Status and Promise
of
CT's and Magnetized Target Fusion

G. A. Wurden*

Los Alamos National Laboratory

*With contributions from A. Hoffman (UW) and D. Hill (LLNL)

Fusion Power Associates
Germantown
Dec. 13, 2004

CT's: Spheromaks & Field Reversed Configurations

At LLNL, the SSPX experiment is investigating spheromak formation, sustainment, and confinement issues. (Hill, Mclean, Wood, Ryutov). At UC-Davis, formation and acceleration of spheromaks. (Hwang)

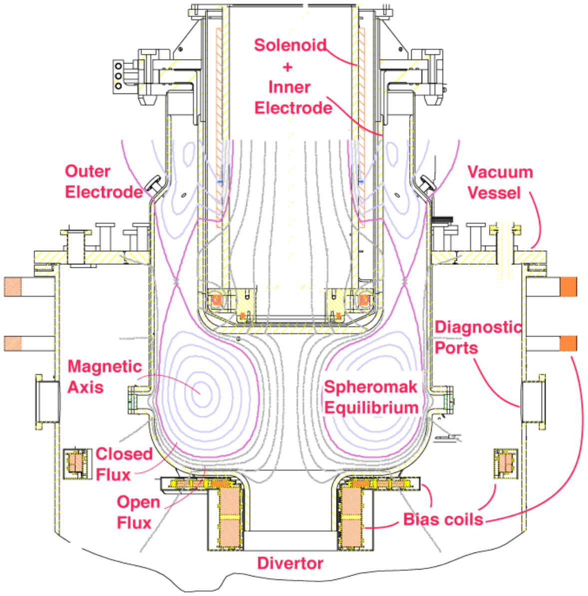
At the U of Washington, field reversed configuration plasmas are studied in both the TCS (being upgraded) and PHD (under construction) experiments, focusing on RMF sustainment and translation/ballistic compression. (Hoffman and Slough)

At LANL, high density FRC's are being studied for use as a target plasma in magnetized target fusion experiments. Plans are underway for plasma/liner implosion experiments in FY07. (Intrator, Wurden, Degnan)

At PPPL, driven FRC experiment, merging spheromaks, and general FRC theory. (Cohen, Ji, Yamada, Belova)

At Swarthmore and Caltech, studies of basic plasmas, aimed at astrophysics and spheromak physics. (Brown, Bellan)

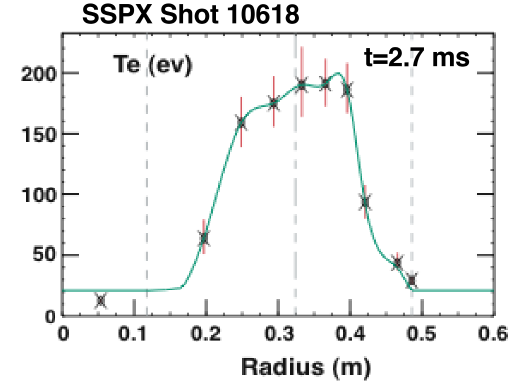
SSPX was built to examine energy confinement and magnetic field generation

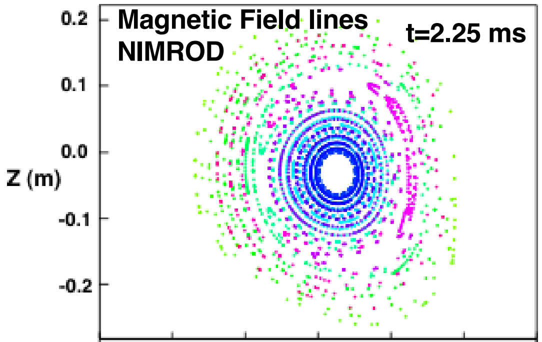


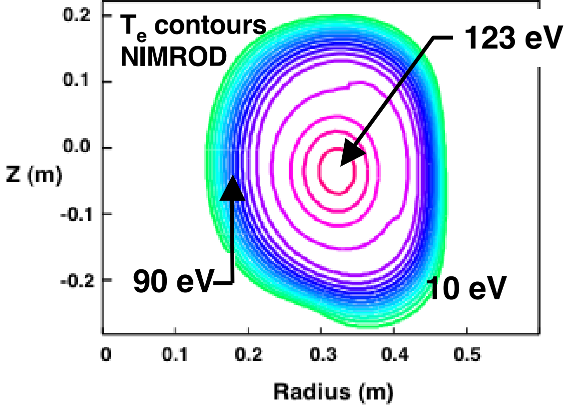
Typical SSPX parameters	
Flux conserver RxH (m)	0.5x0.5
Radius of mag axis (m)	0.31
Minor radius (m)	0.23
Discharge current (kA)	200
Toroidal current (kA)	400
Edge poloidal field (T)	0.2
Pulse length (msec)	3.5
Electron Temperature (eV)	20-200
Ion Temperature (eV)	?-600
Lundquist number, S	10^5
Fluctuations (kHz)	20
Plasma density (m^{-3})	$5x10^{19}$

- **SSPX Operations:**
  - –**The best confinement in SSPX (χ_E~10m^2/s) is obtained with controlled decay.**
  - –**Peak temperature of >200 eV (peak β_e ~5-10%) observed when magnetic fluctuations are small (< 1%).**
  - –**Slow formation and double-formation-pulse discharges yield the highest magnetic field build up in SSPX.**
- **NIMROD simulations**
  - –**Show good closed nested flux surfaces**
  - –**Electron temperatures similar to experiment**

Summary: We are developing improved understanding of energy confinement in high-temperature SSPX plasmas



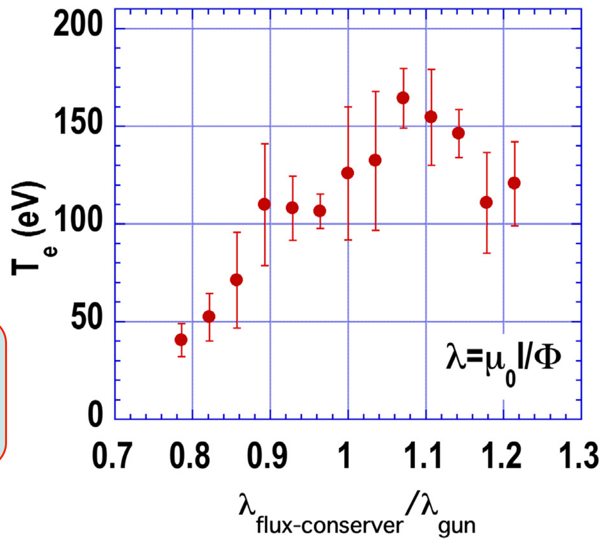




- T_e > 200eV is now obtained routinely in SSPX using the long-pulse sustainment bank.

