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# Magneto-Inertial Fusion (Magnetized Target Fusion)

*or “why should we bother with another  
ICF driver/target scheme?”*

G. A. Wurden

*Fusion Power Associates Annual Meeting and Symposium  
Fusion Energy: Expectations  
Dec. 14-15, 2011*

# Some Observations

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***An economic, functioning fusion reactor  
is a long way in the future***

- Most of us believe we need a fusion energy program
- Therefore we should make long-term plans
- Even science programs need long-term facility plans
- It is a good thing to have a plan A
- It is even a better thing to also have a plan B
- Successful programs have community-based long-term plans, where choices are made.

# Magneto-inertial fusion: Part of a plan B

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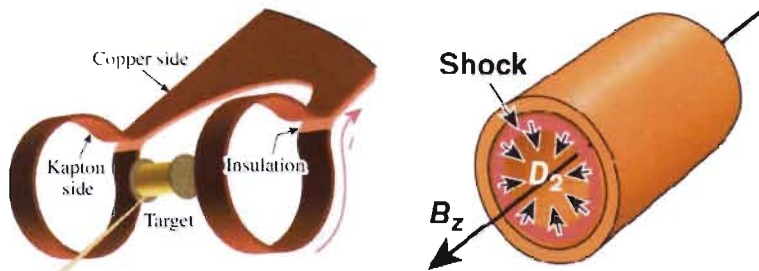
- May allow more efficient drivers, lower cost drivers, lower peak powers, lower implosion velocities, smaller convergence ratios, larger yields, slower repetition rates, easier targeting, the use of non-cryogenic targets, reduced materials problems (if thick liquid walls), and a wider operating space.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

- Magnetized Target Fusion (MTF) demonstration, FRCHX at AFRL in Albuquerque
- Some MIF-IFE reactor considerations
- Musings on the needs of a Fusion Energy Program (whether MFE or IFE)

# 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)



EST. 1943

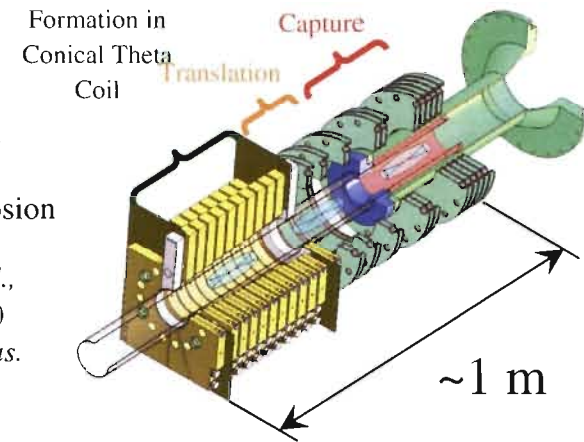
Operated by the Los Alamos National Security, LLC for the DOE/NNSA

## Los Alamos / AFRL

### Field Reversed Configuration Shiva Star FRCHX

~20  $\mu$ s, 0.5 cm/ $\mu$ s liner implosion

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

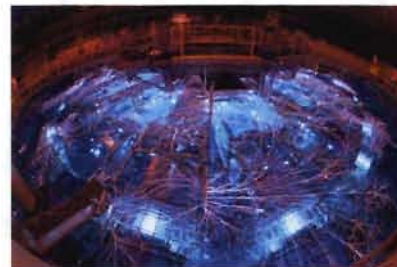
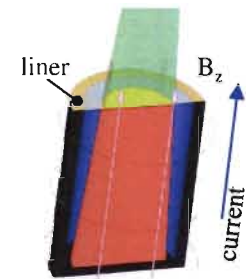


## Sandia National Laboratories

### Magnetized Liner Inertial Fusion

Laser preheated magnetized fuel

LASNEX simulations indicate interesting yields



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

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



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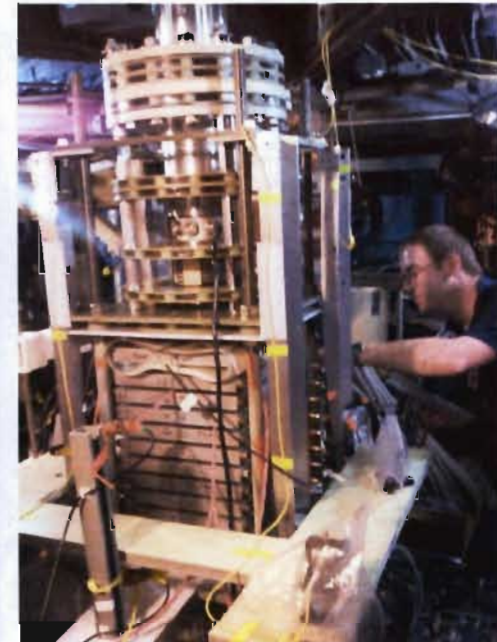
**M. H. Frese, S. D. Frese, J. F. Camacho, S. K. Coffey, V. Makhin** NumerEx LLC, Albuquerque, NM 87106, USA

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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.



