# Magnetized-Target Fusion: an alternative path to fusion

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# This is a joint venture involving multiple national institutions

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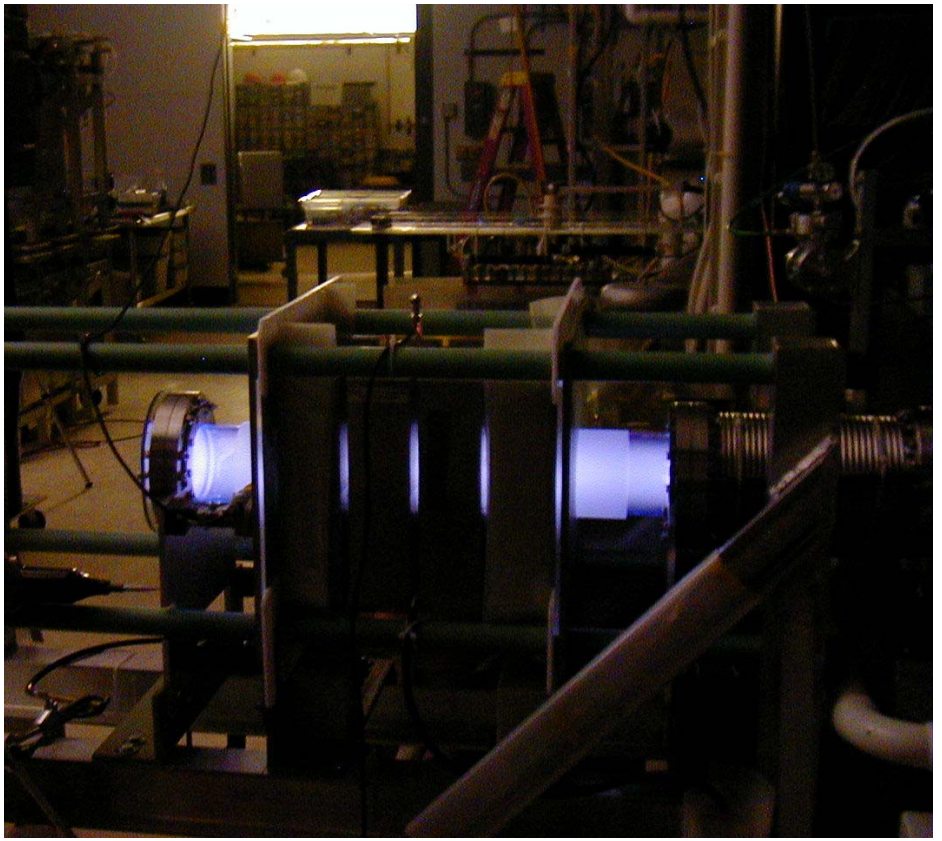
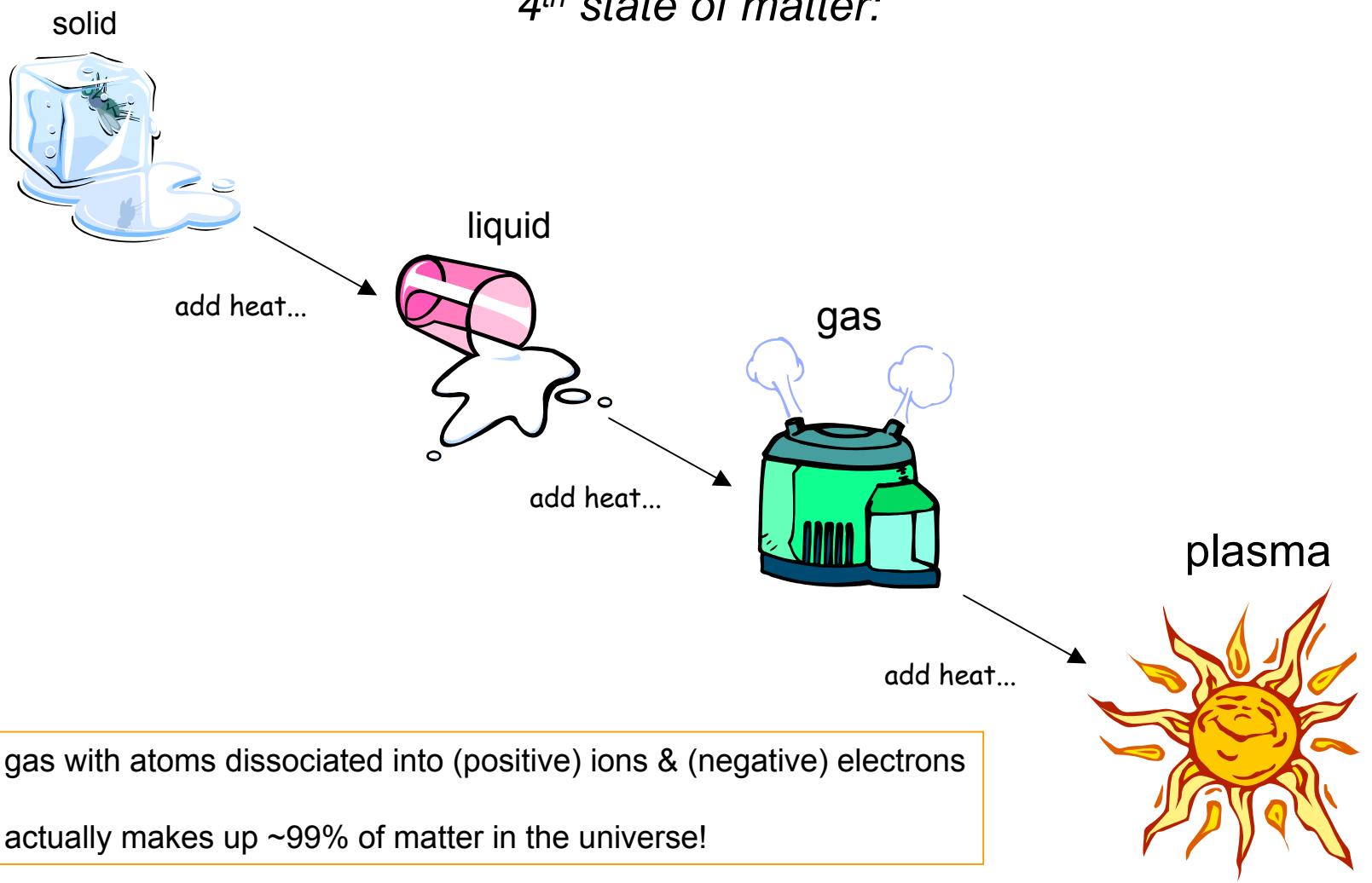
# Outline

- Intro to Fusion
- Traditional Fusion Schemes
- Magnetized Target Fusion
- Field Reversed Configuration
- Future directions



# What is a Plasma?

*4th state of matter:*




- gas with atoms dissociated into (positive) ions & (negative) electrons

- actually makes up ~99% of matter in the universe!

