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COMPUTATIONAL STUDIES OF IMPURITY EFFECTS, IMPURITY CONTROL, AND NEUTRAL BEAM INJECTION IN LARGE TOKAMAKS

PLASMA PHYSICS LABORATORY

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COMPUTATIONAL STUDIES OF IMPURITY EFFECTS, IMPURITY CONTROL, AND NEUTRAL BEAM INJECTION IN LARGE TOKAMAKS

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ABSTRACT

Computational models have been constructed for the Princeton Large Torus (PLT), the Poloidal Divertor Experiment (PDX), and the Tokamak Fusion Test Reactor (TFTR). These models have been calibrated by comparison with current experiments and used to predict plasma parameters and delineate favourable modes of operation for future experiments. The models for PLT emphasize plasma transport and neutral beam injection heating. The models for PDX emphasize the capability of divertors for impurity and recycling control in intense neutral-beam-heated tokamaks, as well as optimization of the MHD properties of divertor-equipped tokamaks. The TFTR calculations stress the fusion aspects of a large, circular cross-section D-T tokamak with intense neutral beam injection.

The calculations indicate that the highest neutron yields on PDX and PLT will be obtained by co- and counter-injection of deuterium beams into a discharge whose density is kept low by reducing the plasma recycling by gettering or a divertor. The highest ion temperatures can also be obtained by injection into low density plasmas. High density plasmas have higher $n\tau_E$'s, but are colder, and have lower neutron yields. For TFTR, the fusion yield can be maximized by a warm-electron, hot-ion mode characterized by an intermediate plasma density ($5 \times 10^{13}/cm^3$) and high power injection (32-45 MW).

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I. COMPUTATI[illegible]

The transport [illegible] neutral injection [illegible] ts of PLT, PDX, and [illegible] been modeled using two one-dimensional, m[illegible] species tokamak transport [illegible] BALDUR, and FPT(Fokker-Planck Transport) [illegible]. The codes [illegible] multi-species Monte-Carlo neutral transport m[illegible] [illegible] in which charge [illegible] neutrals from the neutral beam [illegible] and recombination neutrals [illegible] included. The beam deposition [illegible] for both codes is computed [illegible] Monte-Carlo algorithm [3]. Both [illegible] have [illegible] algorithms [illegible] beam and [illegible] [illegible] calculated [illegible] equ[illegible] [illegible]

[illegible] the [illegible] two dimensional velocity [illegible] [illegible] species is computed using the [illegible] [illegible] collisions [illegible] [illegible] power is [illegible] by a five-fold [illegible] [illegible]. An [illegible] transport model [illegible] $= 1000x(1.4 \times [illegible])$ cm^2/sec, [illegible] more pessimistic than neoclassical [illegible] the ions are assumed, as in BALDUR, to [illegible]

BA[illegible] e.g. [illegible] impurity treatment. [illegible] beam [illegible] is computed [illegible] a simple Fokker-Planck scheme for each [illegible] surface which incl[illegible] pitch angle scattering, slowing-down, and charge exchange [illegible] the beam ions. No orbital effects are included. The [illegible] electrons from the ionization of injected neutral atoms are added to the background electrons. Thermalized beam ions are added to the background plasma. Alpha particle [illegible] is computed with a simple slowing [illegible] which includes loss cones and orbital spreading. The transport model [illegible] used is empirical based on PLT and ALCATOR [7] results, with $\chi_e = 5[illegible]$ [illegible] cm^2/sec, [illegible] n_e cm^2/sec [illegible] $n_e + 5000x(r/a)$ [illegible] cm^2/sec), and χ_i neoclassical. This transport model gives a lower [illegible] broader electron temperature profile than observed on recent PLT experiments. For the PLT neutral injection experiments, a χ_e of the form [illegible]$x10^{13}/n_e T_e$ (eV)] cm^2/sec is used to make the electron temperature profile peaked. Non-equilibrium low-Z impurity radiation is modeled by [illegible] the radiation loss for each hydrogen ionization from 40 eV to [illegible]-2000 eV depending on the impurity level. Convection energy losses are included. Titanium gettering is modeled by recycling as neutral atoms only a fr[illegible] (~90%) of the plasma which flows to the limiter and walls.

II. PLT INJECTION CALCULATIONS

Recent PLT[4] neutral beam injection experiments have been calculated with BALDUR to test the validity of the models and assumptions used in the code, and to assist in analyzing the experimental data. The general agreement was reasonable; however there were important qualitative and quantitative differences between the calculations and the experimental data. Figure 1 shows a comparison [illegible] a low power injection run ($B = 32$ kG, $I = 420$ kA) [5] in which the impurity level has been kept low with titanium gettering with a calculation that assumes that $\chi_e = [illegible]x10^{17}/n_e$ cm^2/sec. Electron conductivities of the form bT^{δ}/n_e were tried, and matches of the calculated profiles, temperature rises, and loop voltages with the PLT results for neutral injection into high density, gettered discharges indicated that [illegible] is ~1.5.

Injection into lower density [illegible] produced higher ion temperatures. [illegible] shows the [illegible] central electron and ion temperatures, electron and ion densities, line average density, Z_{eff}, loop voltage, and [illegible] for a representative case for [illegible] MW of hydrogen injection into deu[illegible] (B_T = [illegible] kG, I_p = [illegible] kA, n_e = [illegible] cm^{-3}, Z_{eff} = [illegible] (mostly carbon)). The [illegible] neoclassical [illegible] conductivity was enhanced by a factor of two. The qualitative features of this calculation are similar to the experiment. As the beam is turned on, the central [illegible] density begins to rise. The central Z_{eff} drops due to dilution of the carbon. The density of beam ions is comparable to the [illegible] density. The [illegible] potential due to [illegible] exceeds the plasma [illegible]. The peak [illegible] temperature is higher than the experiment [illegible] keV [illegible]; however the [illegible] temperature for these very low density [illegible] sensitive [illegible] of the electron [illegible] diffusion [illegible] convective losses [illegible] of [illegible] such as finite orbit [illegible] the [illegible] these [illegible] by a reasonable amount [illegible] in the simulations to 3.5 keV. The [illegible] electron energy has less influence on the [illegible] density [illegible]. The lowest [illegible] is about [illegible].

The highest temperature cases [illegible] MW of deuterium injection into a low density [illegible] cm^{-3}, [illegible] carbon and iron)) discharge. For many of these discharges, [illegible] observed, [illegible] enhanced transport [illegible]. The [illegible] temperature is given on Figure 3 showing the [illegible] calculated ion temperature as a function of time [illegible] conductivity [illegible] been enhanced by factors of [illegible] two [illegible]. The [illegible] of the [illegible] temperature lags slightly the [illegible] temperature [illegible] somewhat more slowly [illegible] the experiment. [illegible] calculated [illegible] temperature saturates after [illegible] ms of injection, [illegible] the beam is turned off.

An interesting feature of both the [illegible] is that [illegible] central electron temperature [illegible] turned on. The electron temperature later recov[illegible] When [illegible] is turned off, the electron temperature [illegible] ion slowing down time) and then begins to fall [illegible] this for [illegible] MW H [illegible] case. In the calculation this is due to the dilution of the hot electrons by the cold electrons formed from the ionization of the fast neutral beam atoms. At the end of the neutral beam pulse, this dilution is ended, and the electron heating is increased for about one slowing down time.

