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 41 September 1995

E-Mail: jar@ornl.gov Phone: (423) 574-1306

Stellarator News is on the Web

Stellarator News now has its own Web page on the Oak Ridge National Laboratory Web Server. The Web address (URL) for this page is

http://www.ornl.gov/fed/stelnews/stelnews.html

On this web page are back issues of *Stellarator News* in Adobe Portable Document Format (PDF) format, PDF files of ORNL stellarator articles, and links to other stellarator home pages throughout the world.

PDF files can be viewed and printed using a free Adobe Acrobat Reader that may be downloaded from

ftp://ftp.adobe.com

Please send any updates and additions to the editor who will endeavor to make this page useful to the stellarator community.

In this issue . . .

Measurement and calculation of radial electric fields in W7-AS

According to neoclassical transport, the radial electric field plays a decisive role in confinement. In the presence of an electric field, especially in the $1/\xi$ regime, strongly reduced transport matrix coefficients are expected. This effect is much more pronounced for the ions than for the electrons.

For fields higher than about 100 V/cm, even the plateau regime for the ions is affected. In addition, strongly reduced transport is expected for the electron root solution, which should be accompanied by strong positive fields. Because the formation of the electric field depends on the radial transport, the simultaneous investigation of particle transport and the fields allows for sensitive tests of neoclassical theory.

To measure the radial electric fields in the stellarator W7-AS we make use of active charge exchange recombination spectroscopy, CXRS, on He III. To obtain stationary conditions, a short He gas puff is appplied at the

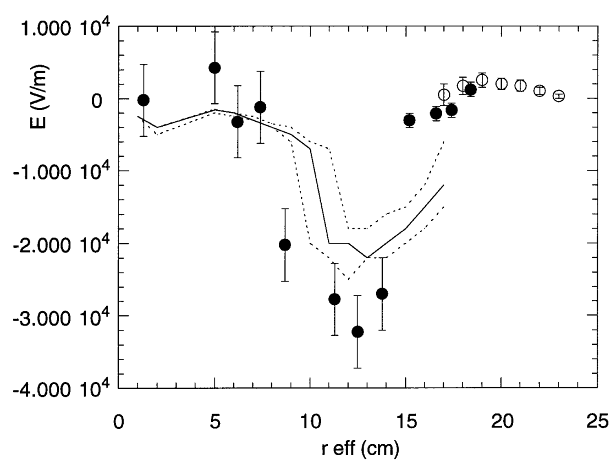

Fig. 1. Radial electric field versus minor effective radius. Dots (spectroscopy) and circles (Langmuir probe) show the result of measurements; the solid line, the neoclassical calculation. The broken lines show the interval of reliability for the calculation. W7-AS shots 30097–30106, $T_e(0)$ = 900eV, $T_i(0)$ = 600eV, mean $n_e = 3 \times 10^{19}$ m^{-3}, B = 2.5 T, 140 GHz ECRH discharges at 400kW.

beginning of a discharge to maintain a He concentration of about 1%. Because the recycling coefficient for He is approximately 1, this level does not change during the discharge. Then spectroscopic measurements of the relevant parameters are performed on this tracer impurity.

A pulsed diagnostic neutral beam injector excites the charge exchange (CX) line radiation. From the Doppler line broadening and the line intensity, the ion temperature and the He III density can be evaluated. Using these results, the ion diamagnetic pressure gradient term can be calculated. This term enters together with the radial electric field and the plasma rotation velocity into the moment balance equation. The rotation velocity is determined by measurement of the CX Doppler line shift. Because the toroidal as well as the poloidal rotation velocities play a role, two independent spectroscopic systems are installed for the observation of the respective velocity components.

In parallel, the electric field is calculated by means of the DKES code, which evaluates the radial proton and electron fluxes within the framework of neoclassical transport theory. Information on the density and temperature profiles as well as the full representation of the magnetic field in Fourier components are the numerical inputs. Charged radial impurity fluxes are calculated by the IONEQ code, which also assumes neoclassical transport. All charged radial fluxes enter the ambipolarity condition, which determines all possible roots for the electric field.

