PRELIMINARY DESIGN OF A SMALL ASPECT RATIO TOKAMAK

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Abstract

The preliminary conceptual design of a small aspect ratio tokamak is presented. This tokamak is based upon the spherical torus concept and will be the prototype (PROTO-ETA) of the Brazilian Advanced Tokamak Experiment (ETA). The device parameters are derived from engineering and empirical physical constraints. The tentative parameter values are aspect ratio $A \gtrsim 1.8$, major radius $R_o = 0.36$ m, vacuum toroidal magnetic field on axis $B_o = 0.65$ T and toroidal plasma current $I_p = 0.38$ MA for an edge safety factor $q_a = 4.5$. A simplified zero dimensional model is employed to predict plasma performance and auxiliary heating requirements. RF-assisted startup and noninductive current drive techniques are envisaged. This study results in a device design based on conservative assumptions which, when builded-up, should allow the investigation of high beta tokamak operation in the first stability regime.

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1. INTRODUCTION

A new toroidal device (ETA) with a small aspect ratio $A \cong 1.5$ and a plasma current in the 1 MA range has been recently proposed to be constructed at the new Brazilian plasma physics centre [1,2]. Such spherical torus RF driven tokamak can potentially achieve very high values of β ($\sim$20%) and its compact geometry is attractive for advanced reactor applications. Since the efficiency of current drive is a crucial parameter for a low aspect ratio steady state device, it was felt necessary to preced the larger experiment by a prototype (PROTO-ETA) which includes a solenoid with limited inductive capability. The inductive approach is quite reliable and will allow the testing of other current drive methods such as RF and DC helicity injection.

The main objective of the prototype experiment is to study the physics of small aspect ratio tokamaks, with particular regard for the dependence of MHD and transport on aspect ratio. In this respect it is important to test the validity of β limits as given by the Troyon scaling. In addition, the device will be used to test efficient current drive techniques and to develop diagnostics systems and the technical expertise necessary for the construction of larger experiments such as ETA. It should be mentioned that in fusion experiments the importance of β is illustrated by the condition to achieve ignition written in the form:

$$\beta \, \tau_E B^2 > 2.3,$$

wich favors high beta configurations such as the spherical torus while keeping the good confinement properties of the tokamak. Furthermore, the increase in B due to paramagnetic effects should improve the fusion efficiency.

In the following section simplified engineering considerations are presented concerning the design of the central column of the device. Details of the physics basis wich determine the expected plasma behavior are given next. Finally, the plasma operating conditions are discussed within the framework of a zero-dimensional model.

2. SIMPLIFIED ENGINEERING DESIGN

The central column represents a critical design area in a spherical torus. The reduced space and the large plasma current that must be generated put severe design constraints on the inductive solenoid, which fits onto the central toroidal field conductors. The inner leg of the toroidal field coils is designed to occupy the minimum possible space consistent with the ampere-turns required to produce the desired magnetic field on axis,

$$N_t I_t = 2\pi R_o B_o / \mu_o = 1.2 \times 10^6 \text{ A}.$$

The major radius R_o was taken to be equal to 0.36 m, which turns out to be about the minimum machine size compatible with the inductive solenoid requirements. The value of the induction on axis, $B_o = 0.65$ T, was chosen to allow the use, at the second harmonic resonance, of the 35 GHz gyrotrons currently being developed in Brazil [3]. The total current will be carried by 12 coils formed by hollow conductors water cooled in parallel. The current density in the inner legs of the toroidal field coils is limited by the temperature rise $\Delta T_t = 60$ K in copper attained during the flattop electrical pulse of $t_t = 2$s duration. Neglecting the heat transfer from the copper to the water during the pulse one has

$$j_t = [\rho_m c_p \Delta T_t / (\rho t_t)]^{1/2} = 72 \ \mathrm{MA/m^2},$$

where $\rho_m = 8960$ kg/m^3 is the mass density, $c_p = 386$ J/kg K is the specific heat and $\rho = 2.0 \times 10^{-8}$ Ωm is the resistivity of copper. The external radius of the central column is, therefore, given by

$$r_e = [N_t I_t / (\pi \lambda_t j_t)]^{1/2} = 0.09 \ \mathrm{m}$$

where $\lambda_t \pi r_e^2$ is the active area of the central column. The packing factor was assumed to be $\lambda_t \cong 0.65$. Instead of hollow conductors it is also possible to use radially cut or laminated bars. This lamination is necessary to provide the desired plasma current risetime determined by the inductive solenoid flux penetration time. The difusion time of magnetic field lines in the toroidal field coil central column can be estimated by the eddy current time scale $\tau_D \sim \mu_o \sigma L^2$, where σ is the conductivity and L is the characteristic length of the system. With appropriate design the solenoid flux exchange time can be reduced to a few milliseconds, indicating that preionization by, for example, electron cyclotron radiation would still be required immediately before current startup.

