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Minimum Streaming Current Requirements for MFTF -
Revised by Recent (r_p/a_1) Scaling in 2XII-B

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February 14, 1979

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Minimum Streaming Current Requirements for MFTF -

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ABSTRACT

The minimum warm ion density necessary to effectively stabilize the DCLC instability in MFTF represents a significant planning requirement. Thus a review of the theoretical predictions for MFTF stabilization is presented here including the recently revised (a_i/r_p) scaling determined from tests with 2XIIB. For the assumptions given the total streaming current requirements range from 1500 to 2800 A, for T_e predicted from .66 to 1 keV and $E_i \sim 50$ keV.

INTRODUCTION

This review of warm plasma and hence stabilizing stream requirements for MFTF represents an update of an informal memo of 7/6/78 which simply took the plasma density fraction $n_w/n \equiv \Delta$ scaling from the early quasi-linear theory given in the MFTF (then MX) proposal² and scaled it to MFTF conditions. Subsequent analysis of measurements on 2XIIB^{3,4} and more detailed computer calculations with Don Pearlstein's linear stability analysis code⁴, show a revised $\Delta \propto (a_i/r_p)^{4/3}$ scaling for 2XIIB conditions, and $\Delta \propto (a_i/r_p)^2$ for more typical MFTF conditions where $a_i/r_p \leq V_{\text{hole}}/V_{\text{hot}}$. The revised predictions for MFTF are given below, the specific goal being to continue to refine the minimum streaming current estimates as much as possible and then adopt the most up-to-date estimates for MFTF planning purposes.

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Basic Physics for Stabilization:

The specific approach taken here is 1) to briefly review quasi-linear theoretical minimum requirements on Δ enough to establish j_{st} scaling, 2) to normalize the predicted streaming requirements so as to fit the available 2XIIB data, 3) to extend the resultant predictions to MFTF conditions, and 4) to discuss the uncertainty in $j_{st}(\text{minimum})$.

1) The essential elements of recent quasi-linear theory and scaling for the DCLC are described in Appendix B of LLL-Prop-142,² and Don Correil's memo³ of 7/3/78. Table I below summarizes the scaling for $\Delta \equiv n_w/n$, including normalization to 2XIIB data in Ref. 3, with $V_h \equiv$ minimum ion velocity for containment with an ambipolar loss-cone "hole," $V_H \equiv$ the hot ion velocity, a_i the ion gyroradius and r_p the characteristic plasma radii or gradient length.

Table I. General Criteria for $\Delta \equiv n_w/n$

Regime ²	Proposal ²	Revised by Correil ³ , and used here
3, where $\frac{v_i}{r_p} \geq \frac{V_h}{V_H}$	$\Delta \geq \left(\frac{V_h}{V_H}\right)^2$	$\Delta \approx 1.5 \left(\frac{V_h}{V_H}\right)^2 \left(\frac{a_i}{r_p}\right)^{4/3}$
2, where $\frac{V_h}{V_H} \leq \frac{a_i}{r_p} \leq \frac{V_h}{V_H}$	$\Delta \geq 2 \left(\frac{V_h}{V_H}\right)^{1/2} \left(\frac{a_i}{r_p}\right)^{3/2}$	$\Delta \sim .36 \left(\frac{V_h}{V_H}\right)^{1/2} \left(\frac{a_i}{r_p}\right)^2$

The following brief treatment to generate j_{st} from the given warm ion fraction follows a memo by Steve Devoto.⁵ For regime 3 the basic requirements from Col. 3 of Table I, with $V_h^2 \sim (2e\phi/m_i)/(R-1)$, and $(n-1)T_e \equiv e\phi$ are:

$$\Delta_3 \approx 1.5 \left(\frac{v_h}{v_H} \right)^2 \left(\frac{a_i}{r_p} \right)^{4/3} \approx \frac{1.5(\eta-1) T_e}{(R-1) E_i} \left(\frac{a_i}{r_p} \right)^{4/3} \quad (1)$$

With $j_{st} = n_w e \bar{v}_w$ and $\bar{v}_w \approx \alpha \sqrt{\frac{e\phi}{m_i}} \approx \alpha \sqrt{\frac{(\eta-1) T_e}{m_i}}$

$$\text{Then } j_{st3} \approx 7.5 \times 10^{-12} \frac{\alpha (\eta-1)^{3/2} n T_e^{3/2}}{(R-1) M_i^{1/2} E_i} \left(\frac{a_i}{r_p} \right)^{4/3} \quad (2)$$

Here α is usually taken as $\sim .5$ (though relatively sensitive and a somewhat unknown parameter with RF turbulence present), η here is taken as ~ 4 to fit the classical ambipolar potential ϕ picture, R is the effective mirror ratio $\{R = R_{vac}/(1-\Delta B/B)\}$, M_i is the ion mass in a.m.u., n is the local hot ion density/cm³ and both T_e and E_i are in keV.

