Staged Magnetic Compression of FRC Targets to Fusion Conditions

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Helion Energy

Project Lead
20 Tesla ARPA-E Experiment
40 Tesla Reactor

MSNW

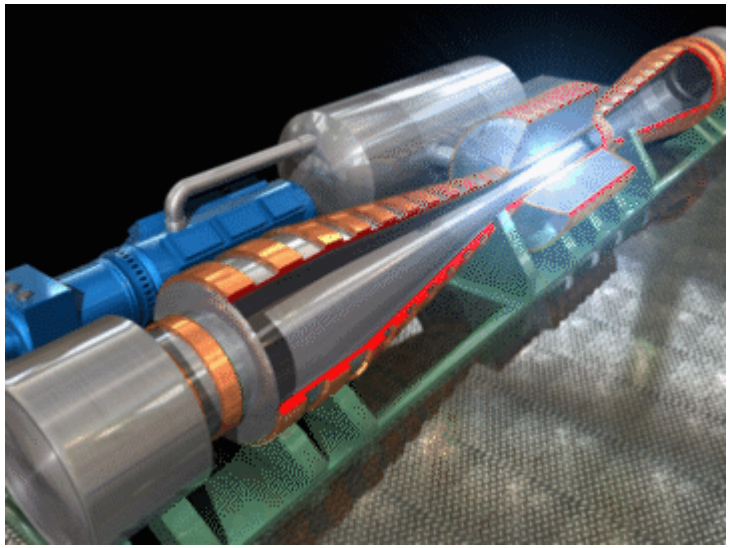
Existing Facilities and Expertise

Theory and Code Development
Implement MHD and Particle Codes

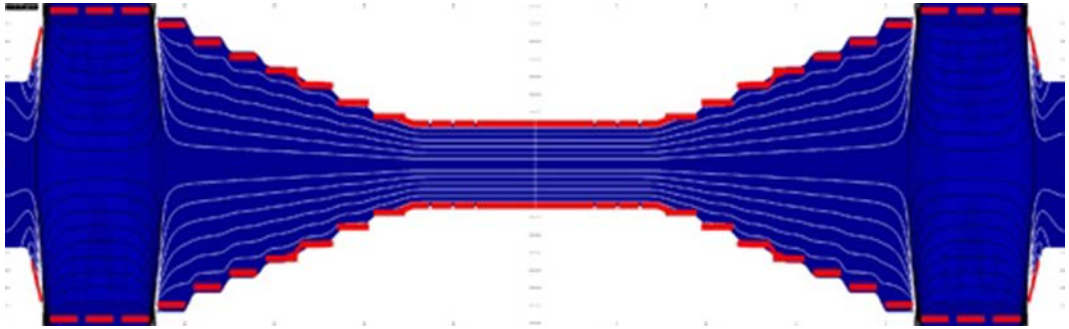
arpa·e MITHRIL CAPRICORN INVESTMENTGROUP

The Fusion Engine

1. **Formation** – Two FRC plasmoids are dynamically formed by sequential field reversal
2. **Acceleration** – FRC plasmoids are accelerated to high velocities (>300 km/s)
3. **Merging** –Two supersonic plasmoids collide and merge converting kinetic into ion thermal energy
4. **Compression** – FRC is magnetically compressed to fusion temperatures
5. **Energy Generation** – Spent plasma, fusion ions, and neutrons are converted to energy



