Design and Construction of the Pulsed High Density (PHD) FRC Experiment

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Small Scale Fusion:
The Pulsed High Density (PHD) FRC Experiment

- *Experimental program that takes advantage of a very compact, high energy density FRC to reach fusion conditions.*
- *The energy required to achieve fusion conditions is transferred to the FRC via simple, relatively low field acceleration/compression coils.*
- *For FRC in smaller, higher density regime, the requirement on the FRC closed poloidal flux is no greater than what has already been achieved*
- *The FRC should remain in a stable regime with regard to MHD modes such as the tilt from formation through burn.*

PHD Fusion Reactor Advantages

•Straight forward extrapolation of demonstrated FRC formation and acceleration techniques

•Simple linear system that would employ superconducting magnets

•Easily varied fusion output power (10s of MW not multi-GW)

•Converter, burn chamber, accelerator and formation sections well separated.

•Direct electric power conversion possible with flux compression from expansion of fusion heated FRC

FRC Reactor Regime Based on Observed Confinement Scaling:

From LSX and earlier expts: $\tau_N = 3.2\text{x}10^{-15}\,\varepsilon^{0.5}\,x_s^{0.8}\,r_s^{2.1}\,n^{0.6}$

(with $x_s = 0.6$ $\varepsilon = 20$) $n\tau \sim 6\text{x}10^{-15}\,r_s^{2}\,n^{1.6}$

Radial Pressure balance:

$$B_e^2 = \left(2\mu_0 n_0 kT(=10\text{keV})\right) = 4\text{x}10^{-21}\,n_0 \Rightarrow n\tau \propto r_s^2\,B_e^3$$

In terms of confining flux ϕ_p: $n\tau \propto \phi_p\,B_e^2$

Reactor	B_e (T)	ϕ (mWb)
MTF	200	0.5 to 1
PHD	30	10
SS FRC	1 - 2	1000

Anticipated Schedule for The Pulsed High Density (PHD) FRC Experiment

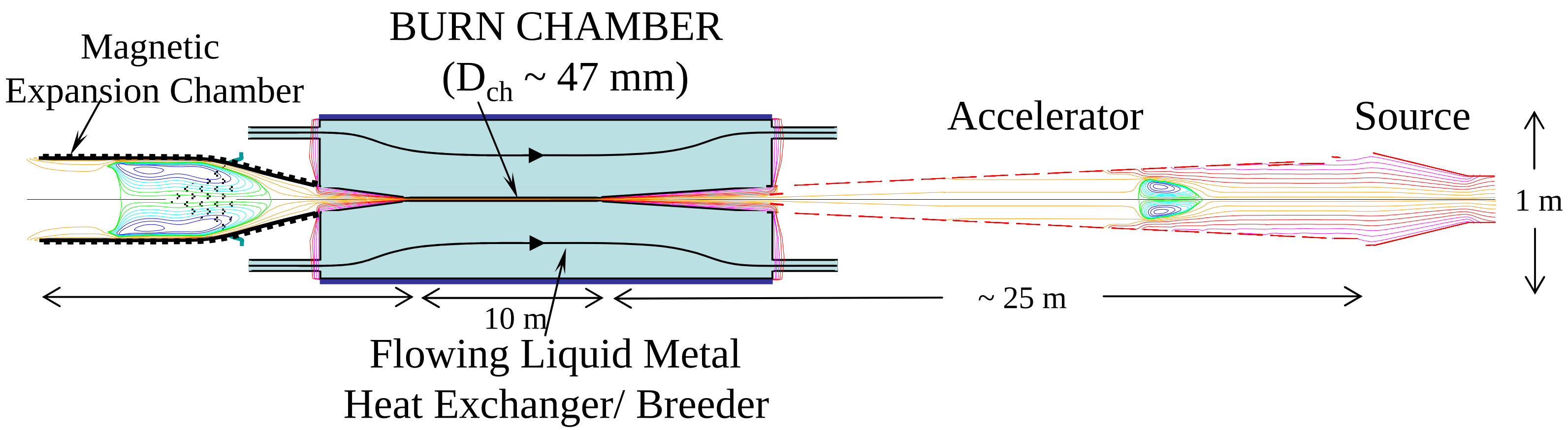
2004 - Construct the FRC source capable of evaluating FRC physics at and beyond the previous limits of poloidal flux, density and elongation.

2005 - Study the confinement and stability of FRCs as a function of the key dimensionless parameters S (~ R/ρ_i) and ε (= L_s /$2r_s$) obtained from recent theoretical studies.

2006
- Design and construct an accelerator for FRC acceleration at $2x10^{10}$ m/s^2.
- Investigate the acceleration/deceleration dynamics of FRC up to a factor of five increase in total FRC energy.
- Compare with 2 and 3D numerical calculations.

2007
- Detailed measurements of the equilibrium FRC in drift/ compression chamber
- With additional funding Thomson scattering and multi-channel interferometer)

Outline of PHD Fusion Concept



1 - FRC formed at low energy (~30 kJ) and relatively low density (~10^{21} m^{-3})

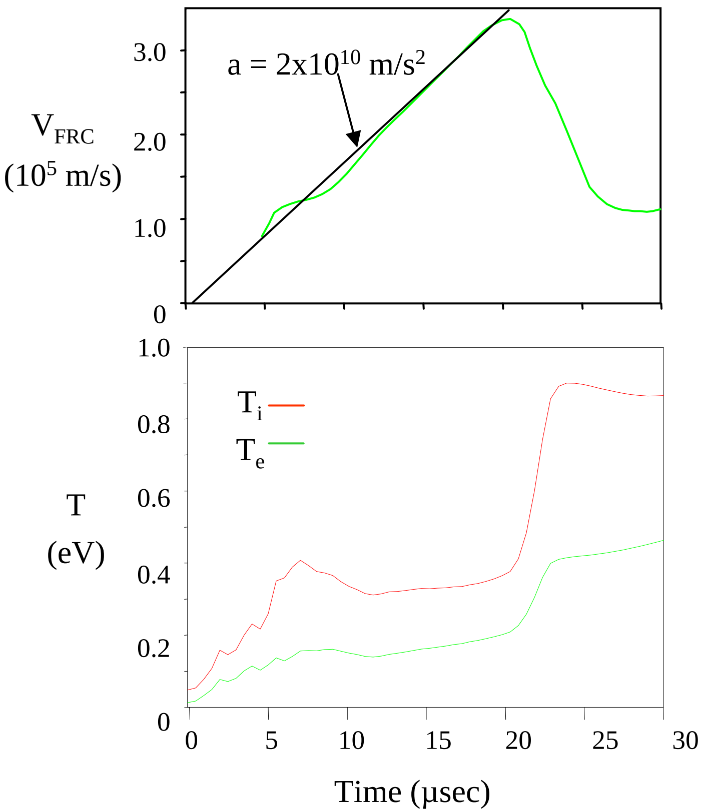
2 - FRC accelerated by low energy propagating magnetic field (~ 0.5 T) to