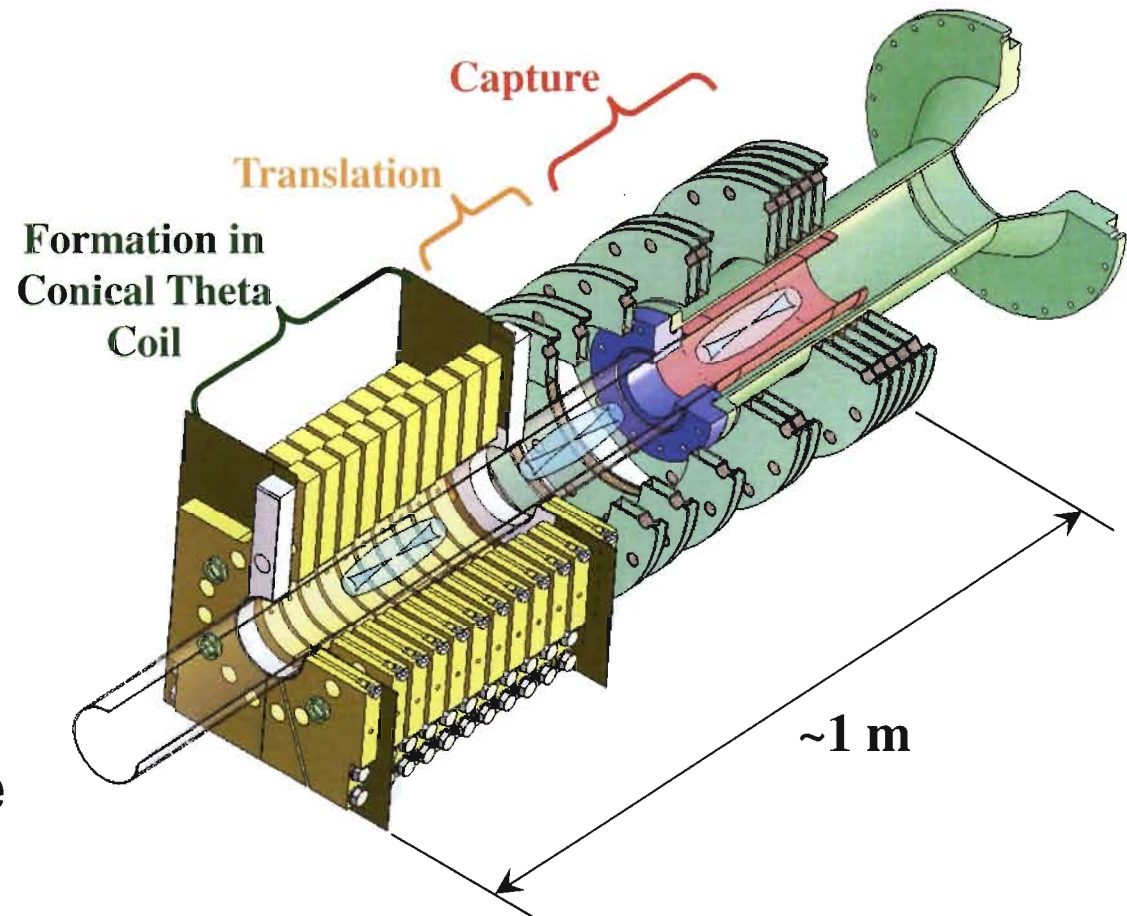


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# FRCHX Schematic

- The FRC is ejected from the formation region by  $J \times B_r$  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

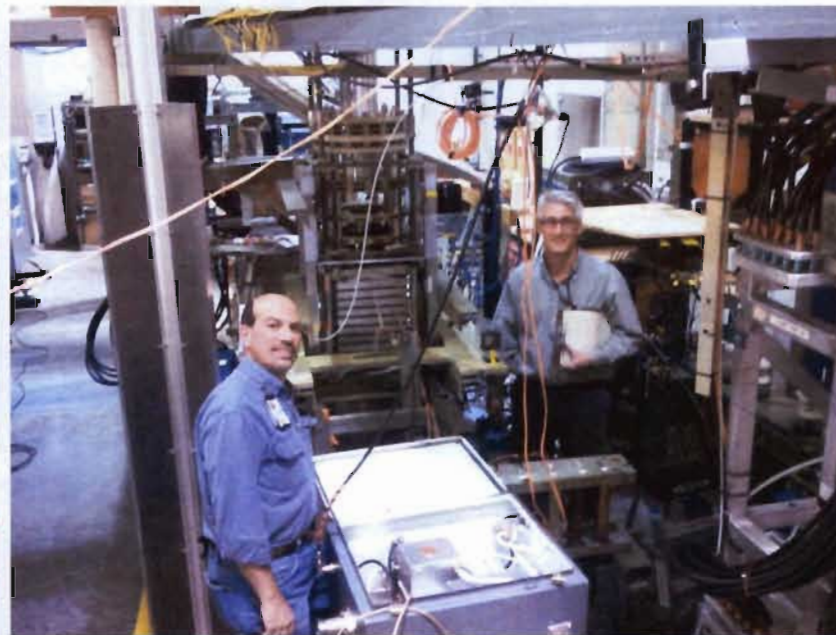




# Magnetized Target Fusion, test of implosion physics



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



Test setup on Dec. 9, 2011

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



Chief engineer Chris Grabowski by the 1<sup>st</sup> full FRC load stack, under Shiva Star



