The importance of the non thermal distribution effects in the evaluation of the RF wave-field and the ion distribution functions in tokamak plasmas

N. Bertelli[1], E. J. Valeo[1], J. P. Lee[2], P. T. Bonoli[2],
M. Gorelenkova[1], D. L. Green[3], E. F. Jaeger[4], C. K. Phillips[1], J. C. Wright[2]
[1] *Princeton Plasma Physics Laboratory, Princeton, NJ 08543, USA*
[2] *Plasma Science and Fusion Center, MIT, Cambridge, MA 02139, USA*
[3] *Oak Ridge National Laboratory, PO Box 2008, Oak Ridge, TN 37831-6169, USA*
[4] *XCEL Engineering Inc., 1066 Commerce Park Drive, Oak Ridge, TN 37830, USA*

Fast wave (FW) heating in the ion cyclotron range of frequency (ICRF) has been successfully used to sustain and control the fusion plasma performance, and it will likely play an important role in the ITER experiment. This paper examines the interaction of FW with both the minority ion population and fast-ion / neutral beam populations by using the recent extension of `TORIC v.5` [1, 2, 3] (code's version implemented in `TRANSP` [4]), which includes non thermal distribution functions for ion species. Similar progress has been done with different RF numerical tools [[5], [6], [7], [8], [9], [10] and references within].

Minority heating regime

In figure 1 we show the contour plots of the fundamental absorption by minority hydrogen (H) in an Alcator C-Mod plasma ($T_{e,0} = 2.8$ keV , $n_{e,0} = 1.8 \times 10^{14}$ m^{-3}, $T_{H,0} = 2.2$ keV, and H concentration = 4%) assuming a bi-Maxwellian distribution for H minority given by

$$f_H(v_\parallel, v_\perp) = (2\pi)^{-3/2}(v_{th,\parallel} v_{th,\perp}^2)^{-1} \exp[-(v_\parallel/v_{th,\parallel})^2 - (v_\perp/v_{th,\perp})^2] \quad (1)$$

where $v_{th,\parallel} = \sqrt{2C_\parallel T(\psi)/m_H}$, $v_{th,\perp} = \sqrt{2C_\perp T(\psi)/m_H}$, with constants $C_\parallel$ and $C_\perp$. In particular, a parameter scan in $C_\parallel$ and $C_\perp$ has been performed with the aim of understanding the impact of the non-Maxwellian effects on the wave electric field and absorbed power density of the H minority. Figures 1(a-c) are obtained for $C_\perp = 1$ and $C_\parallel = 0.5, 1.0, 5.0$, respectively. From these figures one can note that for small $C_\parallel$ the absorption is localized to the resonant layer while it is significantly broadened radially with increasing $C_\parallel$ (note that Fig. 1(b) represents the Maxwellian case). In addition, for $C_\perp = 1$ and $C_\parallel = \{0.5, 1.0, 3.0, 5.0\}$ the corresponding total absorbed power by H minority is $P_H = \{61.27\%, 70.50\%, 90.46\%, 94.18\%\}$, namely, the P_H is increasing for large $C_\parallel$. On the other hand, for $C_\parallel = 1$ and $C_\perp = \{0.5, 1.0, 3.0, 5.0\}$ the corresponding total absorbed power by H minority differs by less than 2%. In conclusion, for IC minority heating regime, the total absorbed power at the H fundamental is insensitive to variations in the perpendicular temperature, but varies with changes in parallel temperature.