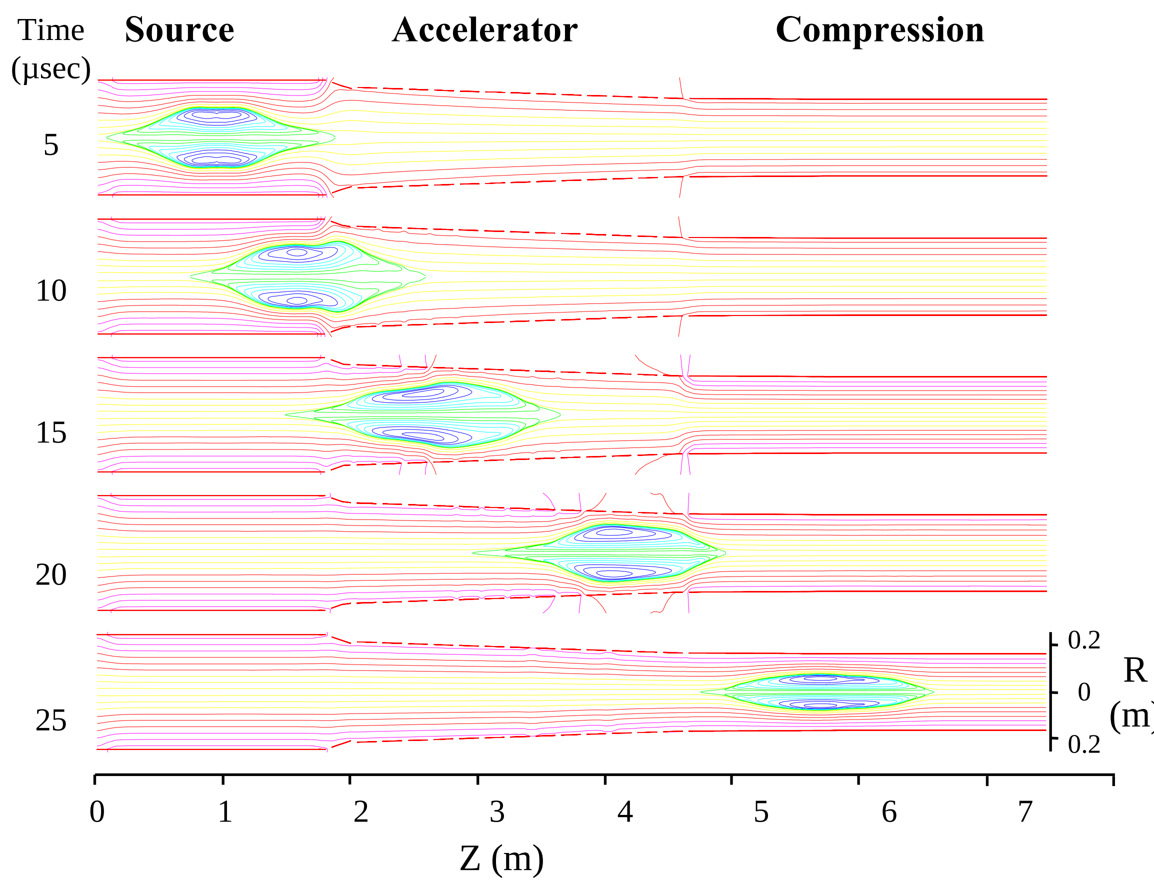
3 - FRC is wall compressed and heated as it decelerates into burn chamber

4 - FRC travels several meters during burn time minimizing wall loading

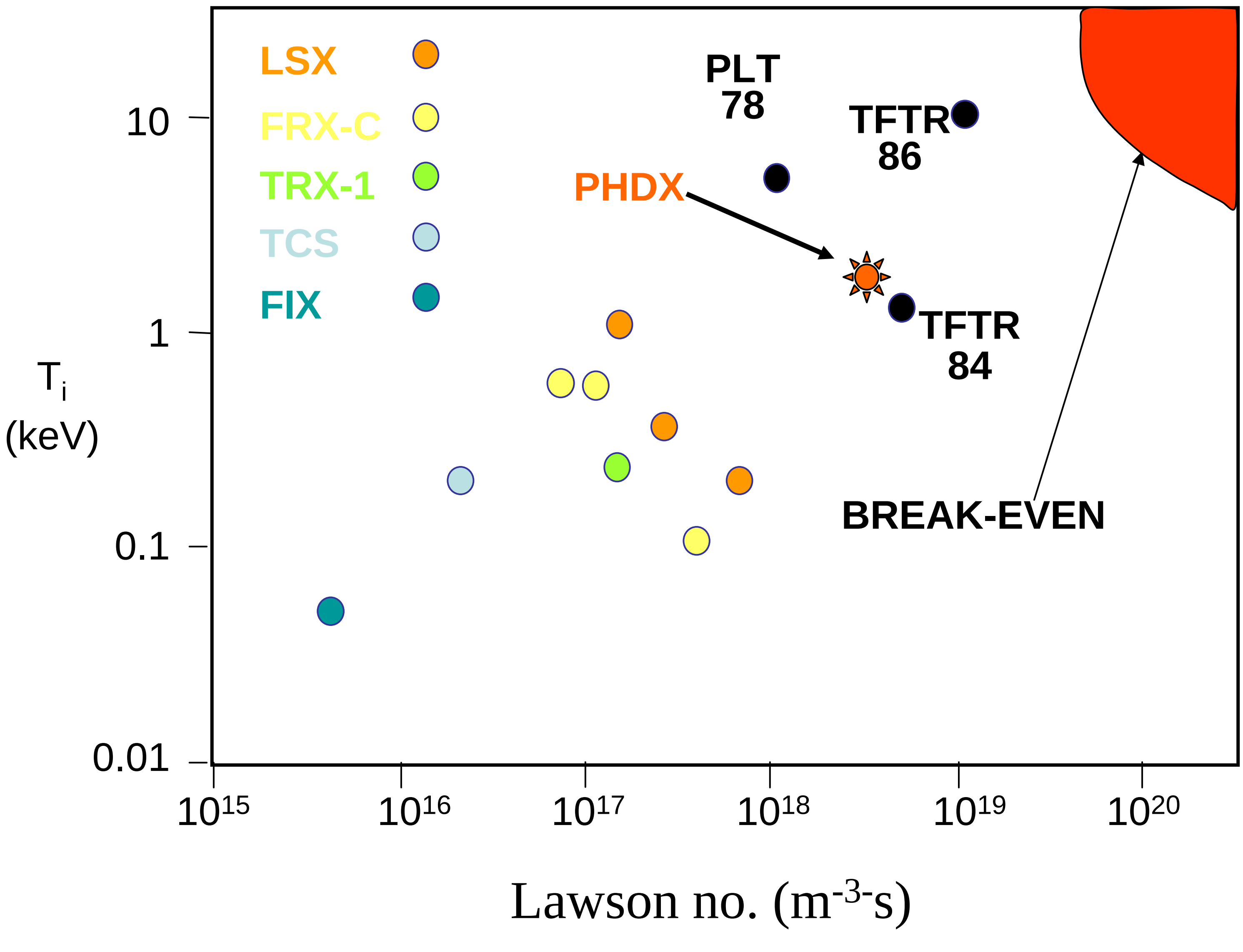
6 - FRC expands and cools converting thermal and magnetic energy
back into stored electrical energy

Resistive 2D MHD calculation of FRC formation, acceleration and compression for the parameters anticipated for PHD

