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LOW-ENERGY NEUTRAL-BEAM INJECTION IN THE
CENTRAL CELL OF TMX-U

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ABSTRACT

Our purpose here is to estimate the central-cell parameters that can be reached by injection of low-energy neutral beams. The main advantages of low energy (2-keV full-energy component) over high energy (15-keV full-energy component) are the following:

- Creation of a beam-fueled, potentially confined, central-cell plasma ($n \approx 10^{13} \text{ cm}^{-3}$, $E_{ic} \approx 1 \text{ keV}$, $T_{ec} \approx 0.4 \text{ keV}$) without the use of cold-gas injection or ICRH heating.
- Reduced shielding requirement against neutrals external to the plasma.

The reasons for these expectations are the larger ionization cross section and plasma radius (normalized to ion gyroradius) for low-energy compared to high-energy beams.

I. DISCUSSION OF RESULTS

In Figures 1 and 2 we plot the solutions to rate equations for peak density $\hat{n}$ and for electron (T_{ec}) and ion (T_{ic}) temperatures with the particle confinement time τ_p as a free parameter. The calculations were made for low- and high-energy beam injection and for 50 kW and zero kW of absorbed ECRH. Confining potentials $\phi_c/T_{ic} = 2$, $\phi_e/T_{ec} = 4$ were assumed for low-energy beam injection and $\phi_c = 0.0 \text{ kV}$, $\phi_e/T_{ec} = 4$ for high-energy beam injection.

The incident neutral-beam current is 150 A for both the low- and high-energy injection. This level of performance has already been attained for high-energy injection. We implicitly assume, on the basis of conversations with the Lawrence Berkeley Laboratory beam group¹, that the same beam divergence and gas efficiency will hold for a low-energy accel-decel arrangement as with the present high-energy beams. Although expected, this would be important to confirm experimentally.

Figure 1. Plasma density $\hat{n}$, ion temperature T_i , and electron temperature T_e are plotted as functions of particle confinement. The curves on the left are for 2-kV beam-extraction voltage while those on the right are for 15 kV. The total neutral beam current incident on the plasma is 150 atom $\cdot$ amps, and 50 kW of auxiliary electron heating has been assumed.

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Figure 2. This is the same as Fig. 1 but with no auxiliary electron heating.

Figure 1 shows the plots of $\hat{n}$, T_{ec} and T_{ic} versus τ_p for 50-kW and Fig. 2 for zero kW absorbed ECRH. To get an idea of where the operating point will be, we show dashed lines to indicate $\hat{n}$ versus τ_p for Pastukov confinement and for ion-ion scattering mirror confinement. For ion-ion scattering, τ_{ii}^{eff} is the effective ion-ion scattering loss time corrected for charge exchange on neutral-beam atoms; τ_{ii} is the uncorrected ion-ion scattering time. Cross-hatched regions at the bottom of the figures indicate the range of confinement times required for exponentiation of the beam-injected plasma. The left edge of a cross-hatched region corresponds to the exponentiation condition for an initial plasma with axial length equal to the injection length (200 cm). The right edge corresponds to a distribution broadened by scattering to the full effective central-cell length of 500 cm.

As an example, take the low-energy beam injection case with 50-kW ECRH in Fig. 1. For exponentiation, a particle confinement time of 6 ms is required during build-up with $\ell \approx 200$ cm (corresponding to a neutral density of $n_0 < 2 \times 10^9 \text{ cm}^{-3}$ inside the plasma) while $\tau_p > 15$ ms is required for the final state isotropic plasma with $\ell = 500$ cm ($n_0 < 0.9 \times 10^9 \text{ cm}^{-3}$). The solutions of the steady-state rate equations are asymptotic to $\tau_p = 15$ ms. If these requirements on τ_p are not met, the beam current per unit volume will be inadequate to sustain a plasma without gas fueling or an auxiliary warm plasma source. Assuming for the moment that the neutral-density requirements are met, the intersection of $\hat{n}$ versus τ_p with $\tau_{pastukov}$ defines an operating point with $\hat{n} = 1.65 \times 10^{13} \text{ cm}^{-3}$, $T_{ic} = 0.64 \text{ keV}$, $T_{ec} = 0.4 \text{ keV}$, and $\tau_p = 27 \text{ ms}$. These parameters are close to the proposal goals. We must emphasize, however, that the operating point depends sensitively on the τ_p actually achieved. For example, if radial transport lowers τ_p to 16 ms, the operating density falls to $2.5 \times 10^{12} \text{ cm}^{-3}$ and if τ_p is less than 15 ms, the beam current assumed will not be sufficient to sustain a beam-fueled, isotropic, potentially confined plasma. Similarly, if there is mirror confinement of the central-cell ions but not potential confinement, the intersection of $\hat{n}$ versus τ_p with τ_{ii}^{eff} defines an operating point at the rather uninteresting density $\hat{n} = 1.7 \times 10^{12} \text{ cm}^{-3}$. From the magnitude of τ_{ii}^{eff} , we note that as long as τ_p is only slightly greater than 15 ms, the effective ion-ion scattering time is short enough to insure that the plasma is isotropic.

