Application of a Rotating Magnetic Field for Confinement Enhancement and Control of MHD Instabilities in the FRC

John Slough

University of Washington

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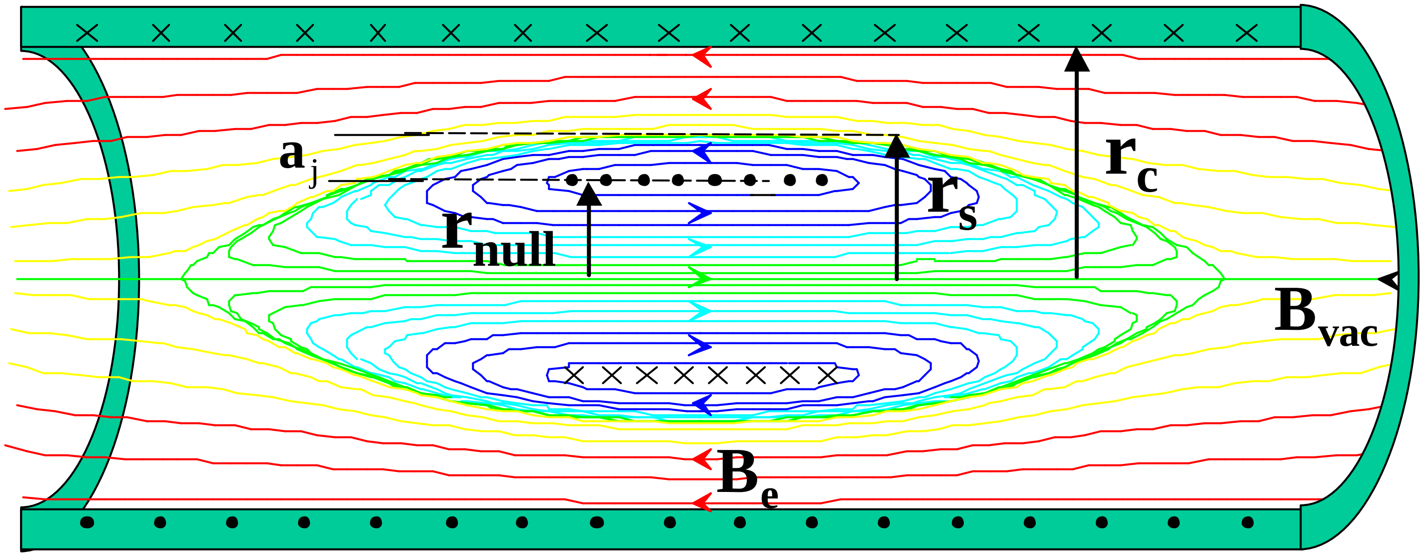
Outline

Field Reversed Configuration
- Formation
- Equilibrium

Challenges for Future Concept Development
- Stability and Confinement
- Small Scale Fusion

Rotating Magnetic Field (RMF)
- RMF for MHD Stability
- RMF for Enhanced Confinement

FRC General Description



Equilibrium in flux conserver:

$$\langle\beta\rangle = 1 - \frac{1}{2}x_s^2$$

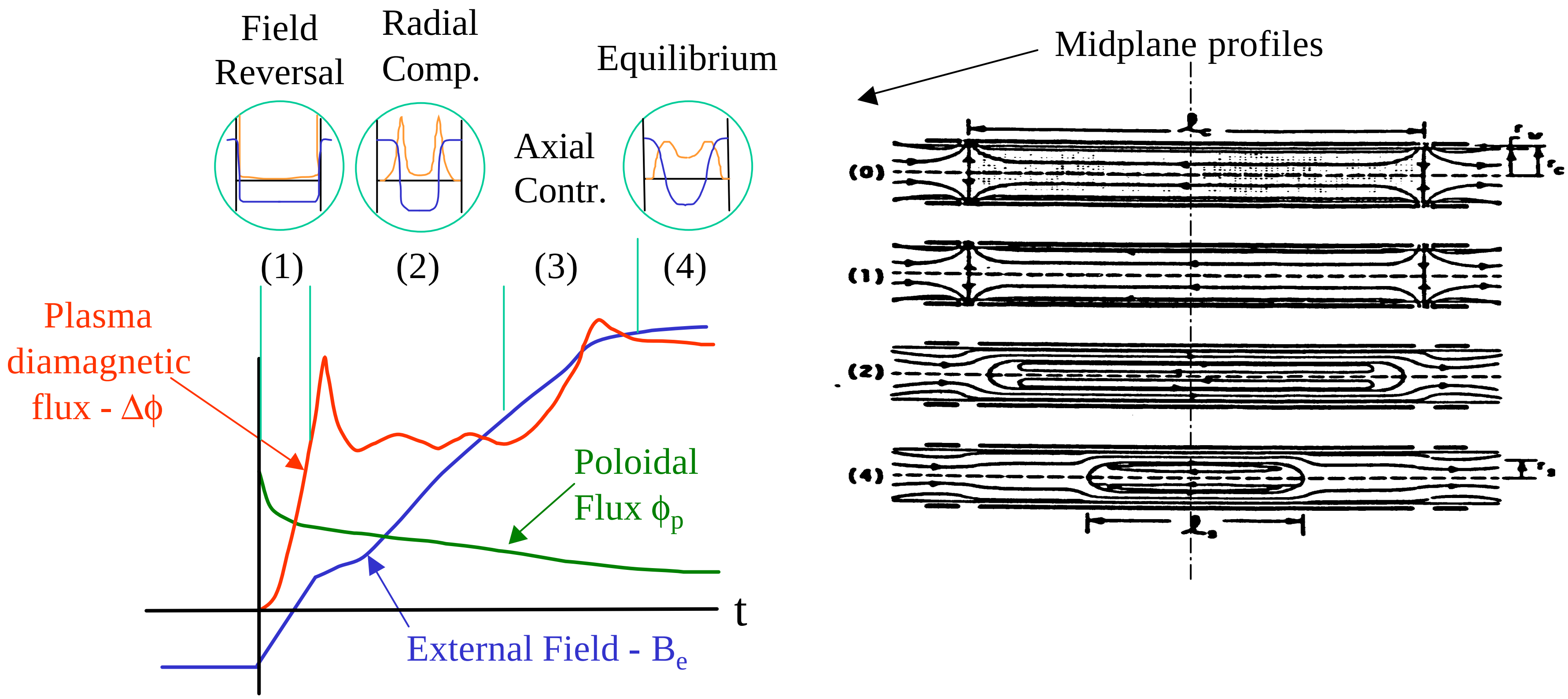
$$B_e = \frac{B_{vac}}{1 - x_s^2}$$

$(x_s = r_s / r_c)$

Stability: $s/\varepsilon < 0.5$ (empirical)
$s/\varepsilon < 0.2$ (MHD w Hall)

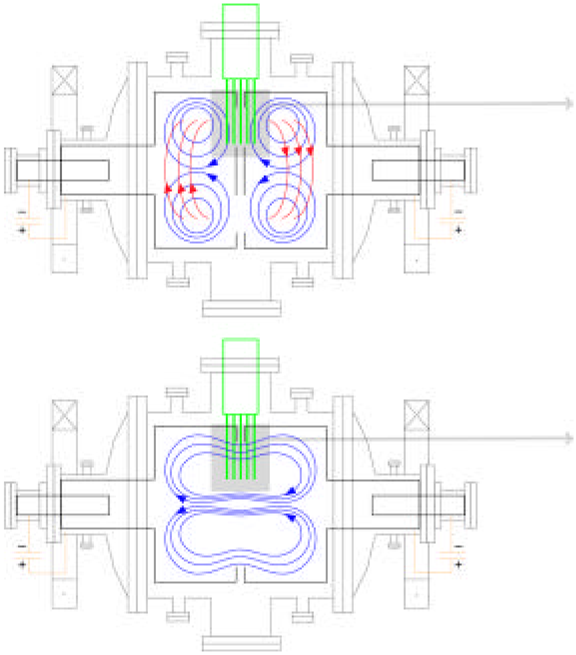
$$s = \int_R^{r_s} \frac{rdr}{r_s \rho_i} \approx \frac{a_\varphi}{\rho_{io}} \qquad \varepsilon = l_s / r_s$$

Reversed Field θ - Pinch Formation of FRC

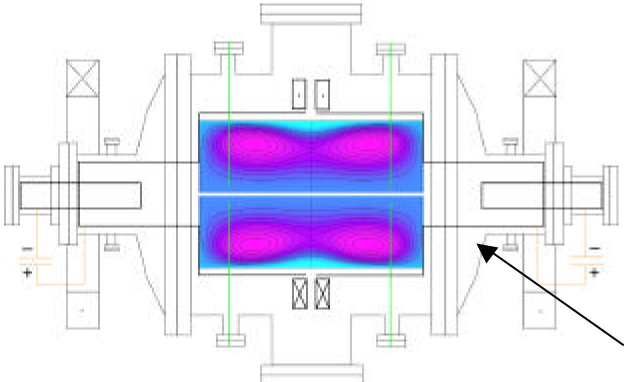


- Field-reversed θ pinch formation is an extremely dynamic process requiring high voltages and excellent uniformity.
- High input powers allow hot (**0.1 – 2.0 keV**) high density **(~1-5x10^{21} m^{-3})** plasmas to be obtained.
- **Best confinement observed with D_N ~ 4 m^2/s with a_f = 0.06 m (LSX) for s £ 4**

Merging of Counter-Helicity Spheromaks to create FRCs (Y.Ono - University of Tokyo)

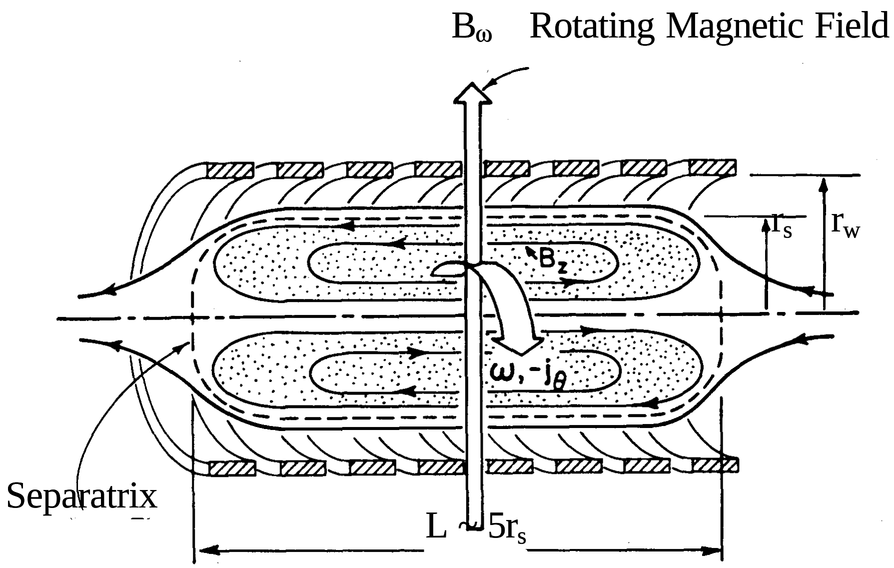


Swarthmore Spheromak Experiment (SSX-FRC)



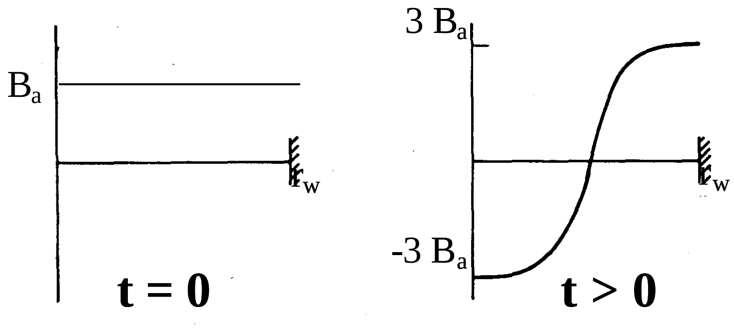
Analytic doublet-CT equilibrium
(P. Parks, GA)

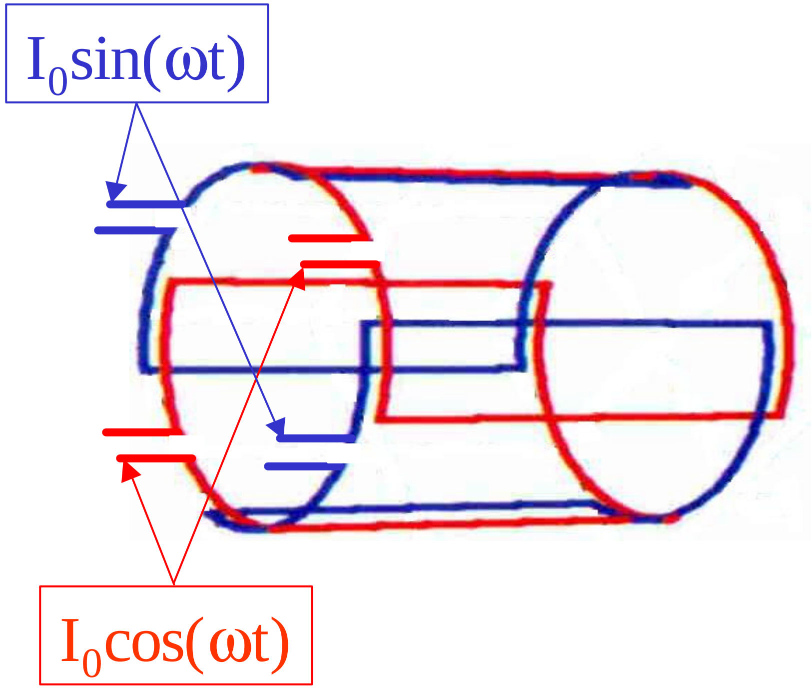
FRC Produced by a Rotating Magnetic Field (RMF)



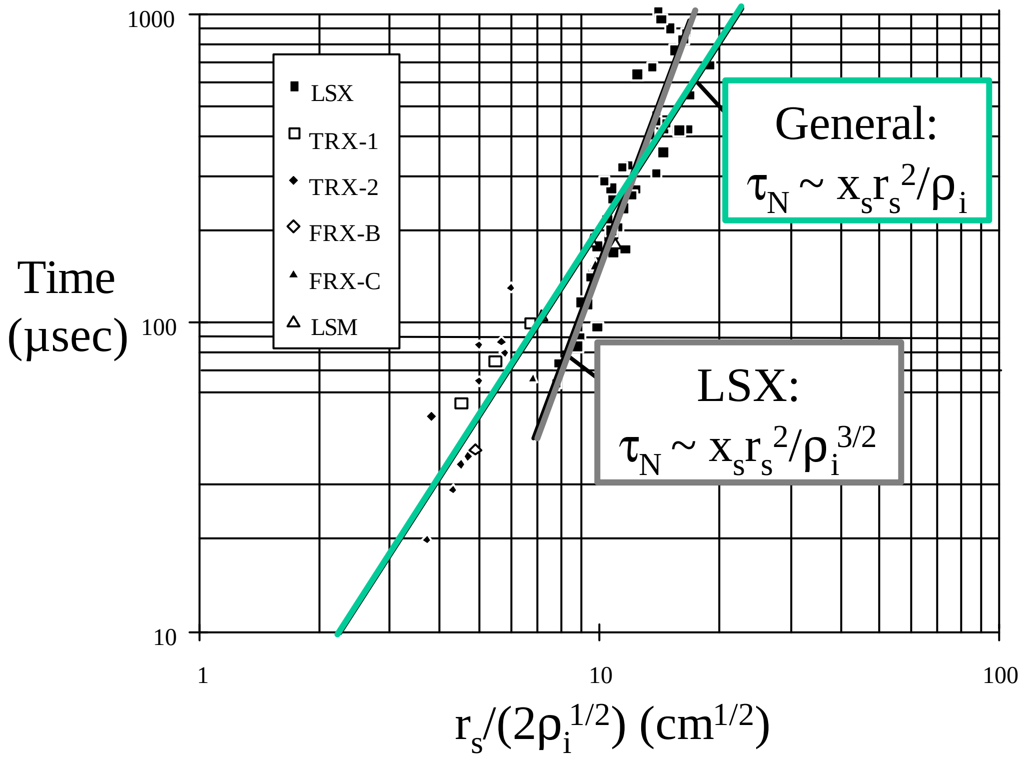
Initial axial magnetic field inside flux conserving coil is B_a.