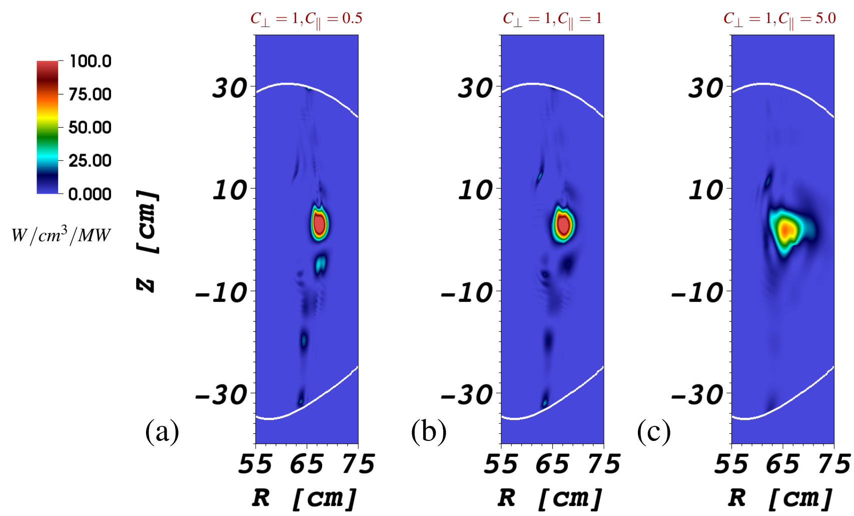

Figure 1: *Contour plots of fundamental absorption by minority hydrogen, represented by a bi-Maxwellian distribution function (see Eq. 1) in an Alcator C-Mod plasma for* $C_\perp = 1.0$ *and different* $C_\parallel$ *values (shown in the plots). The white curve represents the last closed flux surface.*

HHFW heating regime

In NSTX experiment a strong interaction have been observed between the FW and the beam ions [11, 12] therefore it is important to include the effects of non-Maxwellian ions in the RF simulations. A parameter scan in $C_\parallel$ and $C_\perp$ (similarly to the scan done in the ICRF regime) has been performed for a NSTX plasma ($T_{e,0} = 1.1$ keV , $n_{e,0} = 2.5 \times 10^{13}$ m^{-3}, $n_{D-NBI,0} = 2 \times 10^{12}$ m^{-3},) in the high harmonic fast wave heating (HHFW) regime assuming the beam ion species represented by a bi-Maxwellian distribution function as shown in Eq. 1 (note that the beam ion species is deuterium (D)). Unlike the results mentioned above for ICRH regime, we found that the total absorbed power by the beam ions is independent from the variation of the parallel temperature. In fact, for $C_\perp = 1.0$ and $C_\parallel = \{0.5, 1.0, 3.0, 5.0\}$, the corresponding total absorbed power by beam ion species (P_{D-NBI}) is found to vary by less than 1%. However, the power density profile of the beam ions species tends to be localized to the resonant layers for small $C_\parallel$ (see Fig. 2(a)) and broadened for large $C_\parallel$ (see Fig. 2(b) and (c)), as found in ICRF regime. Significant variations of the total absorbed power by the beam ions occurred instead varying the perpendicular temperature. More quantitatively, for $C_\parallel = 1.0$ and $C_\perp = \{0.5, 1.0, 3.0, 5.0\}$, we have $P_{D-NBI} = \{70.06\%, 73.56\%, 62.84\%, 48.48\%\}$. Note that P_{D-NBI} varies not-monotonically with the perpendicular temperature. These simulations indicate that the total absorbed power by the beam ion is very sensitive to variations in the perpendicular temperature, which is an opposite behavior with respect to what we found in the minority heating regime.