Assuming Pastukov confinement, the time required to reach the density $\hat{n} = 1.5 \times 10^{13} \text{ cm}^{-3}$ from an initial ECRH-generated target plasma with $\hat{n} = 5 \times 10^{11} \text{ cm}^{-3}$ is estimated to be about 80 ms with $I_b = 150 \text{ A}$. With Pastukov confinement, the core plasma would be inaccessible to $f = 28 \text{ GHz}$ fundamental ECRH, since $\hat{n} = 1.65 \times 10^{13} \text{ cm}^{-3}$ while the cut-off density is $1.0 \times 10^{13} \text{ cm}^{-3}$. However, the entire plasma is below cut-off for the first 50 ms of build-up; afterwards ECRH would continue to effectively heat plasma electrons outside the cut-off radius ($r_c > 0.6a$ for a parabolic density profile and $n/n_c = 1.65$).

Returning now to the issue of neutral density, $n_0 < 2 \times 10^9 \text{ cm}^{-3}$ in the plasma interior is required during build-up and $n_0 < 0.8 \times 10^9 \text{ cm}^{-3}$ in steady state. The questions are: What pressure external to the plasma can be achieved, and what shielding factor is required? Fast-ion-gage measurements of pressure in the disc liner region before and after the recent beam modifications are described in Sec. III of this paper while steady-state pressures were theoretically calculated in Table III² of an earlier report.

Summarizing these results, we find it reasonable to expect that in the absence of cold-gas fueling, the bounce-average pressure will remain below $1 \times 10^{-6} \text{ Torr}$ for 30 ms and below $2 \times 10^{-6} \text{ Torr}$ in steady state. The initial neutral-shielding factor required during the first 30 ms of build-up is 16.1, essentially equal to the Franck-Condon break-up factor of 15.4.³ This shielding can be provided by a low-density ECRH start-up plasma with $n = 0.5 - 1 \times 10^{12} \text{ cm}^{-3}$, $n\lambda = 1.6$ to $3.3 \times 10^{13} \text{ cm}^{-3}$. In steady state, a shielding factor of approximately 80 is necessary. Gas code calculations with the final-state density $\hat{n} = 1.65 \times 10^{13} \text{ cm}^{-3}$, $n\lambda = 4.4 \times 10^{14} \text{ cm}^{-3}$ predict much higher shielding than this.⁴ Therefore the low-energy beam injection described here seems to provide a route for reaching proposal parameters starting from low density end plugged plasmas.

For comparison, we turn now to the energetic beam-injection case in Fig. 1. A confinement time $\tau_p > 16.5 \text{ ms}$ is required for build-up and $\tau_p > 42 \text{ ms}$ for a steady-state beam-sustained plasma without gas fueling or a continuous warm plasma source. These confinement times are about a factor of 3 greater than required for low-energy beam injection; the corresponding neutral densities also about a factor of 3 less than those achieved with beam injection, neglecting high-pressure regions near gas-fueling locations. Perhaps the proposed halo recycler could provide the additional shielding to make such an experiment work. If such an experiment were successful, the

average ion energy would be higher than could be potentially confined in TMX-U and would resemble Kelly-mode operation. Mirror confinement defines an operating point $n = 1.8 \times 10^{13} \text{ cm}^{-3}$, $T_i = 6 \text{ keV}$, $T_e = 1.2 \text{ keV}$, and $\tau_p = 60 \text{ ms}$.

Finally, we note that in the build-up equations described in the next section, the beam current I_b and confinement time τ_p appear as a product $I_b \tau_p$. If I_b is decreased by a factor of 2 (as if only one-half of the existing high-energy beams were regapped for low-energy injection), then τ_p must increase by a factor of 2 for the solution to remain unchanged. In Fig. 1, this corresponds to moving the curves of $\hat{n}$, T_i , and T_e to the right by a factor of 2. The intersection with the Pastukov confinement curve then changes from $\hat{n} = 1.65 \times 10^{13} \text{ cm}^{-3}$, $\tau_p = 27 \text{ ms}$ to $\hat{n} = 0.95 \times 10^{13} \text{ cm}^{-3}$, $\tau_p = 43 \text{ ms}$.

