BOUNDARY PLASMA MODELLING FOR ITER

Final Report

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Abstract. Under this contract we have contributed to ITER edge plasma physics by improving the numerics and the organization of the B2.5 edge plasma code, by applying the code in a systematic study of the effect of deliberately introduced impurities upon the divertor heat load, by collaborating with colleagues at IPP Garching in their studies of the ITER divertor using the B2/EIRENE code system and in their model validation studies, and by kinetic studies of the possible beneficial effects of magnetic perturbations upon divertor heat load. In regard to the effect of recycling impurities our modelling indicates that it will be possible to radiate up to 200 MW in the edge plasma and divertor if the edge density is sufficiently high ($\simeq 6.0 \times 10^{19}/\text{m}^3$) and if there is maintained a concentration of 1.0% neon or 0.5% argon. This implies that an acceptable working point for ITER may just barely be possible with credit for bremsstrahlung and edge radiation alone, and a robust working point appears possible if consideration is given also to core plasma impurity radiation. In regard to the effect of magnetic perturbations we find that a scenario that relies on external windings requires coils no further than about 0.3 m outside the separatrix, which appears unacceptable given the radiation environment.

Radiative divertor studies. We used the B2.5 code to perform parameter studies of the edge plasma in an ITER-like geometry, with interest in the divertor heat load reduction due to the deliberate introduction of neon or argon as a recycling impurity. B2.5 is a successor to B2 [1] that employs a fluid model for the neutral gas and incorporates a parallel Ohm's law. The aim of our work is the computational assessment of the feasibility of using radiation in the edge and divertor in order to obtain a plasma solution in which the temperature is below 5 eV at any point of wall contact and in which the energy flow to material surface is carried almost entirely by photons and by the recombination energy of charged particles; this is a plasma regime that corresponds to the onset of detachment.

The computational region for these calculations is based on a double-null and somewhat smaller design than the present EDA, and covers the outer scrape-off layer and divertor below the midplane plus a small segment of the region of closed flux surfaces and of the private flux region; this geometry is illustrated in Figure 1. The divertor target plate is set normal to flux surfaces. We used two different impurities: neon and argon, and in all calculations there is also about 10% helium. The dominant species is hydrogen at atomic mass 2.5, representing the D-T mixture. For almost all runs we assumed simple anomalous cross-field transport characterized by particle diffusivity $D = 0.5 \text{ m}^2/\text{s}$ and heat diffusivities $\chi_e = 1.0 \text{ m}^2/\text{s}$ and $\chi_i = 1.0 \text{ m}^2/\text{s}$. Parallel heat and momentum transport is classical, but flux-limited. The equations, given in detail in the Appendix, describe continuity for all charge states of all considered nuclear species (hydrogen, helium, and either neon or argon), parallel momentum balance for all charge states of all nuclear species, charge conservation based on parallel Ohm's law and an anomalous radial current law, electron heat balance, and atom+ion

heat balance. Atomic physics data play an important role in this work; our hydrogen data are due to Stotler [2] based on work of Weisheit et al. [3], and the helium and the atomic physics data for all other species come from the STRAHL code [4].

Boundary conditions were prescribed as follows:

- The interface with the core plasma. Here the density of H^{1+} , of He^{2+} , and of the few dominant charge states of the neon or argon impurity are prescribed; for the other charge states of all nuclear species the flux is set to 0. The parallel flow velocities of all species are set to 0, as is the radial electric current. The two temperatures T_e and T_i are prescribed at a common value. In the present sequence of runs the prescribed densities and temperatures are the controlling parameters.

- The outer wall and the inner boundary of the private flux region. Here we prescribe heat losses proportional to local pressure, charged particle losses proportional to local density times thermal velocity, zero electric current, zero shear on the parallel velocity, and a recycling model for the neutral species. (These boundaries are far enough out that the precise numerical coefficients in the boundary conditions do not have a significant influence on the divertor heat load.)

- The midplane is a symmetry boundary.

- The divertor target plate. We prescribe outflow for all charged species at the common velocity $\sqrt{p/\rho}$ where p is total pressure and ρ is total mass density. Neutrals are produced locally at a rate equal to that of the outflow of charged species. The electric current is given by $J = q_e n_e \sqrt{T_e/m_e} (q_e \phi / T_e - 1)$, the conducted electron heat flux by $q_e = \beta_e n_e T_e \sqrt{T_e/m_e}$ and the conducted ion heat flux by $q_i = \sum_a q_a$, summing over all ion species, where $q_a = \beta_i n_a T_i \sqrt{T_i/m_a}$; here $\beta_e = 0.1$ and $\beta_i = 0.1$. These fluxes are parallel to the field and are multiplied by the local field pitch to get the flux to the plate. We later changed the electric field boundary condition to the proper Bohm sheath condition with account for secondary electron reflection; this changes the electric potential slightly and has almost no influence on the computed heat flux.