# A plasma undergoing fusion…

## our sun

**How do we achieve this in a controlled way & in the lab?**

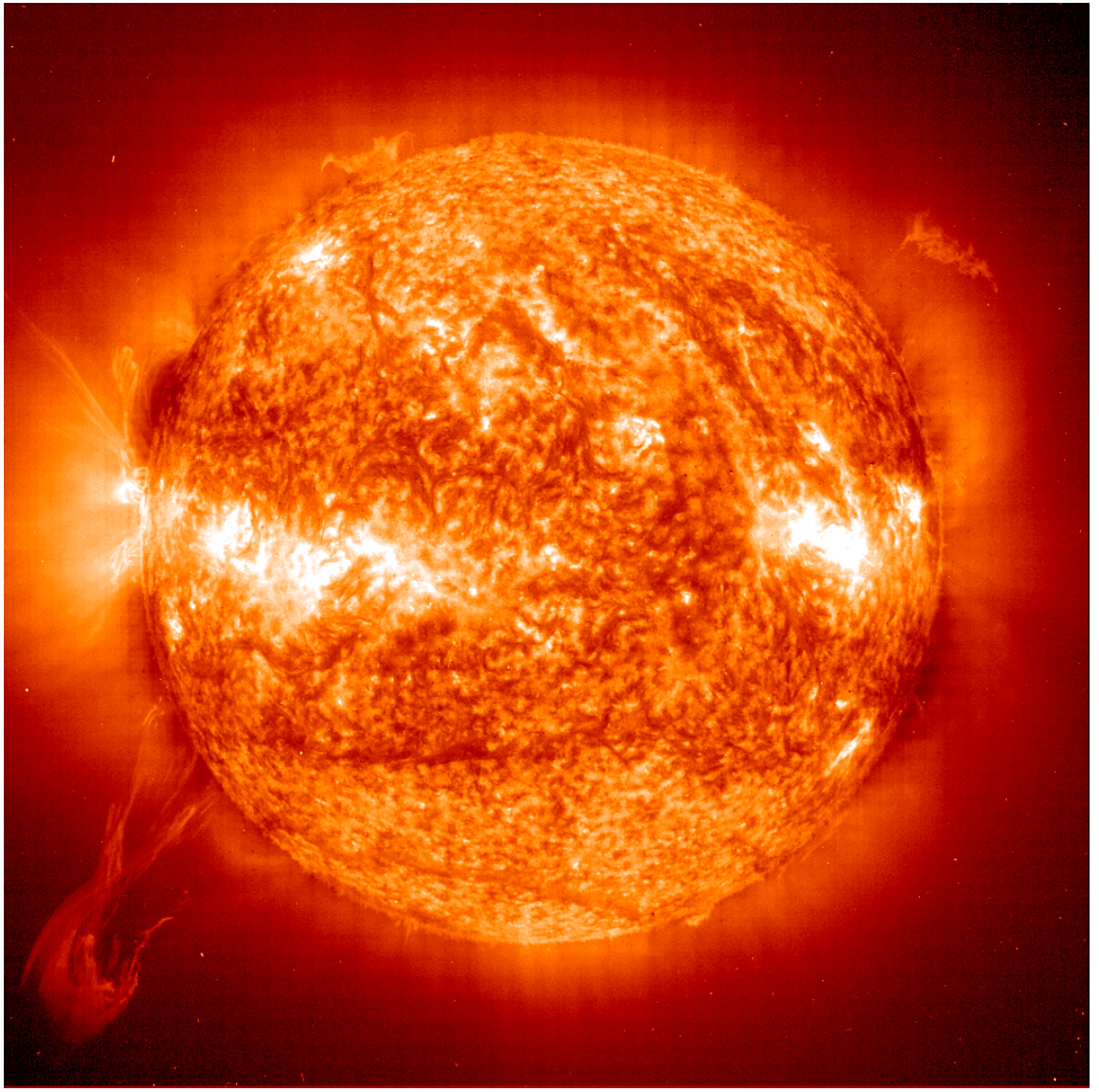


Image taken by SOHO spacecraft

# Controlled Nuclear Fusion

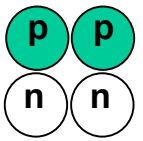
The main idea in nuclear fusion is to 'fuse' two nuclei together to make products whose total mass is less than the originals' --- this missing mass is converted into (lots of) energy

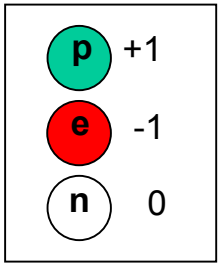
$$E = mc^2$$

**Electromagnetic force** - same charges repel, opposite charges attract

But then, how do nuclei of atoms together?

**$He^4$ nucleus**




**Even though protons have the same charge, nuclear force keeps them together**

**Nuclear force** - very strong but only at subatomic distances

So, in order to achieve nuclear fusion we need to bring the ions close enough for the nuclear force to overcome the electromagnetic repulsion **(~$2 \times 10^{-15}$ m !!!)**

# Controlled Nuclear Fusion

For example, the deuterium (D) and tritium (T) fusion reaction proceeds as follows:

$$\mathbf{D + T \longrightarrow He^4\ (3.52\ MeV) + n\ (14.06\ MeV)}$$

where $D = H^2$ (p+n) deuterium
$T = H^3$ (p+n+n) tritium

Energy of a gas molecule is related to temperature of the gas through

$$E = 3kT/2$$

(average translational kinetic energy of a gas molecule at temperature T)

→ **Need high plasma temperature !**

(turns out need ~10 keV energy for these reactions to occur at a significant rate)

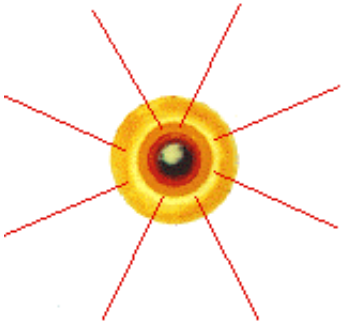
# More Traditional Controlled Fusion Schemes

**Magnetic Confinement Fusion (MFE)**

- long pulses (~$10^{-3}$ sec)
- low initial density (~$10^{14}$ $cm^{-3}$)

  For example:
  **tokamak** (shown) where magnetic fields are used to contain & compress plasma