11. CENTRAL-CELL MODEL

The following three equations are used to model central-cell parameters in steady state:

$$\text{Density; } \frac{\sigma_i}{\sigma_i + \sigma_{cx}} [1 - \exp - (\sigma_i + \sigma_{cx}) \frac{4}{3} \hat{n} a] \frac{I_b}{e} = \frac{\hat{n} V}{\tau_p}, \quad (1)$$

$$\text{Ion power balance; } \frac{E_b - \frac{3}{2} T_i}{\tau_{cx}} + \frac{E_b - T_i - \phi_c}{\tau_p} = \frac{3}{2} \frac{(T_i - T_e)}{\tau_{ie}}, \quad (2)$$

$$\text{Electron power balance; } \frac{3}{2} \frac{(T_i - T_e)}{\tau_{ie}} = \frac{\phi_e + T_e}{\tau_p} - \frac{P_{\mu\lambda}}{\hat{n} V}. \quad (3)$$

Equations (1) to (3) describe a single-component ion plasma with temperature T_i , particle-confinement time τ_p , central density $\hat{n}$, and parabolic radius $a = 20 \text{ cm}$. The confining potential is ϕ_c for ions and ϕ_e for electrons. The ions build up and are sustained by neutral-beam current I_b with mean energy E_b . The vacuum conditions are assumed good enough that charge-exchange energy loss is negligible compared to axial loss and electron drag. The parameter τ_{cx}^b is the time for replacement of a plasma ion by charge exchange on a beam-injected atom:

$$\frac{\hat{n} V}{\tau_{cx} b} = \frac{\sigma_{cx}}{\sigma_i + \sigma_{cx}} [1 - \exp - (\sigma_i + \sigma_{cx}) \frac{4}{3} \hat{n} a] \frac{I_b}{e}$$

or

$$\tau_{cx} b = \frac{\sigma_i}{\sigma_{cx}} \tau_p \quad (4)$$

The electrons are heated by collisions with ions and by ECRH power $P_{\mu\lambda}$.
The plasma volume is defined by

$$\hat{n} V = \int n(\vec{x}) d^3x$$

or

$$V = \frac{1}{2} \pi a^2 L \quad (5)$$

where L is the effective central-cell length. The electron drag time is defined by

$$\frac{\hat{n} V}{\tau_{ie}} = \int \frac{n^2(\vec{x}) d^3x}{(n\tau)_{ie}} \quad (6)$$

where $(n\tau)_{ie} = 1.39 \times 10^{12} T_e(\text{keV})^{3/2}$. For a parabolic density profile, we obtain

$$\frac{\hat{n} V}{n\tau_{ie}} = \frac{3}{2} \times 1.39 \times 10^{12} T_e^{3/2}(\text{keV})$$

or

$$= 2.09 \times 10^{12} T_e^{3/2}(\text{keV}) \quad (7)$$

Equations (1) to (3) were solved for $\hat{n}$, T_i , and T_e with particle confinement time as a free parameter. Solutions were calculated for low energy (2-keV full-energy component $I_b = 150$ A) and high-energy beam injection (15-keV full-energy component, $I_b = 150$ A) and for 50 kW and zero kW of absorbed ECRH power. The results are shown in Figs. 1 and 2, where $\hat{n}$, T_i , and T_e are plotted versus τ_p . The cross section parameters are summarized

in Table 1. The ionization cross section for low-energy beams is greater than for high-energy beams by the velocity ratio $(10/1.33)^{1/2} = 2.7$, and the density will build up for confinement times that are lower by the same ratio. For the calculations in Figs. 1 and 2, confining potentials $\phi_c/T_i = 2$, $\phi_e/T_e = 4$ have been assumed for low-energy and $\phi_c = 0.0$ kV, $\phi_e/T_e = 4$ for high-energy beam injection.

