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ABSTRACT

This paper discusses results of plasma-confinement experiments in the 2XIIB magnetic mirror device. We report experiments attempting to achieve field-reversal using neutral-beam injection in which the central magnetic field is reduced by 90% but field lines are not closed. Experiments with different neutral-beam aiming show that at constant beta both electron temperature and the energy-confinement parameter ($n\tau$) increase at larger radius. Finally, we discuss recent improvements in electron temperature and microinstability measurements.

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INTRODUCTION

At the previous International Atomic Energy Agency meeting we[1] reported results from the 2XIIB magnetic-mirror confinement experiment, which demonstrated that the drift-cyclotron loss-cone (DCLC) mode could be maintained in a quasilinear stable state, that plasma confinement improved with increasing mean ion energy, and that peak beta greater than unity could be achieved on axis. In the last two years we have conducted further experiments, improved plasma parameters, and made additional comparisons with theory. Our new work included field-reversal experiments, large-diameter plasma experiments, and investigations of DCLC stabilization and electron temperature associated with the field-reversed mirror[2] and the tandem mirror[3] configurations being developed as magnetic mirror reactor concepts.

The 2XIIB minimum-B yin-yang magnet set is normally operated at 0.67-T central field with a 2:1 mirror ratio. A schematic of 2XIIB is shown in Fig. 1. Up to 7 MW (500 A equivalent atom current) of neutral deuterium or 4 MW (380 A) of neutral hydrogen are injected by 12 Lawrence Berkeley Laboratory (LBL) 20-kV neutral-beam modules.[4] The plasma is stabilized by streaming plasma supplied either by deuterium (or hydrogen) plasma guns or by neutral gas injected near the mirror throat. The duration of the beams, streams and magnetic field is 10 ms.

FIELD REVERSAL EXPERIMENTS

Closure of magnetic field lines by plasma diamagnetic currents offers the possibility of substantial improvement in plasma confinement relative to open-ended magnetic mirrors. Such magnetic configurations have been created using relativistic electron beams,[5,6] reversed-field theta pinches,[7] and plasma guns.[8]

Our present field-reversal experiments were motivated by the unprecedented high betas achieved in earlier experiments. The largest reduction of vacuum magnetic-field strength was obtained using tangential neutral-beam aiming (Fig. 2a), which enhances the axis-encircling component of the ion diamagnetic current. We inferred a 90% depression of the on-axis magnetic field (field-reversal factor, $\Delta B/B = 0.9$) by approximately 100 kA of circulating ion current. In general beta increases with beam current. We expect further reduction in the magnetic field will result from more intense beam injection or better stabilization. Since electron currents tend to cancel the ion diamagnetic currents, we anticipate that a factor of three increase in neutral-beam current or ion lifetime is required to achieve a substantial volume of closed field lines.[9]

Field-reversal experiments were done at two values of vacuum field strength, $B = 0.67$ T (mirror ratio, $R = 2.0$) and $B = 0.435$T ($R = 1.8$), with the tangential beam-aiming arrangement in Fig. 2a. There were a number of differences in machine conditions between the low-and high-field experiments. Scaling of the measured plasma parameters as functions of injected neutral-beam current, I_b is shown in Figs. 3a and 3b for the two values of vacuum-field strength. Plasma line density increased with injected beam current. The mean plasma radius R_p and axial length L_p, defined as the 1/e point of the line-density profiles, was nearly independent of beam current ($R_p = 6.5$ cm and $L_p = 16$ cm). We obtained these measurements with a multichannel array of neutral-beam attenuation probes.

Electron temperature, T_e, measured by Thomson scattering, increased linearly to 140 eV with beam current for the high-field data (see Fig. 3b). The scatter of these T_e measurements for the low-field data was believed to be associated with the changing vacuum environment of the plasma. We obtained the mean ion-energy measurements in Fig. 3b with a 15-channel charge-exchange analyzer. For both experiments the mean ion energy was independent of beam current. The mean injected-atom energy for these experiments was estimated from the full-, half-, and third-energy fractions measured by the LBL group[4] and from the acceleration voltages, giving $E_b = 14.1$ keV (low field) and $E_b = 13.3$ keV (high field).