For regime 2 from Table I with a revised Δ_2 scaling from Correll's memo³ and a coefficient of .36 chosen so $\Delta_3 = \Delta_2$ at the boundary where $a_i/r_p \sim v_h/v_H \sim 1/6$ for MFTF type parameters, one similarly obtains

$$j_{st2} \approx 1.8 \times 10^{-12} \frac{\alpha (\eta-1)^{3/4} n T_e^{3/4}}{(R-1)^{1/4} E_i^{1/4} M_i^{1/2}} \left(\frac{a_i}{r_p} \right)^2 \quad (3)$$

II) The normalization of Δ_3 and j_{st} to the most recent 2XIIIB data is done for this treatment by Correll in Ref. 3. The change in Δ_3 at $r_p/a_i \sim 2$ from the earlier memo¹ is relatively slight [i.e. a coefficient of ~ 1.3 for Eq. (1) (with $\lambda \sim 1/2$) instead of the 1.5 used here]. However, the substantial reduction implied in both Δ_3 and particularly Δ_2 for other values of (r_p/a_i) scaling is perhaps best illustrated by Fig. 1. This figure shows the consequences of using the original analytic scaling of $\Delta \sim$ independent of a_i/r_p

for regime 3, fitting j_{st} for 2XIIB with $r_p/a_i \sim 2$, and requiring continuity at the boundary region where $a_i/r_p \sim v_h/v_H$ going into regime 2. Note that the typical values of $(v_h/v_H)^2 \approx T_e(n-1)/(R-1)E_i$ attained in 2XIIB or expected in MFTF range from $\sim .01$ up to $\sim .05$. Thus the Δ range for 2XIIB and MFTF shown in Fig. 1 are displaced from the quasi-linear code theoretical curve²⁻⁴ based upon $(v_h/v_H)^2 \approx .1$. The boundary where $v_h/v_H \approx a_i/r_p$ thus also varies with machine and conditions. For MFTF the boundary appears near $r_p/a_i \sim 6$. The revised Δ scaling given in Ref. 3 and 4 and in Table I above is used in this memo.

III) Equations 2 and 3 for j_{st} at the midplane are sufficient to determine the I_{st} requirements for any specific hot ion density profile in MFTF. Two simplified radial density models are considered here, and typical values of j_{st} vs T_e indicated in Fig. 2 for 2XIIB and MFTF conditions.

- 1) A flat central density n_0 and an outer shell of thickness r with linear density dependence from n_0 at $r_p - \delta r/2$ to 0 at $r_p + \delta r/2$.
- 2) A Gaussian distribution of density

$$n = n_0 e^{-\left(\frac{r}{r_p}\right)^2}$$

with a midplane radial averaged $\bar{n} \approx .43 n_0$ (limiting the practical density range for this expression to a factor of 10 or for $r \leq \sqrt{2} r_p$).

The calculation for I_{st} from j_{st} then follows for these two models, assuming only the boundary with $\nabla n \neq 0$ requires stream stabilization and that $(a_i/r_p)_{eff} \sim (1/n)(dn/dr)$. Thus for the

flat top model $(a_i/r_p)_{\text{eff}} \sim a_i/\delta r$ and for the Gaussian model

$$(a_i/r_p)_{\text{eff}} \sim 2 a_i r / r_p^2.$$

1) Flat Top Model for MFTF:

$$n = \frac{n_0 (r_p + \frac{\delta r}{2} - r)}{\delta r}$$

$$\text{for } r_p - \delta r/2 \leq r \leq r_p + \delta r/2$$

$$\text{radius } r_p = 30 \text{ cm; } \delta r \sim 9 \text{ cm}$$

Thus $a_i/\delta r \sim 1/4$ or regime 3

$$I_{st} = \int_{r_p - r/2}^{r_p + r/2} j_{st3} 2\pi r dr = 7.5 \times 10^{-12} \frac{\alpha(n-1)^{3/2}}{(R-1) M_i^2} \frac{n_0}{2} 2\pi r_p \delta r \frac{T_e^{3/2}}{E_i} \left(\frac{a_i}{r}\right)^{4/3} (4)$$

