Simulation study of energetic ion confinement in prolate field-reversed configuration

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Central Questions

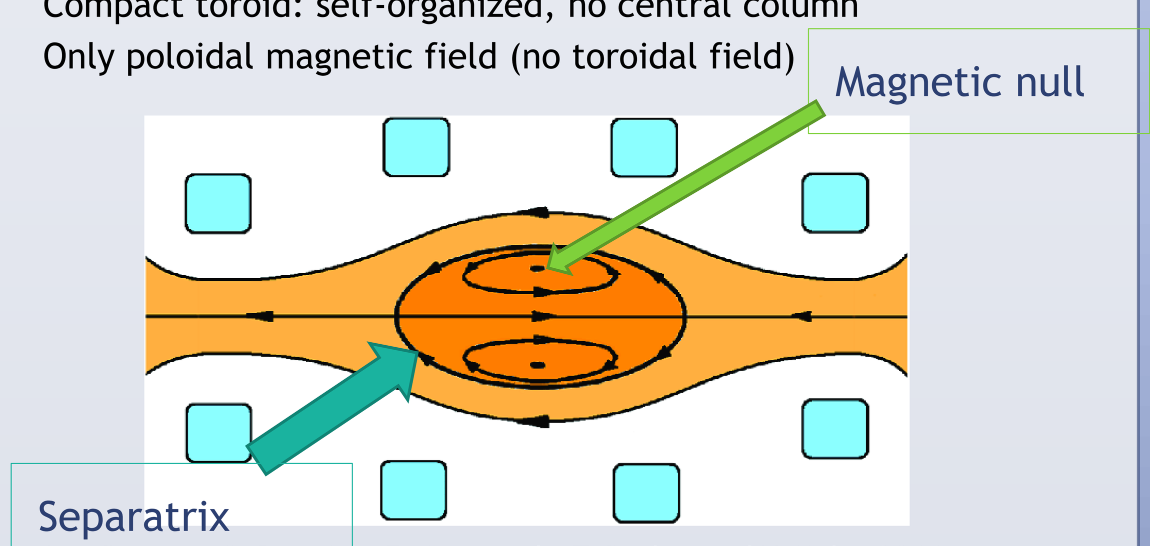
- **How does ion confinement in prolate field-reversed configurations (FRCs) respond to low mode number MHD modes?**
- **How valid is the approximation that FRCs can neglect magnetic mirror effects with respect to confinement?**
- **How does equilibrium confinement change with respect to changes in device size?**

Motivation

- **TAE Technologies'** C-2 field-reversed configuration **(FRC) experiment shows great promise but still raises confinement questions.**
- Low mode-number MHD modes observed to saturate in FRCs.

Field-reversed Configurations

- Compact toroid: self-organized, no central column
- Only poloidal magnetic field (no toroidal field)



J.A. Romero, S. Dettrick, E. Granstedt, T. Roche, and Y. Mok (**2018**). Inference of field reversed configuration topology and dynamics during Alfvenic transients. **Nature Communications.** 9. 691.

FRC Advantages

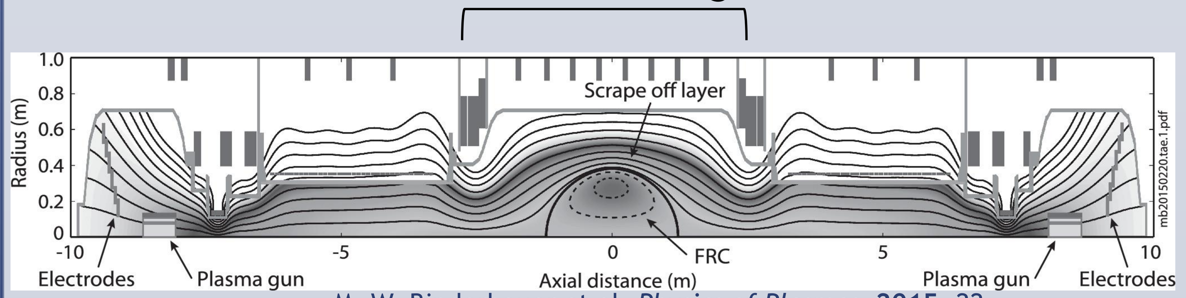
- High-βp due to low field
- **Smaller, more economical devices**
- **Natural divertor**
- **Simple, linear geometry**

FRC Challenges

- MHD model does not capture all features
- Large Larmor radius due to low field near magnetic null
- **Confinement modeling** (largely empirical so far)
- Sustainment
- **Stability to global MHD modes**