Figure 3c shows the plasma beta on axis, $\hat{\beta} = 8\pi\, \hat{n}_i \bar{W}_i / B_{vac}^2$, and the field-reversal parameter, defined to be the field change on axis, divided by the vacuum field

$$\frac{\Delta B}{B_{vac}} = \frac{1}{B_{vac}} \frac{\mu_o}{2\pi} \frac{M}{R_p^2 \left(R_p^2 + L_p^2\right)^{1/2}} \tag{1}$$

The parameter M is the bulk plasma diamagnetic moment measured by a plasma-encircling loop. The relationship between the field change on axis and externally measured dipole moment is derived for a cylindrical current sheet with radius R_p and half-length L_p and is a good approximation to a rigid rotor with Gaussian current-profile $j_\phi = en(o)\Omega r \cdot \exp(-r^2/R_p^2 - z^2/L_p^2)$. The scale lengths R_p and L_p, taken from the line-density profiles, were cross-checked for the low-field data with an array of small magnetic-loop probes that are close to the plasma surface and that measure the shape of the plasma-current distribution.

Fig. 3c shows that $\hat{\beta}$ increases with I_b reaching $\hat{\beta} = 2.3$ for the low field and $\beta = 1.2$ for the high field. Since the plasma length is comparable to the diameter, $\hat{\beta} > 1$ does not imply field reversal. The effect of finite length and the resulting magnetic-field line curvature is included in Eq. 1. For the data at $B_{vac} = 0.435$ T, $\Delta B/B_{vac}$ increases approximately linearly with beam current, reaching an average value $\Delta B/B_{vac} = 0.9 \pm 0.2$ at $I_b = 400$ A. The data at $B_{vac} = 0.67$T increases with beam current, but reaches a lower value $\Delta B/B_{vac} = 0.6 \pm 0.1$ at $I_b = 500$ A.

Figure 4 compares experimental results with the "SUPERLAYER" particle-simulation code[9] for background stream density of 10^{13} cm^{-3}. The experimental data for $B_{vac} = 0.435$T are in reasonable agreement with the code predictions, since these experiments were more strongly dominated by electron drag, which is properly treated in the SUPERLAYER calculations. The high-field data is below the code predictions presumably because these experiments are more strongly dominated by DCLC - mode wave diffusion; which is included in SUPERLAYER as a time independent parameter which was adjusted to match the calculated mean ion energy to measured values.

In Fig. 5a we plot the ion-energy confinement parameter, $\hat{n}\tau_E$. The mean ion-energy lifetime, τ_E, is defined as the stored energy divided by the trapped neutral-beam power. According to quasilinear theory, $\hat{n}\tau_E$ should initially increase as $T_e^{3/2}$ since electron-drag losses decrease and saturates at a limit imposed by the increasing DCLC losses. To support this interpretation, we found that ion-cyclotron fluctuations increased above $T_e = 80$ eV where $\hat{n}\tau_E$ flattens. Further increases in $\hat{n}\tau_E$ require better stabilization, higher ion energy, or larger plasma radius.

LARGE-RADIUS EXPERIMENTS

To maintain marginal stability of the DCLC mode in 2XIIB, it is necessary to supply a warm streaming plasma. Energy exchange with the electrons of this unconfined stabilizing plasma will reduce T_e and hence the energy-containment time of the mirror-trapped ions. The minimum warm-plasma density, n_w, that must be supplied is shown in Fig. 6. These calculations[10] are for $\beta = 0.5$; a hot-plasma energy $W_i = 1/2\, M_i v_H^2 = 15$ keV; a hole size $v_h/v_H = 0.1$; and a warm-stream energy of $v_w/v_H = 0.05$. Simply put, the larger the plasma size, R_p, compared with the ion Larmor radius, a_i, the smaller the fraction of warm to hot plasma necessary for DCLC stability.

To test the scaling of plasma parameters such as T_e and $\hat{n}\tau_E$ with R_p/a_i, we ran the 2XIIB experiment with the neutral-beam aiming configurations shown in Fig. 2. This resulted in changes of R_p/a_i from 2 to 6. The plasma size was determined by the measurements shown in Fig. 7.

