SOME PHYSICS CONSIDERATIONS FOR TEPR DESIGNS*

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Summary

A simplified version of the Oak Ridge Tokamak Transport Code is used to assess the implications of confinement scaling, impurity trapping of neutral beam particles and plasma currents driven by neutral injection. The ORNL, ANL and GAC experimental power reactor reference designs are considered.

Introduction

Success in producing plasmas with long energy confinement times in the next generation of tokamaks will stimulate planning for an Experimental Power Reactor: a device which might produce an amount of power by fusion roughly equal to the power needed for plant operation. At present three groups have developed working reference designs: the Oak Ridge National Laboratory,[1] Argonne National Laboratory,[2] and the General Atomic Company.[3] This paper addresses some areas currently under study to assess their impact on EPR designs. The areas are: confinement scaling, the enhanced trapping of neutral beams by impurities, and the sustenance of plasma current by neutral beam injection.

The confinement scaling of reactor devices is unknown and is being tested in injection experiments on ORMAK, and in the ohmically heated PLT and T10 devices. A recent survey of theoretical predictions[4] has been used for EPR designs, and we apply a slightly different test, based on plasma collisionality, $\nu^*_{e,i}$, to compare the three-reference designs on a common basis. We use a simplified version of the Oak Ridge Tokamak Transport Code[5] to calculate the energy balance.

Intense neutral beams are seen as an important heating mechanism in each EPR design. While the usual criterion for beam trapping is the impact of neutral deuterons on the plasma ions, there has been concern over the effects of trapping by impurity ions. This enhanced trapping increases the energies needed or alternatively, may force adoption of perpendicular injection of the beam.

Ohkawa[6] has suggested the possibility of a steady-state tokamak in which the rotational transform is supplied by a beam-induced current. Recent calculations[7] have improved our estimates of the available beam current, and we calculate the injected beam currents required.

Confinement Scaling

To compare the energy balance and confinement scaling in EPR designs we adopt a simplified version of the model used to describe present experiments, and add the thermonuclear terms of interest. The model treats the plasma densities as prescribed functions of space and time. The correct simulation requires the full treatment of neutral gas and fast ions (Fokker-Planck or moments) and these take substantially different forms for large plasmas with appreciable populations of alpha particles. The fuel is assumed to be a single D-T specie, with atomic mass between 2 and 3 depending on the precise composition. The energy balance equations are:

$$\frac{3}{2}\frac{\partial}{\partial t}[N_e\, T_e(r,t)] = \frac{1}{r}\frac{\partial}{\partial r}[rN_e\chi_e \frac{\partial T_e}{\partial r}] + E\cdot j + Q^e_{injection} + Q^e_{Alphas} - C_{LR}n_e n_Z f(T_e) - 3\frac{m_e}{m_f}\frac{T_e - T_f}{\tau_e} \quad (1)$$

$$\frac{3}{2}\frac{\partial}{\partial t}[N_f\, T_f(r,t)] = \frac{1}{r}(rN_i\chi_i\frac{\partial T_f}{\partial r} + 3\frac{m_e}{m_f}\frac{T_e - T_f}{\tau_e} + Q^f_{injection} + Q^f_{Alphas} \quad (2)$$

The electromagnetic field is described by

$$\frac{\partial B_{Pol}}{\partial t}(r,t) = \frac{\partial E_Z}{\partial r};\; E = \eta(j - j_B);\; \mu_o j = \frac{1}{r}\frac{\partial}{\partial r}(rB_{Pol}) \quad (3)$$

where:

- $N_{e,f}$: electron, fuel densities
- $T_{e,f}$: electron, fuel temperatures
- E, B_{Pol}, j_Z: electric field, poloidal magnetic field, toroidal current density
- j_B: beam-induced current density
- $f(T_e)$: $0.4 + 4.6\, e^{-T_e^2(\mathrm{keV})}$: temperature dependence of line-radiation loss for iron
- $m_{e,f}$: masses of electrons, fuel ions

To represent the plasma transport scaling in the collisionless regime we adopt a model for $\chi_{e,i}$:

$$\chi_e = \chi_{\text{Pseudo-classical}} \cdot [1 + \frac{0.16}{\nu_e^{*2}}]$$

$$\chi_i = \chi_{\text{Neoclassical}} \cdot [1 + .01/\nu_e^{*2}]$$

This depicts unfavorable scaling beginning at a threshold $\nu^*_e \sim 0.4$, $\nu^*_i \sim 0.1$, roughly as predicted by theory.