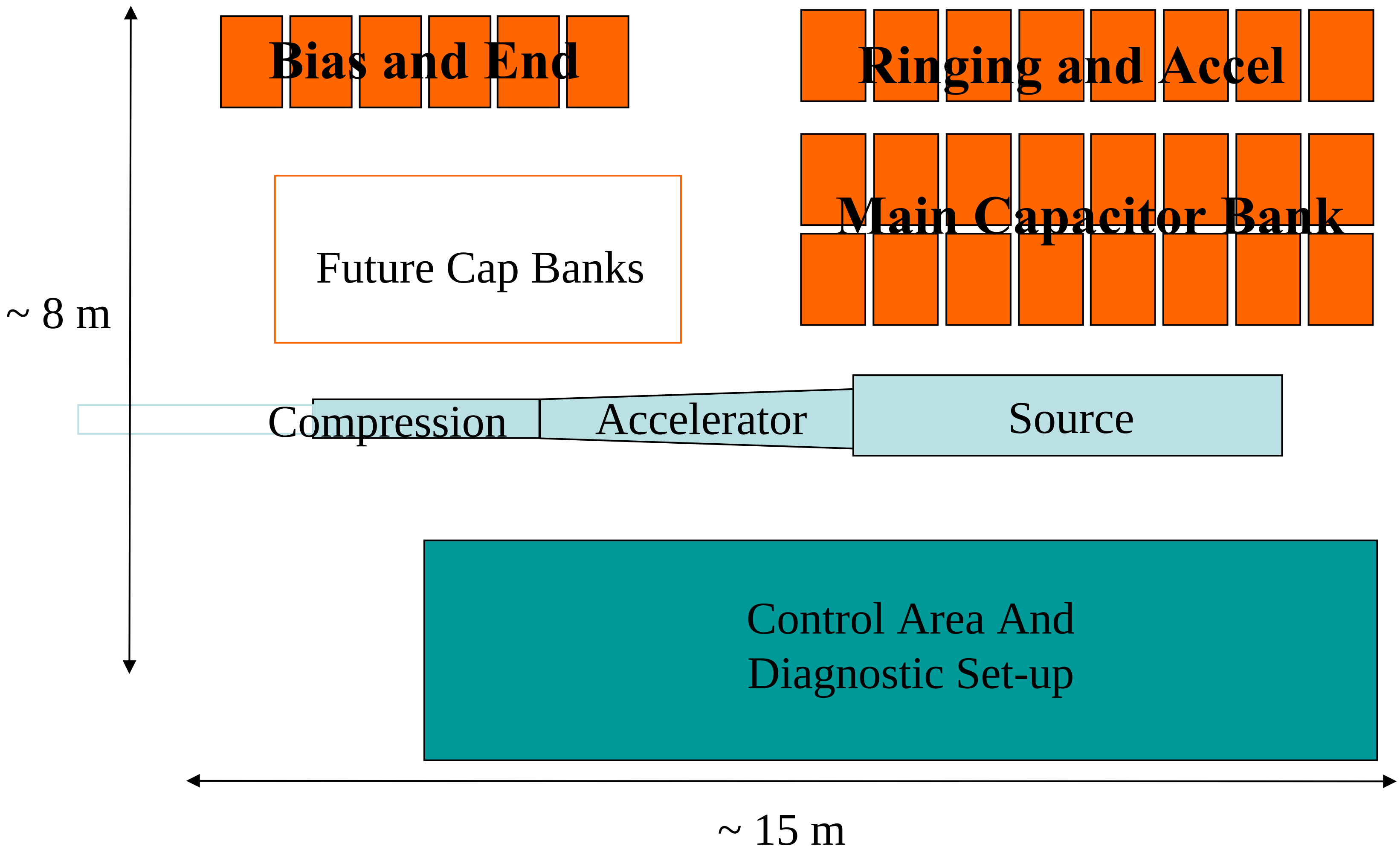




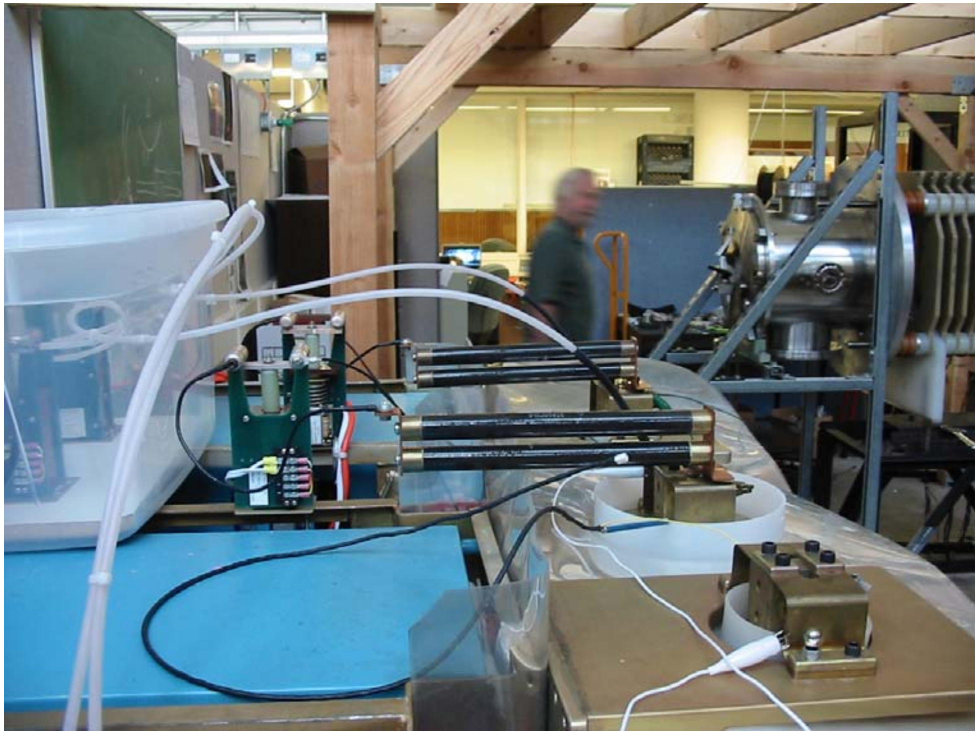
Data point for PHDX is the anticipated result of the proposed experiment based on FRC scaling

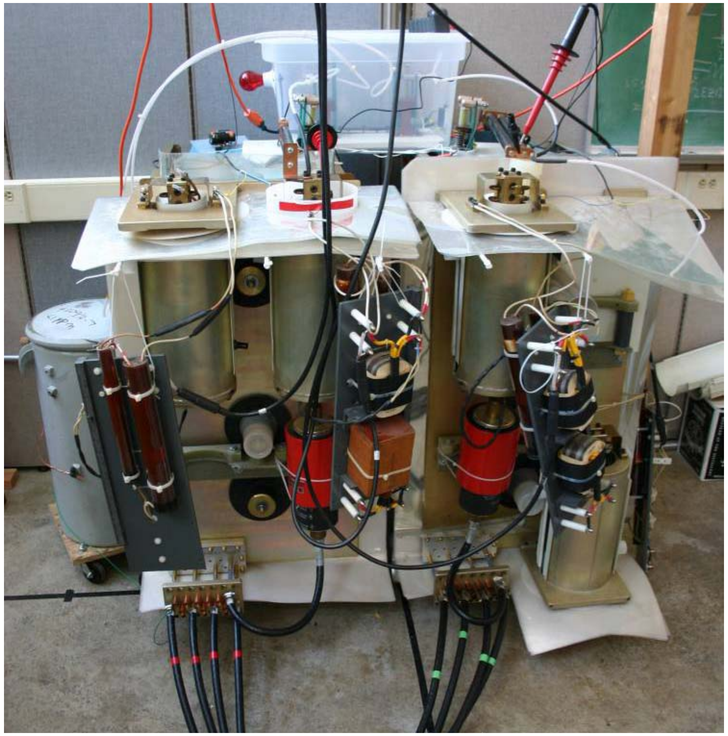


Layout for PHD in Plasma Dynamics Laboratory
Condon Hall, University of Washington