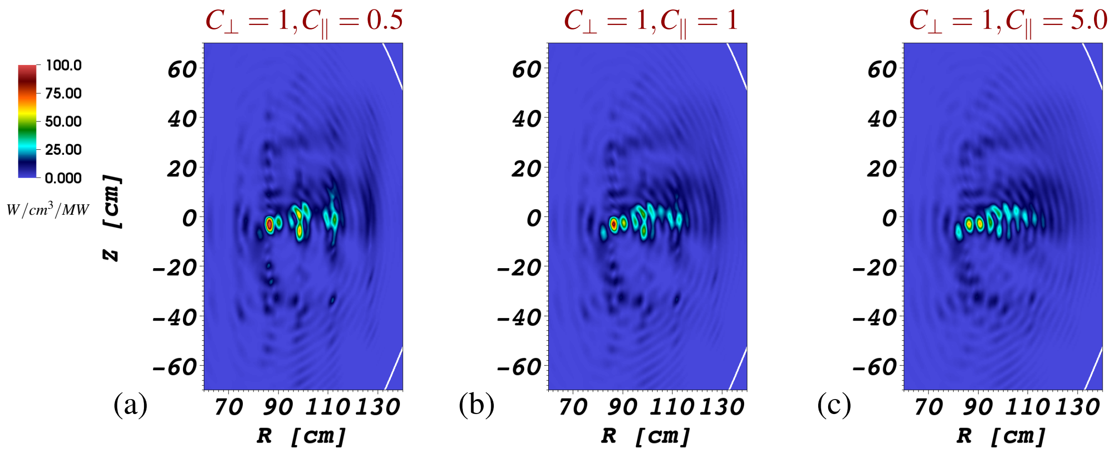

Figure 2: *Contour plots of the absorption by beam ions represented by a bi-Maxwellian distribution function in a NSTX plasma for $C_\perp = 1.0$ and different $C_\parallel$ values (shown in the plots). The white curve represents the last closed flux surface.*

Another functional form of the distribution function for the beam ion species implemented in the recent generalization of `TORIC` v.5 is a slowing-down distribution

$$f_{\mathrm{D-NBI}}(v_\parallel, v_\perp) = \begin{cases} \frac{A}{v_c^3} \frac{1}{1+(v/v_c)^3} & \text{for } v < v_m, \\ 0 & \text{for } v > v_m \end{cases} \tag{2}$$

where $v_m \equiv \sqrt{2E_{\mathrm{D-NBI}}/m_D}$ is the maximum velocity corresponding to the injected energy $E_{\mathrm{D-NBI}}$ of the beam ions. Also, $A = 3/[4\pi \ln(1+\delta^{-3})]$ with $\delta \equiv \frac{v_c}{v_m}$, and $v_c^3 = 3\sqrt{\pi}(m_e/m_D)Z_{\mathrm{eff}} v_{th}^3$ where $Z_{\mathrm{eff}} \equiv \sum_{\mathrm{ions}} \frac{Z_i^2 n_i}{n_e}$. Figure 3 shows the contour plots of the power density of the beam ion species employing Eq. 2 for the NSTX plasma used above for different injected beam ion energy ($E_{\mathrm{D-NBI}} = 30, 60, 90$, and 120 keV) and $Z_{\mathrm{eff}} = 2$. One can note that increasing the injected beam ion energy the absorption profile tends to be broaden and for $E_{\mathrm{D-NBI}} = 30$ keV is still possible to distinguish the resonant layers. In addition, increasing $E_{\mathrm{D-NBI}}$ the total absorbed power of the beam ions varies similarly to the perpendicular temperature scan (i.e., the $C_\perp$ scan) performed for the bi-Maxwellian case. In particular, for $E_{\mathrm{D-NBI}} = 30, 60, 90$, and 120 keV, the corresponding $P_{\mathrm{D-NBI}} = \{77.84\%, 75.85\%, 70.97\%, 64.71\%\}$ showing a not-monotonic behavior as found in the $C_\perp$ scan performed for the bi-Maxwellian case. Finally, a comparison of the components of the wave electric field on the mid-plane for beam ions represented by a slowing-down distribution (solid line - with $E_{\mathrm{D-NBI}} = 90$ keV) and by an equivalent Maxwellian distribution function (dashed line) is shown in figure 4.

