FRC on the Path to Fusion Energy

(Moderate Density Steady-State Approach)

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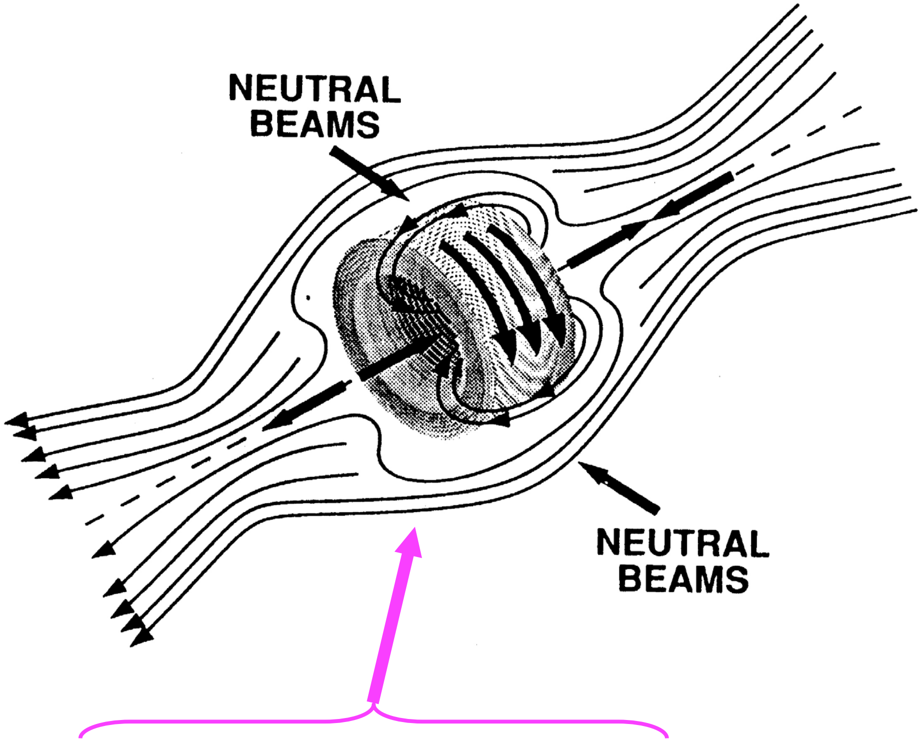
Outline

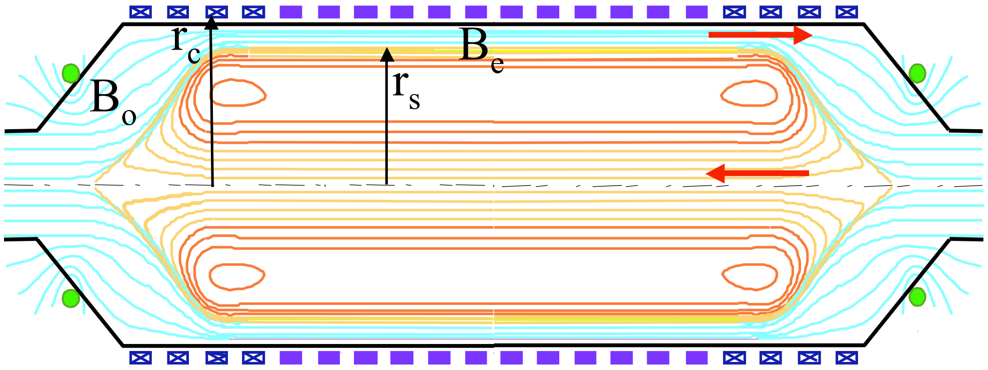
- History – ‘Achieving field reversal’, θ-pinch formation.
- What is an FRC? Why are we interested?
- Recent developments, particularly for steady-state.
- Ultimate promise.

Attempts at Field Reversal have a Long History – supra-thermal ring currents



- ASTRON & Reversed Field Mirrors at LLNL in the 1960s.
- Achieved with pulsed electron rings; ion rings being pursued.

Field Reversed Configurations (FRCs)
(plasma currents producing field reversal)



$x_s \equiv r_s/r_c$

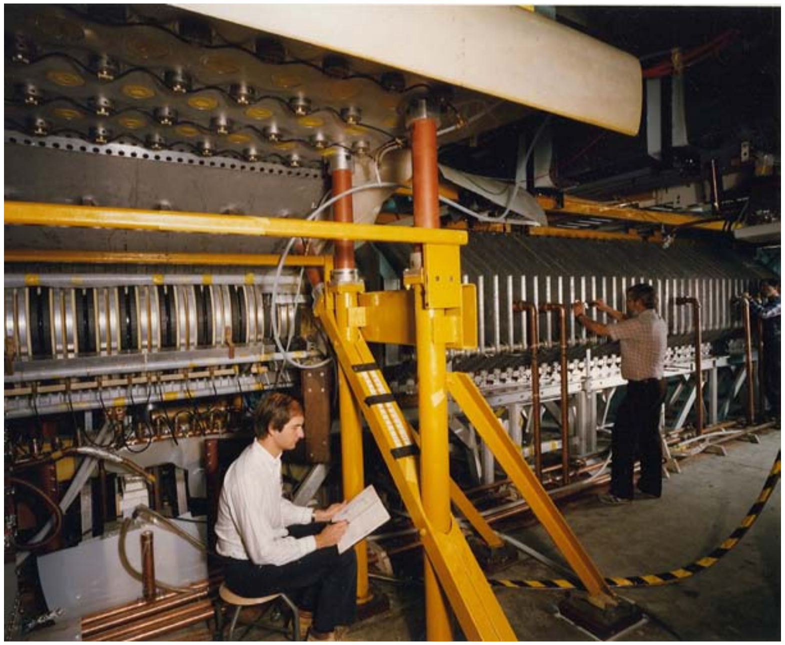
$\langle\beta\rangle = 1 - \_x_s^2$

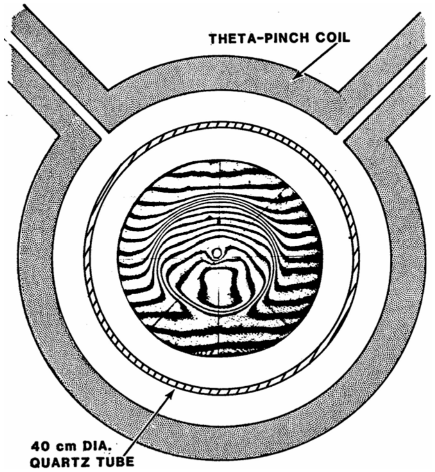
$B_e = B_o/(1-x_s^2)$

- Compact toroid with 'negligible' toroidal field - $0.5 < \langle\beta\rangle < 1.0$
- Simple cylindrical geometry – natural divertor.
- Low magnetic fields – inexpensive reactors & *experiments.*
- Low field region – kinetic physics applies.

υ High voltage θ-pinch formation – best for pulsed approach.

LANL FRXC/T - (1980s)





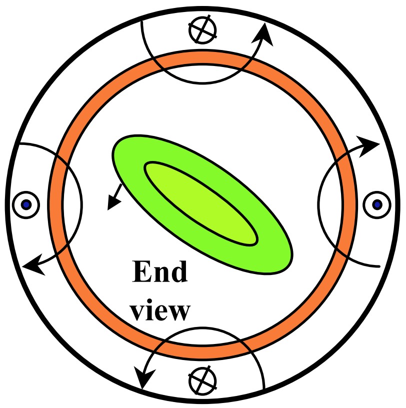
Interferogram taken on FRX-C using holographic interferometry

- FRCs extremely robust – survive dynamic translation, reflection, & capture.
- Translated FRCs develop moderate toroidal fields.
- Evidence of high β minimum energy state in more recent TCS experiments.

- Pulsed plasmas with only ~100s of μsec lifetimes.

