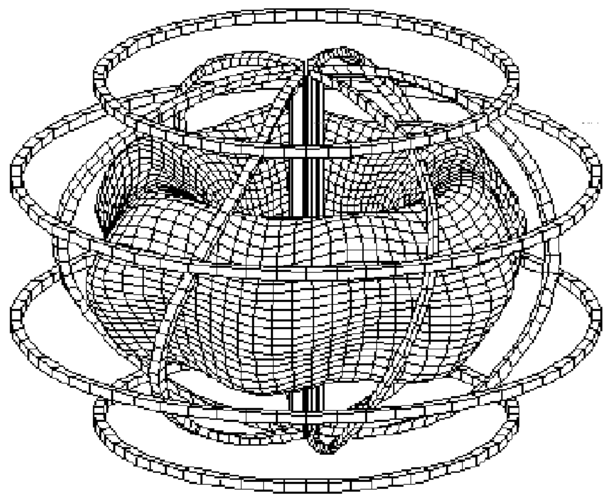

Fig. 1. Configuration of an SS as given in Ref. 1. Shown are the coil system and the last closed vacuum flux surface.

means to excite the plasma current, such as ohmic or auxiliary CD, will be necessary. Such a device will be a stellarator-tokamak hybrid.

Different SS-type devices are under investigation [6] as part of the SMARTH (SMall Aspect Ratio Toroidal Hybrid) project. Present participants are ORNL, the University of Texas at Austin, Auburn University, the University of Tennessee, and the University of Wisconsin. Many scientists from other institutions have been helping us by giving good advice and comments and by supplying their numerical codes or the results of calculations.

This contribution documents the results obtained for the original SS configuration of Ref. 1 (see Fig. 1) with bootstrap current added [3,4]. The size of the device and the plasma parameters are chosen to correspond to the SS2 device of Ref. 4: a_p = 1 m, R_0 = 2 m, B_0 = 1 T, $n_e = 10^{20}$ m^{-3}, T_e = 1 keV, β = 7.5%, I_{bs} = 0.9 MA, P_{heat} = 30 MW. In such a device, according to bootstrap current calculations and to the Large Helical Device (LHD) scaling law, it is possible to reach good plasma parameters without ohmic or auxiliary CD.

Figure 2 shows the radial profile of the vacuum rotational transform (ι) together with its internal (inboard) and external (outbord) components [1] as well as the total rotational transform. One can see that the bootstrap current contribution is significant.

Figure 3 demonstrates the results of Monte Carlo simulations for 640 test protons with energy E = 1 keV in this device. No radial electric field was applied. The simulation time was chosen to be two collision times. The Boozer coordinates are used, so a concentric circle with a normalized radius, ρ, represents a flux surface with the corresponding average normalized minor radius. The density and temperature radial profiles have been chosen to

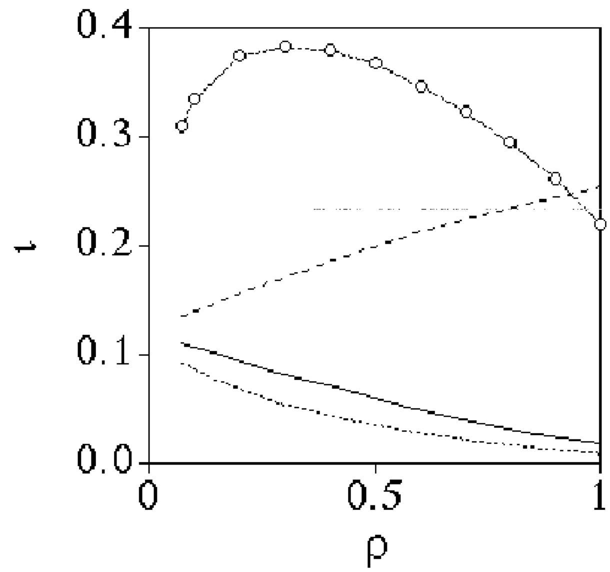

Fig. 2. Radial variation of the vacuum rotational transform (solid curve) and its external (dashed) and internal (dotted) components. The total rotational transform for the case with strong bootstrap current is shown by the curve with circles.

be parabolic. Figure 4 shows the statistics of particle distribution over the flux surfaces for the same case.