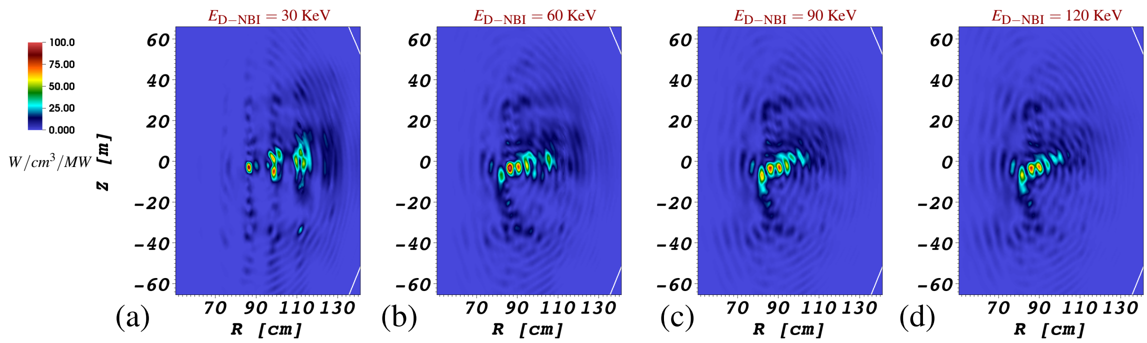

Figure 3: *Contour plots of the absorption by beam ions represented by a slowing down distribution function (see Eq. 2) in a NSTX plasma for different NBI injected energy* E_{D-NBI} *(shown in the plots). The white curve represents the last closed flux surface.*

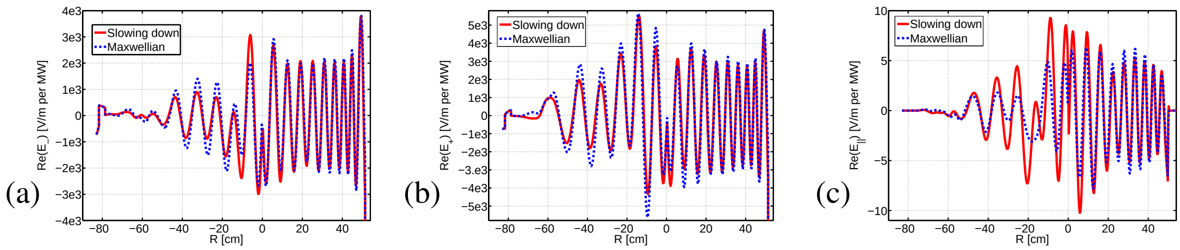

Figure 4: *Real part of the (a) right-handed, (b) left-handed, and (c) parallel wave electric field on the mid-plane as a function of the major radius (with respect to the magnetic axis) for beam ions represented by a slowing-down distribution function for* $E_{D-NBI} = 90$ *KeV and* $Z_{eff} = 2$ *(solid line) and by an equivalent Maxwellian distribution function (dashed line).*

Acknowledgments

This work is supported by U.S. DOE Contract # DE-AC02-09CH11466

References

[1] M. Brambilla , Plasma Phys. Control. Fusion **41**, 1 (1999)
[2] M. Brambilla, Plasma Phys. Control. Fusion **44**, 2423 (2002)
[3] J. C. Wright *et al*, Phys. Plasmas **11**, 2473 (2004)
[4] R. J. Hawryluk Physics Close to Thermonuclear Conditions vol 1 ed B. Coppi et al p 19 (1980)
[5] R. J. Dumont, C. K. Philips, and D. N. Smith, Phys. Plasma, **12** 042508 (2005)
[6] E. F. Jaeger *et al*, Phys. Plasma **13**, 056101 (2006)
[7] S. Murakami *et al*, Nucl. Fusion **46**, S425 (2006)
[8] M. Choi *et al*, Phys. Plasmas **17**, 056102 (2010)
[9] R. Bilato *et al*, Nucl. Fusion **51**, 103034 (2011)
[10] Jucker M. *et al*, Comput. Phys. Commun. **182**, 912 (2011)
[11] E.D. Fredrickson *et al*, Nucl. Fusion **55**, 013012(2015)
[12] N. Bertelli *et al*, AIP Conf. Proc. **1580**, 310 (2014)