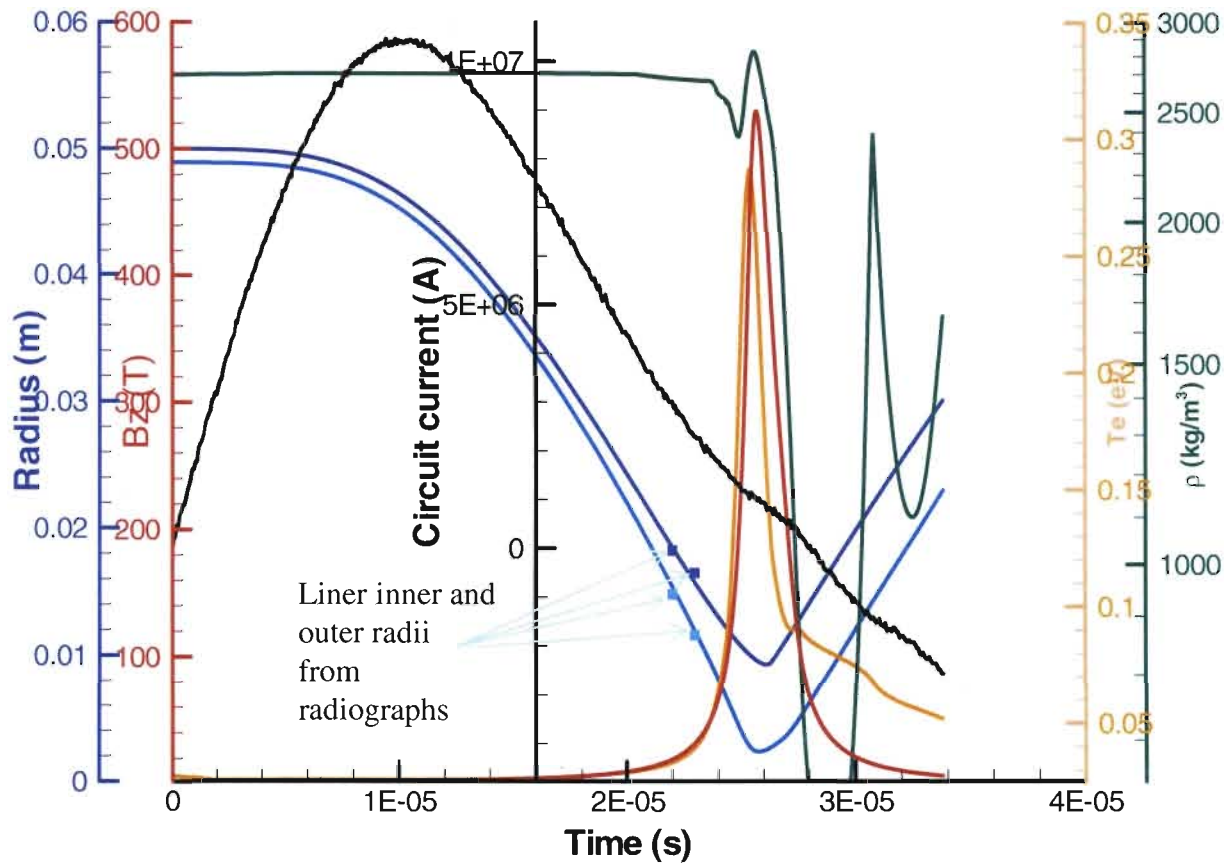
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# Target Plasma Parameters



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

# 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

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## 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<sup>-3</sup>, respectively; trapped flux lifetimes have been only been 6~10  $\mu$ s 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.
- We are working on longer trapped FRC lifetimes, through higher bank settings, better trapping, more uniform preionization, and deploying plasma guns for better preionization and FRC stabilization. Further modifications will be implemented in the next implosion tests in FY12.



## Previous liner implosion solutions: Fast Liner Reactor

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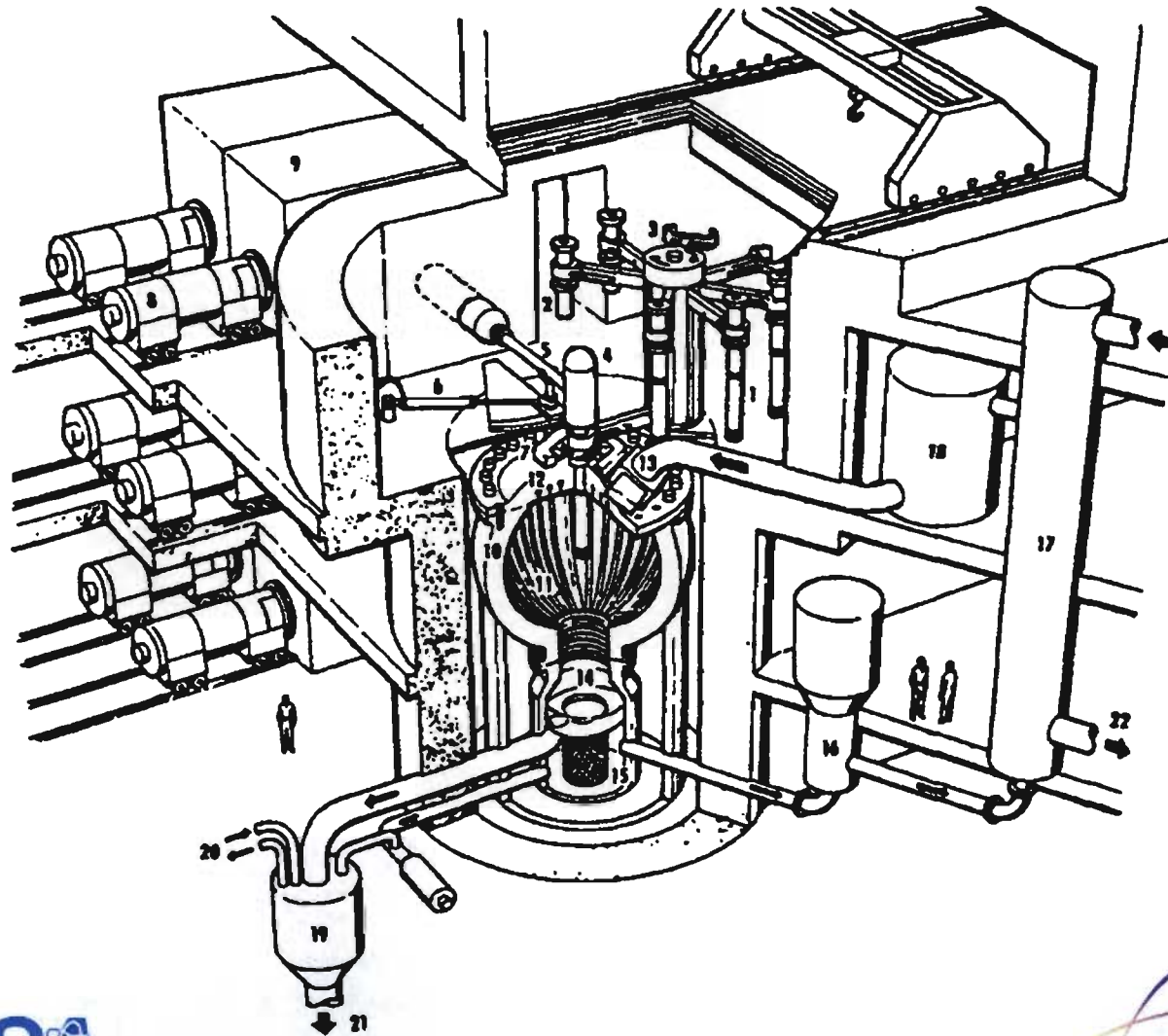
A.R. Sherwood, B.L. Freeman, R.A. Gerwin, T.R. Jarboe, R.A. Krakowski, R.C. Malone, J. Marshall, R.L. Miller, B. Suydam