When comparing results at various values of R_p/a_i, we restricted the data to those with Gaussian-shaped radial profiles with approximately the same beta (0.4). We introduced no beta or density corrections. Figure 8 shows that both T_e (averaged over several shots) and $\hat{n}\tau_E$ increase with larger values of R_p/a_i. The higher values of T_e and $\hat{n}\tau_E$, discussed in the field-reversal section, were obtained at higher values of beta. These values were unattainable at the larger radii since the beam power had to fill a larger volume.

To compare the experimental results of Fig. 8 with the DCLC quasilinear theory, we note that the experimental points lie in the domain of Fig. 6 where $n_w/n \propto (R_p/a_i)^{-4/3}$. The electron temperature has been calculated by equating the heating from ion-electron collisions to the electron power loss (which is assumed to be proportional to stream current times T_e). In this case $T_e \propto (R_p/a_i)^{1/3}$ and $\hat{n}\tau_E \propto T_e^{3/2} \propto (R_p/a_i)^{1/2}$. The measured electron temperatures have such an R_p/a_i dependence but are about 30% below the optimum theoretical value of T_e. One source of this difference is thought to be the poor energy-distribution match between the actual and optimum streaming plasma being supplied to the hot plasma.

DISCUSSION

In addition to the field-reversal and large-radius experiments discussed in previous sections we made a number of fundamental mirror physics measurements relating to DCLC-mode stabilization, DCLC-mode properties, and electron temperature.

Stabilization of the DCLC mode is studied by measuring the stream current with a gridded electrostatic analyzer. The stream current transmitted through the plasma varies during a shot to as low as the minimum value calculated[11] to stabilize the DCLC mode and follows the theoretical scaling with plasma density, ion energy, and electron temperature.

Frequency and azimuthal wavelength measurements of ion-cyclotron oscillations were found to have the characteristics of the DCLC mode[12] Radial rf profile mesurements were made with a multi-tip rf probe outside the mirror cell. This measurement revealed that the DCLC mode had a large radial extent and a single, narrow frequency peak that was the same at all radial positions. The frequency is near the beta-corrected ion-cyclotron frequency at the center.

We increased electron temperature to 140 eV by (a) relocation of streaming-plasma guns and gas-box baffles, (b) increased neutral-beam power, and (c) improvements in vacuum-wall surface conditions. These temperatures were well above those possible if classical thermal conduction is a dominant process. Langmuir-probe measurements external to the mirrors indicated a lower electron-temperature in the ends compared to the center and a rather complex axial temperature profile. A Monte Carlo electron code[13] was used to show that such profiles could be calculated.

In summary, field-reversal experiments reached field-reversal factors up to $\Delta B/B = 0.9$. The large-radius experiments demonstrated improved mirror confinement by size scaling.

Further progress on 2XIIB will rely on improving stabilization techniques that simultaneously increase electron temperature and reduce fluctuation losses. An electron-heating technique demonstrated by Ioffe[14] and at MIT[15] is being investigated on the more energetic 2XIIB plasma. The Tandem Mirror Experiment (TMX),[16] which will begin operation later this year, has provisions for additional and higher energy neutral-beams. TMX is expected to be better stabilized and to have higher electron temperature, since it is stabilized from the solenoid.

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Figure Captions

FIG. 1 The 2XIIB device used for plasma-confinement experiments at Lawrence Livermore Laboratory.

FIG. 2 Beam-aiming configurations shown to scale for (a) field-reversal experiments, (b) head-on injection experiments, and (c) large-diameter plasma experiments.

FIG. 3 Plasma parameters for field-reversal experiments for low-and high-magnetic field strengths as a function of incident neutral-beam current (a) Line density and plasma radius, (b) mean ion energy and electron temperature, and (c) peak beta and field-reversal factor, $\Delta B/B$.

