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23. Modeling of Neutral Beam Ion Loss from CHS Plasmas

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Abstract

Beam ion loss measurements from Compact Helical System (CHS) plasmas under a variety of conditions show a strong loss of ions in the range of pitch angles corresponding to transition orbits at the probe location. A numerical model has been developed which includes the beam ion orbits, and details of the detector, plasma, vessel, and neutral beam geometry. From this, the expected classical (i.e. collisionless single particle orbit) signal at the detector can be computed. Preliminary comparisons between the experimental data and model predictions indicate that the classical behavior of the orbits and the machine geometry are insufficient to explain the observations.

Introduction

CHS [1] is a low aspect ratio helical plasma device. Low aspect ratio is desirable for a fusion plasma device since it requires less material structure to contain a fixed volume of plasma than does a high aspect ratio device, lowering the eventual cost of a reactor. However, the combination of low aspect ratio and helical magnetic field structure tends to produce a large magnetic field ripple that can result in fast ion losses. These losses, especially sizable ones, would be quite detrimental for a reactor. The aim of this work is to compare observed neutral beam ion losses from CHS plasmas with a collisionless prompt loss model to see if that model is adequate to explain the observations.

Experimental details

CHS is an l=8 heliotron/torsatron with a maximum magnetic field on axis of up to 2.0 T. The density can be varied between 0.5 and $5\infty10^{19}$ m^{-3}. Typical electron temperatures are between 300 and 1000 eV. Standard CHS plasmas have major radii at the magnetic axis of 0.88 m to ~1.00 m. The CHS plasmas studied in this work all have ~700 kW of 36 keV hydrogen co-oriented neutral beam injection. For CHS, the co-going beam ions circulate clockwise as seen from above.

A scintillator-based fast ion loss probe, described elsewhere [2], was used to measure the local beam ion loss rate and lost particle characteristics at a single location for a variety of plasma conditions. The probe is located at R=1.20 m, z=+0.12 m, with its aperture oriented 45° from the radial direction so as to accept co-going ions. Fast ions with pitch angles between 40° and 80° and gyroradii between 1.5 and 8.0 cm can be detected by the probe, where the pitch angle is given by $\chi=\arccos(v_{\parallel}/v)$.

Out of the many measurements made during plasma parameter scans, two results are excerpted here for comparison with a numerical model. Figure 1 displays the total measured loss rate of beam ions to the probe when the magnetic axis position of the plasma was varied. The measured loss increases approximately exponentially as the plasma moves outward. Figure 2 displays the loss rate versus pitch angle for a plasma with B_0=0.9 T, R_{axis}=0.949 m, and n_{e0}=2∞10^{19} m^{-3}. This loss has been integrated over all gyroradii, and shows a peak centered at a pitch angle of 50°.

Numerical model of beam ion loss

In an effort to understand the physics which results in the loss of neutral beam ions from CHS, we have followed beam ion orbits using a numerical model that incorporates the vacuum magnetic field, the 3-D shape of the vacuum vessel interior, the probe position, and the source of beam ions. The orbit-following portion of the code simply integrates the Lorentz force law, assuming that the electric field is negligible, and is essentially the same as the code described in Ref. [3]. An ion with energy equal to the beam injection energy is started with a certain pitch angle at the probe location and its orbit is followed backwards in time. The integration of the orbit proceeds in steps small compared to the gyroradius. Each orbit is followed backward in time until it either intersects the vessel wall or a maximum orbit length is reached (typically 300 m). At each step of an orbit, the local source strength of beam ions is computed and then summed over all steps in the orbit. That source strength is computed as the product of the beam ionization rate at the ion's location and a factor quantifying the degree of alignment between the ion's velocity vector and the direction of motion of beam ions ionized at that point. More specifically, that alignment term is $\exp(-\theta_{ba}^2/\theta_{b0}^2)$, where θ_{ba} is the angle between the ion's velocity vector and the beam injection direction and θ_{b0} is the divergence angle of the CHS beam line (~1.2°). The beam ionization rate as a function of location is given by a polynomial fit to a deposition profile computed by the H-FREYA code.[4] The code normalizes the summed source strength along one orbit to the volume integral of the local beam ionization rate and to the probe aperture size and acceptance angles to give an absolute efficiency for that orbit, which is the fraction of the total beam ion current which should reach the detector at that pitch angle. By making an efficiency calculation for each pitch angle that can reach the detector, a profile of loss versus pitch angle can be computed. The code also allows that efficiency to be summed over pitch angle to give the total signal expected in the probe. This total efficiency can then be plotted as a function of plasma parameters.

Figure 1 shows the total beam ion loss to the probe as R_{axis} is scanned. In addition to the experimental measurements, the efficiencies from the numerical model are also plotted. Both sets of data have the same trend with increasing R_{axis} and are fit reasonably by an exponential function. The experimental data, which are not absolutely calibrated, have been normalized to lie on the same scale as the computed efficiency. For this data, the model matches the variation of the loss rate with R_{axis}.

The model has also been run for a plasma with B_0=0.9 T, R_{axis}=0.949 m, and n_{e0}=2∞10^{19} m^{-3}. A plot of the orbit steps which contribute significantly to the total source integral shows that the strongest contribution to the signal at pitch angles of interest arises from areas near the point where the beam enters and leaves the plasma, especially where R>1.3 m. The same inference was previously drawn by Isobe.[5]

Figure 2 displays the experimentally-measured loss as a function of pitch angle for this case, with an arbitrary overall normalization applied. In addition, efficiencies of single orbits are plotted as individual points for a fine scan in pitch angle. These calculated efficiencies vary widely for small changes in initial pitch angle because this range of orbits is of a transitional character: small changes in the mod-B encountered can make the difference between such particles continuing to travel as passing particles or being magnetically mirrored. In the latter case, the orbit always intersects the wall, thus limiting the integral of the beam ion source function along the orbit. A moving average of these individual efficiencies is also plotted in Fig. 2, for comparison with the experimental measurement. Note that, for this averaged data, the peak loss is predicted to occur at a pitch angle of ~42°, markedly different from the peaking at 50° seen in the experimental data.

