Realizing Technologies for Magnetized Target Fusion

20th TOFE 2012
Nashville, TN

Aug 27, 2012

Glen A. Wurden

LA-UR-12-24306

Abstract

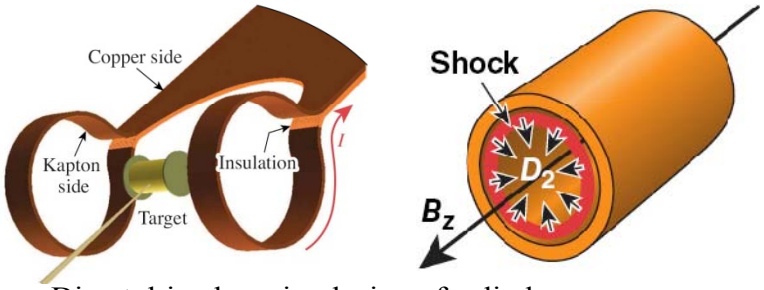
Researchers are making progress with a range of magneto-inertial fusion (MIF) concepts. All of these approaches use the addition of a magnetic field to a target plasma, and then compress the plasma to fusion conditions. The beauty of MIF is that driver power requirements are reduced, compared to classical inertial fusion approaches, and simultaneously the compression timescales can be longer, and required implosion velocities are slower. The presence of a sufficiently large B-field expands the accessibility to ignition, even at lower values of the density-radius product, and can confine fusion alphas. A key constraint is that the lifetime of the MIF target plasma has to be matched to the timescale of the driver technology (whether liners, heavy ions, or lasers). To achieve sufficient burn-up fraction, scaling suggests that larger yields are more effective. To handle the larger yields (GJ level), thick liquid wall chambers are certainly desired (no plasma/neutron damage materials problem) and probably required. With larger yields, slower repetition rates (~0.1-1 Hz) for this intrinsically pulsed approach to fusion are possible, which means that chamber clearing between pulses can be accomplished on timescales that are compatible with simple clearing techniques (flowing liquid droplet curtains). However, demonstration of the required reliable delivery of hundreds of MJ of energy, for millions of pulses per year, is an ongoing pulsed power technical challenge. Supported by OFES and the DOE LANS Contract No. DE-AC52-06NA25396.

Magneto-Inertial Fusion

- A hybrid approach (magnetic + inertial) to achieving fusion plasmas in the laboratory
- It allows access to 1-1000 Megabar pressures and multi-Megagauss fields with macro scale plasmas
- Magnetic fields allow the use of lower velocity drivers for Inertial Fusion Energy (IFE), lower convergence ratios, and larger tamping; which we believe are key advantages
- Experiments with significant neutron yields are possible in the near term
- Multiple driver/target approaches are being tried

A Wide Range of Driver/Target Combinations are possible

U. Rochester LLE



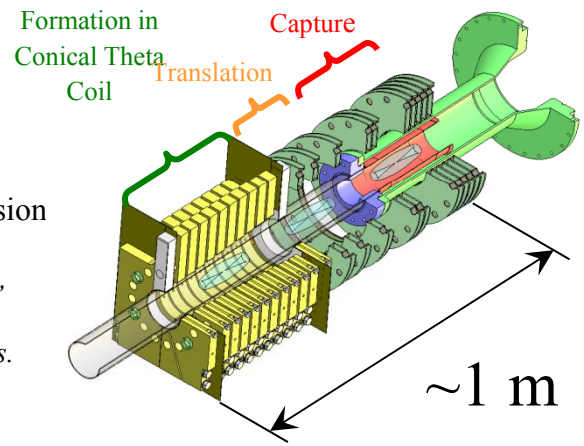
Direct drive laser implosion of cylinders
-- shock pre-heating, high implosion velocity

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

Los Alamos / AFRL

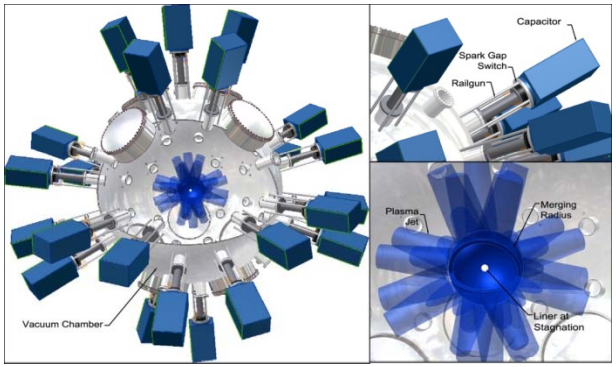
Field Reversed Configuration
Shiva Star FRCHX
~20 µs, 0.5 cm/µs liner implosion

Taccetti, Intrator, Wurden *et al.*, *Rev. Sci, Instr.* 74, 4314 (2003)
Degnan *et al.*, *IEEE Trans. Plas. Sci.* 36, 80 (2008)



Los Alamos / HyperV

Plasma Liner Experiment
Merging plasma jets for remote standoff



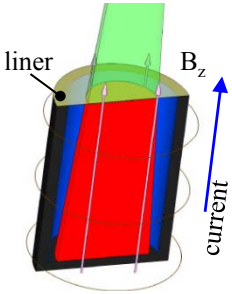
S. C. Hsu, et. al., IEEE Trans Plasm. Sci, 40(5) 1287(2012).

