Field Reversed Configurations

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Presentation to FESAC Alternates Panel
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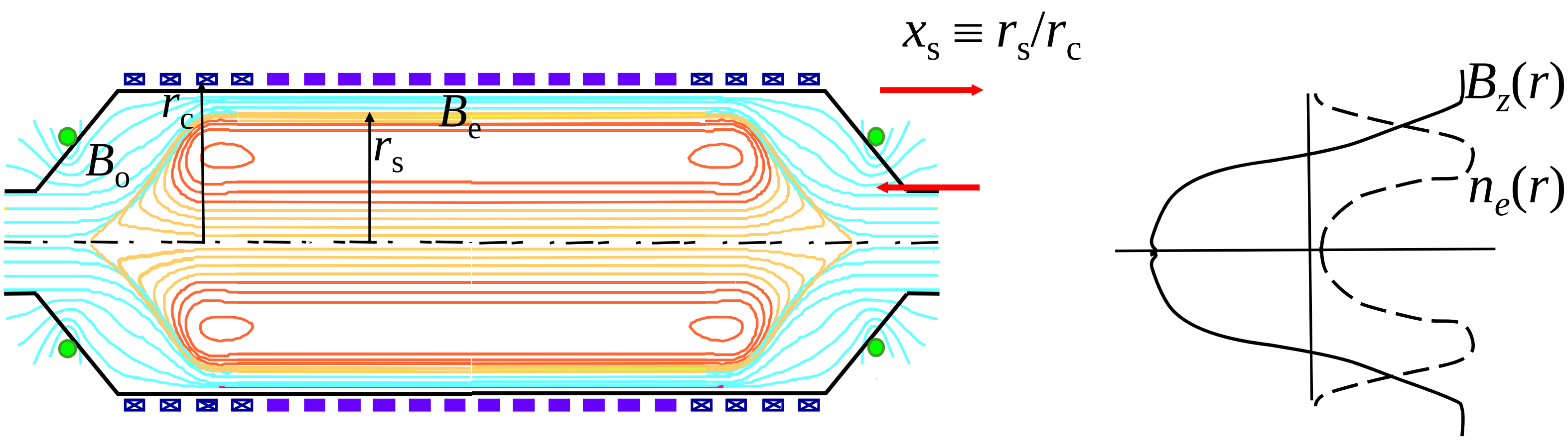
Outline

- FRC reactor advantages
- Major physics issues
  - Stability
  - Current Drive (RMF & TNBI)
  - Confinement
- RMF scaling & how to address issues
- Steady-state and pulsed comparisons

*Very little FRC funding other than TCS over last decade.

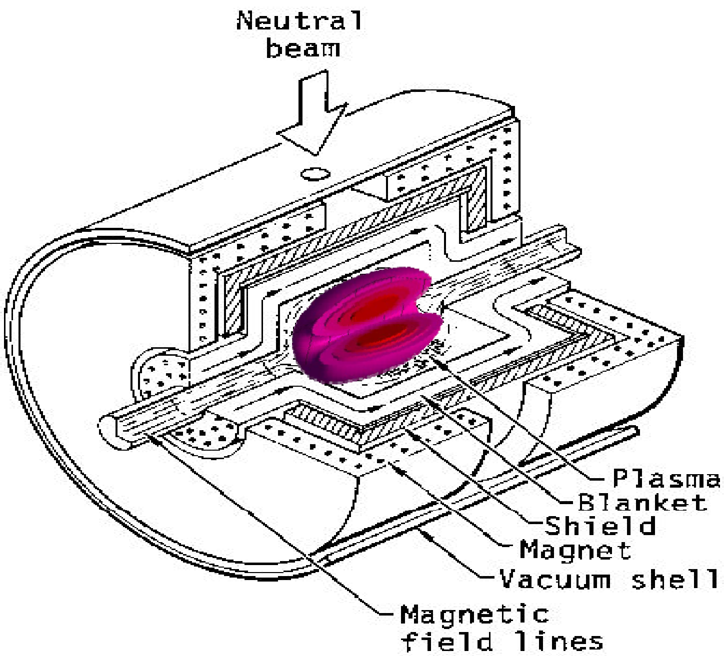
**Some slides will be gone over rapidly due to time constraints, but details are included for later question period.

A Compact Toroid (CT) is the Ideal ‘Engineered’ Toroidal Confinement Geometry



- Linear (or spherical) external vacuum chamber with closed field line plasma configuration.
- Open ends for scrape-off layer plasma flow.
- An FRC (Field Reversed Configuration) with minimal toroidal field must be high $\langle\beta\rangle = 1 - x_s^2/2$. (Minimum $\langle\beta\rangle$ = 50%)
- Density-temperature product fixed by external field (*length variable*). $n_m kT_t = B_e^2/2\mu_o$
- Diamagnetic (azimuthal) toroidal currents. $I' = 2B_e/\mu_o$

FRC Reactor Advantages

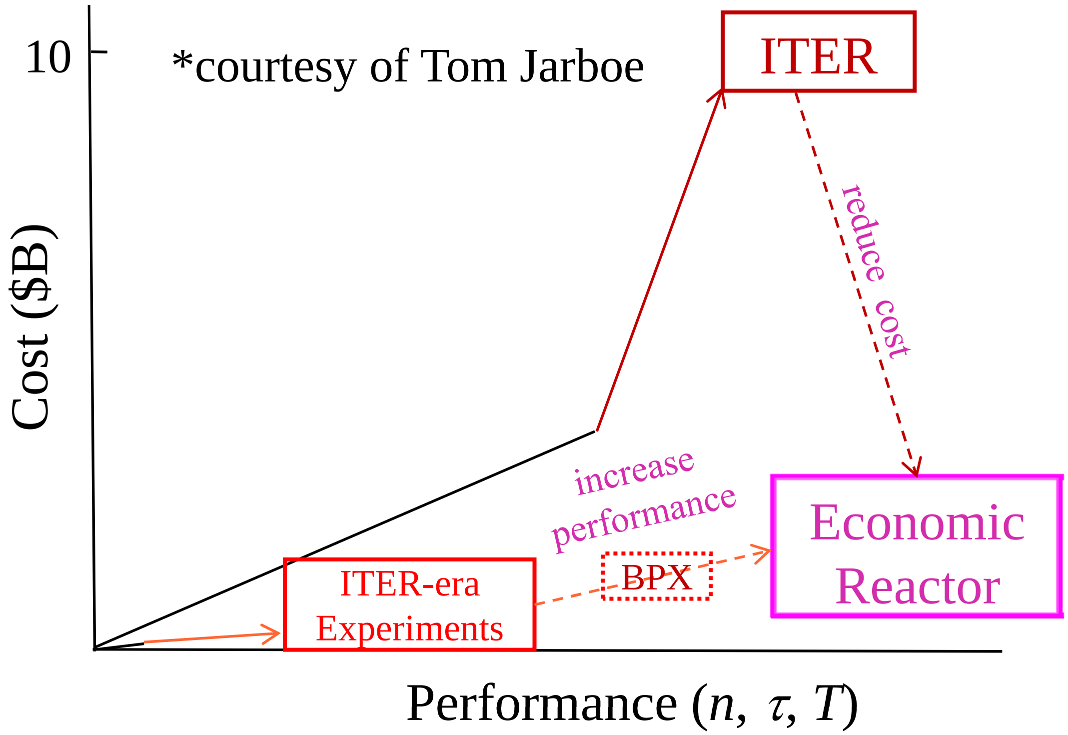


LLNL FRM Schematic (1976)

- Studies (U. Wisconsin, EPRI) show tremendous blanket simplifications due to singly connected linear geometry and lowered cost due to simple low field confinement coils. *Aneutronic fuel options?*
- 'Disruptions' not a problem for diamagnetic plasmas.
- Divertor loadings can be made as low as desired.
- *Rapid development path possible due to small size & cost.*

- **Recent favorable results on low power formation of hot FRCs, steady-state maintenance, stability, and transport make this the right time for an expanded (*relatively inexpensive*) effort.**

Complementary Approaches
(Engineering or Physics Emphasis)



Simple plasma chamber, unrestricted 'divertor', and low field coils make both reactor and the effort to reach reactor conditions much less expensive than for a low β toroidal system!

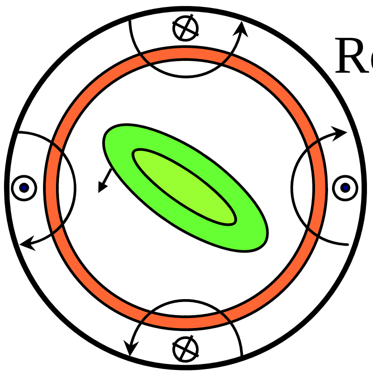
ITER-era goals: Demonstrate combined good confinement & steady-state current drive at kilovolt temperatures, and the theoretical understanding to allow extrapolation to an FRC Burning Plasma Experiment

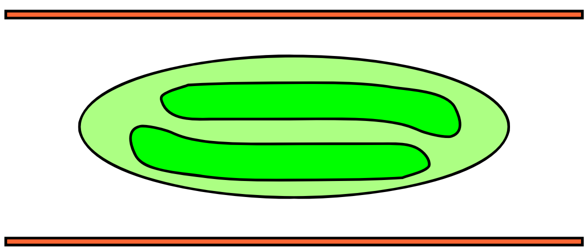
MAJOR FRC ISSUES

- STABILITY
- CONFINEMENT
- CURRENT DRIVE

} Somewhat related for a diamagnetic plasma

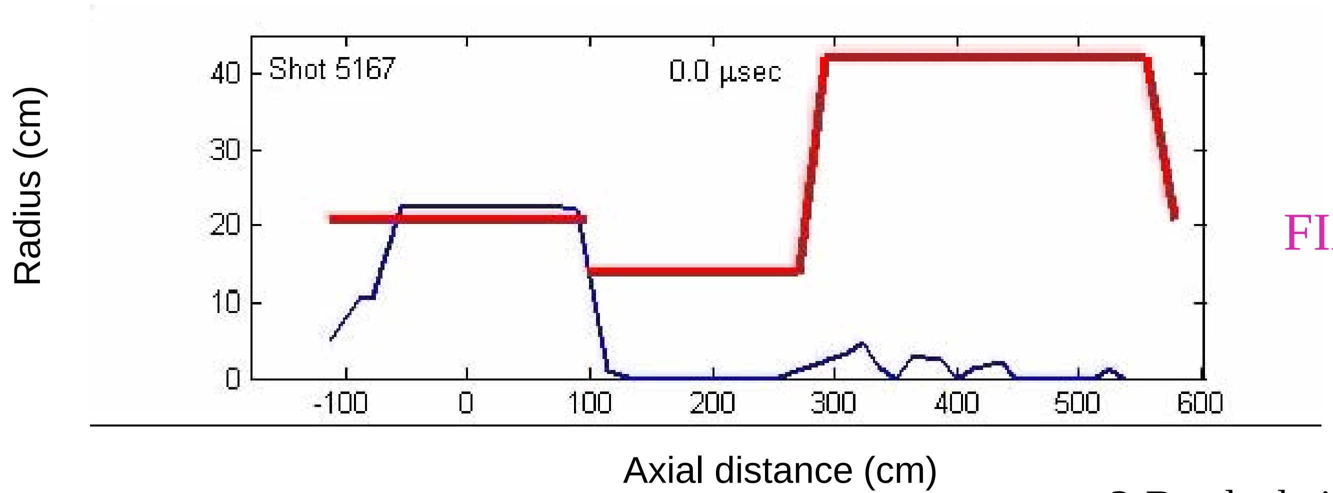
Most Studied Problem - Stability





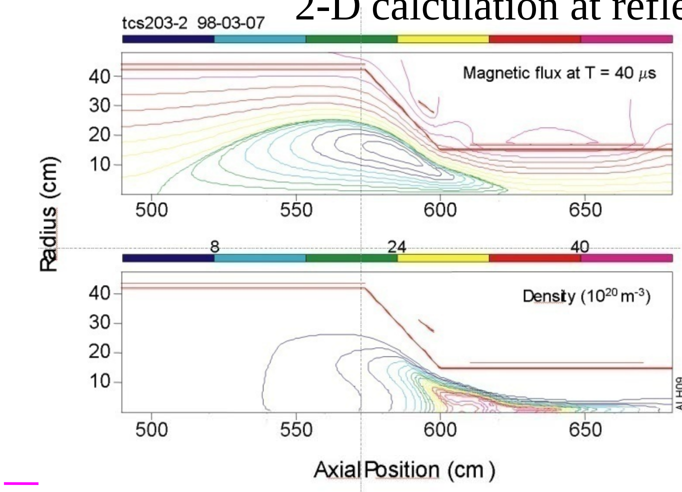
- Ion diamagnetic rotation drives n=2 mode due to centrifugal forces.
  - It has been stabilized by weak multipoles with $B_m^2/2\mu_o$ > centrifugal pressure, *and now by RMF*.
- *Internal tilt* is more insidious - starts out as an axial n=1 shift.
  - Most studied mode theoretically with various ideas proposed for experimental stability.
  - Most studies based on kinetic stabilization due to low $s = \int_R^{r_s} dr/\rho_i$.
  - *Experiments built to produce large s FRCs have not encountered tilt instability.*
  - Oblate FRCs observed stable in merging experiments.

