Magneto-Inertial Fusion
(Magnetized Target Fusion)

or "why should we bother with another ICF driver/target scheme?"

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National Academy of Science IFE Review Panel
Albuquerque

March 31, 2011

LA-UR-11-01898

Magneto-inertial fusion:

A hybrid approach to fusion….ICF with a twist….magnetic fields

- May allow more efficient drivers, lower cost drivers, lower peak powers, lower implosion velocities, smaller convergence ratios, larger yields, slower repetition rates, easier targeting, the use of non-cryogenic targets, reduced materials problems (if thick liquid walls), and a wider operating space.

- Not without introducing some issues of its own,…
  adding a magnetic field, forming a plasma, and making stand-off connections…
  …but sometimes having a different set of problems can be a good thing.

In this Talk:

•Adding magnetic fields to conventional ICF can boost performance (LLE, Omega)

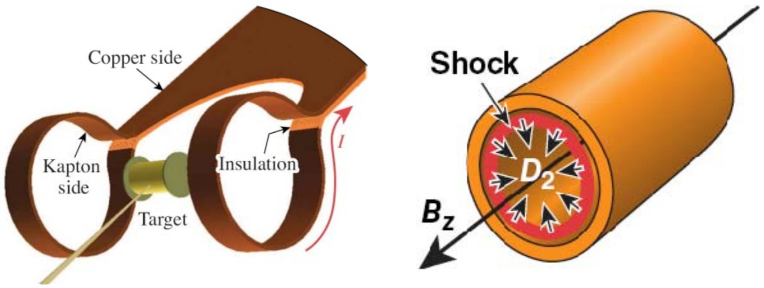
•Magnetized Target Fusion (MTF) demonstration, FRCHX at AFRL in Albuquerque

•Plasma Liner Experiment (PLX) under construction at LANL (an idea with stand-off)

•Some MIF-IFE reactor considerations

A Wide Range of Driver/Target Combinations are possible

U. Rochester LLE



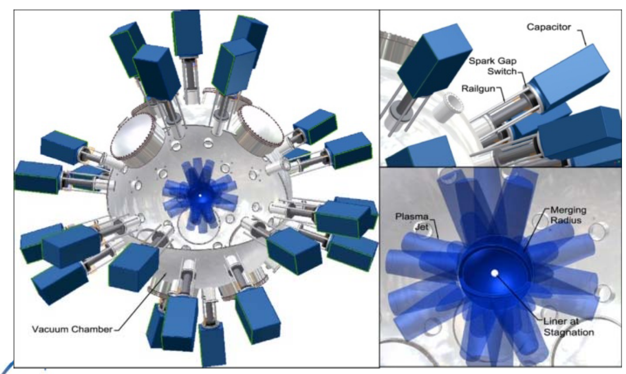
Direct drive laser implosion of cylinders
-- shock pre-heating, high implosion velocity

Gotchev *et al.*, *Rev. Sci. Instr.* 80, 043504 (2009)

Los Alamos / HyperV

Plasma Liner Experiment

Merging plasma jets for remote standoff



A. G. Lynn, et al, *Rev. Sci. Instr.* 81, 10E115 (2010)

Los Alamos / AFRL

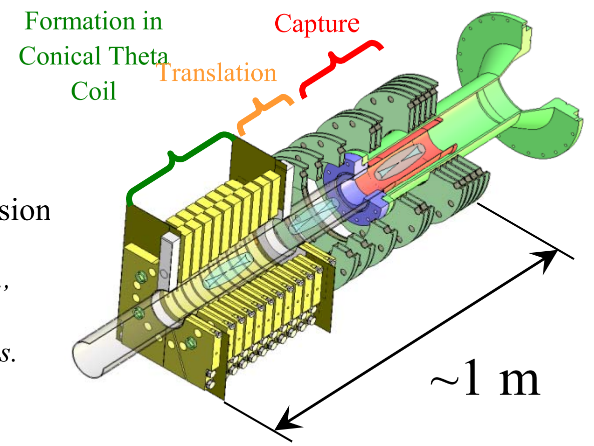
Field Reversed Configuration

Shiva Star FRCHX

~20 μs, 0.5 cm/μs liner implosion

Taccetti, Intrator, Wurden *et al.*, *Rev. Sci, Instr.* 74, 4314 (2003)

Degnan *et al.*, *IEEE Trans. Plas. Sci.* 36, 80 (2008)

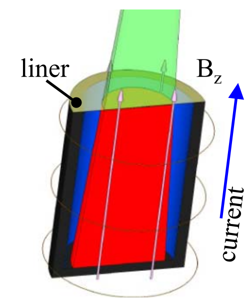


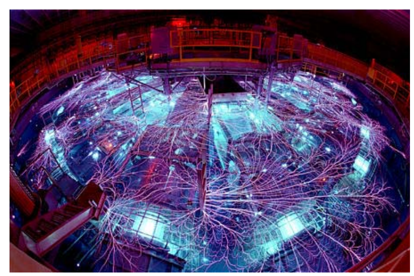
Sandia National Laboratories

Magnetized Liner Inertial Fusion

Laser preheated magnetized fuel

LASNEX simulations indicate interesting yields

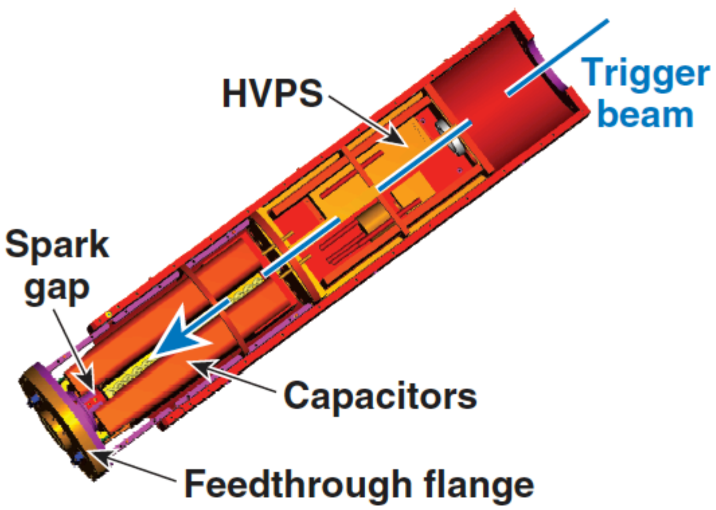




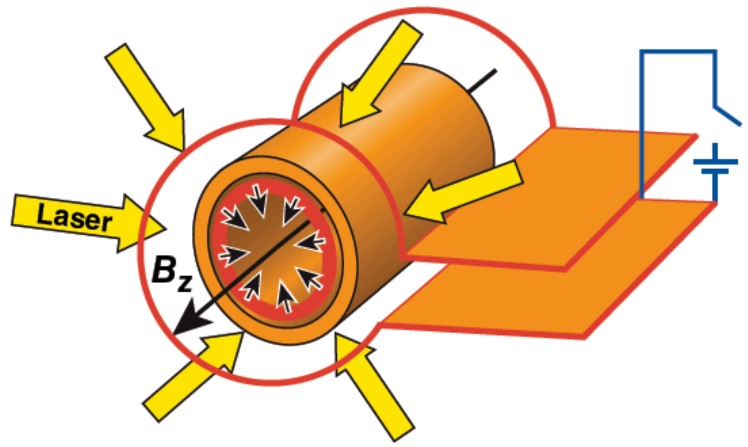
S. A. Slutz, et al., Phys. Plasmas 17, 056303 (2010)

Magnetic flux compression and fusion enhancement in magnetized implosions

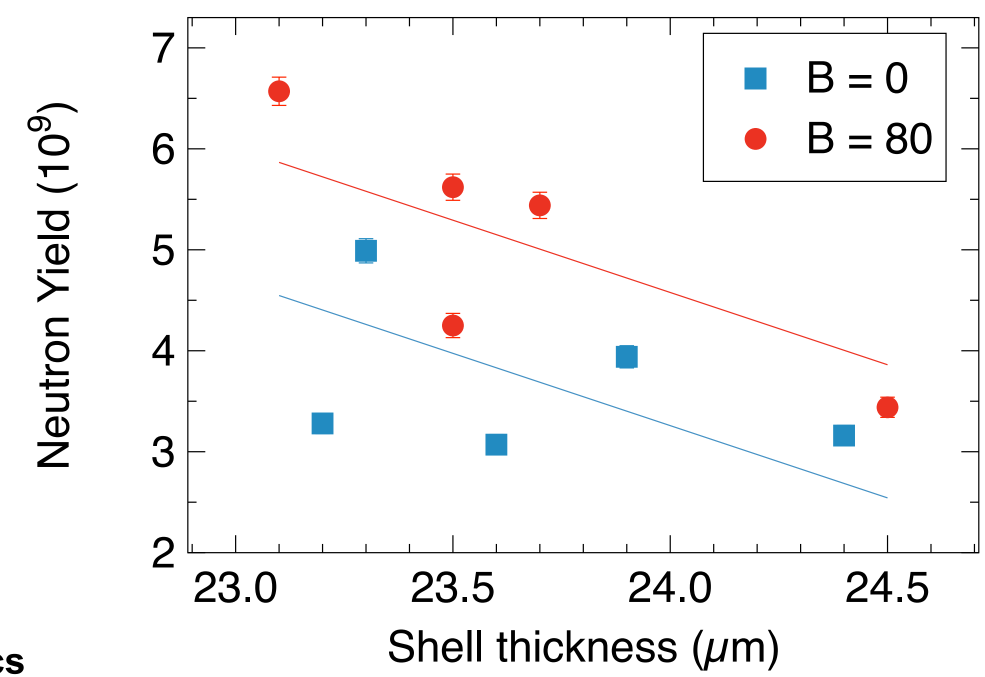
2006
MIFEDS
tested



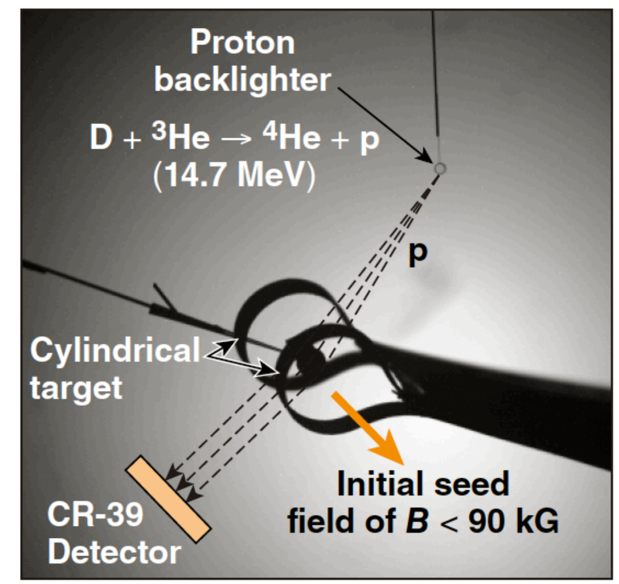
2007
cylindrical compression
first experiments



2010-2011
spherical implosions
fusion enhancement



2008-2009
cylindrical implosions
B-field compression



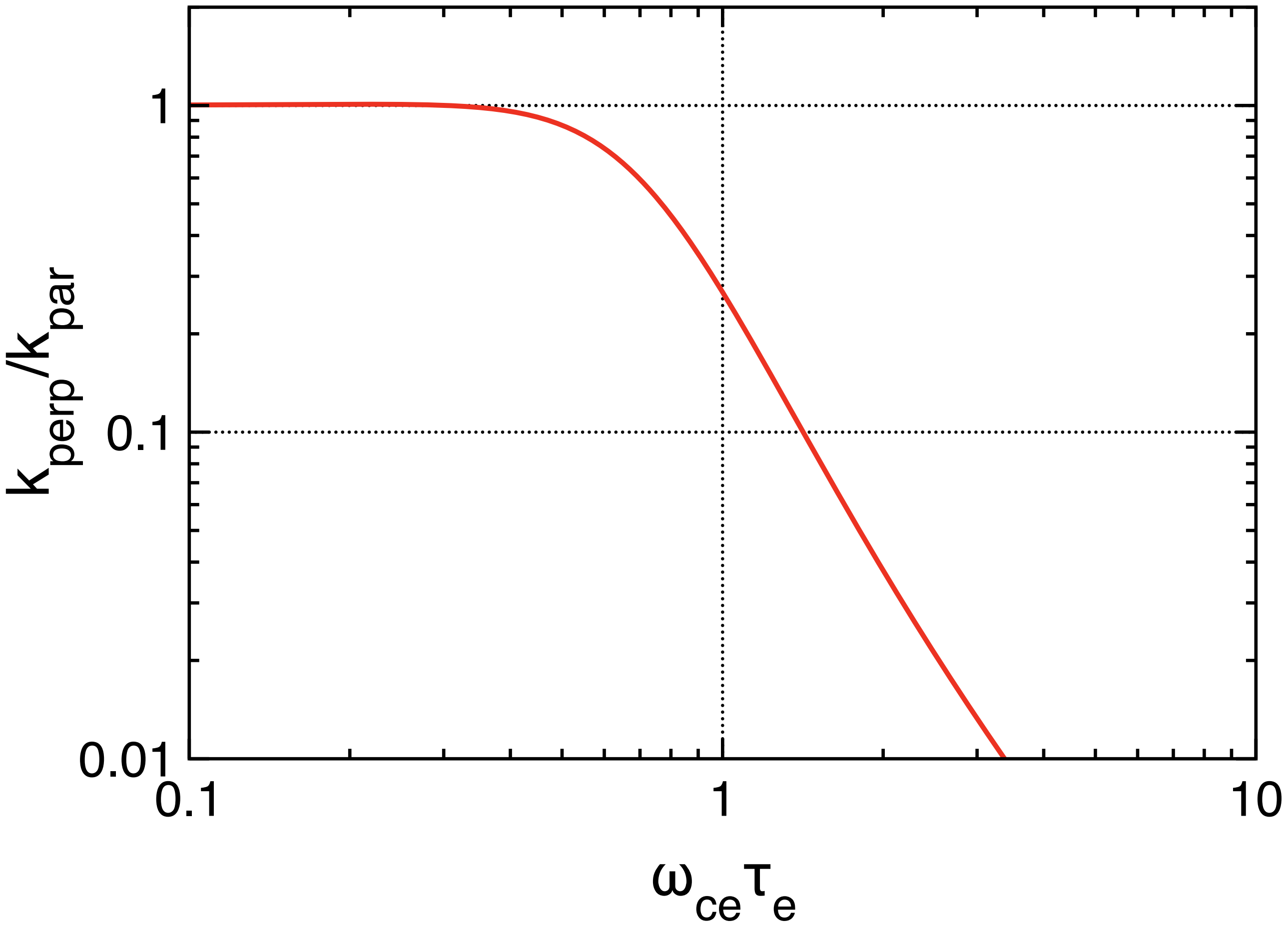
G. Fiksel
University of Rochester
Laboratory for Laser Energetics

Magnetization of plasma electrons inhibits the conduction heat transport

- Particle and energy confinement by magnetic field is the central concept of MCF - tokamaks, stellarators, RFP, etc
- ICF plasma pressure is too high ($\beta = 2\mu_0 P/B^2 >>1$) so the plasma dynamics and particle confinement are only weakly affected by magnetic field
- However, the heat conduction losses can be reduced and the temperature increased
- If B is high enough so $\rho_{L\alpha} < r_{hs}$ alphas can be confined as well

Need 10s of megagauss to magnetize electrons

Reduction of perpendicular thermal conductivity vs magnetization $\omega_{ce}\tau_e$

