Z-Pinches, Pulsed Power, and Fusion

2022 Introduction to Fusion Energy and Plasma Physics Course

Sophia V. R. Rocco [1]

[1]Lawrence Livermore National Laboratory

24 June 2022

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LLNL-PRES-836514

Overview

How did I end up here?

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And why should you listen to me?

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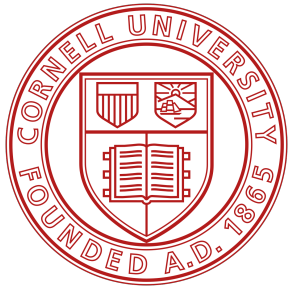

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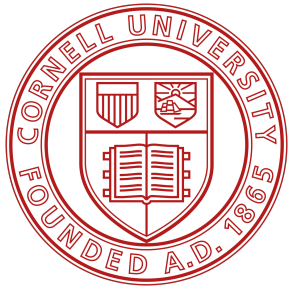

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Laboratory of Plasma
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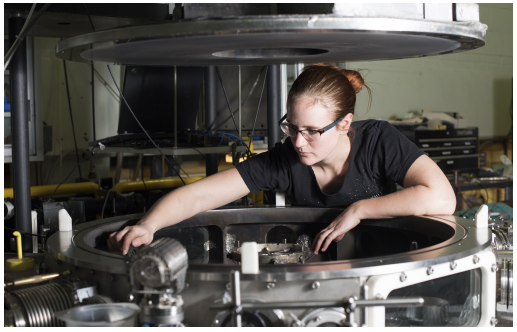

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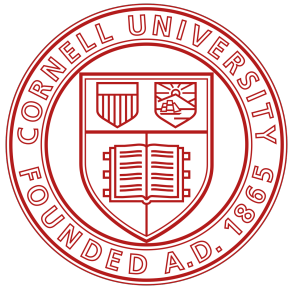

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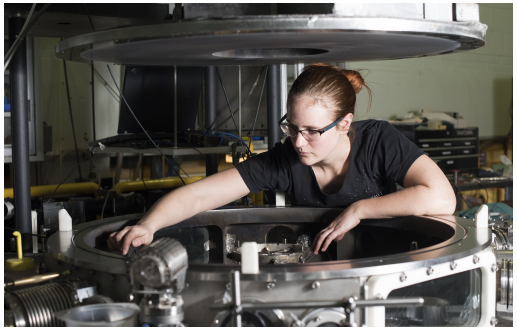

Postdoc 2021-now
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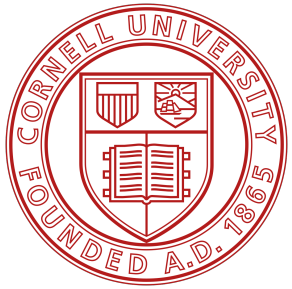

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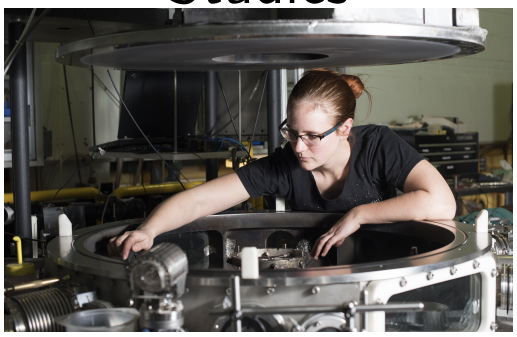