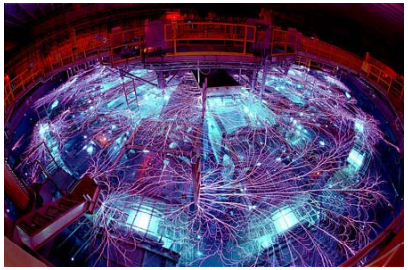
Sandia National Laboratories

Magnetized Liner Inertial Fusion

Laser preheated magnetized fuel

LASNEX simulations indicate interesting yields

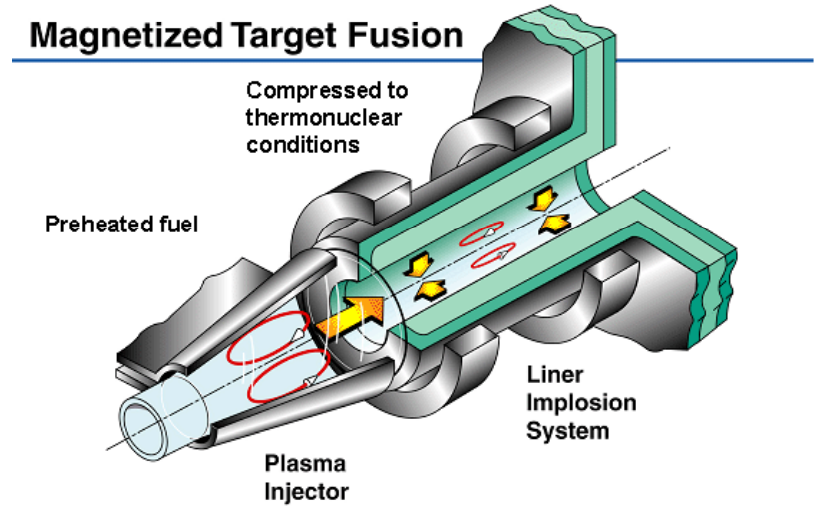




S. A. Slutz, et al., Phys. Plasmas 17, 056303 (2010)

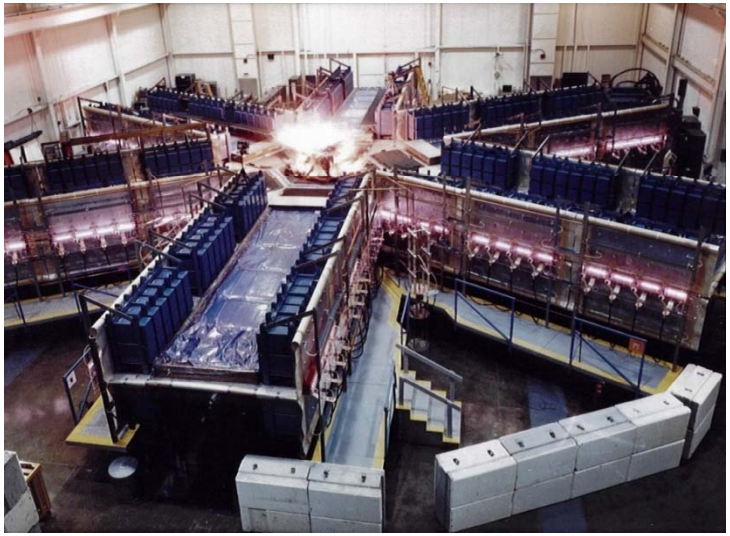
Magnetized Target Fusion (FRC)

CIC-1/00-0126 (11-99)



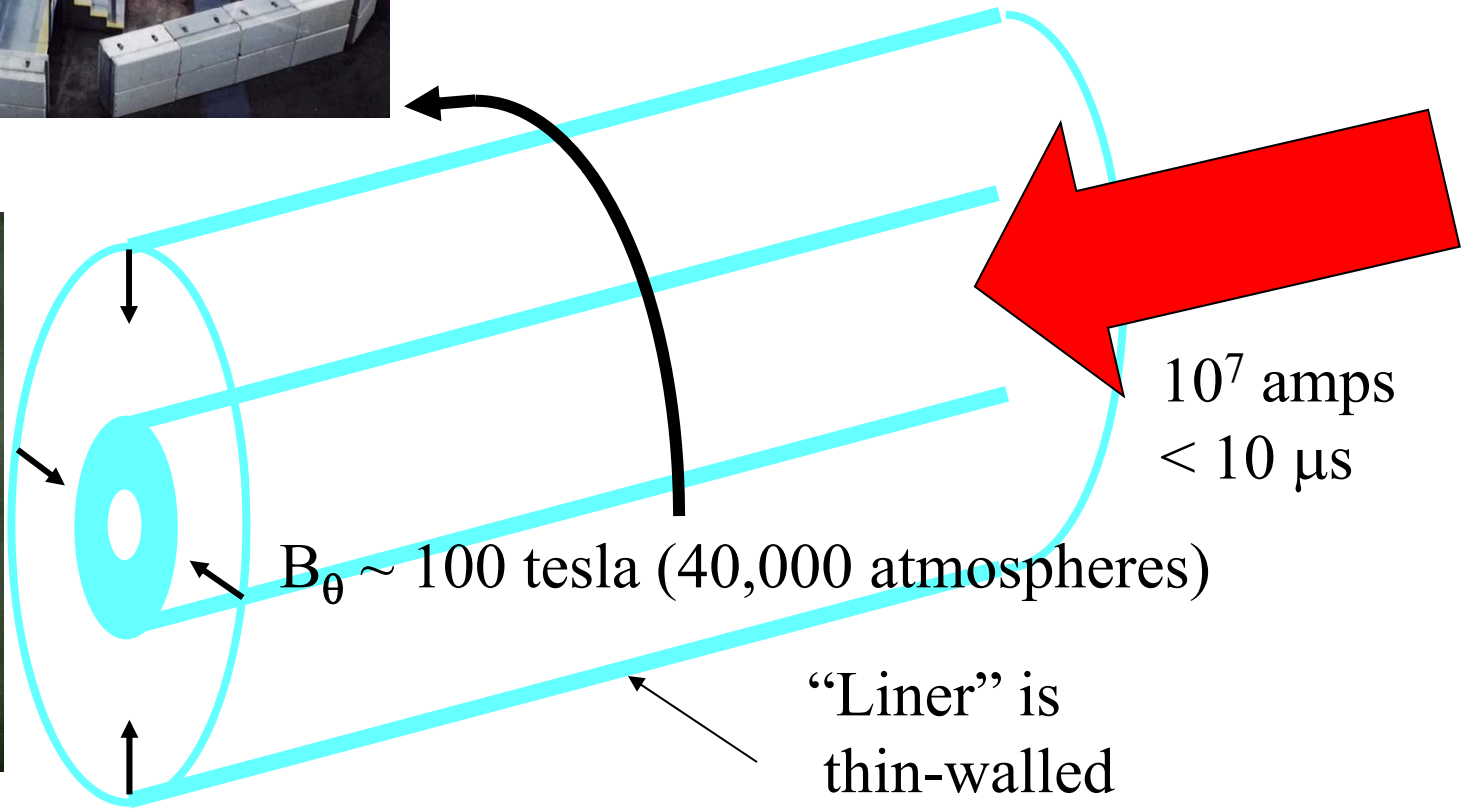
This is a fusion concept where:

- The plasma beta ranges from 0.8 to 1
- The heart of the device fits on a modest table-top
- The plasma density is intermediate ~10^{19} cm^{-3} (MFE~10^{14} cm^{-3}, ICF ~10^{25} cm^{-3})
- The current density can be 1000 MA/m^2
- The magnetic field confining the plasma is 500 Tesla !
- The auxiliary heating power level is ~ 1000 Gigawatts !
- HEDP achieved by “slow” adiabatic compression (to ~1 MBar)
- Research can be conducted with existing facilities and technologies
- In a reactor, on each pulse the liquid first wall is fresh➔ no materials problem!
- The repetition rate would be ~0.1 Hertz, so that there is time to clear the chamber from the previous event

