Auxiliary Plasma Heating and Fueling Models for Use in Particle Simulation Codes

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Abstract

Computational models of a radiofrequency (RF) heating system and neutral-beam injector are presented. These physics packages, when incorporated into a particle simulation code, allow one to simulate the auxiliary heating and fueling of fusion plasmas. The RF-heating package is based upon a quasilinear diffusion equation which describes the slow evolution of the heated particle distribution. The neutral-beam injector package models the charge exchange and impact ionization processes which transfer energy and particles from the beam to the background plasma. Particle simulations of an RF-heated and a neutral-beam-heated simple-mirror plasma are presented.

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1 Introduction

Plasma heating and fueling are two important aspects of controlled fusion research using magnetically confined plasmas. Partial heating of the plasma is possible by means of collisional (resistive) processes as a current flows through the conducting plasma. The resistivity of the plasma varies as its temperature to the negative $3/2$ power. Therefore, as the temperature of the plasma is raised, Ohmic heating becomes less effective. For this reason, auxiliary heating methods have been developed. The most effective means of auxiliary heating have been the injection of neutral particle beams and radiofrequency (RF) waves into the plasma. The first method uses energetic neutral atoms to pass through the applied magnetic field into the plasma, where they are subsequently ionized. In the second case, RF waves are injected into the plasma to accelerate and heat the particles.

The most significant difficulty in fueling the plasma is the confining magnetic field, which reduces the leakage of charged particles from the plasma, but also prevents charged fuel particles from entering the plasma. One solution to this problem has been the injection of neutral atoms across the confining magnetic field into the plasma, where they are ionized by charge exchange and impact ionization processes. Currently, the most widely used forms of plasma fueling are gas puffing, neutral beam injection and frozen-gas pellet injection. The RF-heating package that was developed for use in the TESS code is described in Sec. 2 of this paper, while the neutral beam charge exchange and ionization models are discussed in Sec. 3.

2 The Radiofrequency (RF) Heating Model

Particle confinement in mirror plasmas is based upon the conservation of kinetic energy and the adiabaticity of the magnetic moment, such that the particles bounce back and forth in the magnetic potential well. Only a certain fraction of the particles are trapped or confined by this potential well. The trapped region in $v_{\perp}$ vs. $v_{\parallel}$ space is defined by the mirror magnetic field ratio and the plasma ambipolar electrostatic potential. The main classical loss mechanism for particles in both simple mirror plasmas and in the end plugs of tandem mirror plasmas is collisional detrapping of the particles from this trapped region into the loss cone. Once in the loss cone, the particles are free to transit out the ends of the device, unhindered by the

magnetic field.

Ions in the center-cell region of a tandem mirror device are electrostatically confined by large positive ambipolar potentials which arise in the end plugs of the device. In the simplest model, this potential increases linearly with the electron temperature in the end plugs.

It is possible to improve particle confinement in mirror devices through the injection of radiofrequency waves at the fundamental or some harmonic of the electron cyclotron frequency. This process is termed electron cyclotron resonance heating (ECRH). The increase in the confinement of center cell ions in a tandem mirror is due to the heating of the plug electrons, which results in an increase in the confining electrostatic potential in the plugs. Of secondary interest is the enhancement of electron confinement in a simple mirror or tandem mirror plug, which is due to the preferential increase of the perpendicular velocity relative to the parallel velocity. This leads to hot electrons which are placed farther into the trapped region of velocity space, thereby requiring a longer time to collisionally migrate to the loss boundary in velocity space. This assumes that the hot electrons remain microstable.

2.1 Methodology

The quasilinear RF-heating model of Bernstein and Baxter [1], which treats the heating of mirror-trapped particles, forms the basis of the RF-heating package used in TESS. It is valid for mildly relativistic electrons and nonrelativistic ions in the presence of a cyclotron resonant applied electromagnetic field. The model, based upon the so-called "perturbed-distribution" method (see [4]), assumes that the cyclotron frequency is much higher than the bounce frequency in the magnetic potential well, and then averages over the particle trajectories as they bounce in the well. One of the main results of Reference [1] is the derivation of a quasilinear diffusion equation in the form of a Fokker-Planck equation. This diffusion equation describes the slow evolution of the heated particle distribution function f_0 in ϵ (total energy), μ (magnetic moment) space.

