



FRC on the Path to Fusion Energy

(Moderate Density Steady-State Approach)

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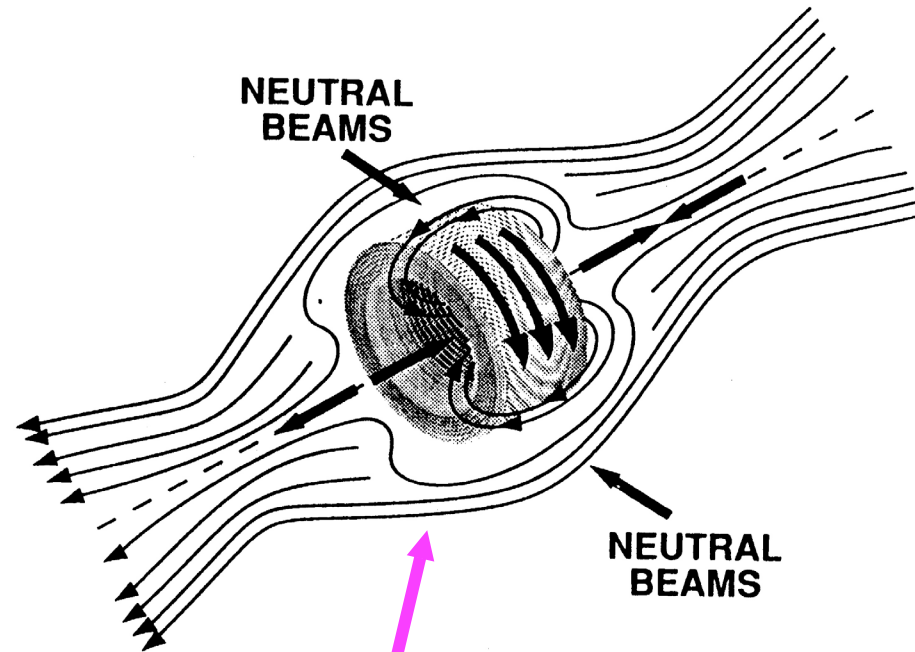
(FPA Meeting on Fusion Pathways to the Future)
(September 27-28, 2006)

Outline



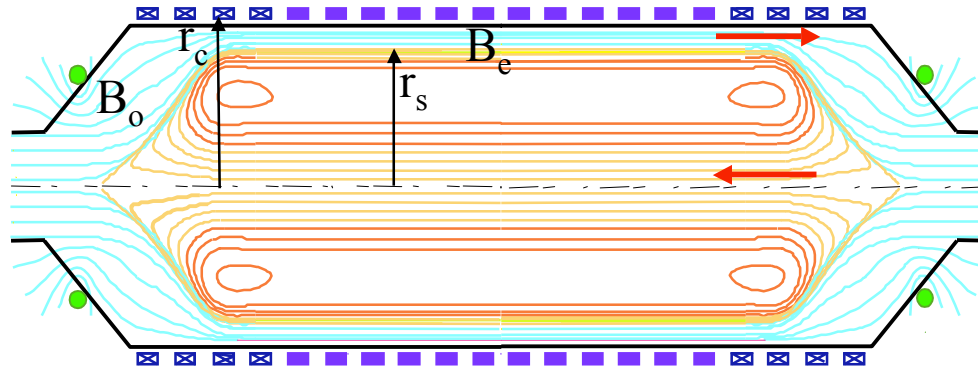
- ◆ History – ‘Achieving field reversal’, θ -pinch formation.
- ◆ What is an FRC? Why are we interested?
- ◆ Recent developments, particularly for steady-state.
- ◆ Ultimate promise.

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)



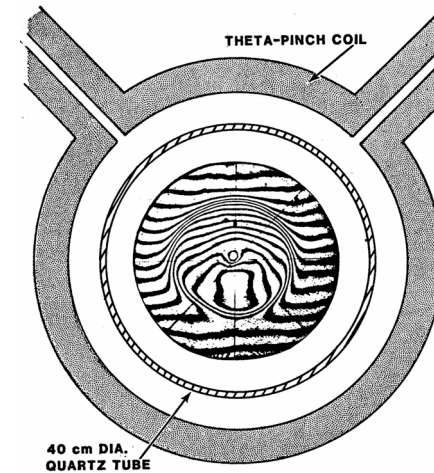
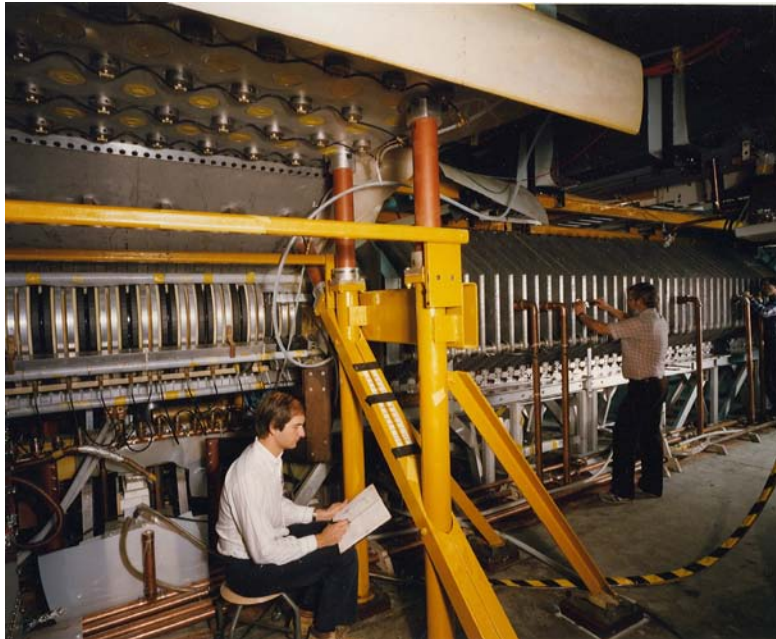
$$x_s \equiv r_s/r_c$$

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

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

- ◆ 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)



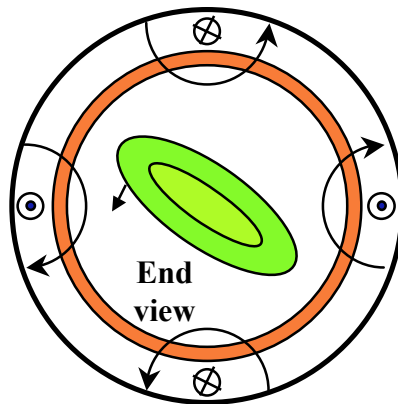
Interferogram taken on FRX-C
using holographic interferometry

- ◆ 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 ~ 100 s of μ sec lifetimes.