2) Gaussian Diffused Density Model:

$$n = n_0 e^{-(r/r_p)^2}$$

$$\text{where } n_0 = 1.16 \times 10^{14}$$

$$\text{for } n = 5 \times 10^{13}$$

$$\text{for } 0 \leq r \leq \sqrt{2} r_p.$$

$$\text{radius } r_p = 30 \text{ cm}$$

For MFTF with $a_i \sim 2.25 \text{ cm}$ and

$$(a_i/r_p)_{\text{eff}} \sim 2a_i r / r_p^2$$

$$\sim 1/6 \text{ for } r = 1.1 r_p.$$

$$I_{stg} = \int_0^{\sqrt{2} r_p} j_{st} 2\pi r dr = \int_0^{1.1 r_p} j_{st(2)} 2\pi r dr + \int_{1.1 r_p}^{\sqrt{2} r_p} j_{st(3)} 2\pi r dr \quad (5)$$

$$\begin{aligned}
&= 1.8 \times 10^{-12} \frac{\alpha(\eta-1)^{3/4} T_e^{3/4} n_o}{(R-1)^{1/4} M_i^{1/2} E_i^{1/4}} \int_0^{1.1 r_p} \frac{1}{2\pi r e} \left(\frac{r}{r_p}\right)^2 \left(\frac{2a_i}{r_p^2}\right)^2 dr \\
&+ 7.5 \times 10^{-12} \frac{\alpha(\eta-1)^{3/2} T_e^{3/2} n_o}{(R-1) M_i^{1/2} E_i} \int_{1.1 r_p}^{\sqrt{2} r_p} \frac{1}{2\pi r e} \left(\frac{r}{r_p}\right)^2 \left(\frac{2a_i}{r_p^2}\right)^{4/3} dr \quad (6)
\end{aligned}$$

$$\begin{aligned}
&\approx 2\pi r_p^2 \left\{ 1.8 \times 10^{-12} \frac{\alpha(\eta-1)^{3/4} T_e^{3/4} n_o}{(R-1)^{1/4} M_i^{1/2} E_i^{1/4}} \left[\left(\frac{2a_i}{r_p}\right)^2 \times .17 \right] \right. \\
&\left. + 7.5 \times 10^{-12} \frac{\alpha(\eta-1)^{3/2} T_e^{3/2} n_o}{(R-1) M_i^{1/2} E_i} \left[\left(\frac{2a_i}{r_p}\right)^{4/3} \times .13 \right] \right\} \quad (7)
\end{aligned}$$

The calculation to determine $\bar{E}_i$ and T_e for a given case depends upon the energy balance between input to electrons from hot ion and electron losses (direct or through $e\phi$ work on ion). Steve Devoto utilizes the following type of approximate equation for the average ion heating loss rate to the electrons equated to the electron energy loss rate assumed dominated by the stream loss flux. Here we add a term for the mirror loss rate and a coefficient ξ to accommodate possible "recycling", and retain the classical definition of η , i.e. $e\phi \equiv (\eta-1)T_e$.

$$\bar{E}_i \left(\frac{n^2}{n\tau_E} \right) = \xi n T_e \left(\frac{j_{st}}{eL_p} + \frac{n^2}{n\tau_c} \right) \quad (8)$$

The general $n\tau_E$ for hot ions loss to cold electrons is:

$$n\tau_E \approx 9.9 \times 10^{12} \frac{M_i T_e^{3/2}}{\ln \Lambda} \quad (9)$$

and the classical ion loss over a mirror by Coulomb scattering is

$$n\tau_c = 2.4 \times 10^{10} \log_{10}(R) E_i^{3/2} . \quad (10)$$

The last term in Eq. (8) is generally neglected as small, but shown here to allow for special cases where $j_{st} \rightarrow 0$.