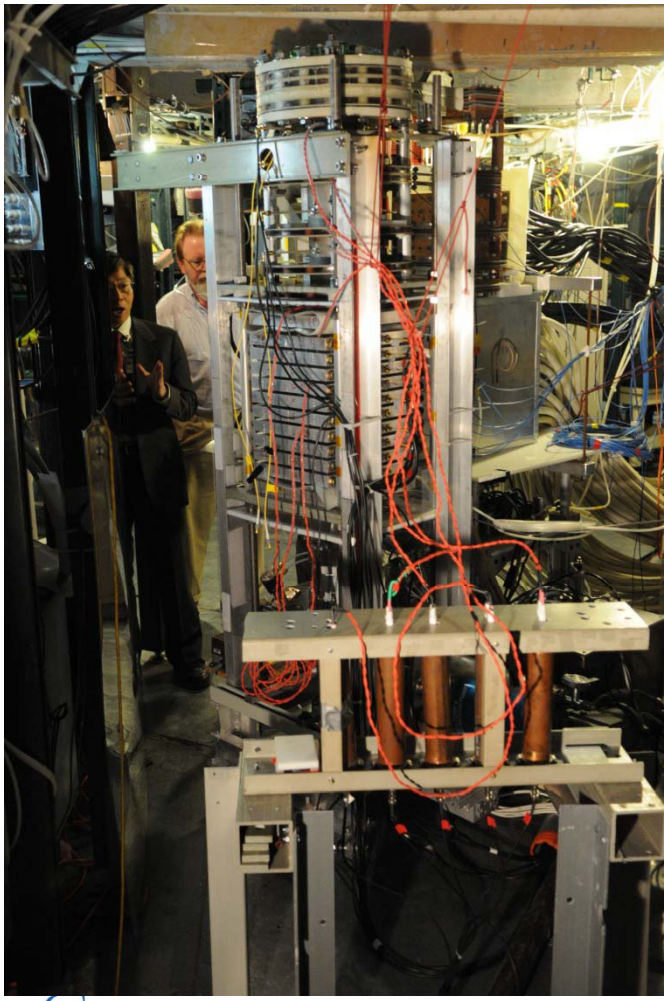


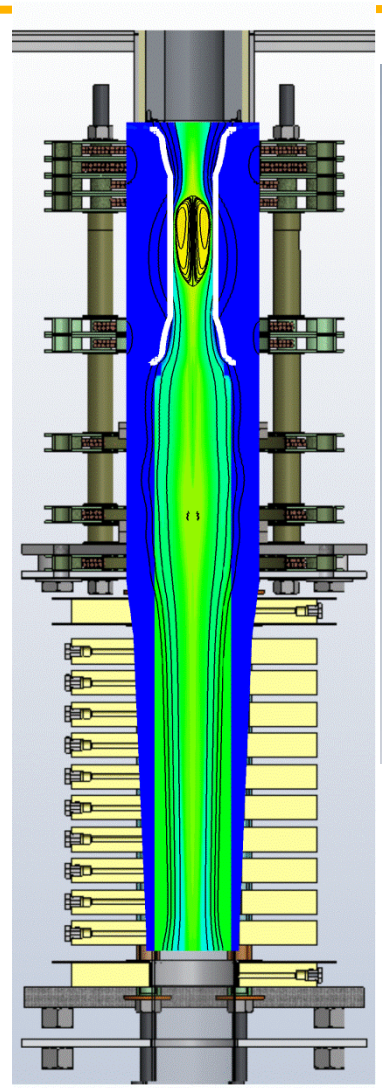
MTF (FRC) uses "can crusher" technology

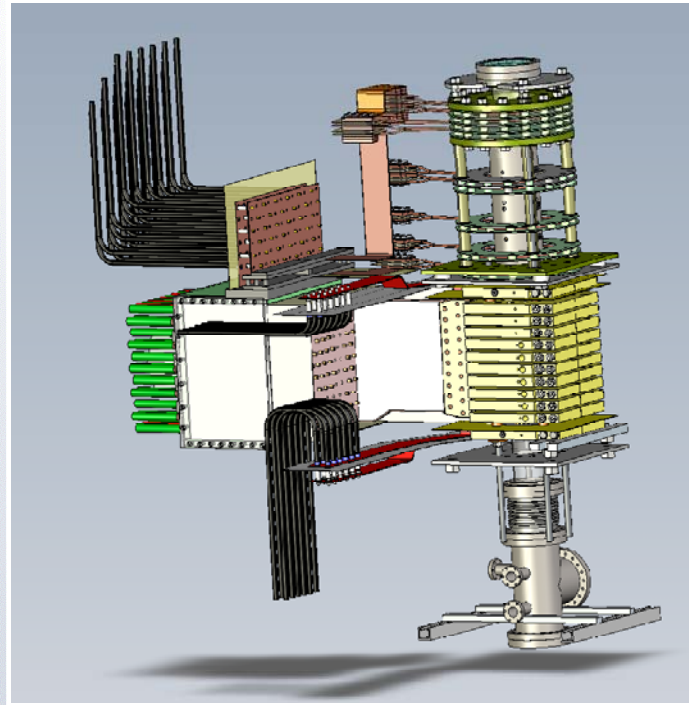
A 1-mm thick aluminum liner is crushed smoothly by J_z x B_Θ force



Magnetized Target Fusion, test of implosion physics





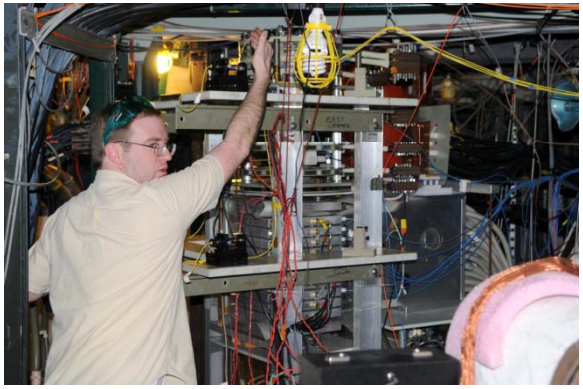


We have had 3 high energy engineering tests shots, followed by the first plasma/liner integrated shot in April 2010. The next shot is planned for Dec 2012, with modified timings and additional hardware to lengthen the FRC lifetime.

Magnetized Target Fusion, test of implosion physics

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

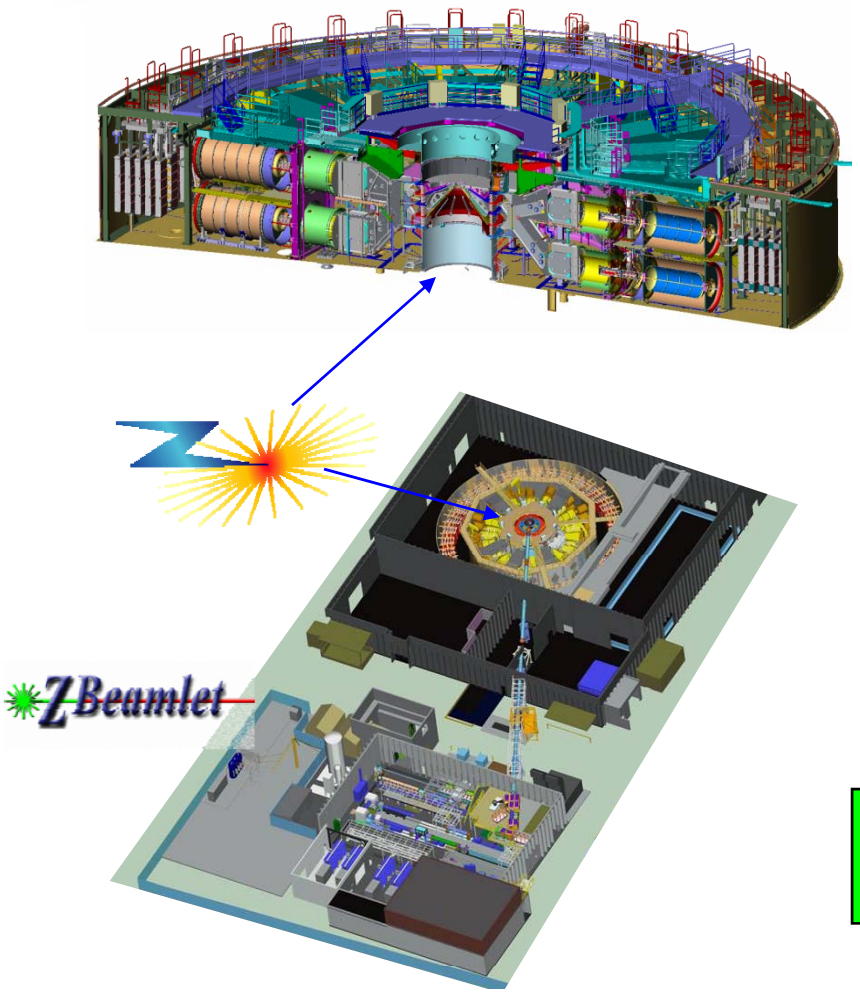
Chief engineer Chris Grabowski by the FRC load stack, under Shiva Star