The general features of these low density, high temperature PLT discharges in which the ion energy confinement is better than the electron energy confinement are exploited by calculations for PDX and TFTR to achieve reactor plasma conditions and to maximize the neutron yield and fusion power.

III. PDX INJECTION CALCULATIONS

In the PDX and TFTR experiments, as well as in higher power PLT experiments, the injected neutral beam power will far exceed the ohmic heating power. By controlling the warm-ion density by gettering or by a magnetic divertor, it should be possible to operate in three different reactor-plasma regimes parameterized by the relative energetic ion density [9]: 1) The energetic-ion regime, where the plasma recycling coefficient R [illegible] 1, n_{hot}/n_c [illegible] 0.3, and the dominant fusion production is by reactions between the energetic ions; 2) The TCT regime, where [illegible] / n_e [illegible] 0.1, and the dominant fusion production is by beam-target reactions; 3) The beam driven thermonuclear regime, where [illegible] / n_e [illegible] 0.1, and the dominant fusion production is by thermonuclear reactions. These regimes are illustrated in Figure [illegible], which shows the dependence of [illegible], the average ion energy, and the neutron production rate on the axial plasma density for 50% co-injection and 50% counter-injection with deuterium beams as calculated by FPT.

The effect of a smaller density variation is illustrated in more detail in Figure [illegible], which shows the effect of varying the plasma [illegible] coefficient [illegible] plasma parameters. The Q_p (fusion power/injected power) and the [illegible] are largest at the small densities, and [illegible] dominant [illegible] from [illegible] between the counter-[illegible] energetic [illegible]

[illegible] keV can be attained [illegible] with intense neutral-beam injection, provided [illegible] is minimized by a [illegible] divertor or getter assembly, [illegible] is performed by the beams [10]. The [illegible] the [illegible] 0.5 n_e, and the warm-ion [illegible] T_i. In PDX-sized plasmas with 4 to 10 megawatts of beam [illegible] keV, D-D fusion-neutron intensities [illegible] neutrons sec are attainable in this energetic-ion mode of operation. The [illegible] energy confinement time needs to satisfy only $n_e\tau_E$ [illegible] $2\times10^{[illegible]}$ sec/cm^3.

IV TFTR CALCULATIONS

The TFTR calculations have concentrated on finding ways to maximize the fusion yield while minimizing the deleterious effects of impurities and transport losses. For the initial power level of 32 megawatts of neutral beam injection, two operating schemes were examined using BALDUR (Table [illegible]). The first is one in which the neutral beams are injected into a small (50 cm radius) discharge at the outer edge of the vacuum vessel for a short time, after which the discharge is compressed adiabatically, as in the ATC experiment. Compression energizes the fast ions and heats the plasma. As can be seen in Table [illegible], this discharge achieves quite high β's (2.3%) and high fusion powers (27 MW), in spite of a large impurity content, and small $n\tau_E$'s. Almost all of the fusion power comes from the two-component reactions (energetic deuterons from the beam reacting with thermal tritons). The compression case has the advantage of a large power density and good neutral beam penetration, and is only a modest (factor of one to three) extrapolation from PLT and ATC results. It is insensitive to impurities in that one can compress after only a few hundred milliseconds of injection if impurities begin to accumulate. The disadvantages are that it does not take full advantage of the plasma current capabilities or vacuum vessel size. Only 50% of the alphas are confined and the discharge has relatively low $n\tau_E$'s.

The second mode is to form a 2.5 MA discharge with a 85 cm radius centered at R = 248 cm, and inject for one-half second. The alphas are well confined and somewhat higher $n\tau_E$'s, especially for the ions, are obtained. Due to the high ion temperature, there is an appreciable fusion yield due to the thermal D-T reactions, although the dominant contributions are still from beam ions reacting with the background plasma (TCT reactions). The ion $n\tau_E$'s are much greater than the electron $n\tau_E$'s. Relying on TCT reactions limits the nuclear power to a range near the injected power level. Thermal reactions can raise the nuclear yield, but require increases in beta,(requiring more injected power), and are more sensitive to reductions in the gross confinement time.

The relative [illegible] ion confinement can be exploited if the injection power is raised [illegible] 45 MW and the beam pulse is extended to one second, as is proposed for a TFTR upgrade. For this case the ion temperatures are very high(23 keV) and the electrons are cooler(14 keV). The ion $n\tau_E$ is four or five times greater than the electron $n\tau_E$, and most of the fusion yield is from the beam driven thermal D-T reactions, with only a modest component from the T-T reactions. This hot-ion, warm-electron mode in which the electrons and ions are only loosely coupled can tolerate poor electron energy confinement compared to the ion energy confinement. Quite large fusion yields are obtained with modest $n\tau_E$'s. Should the ion confinement continue to scale [illegible], and electron losses continue to be large (due to impurities and anomalous processes), the hot-ion, warm-electron plasma is an attractive way to make large fusion powers.

V. PDX DIVERTOR CALCULATION

A key element in estimating the efficiency of [illegible] control techniques is the development of a realistic [illegible] model. We have developed a simple model that self-consistently [illegible] plasma interaction with a limiter or wall. In this limiter/divertor model, sink terms, representing particle and energy loss parallel to field lines into the limiter or divertor, are added to the one dimensional radial transport code in the scrape-off region. For nearly all tokamak plasmas of interest, the scrape-off plasma is collisional and an ion sound model is appropriate for parallel mass flow. At high electron densities (several [illegible] /cm^3), the neutral hydrogen density is sufficiently high in the scrape-off region to exert a charge-exchange drag that reduces the mass flow. In addition, we assume that a classical sheath exists at a non-emitting neutralizer or limiter plate. With these assumptions, the appropriate sink terms for a hydrogen plasma in the density, electron energy and ion energy equations are:

$$S_N = -v_S\, n/L\,(1 + \nu_c / 4 v_S)$$

$$S_e = -5.8\, kT_e S_N$$

$$S_i = -2.0\, kT_i S_N$$

where $v_S = [k(T_i + T_e)/m]^{1/2}$, $\nu_c = n_o \sigma_{cx} v_i$

n_o is the neutral density, σ_{cx} is the charge-exchange cross section, v_i is the ion velocity and 2L is the length of a field line between the limiters or divertors.

The validity of this edge model was tested by comparing calculations with measurements of the edge region of ALCATOR for for a Z=1 discharge where B_z = 55 kG, I = 270 kA, $\bar{n}_e$ = 3.5x10^{14} /cm^3, $T_i(0) \approx T_e(0)$ = 800 eV, the edge parameters were found to be n_e = 5x10^{13}/cm^3, $T_e(a)$= 10 eV and the density fall-off distance was 1 cm.

The transport calculations with χ_e = 7x10^{17}/n_e cm^2/sec, D= 2x10^{17}/n_e cm^2/sec and L = 180 cm gave $T_e(a)$ = 30 eV, $T_i(a)$ = 20 eV, $n_e(a)$ = 4x10^{13} /cm^3 which is reasonable agreement for an initial comparison. The higher edge temperature in the calculation relative to the measurement may be due to: not extending the probe all the way to the limiter edge, residual impurity radiation at the edge or limitations of the model. The computed edge temperatures can be brought into agreement with the measurements by increasing the thermal transport coefficient in the [illegible] region near the plasma surface.