The Bernstein-Baxter formulation of the quasilinear diffusion equation was used by Roglien in the Monte Carlo RF-heated mirror code MCPAT [2,3] and generalized formally by Smith and Cohen [4]. That implementation of the model was translated by Bruce Cohen for use in TESS. The model is based upon the "perturbed-trajectory" method in action (J) - angle (ϕ) space.

where J and ϕ are constants of the particle motion. Since we are interested in long-time-scale (relative to the “correlation” time t_c , cyclotron orbit time t_L , mirror bounce time t_b , etc.), averaging is performed over the angle variables, resulting in the Fokker-Planck equation for the slowly varying heated distribution function f_o

$$\frac{\partial f_o}{\partial t} = -\frac{\partial}{\partial J} (\Gamma_J f_o) + \frac{\partial^2}{\partial J^2} (D_{JJ} f_o) \quad (1)$$

where the coefficient of dynamic friction and the diffusion coefficient are given by

$$\Gamma_J = \langle \Delta J / \Delta t \rangle \quad (2)$$

$$D_{JJ} = \langle (\Delta J)^2 / (2\Delta t) \rangle. \quad (3)$$

Applying the friction-diffusion relation

$$\Gamma_J \approx \frac{dD_{JJ}}{dJ} \quad (4)$$

reduces the Fokker-Planck equation (1) to the form of a standard diffusion equation

$$\frac{\partial f_o}{\partial t} = \frac{\partial}{\partial J} \left(D_{JJ} \frac{df_o}{dJ} \right). \quad (5)$$

For this particular implementation of the model, the action variable J was chosen to be the total particle energy ε , which is a constant of the motion for unheated mirror-trapped particles.

The RF-heating model was incorporated into the particle code in the following way. The region over which the RF power is being injected is defined by a center location Z_{oRF} and a width ΔZ_{RF} . The intensity of the injected RF power varies within the region as

$$E_{RF}(z) = \frac{E_{RF}(Z_{oRF})}{2} \left[1 + \cos \left(\frac{2\pi(z - Z_{oRF})}{\Delta Z_{RF}} \right) \right] \quad (6)$$

where $E_{RF}(Z_{oRF})$ is the maximum amplitude of the RF wave within the region. Particles which lie within this region are tested to determine if they meet the resonance condition $\mathbf{R} = 0$, where

$$\mathbf{R} = \omega_{RF} - \frac{\ell \Omega_s}{\gamma} - \frac{k_{\parallel} p_{\parallel}}{\gamma m_s} \quad (7)$$

with ω_{RF} the frequency of the injected wave, ℓ the cyclotron harmonic number, $\Omega_s = q_s B / m_s c$ the cyclotron frequency for species s , $\gamma = 1 / \sqrt{1 - v^2/c^2}$ the relativistic factor, $k_{\parallel}$ the wave vector parallel to the magnetic field, and $p_{\parallel} = \gamma m_s v_{\parallel}$ the particle momentum parallel to the magnetic field. Finally, m_s and q_s are the species rest mass and charge respectively, and c is the

speed of light. If the value of $\mathbf{R}$ changes sign in one time step, the particle has gone through resonance, and is therefore given a “kick” in energy.