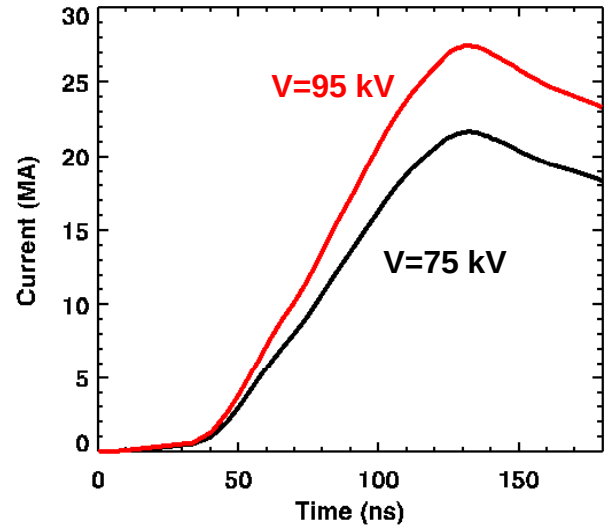


UNM scientist Alan Lynn adjusting multi-chord fiber interferometer on

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

The Z facility contains the worlds largest pulsed power machine and the Z-Beamlet and Z-Petawatt lasers





Magnetically-Driven Cylindrical Implosion

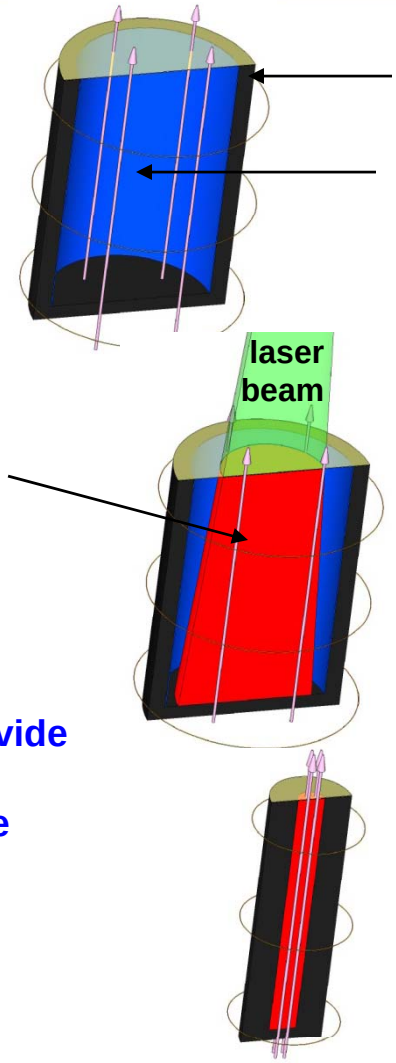
$$P = \frac{B^2}{2\mu_o} = 140\left(\frac{I_{MA}/30}{R_{mm}}\right)^2 MBar$$

By comparison, 140 MBar is generated by 300 eV radiation drive

Steve Slutz, Mark Herman, Mike Cuneo

The Z facility provides an opportunity to test the benefits of fuel magnetization and preheat (MagLIF)

1. An axial magnetic field is applied to inhibit thermal conduction and enhance alpha particle deposition



2. Z Beamlet can ionize and preheat the fuel

3. The Z accelerator can provide the drive current which generates an azimuthal drive field (pressure) to efficiently implode the liner (Z pinch)

Preliminary point design parameters

•Beryllium liner R_0	2.7	mm
•Liner length	5.0	mm
•Aspect Ratio $R_0/\Delta R$	6	
•Initial fuel density	0.003	g/cc
•Final fuel density <on axis>	0.5	g/cc
•Preheat temperature	250	eV
•Peak central averaged Tion	8	keV
•Initial B-field	30	Tesla
•Final peak B-field	13500	Tesla
•Peak current	27	MA
•1D Yield	500	kJ
•Convergence Ratio	23	
•Peak Pressure	3	Gbars

Steve Slutz, Mark Herman, Mike Cuneo

Existing Technology: Lifetime of pulsed power components is an issue

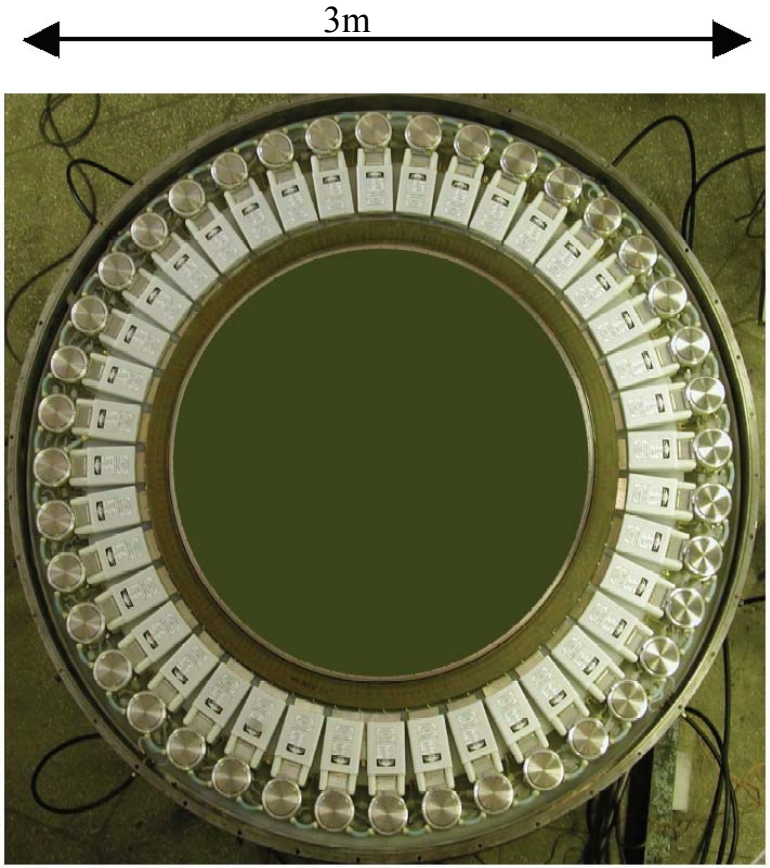
- HV capacitors from General Atomics have rated lifetimes of 10^9 cycles, or 100,000 hours of DC life, subject to reversal constraints.
- 10^8 repetitive shots have been demonstrated at 5 Hz with small prototype switches at 16kV, 2.5 kA/cm^2, by NRL for IFE.
- But presently the highest energy density ones (ATLAS, for example) have only a ~2500 cycle lifetime at 60 kJ and 650kA ratings.

- High Stress Capacitors (33.5 uF, 60 kV, 600 lbs)
- High Current Switches (400kA, 2 Coulombs)
- Paper, foil, & oil Insulation

The technologies that we use today are not ready for million-pulse MIF applications

- Low inductance, rail-gap, plasma switch technologies are good for only a few-hundred pulses before cleaning is required.
- Linear transformer driver (LTD) devices (500kA, 100kV modules) exist, and have been tested in Russia at rep-rate, with gas purging between pulses (36,000+ pulses). They have been proposed for use in an upgraded Z-Machine at Sandia*. But this the lifetime of this technology is still an order of magnitude or more away from reactor needs.

***SANDIA REPORT** SAND2006-5811 Unlimited Release, Printed September 2006
Rapid-fire pulse brings Sandia's Z method closer to goal of developing high-yield fusion reactor, Sandia's press release (April 27 , 2007).



1 MA, 100kV, prototype LTD

Reactor Design?
Engineering concerns similar to 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 MTF 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 $2 \times 6.02 \times 10^{23}$ 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.