- Flatter current profiles ($\lambda_g \sim \lambda_{FC}$) produce lowest fluctuations and best confinement.

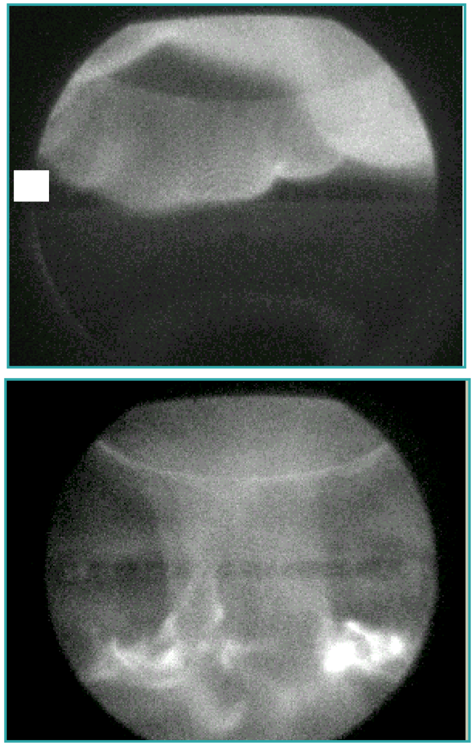
Data from scan of edge current density $\lambda=j/B$.



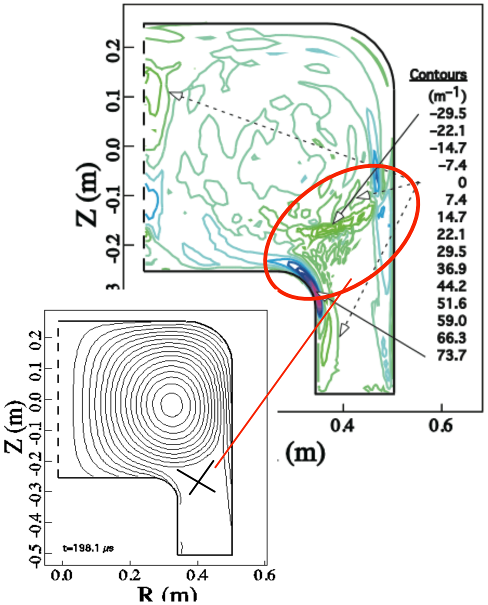
- *Ab initio* NIMROD simulations with realistic thermal conduction match field buildup and features of T_e profile: regions of good confinement surrounded by islands & confined chaotic lines, open field lines at the edge.

See invited presentation [PI1B.003] by B. I. Cohen

Summary: Participation in NSF Center for Magnetic Self Organization supports study of magnetic reconnection in SSPX

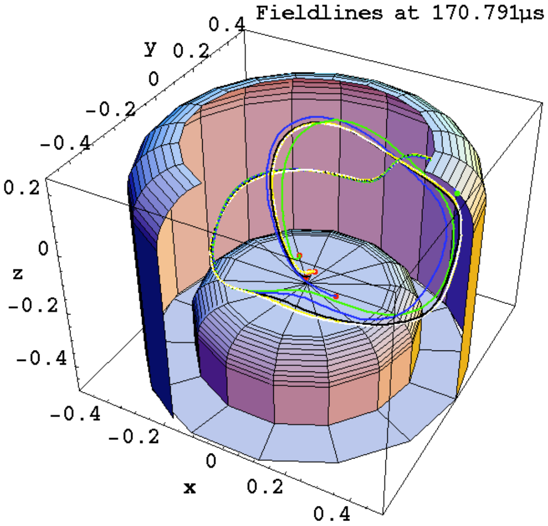


- Fast imaging used to examine magnetic topology during formation: classical “bubble-burst” with a well-defined central column. (Romero-Talamas, Ph. D thesis 2004, Caltech)
- Injector magnetic probe shows formation of x-point at injector