The change in energy that the resonant particle receives is given by

$$\Delta\varepsilon = \Gamma_\varepsilon \Delta t + (6D_{\varepsilon\varepsilon}\Delta t)^{1/2} R_N \quad (8)$$

$$= \left(\frac{dD_{\varepsilon\varepsilon}}{d\varepsilon} \right) \Delta t + (6D_{\varepsilon\varepsilon}\Delta t)^{1/2} R_N \quad (9)$$

where $\varepsilon = \gamma m_s c^2 + q_s \Phi$ is the total particle energy for an electrostatic potential Φ , Δt is the time step and R_N is a uniformly distributed random number in the range $[-1, 1]$. The coefficient of dynamic friction Γ_ε from (2) and the energy diffusion coefficient $D_{\varepsilon\varepsilon}$ from (3) are specified functions of the particle rest mass, charge, parallel velocity, magnetic moment, gyroradius, cyclotron frequency and the parallel and perpendicular wave vectors (see [1]). The derivative of the energy diffusion coefficient with respect to total energy may also be written as

$$\frac{dD_{\varepsilon\varepsilon}}{d\varepsilon} = \frac{\partial D_{\varepsilon\varepsilon}}{\partial \varepsilon} + \alpha \frac{\partial D_{\varepsilon\varepsilon}}{\partial \mu} \quad (10)$$

where $\alpha = (1 - k_{\parallel} v_{\parallel} / \omega_{RF}) / B$ and the magnetic moment $\mu = \gamma^2 m_s v_{\perp}^2 / 2B$.

The first term on the right side of (9) represents the change in total energy due to dynamic friction or drag, while the second term represents the change due to diffusion in ε, μ space. These are the same two processes that are described by the right side of the Fokker-Planck equation (1). Note that the energy increment $\Delta\varepsilon$ may be either positive or negative, such that the particle gains energy from the wave, or vice versa.

Once the total energy increment is known, we calculate the change in the particle parallel momentum and magnetic moment via

$$\Delta p_{\parallel} = \gamma m_s c^2 \frac{k_{\parallel} v_{\parallel}}{\omega_{RF}} \frac{\Delta\varepsilon}{p_{\parallel} c^2} \quad (11)$$

and

$$\Delta\mu = \frac{\gamma}{B} \left(1 - \frac{k_{\parallel} v_{\parallel}}{\omega_{RF}} \right) \Delta\varepsilon = \frac{\gamma}{B} \alpha \Delta\varepsilon. \quad (12)$$

2.2 Simulation Results

In addition to the data required to run the basic electrostatic particle code, TESS also requires the following data for the RF heating model: the center and width of the RF heated region

(Z_{oRF} and ΔZ_{RF}), the wave frequency (ω_{RF}), the cyclotron harmonic number of the wave (ℓ), the peak RF wave amplitude ($E_{RF}(Z_{oRF})$) and the parallel and perpendicular wave vectors ($k_{\parallel}$ and $k_{\perp}$).

Results of the TESS code are compared to those from MCPAT below. For these runs, the magnetic field profiles were specified in both codes, and the self-consistent calculation of the ambipolar electrostatic potential was disabled in TESS, in an effort to more closely compare with MCPAT, which does not have this capability. The runs are therefore simulations of a simple mirror geometry, with ECRH applied at the bottom of the magnetic well. The RF waves are injected essentially perpendicular to the magnetic field at the bottom of the magnetic well, with a small component along the magnetic field. The input data for the runs were $Z_{oRF} = 250\text{cm}$, $\Delta Z_{RF} = 50\text{cm}$, $\omega_{RF} = 8.8 \times 10^{10}\text{rad/sec}$, $E_{RF}(Z_{oRF}) = 3\text{V/cm}$, $\ell = 1$ or fundamental heating, and $k_{\perp} = 1.0\text{cm}^{-1}$ and $k_{\parallel} = 0.1\text{cm}^{-1}$.

The electron velocity-space plots for the RF heated region from TESS and MCPAT are shown in Figure 1. Note the increase in particle density in the regions of high $v_{\perp}$ and low $v_{\parallel}$, which is the indication of preferential heating in the $\perp$ -direction, relative to the $\parallel$ -direction. The initial thermal velocity in each direction is $v_{th} = 4.19 \times 10^8\text{cm/sec}$, such that the most energetic particles have been heated to a maximum velocity $v_{\perp\text{max}} \simeq 6v_{th}$.