FRC Translation Demonstrates Robustness (at least at low s)



FIX & LSX/mod

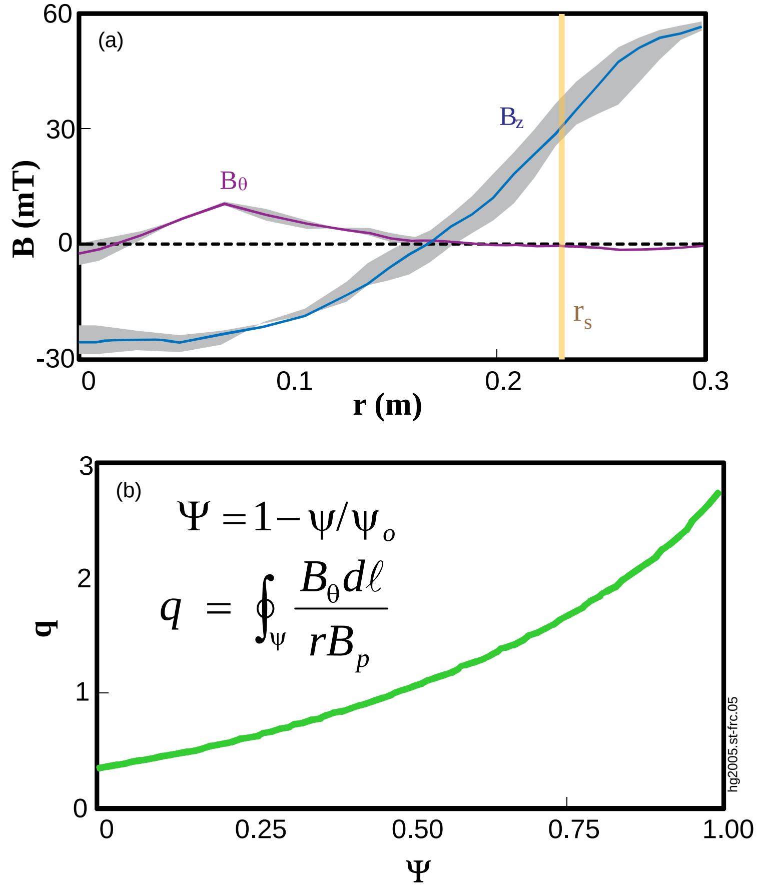
2-D calculation at reflection



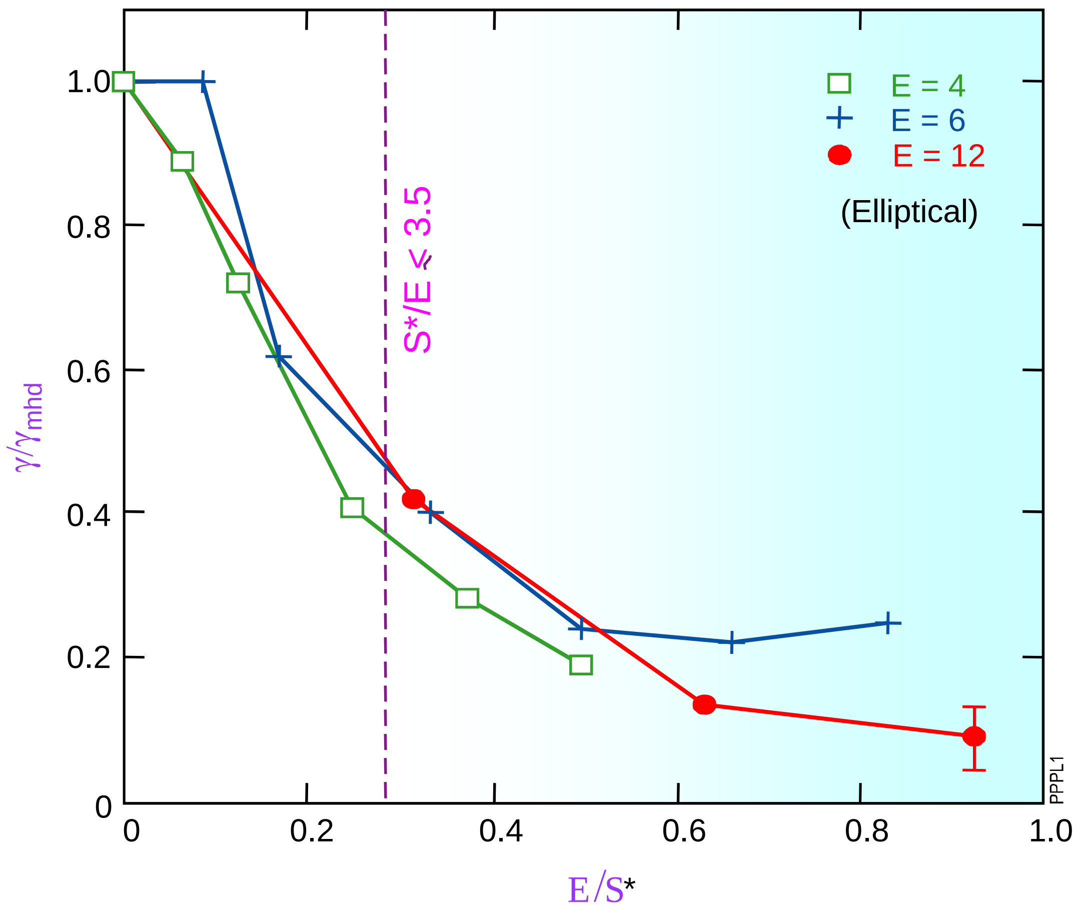
- FRC exhibits remarkable robustness in surviving violent reflections off end mirrors.

High-β Minimum Energy State?

- $B_{toroidal}$ appears, but FRC will be high β as long as $B_\theta << B_z$. (*definition of FRC*)
- Due to large κ and small AR have high q and dq/dψ even with low B_θ/B_z .
- Properties similar to those calculated for high-β Minimum Energy State (MSE). (rotational n=2 distortion stable even without multipole fields.)
- Similar results seen in RMF sustained FRCs.



Growth Rate of Tilt Mode
(from 3D HYM simulation)

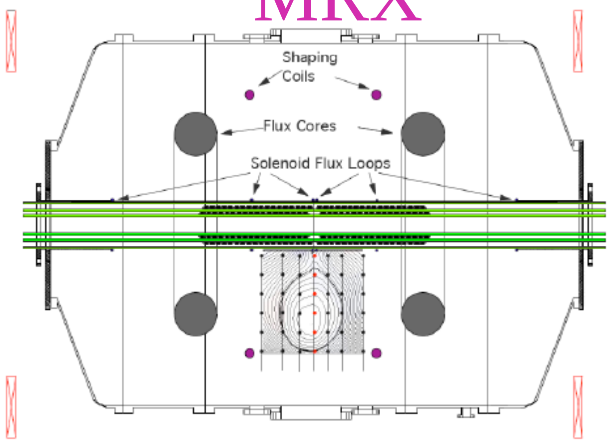


Calculations by E. V. Belova et al.

- Kinetic calculations generally have shown reduction of tilt rate at low *s*, but not positive stabilization, at least in linear phase.
- Other effects are calculated to be important, such as strong flow, residual toroidal field, ion viscosity, Hall effects.
- Recent calculations show oblate FRC can be completely stabilized by fast ion component!

Oblate FRCs formed by spheromak merging

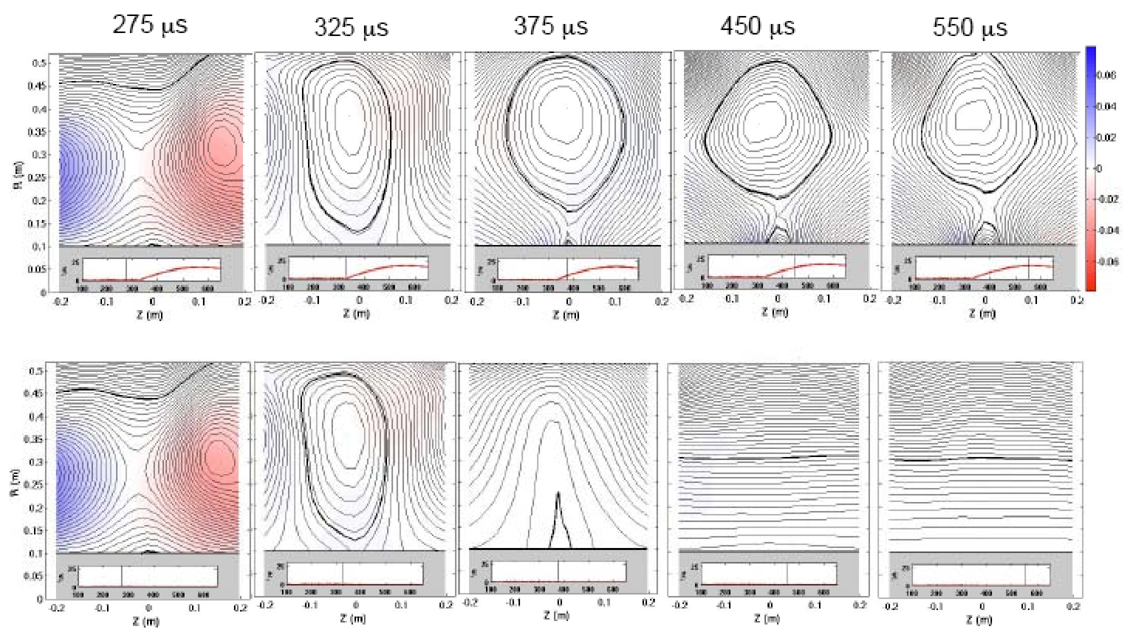
MRX



Inductive core sustainment produces stable oblate FRCs in MRX, but only in heavy gases.

Inductive sustainment using internal solenoid.

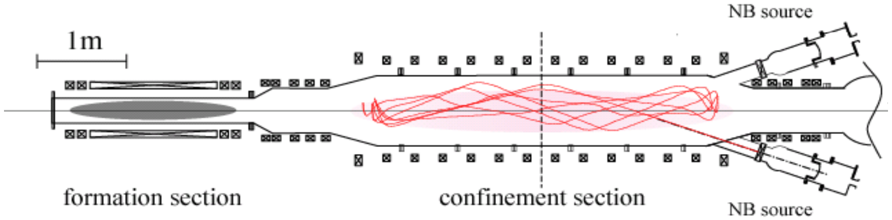
No sustainment.