Artist's animation of the FE



2D Magnetohydrodynamic simulation of the FE

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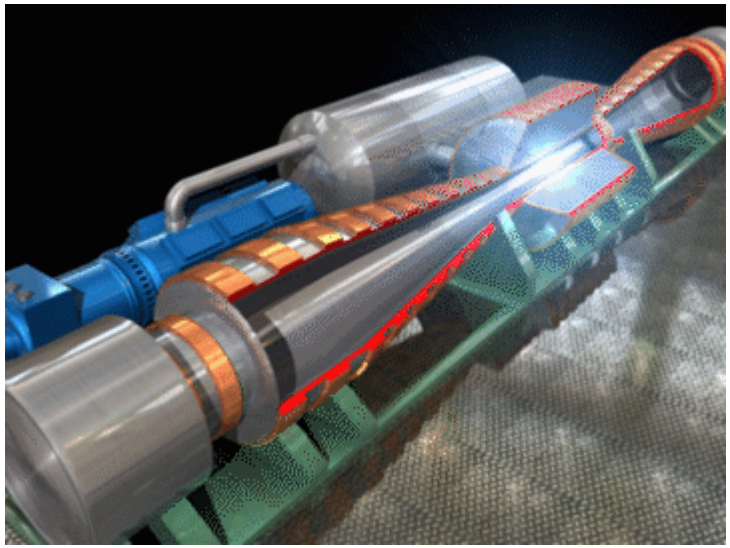

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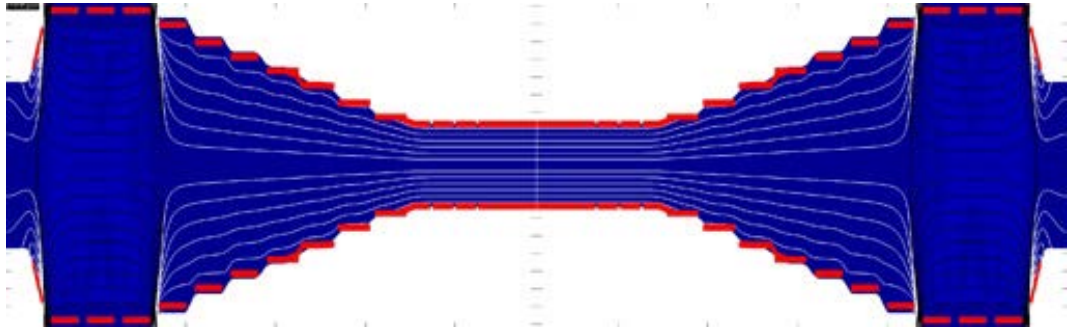

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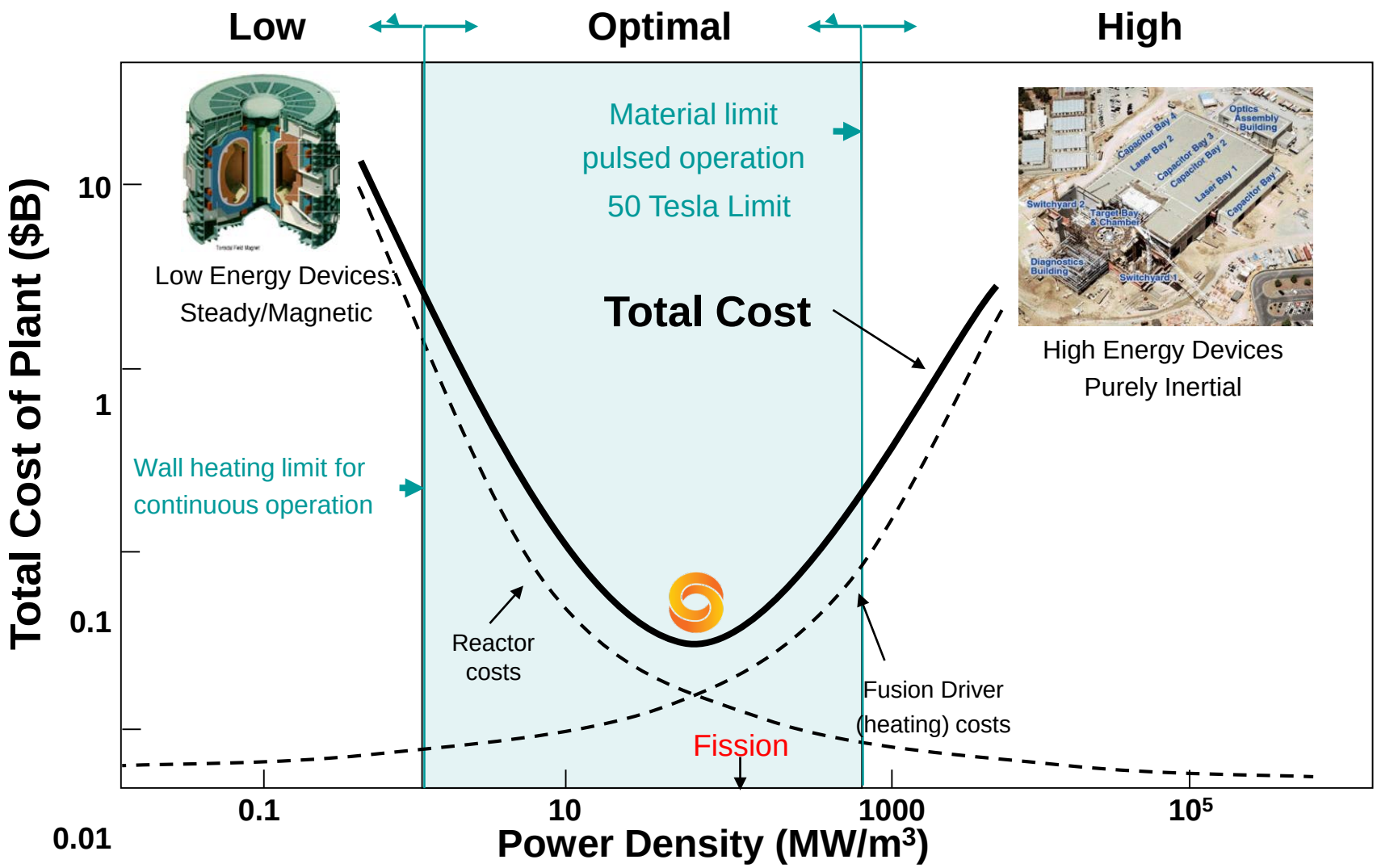
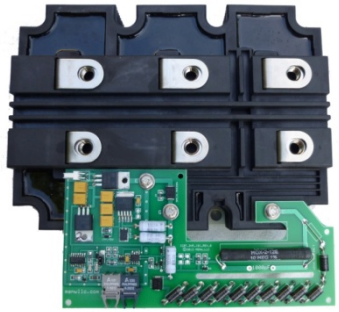
Energy Density

