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Simulation of Equilibrium, Stability, and Transport in Advanced FRCs

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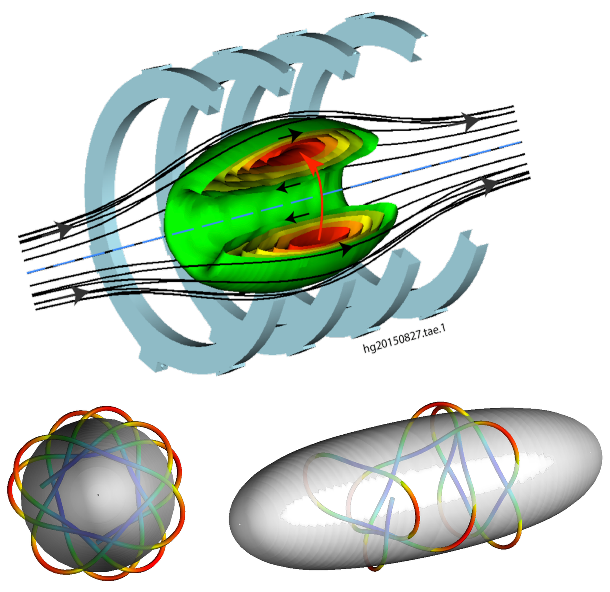
ABSTRACT

- The advanced beam-driven FRC is a Field Reversed Configuration (FRC) with neutral beam (NB) injection, electrode biasing (EB), and magnetic expander divertors. See C-2W overview talk by H. Gota , IAC 1-1, 12th May.
- External actuators bring new features (i) a large energetic ion population, (ii) in-principal capability to adjust the electric field profile in SOL, (iii) a combination of magnetic and electrostatic confinement of electrons
- Theory and simulation efforts have been made to address new features
- Hybrid fluid/kinetic equilibrium shows 50% of plasma pressure is in energetic ions due to NB injection in C-2W
- Global, 3D, cross-separatrix, nonlinear, electrostatic PIC simulations show that the new equilibrium lead to a reduction in non-linear saturation amplitude of electrostatic fluctuations.
- 3D simulations in the SOL find that equilibrium $E\times B$ flow shear can significantly decrease ITG saturation amplitude and ion heat transport . Zonal flow has also been studied. See poster by Z. Lin, TH/P7-7
- 1D2V continuum modeling of electron dynamics in the SOL shows that parallel electron heat loss decreases with increasing divertor expansion ratio and also decreases with negative biasing on the central electrode
- These theoretically predicted changes in equilibrium, stability, and transport characteristics may help to explain the remarkable plasma performance of the C-2W experiment.

BACKGROUND

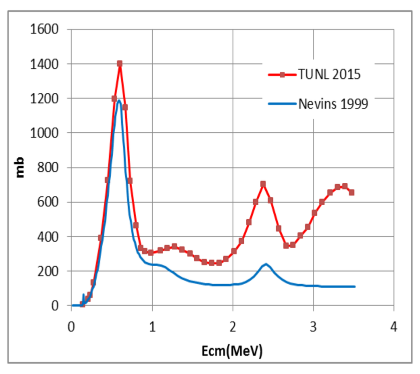
TAE's CONCEPT – ADVANCED BEAM-DRIVEN FRC

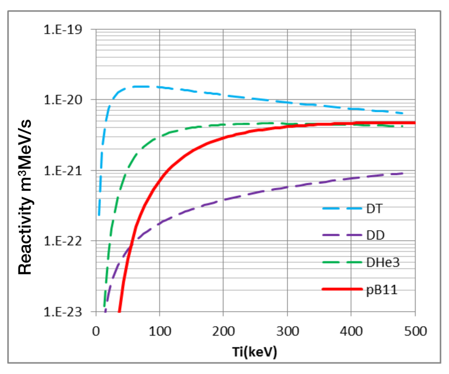
- High plasma β ~ 1
  - Compact and high power density
  - Aneutronic fuel capability
  - Indigenous large orbit particles
- Tangential Neutral Beam Injection
  - Large orbit ion population
  - Increased stability and reduced transport
- Easier design and maintenance due to simple geometry
- Linear unrestricted divertor facilitates power, ash, and impurity removal



Large orbit ions via Neutral Beam injection

TAE's ULTIMATE GOAL: p-11B FUSION





- *p + 11B → ⁴He + ⁴He + ⁴He*
- *Cross section larger than previously believed*
- *Kinetic effects increase reactivity [1]*

- *Advantages*
  - *(Almost) no neutrons*
  - *Benign, readily available fuel*
  - *Little radioactive waste*
  - *Viable economics*

