Magnetized Target Fusion: Potential Path From Science To Practical Fusion Energy

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abstract

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Magneto Inertial Fusion (MIF) inertial adiabatic compression of a plasma fuel target takes advantage of embedded magnetic field to reduce thermal conduction and enhance alpha-particle heating. This allows operation at reduced values of areal density (ρr) for fusion ignition when compared to non magnetized inertial compression approaches. It also relaxes implosion speed (5-100 km/sec), convergence (≈10:1), power, precision, and expense (more efficient pulsed power driver) for requirements for the chosen compression scheme. A wide range of MIF time and length scales can be realized from nearly ICF parameters (time ≈ 100 psec, length ≈ 25μm) to many orders of magnitude larger time scales of micro seconds and cm spatial scales. This versatile set of approaches allows considerable latitude for tackling the engineering and technology problems.

Magnetized Target Fusion (MTF) is a subset of MIF, requiring target plasma formation plus ejection into a solid flux conserving compressor shell or liner that implodes and compresses a plasma target, as shown in Fig. 1. When generalized for MTF the usual ICF burn fraction estimate must include a large tamping correction. The liner has much larger mass than the compressed fuel, which increases the dwell time because it scales as the square root of the total mass. It appears possible to exceed the typical figure of merit $\eta G > 10$ which is the product of (high) driver efficiency η and (small) fusion gain G. We describe a variety of MTF approaches, some conclusions about the scaling characteristics, and show recent data including experimental engineering test shots in a collaboration to realize a physics demonstration of MTF.

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Outline

- Magneto Inertial Fusion: MIF
  - A hybrid (magnetic + inertial) approach to fusion
  - High risk – high payoff
  - Example: Magnetized Target Fusion:MTF
    - FRCHX (AFRL) - Implosion to MegaBar pressure
    - FRXL (LANL) formation
- MIF reactor issues
- Platform for science
  - Compressed plasma = High Energy Density
  - Initial plasma = Field Reversed Configuration

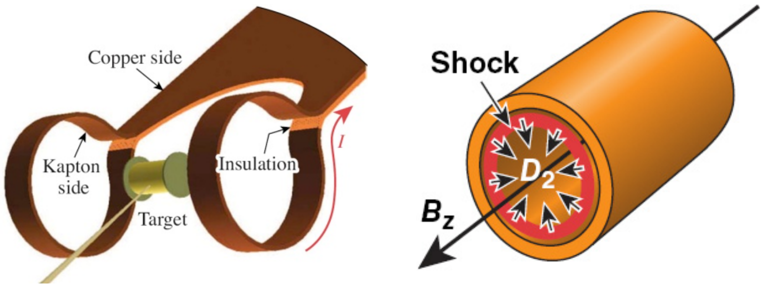
Magneto–inertial fusion

- MIF regime lies between magnetic and inertial fusion approaches
- access to 1-100 Megabar pressures and multi-Megagauss magnetic fields
- Compared to ICF
  - Embedded magnetic field improves confinement
  - macro scale plasmas (μm→ cm)
  - Lower velocity implosion drivers (≈ 0.5cm/μsec)
  - Lower compression ratio (≈ 10:1)

- National Academy of Science IFE Review documents available at: http://fire.pppl.gov/icf_nas_review_2010.html
- Scientific American, May 26, 2011
- Popular Science

Wide Range of Driver/Target Combinations

U. Rochester LLE



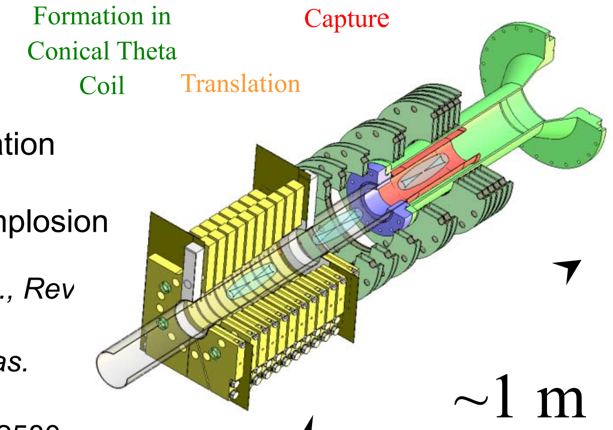
Direct drive laser implosion of cylinders
-- shock pre-heating, high implosion velocity

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

Los Alamos / AFRL

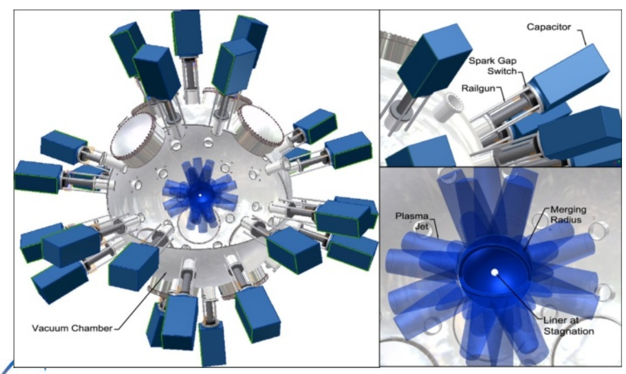
Field Reversed Configuration
Shiva Star FRCHX
~20 μs, 0.5 cm/μs liner implosion

Taccetti, Intrator, Wurden *et al.*, *Rev Sci, Instr.* **74**, 4314 (2003)
Degnan *et al.*, *IEEE Trans. Plas. Sci.* **36**, 80 (2008)
Intrator et al Phys Plas **11**(5), 2580 (2004)



Los Alamos / HyperV

Plasma Liner Experiment
Merging plasma jets for remote standoff



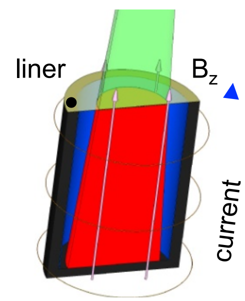
A. G. Lynn, et al, *Rev. Sci. Instr.* 81, 10E115 (2010)

