

# Development of a High Fluence Fusion Neutron Source and Component Test Facility Based on the Magneto-kinetic Compression of FRCs

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# Motivation for CTF based on the FRC

## Criteria for Component Test Facility:

- (1) Provide an environment close to the fusion reactor
  - (a) On the smallest physical scale (cost and timeliness)
  - (b) With the simplest configuration (cost and ease of use)
- (2) It should be capable of evaluating the full tritium fuel cycle.
- (3) It should allow for easy diverter access for evaluation of a range of materials evaluation

## Magneto-kinetic Compression of FRC plasmoids

### ➤ Fusion Power Density scales as $\beta^2 B^4$

- (1) The FRC has the highest  $\langle\beta\rangle$  of all fusion plasmas ( $\langle\beta\rangle \sim 0.8-0.9$ )
- (2) Compression and burn occurs in a simple linear geometry at highest possible B consistent with pulsed solenoidal coil ( $B_z \sim 15-20$  T)
- (3) D-T fusion neutron generation provides more realistic test for materials and tritium breeding
- (4) Diverter outside blanket and remote from burn chamber

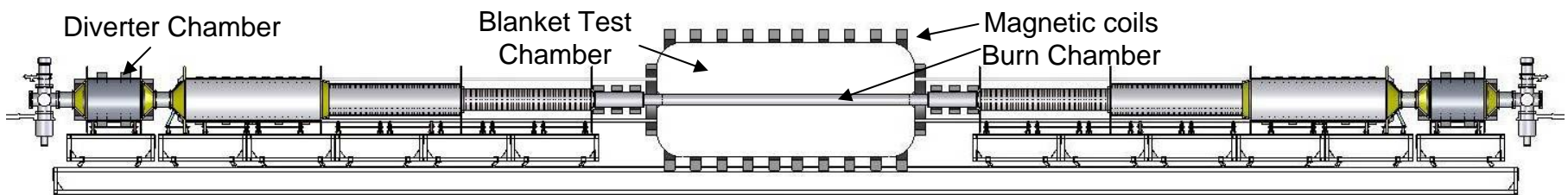
# Component Test Facility based on Pulsed High Density (PHD) FRCs

## PHD FRC neutron source provides

- Remote burn in ideal breeding geometry
- Greatly simplified PFC management
- Direct, High efficiency ion heating to fusion temperature
- Small, compact source maximizes wall loading with minimum environmental impact

## Key Physics Demonstrated:

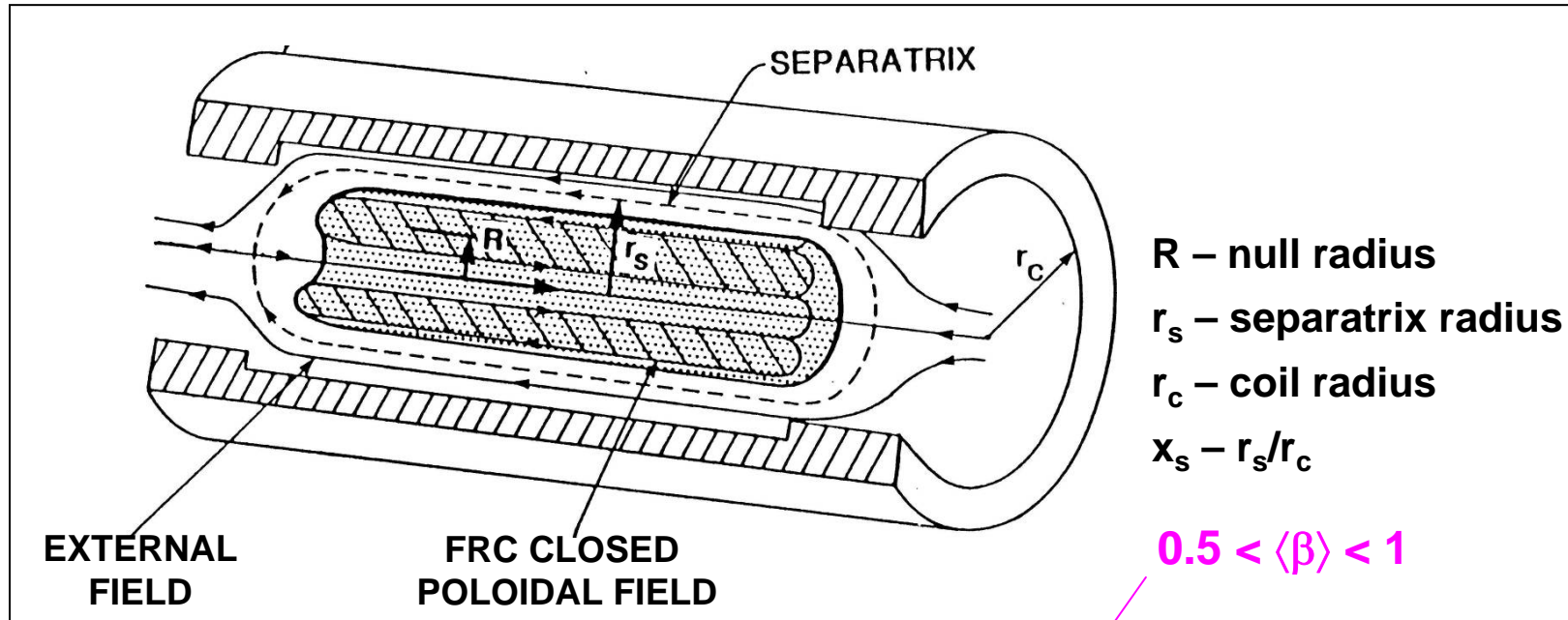
- Kinetic stability from formation thru fusion burn
- Observed transport scaling sufficient for  $Q > 1$
- Magneto-kinetic heating ( $M \sim 3$ ) forming robustly stable FRC
- Confinement scaling better than prediction from *in situ* PHD FRC  $\tau > \tau_{LHD} \sim r^2 n^{1/2}$



Component Test Facility

**Magneto-kinetic heating to fusion temperatures: Kinetic energy is transferred from array of axially sequenced low field coils and thermalized by self compression into high field burn chamber**

# The Field Reversed Configuration (FRC)



**Equilibrium Relations:**

$$P_0 = n_0 kT = \frac{B_{\text{ext}}^2}{2\mu_0}$$

**Radial Pressure Balance**

$$\langle \beta \rangle = \int_0^{r_s} \frac{2\mu_0 P}{B^2} dr = 1 - \frac{1}{2} x_s^2$$

**Axial Pressure Balance**

$$B_{\text{ext}} = \frac{B_{\text{vac}}}{(1 - x_s^2)}$$

**Flux conservation**

# FRC Reactor Regime Based on Observed Confinement Scaling:

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

$$n\tau \sim 6 \times 10^{-15} r_s^2 n^{1.6}$$

(with  $x_s = 0.6$   $\epsilon = 20$ )

Radial Pressure balance:

$$B_e^2 = [2\mu_0 n_0 kT (=10 \text{ keV})] = 4 \times 10^{-21} n_0 \Rightarrow n\tau \propto r_s^2 B_e^3$$

In terms of confining flux  $\phi_p$ :