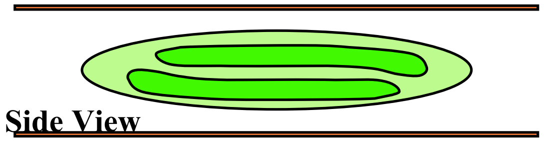
Concerns About Stability

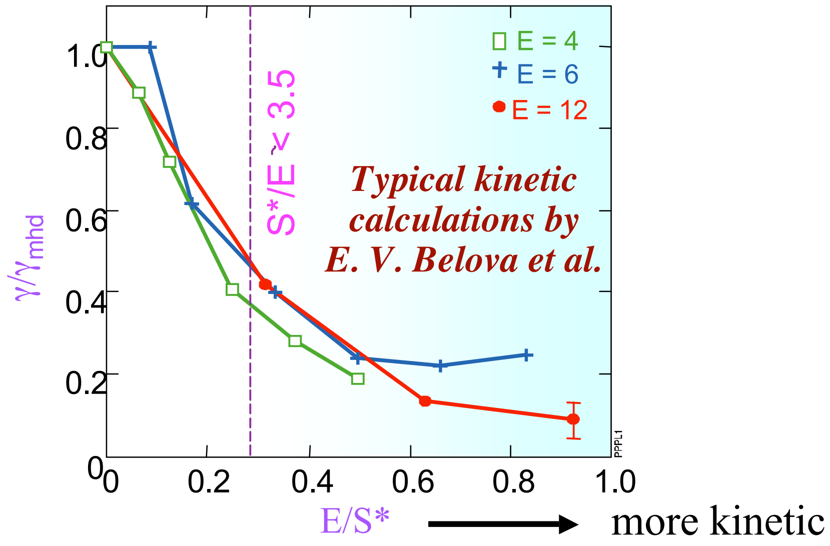
Interchange



- 2-D interchange type instabilities, driven by plasma rotation, have been stabilized by weak multipoles with $B_m^2/2\mu_o$ > centrifugal pressure

Tilt

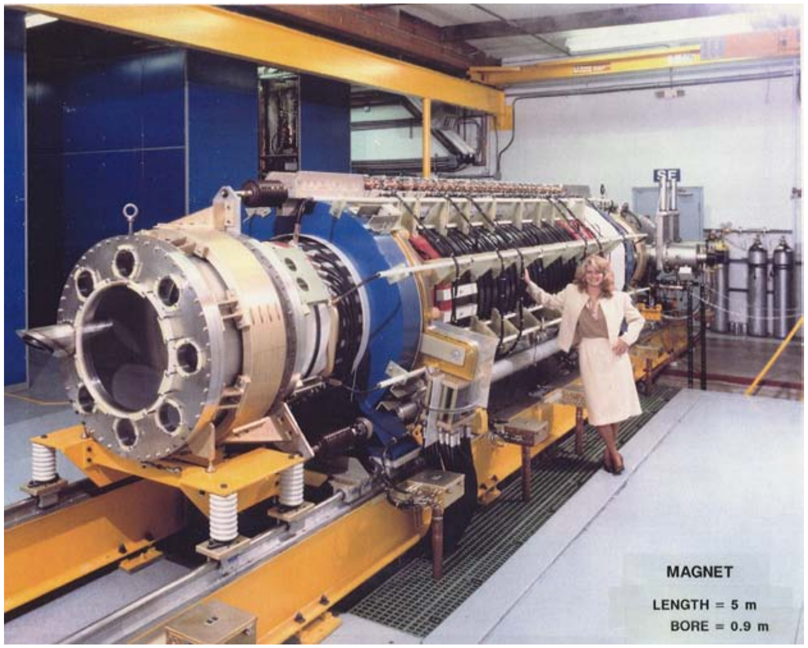


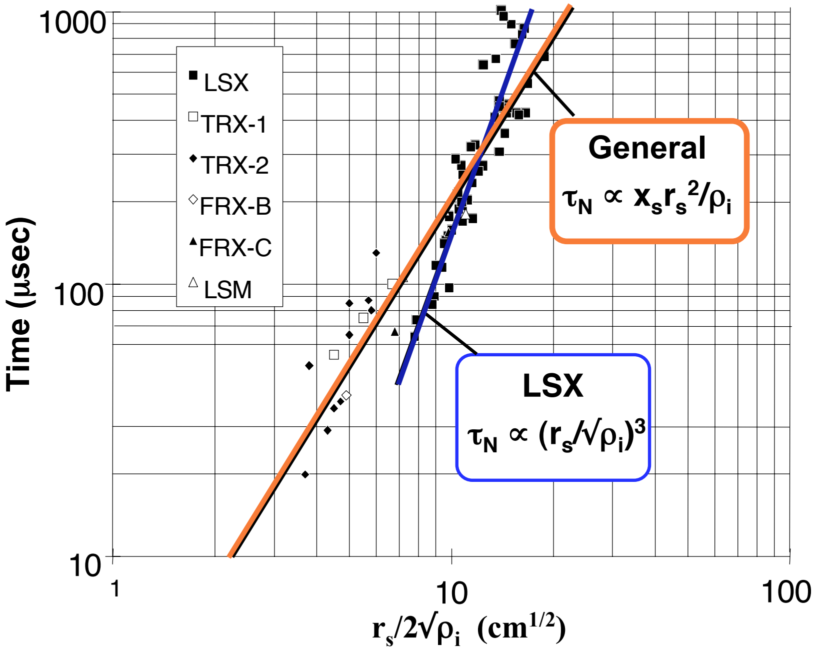


Typical kinetic calculations by E. V. Belova et al.

- Internal tilt is more insidious – kinetic effects are important.

Large s Experiment (LSX) Built at STI to Study Extrapolation to non-Kinetic Regime – (1990).





$$s = \int_R^{r_s} \frac{r\,dr}{r_s \rho_i}$$

Kinetic # of internal gyro-radii parameter

Stable FRCs formed with s up to ~ 4,

$n \sim 10^{21}$ m^{-3}, $n\tau \sim 10^{18}$ m^{-3}s

T_i up to 2 keV T_e up to 0.5 keV

$\tau_\phi \approx \tau_N$ $\tau_E \approx \_\tau_N$

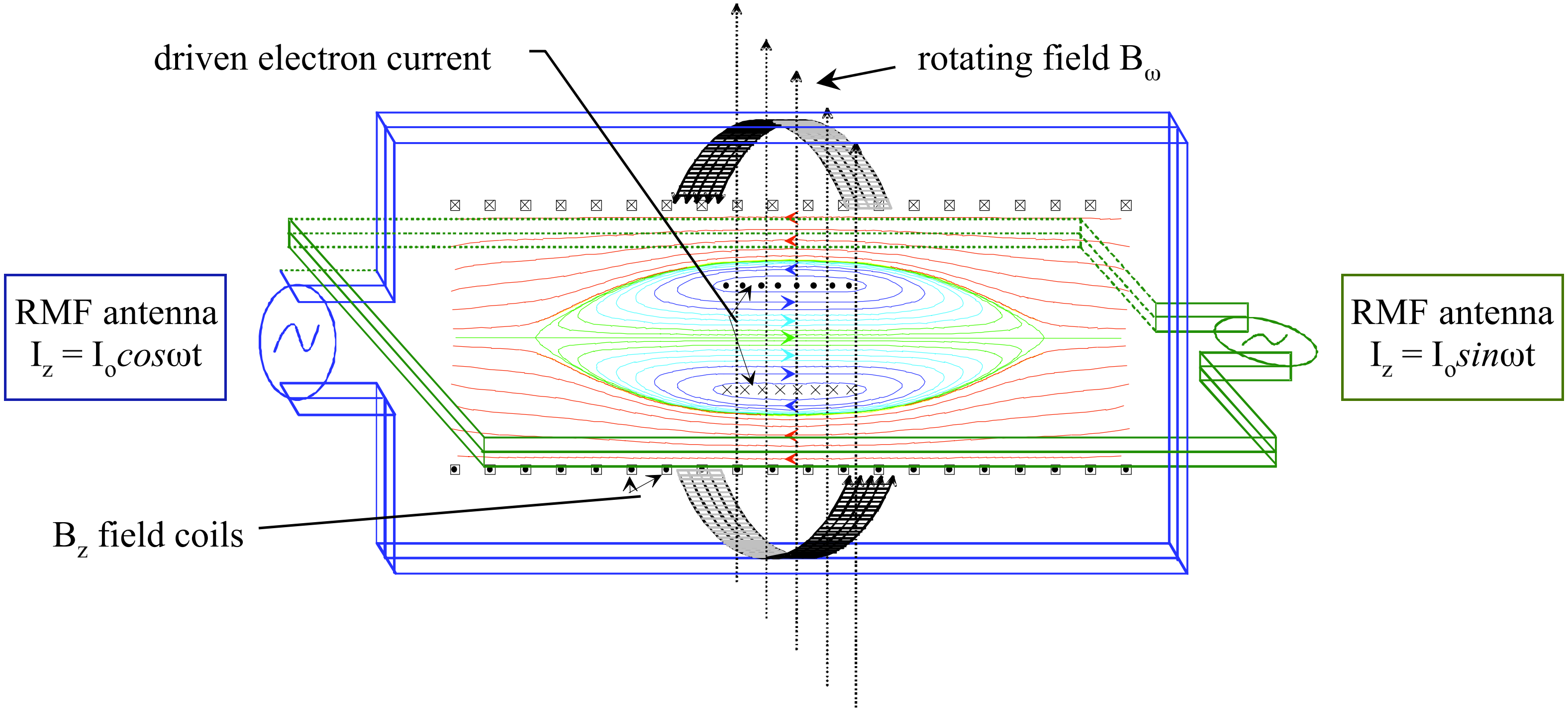
What is needed for *steady-state* compact toroid (CT) reactor?