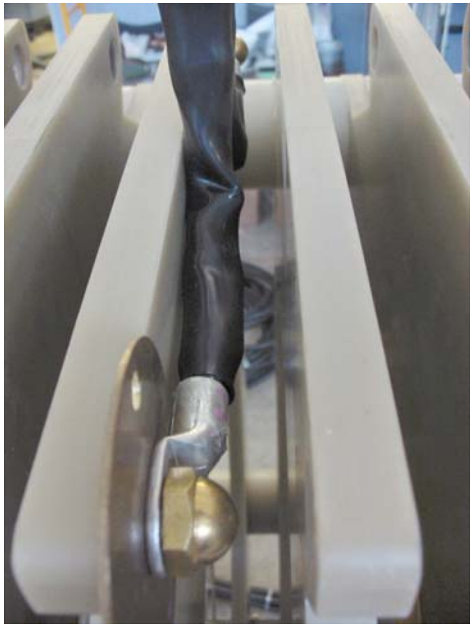
PHD Module Modification and Testing

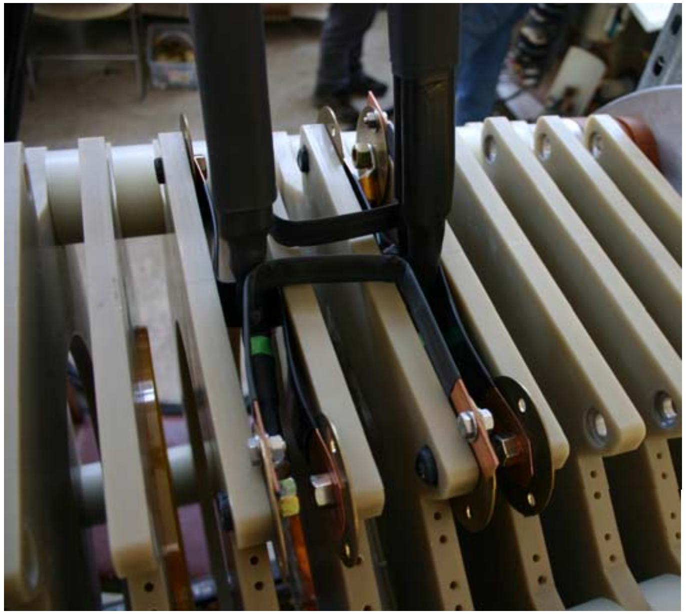


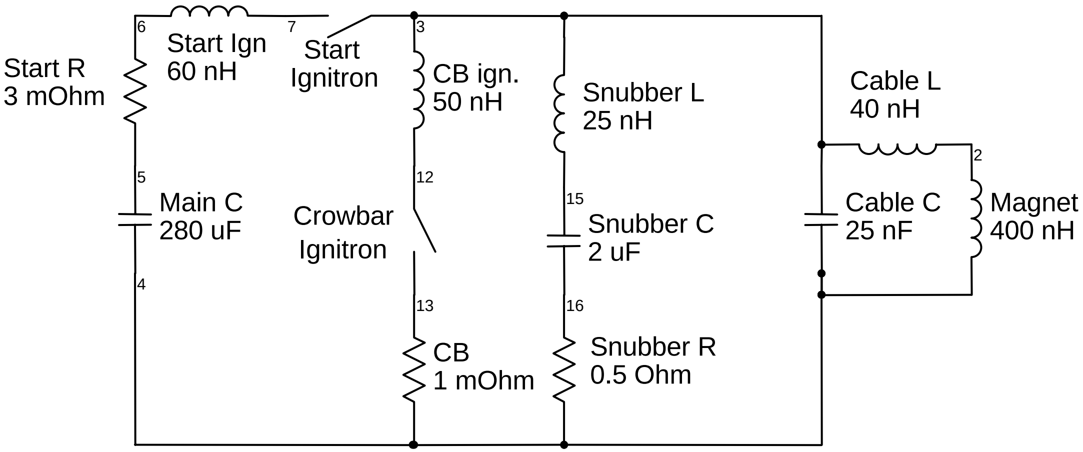


New module design will incorporate the capability for Complete individual module control and monitoring (charge/dump, cap voltage, trigger timing, etc)

