Transport of magnetized kinetic plasma when $\mathbf{J} \cdot \boldsymbol{B} = 0$

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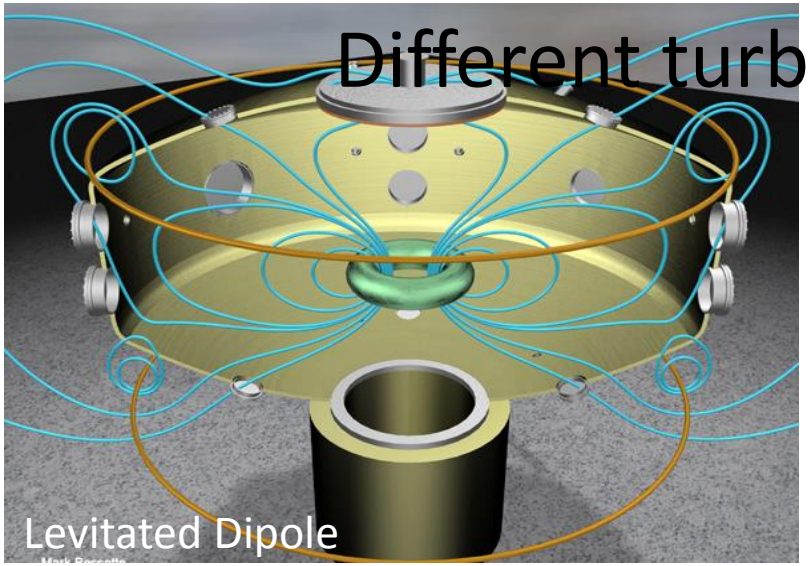
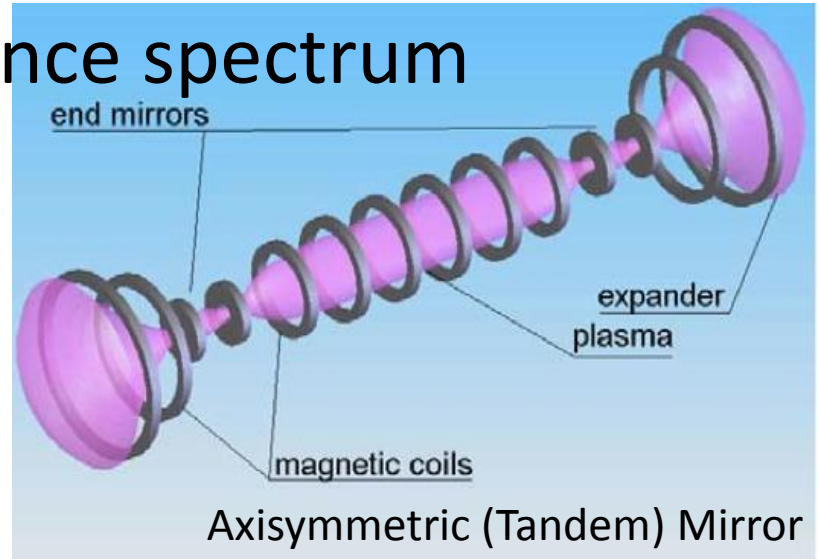
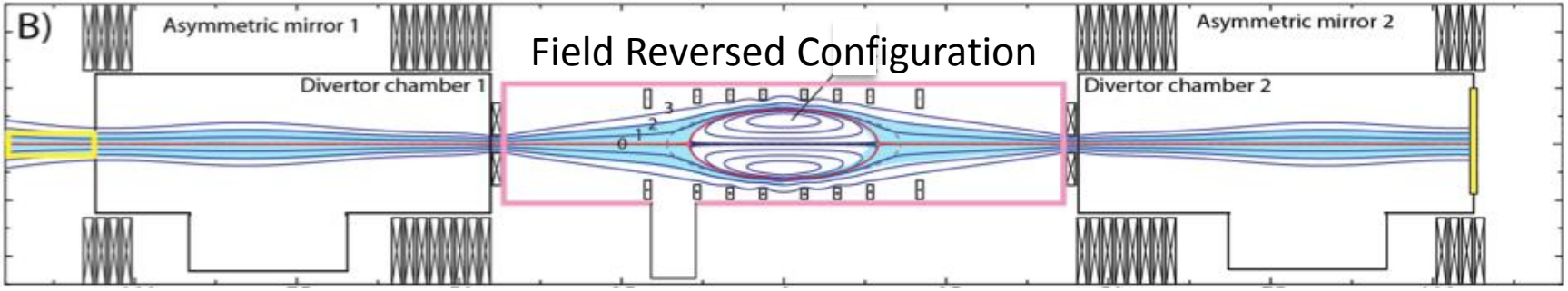
[a]Princeton Plasma Physics Laboratory [b]Budker Institute of Nuclear Physics

No neoclassical transport enhancement

Different turbulence spectrum







A frontier:
Turbulence and transport when q = 0

- The Transport Task Group (*est* 1988) has addressed $\nabla\times\boldsymbol{B}=\lambda\boldsymbol{B}$, *i.e.*, **J||B**. A **frontier** exists at the **opposite** boundary, **J⊥B**.
- A **variety of plasma devices**, with both *open* and *closed* magnetic field lines, have q = 0.
- When q = 0, **perturbations can not rapidly propagate** toroidally around the device. Additionally, the **drift parameter** γ_D may be **low. Both alter the turbulence spectrum hence ⊥ transport**.
- Axial self-organized potentials **alter || transport.**
- q = 0 devices may have very **high** β. Orbits form a 3-D weave *not* foliated drift surfaces. **Full kinetic** treatments are essential.
- **Non-local transport** becomes important.
- Within the past few years, **exciting confinement results** have been obtained in several q = 0 devices.
- **Self-organization** is critical, both during formation and sustainment.

Axisymmetric mirror machine 1: Tandem (LLNL)

- Novel **axisymmetric** stabilization techniques

Demonstrated - divertor coils, pondermotive, plasma rotation (with shear), end wall funnel shape and bias, skewed NBI

Predicted - expander kinetic pressure, Pulsed ECH dynamic stabilization, wall stabilization, non-paraxial end mirrors, and cusp ends

- Important Physics issues in long-pulse ATM

electron confinement, MHD and trapped particle modes, radial transport, microstability, plasma density in expansion-region, plasma potential in end cells

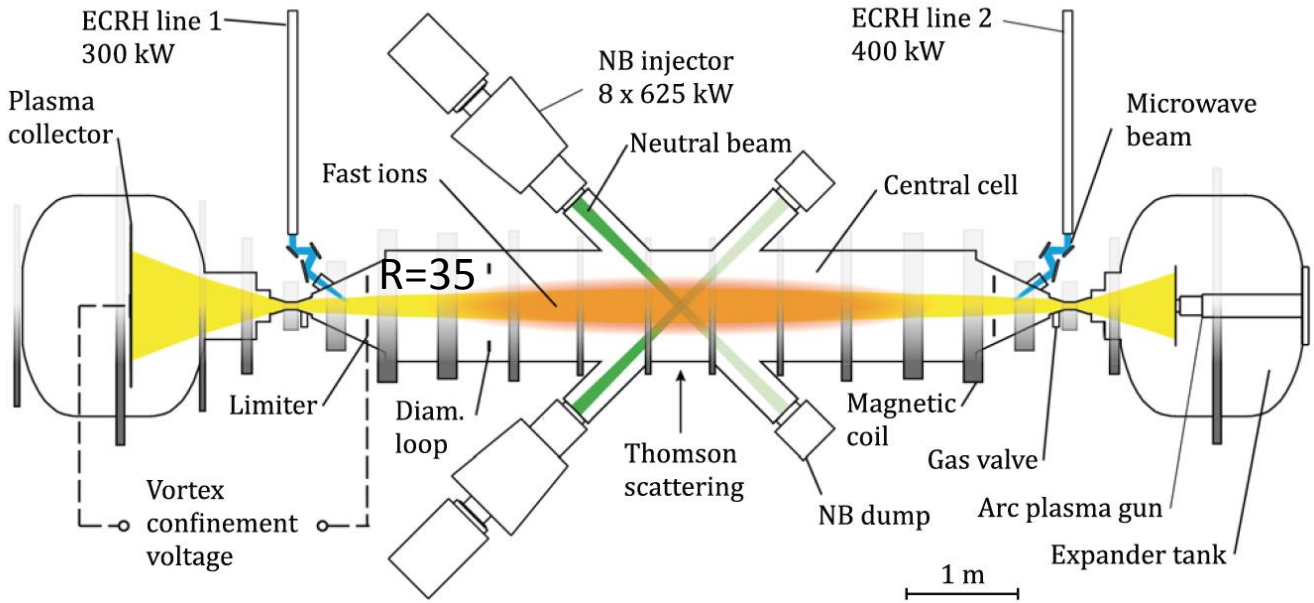
Simonen, *et al.*

Axisymmetric mirror machine 2: Gas dynamic trap

Addition of direct electron heating has resulted in record T_e

T_e ~ 650-900 eV
$E_{i,1}$ ~ 150 eV
$E_{i,2}$ ~ 10 keV
n_e ~ 7×10^{18} m^{-3}
Duration 1 ms