**Inertial Confinement Fusion (ICF)**

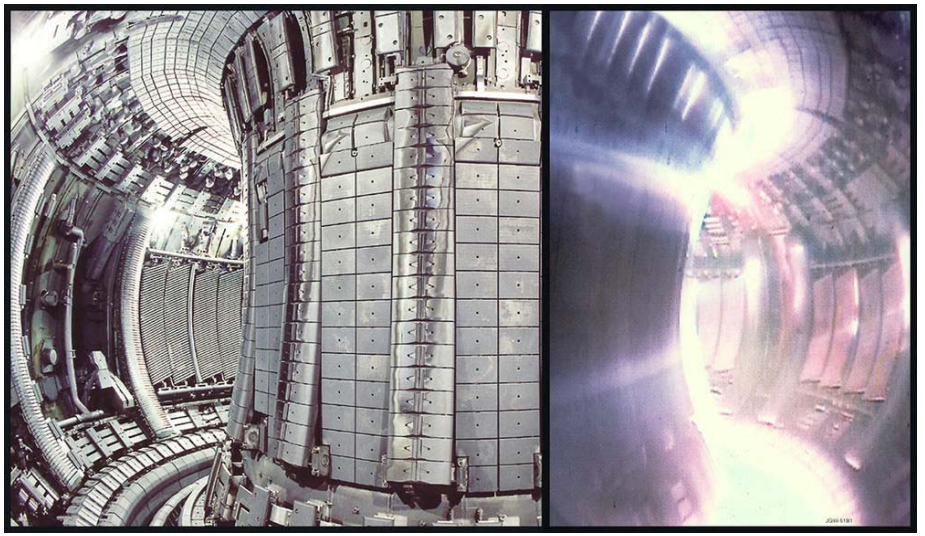


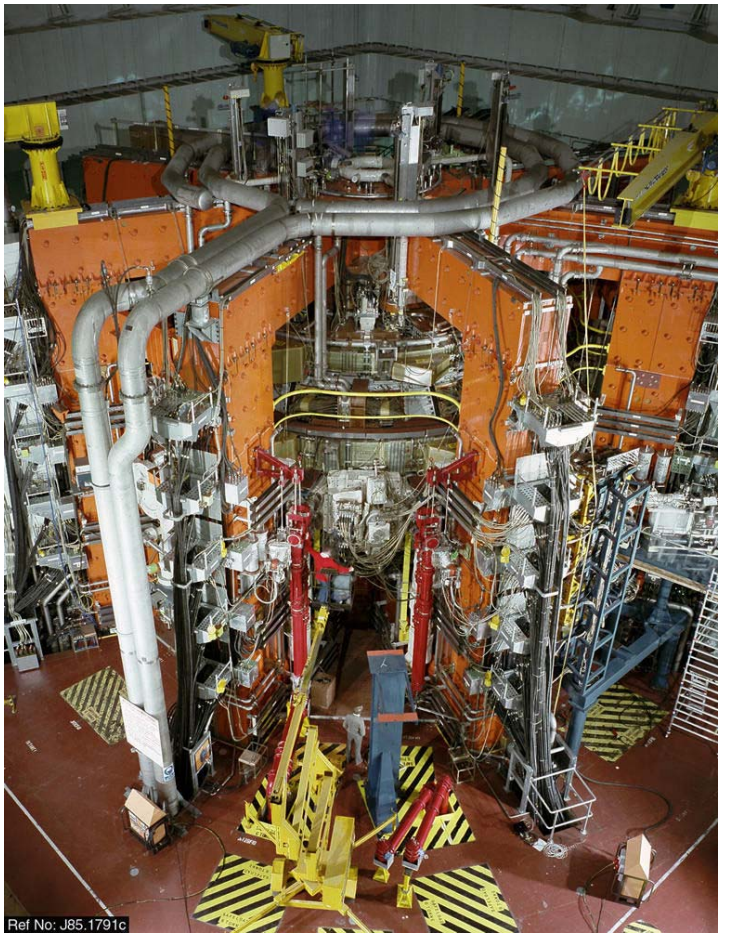
- very short pulses (~$10^{-9}$ sec)
- very high initial density (~$10^{21}$ $cm^{-3}$)

  Solid pellet heated by lasers - expelled gas causes outer shell to compress frozen DT center

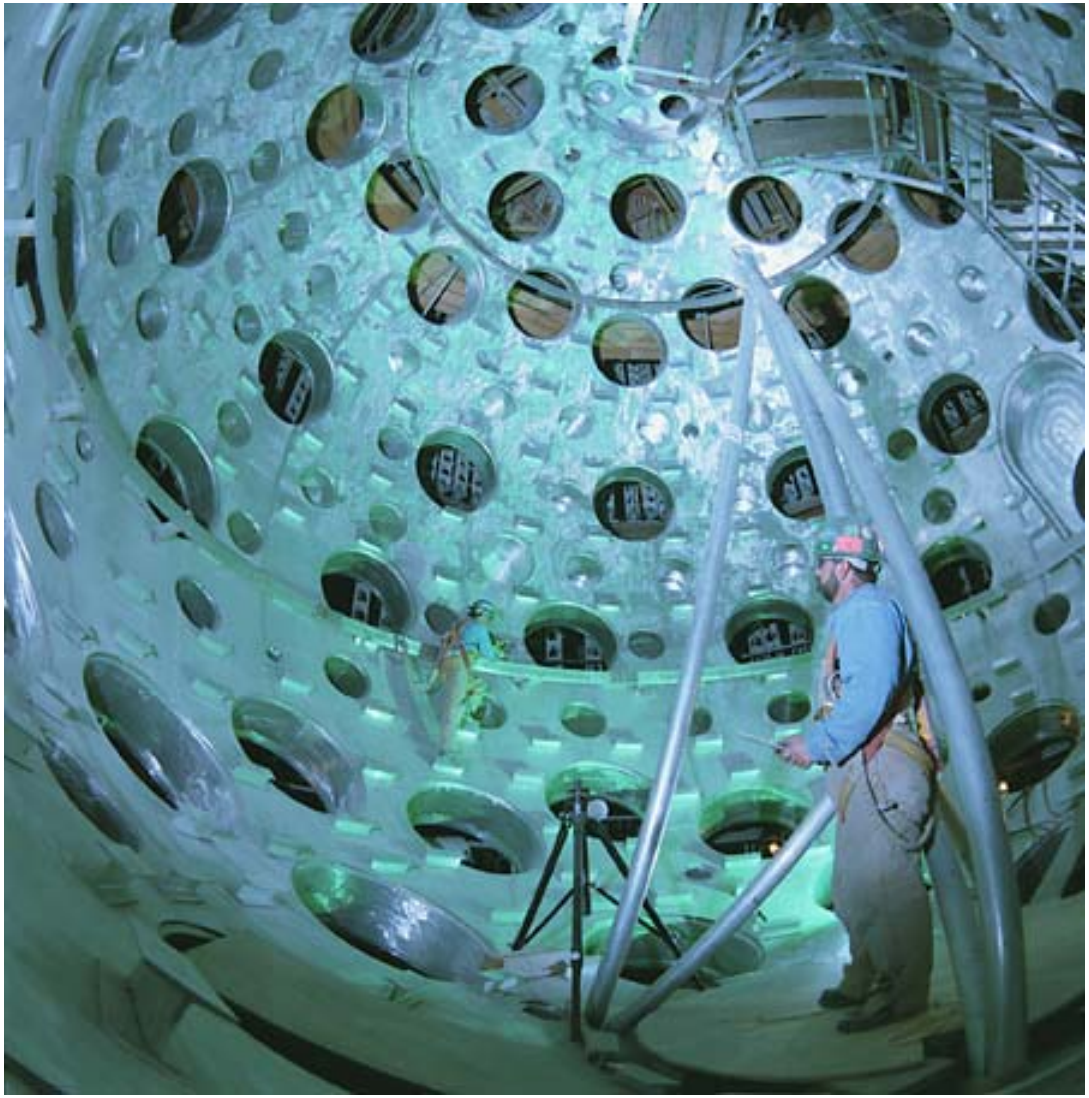
# Joint European Torus - JET

**Inside chamber:**
**evacuated and with plasma**



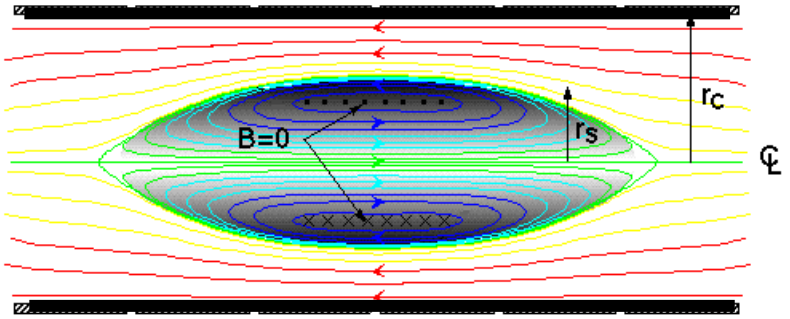


# National Ignition Facility – NIF
## inside target chamber



# MTF: Magnetized Target Fusion

**Magnetic field of at least 5 T in a closed-field line topology**

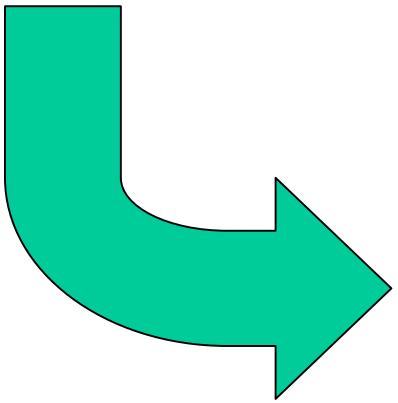


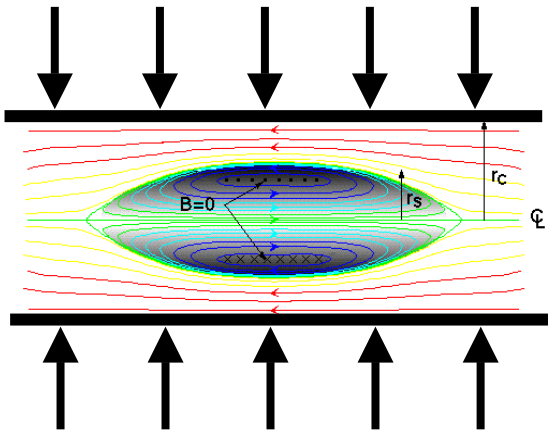

**Density ~ $10^{17}$-$10^{18}$ $cm^{-3}$**

**Free of impurities (reduce radiation losses)**

**$T_e$ ~ 50-300 eV**

**Initial target: *preheated & magnetized***






**Adiabatic ~ cm/μs**

**Subsequent *compression* to fusion conditions**

# Advantages of MTF

Fusion reactivity scales as density squared, which can be increased by many orders of magnitude over conventional MFE.