The He III density profile is evaluated from the CXRS measurements by a recursive algorithm, which determines the attenuation of the diagnostic neutral beam by the plasma. This measured profile is compared with neoclassical IONEQ transport calculations to investigate whether neoclassical processes govern radial impurity particle transport, or whether an anomalous contribution also has to be taken into account.

Up to three roots for the radial electric field are expected: the stable electron root, the ion root, and a third unstable solution. For our neoclassical DKES calculations, however, we find only one possible root for almost all cases under investigation. The calculation predicts a narrow radial region with three solutions only for some electron cyclotron resonant heating (ECRH) discharges.

Figure 1 shows the results of an electric field measurement (closed and open circles) in comparison with the neoclassical calculation (solid line) as a function of the minor effective radius in W7-AS. The open circles result from Langmuir probe measurements [1]. Measurement errors of ±20% are assumed for the input of DKES, and the field is calculated for these error data. The result of that calculation is shown as broken lines.

The result of the measurement is consistent with the calculation. The shape of the field profile is typical for W7-AS, as confirmed by measurements for about 25 different discharges, including purely ECRH or neutral beam injection (NBI) heating scenarios as well as combined heating phases. We find small field values near the plasma center, a negative maximum at about 0.7 times the minor radius, with values for the field between −50 V/cm and −300 V/cm, depending on the density and temperature; small values again near the plasma edge; and small positive values outside the plasma.

All the measurements provide results for the field that are consistent with the ion root solution of the calculation. We never find the electron root solution. The only case with strong positive fields can be observed during a short (about 20 ms) transient phase directly after the ECRH is switched on. But during that phase we have no stationary plasma conditions, therefore an interpretation in terms of stable and stationary roots is not possible.

For the He III density profiles we also find consistency between the measurements and the neoclassical calculations, which indicates that we need no anomalous contribution to describe the impurity transport in W7-AS.

For the case of high $T_e(0)$ (more than about 2 keV), low $T_i(0)$ (less than about 300 eV) and small $n_e(0)$ (less than about 10^{19} m^{-3}), we find from the calculations that even the ion root solution can show small positive values (about +10 V/cm) near the plasma center. The appearance of this effect correlates with the measurement of slightly hollow He III density profiles. Actually the profiles are more hollow than predicted by the neoclassical theory for these cases. This might possibly point to the favorable effect of an additional outward convection of impurities away from the plasma center.

References:
[1]. Grigull, P., private communication.

J. Baldzuhn for the W7-AS Team IPP Garching
EURATOM Association
Germany
E-Mail: baldzuhn@ipp-garching.mpg.de
Phone: 0049-89-3299-1194

Summary of Kurchatov group reports presented at the 10th International Stellarator Conference, Madrid, May 1995

The aim of the report "The Characteristic Features of the Plasma Equilibrium and Stability in Quasisymmetric Configurations" by M. Yu. Isaev, M. I. Mikhailov, V. D. Shafranov, and A. A. Subbotin, is to elucidate the characteristic features of the plasma equilibrium and stability in shearless quasisymmetric (QS) stellarators [1]. For investigations of QS systems over a wide region of different parameters, the paraxial approximation method can be used.

First order calculations and three-dimensional (3D) results [1,2] show that different types of QS configurations exist. The type is defined by the cross-section ellipse rotation number n_1 with respect to the principal normal at a system period.

For small values of system periods N and initial elongation of the magnetic surface cross-section E_0 systems with n_1 = □1/2 (Helias-like) exist. It is difficult to produce a magnetic well in such systems because of the rotation of the magnetic surface cross-section with respect to the principal normal to the magnetic axis. In this regime, the authors find QS systems with high values of equilibrium beta limits (β = 50% for N = 10, E_0 = 2.4 rN/R = 0.2), but without stability even for small beta (see [1]).

For the large values of the period number N and initial values of ellipticity E_0, QS configurations with $n_1 = 0$ (Heliac-like) exist [2]. This type of region grows with an increase of the parameter rN/R (less symmetry destruction), where r and R are minor and major radii of the underlying torus. In the QS configurations with n_1 = 0 one can get close to the straight helical system optimal values of E_0 and rN/R only for large numbers of field period, N. Nevertheless, in systems with $n_1 = 0$, even with small N, equilibrium and stability beta limits are large (β = 7% for N = 4, rN/R = 1 and E_0 = 4.5).