The kinetic energy profiles along the axis of the simple mirror are shown in Figure 2. Note that the TESS result is an instantaneous snapshot, while the MCPAT result is time-averaged. The MCPAT profile from -150cm to 150cm corresponds to the region from 100 to 400cm (the peaks of the magnetic field) on the TESS profile. Note that in each case, the parallel kinetic energy is, on average, half that of the perpendicular kinetic energy. This is because the perpendicular direction comprises two degrees-of-freedom, as compared with one for the parallel direction. The heating is manifested almost entirely in the increase of the perpendicular kinetic energy in the 25cm to either side of the injection center point. TESS gives a maximum perpendicular kinetic energy of 215eV , while MCPAT yields a 200eV maximum value. The large values of the perpendicular kinetic energy near the peaks of the magnetic field in the TESS results are due to particles which are near their turning points, with large values of $v_{\perp}$ and nearly zero values of $v_{\parallel}$. This effect is not seen in the MCPAT results due to the time-averaging of the profile.

a) TESS velocity space density plot.

b) MCPAT velocity space density plot.

Figure 1: Electron $v_{\perp}$, $v_{\parallel}$ velocity space density plots from (a) TESS and (b) MCPAT for the region near the bottom of the magnetic well, showing the preferential increase in perpendicular velocity due to heating by applied electromagnetic waves.

a) Instantaneous kinetic energy profile from TESS.

b) Time-averaged kinetic energy profile from MCPAT.

Figure 2: Electron kinetic energy profiles from (a) TESS and (b) MCPAT showing the increase in perpendicular kinetic energy in the RF-heated region. The RF-heated region is 25cm on either side of the magnetic well minimum.

3 The Neutral Beam Injection Model

The most common method of auxiliary plasma heating presently in use is the injection of energetic neutral particles into the plasma. Heating of the plasma results as these neutrals undergo charge exchange with plasma ions, or are ionized via collisions with the plasma particles. Note that the former mechanism results only in a change in the total particle energy, while the latter also results in an increase in both the ion and electron densities. For this reason, neutral beam injection (NBI) may also be used as a means of fueling the plasma.

Neutral beam injection has been successfully employed for several years to both heat and fuel plasmas in experimental configurations ranging from tokamaks to stellarators to mirror machines. In addition, current-drive schemes which rely on NBI have been proposed for use in the ignited, steady-state tokamaks of the future [5,6]. Two additional uses of NBI are found in tandem mirror devices with thermal barriers. The first is the use of "sloshing" ions in the formation of the thermal barriers. Since the sloshing ions (which are created by injection of neutral beams at some angle $\theta < 90^\circ$ to the axis of the machine) are mirror trapped, the average density at the turning points of these particles in the magnetic well is larger than that at the center of the well, which in turn leads to a potential minimum near the center of the well. This potential dip is necessary to the formation of a thermal barrier which isolates the hot electrons in the plug region from their colder counterparts in the central cell. The second use of NBI in tandem mirrors is to maintain the thermal barrier, by charge exchange "pumping" of the cold, passing ions which become collisionally trapped in the thermal barrier. Lastly, NBI may be used to improve particle confinement in mirror devices via injection of particles in a direction perpendicular to the axis of the machine, such that the injected particles are located sufficiently far from the loss boundary in velocity space.

3.1 Methodology

The neutral-beam-injection package in the TESS code is used to reproduce the effects of charge exchange and impact ionization of the beam as it passes through the background plasma. The code allows for the use of two separate neutral-beam injectors. For each injector, one must specify the center location Z_{oNBI} and width of the beam ΔZ_{NBI} . The beam intensity varies

over this region as

$$I_{NBI}(z) = \frac{I_{NBI}(Z_{oNBI})}{2} \left[1 + \cos \left(\frac{2\pi(z - Z_{oNBI})}{\Delta Z_{NBI}} \right) \right] \quad (13)$$