The thickness s available for the inductive solenoid is determined by geometrical constraints, as illustrated in Fig. 1 which defines the dimensions of the device. Setting the distance d, combination of the thickness of the vacuum vessel inner wall and the distance from the

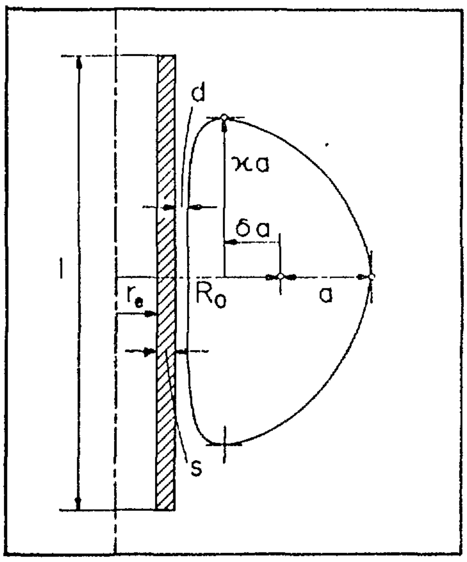

Fig. 1. Definitions of PROTO-ETA dimensions.

wall to the plasma boundary (including space necessary for instrumentation), at 0.03 m the solenoid thickness is

$$s = R_o(1 - \varepsilon) - r_e - d = 0.04\ \text{m},$$

where the inverse aspect ratio is $\varepsilon = 0.56$. The thickness of the inner wall of the vacuum vessel is chosen to be the smallest possible, compatible with the requirements of mechanical strength, to increase the wall electrical resistance and reduce the eddy current induced in the vessel.

The magnetic flux available from a cylindrical coil of infinite length is $\phi_m = \pi\, r_\Omega^2\ B_\Omega$, where $r_\Omega^2 = [(r_e + s)^3 - r_e^3]/(3s)$ and $B_\Omega = \mu_o\, j_\Omega\, \lambda_\Omega\, s$ is the induction at a point inside the coil. The current density in the inductive solenoid is stress-limited and given by

$$j_\Omega \cong \{2\sigma_\phi / [\mu_o\, s\ (r_e + s/2)]\}^{1/2}\ /\ \lambda_\Omega = 250\ \text{MA/m}^2,$$

where the peak tangential stress is $\sigma_\phi = 70$ MPa and the packing factor is $\lambda_\Omega = 0.65$. The solenoid will be made up of 4 radial layers of water cooled hollow conductors wound with opposite helical pitch in order to reduce field errors. The value of the available magnetic flux is

$$\phi_m = (\pi\mu_o/3)\ [(r_e + s)^3 - r_e{}^3]\ j_\Omega\lambda_\Omega = 0.30\ \text{Wb}.$$

Considerable improvement can be obtained if dispersion strengthened copper is used, in which case the value of σ_ϕ can be nearly doubled ($\sim$ 140 MPa) and the available flux increases to 0.42 Wb. Furthermore, the outer coils can provide an increase in the total flux linkage of $\sim$ 20% with respect to the flux due to the solenoid alone. It must be pointed out that in the simple approximation for the stress limit used above it was assumed that the solenoid is a thin-walled cylinder with uniform tension. The actual situation is more complex and the peak tangential stress on the coil is on the small radius edge where the maximum amplitude of the induction is

$$B_{max} = [B_\Omega^2 + (R_o\, B_o/r_e)^2]^{1/2} = 8.4\ \text{T} \qquad (\cong B_\Omega = 8.0\ \text{T}).$$

Assuming a copper temperature increase $\Delta T_\Omega = 60$ K, the maximum equivalent flattop pulse duration can be estimated by

$$t_\Omega = \rho_m\, c_p\, \Delta T_\Omega\ /\ (\rho\, j_\Omega^2) = 0.17\ \text{s}.$$