RMF antenna coils external to the axial coil are shown below..





Measured FRC Particle Confinement



General:
$\tau_N \sim x_s r_s^{2}/\rho_i$

LSX:
$\tau_N \sim x_s r_s^{2}/\rho_i^{3/2}$

From past FRC experiments (Hoffman and Slough, 1993) :

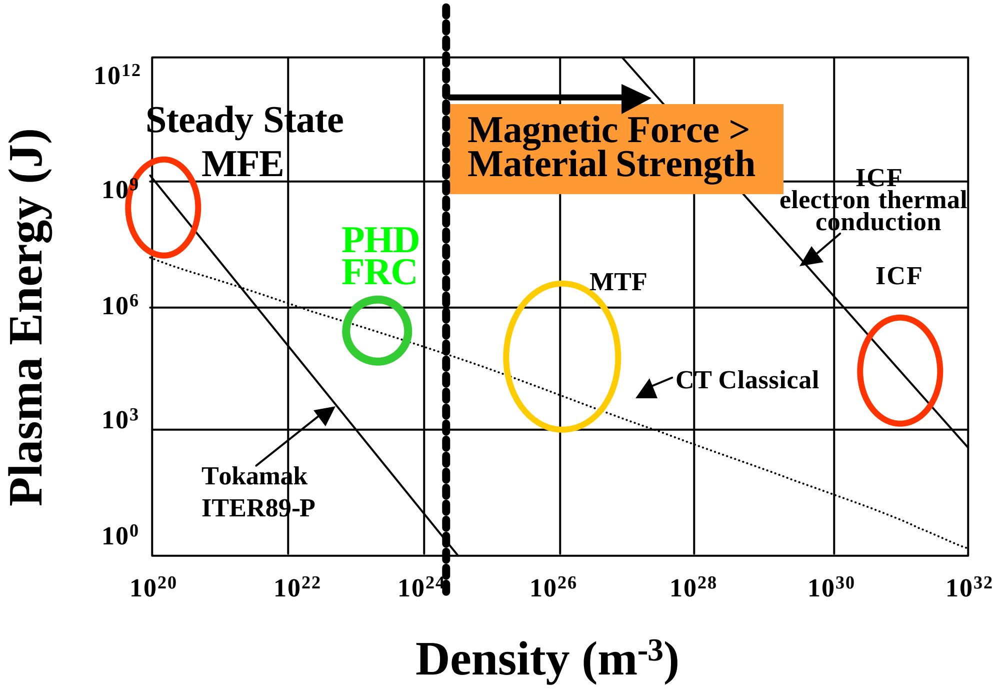
$$\tau_N = 3.2\mathrm{x}10^{-15}\ \varepsilon^{0.5}\ x_s^{0.8}\ r_s^{2.1}\ n^{0.6} \qquad \left(\sim \frac{r_s^{2}}{\rho_i}\right)$$

For a given plasma energy E_p = 3/2NkT$_{fus}$

$$\mathbf{n t \sim r^{2.1}\ n^{1.6} \sim r^{2.1}\ (N/r^{3})^{1.6} \sim r^{-2.7}}$$

Energy requirements vs. plasma density for various Fusion Regimes

(for $n\tau_E = 3\times10^{20}\ \mathrm{m}^{-3}\ \mathrm{sec},\ T_i = 10\ \mathrm{keV}$*, and poloidal* $b \sim 1$ *)*



- Small-scale FRC fusion regime based on confinement scaling observed in previous expts.

- Transport believed to be the result of edge driven microinstability (Lower Hybrid Drift) where $\tau_N \sim R^2/\rho_i$.

Major Physics Issues for Steady State FRC Reactor

1. Continued stability at larger sizes as represented by the parameter s (~ # of internal ion gyroradii)
2. Major confinement improvement at low densities
3. Current (or flux) sustainment at ~ 10 MA level
4. Technical ability to form larger FRCs

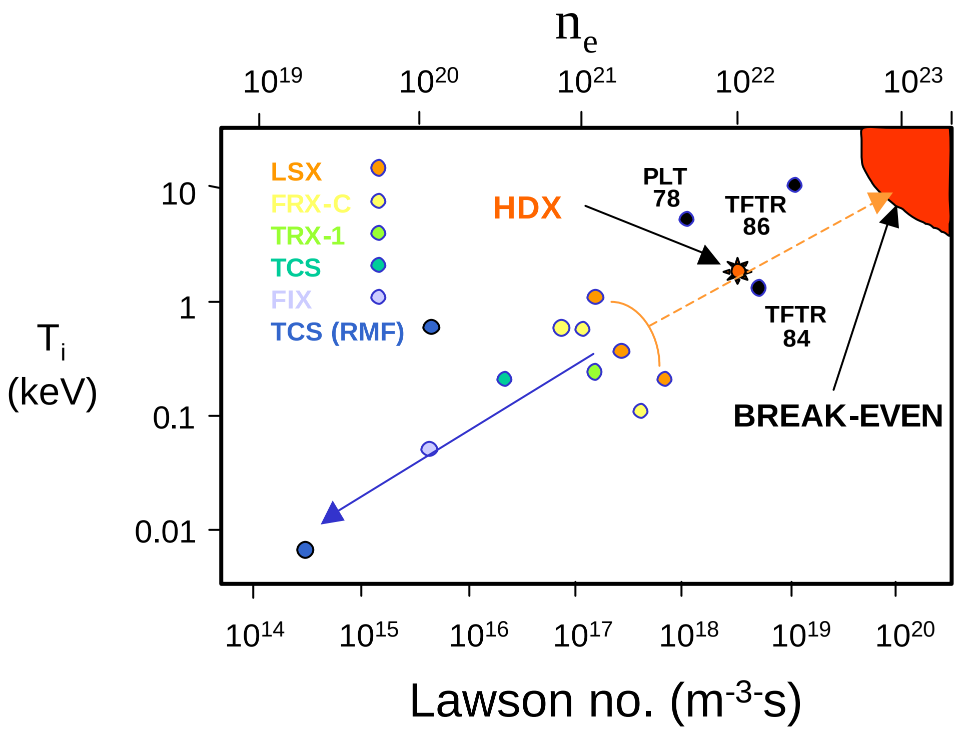
Reactor Issues for Small Scale FRC Fusion

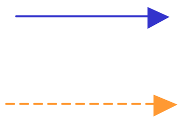
Maintain stability and enhance confinement for higher fusion gain

Lower the required compression field (18 T)

Increased burn time ($\tau_{burn} \sim \tau_{config}$)

Confinement Scaling for Various FRC Experiments

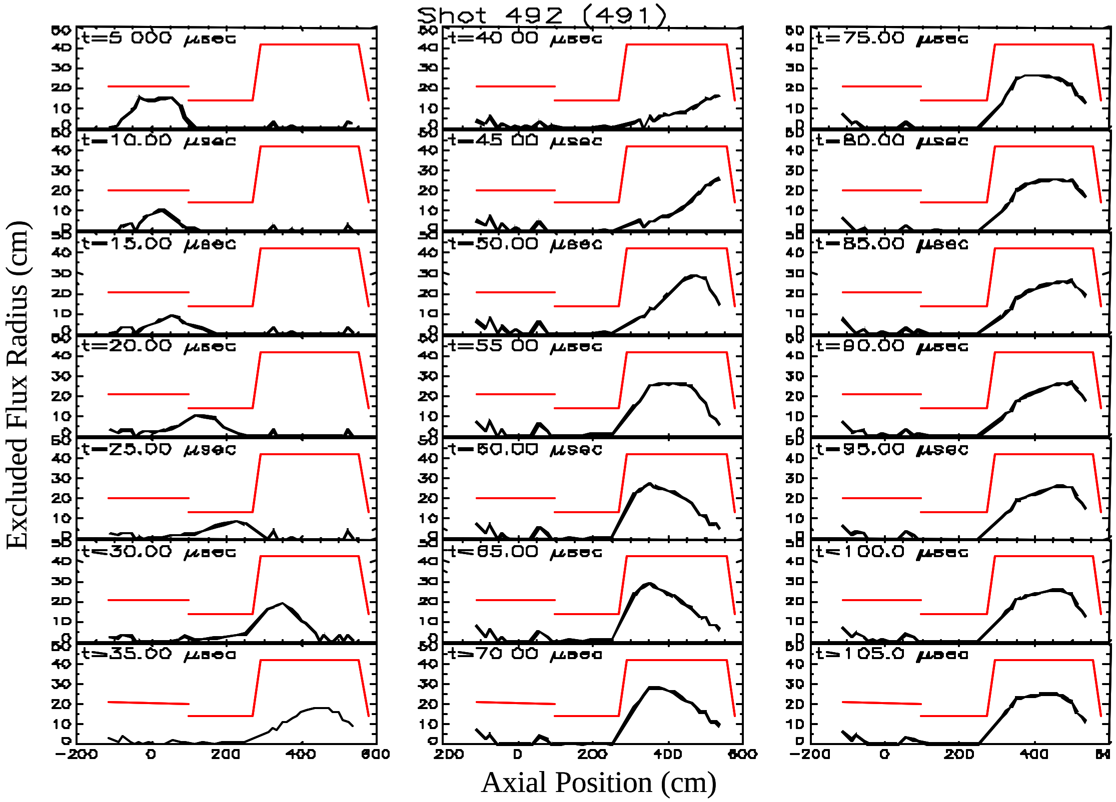




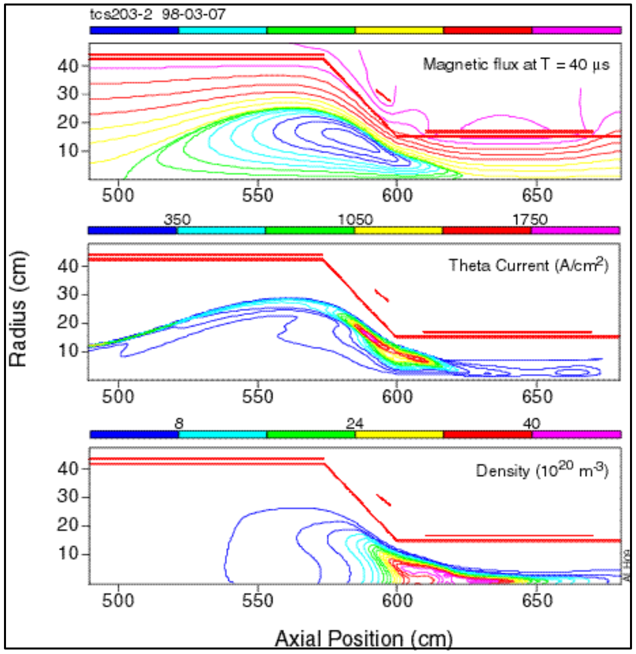
Translation and Expansion

Acceleration and Compression

Translation of FRC into TCS

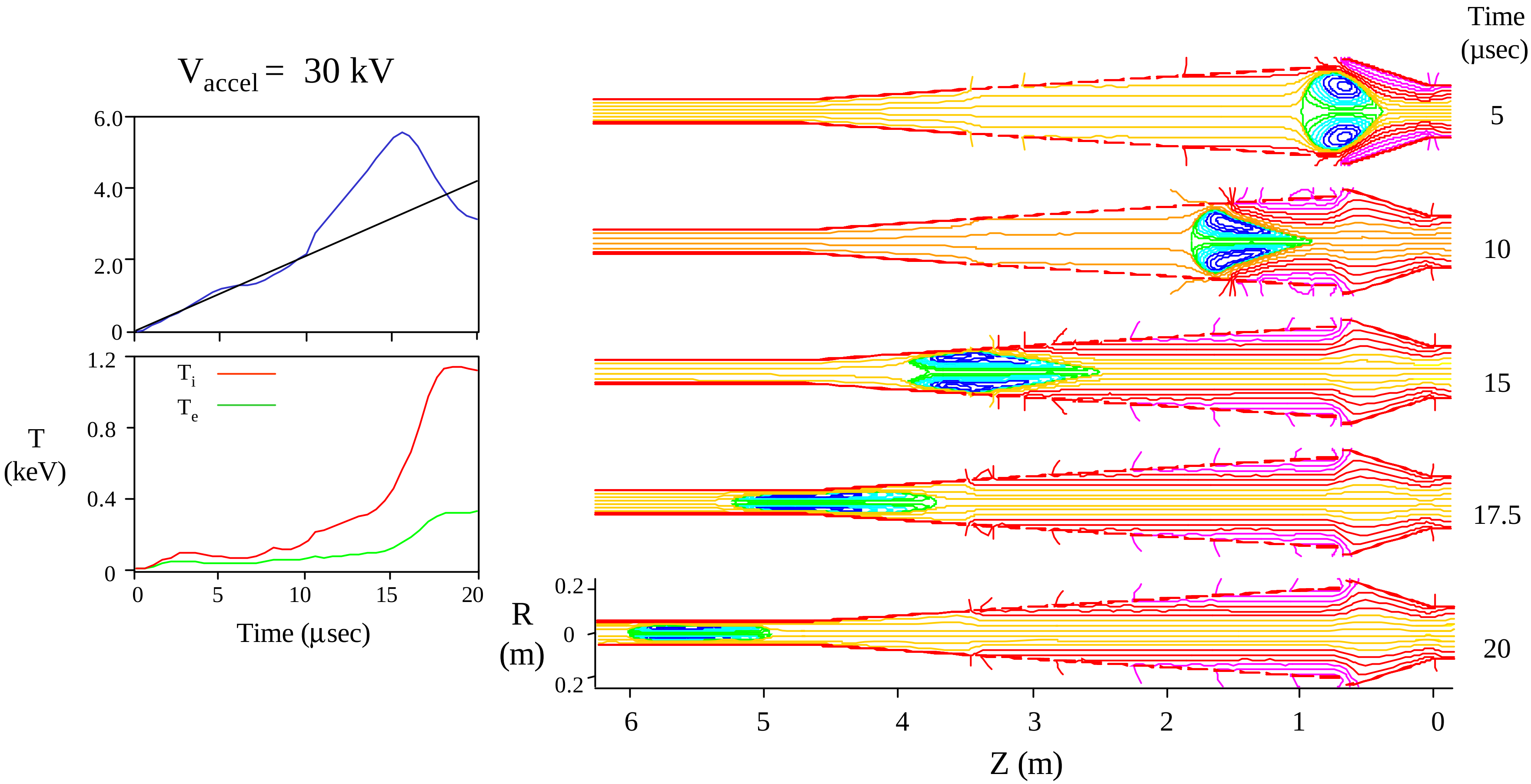


Experimental Measurements



MOQUI Calculated First Reflection Details

Resistive 2D MHD Calculation of FRC with Propagating Magnetic Field (0.4 T)