Concerns About Stability

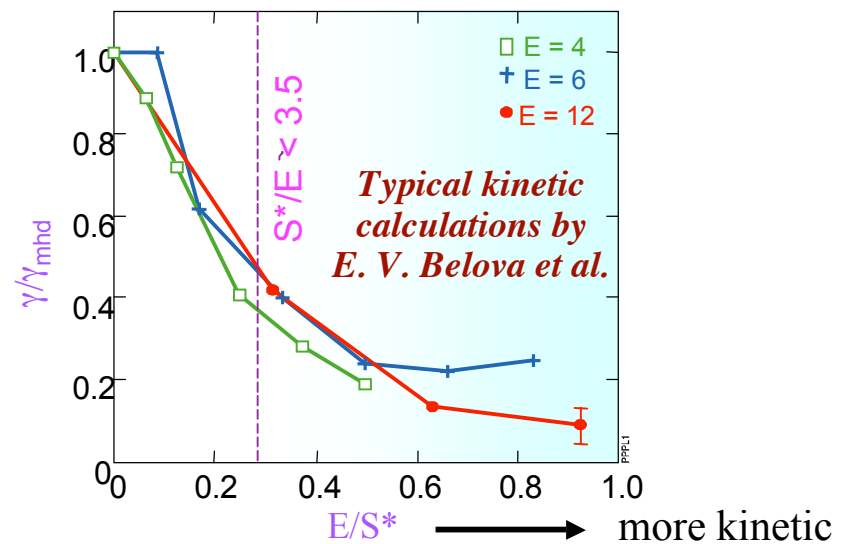
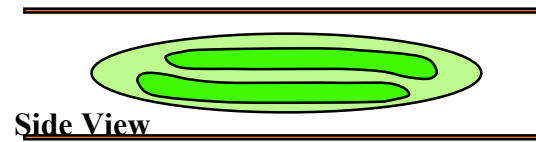


Interchange



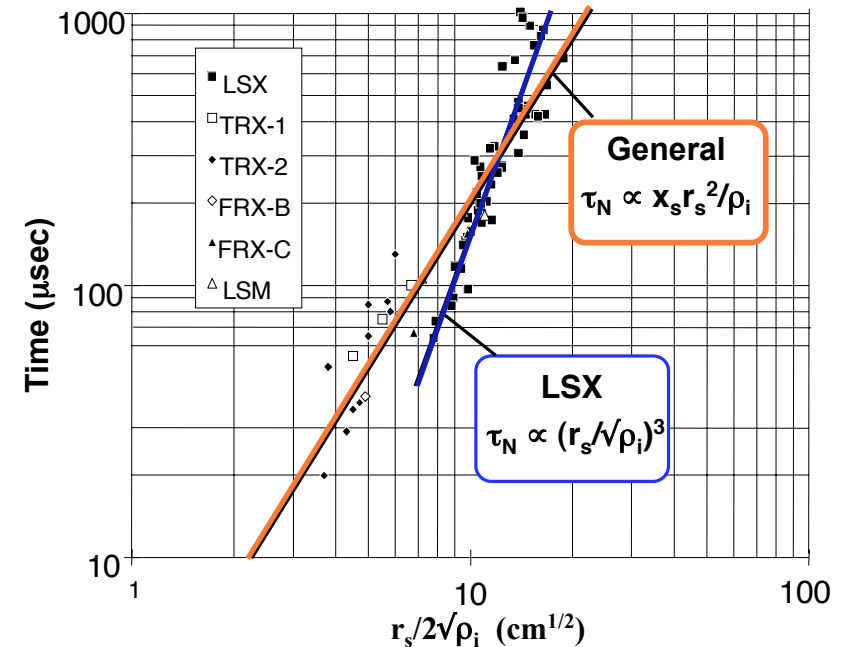
- ◆ 2-D interchange type instabilities, driven by plasma rotation, have been stabilized by weak multipoles with $B_m^2/2\mu_0 > \text{centrifugal pressure}$

Tilt



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

T_i up to 2 keV T_e up to 0.5 keV

$$\tau_\phi \approx \tau_N \quad \tau_E \approx -\tau_N$$

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



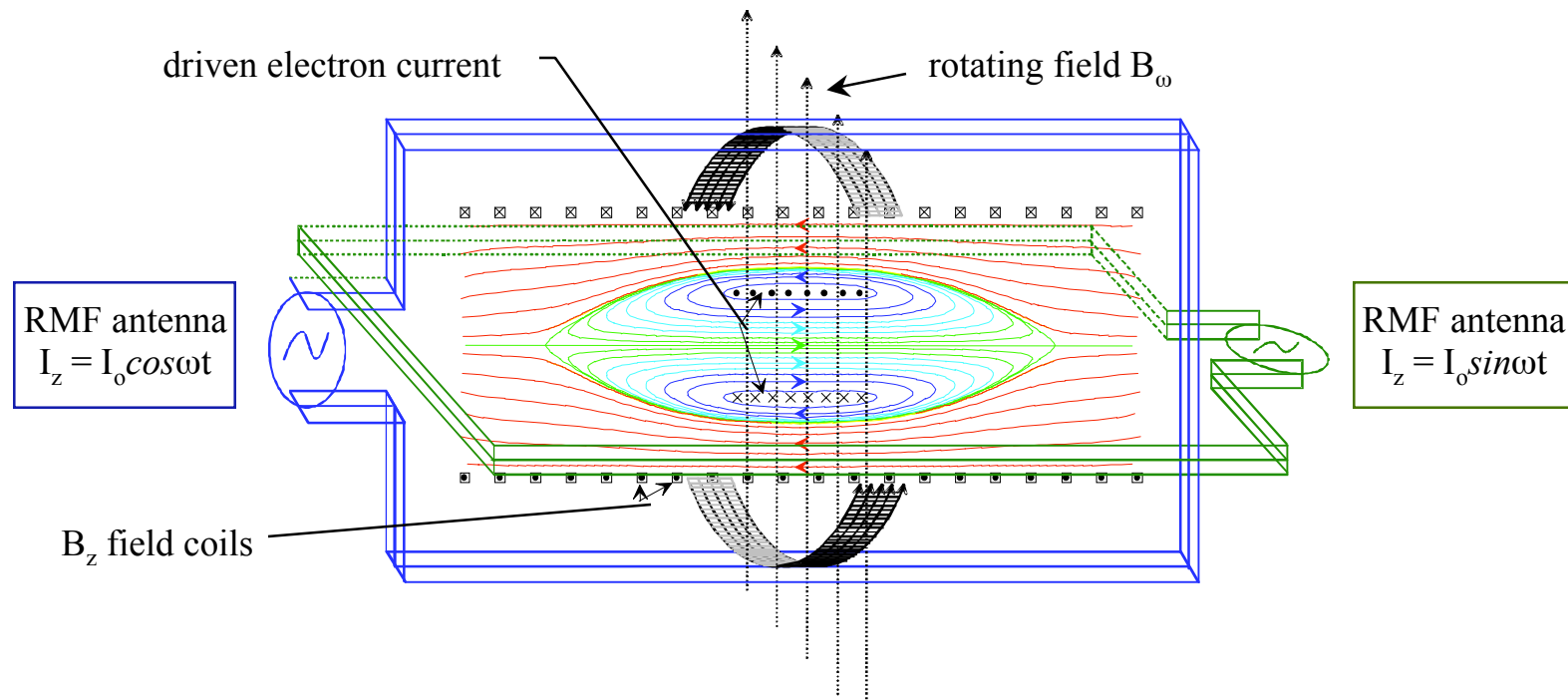
- ◆ Ideal $n_e \sim 1\text{-}2 \times 10^{20} \text{ m}^{-3}$, $T_e = T_i \sim 10 \text{ keV}$, $B_e \sim 1\text{-}1.5 \text{ T}$
- ◆ Continued stability up to $s \sim 20\text{-}30$
- ◆ Sufficient energy confinement - $n\tau_E > 10^{20} \text{ m}^{-3}\text{s}$.
- υ Reactor relevant formation methodology
- ◆ Efficient sustainment of cross-field diamagnetic current I_θ
 - $\eta_\perp$ is anomalous.
 - It is actually the poloidal flux which must be sustained; ($I_\theta = 2B_e/\mu_0$ 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