where $I_{NBI}(Z_{oNBI})$ is the peak beam intensity. Additionally, the code requires the user to input the mean energy of the beam ϵ_{NBI} , the beam thermal energy spread kT_{NBI} , the angle of injection θ_{NBI} relative to the parallel direction, the neutral beam current $\mathcal{I}$ and the rates of charge exchange R_{CX} and impact ionization R_I . An examination of the time scales in fusion-relevant plasmas indicates that the charge exchange and ionization times are of the order of the collisional relaxation times, which are much longer than other physical times (cyclotron orbit time t_L , mirror bounce time t_b , etc.). For this reason, the rates R_{CX} and R_I are multiplied by a collision rate “acceleration” factor. The method of determining the velocity components of the injected particles is discussed in the following two subsections.

4.2.1.1 The Charge Exchange Model

A charge exchange event occurs when a neutral atom transfers one or more electrons to an adjacent ion. This process results in a change in the kinetic energy of the charged and neutral species, with the charged and neutral particle densities remaining constant. If the initial neutral atoms have kinetic energies which are larger than those of the initial ions, the overall effect is heating of the ions at the expense of the neutral atoms. This is the basis of neutral-beam heating of a plasma.

The charge exchange model that is incorporated into the TESS code is similar to one used previously by Cohen, *et. al.* [7] in a study of the stabilization of ion-cyclotron microinstabilities in electrostatic mirror devices. The region over which charge exchange is to take place is divided up into grid cells. The number of ions in a given cell j which are to undergo charge exchange per time step is determined by

$$N_{CX,j} = \min[N_j R_{CX}, N_{CX,max}] (I_{NBI,j} + I_{NBI,j+1}) / 2 \quad (14)$$

where N_j is the number of ions in grid cell j , $I_{NBI,j}$ is the relative beam intensity for grid cell j in the range $[0, 1]$ and $N_{CX,max}$ is the maximum number of charge exchange processes allowed per time step, which is set by the beam current

$$N_{CX,max} = \frac{\mathcal{I} \Delta t}{q} \quad (15)$$

for a neutral beam current I of ions with charge q . (The model assumes that the injected atoms are accelerated, prior to neutralization, at a charge state that is the same as that of the plasma ions.) The minimum function in (14) ensures that the charge exchange rate will not be larger than that associated with the beam current I . N_{CX} ions will undergo a charge exchange event in grid cell j if $N_{CX} > 1$. If $N_{CX} < 1$, a single charge exchange event will take place only if $N_{CX} \geq R_N$, where R_N is a random number in the range $(0, 1)$. The N_{CX} plasma ions in grid cell j that are to undergo charge exchange are chosen randomly from the list N_j .

The velocity components $v_\perp$ and $v_\parallel$ are modified as a result of the charge exchange event; however, the position of the initial and final ion is the same. The velocity components of the new ion are dependent upon the mean energy ϵ_{NBI} and thermal spread kT_{NBI} of the neutral beam, as well as the angle of injection θ_{NBI} . The thermal spread is assumed to be isotropic and Maxwellian in Cartesian velocity space, such that the spread about the mean velocity of the beam is given by

$$\Delta v = \left[(2\Delta\epsilon_{NBI}/m_n) \ln \left(\frac{1+\delta}{1+\delta-R_N} \right) \right]^{1/2} \quad (16)$$

where $\delta = 10^{-8}$ and R_N is a random number in the range $(0, 1)$ and $m_n = m_i + m_e$ is the mass of the neutral atom. The argument of the logarithm ranges in value from 1 to 10^{-8} , representing the limits on the value of the normalized distribution function $\hat{f}(\Delta v)$. The velocity spread in each direction is given by $\Delta v_x = \Delta v \cos(\theta_1) \sin(\theta_2)$, $\Delta v_y = \Delta v \sin(\theta_1) \cos(\theta_2)$ and $\Delta v_z = \Delta v \cos(\theta_2)$, where θ_1 is randomly chosen from the interval $[0, 2\pi]$ and θ_2 is randomly chosen from $[0, \pi]$. The mean velocity components of the beam are defined as $\langle v_x \rangle = \langle v \rangle \sin(\theta_{NBI}) \cos(\theta_3)$, $\langle v_y \rangle = \langle v \rangle \sin(\theta_{NBI}) \sin(\theta_3)$ and $\langle v_z \rangle = \langle v \rangle \cos(\theta_{NBI})$ where the average beam velocity is