- FRC confinemnt scaling $\Rightarrow n\tau \sim 10^{19}$ m^{-3}-s at T > 1 keV after compression

PHD Burn Parameters for FRC

Assume: $\mathbf{B_{vac} = 18\ T}$ **(SCC),** $\mathbf{x_s = r_s/r_c = 0.6}$ $\mathbf{e = l_s/2r_s = 20}$

$$t_N = 3.2\mathrm{x}10^{-15}\ e^{0.5}\ x_s^{0.8}\ r_s^{2.1}\ n^{0.6}$$

For a flux conserving vacuum wall (pipe):

$B_e = B_{vac} / (1-x_s^2),$ ⇒ $\boxed{B_e = 28\ T}$

From pressure balance with $T_e + T_i$ ~ 10 keV:

$B_e^2/2\mu_0 = n\ k\ (T_e + T_i)$ ⇒ $\boxed{n_{max} = 2\mathrm{x}10^{23}\ m^{-3}}$

Set nt ~ $1\mathrm{x}10^{20}\ m^{-2}\ s$ (Lawson) t ~ 500 msec

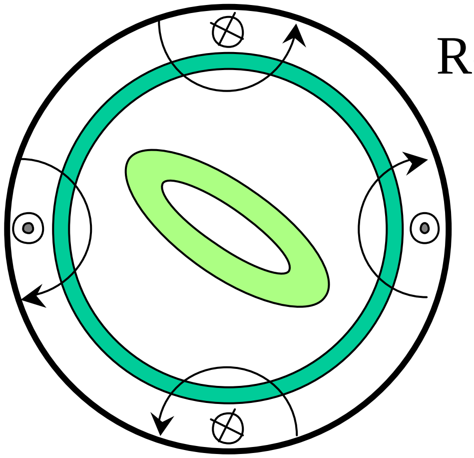
From FRC scaling given above we can solve for $\boxed{r_s = 2.8\ cm}$

Coil Radius ($x_s = 0.6$) ⇒ $(r_c = 4.7\ cm)$ $r_c - r_s \sim 30\, r_{ie}$

Energy in FRC plasma (ellipsoid)

$3/2 <\beta> n_{max}\ kT\ (4/3\pi\varepsilon r_s^3)$ ⇒ $\boxed{E_p = 720\ kJ}$

Instabilities Observed in FRCs



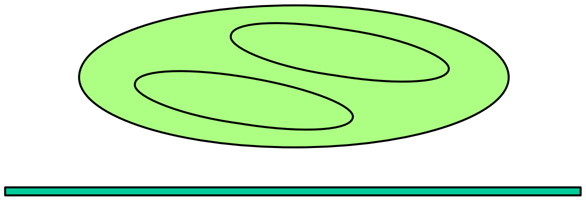
Rotational

n=2

End

View

- Rotational mode is driven by centrifugal forces from particle loss and/or end-shorting of radial E field.
- Mode limits FRC lifetime to ~ ½ τ_N



Internal Tilt

Side View

- Internal tilt starts out as an axial n=1 shift mode. Only clearly observed in recent expts. (Cothran, Brown, Schaeffer)
- Mode limits FRC lifetime ~3 axial Alfven times.

FRC Stability (Theory)

Basic MHD

- Bad curvature produces MHD instability to tilt, interchange and ballooning modes. Compressibility stabilizes interchange modes.

MHD with FLR and Hall (two fluid effects)

- Both effects cause the ion and electron disturbances to get out of phase: Tilt growth rate reduced but not stabilized for FLR (Ishida and Steinhauer, Belova)
- Tilt stability for $s/\varepsilon < 0.2$ from Hall Term (Barnes)

Relaxed States with Flow

- High-beta *possible;* sheared flow *necessary* in relaxed states
  - find proper relaxation principle (Steinhauer, Ishida, Mahajan, Yoshida, Dasgupta)

FRC Stability (Experiment)

- FRC tilt stable for $s/\varepsilon < 0.5$
- FRC grossly stable except for rotational modes

FRC Stability in PHD Fusion Regime

s /e parameter

$s= \varphi /(2\pi\, r_s\, B_e\, \rho_{ie})$

FRC poloidal flux:

$\varphi = \pi\, r_c^{\,2}\, B_e\, (x_s/\sqrt{2})^{3.5}$

j = 9.5 mWb

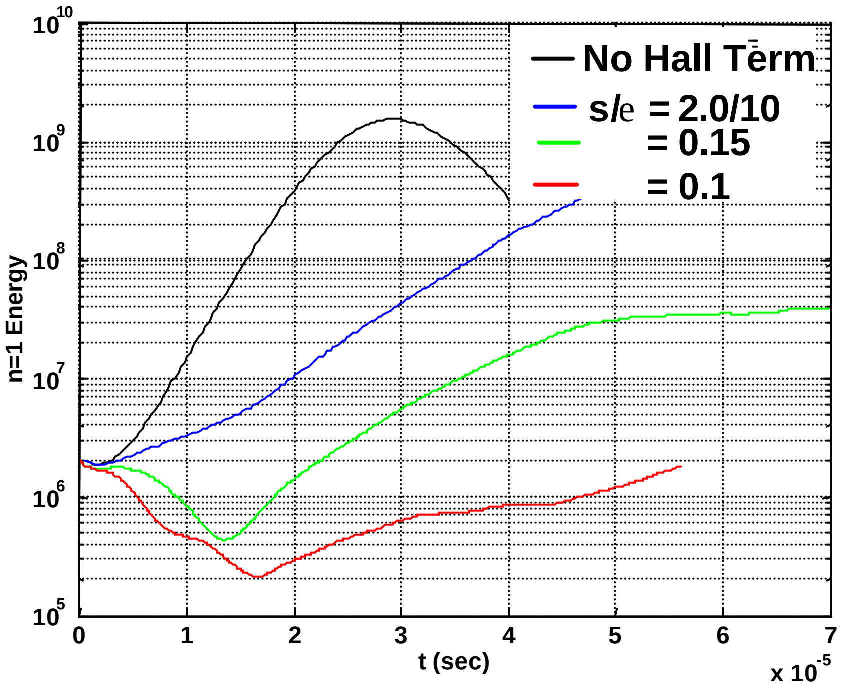
Empirically from LSX data

$s/\varepsilon < 0.5$

for gross stability **AND** good confinement

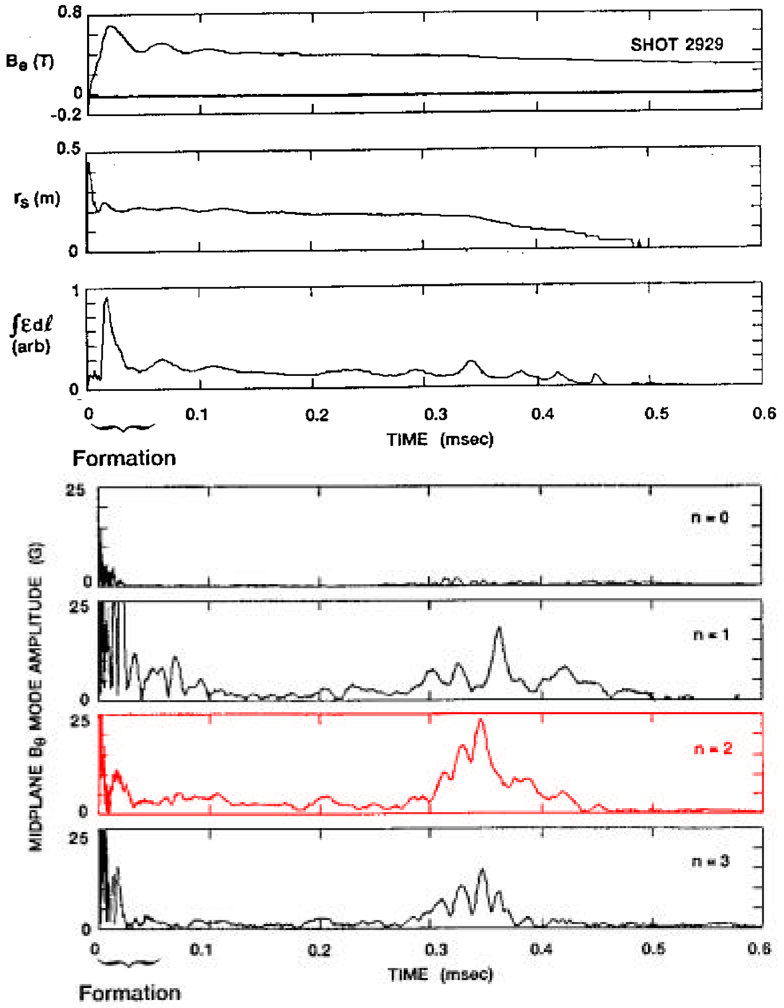
PHD FRC: **s/e = 2.4/20 = 0.12**

Recent 3D MHD Results
Internal Tilt Stability
(Barnes and Milroy)



PHD FRC in MHD Stable Regime

FRC Stability at s/ε ~ 0.5

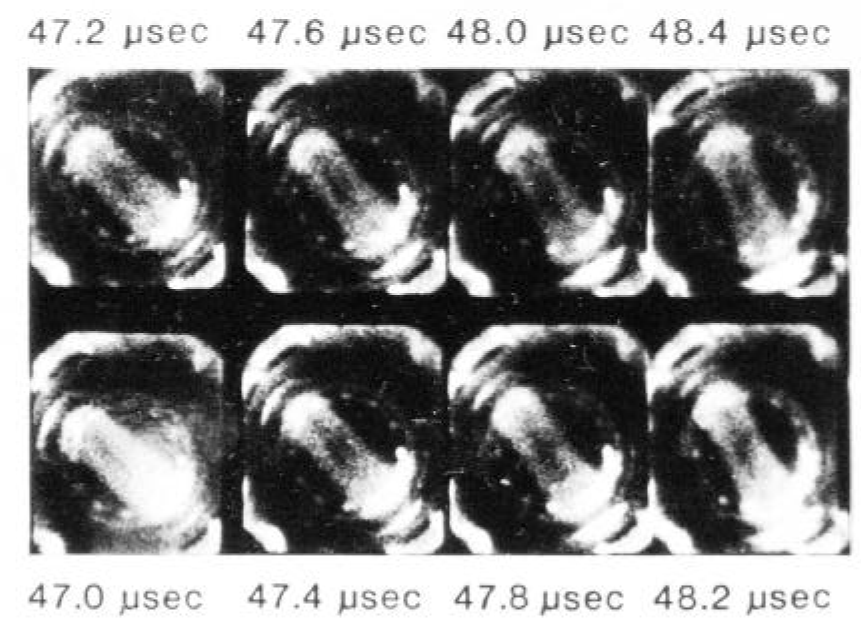


Data taken on LSX at s ~ 3.5

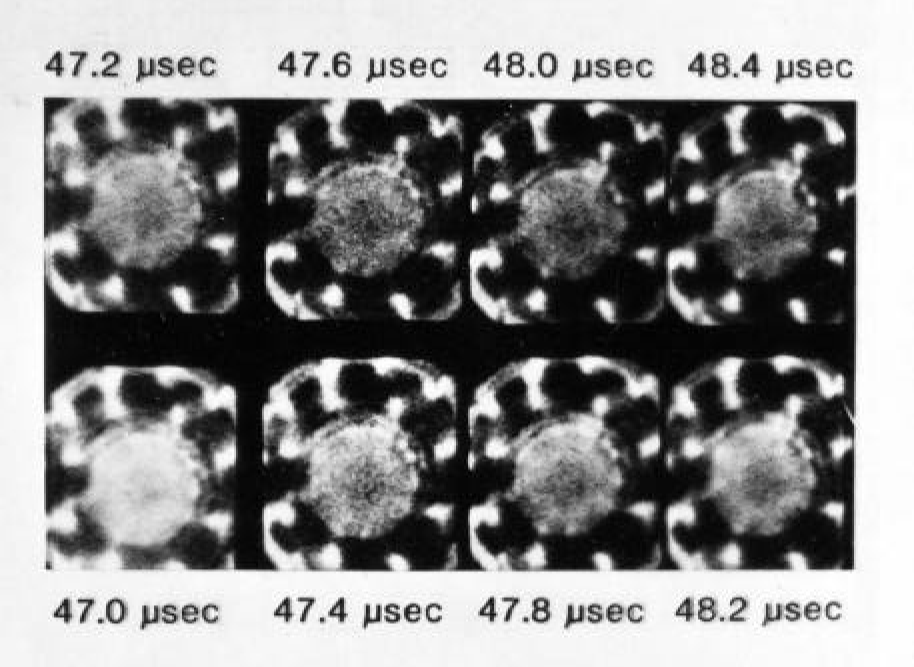
- Much n=1 activity during formation, but dies away if distortions not too large
- Formation distortions not primarily related to s, but to axial dynamics and low axial viscosity (low T_i)
- Rotational mode (mostly n=2) grows from equilibrium when multipole fields not used

Stabilization of n=2 Rotational mode

(First demonstrated at U. of Osaka w quadrupole)