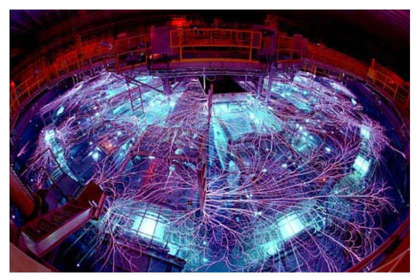
Sandia National Laboratories

Magnetized Liner Inertial Fusion

Laser preheated magnetized fuel

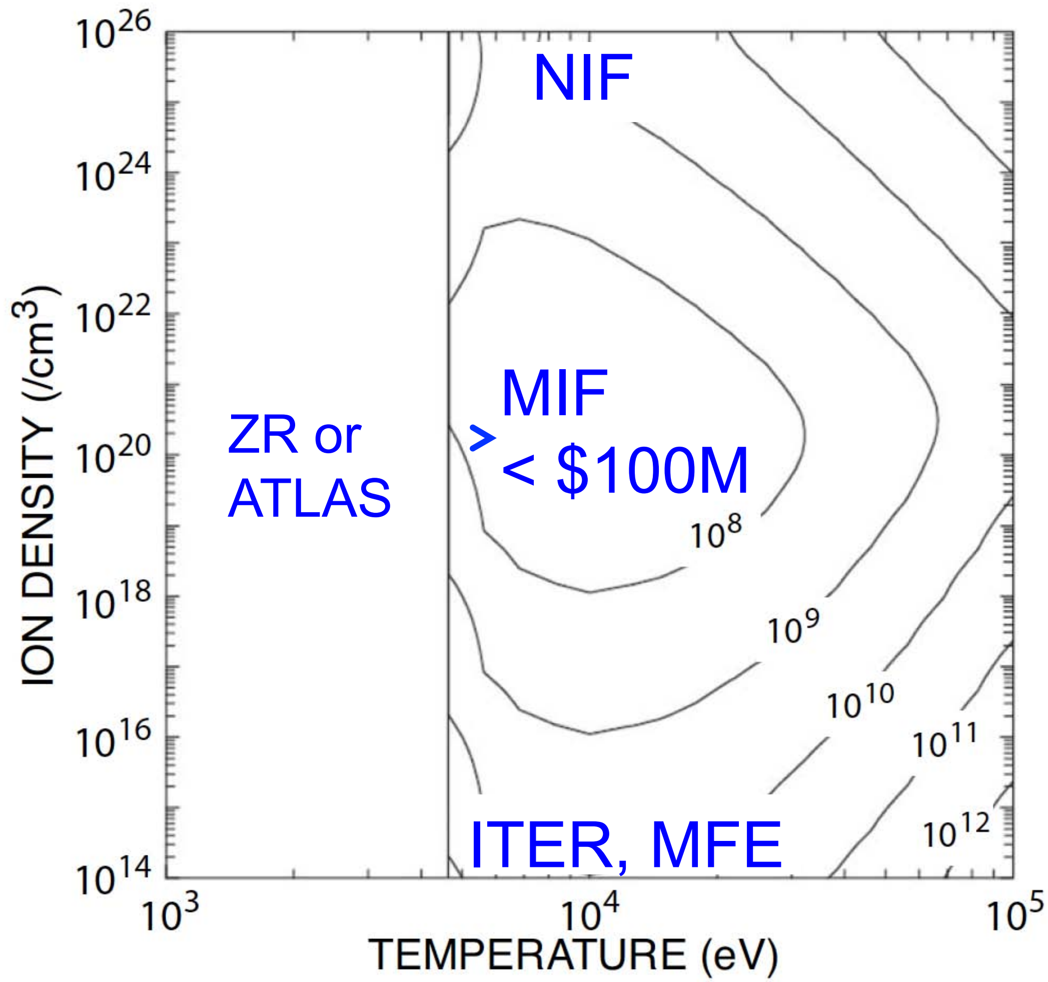
LASNEX simulations indicate interesting yields





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

MIF could be a low cost alternative



From Fig. 7: Lindemuth & Siemon, Amer Journ Phys, **77**(5), 407, (2009)

Facility US$ cost:
- plasma energy E_{PLAS}
- heating power P_{HEAT}
- Bohm loss rate

$Cost = c_1 E_{PLAS} + c_2 P_{HEAT}$

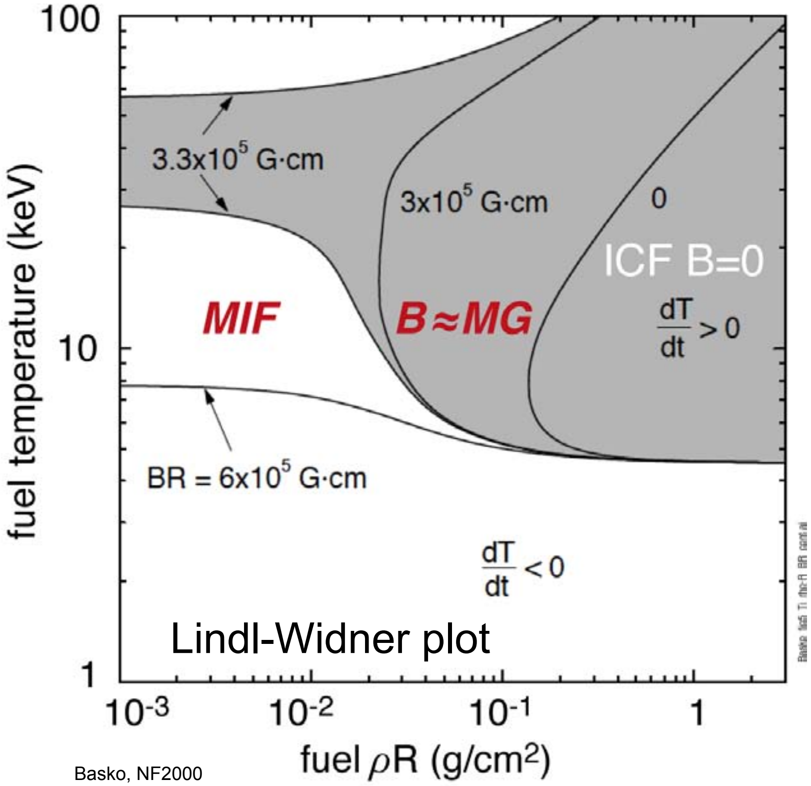
$\approx \$10B\ E_{PLAS} / E_{ITER} + \$3B\ P_{HEAT} / P_{NIF}$