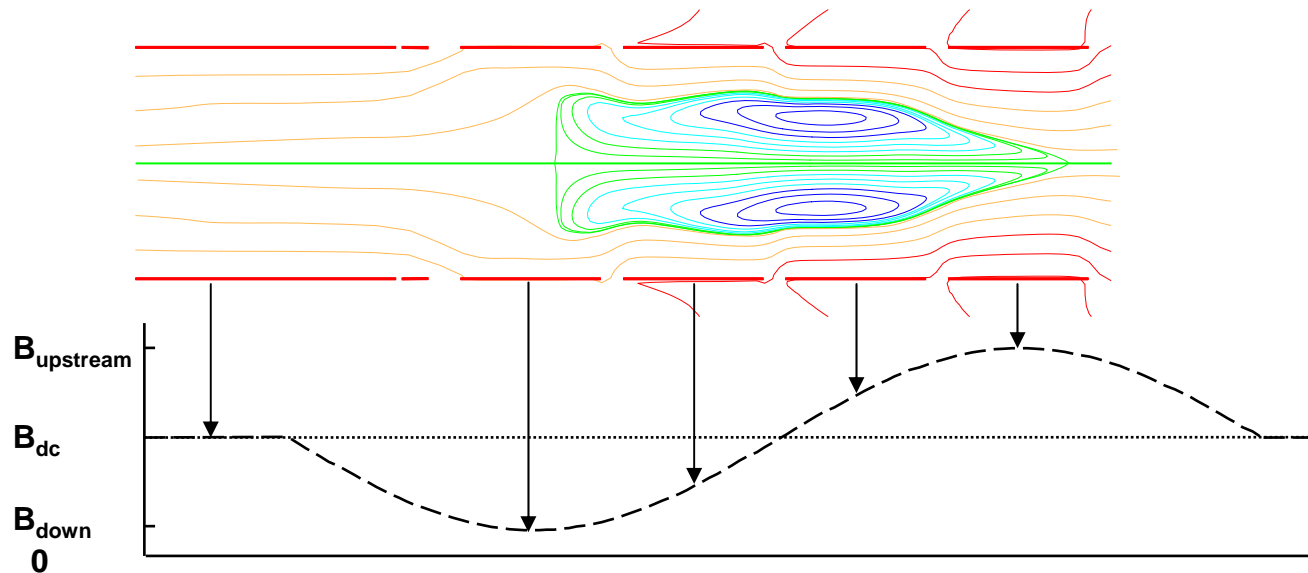
$$n\tau \propto \phi_p B_e^2$$

Regime of Interest here

Reactor	$B_e$ (T)	$\phi$ (mWb)
MTF	200	0.5 to 1
<b>IPA</b>	<b>20</b>	<b>20</b>
SS FRC	1 - 2	1000

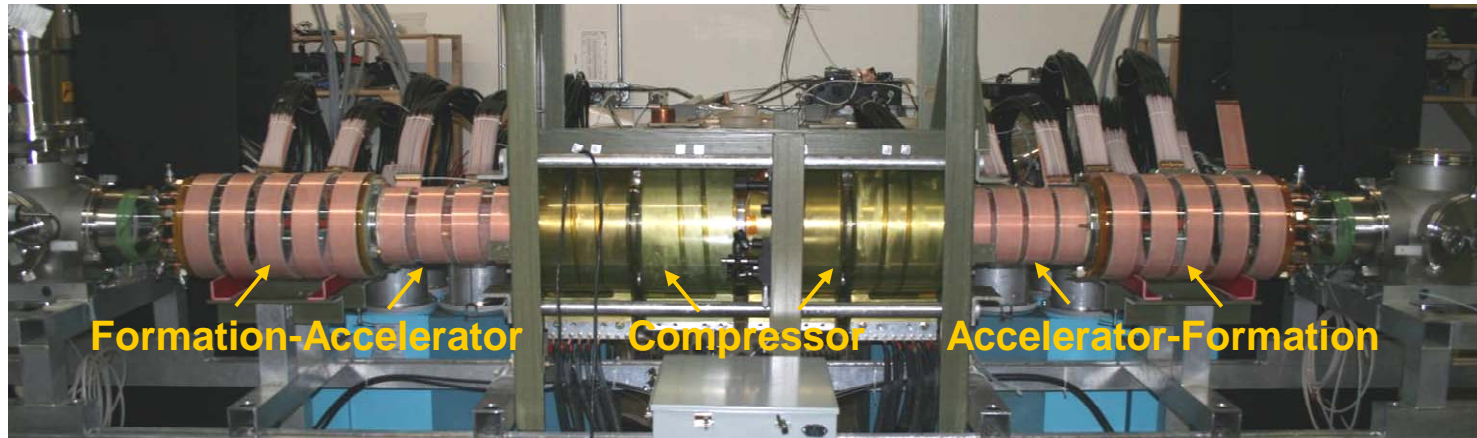
# Inductive Plasmoid Accelerator (IPA):

## FRC Plasmoid Acceleration Method Employed in IPA



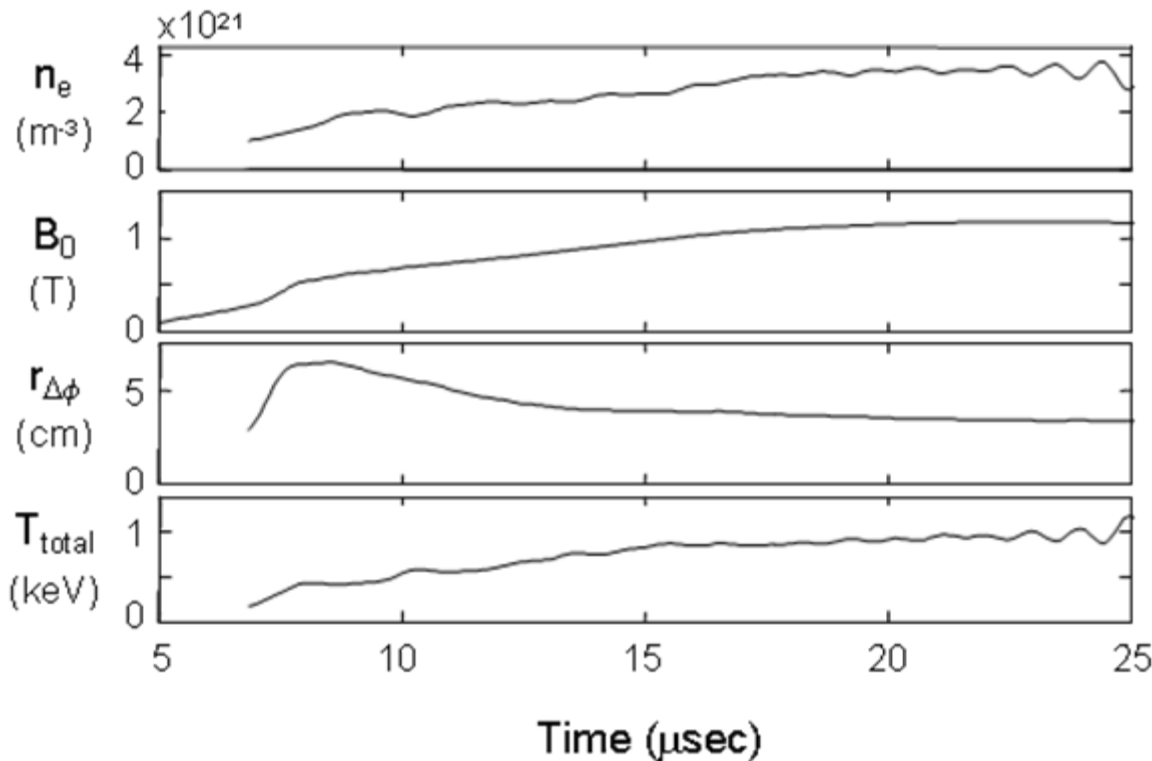
- Upper plot of flux contours taken from numerical calculations for discharge 1647 during the acceleration of an FRC plasmoid
- Bottom plot illustrates phasing of the accelerator coils  
Each coil in turn is switched on for one complete cycle.  
Phase of each coil at time of calculation is indicated by arrow

# The Inductive Plasma Accelerator is a Device Designed to Create Fusion Relevant, High Energy Density FRC Plasmas



- (1) With IPA a series of sequentially fired axial field coils accelerating two FRCs toward one another at a relative velocity of 400-800 km/s
- (2) The two FRCs collide and merge, thermalizing their directed kinetic energy resulting in ions with temperatures of several hundred eV to several keV.
- (3) The FRC plasmoids are compressed radially as they merge
  - The resulting FRC was stable and well confined – decaying more slowly than insitu formed FRCs.
  - The neutron flux was significantly higher than anticipated based on the radial pressure balance temperature