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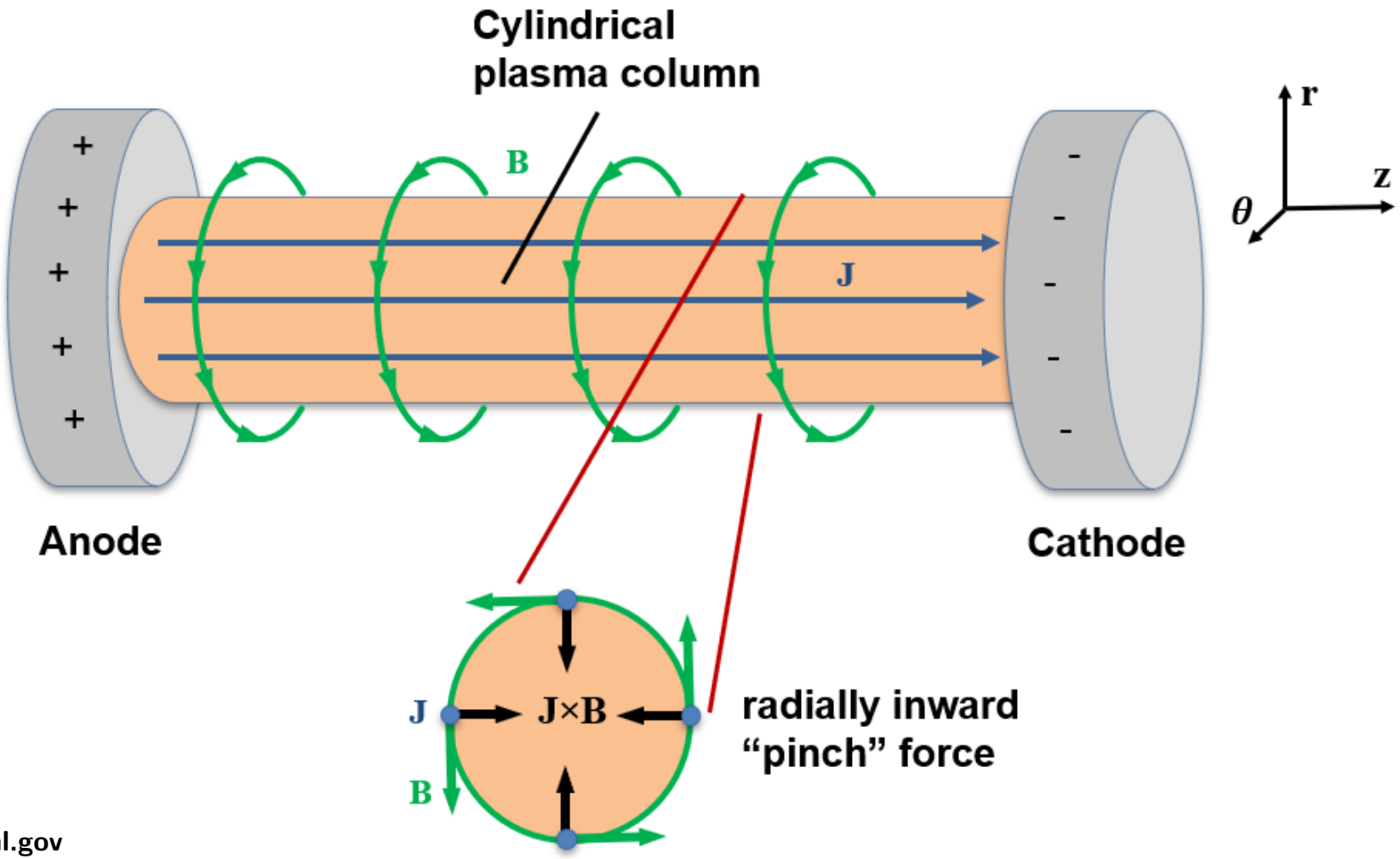
A Z-pinch is a result of the Lorentz force counteracted by a plasma's pressure