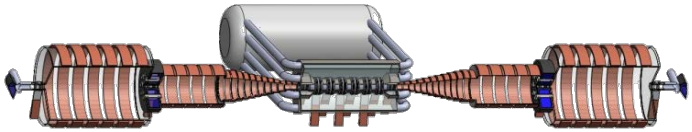


Key Approach

Developed to be economically competitive

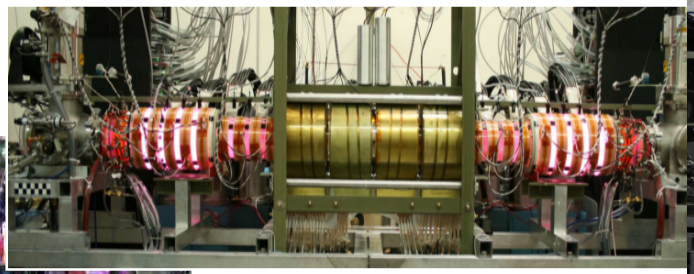
- 50 MW - rapid development, modular power markets
- Direct fusion particle energy to electricity- output efficiency
- Magnetic/Inductive compression – input efficiency and <$0.03/MJ



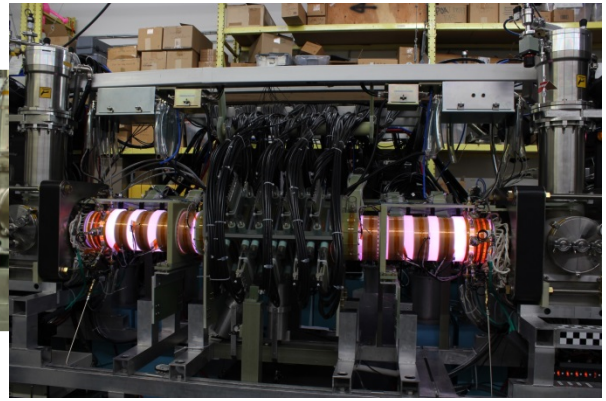


Technology Demonstrators

IPA



IPA-C



Grande

LSX, PhD – Full Scale & Stability	Millisecond lifetime
IPA – Merging	Merged FRC confinement
IPA-C – Heating and compression	1 keV D ions, neutrons
Grande – High field operation	5+ keV D ions, neutrons