3. PHYSICS MODELS AND CONSTRAINTS

The equilibrium toroidal plasma current depends on the true MHD safety factor q_a (at the plasma edge), the induction B_o, the aspect ratio $A = a/R_o = \varepsilon^{-1}$ and the plasma shape (elongation κ, triangularity δ), according to

$$I_p = \frac{2\pi\ a^2\ \kappa\ B_o}{\mu_o\ R_o\ q_c} \left(\frac{1 + \kappa^2}{2\kappa}\right) = \frac{2\pi\ a^2\ \kappa\ B_o}{\mu_o\ R_o\ q_a} \left(\frac{1 + \kappa^2}{2\kappa}\right) f\,(\varepsilon,\ \kappa,\ \delta,),$$

where $q_a = q_c\ f\ (\varepsilon,\ \kappa,\ \delta)$, $q_c = q_*\ (1 + \kappa^2)\ /\ (2\kappa)$ is the equivalent cylindrical safety factor and q_* is the kink safety factor. The function $f\ (\varepsilon,\ \kappa,\ \delta)$ can be fitted by [4]

$$f(\varepsilon,\ \kappa,\ \delta) = (1.12 - 0.99\varepsilon + 0.11\kappa + 0.47\delta)\ /\ (1 - \varepsilon^2)^2.$$

For an edge safety factor $q_a = 4.5$, near natural elongation $\kappa = 1.8$ and triangularity $\delta = 0.6$ ($q_c = 2.0$) the plasma current is $I_p = 0.38$ MA.

The density is limited, for stable ohmically heated tokamak operation, by the Murakami-Hugill density limit [5]

$$n_{MH} = 1.5\ B_o\ /\ (q_c\ R_o) \cong 1.3 \quad \text{(in units of } 10^{20}\ \text{m}^{-3}\text{)}.$$

For auxiliary heated plasmas the limit is given by

$$n_{MH}\ (\text{aux}) = 2.1\ B_o/(q_c\ R_o) \cong 1.9 \quad \text{(in units of } 10^{20}\ \text{m}^{-3}\text{)}.$$

The critical volume-averaged value of beta that can be reached within ideal MHD stability is given by the Troyon scaling law [6]

$$\beta_c = 0.035 \times 10^{-6}\ I_p\ /\ (a\,B_o) \cong 0.10.$$

The critical value of β has a strong dependence with the inverse aspect ratio ε (for $\varepsilon \gtrsim 0.5$) as shown in Fig. 2, where the target operating point for the PROTO-ETA device is indicated.

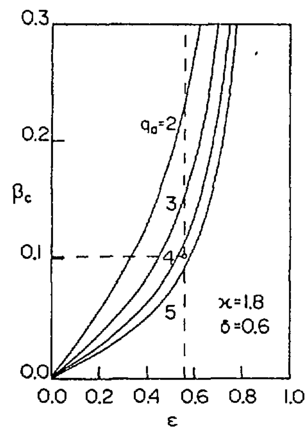

Fig. 2. Variation of the critical value of β with the inverse aspect ratio ε, according to the Troyon scaling law (the target operating point for PROTO-ETA is indicated).

The confinement is described globally by combined ohmic and auxiliary heating scalings

$$\tau_E = (1/\tau_\Omega^2 + 1/\tau_A^2)^{-1/2},$$

where τ_Ω is given by the Neo-Alcator scaling law

$$\tau_\Omega = \tau_{NA} = 0.071\ n_{20}\ a\, R_o^2\ q_c$$

and τ_A by the Kaye-Goldston L-mode confinement time [7]

$$\tau_A = \tau_{KG}^L = 6.02 \times 10^{-6}\ I_p^{1.24}\ R_o^{1.65}\ \kappa^{0.28}\ n_{20}^{0.26}\ A_i^{0.5} / (W_A^{0.58}\ a^{0.49}\ B_o^{0.09}),$$

where A_i is the ion atomic mass number and W_A is the auxiliary power deposited in the plasma. In general, for H-mode confinement one can take $\tau_A = \tau_{KG}^H \cong 2\,\tau_{KG}^L$. The global confinement model here considered leads to some of the most pessimistic predictions.