- Ideal $n_e \sim 1\text{-}2\times10^{20}$ m^{-3}, $T_e = T_i \sim 10$ keV, **$B_e \sim$ 1-1.5T**
- Continued stability up to $s \sim 20\text{-}30$
- Sufficient energy confinement - $n\tau_E > 10^{20}$ m^{-3}s.
- υ Reactor relevant formation methodology
- Efficient sustainment of cross-field diamagnetic current I_θ
  - **$\eta_\perp$ is anomalous**.
  - It is actually the poloidal flux which must be sustained; ($I_\theta = 2B_e/\mu_o$ simply due to diamagnetism)

Techniques for Sustaining FRCs (also enhance stability)

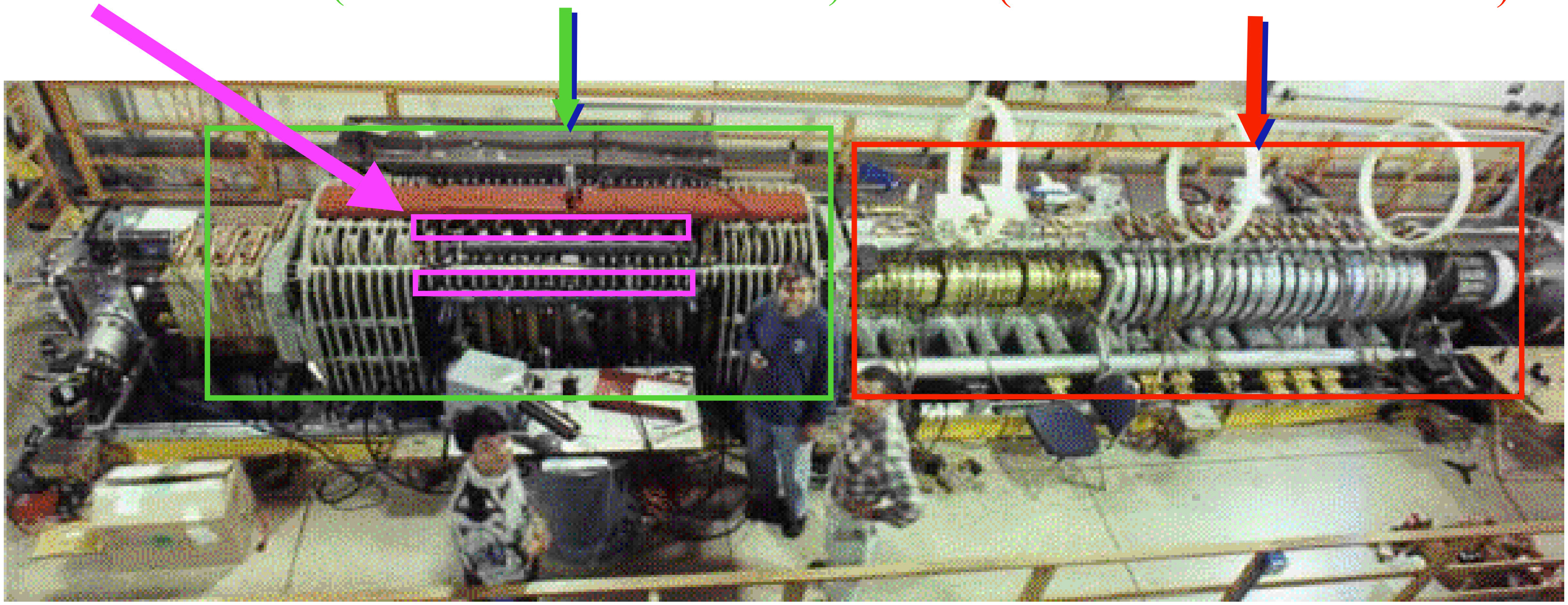
- Tangential Neutral Beam Injection (TNBI)
  - Kinetic ions should be stabilizing (low s particles).
  - Studied in Japan and proposed by PPPL & UW. *No current experiments.*
- Rotating Magnetic Fields (RMF) can drive electrons in same manner as induction motor. (Also formation technique.)
  - Provides stabilizing inward radial force
  - Developed in Australia and adopted by UW. *Recently demonstrated in TCS.*
- **Key parameter is anomalous cross field resistivity, $\eta_\perp$, since it determines current drive** (or flux sustainment) **power requirements.**
  - ***All transport may be related to this parameter.***

RMF Current Drive (dipole fields)



- Simple loop antennas with ~10-200 kHz RF phased 90° apart
- ‘Drag’ electrons along with rotating radial field

TCS
(Translation, Confinement, Sustainment)



RMF Antennas

TCS Chamber

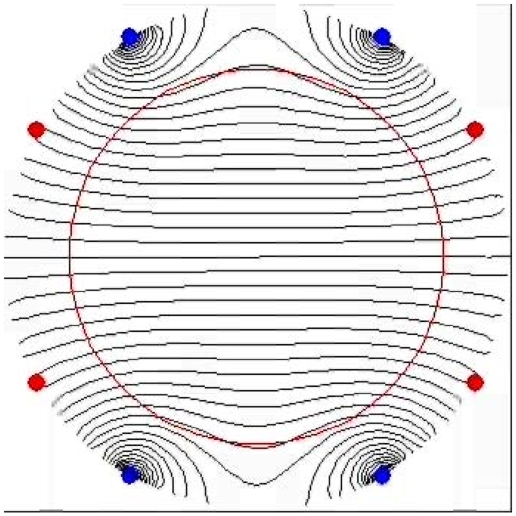
(confinement & RMF drive)

LSX/mod

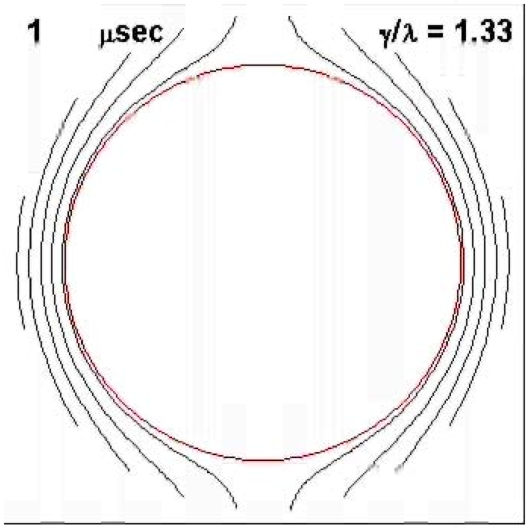
(formation & ‘acceleration’)

Primarily interested in FRC formation & sustainment by RMF alone.