Current Programs

VENTI	12 Tesla Compression
FEP	20 Tesla Compression
FEP-G	40 Tesla Reactor

Fusion Gain Scaling Based on Past FRC Confinement

$$E_{fus} \cong 1.2 \times 10^{-12}\, n^2 \langle \sigma v \rangle\, \tau_N\, Vol_{FRC}$$

Collision cross section:

$$\langle \sigma v \rangle \cong 4\text{x}10^{-33}\, T_i^{2.6}(\text{eV})$$

Empirical FRC confinement scaling

$$\tau_N = 3.2 \times 10^{-15}\, \varepsilon^{0.5}\, x_s^{0.8}\, r_s^{2.1}\, n^{0.6}$$

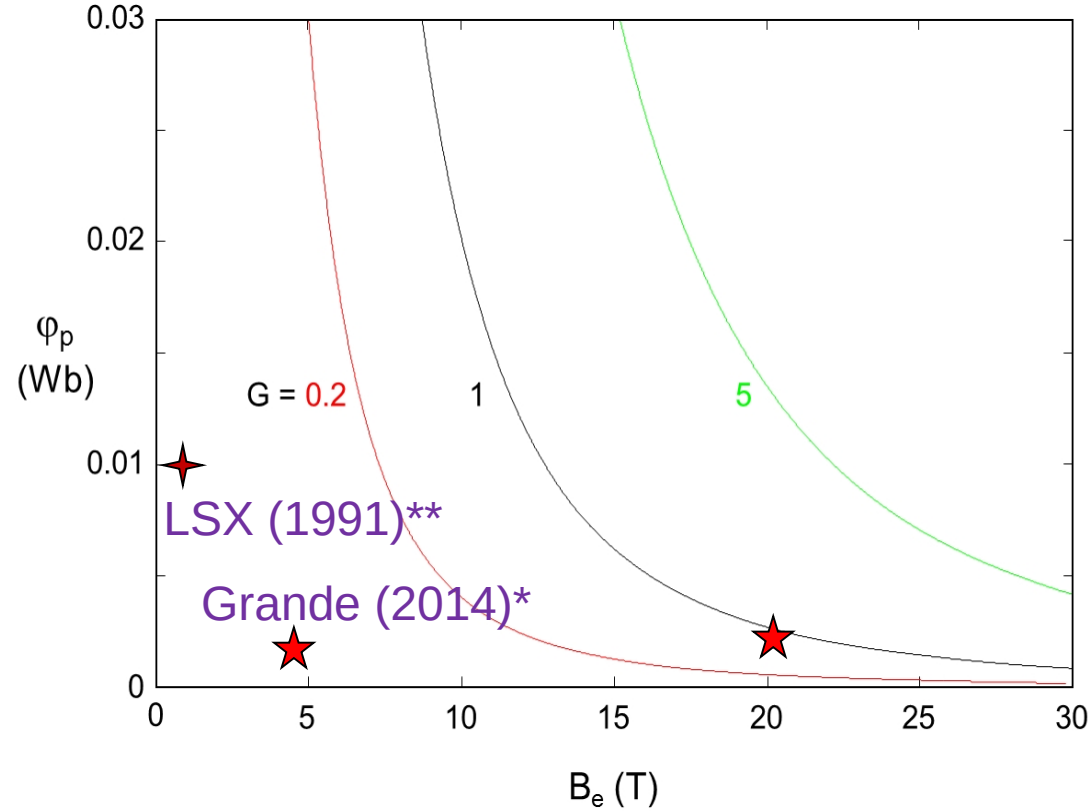
FRC energy:

$$E_{FRC} = \frac{3}{2} Nk(T_e + T_i) \cdot Vol_{FRC} \cong \frac{B_e^2}{2\mu_0} \pi r_s^2 l_s$$