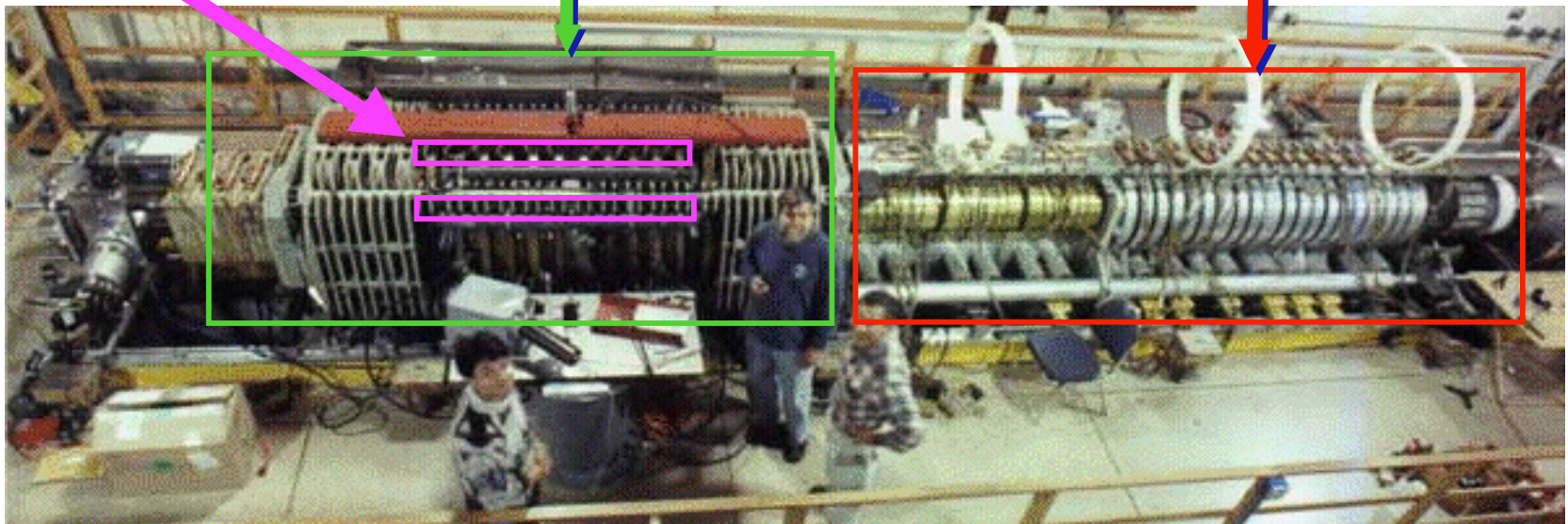
(Translation, Confinement, Sustainment)



RMF
Antennas

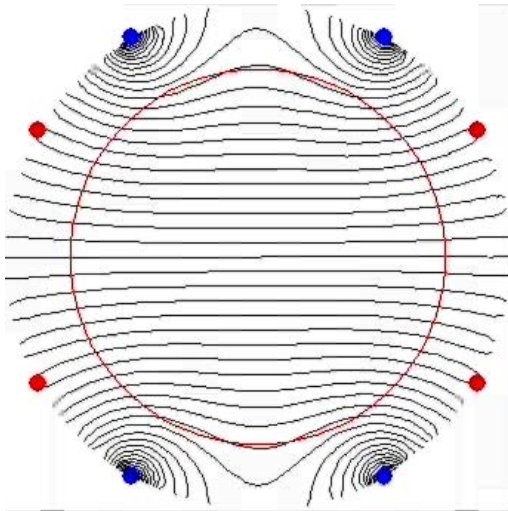
TCS Chamber
(confinement & RMF drive)

LSX/mod
(formation & 'acceleration')

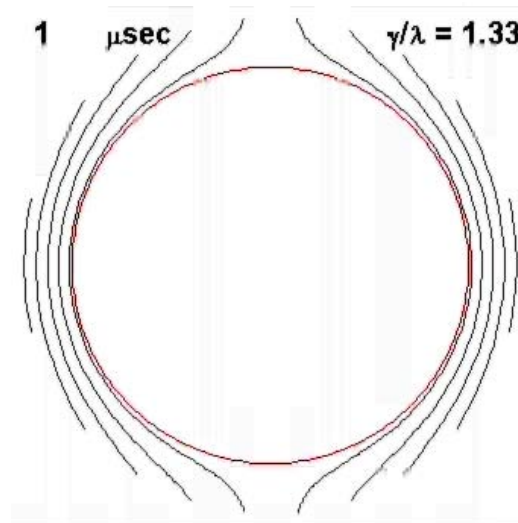


Primarily interested in FRC formation & sustainment by RMF alone.

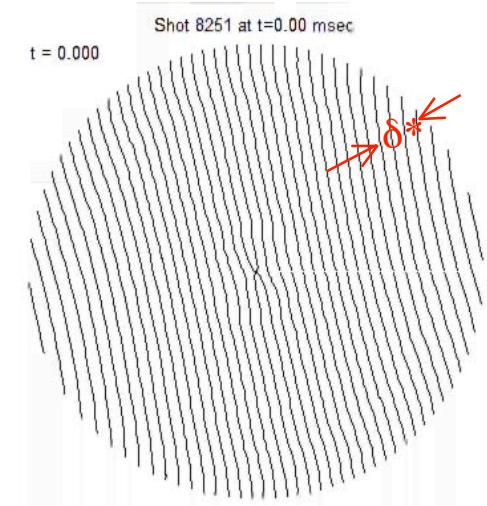
Partial RMF Penetration is Natural Occurrence



Vacuum **calculation** in lab frame of reference



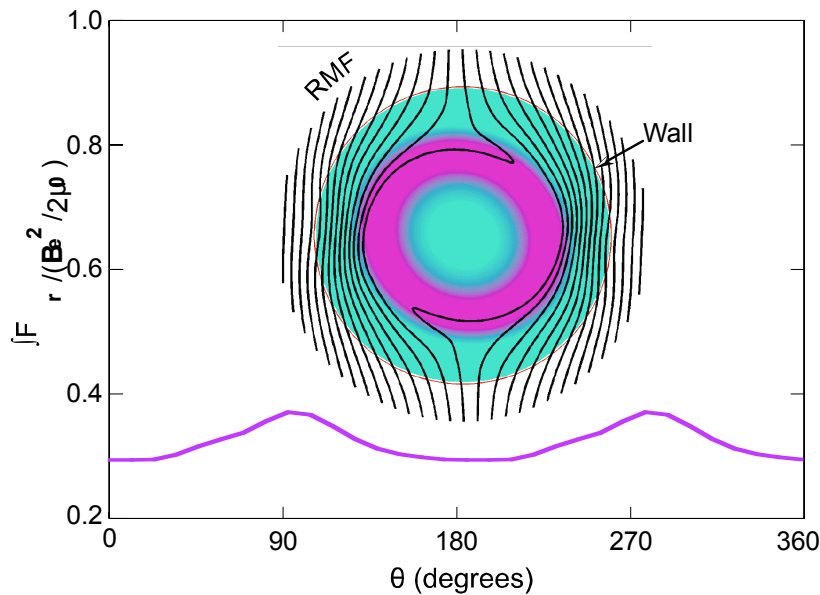
Plasma **calculation** in RMF frame of reference.
(Calculation needs to start from already formed FRC)