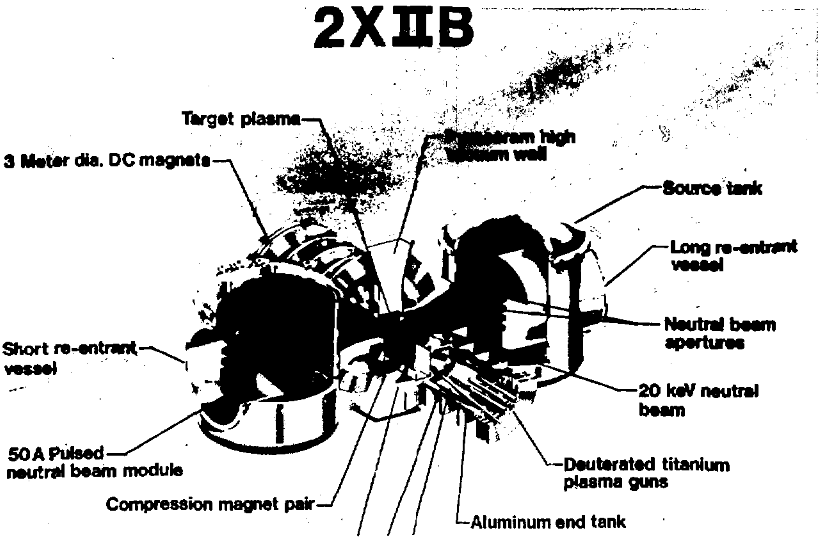
FIG. 4 Comparison of experimental data with SUPERLAYER particle-stimulation code.

FIG. 5 Comparison of $\hat{n}\,\tau_E$ with electron temperature.

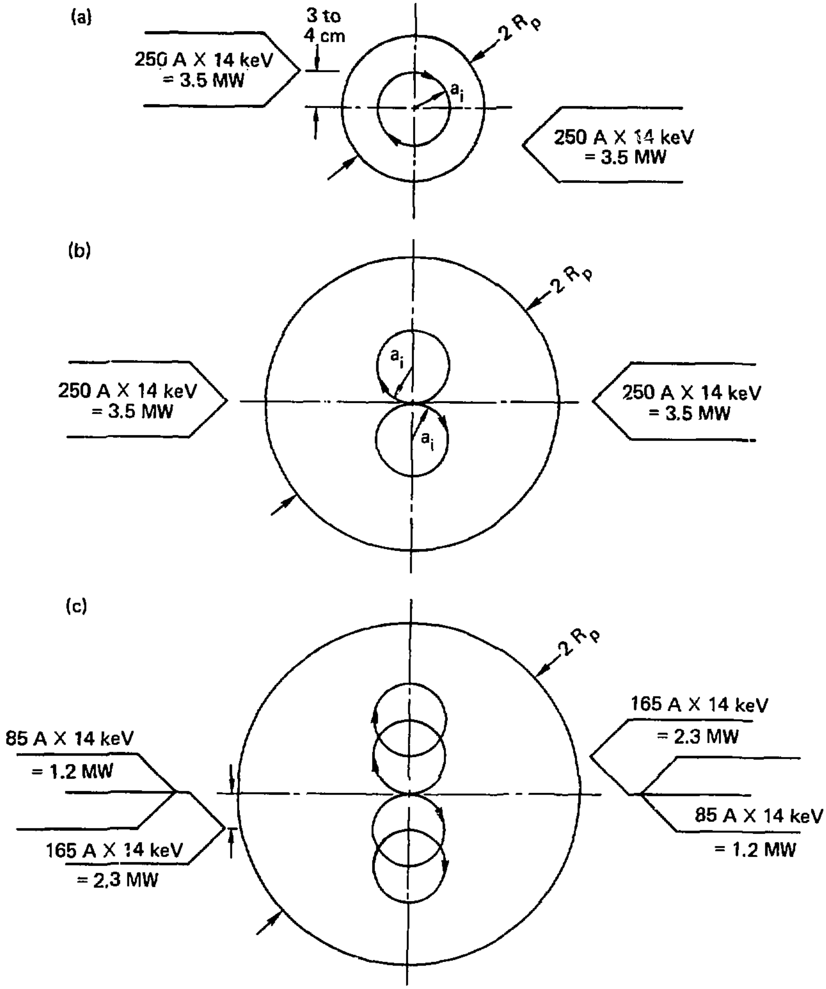
FIG. 6 Theoretical minimum-required stream density normalized to hot-ion density vs plasma radius for 2XIIB plasma parameters.

FIG. 7 Radial density-profile measurements of large-diameter 2XIIB plasma.