Similar calculations were carried out for ions and electrons and for different minor radii. For comparison, calculations have been carried out also for an equivalent tokamak, i.e., for an axisymmetric plasma with the same minor and major radii and the same temperature and density, but with the rotational transform of a typical tokamak: $\iota(\rho) = 1 - 2\rho^2/3$. The results, shown in Fig. 5, indicate that neoclassical diffusion coefficients near the plasma edge in an SS are almost the same as in a

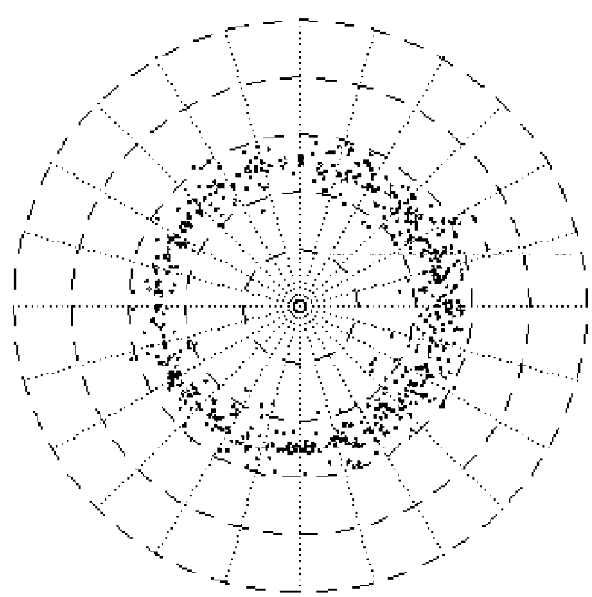

Fig. 3. Final locations of 640 test protons. The starting radius is ρ = 0.5.

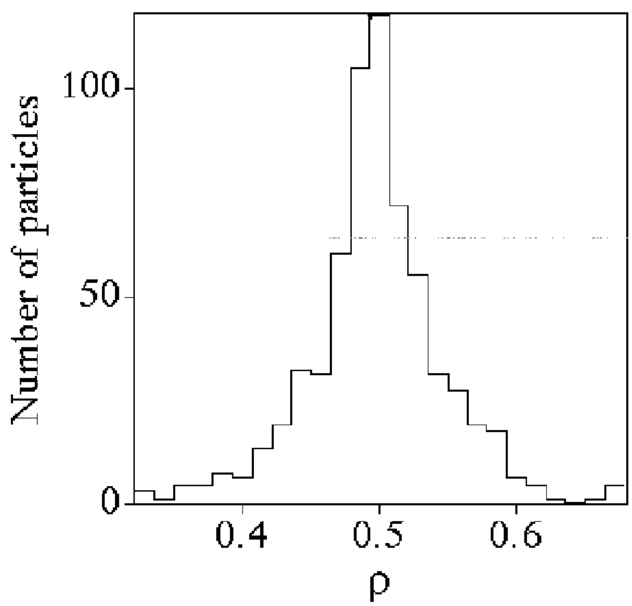

Fig. 4. Distribution of protons over the flux surfaces.

tokamak, while near the magnetic axis diffusion in an SS is somewhat larger. This is a very promising result, showing that transport in SS might be almost as good as in a tokamak and that a transport barrier exists at the plasma edge.

Another important result (the detailed description will be given elsewhere) was obtained at our request by W. A. Cooper running his code TERPSICHORE [7] for ballooning and Mercier stability criteria. His calculations for the SS configuration considered here, for a volume average beta $\langle\beta\rangle$ = 7.5% and a hollow current profile, show 3-D ideal MHD stability at all radii.

In conclusion, SS research has only recently begun, and the particular SS configuration discussed here is probably far from optimal. Still, it demonstrates several attractive features. We see the SS approach as an unexplored area of magnetic confinement with the potential to develop physics which might provide significant advantages for a future thermonuclear reactor. A broad base of coherent theoretical and experimental research is necessary for advancing this novel concept to its full potential.