Using parameters of the reference designs at ORNL, ANL and GAC, we have obtained the resulting plasma parameters for the same model assumptions. These are -

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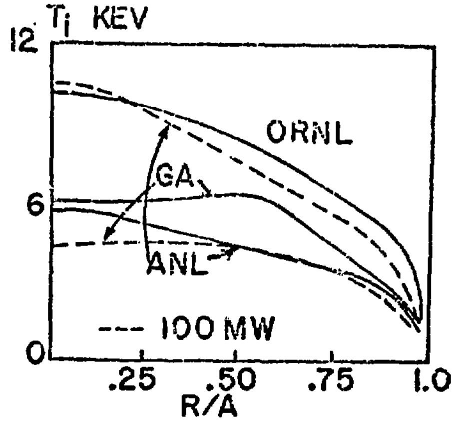

Figure 1. Radially dependent ion temperature behavior for 100 MW of neutral beam injection into ORNL, ANL, GAC-EPR reference designs.

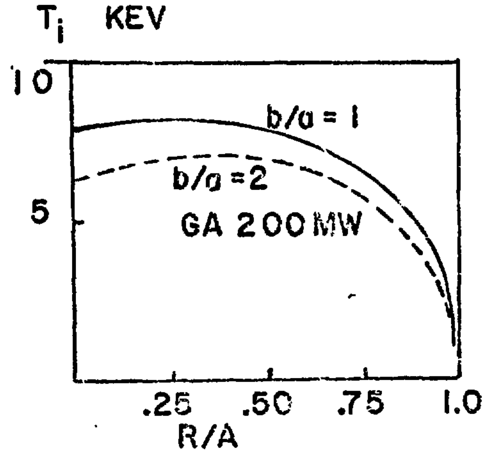

Figure 2. Radially dependent ion temperature behavior for 200 MW of neutral beam injection into GAC-EPR reference design for plasma elongations of b/a = 1, b/a = 2.

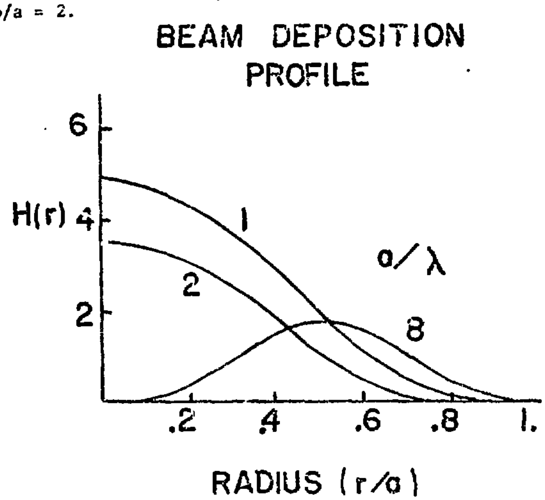

Figure 3. Neutral beam deposition profiles for plasma radius to mean free path ratios of 1, 2, and 8.

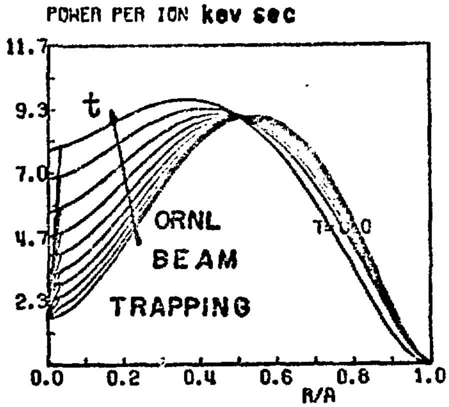

Figure 4. Effect of impurity trapping on neutral beam deposition profile in ORNL-EPR.

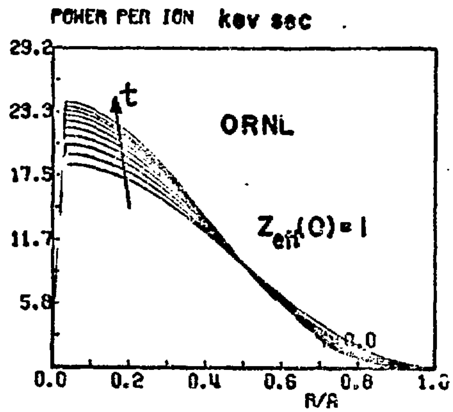

Figure 5. Neutral beam deposition profile for initially clean plasma case. Impurity trapping effects of Figure 4 are delayed in time in this case.

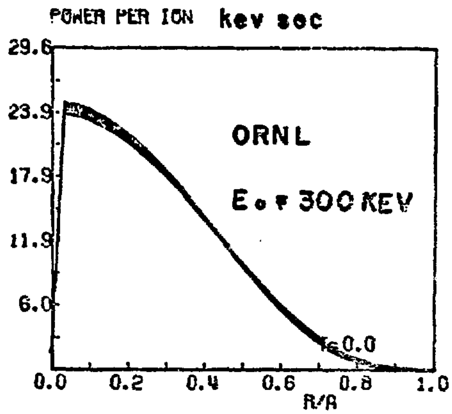

Figure 6. Neutral beam deposition profile for increased beam energy. Impurity trapping effects are eliminated due to the high injection energy.

shown in Figure 1. Figure 1 also shows results of all cases with the same (100 MW) injection power.