# FRC Parameters Measured on IPA with Magnetic Compression



## Diagnostics Employed

Midplane HeNe Interferometer + Excluded Flux Signal

External Magnetic probe

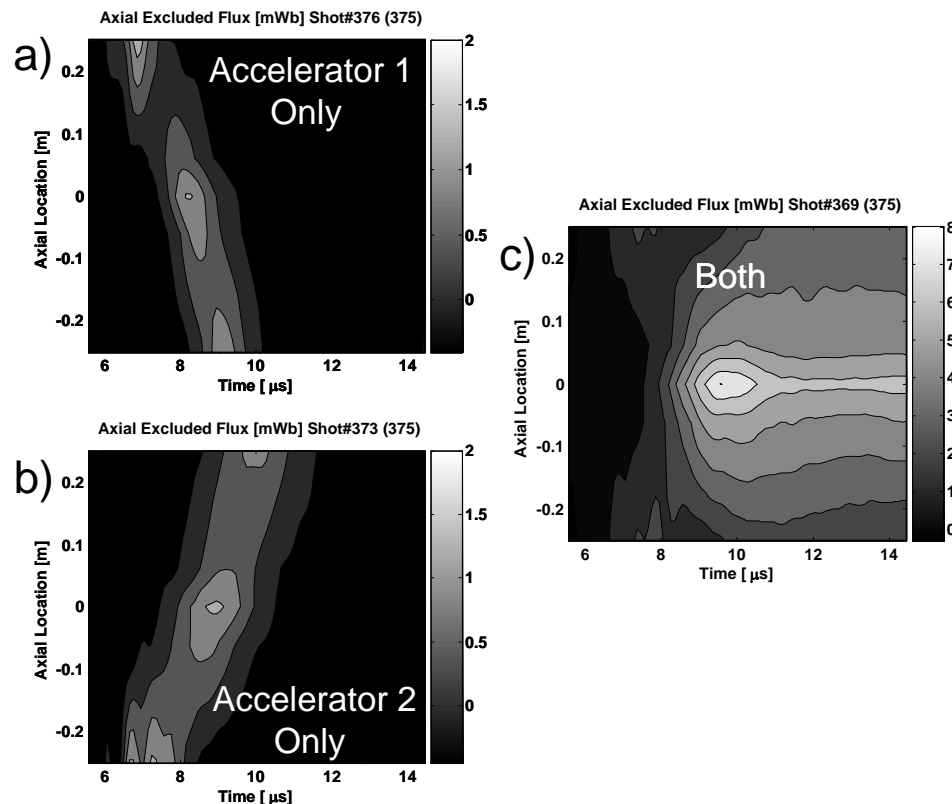
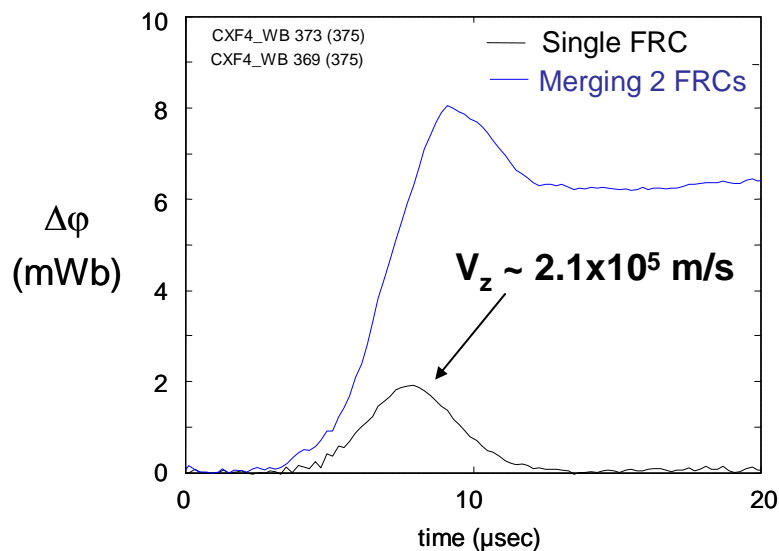
Excluded Flux from flux and B-dot loops +  $B_0$

Radial pressure balance Eq.  $\left( \frac{B_0^2}{2\mu_0} = n k T_{total} \right)$  +  $n_e$  and  $B_0$

**Supersonic Merging Process is Observed to Form Stable and Quiescent FRC Target for Simultaneous Compression**

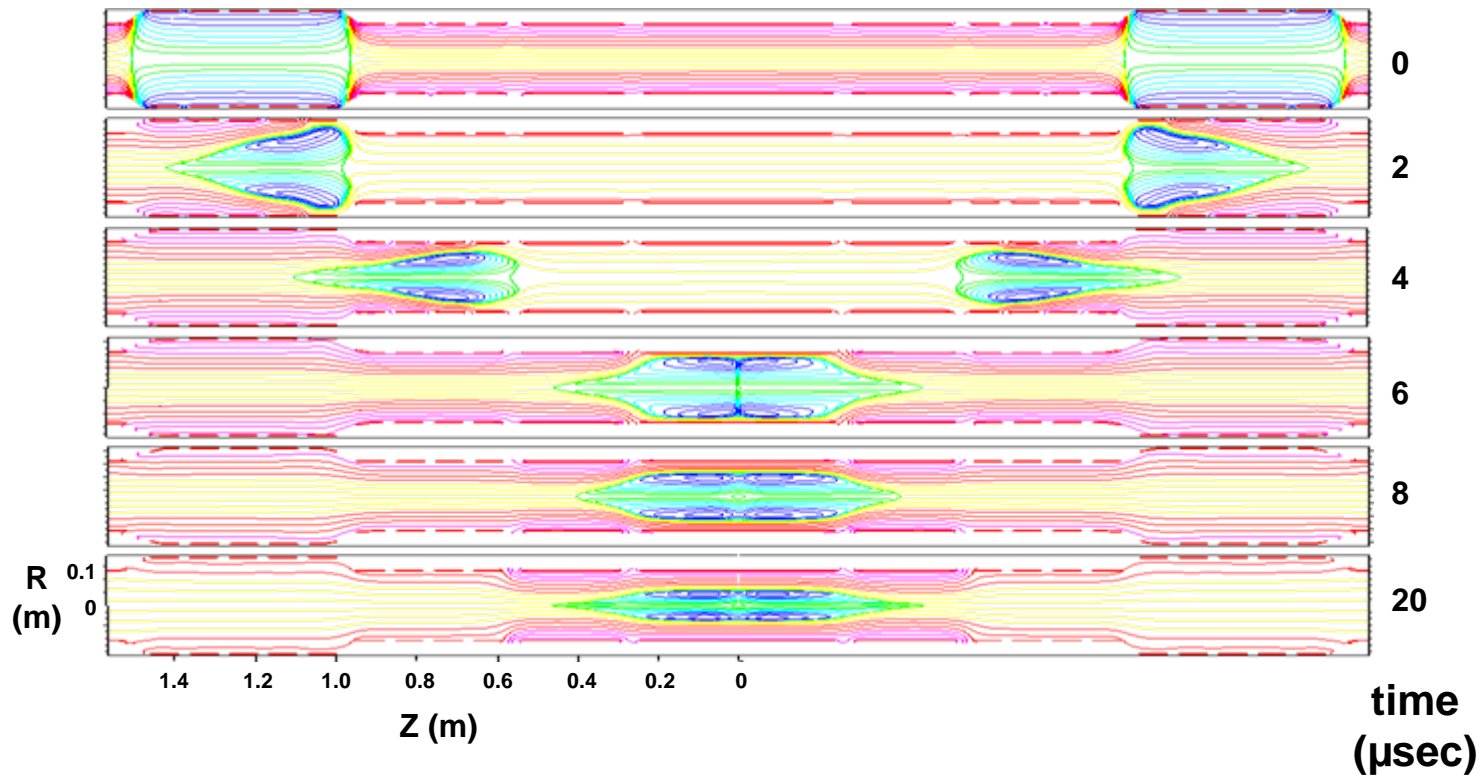
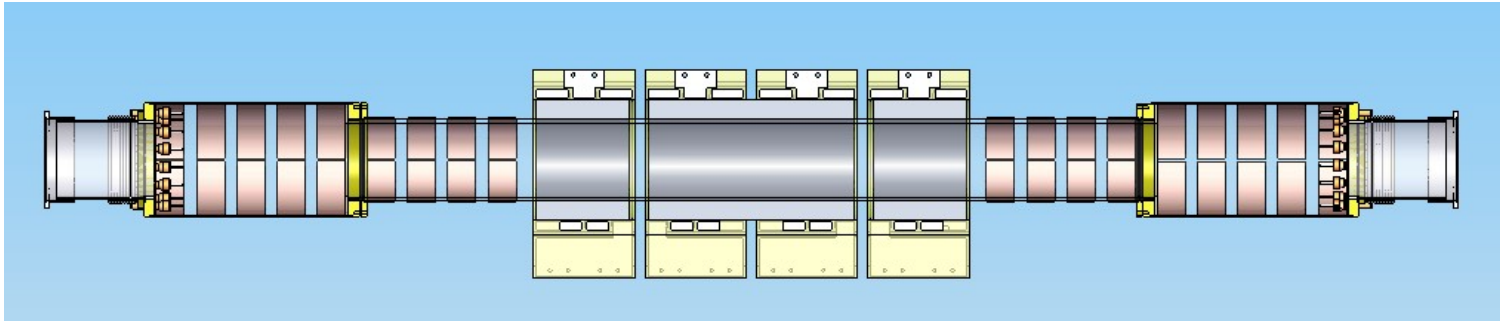
# FRC Dynamic Behavior Exhibited in Excluded Flux (Diamagnetism) from Diagnostic Array in Merging Chamber FRC