Available FRC Formation Methods

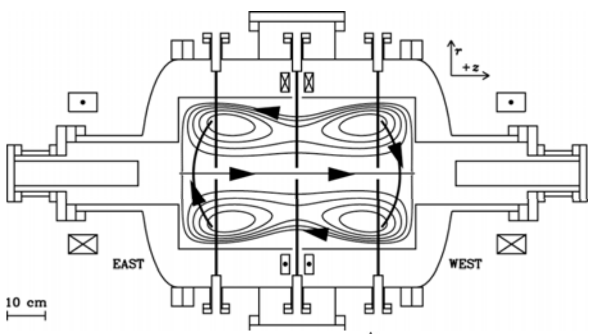
(hard to overcome initial radiation barriers at high β)

(need Wb of flux for a steady-state reactor)



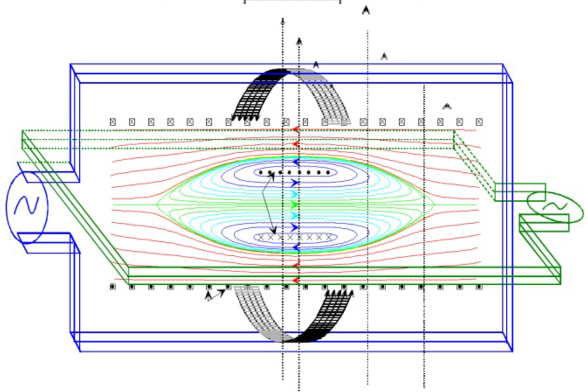
Theta Pinch Formation and Translation/Expansion (LSX limited to ϕ_p ~ 10-20 mWb)

(Formation power input ~ 10s of GW)



Merging Spheromak Formation (slower formation – flux limits unknown)

(Formation power input ~ 100 MW)

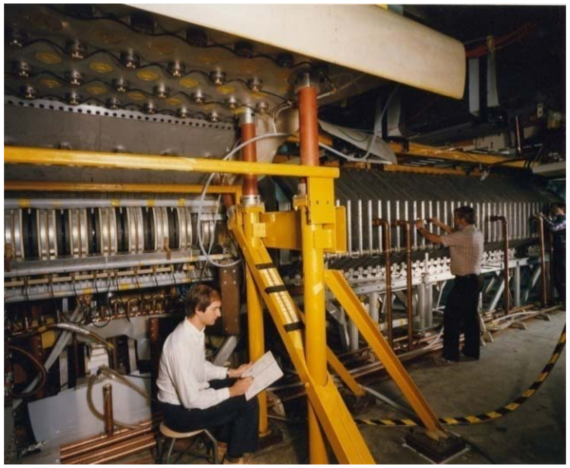


Rotating Magnetic Field Formation (also current drive mechanism – no fundamental flux limit)

(Formation power input ~ 1 MW)

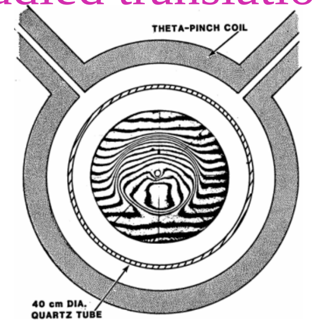
High Power (GW) θ-Pinch Facilities

(historical approach, but now mostly of interest for high density pulsed approaches)

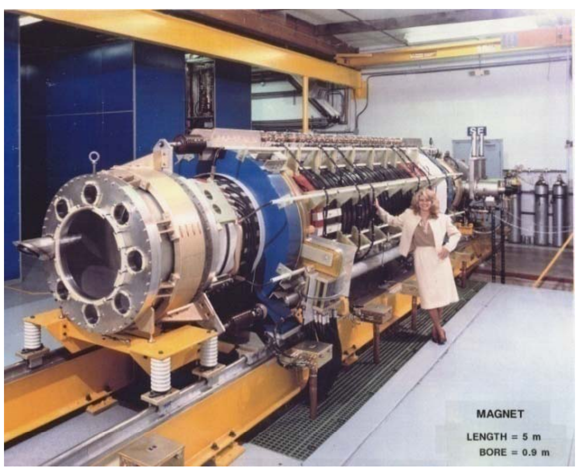


FRXC/T (LLNL - early 1980s)

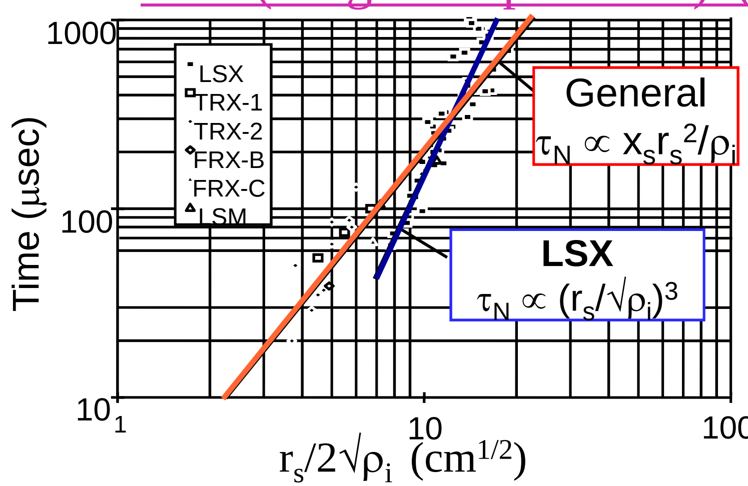
Studied translation & adiabatic compression



Interferogram taken on FRX-C using holography

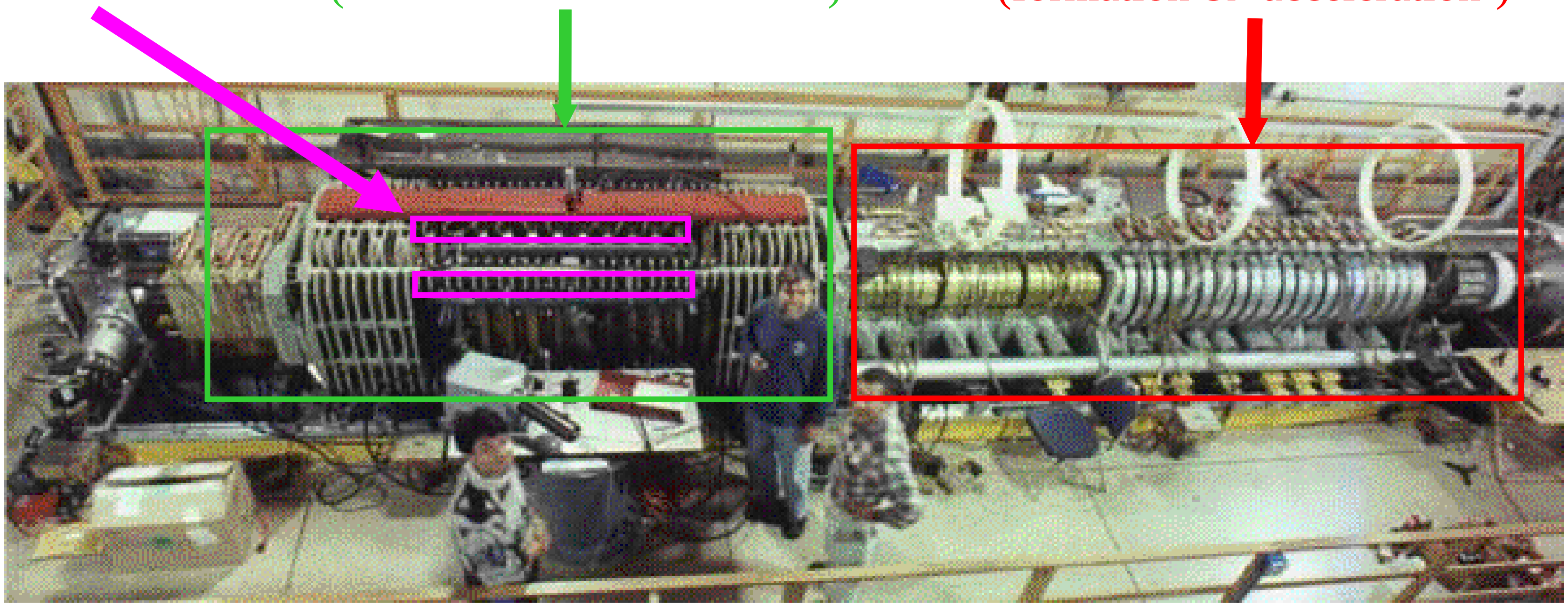


LSX (Large *s* Experiment) (STI - 1991)



Much better than Bohm confinement ($D_\perp$ ~ 5 m^2/s). Demonstrated stability up to *s* = 4.

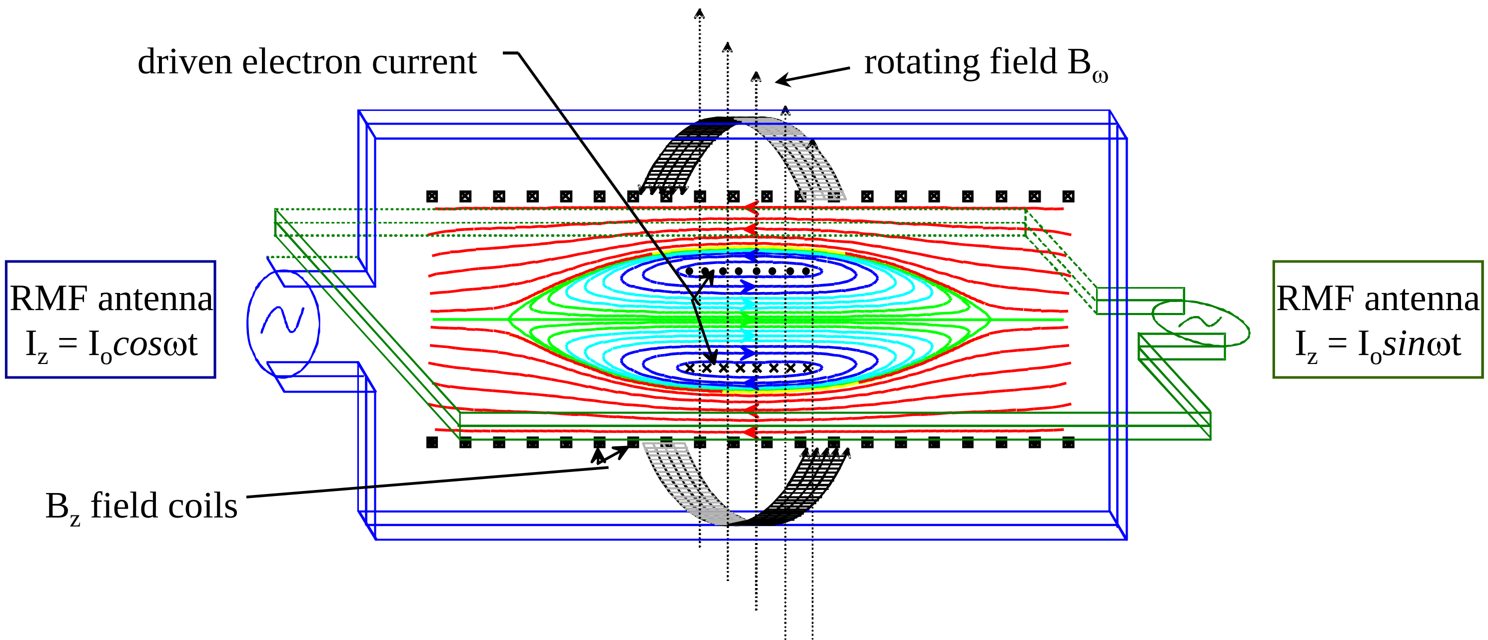
TCS Device



- Study **Formation** & **Sustainment** of RMF driven FRCs**.**
  - Either form FRCs directly using RMF alone, or translate and expand theta-pinch formed FRCs from LSX/mod *(now not needed*).