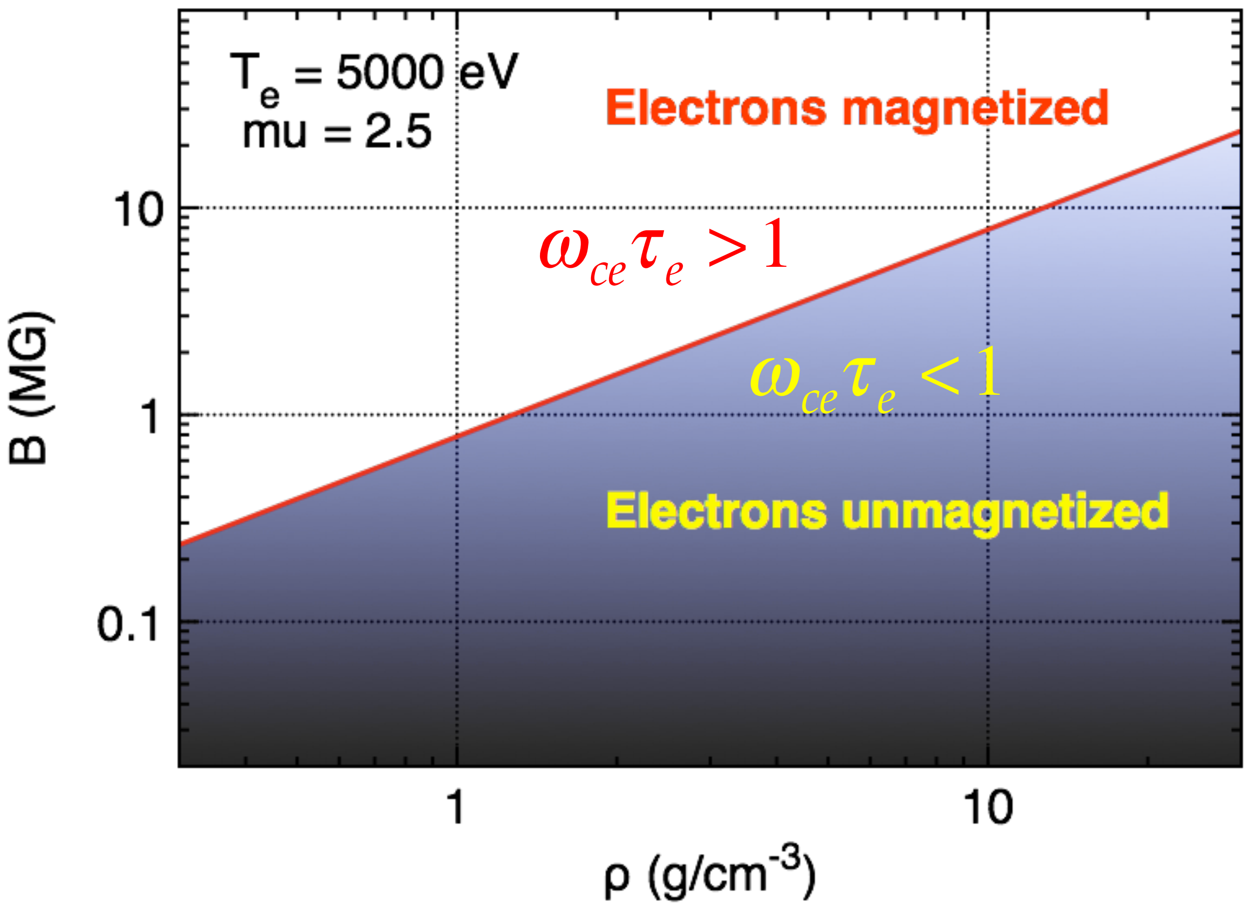


ω_{ce} **- electron cyclotron frequency**

τ_e **- electron collision time**

Need 10s of MG to magnetize electrons

Need 100s of MG to confine alphas



High B can be created by compression of a seed field

Compression must be faster than magnetic diffusion

$$\tau_{comp} = R / V_i$$

$$\tau_{diff} = R^2 / D_m = \mu_0 R^2 / \eta$$

$$\tau_{diff} / \tau_{comp} \equiv R_m \gg 1$$ **magnetic Reynolds number**

If compression is fast enough → **magnetic flux is conserved**

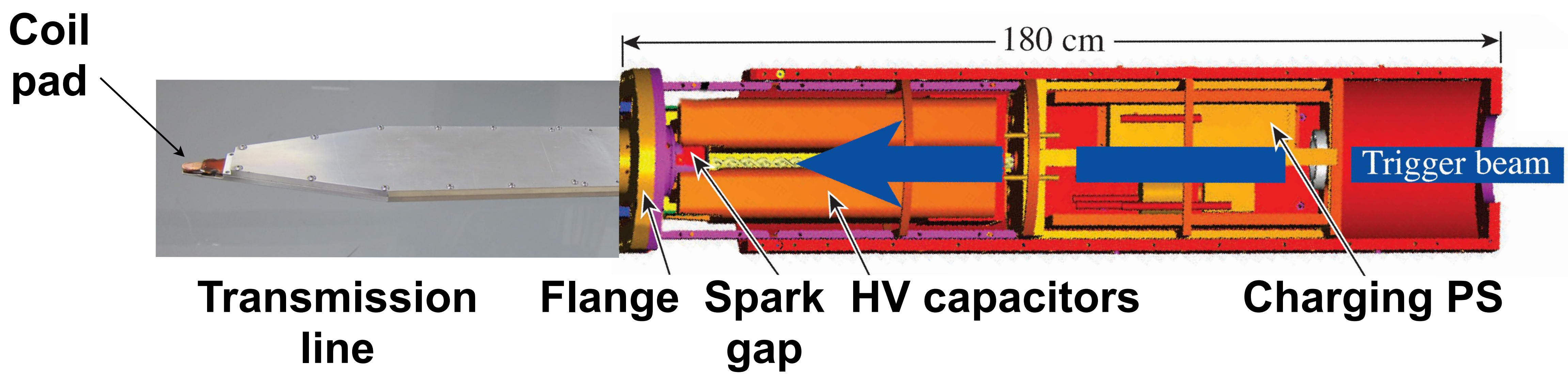
$$V_i(\text{cm/s}) >> \frac{D_m}{R} = 6 \times 10^5 \left(\frac{100}{T_e} \right)^{3/2} \frac{100}{R(\mu\text{m})} \frac{\ln \Lambda}{7}$$

$$B_0 r_0^2 = B r^2$$

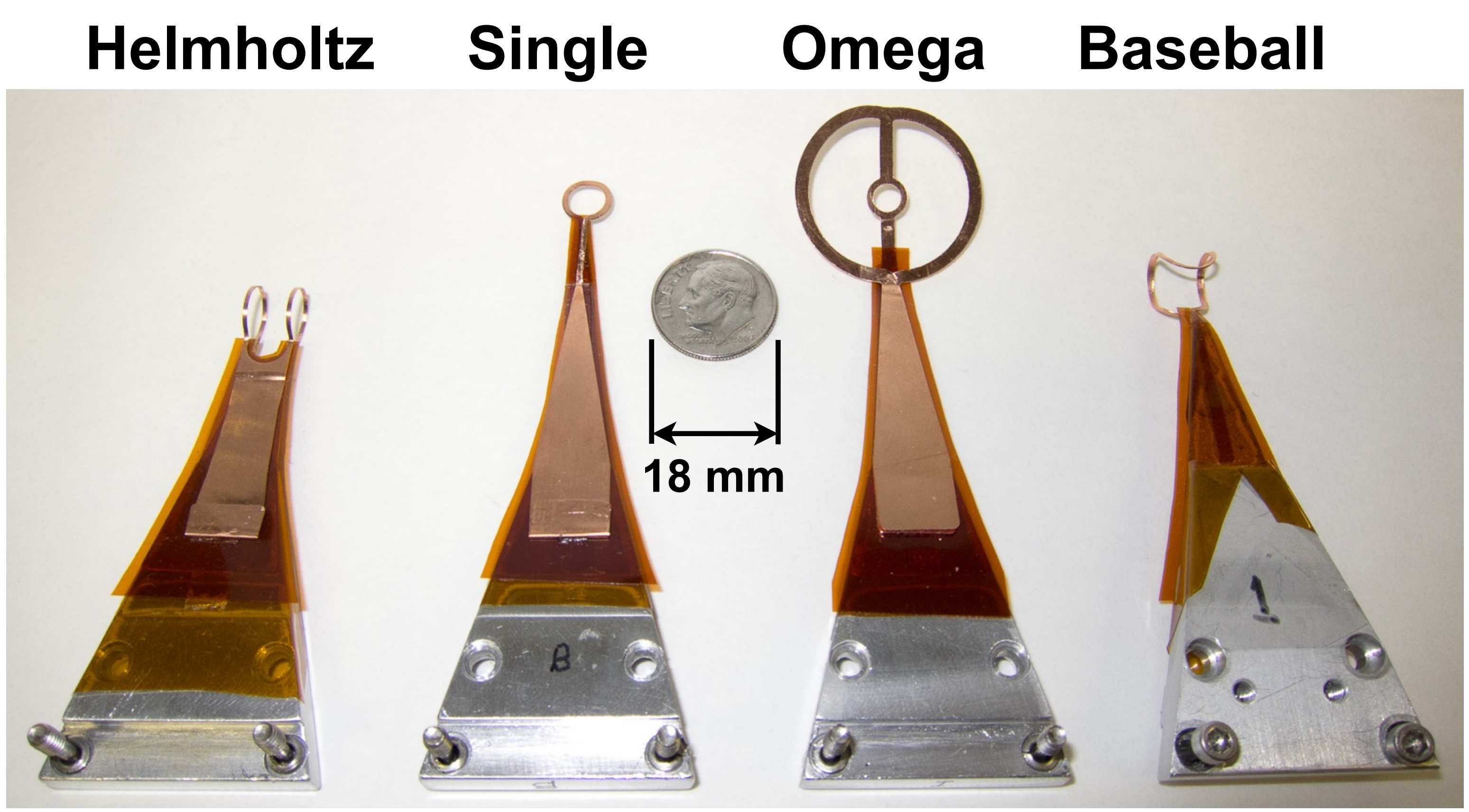
Field is amplified as the (target convergence)²

$$B = B_0 \left(r_0 / r \right)^2$$

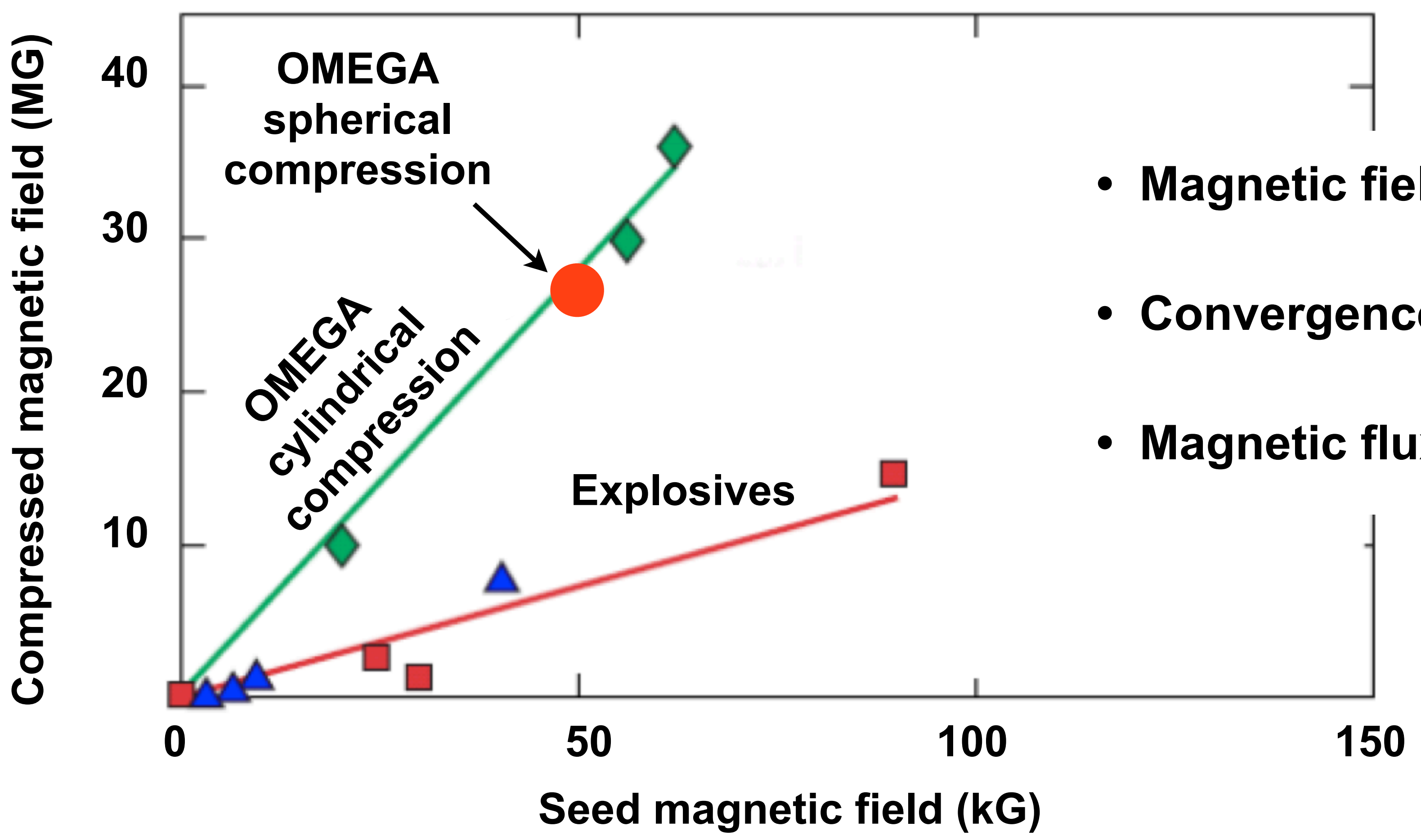
MIFEDS - Magneto-Inertial Fusion Electrical Discharge System was designed to create strong seed field



- Various coils were tested
- Seed fields up to 150 kG can be obtained (depends on the coil geometry)



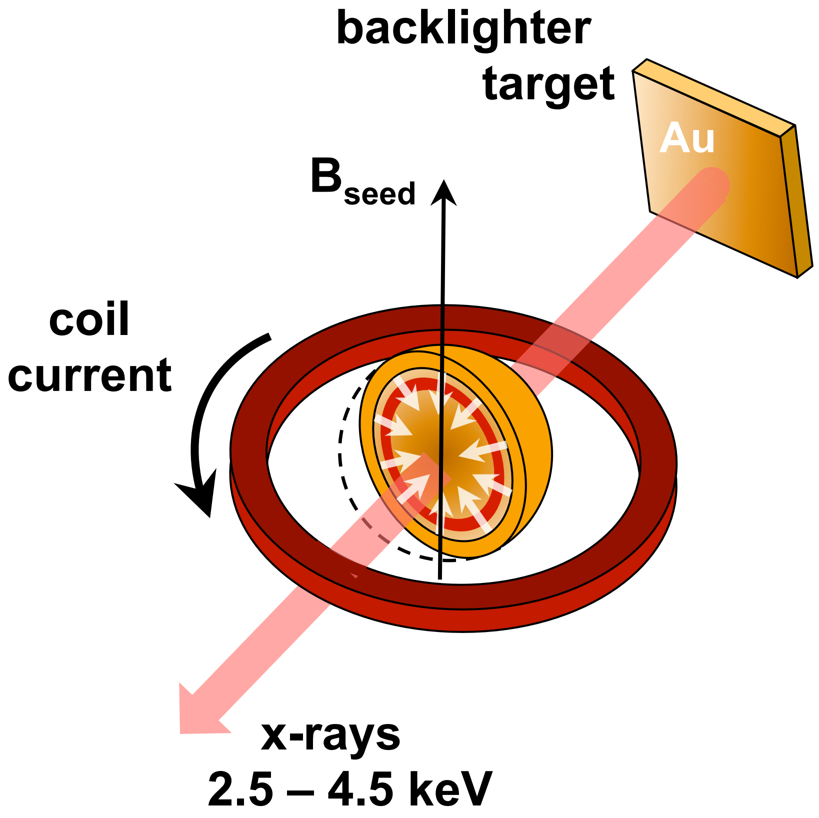
Field compression ~ 500 agrees with flux conservation



- Magnetic field compression ~ 500
- Convergence^2 ~ 500
- Magnetic flux is conserved!

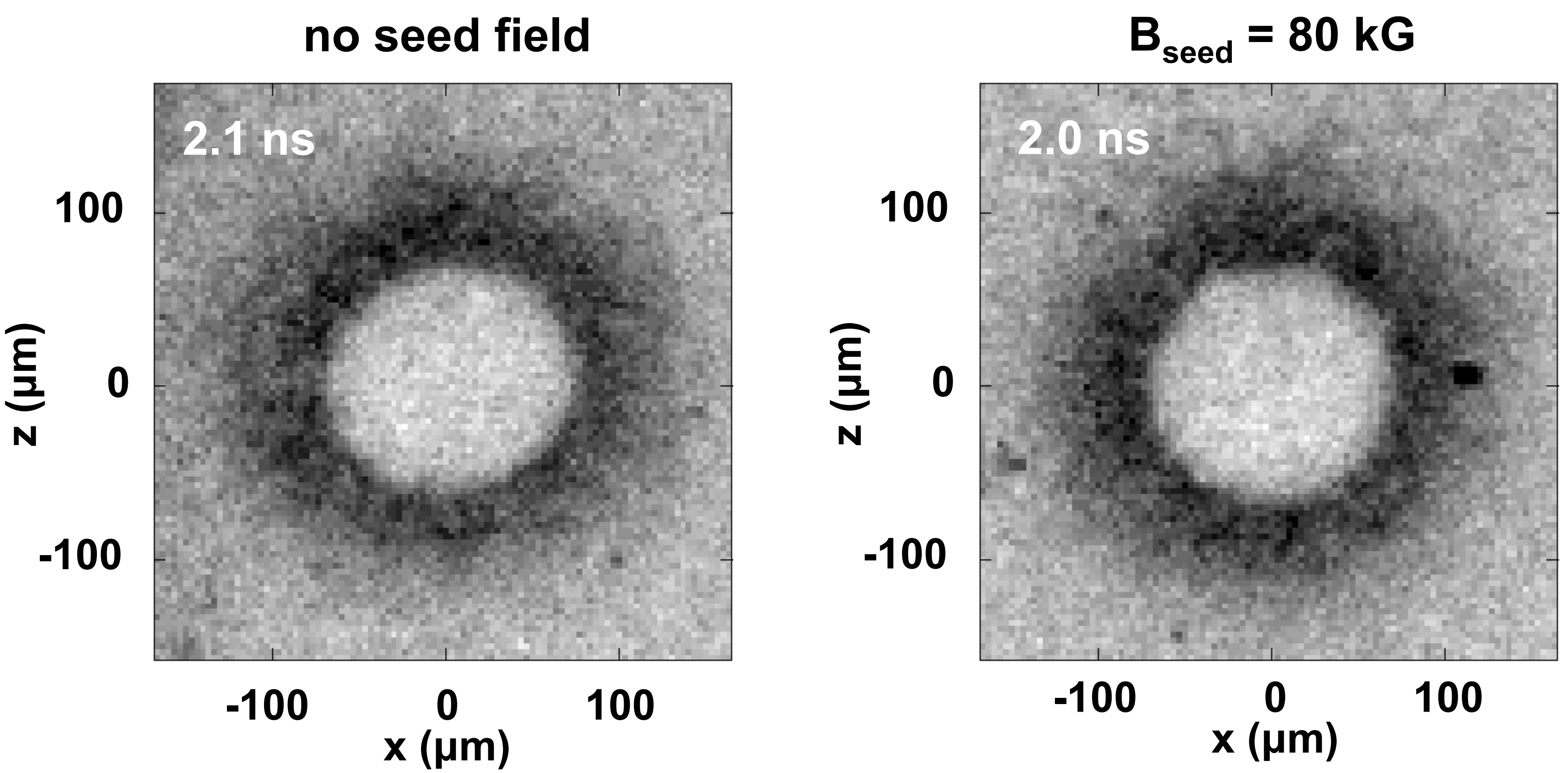
Fusion enhancement in spherical implosions was measured in PDD laser geometry