$R = n_D n_T <\sigma_{DT} v> = 1/4\ n^2 <\sigma_{DT} v>$

thermonuclear reaction rate /unit volume

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All characteristic plasma scale-lengths decrease with increasing density. Hence, system size is naturally reduced at a high density.

(e.g. mean free path, gyro radius at fixed beta, $c/\omega_p$ , $\lambda_{debye}$ , …)

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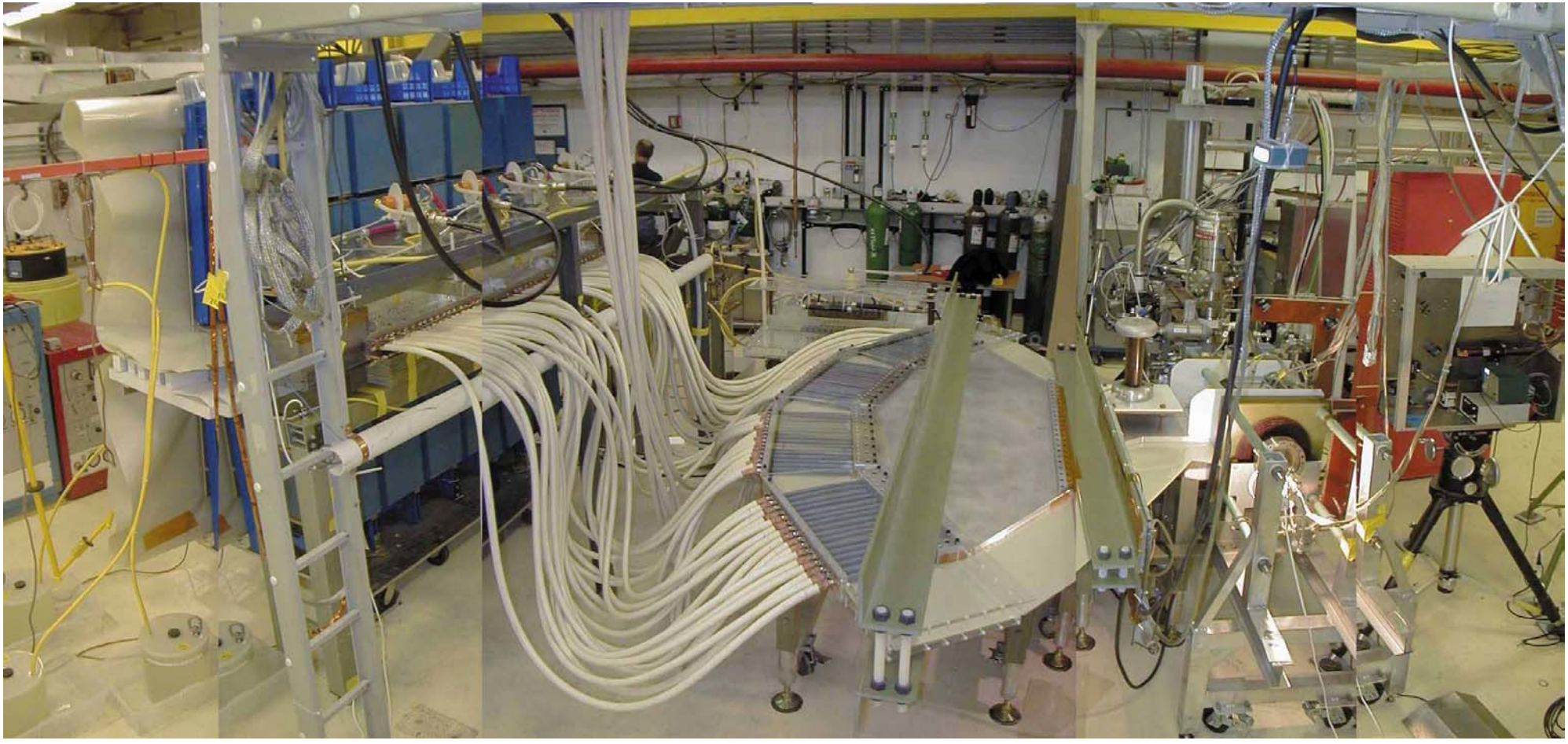
Magnetic insulation greatly reduces the required power and precision to compressionally-heat plasma to fusion-relevant conditions compared with ICF, and brings the pulsed-power requirements within reach of existing facilities.

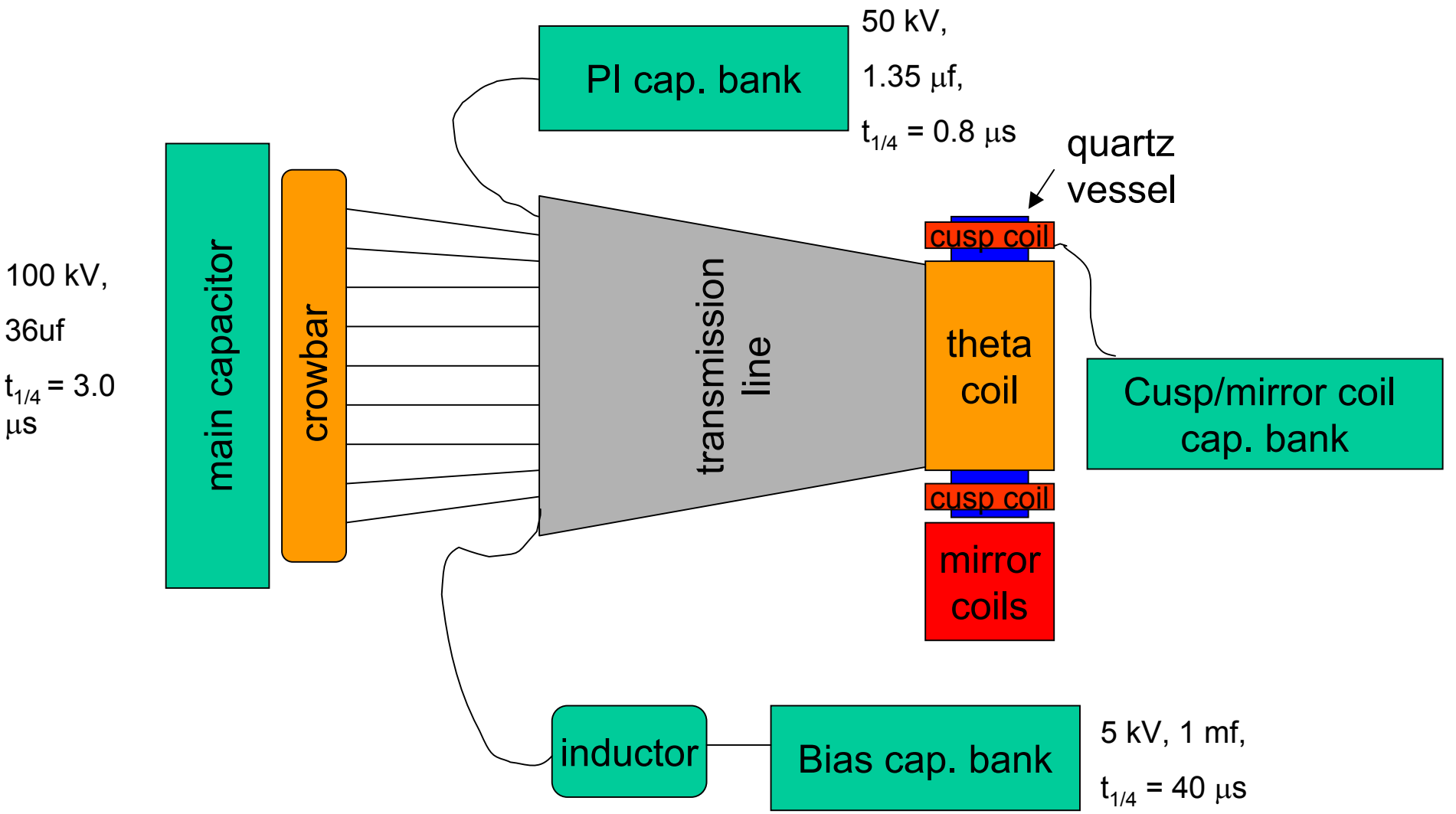
Shiva-Star (Air Force Res. Lab, Albuquerque)