P. A. Bagryansky, *et al.*, PRL 114, 205001 (2015)



Free-streaming (or Spitzer) electron loss predicts T_e < 100 eV

Mechanism suggested for **axial loss suppression**

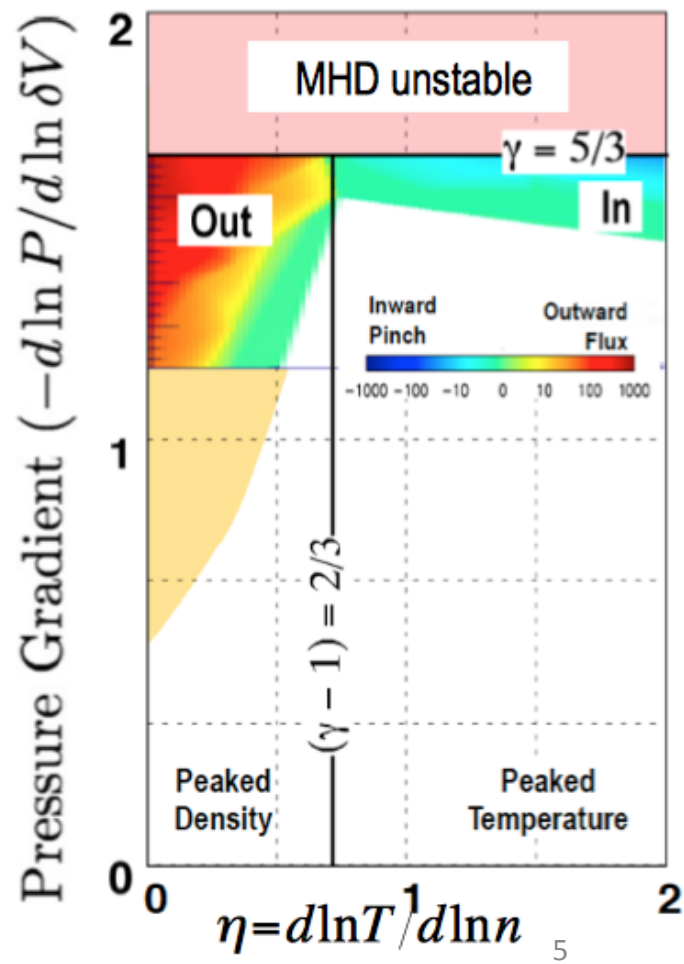
-Trapped electrons in expansion region (Konkashbaev, Ryutov...)

Mechanism for **suppressing radial losses** (saturate MHD at low level)

-Vortex confinement: rotating edge plasma by plate biasing (Beklemishev..)

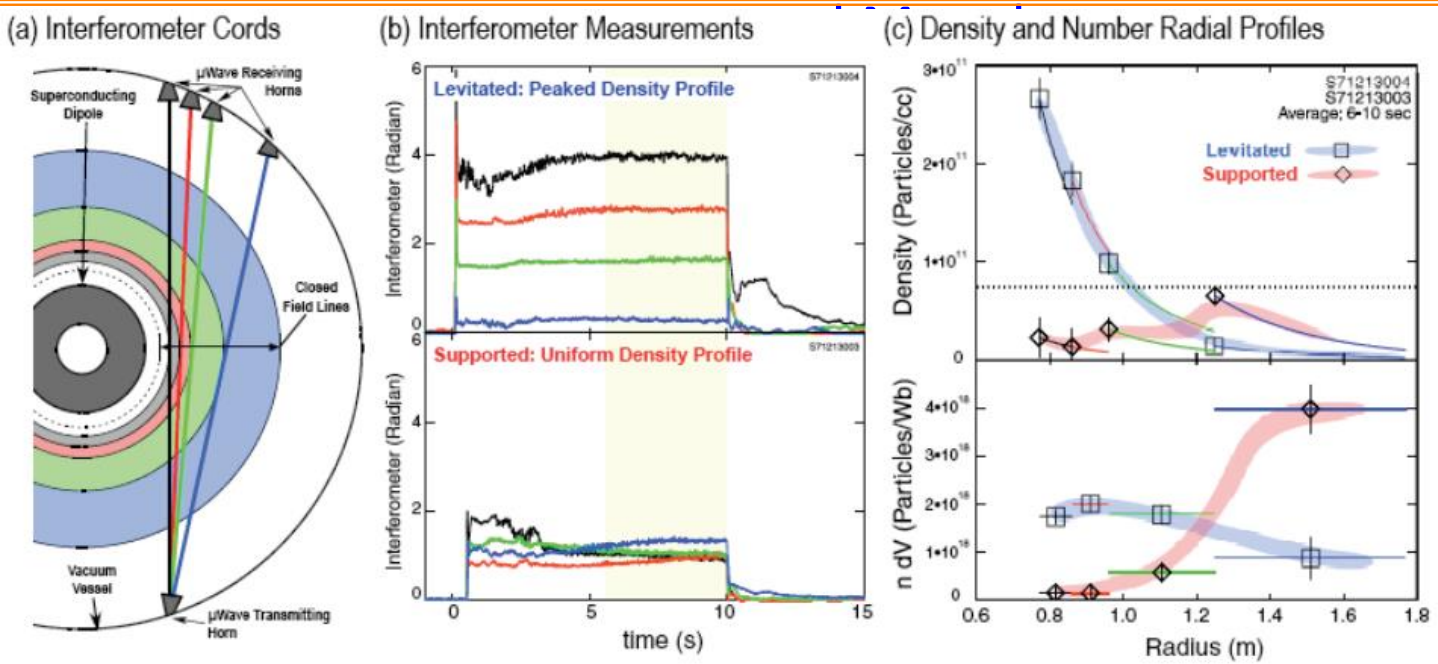
Levitated dipole (LDX): J. Kesner, M. Mauel, *et al.*

- **Low-frequency MHD and drift-mode, both flute-like, instabilities** dominated plasma dynamics.
- **High peak** β(> 50%) achieved with levitation.
- **Turbulence** created a strong inward particle pinch that drove the plasma to a very steep profile: first clear observation of a strong inward turbulent pinch in a laboratory plasma. *Outwards energy flow accompanies inwards density pinch & visa versa.*
- Strong link to **space plasma physics.**



Kobayashi, Rogers, Dorland, PRL (2010)