- Single-coil provides stronger seed-fields, less interference with laser paths
- 40 beams were used in a polar-direct-drive setup*
- Implosion uniformity is diagnosed using x-ray BL radiography
- nTOF was used for Ti and neutron yield

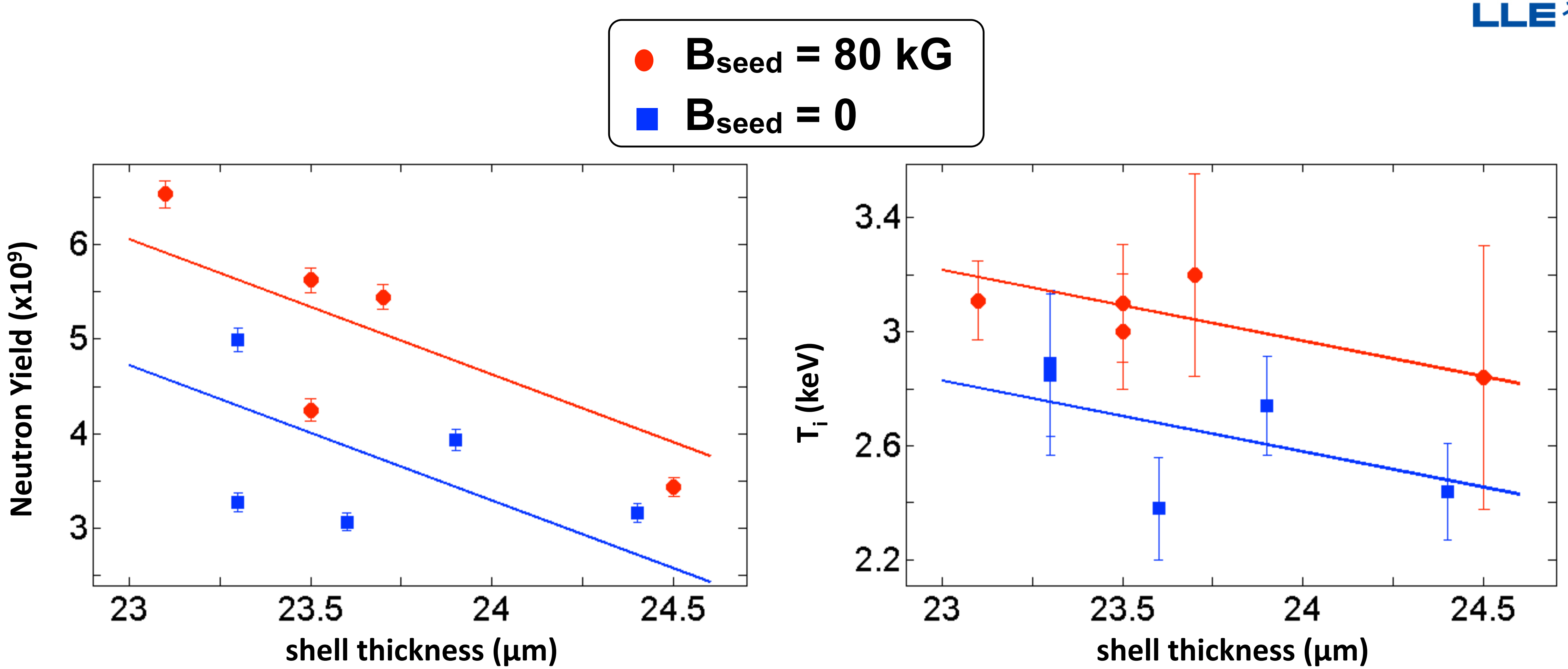


*F. J. Marshall *et al.*, Phys. Rev. Lett. **102**, 185004 (2009)

X-ray backlighter data shows good uniformity with and without an applied magnetic field



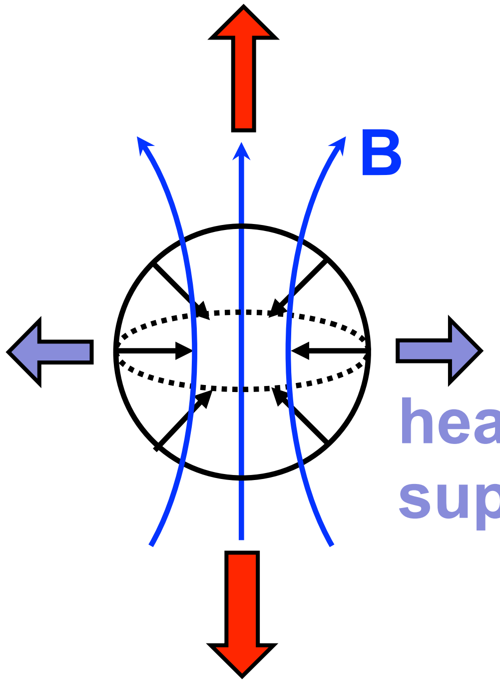
We observe a 15% ion temperature increase and 30% fusion yield enhancement for magnetized targets



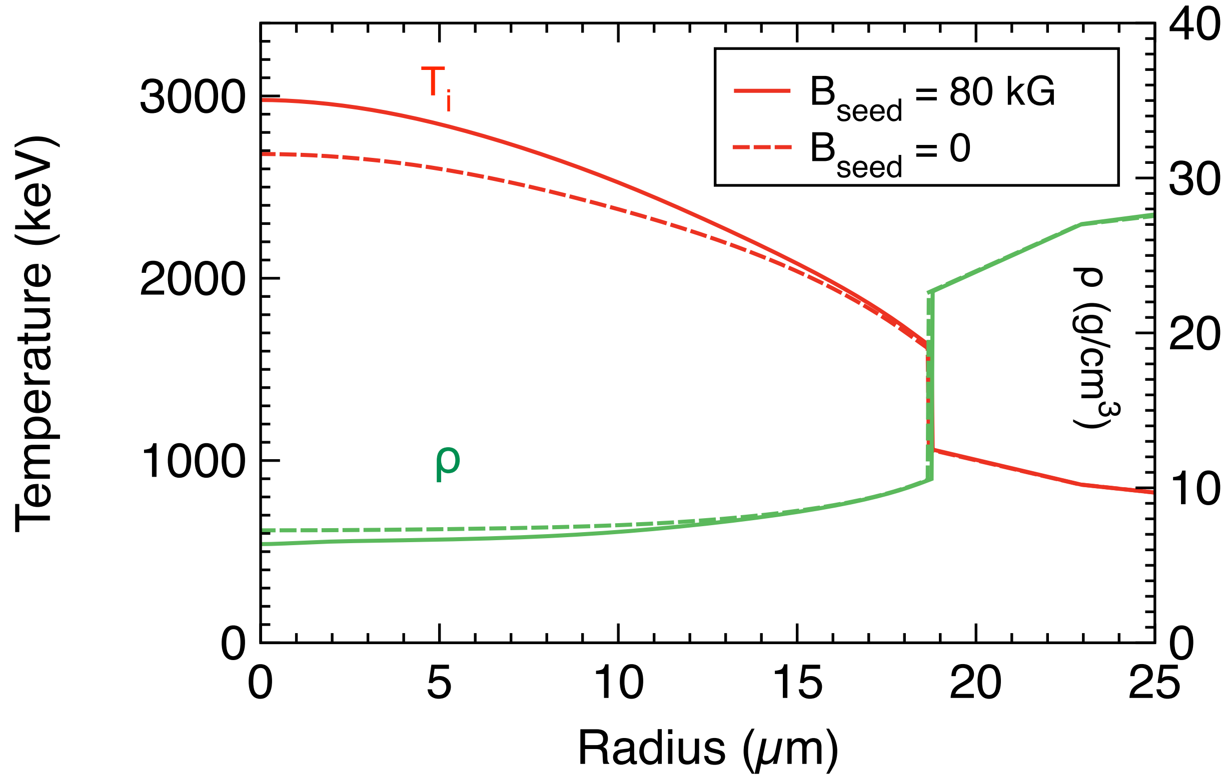
- Fusion performance scales with shell thickness*
- Linear regression fit reveals clear enhancement of magnetized hot spot performance

*F. J. Marshall *et al.*, Phys. Plasmas **7**, 1006 (2000)

The enhancement is small because the magnetic lines are open



Lilac-MHD simulation



- Ratio of open field lines to target surface area = 1/2
- 1D Lilac-MHD is used to simulate equatorial plane of a spherical implosion
- Heat conductivities calculated based on Braginskii coefficients
- Simulations result in 8% increase in T_i and 15% increase in yield

The FRCHX Team (Albuquerque Meeting, Feb 4, 2011)

C. Grabowski, J. H. Degnan, D. J. Amdahl, R. Delaney, M. Domonkos, F. M. Lehr, P. R. Robinson, E. L. Ruden, W. White, H. Wood

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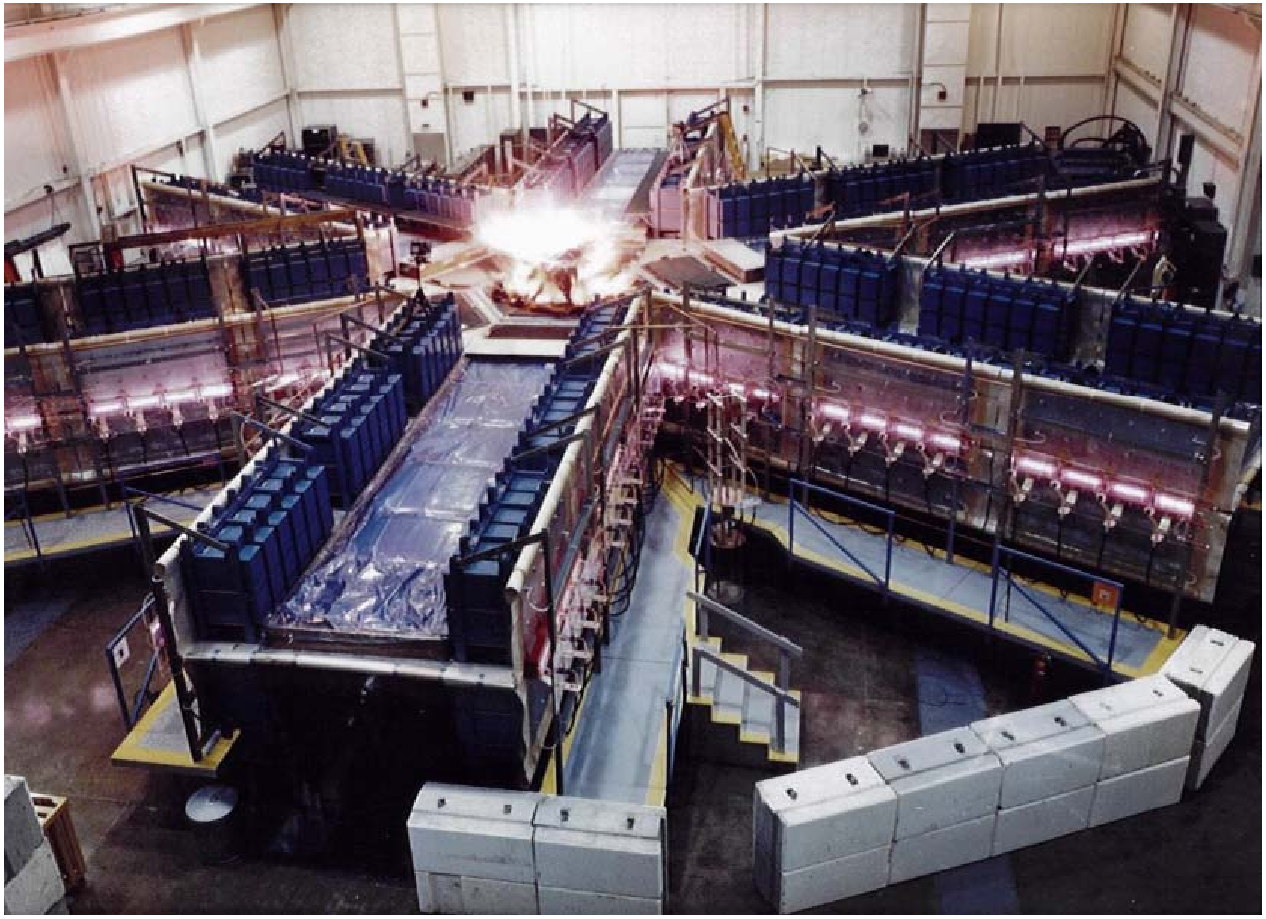
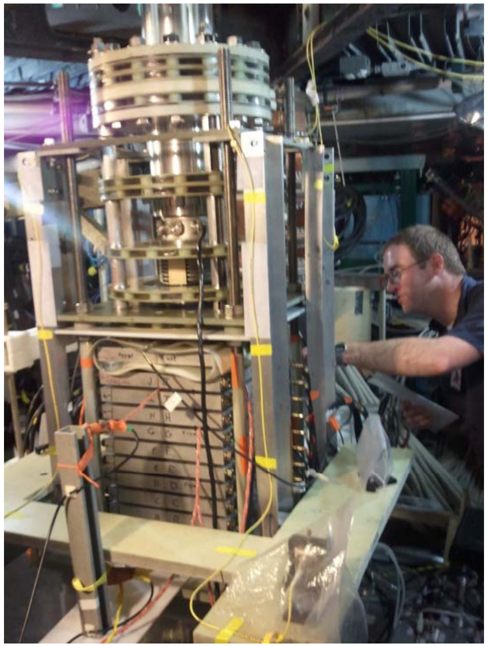
A. G. Lynn, N. F. Roderick, and students University of New Mexico, Albuquerque, NM 87131, USA

Shiva Star is an Air Force pulsed power facility

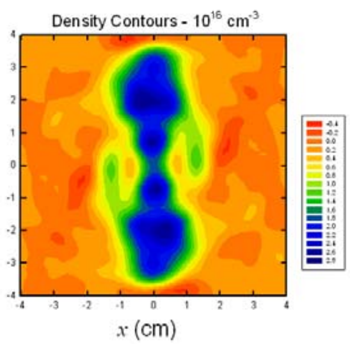


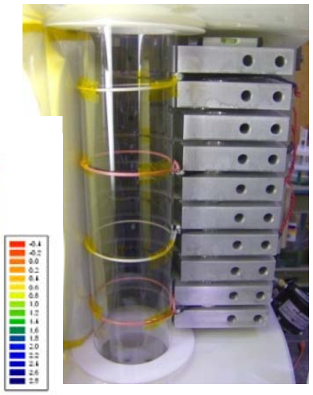


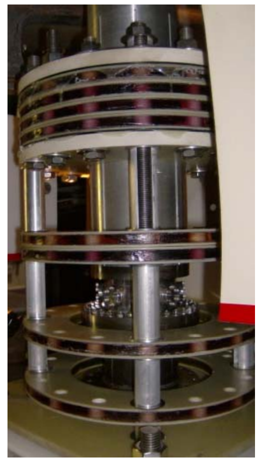
Shiva Star can store 9 MJ of energy with 1.3 mF of capacitors, at up to 120kV. More typically, at 4.5 MJ, it delivers 12 MA of current to crush a 30-cm tall, 10 cm diameter, 1 mm thick, 300 gm Aluminum cylindrical liner load in FRCHX, which is located under the center of Shiva Star.