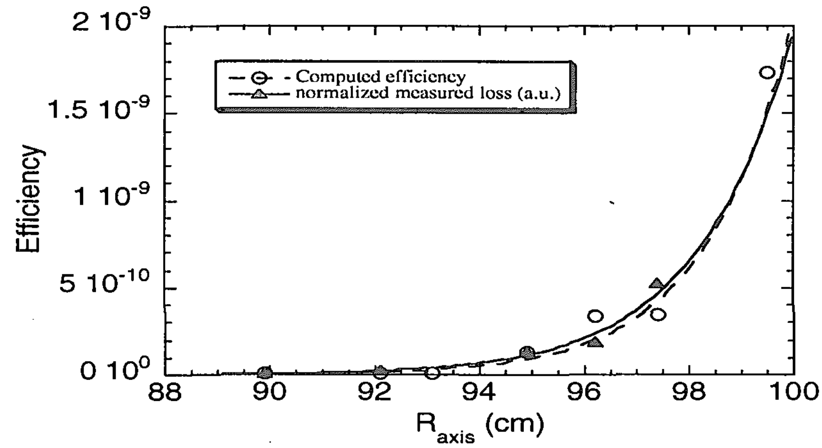

Figure 1: *The measured loss rate (arbitrary normalization) and the computed detector efficiency as a function of plasma axis position, with exponential curves fitted to each.*

Discussion

The model correctly reproduces the experimental variation of the loss rate with R_{axis}. However, the computed loss versus pitch angle differs distinctly from the experimental result. We hypothesize that the variation of the loss rate with axis position is governed predominantly by the relative positions of the plasma, vessel wall, and probe, and is somewhat insensitive to the exact source function of the lost beam ions. That would allow the model to match the scaling seen in the axis position scan (Fig. 1), but not match the results shown in Fig. 2

Since the model incorporates the physics relevant to prompt orbit loss of beam ions, but does not reproduce the measured loss as a function of pitch angle, we conclude that the loss of beam ions from CHS plasmas does not arise exclusively from prompt loss. Some additional mechanism must be invoked to produce the pitch angle profile seen. Candidate mechanisms that could affect the profile include: collisional pitch angle scattering, the radial electric field, low-level MHD activity, and error fields. It was previously observed in CHS that electron cyclotron heating, which causes significant changes in the radial electric field, caused a doubling of the loss rate. So, this would seem to be a strong candidate for further investigation. Collisional pitch angle scattering has been seen to cause sizable changes in the beam ion loss from the W7-AS stellarator[6], which suggests that the effect of collisions on the beam ion distribution should also be accounted for in the calculation of the loss. That some sort of diffusive or scattering process is at work is also suggested by the strength of the measured signal at a pitch angle of 50°. This is the bounding pitch angle between trapped or mirrored orbits and passing (and transition) orbits. Enhanced loss at this boundary pitch angle could arise from pitch angle diffusion of the beam ions, akin to observations of MHD-induced loss of fusion products at the trapped/passing boundary pitch angle in TFTR.[7]

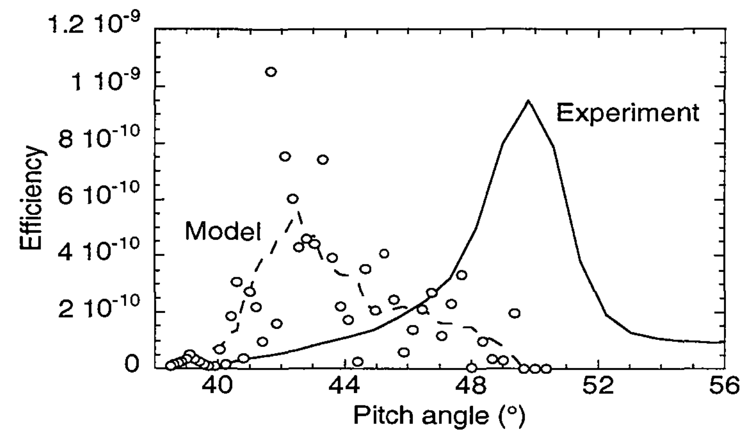

Figure 2 : *Measured loss (arbitrary normalization) and model orbit efficiency as a function of pitch angle for B=0.9 T, R_{axis}=0.949 m. The circles are individual orbit efficiencies and the dashed line is the running average of them.*

Conclusion

A prompt orbit loss model which includes a realistic beam ion source function does not reproduce the measured pitch angle distribution of lost beam ions in CHS. Additional mechanisms, such as collisional pitch angle scattering, the radial electric field, low-level MHD activity, and error fields must also play a significant role in the loss.

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References

[1] K. Nishimura, *et al., Fusion Tech.* **17**, 86 (1990).
[2] D. S. Darrow, *et al., J. Plasma Fusion Res. SERIES* **1**, 362 (1998).
[3] J. Felt, *et al., Rev. Sci. Instrum.* **61**, 3262 (1990).
[4] s. Murakami, *Trans. Fusion Technology* **27**, 256 (1995)
[5] M. Isobe, *et al., Rev. Sci. Instrum.* **70**, 827-830 (1999).
[6] A. Werner, *et al.,* these proceedings.
[7] S. Zweben, *et al., Nucl. Fusion* **35**, 893 (1995).