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Calculation of Neutral Beam Injection Into SSPX*

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The SSPX spheromak experiment has achieved electron temperatures of 350eV and confinement consistent with closed magnetic surfaces. In addition, there is evidence that the experiment may be up against an operational beta limit for Ohmic heating. To test this barrier, there are firm plans to add two 0.9MW Neutral Beam (NB) sources to the experiment. A question is whether the limit is due to instability. Since the deposited Ohmic power in the core is relatively small the additional power from the beams is sufficient to significantly increase the electron temperature. Here we present results of computations that will support this contention. We have developed a new NB module to calculate the orbits of the injected fast-ions. The previous computation made heavy use of tokamak ordering which fails for a tight-aspect-ratio device, where $B_{tor} \sim B_{pol}$.

The model calculates the deposition from the NFREYA package [1]. The neutral from the CX deposition is assumed to be ionized in place, a high-density approximation. The fast ions are then assumed to fill a constant angular momentum orbit. And finally, the fast ions immediately assume the form of a dragged down distribution. Transfer rates are then calculated from this distribution function [2]. The differential times are computed from the orbit times and the particle weights in each flux zone (the sampling bin) are proportional to the time spent in the zone. From this information the flux-surface-averaged profiles are obtained and fed into the appropriate transport equation. This procedure is clearly approximate, but accurate enough to help guide experiments. A major advantage is speed: 5000 particles can be processed in under 4s on our fastest LINUX box. This speed adds flexibility by enabling a “large” number of predictive studies. Similar approximations, without the accurate orbit calculation presented here, had some success comparing with experiment and TRANSP [3]. Since our procedure does not have multiple CX and relies on disparate time scales, more detailed understanding requires a “complete” NB package such as the NUBEAM [4] module, which follows injected fast ions along with their generations until they enter the main thermal distribution.

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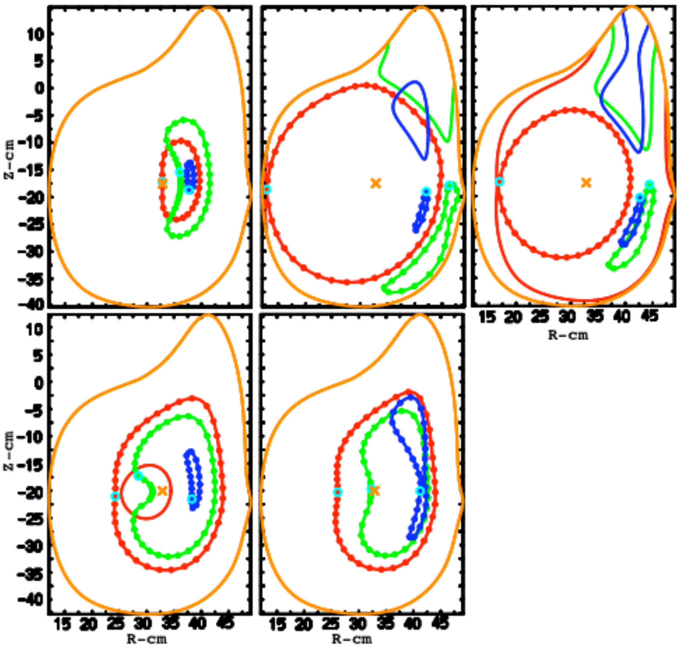
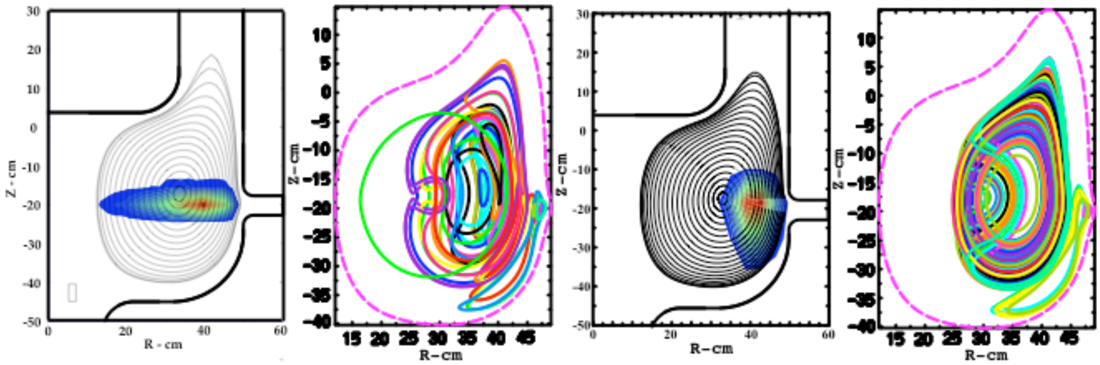
To compute the orbits we use a rectangular grid in (ψ,θ), the flux coordinates. An injected particle is born inside of a box in this space and exits through a side. We only consider boxes with two crossings for a given angular momentum. At the extrema of the orbits, there might be four crossings; these are clearly ignored. The coordinates of all crossings back to the birth box are stored. To determine the crossings we use $(\psi-\psi_{angM})^2-(v_{||}\ Fmc/e\mathbf{B})^2 = 0$ rather than the angular momentum since it is well defined for $v_{||}^2 < 0$. Here $v_{||}^2 = 2(E-\mu\mathbf{B})/m$; in this drift approximation μ is a constant of the motion. Note that this form has spurious solutions but by following from box to box they are avoided. Differential times are then computed from either $d\psi/\dot{\psi}$ or $d\theta/\dot{\theta}$. The cumulative time in a "flux zone" determines the relative weights. Where $d\psi\sim0$ and $\dot{\psi}\sim0$, we use $d\theta/\dot{\theta}$ and conversely. In tight-aspect-ratio configurations such as spheromaks and spherical tokamaks the orbits can be rather exotic, since $B_{pol}\sim B_{tor.}$. To the left we show typical fast-ion orbits (25 KeV normal injection) for SSPX. The red curves show a passing orbit, the green curves show a trapped orbit and the blue curves show a "potato" orbit.