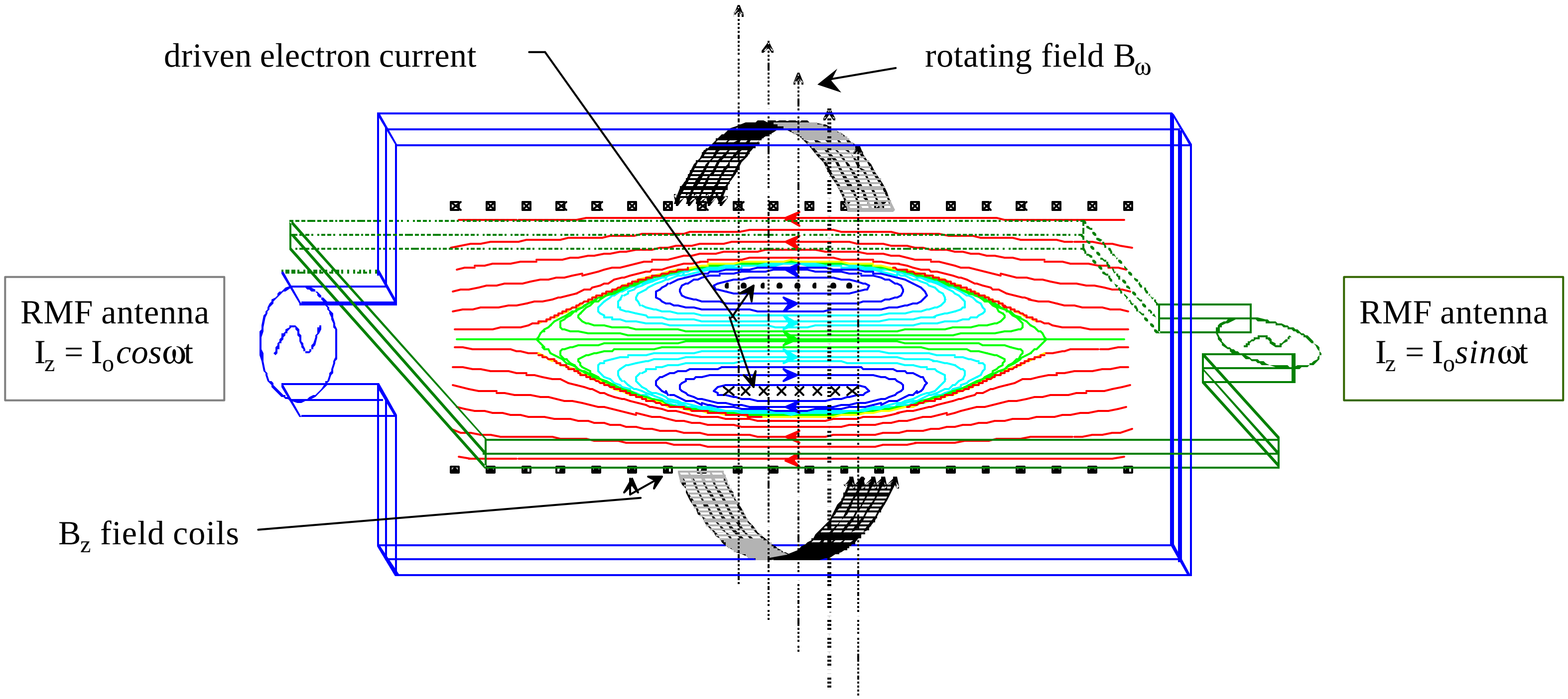
No Stabilization



Octopole Stabilization

- Significant wall contact due to plasma flow onto static multipole field
- Large plasma distortion (quadrupole) from static field created turbulent boundary in LSX at s>2

RMF Current Drive



- ‘Drag’ Electrons Along With Rotating Radial Field
  - Must have $\omega_{ci} < \omega << \omega_{ce}$ for electrons, but not ions, to follow rotation
- Electrons Magnetized on Rotating Field Lines ($\omega_{ce}\tau >> 1$)
  - Necessary for efficient current drive
  - Absolutely necessary for rotating field penetration

Control of Diffusive Losses with RMF

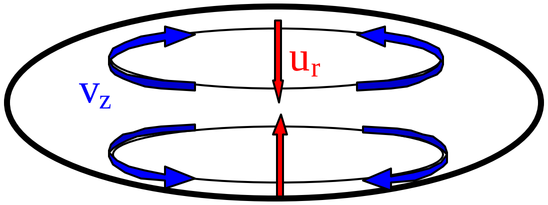
Gen. Ohm’s Law (θ comp): $E_\theta = \eta\, j_\theta - \frac{1}{ne} u_r B_z - \frac{1}{ne} \langle j_z B_r \rangle$

From synchronous electron motion: $j_\theta = -ne\omega r$

From first order term for screening current j_z

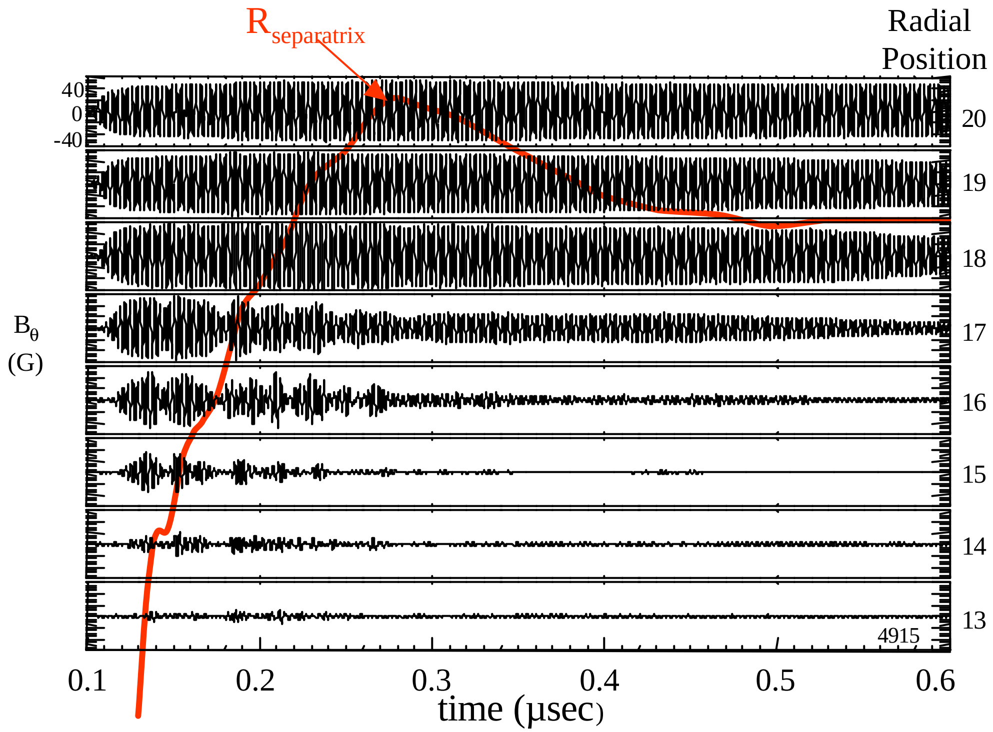
$$\langle j_z B_r \rangle = \left[2\left(\frac{\nu_{ei}}{\omega_{ce}} \right) ne\omega r \right] B_\omega \langle \cos^2\theta \rangle = \eta\, j_\theta\, ne$$

This drive term opposes the dissipative ηj_θ term, and stops diffusive losses ($u_r \sim 0$) in steady state ($E \sim 0$):

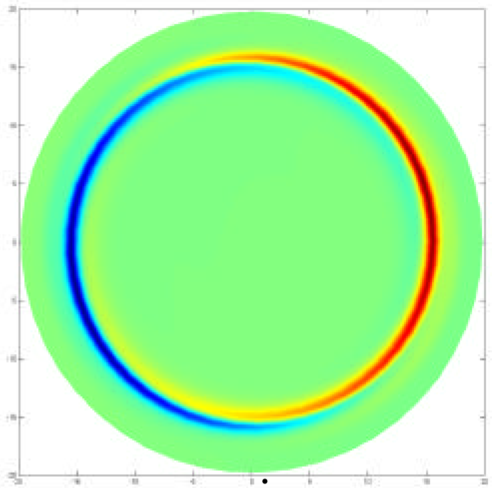


FRC Confinement by RMF Field

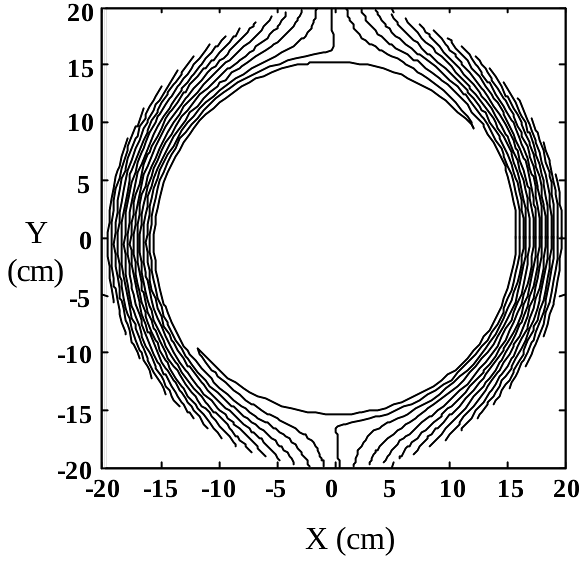
- Axial currents inside FRC limit RMF ~ 2 cm penetration past separatrix
- Strong radial flow $u_r B_z \sim \langle j_z B_r \rangle / en$ is obtained
- Minimum energy and particle loss observed under these conditions