Overview of FRCHX

* Grabowski, Degnan, et al., APS-DPP 2010 posters







Integrated Technologies

- FRC formation, translation, and capture
- Solid liner implosions
- MHD modeling in concert with electromagnetics modeling yields end-to-end simulation with high correlation to experimental hardware
- Pulsed power, plasma, and neutron generation diagnostics

Description

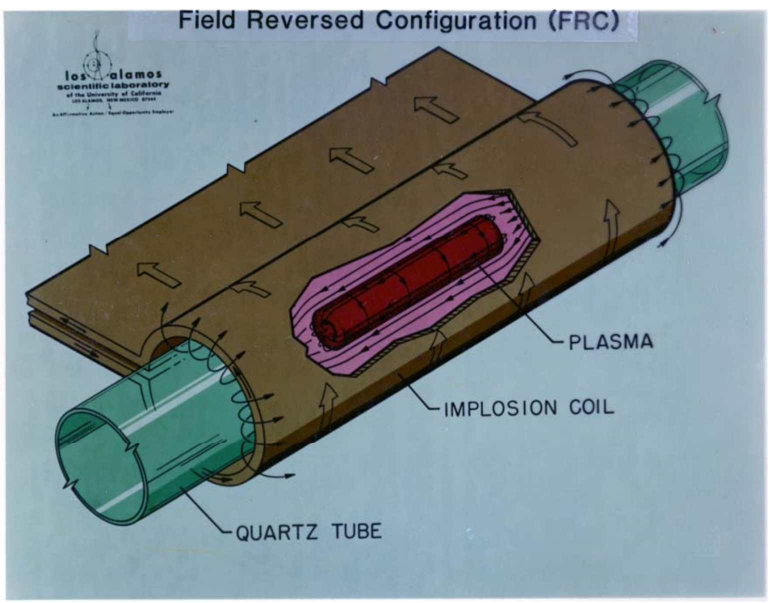
- Magnetized plasma compression provides an intermediate and low cost approach to HED plasmas
- One application: magneto-inertial fusion pathway between ICF and MFE
- Compact toroid (CT) insulates dense hot plasma from low temperature impurity species
- Field reversed configuration is an attractive CT
- Liner implosion to drive compression and heating of the FRC

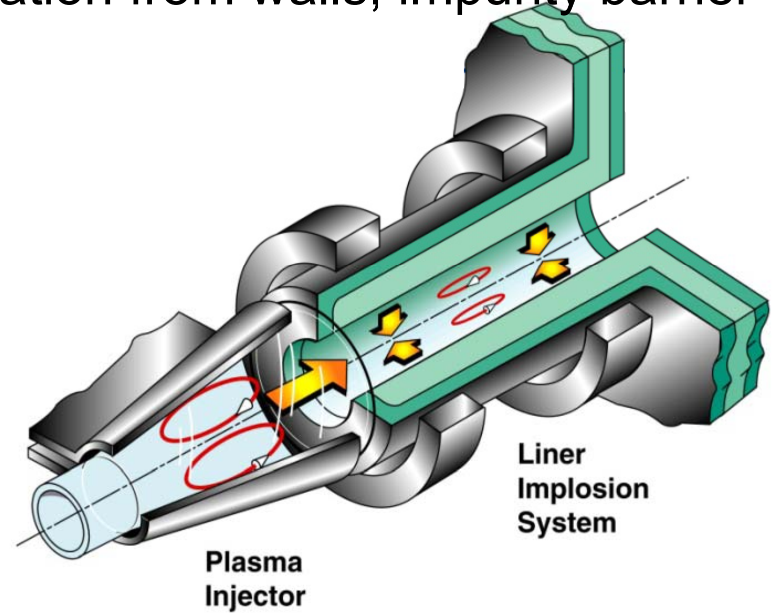
Research Areas

- In-depth study of the fundamentals of physics of HED laboratory plasmas in the presence of high magnetic fields
    - ◊ Magneto-inertial fusion
    - ◊ Studies of particle transport in highly magnetized, dense plasmas
    - ◊ FRC Plasma instabilities

Choosing the Target

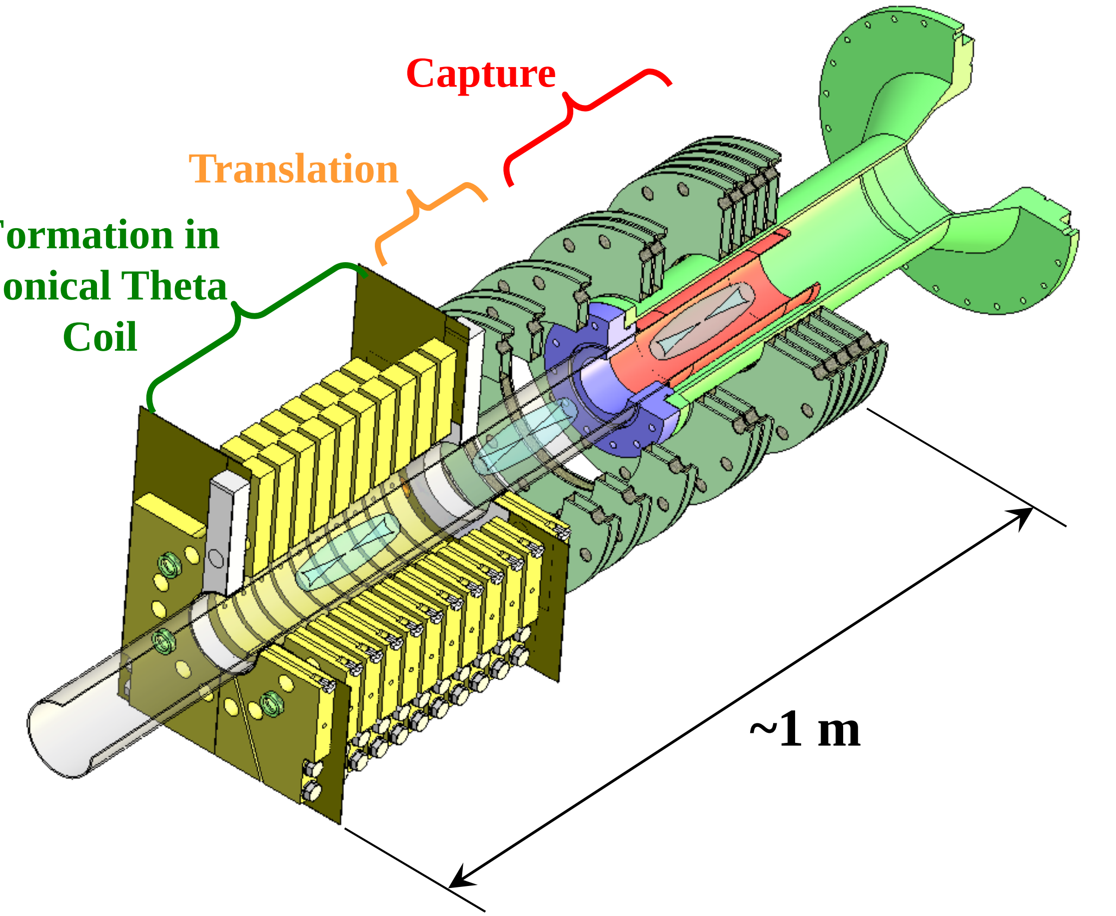
- Advantages of Field Reversed Configurations (FRC's) for HED plasmas:
  - Simple cylindrical geometry
  - High β (β ~ 1) and high power density → compact system
  - Translatable → formation and adiabatic heating regions can be separated
  - Natural separatrix diverter – isolation from walls, impurity barrier





FRC Translation

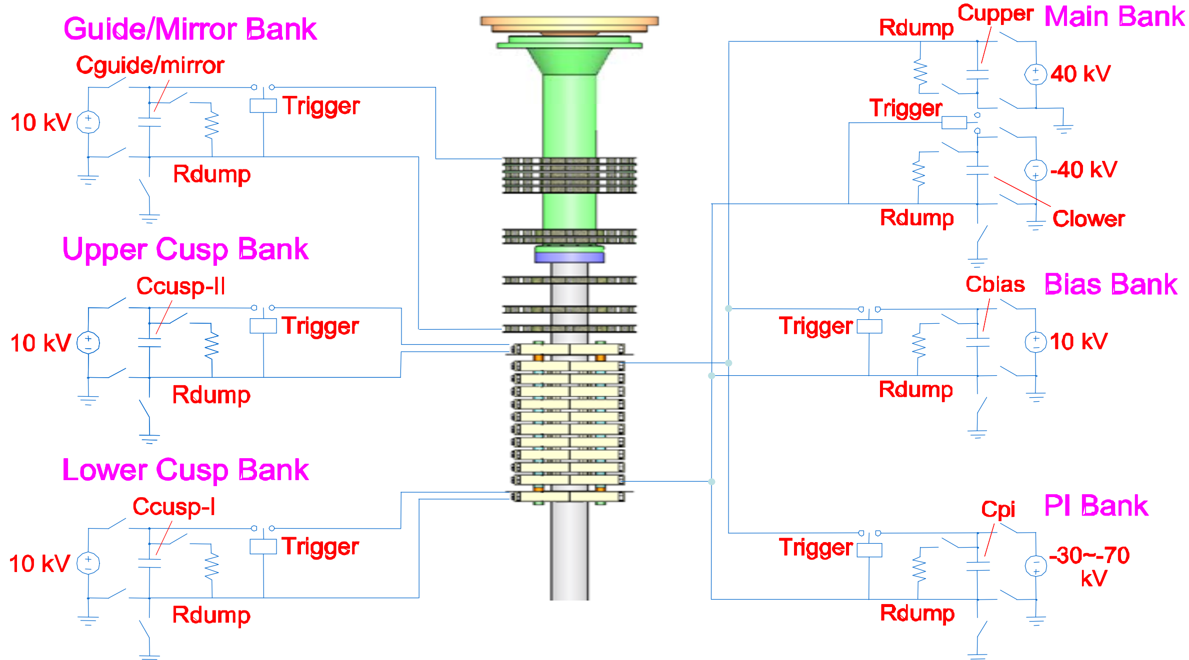
- The FRC is ejected from the formation region by J x B_r forces
- Fields along the short translation region keep the FRC from expanding
- Lower and Upper mirror fields form a capture region for the FRC that stops it within the center of the liner



Target Plasma Parameters

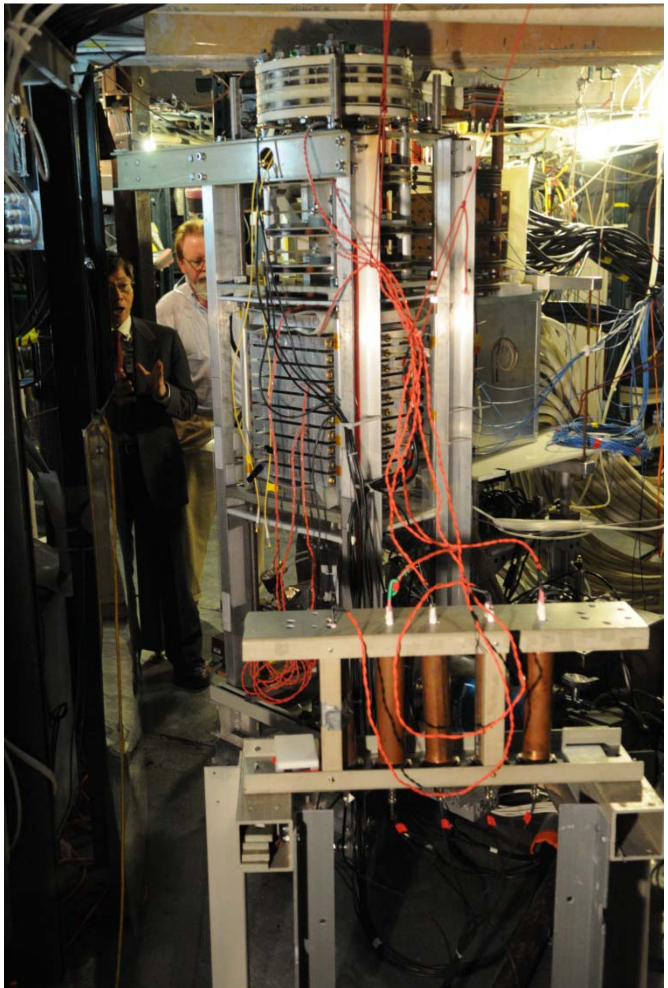
- Present and Projected FRC Parameters
  - In formation region of experiment
    - $n \sim 10^{17}$ cm^{-3}
    - $T \sim 100 – 300$ eV
    - Poloidal $B \sim 2 - 5$ T
  - After solid liner compression (Megabar pressures)
    - $n > 10^{19}$ cm^{-3}
    - $T \rightarrow 3\text{-}5$ keV
    - Poloidal $B \sim 300 - 500$ T
- Initial plasma lifetime confinement time > 10 μs needed
- Final plasma lifetime ~ 200 nsec at peak compression

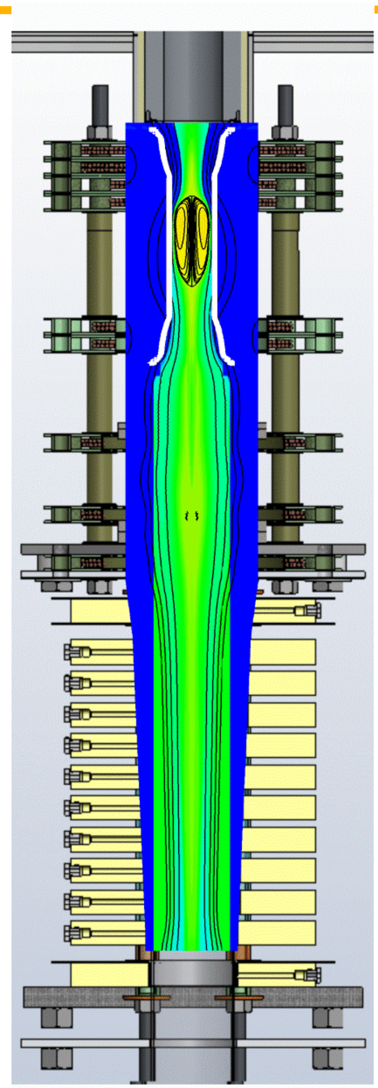
Pulsed Power Systems

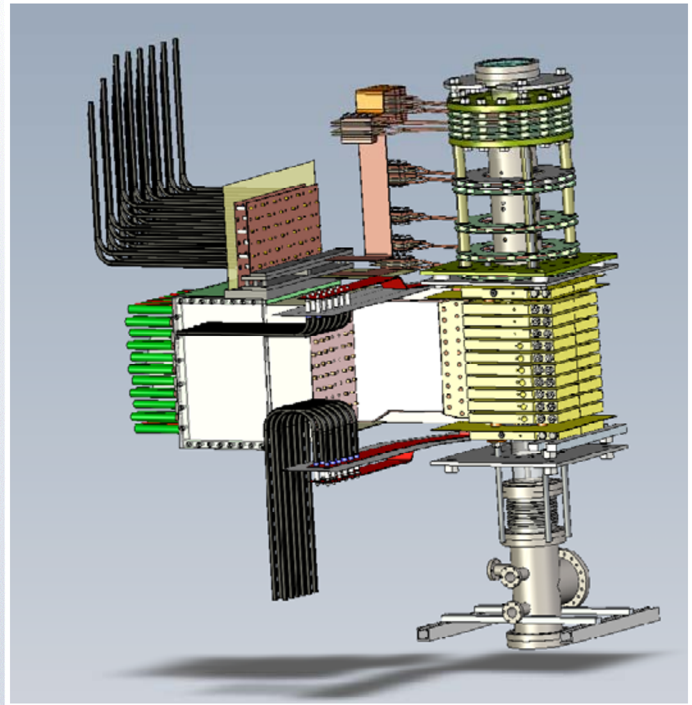


- **Bias bank** – *Consists of two cap bank modules, ~2.5 mF per module*
- **PI bank** – *Single 2.1 μF capacitor, oscillation frequency of ~230 kHz*
- **Main bank** – *Single Shiva Star bank module, caps turned sideways to reduce bank height (Cupper = Clower = 72 μF); bank is crowbarred near peak current*
- **Upper and Lower Cusp banks** – *three 500 μF capacitors each, switched with ignitrons*
- **Guide/Mirror Bank** – *total capacitance of 12 mF, switched with 6 ignitrons*
- **Shiva Star** – *to drive the liner implosion, 36 modules, ~1.3 mF total C*

Magnetized Target Fusion, test of implosion physics





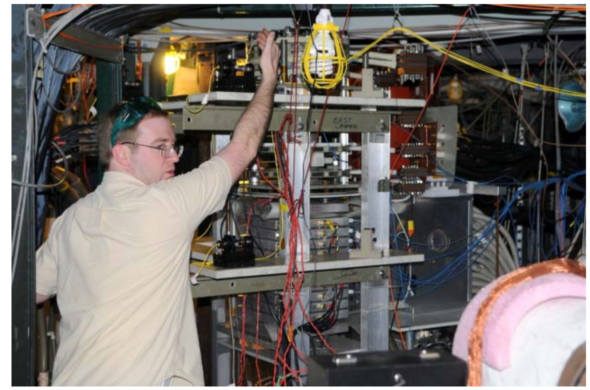


The FRC source/liner assembly (left), a MACH2 model of the translating and imploding plasma and liner (middle), and a CAD drawing of the system, including power feeds (right).

Magnetized Target Fusion, test of implosion physics

Project leader Jim Degnan next to remains of the coils from the second engineering test shot.