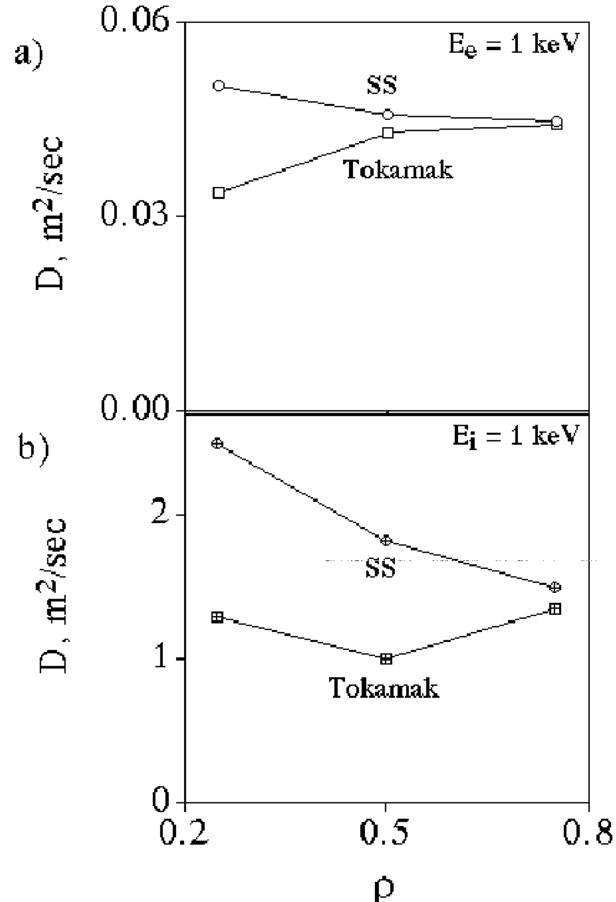

Fig. 5. Comparison of diffusion coefficients for (a) electrons and (b) protons in an SS and in an equivalent tokamak.

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European stellarator contributions to the 19th SOFT, Lisboa, Portugal, 16–20 September 1996

The 19th Symposium on Fusion Technology (SOFT) was held in the *Culturgest Congress Center* of the *Caixa Geral de Depósitos* in Lisboa, organized by the Portuguese Centro de Fusão Nuclear on behalf of the Association EURATOM-IST (Instituto Superior Técnico). A World Wide Web site gives further information on the general agenda of this meeting; see the URL

http://www.cfn.ist.utl.pt/english/soft96/.

The majority of the contributions came from the European fusion laboratories and facilities, but there were also a number of papers from other parts of the world, including the United States, Canada, Japan, the states of the former Soviet Union, India, Korea, and Brazil.

The conference opened with the presentation of invited papers. Ch. Maisonnier discussed the European fusion program. Three invited papers on ITER followed, G. Grieger gave an overview of the Wendelstein 7-X project. Other invited and contributed papers addressed the design, construction and operation of fusion experiments and the technologies that are being developed for next-step devices and future fusion reactors. Most of the contributions dealt with tokamak devices, as well as with their environmental components. Stellarator configurations were treated in a total of 24 papers. The Japanese Large Helical Device (LHD) was discussed in nine papers. The European stellarator contributions dealt with the Spanish Flexible Heliac TJ-II (five contributions) and the German Advanced Stellarator Wendelstein 7-X (W7-X, nine contributions). One paper discussed the upgrading of the neutral beam injection (NBI) power for the Garching W7-AS stellarator. TJ-II is treated in the first part of this overview, because this experiment is in an advanced state of construction. Information about these stellarators appears on the World Wide Web at:

http://www.nifs.ac.jp/~LHDhp/index.htm
http://www-fusion.ciemat.es/fusion/TJII/TJII.htm
http://www.ipp.mpg.de/ipp/w7x.eng.html
http://www.ipp.mpg.de/ipp/w7as.eng.html

Flexible Heliac TJ-II

The final assembly and the present status of TJ-II were presented by J. Botija et al. Additional details are presented in the lead article of this issue. The assembly of the TJ-II device is characterized by its complicated geometry, its narrow tolerances, the small clearances between components, and the high geometrical precision required. An overall view of TJ-II is shown in Fig. 1.