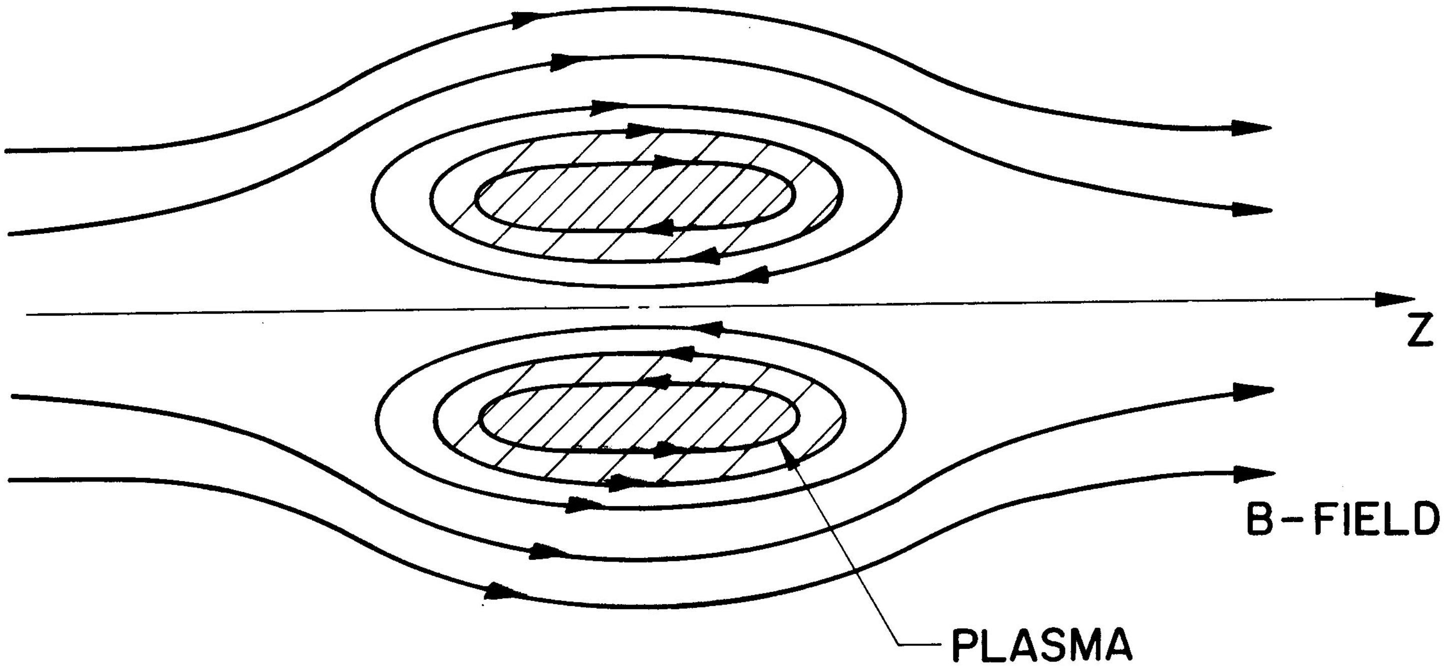


NIMROD simulation shows reconnection is generated by current sheets with negative $\lambda = \mu_0 j \cdot B/B^2$ — These are strongest near the X-point.

Field-line tracing (Tom Kopriva, U. Wisconsin) using NIMROD shows that reconnection changes magnetic topology: linked field lines appear after spheromak formation.

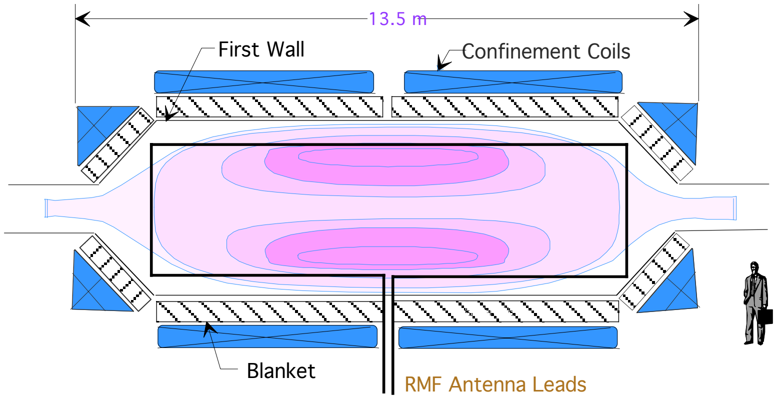


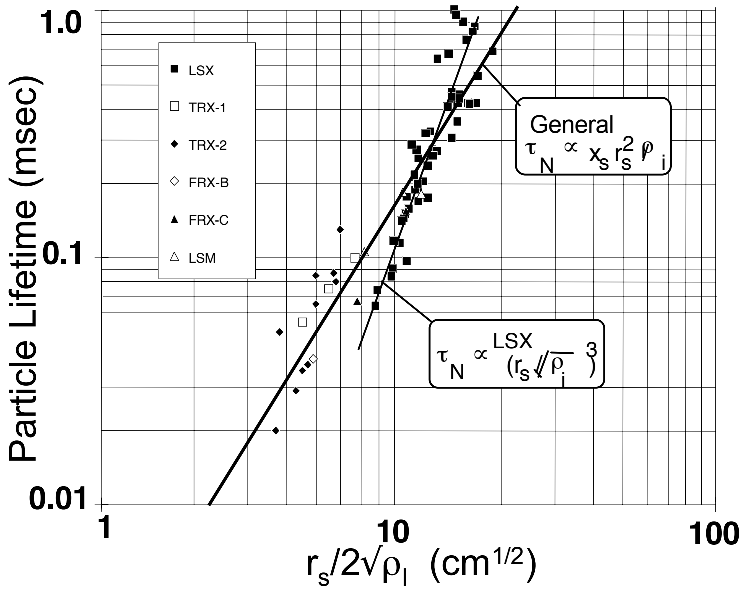
Smoke-ring-like Field Reversed Configuration



FRC is a high beta plasma object, and easy to translate

Reactor Promise of conventional FRCs



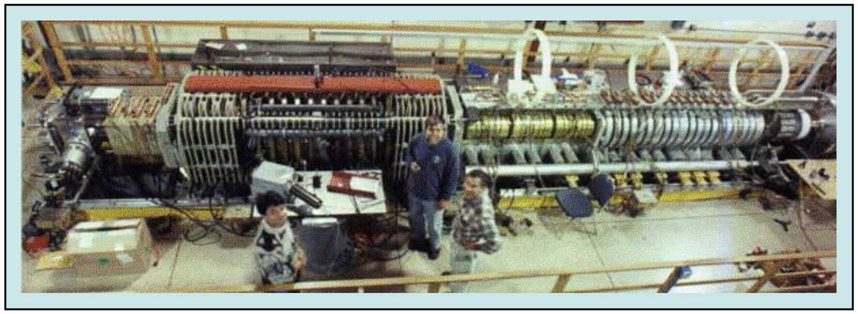


- Low complexity due to low field, solenoidal magnet system with natural linear divertor
  - Small reactor core with relatively easy maintenance
  - Simple ash removal - particle loss is principal loss mechanism
- Cost effective development path
- Simple current sustainment possible using RMF
- Advanced fuel potential due to high beta
- Direct conversion possible if use D-^{3}He