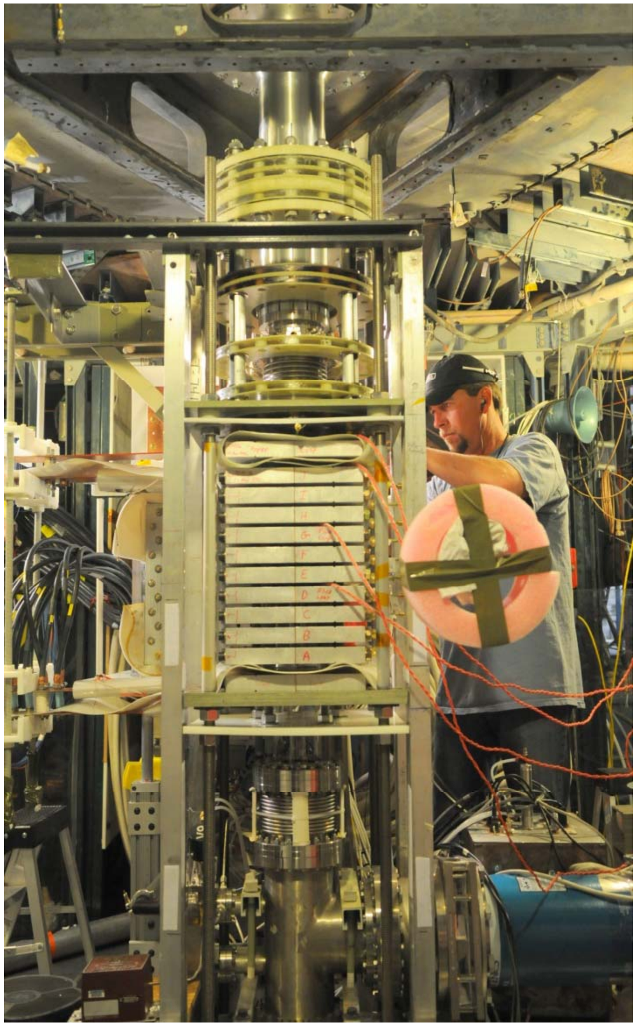
Chief engineer Chris Grabowski by the FRC load stack, under Shiva Star

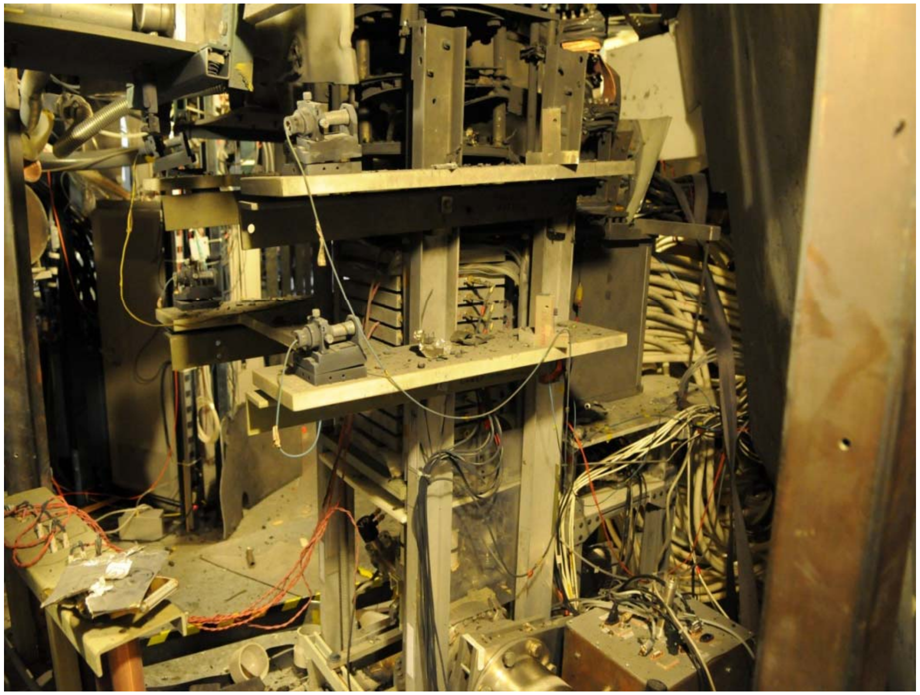


UNM scientist Alan Lynn adjusting 2-chord fiber interferometer on FRCHX

Actual deformable Aluminum liner for the next shot. (Slotted current return assemblies in the background)

HEDLP Magnetized Target Fusion, LANL/AFRL FRCHX





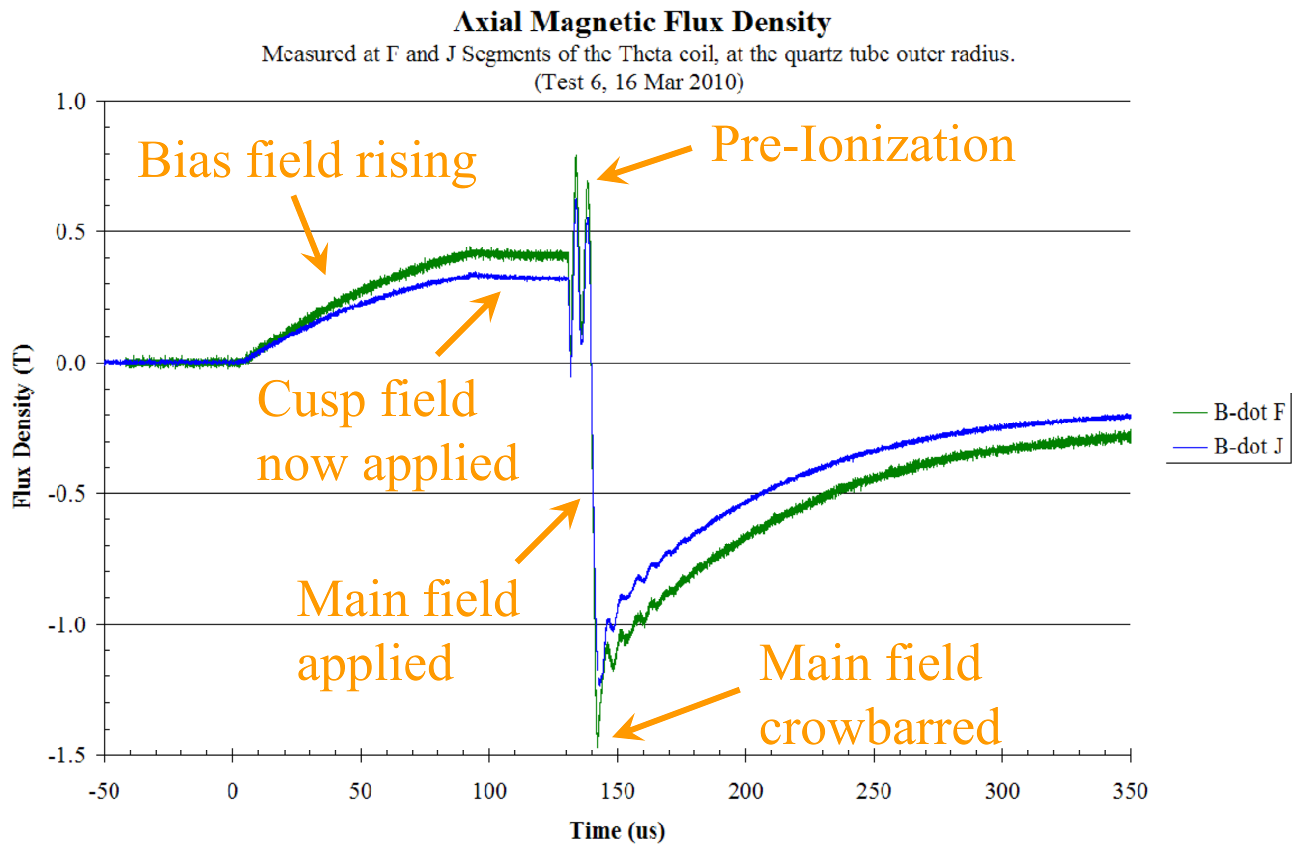
Our first full-up systems test was April 16, 2010. An engineering success, with interesting physics, but a failed compression. The second shot in this series is being readied & tested now.

FRCHX Test Milestones
Past 12 Months

Event	Date	Significance
Confirmed translation and capture of an FRC plasma in the extended quartz tube test setup	Feb 2010	This was the first confirmation of successful FRC translation and capture in the AFRL experiment. Densities and temperatures were appropriate for a compression-heating experiment, though lifetimes were short.
Confirmed translation and inferred capture of an FRC plasma in the compression-heating test setup	Apr 2010	Confirmation of FRC entry into the liner without observation of any plasma returning from the liner was a pre-requisite for performing the compression heating test.
Performed first FRC compression heating test	Apr 16, 2010	This was the first ever reported solid liner compression test of an FRC plasma in a laboratory environment.
Confirmed FRC capture with a mock-up of the compression heating test hardware	Sep 2010	B-dot probes inserted from above into the liner confirmed, for the parameters that were used in the April 16 test, that plasma was captured in the liner but that the trapped flux lifetime, as suspected, ended before compression would have been completed.

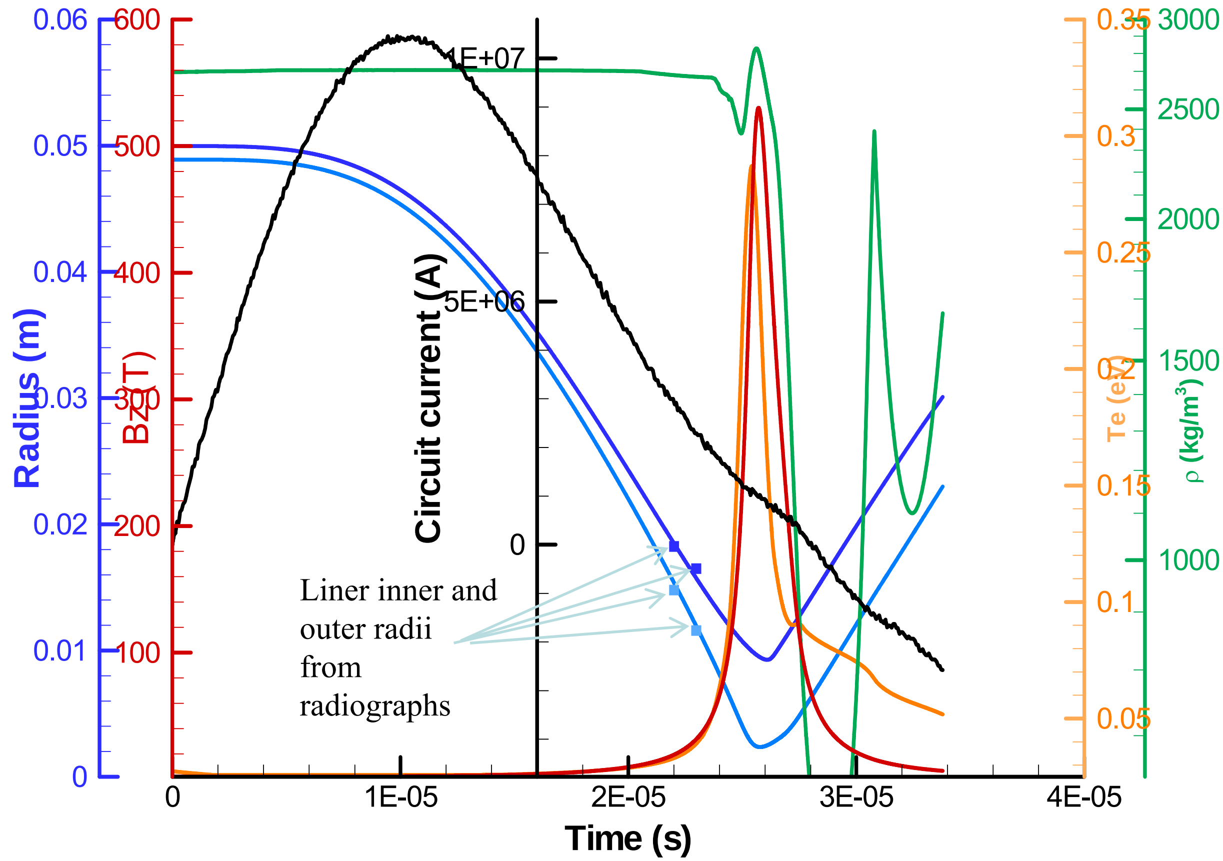
B-dot Probe Measurements

Formation Region



- Axial magnetic probe signal shows field vs. time from Bias, Cusp, Pre-Ionization, and Main Theta discharges.
- All discharges except that of the Cusp are through the 10-segment Theta coil.

MHD simulation using experimental current agrees with radiography on liner radius vs time

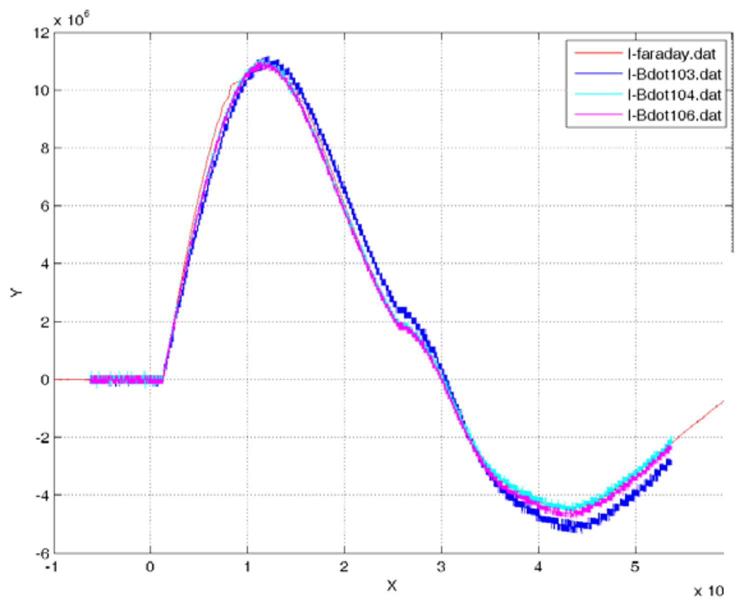


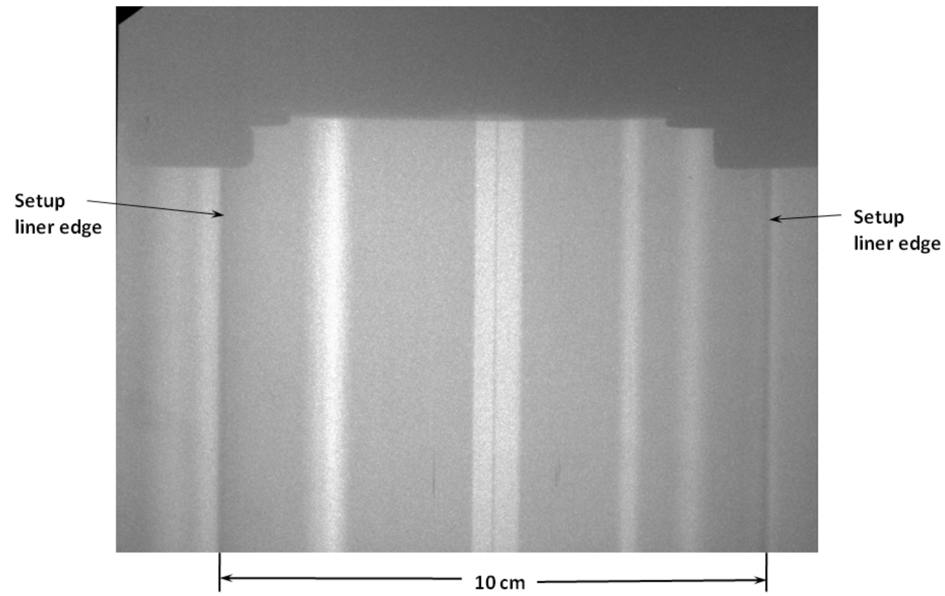
NumerX MACH2 results for Shiva Star liner compression for 2 Tesla initial axial magnetic field

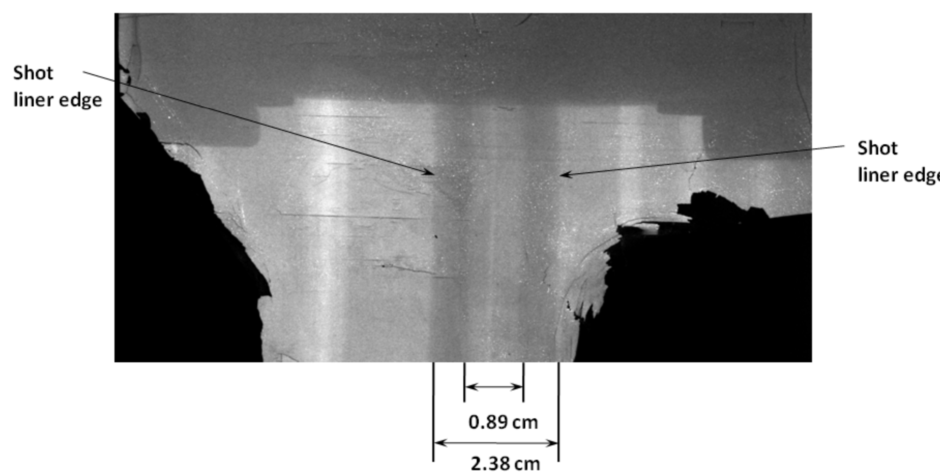
Calculated peak field is 540 Tesla

Despite heavy debris damage to digital film we obtained useful radiograph

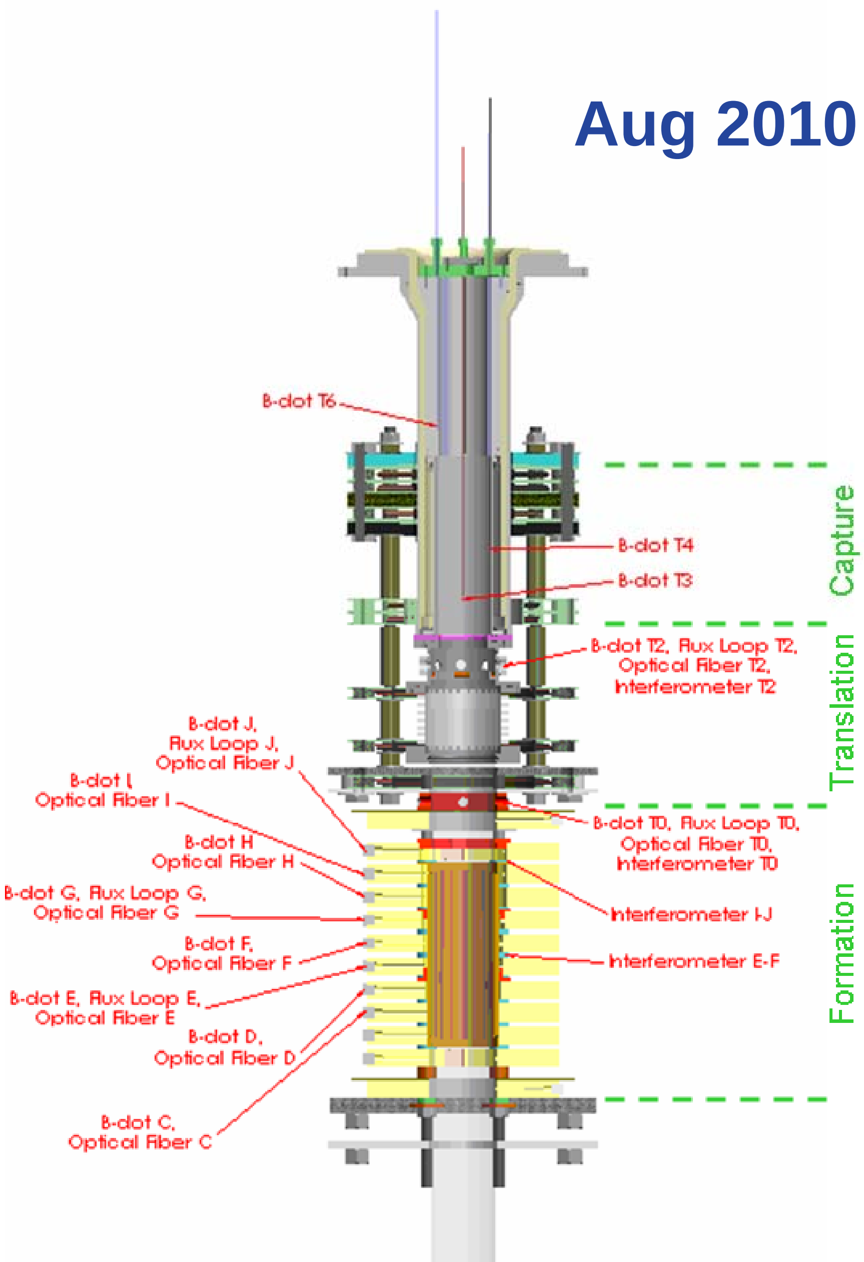
Implosion - compression experiment radiograph obtained at 22.985 μs after start of implosion discharge current indicates that liner imploded symmetrically, with little or no instability growth, and achieved 11 times radial compression of inner surface. Faraday rotation and inductive current probes indicated ~ 11 MA implosion current with 10 μs rise time.