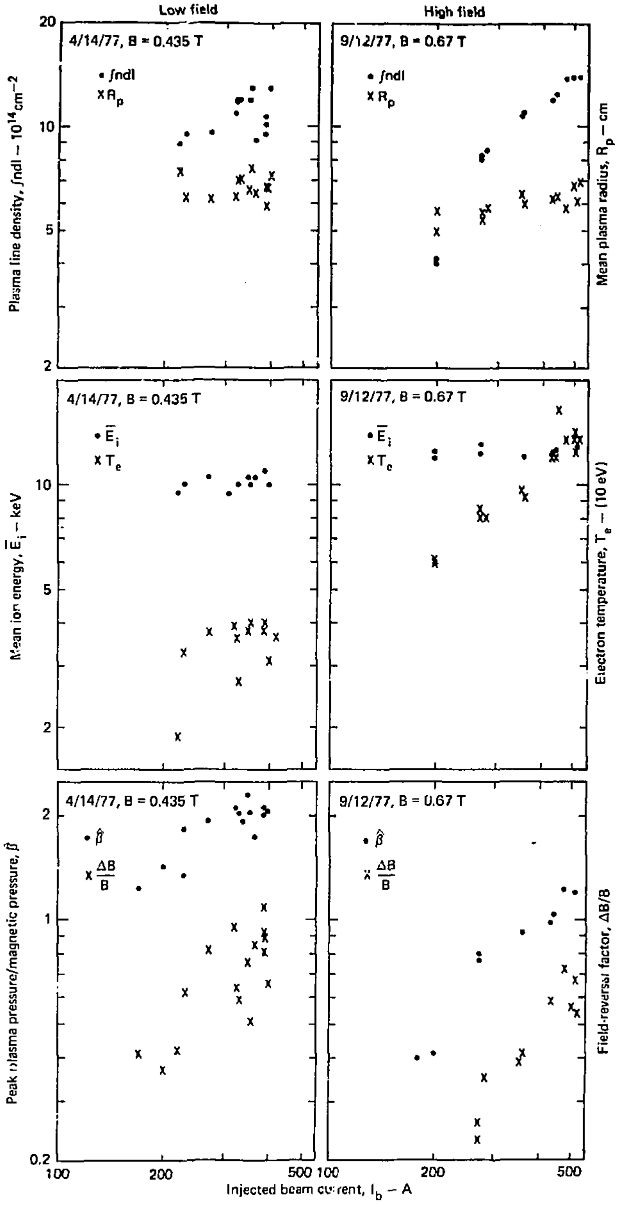
FIG. 8 Electron temperature and $\hat{n}\,\tau_E$ scaling with R_p/a_i for constant beta. Solid data points depict deuterium; open points depict hydrogen.



