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Self-consistent ICRF simulations in fully shaped anisotropic plasmas

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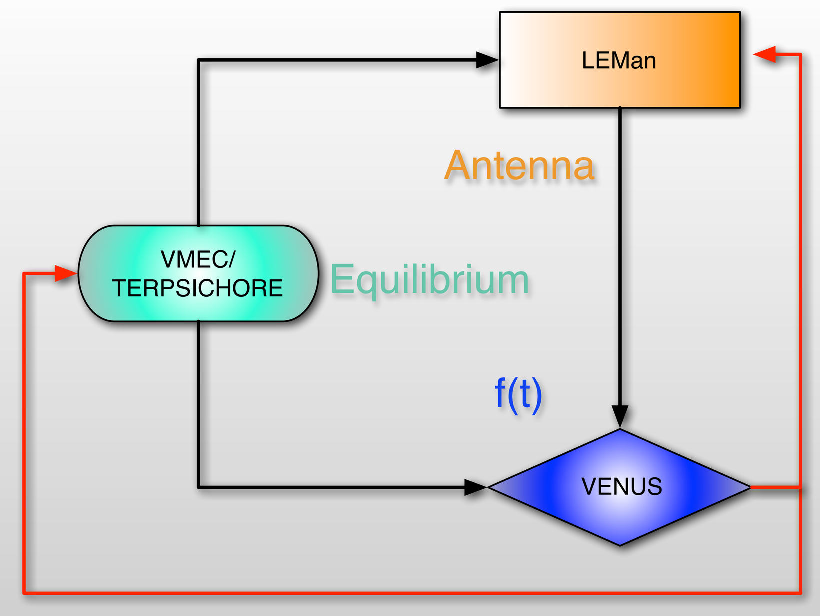
Overview: Self-consistent model of ICRH

For self-consistent ICRF heating simulations, four codes have been coupled: VMEC[1] provides a fully shaped, anisotropic 3D MHD equilibrium (bi-Maxwellian distribution function), transferred to Boozer coordinates by TERPSICHORE[2]. The full-wave code LEMan[3,4] provides the IC wave field, power deposition and wave numbers (new anisotropic dielectric tensor and upshifted k). Finally, VENUS[5,6] computes the evolution of the distribution function due to ICRF heating and Coulomb collisions on the background thermal plasma (using Monte Carlo operators for Coulomb collisions and ICRH).



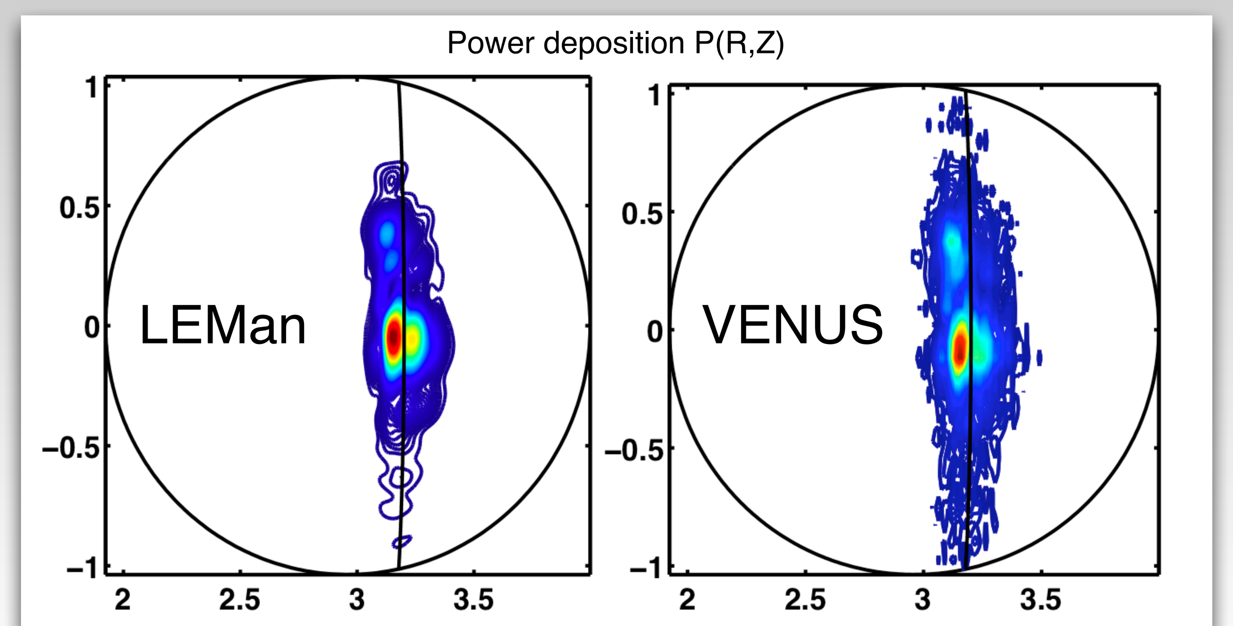
$$F_h(\psi,E,\mu) \sim \exp\left[-\frac{\mu B_c}{T_\perp(\psi)} - \frac{|E-\mu B_c|}{T_\parallel(\psi)}\right]$$