Los Alamos Scientific Laboratory proposal, LA-6707-P, (1977)

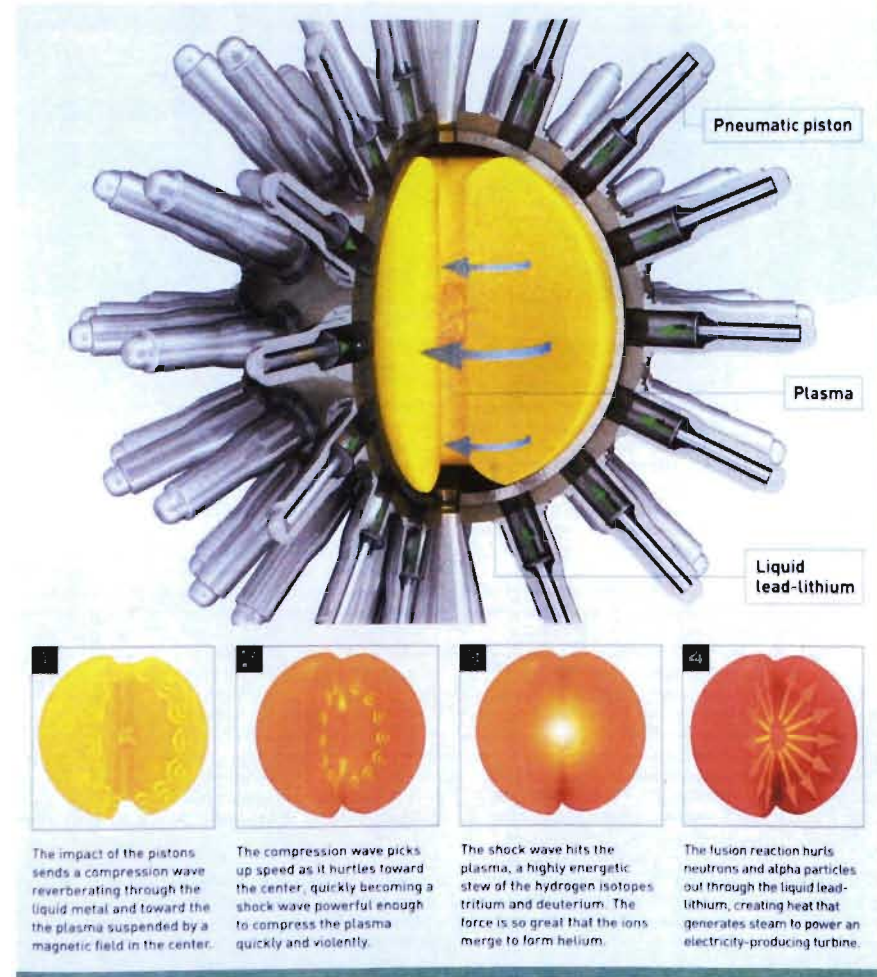
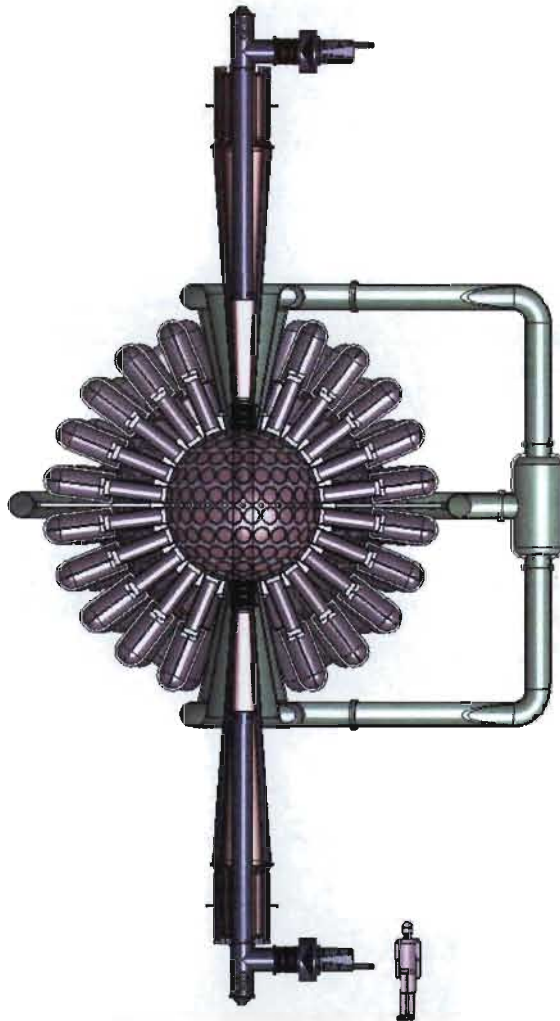
### **Title: Fast liner proposal**