FRC internal (poloidal) flux:

$$\varphi_p \cong \frac{r_s^3}{r_c} B_e \quad \Rightarrow \quad r_s = \left(\frac{r_c\, \varphi_p}{B_e} \right)^{1/3}$$

$$G = \frac{E_{fus}}{E_{FRC}} = 0.093\, B_e^{2.4}\, \varphi_p^{0.82}\, l_s^{0.5}$$



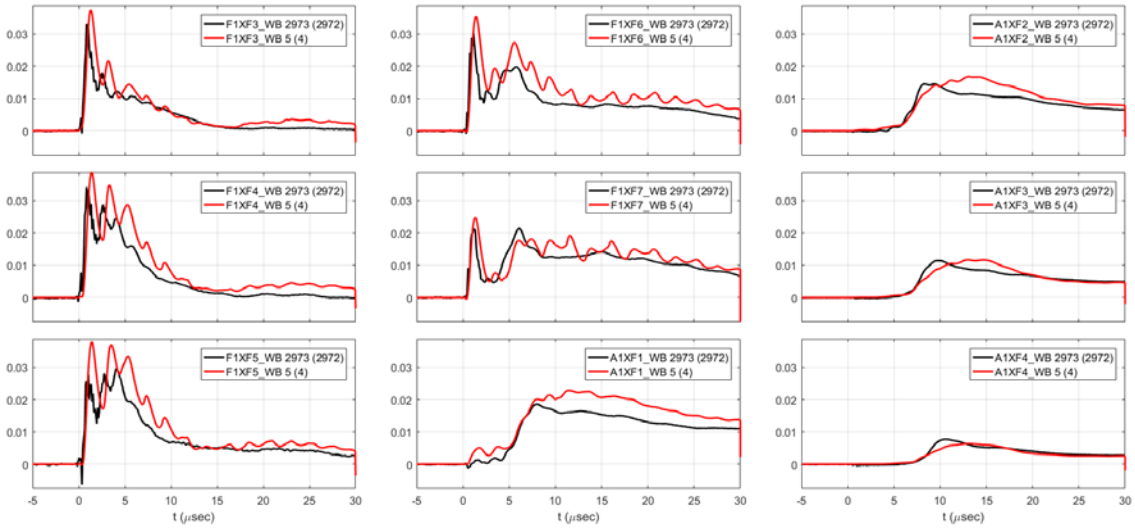
Gain contours as a function of the FRC poloidal flux and compression magnetic field.
(FRC length l_s = 1 m)

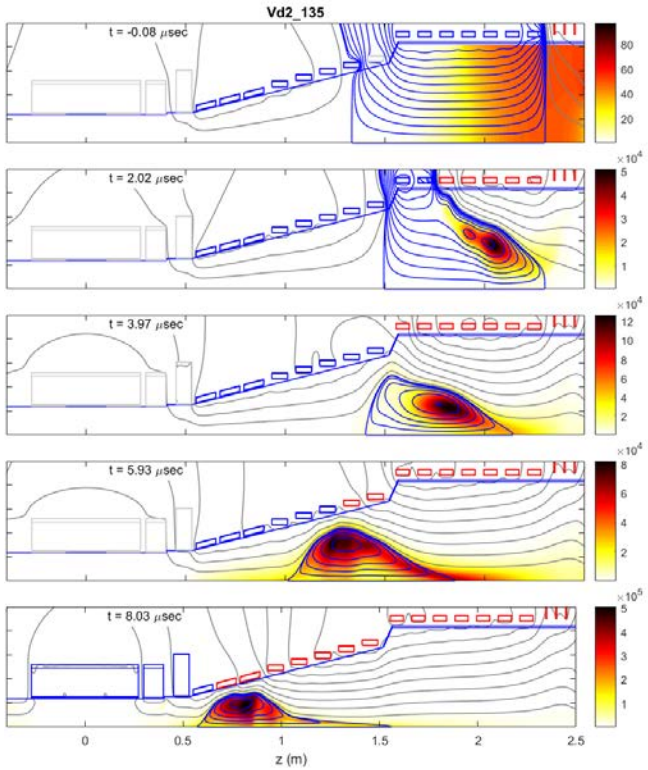
* T_i ~ 4 keV l_s ~ 0.4 m ** T_i ~ 0.3 keV, l_s = 3 m