$$\epsilon^h = \epsilon^h\left(\frac{B_c}{B}, \frac{T_\perp}{T_\parallel}, T_\parallel\right), \text{upshifted } k_\parallel$$

$$\Delta^{\mathrm{Coul}}\left(\frac{v_\parallel}{v}, E\right), \quad \Delta^{\mathrm{IC}}(v_\parallel, v_\perp)$$

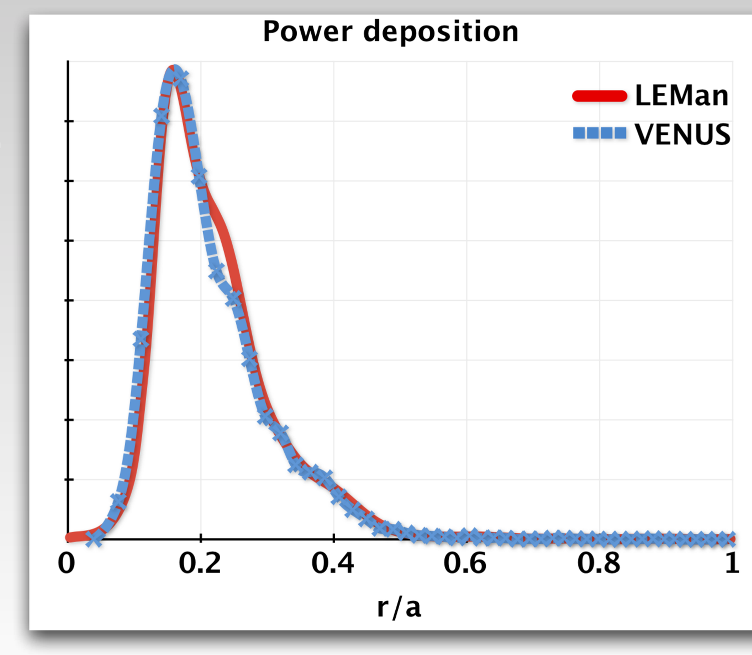
$$p^h_\parallel; p^h_\perp, n^h, \frac{T_\perp}{T_\parallel}, T_\parallel; f$$