A concise representation of the main point of our modelling is given in Figures 2 and 3, which show the conducted plus convected heat flux to the divertor target plate as a function of the impurity density at the core plasma interface for various input power levels and various core plasma densities. Figure 2 is for the case of neon impurity and Figure 3 is for argon impurity. In each case we consider three different levels of total power into the computational region, and two different assumed electron densities at the core plasma interface.

The three power levels are 130 MW, 165 MW, and 200 MW. Which of these is considered the most relevant depends on one's assessment of temporal and spatial inhomogeneities in the divertor heat load. For a symmetric steady state we would estimate that a maximum of 200 MW flows into the entire scrape-off layer, and no more than 80 MW flows into a single outboard divertor in a double-null configuration. On the other hand, if the power is exhausted through giant elms the peak power load

would be several times higher. Our case of 165 MW corresponds to about a factor of two peaking.

The two electron densities considered are $4.0 \times 10^{19}/\text{m}^3$ and $6.0 \times 10^{19}/\text{m}^3$ from hydrogen, helium, and the considered impurity. In all cases we specified a helium density at the core that was 10% of the electron density. The prescribed impurity density at the core plasma is shown on the horizontal axis. The impurity density in the core will in practice have to be maintained by some feedback control on the impurity gas feed and the pumping, but we did not attempt to include that feedback explicitly in our modelling.

In the parameter scans the impurity density in the core plasma is increased up to the level at which the conducted heat flux to the plate falls to about 10 MW or less. At this point the electron temperature at the plate is everywhere below 2 eV, and the plasma and neutral density in a small region just before the plate increases to several times $10^{21}/\text{m}^3$. The 10 eV contour is removed from the plate by only a few cm at the separatrix strike point, so these are still traditional high recycling solutions and not gas target ones. About 30% of the power is lost by hydrogen radiation and recycling, about 10% by that of helium, and 60% by that of neon or argon.

As an example, electron density and temperature profiles for one case are shown in Figures 4 and 5. This case has an electron density at the core plasma interface of $6.0 \times 10^{19}/\text{m}^3$, a power into the computational region of 165 MW, and a neon concentration of 0.6% at the core plasma interface. The conducted power to the plate is 20 MW. In addition, the recombination energy of the particle flux to the plate contributes 28 MW. The peak power flux density at the plate, without considering plate inclination, is $44 \text{ MW}/\text{m}^2$ conducted and $16 \text{ MW}/\text{m}^2$ recombination; adding these together and assuming a factor of five reduction for plate tilt we obtain $12 \text{ MW}/\text{m}^2$ normal to the plate. The parameter scan of which this run was a part shows that at slightly higher neon concentration (0.8%) the conducted energy flux to the plate falls to below 10 MW and a cool plasma solution at the plate is achieved; however, the recombination energy flux to the plate remains almost unchanged at 28 MW.

Code development and collaborations. The B2.5 code was cleaned up so that it would be a useful tool for other ITER modellers and for model validation studies. The revised code was made available to Ken Werley of LANL for ITER studies among other work, to Rajesh Maingi of ORNL/GA for model validation studies on D-IIID, and to David Ruzic of University of Illinois for use in connection with pumping optimization studies.

The ITER Joint Central Team at Garching made the choice to use the coupled fluid/Monte Carlo code system B2/EIRENE for their in-house modelling. In collaboration with R. Schneider of IPP the coupling between B2 and EIRENE was improved by careful linearization of the source terms from EIRENE, making it possible to perform fully coupled fluid plasma and Monte Carlo neutral gas simulations of a cold

high-recycling ITER divertor. In this work, done at IPP Garching and described in detail in [5], the V-shaped and the gas-bag divertor were compared. The results indicate easier access to the cold high-recycling regime and a more stable solution in the V-shaped geometry.