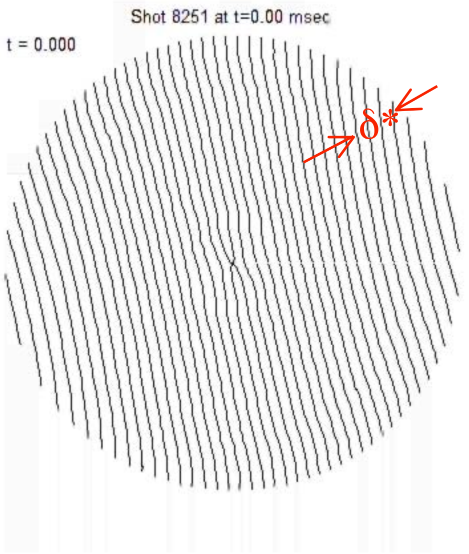
Partial RMF Penetration is Natural Occurrence



Vacuum **calculation** in lab frame of reference



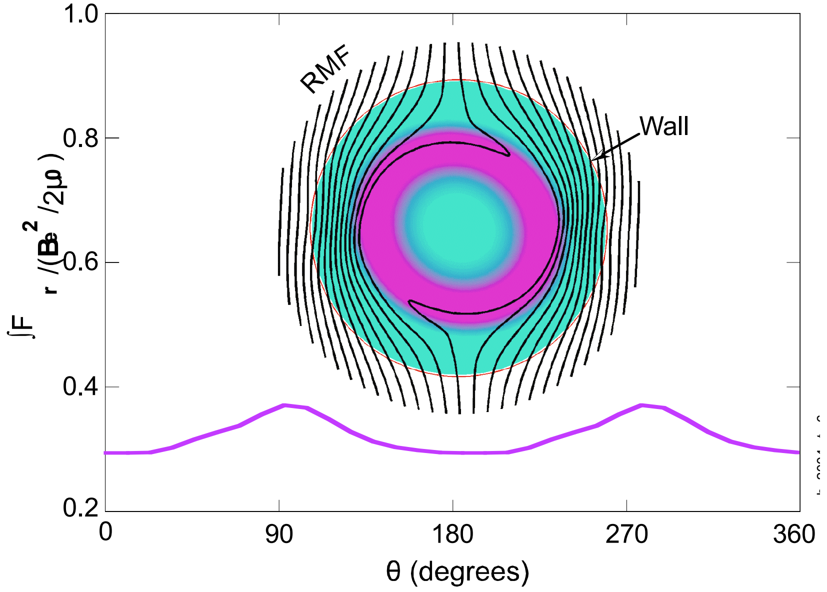
Plasma **calculation** in RMF frame of reference.
(Calculation needs to start from already formed FRC)



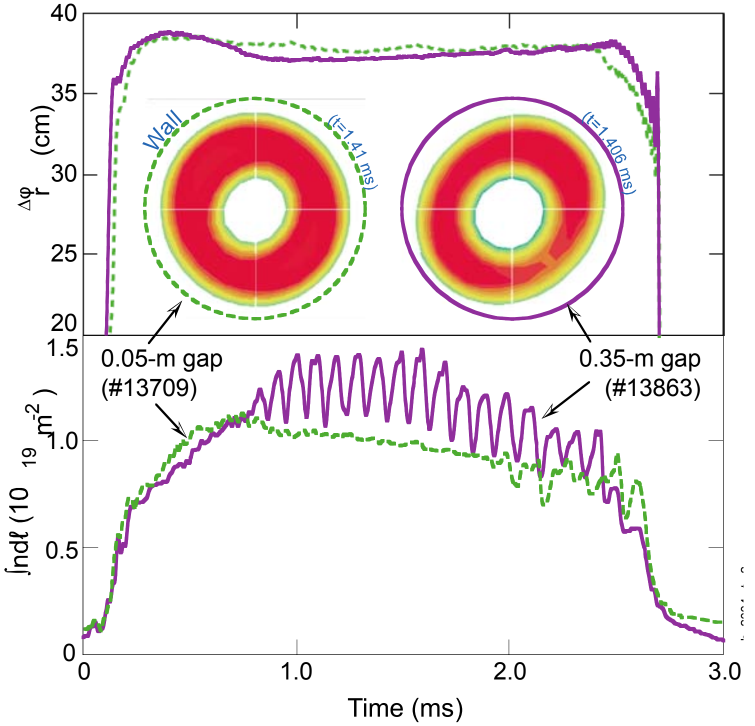
Plasma **measurement** in RMF frame of reference

$$\boxed{T_{RMF} = \frac{2\pi r_s^2 B_\omega^2}{\mu_o}\,\frac{\delta^*}{r_s}}$$

2D Interchange Stability Provided by Partially Penetrated RMF

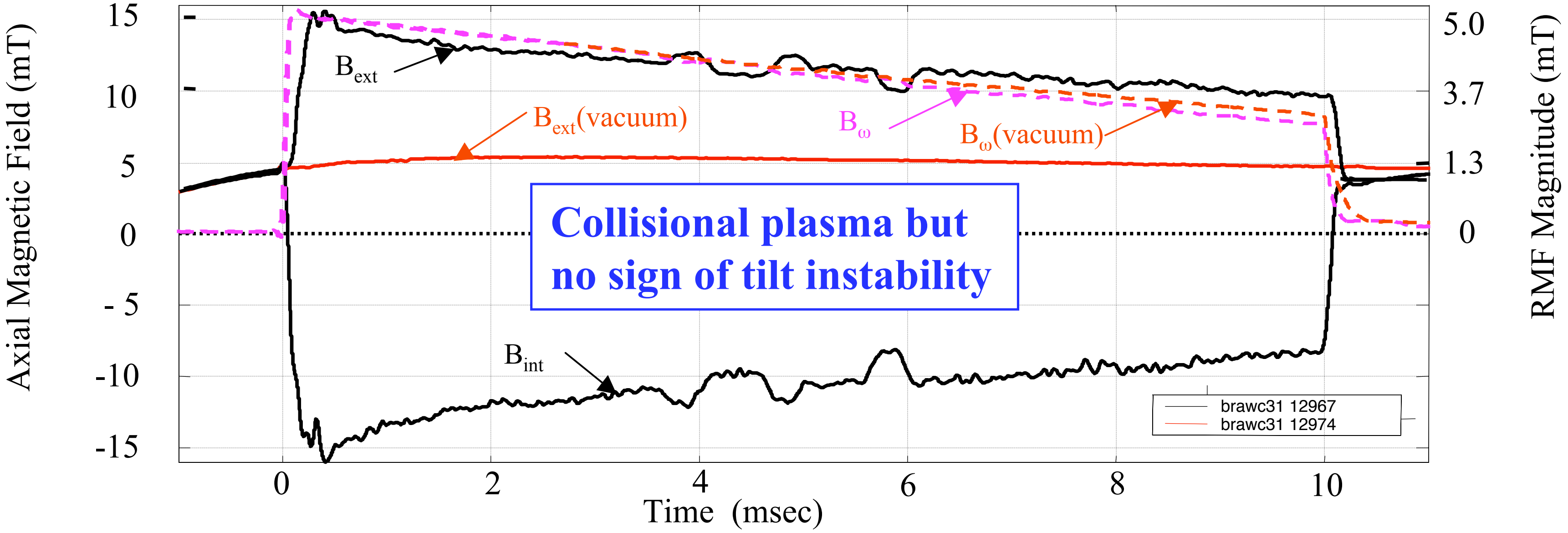


Calculations show strong restoring forces to rotationally driven interchange instabilities, such as the ubiquitous rotating n=2.



Observation of stabilizing effect on rotational n=2 instability when RMF antennas extend over central region

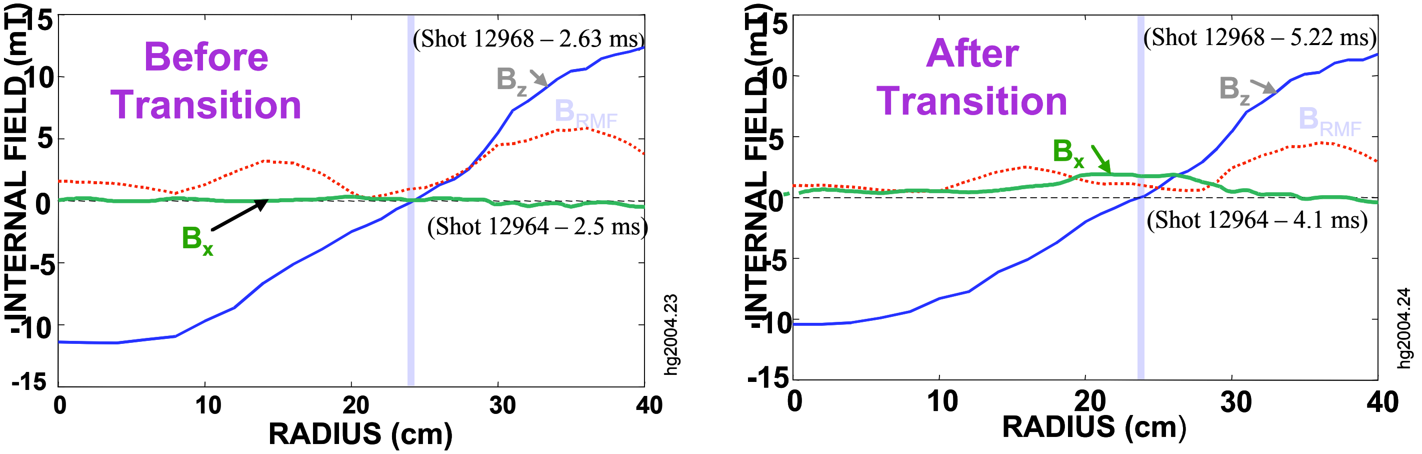
RMF also reverses radial particle diffusion & results in long particle lifetime