Current Theoretical Efforts

Recent Progress with Cygnus FRC code

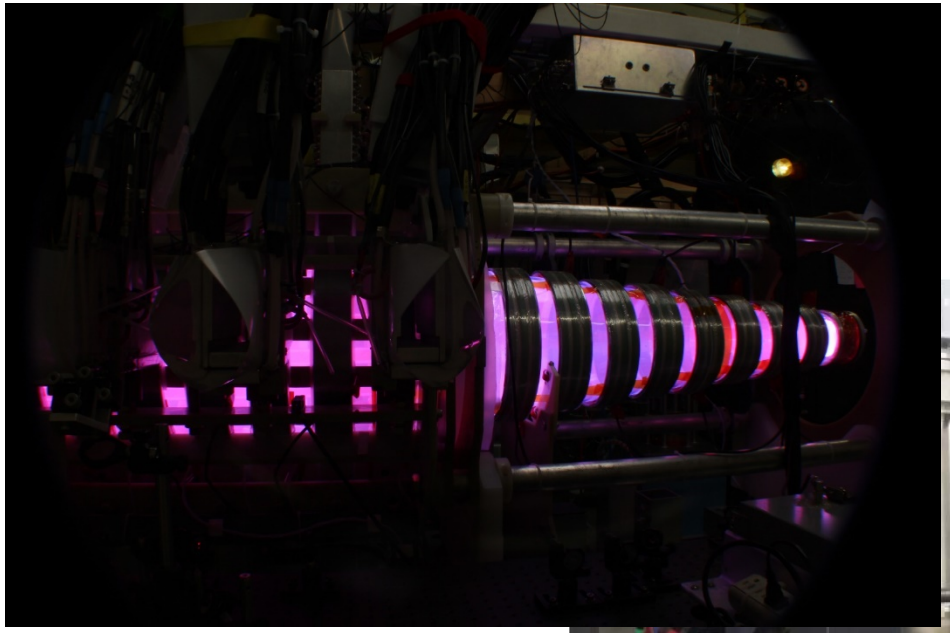
- **Successful Benchmarking with VENTI Experiment**
  - Vacuum shots compared with Venti data
  - Using Cygnus for circuit, timing, and operational design
  - PI shots compared with Venti-form data
  - FRC shots ongoing