Levitated dipole (LDX): FESAC 2011 Kesner



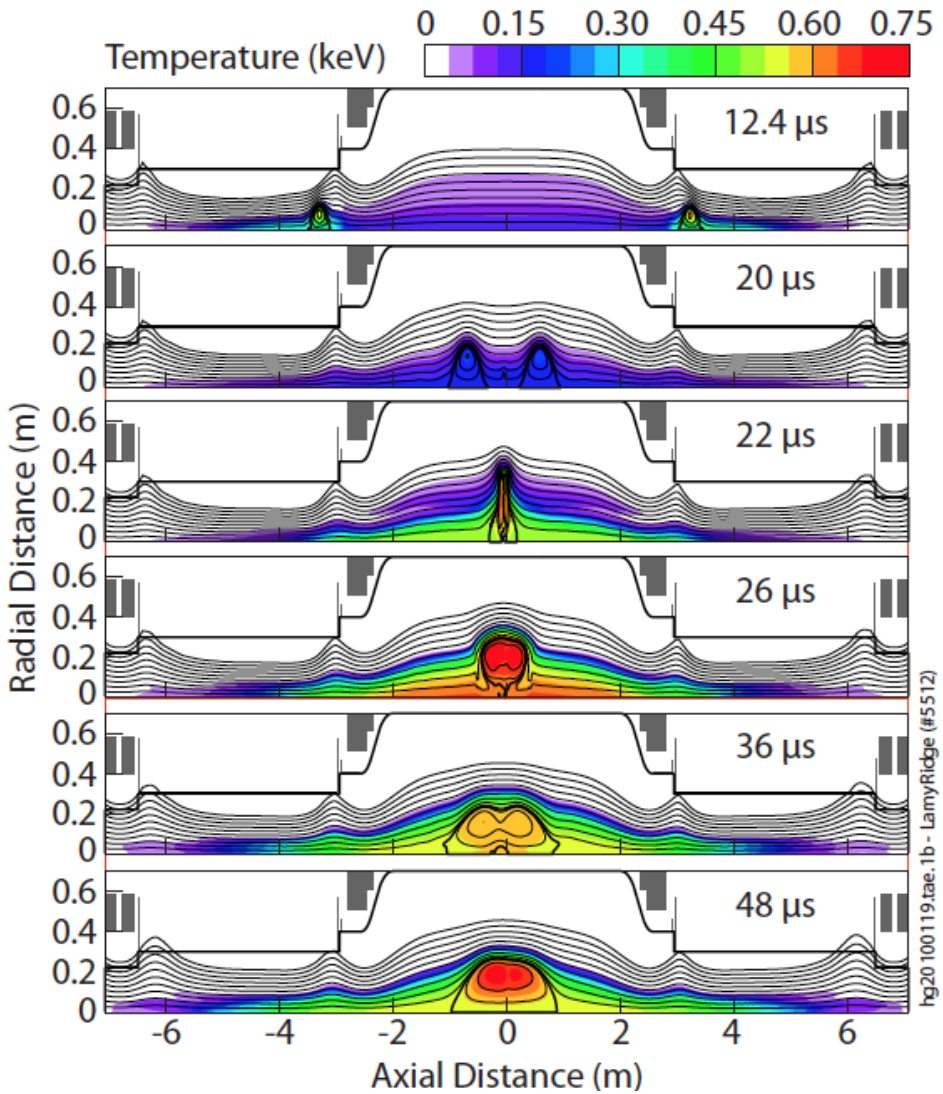
Strong density peaking during levitation

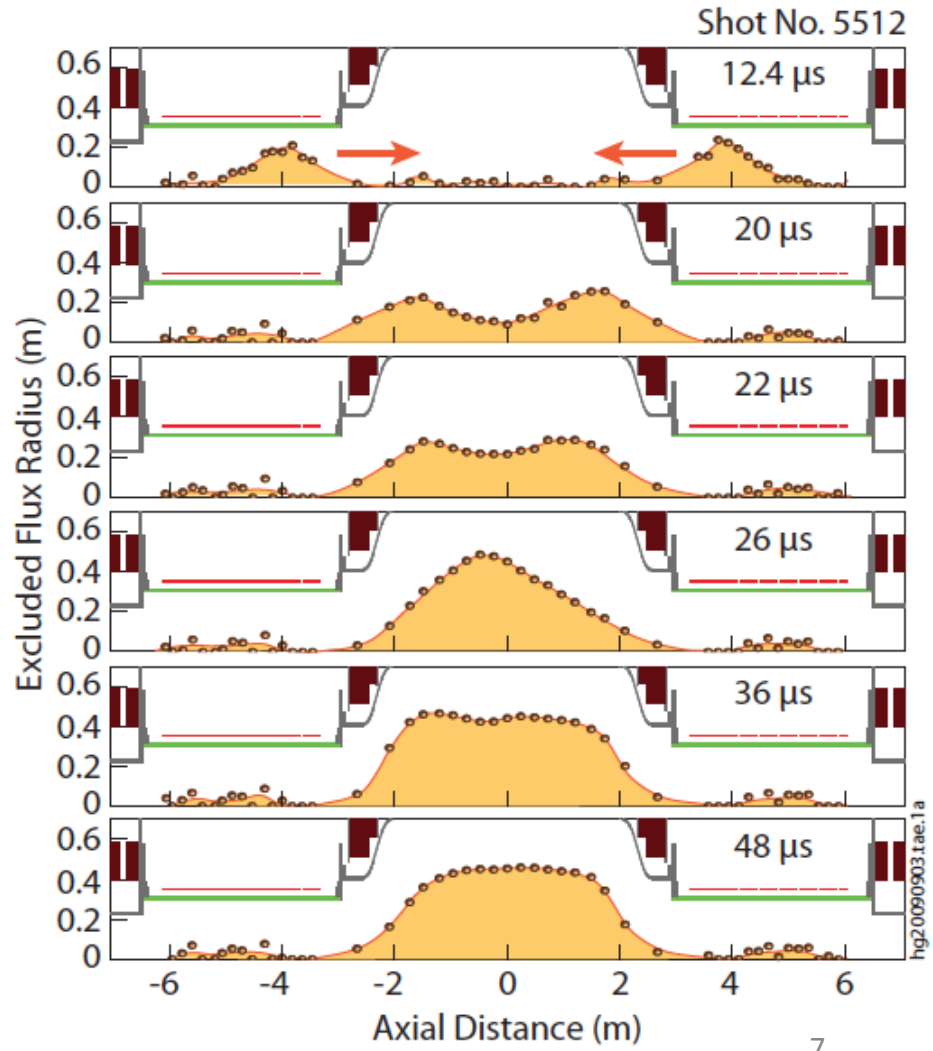
Important LDX features wrt T&T

- Strong pinch compared to q > 0 devices: trapped particles
- q = 0 makes both MHD and drift modes flute-like
- Decoupled τ_E and τ_n with $\tau_E / \tau_n \sim 10\text{-}50$
- Invariant internal profiles set by geometric expansion
- Excellent for advanced fuels

FRC: TriAlpha Energy Corp (C2 device)

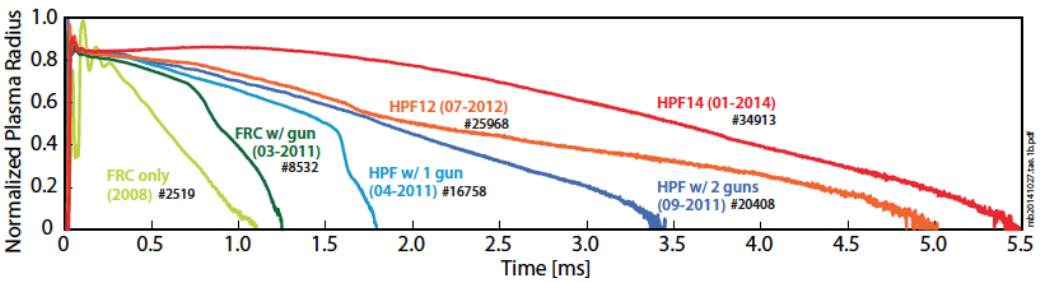
Innovative (high speed) merging technique