Equation 8 above can be integrated over z for a bounce averaged "local" prediction of T_e without radial mixing. For the streaming current densities from equations 2 and 3 the $T_e(r)$ predictions for MFTF in the two r_p/a_i regimes are:

$$T_{e3} = 6.8 \times 10^{-6} \left[\frac{n_0 L_p E_i^2 C_{BL} \ln \Lambda (R-1)}{\alpha M^{1/2} (\eta-1)^{3/2} \eta \xi} \right]^{1/4} \left(\frac{r_p}{a_i} \right)^{1/3} \quad (11)$$

$$\text{with } C_{BL} \equiv \frac{2}{n_0^2 L_p} \int_0^{L_p/2} n^2(z) dz , \text{ or}$$

$$T_{e2} = 6.8 \times 10^{-7} \left[\frac{n_0 L_p E_i^{5/4} C_{BL} \ln \Lambda (R-1)^{1/4}}{\alpha M^{1/2} (\eta-1)^{3/4} \eta \xi} \chi \left(\frac{r_p}{a_i} \right)^2 \right]^{4/13} \quad (12)$$

Typical local T_e predictions of equations 11 and 12 are shown in Fig. 3 with $C_{BL} n_0 \sim 5 \times 10^{13}$ for 2XII3 with $\bar{E}_i \sim 13$ keV, or MFTF with $\bar{E}_i \sim 50$ keV. Note again that the warm fraction Δ boundary for MFTF occurs near $r_p/a_i \sim 6$.

Equations (4) and (7) together with (8), (9), and (10) can then be used to derive a relationship for $\bar{T}_e$, assuming that E_i and T_e are approximately constant over the plasma volume to be stabilized. Integrating the LHS of Eq. (8) over r and z and using the results of Eqs. (4) and (7) multiplied by L_p from the dz integration of the RHS for the two models yields as follows:

For the flat top model (in regime 3) for MFTF

a) Keeping the central region separate from the stabilized
the boundary region in the boundary:

$$\frac{E_i}{n\tau_E} \left(\frac{n_0^2 2\pi r_p \delta r}{3} \right) C_{BL} L_p$$

$$\approx \xi n T_e \left[\frac{j_{st3} \left(\frac{n_0}{2}, \frac{a_i}{\delta r} \right)}{e L_p} 2\pi r_p \delta r \right] L_p \quad (13)$$

thus

$$T_e)_{\text{boundary}} \approx 6.8 \times 10^{-6} \left\{ \frac{2/3 n_0^2 \bar{E}_i^{-2} L_p \ln \Lambda (R-1) C_{BL}}{\alpha \xi n M_i^{1/2} (n-1)^{3/2}} \right\}^{1/4} \left(\frac{\delta r}{a_i} \right)^{1/3} \quad (14)$$

$$\text{where } C_{BL} \equiv \frac{2}{n_0^2 L_p} \int_0^{L_p/2} n^2 dz \sim .56 \text{ for } n(z) = n_0 e^{-\left(\frac{2z}{L_p}\right)^2} \quad (15)$$

Eq. (12) predicts that the stabilized boundary of a flat top MFTF distribution would have a $T_e \approx .66$ keV and require an $I_{st} \approx 1500$ A for $n_0 = 10^{14}$, $\bar{E}_i = 50$ keV, $L_p \sim 112$ cm, $\ln \Lambda \sim 15$, $R_{eff} \approx 2.3$ ($\bar{\beta} = .25$), $M = 2$, $\alpha = .5$, $\eta = 4$, $\xi = 1$, and $\delta r/a_i \sim 4$.

In this case T_e in the central region would have a classical T_e (and $n\tau_E$) e.g. from Eq. (8) for $r \leq r_p - \delta r/2$.

$$\frac{E_i}{n\tau_E} \left[n_0^2 \pi \left(r_p - \frac{\delta r}{2} \right)^2 C_{BL} L_p \right] = \xi n T_e \left[\frac{n_0^2 \pi \left(r_p - \frac{\delta r}{2} \right)^2}{n\tau_c} C_{BL} L_p \right] \quad (16)$$

thus $T_e)_{\text{central}} \approx .082 E_i \sim 4.1$ keV here.

b) An alternate model requiring that T_e be uniform
throughout both the central and edge volume yields

$$\frac{E_i}{n\tau_E} \left[n_0^2 C_{BL} L_p \pi \left(r_p - \frac{r}{2} \right)^2 + \frac{n_0^2}{3} C_{BL} L_p 2\pi r_p \delta r \right] \quad (17)$$

$$= \xi n T_e \left[\frac{j_{st3} \left(\frac{n_0}{2}; \frac{a_i}{\delta r} \right)}{e L_p} + 2\pi r_p \delta r L_p + n_0^2 \frac{C_{BL} L_p \pi (r_p - \delta r/2)^2}{(n\tau)_c} \right] \quad (18)$$