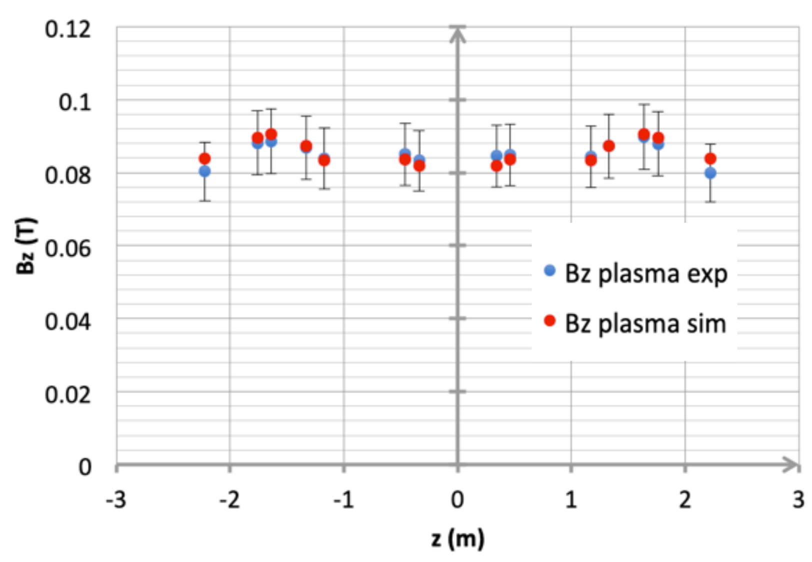
BEAM-DRIVEN FRC EQUILIBRIUM

HYBRID KINETIC/FLUID MODEL

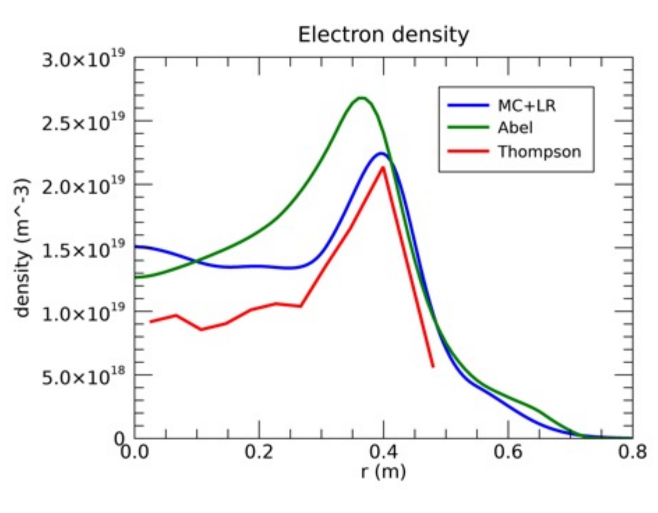
- Monte Carlo model for fully kinetic simulation of neutral beam injection [2] coupled to
- Equilibrium solver with Greens' function method to couple exterior vacuum field from coils to interior generalized Grad-Shafranov solution with multiple ion species and rotation [3]

RECONSTRUCTION

- Model matched to experimental measurements:
  - Interior plasma profile measurements:
    - Electron density from Thomson scattering and from Abel-inverted FIR interferometry
    - Electron temperature from Thomson scattering
    - Thermal ion rotation from CHERS diagnostic
  - Exterior magnetic measurements:
    - Poloidal flux and Bz along the wall, both in vacuum and in presence of the FRC
  - Neutral beam shinethrough from SEE detectors

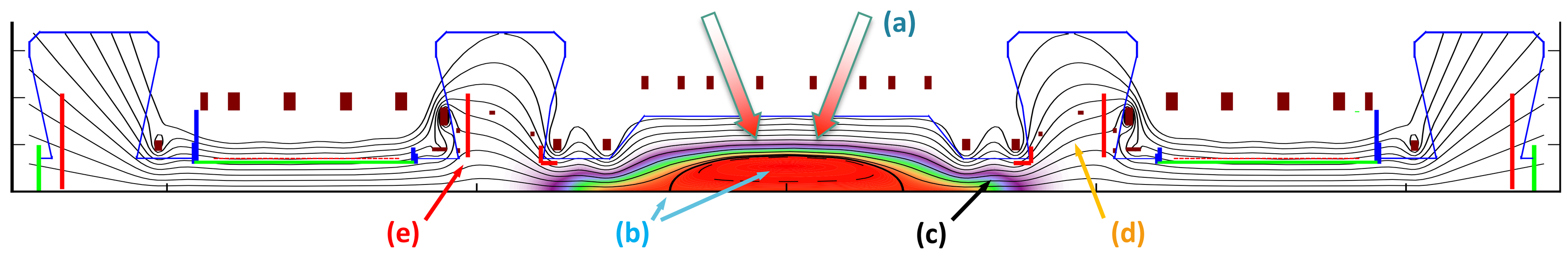


Total B_z at probe locations for shot 119701: experimental measurements (blue points) and equilibrium reconstruction values (red points)



Electron density radial profile: Thomson (red line) Abel-inverted FIR (green line), equilibrium reconstruction (blue line).