TAE Technologies' Experiment

Simulation Region

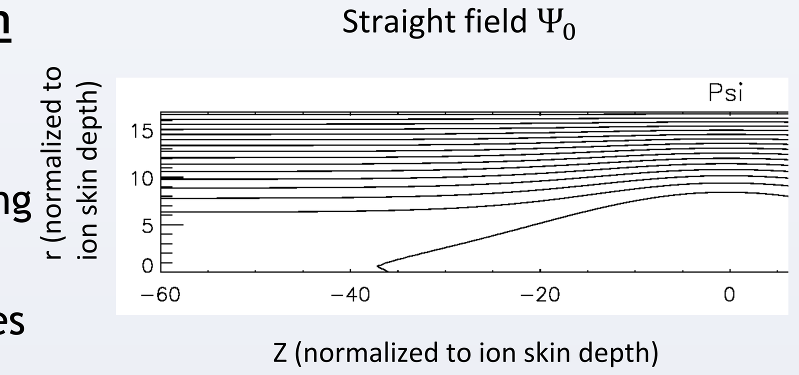


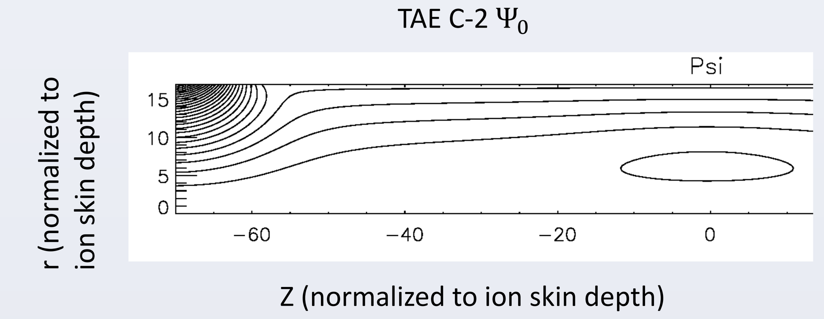
M. W. Binderbauer et al. *Physics of Plasmas* 2015, 22

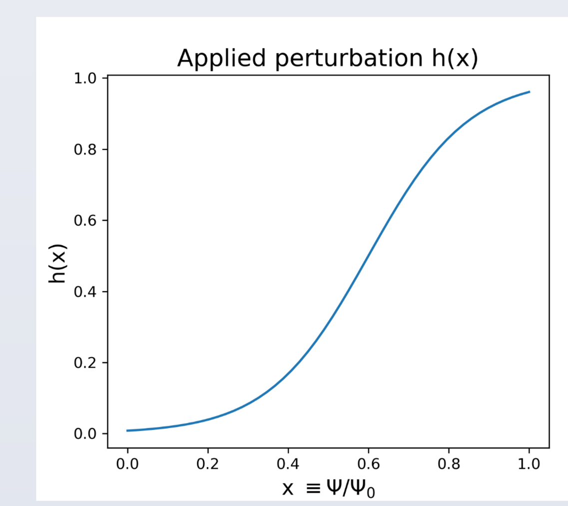
- B_{sep} = 0.6
- Chamber length ~ 4 m, Chamber radius ~ 0.7 m
- Separatrix radius ~ 0.35 m, Separatrix half-length 1.5 m
- Be ~ 0.1 T
- ne ~ 3×10^{19} m^{-3}
- $500 million private funding