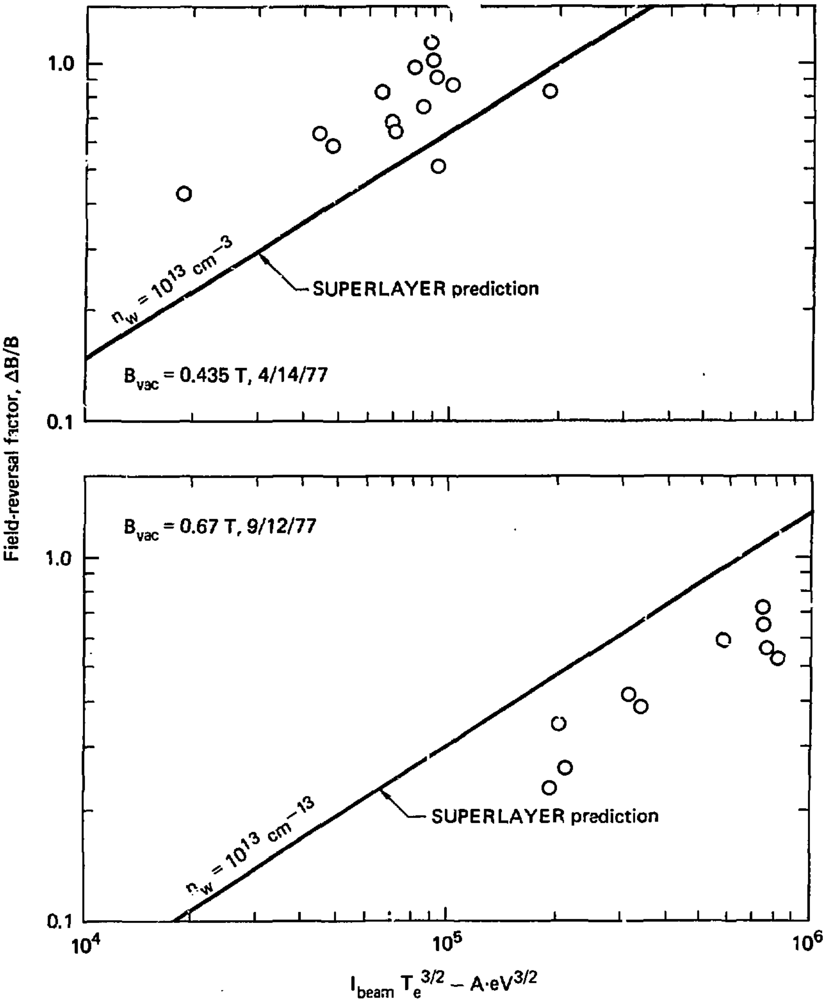
Simonen - Fig. 1



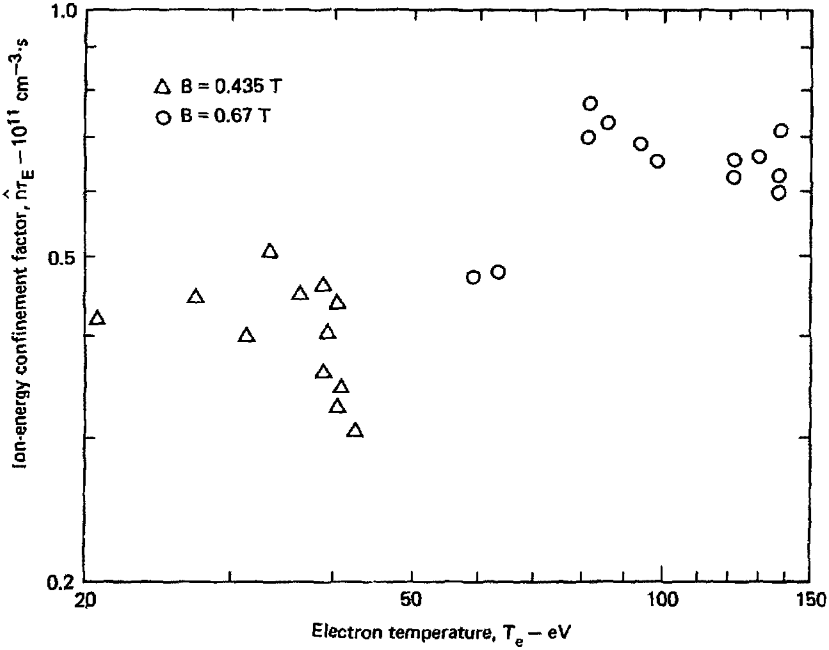
Simonen - Fig. 2



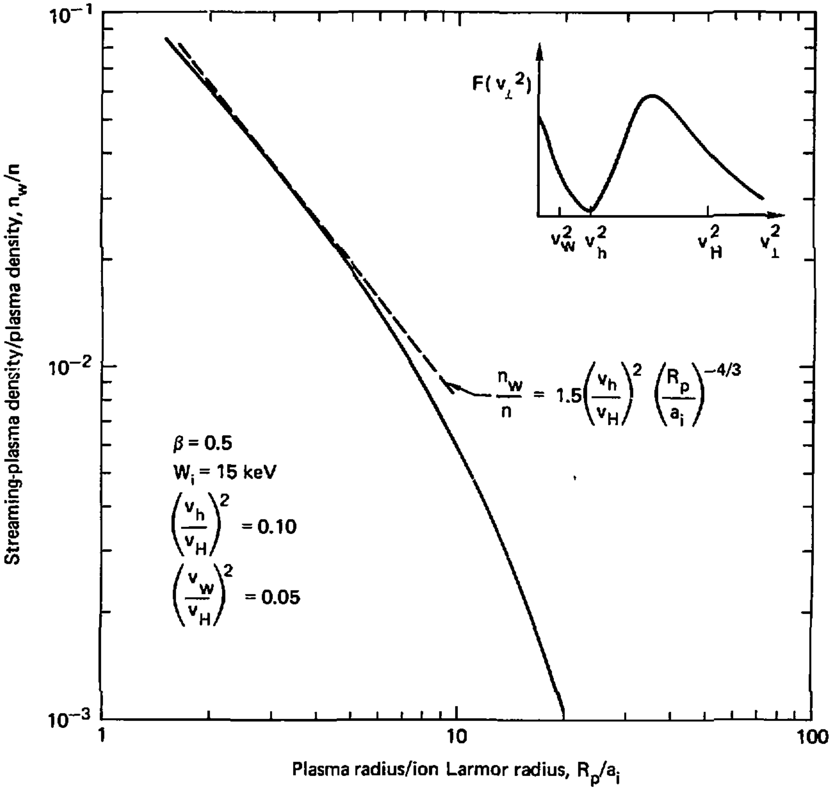
Simonen - Fig. 3