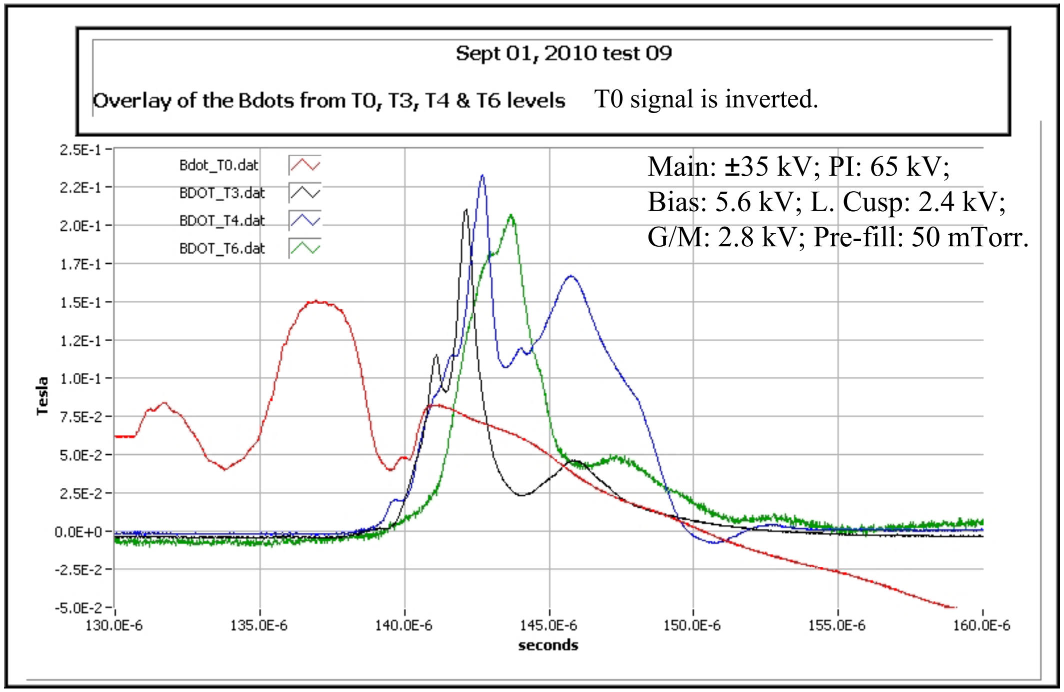


Aug 2010 – Present Test Setup



FRCHX under the Shiva bank (Nov. 2010).

B-dot Probe Measurements
Guide Field Matching Compression-Heating Test

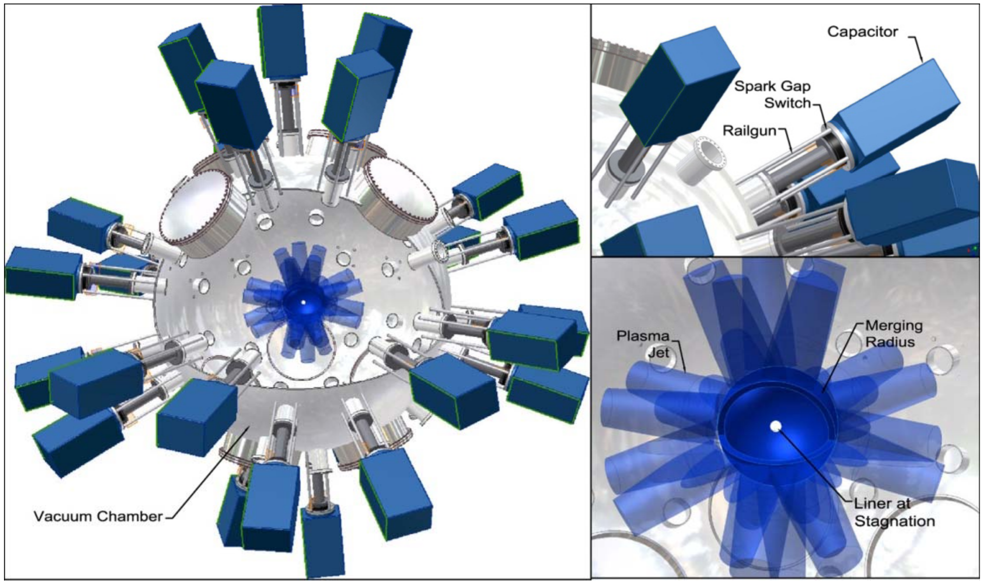


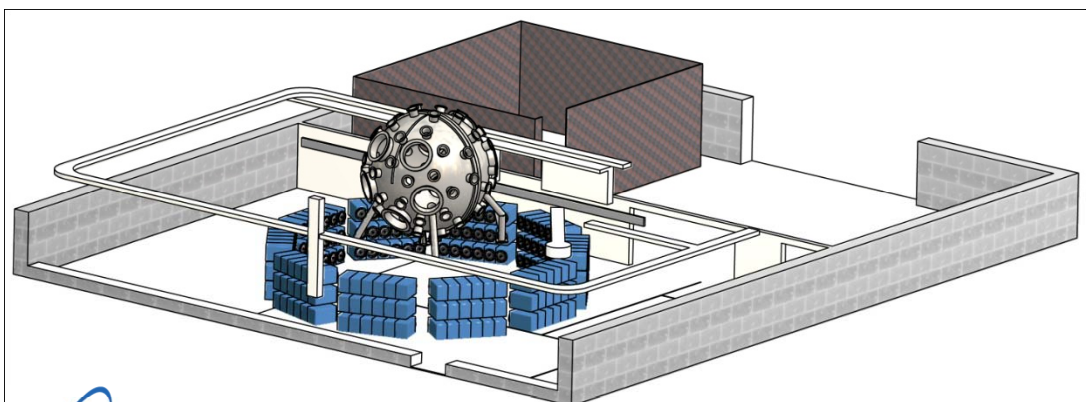
- Strong T6 signal observed.
- Secondary peaks on T4 and T3 signals after the first T6 peak; secondary peak on T6 signal, as well.
- At least some plasma captured; elasticity of the FRC allowing it to stretch beyond the upper mirror while a portion remains trapped between the mirrors.

FRCHX Test Summary

- Numerous FRC formation, translation, injection, and capture experiments have been conducted to characterize FRC T, n, and lifetime with FRCHX.
- Three capture region configurations were implemented:
  - An extended quartz tube through the capture region to facilitate diagnostic access
  - The complete compression-heating hardware configuration
  - A mock up of the liner with modified upper electrode and top flange to allow B-dot probe insertion into the liner
- Plasma T and n have typically been 200~300 eV and 10^{16}~10^{17} cm^{-3}, respectively; trapped flux lifetimes have been only been 6~10 μs in duration.
- MHD simulations are being closely coupled to the experiment to aid in improvements.
- The first full-up implosion test (April 16, 2010) was an engineering success. However, no useful plasma survived long enough in the capture region.
- A second implosion load assembly is ready, and is being statically tested now off to the side of Shiva Star.
- We are working on longer trapped FRC lifetimes, through higher bank settings, better trapping, more uniform preionizaiton. Further modifications will be implemented in the next implosion test in FY11.

Plasma Liner Experiment (PLX) will merge 30 plasma jets to create cm and μs scale plasmas approaching HED conditions (~0.1 Mbar)



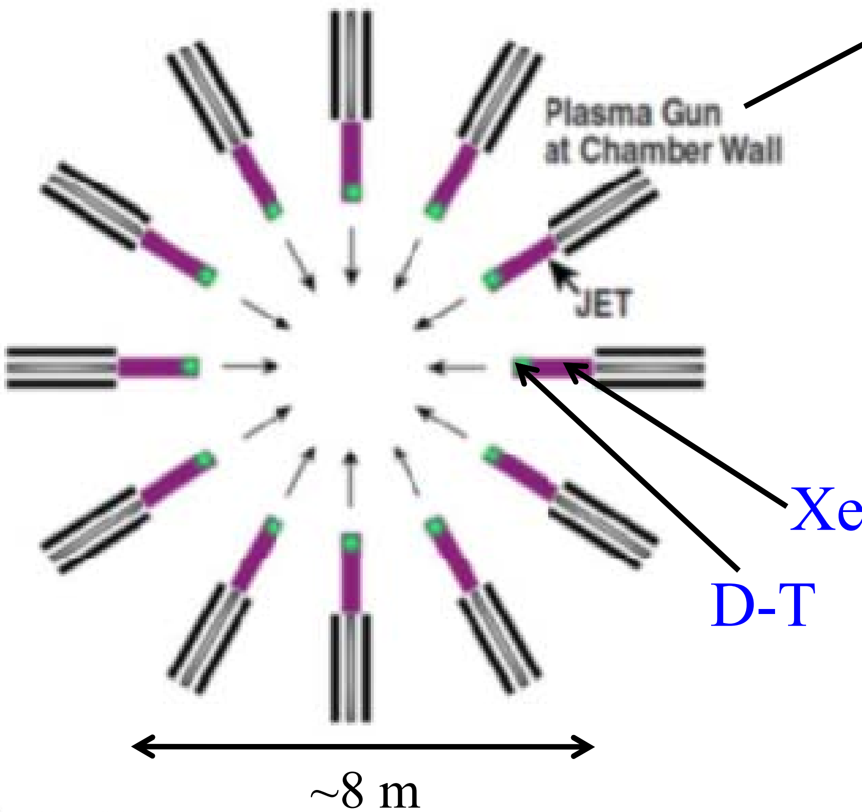


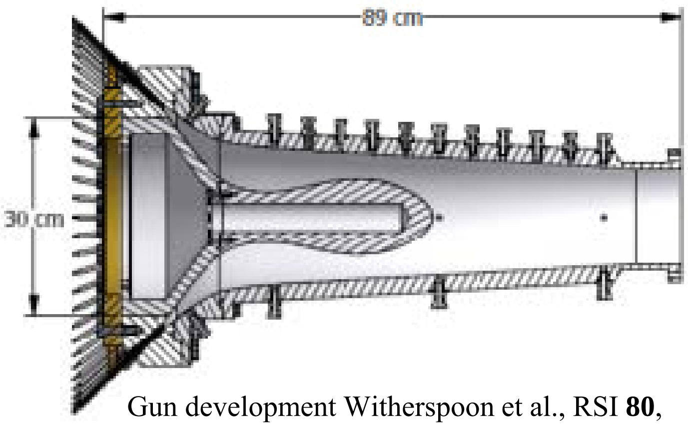
- Scientific goals: predictive understanding of jet propagation/merging, spherical plasma liner formation/convergence/stagnation, and "standoff" magnetization
- Motivations: enable platform for discovery-driven HEDLP science, especially magnetized HEDP, and standoff embodiment of magneto-inertial fusion
- Status: Phase 1 construction nearing completion with first experiments in 2011

Drawing by David Van Doren, HyperV

Plasma liner embodiment of MIF offers standoff and versatility for optimizing implosion and burn

Spherical array of economic, efficient plasma guns to launch composite plasma jets forming imploding plasma liner:





Gun development Witherspoon et al., RSI **80**, 083506 (2009).

V_{gun} ~ 10's kV, I_{gun} ~ 1 MA

$\langle n_{jet} \rangle$ ~ $10^{17\text{-}18}$ cm^{-3}

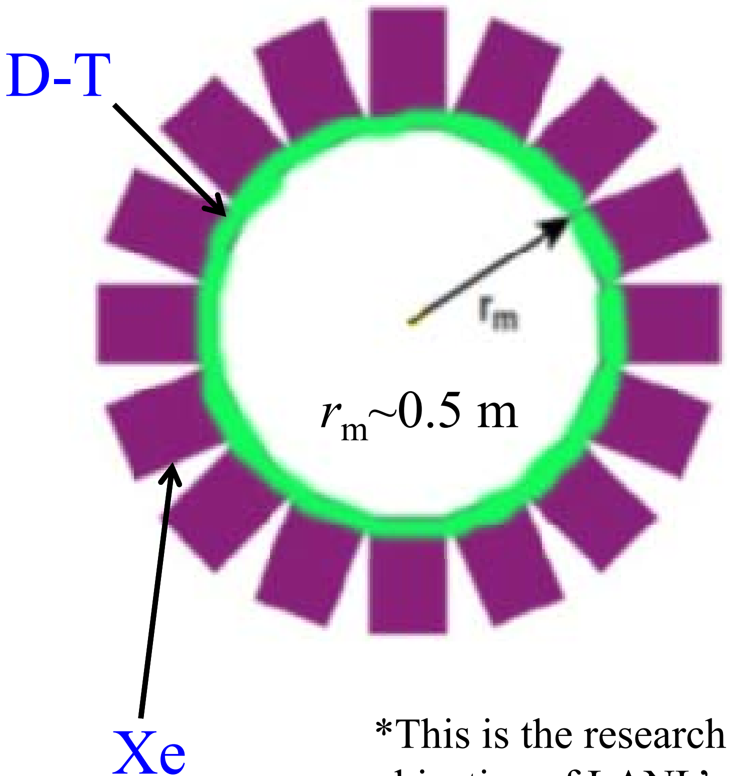
T_{jet} ~ 2 eV

M_{jet} ~ 20 mg

E_{jet} ~ 64 kJ

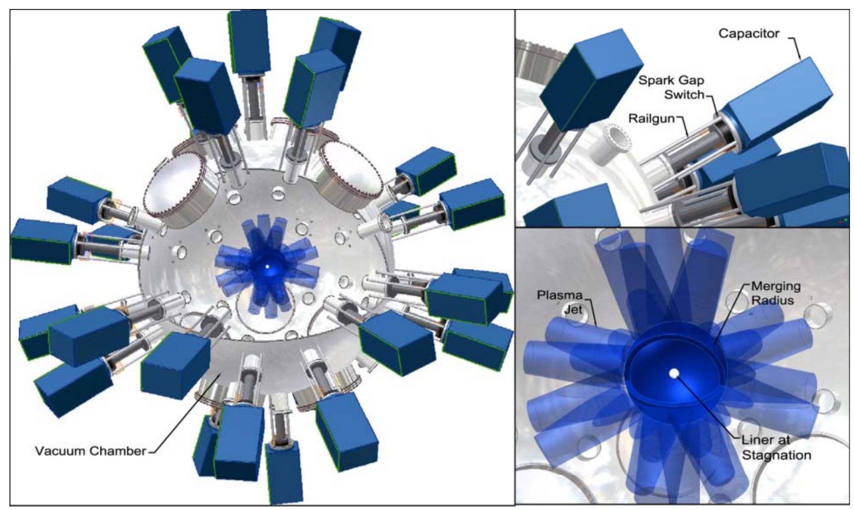
Concept reference Thio et al., J Fusion Energy **20**, 1 (2002).