- Employing a single accelerator, the FRC transits the compression section (a and b)
- Simultaneous firing (c) shows merging
- Excluded flux measurements indicate the FRCs do merge and decay over  $\sim 40 \mu\text{s}$



Contour plots of  $\Delta\phi$  axially along compression chamber

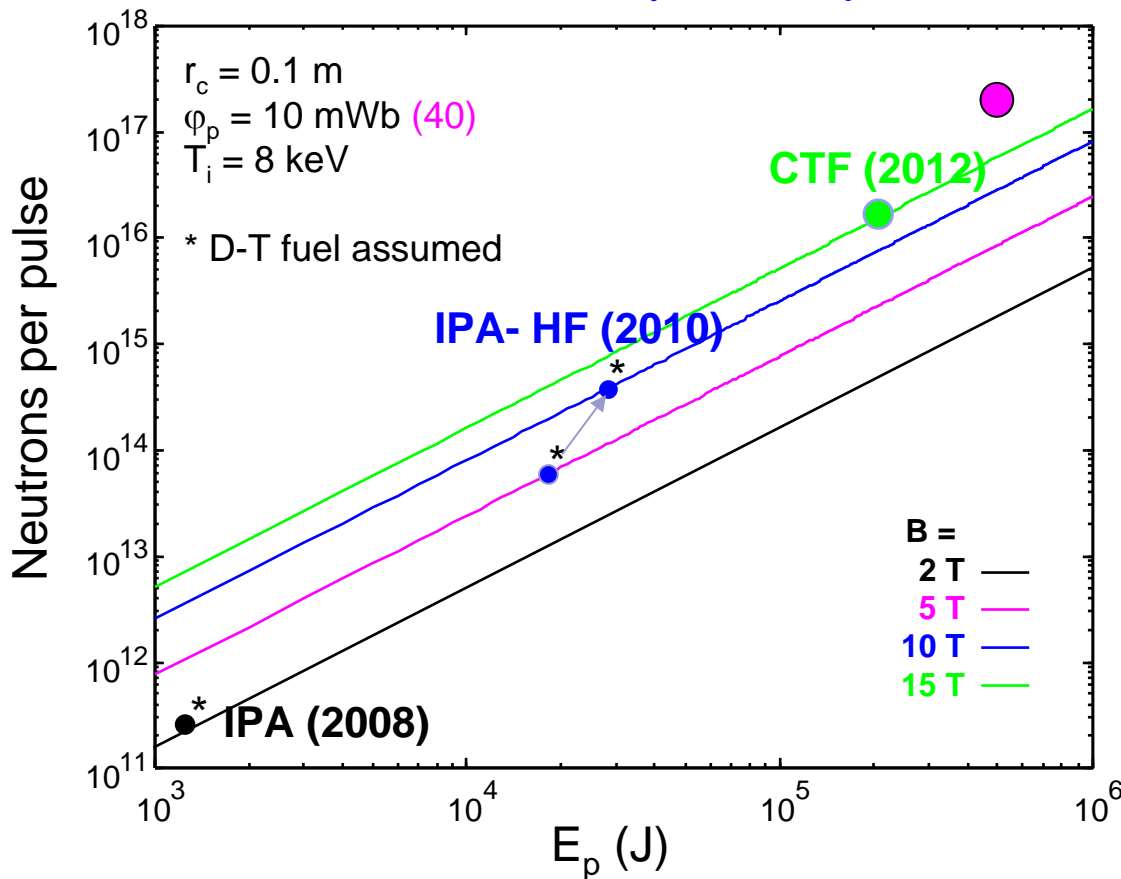
# 2D MHD Calculations Based on Measurements and Results from IPA (2008)



# Development Plan for FRC Based CTF

Increasing Fusion Neutron Production Enables Several Applications Such as Fissile Fuel Breeding, and Waste Transmutation

$$N_{\text{neut}} = 2.62 \times 10^{31} \frac{B^{7/4} E_p^{3/2} \sqrt{\phi_p}}{r_c^{1/3}} \frac{\langle \sigma v \rangle_{\text{DT}}}{T_i^{2.6}}$$



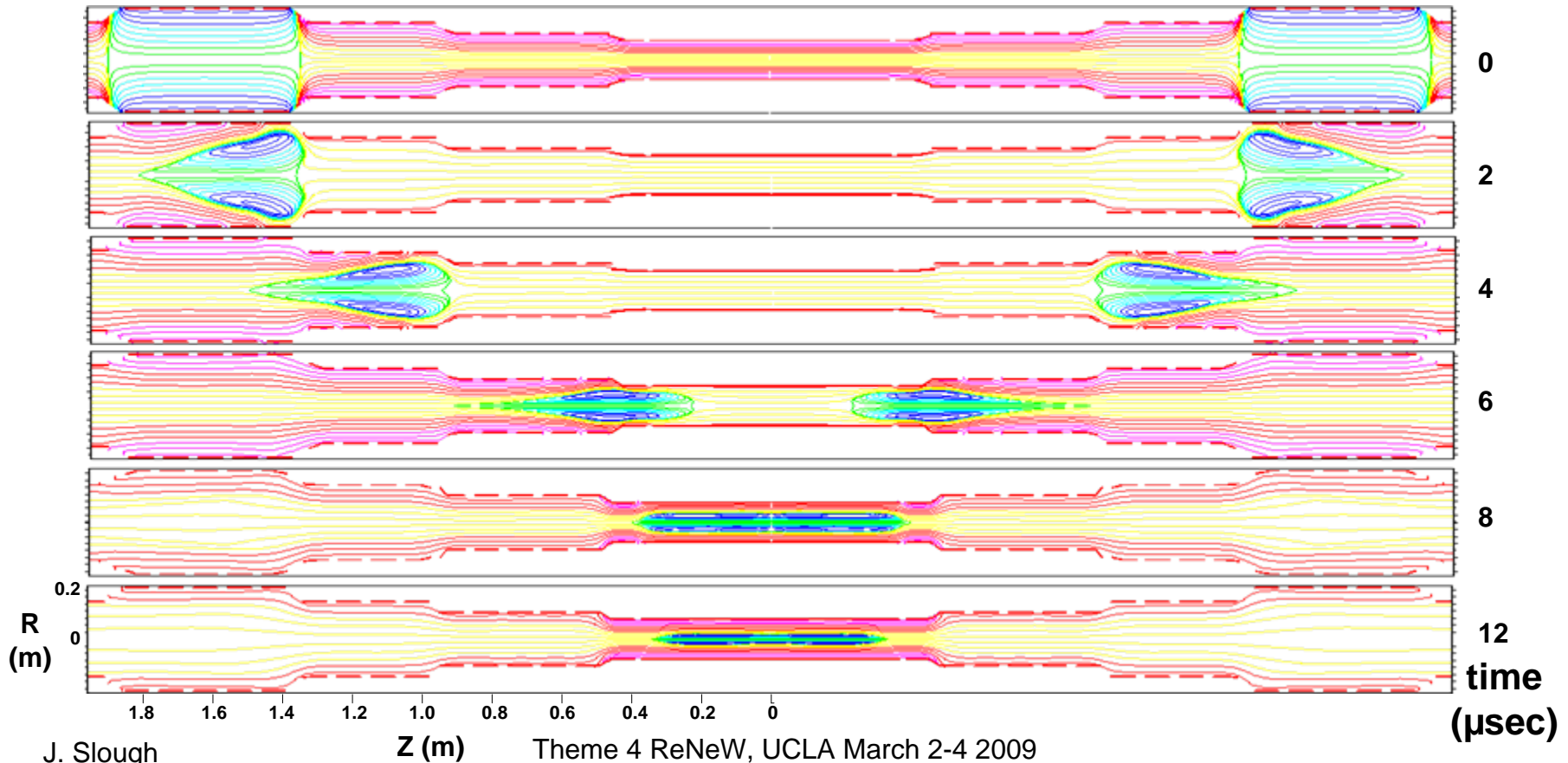
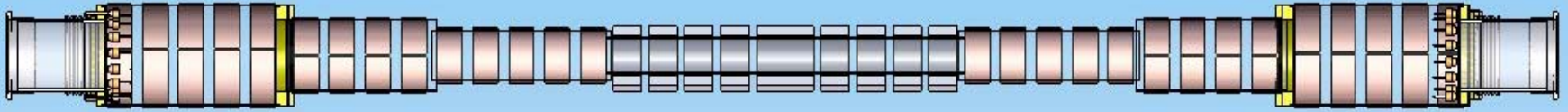
**Phase 0:**  
Proof of Concept  
Demonstrated 2008