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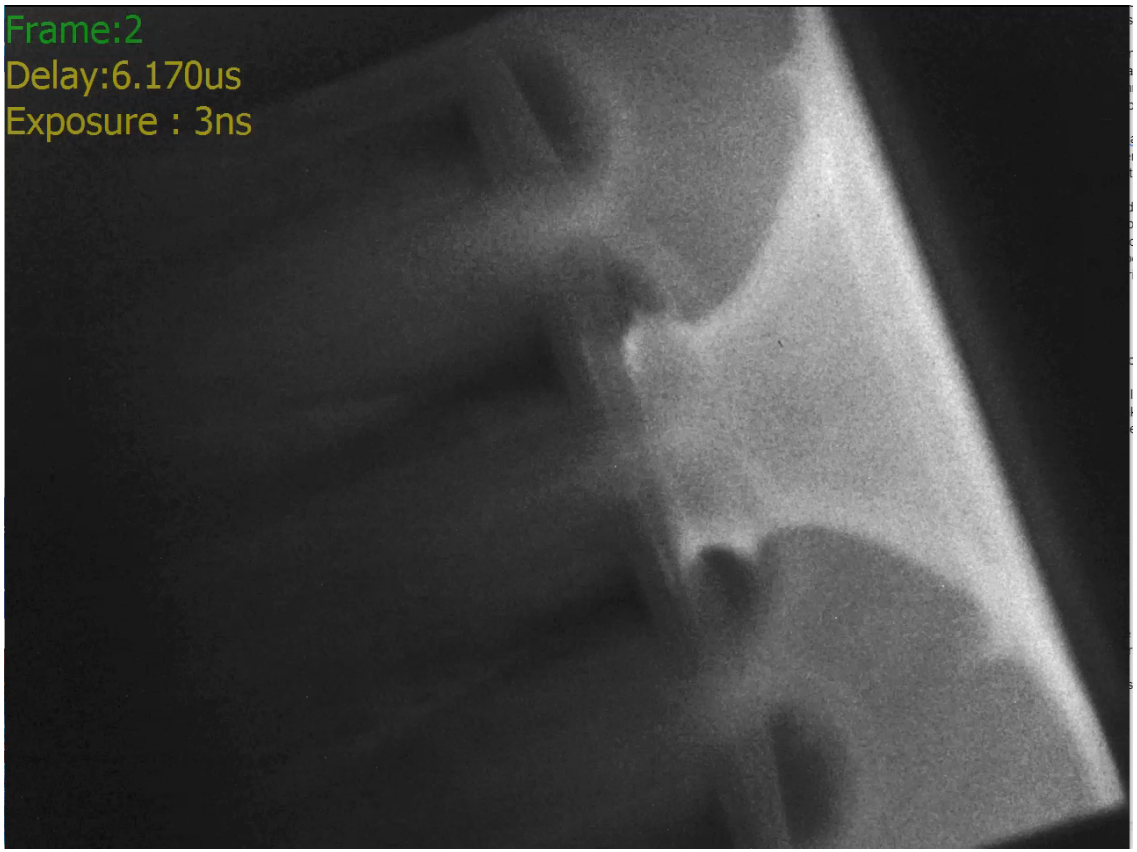