Non-Axisymmetric Magnetic Perturbations. We investigated whether deliberate external magnetic field perturbations could be employed to reduce the peak heat load on the divertor target plate in ITER. The approach relied on a grid-free random-walk method to solve a highly anisotropic model heat transport equation in a realistic perturbed tokamak magnetic field. The walkers are launched in the core plasma and make small steps across the magnetic field and long steps along the field lines; the latter steps are evaluated by accurate field line integration. The partial differential equation solved is $\nabla \cdot \mathbf{Q} = 0$ where $\mathbf{Q} = -\kappa_{\parallel} \nabla_{\parallel} T - \kappa_{\perp} \nabla T$. The distribution of points where the walkers cross the boundary is interpreted as the heat load on the boundary. This is a model equation, because we do not consider the dependence of $\kappa_{\parallel}$ on temperature, nor do we solve for a consistent density profile. Only the (constant) ratio of parallel to perpendicular diffusivity is important.

Since thousands of walkers have to be followed to obtain accurate statistics, and since each walker can wander around for thousands of steps before reaching the boundary, it is essential to have a very efficient representation of the magnetic field. Our work evolved through two stages in this regard. At first we relied on a set of local toroidal harmonic expansions for the axisymmetric part of the magnetic field, and on a representation as a sum of dipole fields for the perturbation. Later, following a suggestion of J. Nührenberg of IPP Garching, we used local Hermite interpolation on data representing the function values and first derivatives of all components of the magnetic field on a regular mesh.

The present random-walk calculation shares some features with "deep penetration" problems in Monte Carlo neutron transport studies. Our walkers are launched in the interior of the plasma, but all that we are interested in is the distribution of points on the boundary at which, after many steps, they eventually leave the domain of the calculation. The efficiency of this random walk calculation is greatly improved by judicious use of splitting and Russian roulette. We divide the computational region up into zones, with zone boundaries defined by the equilibrium magnetic flux surfaces. On each zone a "target weight" is defined; the target weights decrease exponentially as we move towards the outside of the confinement region. The particles are launched in the inside with unit weight; at any stage, if a particle weight exceeds the target weight of the region it is in by some factor then the particle is split in two with each new particle carrying half the weight; on the other hand, if a particle weight is less than the target weight by some factor then it is terminated with probability 0.5, doubling its weight if it survives.

We performed calculations for a magnetic equilibrium representing an up-down symmetric double-null SSAT/TPX (equilibrium 92047, July 1992, courtesy of R. Bulmer of LLNL). This device has major radius $R_0 = 2.25$ m. All our calculations scale linearly with geometry, so we obtain results relevant to ITER by multiplying all geometry data by a factor of about 3. The equilibrium is shown in Fig. 6.

The analytical representation of the equilibrium magnetic field that is used for our calculations is obtained via a wire model for the plasma current. That representation is accurate near and outside the separatrix. It degrades in the core plasma, but that is immaterial for our studies. The magnetic geometry of the wire model is shown in Fig. 7.

In engineering practice we expect that the magnetic field perturbation would be created by a large set of coils mounted on or inside the vacuum vessel, but for this exploratory study we represented the perturbation as a superposition of magnetic dipole fields. The dipoles were located along several rings outside the plasma. The number and placement of these rings, the dominant toroidal mode number of the perturbation, the toroidal phase difference between the perturbation on different rings, and the amplitude of the perturbation were all subject to optimization. Here we present results only for the most favourable configuration studied, which involved six toroidal rings (in two pairs of three symmetric with respect to the equatorial plane), located as indicated on Fig. 7. The perturbation has dominant toroidal mode number equal to 8. The maximum amplitude of the perturbed magnetic field at the separatrix is 3.2 percent of the local equilibrium toroidal magnetic field.

Figure 8 shows a Poincaré plot of the magnetic field structure under the influence of this perturbation. The perturbation has destroyed the outermost 18% of the radius of good flux surfaces when measured on the inboard side of the torus. Due to the Shafranov shift this translates to a destruction of the outermost 14% of the radius of good flux surfaces on average. Somewhat arbitrarily we view this as a maximum permissible level of perturbation. In all our optimization studies we selected the amplitude of the perturbing field to result in this same level of destruction of good flux surfaces.

In Fig. 9 is shown the distribution of points on the lower boundary where the random walkers leave the domain. Without perturbation the corresponding picture is composed of just one ring, widened only by the process of microscopic physical diffusion. Under the influence of the perturbation the simple ring is replaced by a spiral with toroidal mode number 8. Thereby the heat load is deposited in many bands at any given toroidal location.

The reader is warned that Fig. 9 is misleading in an important respect. As discussed above, we employ weighted random walkers, and the typical weight of a walker is much less at larger values of x than at smaller values. In contrast to the

impression obtained from Fig. 9, most of the weight falls in the region between $x = 2.02$ and $x = 2.06$.