Note: To model the elliptical cases in the GAC design we have adopted a constant current model for the flux surfaces:

We have replaced the radial equations 1-3 by a flux dependent set, i.e., (1) becomes

$$\frac{3}{2}\frac{\partial}{\partial t}\left[N_e T_e(\Psi,t)\right] = \frac{1}{V'}\frac{\partial}{\partial \Psi}\left[\langle \chi N_e |\nabla\Psi|^2\rangle \frac{1}{V'}\frac{\partial T_e}{\partial \Psi}\right] + \ldots$$

where $V'(\Psi) = \frac{(\pi ab)(2\pi R_o)}{\Psi_{wall}}$ with $x = R_o + a\cos\theta\sqrt{\Psi/\Psi_{wall}}$

$y = b\sin\theta\sqrt{\Psi/\Psi_{wall}}$

then

$$\langle\varphi\rangle \equiv \frac{\int_\Psi \frac{ds}{|\nabla\Psi|}\varphi}{\int_\Psi \frac{ds}{|\nabla\Psi|}} = \frac{1}{2\pi}\int_0^{2\pi} d\theta\, \varphi(\Psi,\theta).$$

We thus change the transport coefficients by a factor

$$\alpha_E \equiv \frac{1 + (b/a)^2}{2(b/a)}.$$

The results of successive elongation (for $\frac{b}{a} = 1$, $\frac{b}{a} = 2$) are shown in Figure 2.

Beam Trapping

Calculation of the necessary beam energies is heavily dependent on the trapping mechanism. Ion impact ionization is the dominant trapping process with the $\varepsilon_o > 100$ keV energies envisioned for EPR. The trapping by impact ionization on impurity ions must also be considered. If the original inverse mean free path was $\sigma_f n_f$, the new value is

$$n_f\sigma_f + n_Z Z^2\sigma_f, \text{ or } n_e Z_{eff}\sigma_f \text{ where}$$

$$Z_{eff} \equiv \frac{n_f + n_Z Z^2}{n_e}.$$

Thus, as Z_{eff} increases, the beam is trapped farther to the outside of the plasma, a region with higher loss rates due to charge exchange. As the energy is deposited in this region and transferred more readily to the wall, the impurity level is increased; and the beam is trapped even nearer to the plasma boundary.

A complete calculation would require a self-consistent solution for the beam deposition profile as is done with the full transport code[5] after the prescription of Callen, et al.[7] Based on sample calculations of the profile for large systems, we have devised an approximate formula for H(r) as a function of a/λ (ratio of plasma radius to mean free path). It is:

$$H(r) = K\left\{\frac{(1 - r^2/a^2)^4}{(a/\lambda)^2} + \left[1 - (2r/a - 1)^2\right]^2 \left[\frac{a/\lambda - 1}{6}\right]^2\right\}$$

$$K = \frac{15}{\frac{3}{(a/\lambda)^2} + 10\left[\frac{a/\lambda - 1}{6}\right]^2}$$

The resulting curves are shown in Figure 3.

Assuming that the ion energy transfer in equation (2) is carried from the plasma as charge exchange loss, and assuming an impurity evolution of 5.10^{-6} atoms/eV of charge exchange loss (as is suggested by detailed calculations of the spectrum)[8], we find the instability as shown in Figure 4. The initial cleanliness of the system can delay the onset (Figure 5) and choosing higher beam energies can ameliorate it (Figure 6).

Beam-Induced Current

When the fast ions which result from neutral beam injection thermalize in the background plasma, there is a momentum transfer to the plasma electrons and a resulting current. The current density so produced is,[7]

$$\Delta J = \frac{I_B}{V} v_B \tau_s K_e \times 0.67 \qquad (Z_{eff} = 3)$$

for a monoenergetic deuteron beam. I_B is the injected beam current, V_B the initial speed of a beam particle, τ_s the initial slowing down time constant for fast ions due to electron friction, and K_e a momentum transfer function (cf. ref. 7). Using the ORNL reference design parameters as typical,

$$\frac{\Delta I}{I_B} \approx 10^4.$$

Thus, by injecting a 200 keV deuteron beam of 720 A, the plasma current requirements could be supplied entirely by the injected beam. This is equivalent to 150 MW of injection power and exceeds the planned injection level by 50%.

Conclusion

A uniform comparison of the performance of the ANL, GAC and ORNL-EPR reference designs using the same plasma model has been presented. Results are shown in Figure 1. Neutral beam trapping which results from enhanced attenuation due to impurities has been exhibited. To alleviate this effect, either a high vacuum design to meet plasma purity requirements or an increased neutral beam energy may be necessary. Finally, sustenance of the EPR plasma current by neutral beam injection seems unlikely due to the large injection current required.

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