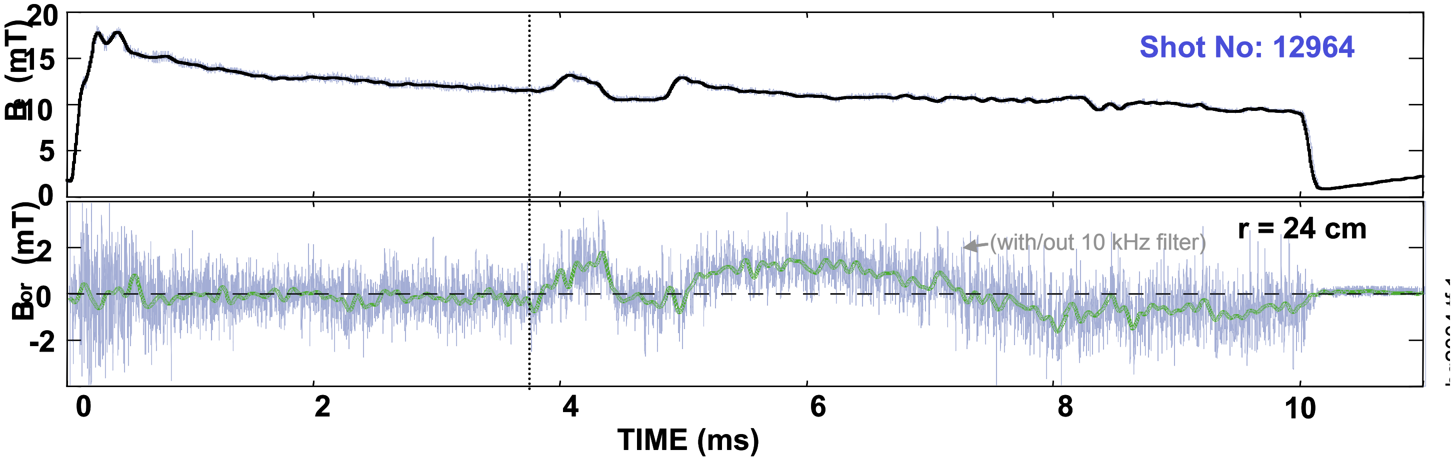


Collisional plasma but no sign of tilt instability

- Nominal 'τ_N' extended by at least factor of 10.
- 'Steady-state' sustainment due to recycling with pulse length only limited by RMF power supply.

Also see spontaneous toroidal field development: further evidence for a minimum energy state (MES)





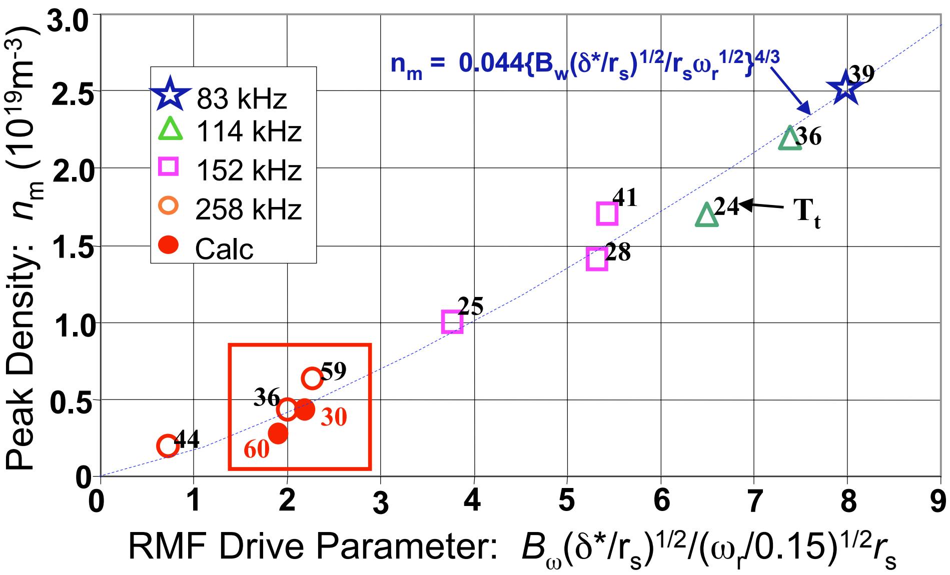
Plasma density depends on $\eta_\perp$

Resistive Torque

$$T_\eta \propto \eta_\perp n_e^{3/2} T_t^{1/2} r_s^{2}.$$

$$\eta_\perp \sim \frac{50}{n_m^{1/2}(10^{19}\,\mathrm{m}^{-3})} \quad \mu\Omega\text{–m}$$

Same as seen in high density θ-pinch formed decaying FRCs

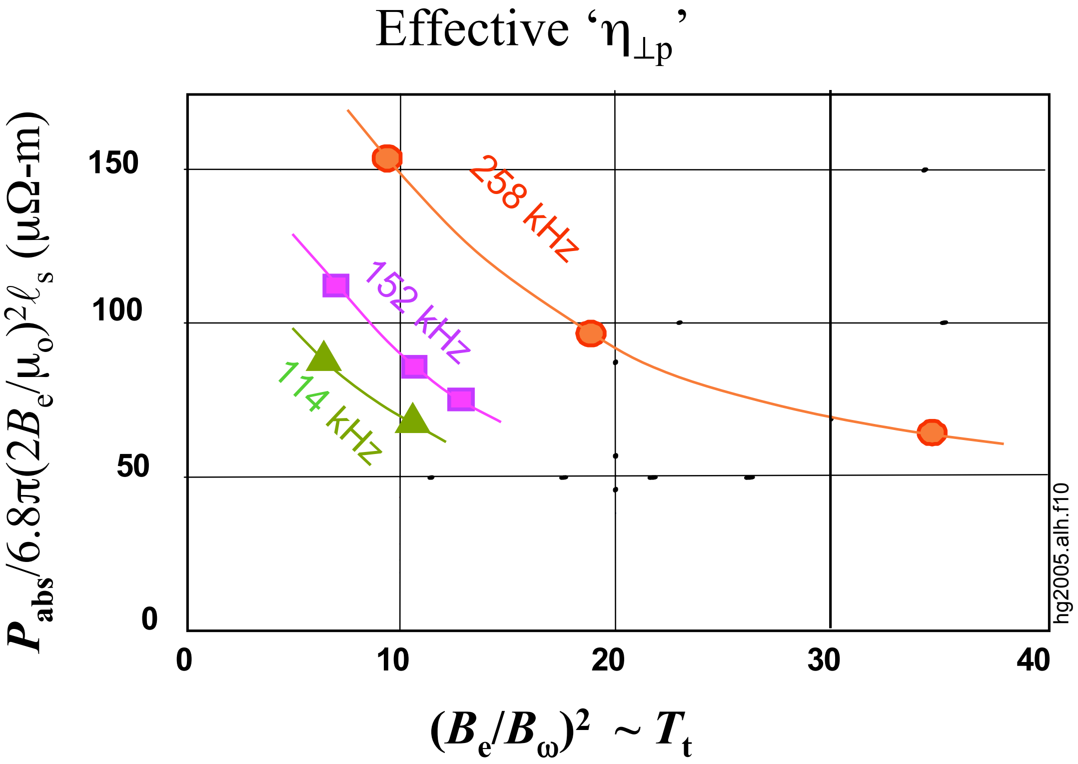


◆ Also see rapid reductions in $\eta_\perp$ with increasing temperature.

υ (In calculations with constant $\eta_{\perp,}$ n_m decreases with T_t, while experimentally it increases).

υ Observed dependencies are characteristic of $\eta_\perp$ decreasing with v_{de}/v_{sound}, as seen in all empirical scaling, and supported by recent two-fluid numerical calculations.