Results from PHD Circuit Analysis

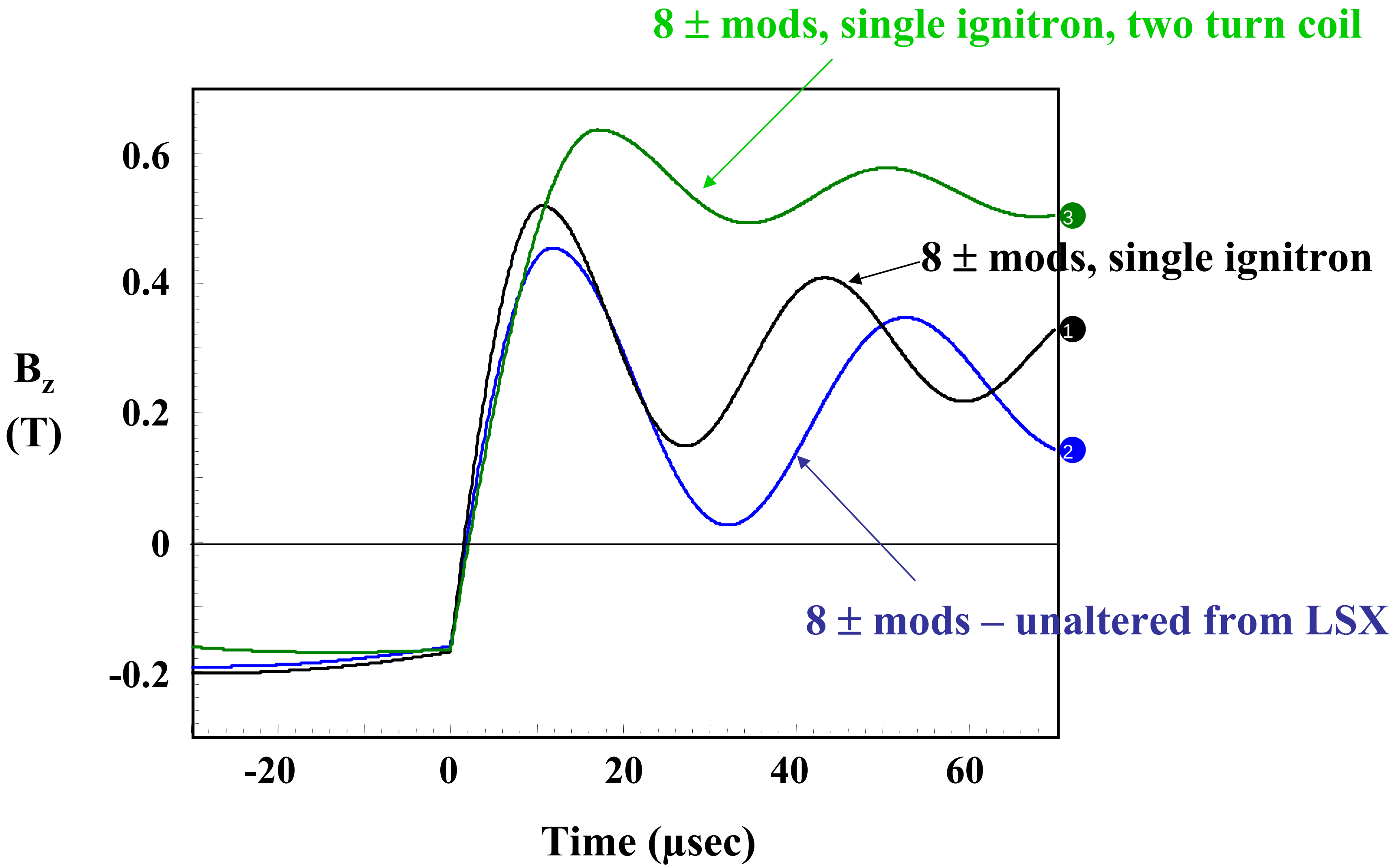






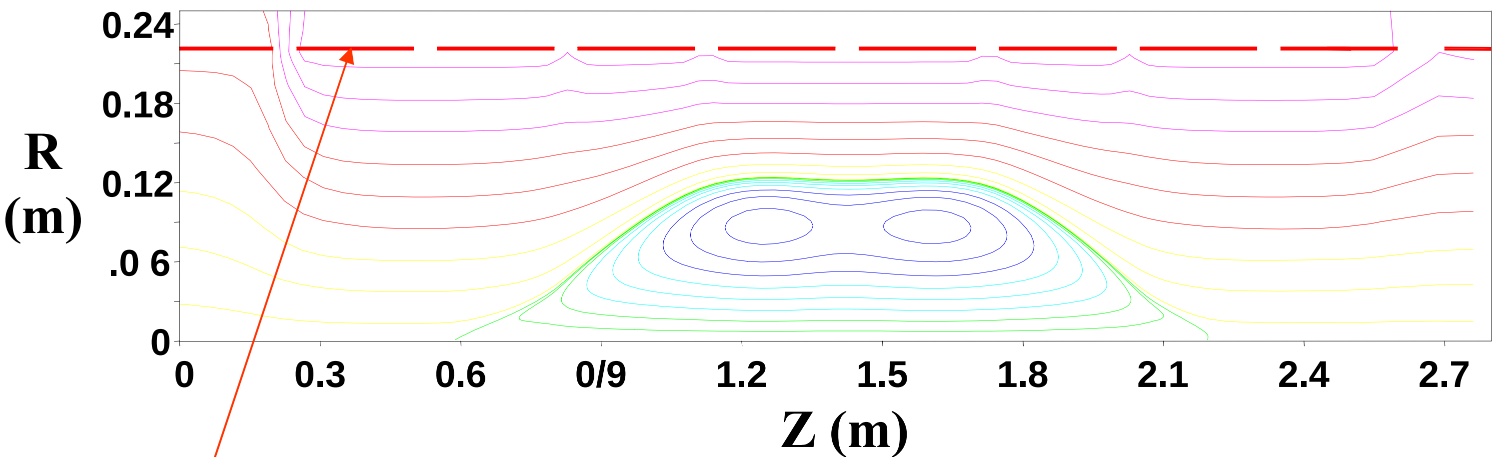
2 turn coil required for both energy transfer and reduction of crowbar current modulation

SPICE modeling of Main Bank Performance



MOQUI 2-D MHD Calculation for PHD Bank Parameters

B_{bias} = 0.15 T, ΔB_{vac} = 0.85 T P_n (D_2) = 15 mTorr



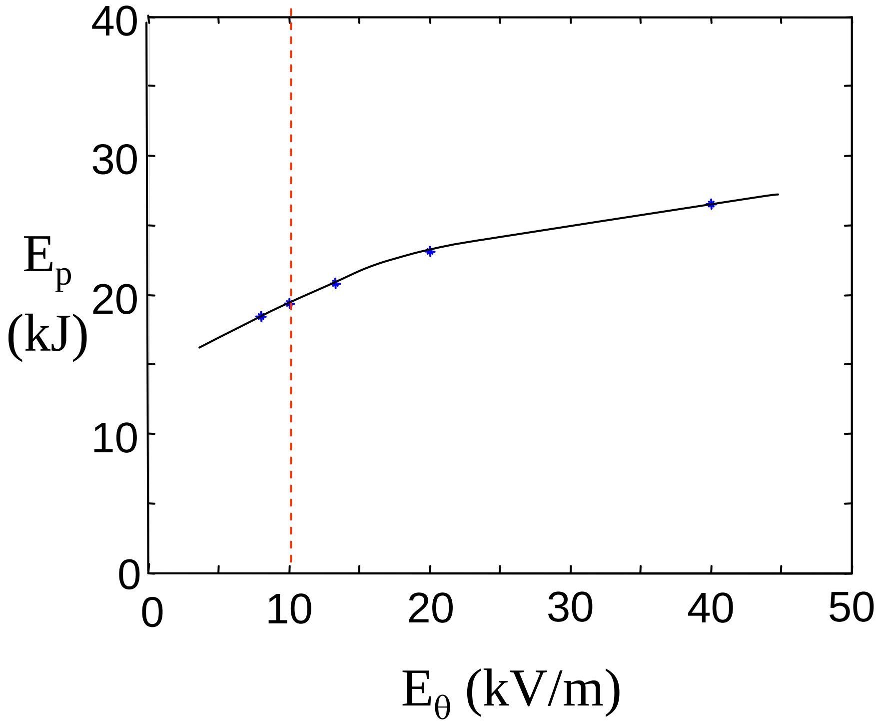
t=20 μs

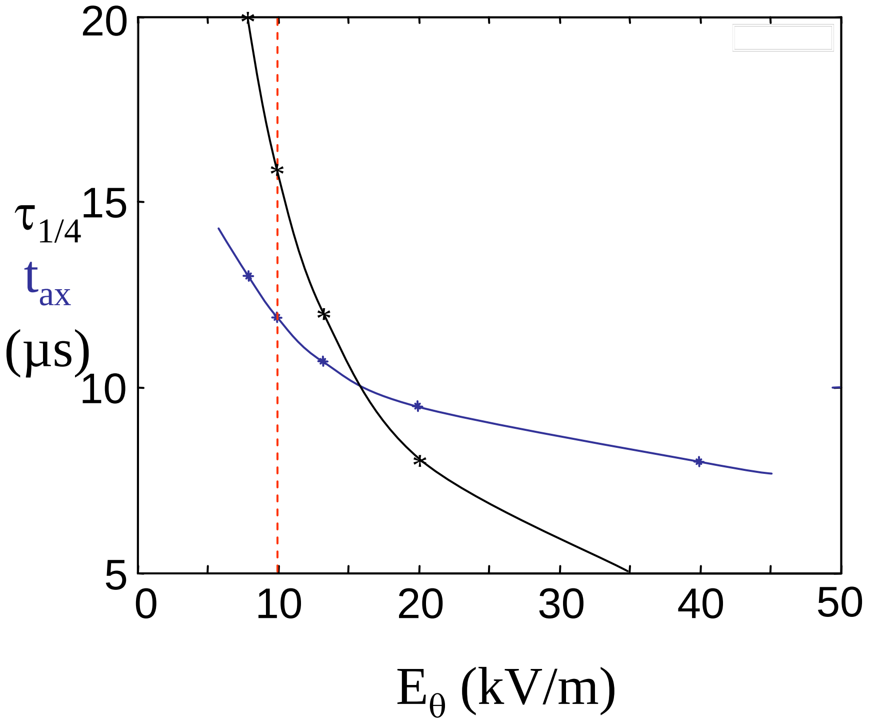
1 module at V= ± 20 kV per set of 3 two-turn coil pairs

B_e = 1.0 T, T_e +T_i = 300 eV, r_s = 12.5 cm, n_m= 8.5x10^{21} m^{-3}

S* (= $r_s \cdot \omega_{pi}/c$) = 36 E (= $l_s/2r_s$) = 6 (S* < 4E)