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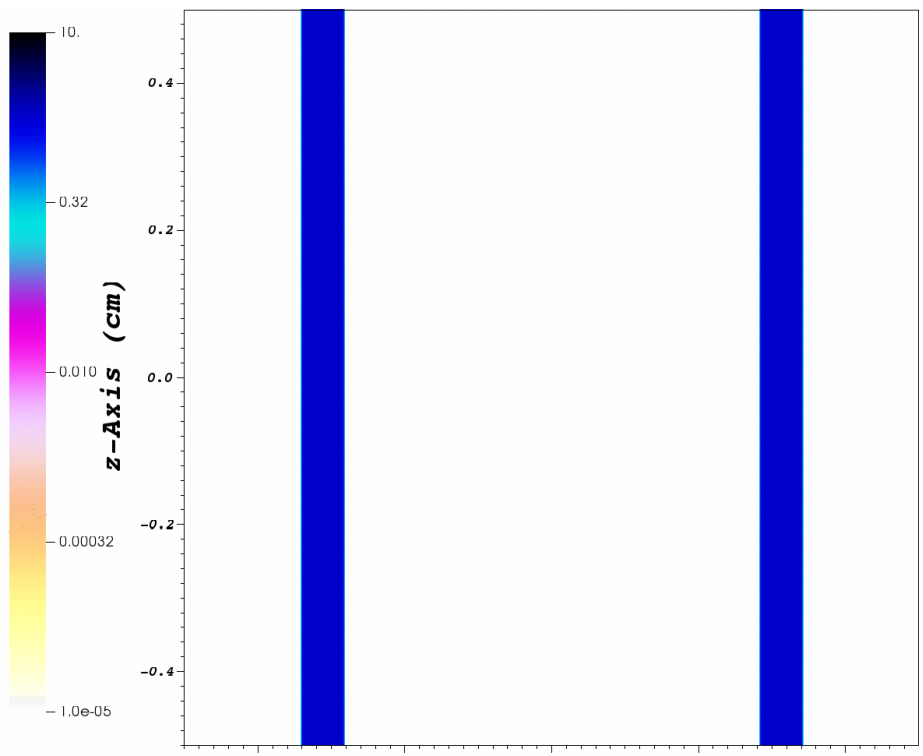
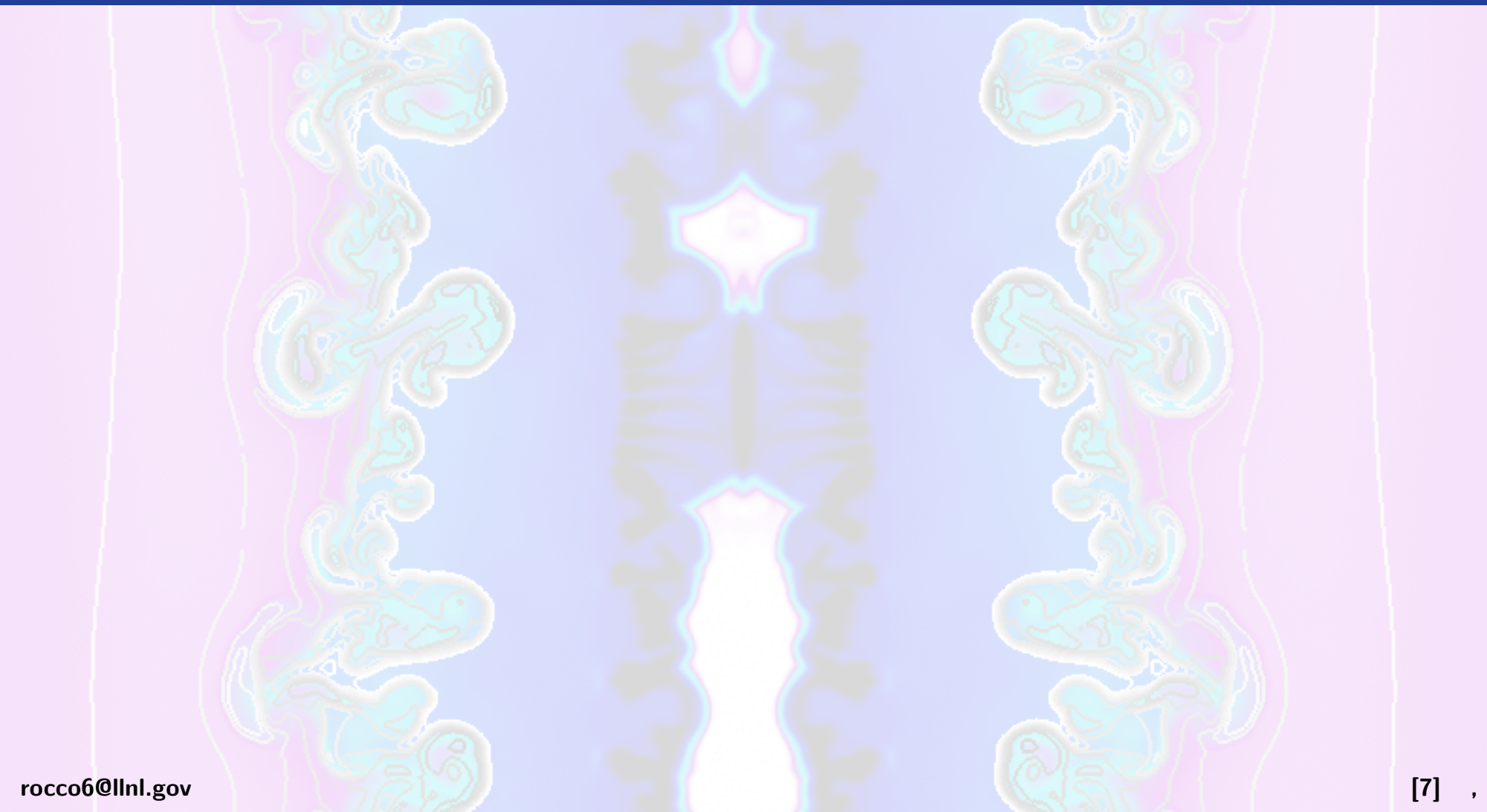


A variety of analytic models are used to describe Z-pinch dynamics



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Effectively all models describe a cylindrical implosion that can be described by conservation of momentum:

$$\frac{D(\rho \mathbf{u})}{Dt} = \nabla \cdot \underline{\underline{\Pi}} + \mathbf{J} \times \mathbf{B} - \nabla p + \mathbf{F}$$

The **Bennett Relation** is a steady state solution to a Z-pinch plasma

Assumptions:

1. A cylindrical column of fully ionized quasineutral plasma
2. Ideal gas law $P = Nk_B T$

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N is the number of particles per unit length, k_B is Boltzmann's constant, $T_{e,i}$ the temperature of the electrons and ions respectively