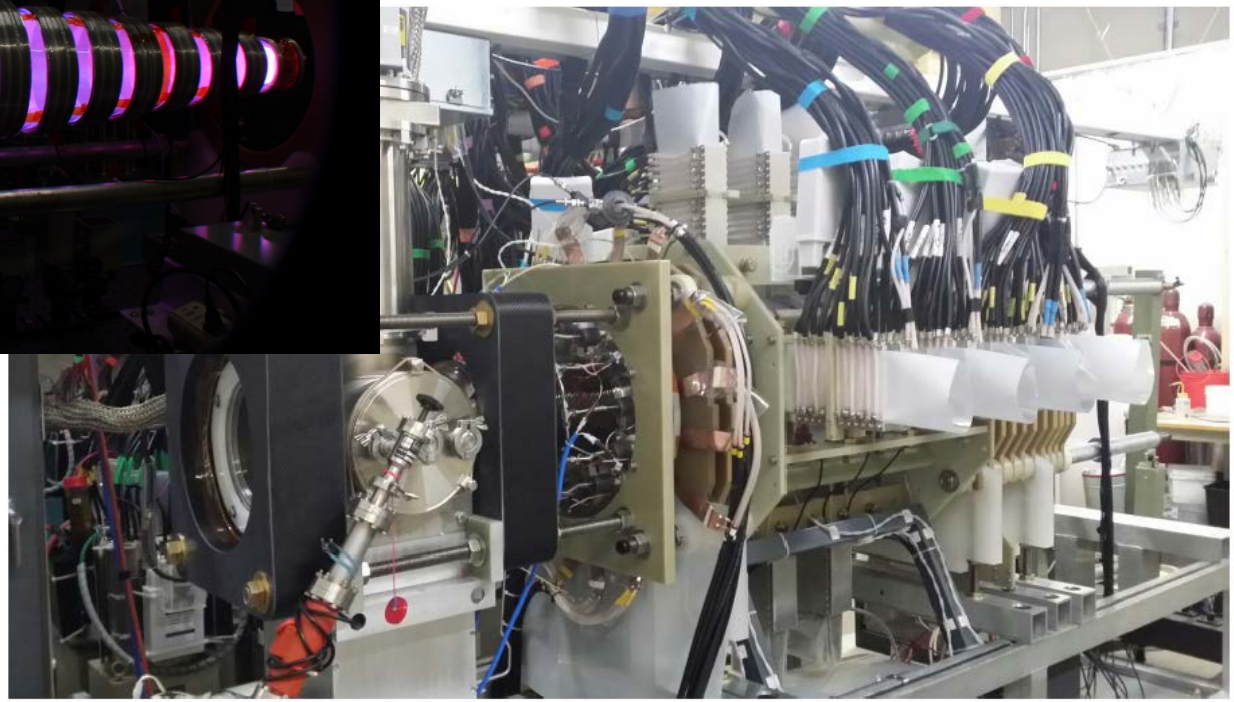


Current Experimental Effort

Operating Venti Formation Test Facility



- 5+ mWb FRC
- 1E21 m^{-3} density

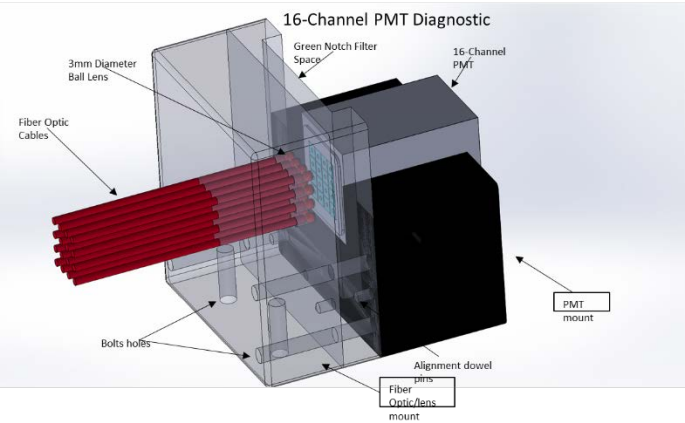


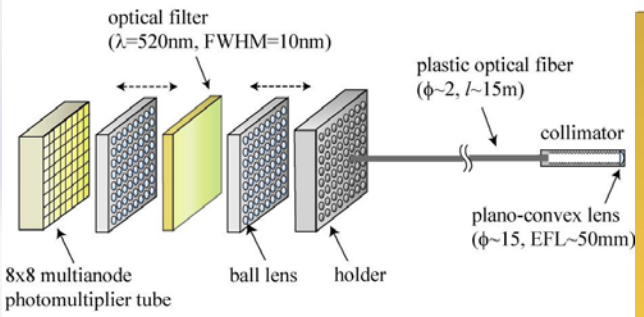
- 300+ eV formation
- 100's of shots

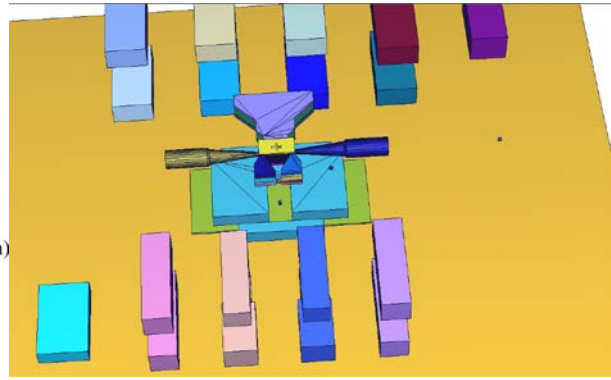
Current Experimental Effort

Diagnostic Packages

Quantity Measured	Diagnostics
1. FRC geometry, Confinement (t_j, t_N, t_E)	Compensated flux loop arrays, Gated pin-hole x-ray camera
2. FRC line density n(t), $T_{tot}(t)$	HeNe interferometer, 1.5 micron fiber interferometers
3. Radiated power (t), Impurities (t)	16 channel Bremsstrahlung tomography, several spectrometers
4. FRC velocity, Ion Temperature $T_i(z,t)$	16 ch Doppler spectrometer, Spatially resolved single time PI-MAX spectrometer.
5. Electron Temperature $T_e(t)$	Filtered soft x-ray detector array
6. FRC stability (tilt, interchange, Helmholtz)	External B loops with and end-on X-ray and visible imaging
7. Fusion power output $T_i(t)$, $P_{fus}(W)$	Yttrium yield detector, 4 fast scintillator neutron and gamma detectors, MCNP modeling







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Current Experimental Effort

Venti – 20 Tesla Compression

Goals

- Deuterium-Deuterium fusion
- 40 cm FRC formation and acceleration
- 20 Tesla peak compression
- 1E23 m^{-3} Deuterium compressed density
- 8+ keV compressed ion temperature

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Energy Generation from Fusion at a Fraction of the Cost and Time