2D MHD Calculation

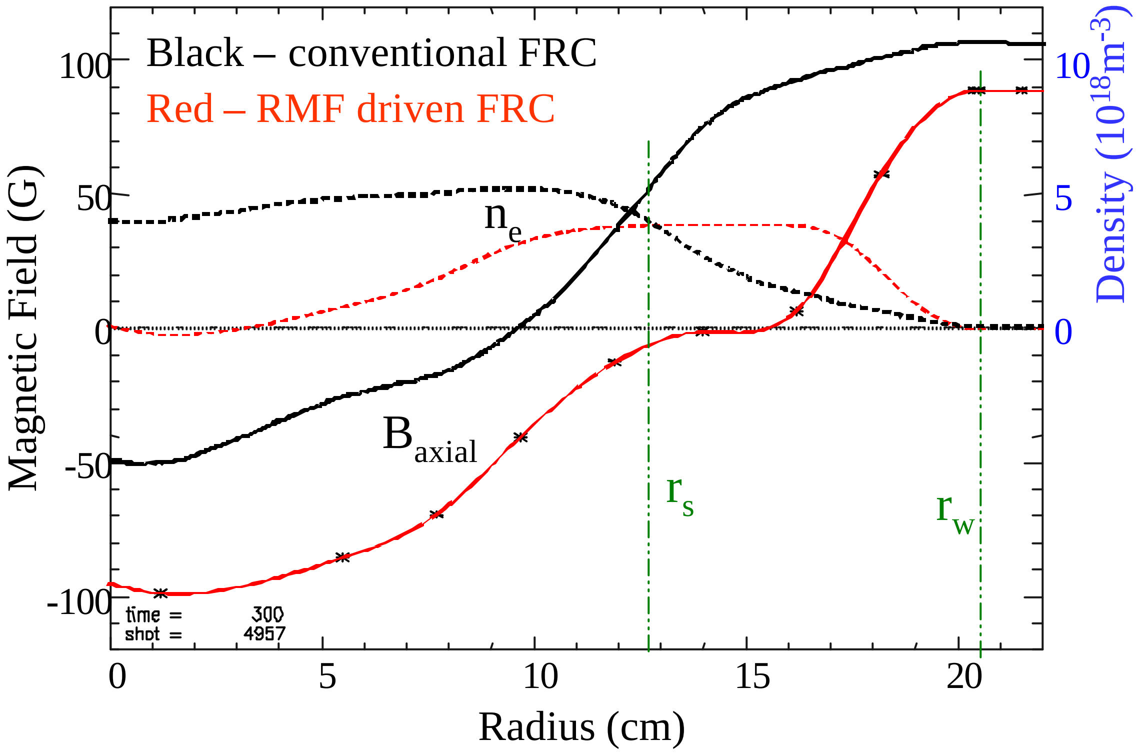


j_z

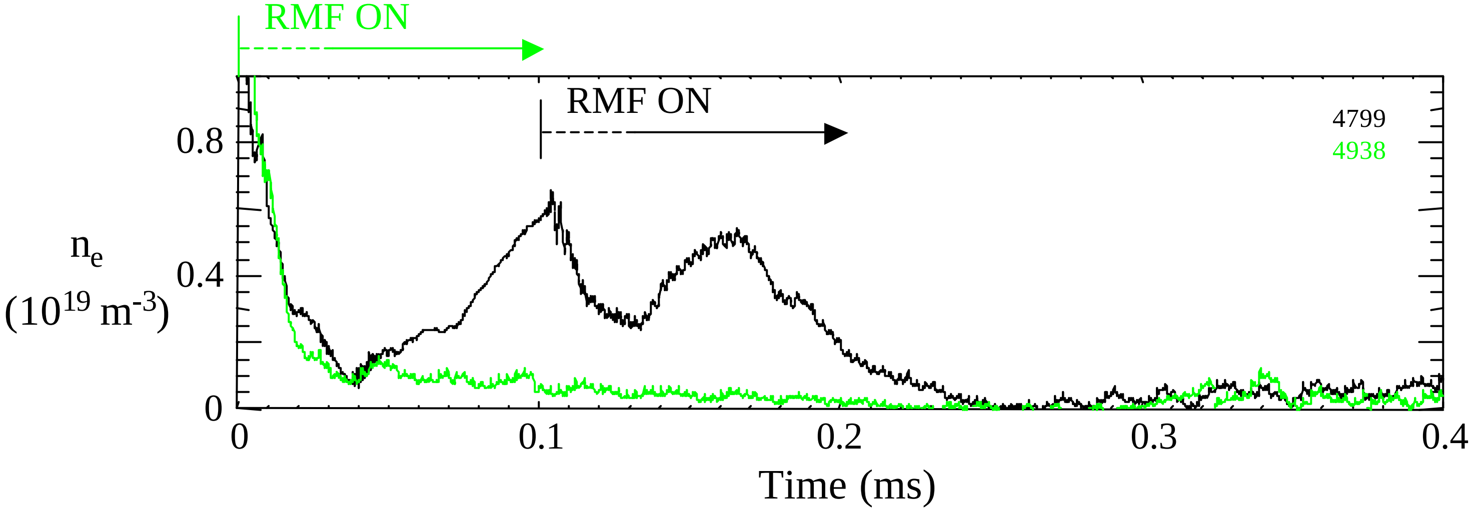


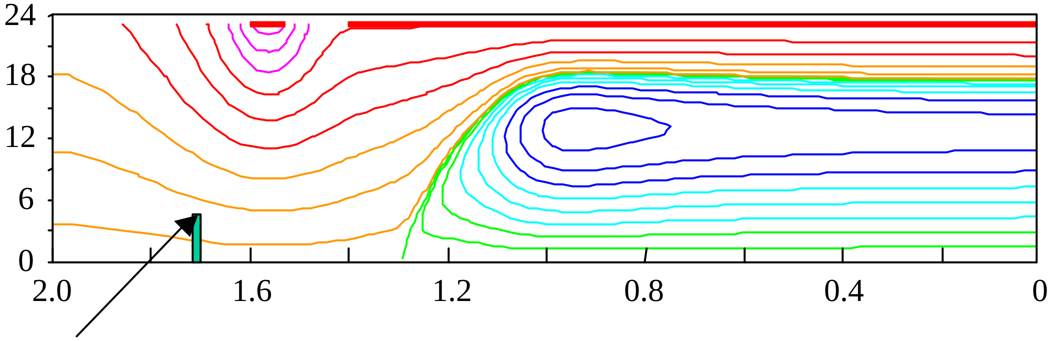
B_{RMF} Field

Internal Profile Measurements from STX Experiment



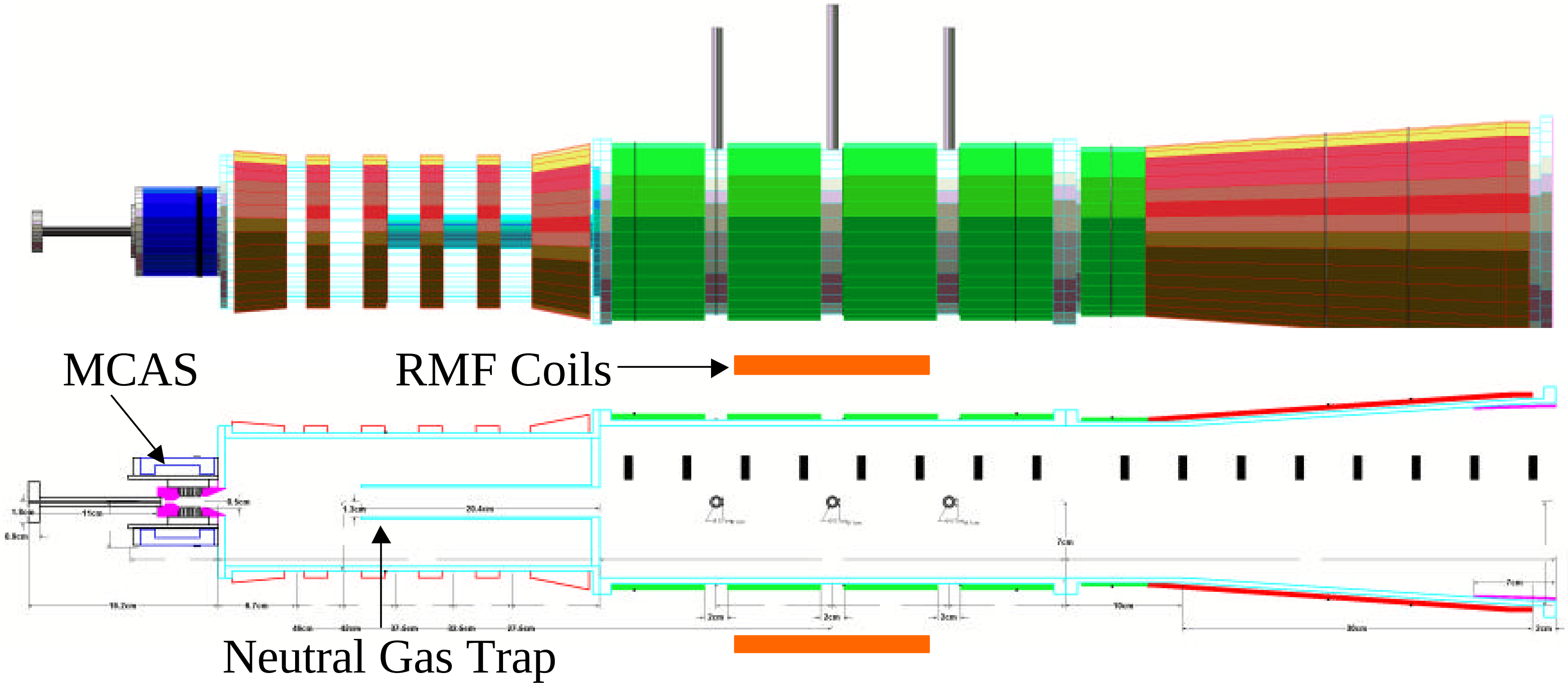
Plasma Density in FRC Jet During Sustainment

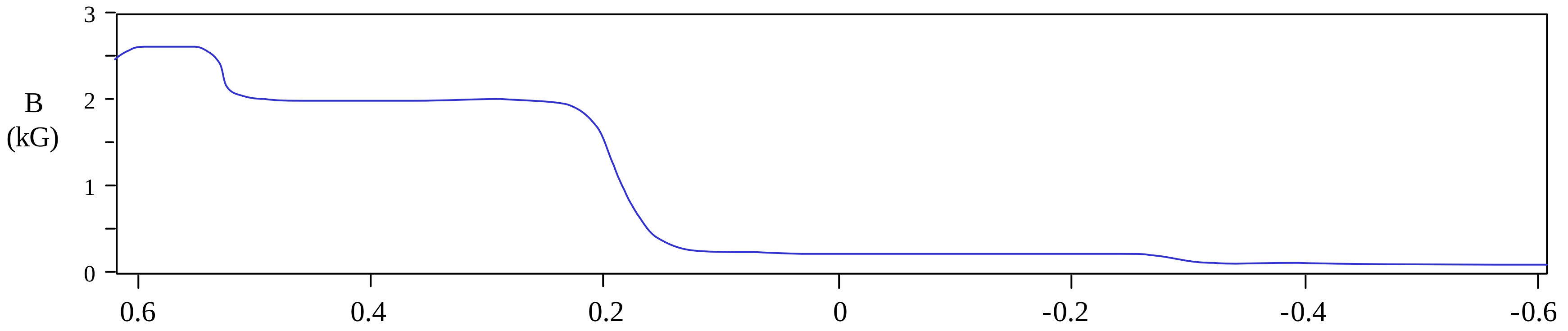




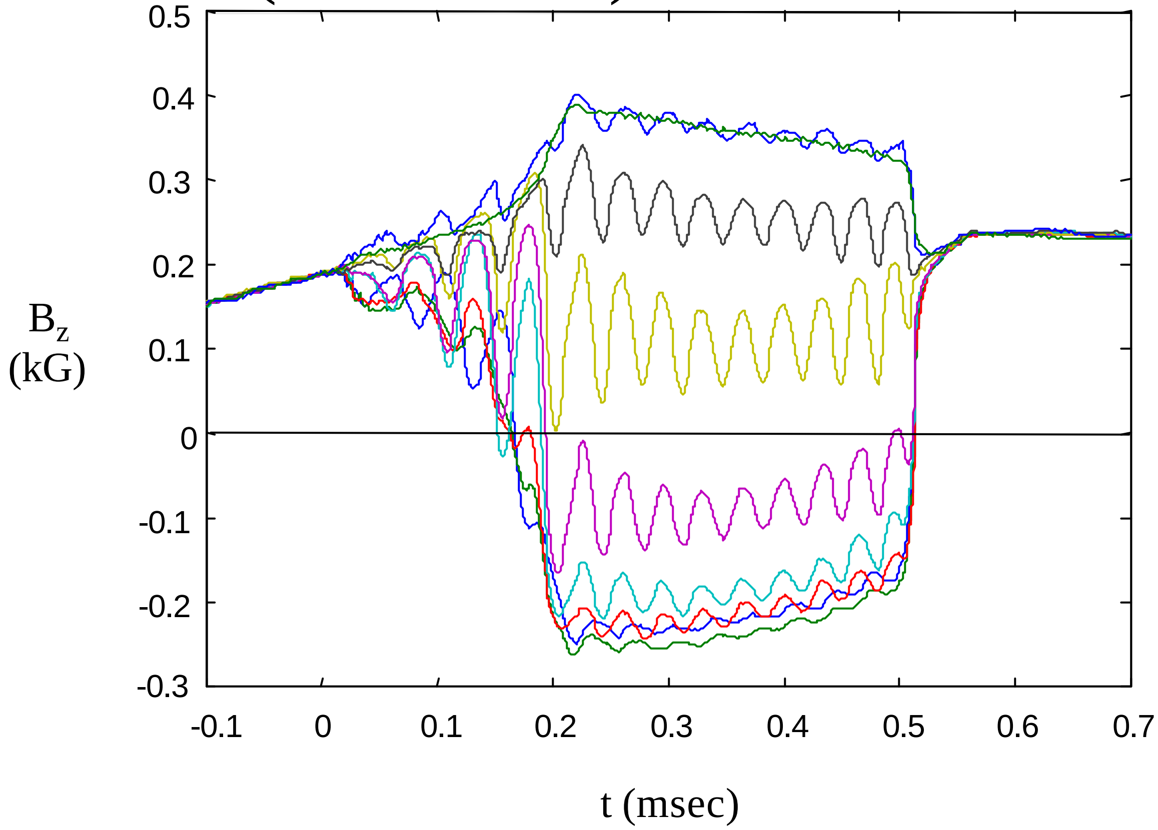
Position of triple probe in jet

STX-HF Experimental Layout





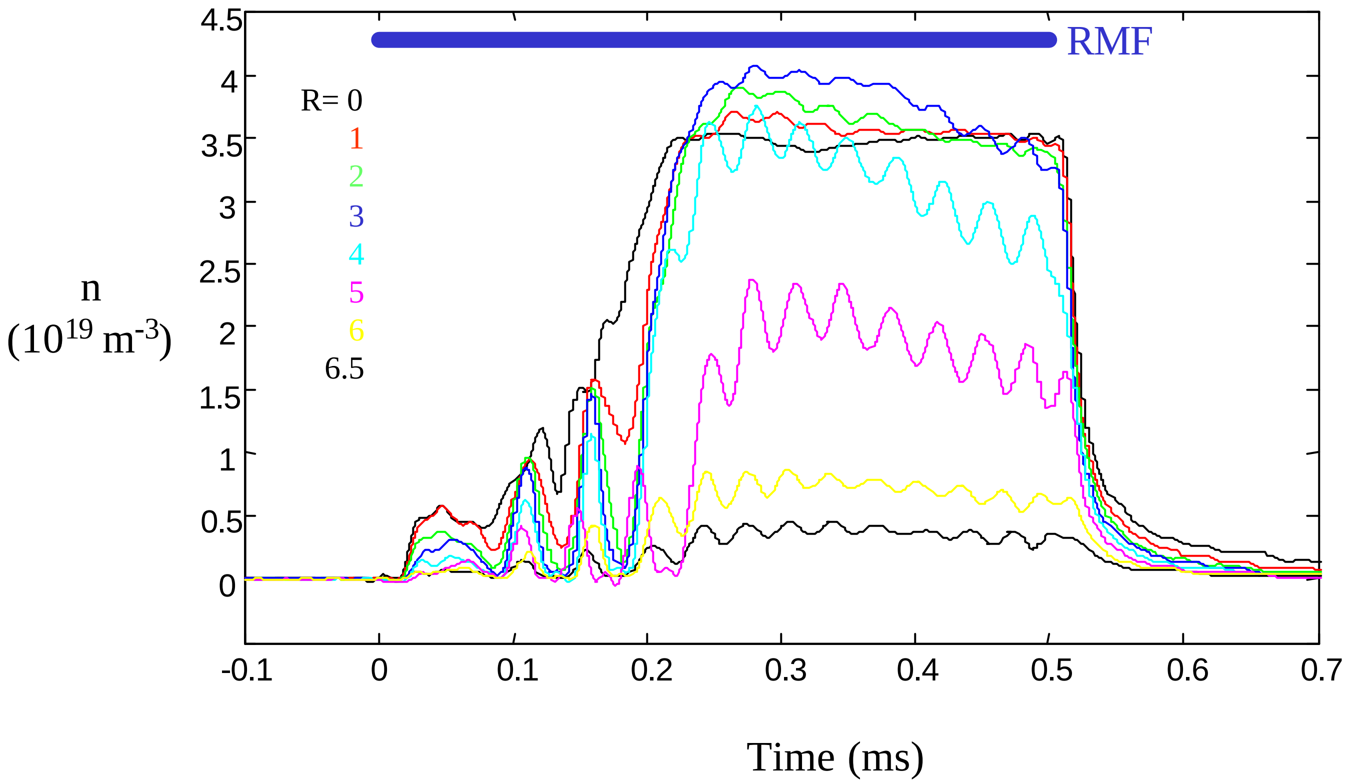
Internal B_z Profile During RMF (0 to 0.5 ms) on STX-HF



For RMF drive the magnitude of B_ω: $B_e \cong \left(\frac{\mu_0 \omega}{9\eta}\right)^{1/2} r_c B_\omega$

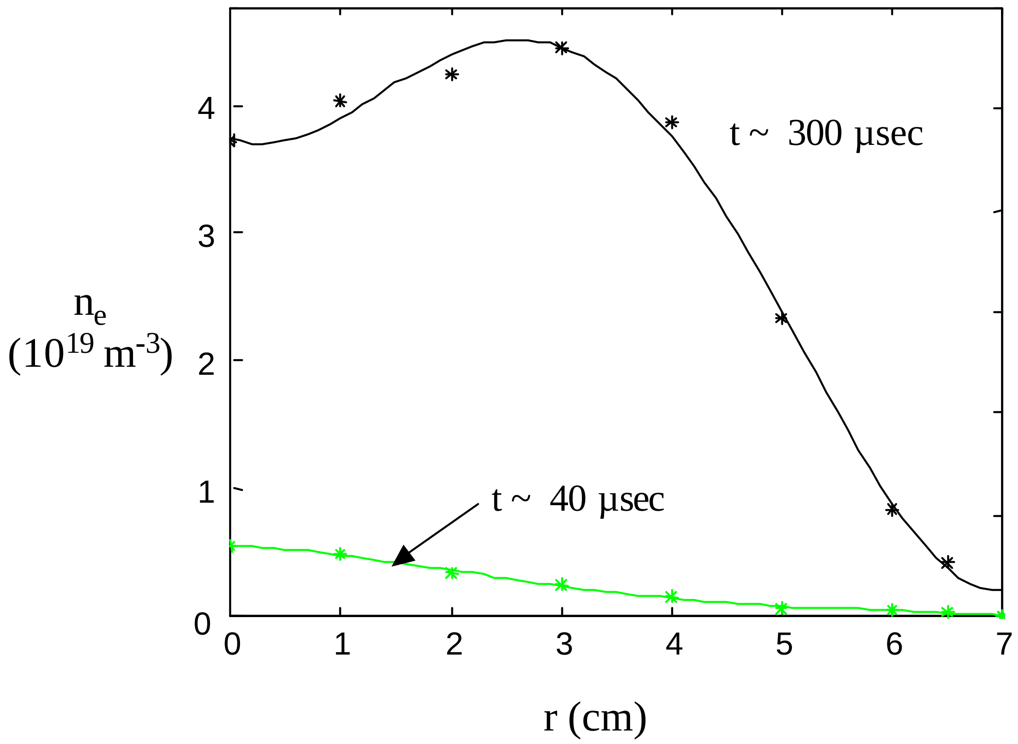
In terms of antenna power P_ω: $B_e \sim \left(\frac{P_\omega}{r_c}\right)^{1/2}$

Density profile from Langmuir probe at Z= -10 cm



Enhanced particle confinement from RMF

Density profile at z = -10 cm from Langmuir probe



For RR profile: $t = \frac{m_0 r_s^2}{16\, h_\perp}$

For size (r_s ~ 0.05) resistivity inferred for STX-HF:

$T_e \sim 10 - 30\ \text{eV} \Rightarrow \eta_\perp \sim 60 - 30\ \mu\Omega\text{-m}$

$\tau = 4 - 8\ \mu\text{sec}$

Ratio of line density: $\left(n_L = 2p \int n_e r dr\right)$

$$\frac{n_L\,(t = 300)}{n_L\,(t = 40)} \ \square\ 25 \ \Rightarrow\ t_n = 25 t_{\text{transit}} = 120\, m\,\text{sec}$$