Measured Conditions using
Fast Theta-Pinch Formation

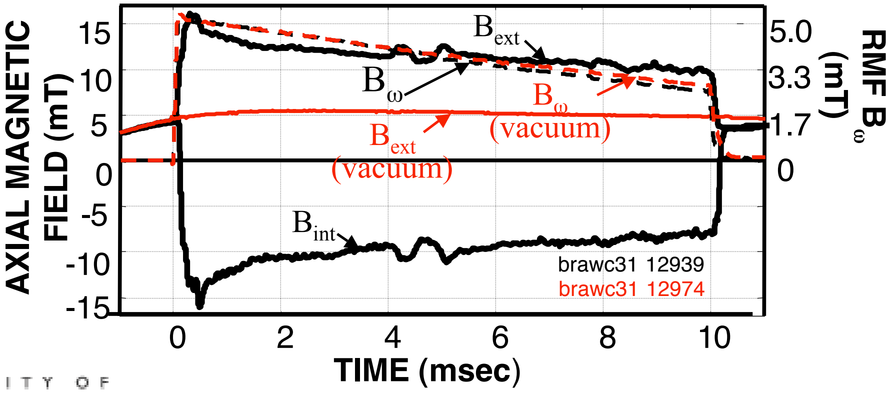
- Density: $n_e \sim 1\text{-}5\times10^{21}\ m^{-3}$
- Energy Lifetime: $\tau_E \sim 0.5$ msec
- Temperature: $T_e \sim 0.1 - 0.5$ keV
  $T_i \sim 0.1 - 2.0$ keV
- Configuration Lifetime: ~ 0.1 – 0.5 ms
  - Limited by flux decay or rotational n=2 instability

Status of U of Washington “TCS” FRC Sustainment Experiment



- The overall objective is to produce and sustain hot FRCs using technology suitable for expansion to large sizes. Generation & sustainment has been demonstrated, and the theory developed for RMF current drive.
- Current approach is to improve vacuum system commensurate with a steady-state experiment to allow for high temperatures.
- Additional heating and current drive methods will be developed in the future to produce large s.

- FY04 Funding: $1,700,000
- FY04 Accomplishments:
  - Sustained FRCs for 10 msec using rotating magnetic fields (RMF).
  - Stabilized rotationally driven instabilities using RMF.
  - Produced higher performance mode with minor toroidal field.
  - Observed natural relaxation to high beta compact toroid.
  - Completed design and major procurements for high quality, bakable plasma chamber



UNIVERSITY OF WASHINGTON

Magneto-Inertial Fusion:
An old idea….

Involving the application of a magnetic field to inhibit heat flow in an inertially compressed (high pressure) target plasma, and thereby ease the driver requirements.

It can take on many possible implementations, both for targets and drivers.

At 1 Megabar pressure (or higher), it is in the regime of High Energy Density Physics (HEDP).

Early proponents of the topic include: R. K. Kurtmullaev, A. Velikovich, J. G. Linhart, T. Armstrong, F. L. Ribe, R. Gerwin, R. Bangerter, D. Ryutov, J. H. Hammer, R. D. Jones, M. J. Schaffer, W. C. Mead, R. C. Kirkpatrick, I. R. Lindemuth, R. W. Moses, T. Jarboe, R. Siemon, and probably others I didn't list.

Definition of Magnetized Target Fusion

- MTF is a concept that covers a subset of MIF scenarios.
- For MTF, one must form an initial plasma “target” with an embedded magnetic field. It isn’t just a cold fuel capsule with an added magnetic field. The desired target plasma temperature is in the range of 50-300 eV.
- At Los Alamos National Lab and the Air Force Research Laboratory, the MTF approach that we have in mind, involves using electromagnetically driven solid liners to adiabatically compress not only a magnetically-insulated, but a magnetically-confined plasma (the β~1 FRC). We chose this approach because it is the least restrictive, and in our view, the most likely path to succeed at demonstrating MTF principles.
- There are many other MTF scenarios, which use plasma liners, or assembly of plasma liners with converging plasma jets, or spheromaks, or use wall-confined (β>>1) plasmas. These other approaches offer their own particular advantages and disadvantages.