The plasma flux requirement has both an inductive and a resistive component

$$\phi_m = \Delta(L_p I_p) + \int_o^{t_p} R_p\ I_p\ dt.$$

Assuming a constant current sequence, the required flux can be estimated by

$$\phi_m = L_p I_p + R_p I_p t_p,$$

where the plasma resistance R_p was assumed constant during the equivalent flattop pulse duration t_p. The plasma inductance can be aproximated by

$$L_p = \mu_o\, R_o\{\ln[8\, R_o/(a\sqrt{\kappa})] + l_i / 2 - 2\},$$

where the value of the plasma internal inductance depends on the current profile according to

$$l_i = \begin{cases} 0.6 - \text{broad profile} \\ 0.8 - \text{normal profile} \\ 1.0 - \text{peaked profile} \end{cases}$$

Taking $l_i \cong 0.8$ one has $L_p = 0.35\ \mu H$. In order to calculate the plasma resistance one has to estimate the electron temperature, which is done in the next section.

4. PLASMA PERFORMANCE

The physics parameters space of a tokamak experiment can be explored in a very simple way using a global (zero-dimensional) model [8]. The global power balance equation is

$$\partial Q / \partial t = -Q / \tau_E - W_R + W_\Omega + W_A,$$

where the total plasma energy is

$$Q = (3/2) < n_e T_e + n_i T_i > V_p.$$

Defining the density-averaged temperature $T = <n_e T_e + n_i T_i>/<n_e + n_i>$ and the average density $n = <n_e + n_i>/2$, the expression for Q becomes

$$Q = 3n\ T\ V_p = 4.81 \times 10^4\ n_{20}\ T\ V_p,$$

where the density is in units of 10^{20} m^{-3}, the temperature is in keV (these units are used in all pratical expressions in this work) and $V_p = 2\pi^2 a^2 \kappa R_o$ is the plasma volume. It must be pointed out that in calculating volume-averaged quantities the plasma poloidal cross-section is assumed elliptical so that the plasma minor cross-sectional area is $A_p = \pi\ a^2\ \kappa$ and the plasma surface area is $A_s = 4\pi^2\ [(1 + \kappa^2) / 2]^{1/2}\ a R_o$. The corrections due to triangularity are kept only in the factor $f(\varepsilon, \kappa, \delta)$ relating the MHD and cylindrical safety factors. The power loss due to transport is Q/τ_E, where τ_E is the energy confinement time described in the previous section.

The power density loss due to radiation (Bremsstrahlung) is given by

$$P_R = e^6\ g\ Z^2\ n_e\ n_z\ T_e{}^{1/2} / [6(3/2)^{1/2} \pi^{3/2} \varepsilon_o^3\ c^3\ h\ m_e{}^{3/2}]$$
$$= 5.35 \times 10^3\ Z_{eff}\ (n_e/10^{20})^2\ T_e{}^{1/2},$$

where the Gaunt factor $1<g<1.2$, which corrects for electron-electron collisions and relativistic effects, was taken equal to $2\sqrt{3}/\pi$ and $Z_{eff} = \Sigma\ n_i\ Z_i{}^2 / n_e$ is the effective ion charge. The volume averaged power density loss due to radiation is

$$<P_R> = (2\pi / A_p) \int_o^{a*} P_R\ r\ d r,$$

where $a_* = (ab)^{1/2} = \sqrt{\kappa}\ a$ is the minor radius of the equivalent circular plasma cross section ($A_p = \pi\ a_*^2$). Assuming parabolic profiles of the form

$$n(r) = n_o(1 - r^2/a_*^2),$$
$$T(r) = T_o(1 - r^2/a_*^2),$$
$$j_p(r) = j_o(1 - r^2/a_*^2)^{3/2},$$

the average density, density-averaged temperature, and average current density are

$$n = (2\pi/A_p) \int_0^{a*} n(r)\, r\, dr = n_o/2,$$
$$T = [2\pi/(n\, A_p)] \int_0^{a*} n(r)\, T(r)\, r\, dr = 2\, T_o/3,$$
$$j_p = (2\pi/A_p) \int_0^{a*} j_p(r)\, r\, dr = 2\, j_o/5.$$

Therefore, the average value of P_R can be written in the form

$$\langle P_R \rangle = 5.35 \times 10^3\, g_R\, Z_{eff}\, n_{20}^2\, T^{1/2},$$

where the radiation profile factor g_R is calculated by

$$g_R = (2\pi / A_p) \int_0^{a*} [n_{20}^2(r)\, T^{1/2}(r) / (n_{20}^2\, T^{1/2})]\, r\, dr = (8/7)\, (3/2)^{1/2} = 1.40.$$