From Eq. (1) it follows that there are no solutions unless the particle confinement time is greater than a critical value given by

$$\tau_p^{\text{crit}} = \frac{eV}{\frac{4}{3} a \sigma_i I_b}, \quad (8)$$

which corresponds to $d\hat{n}/dt > 0$ initially. Setting $\tau_p^{\text{crit}} = \tau_{cx} = 1/n_0 \langle \sigma v \rangle_{cx}$ then gives upper bounds on neutral density. Values for τ_p^{crit} are calculated for initial build-up with a plasma length $L = 200$ cm, corresponding to the beam-injection length and for steady state with $L = 500$ cm. The results are indicated as the cross-hatched regions along the horizontal axes of Figs. 1 and 2 and are tabulated in Table 2, along with the upper bound on neutral density and the required plasma-shielding factor. The shielding factor is defined as the ratio of external neutral density to neutral density inside the plasma, with $P_{\text{ext}} \leq 1 \times 10^{-6}$ Torr during initial build-up and $\leq 2 \times 10^{-6}$ Torr in steady state.

The intersection of a particular confinement scaling law with the $\hat{n}$ versus τ_p curves in Figs. 1 and 2 defines operating points. For the low-energy case, we take the Pastukov expression

$$\hat{n}_{\tau_{\text{Past.}}} = \frac{3}{2} (n\tau_0) \frac{\sqrt{\pi}}{2} \frac{R+1}{R} \ln(2R+2) \frac{e\phi_c \exp\left(\frac{e\phi_c}{T_i}\right)}{T_i \left(1 + \frac{T_i}{2e\phi_c}\right)}, \quad (9)$$

$$n\tau_0 = 1.35 \times 10^{10} E_i(\text{keV})^{3/2}.$$

The factor $3/2$ arises from the volume integral as in Eq. 6. Substituting

mirror ratio $R = \frac{8}{3}$ and $\frac{e\phi_c}{T_i} = 2$ in Eq. (9) yields

Table 1. Parameters for low- and high-energy beam injection.

Parameter	Beam injection	
	Low-energy	High-energy
Full energy (keV)	2.0	15
Mean energy (keV)	1.33	10
σ_i (cm ⁻²)	0.83×10^{-15}	0.3×10^{-15}
σ_{cx} (cm ⁻²)	2.2×10^{-15}	1.33×10^{-15}
$\sigma_i + \sigma_{cx}$ (cm ⁻²)	3.0×10^{-15}	1.6×10^{-15}
$\sigma_i / (\sigma_i + \sigma_{cx})$	0.27	0.19
a/ρ_i	8.0	2.9

Table 2. Critical confinement time, neutral density, and shielding factor.

	Length (cm)	2-keV Injection	15-keV Injection
τ_p^{crit}	200	6 ms	16.4 ms
	500	15 ms	41 ms
n_0^{crit}	200	$2 \times 10^9 \text{ cm}^{-3}$	$0.62 \times 10^9 \text{ cm}^{-3}$
	500	$0.8 \times 10^9 \text{ cm}^{-3}$	$0.25 \times 10^9 \text{ cm}^{-3}$
S	200	16	52
	500	80	260

$$\hat{n}_{\tau_{\text{Past.}}} = 4.45 \times 10^{11} E_i^{3/2} \text{ (keV)} . \quad (10)$$

For mirror confinement, we have

$$\tau_{ii}^{\text{eff}} = \tau_{cx}^b \left[\exp \frac{\tau_{ii}}{\tau_{cx}^b} - 1 \right] , \quad (11)$$

where τ_{cx}^b is defined in Eq. (4) and

$$\hat{n}_{\tau_{ii}} = 2 \times \frac{3}{2} \times 1.74 \times 10^{10} \left(\frac{2}{\pi} \delta\phi \right)^2 E_i \text{ (keV)}^{3/2} . \quad (12)$$

In Eq. (12), $\delta\phi$ is the difference between the injection angle and the loss cone boundary. The factor $3/2$ comes from volume averaging. The factor of 2 arises from counting only those ions that scatter toward the loss cone as lost, thus excluding ions that scatter toward a larger pitch angle.

Substituting $\delta\phi = \pi/4$,

$$n_{\tau_{ii}} = 1.31 \times 10^{10} E_i \text{ (keV)}^{3/2} . \quad (13)$$

Equations (9) and (11) are plotted as the dashed lines in Figs. 1 and 2.

III. PRESSURE IN THE CENTRAL-CELL DISC-LINER REGION

Figure 3 shows pressure versus time in the disc liner region before re-aiming the beams. On a plasma shot (Fig. 3c), the pressure rises to 1.5×10^{-5} Torr with four central-cell beams selected. Figure 4 indicates the improvement in pressure after relocating the beams for off-midplane normal injection², first, with some open cracks remaining between the first injector and the plasma regions and, finally, with those cracks closed up. On a plasma shot (Fig. 4f), the pressure rises to 0.6×10^{-6} Torr with seven beams selected.