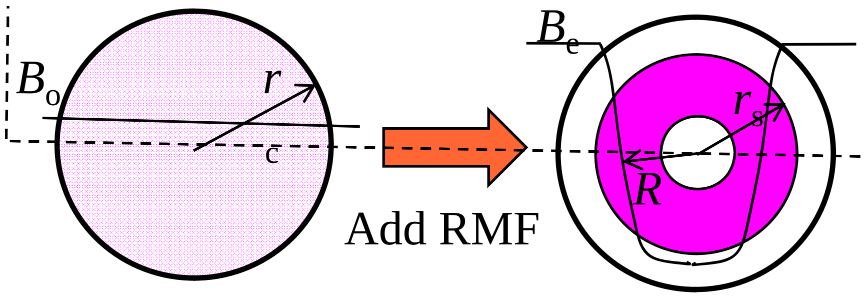
RMF Current Drive

(pioneered by I. Jones at Flinders University)

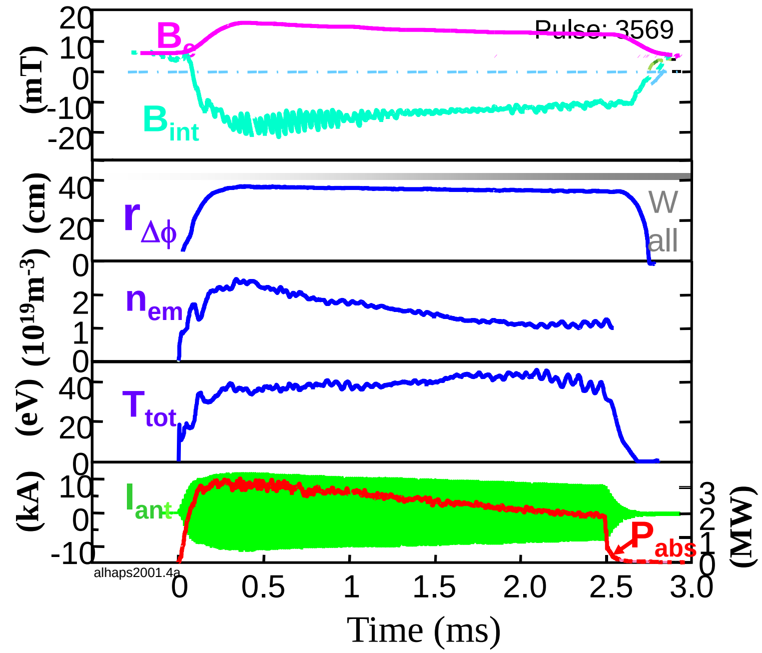


- 'Drag' Electrons Along With Rotating Radial Field ($F_\theta \sim \langle V_{ez} B_r \rangle$ force)
  - Must have $\omega_{ci} < \omega << \omega_{ce}$, and $\omega_{ce}\tau >> 1$ for electrons, but not ions, to follow rotation
- Deep penetration into highly conducting column possible due to near synchronous outer electron rotation ($\omega_{edge} \sim \omega$).

Basic RMF Physics
(developed by Flinder's University group)



$x_s \equiv r_s/r_c \quad B_e = B_o/(1-x_s^2)$

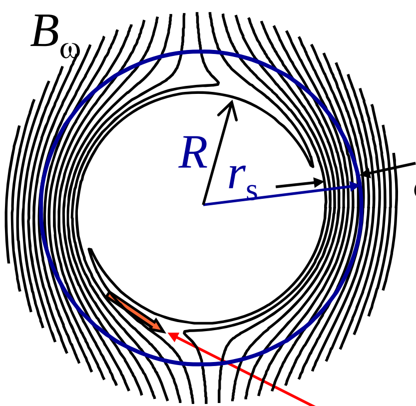


- $E_\theta = \eta_\perp j_\theta + v_{er}B_z + \langle -V_{ez}B_r \rangle$
- RMF torque on electrons:
  $\mathbf{T'}_{rmf} \approx 0.2\pi r_s^2 B_\omega^2/\mu_o$.
- Opposed by electron-ion friction:
  $\mathbf{T'}_\eta \propto \pi r_s^2 \eta_\perp (B_e/\mu_o)^2 (n_e/T_t)^{1/2}$.
- $d\phi_p/dt = 2\pi R E_\theta(R) \propto (\mathbf{T'}_{rmf} - \mathbf{T'}_\eta)$

$$n_m(10^{20}\,\mathrm{m}^{-3}) = \frac{1.2 B_\omega^{4/3}(\mathrm{mT})}{\langle \eta_\perp(\mu\Omega\text{–m})\rangle^{2/3} T_t^{1/3}(\mathrm{eV})} \; *$$

*basis of determining $\eta_\perp$ = 10-100 μΩ-m
(η_{cl} = 0.5-5 μΩ-m at T_e = 30-200 eV)

FRC flux sustainment requires partial RMF penetration

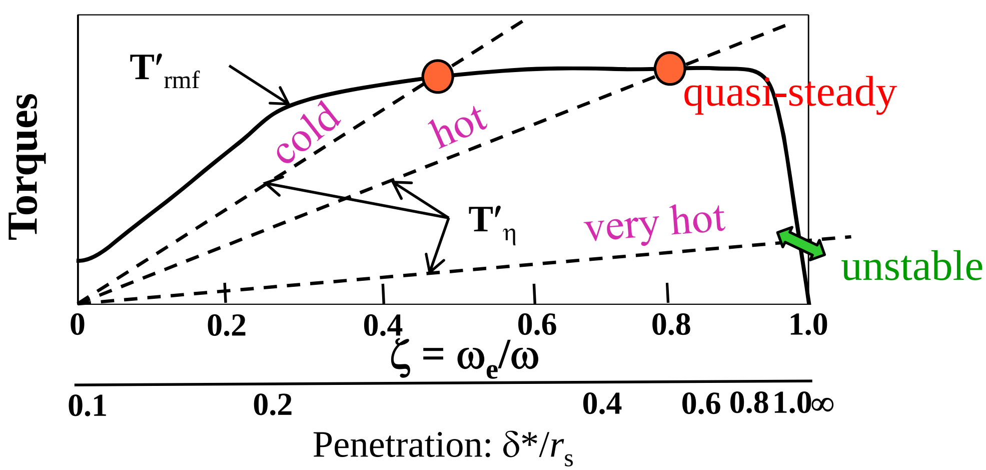


$$\delta = \sqrt{\frac{2\eta_{//}}{\mu_o \omega}} \sim \sqrt{\frac{10^{-4}\,\Omega\text{–m}}{10^{-6}\times 10^{6}}} \sim 1\text{cm}$$

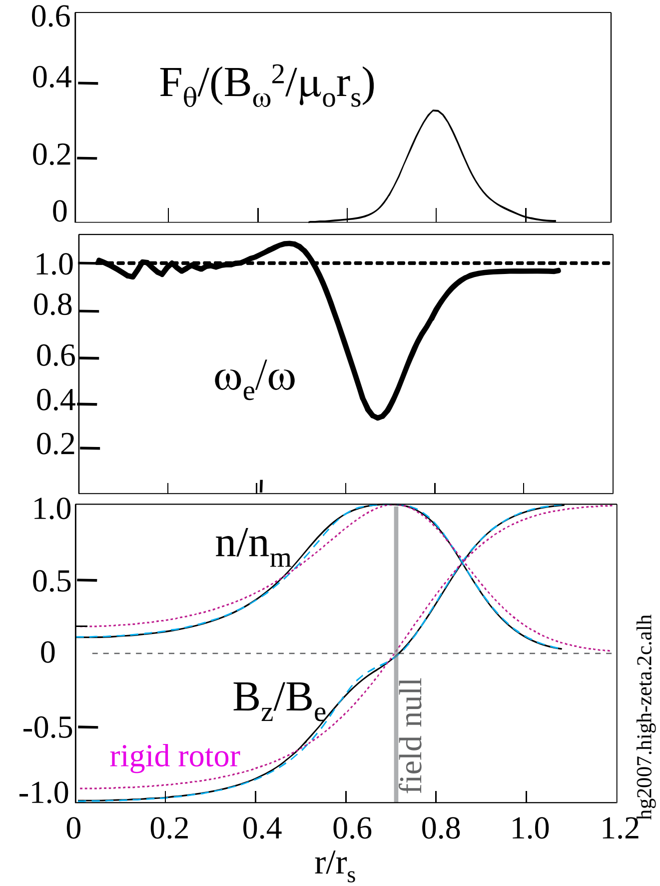
$$\delta^* = \sqrt{\frac{2\eta_{//}}{\mu_o \varpi}} \qquad \varpi = \omega - \omega_e$$

$$\zeta = \frac{\langle \omega_e \rangle}{\omega} \propto \sqrt{\frac{T_t}{n_e}}$$

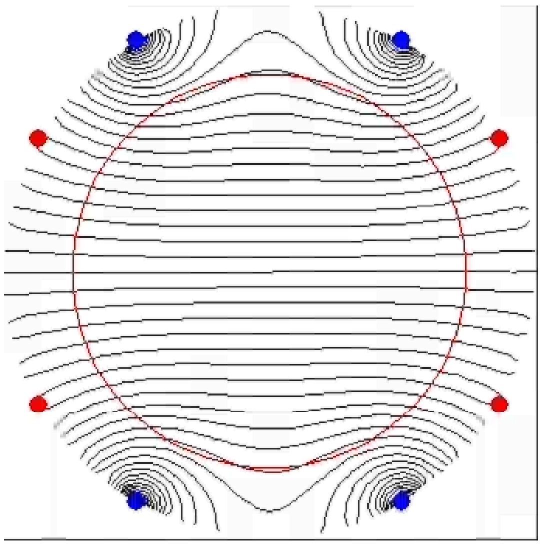
RMF Force: $ne\langle -v_{ez} B_r \rangle \propto B_\omega^2/\mu_o$.



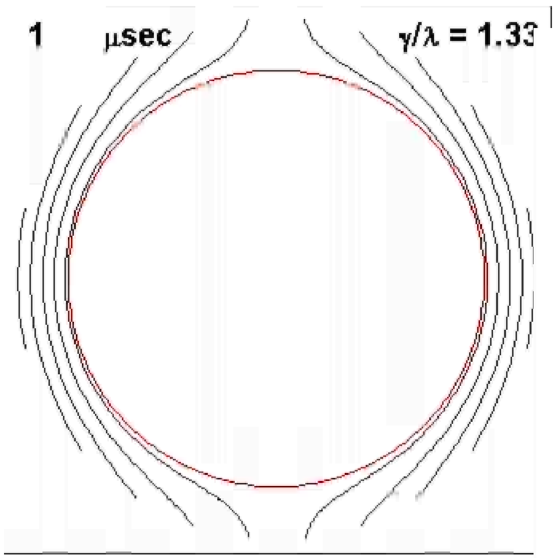
$\zeta = \omega_e/\omega = 0.8$ Calculation



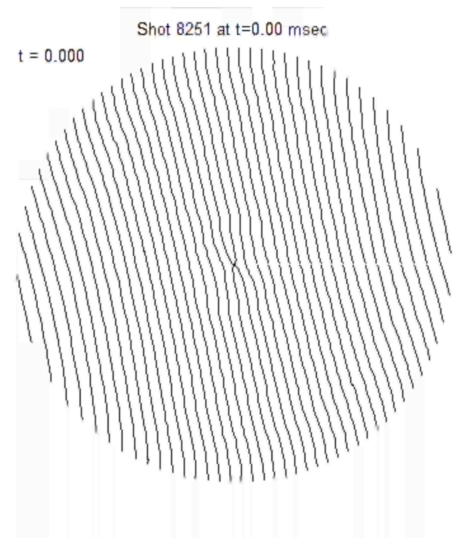
RMF Penetration Movies



Vacuum **calculation** in lab frame of reference



Plasma **calculation** in RMF frame of reference, with uniform resistivity.
(Calculation starts from already formed FRC)