The total power loss due to radiation is

$$W_R = \langle P_R \rangle\, V_p = 7.49 \times 10^3\, Z_{eff}\, n_{20}^2\, T^{1/2}\, V_p.$$

The ohmic power density is $P_\Omega = \eta(j_\phi{}^2 + j_\theta{}^2)$, where η is the Spitzer classical resistivity corrected for trapped particle effects

$$\eta = 0.51\, m_e{}^{1/2}\, e^2\, \gamma_{neo}\, \gamma_i\, \ln\Lambda \,/\, [3\varepsilon_o{}^2\, (2\pi\, T_e)^{3/2}]$$
$$= 1.66 \times 10^{-9}\, \gamma_{neo}\, \gamma_i\, \ln\Lambda \,/\, T_e{}^{3/2}.$$

For T_e in keV, the Coulomb logarithm is given by

$$\ln\Lambda = 15.2 - (1/2)\ln(n_e/10^{20}) + \ln T_e \cong 14$$

and γ_i is a factor which accounts for the presence of impurities

$$\gamma_i = 0.580\, Z_{eff} + 0.773\, Z_{eff} \,/\, (0.840 + Z_{eff}).$$

The local neoclassical resistivity enhancement factor (at low collisionality $\nu_e{}^* < 1$) is approximated by

$$\gamma_{neo} \cong [1 - (r/R_o)^{1/2}]^{-2}.$$

Note: the electron collisionality is

$$\nu_e{}^* = \nu_{ei}\, q\, R_o \,/\, [v_e (r/R_o)^{3/2}] = 4.90 \times 10^{-24}\, n_e \ln\Lambda\, Z_{eff}\, q\, R_o{}^{5/2} \,/\, (T_e{}^2\, r^{3/2}),$$

which, at the plasma edge, becomes

$$\nu_e{}^* \cong 6.86 \times 10^{-3}\, n_{20}\, Z_{eff}\, q_a\, R_o \,/\, (T^2\, \varepsilon^{3/2}).$$

The average ohmic power density is calculated neglecting the poloidal current contribution (this can be a strong, but conservative assumption, for a spherical torus equilibrium)

$$\langle P_\Omega \rangle = \langle \eta\, (j_\phi{}^2 + j_\theta{}^2) \rangle \cong \langle \eta\, j_p{}^2 \rangle,$$

where the average current density is given in terms of the total plasma current by $j_p = I_p / A_p$ and

$$j_p(r) = (5/2)\ (I_p/A_p)\ (1 - r^2 / a_*^2)^{3/2}.$$

The current density on axis is

$$j_p(0) = [5 B_o / (\mu_o R_o q_c)]\ [(1 + \kappa^2) / (2\kappa)] = [2 B_o / \mu_o R_o q_o)]\ [(1 + \kappa^2)/(2\kappa)],$$

where $q_o = 2\, q_c/5$ is the safety factor on axis for the assumed profiles. Hence, the average ohmic power density can be written in the form

$$<P_\Omega> \cong \eta_s\ (T)\ g_\Omega\ g_{neo}\ (I_p/A_p)^2,$$

where η_s (T) is the Spitzer classical resistivity evaluated at the density-weighted average temperature

$$\eta_s(T) = 1.66 \times 10^{-9}\ \gamma_i \ln \Lambda / T^{3/2} = 2.33 \times 10^{-8}\ \gamma_i / T^{3/2},$$

the ohmic power profile factor is

$$g_\Omega = (25/3)\ (2/3)^{1/2}\ a_*^{-2} \int_0^{a_*} (1 - r^2/a^2)^{3/2}\ r\, d\, r = (5/3)(2/3)^{1/2} = 1.36,$$

and the neoclassical resistivity enhancement factor is

$$g_{neo} = [\int_0^{a_*} \gamma_{neo}(r)\ (1 - r^2/a_*^2)^{3/2}\ r\, d\, r\,] / [\int_0^{a_*} (1 - r^2/a_*^2)^{3/2}\ r\, d\, r].$$