Low, Medium, and High Pressure MTF Regimes

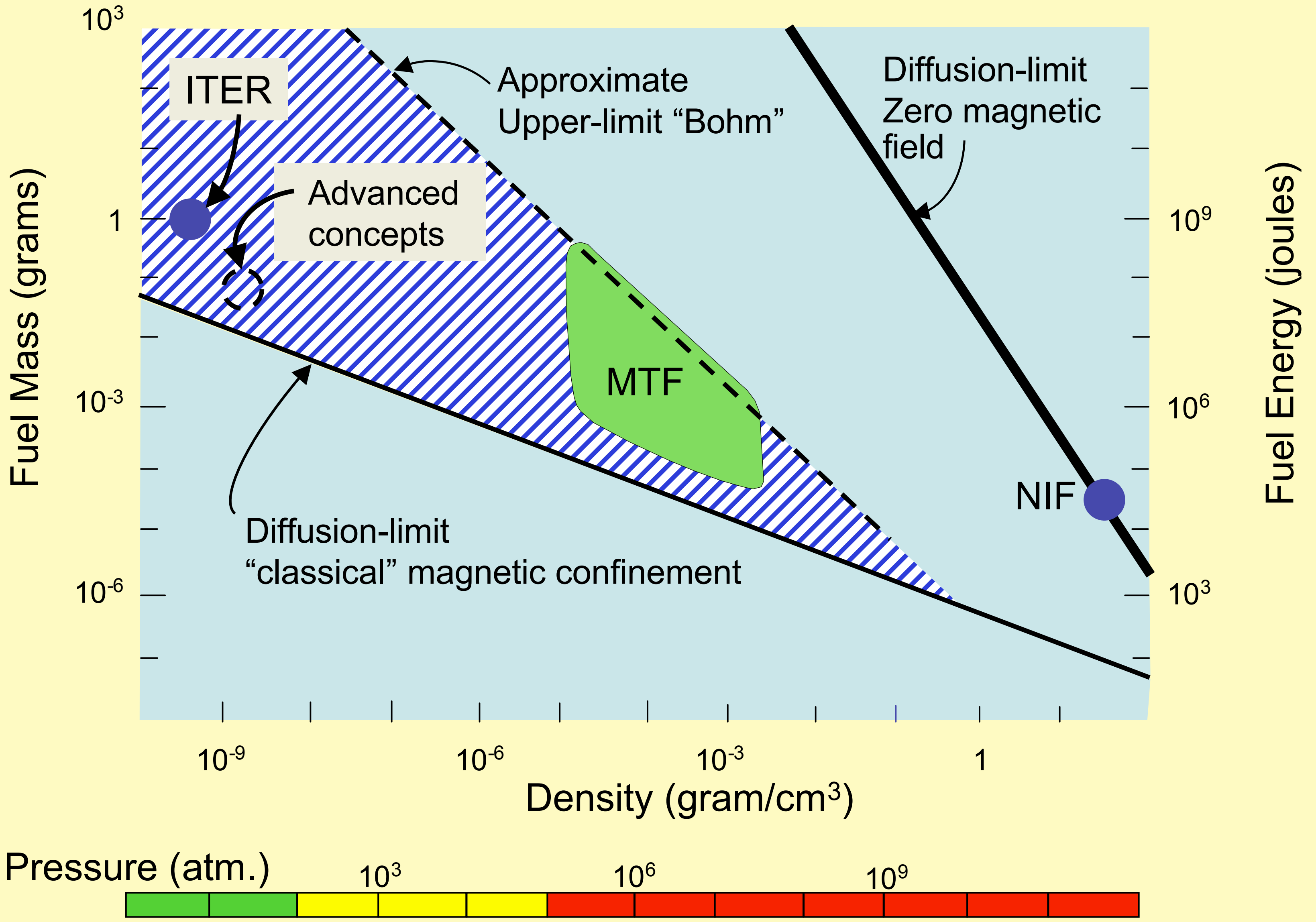
- Low pressure (< 10 kbar), resembling LINUS or UC Berkeley compression of a spheromak, which allows for minimum damage to equipment on each pulse
- Medium pressure (0.01-10 Megabar) is appropriate for electromagnetically driven solid metal liners (the approach we chose for MTF). Batch burn.
- High pressure (> 10 Megabar) resembles conditions closer to inertial fusion conditions, in Z or heavy ion drivers. Advantage of the possibility of burning cold fuel, for higher yields.

Special issues associated with MIF

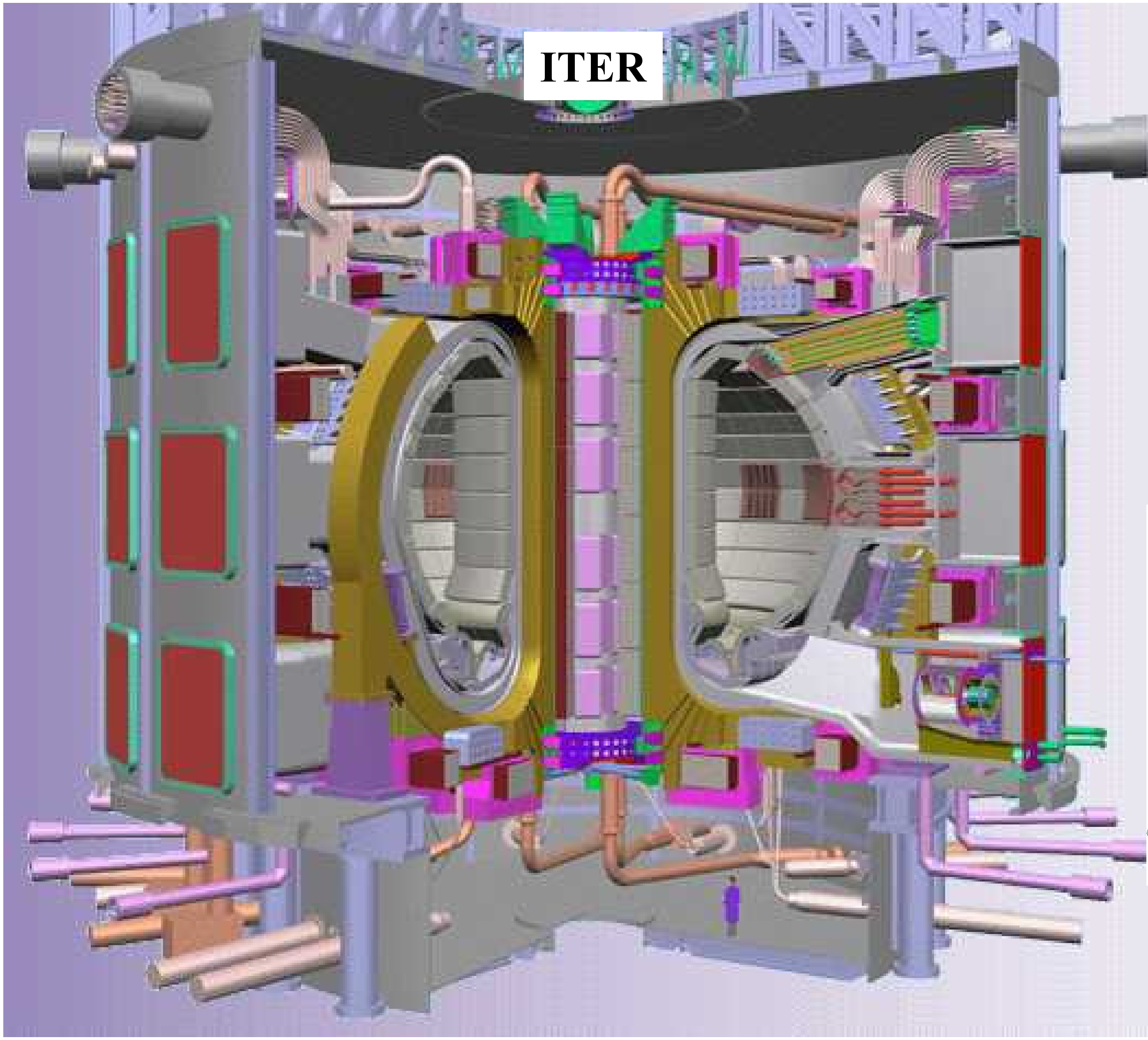
- Required _R of target is lower than with ICF (because the B-field helps)
- Compare slowing down time of alphas relative to configuration lifetime. If BR> 0.3 MGauss-cm, then thermonuclear self-heating can occur.
- Target symmetry is strongly affected by presence of a magnetic field
- The lower density burn regimes of MIF are in “batch burn mode”, with fractional burn-up of only a few %, and gains are less than ~ 20.
- High-end density regimes for MIF should be able to burn cold fuel at the boundary.
- There may be more materials near the center of the chamber (due to liner and leads), and therefore there are associated issues with (non-plasma, non-radiation) blast debris.
- Cost of replacement parts relative to value of energy produced.
- Standoff from the location of fusion burn.
- Rep-rating a bigger absolute yield, but at a lower frequency (~0.1 Hertz). Lifetime of the pulsed-power driver elements.