The initial target fuel load must be "preheated" to 200 eV (Te+Ti). This is an energy investment of $2 \times (20 \times 10^{-3}) \times 6 \times 10^{23} \times 200$ eV = 4.8×10^{24} eV, or 0.75×10^{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) (3)

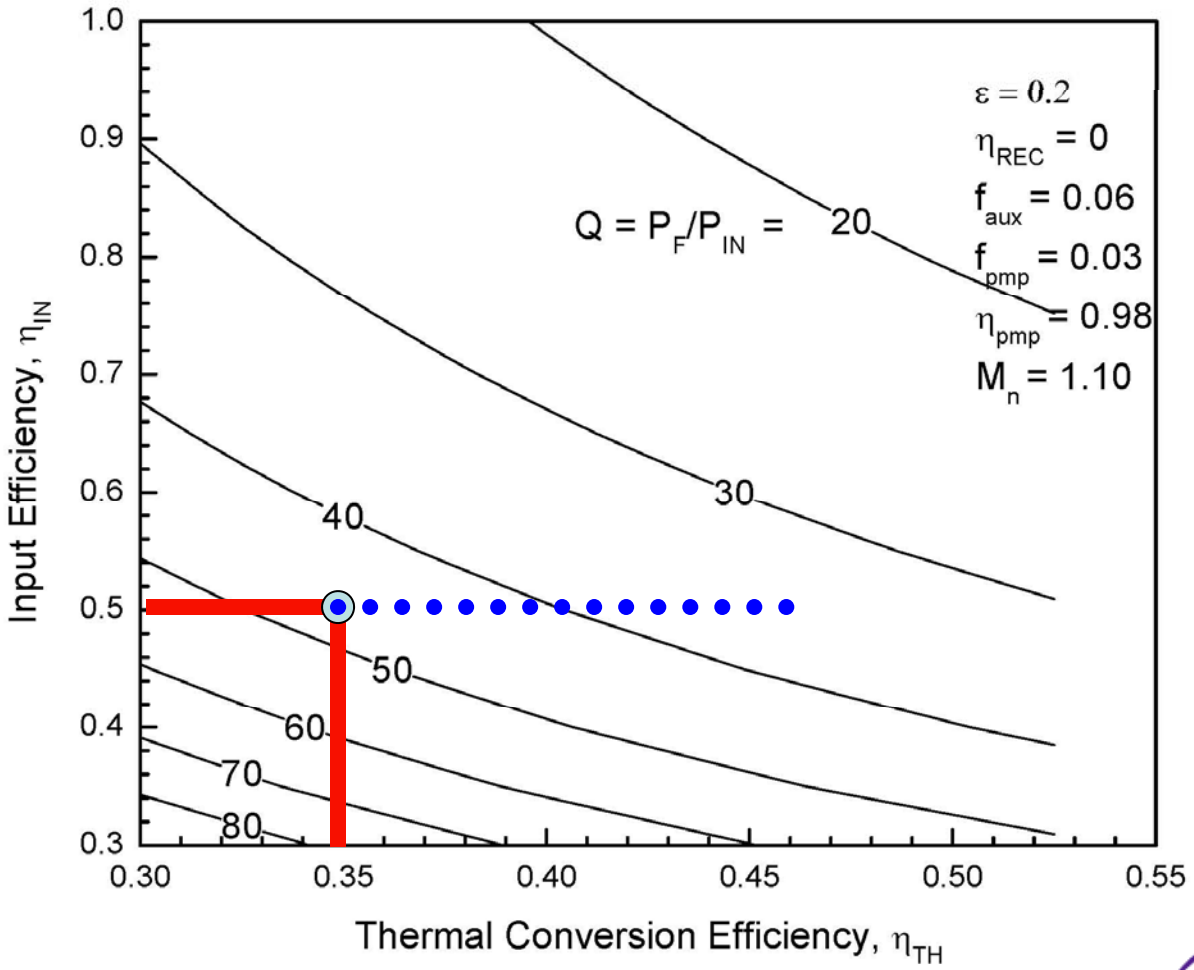
For a 10% DT fuel burnup fraction, an $n\tau_{dwell} \sim 2\times10^{15}$ cm^{-3}sec at 10 keV is required. For example, a final density of 10^{21} cm^{-3} and a liner dwell time of 1μsec would do the trick. This exceeds our projected initial experiments by a factor of ~100.

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. L. 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, then it is easy to double the Q.

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 $7x10^4$ 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, 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.

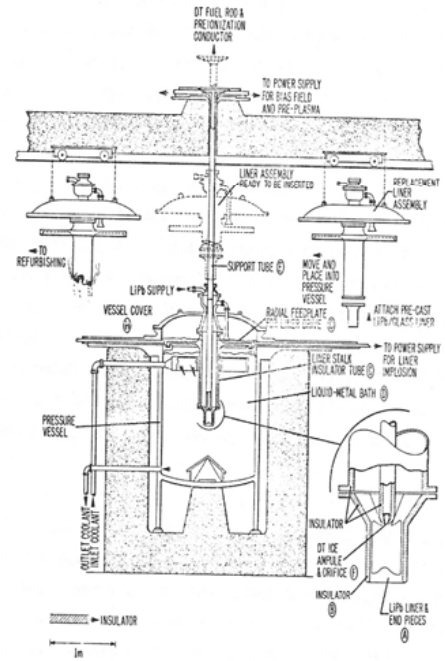
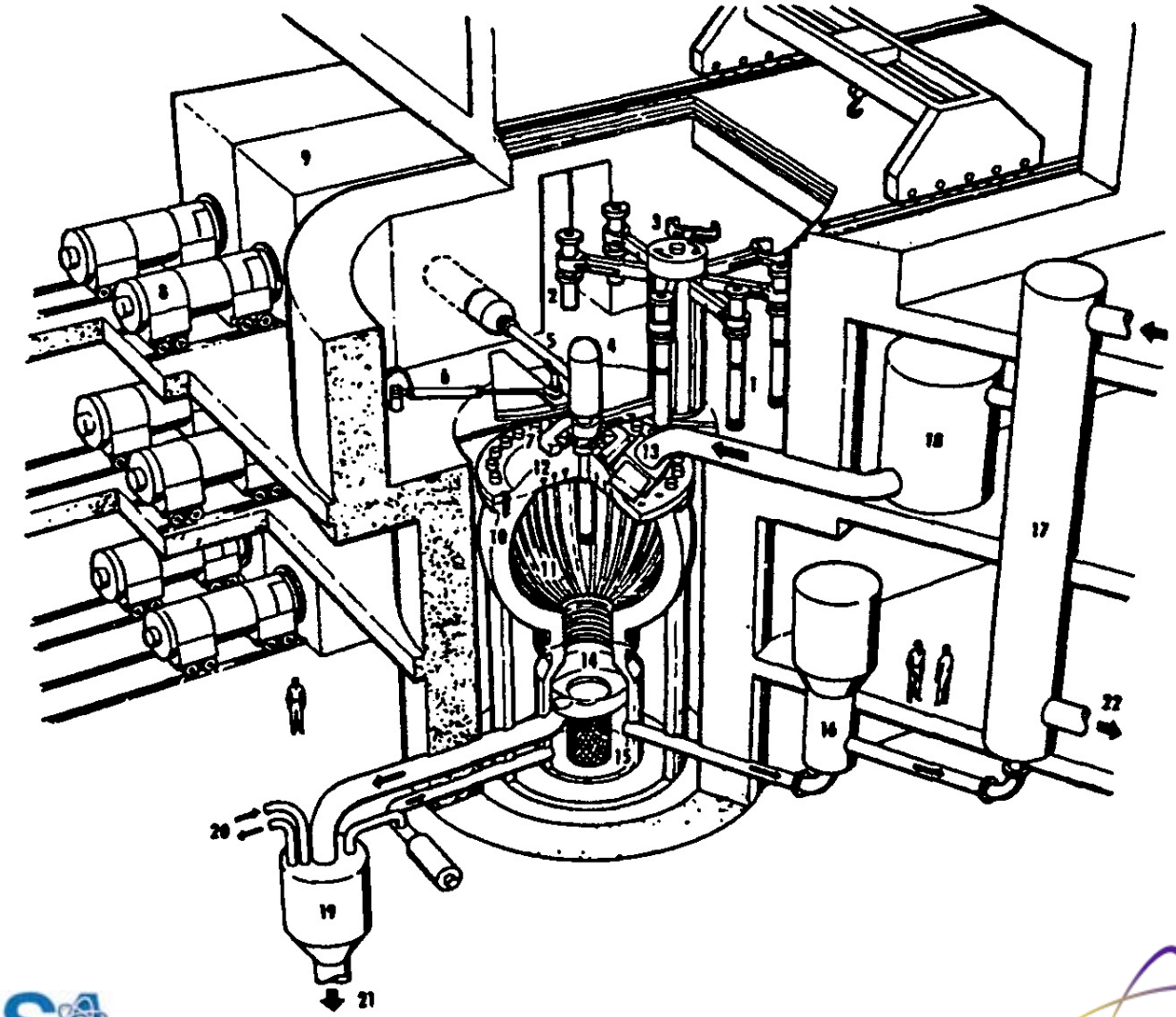