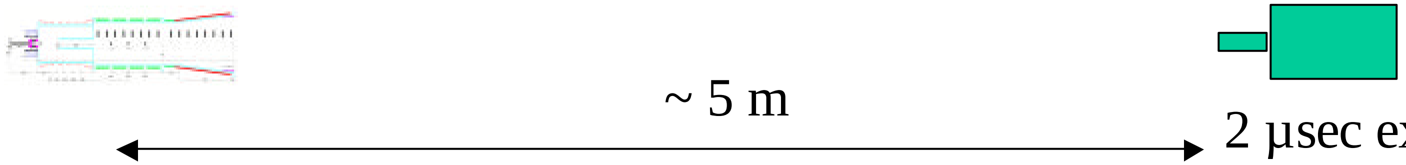
RMF must provide >> classical confinement

RMF CT Formation

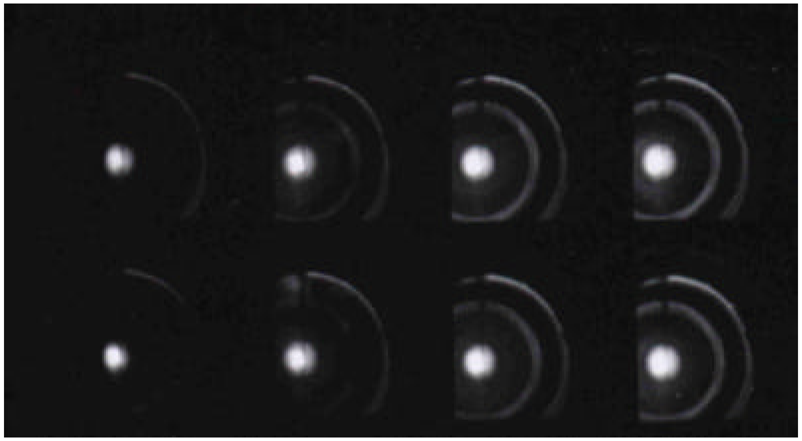
End-on Filtered (510-600 nm) Plasma Emission

Plasma: r ~ 0.05 m
l ~ 0.25 m

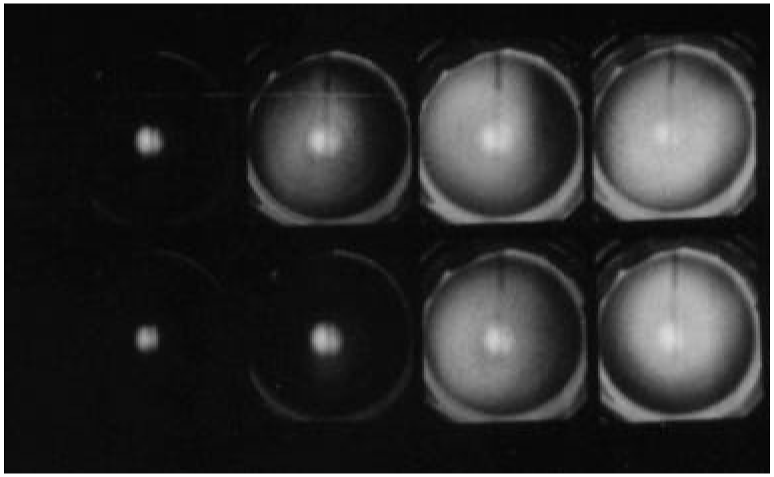
Imacon fast
framing camera



2 μsec exp

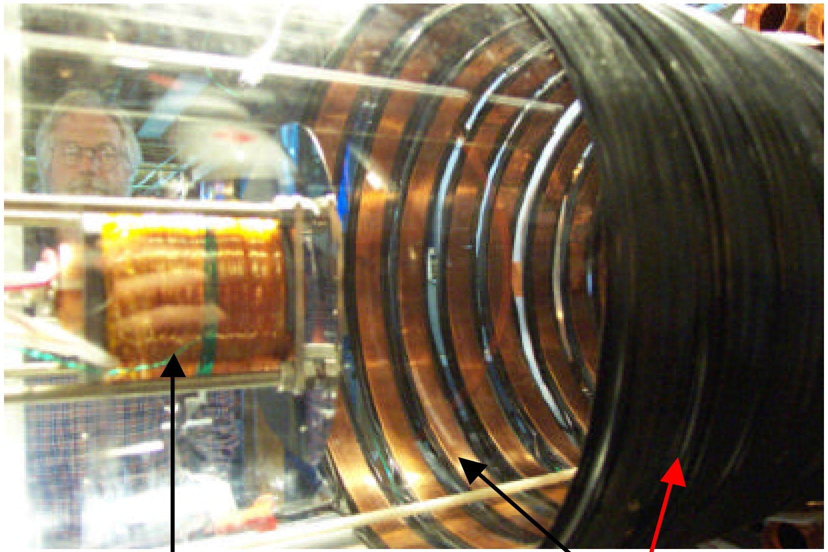


NO RMF



RMF On at t=0

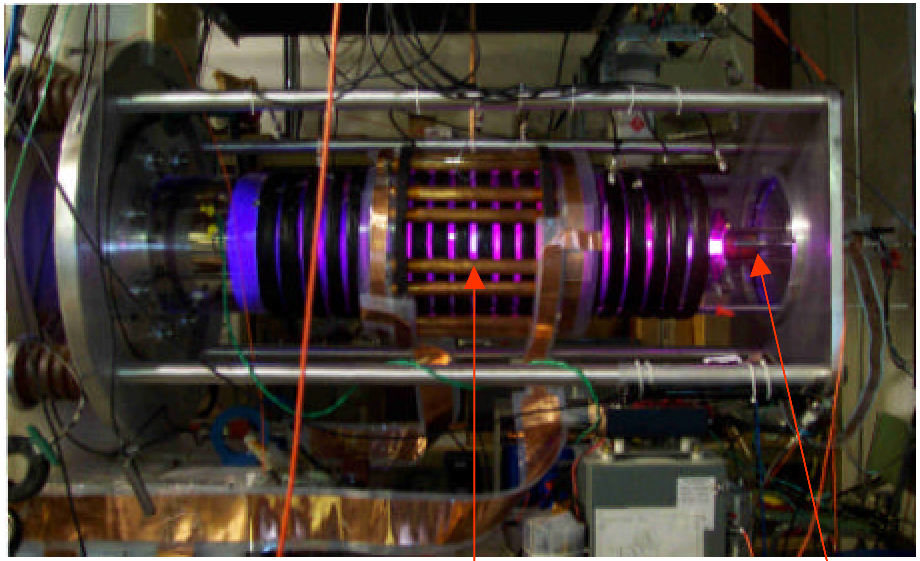
Control of Rotational Modes with RQMF



Magnetized Cascaded Arc Source

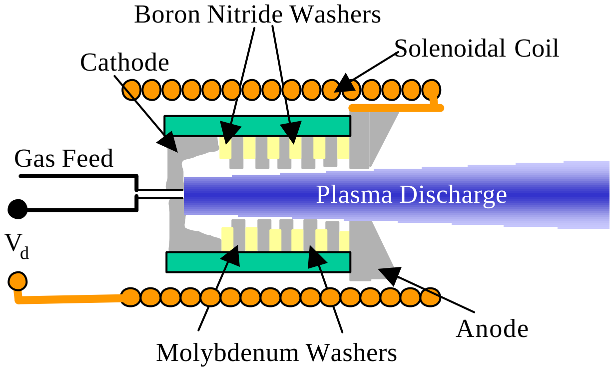
Flux Conserving Rings

Solenoidal Magnet

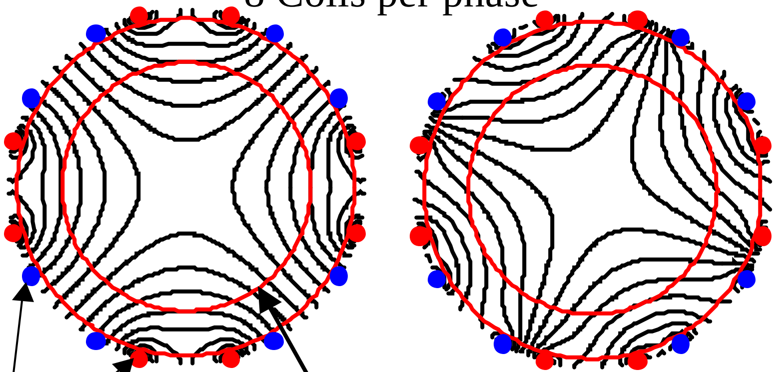


Rotating Quadrupole Antenna

Source



8 Coils per phase



Copper tubes

Vacuum wall

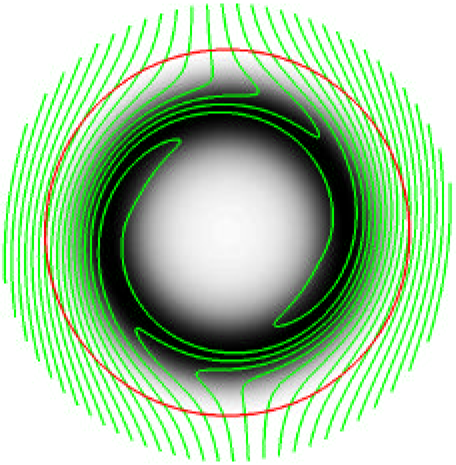
R_{quad} = .17 m

R_{rings} = .14 m

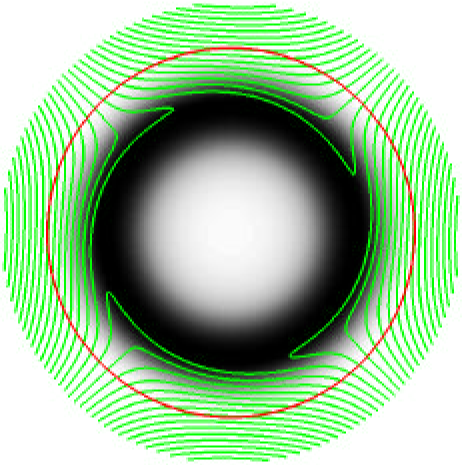
R_{wall} = .135 m

Magnetic field lines and density maps from numerical simulations of RMF current drive.

Dipole:



Quadrupole:



$$A_{zn} = \sum_n \left\{ a_n \left(\frac{r}{R}\right)^n + b_n \left(\frac{r}{R}\right)^{-n} \right\} e^{inq}$$

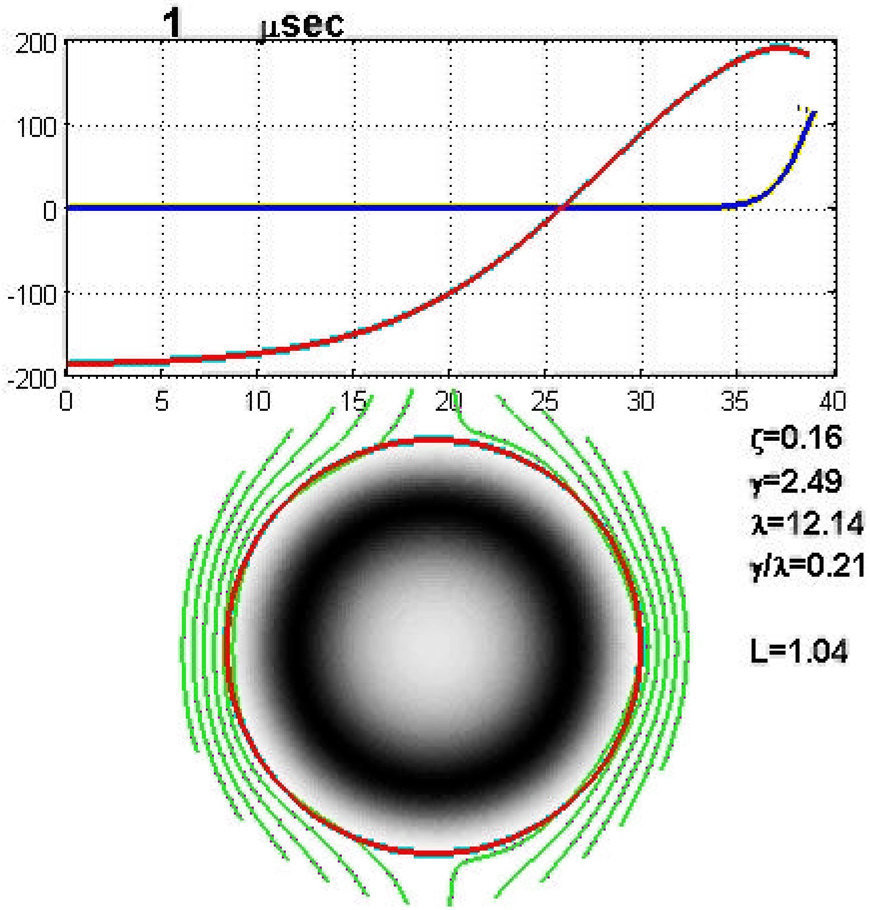
$$B_q = -\sum_n \left(\frac{a_n n}{R}\left(\frac{r}{R}\right)^{n-1} - \frac{b_n n}{R}\left(\frac{r}{R}\right)^{-(n+1)} \right) e^{inq}$$

$$B_r = i\sum_n \left(\frac{a_n n}{R}\left(\frac{r}{R}\right)^{n-1} + \frac{b_n n}{R}\left(\frac{r}{R}\right)^{-(n+1)} \right) e^{inq}$$

The parameter a_n is from external currents, and ß_n is from internal currents. If there is no plasma, $\text{ß}_n=0$, and $B_{r,\theta} \sim r^{n-1}$.