The edge parameters for a Z=1 PDX plasma (a = 56 cm, R = 130 cm, [illegible] kA and B_t = [illegible] kG) were calculated using this model for the case of [illegible] perpendicular injection of hydrogen beams into a hydrogen plasma (Figure [illegible]). At low electron densities, the edge electron temperature is relatively high ([illegible] 100 eV) and would produce a sheath drop for escaping ions of [illegible] 400 eV which would cause significant sputtering of the divertor or limiter plate. At higher densities, the edge temperature of electrons and ions is [illegible] 20 eV, in which case sputtering should be significantly reduced.

In [illegible] studying the background plasma interaction in the [illegible] scrapeoff region, a similar model has been used to analyze [illegible] impurity(oxygen [illegible]) transport in the region. Once again in the scrapeoff region there is a sink term corresponding to a flow of [illegible] ions into the [illegible] the [illegible] speed. The transport equation for [illegible] ionization state [illegible] including ionization, recombination, [illegible] due to neoclassical [illegible] transport in addition to anomalous transport [illegible] neoclassical fluxes [illegible] impurity-impurity collisions between the [illegible] ionization states [illegible] and also with the background [illegible]. These calculations [illegible] into account the mixed collisionality regime [illegible] the background plasma [illegible] impurities. The anomalous diffusion coefficient is assumed for simplicity to be [illegible] constant. As shown in Figure [illegible] parameters typical of an ohmically heated PLT discharge, the particle replacement time (total impurity density/neutral impurity influx required to maintain a quasi-steady state) is finite though relatively small in comparison with experimental measurements. The inclusion of anomalous transport results in a considerable decrease in the recycling time, which is also a strong function of the edge density and temperature profile for the [illegible] parameters. Clearly by modifying the edge parameters it appears [illegible] possible to substantially alter the recycling time, which may be [illegible] important for the successful operation of a divertor.

VI. PDX MHD CALCULATIONS

Divertor configurations possess different MHD equilibrium and stability properties compared with conventional circular tokamaks. To determine if the transport predictions are consistent with our understanding of ideal MHD stability, we have carried out a study using the stability code PEST [illegible] for plasma parameters appropriate to PDX and possible upgrades.

The ideal MHD model used employs quite flat current profiles consistent with our expectation that shielding impurity inflow will reduce the extent of the low temperature resistive region around the plasma edge. The plasma-vacuum interface is taken to lie just within the ideal MHD separatrix surface, and q at the limiter is taken to be small (~2.5 to 2.7) thus avoiding the computational difficulties associated with separatrices. The results of these studies are consistent with the more general parameter surveys of Frieman, et al. [11], and indicate that [illegible] of 5% may be stable in the PDX device. Large elongation (b/a [illegible] 2), small aspect ratio and triangularity all increase the possible [illegible] -values approximately as [illegible] $[a/Rq^2]\times(b/a)$ [12]. Free boundary(n=1) modes generally set the lower limit within the ideal MHD model. Since these modes clearly depend strongly on the current profile near the edge of the plasma, one might hope that divertor control may allow experimental study of this aspect of MHD theory.

Thus the magnetic field configuration to achieve maximum <β> can be optimized with a combination of elongation and introduction of a divertor. An example of these configurations is shown in Figure 9 where the usuage of available area with a given toroidal coil cross-section was maximized with a single-null divertor. In this configuration, the required divertor current is about 60% of the plasma current.

VII. HIGH-Z IMPURITY RADIATION

Our previous calculations [4] have shown that radiation from such metals as tungsten can be an important energy loss for tokamaks. It has been found that in PLT experiments [13] that the presence of tungsten in the form of limiters inhibits plasma heating by neutral beams. Our previous calculations used an "average ion" model. We have improved upon the model by using the same prescriptions for the atomic processes as before [4] to construct a code to calculate the rates (recombination, ionization, and excitation) for individual ionic species(e, g. Fe^{+22}, etc.). In addition, we have included dielectronic recombination due to inner shell excitations which had been neglected. The coronal equilibrium results for the radiative rates are very simliar to the previous results, with the main difference being that there is now less structure in the radiative rates near closed shells due to additional dielectronic recombination near closed shells(Figure 10). Figure 11 shows the equilibrium ionic fractions as a function of T_e.

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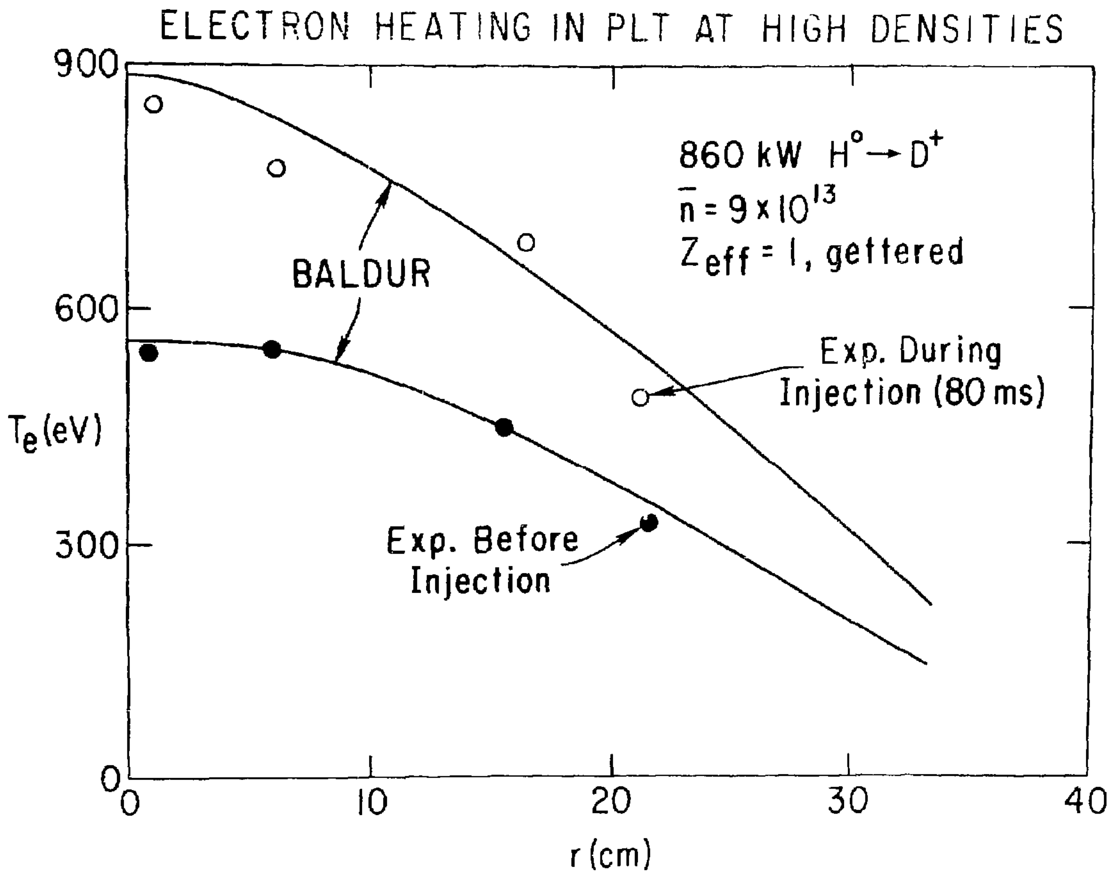

Fig. 1. Electron temperature profiles for PLT just before injection and after 80 ms of injection (B_z = 32 KG, I = 400 KA). The points [illegible] the measured temperature and the line is the BALDUR calculation [illegible] $K_e = 5 \times 10^{17}/n_e$.