Model check



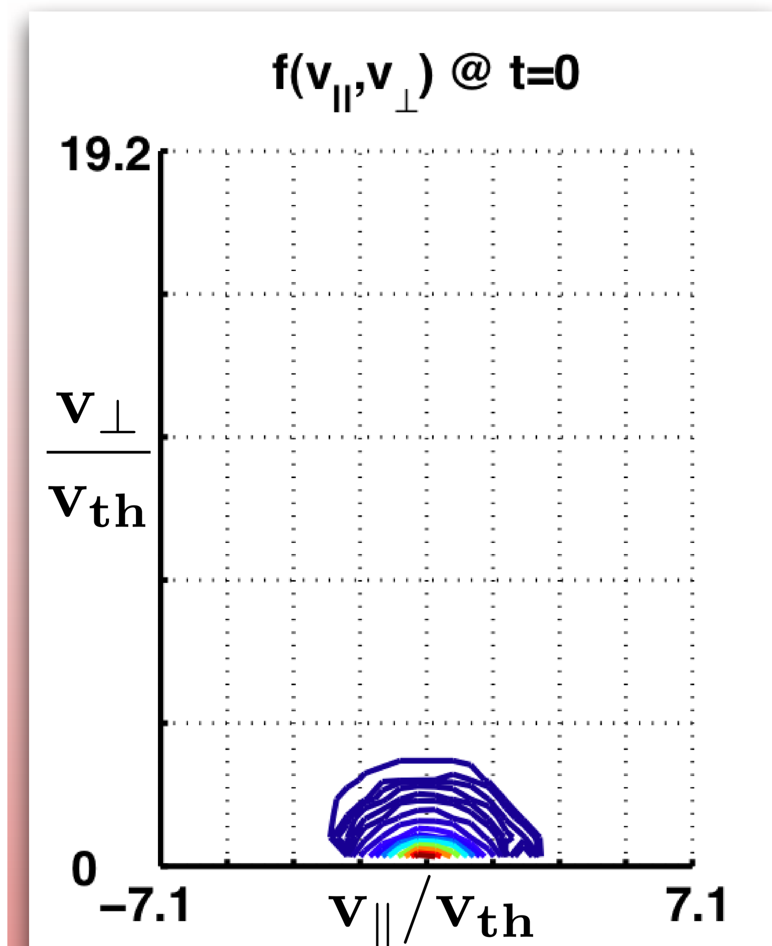
Use a simple, circular equilibrium with flat temperature and density profiles: 1% thermal Hydrogen minority in a Deuterium background. Power deposition in the wave code LEMan and in the PIC code VENUS agree well. In VENUS, power is deposited using Monte Carlo operators in velocity space[7,8]. Benchmark with SELFO[9] is underway.

For ICRH:
$$\omega = \Omega_c + k_\parallel v_\parallel \Longrightarrow \begin{array}{ccc} \Delta v_\perp & \sim & |E_+ J_0 + E_- J_1| \\ \Delta v_\parallel & = & k_\parallel v_\perp \Delta v_\perp / \Omega \end{array}$$

