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On the Accessibility of High β - States and Long Pulse Durations in Tight Aspect Ratio Plasmas

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1 Introduction

Due to the encouraging results produced by the START (Small Tight Aspect Ratio Tokamak) experiment new fields in tokamak physics became important, such as natural elongation of the plasma cross-section, edge safety factors which strongly exceed the cylindrical values, paramagnetic states at low toroidal fields, partly isodynamic equilibria, a natural divertor configuration, avoiding the classical divertor coils and strongly enhanced bootstrap current at low aspect ratio [1].

However, since only a comparatively small primary solenoid can be implemented, the achievement of long pulse durations could be a severe problem.

To overcome this problem, essentially the bootstrap effect is considered [2] which it is predicted to become dominating if β_p approaches unity. Since the total β must stay below the Culham - Lausanne ('Troyon') limit, it is not possible to increase the bootstrap fraction only by increasing the heating power. Instead one has to consider an increase the minor half axis (at constant aspect ratio). This will also decrease the index for the divertor power handling $I_{div} = \frac{P}{R_{div}}$.

2 Plasma equilibrium

The treatment of the semifree and the free boundary value problem is based on the Grad - Shafranov equation, a partial differential equation (PDE) ([1]):

$$\Delta^* \psi = -\mu_0 R^2 \frac{dp(\psi)}{d\psi} - f(\psi) \frac{df}{d\psi} = \mu_0 R\, j_\phi \tag{1}$$

Δ^* is the standard toroidal elliptic operator and $j_\phi(R,z)$ (>0) the toroidal current density. ψ is the poloidal flux function. The f - function $f(\psi)$ can be obtained from [2]

$$\frac{f'f}{R\mu_0} = -(j_a B_t + j_b B_t) + \frac{B_t^2}{< B^2 >} R\, p' \tag{2}$$

The prime denotes the derivative $\frac{d}{d\psi}$. The expression (2) accounts for the (local) ohmic current density $\vec{j}^a$, the bootstrap current density $\vec{j}^b$, the diamagnetic current and the Pfirsch - Schlüter current density [1]. The quantities j_a and j_b are defined as $j_a = \frac{<\vec{j}^a \vec{B}>}{<B^2>}$ and $j_b = \frac{<\vec{j}^b \vec{B}>}{<B^2>}$. The boundary values for ψ on the rectangle surrounding the computational domain are obtained from the coil data and the plasma current distribution. [1].

The iteration of equation (1) proceeds until convergence concerning the flux function $\psi(R,z)$ is achieved.

By means of flux function ψ and the f - function f(ψ) the 2d - distribution of the toroidal current density j_t, the poloidal current density j_p, the poloidal field B_p and the toroidal field B_t can be obtained. Also the geodesic field line curvature can be computed by means of the flux- and f-function [1].

The toroidal component of the bootstrap current density, which is needed for the equilibrium iteration, is given by

$$j_b = -\frac{B_t}{< B^2 >} f(\psi) p_e \left[K_{13}^W \left[\frac{p_e'}{p_e} + \frac{T_i}{Z\, T_e} \left(\frac{p_i'}{p_i} - \alpha_W \frac{T_i'}{T_i} \right) \right] - K_{23}^W \frac{T_e'}{T_e} \right] \tag{3}$$

The neoclassical coefficients account for the different collisionalities of trapped and passing particles. The dependence of these coefficients on the trapped particles fraction and on the effective charge number are given in [2].

3 Results

In the following the equilibrium properties of a plasma with the profiles $f_i = f_{max_i}(1 - x^{\alpha_i})^{\beta_i}$ are discussed. i=1 stand for the plasma density, i=2 for the electron temperature and i=3 for the ion temperature. The profile parameters are $\alpha_{1-3} = 2.5$, $\beta_{1-3} = 1$, $f_{max_1} = 8\ 10^{13} cm^{-3}$ and $f_{max_{2,3}} = 2.5\ keV$.

Fig. 1 displays the flat top plasma equilibrium belonging to the aforementioned plasma parameters. The shaping coils are switched off so that the plasma has its natural elongation of $\kappa_{nat} = 1.6$.

In Fig. 2 the divertor coils are switched on ($I_{div} = 0.3$ MA). As a consequence the elongation increases to $\kappa = 2$. The plasma boundary does not touch the centerpost anymore.

The distribution of the bootstrap current density (Fig. 3) is characterized by the zero at the magnetic axis and by the strong peak at the inboard side due to the fact that the j_b scales roughly with $\frac{1}{R}$. The maximum value is $j_{b_{max}} = 0.39 \frac{MA}{m^2}$ corresponding to a total bootstrap current of $I_b = 2.37$ MA.

Fig. 4 shows a contourplot of the total field characterized by the peaks due to the poloidal field coils and a magnetic well just in front of the outer poloidal field coils. It is generated by the diamagnetism due to the large poloidal $\beta_p = 1.1$. The diamagnetism reduces the toroidal field and therefore the total field at the outboard side where the pressure gradient is large. Calculations at low β show that the magnetic well disappears. Fig. 4 also shows that at the outboard side of the magnetic well, i. e. for R $> R_{well}$, the lines $|\vec{B}_{tot}|$ = const are roughly parallel to the flux surfaces ψ = const. (R_{well} is the radius of the local minimum of $|\vec{B}_{tot}|$.)