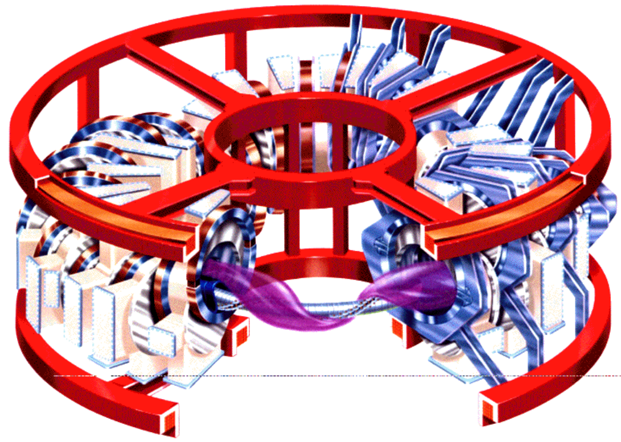

Fig. 1. An overall view of TJ-II.

L. Kirpitchev at al. discussed the monitoring and digital control system for the 130-MVA pulse generator system of TJ-II. The magnet system of TJ-II consists of seven independent coil systems which allow the creation of a wide range of magnetic field configurations. These seven coil systems are fed separately from seven digitally controlled 12-pulse converters. The output DC currents range from 5 kA to 35 kA and are continuously controllable between zero and their rated maximum value. The DC output voltage of the converters varies from 150 V to 1050 V. The converters are supplied by a synchronous generator which has a nominal output pulse power of 130 MVA for 3 seconds and an energy of 100 MJ per pulse.

The monitoring and control system comprises one central computer and two satellites. The central computer is responsible for the system management and data storage; it provides database and server capabilities for the user interfaces. One of the satellite computers does the input-output control and data acquisition for the generator; the other one provides these functions for the converters. Unix™ work stations will be used as operator interfaces for the local control, as well as for the remote control of the power supply system from the central control room of TJ-II.

A simulation of the complete power supply system for TJ-II was presented by J. Acero et al. of the JEMA S.A. company. Key features included in the simulation are (i) the 12 pulse rectifiers, (ii) the input power transformers, (iii) the control current circuits, (iv) the control coils between the parallel converters, (v) the stellarator coil system including temperature-dependent resistance and magnetic coupling, and (vi) a new synchronous machine model based on flux equations and including variable magnetic saturation. These modules have been combined to carry out a complete simulation of the system in order to analyze its overall behavior. The simulation results show that the model complies with existing equipment and previous calculations. The model can now be used to simulate other load conditions, faults, etc.

R. Martin et al. reported on an electron cyclotron resonance heating (ECRH) system for the TJ-II experiment. The special microwave power modulation system was designed to investigate the anomalous transport and low-frequency drift turbulence in the plasma. The system allows modulation of the output voltage with respect to the stable mean level in the range 30–70 kV with an amplitude of up to 5 kV. A 100% modulation in microwave power can be produced. A first transmission line has been designed to launch the microwave beam into the plasma with a linear polarization. The construction of this transmission line has been completed, and the mirrors and adjustment devices are ready for installation and for starting cold tests. The output wave beam after the second transmission line can be launched at an angle of ±15 degrees with respect to the perpendicular direction and has an elliptical polarization for excitation of the X-mode into the plasma of TJ-II with high efficiency. Each transmission line is fed by a 400-kW, 0.5-s gyrotron at 53.2 GHz. Owing to the internal converter, the gyrotrons have an output wave beam in the form of a free space TEM_{00} mode. The quasioptical transmission lines attain the features of low ohmic losses, low diffraction losses, high-power capability, inherent mode filtering, and a relatively simple design.

Engineering aspects of an advanced heavy ion beam diagnostic for the TJ-II stellarator were presented by A. Malaquias et al. The diagnostic has been developed to simultaneously use two different detection systems for the secondary ions: a multiple-cell array detector and a Proca-Green electrostatic energy analyzer. This innovative design is based on numerical simulations of ion trajectories and beam attenuation for different experimental conditions of TJ-II, taking into account the 3-D magnetic field configuration and the equilibrium profiles of the plasma density and electron temperature. The multiple-cell array detector, placed in a vertical plane at a distance of 16 cm from the TJ-II output port, has overall dimensions of 40 cm × 20 cm and about 100 individual copper cells. Its position was optimized in order to collect all of the secondary ions and to reduce the overlapping effect of the incoming tertiary ions. The Proca-Green electrostatic energy analyzer is placed at a distance of 1 m from the output port of TJ-II. The system has about 150 channels.