**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)

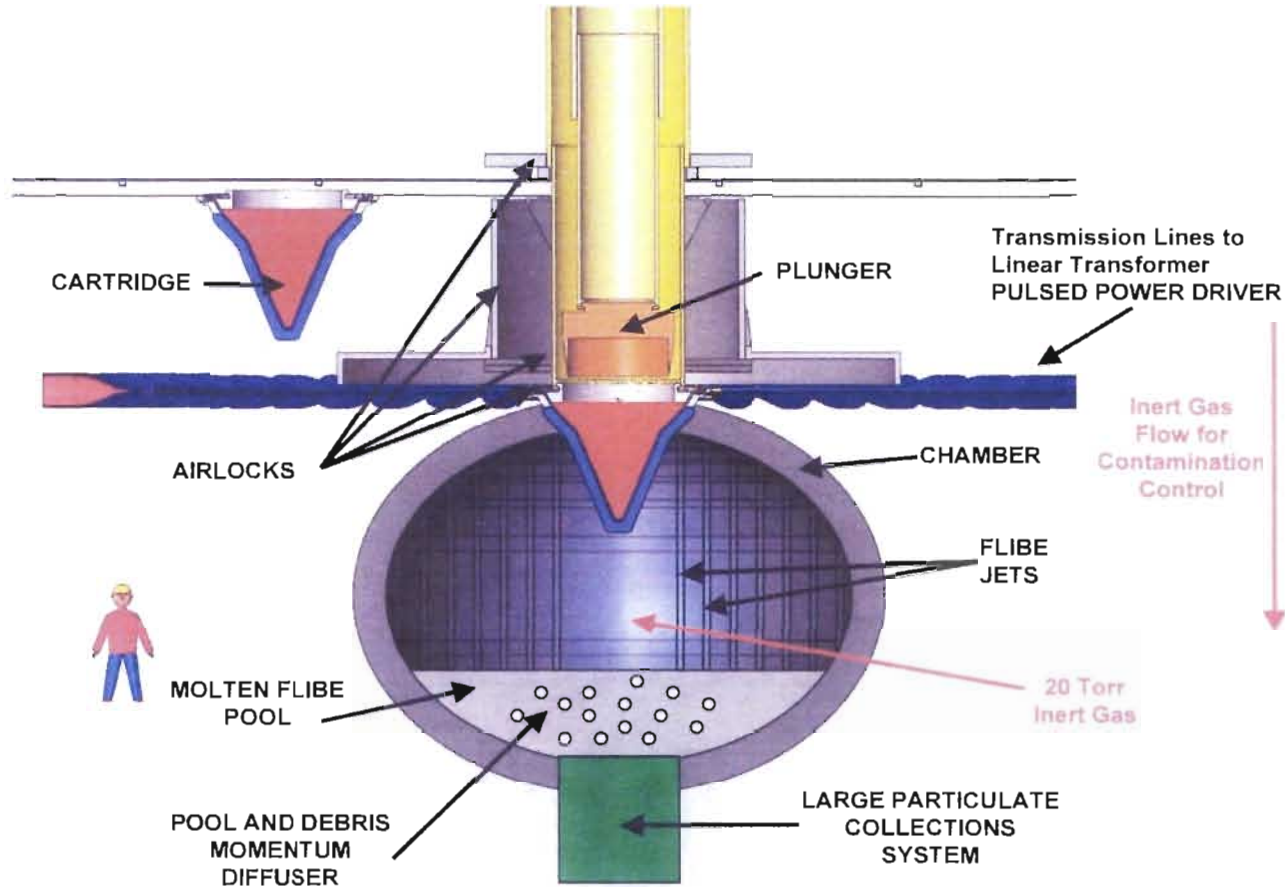


Popular Science, pg. 64-71, Jan. 2009

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