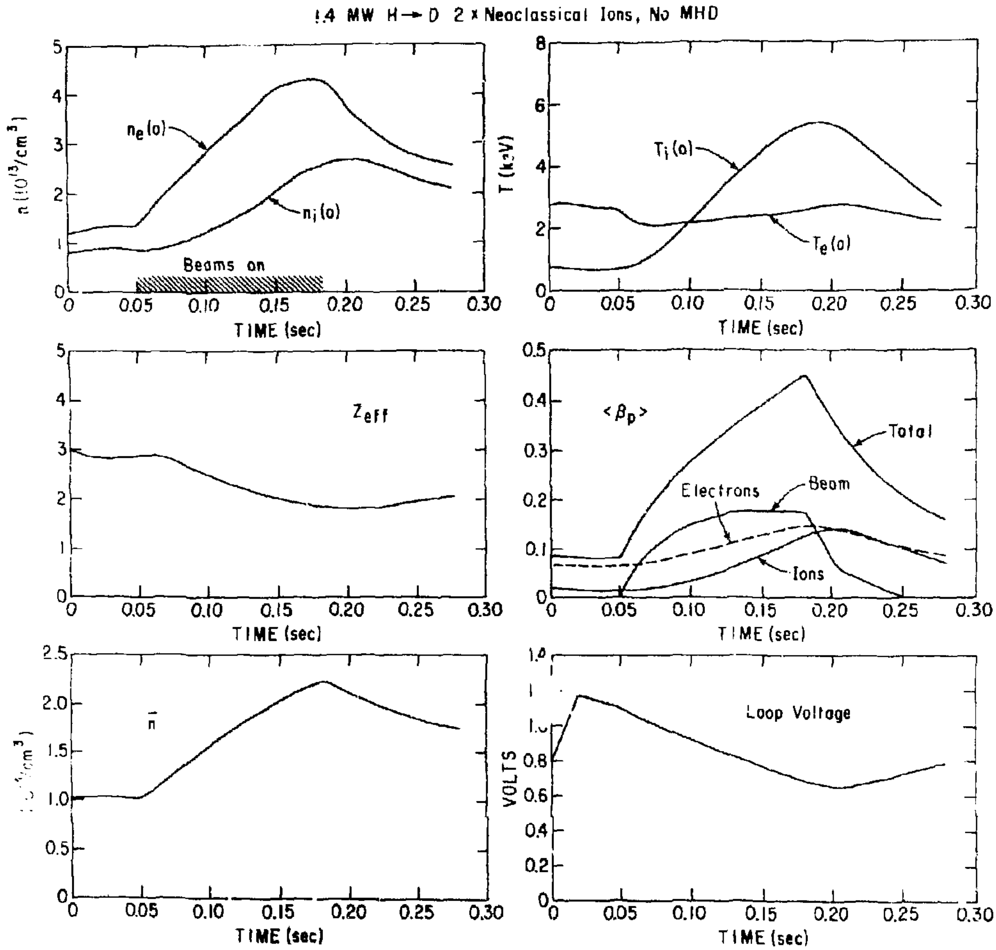

Fig. 2. BALDUR calculation of 1.4 MW H injection into D for PLT (B_z = 32 KG, I = 480 KA, $\bar{n}$ (t = 0) = 10^{13} cm^{-3}, Z_{eff} = 3) with the ion neoclassical conduction enhanced by factor of 2.

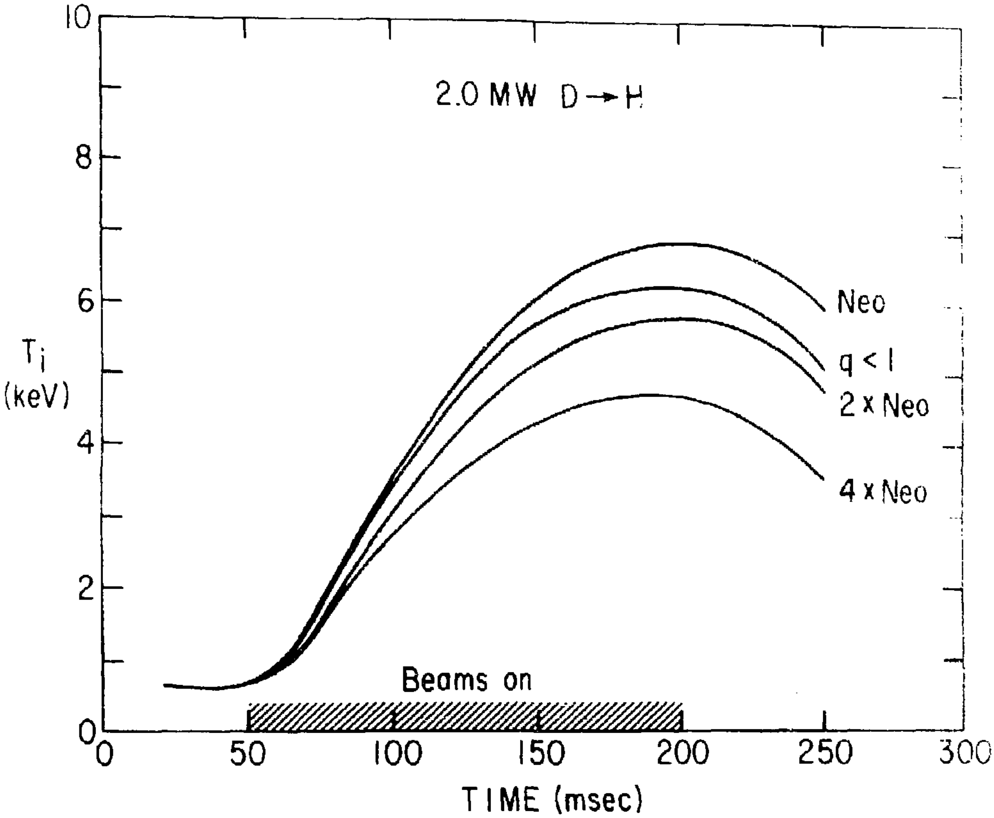

Fig. 3. BALDUR calculations of ion heating on PLT (2.0 MW of D into H, B_z = 32 KG, I = 480 KA, $\bar{n}$ (t = 0) = 10^{13} cm^{-3}, Z_{eff} = 4). The experimentally determined temperature reaches 5.5 keV, and saturates after 100 msec. (782250)