Numerical Calculation of FRC Formation as a Function of Coil Voltage





- Energy coupling into FRC is a weak function of E_θ, as expected at high bias
- Formation time (~ t_{ax}) should ideally be ~ $\tau_{1/4}$
- PHD design point is not ideal from formation flux loss point of view

Flux Trapping Dependence from Scaling Formula and TRX Measurements

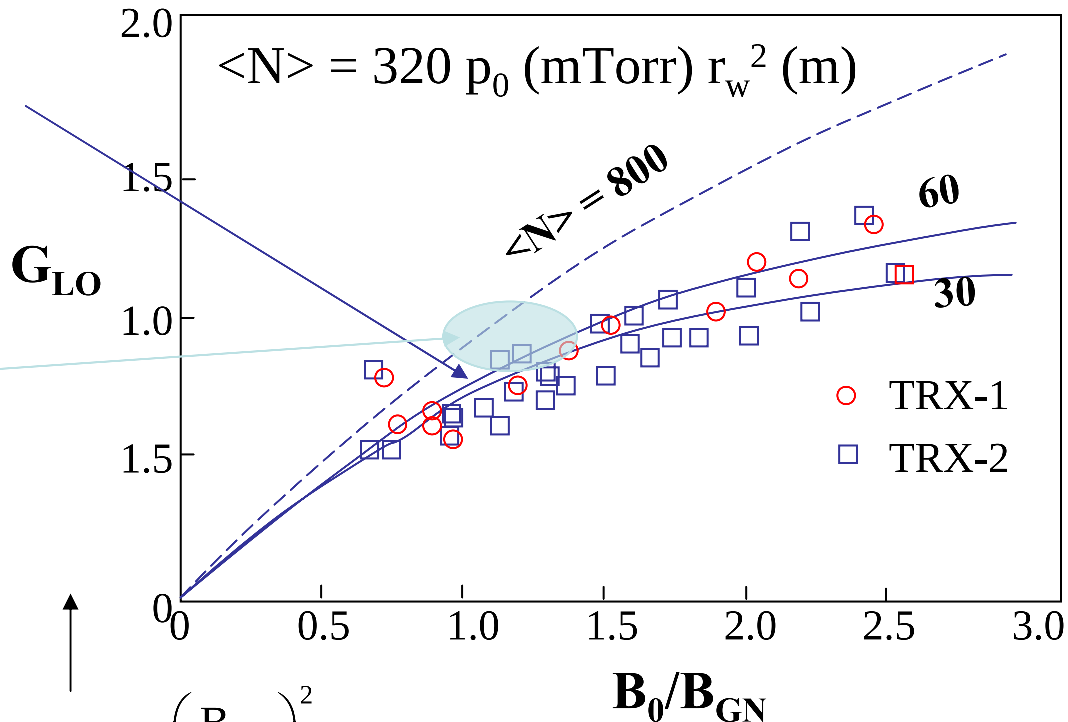
BGN is the field at which the radial Alfven time equals the reversal time

$$B_{GN} = (\mu_0 \rho)^{1/4} E_\theta^{\ 1/2}$$

$$B_{GN}\,(\mathrm{T}) = 0.019\ [\ A_i\, p_0(\mathrm{mTorr})]^{1/4}\ [E_\theta\ (\mathrm{kV/m})]^{1/2}$$

Flux loss:

$$\frac{B_{LO}}{B_0} = e^{-\left(0.75\frac{B_0}{B_{GN}}\langle N\rangle^{-1/4}\right)}$$



For PHD:

$\langle N\rangle \sim 100$

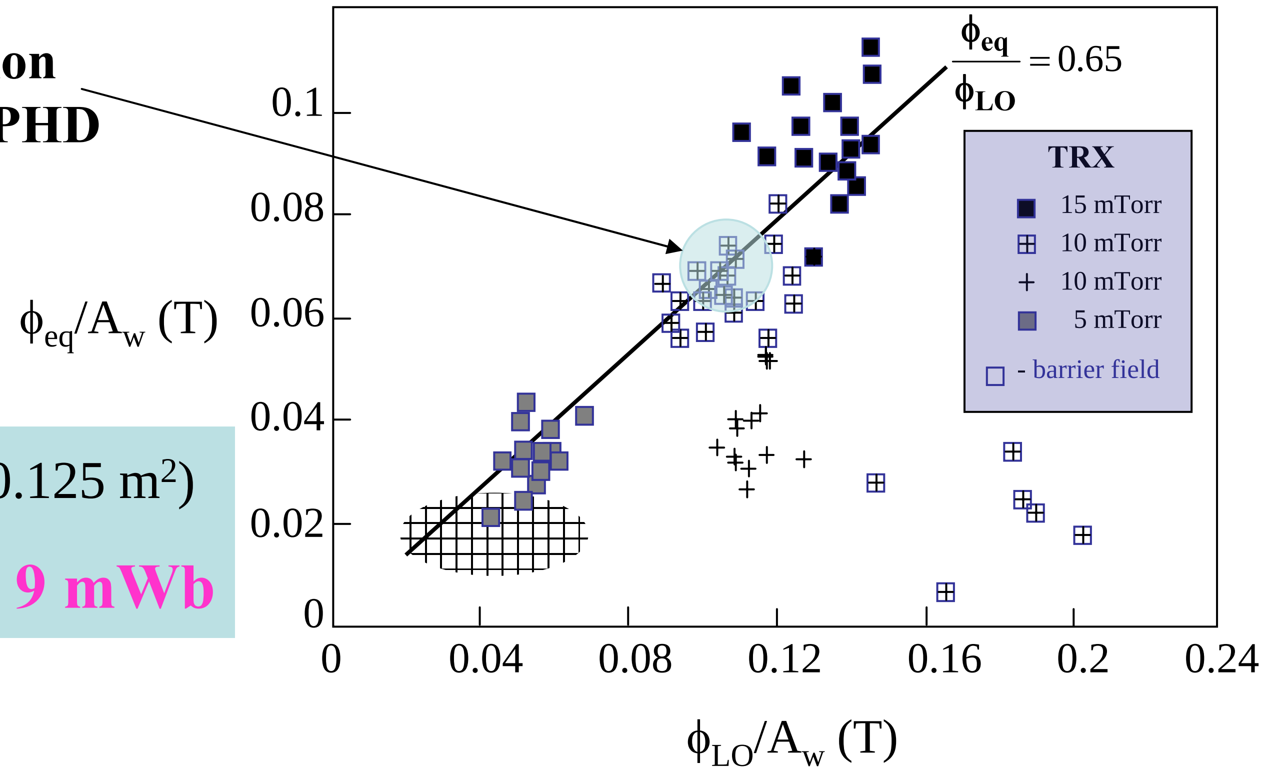
$B_{GN} = 0.13$ T

$B_{LO} = 0.75\ B_0$

$$\frac{t_{LO}}{t_A} \equiv G_{LO}^2 = \left(\frac{B_{LO}}{B_{GN}}\right)^2$$

Poloidal flux in the equilibrium FRC as a function of lift-off flux

Anticipated Region of operation for PHD



For PHD ($A_w = 0.125\ m^2$)

$\phi_{eq} = 0.65\phi_{LO} \sim 9$ mWb

- *both quantities are normalized to the cross-sectional area inside the vacuum wall boundary.*
- *All discharges employed a static D_2 fill gas.*
- *The crossed-hatch area covers the operating regime in previous experiments without barrier fields or programmed formation.*