Plasma **measurement** in RMF frame of reference

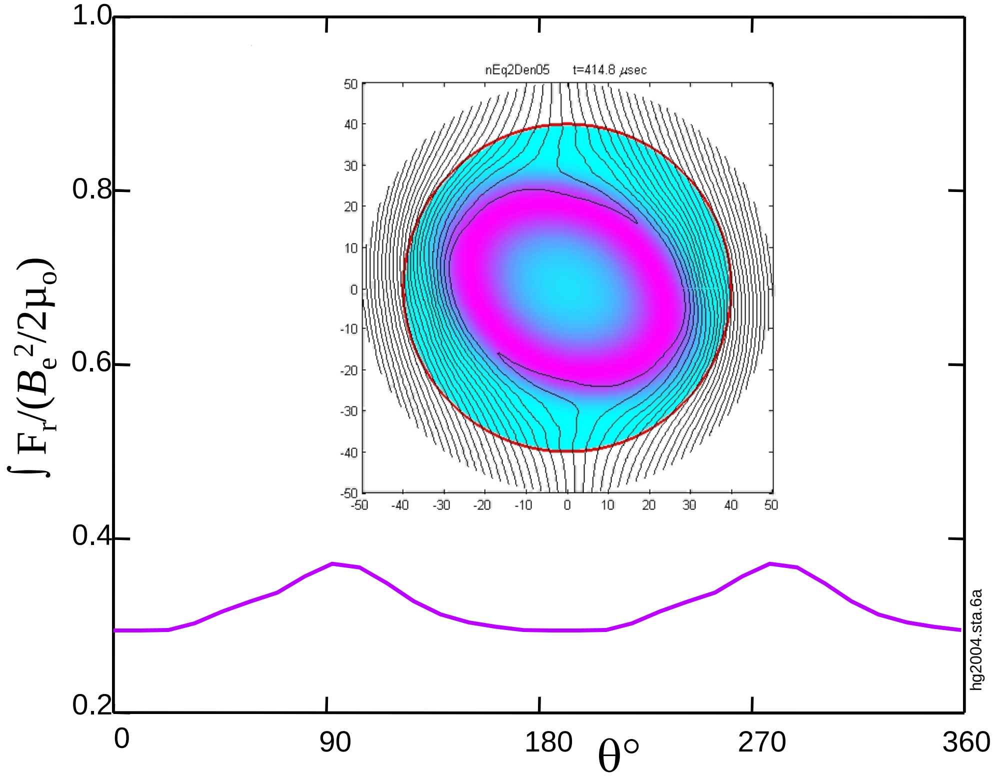
Partially Penetrated RMF Can Stabilize Interchange Instabilities

(This has applicability well beyond FRCs)

- The radial inward force produced by a partially penetrated dipole RMF with an elliptical distortion ξ is given by,

$$F_r(r,\theta) = -\langle j_z B_\theta \rangle$$

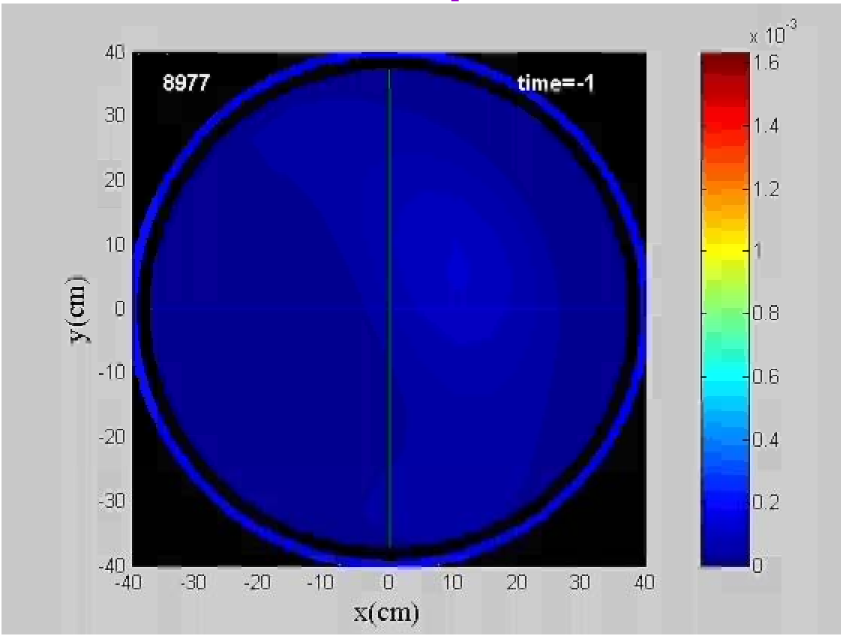
$$= -\frac{2B_\omega^2}{\mu_o \delta^*}\frac{r_s}{r} e^{-2\left(\frac{r_s - r}{\delta^*}\right)}\left\{1+\frac{\xi}{r}\right\}$$



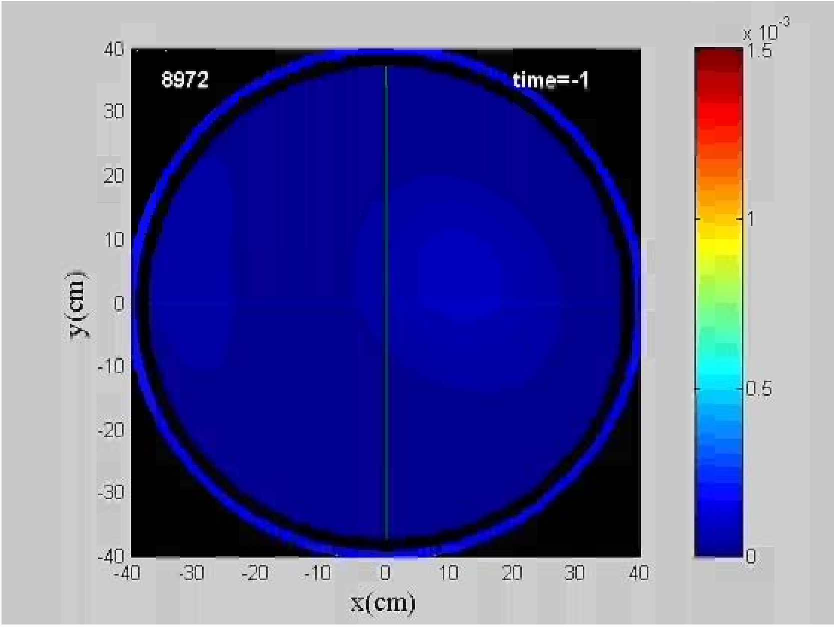
Stable if $B_\omega^{\,2}/\mu_o > 1.3\langle\rho\rangle\Omega^2 r_s^{\,2}$. (Similar to previous multipole stabilization.)

Tomography Illustrates RMF Stabilization of FRC when Stability Criterion Satisfied

Standard Operation

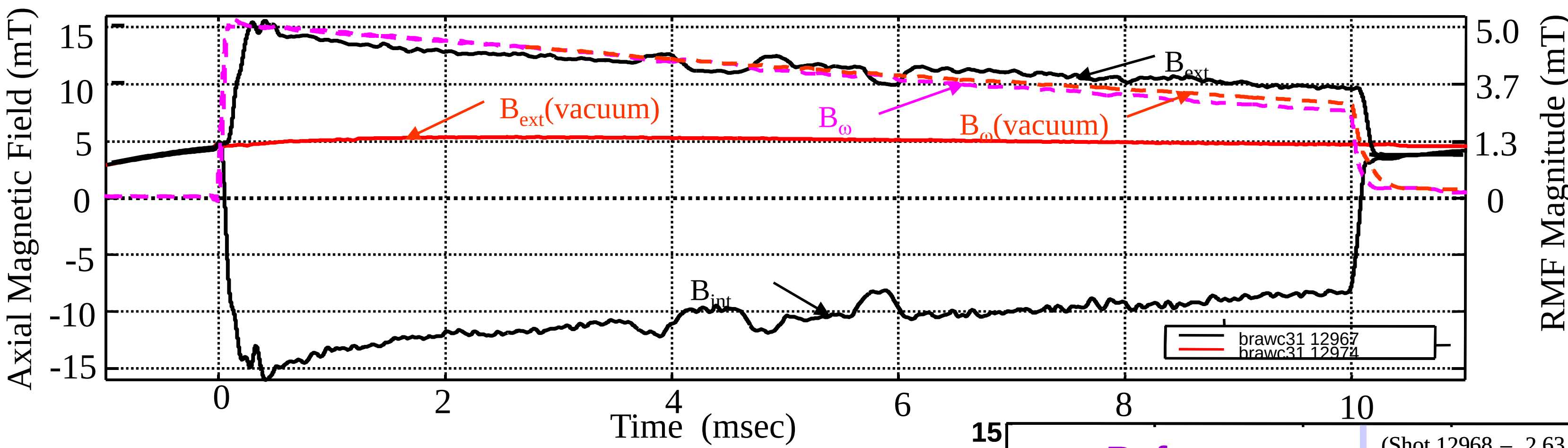


Reduced Central RMF

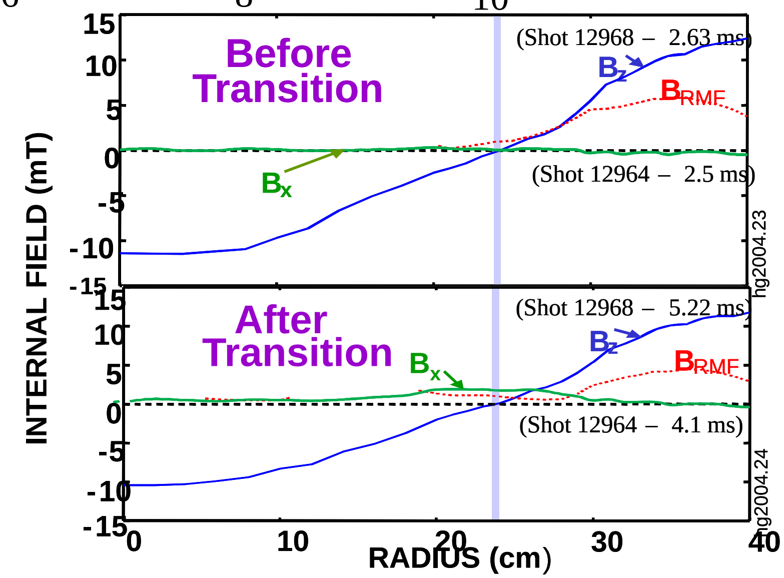


- The n=2 rotational instability is ubiquitous in θ-pinch formed FRCs due to ion spin-up in ion diamagnetic direction.
- Bulk plasma rotation always occurs in present RMF driven FRCs due to uncompensated torque on plasma electrons.

Long Time FRC Sustainment

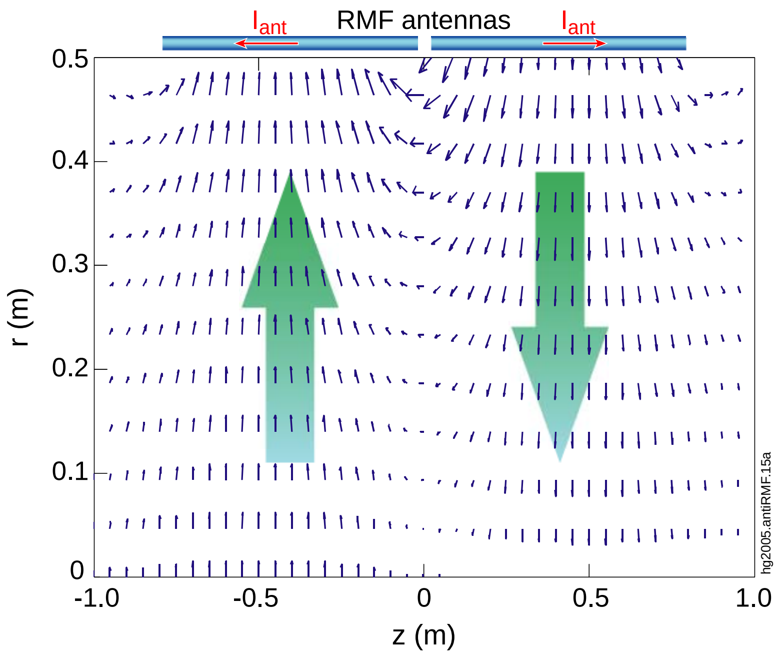


- Pulse time only limited by RMF power supply.
- No sign seen of any tilt instability.
- After ~4 msec, transition occurs to higher performance mode.
  - Spontaneous toroidal field development.
  - RMF penetration profile changes.
  - Lowering of interior resistivity.