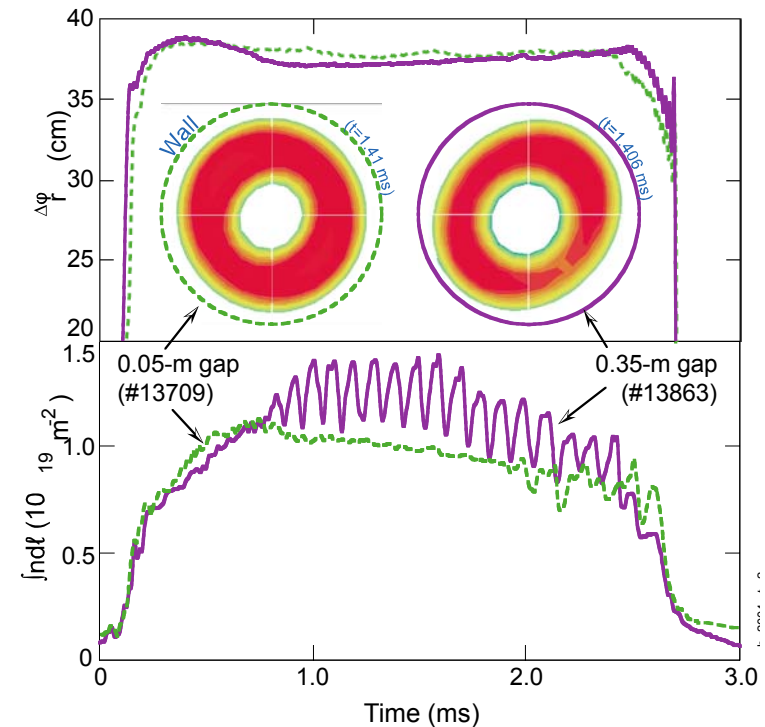
Plasma **measurement** in RMF frame of reference

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

2D Interchange Stability Provided by Partially Penetrated RMF

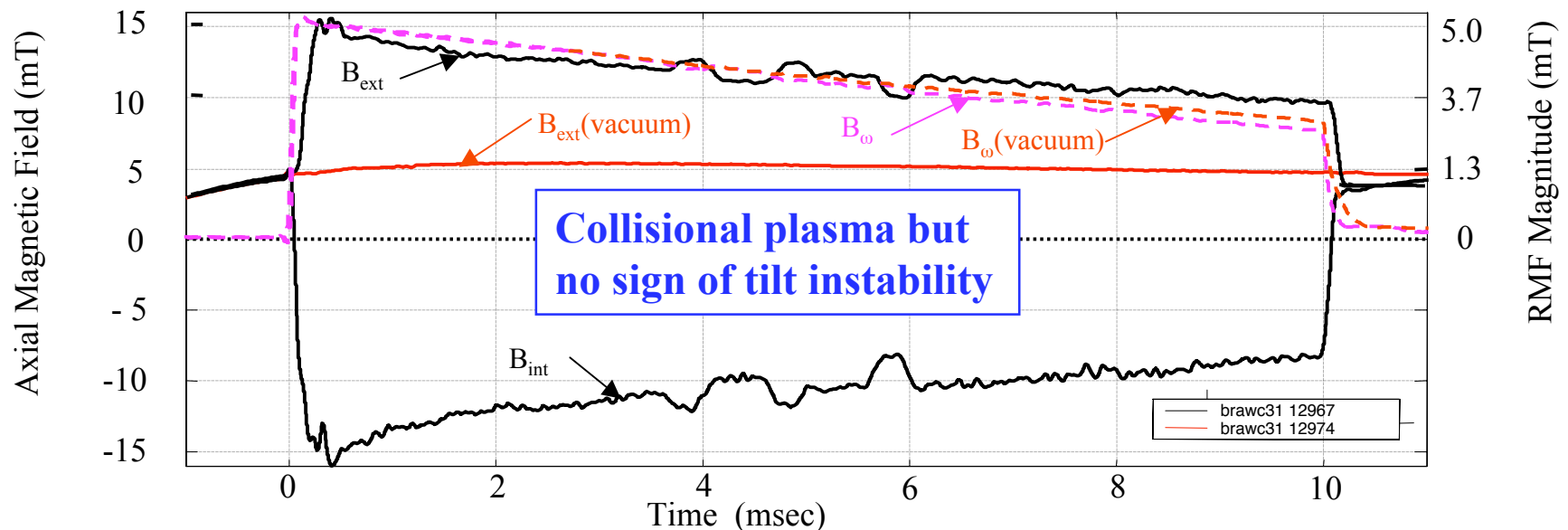


Calculations show strong restoring forces to rotationally driven interchange instabilities, such as the ubiquitous rotating $n=2$.



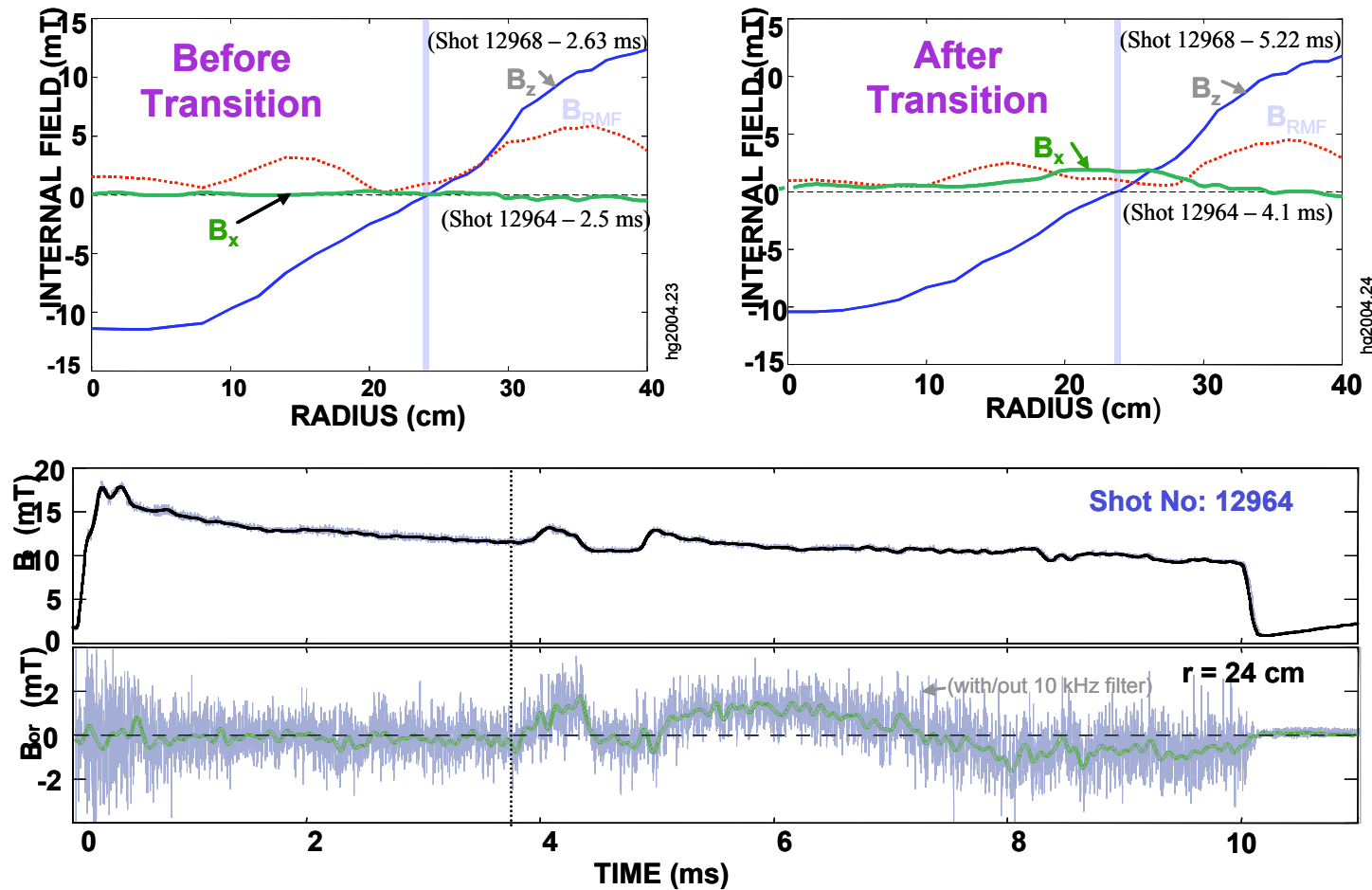
Observation of stabilizing effect on rotational $n=2$ instability when RMF antennas extend over central region