$$\langle v \rangle = \sqrt{2\epsilon_{NBI}/m_n} \quad (17)$$

and θ_3 is randomly chosen from $[0, 2\pi]$. The model also assumes that particles are injected in the positive and negative $\parallel$ or z direction in equal numbers. Therefore, the resultant injected particle velocity components are $v_x = \langle v_x \rangle + \Delta v_x$, $v_y = \langle v_y \rangle + \Delta v_y$ and $v_\parallel = v_z = \pm(\langle v_z \rangle + \Delta v_z)$. Finally, note that $v_\perp = \sqrt{v_x^2 + v_y^2}$. These velocity components are then used to calculate the relativistic factor γ , the parallel momentum p_z and magnetic moment μ for the ion.

4.2.1.2 The Impact Ionization Model

Neutral atoms may also be ionized via collisions with the charged particles of the plasma.

If the charged particles strike the atoms with sufficient force, one or more electrons will be stripped from the neutral atom. For atoms which are isotopically identical to the plasma ions, this process results in an increase in the plasma electron and ion density. When an energetic neutral beam is injected into the plasma, the overall effect is an increase in both the temperature and density of the plasma.

The impact ionization model is based upon the charge exchange algorithm which is described in the previous paragraphs. The number of electron-ion pairs that are to be injected into a given cell j per time step is

$$N_{I_j} = \min [N_j R_I, N_{I_{\max}}] (I_{NB I_j} + I_{NB I_{j+1}}) / 2 \quad (18)$$

with $N_{I_{\max}}$ the maximum number of particle pairs injected into grid cell j by a neutral beam of current I

$$N_{I_{\max}} = \frac{I \Delta t R_I}{q R_{CX}}. \quad (19)$$

For the case $N_{I_{\max}} < 1$, the method employed in the charge exchange model is also used here.

The electron-ion pairs are injected at the same position, which is chosen randomly in the grid cell. The velocity components of the neutral atom are calculated in the same manner as those of the new ion in the charge exchange model. A major assumption of this model is that the velocity components of the injected electron and ion are the same as those of the injected neutral atom. This means that there will be no electrostatic source sheath created as a result of the injection of the electron-ion pairs, since $v_{||e} = v_{||i}$ (i. e. no separation of the injected charge). The injected particle velocity components are used to calculate the relativistic factor γ , the parallel momentum p_z and magnetic moment μ , which are then written into the permanent particle arrays. If the number of particles injected per time step exceeds the free space at the end of the permanent particle arrays, the arrays are dynamically expanded by the input variable N_{expand} . In order to reduce the amount of time spent expanding the arrays, N_{expand} is chosen such that there are of order 100 time steps between successive array expansions.

3.2 Simulation Results

The characteristics of the charge exchange and impact ionization models are demonstrated via the simulation of a neutral-beam-heated simple mirror plasma. The neutral beam is injected

perpendicular to the magnetic field at the bottom of the magnetic well. The high energy ($\epsilon_{NBI} = 1\text{keV}$), warm ($kT_{NBI} = 250\text{eV}$) neutral beam impinges upon a low temperature plasma ($kT_e = kT_i = 50\text{eV}$) of mass ratio $m_i/m_e = 100$. The other input data values for the run are $Z_{oNBI} = 180\text{cm}$, $\Delta Z_{NBI} = 100\text{cm}$, $\theta_{NBI} = 90^\circ$, $I = 0.225$ Statcoulombs/sec, $R_{CX} = 0.020$ and $R_I = 0.007$. The ratio R_{CX}/R_I is chosen to be the ratio of the charge exchange to impact ionization cross-sections, which are a function of the beam energy, plasma temperature and mass of the injected atom [8].