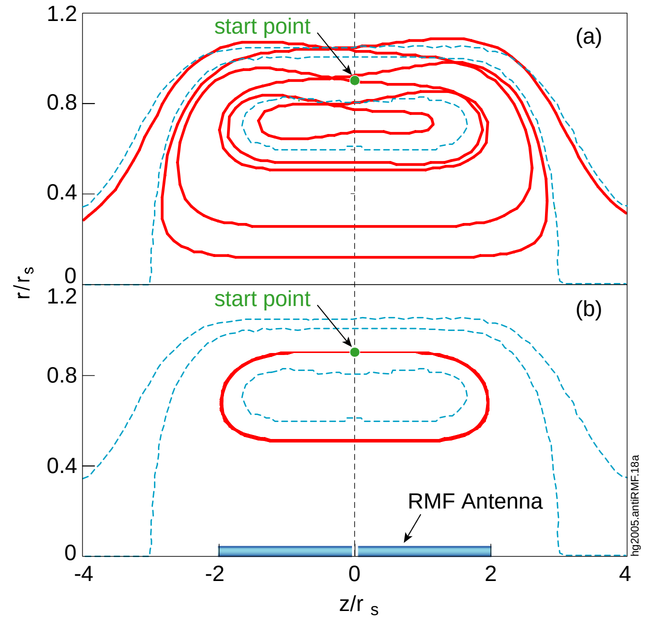


Odd-parity RMF Current Drive

(Developed by Cohen & Milroy during PPPL support of Universities program)



Anti-Symmetric RMF Field Pattern in Vacuum

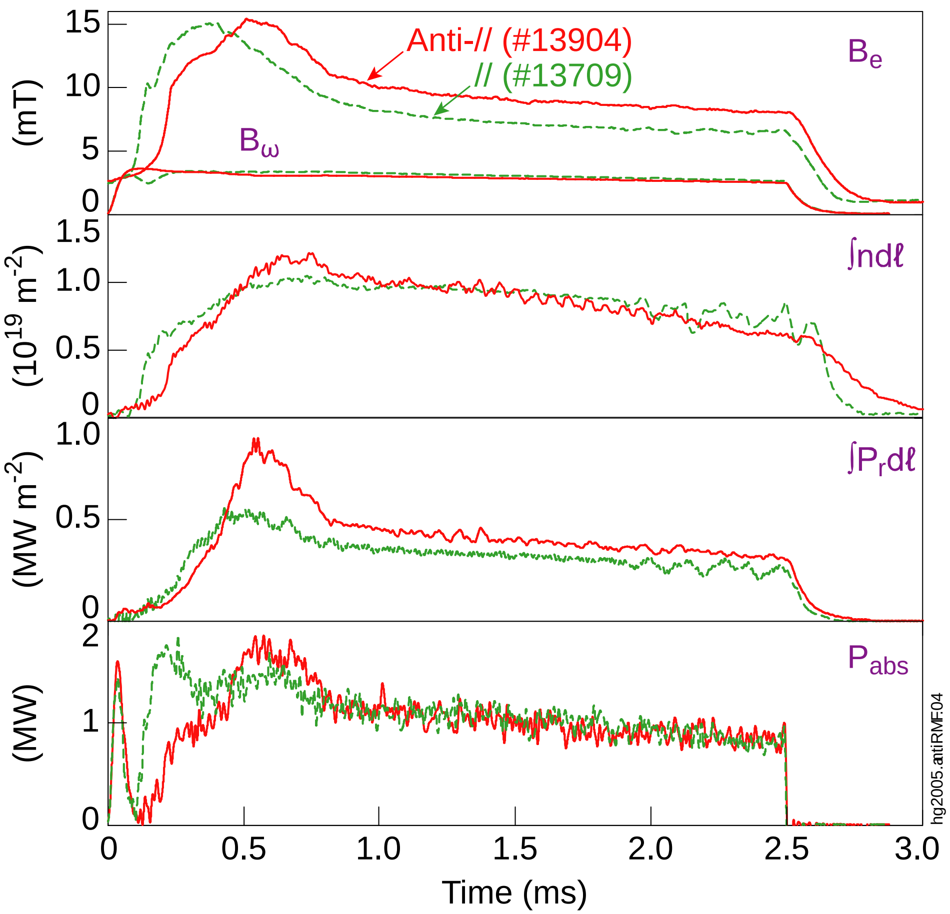


Field Line Tracings for Even (top) & Odd-Parity RMF (bottom)

$B_\omega/B_e = 0.25$, $\delta^*/r_s = 0.15$

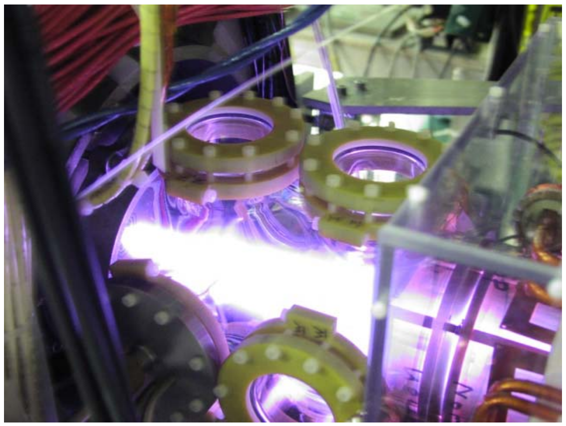
(partial penetration is great advantage since B_r is small)

Reduction of Convection/Conduction Losses with Odd-Parity RMF Current Drive?



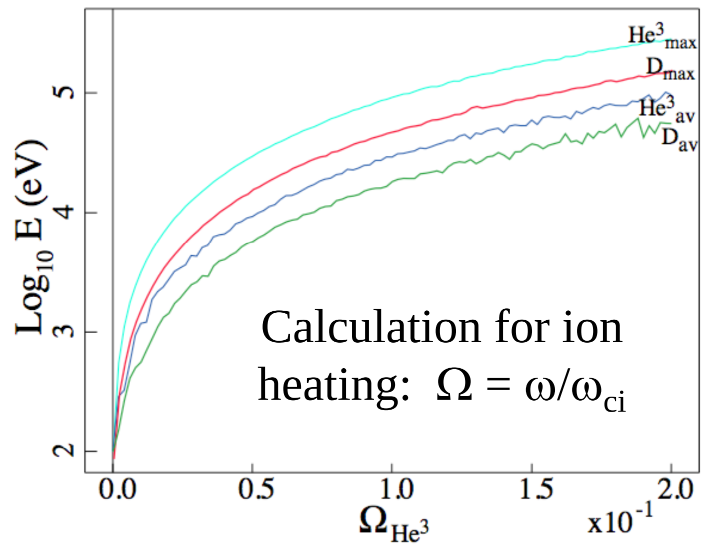
- Odd-parity, or anti-parallel, RMF drive is just as effective as even-parity drive, as evidenced by same achieved density and absorbed power.
- Magnetic field B_e is increased with odd-parity drive due to higher realized temperature, although still limited by radiation barriers.
- *Exact reasons for improved TCS performance are not well understood since TCSU achieves high T_t even with even-parity operation.*
- Odd-parity operation may not be important for present low *s* experiments since mostly uniform temperature, but should be critical for high *s* conditions!

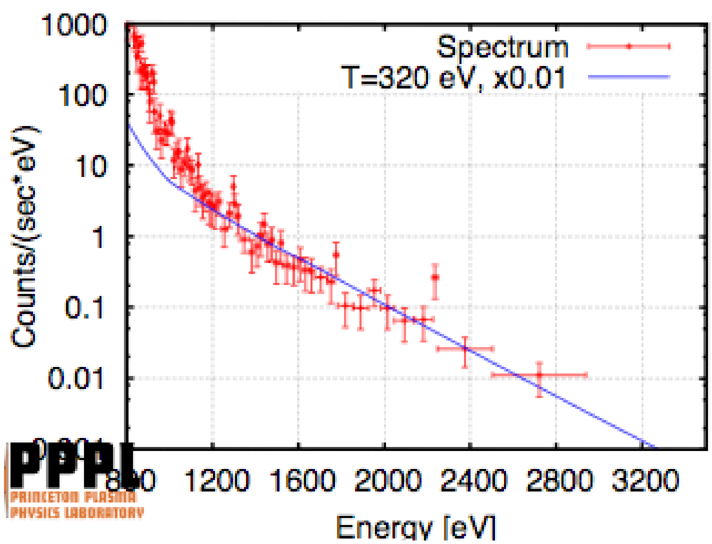
RMF can provide strong heating for both mirrors and FRCs



PFRC

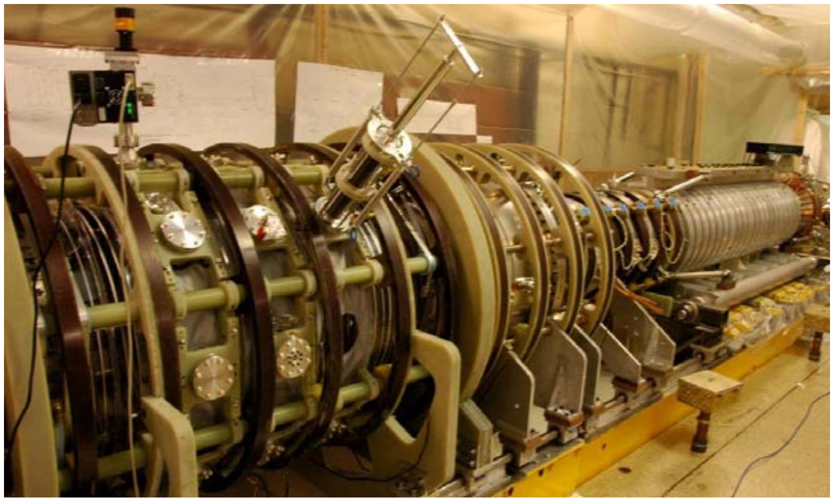
Mirror ratio ~ 6



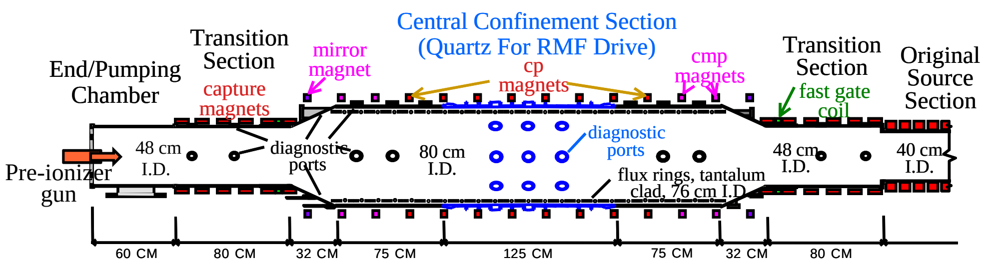


RMF penetrating to the FRC field null can provide preferential heating of different ion species.

TCS-upgrade built to control recycling of impurities and D_2



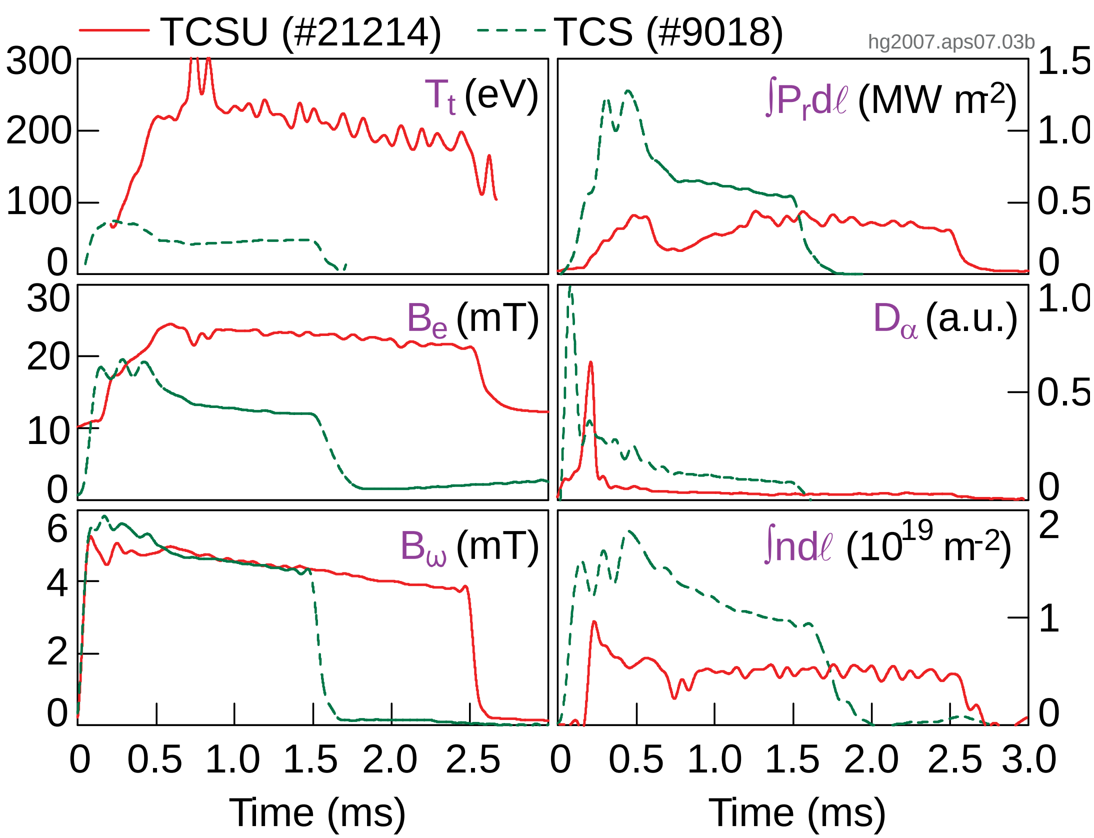
Completed early 2007



- Bakable (to 200°C), mostly all-metal construction.
- Extensive glow-discharge cleaning with provisions for wall-conditioning.
- Base vacuum pressure reduced from ~10^{-7} Torr to ~10^{-9} Torr.
- Impurity leakage in 1 day less than N_{FRC} (~10^{19}).
- SOL strike points far from FRC.
- Even or odd-parity RMF antennas.
- LSX/mod not needed to overcome initial radiation barriers.