**Phase 1:**  
IPA-HF  
 $N_{\text{neut}} \sim 10^{15}/\text{pulse}$

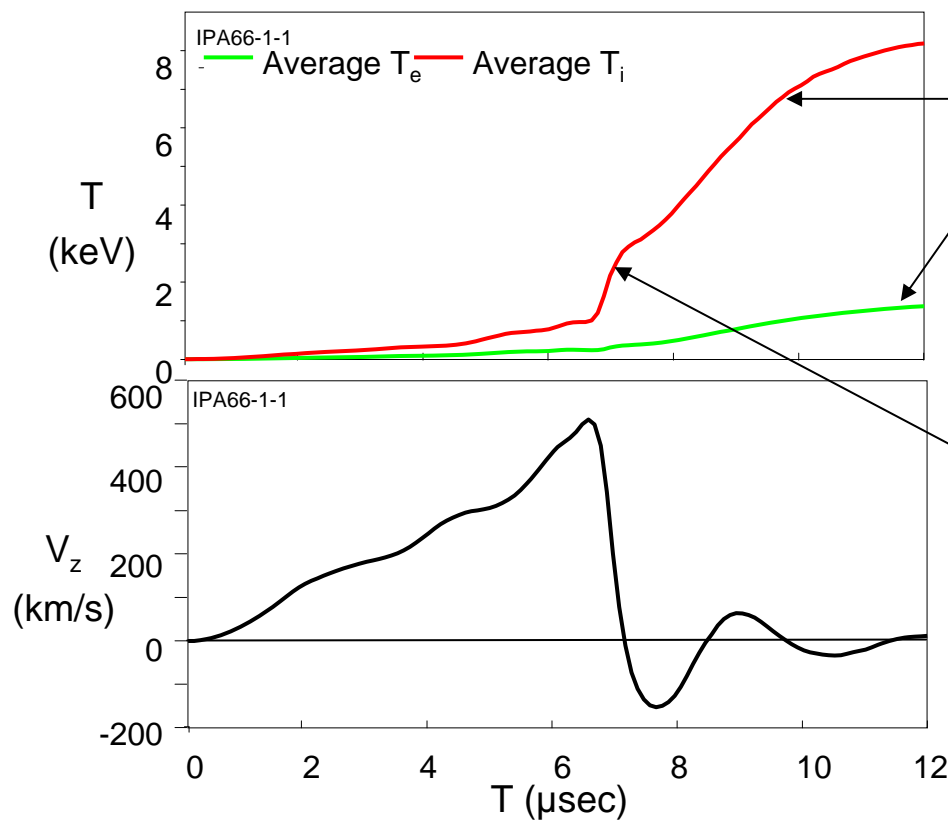
**Phase 2:**  
CTF  
(IPA-HF @ 800 Hz?)

**Phase 3:**  
 $Q=1.5$   
Thorium Breeder  
Large Scale  
Transmutation  
Of High Level Waste

# MHD Calculation for Next Step Experiment: IPA-HF



- **IPA-HF increases plasmoid KE and TE prior to compression**
- **Optimum yield  $T_i$  attained quickly maximizing neutron yield**