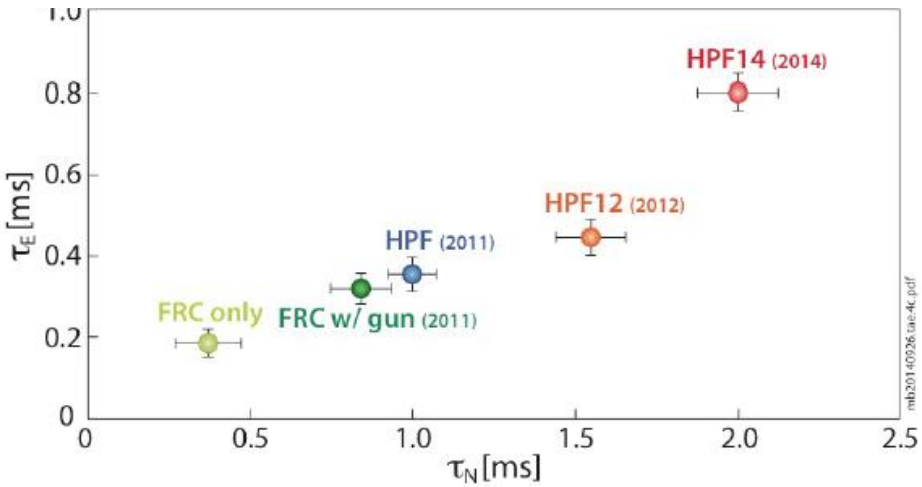


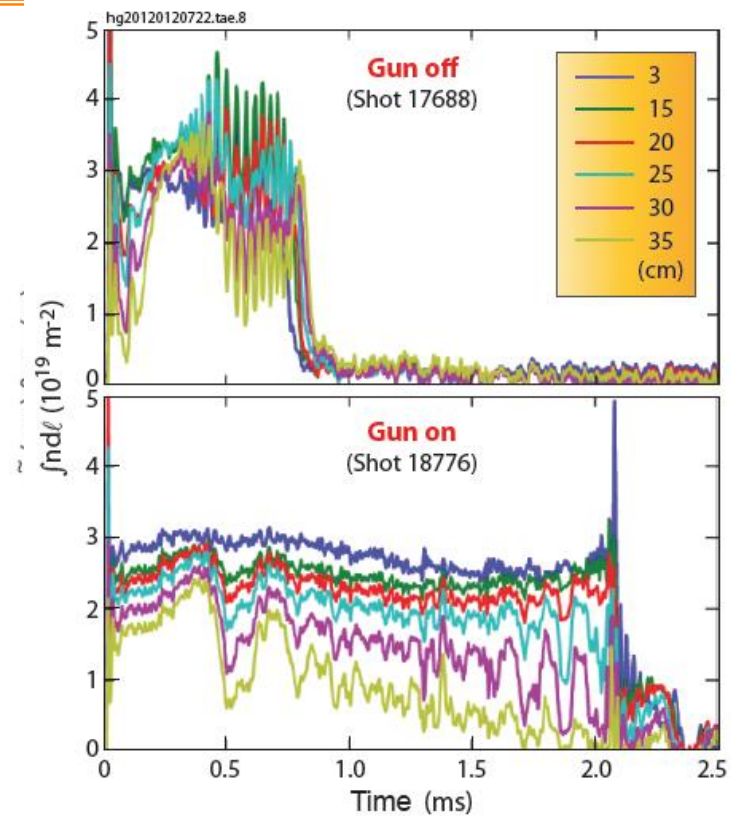


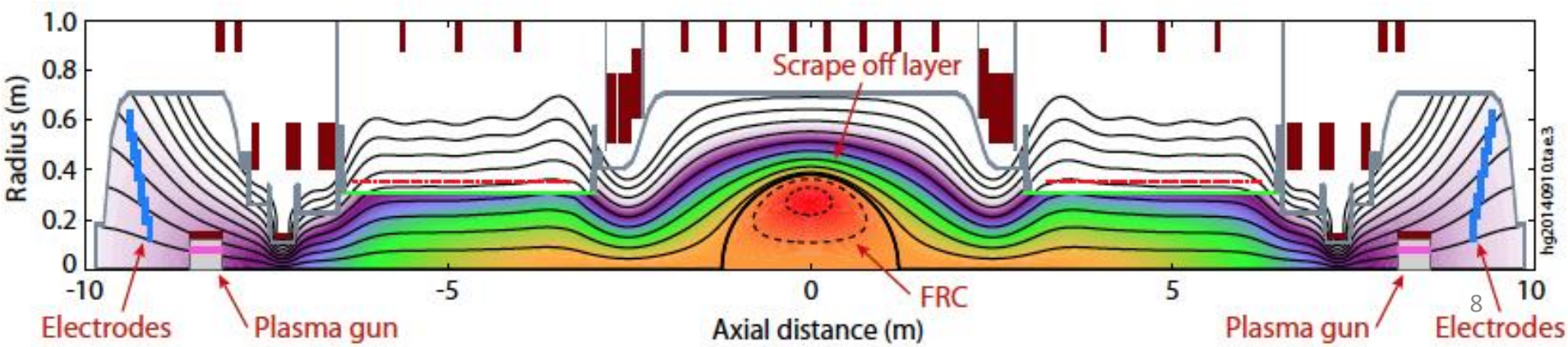
Rostoker, Binderbauer, Tuszewski, Guo…

C2 device with guns and biasing: Improved energy and flux confinement





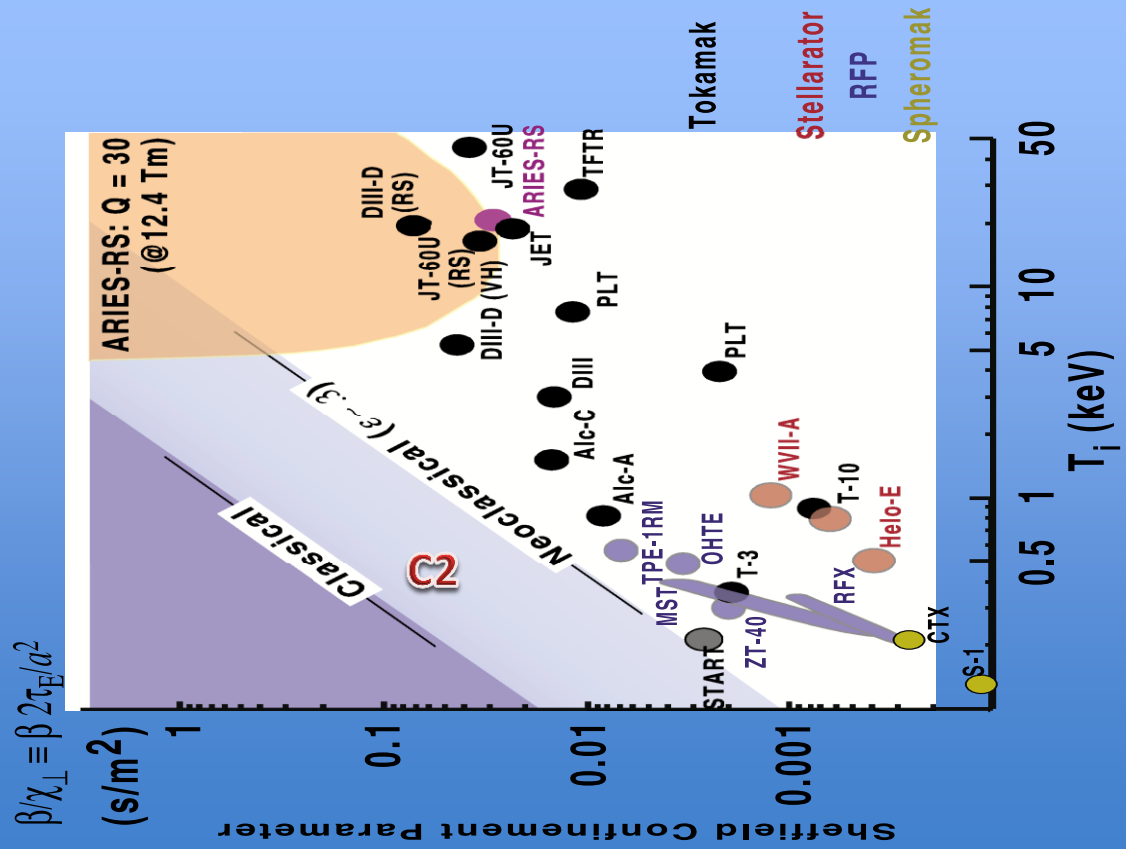




Energy confinement C2

PRL 108, 255008 (2012) PHYSICAL REVIEW LETTERS week ending 22 JUNE 2012

Field Reversed Configuration Confinement Enhancement through Edge Biasing and Neutral Beam Injection