Where

E_{ITER} = 320 MegaJoule

P_{NIF} = 1.1×10^{14} Watt

MIF operates at reduced ρR



Basko, NF2000

- Compression $r_0/r \approx 10\text{-}15$
- B ≈ 3-6 MG
- BR ≈ 0.6 MG-cm
- P ≈ Mbar

FRXL

- $n_{D0} \approx 5 \times 10^{16} cm^{-3}$
- $\rho_{D0} \approx 1$ ngm/cm^3

<u>*compressed*</u>

- $\rho_{Dc}R \approx 20$ ngm/cm^2
- Fuel mass ≈ 1 μgm

Next: FRC cannon (inductive acceleration)

$n_{D0} \approx 10^{18}\ cm^{-3}$

$\rho_{D0} \approx 3\ \mu$gm/cm^3

<u>*Compressed:*</u> $\rho_{Dc}R \approx 0.2$ mgm/cm^2, Fuel mass ≈ 3 mgm

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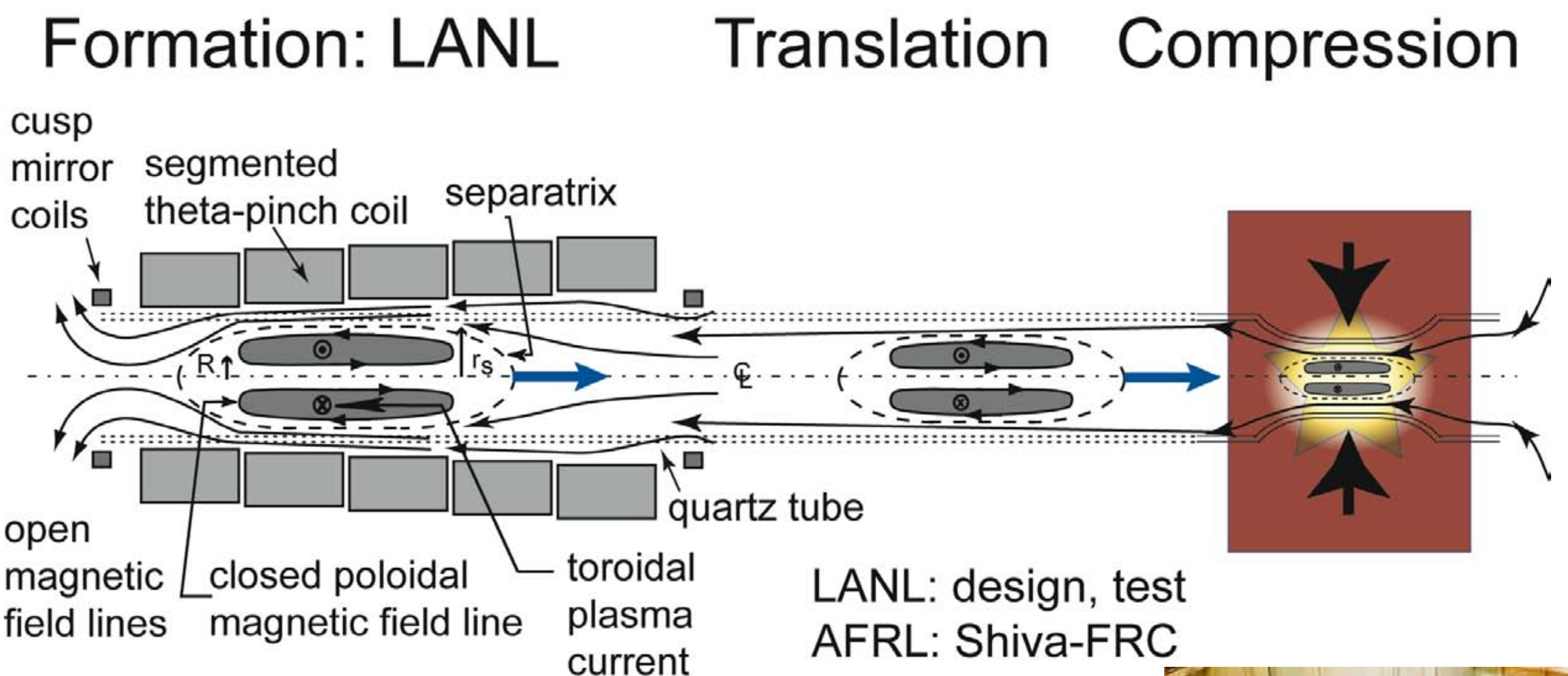
MIF collaborations

- Air Force Research Laboratory - Kirtland Albuquerque: first solid liner on plasma experiment
- LANL: plasma target development, translation physics
- Univ Nevada-Reno: Z pinch plasma surface interactions

MTF: subset of MIF



LANL: design, test
AFRL: Shiva-FRC

- Target: Field Reversed Configuration
- High plasma/magnetic pressure: β
- Natural divertor isolates walls, impurities