SKETCH OF C-2W EXPERIMENT



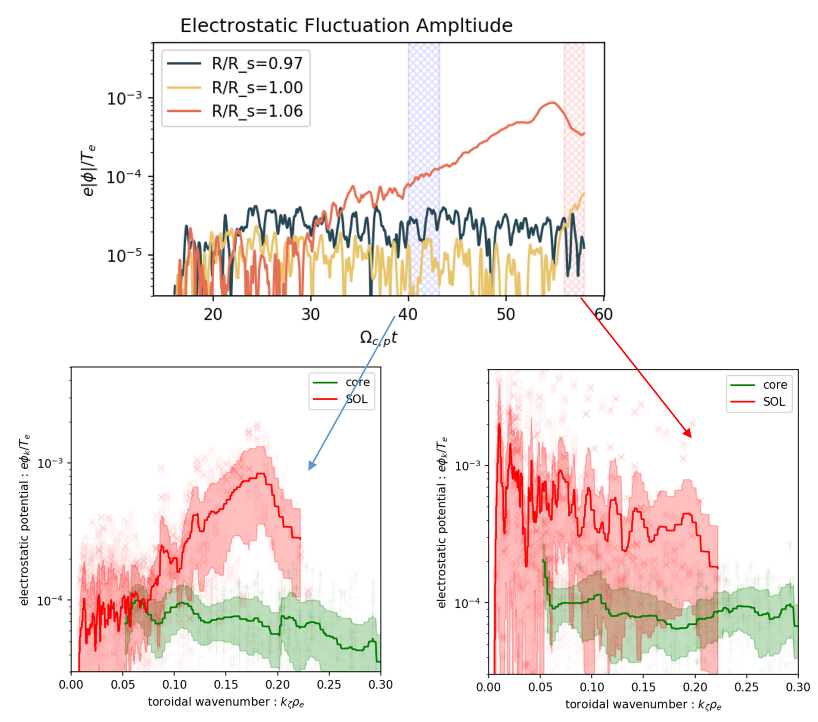
The C-2W experiment [4] in cylindrical cross-section. Thin black lines are magnetic field lines, with the thicker black line denoting the separatrix. Arrows at (a) indicates the direction of neutral beam (NB) injection. Regions of null magnetic field at the O-point and X-points are indicated by (b). A magnetic mirror is shown at (c). One of the magnetic field expander divertors is indicated by (d). Red lines such as (e) indicate electrodes used for biasing (EB).

STABILITY AND TRANSPORT

GLOBAL 3D ANC [5,6] SIMULATIONS

C-2W equilibrium including beam ions

- Short wavelength ETG-like instability in SOL
- No linear instabilities in core
- Saturated amplitude lower than previous C-2/C-2U cases



3D GTC-X [7,8] SIMULATIONS IN SOL

Including equilibrium sheared flows

- Reduces linear ITG growth rate
- Reduces saturation amplitude and heat transport (change in eddy size + decrease in turbulence intensity)

Including nonlinearly generated self-consistent zonal flows

- Reduces ITG saturation amplitude and heat transport
- Zonal flows only damped collisionally in ideal FRC (collisions do not affect linear growth rates)

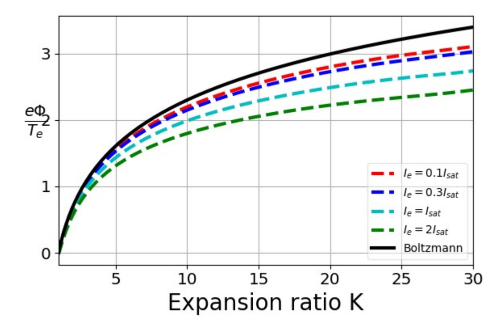
1D2V KSOL [9] SIMULATIONS

Continuum Vlasov-Fokker-Planck for electron dynamics

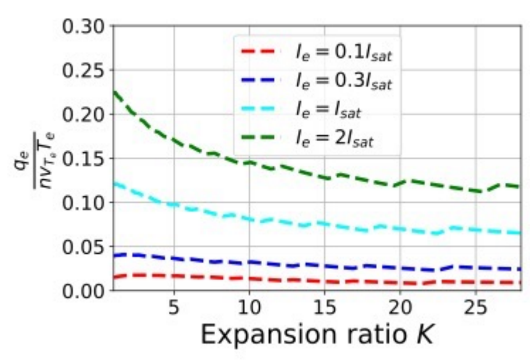
- Flux tube expands in cross section as it enters the expander divertor, leading to drop in electron pressure
- A pre-sheath potential forms due to drop in B and P:

$$\frac{dP_{\parallel}}{dl} + (P_{\perp} - P_{\parallel})\frac{d\ln B}{dl} + en\frac{d\phi}{dl} = 0$$

- Parallel electron heat loss in the expander divertor decreases along the field line and decreases with negative biasing



Pre-sheath along field line



Heat flux vs magnetic expansion

SUMMARY

- Novel features of the C-2W experiment have stimulated further development of equilibrium, stability, and transport models.
- Hybrid fluid/kinetic equilibrium reconstruction of C-2W plasmas show that 50% of total plasma pressure is in the fast ions, and thermal plasma profiles are significantly modified.
- Experimentally validated 3D kinetic PIC transport models ANC and GTC-X show that the novel equilibrium features lead to a reduction in turbulent transport.
- 1D2V continuum modeling of the electron Vlasov-Fokker-Planck equation shows that parallel electron heat loss decreases with increasing divertor expansion ratio and also decreases with negative biasing on the central electrode
- The theoretical observations may help to explain the remarkable plasma performance of the C-2W experiment.

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