Results

- Fulfillment of the QS condition yields configurations with high equilibrium beta limit for both n_1 = 0 and n_1 = □1/2 types of QS stellarators.
- The possibility of creating a magnetic well is rather simply realized in the $n_1 = 0$ type of systems. So in this case Mercier stability can be achieved for large beta. For the n_1 = □1/2 type of system, QS configurations with a magnetic well were not found.

In the paper "The Effect of Shearless Stellarator Rotational Transform on the Tokamak Plasma Stability," by M. I. Mikhailov, V. D. Shafranov, and A. A. Subbotin, the stability of the straight pressureless current column with an external helical field was considered in the stellarator approximation. The Principle of Successive Current Layers (SCL), developed for tokamaks in Ref. [3], is used for the analysis. The generalization of this principle is presented for the case of a current column with a helical field and a conducting shell. It was shown that the most dangerous ideal and tearing modes with m/n = 2/1, 3/2, 4/3 can be stabilized by a helical field even in configurations with total rotational transform on the magnetic axis equal to unity. Note that in a pure tokamak it is impossible to stabilize the corresponding ideal modes when the rotational transform on the axis is equal to unity, which follows from the SCL principle [3].

The result obtained shows that both ideal and tearing 2/1 modes can be stabilized by imposing a small stellarator rotational transform, $\iota_h \sim 0.1 - 0.2$, over a wide region of total current values. This does not contradict with well-known observations on W7-A [2] where discharges were shown to became disruption-free at $\iota_h > 0.15$.

References:

[1]. Nuhrenberg J., Zille R., Phys. Lett. A. **129**, (1988) 113.

[2]. Isaev M.Yu., Mikhailov M.I., Shafranov V.D., Plasma Physics Reports **20**, (1994) 315.

[3]. Zakharov L.E., Fizika Plasmy **7**, (1981) 1295.

[4]. WVII-A Team. "Proc. Seventh Int. Conf. on Controlled Fusion (Innsbruck, 1978)" **2**, 265.

M. Yu.Isaev
Russian Research Center "Kurchatov Institute"
Institute of Nuclear Fusion
Moscow, Russia 123182

FAX: 095- 9430073
E-mail: isaev@qq.nfi.kiae.su

Errata

In the last issue of *Stellarator News*, the article about H1, said, "In quasicontinuous mode (continuous $B_0 > 2$ T, pulsed plasma)." The field should have been $B_0 < 0.2$T.

ORNL Area Code Changed

Effective September 11, 1995, the area code of all East Tennessee telephone numbers changed from 615 to 423.

Garching contributions to the Tenth International Conference on Stellarators: W7-AS, W7-X and HSR

Twelve papers were presented by IPP Garching as oral contributions at the meeting; another six papers were given as posters. This summary begins with confinement issues as a major field of interest, followed by discussions of island effects and aspects of the Helias reactor, irrespective of the sequence in the program at the meeting. Contributions by other institutions, co-authored by members of IPP Garching, are not reported here.

Results of experiments in W7-AS to achieve both high ion and electron temperatures above 1 keV in the same discharge were presented in a poster by M. Kick. Peak values of $T_i(0)$ = 1.35 keV and $T_e(0)$ = 1.75 keV were found at 2.5 T in W7-AS for ι = 0.35 with an inward-shifted axis position, using two neutral beam sources in the co direction combined with 140 GHz ECRH. An energy balance of the discharges of this high-temperature campaign is also being performed for discharges with some change in the magnetic field modulation on axis (modified mirror ratio, see below).

These values were surpassed in the week after the conference in a similar combined discharge with three neutral beam sources, yielding maximum values of $T_i(0)$ = 1.7 keV and $T_e(0)$ = 1.8 keV in shot #31463. The highest volume-averaged beta-value in W7-AS was 1.7%, obtained in the discharge #31114 at 1.25 T with full neutral-beam heating power and increased density.

H-mode studies on W7-AS were reviewed by F. Wagner. The H-mode is seen in a narrow window near ι = 0.53 using ECRH or NBI to heat the plasma. Major characteristics compare well with those known in tokamaks, but the improvement of the energy confinement is smaller. Details within the edge transport barrier and the operational conditions were studied with improved diagnostics. The L-H transition is accompanied by a reduction of fluctuations and a drop in the space potential which is correlated with an increased poloidal rotation. The power threshold can be smaller than in tokamaks; in ECRH plasmas the H-mode is seen when the machine is running at fields of either 1.25 T or 2.5 T.