$nT = B^2\beta$

$\tau = a^2/\chi$

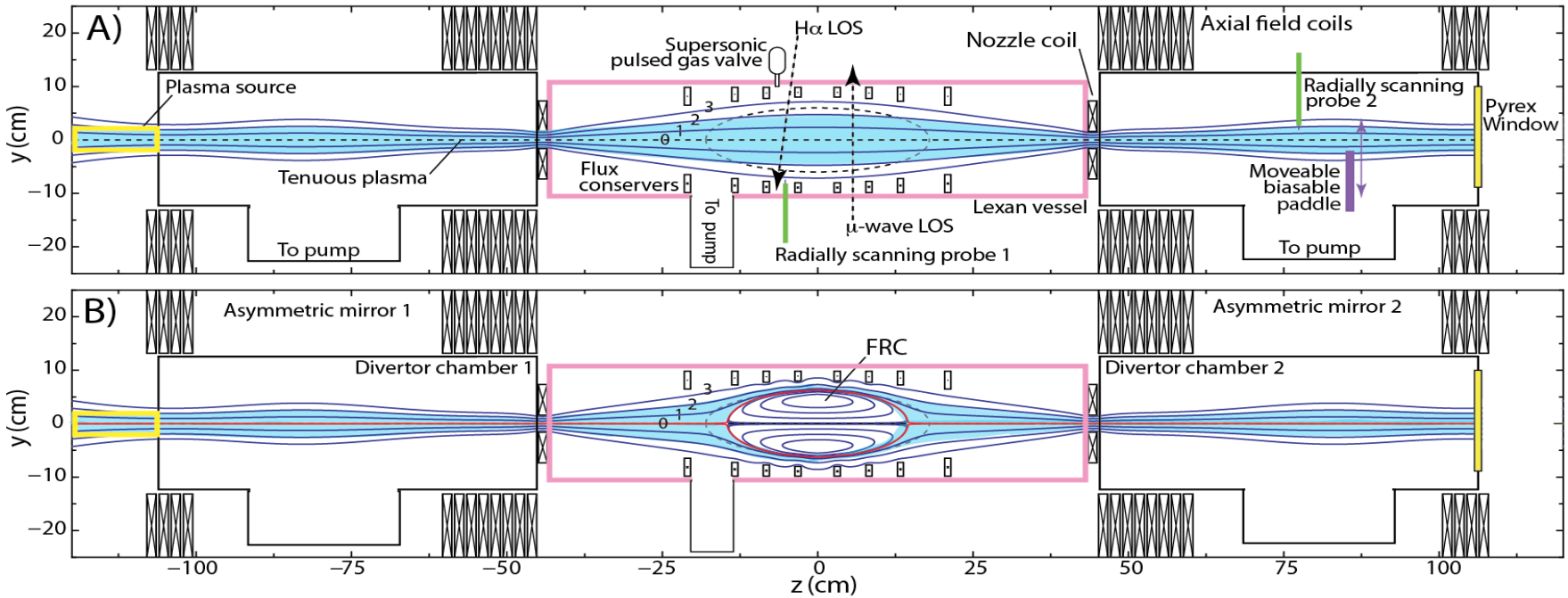
$n\tau T = B^2 a^2 \beta/\chi$

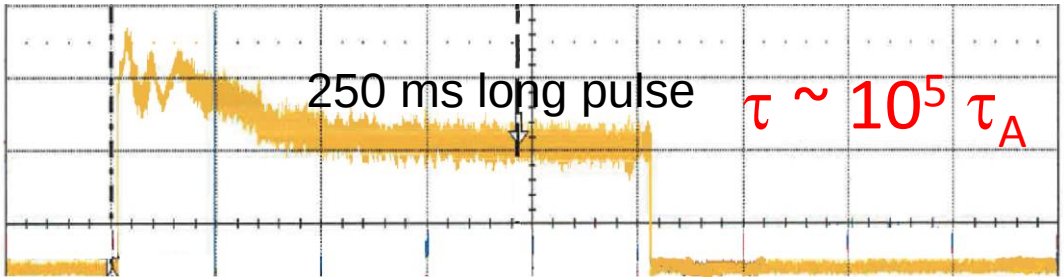
Sheffield 1985, courtesy: J. Kesner & M. Mauel

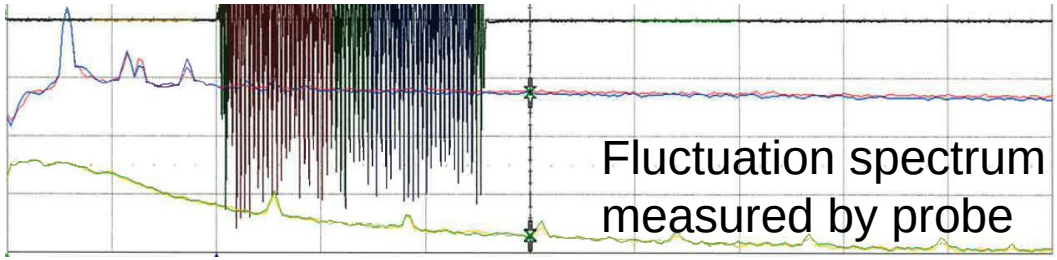
Princeton Field Reversed Configuration:

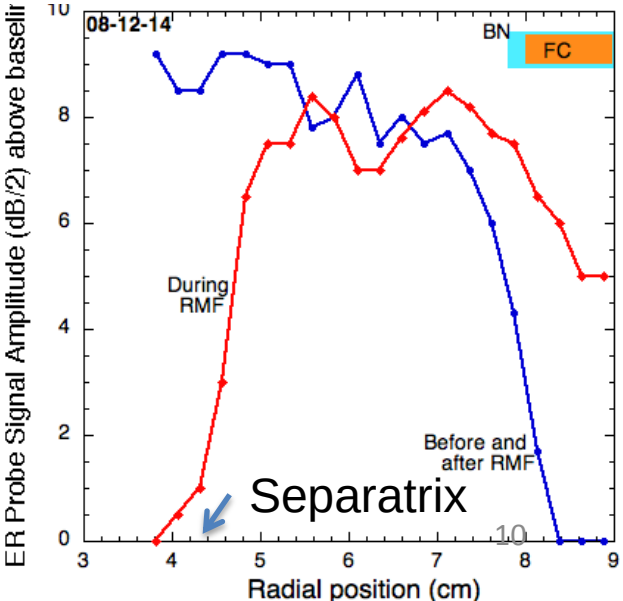
RMF_o formed, heated and sustained

1st Goal: to close field lines, form a separatrix and improve confinement





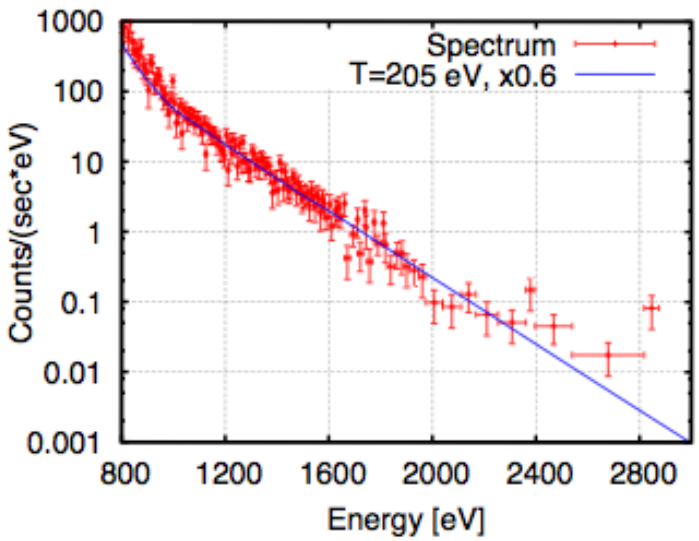


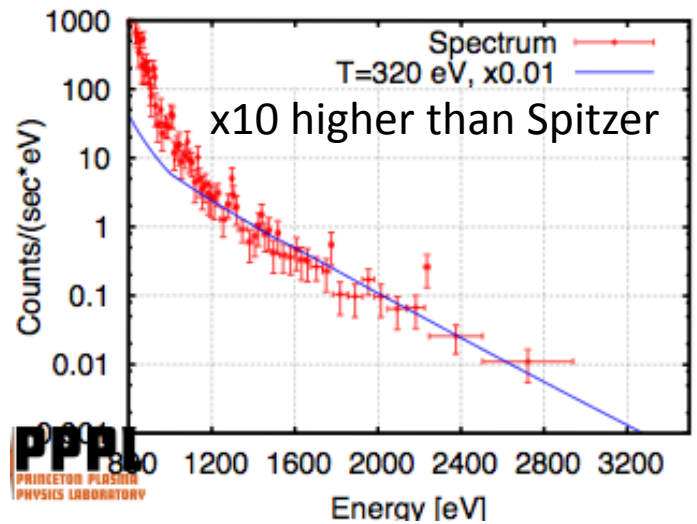


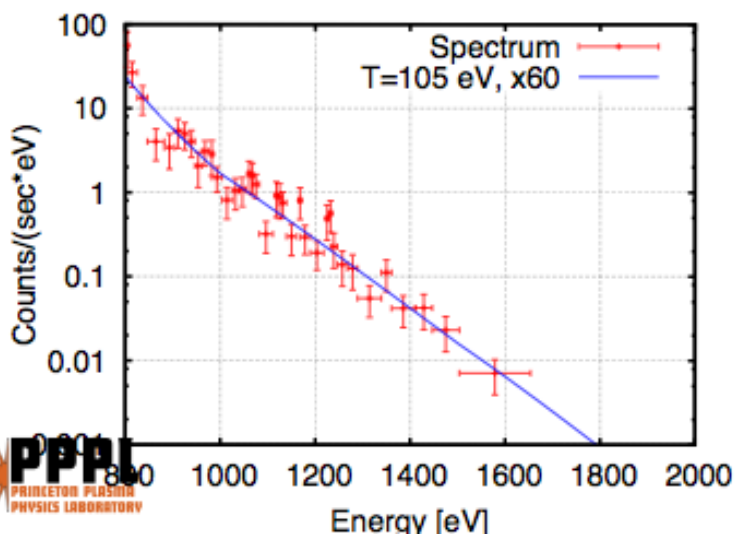
Princeton Field Reversed Configuration

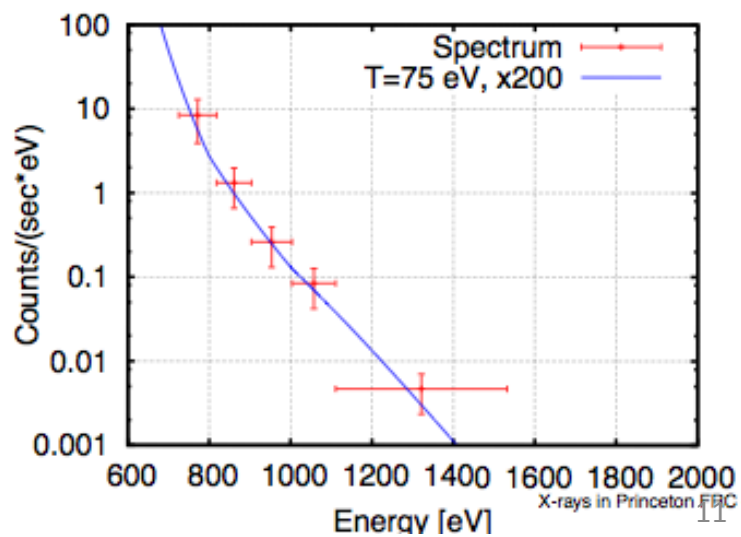
2nd Goal: RMF_o-heated electrons

P_a ~ 6-12 kW, n_e ~ 0.7 -2 x 10^{12} cm^{-3}

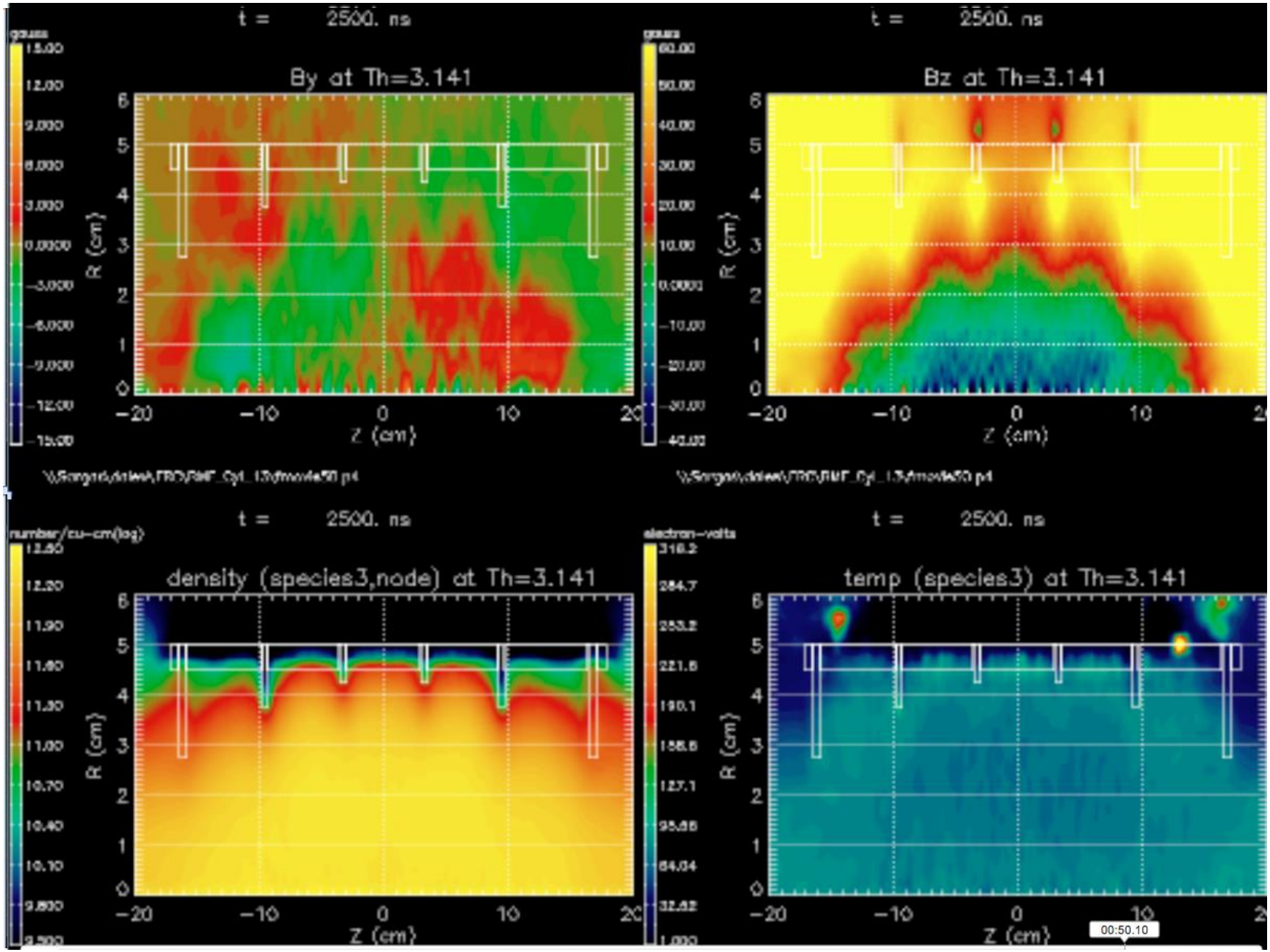








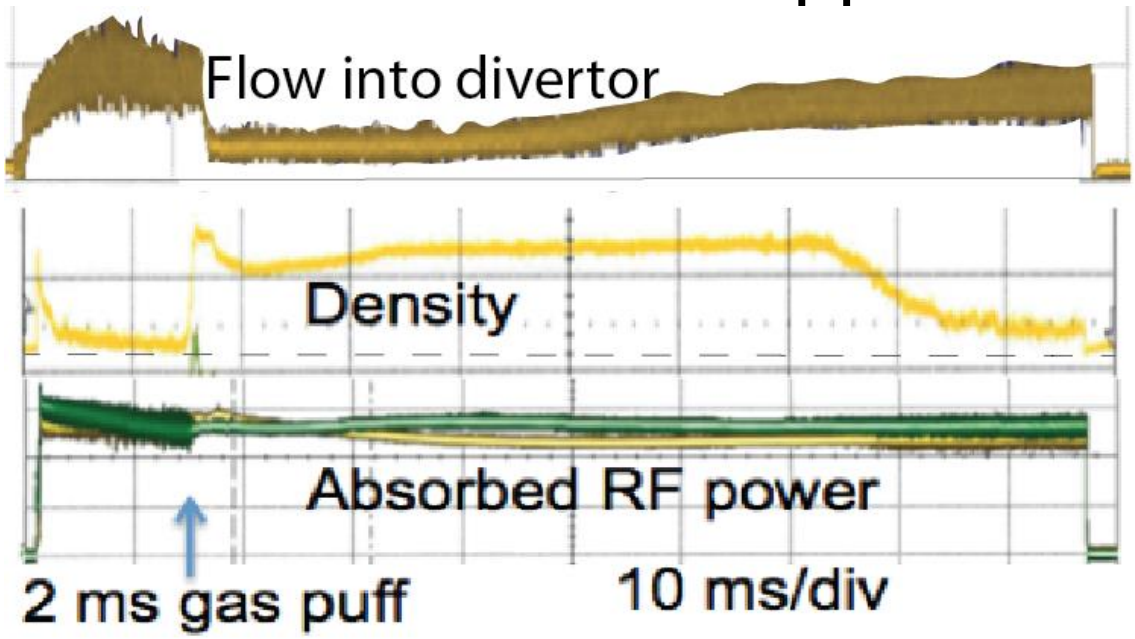
Princeton Field Reversed Configuration Modelling



Princeton Field Reversed Configuration: Next steps

- Ion heating

  $\gamma_D = v_{d,e}/v_{th,I}$ will drop below 1
- MHD and drift turbulence suppression studies



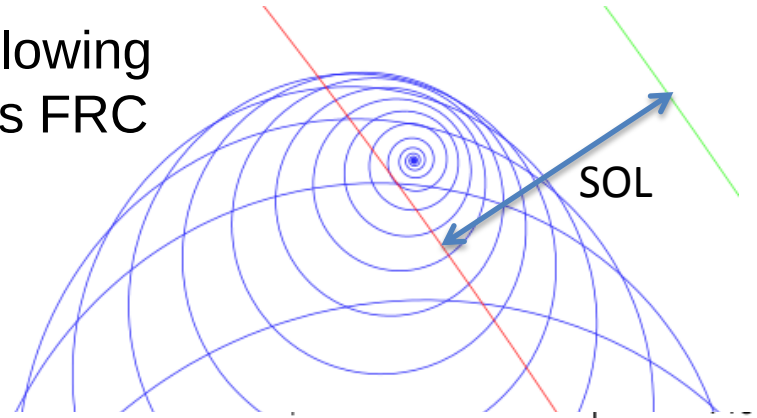
- Current sustainment against electron drag
- GDT operational modes
- Non-local transport studies