Garching Stellarators

The invited lecture on stellarators was presented by G. Grieger of IPP Garching on “The Wendelstein 7-X Project.” Approval for this device was given in 1995, and planning work on the site in Greifswald in Mecklenburg-Vorpommern has started.

Grieger pointed out that there is general agreement that concept improvements for a future fusion reactor are needed. The stellarator concept promises these desired improvements, removing the limitations imposed by strong net toroidal current and the correlated danger of disruptions, by allowing steady-state operation of the fusion power plant. The HELIAS concept developed at IPP Garching embodies the advantages of the stellarator concept by optimization of the magnetic configuration. HELIAS systems are characterized by small neoclassical losses. There is no bootstrap current and no need for current drive and feedback position control. There is also no density limit except for the usual limit of impurity concentration. In essence, operation of such power stations is expected to be much more benign and to require less circulating power than otherwise possible.

The Wendelstein 7-X device is designed to provide an integral concept test of such stellarators. It possesses the magnetic configuration and the potential for steady-state operation. The coil system of W7-X will beentirely superconducting, and the ECRH heating system will be capable of continuous wave (CW) operation. The available range of operating parameters will approach the reactor values of the most essential dimensionless parameters: the normalized mean free path, the ratio between plasma radius and ion gyroradius, and the relative plasma pressure beta. The behavior of alpha particles will be studied by injection of high-energy particles.

Newly developed superconducting cable allows the use of NbTi even under power plant conditions. The initial divertor concept is a first solution which permits full collection of particles under all operating conditions and at tolerable power densities; the final divertor system will be developed using W7-X operating experience. Numerical plasma parameters, such as the ion and electron temperature and the plasma density, to be obtained in various scenarios of W7-X operation are listed in *Stellarator News*, Issue 47.

Grieger’s invited lecture was accompanied by a number of poster presentations on the development of W7-X. These presentations treated specific issues of W7-X such as the coil system and its mechanical support; the magnet system of a future fusion reactor; the mechanical stability of the W7-X vacuum vessel; details of the full-size W7-X DEMO Coil, which is presently under construction, presented by the Noell company; the divertor design for W7-X, including detailed questions of the target plate prototypes; and the design of the 140-GHz, 10-MW CW ECRH heating system.

Results of the conductor development for W7-X were given by W. Maurer et al. A cable-in-conduit conductor is used for W7-X, made from a 4-stage cable of 192 superconducting NbTi/Cu strands in a jacket of a special aluminum alloy, at unit lengths of about 200 m. This type of conductor is soft for winding the non-planar coils and is hardened afterwards. This conductor is available from two European companies that use different manufacturing processes. Initial tests performed at the Forschungszentrum Karlsruhe have yielded the single-strand behavior and the performance of conductor triplets versus temperature and magnetic field by observing the critical current.

The second part of the test program concerned two solenoids wound from an unit length of the conductor, demonstrating the quench current vs magnetic field, ramp rate, sweeping, and safety discharges. These tests confirm the conductor principle chosen for W7-X, although some degradation of the test coil quench current was seen. Reasons for that were found, but a degradation during conductor production and solenoid winding remains, representing about 10% of the sum of the critical current of virgin strands. A degradation of that order of magnitude is taken into account for the design of the final conductor for W7-X.

A local stress analysis of a coil winding pack of W7-X was presented by N. Jaksic et al. The coil system of W7-X consists of 50 nonplanar field coils and 20 additional planar coils. There are only 5 different coil shapes in the nonplanar coil system and 2 different shapes in the planar one. The magnetic force density distributions are locally different. Nonplanar coil 3 was selected to perform a local stress analysis with high resolution. A very fine subdivision of one slice of the winding pack cross section was carried out, considering the 120 conductors, their aluminum alloy jacket, and the surrounding insulation, as shown in Fig. 2. The magnetic forces on this modular coil were calculated for the individual 120 windings with the EFFI code, taking into account the entire coil system for the standard case of 3 T on axis.