Simulation Details

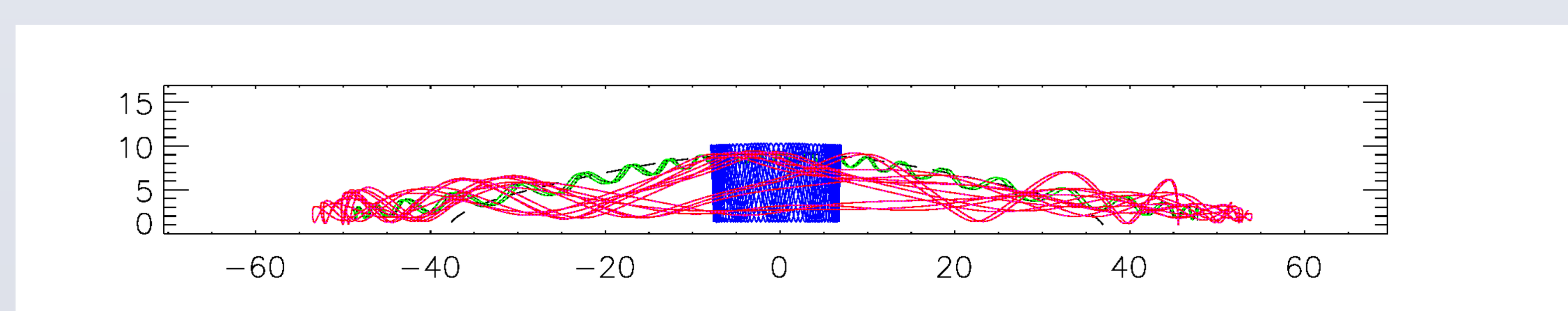
- **Initial condition:** Electric and Magnetic fields generated by **Grad-Shafranov equilibrium**
- **One million ions** loaded into simulation region with **Maxwellian velocity distribution**
- **HYM code utilized for simulation**
  - Fully parallelized with 3D domain decomposition/MPI and good processor scaling
  - Initial particle distribution function f_0 assumed to be known analytically
  - Perturbed distribution function: $\delta f = f - f_0$ integrated across particle trajectories
  - Particles each assigned weights: $w = \delta f/f$
- **TAE parameters used for base case; also examined twice the size and half the size**
- **Ion confinement studied in following cases:**
  1. Differing mirror ratios: mirror coils (r_{mirr}=3) compared to straight field (r_{mirr} = 1)
  2. Differing device sizes: $S^* \equiv \frac{R_{sep}}{\text{ion skin depth}}$, for $S^* \sim 4.25, 8.5, 17$ (TAE has $S^* \sim 8.5$.)
  3. Perturbations applied: n=1 and n=4 tilt-like and radial modes
- **Perturbations applied:**
  - **Tilt-like:** $v_z = Ah(x)\cos\Phi;\ \Phi \equiv (n\varphi - \omega t),\ x \equiv \frac{\Psi}{\Psi_0},\ h(x) = \frac{1+\tanh(4x-2.4)}{2}$
  - **Radial:** $v_r = Ah(x)\cos\Phi$; A = $0.1 v_A$, ω=$0.1\,\omega_{ci}$
  - Corresponding flows added to satisfy **incompressible flow** condition and linearized Ohm's Law
  - Unconfined particles allowed to escape first; perturbation applied at t=850 (89 μs)
- Particle loss defined as particle contacting axial or radial wall of simulation
- **Particles sorted** into categories: 1) escaped, 2) FRC-confined ($|z|<Z_s$), 3) Mirror-confined