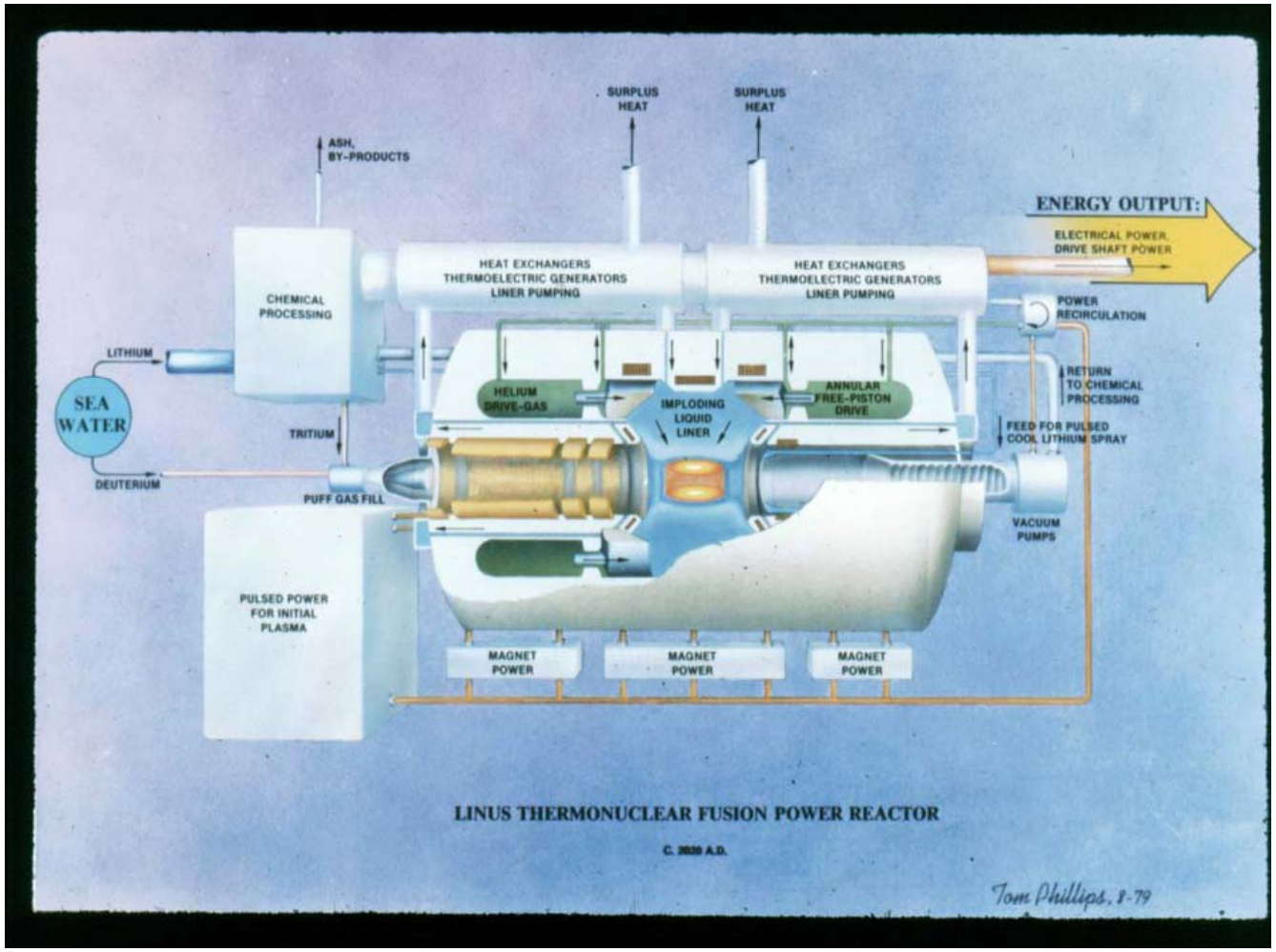
Fig. IV-6.

Schematic diagram of a fast-liner inertially confined reactor (FLICR). Refer to text for description of operation.

LANL Fast Liner Power plant schematic (LA-7686-MS Krakowski, et al. Feb 1979)