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



- ◆ 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 $\eta_{\perp}$

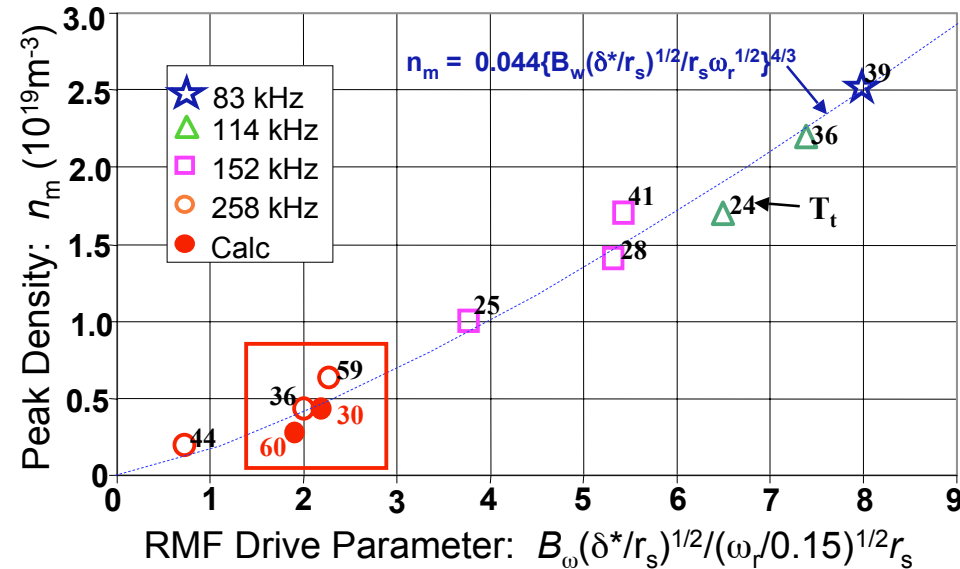


Resistive Torque

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

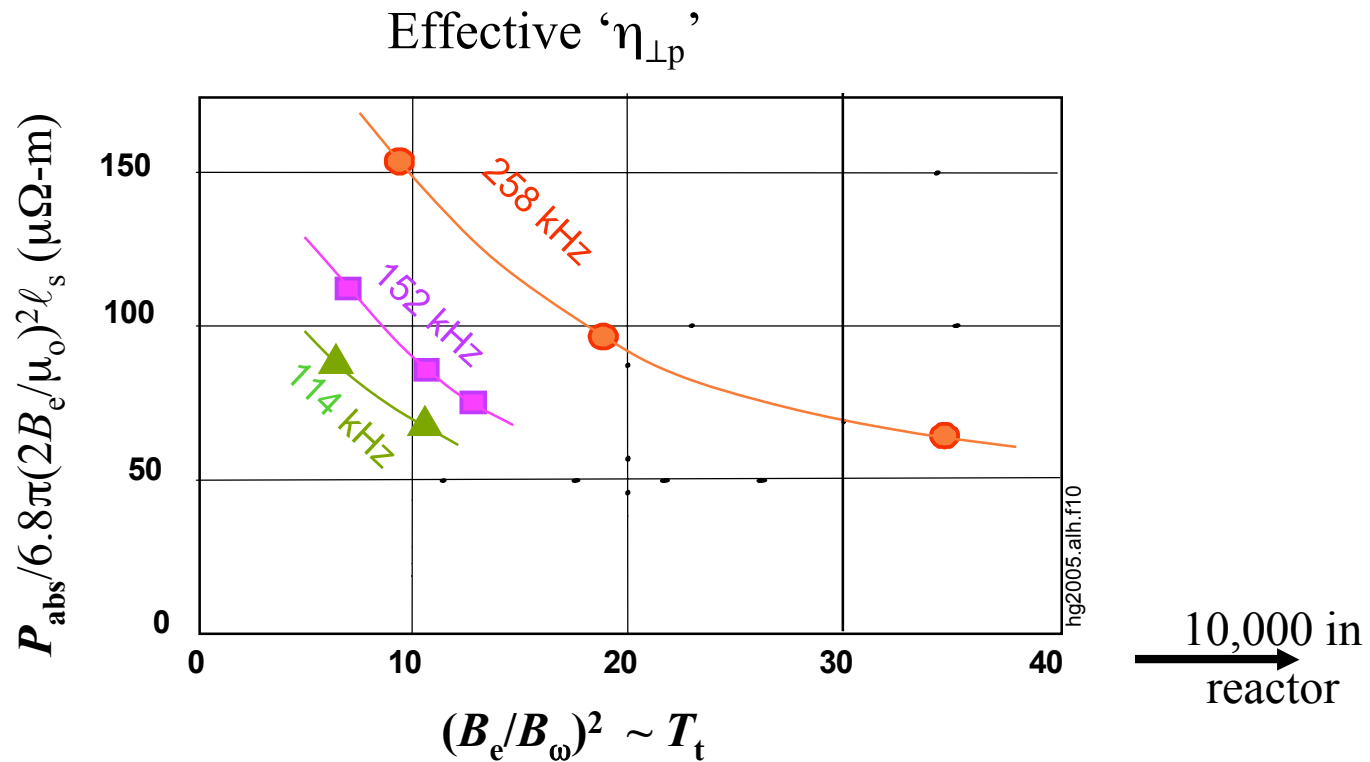
$$\eta_{\perp} \sim \frac{50}{n_m^{1/2} (10^{19} \text{ m}^{-3})} \mu\Omega\text{-m}$$

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



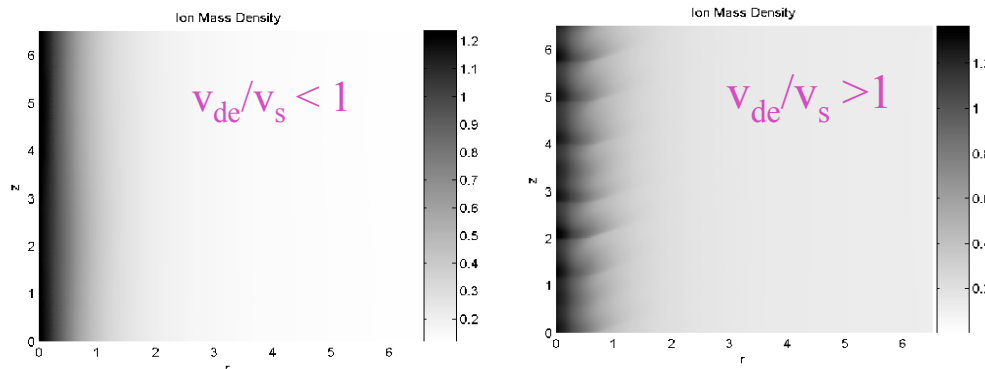
Experimental results described well by empirical
'Chodura' formula, dependent on v_{de}/v_s .