The effect of the perturbation is very visible in some reduced parameters of the distribution of hits on the boundary. The root mean square deviation (properly weighted) of the distribution of radial coordinates of hits on the lower boundary equals 3.1 mm in the case of no perturbation, and equals 21 mm in the case with perturbation. The full width at half maximum of the same distribution function equals 4 mm in the case of no perturbation and equals 30 mm in the case with perturbation. (Remember that these measures scale up by a factor of 3 when we consider ITER instead of TPX/SSAT.)

The calculation discussed above was done at a ratio $\kappa_0/\kappa_{\parallel} = 10^{-8}$. For larger values of the perpendicular diffusivity the difference between cases with and without perturbation is less pronounced. However, the beneficial spreading of the heat load will be amplified in a manner not considered in the present calculation by the reduction of parallel heat conduction associated with the cooling of the plasma. We conclude that deliberate external perturbations may spread the heat load over about 0.1 m perpendicular to flux surfaces at the ITER divertor, even for very small values of the anomalous perpendicular diffusivity. However, active perturbing coils need to be placed no further than about 0.3 m outside the separatrix, which appears unacceptable given the radiation environment. It needs further study whether magnetic perturbations from currents flowing directly in the edge plasma can provide an attractive means for spreading the divertor heat load.

Appendix: Equations for B2.5. The equations are written on a curvilinear orthogonal coordinate system. The x -coordinate varies along flux surfaces and the y -coordinate varies perpendicular to flux surfaces. The metric coefficients are $h_x = 1/\|\nabla x\|$, $h_y = 1/\|\nabla y\|$ and $\sqrt{g} = 2\pi R h_x h_y$, where R is the local major radius. Components of a vector are the projections on unit basis vectors; they are not the contravariant or covariant components.

The continuity equation for any atomic species a (neutral or charged) is

$$\frac{\partial n_a}{\partial t} + \frac{1}{\sqrt{g}} \frac{\partial}{\partial x} \left(\frac{\sqrt{g}}{h_x} \Gamma_{ax} \right) + \frac{1}{\sqrt{g}} \frac{\partial}{\partial y} \left(\frac{\sqrt{g}}{h_y} \Gamma_{ay} \right) = S_a^n \quad (1)$$

In general, the expressions for the particle fluxes are:

$$\begin{aligned} \Gamma_{ax} &= \left(u_{ax}^{\text{anom}} + \frac{B_x}{B} u_{\parallel a} \right) n_a - D_a^n \frac{1}{h_x} \frac{\partial n_a}{\partial x} - D_a^p \frac{1}{h_x} \frac{\partial p_a}{\partial x} \\ \Gamma_{ay} &= u_{ay}^{\text{anom}} n_a - D_a^n \frac{1}{h_y} \frac{\partial n_a}{\partial y} - D_a^p \frac{1}{h_y} \frac{\partial p_a}{\partial y} \end{aligned}$$

where $p_a = n_a(T_i + Z_a T_e)$. The term $(B_x/B)u_{\parallel a} n_a$ represents the poloidal projection of parallel flow, and the coefficients u_{ax}^{anom} , u_{ay}^{anom} , D_a^n and D_a^p specify the anomalous

transport. In this study, for the bulk species we only employed D_a^n (so $u_{ax}^{\text{anom}} = 0$, $u_{ay}^{\text{anom}} = 0$, $D_a^p = 0$).

The equation of parallel momentum balance for any atomic species a is

$$\begin{aligned} \frac{\partial}{\partial t} (m_a n_a u_{\parallel a}) + \frac{1}{\sqrt{g}} \frac{\partial}{\partial x} \left(\frac{\sqrt{g}}{h_x} \Gamma_{ax}^m \right) + \frac{1}{\sqrt{g}} \frac{\partial}{\partial y} \left(\frac{\sqrt{g}}{h_y} \Gamma_{ay}^m \right) = \\ - \frac{B_x}{B} \left(\frac{1}{h_x} \frac{\partial}{\partial x} n_a T_i + \frac{Z_a n_a}{n_e} \frac{1}{h_x} \frac{\partial}{\partial x} n_e T_e \right) + \\ \sum_b f_{ab} (u_{\parallel b} - u_{\parallel a}) + e n_e \frac{B_x}{B} \hat{E}_x Z_a n_a \left(\frac{1}{n_e} - \frac{Z_a}{n_{e2}} \right) + S_a^m \end{aligned} \quad (2)$$