6. Z-IFE Power Plant

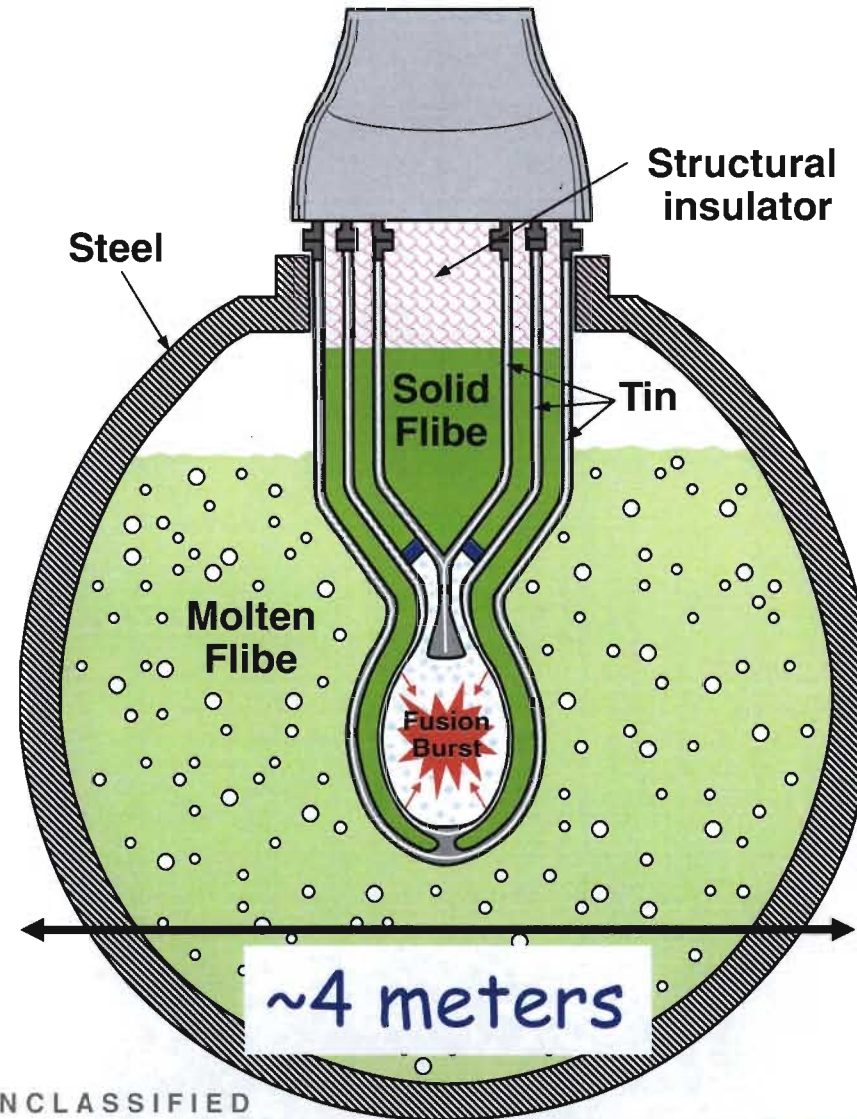
## BASE Z-IFE UNIT





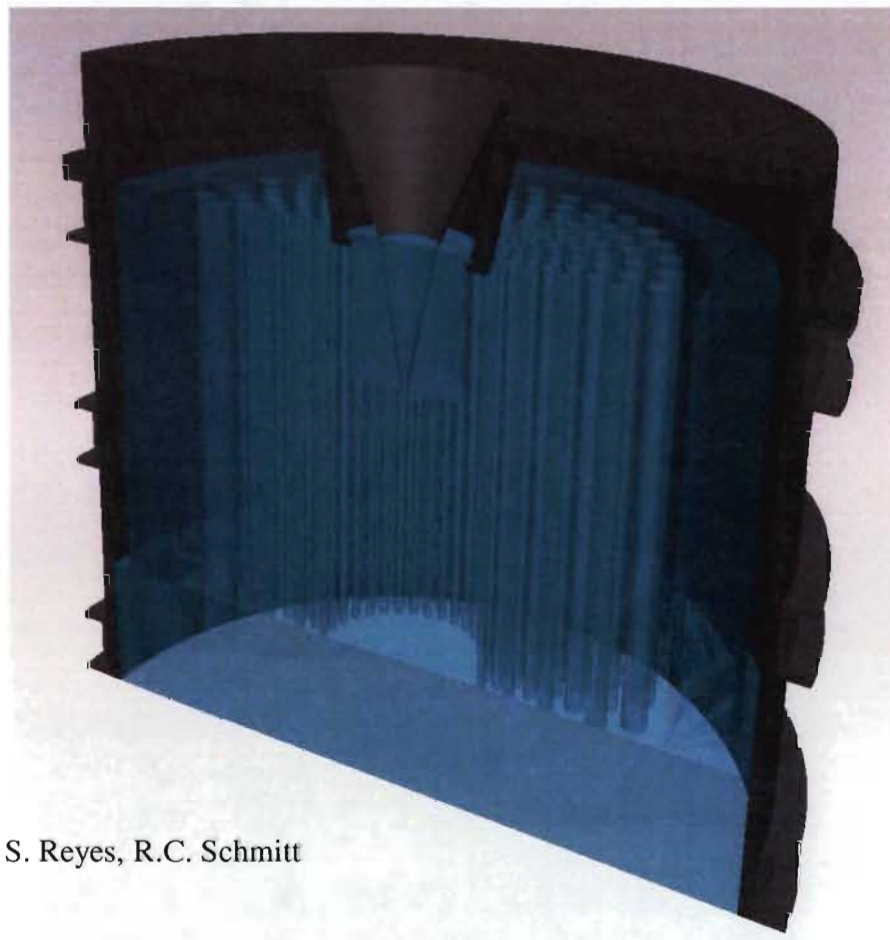
## One vision of an MTF reactor, with miscible materials