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

Provided best numerical match to
formation and translation experiments

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

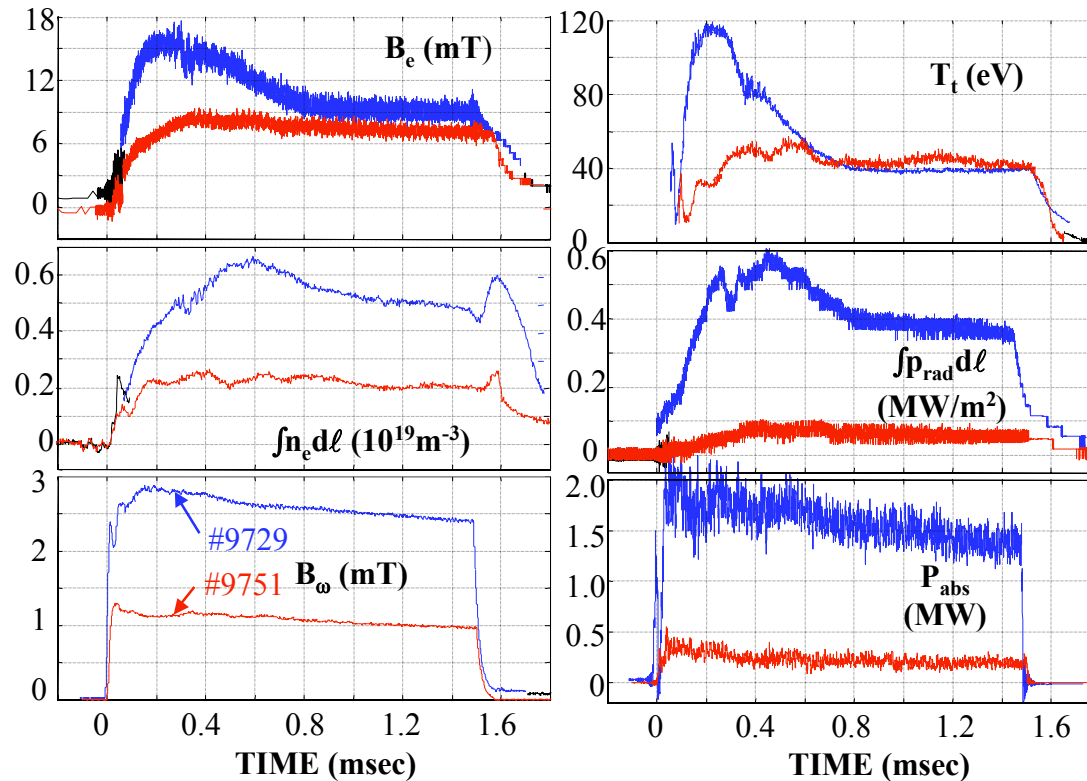


*Non-linear 2-fluid calculations of instabilities in a Z-pinch by
Loverich & Shumlak for various v_{de}/v_s .

Projected v_{de}/v_s ratios

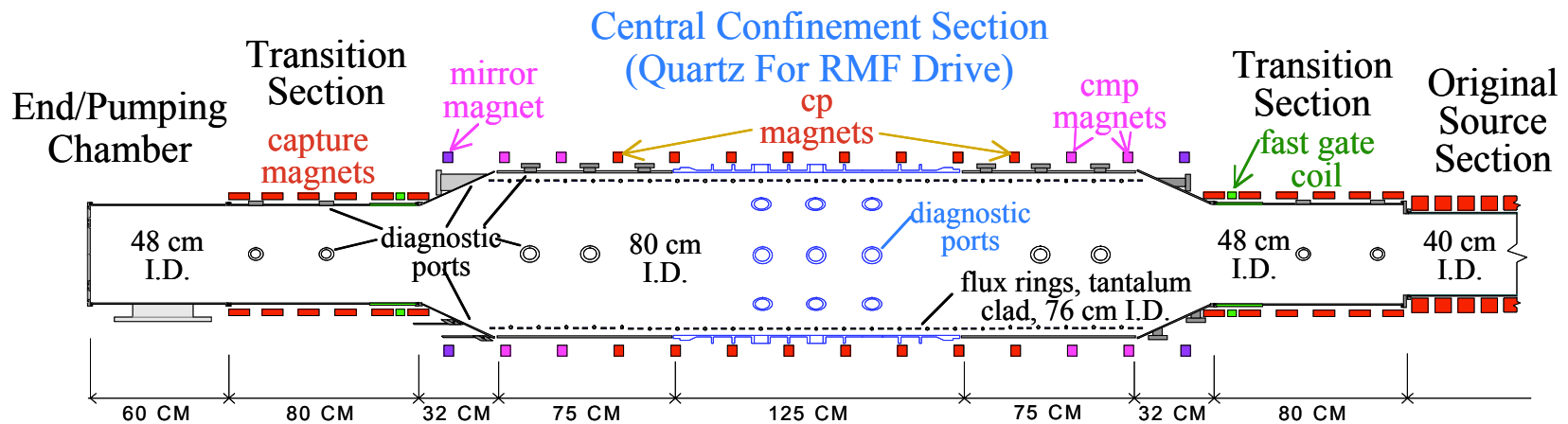
	TCS	TCSU (goals)	Reactor
$n_e (10^{20} \text{ m}^{-3})$	0.2	0.3	1.0
$T_i (\text{keV})$	0.05	0.3	25
$B_e (\text{T})$	0.02	0.06	1.0
$r_s (\text{m})$	0.4	0.35	2.5
$f_\omega (\text{kHz})$	100	100	10
v_{de}/v_s	4	1.5	0.1

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



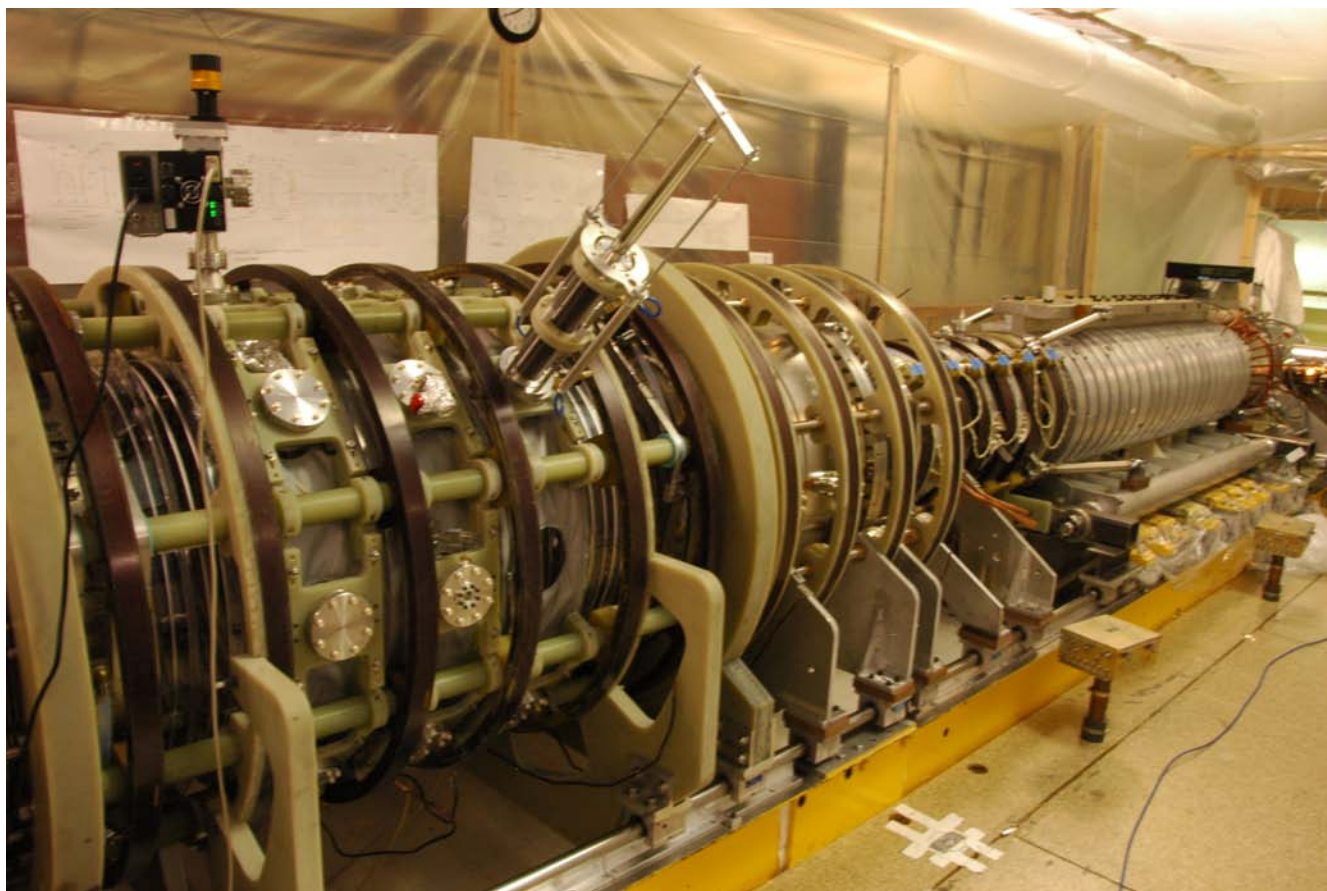
Operation at High $\omega = 1.62 \times 10^6 \text{ s}^{-1}$ and Low B_ω with *symmetric* RMF current drive & *θ -pinch vacuum technology*