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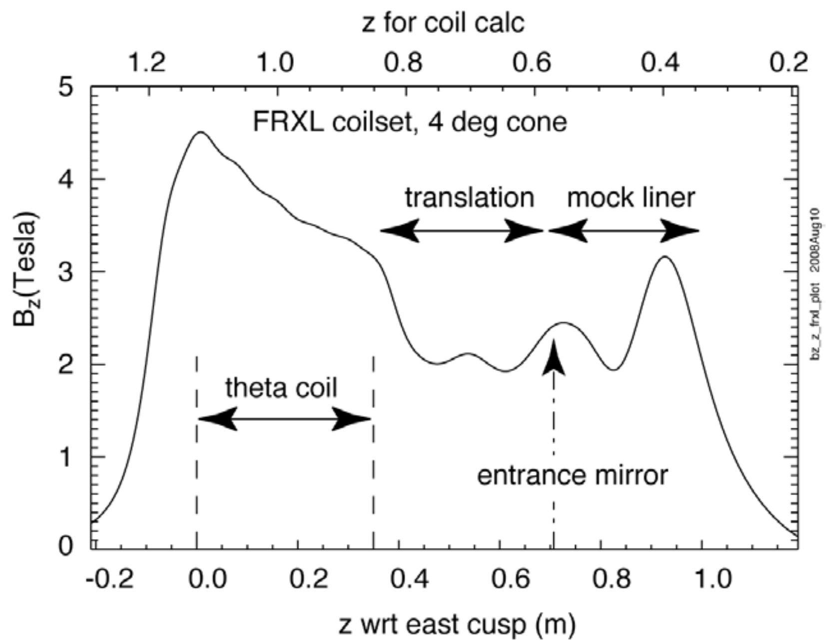
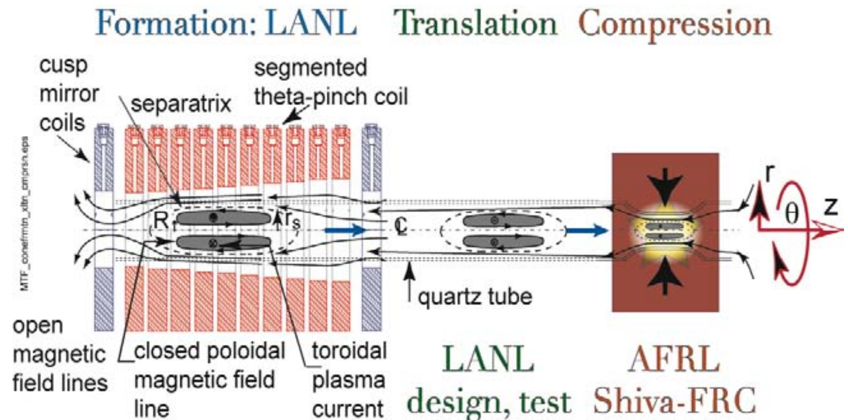
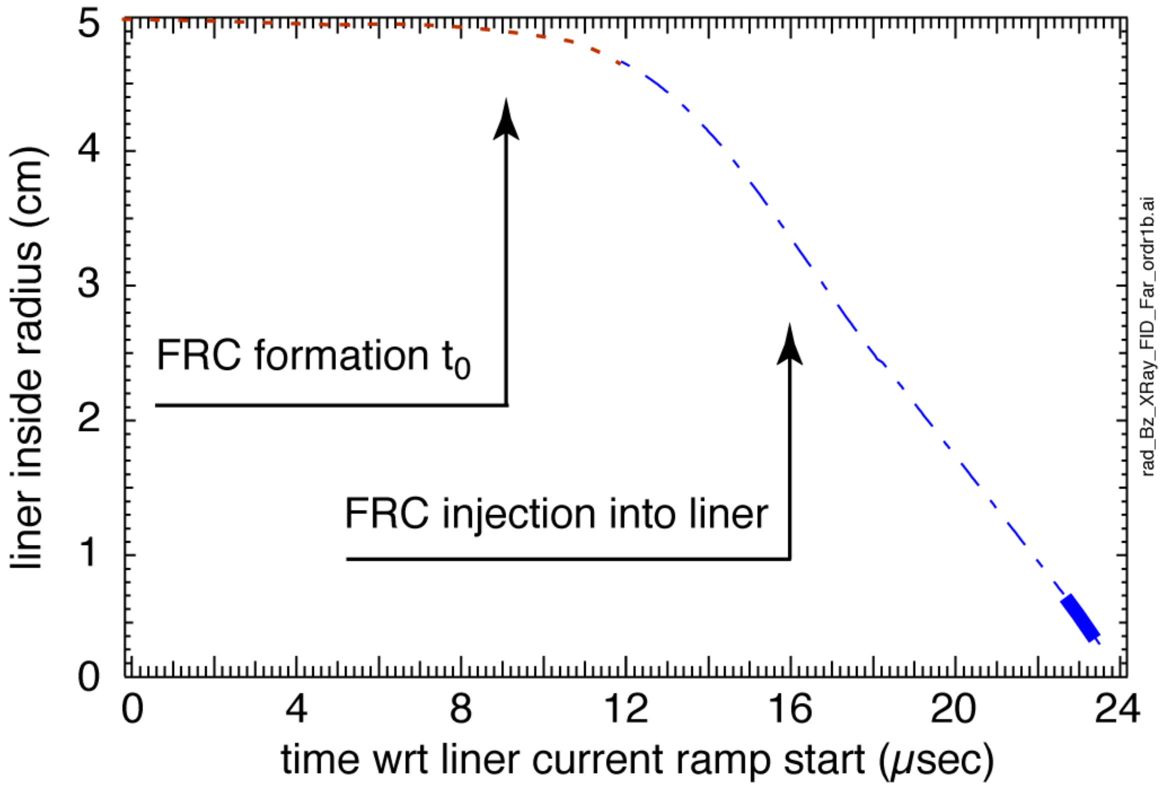
$B_z(z)$ profile design point

Intrator et al, Journ Fusn Energy (2008)