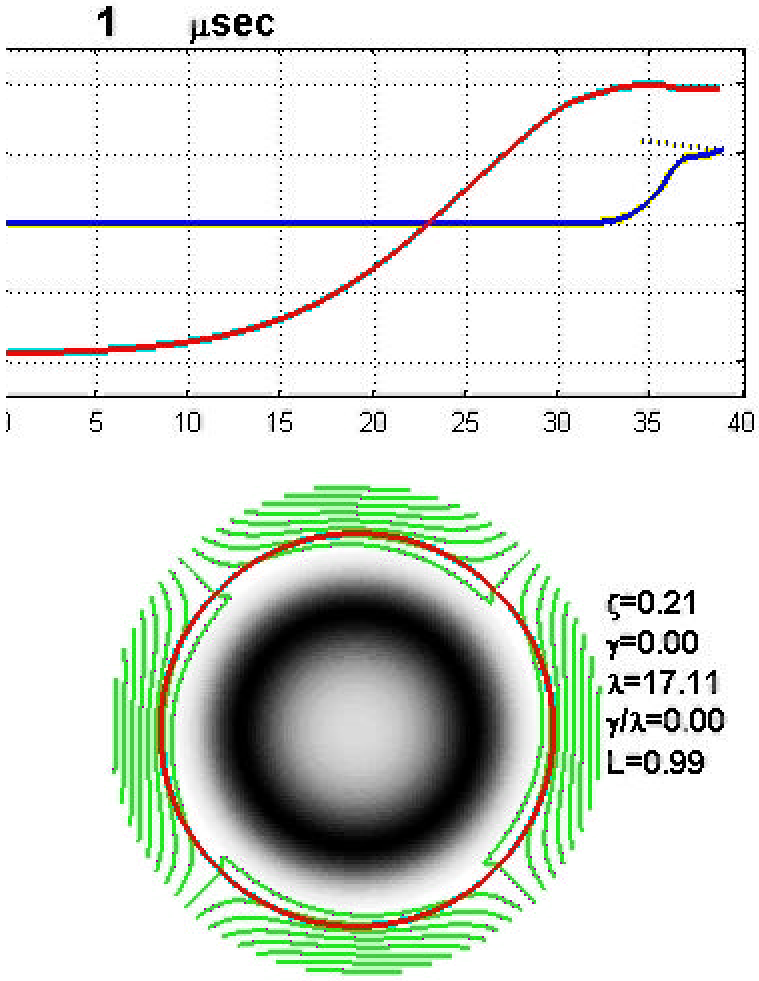
n=1 ➔ rotating dipole (normal RMF)
n=2 ➔ rotating quadrupole (current expt.)
n=3 ➔ octopole field (may be explored)

Dipole Calculation



Transport inhibited by lack of penetration control

Quadrupole Calculation

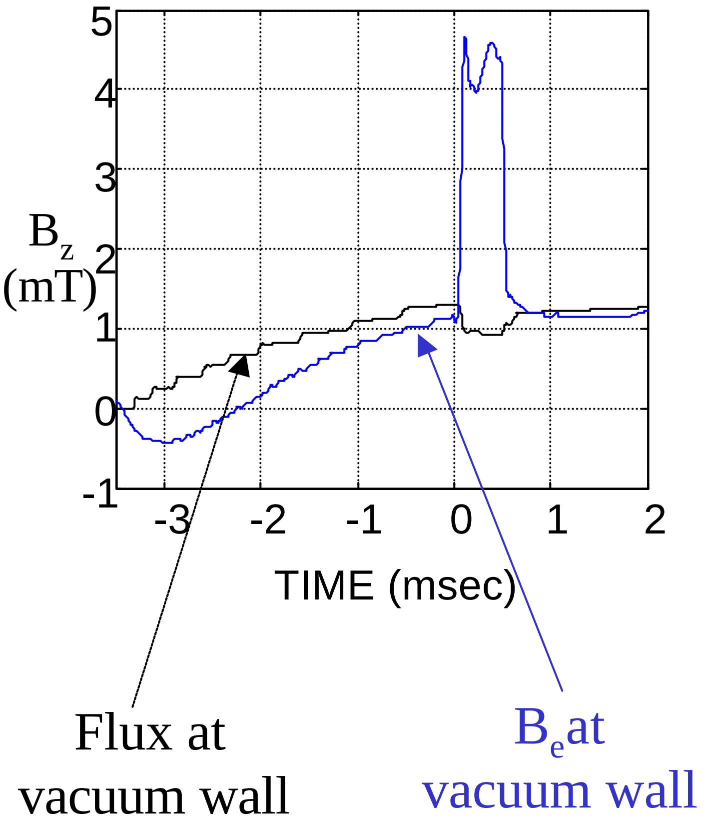


Radial penetration naturally limited By 1/r. Can also be controlled by amplitude feedback

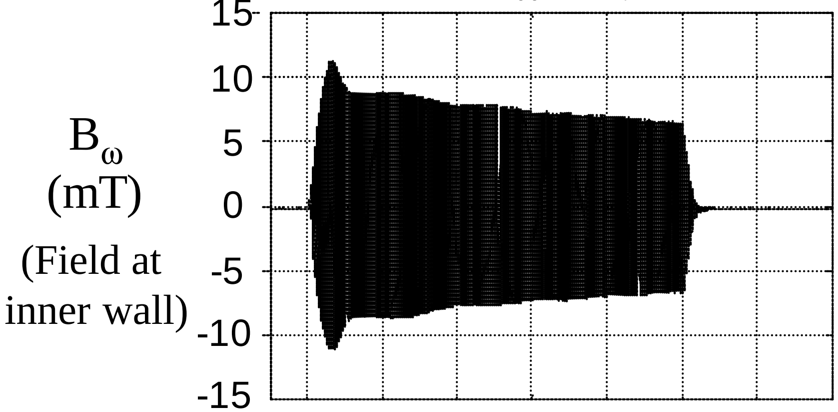
Initial Experiments with Quadrupole Current Drive

Magnetic Field Time Histories

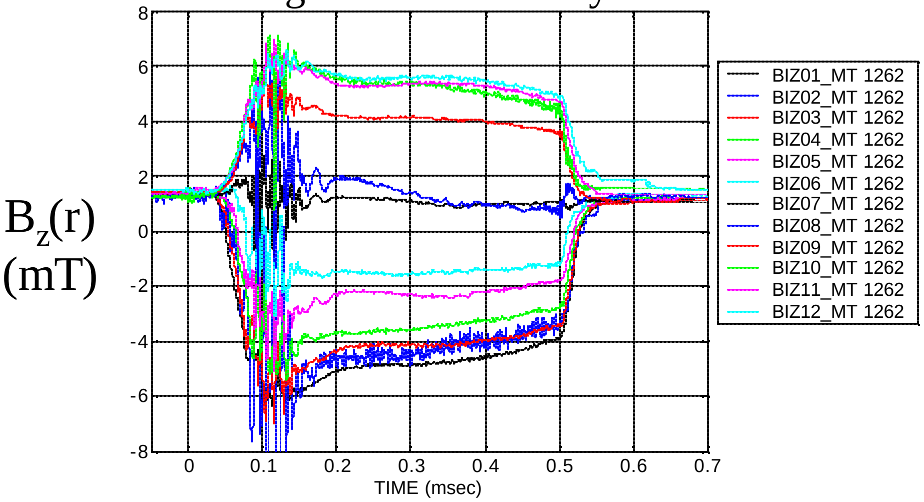
Magnetic Field Time History



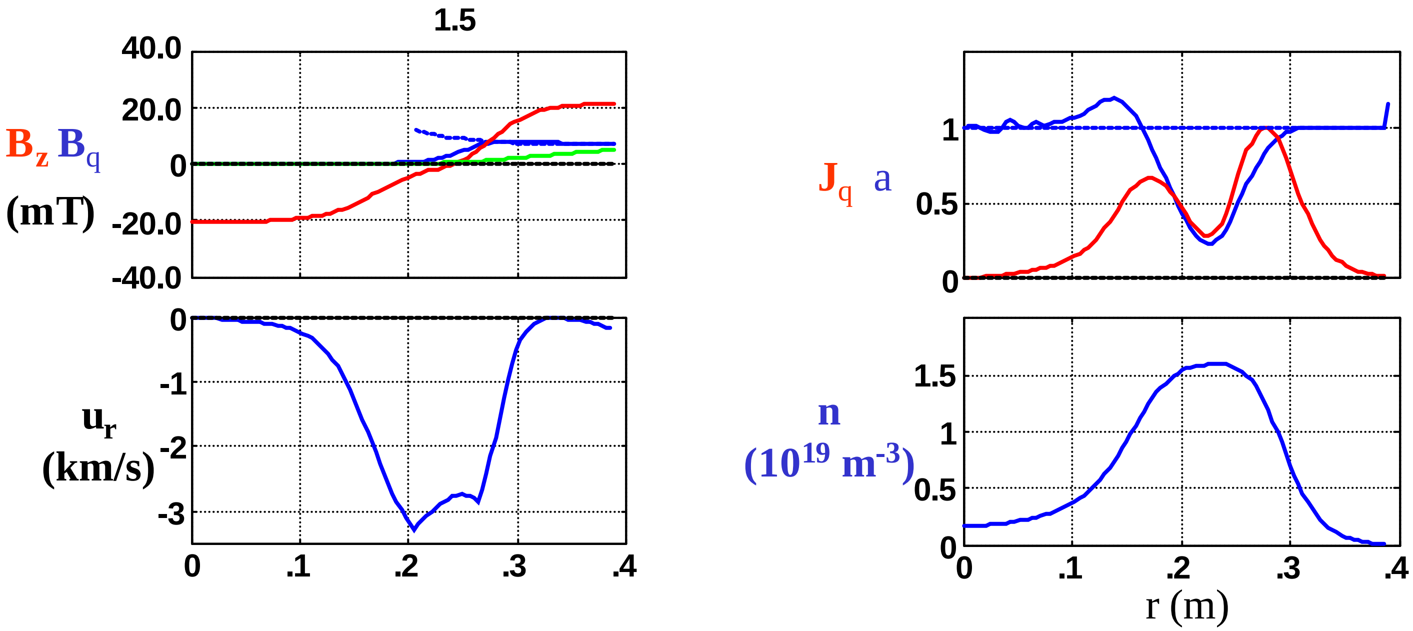
ω = 2.5x10⁶ rad/s



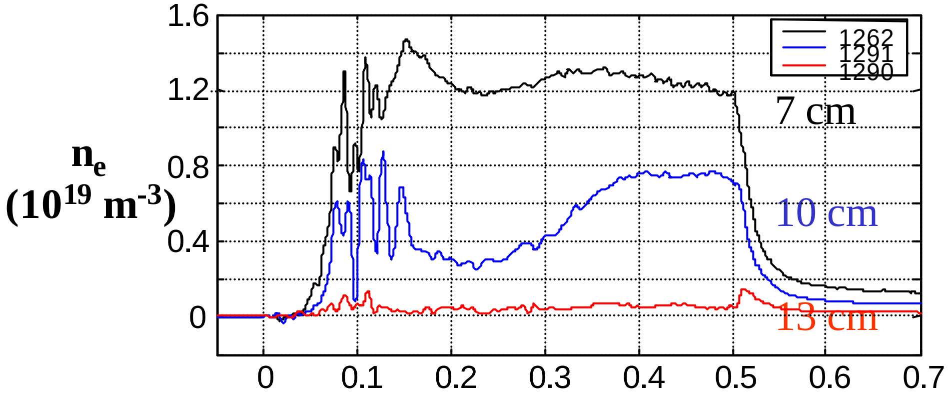
B(r) from Internal Magnetic Probe Array

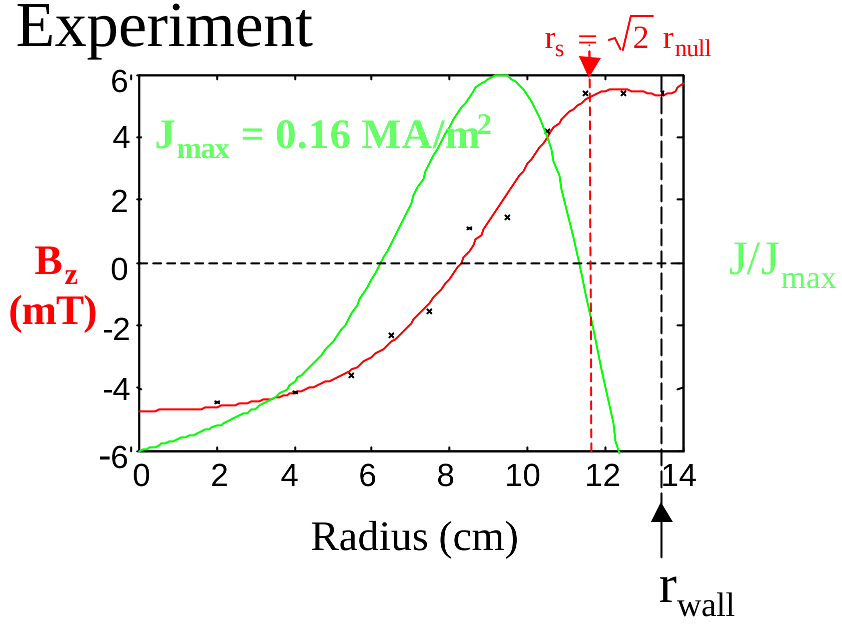


Radial Profiles (2D Quadrupole Calculation)



Radial Profiles from Experiment





Summary

- Small-scale FRC fusion reduces stability and confinement issues to those observed in past FRC experiments

- Rotating Quadrupole field Stabilizes FRC to rotational modes
  - ➢ Does not allow for plasma flow to wall
  - ➢ Does not distort FRC or drive edge turbulence

- Rotating magnetic field enhances FRC confinement
  - ➢ Drives an inward diffusion that opposes the normal diffusive decay
  - ➢ Reduces density gradient at separatrix eliminating the drive from microinstabilities (LHD)

RMF Induced Ion Rotation

Ion Spin-up Time: $\tau_s = \frac{m_i}{m_e}\frac{1}{\nu_{ei}} = \frac{m_i}{ne^2\eta_\perp}$

For n (10^{19} m^{-3}), η (μΩ-m), m (m_H) $t_s = \frac{12.5}{n_{19} h_{m\Omega}}$ msec

STX-HF: n_{19} ~ 5 (10), η ~ 60 (30), ⇒ τ_s ~ 40 μsec

Ion spin-up momentum is lost in τ_N ~ 100 μsec. The fraction of spin-up, α (= $u_{i\theta}/u_{e\theta}$):

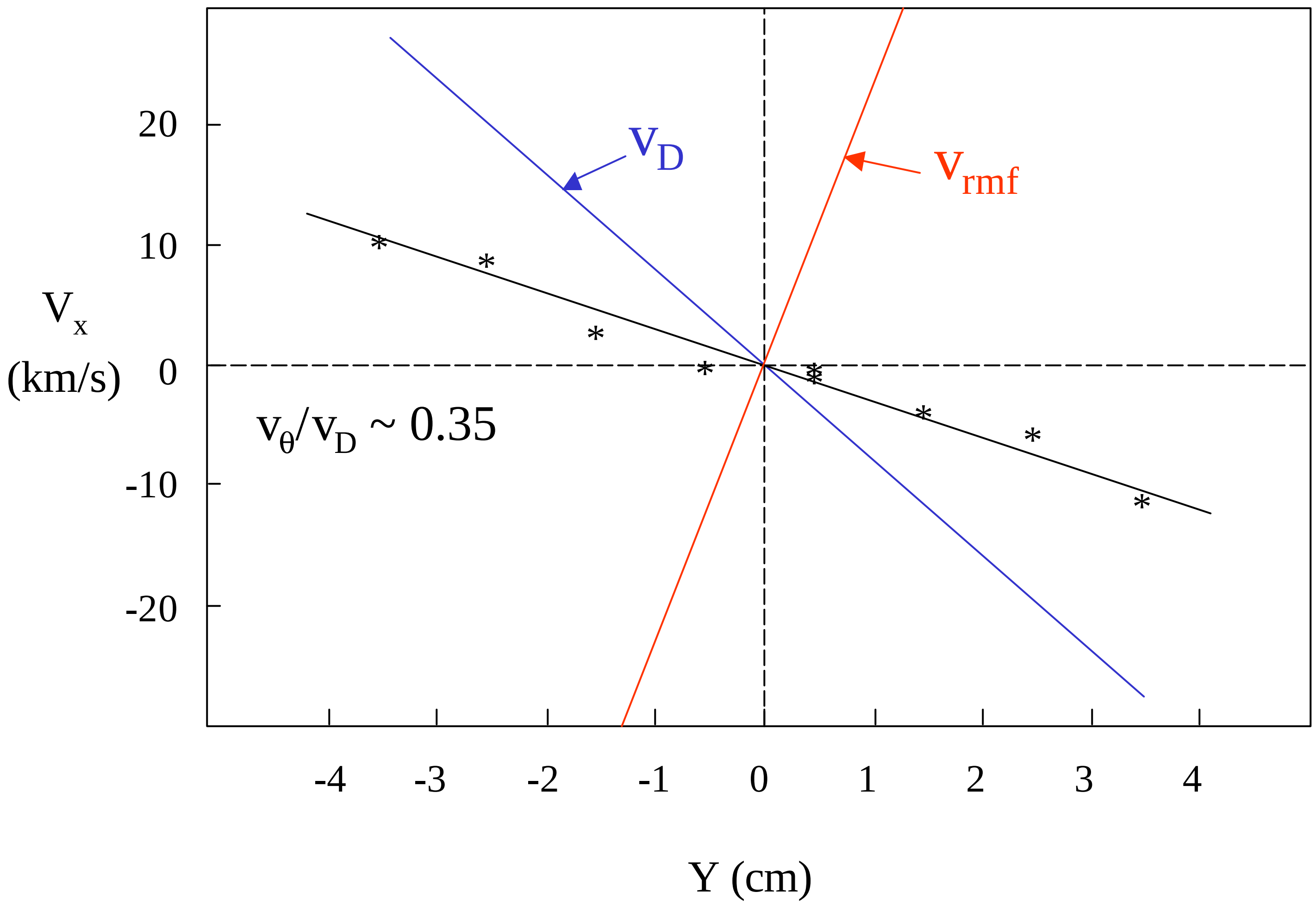
$$a = \left[1 + \frac{t_s}{t_N}\right]^{-1} = 0.7$$