J. Baldzuhn compared measurements and calculations of radial electric fields in W7-AS. This interesting paper is given in more detail as separate contribution to the present issue of *Stellarator News*.

H. Wobig commented on aspects of plasma rotation in toroidal systems by averaging the momentum balance equation. Three damping coefficients are derived numerically. Poloidal rotation and possibly H-mode confinement should be more easily achievable in W7-X than in W7-AS or in an l = 2 stellarator.

In the transport session, U. Stroth discussed energy confinement scalings from the International Stellarator Database which covers about 860 discharges from ATF, CHS, Heliotron E, W7-A and W7-AS, produced by ECRH, NBI or in combined operation. The main dependencies of this scaling are similar to the Lackner-Gottardi scaling, and values are comparable to tokamak L-mode scaling. A paper is being prepared for submission to Nuclear Fusion.

Recent transport studies in W7-AS were reported in another paper by U. Stroth. The use of ECRH at 140 GHz and 2.5 T allows one to extend the density range above 10^{20} m^{-3}. Transport analyses of the power balance of ECRH plasmas and heat wave techniques yield nearly identical γ_e-values. They indicate that γ_e does not depend on T_e nor on T_e. A model is discussed where γ_e varies with changes of the applied power faster than the diffusive time scale.

Experiments in W7-AS with modified mirror ratio were discussed by F. Rau from the W7-X Team. A definite influence of trapped electrons is seen on the loop voltage to balance the bootstrap current and the direction of ECCD-induced currents at low ι and 1.25 T. When changing from a configuration with a positive mirror ratio, MR = 10% (local maximum axis field in the toroidal plane of large curvature), to that with MR = −10% (local minimum axis field in this plane), the loop voltage is reduced by a factor of about three. ECCD-induced currents are much smaller and flow in reversed direction for the latter configuration, in agreement with theory. No drastic effects were found so far on the gross confinement of ECRH and NBI plasmas. Diamagnetic energies and plasma temperatures are reduced in a configuration at MR = 6% by about 10% in the recent high-T_i experiments, compared to their respective values obtained under standard operation of W7-AS with inward axis shift.

J. Geiger gave two theoretical papers in the context of mirror configurations: on ion confinement in transport optimized configurations, and on MHD-issues. Neoclassical transport is reduced in W7-AS at low ι for a rather small positive mirror ratio, comparable to the effect of an inward axis shift of the standard case. The analyses of resistive interchange modes show reduced stability for configurations with increasing positive values of the mirror ratio due to a reduction of the magnetic well; at large *MR* = 20% instability is indicated near the configuration edge which is already in the vacuum field. Pertinent experiments were initiated just after the conference.

In the session on MHD effects, A. Weller gave new results on global Alfvén eigenmodes in W7-AS. These modes may be important for tokamaks with flat or inverted *q*-profiles. Such modes are seen in NBI plasmas of W7-AS at ι ~ 1/3 in the range of 10–40 kHz. They were identified in experiments at varied magnetic field strength; further studies with waves launched by an external antenna are being prepared. For reactor plasmas alpha-particle losses due to Alfvén modes might lead to a reduced heating power and enhanced wall damage.

Magnetic islands, occurring in stellarators at rational ι for vacuum fields and at finite beta values are an important field of numerical research and are receiving increased attention. Self-healing of islands at finite beta values had been reported earlier for the MHD-stable system W7-X using the HINT code. U. Schwenn gave complementary results from this code for an MHD-unstable l = 1, 2 configuration with 5 field periods and magnetic islands at ι = 5/5 between well-formed magnetic surfaces of the vacuum field. Finite-beta computations demonstrate self-healing (thin islands at ι =10/10) and subsequent growth of these islands with interchanged positions of X- and O-points for values of beta = 0.9 Ö 1.0 Ö 1.1%. These results will be used as input for further stability studies.