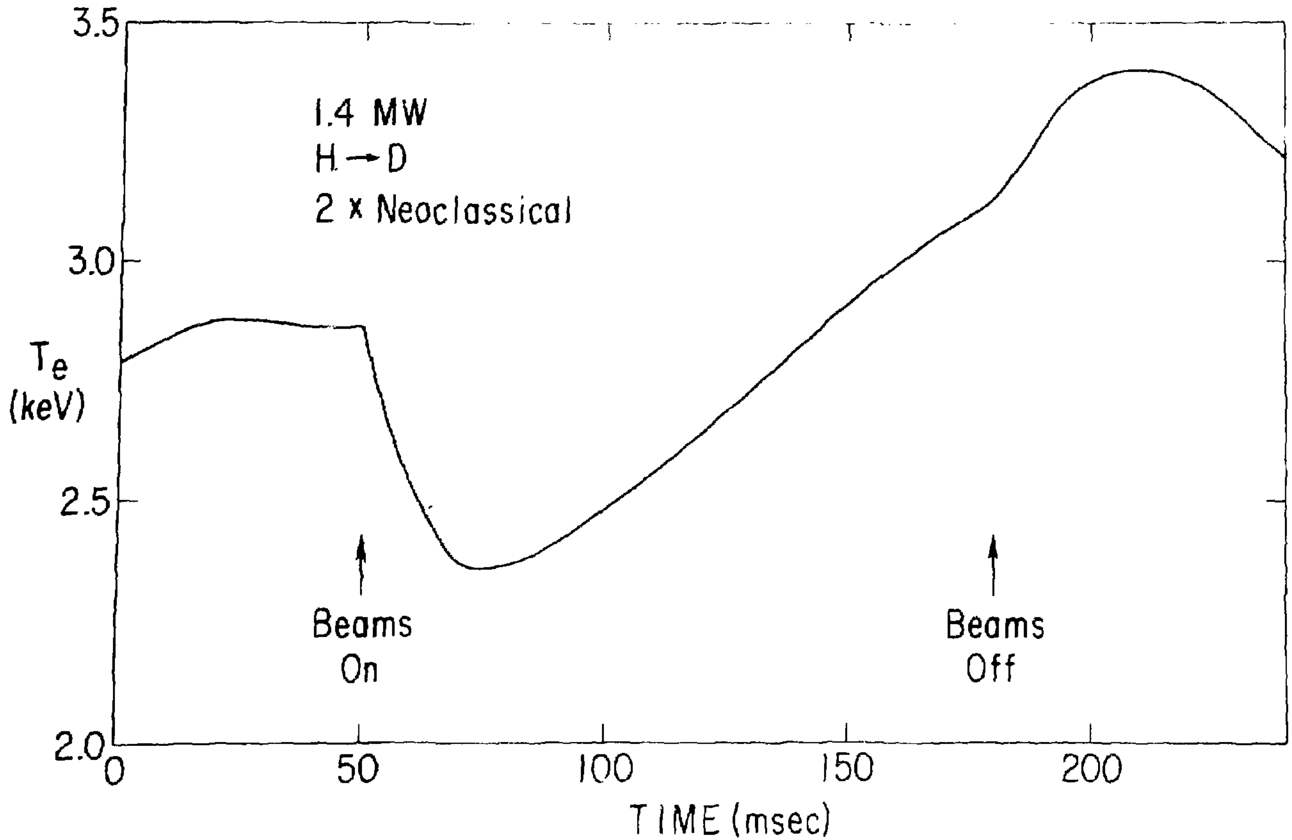

Fig. 4. BALDUR calculation of the central electron temperature during injection for a 1.4 MW H → D PLT experiment (B_z = 32 KG, I = 480 KA, $\bar{n}(t = 0) = 10^{13}/cm^3$, Z_{eff} = 3). The fast ion slowing down time is about 30 msec at the end of the beam pulse.

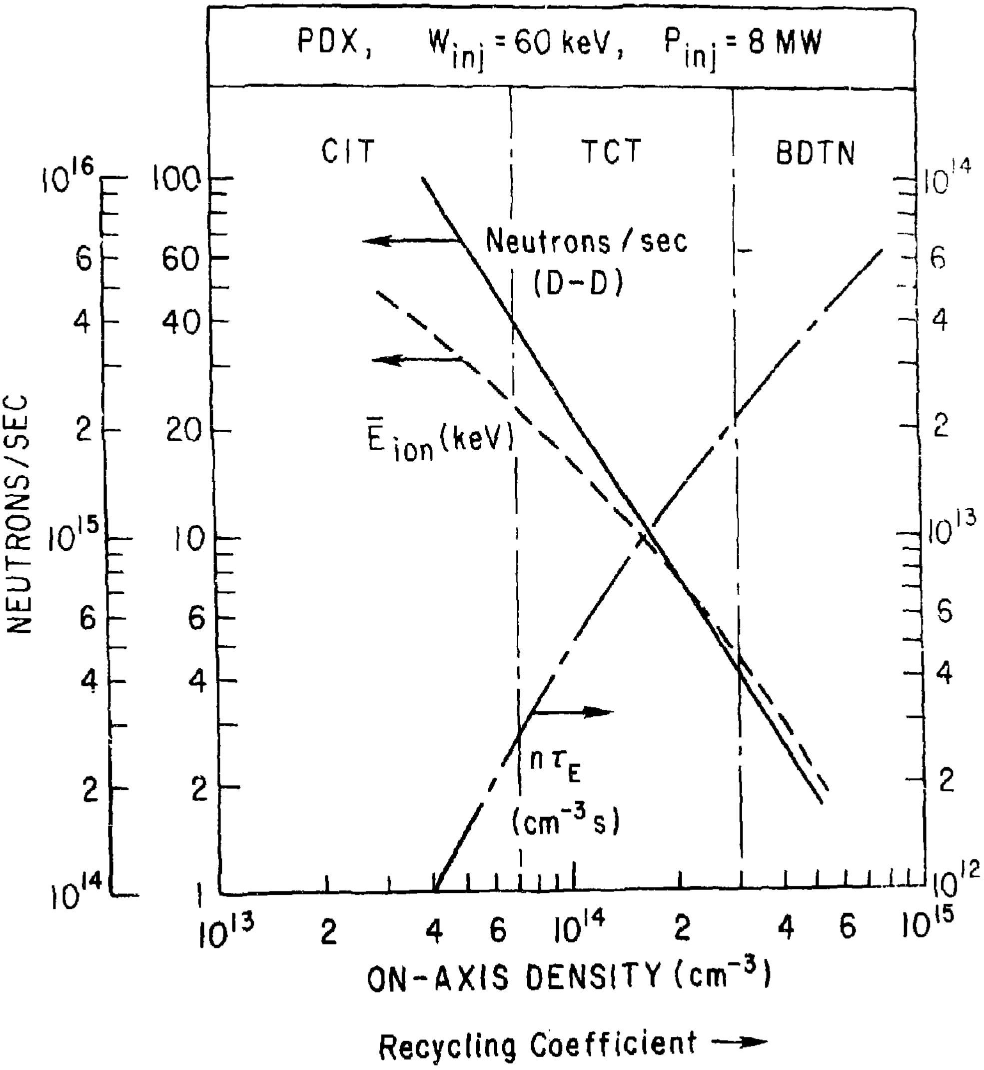

Fig. 5. The neutron yield, average ion energy, and nτ for PDX with 8 MW of 60 keV deuterium (equal co- and counter) injection into deuterium showing the effect of varying the central electron density.