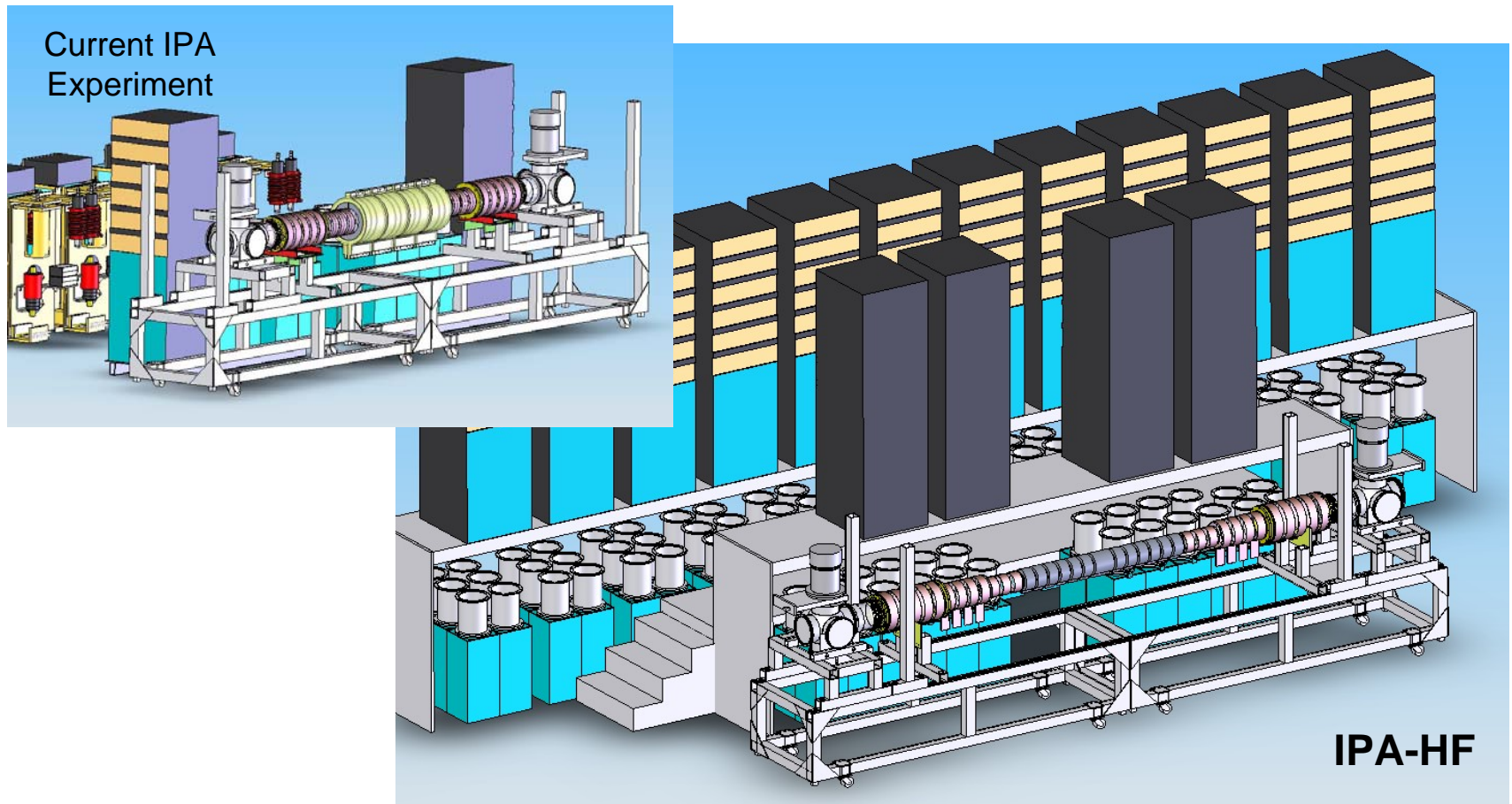


Compressional heating  
adiabatically heats both  
ions and electrons

Supersonic collisional  
merging heats only ions

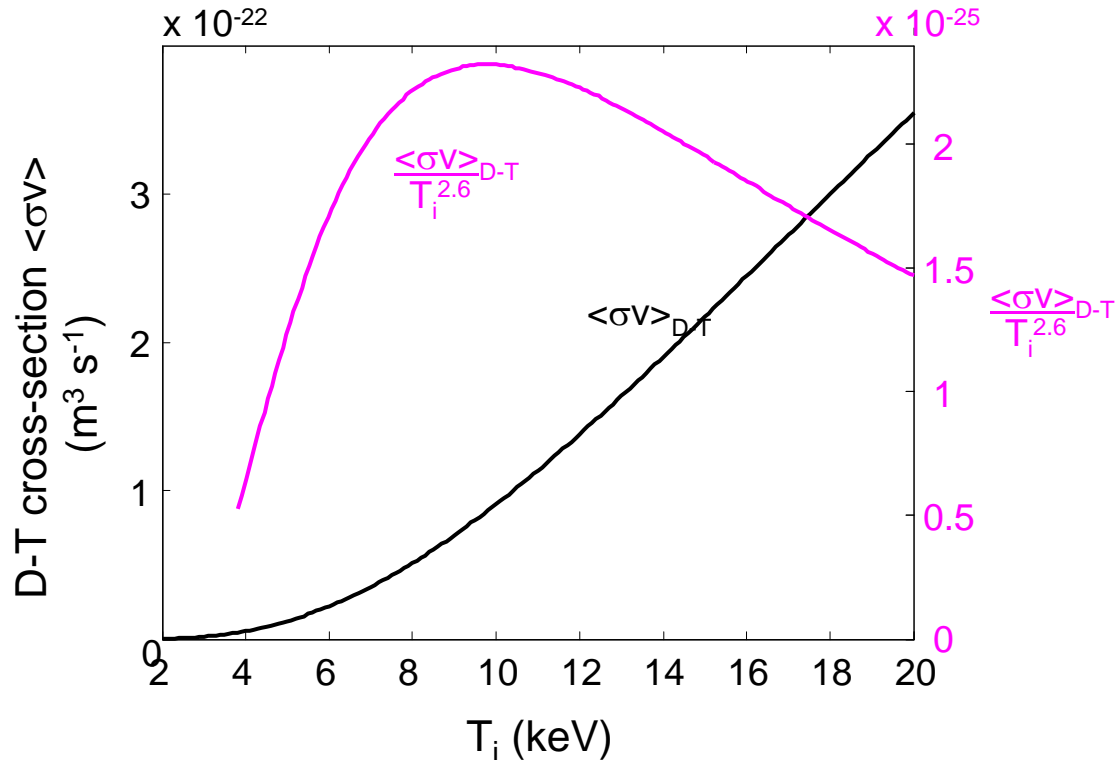
**Ions remain much hotter than  
Electrons for FRC lifetime  
in IPA-HF**

# Compression Experiment: IPA-HF



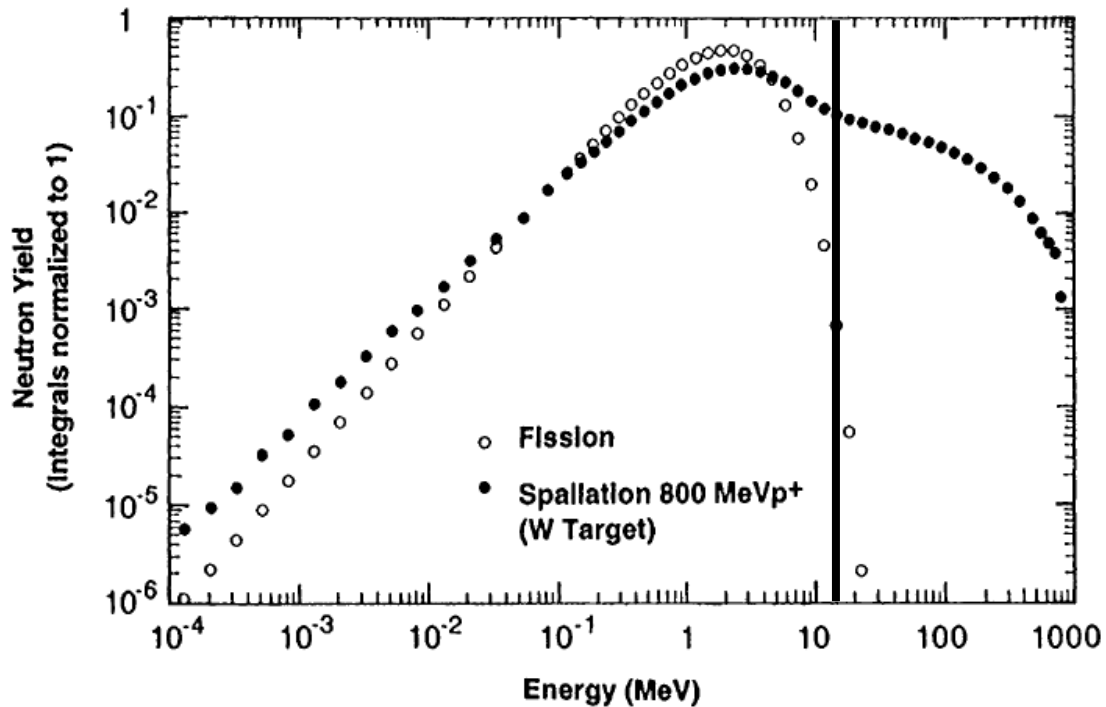
- IPA-HFC will provide verification of scaling at compression fields up to 10 T
- This requires a capacitor bank upgrade (~1/2 MJ)
- FRC plasmoid parameters at or near those desired for CTF

# Temperature Dependence of Neutron Production



**For a given energy input to the plasma, The optimum neutron yield is at a somewhat lower temperature than Lawson for FRC scaling**

# Employment of D-T Fusion Neutron Source is Optimum for Both Materials Damage Studies as well as Tritium Processes In Blanket and Diverter