Magnetic islands in W7-X at ι = 5/6, 5/5 or 5/4 can be established at the edge of the configuration; their separatrices are used as key elements in the definition of its divertor. As shown by J. Kisslinger in Monte-Carlo studies, deleterious effects of ‘leading edges’ can be avoided by proper design of the divertor target and baffle plates. A system of 10 units has been chosen for the W7-X divertor, arranged in the vicinity of the ‘bean-shaped’ cross-section of this device. A heat load of 10 MW/m^2 can be removed by its water-cooled elements. Additional saddle-shaped control coils with moderate currents allow one to control the size and phase of the edge islands for W 7-X and even to establish an ergodic region at the boundary. Effects of neutral particles are calculated with the EIRENE code, e.g., to demonstrate possibilities for an effective pumping scheme.

E. Strumberger gave more details of the 3-D field line structure and the scrape off layer (SOL) modeling in W7-X: radially ordered layers of field lines exist for the three rational edge-ι values, with lengths decreasing from larger than 200 m to less than 15 m, starting outside the separatrix and going towards the target plates. Additional cross-field diffusion increases the wetted area.

Scoping studies aimed at an island divertor for W7-AS have been initiated. A tentative divertor system was defined by J. Kisslinger, comprising 10 units of target and baffle plates. Saddle-shaped control coils provide the means to influence the edge resonances, e.g., at ι = 5/9. P. Grigull presented results of probe measurements in the edge region of W7-AS and derived a scaling of the perpendicular particle transport coefficient as $D_\perp$ proportional to $(P - P_{rad})^{0.85}\ n^{-1}$.

Topological aspects of the edge structure in W7-AS were discussed by J. Hofmann for the range 0.42 < ι < 0.64, using Langmuir probe data, H_α detectors and side-on observation by a TV camera. Details of this investigation were reported in *Stellarator News* Issue 38. New data demonstrate the persistence of the 5/*m* resonances near the edge at increased beta values.

Effects of impurities have recently been reported to improve edge conditions in tokamaks close to the divertor. A campaign was started to study the plasma response to impurity injection in W7-AS via an erosion probe and N_2-puffing. Initial results were reported by D. Hildebrandt.

Stellarators have some inherent advantages over tokamaks in their reactor prospects. A review on Helias reactor studies was given by H. Wobig. The HSR system is similar to W7-X: 50 non-planar modular NbTi coils with 5 T axis field (1.8 K operation), *R* = 22 m, *a* = 1.8m, 3–3.6 GW fusion power output, depending on the assumed density. Global scaling laws, local transport analyses and self-consistent calculations of temperatures and electric fields (ASTRA-code) demonstrate an ignition margin of about 1.1. The start-up heating is 50–80 MW. Two options for maintenance exist for HSR. Separation of the coil set for radial shift requires cutting seals of lateral endplates, exchanging damaged parts by side-on action, and rewelding the seals of new endplates. A critical issue is whether the coils can be kept cold during these operations. The second maintenance option is similar to tokamaks and replaces the first wall/blanket modules through ports. A possible solution was shown for the shape of such first wall/blanket modules. Divertor elements are to be maintained through ports in both options.

Similar divertor elements for W7-X were discussed by J. Kisslinger for the Helias reactor study, HSR. They are designed for ι = 5/5. In order to stay within technical limits of present achievable power loads, a substantial fraction of edge radiation is required for full reactor power.

E. Harmeyer detailed engineering questions of electromagnetic forces and related stresses in the coil system of HSR. Reasonable peak values have been obtained for the stresses in the modular coils: about 160 MPa tensile stress, about 30 MPa shear stress, and about 60 MPa compression stress were found at certain points in the coil winding packs. The maximum value of the equivalent stress in the coil housing was about 600 MPa. These values are within engineering margins.

The session of new devices was chaired by H. Wobig, IPP. He briefly commented on the present status of the W7-X Project. The procedure to receive EURATOM Phase II Preferential Support for W7-X was initiated in June 1994. Intensive discussions with various groups of experts were finished. A positive decision to construct W7-X at Greifswald, Germany is expected within the next months. Engineering details of W7-X were detailed in *Stellarator News* Issue 39.

F. Rau for the W7-AS and W7-X Teams
IPP Garching, EURATOM Association
Germany

E-Mail: ffr@ipp-garching.mpg.de
Phone: 0049-89-3299-1770