Atlas (LANL)

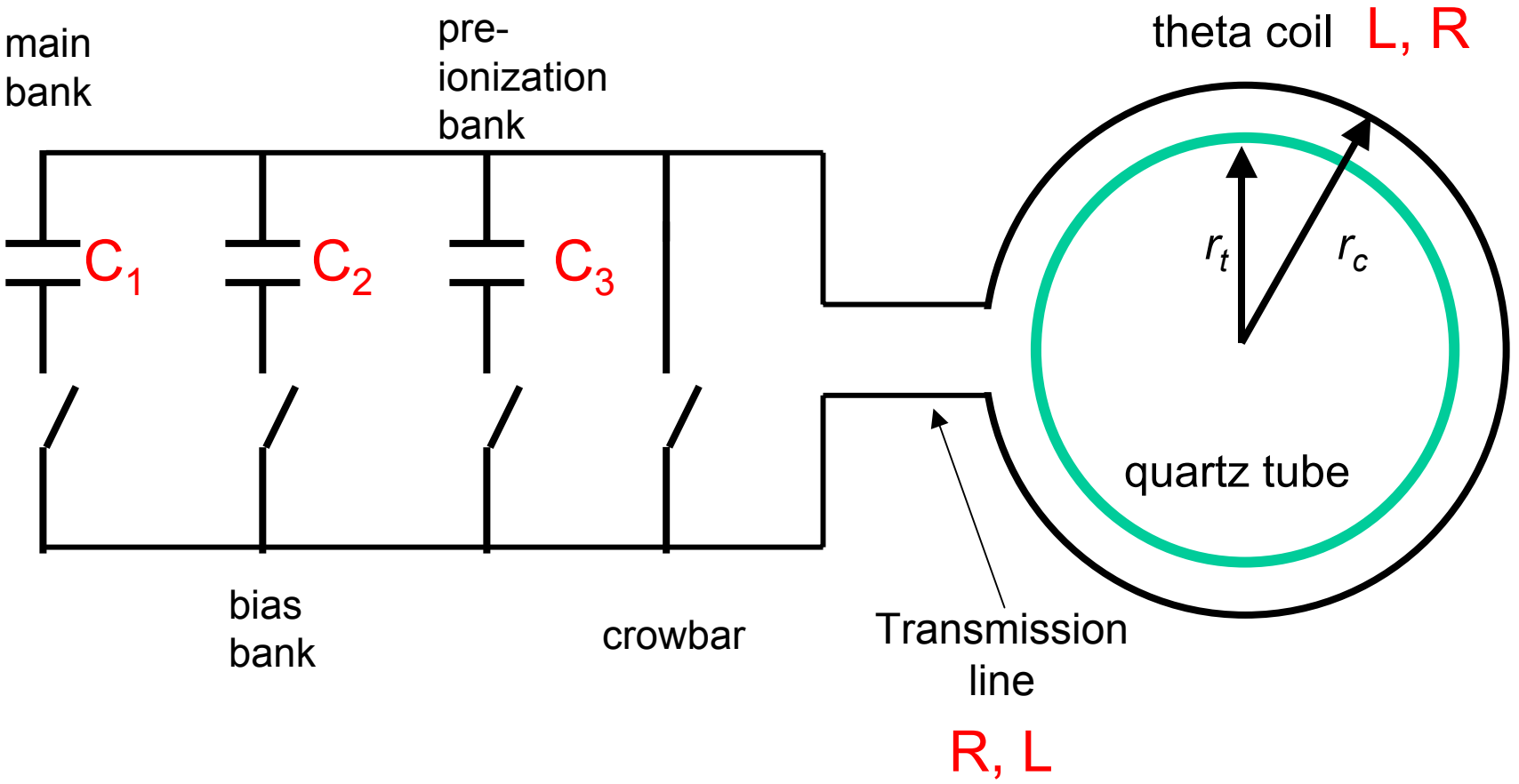
# FRX-L
## (Field Reversed eXperiment – Liner)