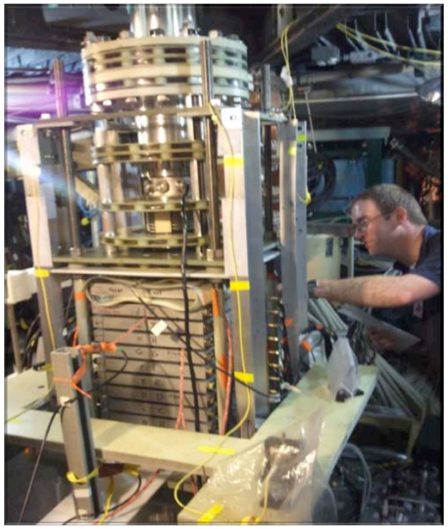
FRC formation & launch after liner t_0

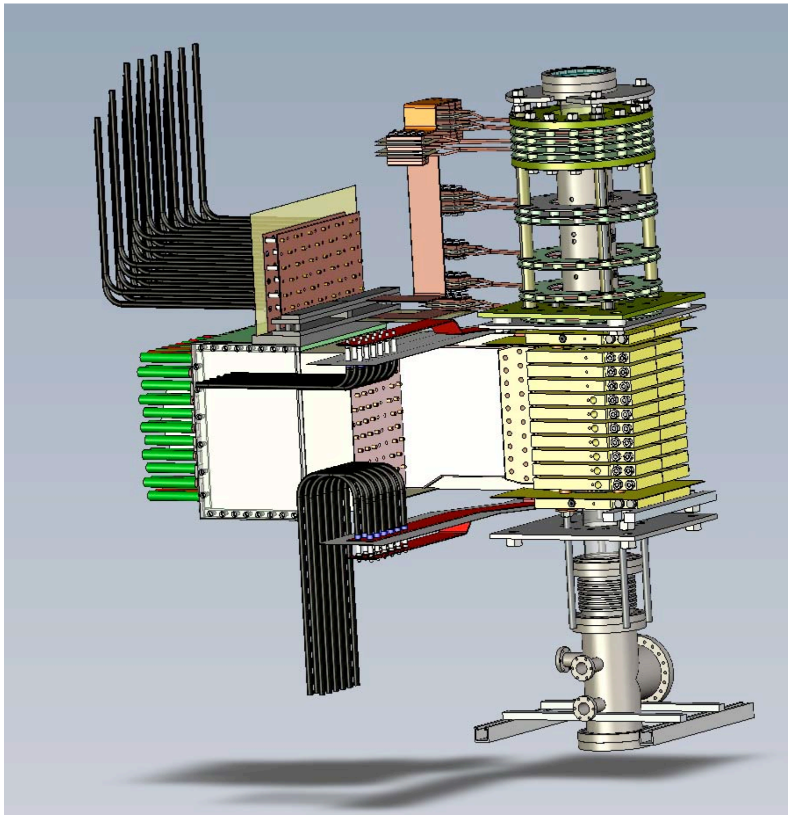


- Intrator et al, *Adiabatic model and design of a translating Field Reversed Configuration*, Physics of Plasmas. 2008;**15**: 042505.
- Intrator et al, *Experimental measurements of a converging flux conserver suitable for compressing a field reversed configuration for magnetized target fusion*. Nuclear Fusion. 2002;**42**: 211-22.

- Time sequence of liner current initiation and FRC formation, translation.
- Experimentally measured inside radius r(t) of aluminum liner implosion onto vacuum B field

Shiva Star: Air Force pulsed power





Shiva Star (photo left) 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 (photo right).

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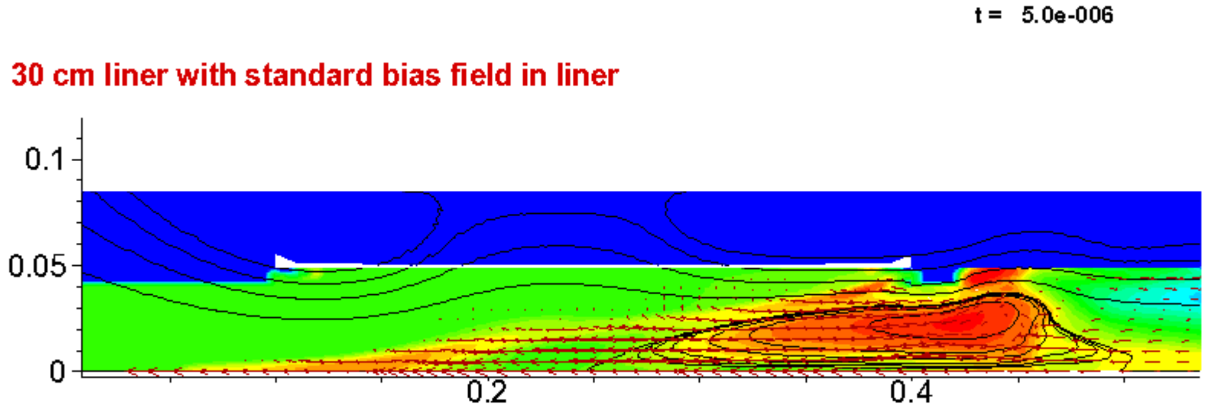
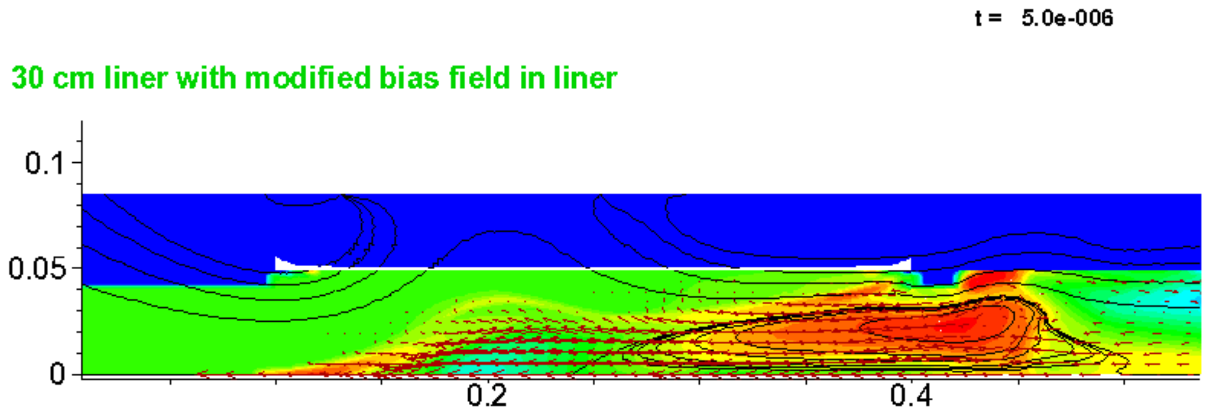
FRCHX progress