- All target material recycled
- 15 sec per pulse
- Flibe primary coolant at 550 °C ( $T_{\text{melt}} = 459 \text{ °C}$ )
- Tin  $T_{\text{melt}} = 232 \text{ °C}$
- 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<sup>3</sup> 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

## Summary: Key Issues with Magnetized Target Fusion

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- Q of  $\sim 40$  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 high convergence
  - but not target tracking

# Musings: The USA has no plan for fusion energy

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- We have now a “science program” for MFE and no program for IFE.
- The science program is perfectly able (and even rewarded) to put more widgets onto its gadgets in order to “do better science”. The mentality is: “If there isn’t “enough” money for new gadgets, then we will just have to hunker down doing widgetry until the time is ripe”.
- At the same time, we are told that ITER is our mission. We have been told that everything we do must support ITER. No ICC’s for their own sake. But FES has not given any fusion energy program plan to Congress, even though it has been asked at least three times in recent years. If ITER collapses for any reason, then where are we?
- The reality is that as a community, we have questions that must be asked, pondered, and decided upon collectively, or it will be done “for us”.



## My Expectations are basic and straightforward:

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*We must change our way of doing the business of fusion research*

Many have noted we have credibility problems. Why is this?

Is it overpromising? Our previous plans were not realistic. Our present plan is nonexistent?

Is it because of lack of demonstrated solutions (...to breeding, to plasma control, etc)?

Is it because of miracle materials needs (ie, solid material damage from neutrons/plasma)?

Is it because of complexity? Which affects reliability and availability?

Is it due to the need to give more emphasis to engineering issues?

Is it because of large scale and long development times? 40 years for ITER?

And ITER makes no electricity?

Is it because the machines & economics looks unattractive to any electric utility?

Is it because we aren't "unified" and we "bicker too much"?

I posit that all of these points above are issues that have to be solved for a realistic fusion energy plan. Furthermore, if the present "path" looks difficult with respect to these issues, then we must re-examine ALL of our assumptions.

## Resources are limited. We must plan for the future

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The only new MFE facility in the USA, has private (not FES) funding:  
(the Tri-Alpha “C-2” beam driven FRC experiment)

The most recent machine FES was building, was the NCSX stellarator,  
but it was cancelled May 22, 2008.

The biggest MFE facilities, just built, or being built, are overseas:  
KSTAR, EAST, W7-X, JT-60SA, IFMIF, ITER

Certainly we should collaborate on them.....that should be/is part of a plan.

### **Question:**

Do we want to be running ANY of our “big” 20-30 year old MFE machines  
10 years from now?

If the answer is NO....then what is the plan?

If the answer is YES.... then what is the plan?

# The Peer-Competed part of the FES budget is a small Fraction

Solicitation	Date issued	Proposals due	\$ anticipated
Theoretical Research in Magnetic Fusion Energy Science	Mar 21, 2011	May 26, 2011	\$3.3M
NSF/DOE Partnership in Basic Plasma Science and Engineering	Oct 6, 2010	Oct 7, 2011	\$2M – joint with NSF
National Spherical Torus Experiment: Diagnostic Measurements of Spherical Torus Plasmas	Aug 1, 2011	Oct 18, 2011	\$2M.
Scientific Discovery through Advanced Computing: Scientific Computation Application Partnerships in Fusion Energy Science	Aug 3, 2011	Oct 26, 2011	\$6.6M, FES & ASCR
High Energy Density Laboratory Plasmas	Sept 8, 2011	Nov 3, 2011	\$14M
Materials Solicitation with Focus on Structural Materials, Blanket First Walls, and Divertor Plasma Facing Components	Oct 17, 2011	Dec 23, 2011	\$2.6M

This adds up to \$30.6M being competed this year (out of > \$300M total).

To have a national effort on materials, with only \$2.6M available for competition?

(A single Energy Frontier Research Center (EFRC) is typically \$5M/year)

To have a national HEDLP program, that has nearly 200 proposals competing for \$14M?

To not have a needed national Fusion Simulation Project?

## US-ITER estimated project costs are pushing \$2.6B at this time\*

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- Plans and scenarios to deal with these costs, the bulk of which occur before 2020, need to be discussed by and with the community.
- It doesn't matter if the goals change next week or next month, or if we don't have firm cost estimates yet. We need an open process.
- We need to collectively talk about ideal, non-ideal, flat, etc, budget scenarios, and what they would mean to the US plasma programs and to our ability to deliver for ITER.
- This need has nothing to do with embargoed FES out-year budget requests.
- We also need to talk about the scenario of withdrawing from ITER, what the closeout costs would be, and what a “plan” would look like for that case.

\*There is no official public number



## What national process for a Fusion Energy plan should we have?

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- Back in the Snowmass (1999-2002) era, we at least had open community discussions and Town Meetings. We also came to an agreement for going forward with ITER, which specifically excluded consuming the base program to pay for ITER. Our “Priorities Panel” never actually established priorities.
- We have had a recent 2011 MFE Roadmapping Workshop, which is a start, especially for international connections.
- The HEPAP P5 (Particle Physics Project Prioritization Plan) May 29, 2008 report is an example of a community-driven strategic plan.