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.

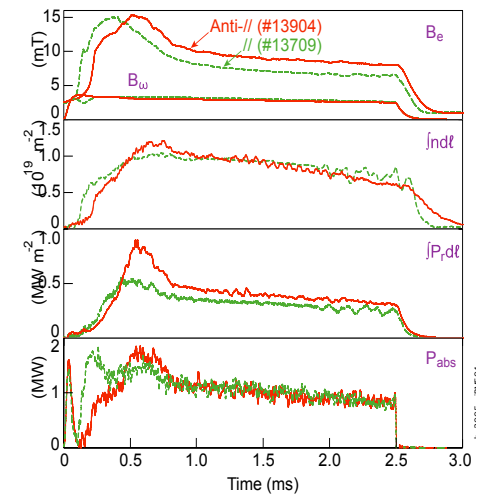
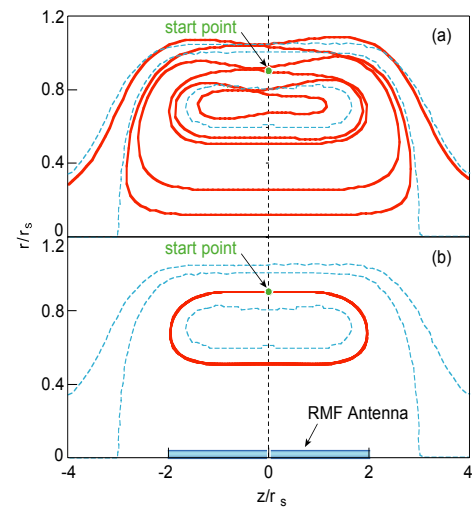
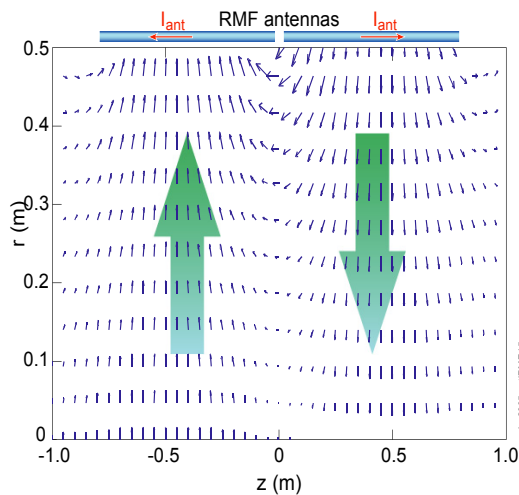
TCS/upgrade



Recent Interesting Results



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

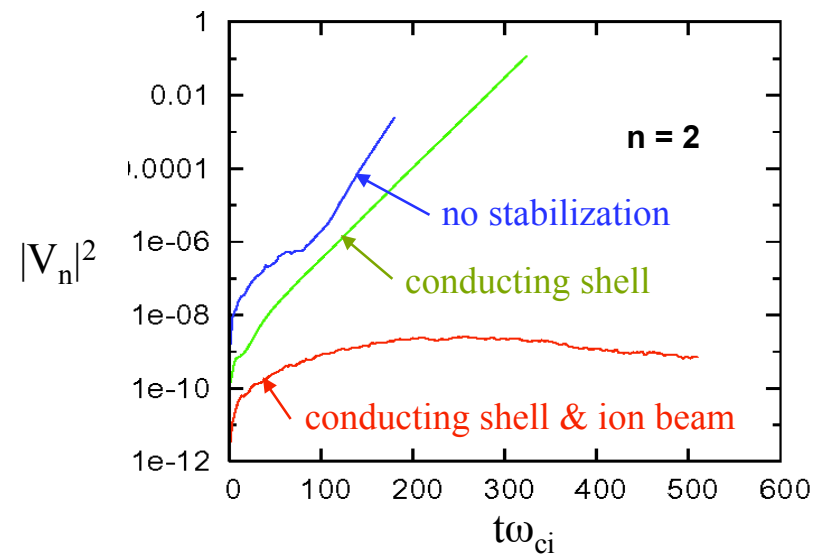
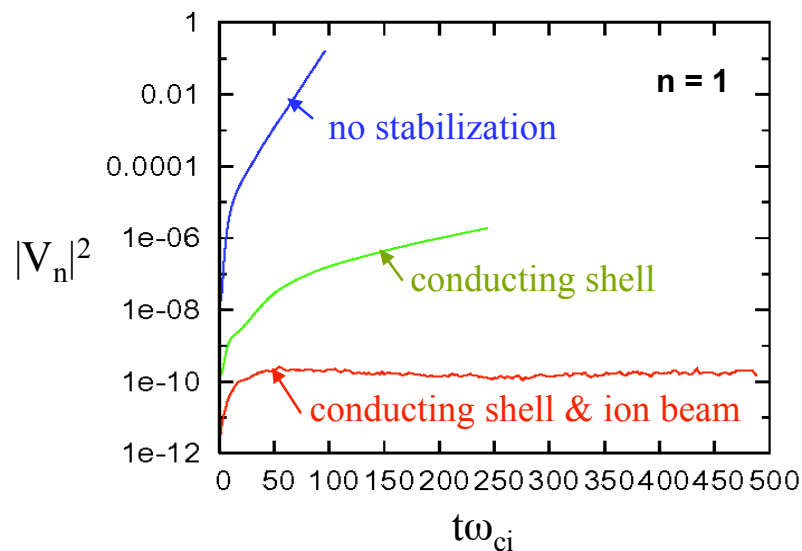