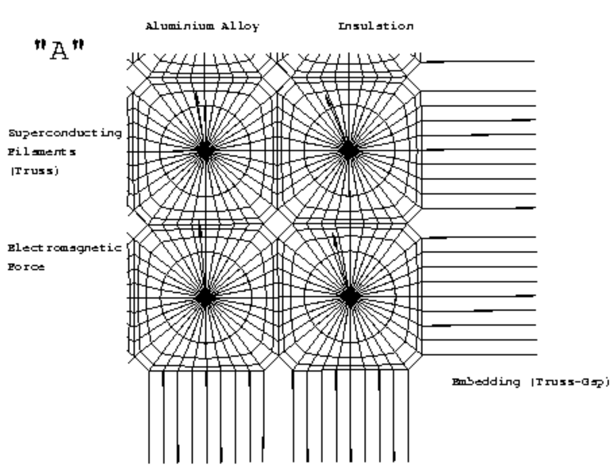

Fig. 2. Detail "A" shows the FE subdivision of the coil crosssection close to the coil corner.

Because of the different local coil curvatures and the slightly helical arrangement of the coils, these forces are inhomogeneously distributed. A scheme of mutual support between the coils of one field period was provided in order to balance the magnetic forces of the coil system. The local magnetic forces were inputs for the stress analysis. The finite element (FE) calculation of the mechanical stress distribution inside the conductors and their insulation was done using the ADINA code. The FE model of the considered slice consists of 31,596 nodes totally. The results of this local analysis are in good agreement with those of the earlier global analysis. The maximum effective stress (about 200 MPa) of the aluminum alloy is far below technical limits. For the insulation material between the conductors the Tsai-Wu criterion was calculated. It also indicates a sufficient safety value.

Issues of the coil system of a future fusion reactor were discussed by E. Harmeyer et al. in a contribution on the modular coils of a Helias reactor (HSR). The coil system of HSR is a scaled version of the magnetic configuration of W7-X. The magnetic field is generated by a single set of 50 modular nonplanar coils. Sufficient space for blanket and shield is provided between coils and plasma. The size of the system is furthermore determined by sufficient plasma confinement to reach ignition. The maximum magnetic field at the coils is about 10.6 T, which allows the use of NbTi technology. The system considered has a major radius of 22 m, a mean coil radius of 5 m, and an average magnetic field on axis of 5 T at a stored magnetic energy of 110 GJ.

The 50 modular nonplanar coils that generate the magnetic field have only 5 different coil shapes. The magnetic forces of the modular coils are calculated using the EFFI code, at a refined subdivision of 4×4 elements over the coil crosssection. The maximum net coil force amounts to about 140 MN in HSR. The local magnetic force densities are transformed to nodal forces, acting at the finite-element model by means of shape functions. The coils of HSR were surrounded by a strong stainless steel housing,

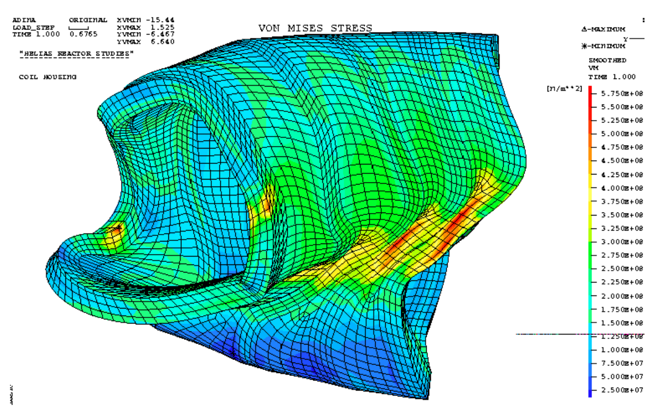

Fig. 3. Von Mises stress distribution in the toroidal shell of HSR.

with thicknesses of 30 cm at the outer coil face and of 15 cm at the three other sides.

For the nonlinear FE calculations the ADINA code was used, covering half of a field period and employing the stellarator symmetry. “Contact elements” derived from a nonlinear stress-strain characteristic were introduced between the coil winding pack and the coil housing. The coils of a field period are connected to a module and supported by a common vault. As a first step, the intercoil structure was modeled uniformly between the coils as a toroidal shell. For the material data of a conductor developed earlier as input for the winding pack, the results of the FE computations show that the values obtained are within the technical limits. The maximum equivalent stress in the support structure of stainless steel amounts to about 580 MPa, see Fig. 3. Further iteration steps must be done, varying the geometry of the coil support structure in order to minimize the amount of structural material, to equalize the stress distributions, and to account for the necessary ports of HSR.