For MFTF conditions the last term involving $(n\tau)_c$ is negligible, thus here

$$T_e \approx 6.8 \times 10^{-6} \left[\frac{E_i^2 n_0 C_{BL} L_p \ln(R-1)}{\alpha M_i^{1/2} (n-1)^{3/2} \xi n} \times \left\{ \frac{(r_p - \delta r/2)^2 + \frac{2}{3} r_p \delta r}{r_p \delta r} \right\}^{1/4} \left(\frac{\delta r}{a_i} \right)^{1/3} \right] \quad (19)$$

For MFTF conditions (given under a above) this predicts $T_e \sim 1$ KeV, but with the higher T_e , $I_{st} \approx 2800$ A is now required to stabilize the δr boundary.

For the Gaussian case with T_e assumed uniform throughout and with $(a_i/r_p)_{eff} \approx 2a_i/r_p^2 \approx 1/6$ for $r = 1.1 r_p$, one has:

$$\frac{E_i C_{BL} n_0^2 L_p \ln(.49) \pi r_p^2}{10^{13} M_i T_e^{3/2}} = \frac{\xi n T_e I_{st(g)} L_p}{e L_p} \quad (20)$$

or from Eq. (7)

$$\frac{e E_i C_{BL} n_0^2 L_p \ln(.49)}{2 \times 10^{13} M_i \xi n} \approx T_e^{5/2} \left\{ .117 j_2 \left(n_0; \frac{2a_i}{r_p} \right) + .13 j_3 \left(n_0; \frac{2a_i}{r_p} \right) \right\} \quad (21)$$

The iterative solution to Eq. (17) for MFTF conditions yields $T_e \sim .9$ keV, for $I_{st(g)} \approx 2200$ A.

At this point one would like to adopt a simple ion energy loss model, to relate E_i to input parameters. Three common models are 1) electron drag dominated, 2) charge exchange dominated, and 3) RF fluctuation dominated. Again generally following Steve Devoto's memo⁵:

1) For the electron drag dominated regime the average ion energy E_i is related to E_{IN} by:

$$\frac{n^2 E_i}{n \tau_E} = \frac{n^2 (E_{IN} - E_{OUT})}{n \tau_p} \quad (22)$$

following the definitions of the hot ion energy loss rate τ_E and the hot ion particle loss rate τ_p . For the drag dominated case

$$E_{OUT} \approx \frac{(\eta - 1) T_e}{(R - 1)} \ll E_{IN}$$

$$\frac{n^2 E_i}{n \tau_E} \approx \frac{n^2 E_{IN}}{n \tau_p} \quad (23)$$

since $E_i \sim E_{IN} e^{-t/\tau_E}$ at least ignoring charge exchange;

$$\ln \left(\frac{E_{IN}}{E_{OUT}} \right) = \frac{\tau_p}{\tau_E} \quad (24)$$

$$E_i = E_{IN} / \ln \left\{ \frac{E_{IN}(R - 1)}{(\eta - 1) T_e} \right\} \quad (25)$$

2) For high rates of charge exchange $\bar{E}_i \sim E_{IN}$ and T_e must be determined by self-consistent energy balance with power.

3) For R.F dominated losses one presently must use a code calculation. In this case E_i depends upon the relative cooling by electrons and the heating by RF (as a result E_i can exceed E_{IN}). The R.F. level so far is an ad hoc fit to match predictions to match 2XII B data.

Unfortunately no single model for $\bar{E}_i$ seems completely adequate to fit 2XII data. This problem and the resultant uncertainty is discussed further below; here $\bar{E}_i \sim E_i(IN)$ is assumed as the best general fit to 2XII B data.