- 2010 April
  - Translation observed and capture inferred in non implosion data
- 2010 April 16
  - First FRC engineering test: formation & compression
  - no neutron or SXR signatures
  - FRC lifetime did not last through compression time
- 2011
  - Working on methods to increase FRC lifetime
  - Plasma gun injection, deeper mirror well, RF preionization, trigger timing, inductive FRC acceleration
  - Waiting for Chicago to release DOE funds

Mach2 model guides next shots (Numerex)



Part of FRC doesn't make it in



Deeper trough, better capture

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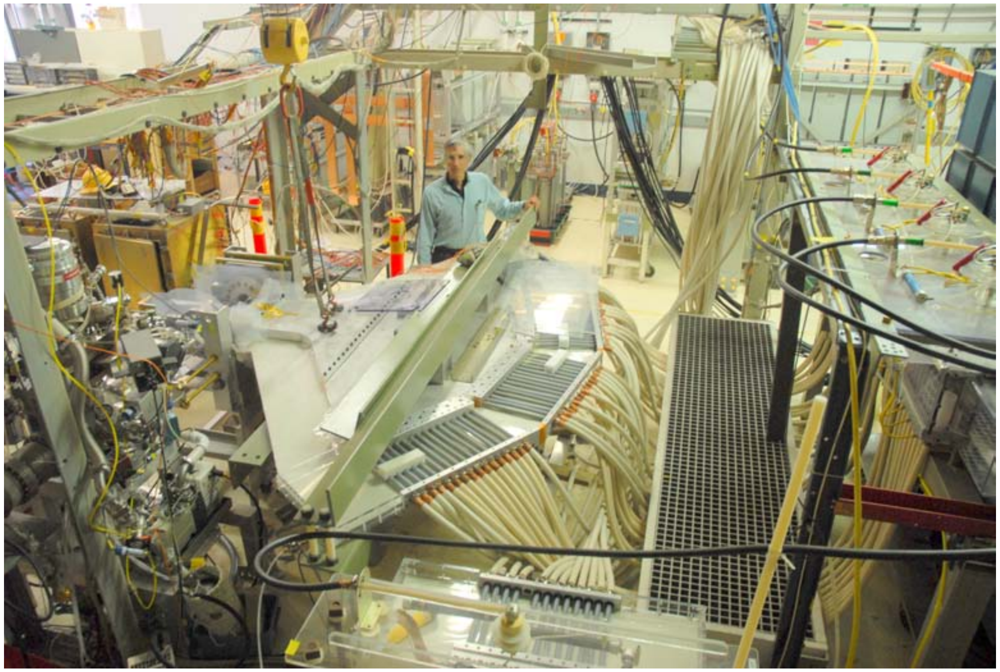
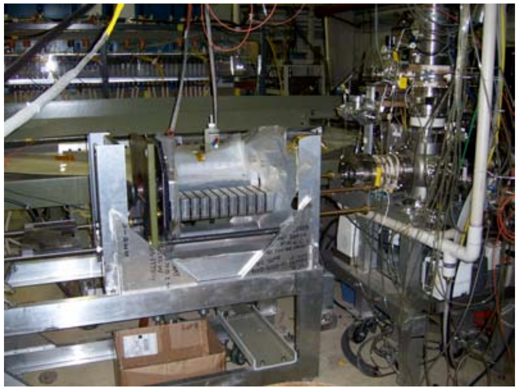
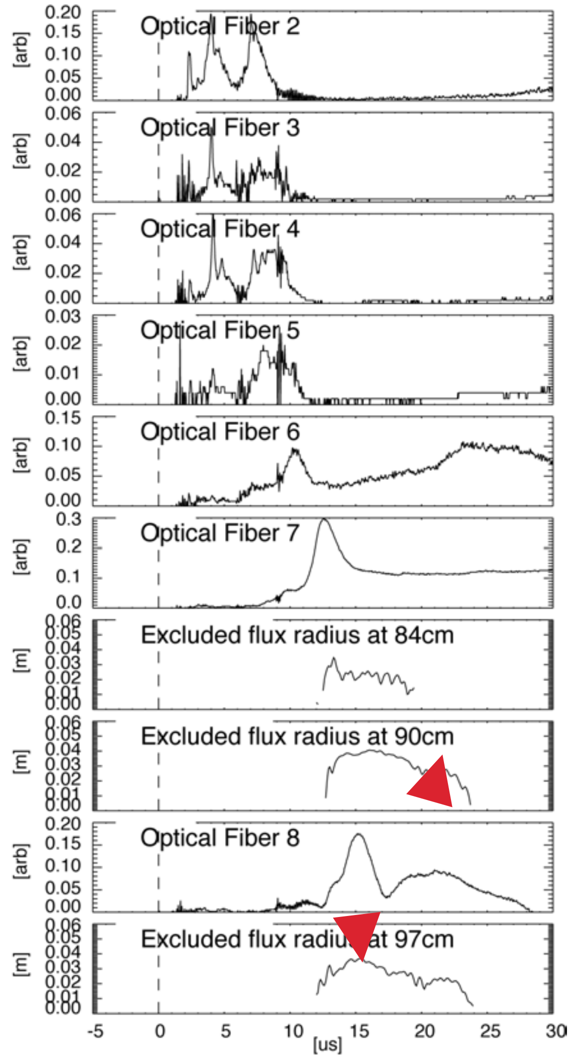
MTF experiments





A small size experiment .....