The full-size nonplanar test coil for W7-X, the W7-X DEMO Coil, which is now under construction, was described in two presentations made by H. Kronhardt et al. of the Noell company at Wuerzburg, Germany. The first one described the determination of compound properties for superconducting magnets by a combined theoretical and experimental method, and the second one treated test results of a new type of coil embedding.

The FE calculations for large superconducting magnets are generally carried out using empirical values for the compound material constants such as Young’s modulus, shear modulus, Poisson’s ratio, and the thermal expansion coefficients. These values are usually obtained by means of linear mixing rules, which can only be applied conditionally, or which are derived from similarly constructed magnets. It is extremely difficult to verify these values, so verification is generally carried out for special applications only. The report showed comprehensive results from a combined theoretical and experimental method for determining composite properties. The calculation steps necessary for an exact determination of the material and composite data were described using the coil winding of the W7-X DEMO Coil as an example. A correction of calculated values with proven experimental values, combined with additional calculations using relations obtained between several properties, supplied reliable results. These are needed for further FE analysis of the stress distribution in the coil system.

In the second contribution, the embedding of the winding pack in the steel housing for the W7-X DEMO Coil was treated. It was pointed out that the embedding material guarantees a close linkage between the housing and the winding pack at low temperatures and also provides the best possible heat exchange between the components during both operation and the cooling phase. The main task of the coil embedding material is to transfer forces induced in the windings to the coil housing and support structure. The coil embedding material therefore is mechanically highly stressed. The manufacturing process of the embedding allows the creation of specific temperature-dependent initial stresses within the coils. Because of the highly shaped coil form, the embedding can be manufactured only after sealing the coil housing. The requirements of the embedding material were defined on the basis of completed FE analyses. The embedding material must be able to withstand tensile and pressure stresses of about 110 MPa; initial stresses at room temperature of about 50 MPa can be applied to the winding pack. An outlook was given of how the new embedding design can be applied to planar coils such as in tokamaks.

A buckling analysis of the W7-X inner vacuum vessel (test cryostat) has been carried out by J. Simon-Weidner et al. for half a field period, which is one-tenth of the total vacuum vessel of W7-X. General assumptions for the calculation of the stainless steel test cryostat were soft ends excluding the lids, taking into account the port for neutral beam injection, a wall thickness of 15 mm, a maximum outside pressure of 1 bar, and the use of a doubled gravity constant in order to consider the additional weight of the inner vessel components. The buckling analysis was performed with the FE code ADINA. The results of the calculations show loading factors for the first 10 buckling modes which are within safe limits. In Fig. 4 the effective stress distribution of the W7-X test cryostat is shown. This test cryostat is now under construction. The safety of this component was confirmed by another independent calculation.

H. Greuner et al. discussed two aspects of the W7-X divertor: the general divertor engineering and the design, manufacturing, and testing of target plate prototypes. A divertor system capable of steady-state operation with a

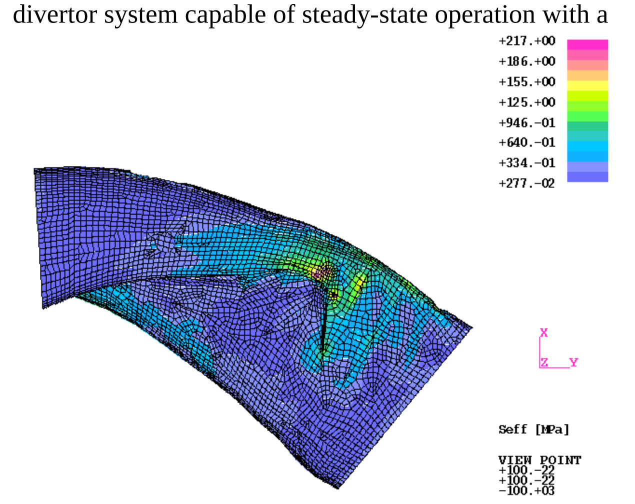

Fig. 4. Effective stress distribution in the W7-X test cryostat.

heating power of 10 MW has been developed. In relation to the five-fold symmetry of the magnetic configuration, 10 divertor units are arranged to achieve effective particle and energy exhaust for a wide range of operating parameters. The divertor units combine target plates, baffle plates, and a turbomolecular pumping system supplemented by cryogenic panels. Control coils are integrated into the divertor units in order to adjust the magnetic properties of the boundary and to influence the plasma outflow. Alternating currents in the control coils with frequencies of up to 20 Hz superimposed on the stationary direct currents make it possible toenlarge the deposition area of the plasma flow onto the target plates.