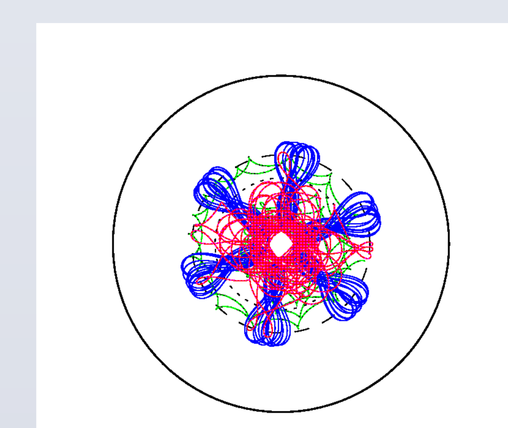






Several Particle Trajectories

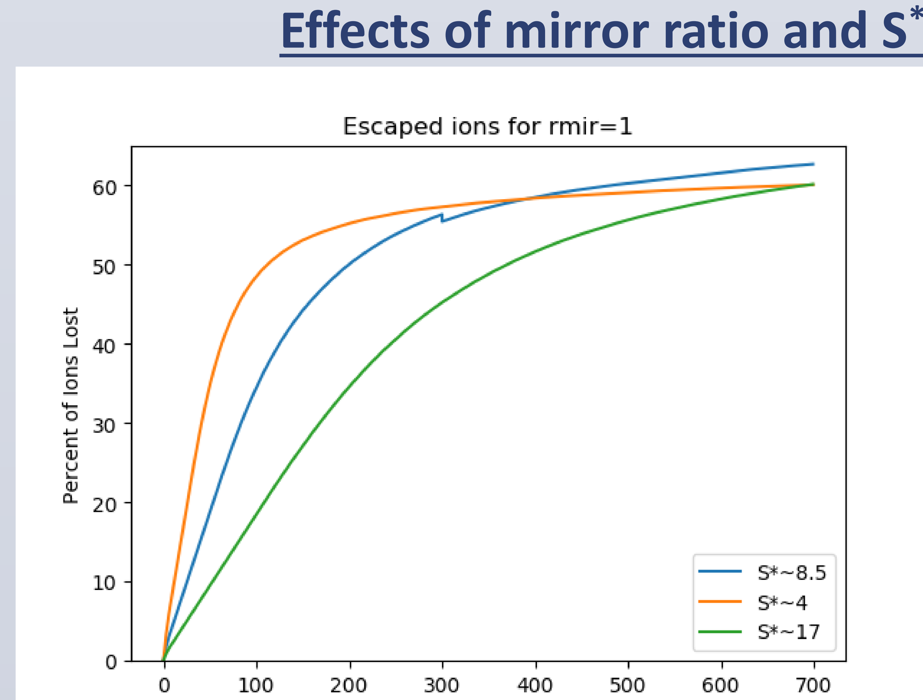




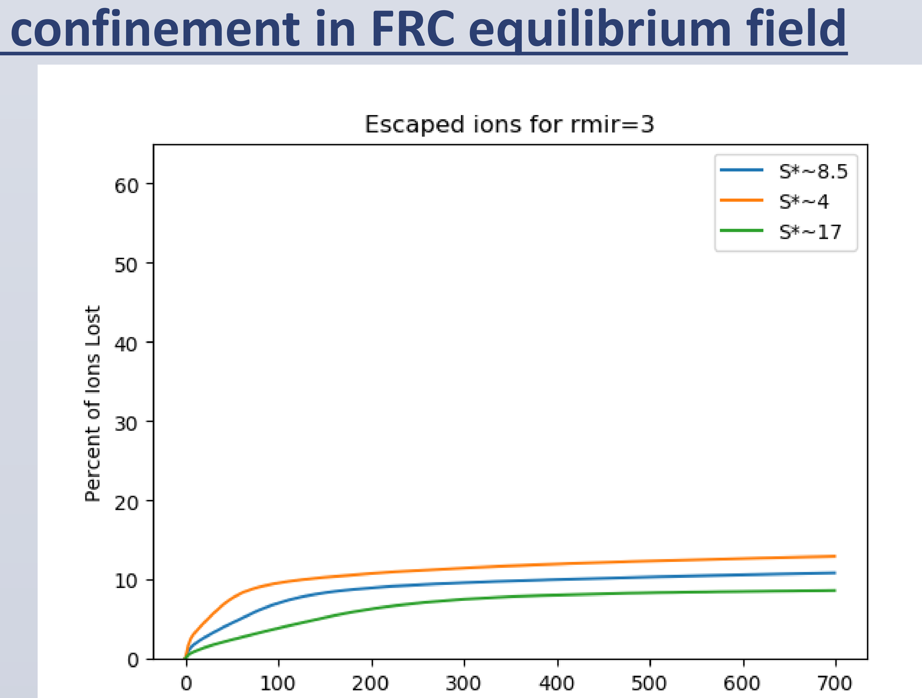
- Mirror confinement condition: $E = \mu B + \frac{v_{par}^2}{2}$ ($\mu \geq \frac{E}{B}$), energy is conserved, and μ is roughly conserved.
- As B increases near mirror coils, parallel velocity decreases until particle is reflected
- μ is not conserved for transits across midplane, leading to stochastic diffusion in velocity space.

- Blue: well-confined within FRC region
- Green: mirror-confined
- Red: stochastic, mirror-confined