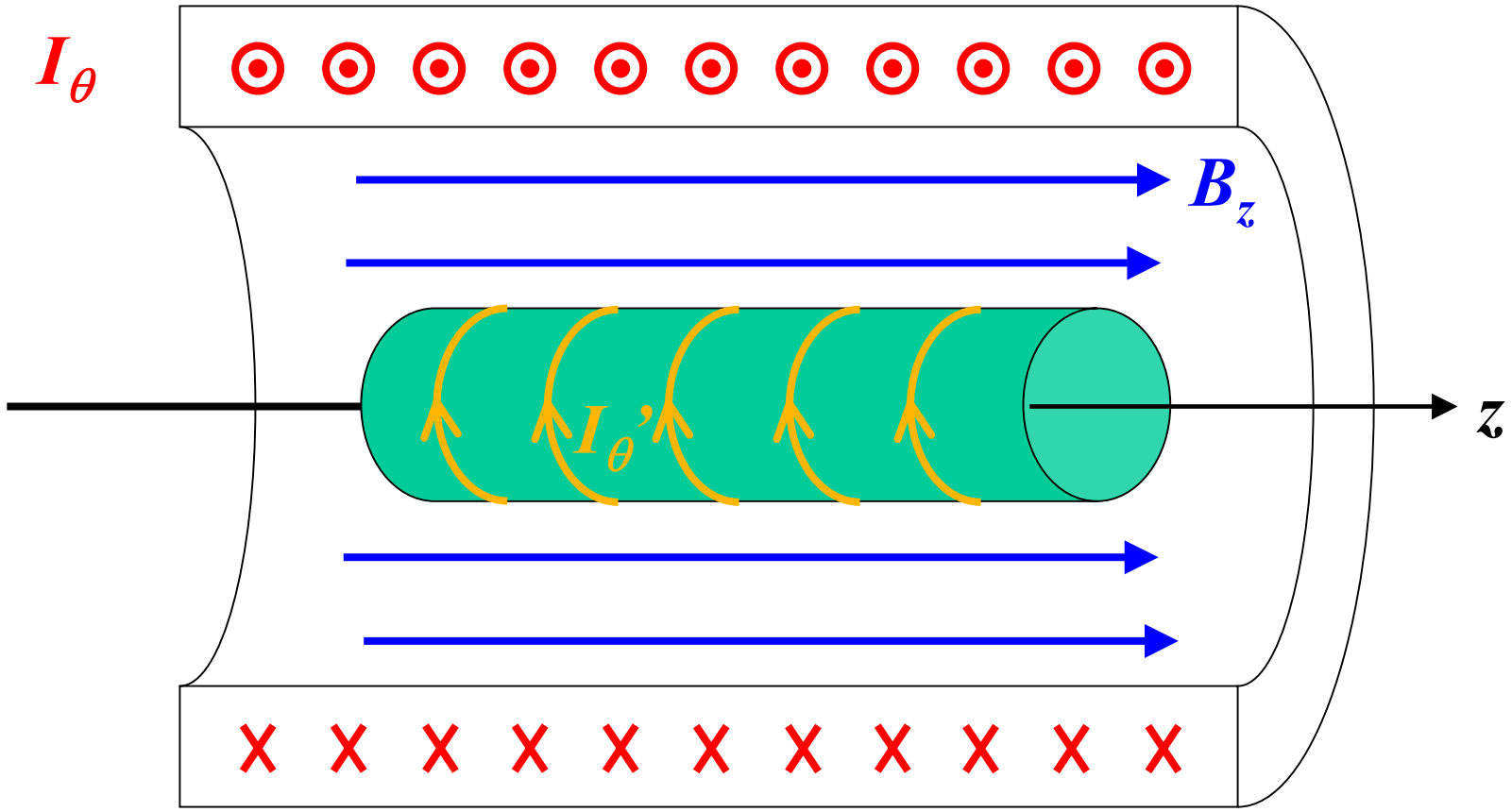
# FRX-L Block Diagram



# Simplified Field Reversed Theta Pinch Circuit

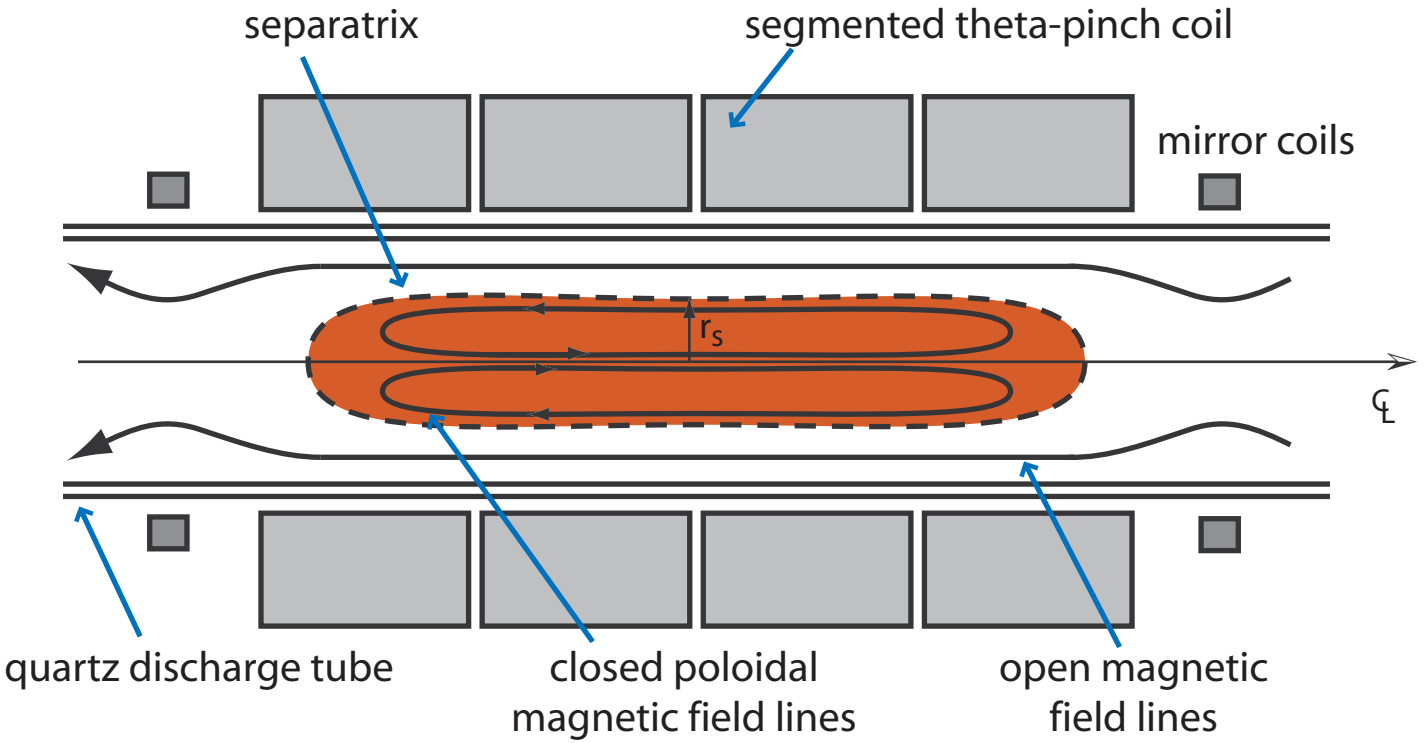


# Theta Pinch Physics

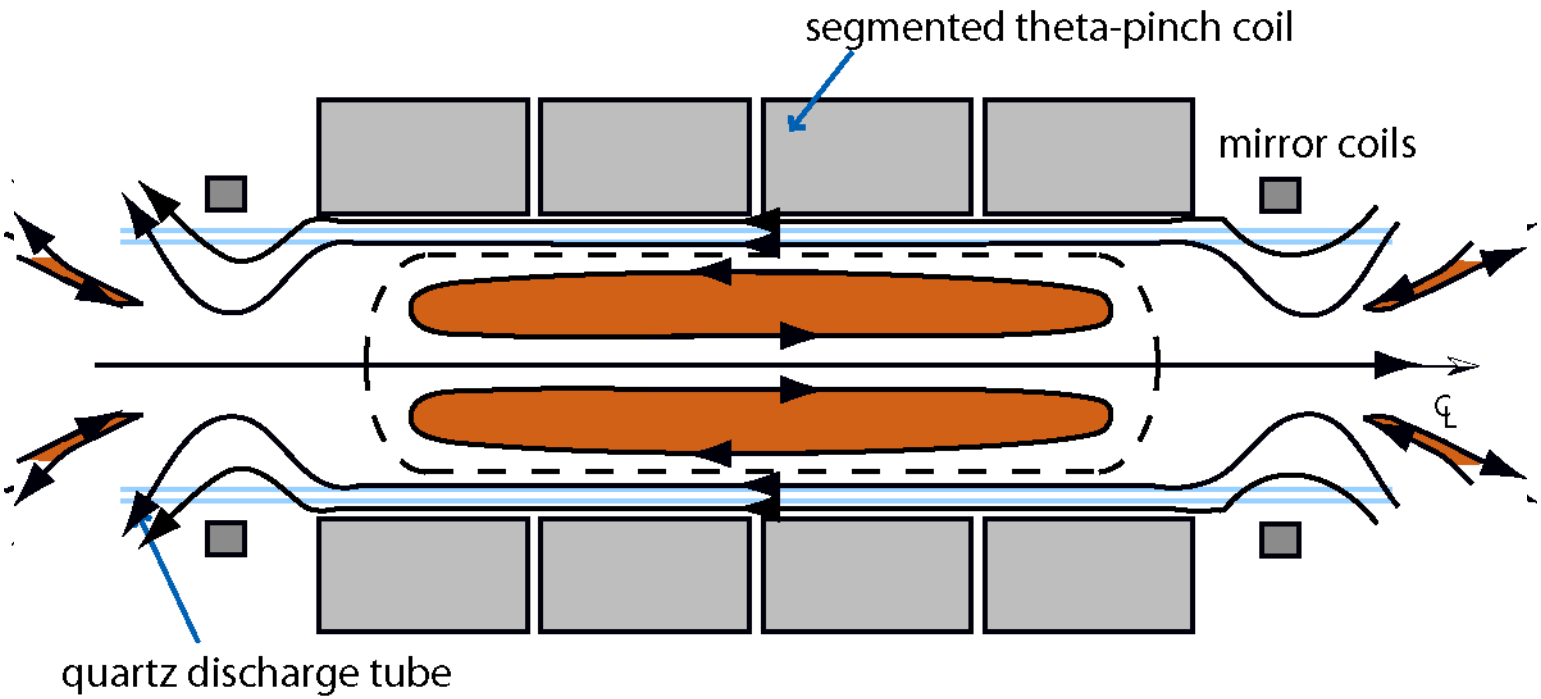


# Field Reversed Configuration

The FRC is an elongated compact toroid that is formed without toroidal field. The FRC consists of a closed-field-line torus inside a separatrix and an open-field-line *sheath* outside the separatrix. Equilibrium in a FRC is a balance of magnetic field pressure and plasma pressure in the radial direction, and field-line tension and plasma pressure in the axial direction.