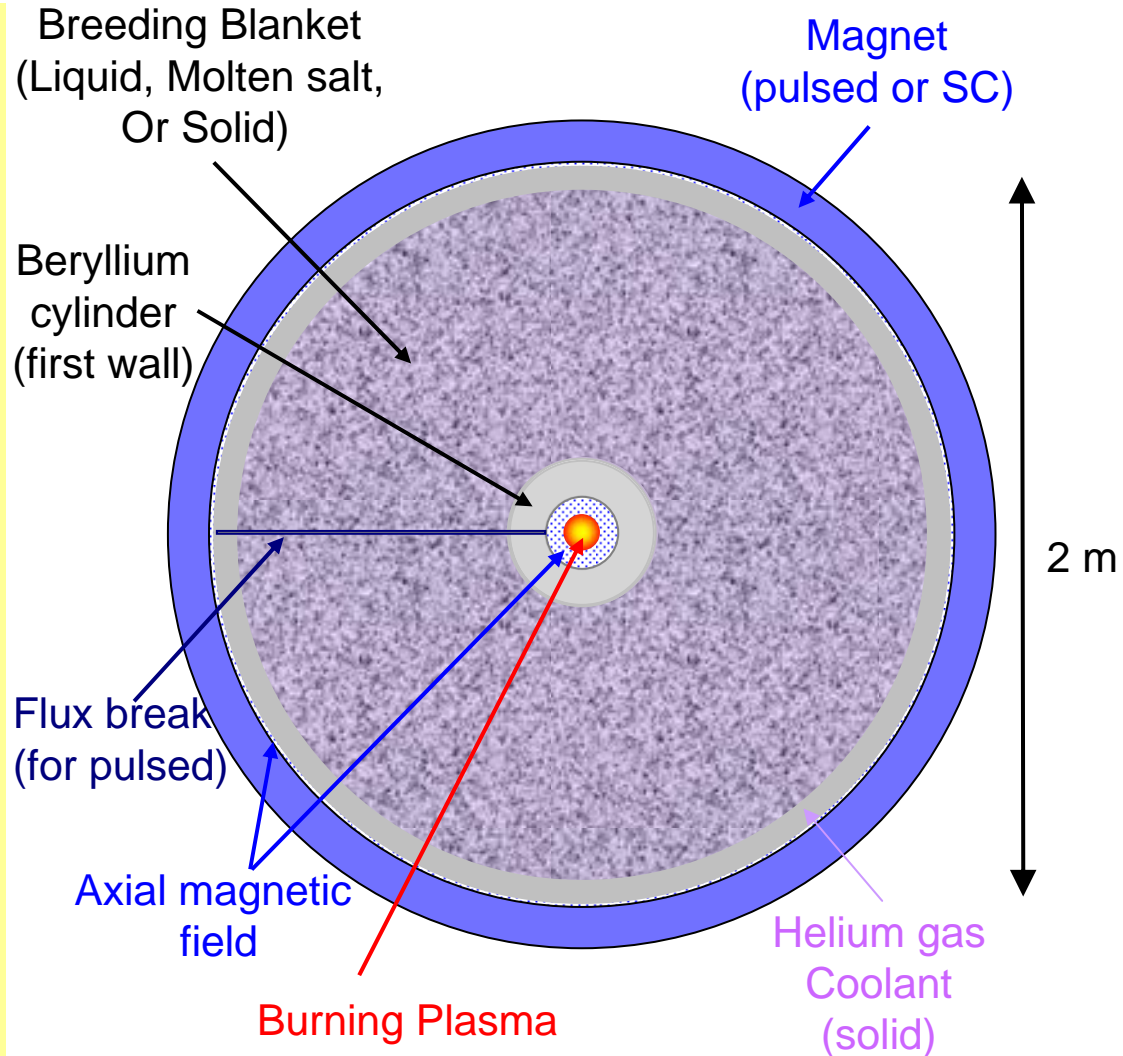
# Flexible Blanket for Breeding Studies

**Blanket coverage should be close to 100%;**

- **Point-like neutron source**
- **Long cylinder with only small on-axis ports for diverter.**
- **No beam, antenna, or pumping ports**

**No significant structural elements between blanket and plasma:**

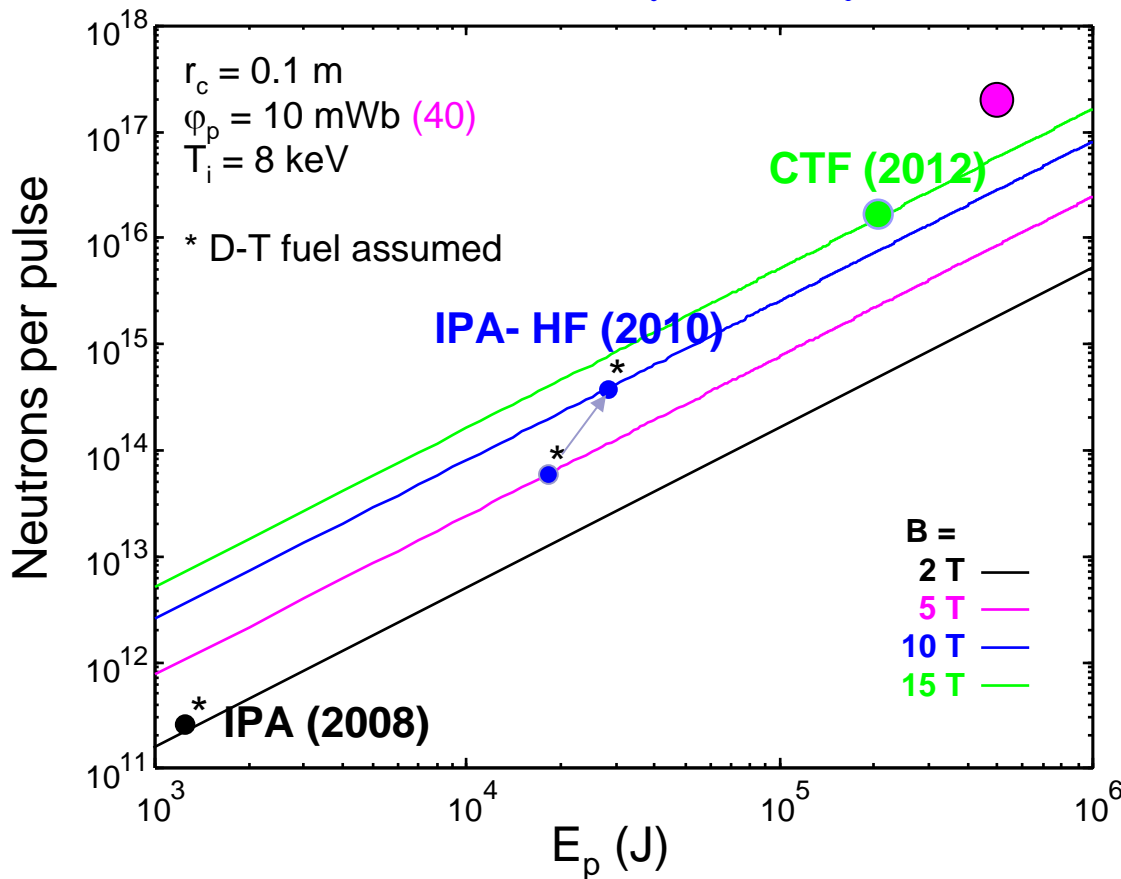
- **PFC - structural Be (10 cm)**
- **End supported, rigid cylinders**
- **Simple, flow through geometry**



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**Phase 0:**  
Proof of Concept  
Demonstrated 2008

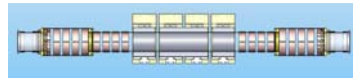
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**Phase 2:**  
CTF  
(IPA-HF @ 800 Hz?)

**Phase 3:**  
 $Q=1.5$   
Thorium Breeder  
Large Scale  
Transmutation  
Of High Level Waste

# Timeline and Cost for FRC Based CTF

Method for producing suitable fusion plasma demonstrated:



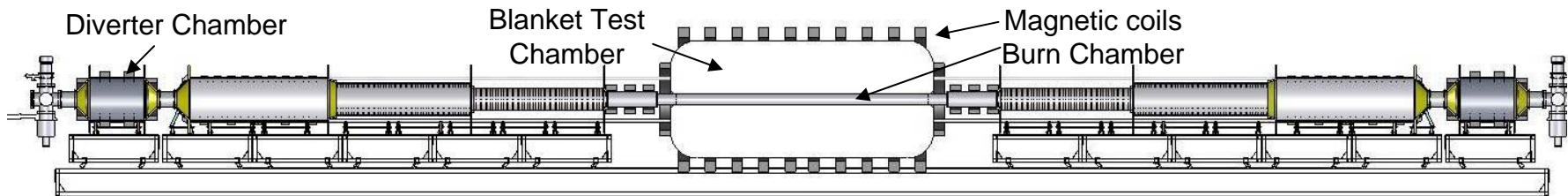
IPA Experiment (2008) ~ \$600k

Optimum Fusion  $T_i$  reached with  $N_{\text{neut}} \sim 5 \times 10^{14}$  /pulse