FRXL translation & capture data



Data 2.6° θ coil

- Magnetics: Bdot and flux loops at the chamber wall
- total light emission from the plasma at several axial locations
- The FRC translates then rebounds then is trapped in mirror region (shorter than FRC !).
- decay ≈ 10 us from coming to rest

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MIF + reactor issues

- MIF could benefit from
  - Higher density => alpha energy deposition in fuel
  - Liquid walls could absorb neutrons, shock, heat
  - Increase dwell time to ≈ radiation loss time
- Compared with ICF:
  - Lower (than ICF) rep rate to clear debris and walls
  - ICF style target tracking is not necessary
- problems are very different from MFE
  - Less materials development necessary
  - Need pulsed power switching development
  - Need recyclable transmission line and/or driver standoff

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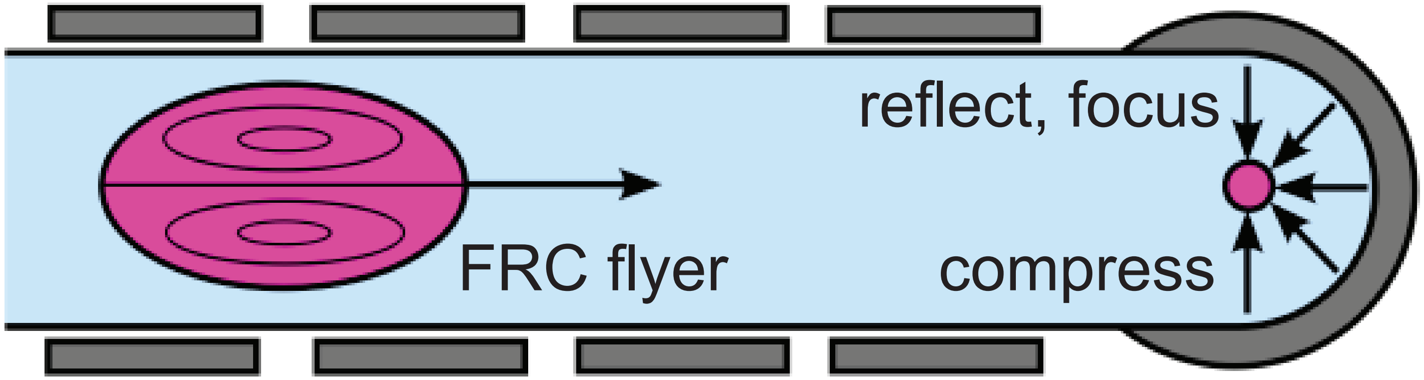
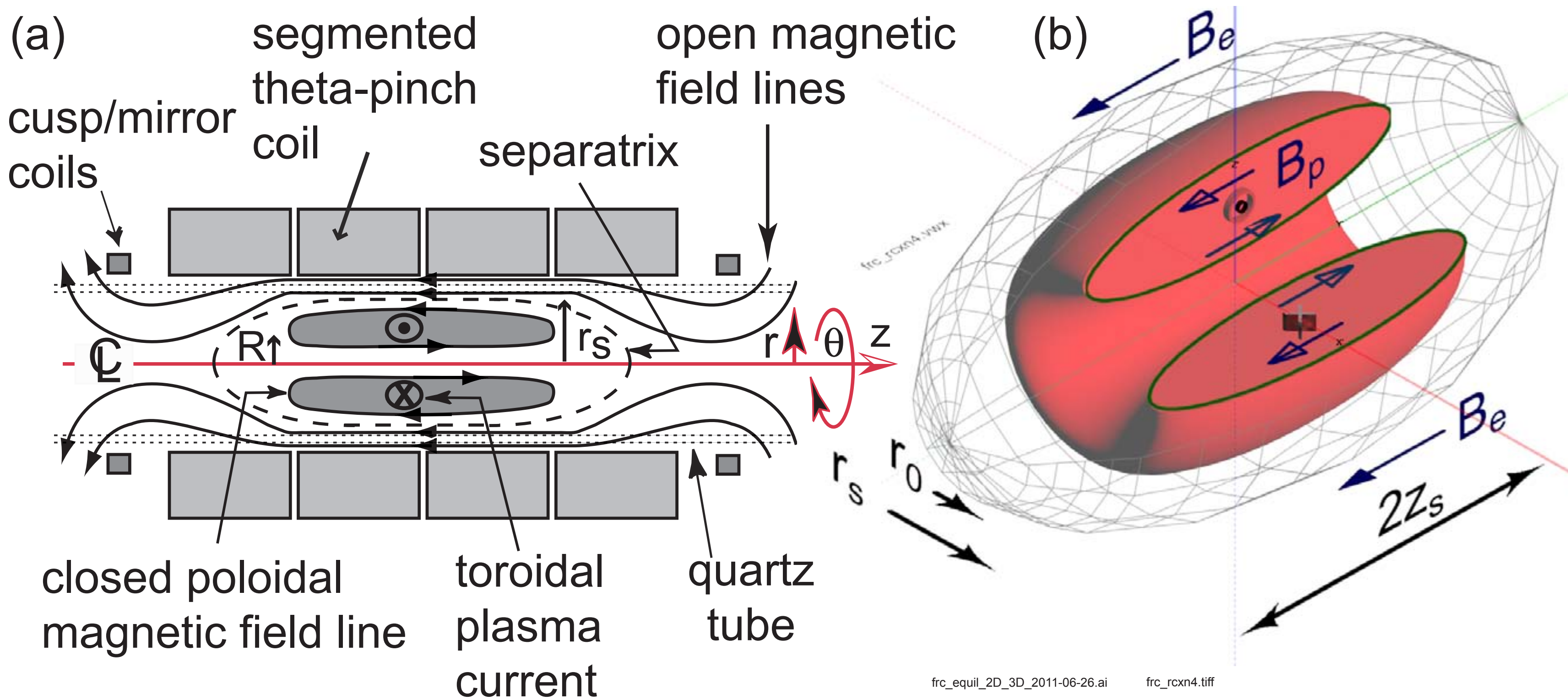
HED physics platform



- Dramatically relax technical hurdles for inexpensive access to HED regimes (≈ Mbar)
- Distribute power and energy over large spatial and temporal scales: *Inductive acceleration*
- High momentum flyer plasma meets its own reflection and is compressed
- Repetitive FRCs can increase dwell time