A rough approximation, in the parameters range of interest, is given by

$$g_{neo} \cong [1 - 0.767\ (\sqrt{\kappa}\ \varepsilon)^{1/2}]^{-2}.$$

Finally, the total ohmic power is given by

$$W_\Omega = <P_\Omega>\ V_p\ = \eta_s\ (T)\ g_\Omega\ g_{neo}\ V_p\ (I_p/A_p)^2 = R_p I_p{}^2,$$

where the plasma resistance is defined by

$$R_p = 3.17 \times 10^{-8}\ \gamma_i\ g_{neo}\ V_p/(T^{3/2}\ A_p{}^2).$$

The plasma parameters operating space is shown in Fig. 3 for the prototype experiment. The ohmic equilibrium contour corresponds to a steady-state solution of the global power balance equation when no auxiliary power ($W_A = 0$) is added. The plasma temperature in this case, assuming $Z_{eff} \cong 2$, is $T \cong 0.41$ keV. One verifies that, for a plasma density near the lower Murakami-Hugill limit, $\beta = 0.0805\ n_{20}\ T/B_o^2$ reaches the critical value given by the Troyon scaling law.

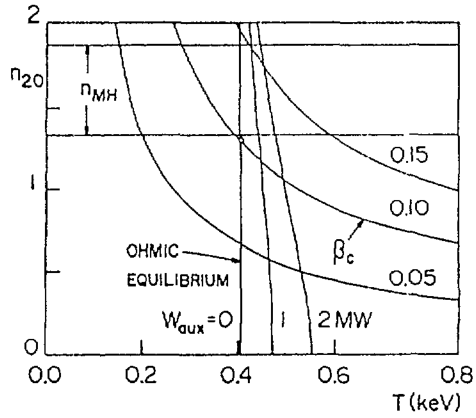

Fig. 3. Steady-state contours in plasma parameters operating space for the PROTO-ETA device.

Fig. 3 shows, also, auxiliary power contours for $W_A=1$ and 2 MW. Additional heating opens the possibility of operation at lower densities or at β values above the Troyon limit. The most sucessful technique for auxiliary heating of tokamak plasmas has been the injection of high-energy neutral particles [9]. To ensure adequate heating of the plasma interior it is necessary to preferentially deposite the particle beam energy in the center of the plasma acoording to the criterion $a/\lambda \leqq 4$, where λ is the beam trapping length

$$\lambda = 1/(n_o \sigma_{eff}) \cong 5.5 \times 10^{17} E_b / (A_b n_o Z_{eff}^{\gamma}) \qquad (0 < \gamma < 1),$$

E_b is the energy of the neutral particles and A_b the atomic mass in amu. Since the central density $n_o = 2n$, one can estimate the minimum energy necessary to heat the center region

$$E_b > 91 A_b Z_{eff}^{\gamma} a n_{20} .$$

For the small size prototype experiment, a 20 keV beam energy should suffice for adequate heating. Since this energy value is above the critical energy $E_c = 14.8 A_b T_e/A_i^{2/3}$, the energetic ions will preferentially heat the plasma electrons (for $T_e = 0.41$ keV about 40% of the injected particle energy is transfered to the ions [10]). A major effect in the determination of the loss rate of energetic ions is the toroidal field ripple, which must be kept at a minimum. This effect should be taken in account in the design of the toroidal field coils.

In order to improve plasma performance, and possibly operate in the H-mode of confinement, a divertor is being considered in the PROTO-ETA device. The discharge should operate with a single null magnetic configuration and the divertor plates will be located in a pumping chamber in the lower part of the device. This configuration will permit the production of a broad current profile and the separation of the high impurity level scrapeoff region from the current channel. Provision will be made for biasing the toroidal divertor plates with respect to one another to test current drive by DC-helicity injection [11]. This scheme, if demonstrated for tokamaks, should lead to an efficient and simple current drive system, where the power is derived from a relatively low voltage (200 ∿ 300 V) DC source. Furthermore, the current drive efficiency by this method is not limited by the plasma density, a feature which is particularly atractive for tokamak reactor applications.

Another current drive scheme that should be tried employs whistler waves with $f_{LH} << f << f_{ce}$, also known as lower hybrid current drive (LHCD). One advantage of this scheme is that the whole wave energy can be coupled to the electrons by an adequate choice of wave frequency. Also, high power sources are readily available and very reliable, and the coupling technology is well known and very efficient. On the other hand, from the theory of RF current drive it is well known that the efficiency is proportional to $1/n_{\parallel}^2$ and it has been observed experimentally to fall off with $\omega_{pe}^2/\omega_{ce}^2$. From preliminary ray tracing calculations it was found that the plasma centre can only be accessed by waves with high $n_{\parallel}$ ($\gtrsim 4$) and typical values of $\omega_{pe}^2/\omega_{ce}^2$ are very high (~ 2), which would seriously hinder this current drive scheme. A ray tracing study in a more realistic magnetic field geometry, including paramagnetic effects, is underway to allow a better evaluation.