Jets merge to form imploding spherical plasma "liner"*



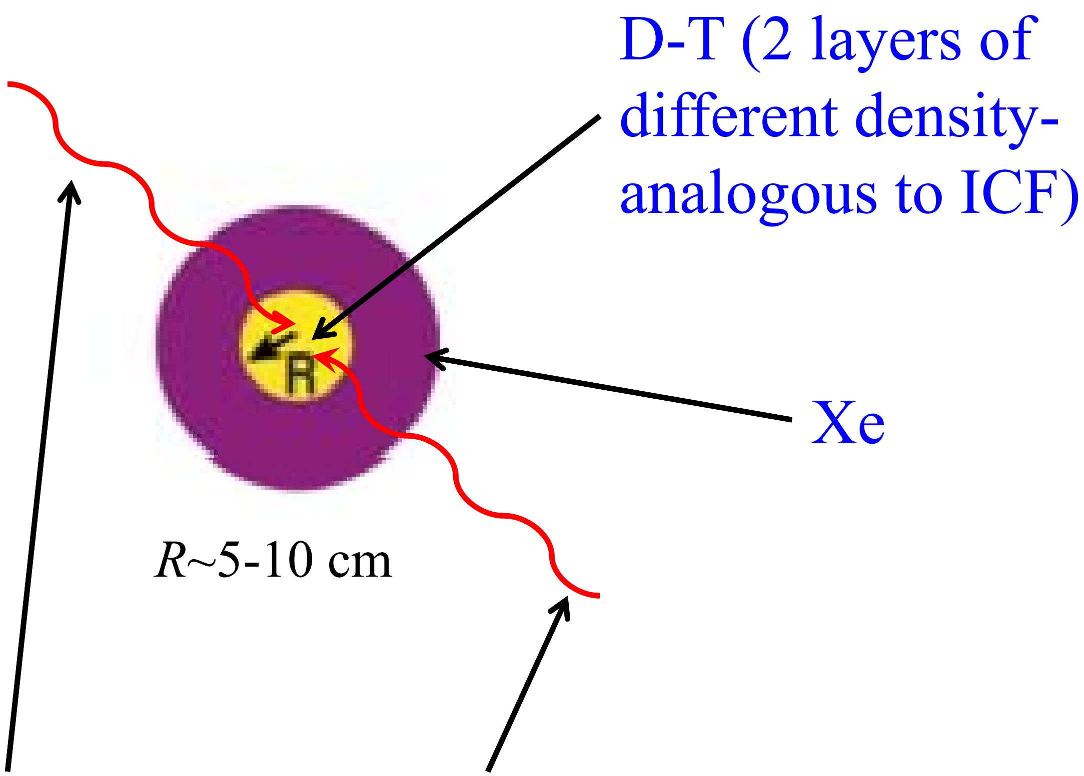
U_{liner} ~ 80 km/s (8 cm/μs)
M_{liner} ~ 4 g
E_{liner} ~ 13 MJ
N_{jet}~200
$\tau_{transit}$ ~ 10's of μs

*This is the research objective of LANL's Plasma Liner Experiment (N_{jet}=30, E_{liner}≈300 kJ), funded by the DOE Joint Program in HEDLP.



Shortly before reaching peak compression, inner DT portion of plasma liner is magnetized to few Tesla level

Beat wave current drive Rogers & Hwang, PRL **68**, 3877 (1992).



One possible method: Fire lasers for driving current (via beat wave resonance) and magnetizing the inner DT portion of the jet (IR, kJ, TW class lasers needed)

Plasma Liner: Final compression amplifies B field to ~50-100 Tesla and heats inner DT layer to fusion temperatures

R~0.5 cm

- Inner DT layer burns (~10% burn-up)
- Aim is to heat and partially burn the denser outer DT layer (“afterburner”) by α’s and outgoing shock, amplifying the yield
- Xe layer would reduce radiation losses and enhance the confinement time (~1 μs)

Reference case:

DT fusion yield ~ 300 MJ
Total liner energy ~ 13 MJ
Energy gain > 20
Wall plug efficiency ~ 0.5
Gain-efficiency product > 10
At 1 Hz ➔ ~300 MW average power (~100 MW electric)
Goal is to use thick liquid wall

Reactor Design?
Engineering concerns similar to conventional Inertial Fusion Energy

- Pulsed loading
- Chamber survival
- Driver efficiency
- Interface to standoff driver?
- Cost of replaceable parts?
- How to get more tritium breeding?
- How to minimize recirculating power?
- Pulsed power reliability (millions of shots)

Reactor Design? Start from the End Point

- Consider a 4.1 GigaJoule yield (1 metric ton) from a pulsed MIF device.
- Consider a rep-rate of 0.1 Herz, which gives more time to clear the chamber.
- Pick a thermal conversion efficiency to electricity of 35%, so one would produce 1.4 GJ electric per pulse (gross, not net), or 140 MW electricity (average).
- Use a thick liquid curtains, with liquid pool at the bottom of the chamber. The liquid will absorb neutrons, and breed tritium. Have voids to dissipate shock from the explosion, and cushion the solid backing wall of the system.

Basic points to consider (1)

3.6 MJoules = 1 kW-Hour

There are 31.5 million seconds in a year.

10 cents/kWH means 1 GigaJoule of electricity is worth $27.8

At 35% conversion efficiency, then 4.1 GJ thermal is worth only $40 of electricity

One metric ton (1000 kg) of high explosive has an energy content of 4.1 GJ

To produce 4.1 GJ from DT fusion, at 17.6 MeV per DT reaction, and 1 eV = 1.6×10^{-19} Joules, one has 2.8×10^{-12} Joules per DT reaction; so you need 1.4×10^{21} reactions per 4.1 GJ released.

Basic points (continued) (2)

A mole of D2 is $2x6.02x10^{23}$ D atoms, and same for mole of T2. So each 4.1 GJ pulse burns up approximately 1 milliMole of D2, and 1 milliMole of T2. D2 has a molecular weight of 4 grams/Mole, and T2 has a molecular weight of 6 grams/mole

If the fractional burn-up of DT is 10%, then you need 10 milliMoles of each, in the final compressed MTF plasma. At least 20 milliMoles of each in the beginning target plasma, assuming 50% plasma inventory losses during translation from the formation region. (This exercise will assume no cold fuel is available for alphas to burn into).

The initial target fuel load must be "preheated" to 200 eV (Te+Ti). This is an energy investment of $2x(20 \times 10^{-3}) \times 6x10^{23} \times 200$ eV = $4.8x10^{24}$ eV, or $0.75x10^{6}$ Joules, or .75 MJ. Add in a factor of 2x for formation losses, so we are talking 1.5 MJ of energy needed to form the MTF "target" plasma.

Basic points (continued) (3)

Then the gain is 4100 / 1.5 = 2733 relative to the initial plasma energy content. Work also had to be done to compress the initial plasma to get it to the final state. The energy content of the final state is defined to be same number of particles, heated up to 8 keV. The temperature increase (energy content increase) is 8000/200 = 40. Assume the liner drive energy is about 2x the final plasma energy. Then the system has a gain (classic Q_{DT}) ~ 34.

If the electric-to-liner drive efficiency is ~50%, the system gain is reduced to ~17, when considered from wall plug to thermal output. (i.e., you needed to put in 240 MJ into the pulsed energy storage to get 4.1 GJ thermal out from pure fusion). If conversion to electricity is 35% efficient, then electricity output is 1.4 GJ, so the minimum recirculating power is about 18% . If the rep-rate is 0.1 Hz, the average electric output is 140 MW.

So a 10% fractional burn-up is adequate performance from a fusion-only, MTF batch-burn system if the liner coupling efficiency is 50%.

Basic points (continued) (4)

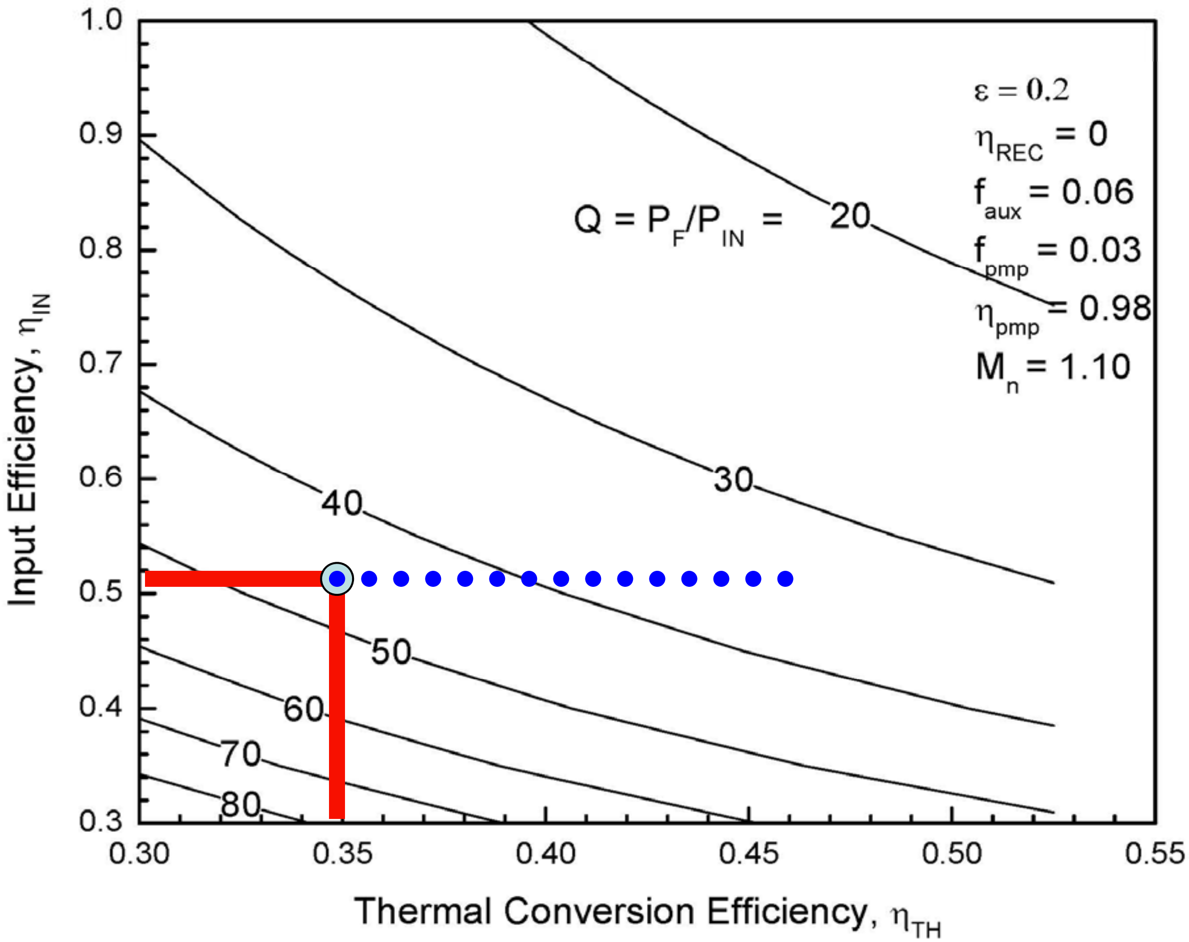
For a 10% DT fuel burnup fraction, an $n\tau_{dwell} \sim 2\times10^{15}$ cm^{-3}sec at 10 keV is required. For example, a final density of 10^{21} cm^{-3} and a liner dwell time of 1μsec would do the trick. This exceeds our projected initial experiments by a factor of ~100.

Further points:

•The price of all the destroyed components, accounting for their remanufacture, should not exceed 10% of the value of the electricity produced. So, a few dollars per pulse is all that is allowed.

•The value of 100 MW of net electricity, produced for one year, at $0.1/kWH, is only ~$100M. If you need a 30 year payback time on your capital equipment, then the plant cost shouldn't exceed $3B, at zero percent interest! Increasing the rep rate would be a huge win, but you have to be able to reload and clear the chamber between pulses.

Looking a little more closely: To have 20% recirculating power, with 50% wall-plug-to-plasma heating efficiency, 35% thermal-to-electric, and some credit from exothermic n-Li reaction, you still need Q ~45



R. A. Miller
Decysive Systems

Can the neutron energy multiplier be bigger than 1.1?

•Why is it 1.1 for "pure" fusion?….because we take an exothermic energy credit for n-Li reactions in a blanket.

•Are there other possibilites? Yes……..**Fusion-Fission Hybrids, because each fusion is good at making an energetic neutron, while each low energy neutron can cause a fission event with a lot of energy. The fusion neutron can also first be multiplied, giving even more low energy neutrons.**

•If the blanket is 0.6 meter thick hot liquid FLIBE with 10% UF4, one can protect standard solid structural elements for a long life (~30 years), while getting a tritium breeding ratio of >1.1, and an energy amplification of 1.9 (due to fission in the blanket!). [Mustafa Ubeyli, Journal of Fusion Energy, Vol. 25, no. 1-2, pg 67-72, (2006)]

•So, as most of us know, if you are willing to be a fissile breeder, it is easy to double the Q.

• The caveat of course, is all the issues associated with having a fissile blanket sitting around your chamber….

Thick liquid wall recirculation is not a big energy hit

• The chemical composition of pure FLIBE is Li_2BeF_4.

• If the chamber size is a cylinder, with a radius of 3 meters, and similar length, then the minimum amount of hot FLIBE out on the wall, is about 35 cubic meters.

• FLIBE has a density of 2 gm/cc, or 8.5x10^22 atoms/cc. This is an exposed blanket inventory of about 7×10^4 kg, or 70 metric tons. If it "falls" under gravity, a distance of, say, 5 meters, then the gravitational potential energy MgH is 3.5 MJ. Under gravity free-fall, it also takes only 1 second for this material to fall 5 meters.

• So you will need to invest 3.5 MW, or even twice that, continuously, to keep it circulating, which adds to the recirculating power we have already discussed, but for our assumed 140 MW average electric power output, is not a big issue relative to the required pulsed power energy storage.

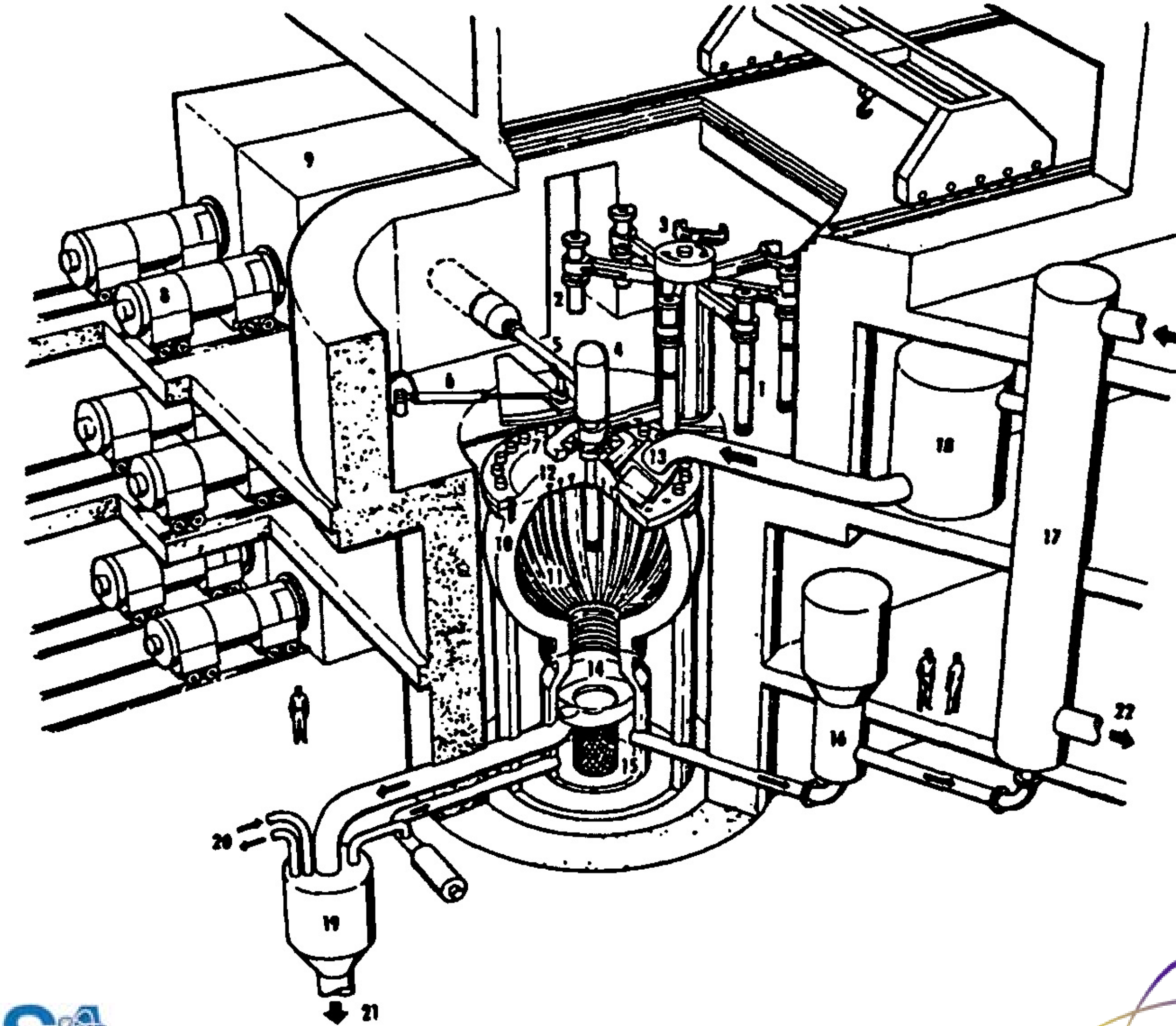
Previous liner implosion solutions: Fast Liner Reactor

A.R. Sherwood, B.L. Freeman, R.A. Gerwin, T.R. Jarboe, R.A. Krakowski, R.C. Malone, J. Marshall, R.L.Miller, B. Suydam