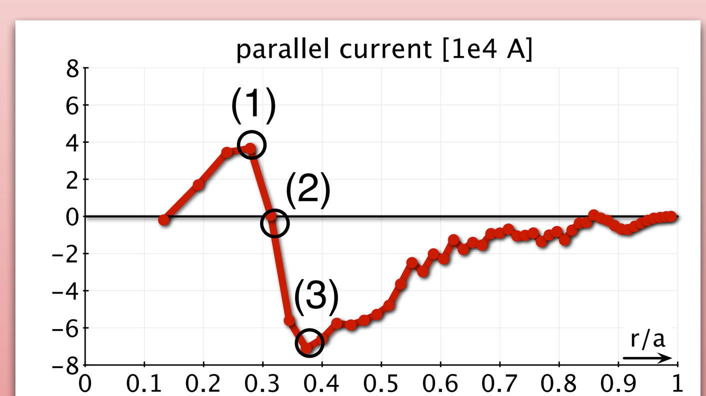


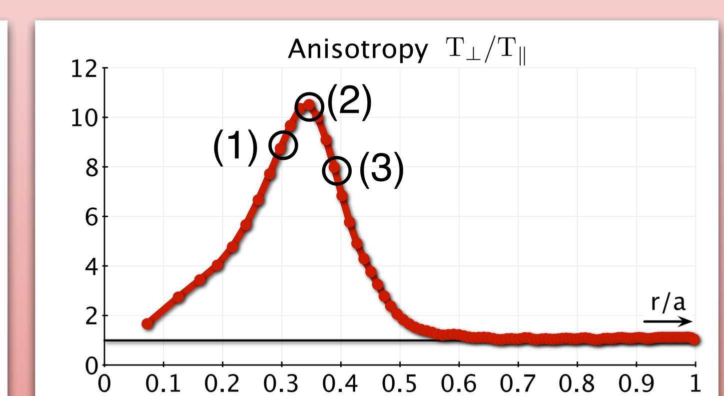
$T^H_\parallel = T^H_\perp = T^D_{th} = T^e_{th} = 5\mathrm{keV}; \; n_e = 4e19\mathrm{m}^{-3}, n_D = 0.99 n_e, n_H = 0.02 n_D; \; R_0 = 3\mathrm{m}, a = 1.04\mathrm{m}; \quad B_0 = 3.45\mathrm{T}, B_c = 3.24\mathrm{T}, \beta = 1.3\%$