Relative current drive power also decreases with temperature



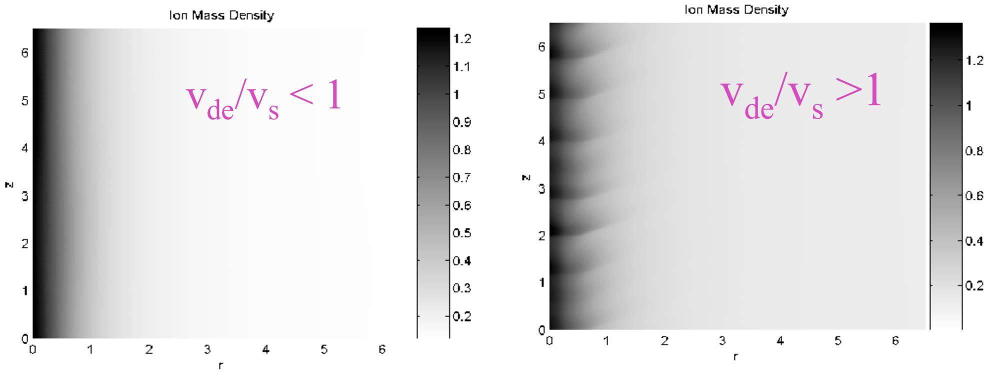
10,000 in reactor

Experimental results described well by empirical ‘Chodura’ formula, dependent on v_{de}/v_s.

$$\eta_{\mathrm{Chod}} = \frac{1050}{n_e^{1/2}(10^{19}\,\mathrm{m}^{-3})}\left(1 - e^{-v_{de}/v_{ti}}\right)\ \mu\Omega\text{–m}$$

Provided best numerical match to formation and translation experiments

Strong v_{de}/v_s scaling supported by recent numerical calculations.

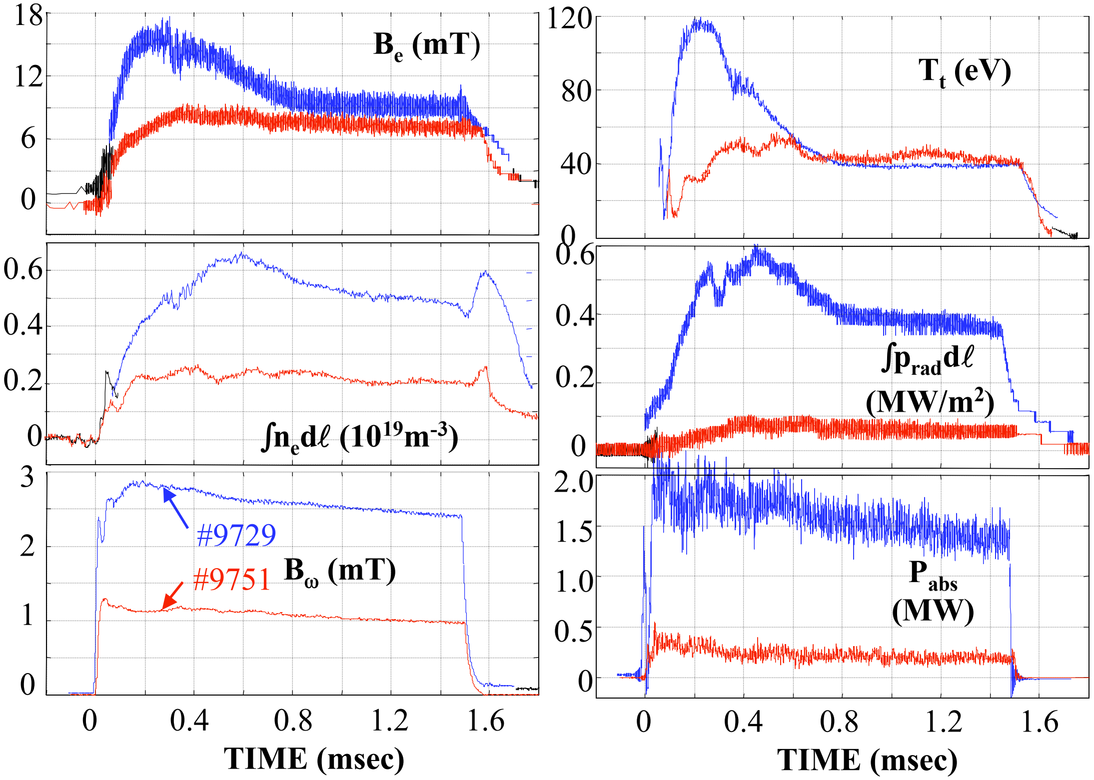


***Non-linear 2-fluid calculations of instabilities in a Z-pinch by Loverich & Shumlak for various v_{de}/v_s.**

Projected v_{de}/v_s ratios

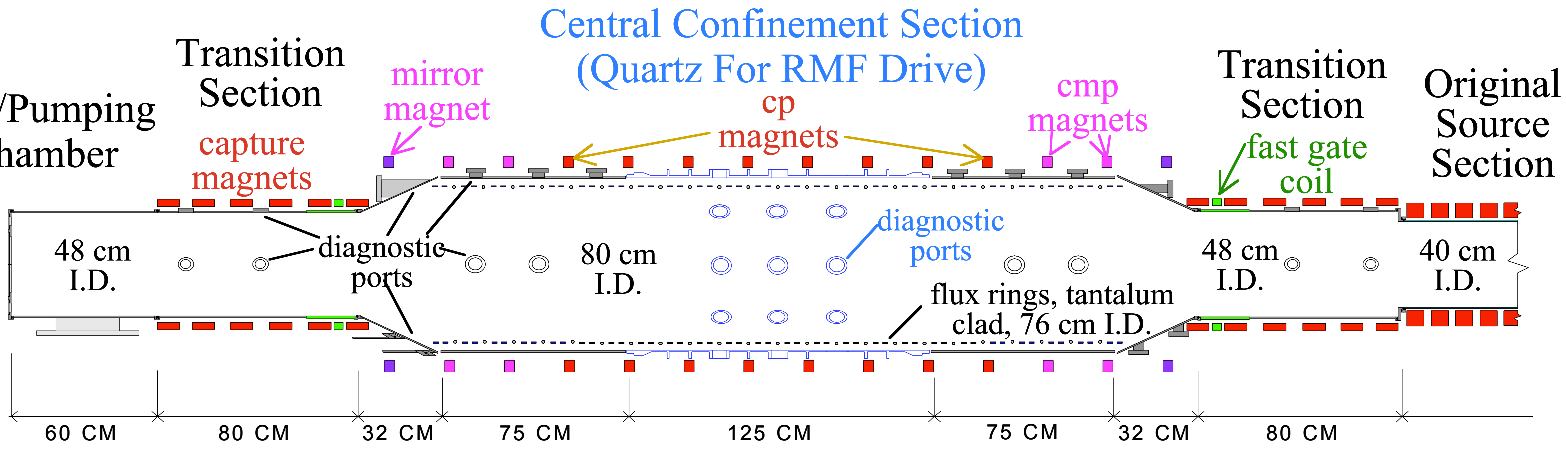
	TCS	TCSU (goals)	Reactor
$n_e\,(10^{20}\mathrm{m}^{-3})$	0.2	0.3	1.0
T_t (keV)	0.05	0.3	25
B_e (T)	0.02	0.06	1.0
r_s (m)	0.4	0.35	2.5
f_ω (kHz)	100	100	10
v_{de}/v_s	**4**	**1.5**	**0.1**

TCS Temperature (and Flux) Limited in Present Experiments – at least partially by impurities