The calculations show that a 'Long Pulsed Spherical Torus', mainly resorting to the bootstrap current, should be feasible if the aforementioned profile parameters can be realized and if the minor half axis of the device is large enough. 'LPST' fits well to the family of ST's aiming at a β_p=1 Since the minor half axis of e. g. NSTX and MAST is smaller than that of LPST an increase of T_{e_0}, T_{i_0} by roughly a factor 2 is necessary to reach the same β_p=1 and thus the same bootstrap fraction. In fact, for NSTX a large bootstrap fractions ($\approx 80\%$) is predicted at $\approx T_{e_0}, T_{i_0}$ =5 keV.

References

[1] A. Nicolai, Equilibrium Properties and Main Design Parameters of a Long Pulsed Spherical Torus, Report Juel - 3727, FZ - Juelich (1999)

[2] H. R. Wilson, Bootstrap current Modelling in Tight Aspect Ratio Tokamaks, Report UKAEA FUS 271, July 1994

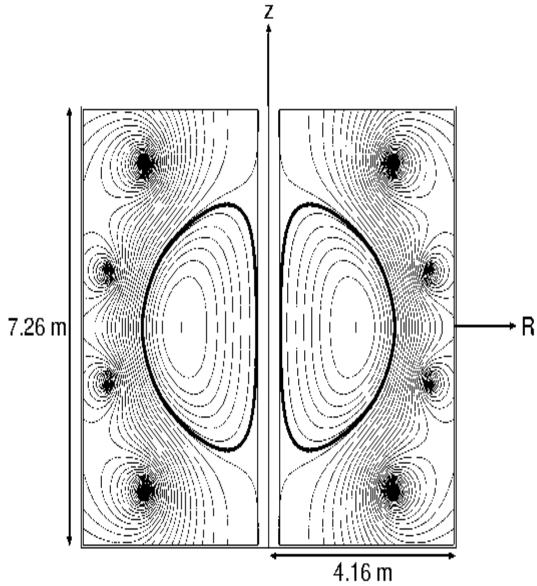

Fig. 1

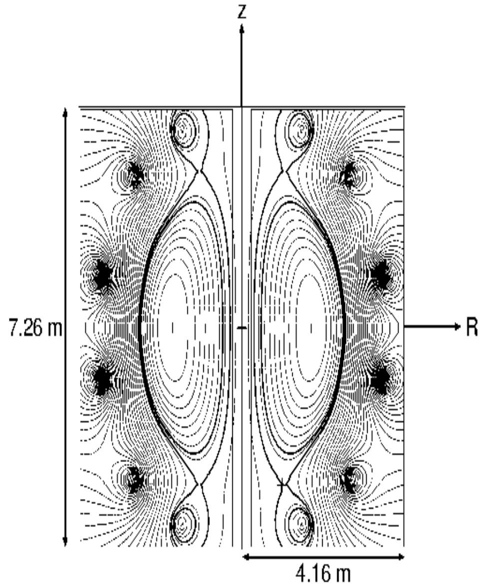

Fig. 2

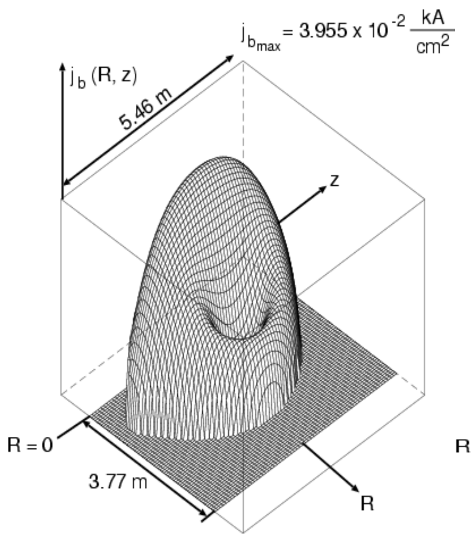

Fig. 3

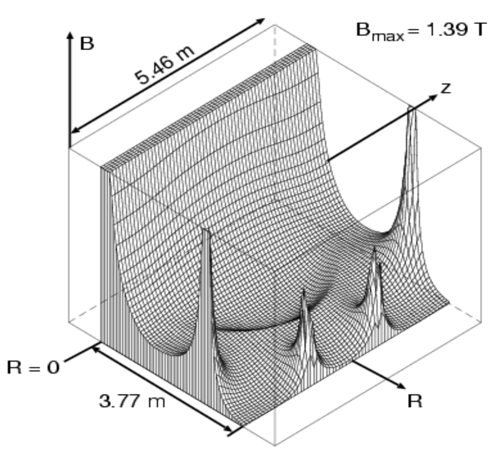

Fig. 4

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