Temporal evolution with ICRH

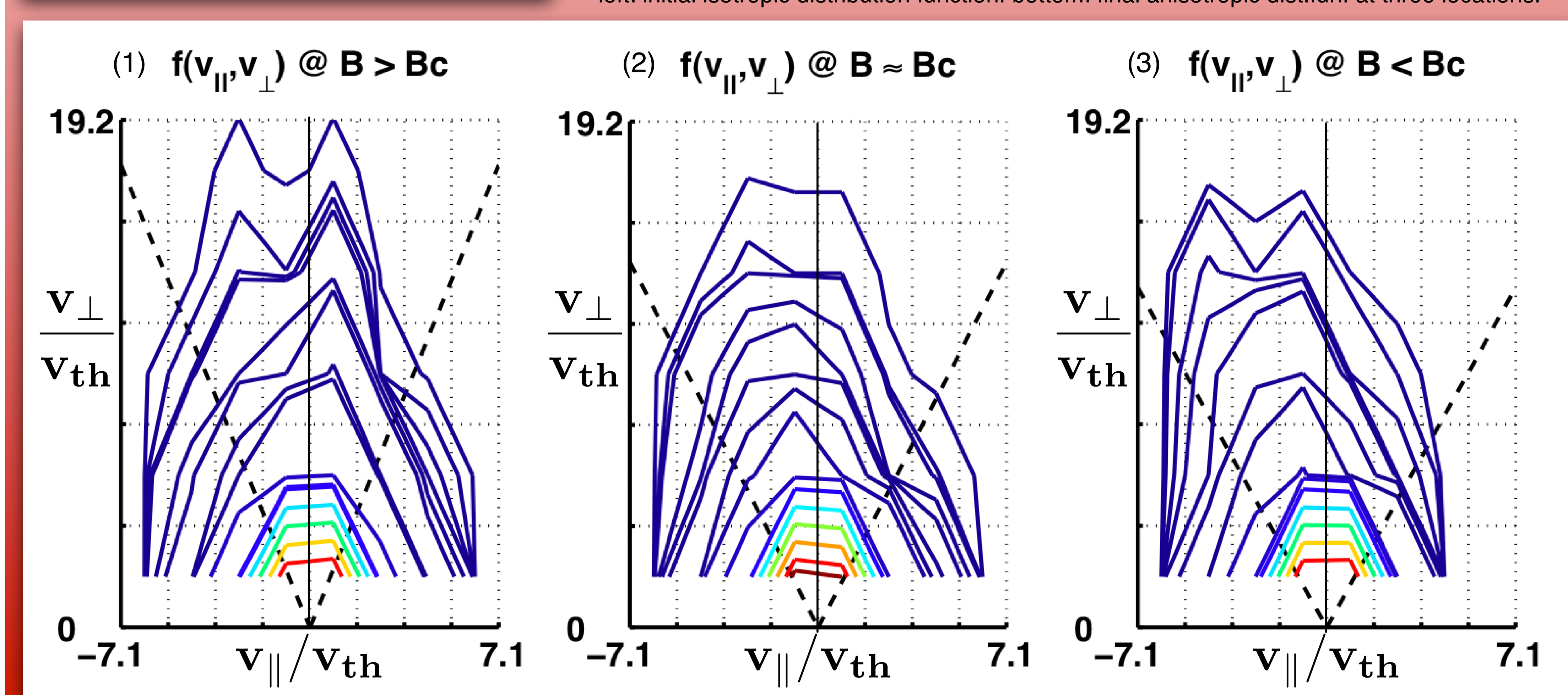


Load initially isotropic Maxwellian (5keV) and let evolve for ~3 slowing down times with 3MW ICRH power. High energy tail and anisotropy develop, including currents (ICCD) changing sign on either side of the resonant layer (defined by B=Bc). The thermal velocity for the normalisations in the plots corresponds to 5keV.



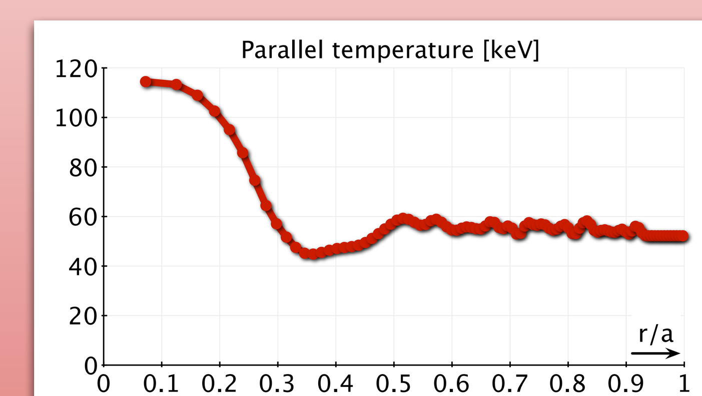


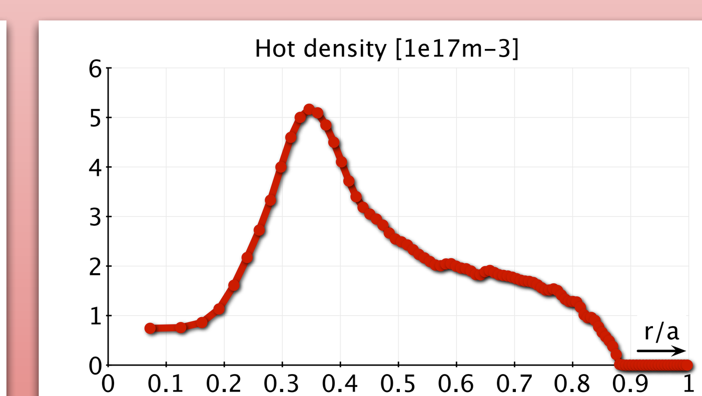
top: final parallel current and anisotropy as functions of r/a. Points (1)-(3) are shown below.
left: initial isotropic distribution function. bottom: final anisotropic dist.fun. at three locations.