IPA-HF (2010) ~ \$2.5 M

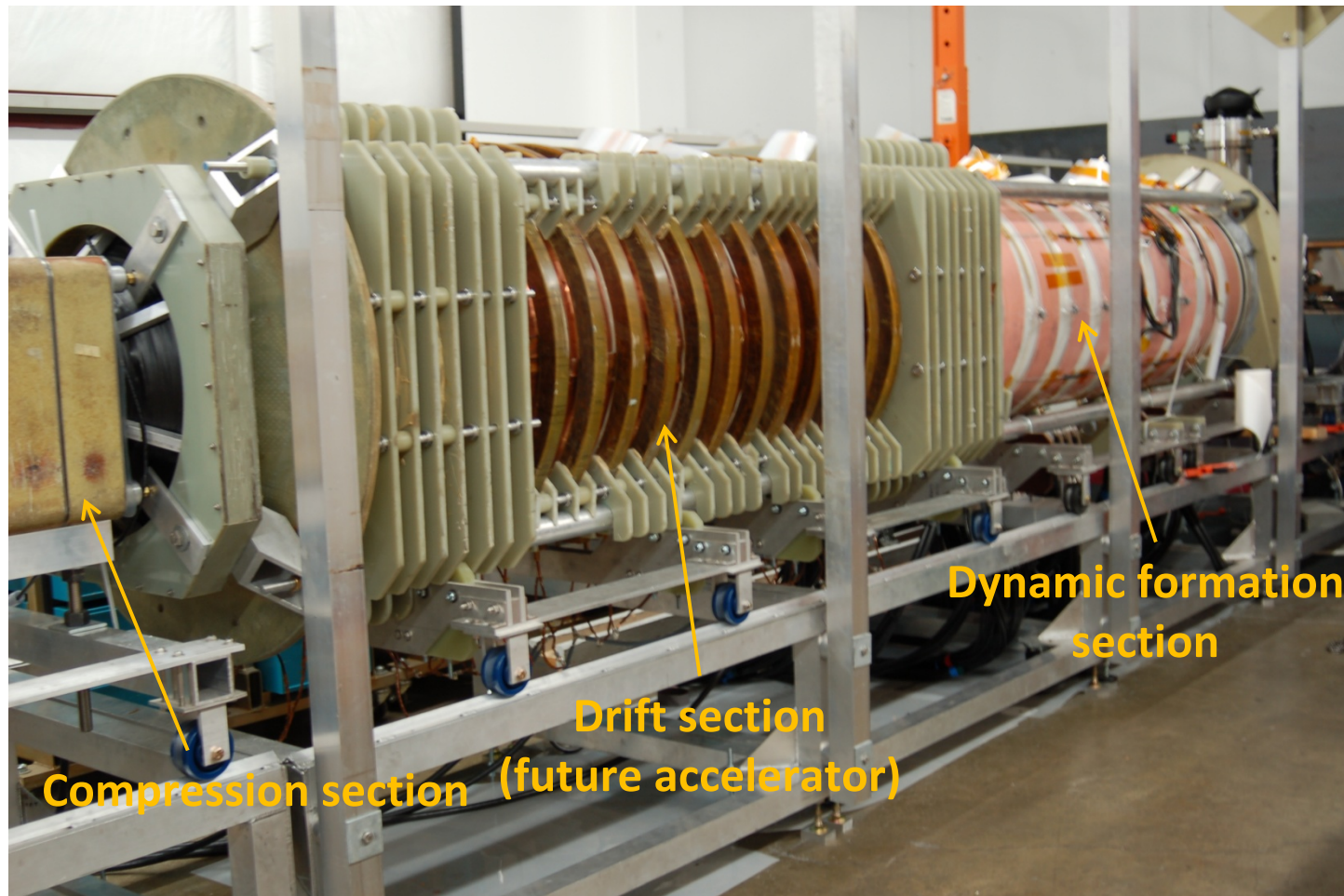
Rep Rated IPA at sufficient fluence for  $P_{\text{neut}}(\text{wall}) > 1 \text{ MW/m}^2$



Component Test Facility (2012) ~ \$30 M

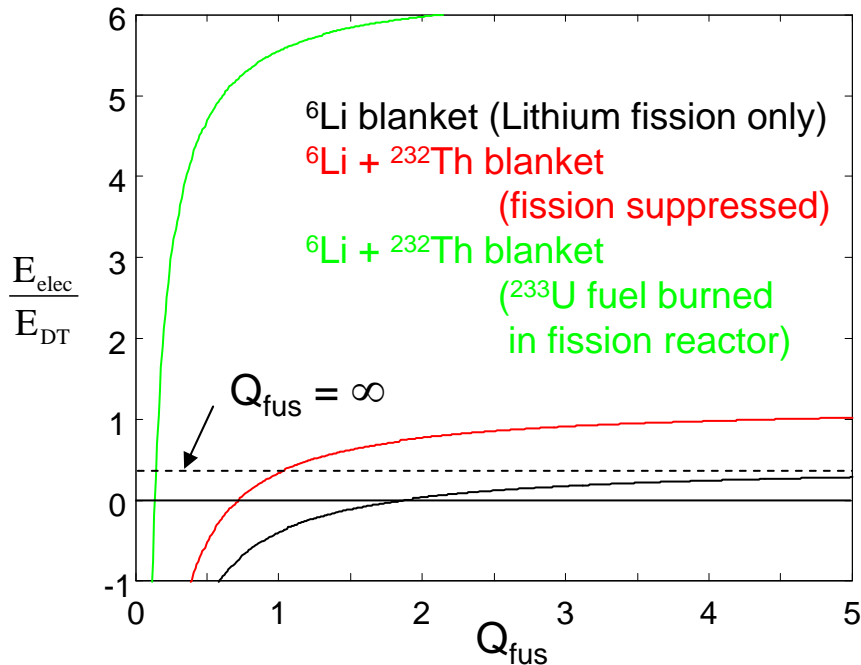


# UW Plasma Dynamics Laboratory



**FRC device at scale desired formation section for CTF has been Achieved on the PHD device at the University of Washington**

# Low Q More Than Sufficient for Fissile/Fusile Breeder Reactor



$$\frac{E_{elec}}{E_{DT}} = \frac{1}{\eta_{th} Q} (\eta_{th} + (1 + M_{bl}) \eta_{in} \eta_{th} Q - 1)$$

$E_{DT}$  - energy from fusion reaction  
 = **17.6 MeV**  $\times N_{DT}$

$\eta_{th}$  - therm. to elect. conv. eff. = **0.4**

$\eta_{in}$  - ion heating efficiency = **0.7**

$M_{bl}$  - effective blanket multiplication

= **0.14** [ ${}^6\text{Li} \Rightarrow 1.1 \text{ T} + 4.8 \text{ MeV}$ ]

= **2.0** [ ${}^6\text{Li}, {}^{232}\text{Th} \Rightarrow 1.1 \text{ T}, 1.3 {}^{233}\text{U} + 49 \text{ MeV}$ ]

= **5.0** [ ${}^{233}\text{U}, n \Rightarrow \text{FP}, 2.5 n + 198 \text{ MeV}$ ]

- Fusion electrical energy generation per fusion increases little beyond  $Q_{fus} \sim 5$  with high ion heating efficiency
- Blanket heating from fissile fuel production dominates electrical energy production for  $Q_{fus} > 1$
- Even for  $Q < 1$  additional energy generation from bred fissile fuel dwarfs energy production from  $Q = \infty$  fusion alone

# Summary

## The pulsed FRC based CTF:

- (1) Reduces by orders of magnitude the scale and complexity involved in a CTF based on a spallation source, ST or tokamak
- (2) Provides for a vastly lower cost, risk and a much shorter timescale for implementation
- (3) Can address both material exposure issues in blanket as well as diverters.
- (4) Can address crucial Tritium fueling concerns –  
**(I) Inventory, (II) Production, (III) Processing, and (IV) Recovery**

All are without resolution

All represent potential show-stoppers for DT fusion.

- (5) Can be further developed to contribute to energy production in the near term
  - (I) fissile/fusile breeder
  - (II) Waste transmutation/burner