Topic: IAC-TH

CQL3D-M, A 3D Nonlinear, Bounce-Averaged Fokker-Planck Collision Model Coupled with Neutrals for Magnetic Mirrors, with Fusion Applications

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The CQL3D-M continuum finite-difference bounce-averaged Fokker-Planck code for modeling of magnetic mirror plasmas is an adaption and enhancement of the CQL3D code for tokamaks [Harvey and McCoy, 1992]. The code is run in a fully nonlinear collisional mode with collision coefficients based on the non-thermal distribution functions, giving f(u,theta,rho;t). This is a substantial new application compared to the usual tokamak-type modeling based on calculating the deviation of the electron-ion distribution functions from given radial profiles of Maxwellians. The calculation thereby conserves particles, momentum, and energy. With neutral beam and other sources, the resulting distributions give the time-evolving balance between inputs and the plasma losses to the magnetic loss cone, radiation, and radial transport. The quasilinear RF model for electron and ion diffusion is inherited from the CQL3D code. Confinement is due to the magnetic trapping and a parallel electric field which maintains ambipolar flow of the electrons and ions, preserving charge balance. Radial transport including particle pinch is available in the model, but not yet included here.

Parallel electric field is found by iterative procedure in such a way as to achieve $n_e(z)=n_i(z)$ at every point along magnetic field line. Also, at the last point, a jump condition is imposed to simulate a voltage sheath at the ending plate, this is done to achieve equal ion and electron parallel fluxes. As a result, the procedure provides convergence to the potential drop $e\Phi/T_e$ ~4.5-5.0, as expected.

Fig. 1 gives results of an illustrative DT fusion case for the BEAM [Forest,2023] conceptual mirror. Injected NB power is 5MW D and 5 MW T. From 1(e), near SS is achieved after 1.2 s. Fusion power is 3 MW, for absorbed beam power 7 MW. Further optimizations are anticipated.

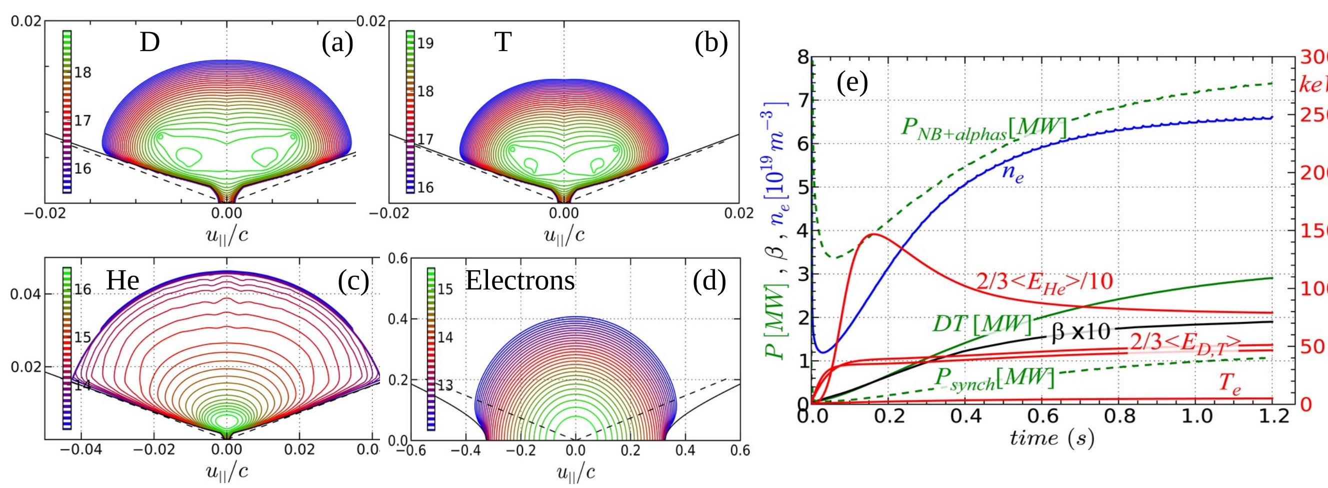

Fig.1. Distribution functions of (a-c) ions and (d) electrons in BEAM machine with injected P_{NBI}=5MW(D) +5MW(T). Shown are solutions of FPE at t =1.2s, z =0, ρ =0.17. Also shown (e) time history of deposited NB power (with added power of alphas), density, average energy of plasma species, DT fusion power (alphas+neutrons), synchrotron emitted power and plasma beta.