For the data in Fig. 4, the disc liners were cold while those in Fig. 3 were warm. Previous data³ indicates that cooling the liners reduces the measured fast-ionization gauge (FIG) data by a factor of 2. Therefore, we estimate that near the plasma the pressure may be rising to approximately

Figure 3. Central-cell disc-region pressure with 70°-beam injection at the midplane: (a) Beam arcs plus accel voltage, (b) beam arcs only, (c) plasma shot with beam injection, (d) plasma shot without beam injection. For these shots, the LN disc liners were warm and four LBL 20-kV, 50-A beam modules were used.

Figure 4. Central-cell disc-region pressure with off-midplane beam injection (disc liners cold): (a) and (d), beam plus accel voltage; (b) and (e), beam arcs only; (c) and (f), plasma shot with beam injection. (a), (b), and (c) were taken before closing "cracks" near central-cell disc liners and (d), (e), and (f) were taken after closing cracks. For these shots, seven LBL 20-kV, 50-A beam modules were used.

$2 \times 0.6 \times 10^{-6} = 1.2 \times 10^{-6}$ Torr, in close agreement with a calculated estimate of 1.4×10^{-6} Torr in the disc-liner region.² The calculations also estimated that the pressure, neglecting gas-fueling contributions, would be higher (2.4×10^{-6} Torr) in the rectangular plasma regions adjacent to the disc region and that the bounce-average pressure in the combined disc-rectangular region was equal to 2×10^{-6} Torr. In the absence of measurements in the rectangular regions, we use 2×10^{-6} Torr for estimating neutral density of a steady-state beam-sustained central-cell plasma with no cold-gas fueling. Similarly, from the time dependence of pressure measured in the disc region, we estimate $P < 1 \times 10^{-6}$ Torr for the first 30 ms of beam injection. These pressures were used in Table 2 to calculate the shielding factor required for a beam-sustained plasma.

Comparing the plasma shots in Fig. 4c and f, we note that closing the cracks between the first injector and disc-liner regions reduced the pressure by a factor of 2--from 1.2×10^{-6} Torr to 0.6×10^{-6} Torr. It is possible that a substantial fraction of the pressure now remaining in Fig. 4f is due to cold-gas fueling in the central cell, in which case we have conservatively estimated the pressure of a beam-fueled plasma and the shielding factors in Table 2. The reason for this conjecture is that in Fig. 3d, a pressure increase of 0.4×10^{-6} Torr was measured on a plasma shot with gas fueling but no beam injection.

IV. TIME-DEPENDENT BUILD-UP

Initially, we imagine starting out with a relatively cold, potentially confined, central-cell plasma created by ECRH and gas and with density $\hat{n} = 5 \times 10^{11} \text{ cm}^{-3}$. When the beams are first turned on, charge exchange will contribute to the initial build-up of beam-trapped ions. The central-cell plasma will shrink from 500 cm to the beam-injection length of 200 cm, and the density will increase by a factor $500/200 = 2.5$ to $\hat{n} = 1.25 \times 10^{12} \text{ cm}^{-3}$. The time scale for this first stage of beam injection will be approximately τ_{cx}^b , which in the thin plasma limit is

$$\tau_{cx}^b = \frac{eV}{\frac{4}{3} \sigma_{cx}^a l_b} = 5.7 \text{ ms} \quad (14)$$

The ion distribution will then spread axially by ion-ion scattering until the effective length is again 500 cm. The time scale for this second stage is τ_{ii}^{eff} ,

$$\tau_{ii}^{eff} = \tau_{cx}^b \left[\exp \frac{\tau_{ii}}{\tau_{cx}^b} - 1 \right] = 30 \text{ ms} . \quad (15)$$

The plasma will then continue to build up by ionization trapping according to

$$V \frac{d\hat{n}}{dt} = \frac{\sigma_i}{\sigma_i + \sigma_{cx}} \left[1 - \exp - (\sigma_i + \sigma_x) \frac{4}{3} \hat{n} a \right] \frac{I_b}{e} - \frac{\hat{n}}{\tau_p} V . \quad (16)$$

Equation 16 is plotted in Fig. 5 for low-energy beam injection, assuming Pastukov confinement with $\phi_c/T_i = 2.0$. The total time to reach the equilibrium density $n = 1.65 \times 10^{13} \text{ cm}^{-3}$ is about 125 ms; $n = 1.5 \times 10^{13} \text{ cm}^{-3}$ is exceeded after about 80 ms.

Figure 5. Time-dependent build-up of central-cell density for 150 atom-A of 2-kV-beam injection and assuming Pastukov confinement.

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