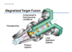
IM-1/0476 03/01 R. Siemon

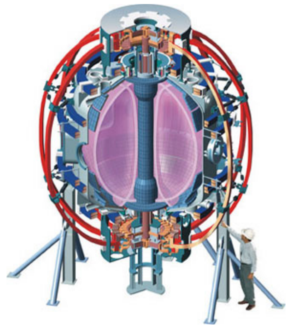
Required DT Fuel Mass

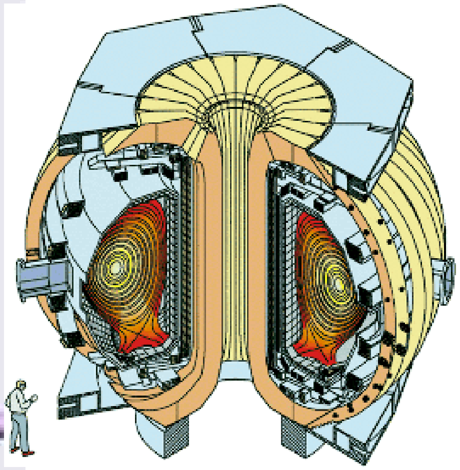


Some Fusion Experiments

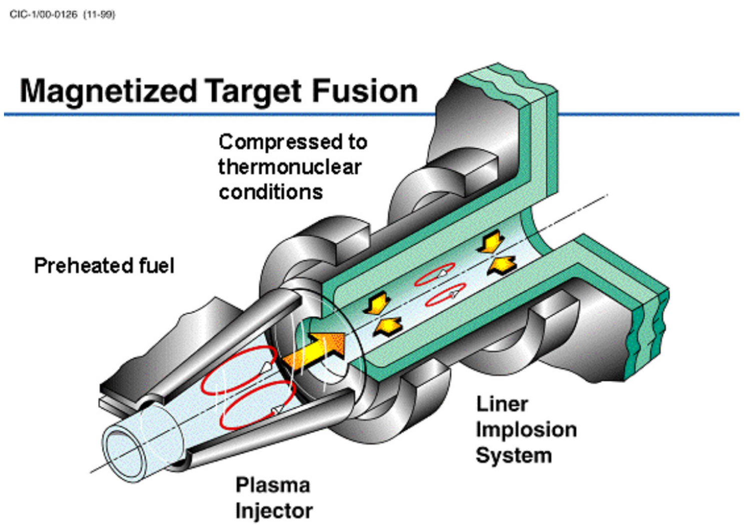

ITER


MTF (Los Alamos)


National Spherical
Torus Experiment
NSTX (Princeton)


DIII-D Tokamak
General Atomics
(San Diego)

Magnetized Target Fusion:

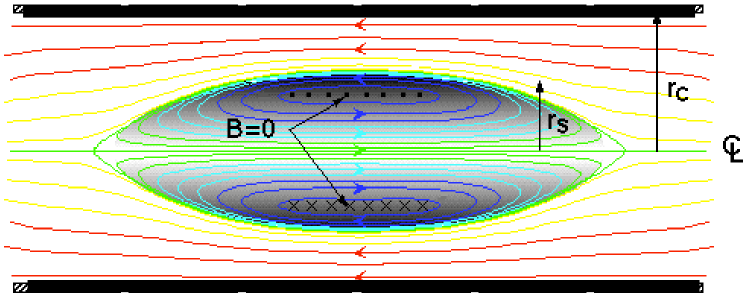


Our choice of parameter space

Imagine 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 final plasma density is ~10^{19} cm^{-3}
- The magnetic field confining the plasma is 500 Tesla !
- The auxiliary heating power level is ~ 1000 Gigawatts !
- The heating is “slow” adiabatic compression
- Most of the initial physics research can be conducted with existing facilities and technology
- In a reactor, on each pulse the liquid first wall would be fresh
- The repetition rate is ~0.1 Hertz, so that there is time to clear the chamber from the previous event

MTF using the FRC as target plasma



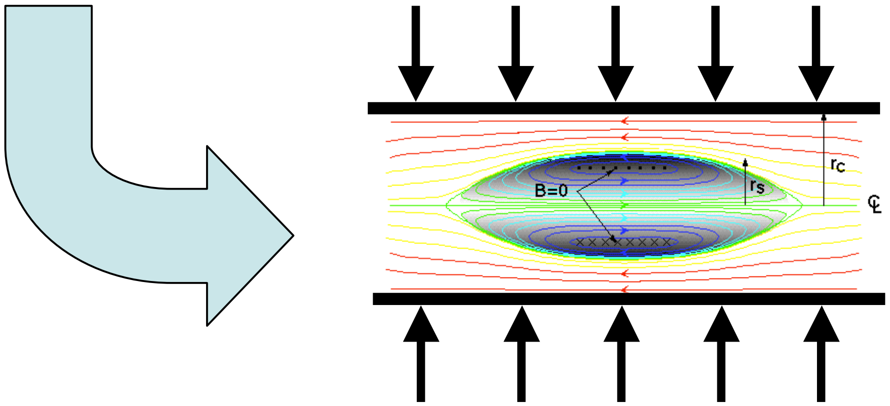
Magnetic field of ~ 3-5 T in a closed-field line topology