# FRC formation sequence



# Phase 1: FRC formation

**FRC Goal Parameters:**

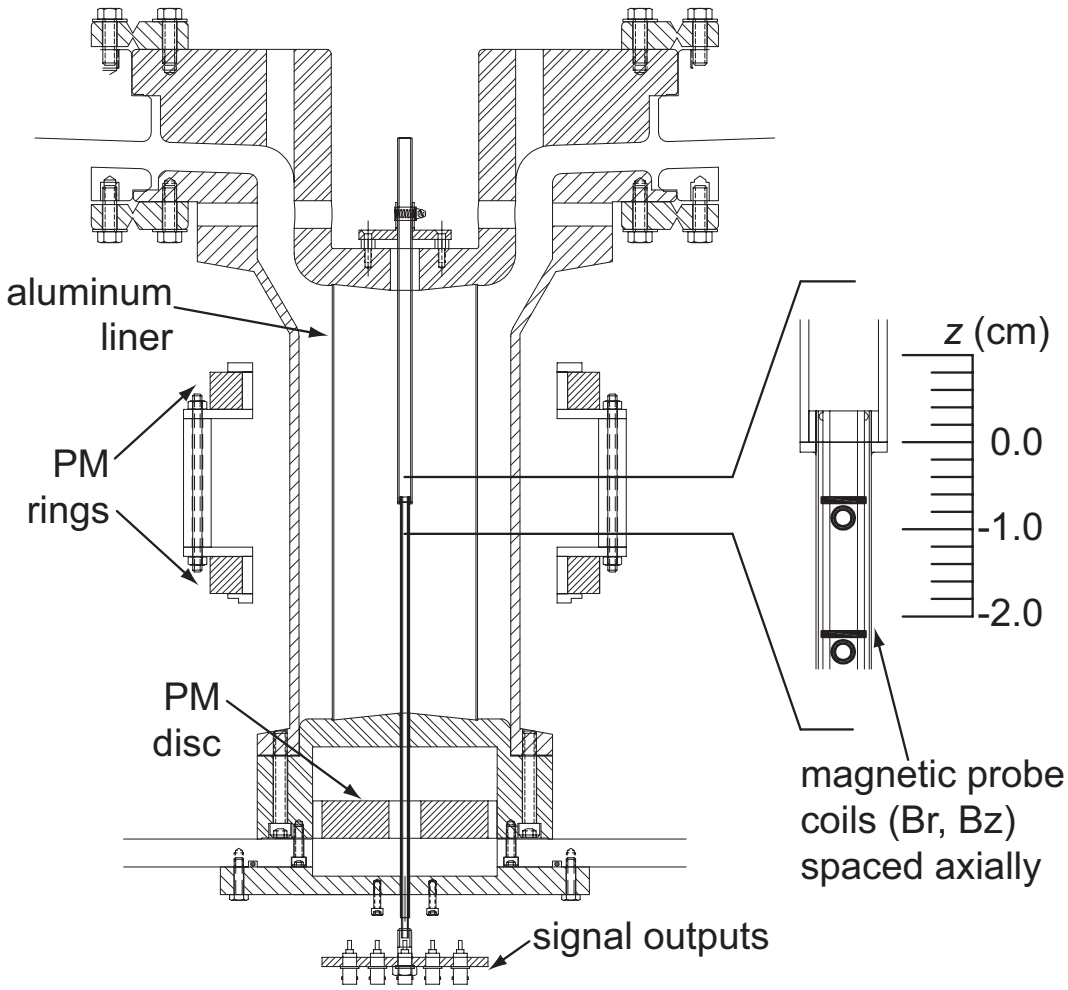
- density $n \sim 10^{17}$ cm$^{-3}$
- temperature $T_e \sim T_i \sim 300$ eV
- lifetime $\tau_E > 10$ μs