Technology Summary

- Power density scales as $\beta^2 B^4$ - the Fusion Engine will operate at the highest β and steady B of all fusion plasmas
- Cylindrical geometry with external exhaust thereby solving blanket and divertor materials issues
- Staged compression and magnetic energy recovery assure high electrical efficiency and rapid pulse repetition rates

Technology Impact

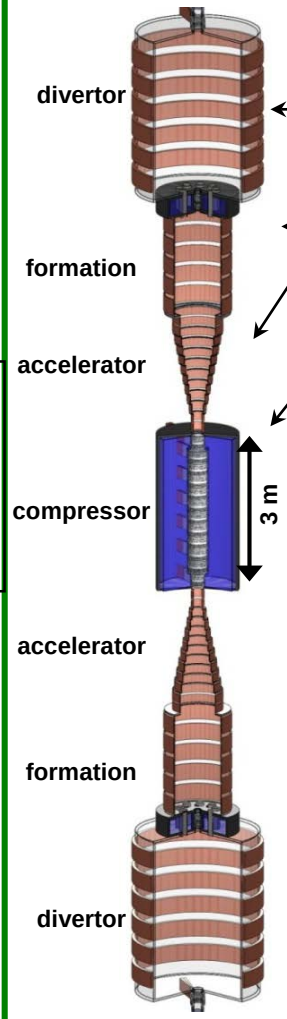
- Scale and complexity of fusion reactor greatly reduced
- Fusion Engine Prototype will demonstrate multi-keV ions, densities up to 10^{24} m^{-3}, with the potential for breakeven

Proposed Targets

Metric	State of the Art - NIF	Fusion Engine Prototype
Facility & Op. Cost ($)	> 5 Billion	0.01 Billion
Time to full power operation	15 yrs	2 yrs
η_d (=E_{plasma} /E_{spent}) · Gain *With mag. energy recovery η=0.7	5×10^{-5} ·1.5	0.2*·1.2
Rep Rate (shots/month)	20	2000

Fusion Engine

50 MW_e @ 2Hz

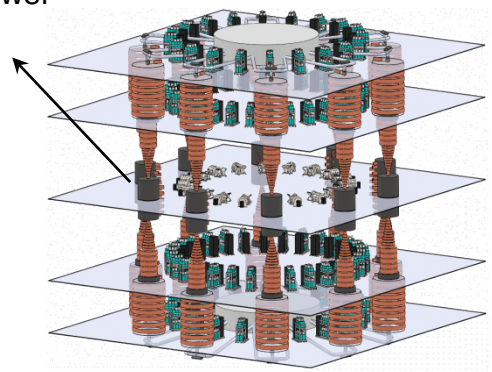


Large external divertor: mitigates power loading and provides for exhaust plasma energy recovery at high thermodynamic efficiency.

Magneto-kinetic accel/compression: direct, high efficiency ion heating to fusion temperature

Remote burn: ideal breeding geometry. Flowing heat exchanger solves Tritium breeding issues

Modular reactor design: lower cost, risk, greater availability, flexible siting, on-demand & base load power



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