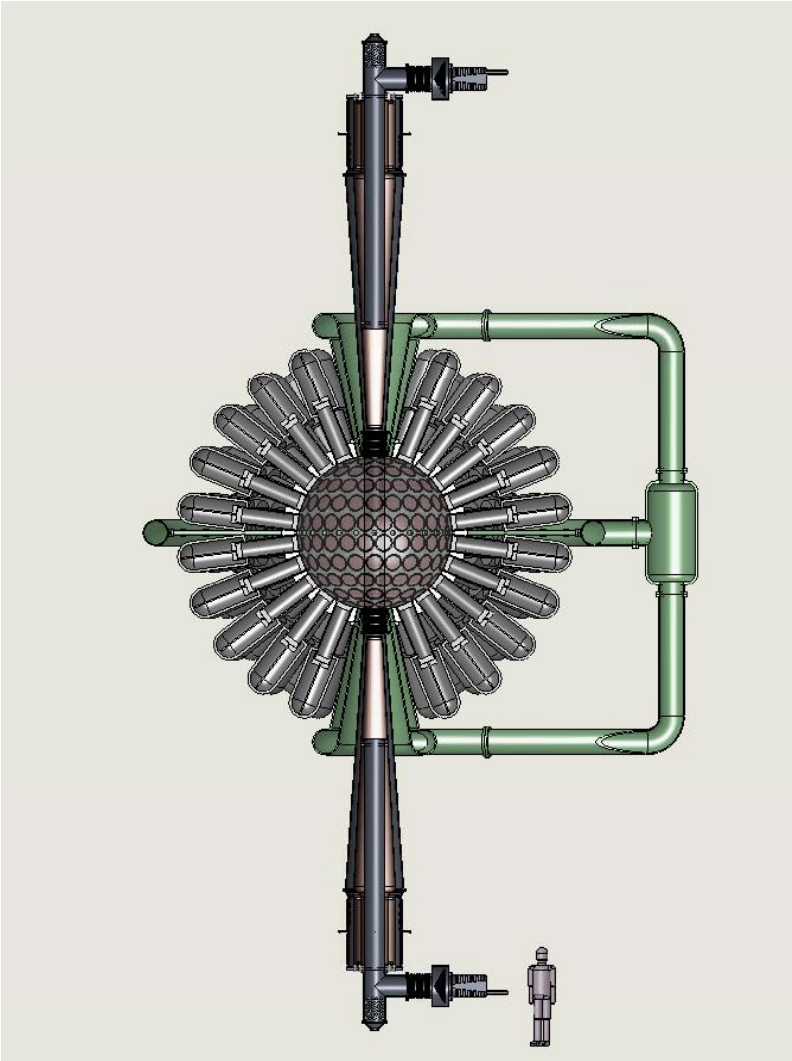
NRL's LINUS (Slow Liner) Study 1979

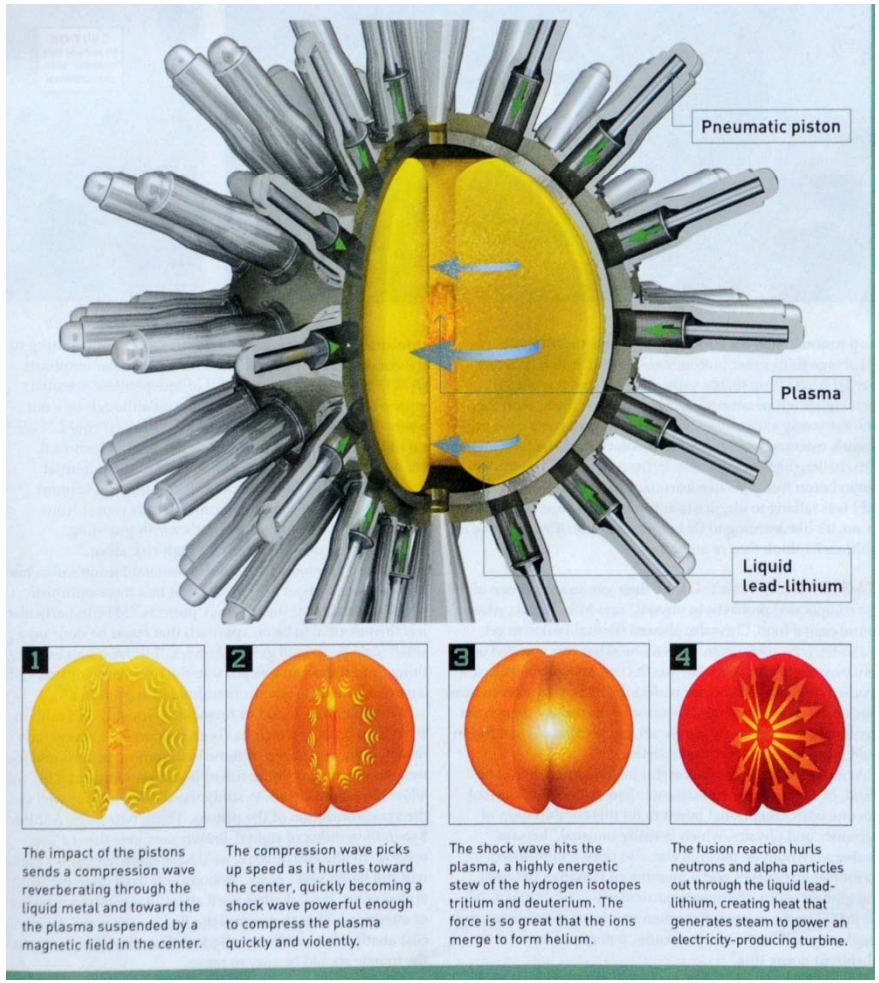


The real issue however was, what plasma (lifetime) was actually compatible with this driver?

NRL Memorandum Report 4092, Sept. 28, 1979, P. Turchi, et al.

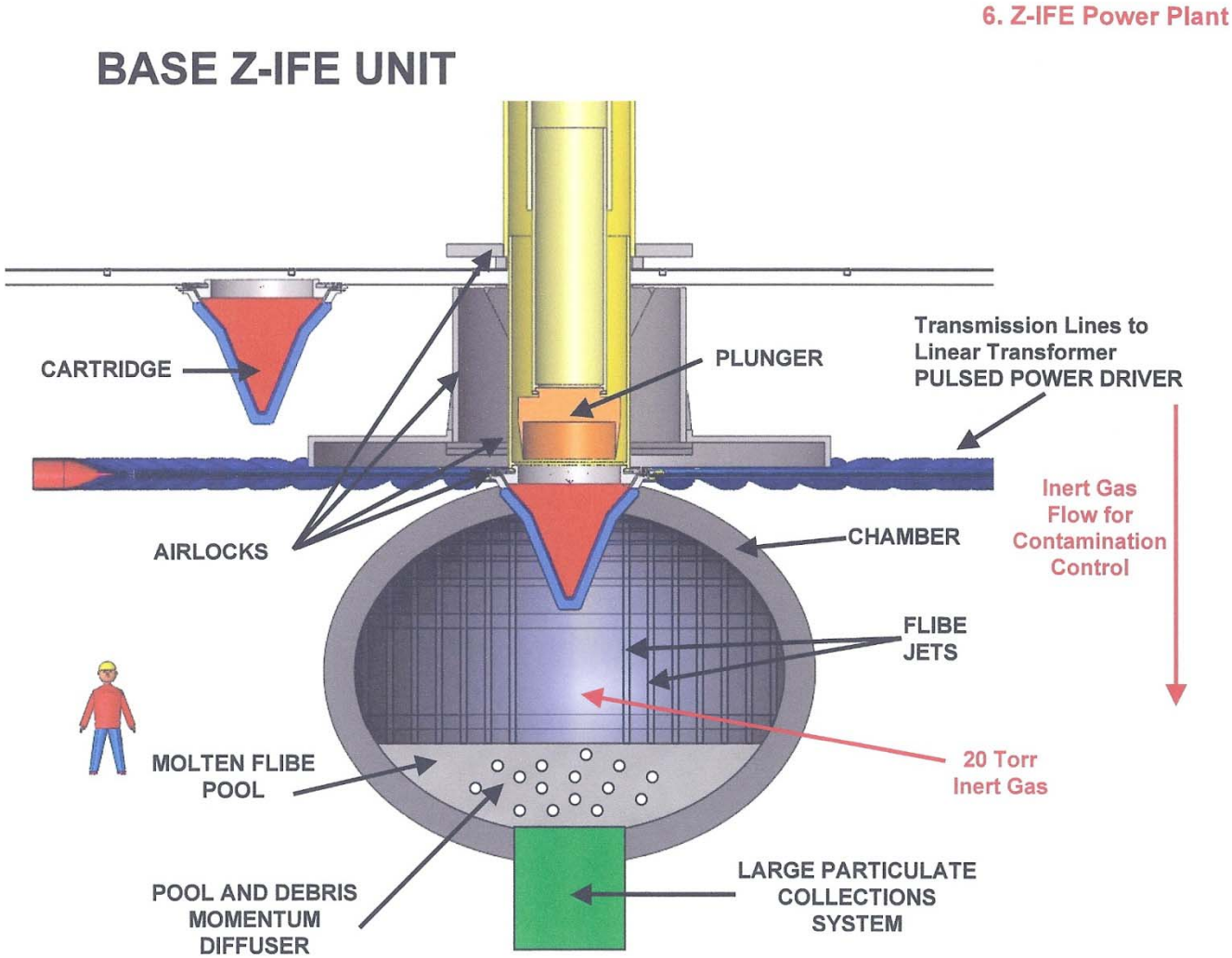
Acoustic piston drivers for MTF: General Fusion (Vancouver, Canada)