The modular arrangement of divertor target plates and their cooling lines is shown in Fig. 5. The general layout of the W7-X divertor system was depicted in *Stellarator News*, Issue 47, Fig. 7. The target plates are designed for a stationary power load of up to 10 MW/m^2. They are critical components, consisting of single actively cooled "standard" elements of 50 mm width. Their lengths vary from 160 to 480 mm. Most elements are bent at an angle of 2 to 20 degrees. In a first step of the R&D program, four straight prototypes of W7-X target elements based on the flat channel concept, were designed and were manufactured by two different companies. They are being tested in the electron beam facility JUDITH of KFA Jülich.

L. Empacher et al. presented the conceptual design of the 10-MW CW ECRH heating system for W7-X, which will operating at 140 GHz, the frequency for the second harmonic electron cyclotron resonance at 2.5 T. The design concept of the system is based on the guideline of simplifying the system to the largest possible extent, which results in a cost-effective and reliable solution. The generator system consists of 10 gyrotrons with a power output of 1 MW each in CW operation (30-minute discharges). The high voltage power supplies and other auxiliary systems, such as cooling, liquid helium, and liquid nitrogen supplies, will be installed next to the gyrotrons.

The microwaves will be transmitted by free space propagation with the help of reflecting optical elements. The beams from the gyrotrons are transformed by two matching mirrors into axisymmetric Gaussian beams having the appropriate parameters. After being reflected from a pair of polarizing mirrors, the beams are combined on two-plane mirror arrays and directed into two multibeam waveguides for joint transmission into the torus hall. Near the experiment, the beams are separated again by beam distribution optics and directed into the plasma by means of plug-in launchers. These launchers will permit vertical and horizontal beam positioning to ensure the flexibility needed for the physics program. Pick-up waveguides inside the vessel, opposite the antennas, will be installed

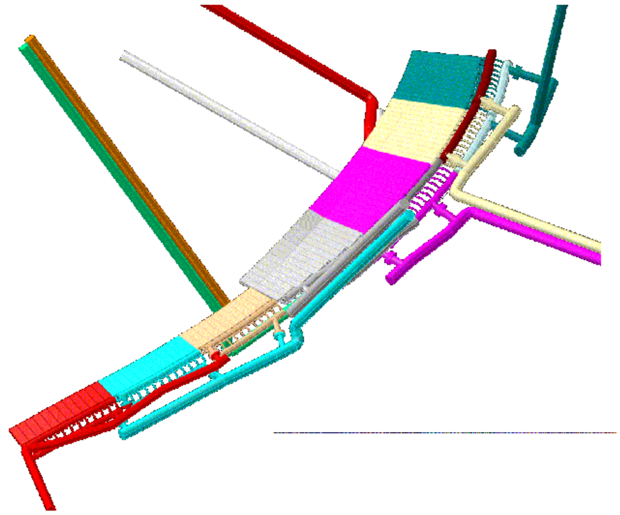

Fig. 5. Arrangement of one module of divertor target plates.

to determine beam parameters as well as absorption and reflection in the plasma.

To ensure reliable operation of the ECRH system, a variety of diagnostic techniques will be used. Two lower frequency gyrotrons are envisaged for plasma start-up in high-beta experiments at low magnetic field.

Upgrading of the neutral beam injection power for the W7-AS stellarator was discussed by W. Ott et al. In earlier NBI experiments at W7-AS, two injector systems with opposite directions were used, yielding 1.5 MW in total. In order to approach increased beta values, the available NBI power was upgraded by doubling the number of ion sources from four to eight and increasing the acceleration voltage from 45 kV to 50 kV. This enhancement also appears to have improved the beam quality. Thus a total of 3.5 MW of NBI power into the torus was attained.

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