TCSU Results (f_ω = 117 kHz)

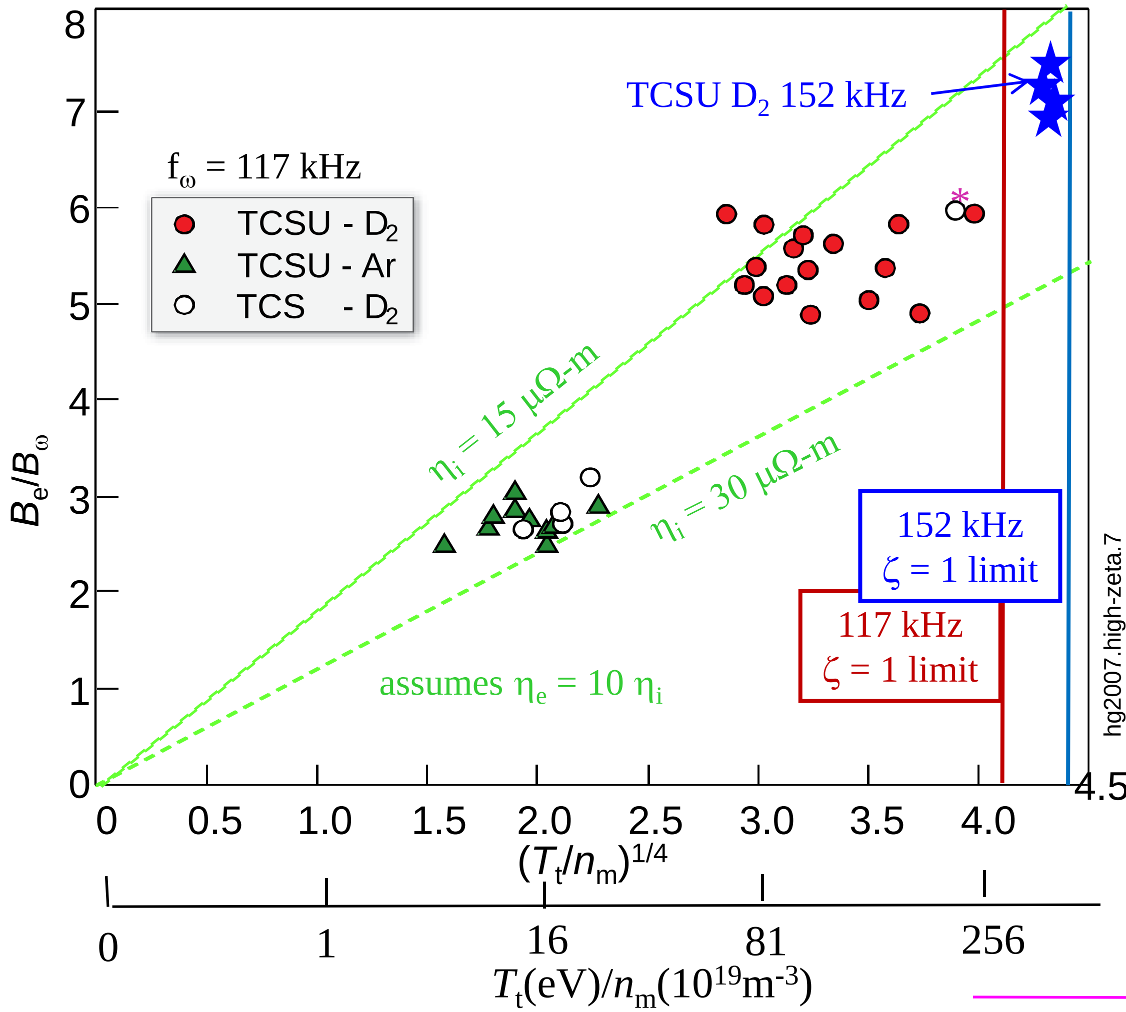
(baking & discharge cleaning only – external flux rings)



(Pulse lengths kept short for best, vibration limited, interferometer accuracy.)

- Radiated power reduced. Recycling (as indicated by D_α line radiation) also strongly reduced.
- Temperature close to $\zeta \rightarrow 1$ limit.
- B_e nearly doubled due to higher T_t for similar B_ω.

Measured B_e/B_ω Ratios Yield Cross-Field Resistivities

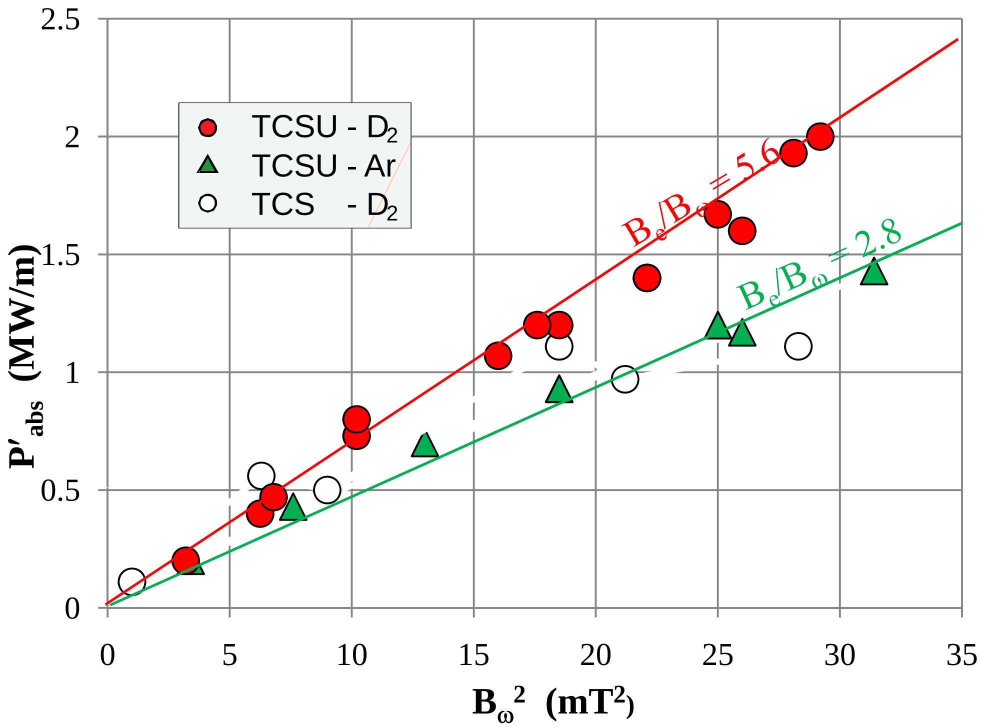


$$\frac{B_e}{B_\omega} = 13.1\frac{\left(T_t(\text{eV})/n_m(10^{19}\,\text{m}^{-3})\right)^{1/4}}{\left\langle \eta_{avg}(\mu\Omega\text{–m})\right\rangle^{1/2}}$$

$$\zeta = \langle\omega_e\rangle/\omega \propto B_e/n_e \propto \sqrt{T_t/n_e}$$

- Maximum experimental T_t/n_m ratio of 250 in Deuterium close to ζ = 1 limit of 280 for f_ω = 117 kHz.
- Resistivity certainly no worse at higher temperature, and most likely somewhat better!
- Extended at higher frequency in agreement with RMF theory.

Plotting P'_{abs} versus $B_\omega{}^2$ reveals true nature of power absorption



$$\text{EXP}: \; P'_{abs} = \underbrace{40{,}000 B_\omega^2(\text{mT})}_{P_{RF}} + \underbrace{1000 B_e^2(\text{mT})}_{P_\theta} \;\text{W/m}$$

<u>Calculation</u>

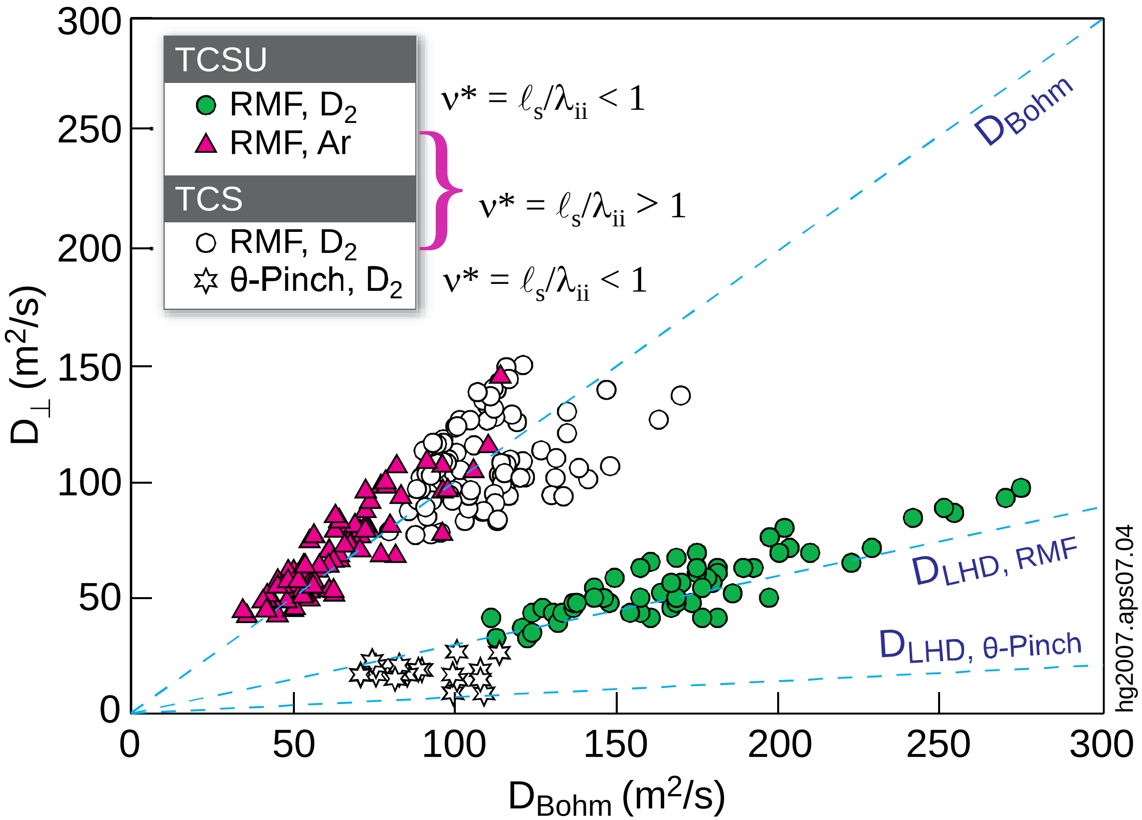
$$P_\theta = \int_0^{r_s} \eta_\perp j_\theta^2 2\pi r dr \ell_s \approx 1.4\pi \left(\frac{2B_e}{\mu_o}\right)^2 \langle \eta_\perp \rangle \ell_s$$

$$P'_\theta \approx 10 B_e^2(\text{mT})\big(0.58\eta_i + 0.42\eta_e(\mu\Omega\text{–m})\big) \;\text{W/m}$$

The absorbed power due to $\eta_\perp j_\theta{}^2$ yields a central resistivity of $\eta_i \approx$ 23 μΩ-m, essentially the same as calculated from torque balance!