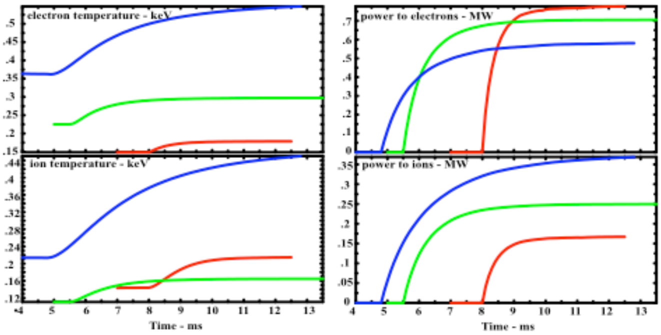


Next shown are the beam coverage for normal and tangential injection. The dashed curve shows the plasma boundary. Directly below we show the deposition and sample orbits footprints for normal and tangential injection. The performance of

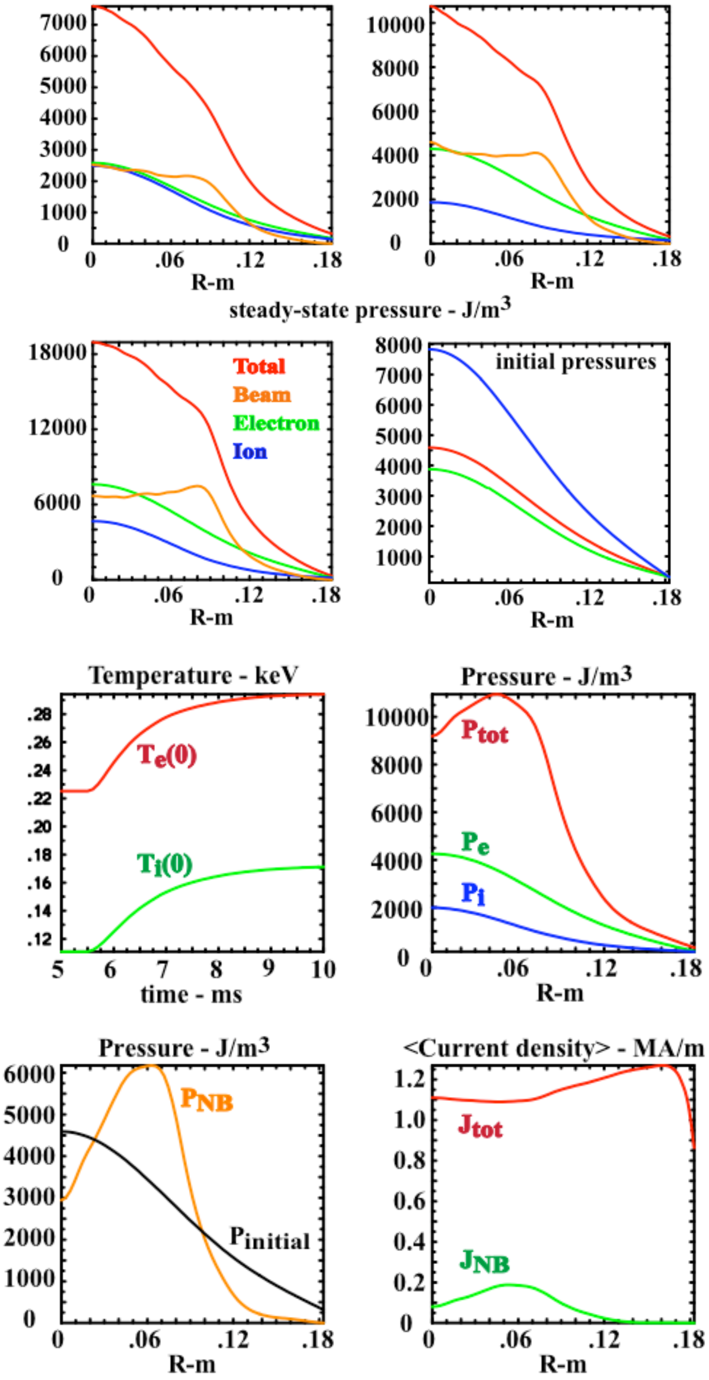


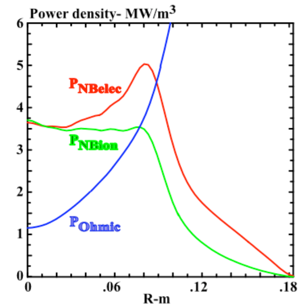
neutral beam injection is determined for three equilibrium targets; on-axis T_e =360ev, T_e =225ev and T_e =150ev. The target equilibria are determined from CORSICA [5] reconstructions constrained by probe magnetic data and λ_{gun}. The electron χ_e is determined from power balance for each shot. There is no experimental information about T_i and χ_i. For the present, χ_i is chosen to keep $T_e \sim T_i$. Similarly, Ohm's law is not evolved; rather, the q-profile from the reconstruction and the toroidal current are held fixed. Otherwise in the fixed boundary analysis used, the q-profile would rapidly depart from its reconstructed value. To properly model core flux diffusion requires a free-boundary analysis with current on the open field lines and hyper-resistivity to fix the value of $\lambda=\mu_0 J_{||}/\mathbf{B}$ at the spheromak edge to its reconstructed value. Such analyses have been used to model time dependent experimental runs producing q-profiles in good agreement with the reconstructed values [6].

Next, selected results are shown for 1.5 MW of injected power. First we consider evolution of the on-axis temperature and power deposition. We see that provided the good-target duration is of order several ms there can be significant heating. Specifically, as we show in the time evolution plots, the two higher starting electron temperatures show an increase of order 30 to 50%. At the lowest starting temperature the increase is minimal. Perhaps more important is the increase in plasma pressure due to both the temperature rise and the substantial beam pressure. In the next figure we show profile plots of the total and component pressures at steady state along with the profiles of the initial total pressures. Also shown are profiles of the power density deposition from the NB's as well as the Ohmic power density deposition. We see that in the plasma core the beam deposition dominates.In the SSPX experiment it is found that in the high temperature discharges (T_e >200ev) the q-profile avoids the n=2, m=2 and n=3, m=2 resonance in the core. This q-profile information comes from CORSICA reconstruction of the equilibrium. With tangential injection the NB current density is of order 20% of the total, thus opening the possibility of modifying the q-profile. The figure below shows this and selected results from tangential injection.



The impact of NB injection is summarized with the following statements. The NB power in the core exceeds the Ohmic power. The beam is capable of providing a significant increase in the electron temperature if the target duration is of order 2ms. With the increased pressure, the experiment can test the operational beta limit so far observed. Tangential injection suggests that significant current drive is possible. And finally, an important question is whether the observed magnetic fluctuations will induce fast ion losses that seriously degrade the beam deposition rate.





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