Effects of mirror ratio and S* on ion confinement in FRC equilibrium field

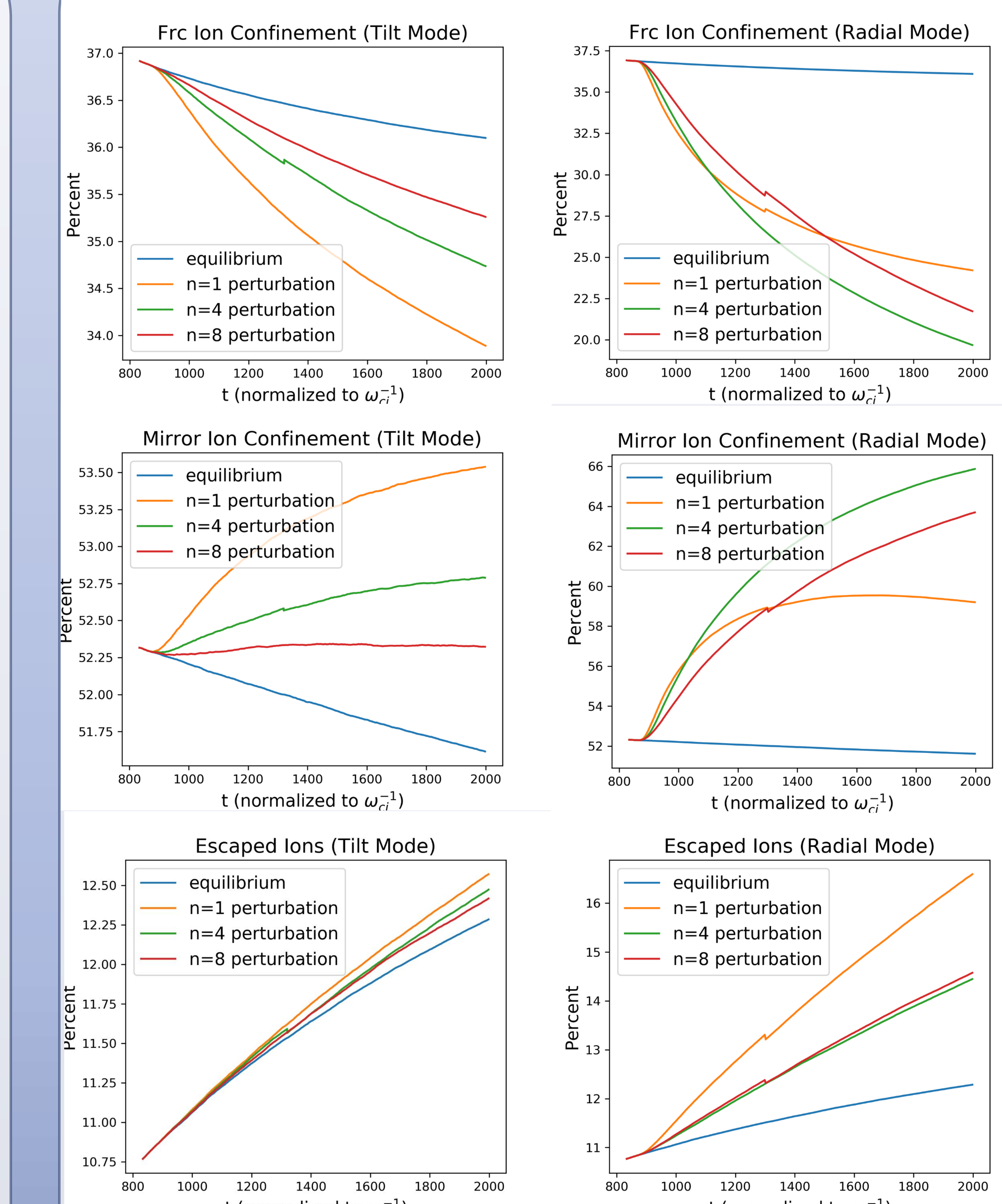


- For t < 200, most losses are along open field lines.
- For t > 400, stochastic obit losses; larger for large S*.
- All particles are FRC-confined.

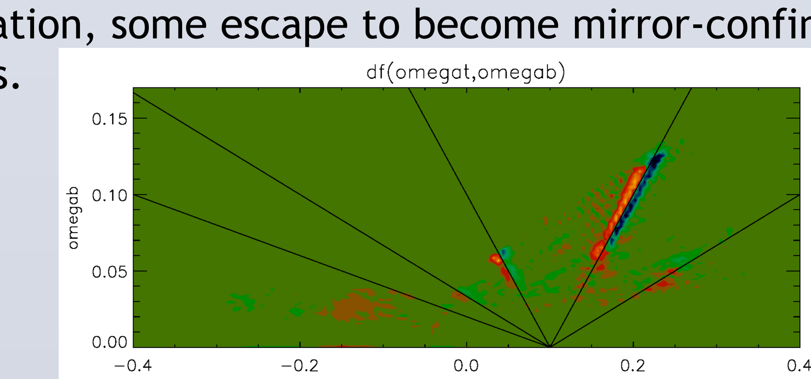


- For t < 100, most losses are along open field lines.
- For t > 200, losses due to non-adiabatic diffusion in velocity space (μ ≠ const.) **Losses scale with $\sqrt{t}$**
- **Roughly half of particles are mirror-confined and half are FRC-confined**

Effect of added perturbation on FRC-confined ions



- **The radial mode has a 15x greater effect on particle loss than the tilt mode over the 120 μs perturbation duration.**
- FRC-confinement decreases with mode number for the tilt mode case.
- Perturbations are localized to FRC region, but for the radial case, some stochastic mirror particles can experience a decrease in perpendicular velocity, entering the loss cone.
- As resonant FRC-confined particles gain energy from the perturbation, some escape to become mirror-confined particles.



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