# Phase 2: FRC Translation into Liner

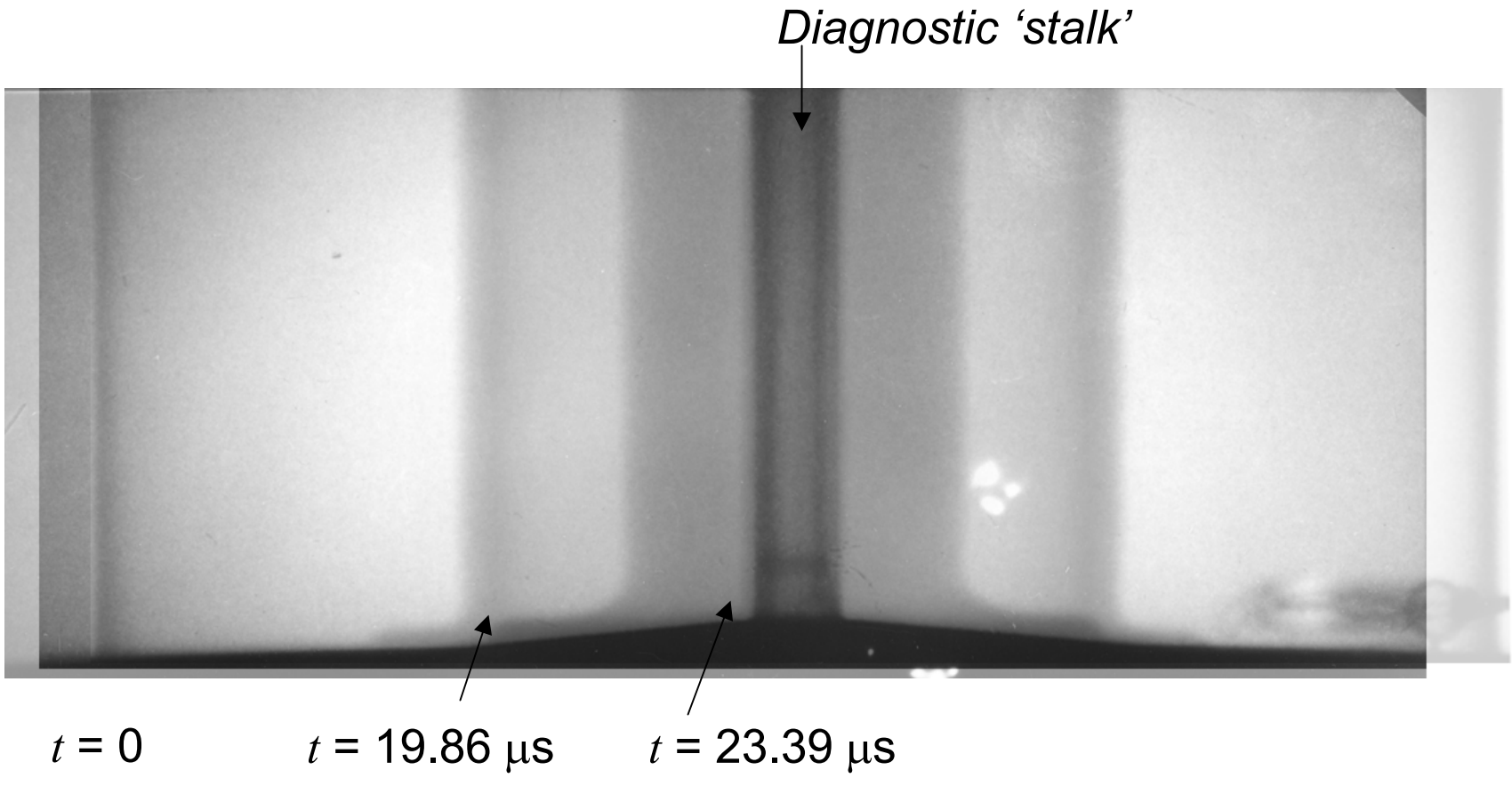
**FRC inside liner:**

- liner $r_{wall} = 5$ cm
- plasma $r_s \sim 3$ cm
- plasma $l_s = 30$ cm

# Liner Compression onto Vacuum



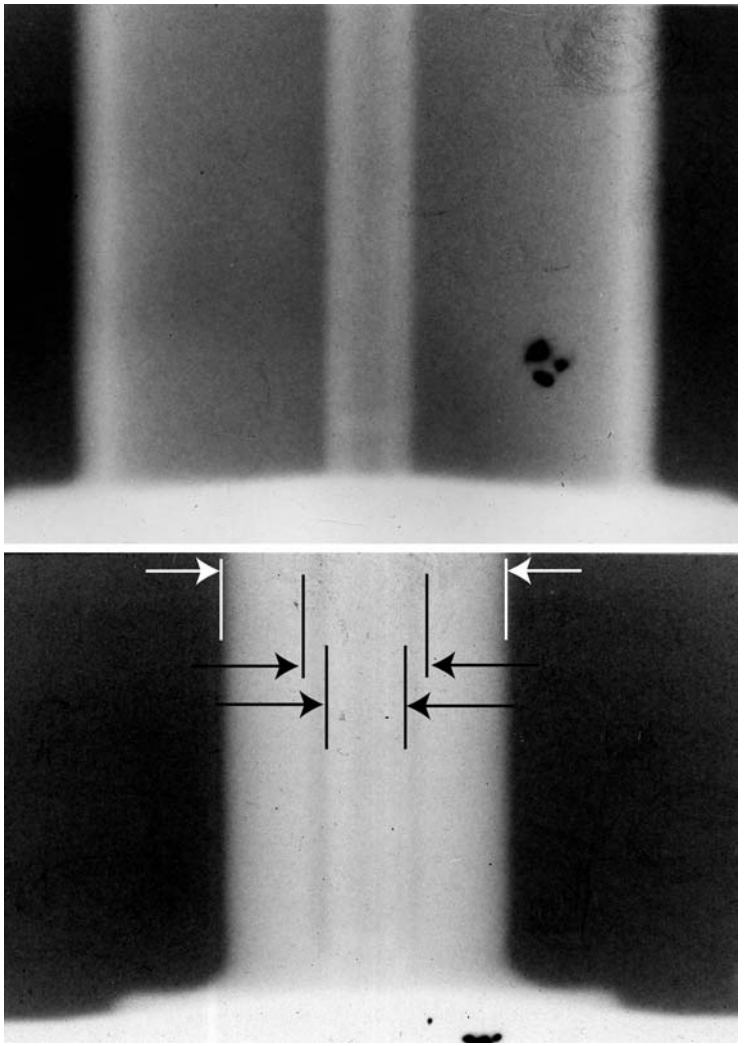
# X-radiographs
## composite shot of lower position



# X-radiographs
## first liner compression

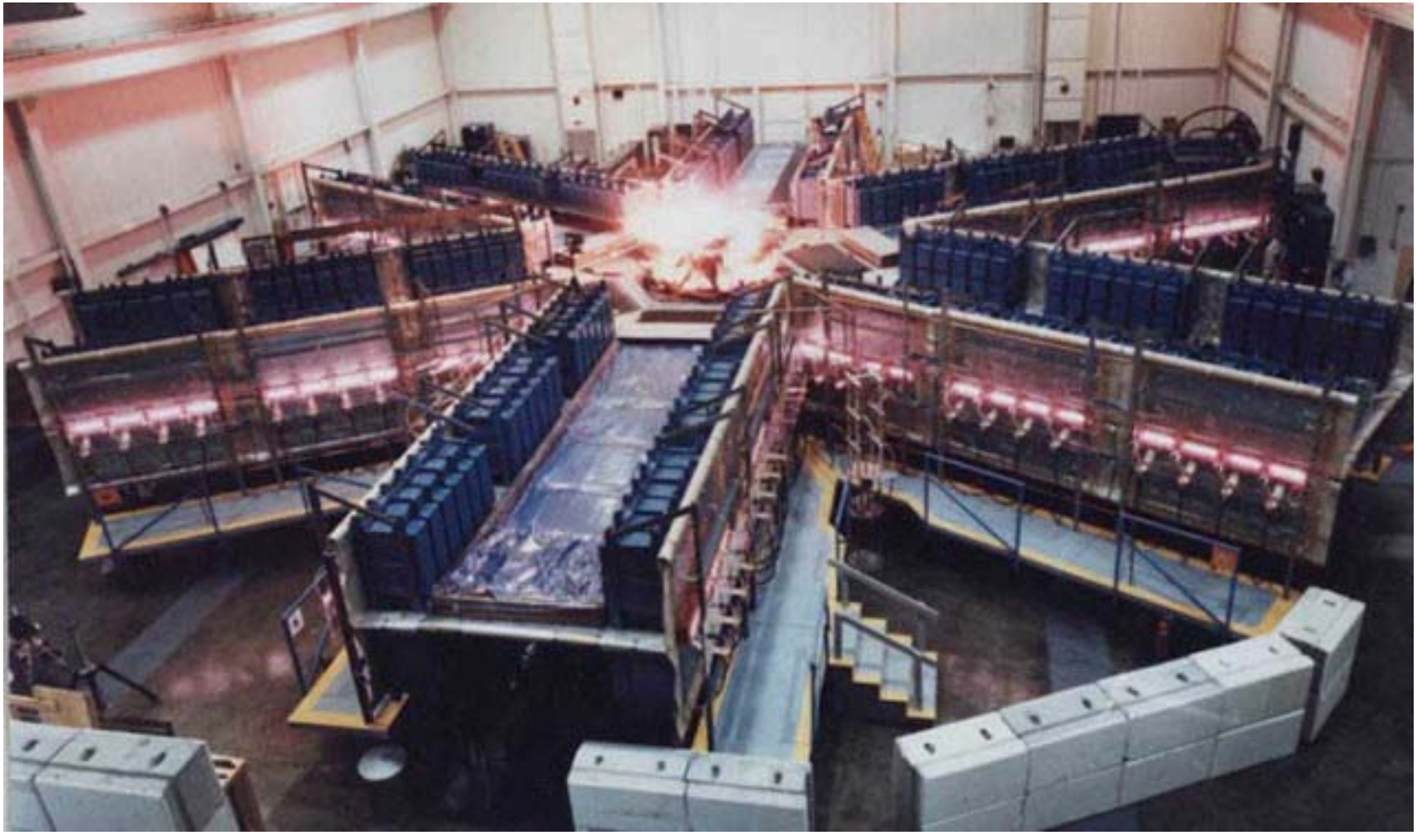
$t$ = 19.86 μs

$t$ = 23.39 μs



# Shiva-Star

## Air Force Research Laboratory - Albuquerque



# Atlas

## Los Alamos National Laboratory

# Conclusion and Future Directions

- MTF: method by which magnetized plasma of $T_e$~300 eV and $n$~$10^{17}$cm$^{-3}$ is imploded to fusion conditions
- FRC FORMATION currently under investigation
- Two successful 30-cm long, 10-cm diameter aluminum liner shots onto vacuum

# Web Links to learn more about FUSION

fusion.lanl.gov

fusioned.gat.com

fusedweb.pppl.gov