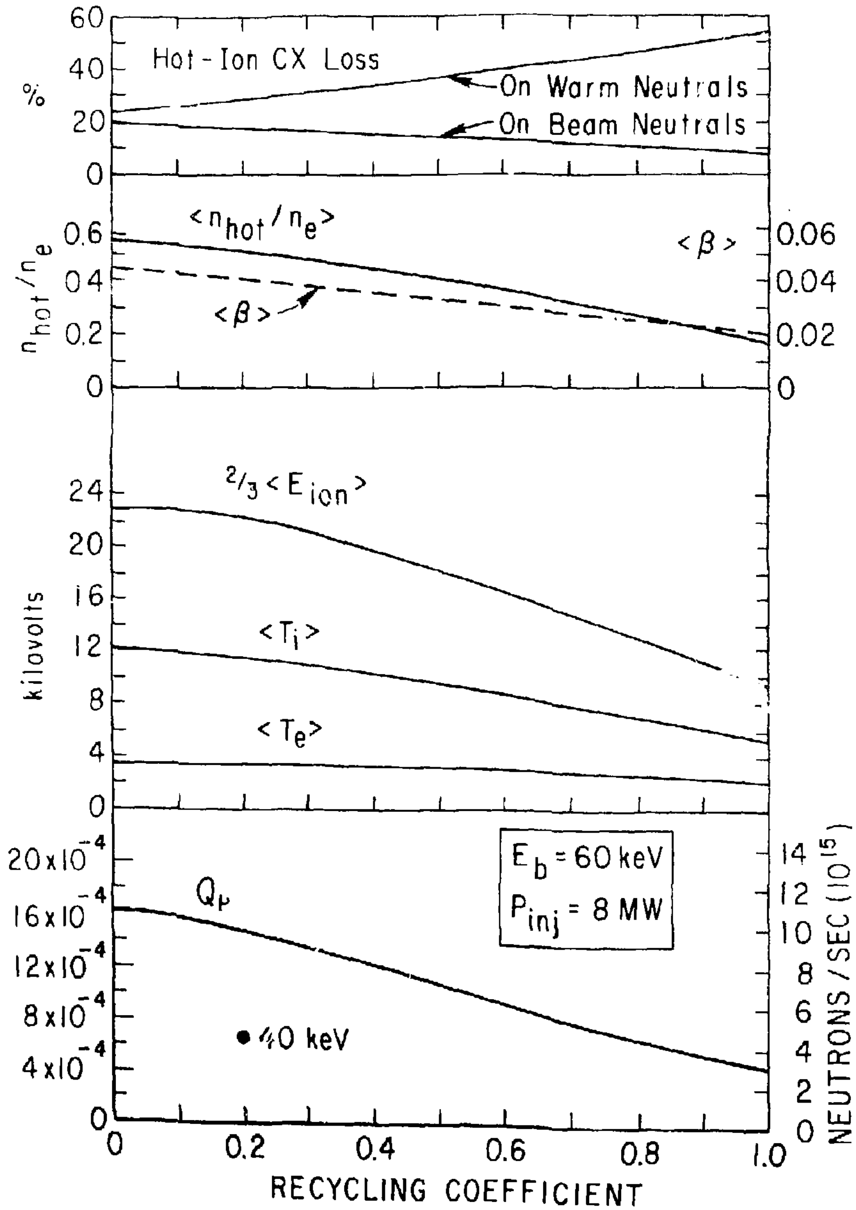

Fig. 6. Plasma parameters for PDX with 8 MW of 60 keV deuterium (equal co- and counter) injection into deuterium showing the variation with the recycling coefficients.

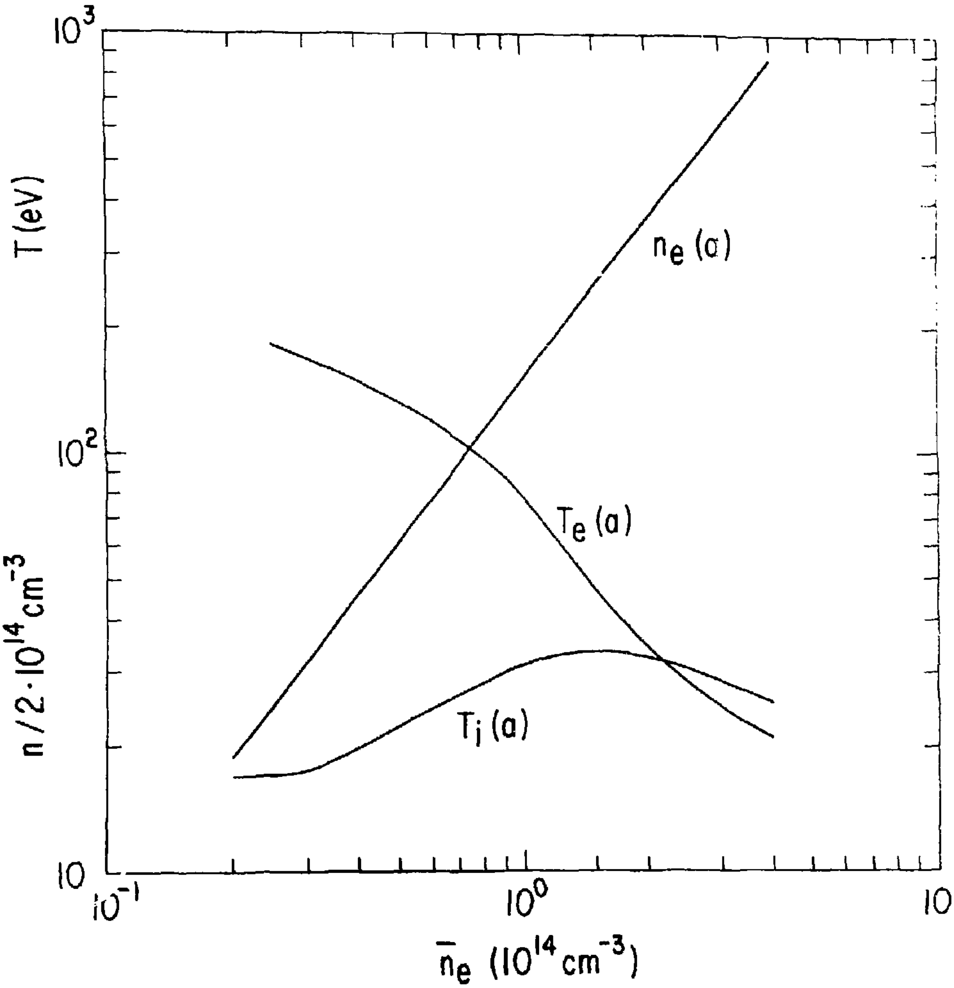

Fig. 7. Edge parameters for a PDX plasma with 6 MW of hydrogen injection into hydrogen as a function of the line average electron density.