In lower temperature experimental plasmas, it can be particularly important to include the effects of neutrals in the modeling. CQL3D-M is being coupled to the FIDASIM Monte Carlo neutrals code [Geiger, 2020]. This provides a fully kinetic model for the neutral beam deposition which includes CX halo neutrals production, and radial transport of energy, particles, and momentum internally in the plasma region and to the chamber wall. Gas puffing sources and recycling from the chamber wall have thus far also been included in the modeling. The overall aim of the numerical project is to kinetically model all the particles in the chamber, ionized and neutral species, in an energy, particle, and momentum conserving mode.

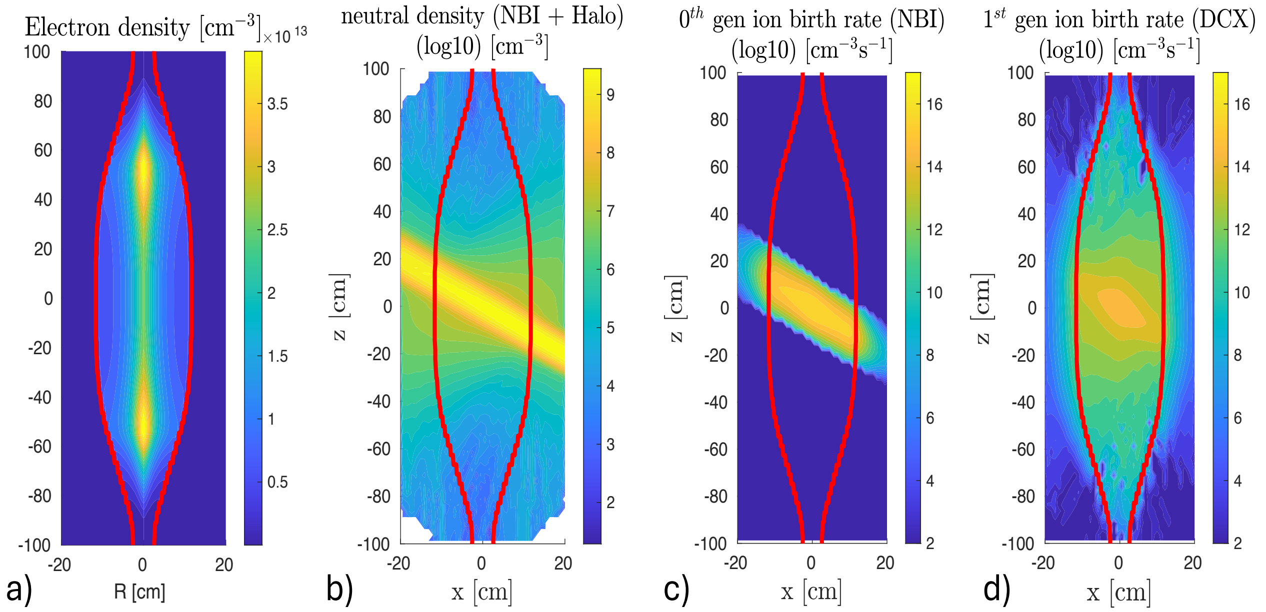

Fig. 2. WHAM simulation with NB power at 45 deg. (a) Resulting electron density, (b) neutral density of beam including halo particles, (c) primary ion birth rate from beam, (d) ion rate from halos.

CQL3D-M has been employed in the design of the WHAM Wisconsin High Temperature Superconducting Mirror experiment [Endrizzi, 2023], the BEAM next generation mirror [Forest, 2024], and as part of an integrated mirror modeling suite [Frank, 2024]. The distribution functions from neutral beam injection have been taken as a starting point of DCLC analysis with a PIC code [Tran2025].

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