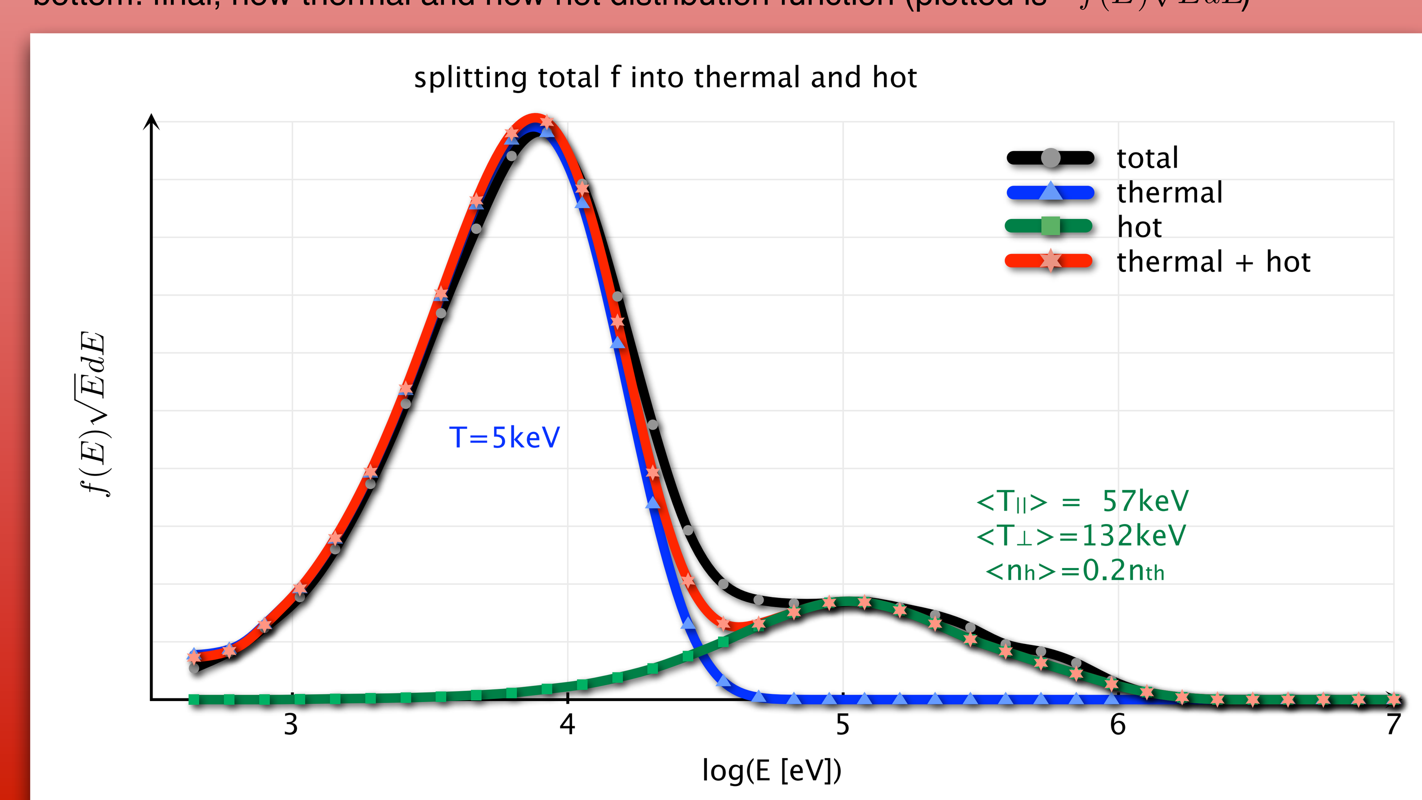
Splitting the distribtion function

After saturation (Coulomb collisions on background cancel ICRH), the distribution function can be split into a thermal and a hot part. Assuming anisotropy coming entirely from the hot population (thermal being isotropic), the average temperatures (parallel and perpendicular) can be found. The hot density is estimated from the integrals over the new thermal and hot distribution functions (here ~20% hot).





top: final parallel temperature and density as functions of r/a after splitting into thermal/hot.
bottom: final, new thermal and new hot distribution function (plotted is $f(E)\sqrt{E}dE$)



CONCLUSIONS

- The coupled numerical model for ICRH in fully shaped 3D plasmas has undergone first testing and shown very good behaviour (e.g. power deposition).
- First benchmark efforts with SELFO (not shown here) are encouraging.
- In a simple geometry (circular, flat profiles), the resulting distribution function is consistent with what we expect.

FUTURE WORK

- Conclude benchmarking with SELFO.
- Test on more complex geometries, where self-consistent iterations of the model are expected to evolve the dielectric tensor and the equilibrium.
- Apply the code to realistic plasmas: Compare e.g. JET shots with simulations. Study the effect of upshift in highly polarized E-field.
- Include 3D effects such as magnetic ripple.

References

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