The momentum fluxes are

$$\Gamma_{ax}^m = m_a \Gamma_{ax} u_{\parallel a} - \eta_{ax} \frac{1}{h_x} \frac{\partial u_{\parallel a}}{\partial x},$$

$$\Gamma_{ay}^m = m_a \Gamma_{ay} u_{\parallel a} - \eta_{ay} \frac{1}{h_y} \frac{\partial u_{\parallel a}}{\partial y}.$$

The modified electric field is $\hat{E}_x = (1/en_e)(1/h_x)\partial p_e/\partial x - (1/h_x)\partial\phi/\partial x$, the coefficients f_{ab} are the classical friction coefficients, and $n_{e2} = \sum_a Z_a^2 n_a$.

The charge conservation equation, which governs the electric potential, is

$$\frac{1}{\sqrt{g}} \frac{\partial}{\partial x} \left(\frac{\sqrt{g}}{h_x} J_x \right) + \frac{1}{\sqrt{g}} \frac{\partial}{\partial y} \left(\frac{\sqrt{g}}{h_y} J_y \right) = 0 \quad (3)$$

where $J_x = (B_x/B)J_{\parallel}$, $J_{\parallel} = \sigma_{\parallel} \hat{E}_{\parallel} - \alpha_{\parallel} \partial_{\parallel} T_e$, and $J_y = \sigma_y \hat{E}_y - \alpha_y (1/h_y) \partial T_e / \partial y$; the parallel transport is classical and the perpendicular is anomalous using very small transport coefficients.

The two heat equations are

$$\begin{aligned} \frac{\partial}{\partial t} \left(\frac{3}{2} n_e T_e \right) + \frac{1}{\sqrt{g}} \frac{\partial}{\partial x} \left(\frac{\sqrt{g}}{h_x} Q_{ex} \right) + \frac{1}{\sqrt{g}} \frac{\partial}{\partial y} \left(\frac{\sqrt{g}}{h_y} Q_{ey} \right) = \\ - \frac{1}{h_x} \frac{\partial u_{ex}}{\partial x} n_e T_e + J_x \hat{E}_x + J_y \hat{E}_y - k_{ei} (T_e - T_i) + S_e^H \end{aligned} \quad (4)$$

$$\begin{aligned} \frac{\partial}{\partial t} \left(\frac{3}{2} \sum_a n_a T_i \right) + \frac{1}{\sqrt{g}} \frac{\partial}{\partial x} \left(\frac{\sqrt{g}}{h_x} Q_{ix} \right) + \frac{1}{\sqrt{g}} \frac{\partial}{\partial y} \left(\frac{\sqrt{g}}{h_y} Q_{iy} \right) = \\ - \sum_a \frac{1}{h_x} \frac{\partial u_{ax}}{\partial x} n_a T_i + \sum_a \eta_{a\parallel} (\partial_{\parallel} u_a)^2 + \\ \sum_{ab} F_{ab} (u_{\parallel b} - u_{\parallel a}) + k_{ei} (T_e - T_i) + S_i^H \end{aligned} \quad (5)$$

where the heat fluxes are $Q_{ex} = (3/2)\Gamma_{ex}T_e - \kappa_{ex}(1/h_x)\partial T_e/\partial x + \alpha_{ex}T_e\hat{E}_x$, $Q_{ey} = (5/2)\Gamma_{ey}T_e - \kappa_{ey}(1/h_y)\partial T_e/\partial y + \alpha_{ey}T_e\hat{E}_y$, $Q_{ix} = (3/2)\Gamma_{ix}T_i - \kappa_{ix}(1/h_x)\partial T_i/\partial x$, and $Q_{iy} = (5/2)\Gamma_{iy}T_i - \kappa_{iy}(1/h_y)\partial T_i/\partial y$. The term $k_{ei}(T_e - T_i)$ is the classical electron-ion heat equilibration. The transport coefficients κ_{ex} , α_{ex} , and κ_{ix} are classical, flux-limited, and taking account the magnetic field pitch. F_{ab} is the friction force between species a and b .

The source terms S_a^n , S_a^m , S_e^H and S_i^H represent atomic physics processes of ionization recombination, radiation, and charge exchange.

References.