Since the ionization model assumes that the injected electrons and ions have the same velocity components, the injected electron kinetic energy is approximately m_e/m_i times that of the ion. For large mass ratios, the ion kinetic energy is effectively the beam energy. In addition, the charge exchange process leads only to an increase in the ion kinetic energy. Therefore, one expects to see substantial heating of the ions and only minimal heating of the electrons.

The kinetic energy profiles for the ions and electrons are shown in Figure 3. The dashed and solid lines represent the perpendicular and parallel kinetic energy profiles respectively. (The dash-dotted line is the profile of the magnetic field intensity.) Note that for each of the species, the kinetic energy components are minimized near the peaks in the magnetic field intensity, resulting from the decreased particle densities in these regions. Figure 3a shows that the ions are the principal recipients of the injected energy, with a peak perpendicular kinetic energy of $\epsilon_{\perp,i,max} \simeq 1\text{keV}$ and a peak parallel kinetic energy of $\epsilon_{\parallel,i,max} \simeq 100\text{eV}$. The fact that the neutral beam was injected perpendicular to the magnetic field lines accounts for the large ratio of the perpendicular to parallel kinetic energies. The peak perpendicular and parallel electron kinetic energies (Figure 3b) are $\epsilon_{\perp,e,max} \simeq 50\text{eV}$ and $\epsilon_{\parallel,e,max} \simeq 25\text{eV}$ respectively. (Note that the kinetic energy of a species is one-half the species temperature.) The effect of neutral-beam injection on the electrons has been a doubling of the perpendicular kinetic energy, with almost no increase in the parallel kinetic energy. These results are consistent with the expectations of the previous paragraph. The ion perpendicular kinetic energy profile (Figure 3a) shows the effect of the spatial variation of the beam intensity on the heating of the particles. The peak intensity of the beam lies at $z = 180\text{cm}$.

The species perpendicular-velocity phase space scatter plots are shown in Figure 4. Again we note that the ions are heated to a much larger degree than are the electrons. Figure 4a indicates that the injected ions have peak perpendicular velocities of $v_{\perp,i,max} \simeq 11v_{th,i}$. (The

a) Ion kinetic energy profiles.

b) Electron kinetic energy profiles.

Figure 3: Profiles of the (a) ion and (b) electron perpendicular and parallel kinetic energy profiles for the case of a neutral beam heated simple mirror plasma. The beam is injected perpendicular to the magnetic field lines at the bottom of the magnetic well.

solid horizontal lines represent the species thermal velocity). The injected electrons have peak perpendicular velocities that are only $\simeq 10\%$ larger than those in the background Maxwellian distribution.

Finally, the species velocity-space plots for the spatial region between the two magnetic field peaks are presented in Figure 5. Figure 5a clearly shows the injected ions (with large values of $v_{\perp}$) and the background Maxwellian ions. Note the large population of injected ions that lie above the background population, with $v_{\perp} \gtrsim 1.25 \times 10^8$ cm/sec. The wide range of $v_{\parallel}$ -space that they occupy is due to the fact that the injected ions have finite values of $v_{\parallel}$, hence they bounce in the magnetic well. The electron velocity-space plot (Figure 5b) shows only a small deviation from a Maxwellian as a result of the neutral beam injection.

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a) Ion perpendicular-velocity phase space.

b) Electron perpendicular-velocity phase space.

Figure 4: Perpendicular-velocity phase space scatter plots of the (a) ions and (b) electrons for the case of a neutral beam heated simple mirror plasma. The beam is injected perpendicular to the magnetic field lines at the bottom of the magnetic well.

a) Ion $v_{\parallel}, v_{\perp}$ velocity space.

b) Electron $v_{\parallel}, v_{\perp}$ velocity space.

Figure 5: Velocity space plots of the (a) ions and (b) electrons for the case of a neutral beam heated simple mirror plasma. The beam is injected perpendicular to the magnetic field lines at the bottom of the magnetic well.