Not ignorable
For STX-HF

From radial component of gen. Ohm's law: $u_q = -\frac{E_r}{B_z} + \frac{1}{neB_z}\frac{dp_i}{dr}$

Ion diamagnetic drift
Opposite dir. to spin-up

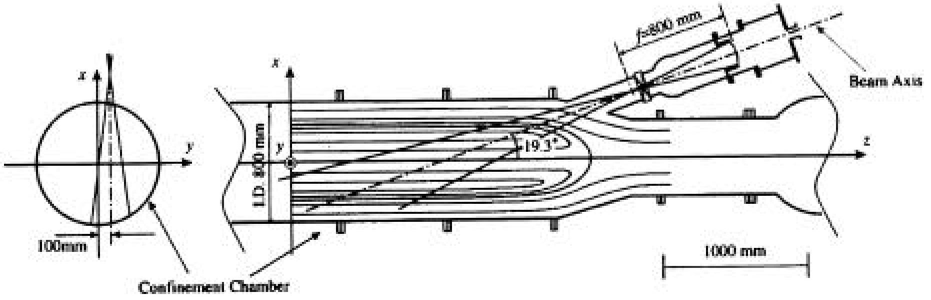
Shift of He II Line Center as a Function of Impact Parameter



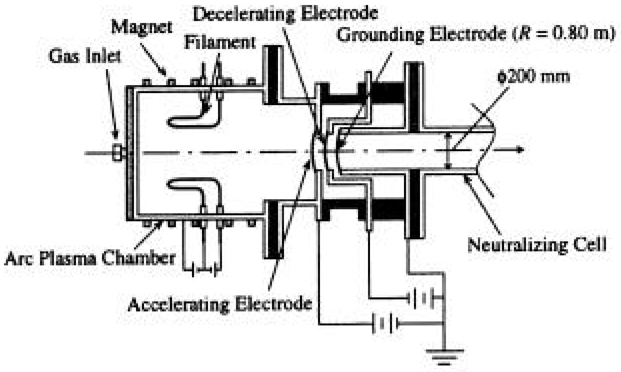
$v_\theta/v_D \sim 0.35$

Enhanced Confinement Using Neutral Beams on FIX

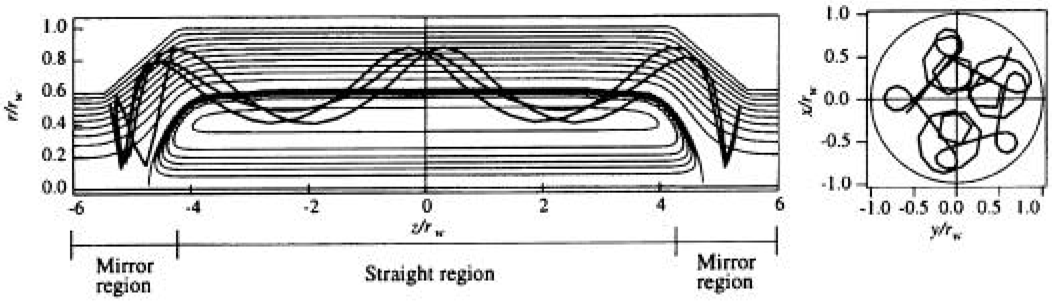
NB injection geometry on 80-cm diameter FIX confinement chamber



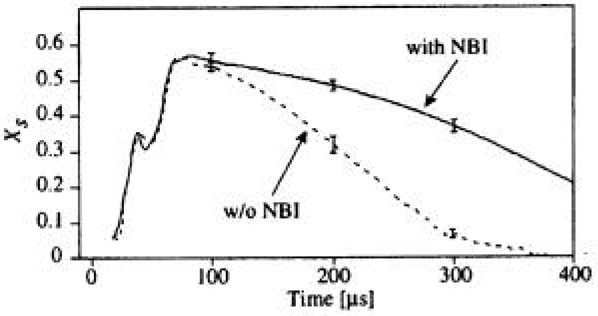
Simple 15-25 kV NB Injector



Resultant ion orbits in low flux FIX FRC

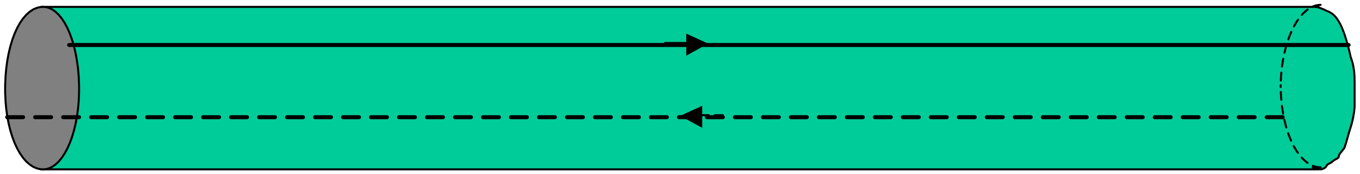


Measured enhanced lifetime

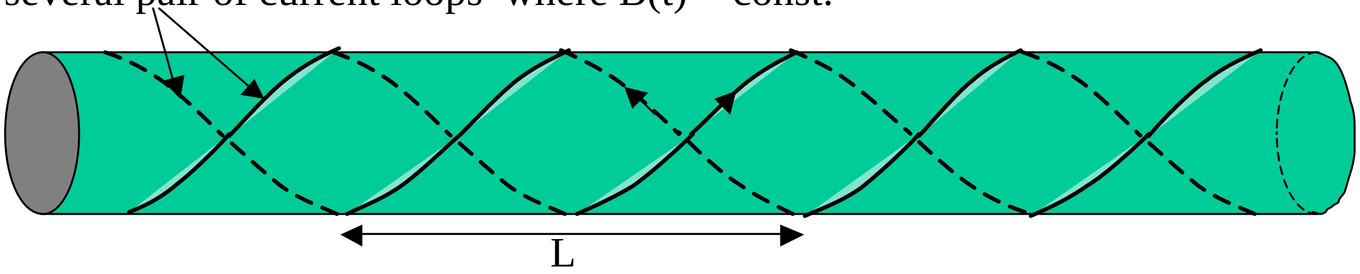


RMF Confinement and Drive from Steady Coils

One of two loops for RMF in stationary FRC where $B(t) \sim \sin\omega t$



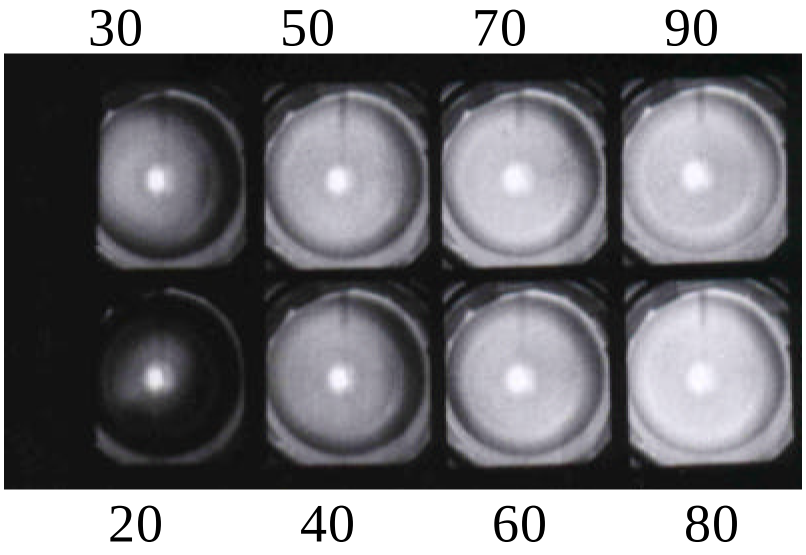
One of several pair of current loops where $B(t)$ = const.

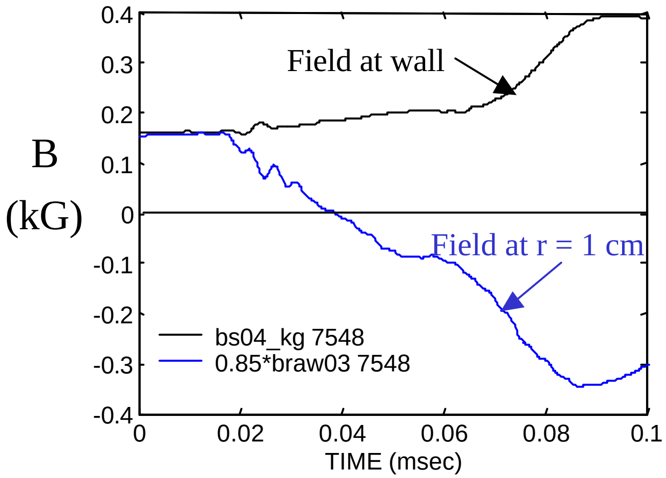


In frame of FRC traveling at velocity v_{FRC}, the transverse field rotates at a frequency $\omega = 2\pi v_{FRC}/L$:

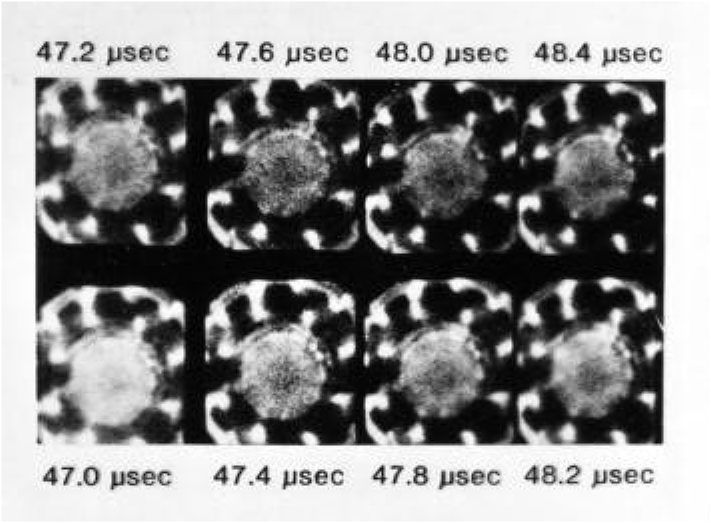
$$\omega = 9\text{x}10^6 \text{ and } L = 0.10 \text{ m} \Rightarrow v_{FRC} = 1.4\text{x}10^5 \text{ m/s}$$

Wall Protection from RMF Induced Flow





“Conventional” CT
With Steady Transverse →
(Octopole) Magnetic Field

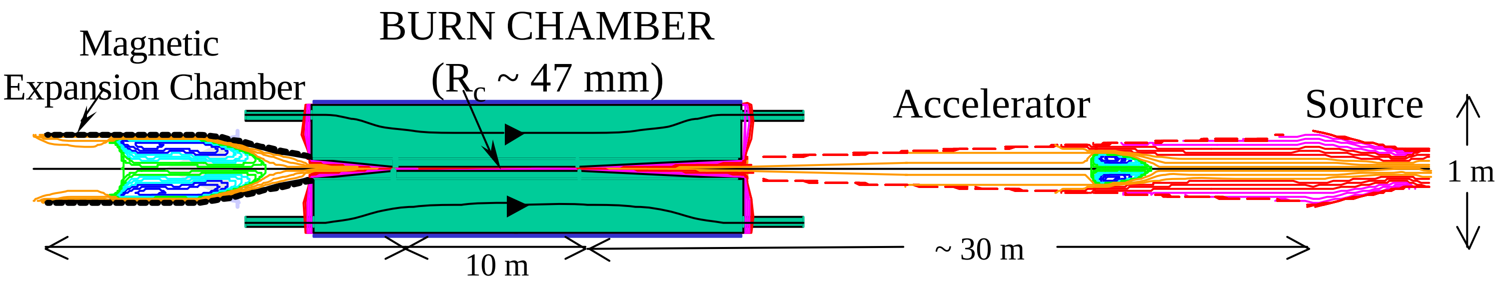


PHD Fusion Reactor Summary

- Straight forward extrapolation of demonstrated FRC formation and acceleration techniques
- Simple linear system that could employ superconducting magnets
- Easily varied fusion output power (10s of MW not multi-GW)
- Low cost development path to demonstration ~ 10 M$ not 10 G$
- Converter, burn chamber, accelerator and formation sections
- well separated.
- Direct electric power conversion possible with flux compression

from expansion of fusion heated FRC

PHD Accelerator Parameters



From energy conservation:

$$v_{FRC} = (5kT_{fus}/m_{DT})^{1/2} \sim 1\text{x}10^{6} \text{ m/s}$$

For constant acceleration a ($2\text{x}10^{10}$ m/s^2), accelerator length L_{acc}:

$$L_{acc} = v_{FRC}^{2} / 2a \sim 25 \text{ m} \qquad t_{\mathbf{acc}} \sim \mathbf{50\ \mu sec}$$

Burn chamber length: $L_{burn} \leq v_b\ \tau_E \sim (2\text{x}10^{4} \text{ m/s})(5\text{x}10^{-4} \text{ s})$

$$L_{burn} \sim 10 \text{ m}$$

Fusion Power: $P_{fus} = G \cdot E_p \cdot \text{rep rate} = (10)(700 \text{ kJ})\cdot(10)$

$$P_{fus} \sim 70 \text{ MW} \quad @10 \text{ s}^{-1} \text{ (duty cycle} \sim 0.5\%)$$