- [1] B. J. Braams, "Computational studies in tokamak equilibrium and transport" (thesis, University of Utrecht, the Netherlands, 1986).
- [2] D. P. Stotler, D. E. Post and D. Reiter, *A Collisional-Radiative Model of Hydrogen for High-Recycling Divertors*, Bull. Am. Phys. Soc. **38**, 1919.
- [3] Jon C. Weisheit, *Recombination in Dense Plasmas*, J. Phys. B (Atom. Molec. Phys.) **8**, 2556.
- [4] K. Behringer, *Description of the Impurity Transport Code STRAHL*, JET Report R(87)08, 1987.
- [5] R. Schneider, D. Reiter, D. P. Coster, J. Neuhauser, K. Lackner, and B. J. Braams, *Analysis of Cold Divertor Concepts for ITER*, J. Nucl. Mater. **220-222**, 1076-1080.

Figure Captions.

Fig. 1: The geometry and mesh for the parameter scans. There are 80 cells in the poloidal direction and 36 in the radial direction, concentrated near the target plate and along the separatrix. The geometry extends up to the midplane.

Fig. 2: Neon scan. The horizontal axis shows the assumed neon density at the core plasma interface, the vertical axis shows the heat flux to the divertor target (not including potential energy of recombination). The six curves are labelled (4a,6a,4b,6b,4c,6c); the digit indicates the electron density at the core plasma interface ($4.0 \times 10^{19}/\text{m}^3$ or $6.0 \times 10^{19}/\text{m}^3$) and the letter indicates the power into the computational region (a, 130 MW; b, 165 MW; c, 200 MW).

Fig. 3: Argon scan. The horizontal axis shows the assumed argon density at the core plasma interface; other data as in Figure 3.

Fig. 4: Contour plot of electron density for the example calculation. Note the high-density region just below the x-point ($n_e \leq 1.52 \times 10^{21}/\text{m}^3$) and near the target plate ($n_e \leq 7.07 \times 10^{21}/\text{m}^3$).

Fig. 5: Contour plot of electron temperature for the example calculation.

Fig. 6: SSAT/TPX equilibrium #92047, courtesy of R. Bulmer (LLNL). For the purpose of our studies a relevant ITER geometry is obtained by scaling all dimensions up by a factor 3.

Fig. 7: The flux surfaces associated with our wire model of the equilibrium. The two pairs of three circles on the outboard side indicate the rings of locations of the perturbing coils for the study presented in the text. At each toroidal location, the three magnetic dipoles have relative magnitude (1, -2, 1). The toroidal mode number is 8. A toroidal phase shift between the upper and lower triplet has been optimized to get the largest effect on heat load relative to the destruction of core plasma.

Fig. 8: The Poincaré plot (on the lower inboard region of the poloidal cross-section) showing the perturbed magnetic geometry. 40 starters were followed for a maximum of 1000 toroidal transits or until the field line leaves the domain of the plot. The perturbation has destroyed the outermost 90 mm of flux surfaces (measured on the inboard side), and has created some islands.

Fig. 9: A scatterplot showing the location of points where the random walkers leave the domain at the lower outboard divertor (the plane $z = -1.60$). The x -coordinate represents major radius, and the y -coordinate represents toroidal angle (in the range $(0, \pi/4)$ because of eightfold periodicity).

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Figure 1

Figure 2

Figure 3

Figure 4

logarithmic scale

-4.00E+00

Figure 5

SSAT/Std @Jmin #92047-00

3

Ro, a, A :	2.250	0.500	4.500
Ip, Bo @ R :	1.850	3.350	2.250
β_{tor} , g [%]:	3.867	3.500	
β_{pol} :	1.946	1.411	1.447
li :	0.942	0.683	0.700
$q(0)$, q_{95} , *:	1.050	3.000	2.155
κ_{95} , κ_x :	1.813	2.000	
δ_{95} , δ_x :	0.470	0.800	
axis R,Z, ΔR :	2.308	0.000	0.058
XptU R,Z, ψ :	1.850	1.000	-2.044
Spt R,Z, Δx :	1.654	1.040	0.200
Spt R,Z, Δx :	1.959	1.385	0.400
$\langle \psi_e \rangle$, $\psi_e(0)$:	-9.459	-9.660	
L_p [μH]:	4.997	4.488	
$\psi(0)$, $\Delta \psi$, ϕ :	1.122	-12.664	1.622
$W_{tot,c}$ [MJ]:	62.780	71.759	3
Bmax, fmax :	3.744	0.332	1 1
ALFA, BETP :	1.250	1.000	3
ALFB, BETF :	0.835	1.285	5 2
BETAJ, β_{ps3} :	0.871	1.447	

Figure 6

07/16/92y

Figure 7

Figure 8

Figure 9