IV) Discussion of the Predictions for T_e , J_{st} , and I_{st} for MFIF. The accuracy of these predictions depends upon the validity

of the models and the set of associated plasma parameters. To assess this uncertainty it is useful to compare predictions with 1) available data from 2XIIB, and 2) largely independent code calculations

1) Comparison with 2XIIB measurements

Equation (2) indicating $j_{st} \sim 120 \text{ mA/cm}^2$ was normalized to fit 2XIIB data for the conditions of Ref. 3, so is not a test. However, the coefficients for Δ and j_{st} are found to be encouragingly close to theoretical choices, for measured values of T_e and $\bar{E}_i$. The calculation of T_e from the 2XIIB parameters, however, yields a test of the energy balance model of Eq. (8). For a regime 3 Gaussian approximation, Eqs. (2) and (8) yield an equation similar to (11):

$$\bar{T}_e \sim 6.8 \times 10^{-6} \left\{ \frac{.78 n_0 E_i^2 L_p \ln(R-1) C_{BL}}{\alpha M^{1/2} \xi n(n-1)^{3/2}} \right\}^{1/4} \left\{ \frac{r_p}{2a_i} \right\}^{1/3} \quad (26)$$

This equation predicts a $T_e \sim 150 \text{ eV}$ and a $j_{st} \sim .62 \text{ A/cm}^2$ for 2XIIB for $\alpha = .5$, $n = 4$, $R_{eff} = 2.5$ ($\beta \sim .4$), $M = 2$, $n_0 \sim 3 \times 10^{13}$, $\xi \sim 1$, $\bar{E}_i \sim 13 \text{ keV}$, $r_p \sim 10 \text{ cm}$, $L_p \sim 25 \text{ cm}$. The measured $T_e \sim 50$ to 60 eV for these conditions and $j_{st} \sim 100 \text{ mA/cm}^2$ is in sharp contrast with this indicating that the physics of the electron energy balance equation is incomplete, with errors $\sim$ a factor of 2 (high). This discrepancy can be adjusted by increasing the recycling factor ξ up to 40, for $\xi n \geq 160$ as discussed by Fowler⁶. Candidate electron flow and hence energy loss terms to explain this high effective ξ include 1) turbulence enhanced radial diffusion⁷, 2) surface ionization of background gas from walls or excess cold gas from the streaming guns/gas box, and 3) radiation losses from impur (estimated by Drake⁸ to be $\leq 10\%$ of total loss). It should be noted that higher T_e values have of course been achieved on 2XIIB, but under conditions, where j_{st} and a_i/r_p were not as well defined

2) A second check by comparison with of relevant code calculations for MFTF is more difficult. Tom Rognlien⁹ and John Stewart scaled the 2XII normalized 1-D quasi-linear code¹⁰ calculation to MFTF parameters. For beam deposition in the flat-topped model used for Eq. (4) they have calculated I_{st} requirements in the boundary with $\bar{n} \sim n_0/2$ for various boundary δr (determines wave number; $\omega = \omega_{ci}$) thicknesses from 5 cm to 30 cm. Fig. 4 below shows predicted values of $\bar{E}_i$, $\bar{T}_e$, and ϕ_{RF} for the I_{st} (min) given as a function of mean density n for the case $r_p = 30$ and $\delta r = 10$ cm. This code calculation for T_e also does not correctly predict 2XIIIB values, and neglects expected effects of the boundary density gradient. Note also that the calculated plasma density increases with I_{st} , so strictly speaking the $I_{st}(\text{min})$ given is not a true minimum, but rather the amount beyond which the density tends to limit and no longer scale up with I_{st} .

In summary Table 3 shows predictions for MFTF (discussed above).

Table II. MFTF Stabilizing Stream Requirements

Model	$T_e(\text{keV})$	$J_{st}(\text{A/cm}^2)$	$I_{st}(\text{A}) -$ (over area)
Flat Top:			
Separate-boundary	.66	.90	$1500 - (2\pi r_p \delta r)$
-central	4.2	0	0
Combined ave. T_e	1.0	1.67	$2800 - (2\pi r_p \delta r)$
Gaussian	.9	.39	$2200 - (2\pi r_p^2)$

References

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Theoretical Warm Plasma Fraction (n_w/n) vs (r_p/a_i)

Local j_{ST} vs T_e

Fig 2

Local T_e vs (r_p/a_i)

fig. 3

R_{cl} 7.1 $\frac{R_{cl}}{L}$
 T_c $\frac{R_{cl}}{L}$ $\frac{R_{cl}}{L}$

$R_p = 30 \text{ cm}$
 $\delta r \sim 10 \text{ cm}$
 $\bar{n} \sim n_0/2$

$\bar{n}_H/\text{cm}^3$

Fig 4