(1) *US Particle Physics: Scientific Opportunities, A Strategic Plan*

[http://science.energy.gov/~media/hep/pdf/files/pdfs/p5\\_report\\_06022008.pdf](http://science.energy.gov/~media/hep/pdf/files/pdfs/p5_report_06022008.pdf)

## Reactor Design?

### Engineering concerns similar to conventional Inertial Fusion Energy

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- 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

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- 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  $1 \text{ eV} = 1.6 \times 10^{-19} \text{ Joules}$ , one has  $2.8 \times 10^{-12} \text{ Joules per DT reaction}$ ; so you need  $1.4 \times 10^{21}$  reactions per 4.1 GJ released.



## Basic points (continued)

(2)

A mole of D<sub>2</sub> is  $2 \times 6.02 \times 10^{23}$  D atoms, and same for mole of T<sub>2</sub>. So each 4.1 GJ pulse burns up approximately 1 milliMole of D<sub>2</sub>, and 1 milliMole of T<sub>2</sub>. D<sub>2</sub> has a molecular weight of 4 grams/Mole, and T<sub>2</sub> 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  $2 \times (20 \times 10^{-3}) \times 6 \times 10^{23} \times 200 \text{ eV} = 4.8 \times 10^{24} \text{ eV}$ , or  $0.75 \times 10^6 \text{ Joules}$ , 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  $Q_{DT}$ )  $\sim 34$ .

If the electric-to-liner drive efficiency is  $\sim 50\%$ , the system gain is reduced to  $\sim 17$ , 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)

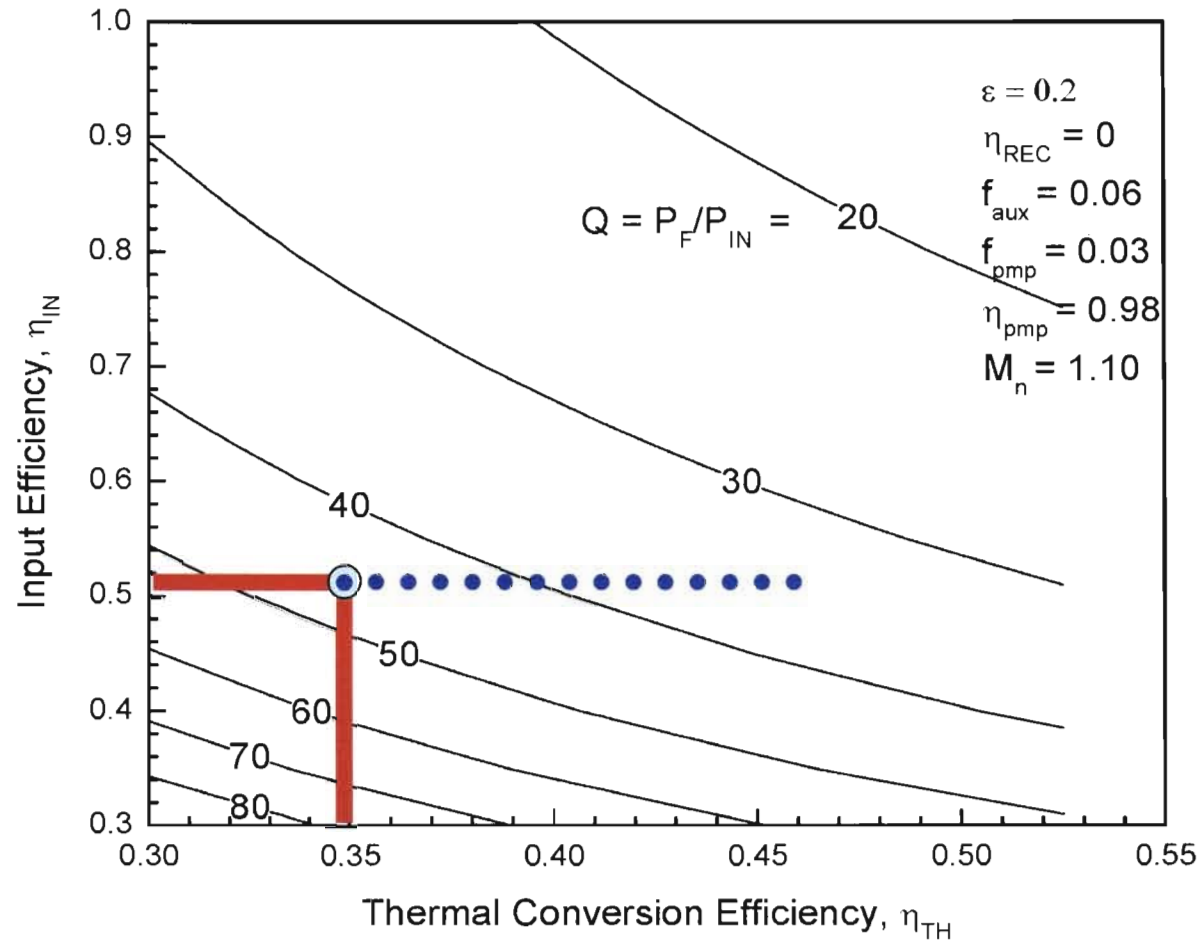
(4)

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

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  $\sim \$100\text{M}$ . 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  $Q \sim 45$



R. A. Miller  
Decysive Systems



# Thick liquid wall recirculation is not a big energy hit

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- The chemical composition of pure FLIBE is  $\text{Li}_2\text{BeF}_4$ .
- 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  $8.5 \times 10^{22}$  atoms/cc. This is an exposed blanket inventory of about  $7 \times 10^4$  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.