- ***RMF scaling is well understood, and favors higher temperatures!***

Can study confinement in low collisionality regime - LHD-type scaling rather than Bohm



$D_\perp = \langle \eta_\perp \rangle / \mu_o$ determined by torque balance or flux lifetime.

$$D_{\text{Bohm}} = \frac{T_e(\text{eV})}{16 B_e(\text{T})} \quad \text{assuming } T_e = T_t/2$$

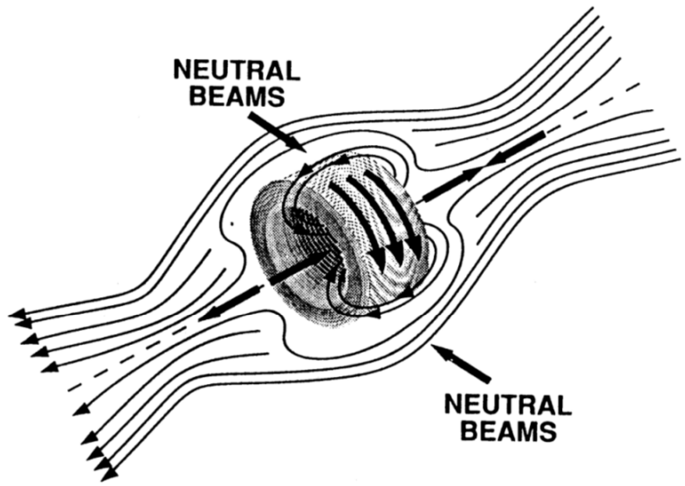
$$D_{\text{LHD}} = 0.15 D_{\text{Bohm}} \frac{(V_{\text{de}}/V_i)^2}{1 + \frac{\pi}{8}(V_{\text{de}}/V_i)^2}$$

$$(V_{\text{de}}/V_i) = \frac{1.7 T_t^{1/2}(\text{eV})}{B_e(\text{mT}) r_s(\text{m})}$$

It is essential to obtain such improvement for steady-state FRCs to scale to reactor parameters!

V_{de}/V_i is ~2.5 for TCSU and scales as $1/(n_e^{1/2} r_s)$, **which points out the need for a larger, more powerful machine to make dramatic improvements!**

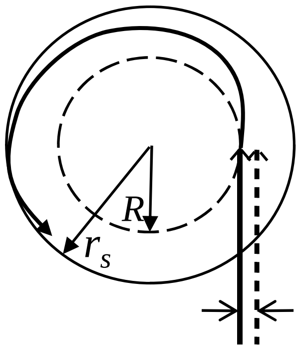
Neutral Beam Injection (NBI) attempted in 2XIIB to produce Field Reversed Mirror (FRM)



- Mirror ‘advantages’ were linear geometry with possible near-classical radial transport.
- FRM was one of two early ‘Q-enhancement’ approaches to plug mirror ends.
- Cannot produce field reversal by simple diamagnetism, and it may not be possible to do this slowly with Tangential NBI (TNBI).
- If have pre-existing FRC it will be straightforward to trap fast charge-exchange ions.
- Total azimuthal current is specified by FRC pressure gradients and flux: Fast ions will initially just replace some of the bulk electron current.

TNBI is an ideal complement to RMF since it inserts momentum in the opposite direction.

TNBI Monte-Carlo Calculations



$0.1r_s$ is ideal beam width

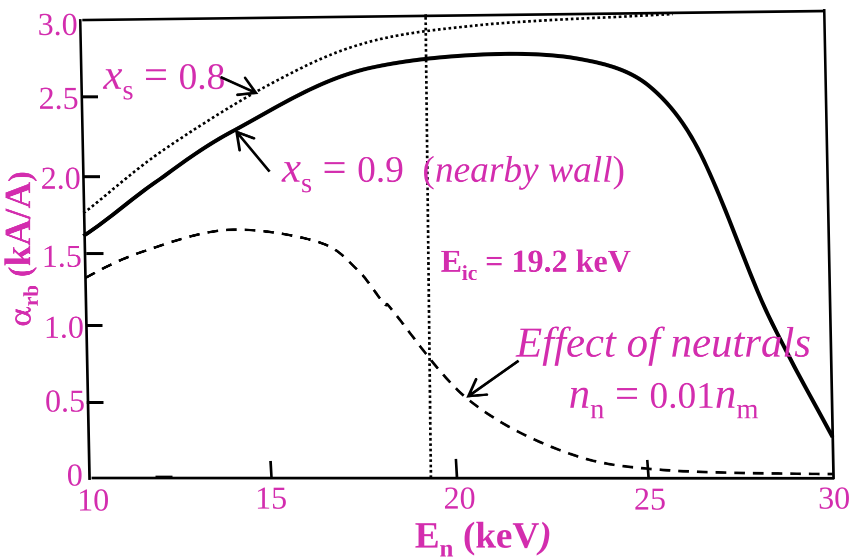
Critical orbit:

$$E_{ic}(\text{keV}) = \frac{0.0144}{A_i}\left(\frac{\phi_p(mWb)}{r_s(m)}\right)^2$$

Calculations performed for 45 mWb FRC conditions which would be achievable in ITER-era facility without improvements in TCSU resistivities. (r_s = 0.9 m, B_e = 60 mT, $n_e = 0.15\text{x}10^{20}\text{m}^{-3}$, T_e = 320 eV)

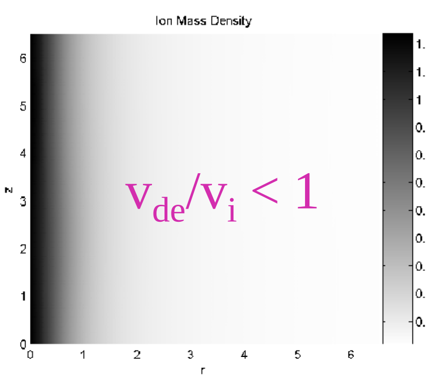
$$I_{ring} = \frac{\tau_s}{2\pi r/\text{v}_b} I_{beam} \qquad \tau_s \approx \frac{0.02\, T_e^{2/3}(keV)}{n_e(10^{20}\text{m}^{-3})}\ \text{sec}$$

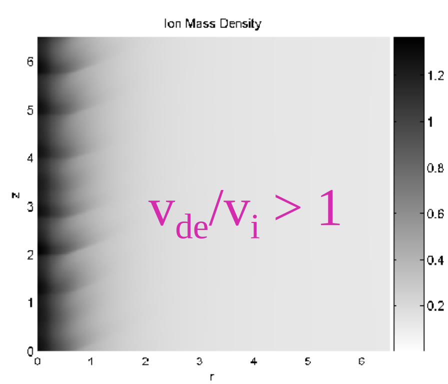
$$\alpha_{rb} \equiv \frac{I_{ring}}{I_b} = 0.75\frac{T_e^{2/3}(\text{keV})E_b^{1/2}(\text{keV})}{A_i^{1/2} n_e(10^{20}\text{m}^{-3})R(\text{m})}\ \text{kA/A}$$



FRC confinement improvements depend on reductions in anomalous transport

- Recent calculations show $\eta_\perp$ strongly reduced with $V_{de}/V_i < 1$
  - J. Loverich & U. Shumlak, '*Non-linear 2-fluid studies*' POP (2006)
  - B. Rogers, '*Gyrokinetic simulations of plasma turbulence*" 2007 DPP GI2
- Tandem mirror results showing long radial diffusion lifetimes in Gamma 10
  - T. Cho, 'High confinement …' 2007 DPP GI6
  - Radial τ_E ~ 60-80 msec with ~ δ_n ~ 20 cm. (TCSU has δ_n ~ 8 cm)
- $V_{de}/V_i \propto 1/n^{1/2}R$: extremely favorable for larger facility





Loverich & Shumlak calculations showing rapid turn-on of strong turbulence in diamagnetic plasmas when V_{de}/V_i exceeds unity, in agreement with many empirical scaling observations.

Need $s > 3$ to see internal confinement, and $E_{ic} > 15$ keV for TNBI

Parameter	TCSU	ITER-era FRC		Reactor
f_ω (kHz)	150	30		10
r_s (m)	0.37	0.9	0.9	2.0
B_e (T)	0.03	0.06	0.12	1.8
ϕ_p (Wb)	0.0035	**0.045***	**0.090****	4.5
T_i, T_e (keV)	0.12	0.32	0.65	10
n_e (10^{20}m^{-3})	0.1	0.15	0.3	4.0
s (in deuterium)	1.0	3.0	4.2	30
λ_{ii} (m)	25	150	300	5,000
ρ_{ci} (m)	0.06	0.04	0.03	0.01
V_{de}/V_s	3	0.65	0.47	0.05
A_i	2	2	2	2.5
E_{ic} (keV)	1.3	18	72	24,000

TNBI should improve these values

s can be increased by $\sqrt{2}$ using hydrogen

} governs $\eta_\perp$?

Optimal TNBI energy below E_{ic}.

*obtainable with no decrease in $\eta_\perp$.

** requires decrease in by $\eta_\perp$ factor of 4.

Pulsed vs Steady-State

$$n\tau_{Ereq} \approx \frac{nr_s^2}{8D_\perp} \propto \frac{(r_s B_e)^2}{D_\perp}$$

For a given $n\tau_{\mathrm{Ereq}}$ and $D_\perp$; steady-state or pulsed, FRCs must operate at the same value of $r_s B_e$.

$$s \approx \frac{48 x_s^{0.3}(r_s(\mathrm{m}) B_e(\mathrm{T}))}{\sqrt{A_i T_i(\mathrm{keV})}}$$

For a given $n\tau_{\mathrm{Ereq}}$ and $D_\perp$; steady-state or pulsed, FRCs will have the same *s* value.

Pulsed Advantages

- Less required flux, should make formation easier. ($\phi_p \propto r_s^2 B_e$).
- Higher density may make it more likely to reach $D_\perp < 1$ m^2/sec.
- If $D_\perp$ can be made ~ 0.01 m^2/sec, can operate at low *s*. ($r_s B_e \propto \sqrt{D_\perp}$).

Pulsed Disavantages

- Pulsed operation will most likely require larger $n\tau_E$ for same ‘Q’.
- Rapid repetition rate may be difficult, and material fatigue a problem.
- Large ratio of blanket volume to first-wall area will affect economics.

Options for FRC reactors

Numbers based on T = 10 keV and $n\tau$ = 5×10^{20} $m^{-3}s$.

Type	r_s (m)	B_e (T)	n_e (m^{-3})	τ_{Ereq}	ϕ_p (Wb)	s	$D_{\perp req}$ (m^2/s)	D_{Bohm} (m^2/s)	Req. $D_\perp/D_B$	v_{de}/v_t
S-S	2.0	2	5×10^{20}	1 sec	6	35	0.5	300	0.002	0.005
PHD	0.06	28	10^{23}	5 msec	0.075	15	0.1	20	0.005	0.01
MTF	0.006	630	5×10^{25}	10 μsec	0.017	35	0.5	1	0.5	0.005

*high s stability question cannot be avoided for a pure fusion reactor unless $D_\perp \sim 0.01$ m^2/sec. Fission-fusion could be an important application for FRCs, especially for pulsed FRCs.

Conclusions

- FRCs are a high risk, high reward approach to fusion.
- Cost of ITER-era new facilities are modest ~$30M.
- The physics is extremely interesting.
- There are enough encouraging results to justify performing critical experiments.