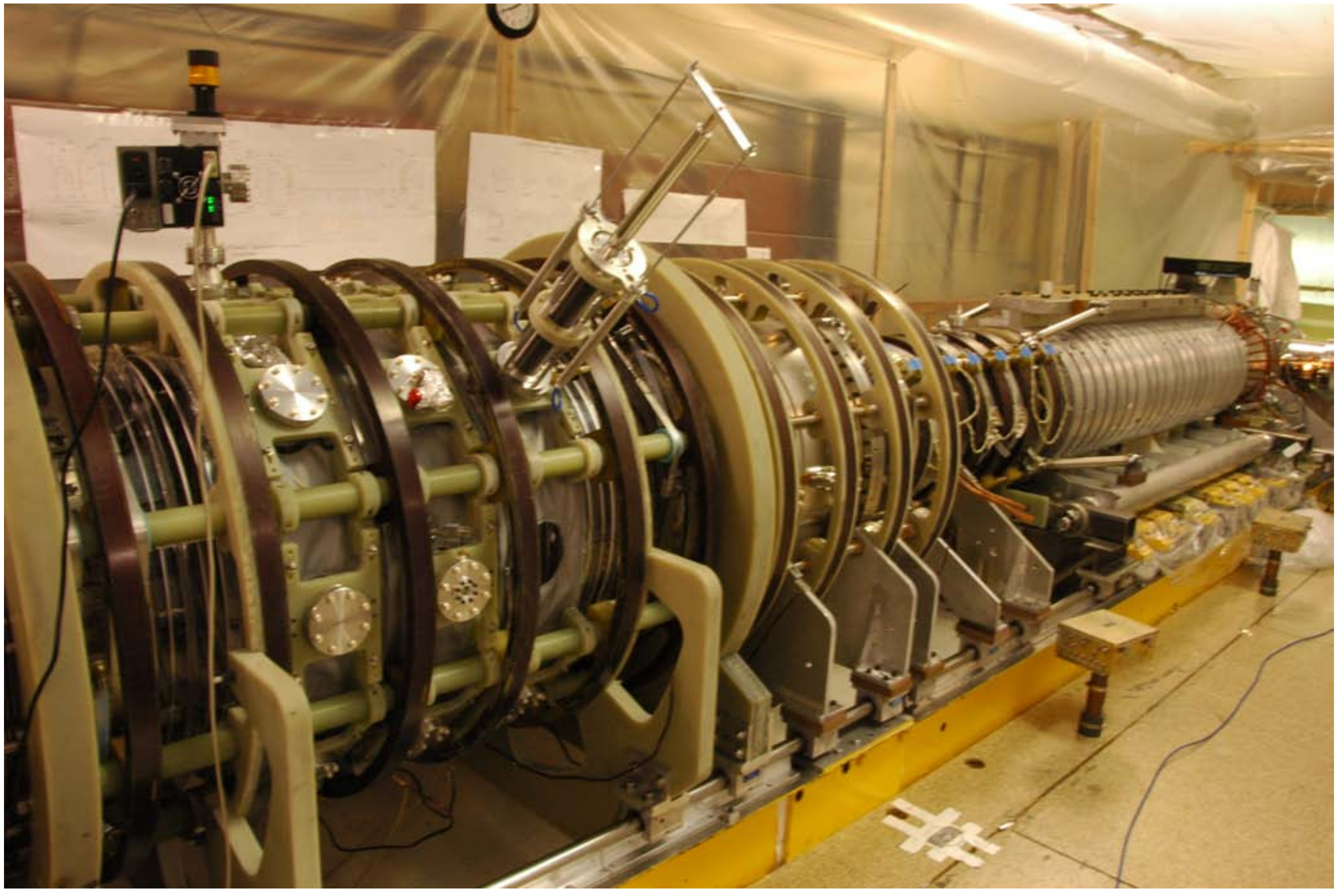
Operation at High $\omega = 1.62\text{x}10^6$ s^{-1} and Low B_ω with *symmetric* RMF current drive & *θ-pinch vacuum technology*

TCS/upgrade Built to Reduce Impurity Level and Radiative Losses



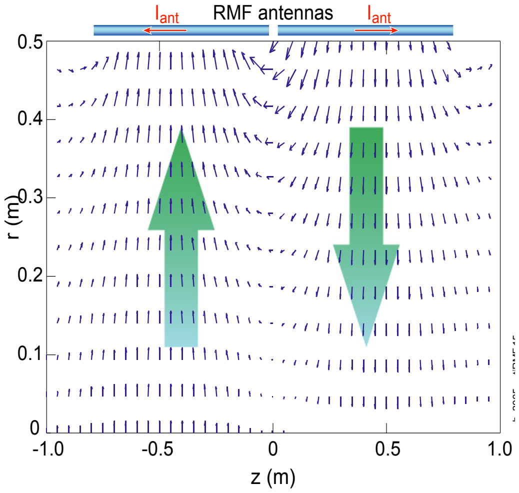
- Larger, metal input section to avoid translated FRC contact with quartz.
- Protective tantalum covered flux rings under quartz RMF drive section.
- Elimination of Viton “O-rings” to allow bakeout and discharge cleaning.
- Ti-gettering or siliconization wall conditioning.

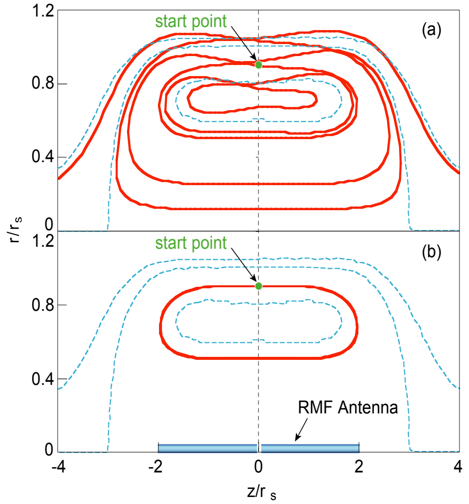
TCS/upgrade

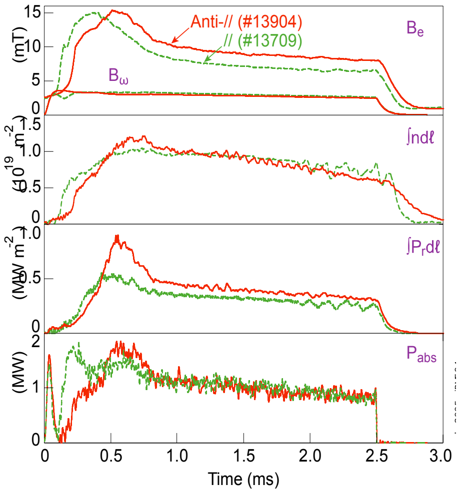


Recent Interesting Results

- Anti-symmetric RMF (originally proposed theoretically) results in completely closed field lines and, hopefully, good thermal confinement.



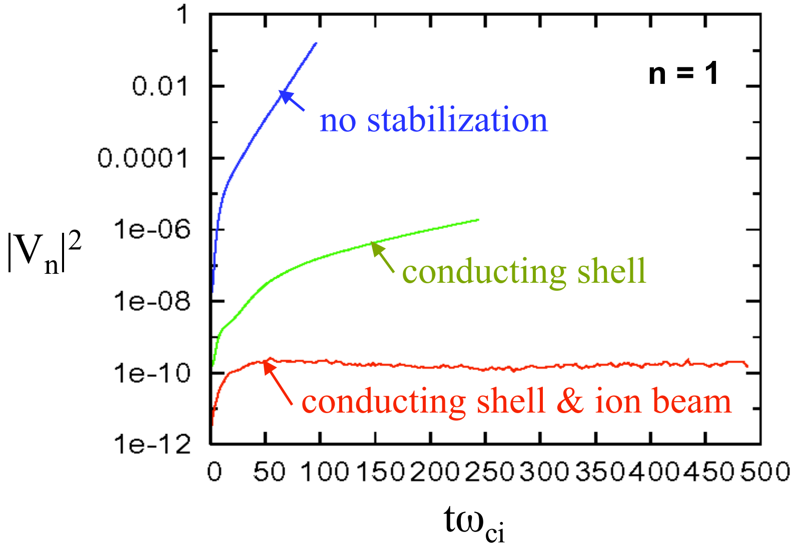


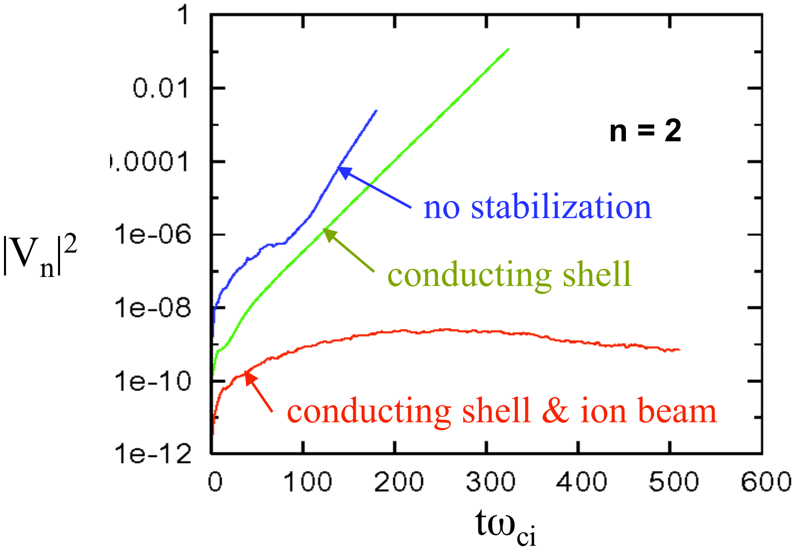


Recent PPPL kinetic calculations show promise of complete stability

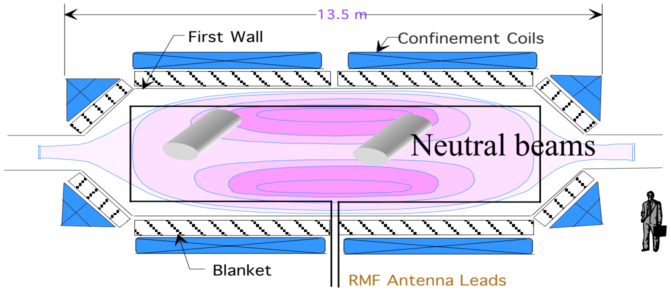
HYM simulations for oblate FRCs (E~1) with a close-fitting conducting shell and energetic beam ion stabilization:

- *Linearly stable with respect to the n=1 tilt mode and the n=2 modes*
- *Residual instabilities saturate nonlinearly at small amplitudes*
- *Configuration remains **MHD** stable, if current is sustained.*



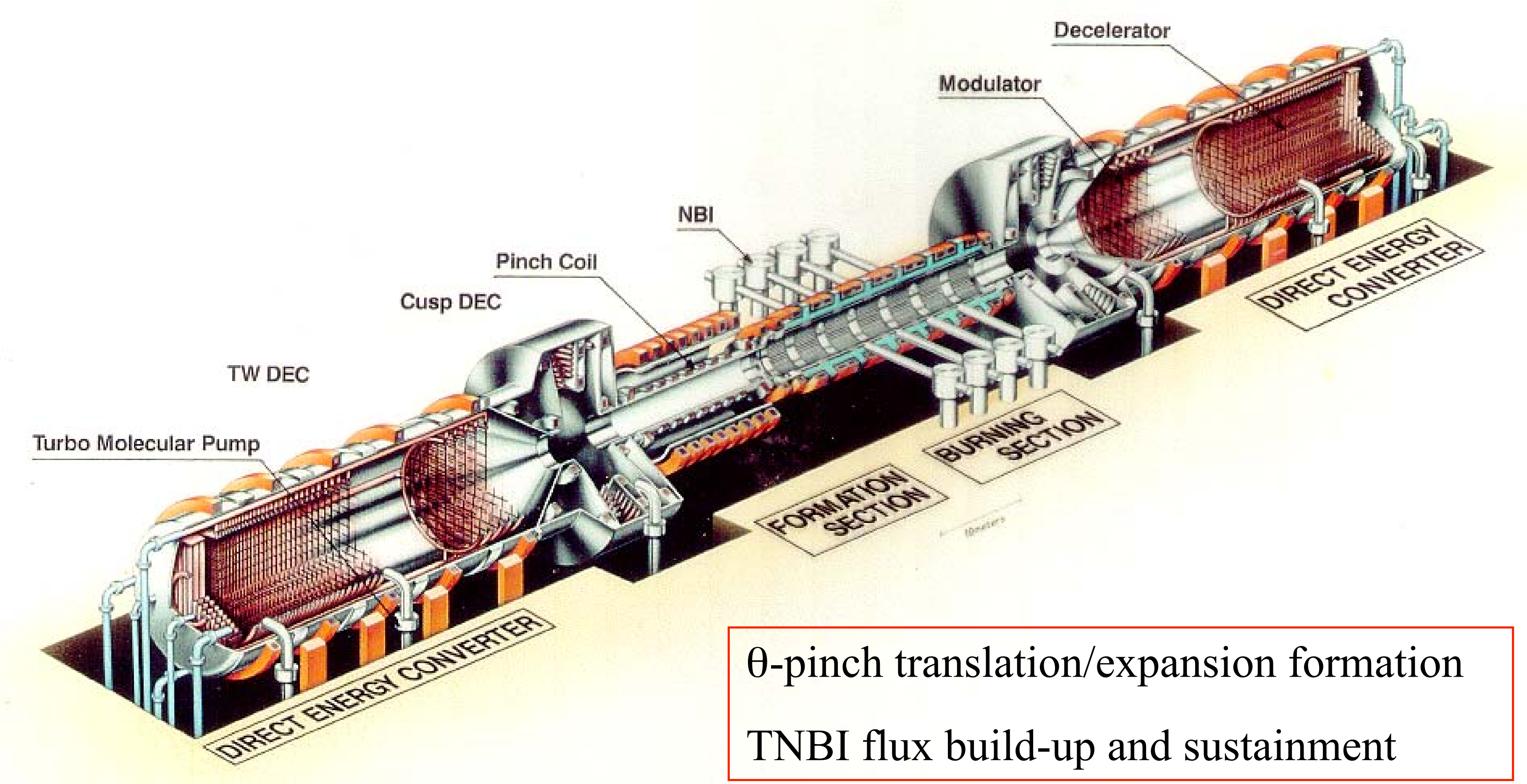


Summary



- FRCs are a simple, surprisingly robust confinement scheme.
- Unique plasma configuration:
  - Ideal reactor attributes (high β, simple geometry with natural divertor, advanced fuel potential).
  - Interesting plasma studies of $\eta_\perp$ and high-β MES in simple geometry.
- Formation and sustainment has been demonstrated by RMF.
- RMF with TNBI could provide stability and efficient current drive.
- $\eta_\perp$ scaling with v_{de}/v_s is favorable for reactor.
- If TCSU is successful, the next step would be a larger device, including TNBI.
  - with lower v_{de}/v_s.
- **RMF current drive is simple, robust, and now relatively inexpensive!**

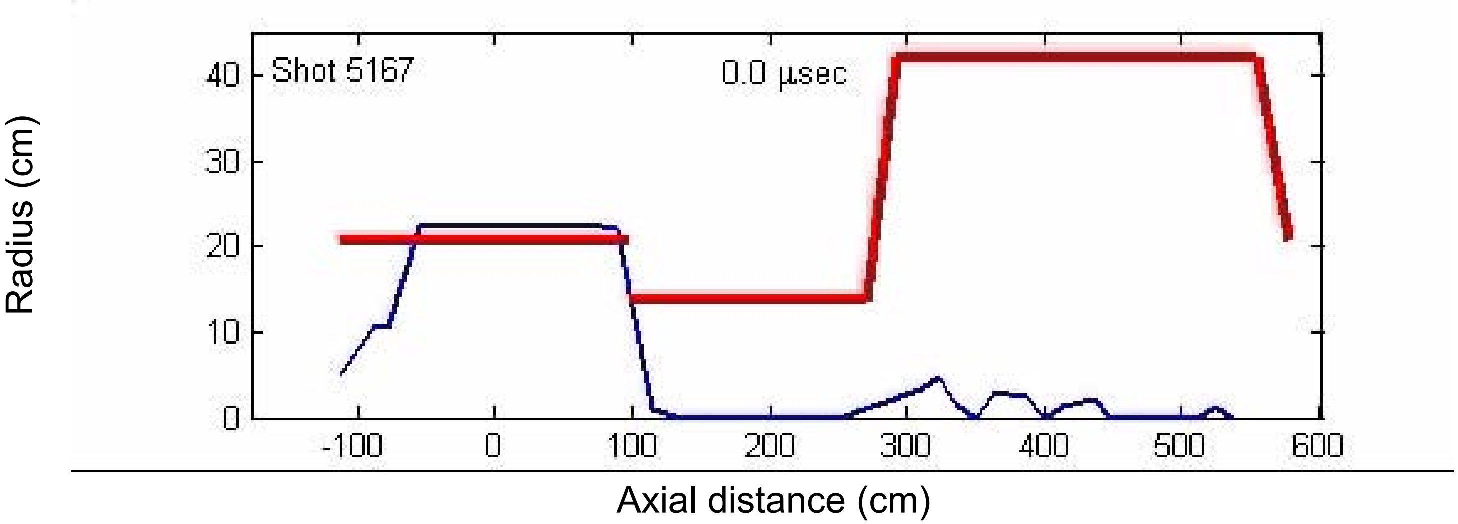
ARTEMIS Design (D-^{3}He)



θ-pinch translation/expansion formation

TNBI flux build-up and sustainment

FRC Translation Demonstrates Robustness (at least at low s)



- Wanted to reduce n_e from **$5x10^{21}$ m^{-3}** in formation section **(B_e~ 0.5-1.0 T)** to **$5x10^{19}$** in TCS sustainment chamber **(B_e ~ 50-100 mT)** without significantly degrading temperature.
- This is made possible by non-isentropic recovery of high (~ 400 km/s) translation energy.
- FRC exhibits remarkable robustness in surviving violent reflections off end mirrors.