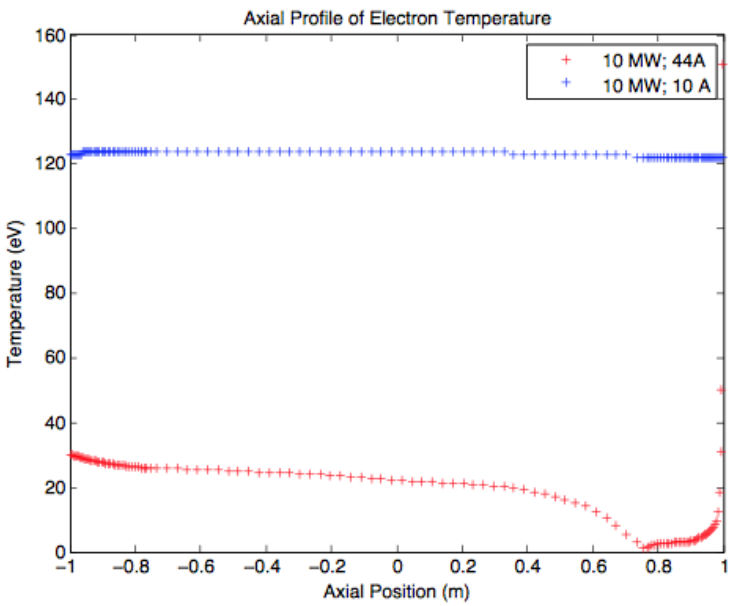
Non-local heat and particle transport into SOL of *small* FRCs