Recent PPPL kinetic calculations show promise of complete stability

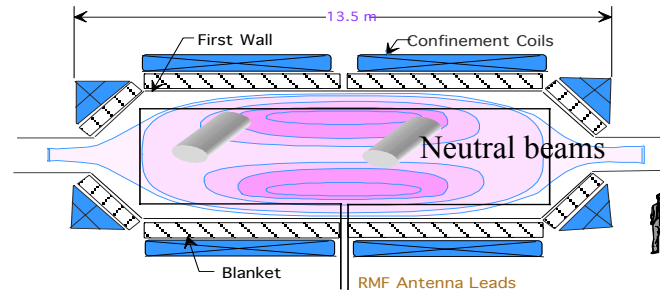


HYM simulations for oblate FRCs ($E \sim 1$) with a close-fitting conducting shell and energetic beam ion stabilization:

- *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.*

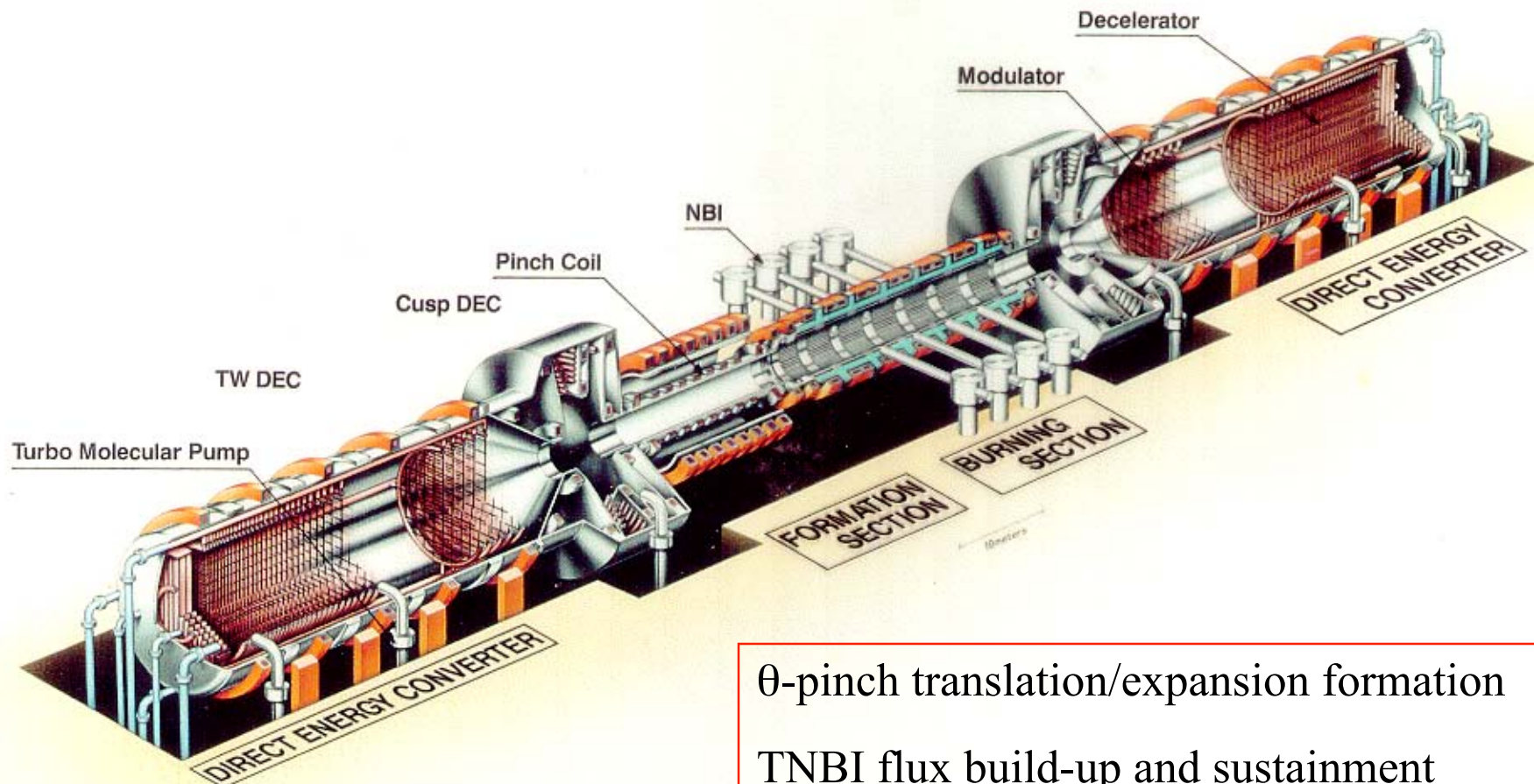


Summary



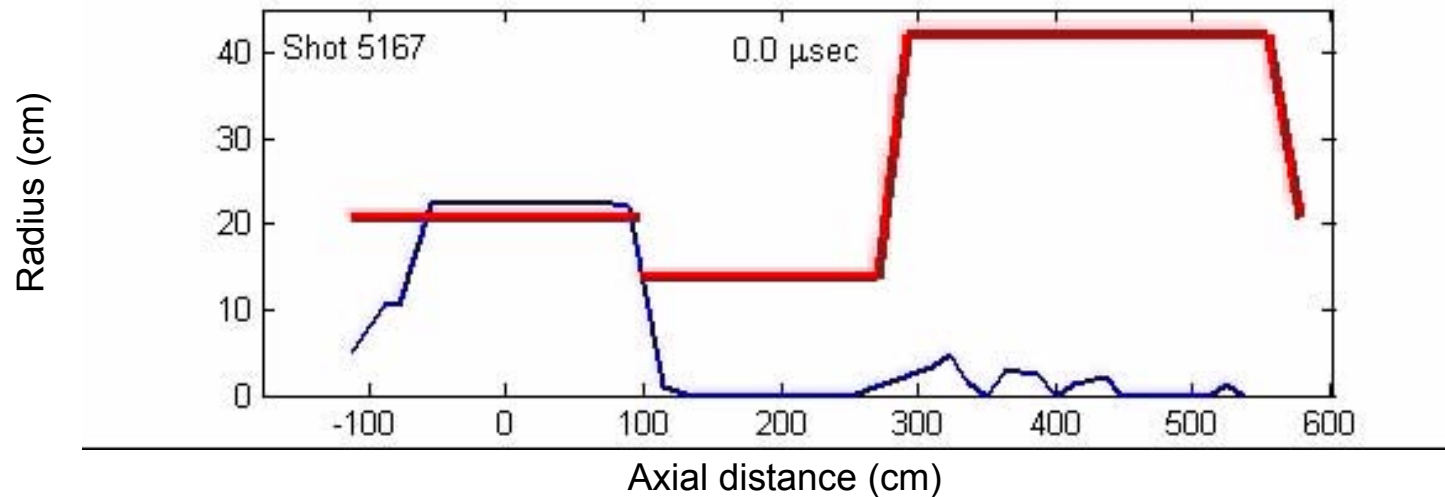
- ◆ FRCs are a simple, surprisingly robust confinement scheme.
- ◆ Unique plasma configuration:
 - Ideal reactor attributes (high β , simple geometry with natural divertor, advanced fuel potential).
 - Interesting plasma studies of $\eta_{\perp}$ and high- β MES in simple geometry.
- ◆ Formation and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

ARTEMIS Design (D-³He)



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 $5 \times 10^{21} \text{ m}^{-3}$ in formation section ($B_e \sim 0.5\text{-}1.0 \text{ T}$) to 5×10^{19} in TCS sustainment chamber ($B_e \sim 50\text{-}100 \text{ mT}$) without significantly degrading temperature.
- This is made possible by non-isentropic recovery of high ($\sim 400 \text{ km/s}$) translation energy.
- FRC exhibits remarkable robustness in surviving violent reflections off end mirrors.