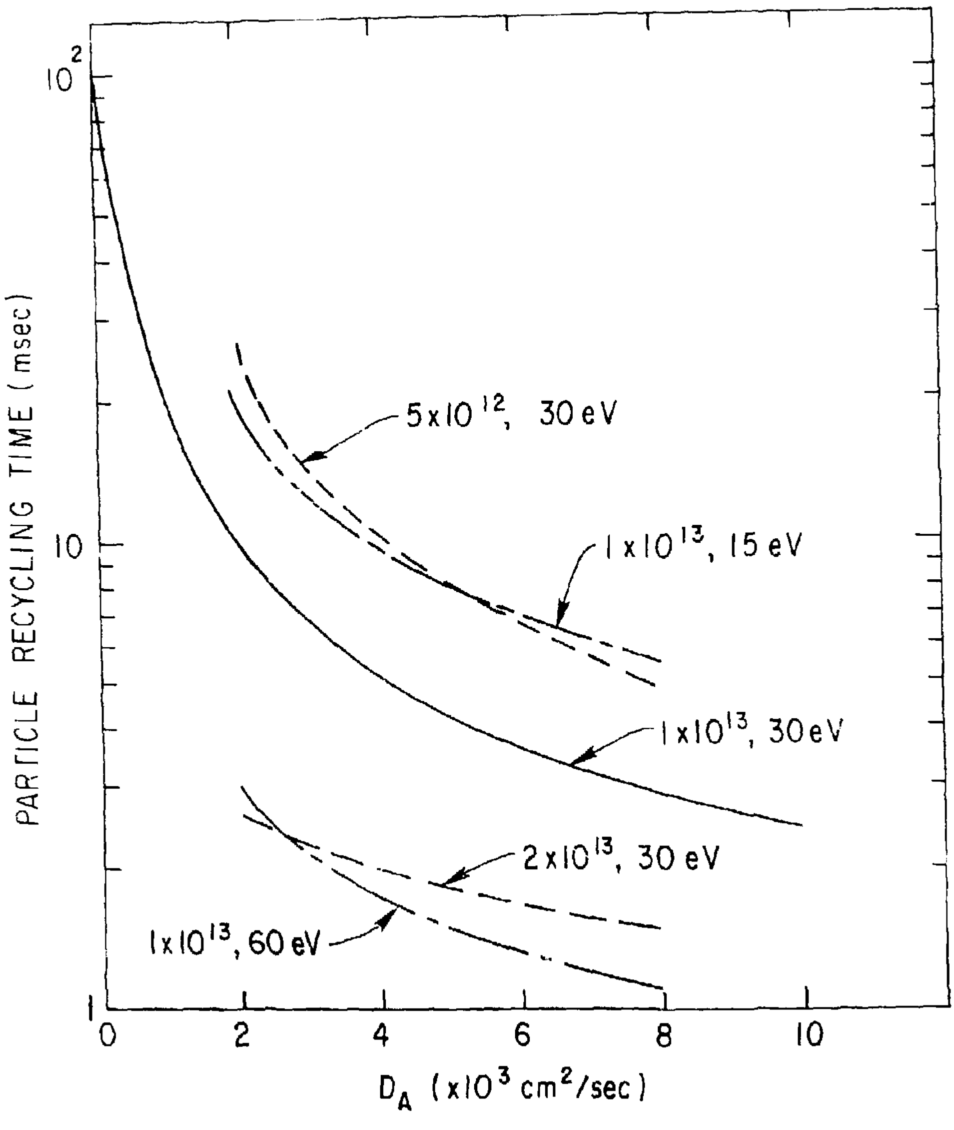

Fig. 8. Oxygen particle recycling time as a function of anomalous diffusion (D_A) for different edge densities and temperatures.

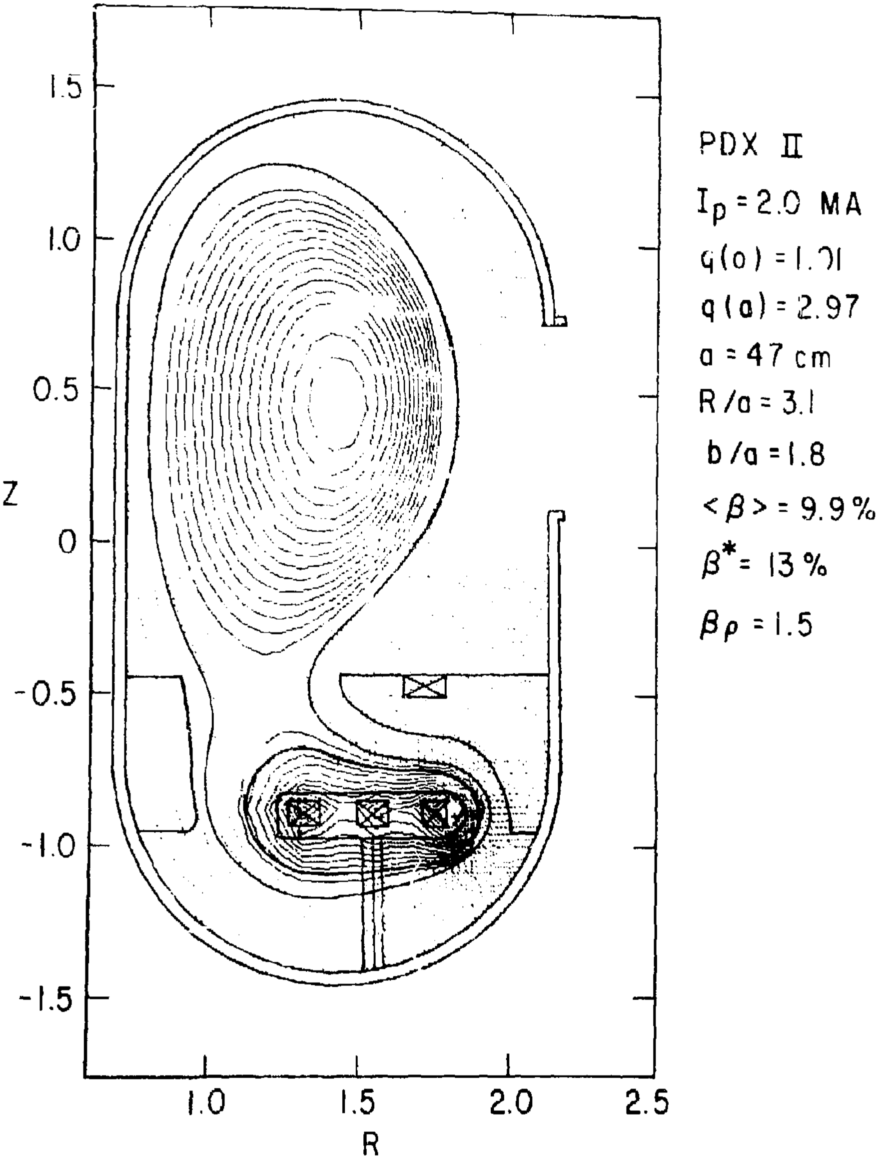

Fig. 9. Magnetic configuration with asymmetric divertor (z, R in meters).