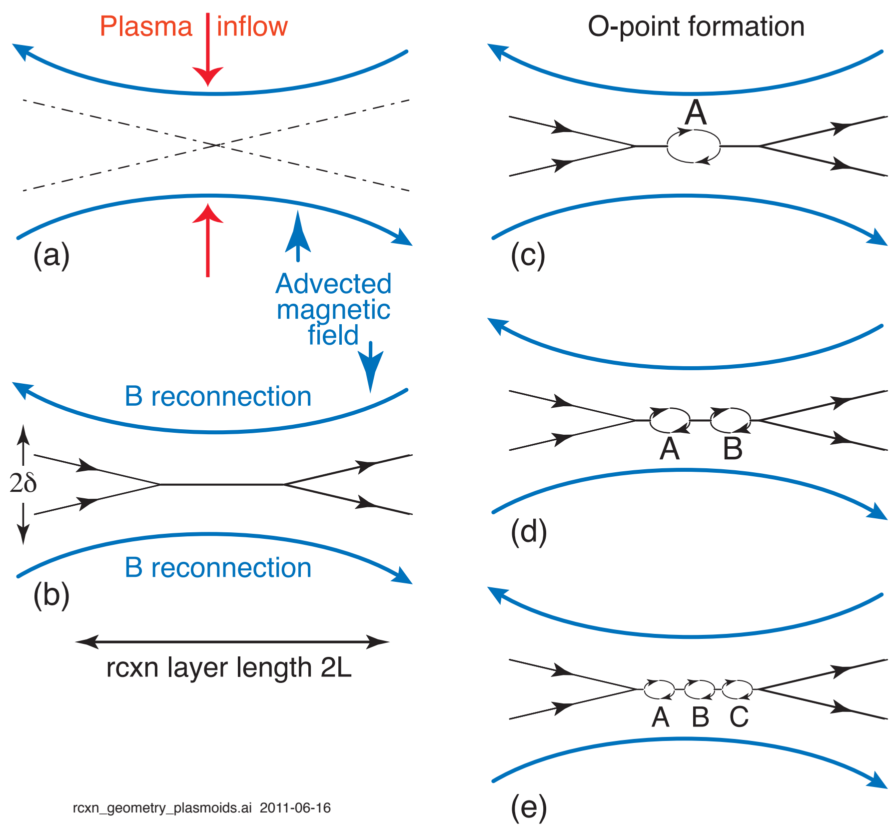
FRC physics experiments



Field Reversed Configuration

Emerging reconnection paradigm

FRCs are collisionless and large, and can probe reconnection physics

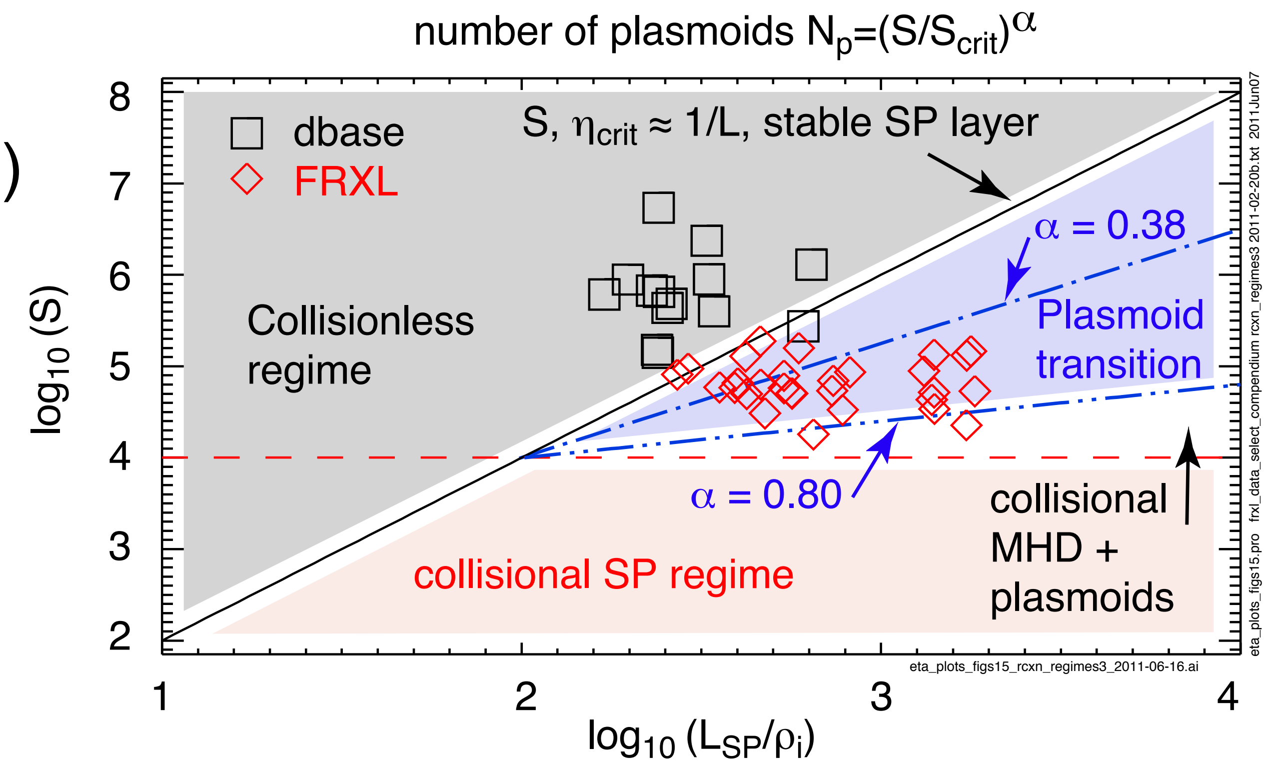


Can internal structure differ from the outside?

MHD physics: reconnection

FRC worldwide database extended by FRXL spans a huge range of collisionality, system size

$S = Lv_A/(\eta/\mu_0)$



Other MIF talks

- Lindemuth: Fusion parameter space from first principles - SO4A-5 (Thurs, 11:45AM)
- Hsu: Plasma liner experiments - IO4A-5 (Tues 4:15PM)
- Degnan, Grabowski: Magnetized Target Fusion - IP1B-14 (Mon morning)
- VanDevender: Z Pinch power stack – SO4B-4 (Thur 11:05AM) CC24A

Summary

- MIF: hybrid fusion approach between inertial and magnetic fusion
- High risk – high payoff route
- MTF: first attempts at experiments = AFRL-LANL collaboration
- Reactor issues for MIF
- Physics platform: HED and MHD