UW collaboration on MTF

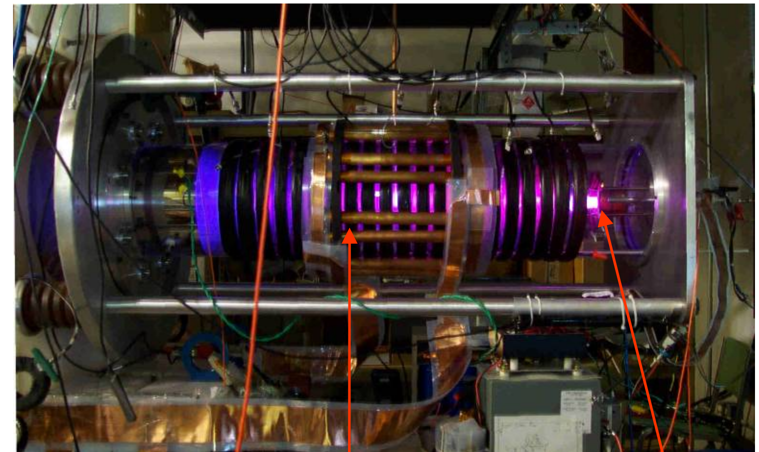
Rotating Barrier Field for Ion Spin-up Control

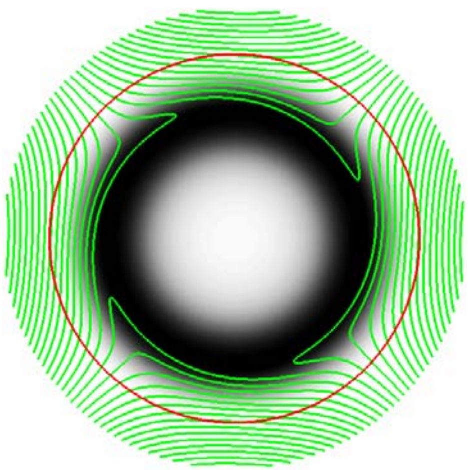
During Field Reversal:

•Counter-rotate ions ⇒ increase FRC stable period

•Increase lift-off flux in FRC

•Reduce impurity pick-up

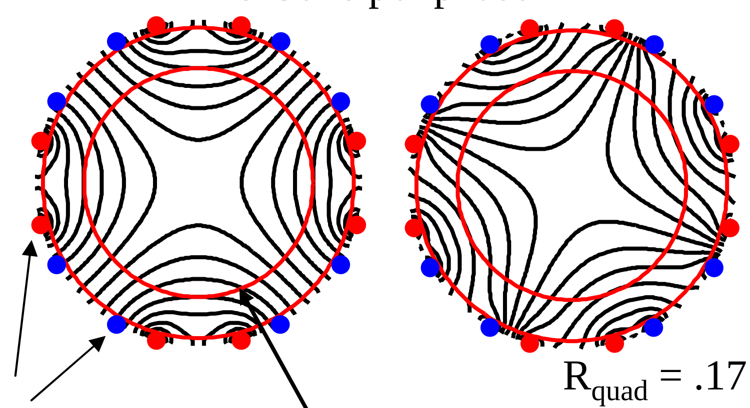




Equilibrium:

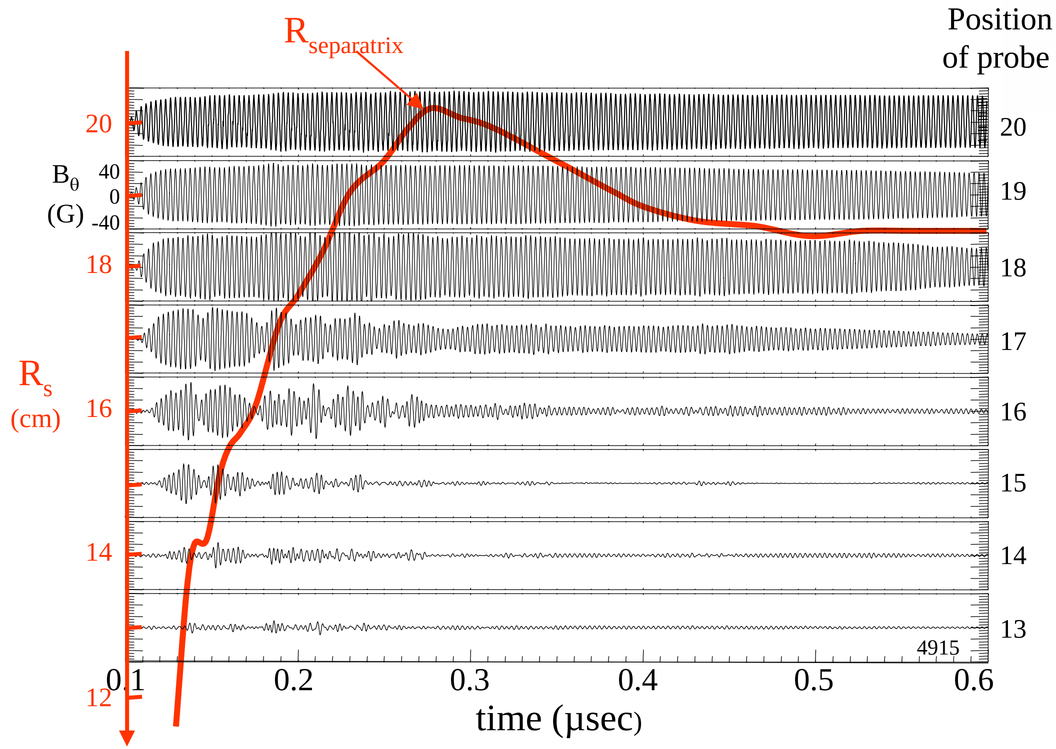
•Provide rotational stabilization

•Improve particle confinement

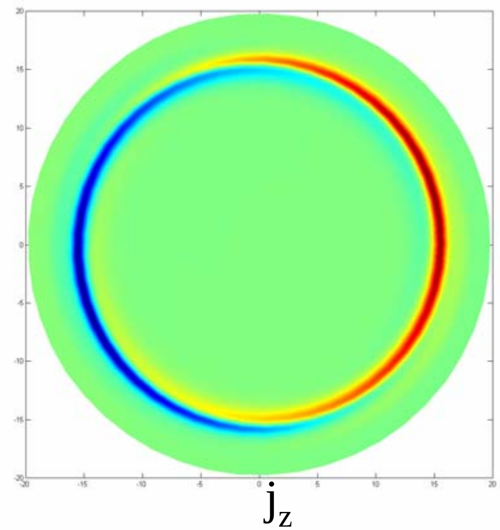


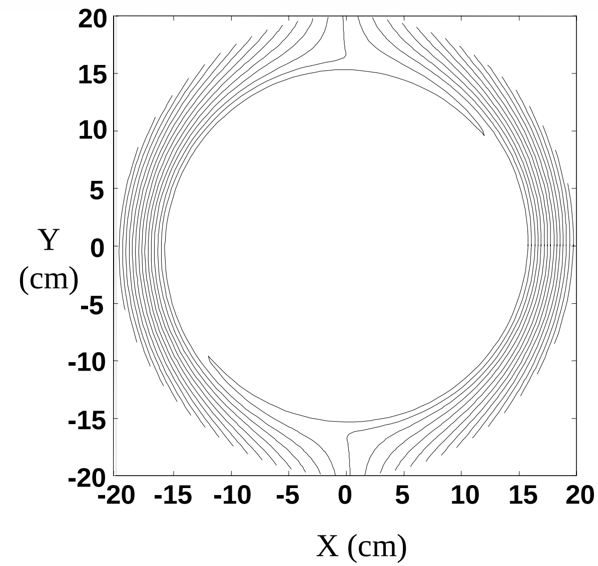
Screening of RMF Field by Plasma on STX

- Axial currents inside FRC limit RMF ~ 2 cm penetration past separatrix
- Axial current sheath is thin: ~ 1 cm
- Maximum radial force $\langle j_z B_\theta \rangle$ is obtained
- Minimum energy and particle loss observed under these conditions