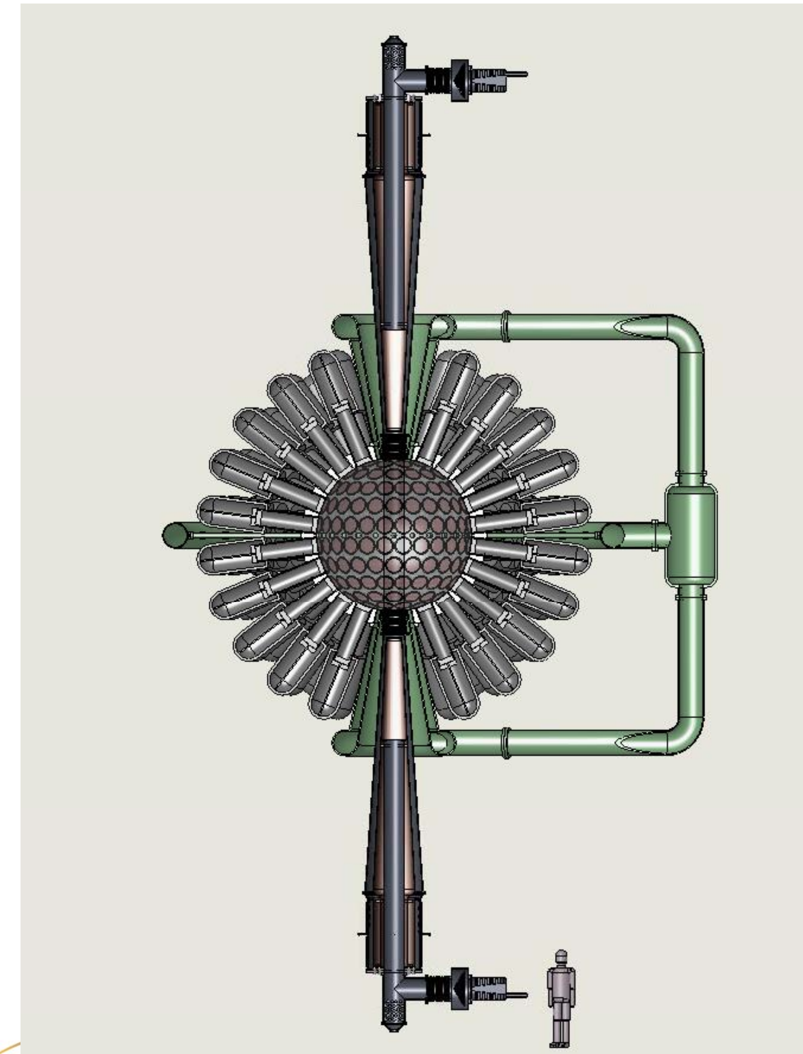
Los Alamos Scientific Laboratory proposal, LA-6707-P, (1977)
Title: Fast liner proposal

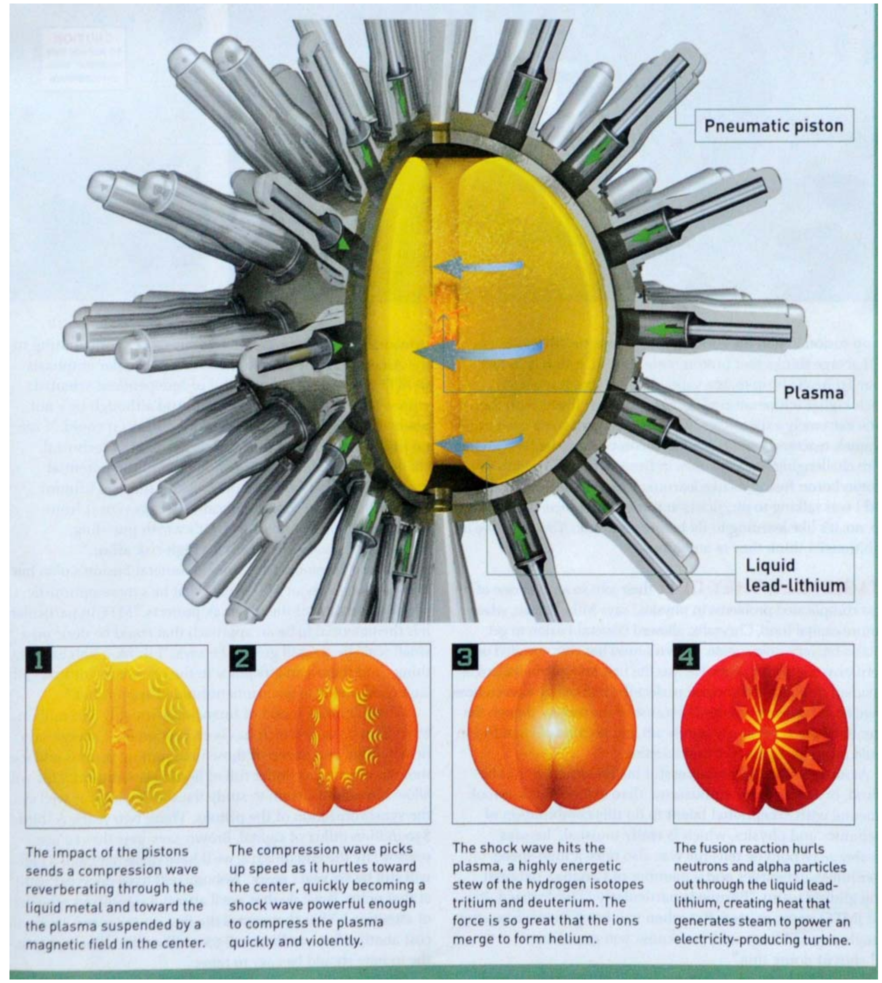
Abstract: This is a proposal to study, both theoretically and experimentally, the possibility of making a fusion reactor by magnetically imploding a cylindrical metallic shell on a prepared plasma. The approach is characterized by the following features: (1) the non-rotating liner would be driven by an axial current, (2) the plasma would also carry an axial current that provides an azimuthal magnetic field for thermal insulation in both the radial and longitudinal directions, (3) solid end plugs would be utilized to prevent axial loss of particles, and (4) liner speeds would be in the 10^6 cm/s range. Our preliminary calculations indicate (1) that the energetics are favorable (energy inputs of about 10 MJ might produce a machine in the break-even regime), (2) that radiation and heat losses could be made tolerable, (3) that alpha-particle heating could be made very effective, and (4) that Taylor instabilities in a fast liner might be harmless because of the large viscosities at high pressures. A preliminary conceptual design of the sort of fusion reactor that might result from such an approach is discussed, as are some of the relevant reactor scaling arguments.

LANL Fast Liner Power plant schematic (Krakowski, et al. ~ 1980)



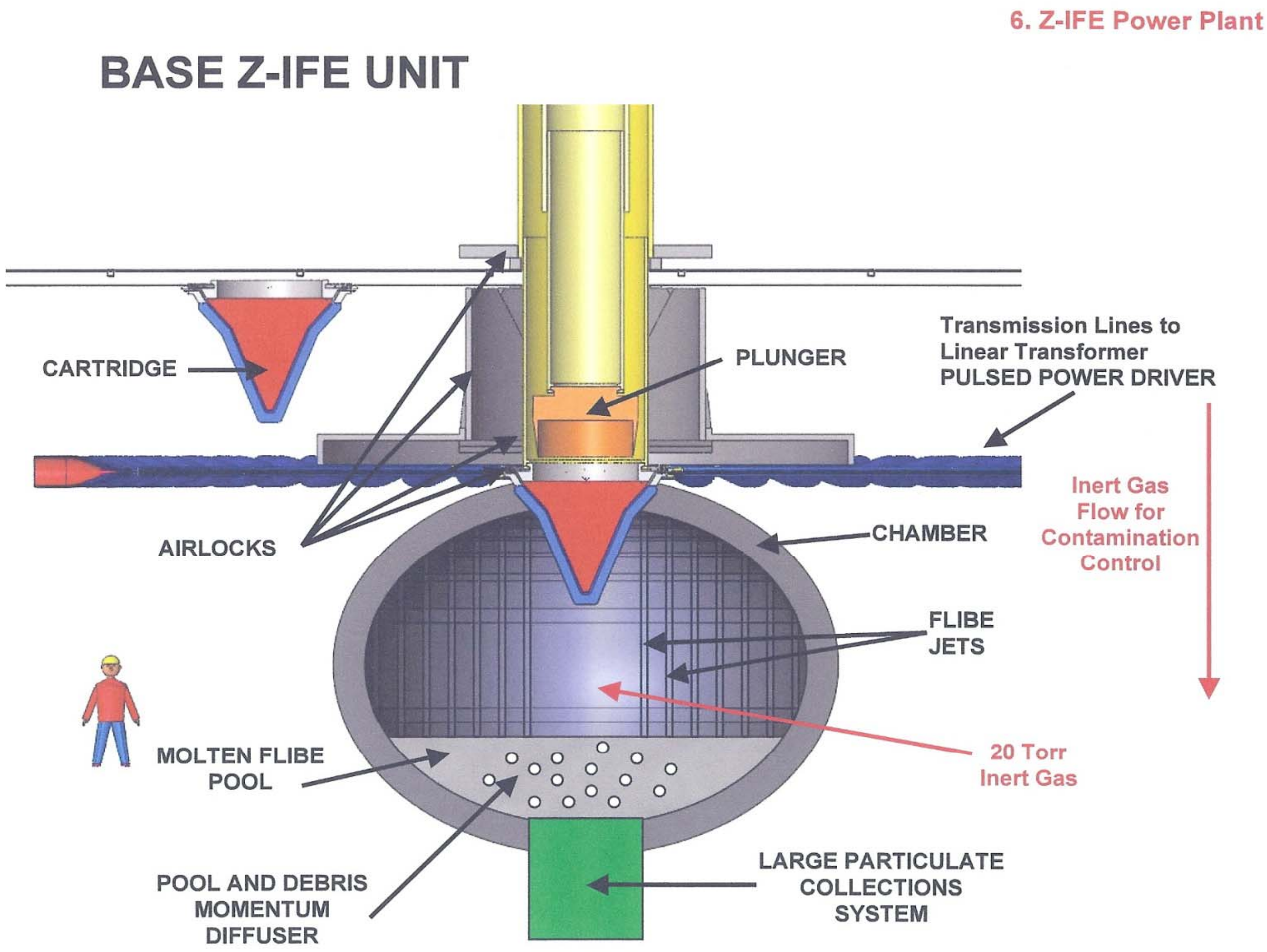
Acoustic piston drivers for MTF: General Fusion (Vancouver, Canada)





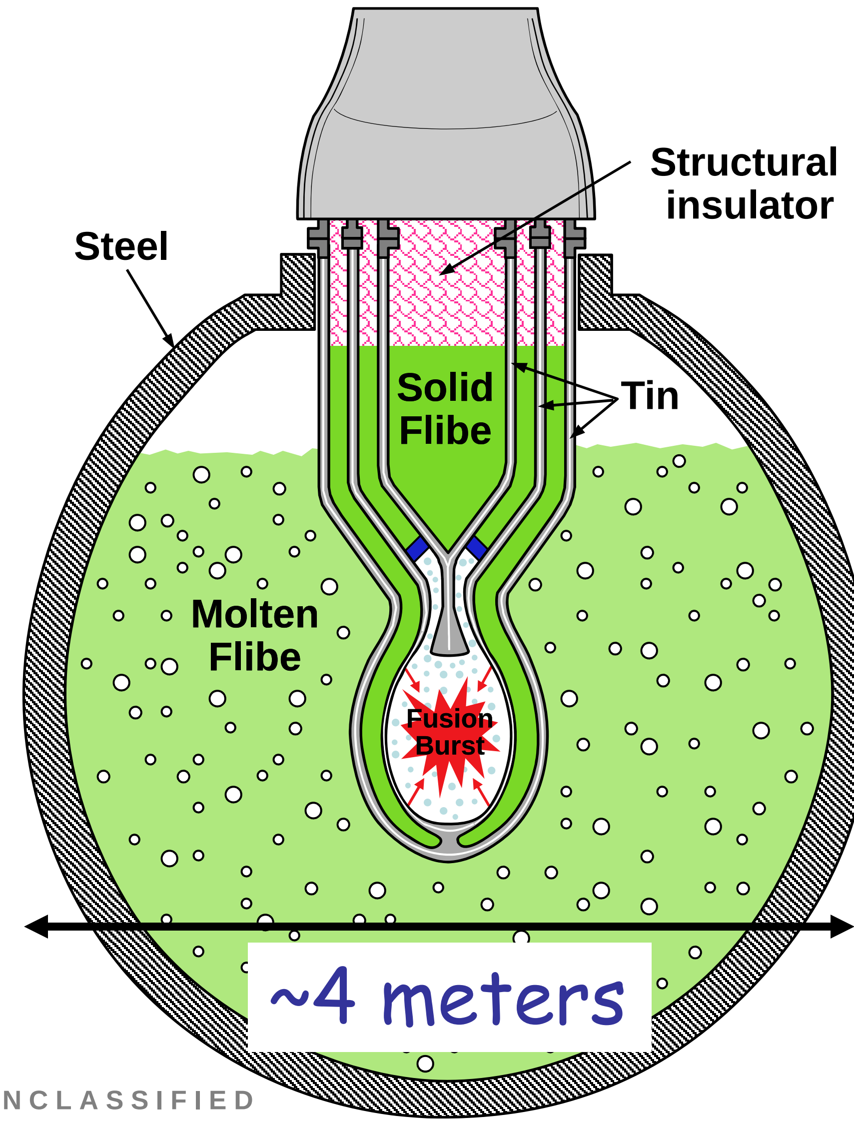
Popular Science, pg. 64-71, Jan. 2009

Sandia Z-IFE Power Plant Schematic (Craig Olson, et al.)



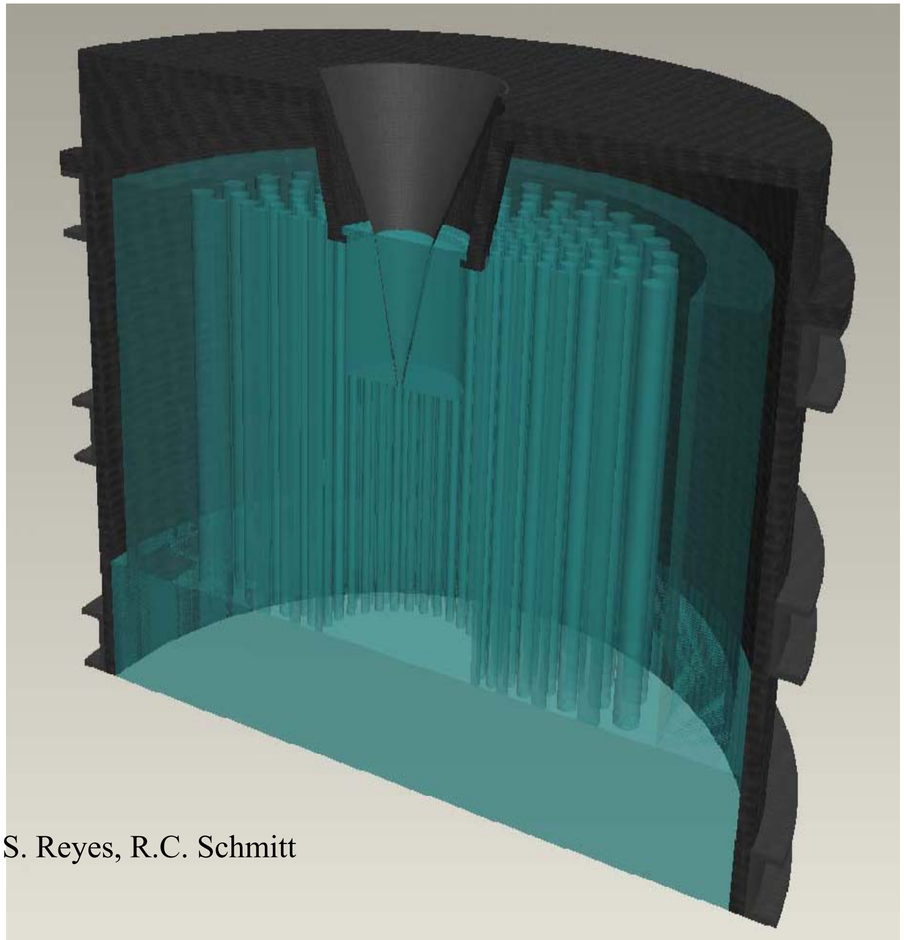
One vision of an MTF reactor, with miscible materials

- All target material recycled
- 15 sec per pulse
- Flibe primary coolant at 550 °C (T_{melt} = 459 °C)
- Tin T_{melt} = 232 °C
- P. Peterson, UC Berkeley, ~1998



LLNL (3-month) Z-IFE concept design study*

- Higher fusion yields per chamber are more economic
- 12-m diameter chamber, 3-m thick region with FLIBE flowing columns (66% void fraction). ~300 m^3 of FLIBE
- Issue: Mitigation of shocks on the final wall from 20 GJ yield in a Z-IFE scenario with liquid pool at bottom



*UCRL-TR-207101 Analyses in Support of Z-IFE: LLNL Progress Report for FY-04
W.R. Meier, R.P. Abbott, J.F. Latkowski, R.W. Moir, S. Reyes, R.C. Schmitt
October 8, 2004

Differences & similarities between MTF and Z-IFE reactors

- Both envision reactors with multi-GJ yields, and probably liquid first walls

- Both envision slower rep rates (~0.1 Hz) than conventional IFE, with resultant advantages in clearing the chamber and setting up the target

- Both require target standoff delivery of energy to the imploder (liner/wire array)

- Neither requires target tracking in the reactor chamber

- Z-IFE expects higher Q (due to burning cold-fuel) than batch-burn MTF

- MTF delivers energy on slower timescales, with lower driver voltages, than Z-IFE

- MTF compression ratios and implosion velocities are smaller than needed by Z-IFE

- MTF needs a higher quality vacuum (for its target plasma) than Z-IFE

- It may be possible to combine magnetic insulation with a Z-IFE target

Summary: Key Issues

With Magnetized Target Fusion:

- **Q of ~40 is needed (if pure fusion), or alternatively better than 10% fractional burn-up of DT fuel.**
- **Reliable (millions of pulses, MTBF) pulsed power switching and energy storage components**
- **Liquid blanket development, liquid wall handling and chemical separation technologies**
- **So-called "recyclable transmission line"/ driver stand-off system demonstration**

-- but not fusion materials development
-- but not target tracking

Additional References

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