Density ~ 10^{17} cm^{-3}

Free of impurities (reduce radiation losses)

T_e ~ 50-300 eV

Initial target: *preheated & magnetized*

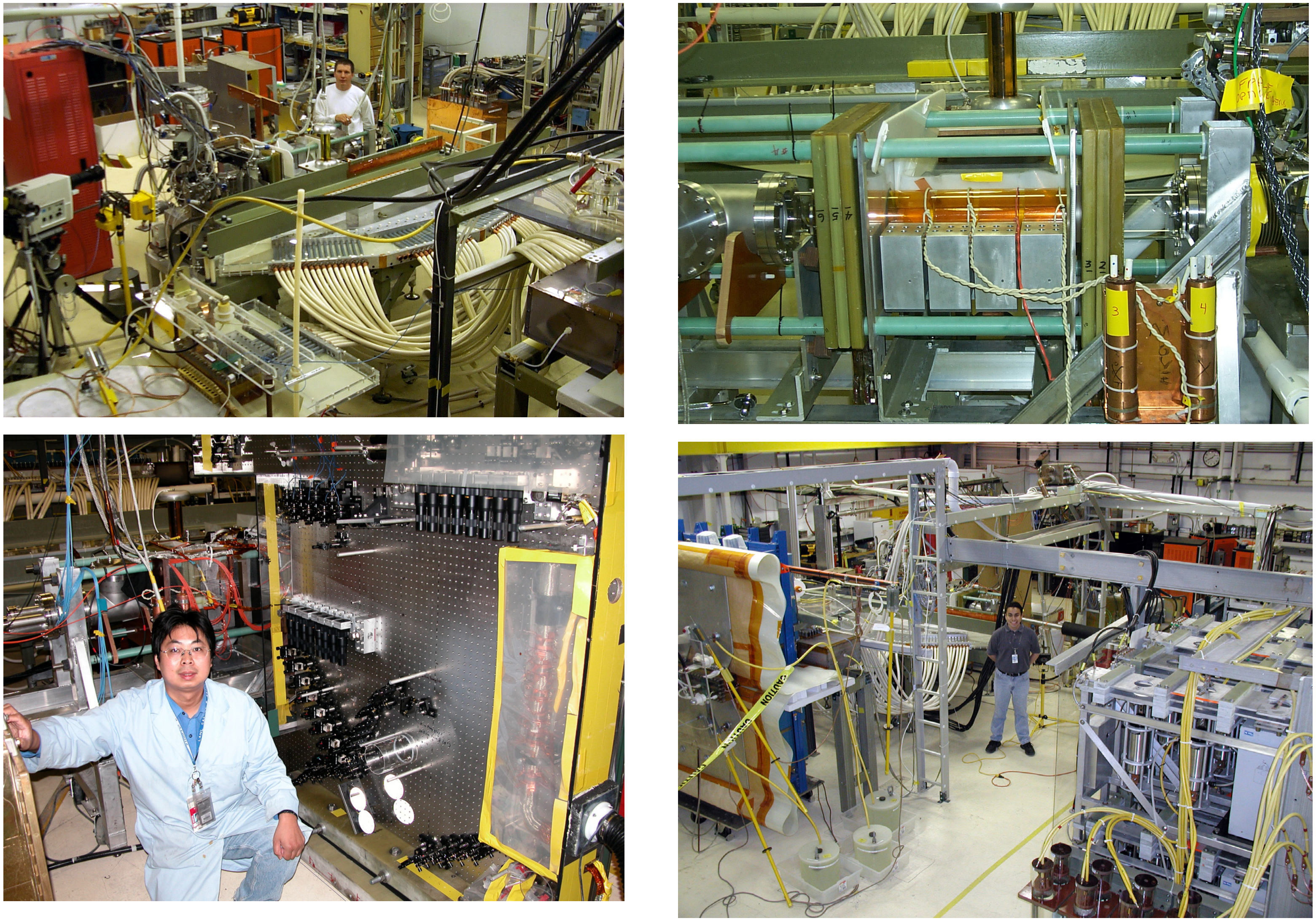


Liner Compression
~ 1 cm/μs

~ factor of 10x in radius

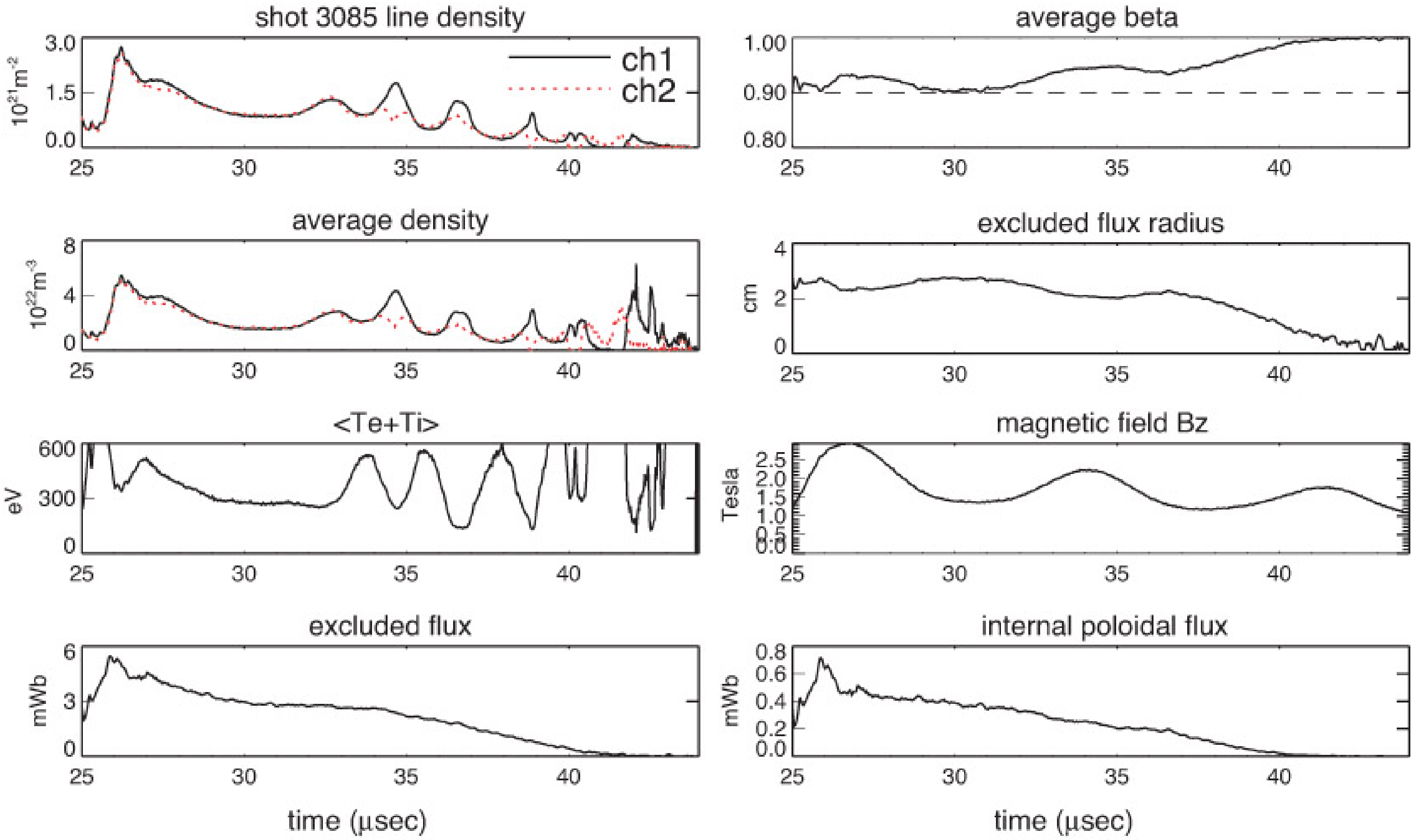
adiabatically compressed
to fusion relevant conditions

FRX-L: The Field Reversed Configuration (FRC) Plasma Injector for MTF



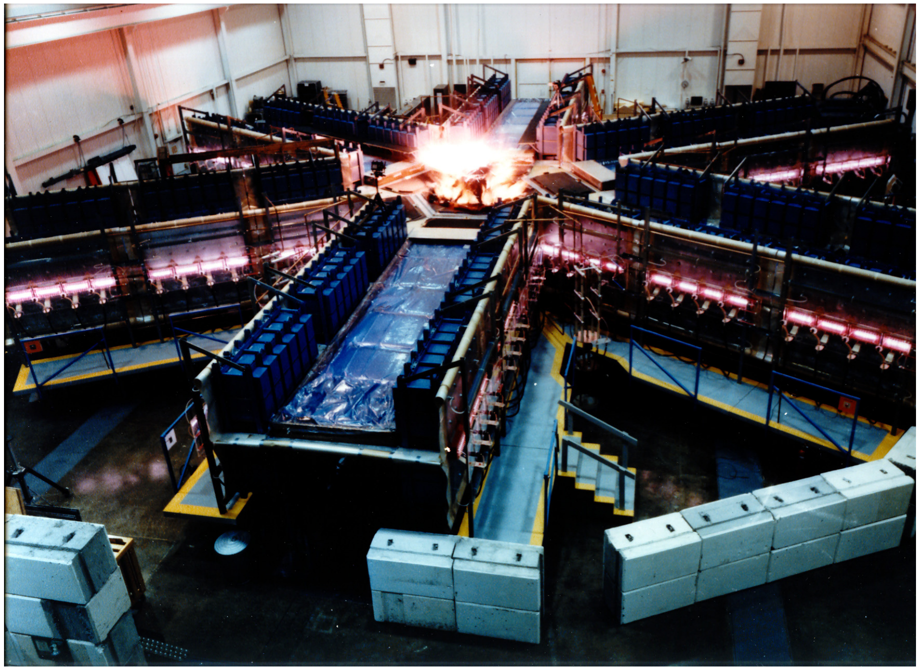
FRX-L Field Reversed Configuration Target Plasma Data

Plasma performance is adequate for initial integration to a plasma/liner experiment



Goal: First FRC plasma/liner implosion physics demonstration in FY07

A shaped liner with an 8-cm open aperture, compatible with accepting a translated FRC was successfully tested in a vacuum shot at Shiva Star in December 2003.



- 82 kV, 1300 uF, 44 nH for Z-pinch driven long liner experiments
- 4.4 MJ energy storage gives 1.5 MJ in liner KE
- ~11 Megamp, ~10 μsec risetime discharge implodes 30 cm long, 10 cm diameter, 1.1 mm thick Al liner in 24 μsec

Magnetized Target Fusion:

Reference Materials

- **Our web pages: http://fusionenergy.lanl.gov and http://wsx.lanl.gov**
- ***“*Amplification of magnetic fields and heating of plasma by a collapsing metallic shell*”*, by Linhart, Knoepfel, and Gourlain***, Nuclear Fusion, CN-10/11, supl. Pt. 2, 733 (1962).*
- **“Why Magnetized Target Fusion Offers a Low-Cost Development Path for Fusion Energy”, by Siemon, Lindemuth, and Schoenberg,** *Comments Plasma Phys. Controlled Fusion, Vol 18, No. 6, pg 363-386 (1999).*
- **“Scaling Relations for High-Gain Magnetized Target Fusion Systems”, by D. C. Barnes,** *Comments Plasma Phys. Controlled Fusion, Vol 18, No. 2, pg 71-84 (1997).*
- **“Magnetized Target Fusion: An Overview”, by R. C. Kirkpatrick, I. R. Lindemuth, M. S. Ward,** *Fusion Technology, Vol 27, pg 201 (1995).*