Table 1 summarizes the design parameters of the PROTO-ETA device. The basic parameters are initially specified, allowing the calculation of all plasma equilibrium parameters according to the physical constraints presented in this work. Finally, the plasma performance parameters are calculated assuming ohmic equilibrium ($W_A = 0$) and operation at the density limit ($n_{20} = n_{MH}$).

TABLE 1. PARAMETERS OF THE PROTO-ETA DEVICE

BASIC PARAMETERS (INPUT)	
- Inverse aspect ratio, ε	0.56
- Elongation, κ	1.80
- Triangularity, δ	0.60
- Major toroidal radius, R_o(m)	0.36
- On-axis toroidal induction, B_o(T)	0.65
- Edge-plasma safety factor, q_a	4.5
- Ion atomic mass number, A_i	1
- Effective ion charge, Z_{eff}	2.0
PLASMA EQUILIBRIUM	
- Toroidal plasma current, I_p(MA)	0.38
- Cylindrical safety factor, q_c	2.0
- On-axis safety factor, q_o	0.80
- Murakami-Hugill density limit, n_{MH} (10^{20} m^{-3})	1.3
-Troyon beta limit, β_c	0.10
- Plasma inductance, L_p(μH)	0.35
- Plasma volume, V_p(m^3)	0.52
- Plasma poloidal cross-sectional area, A_p(m^2)	0.23
- Plasma surface area, A_s(m^2)	3.6
PLASMA PERFORMANCE (OHMIC EQUILIBRIUM, $n_{20} = n_{MH}$)	
- Density-averaged plasma temperature, T(keV)	0.41
- Ohmic power, W_Ω(MW)	2.7
- Radiated power, W_R(kW)	8.8
- Plasma energy, Q(kJ)	14
- Energy confinement time, τ_E(ms)	5.0
- Plasma resistance, R_p($\mu\Omega$)	18
- Equivalent flattop pulse duration, t_p(ms)	24 ($\phi_m = 0.30$ Wb)

REFERENCES

[1] GALVÃO, R.M.O.; GOES, L.C.S.; LUDWIG, G.O.; MONTES, A.; UEDA, M. "Proceedings of the Energy Independence Conference on Fusion Energy and Plasma Physics, 17-21 August, 1987, Rio de Janeiro, Brazil, P.H. Sakanaka (Editor) (World Scientific, Singapore, 1988), p. 471.

[2] ROBINSON, D.C. Nuclear Fusion 28, 331 (1988).

[3] BARROSO, J.J.; CASTRO, P.J.; CORREA, R.A.; GALVÃO, G.P.; LUDWIG, G.O.; MONTES, A.; NONO, M.C.A.; ROSSI, J.O. "Proceedings of the Energy Independence Conference on Fusion Energy and Plasma Physics, 17-21 August, 1987, Rio de Janeiro, Brazil, P.H. Sakanaka (Editor) (World Scientific, Singapore, 1988), p. 226.

[4] SELCOW, E.C.; PENG, Y-K.M.; UCKAN, N.A.; HOULBERG, W.A. "Proceedings of the 11th Symposium on Fusion Engineering, Austin, Texas, 18-22 November, 1985, p. 1111.

[5] MURAKAMI, M.; CALLEN, J.D.; BERRY, L.A. Nuclear Fusion 16, 347 (1976).

[6] TROYON, F.; GRUBER, R.; SAURENMANN, H.; SEMENZATO, S.; SUCCI, S. Plasma Phys. Controlled Fusion 26, 209 (1984).

[7] KAYE, S.M.; GOLDSTON, R.J. Nuclear Fusion 25, 65 (1985).

[8] UCKAN, N.A.; SHEFFIELD, J. In "Tokamak Start-Up", H. Knoepfel (Editor) (Plenum Press, 1986) p. 45.

[9] MENON, M.M. Proc. of the IEEE 69, 1012 (1981).

[10] SWEETMAN, D.R. Nuclear Fusion 13, 157 (1973).

[11] ONO, M.; GREENE, G.J.; DARROW, D.; FOREST, C.; PARK, H.; STIX, T.H. Phys. Rev. Lett. 59, 2165 (1987).

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