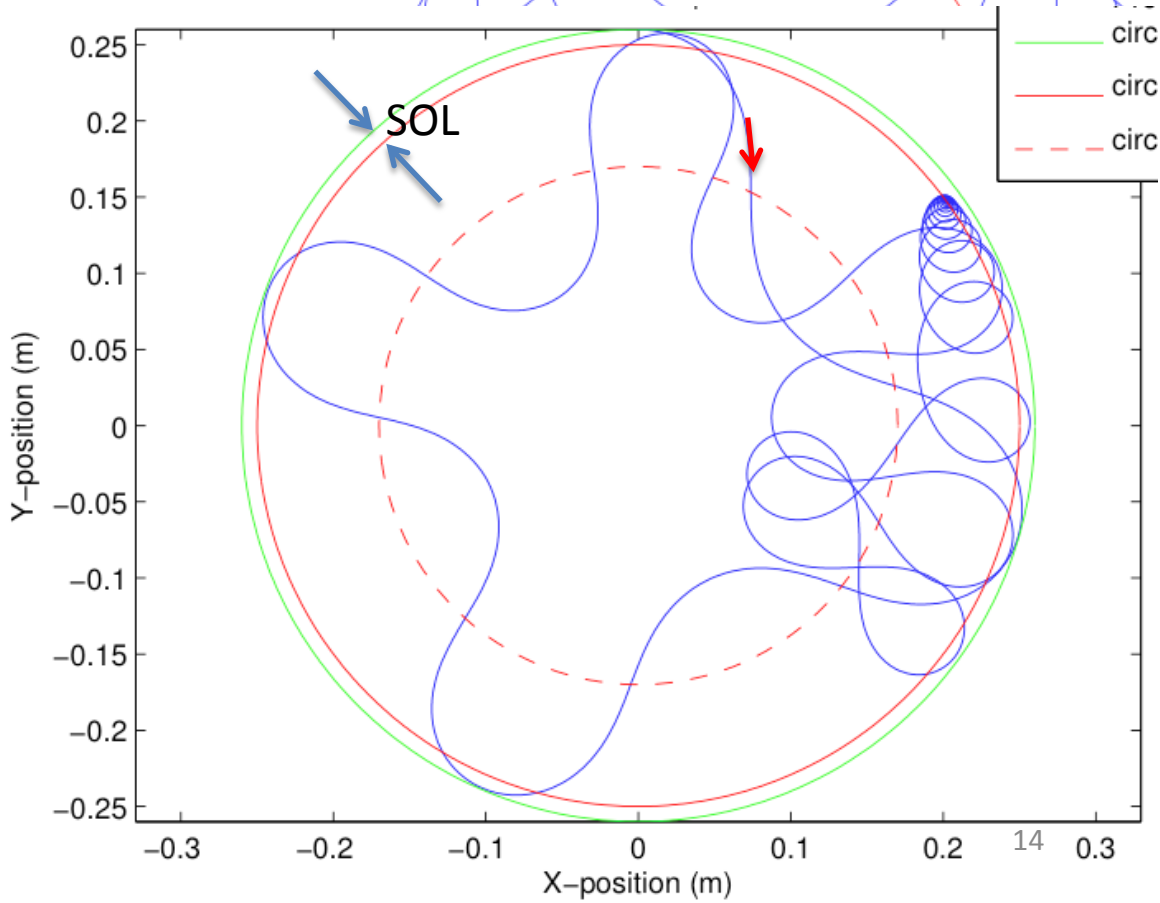
$s = 0.3r_s/\rho_i$

Fusion product	s
^{3}He	8.05
T	3.65
P	3.63
^{4}He	3.38

Trajectory of Triton slowing down in 25-cm radius FRC







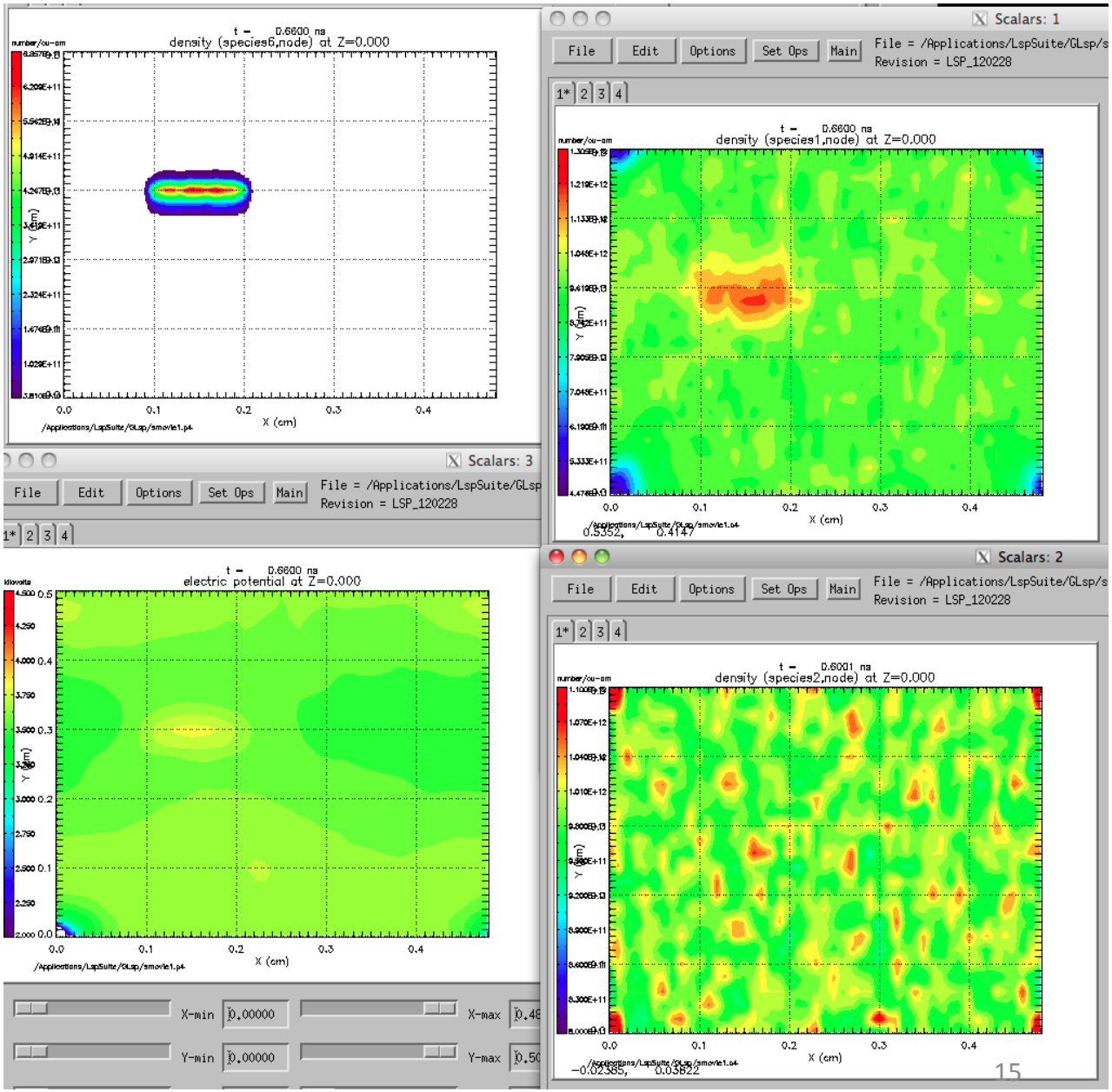
Fast ion slowing down in the FRC SOL

Novel conditions

$v_{EP} > v_{th,e}$

$v_{EP} \perp B$

$\rho_e < \lambda_D$



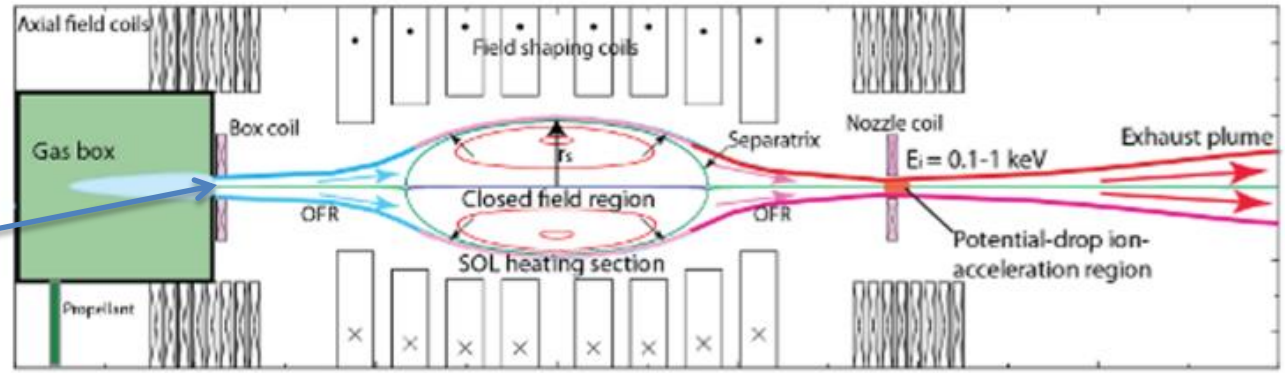
Numerical: Lsp

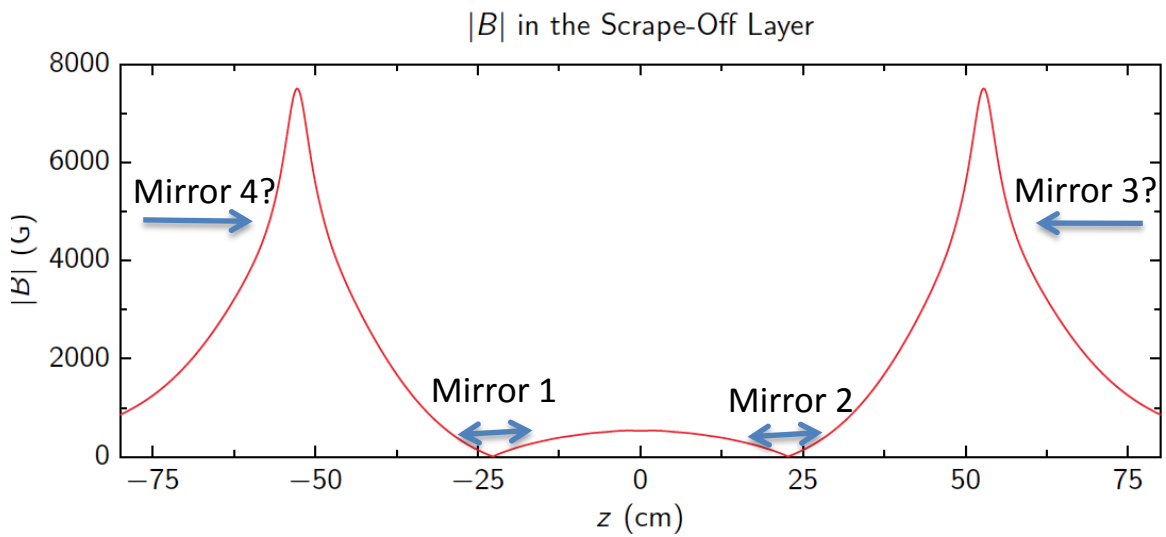
Related analytic:
Ware & Wiley

The FRC as GDT and a Dual Tandem mirror machine

High mirror ratio

High ion flow through mirror and in SOL





FRC loss cone, $-1/12 > p_\phi > 0$, is mirror trapped.

SOL would have relatively low T_e and T_i, even in a reactor.

Summary: Turbulence and Transport when q = 0

Exciting experiments; Promising theoretical techniques; Many mysteries

Common cross-device fundamental physics

- LDX: Low frequency turbulence, High τ_E/τ_n, importance of compressibility

- ASM: axisymmetric stabilization, record T_e, classical radial confinement, suppressed axial losses

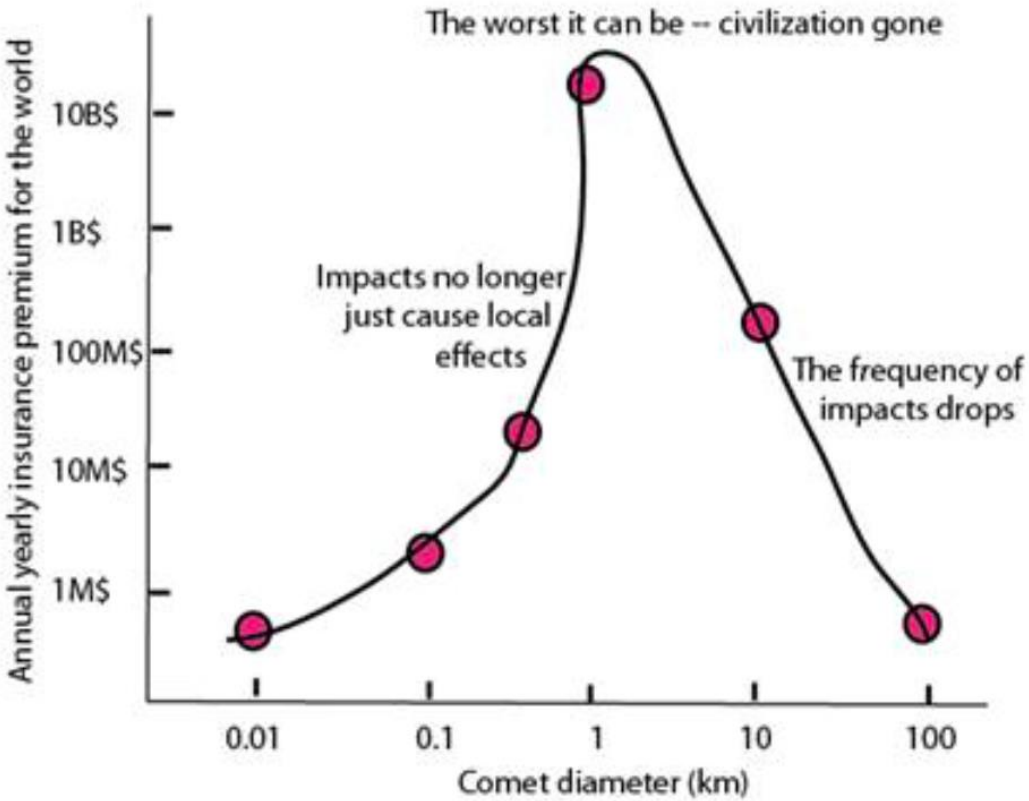
FRCs

- TriAlpha: Supersonic merging, shear stabilized, near classical τ_E
- PFRC: Electron heating, ion heating, stabilization results, non-local transport, GDT and Tandem mirror capabilities

Abundant opportunities on numerous facilities for challenging plasma physics research at an important, relevant, poorly understood frontier

Applications

- Smaller and cleaner fusion power plants
- Spacecraft propulsion
  - Manned exploration
  - DATA Transmission
  - Planetary defense



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