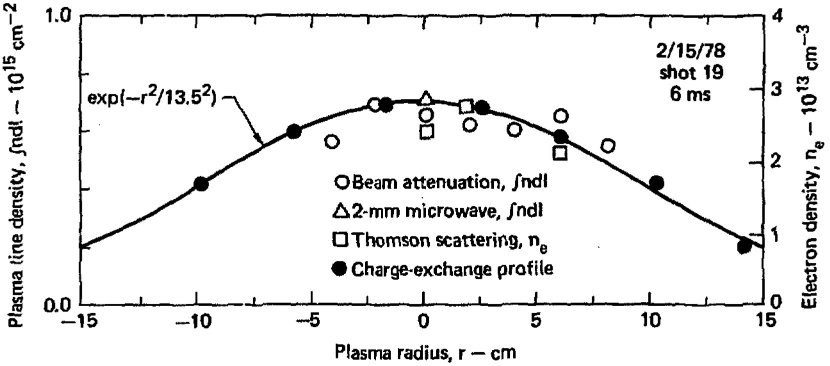
Simonen - Fig. 4



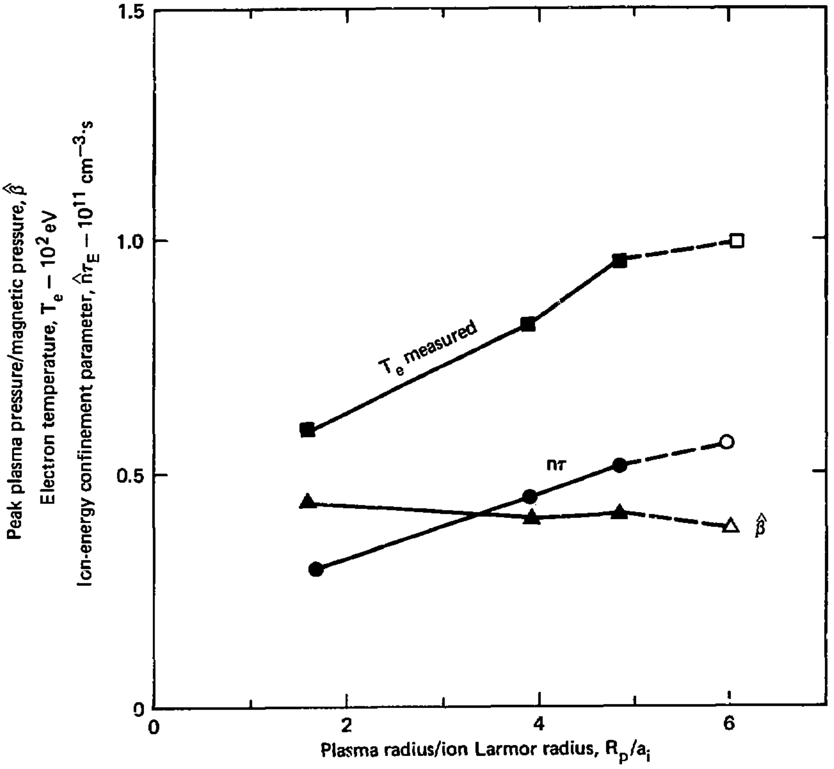
Simonen - Fig. 5



Simonen - Fig. 6



Simonen - Fig. 7



Simonen - Fig. 8