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Simulation of Equilibrium, Stability, and Transport in Advanced FRCs

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The Advanced FRC is a Field Reversed Configuration maintained by neutral beam (NB) injection and electrode biasing (EB), with scrape-off-layer (SOL) pumping and electron heat confinement provided by expander divertors. This alternate magnetic confinement system has been developed at TAE Technologies, Inc in the C-2 [1,2], C-2U [3,4], and C-2W [5] series of devices. In this paper we summarize the recent developments in the simulation of equilibrium, stability, and transport of this configuration. For illustration, the C-2W Advanced FRC configuration [5] is sketched in Figure 1.

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As indicated in the figure, the plasma is confined in a region which includes a true magnetic null at the O-point and at the two X-points. The magnetic field reversal and closed magnetic geometry is provided largely by diamagnetic current, which peaks around the separatrix. The ion orbits are comparable in size to the FRC and many are betatron orbits rather than drift orbits. About half of the plasma lies inside the separatrix, and about half is in the SOL. The SOL is collisionless and exploits a combination of magnetic and electrostatic confinement.

Equilibrium of the FRC is studied with several models including one which allows multiple ion species with strong toroidal ion rotation [6]. This has recently been coupled to a fast ion Monte Carlo code which models the NB injected fast ions, to create a hybrid fluid/kinetic equilibrium model which can accommodate a significant (> 50%) anisotropic fast ion pressure component. It is found that the separatrix shape is influenced by a combination of external magnetic field shaping, the ratio of edge pressure to O-point pressure, and the degree of anisotropy of the energetic ion population.

Global stability of the FRC is studied using the FPIC and HYM [7] hybrid PIC codes. These codes agree on the well-known kinetic stabilization of the internal MHD tilt mode of the FRC. It has previously been shown with HYM that NB injection into FRC plasmas can have a stabilizing or destabilizing effect on global MHD modes depending on the mode and beam parameters [8]. On C-2W it has been shown experimentally that EB can be stabilizing or destabilizing to radial modes depending on the sign of applied bias. A remarkable discovery of the C-2W experiment is a new operating regime where these external actuators, NB injection and EB, have a synergistic effect when applied simultaneously, leading to much more stable and long-lasting plasmas than when either actuator is used alone. The FPIC and HYM codes are being used to understand this important synergistic effect.

Global confinement in macroscopically stable FRC plasmas is due to a combination of perpendicular confinement by magnetic field inside the separatrix, and parallel confinement by magnetic field gradients and electric fields in the SOL. The perpendicular and parallel transport are coupled [9]. Reduced modeling of global transport has been performed using a hybrid fast ion + MHD code to characterize the global interaction of perpendicular transport in the FRC, parallel outflow in the SOL, and field line expansion and electrostatic potential formation in the expander divertor [10]. The same code has been used to study equilibrium relaxation, spin-up, and development of equilibrium rotation velocity under the influence of EB and NB external actuators.

Parallel electron heat transport modeling in the SOL has been performed using a custom developed 1d2v continuum code [11]. As expected, it has been shown that a pre-sheath potential is formed in the expanding magnetic field of the divertor, which helps to confine plasma electrons and reduces the amount of cold electron emission from the walls. Simulations predict that parallel electron heat loss is close to the minimal theoretical limit, a result which has been validated by experimental diagnostics. This helps to explain another remarkable discovery of the C-2W experiment, which is a high Te operating regime.

Perpendicular turbulent transport is being modeled using the 3D particle-in-cell codes ANC [12] and GTC [13]. In previous simulations [14–16] a gyrokinetic particle push was used meaning that the magnetic null regions had to be removed from the simulation domain. Nevertheless, non-linear simulations found qualitative agreement in fluctuation spectrum with experimental Doppler Back Scattering measurements [15]. To include the magnetic null regions in global simulations, which entail a significant fraction of figure-8 and betatron orbits, a "blended"drift-Lorentz particle pusher [17] has recently been implemented, and a new ⊠⊠ model has been developed and applied. Using this new particle model, linear and non-linear results are consistent with the previous gyrokinetic simulations. The new turbulence simulations also include kinetic electron effects which were previously removed in global simulations [15,16] (but kept in local simulations [12,14]). The resulting model has been used to compute the perpendicular ion and electron heat conductivity due to turbulent transport.

The combination of insights gleaned from simulations of plasma self-organization and equilibrium, the influence of external actuators on global stability, and global, coupled perpendicular and parallel transport, are being used to help design a next step Advanced FRC device.

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