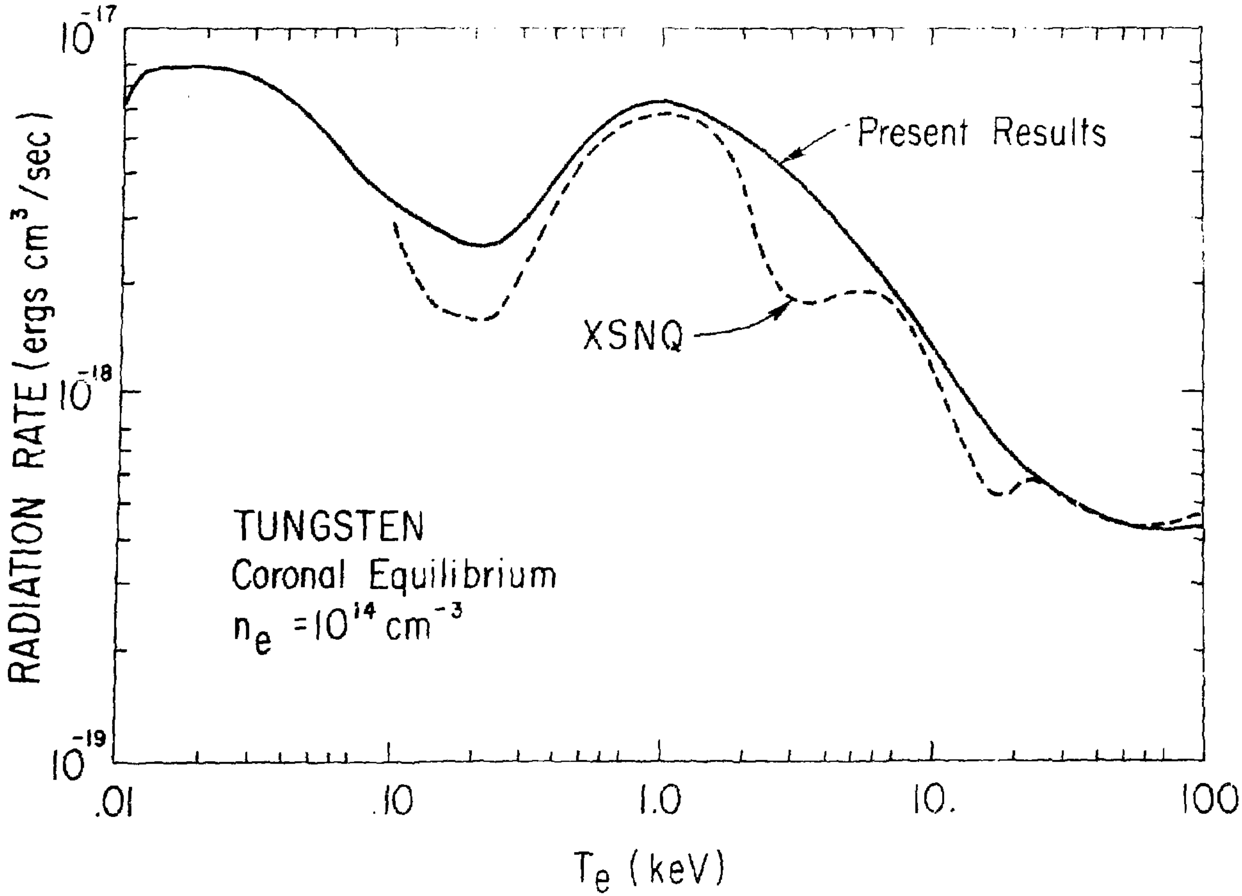

Fig. 10. [illegible] [illegible]ate radiative rates as a function of temperature for tungsten for [illegible] [illegible] average ion model (XSNQ) and present results.

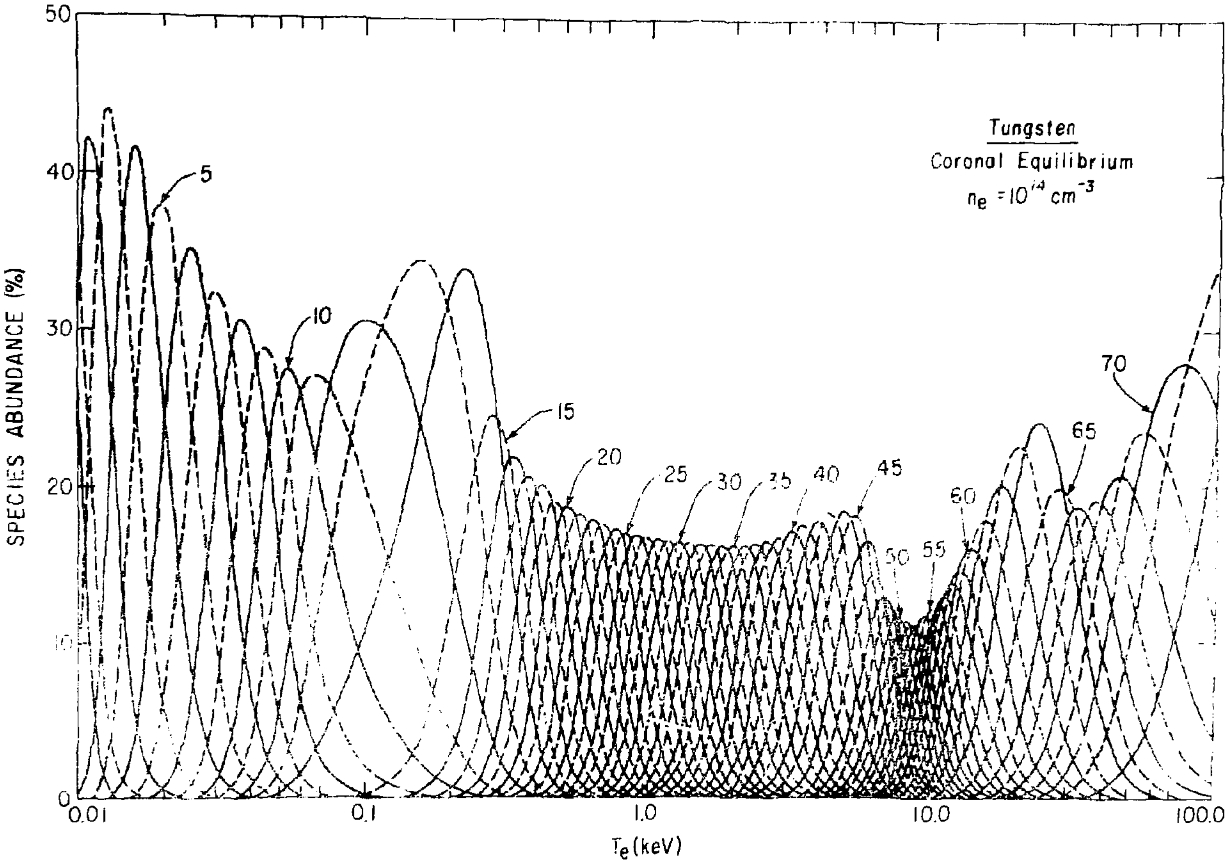

Fig. 11. Steady state relative [illegible] as a function of electron temperature.