2D MHD Calculation

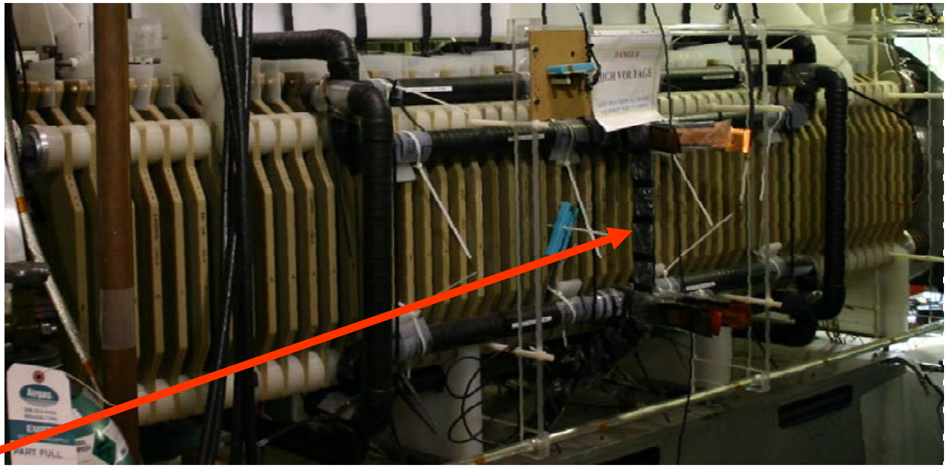




B_{RMF} Field

Rotating Barrier Field on PHD

Counter-torque on ions: $\omega_{RMF} \geq \omega_{ci}$
Barrier field: $B_{RMF} \sim B_{Lo}$



For $B_{LO} = 0.1$ T $\Rightarrow$

B_{RMF}(vac) ~ 0.05 T

For D ions and $2\omega_{RMF} = \omega_{ci} \Rightarrow$

$\omega_{RMF} = 1.2$ Mrad/s

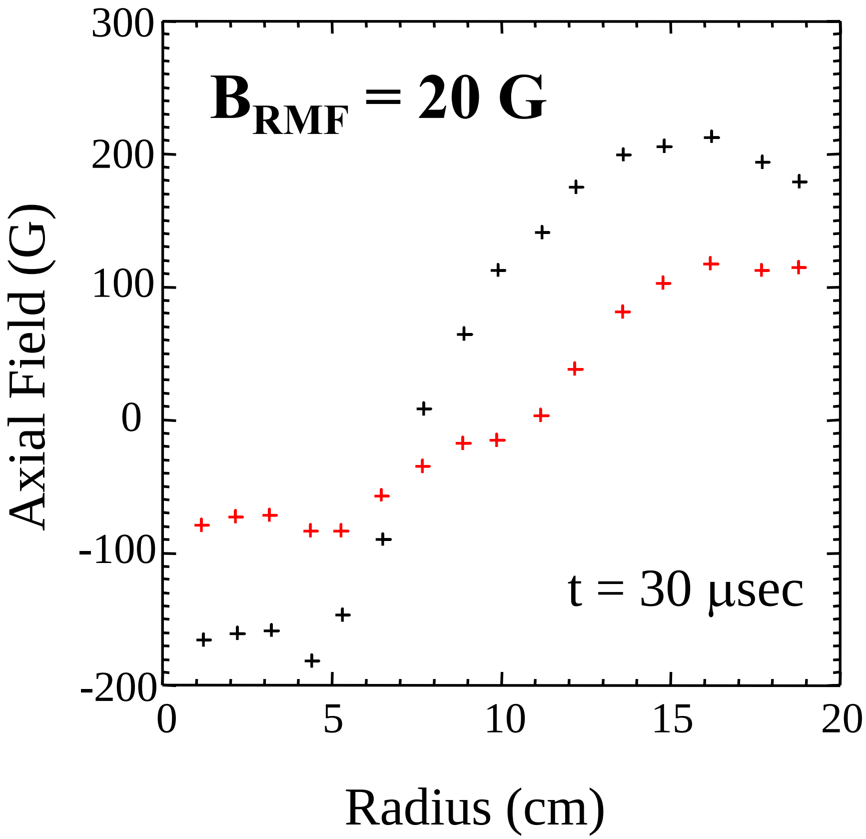
For four-fed dipole antenna, $L_{ant} = 0.4\ \mu H$ so that total current required is:

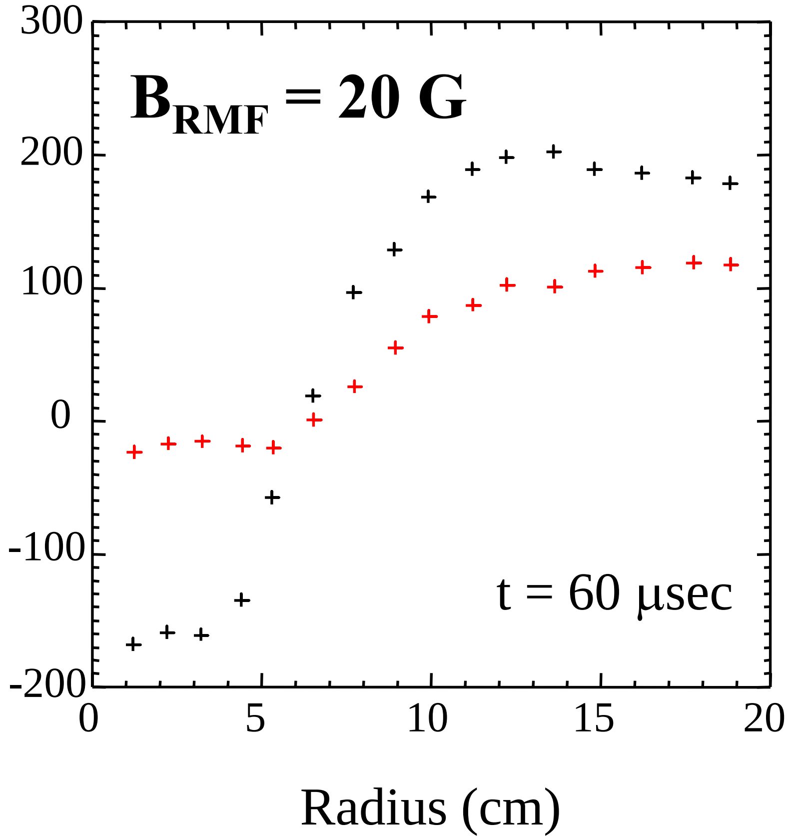
$I_{tot} = 100$ kA and

$V = \omega L_{ant} \cdot I_{tot} = 50$ kV

FRC Internal Field Profiles w and w/o RMF on STX

shots 2948, 2945





Black Trace = RMF On, Red Trace = RMF Off

Summary

- PHD is designed to explore and operate at FRC stability boundary
- PHD design point will provide the flux necessary for fusion gain in the reactor regime
- FRC acceleration has been demonstrated previously with ($a > 10^{10}$ m/s^2), and PHD will extend these results in compression
- Hopefully PHD will provide a path to achieve keV plasmas with significantly increased confinement parameters required to move toward a fusion breakeven experiment