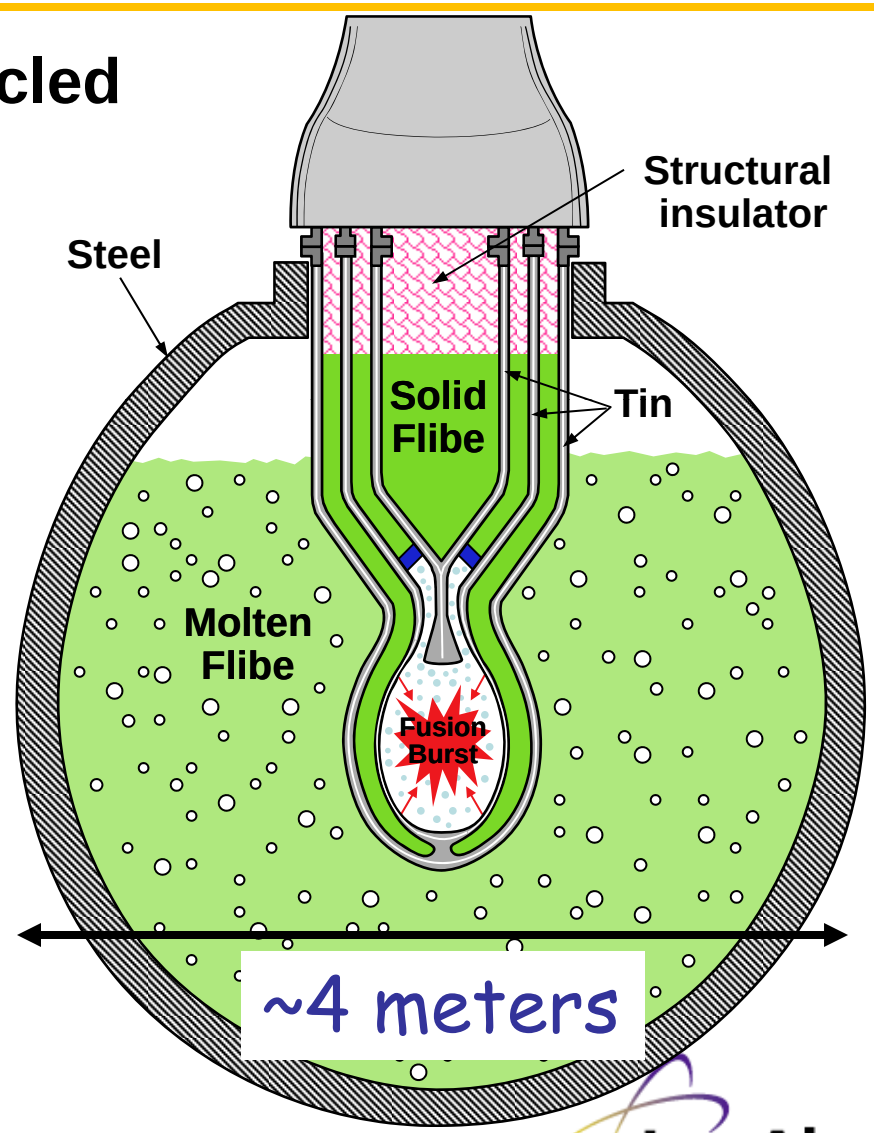
Popular Science, pg. 64-71, Jan. 2009

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 ^{o}C (T_{melt} = 459 ^{o}C)
- Tin T_{melt} = 232 ^{o}C
- P. Peterson, UC Berkeley, ~1998

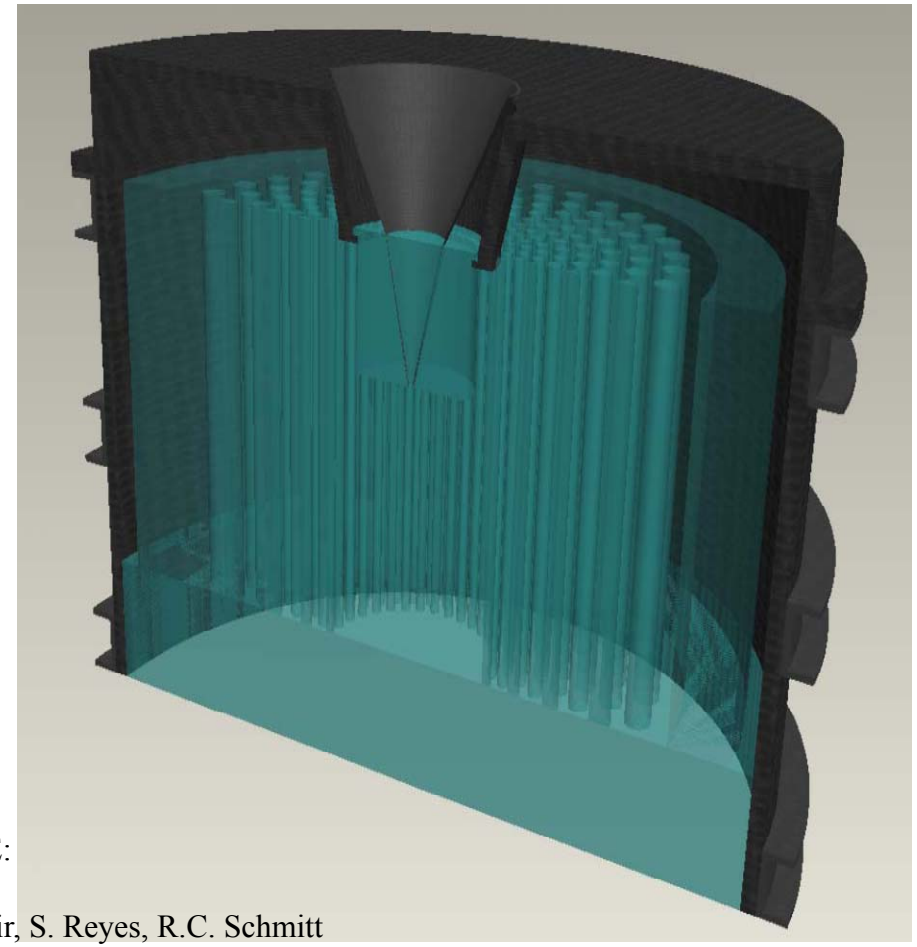


LLNL (3-month) Z-IFE concept design study*

•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/FRC 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 IFE, with resultant advantages in clearing the chamber and setting up the target
- Both require target standoff delivery of energy to the imploder
- 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 (ie, MagLIF)

References

R. Moir "The logic behind thick, liquid-walled, fusion concepts". LLNL UCRL-JC-115748, 1994.

R. W. Moir, R. H. Bulmer, K. Gulec, P. Fogarty, B. Nelson, M. Ohnishi, M. Resnick, T. D. Rognlien, J. F. Santarius, and D. K. Sze, "Thick Liquid-Walled, Field-Reversed Configuration Magnetic Fusion Power Plant," Fusion Technology, 2, 2, Part 2 (March 2001) 758.

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Summary: Key Issues

With Magnetized Target Fusion, you need:

- Q of ~40 (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
-- no cryogenic targets
-- no target-tracking