Z-pinches are highly unstable in a bunch of fun, different ways

Alphabet soup

- **RTI:** Rayleigh-Taylor Instability
- **MRTI:** Magneto-Rayleigh-Taylor Instability
- **RMI:** Richtmeyer-Meshkov Instability
- **ETI:** Electro-thermal Instability
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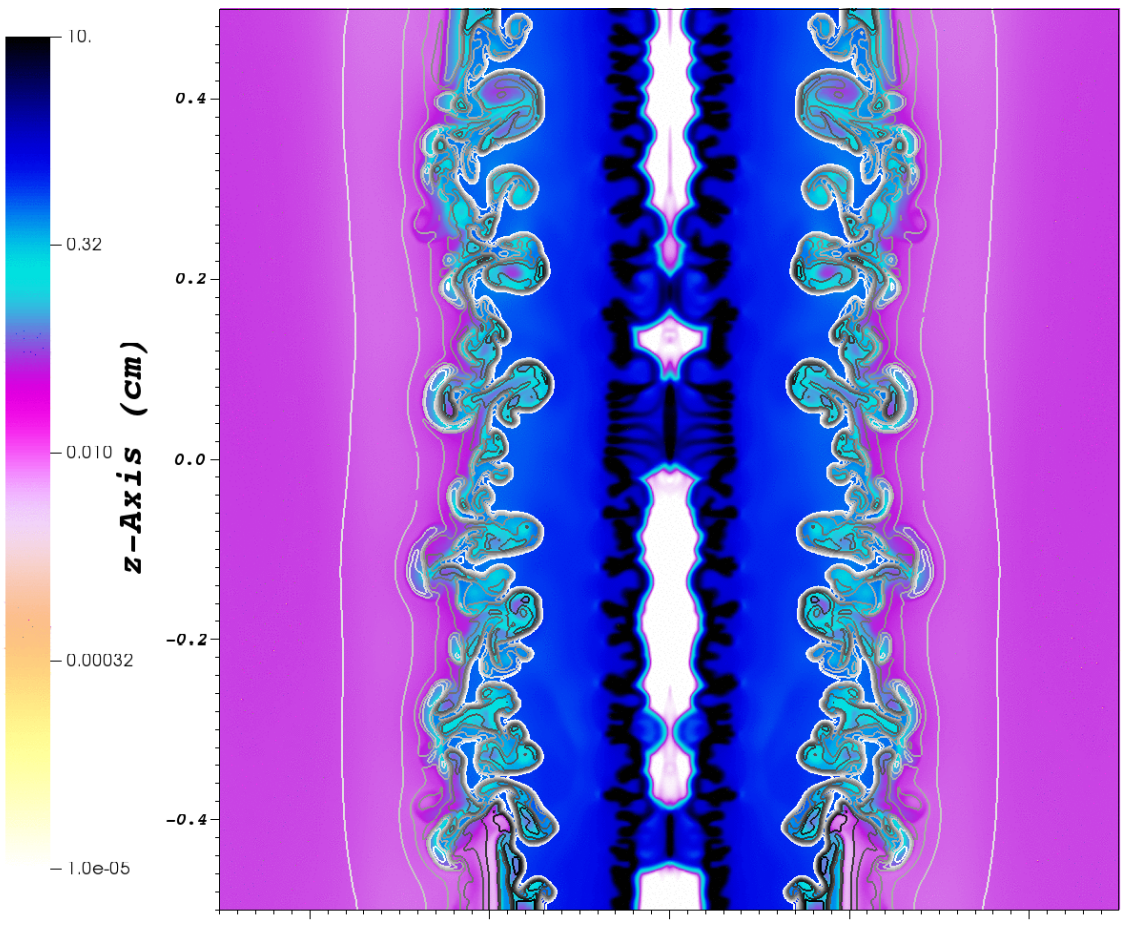

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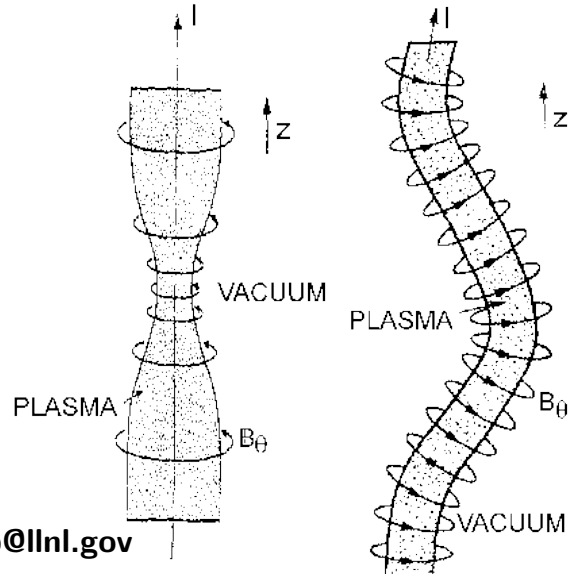
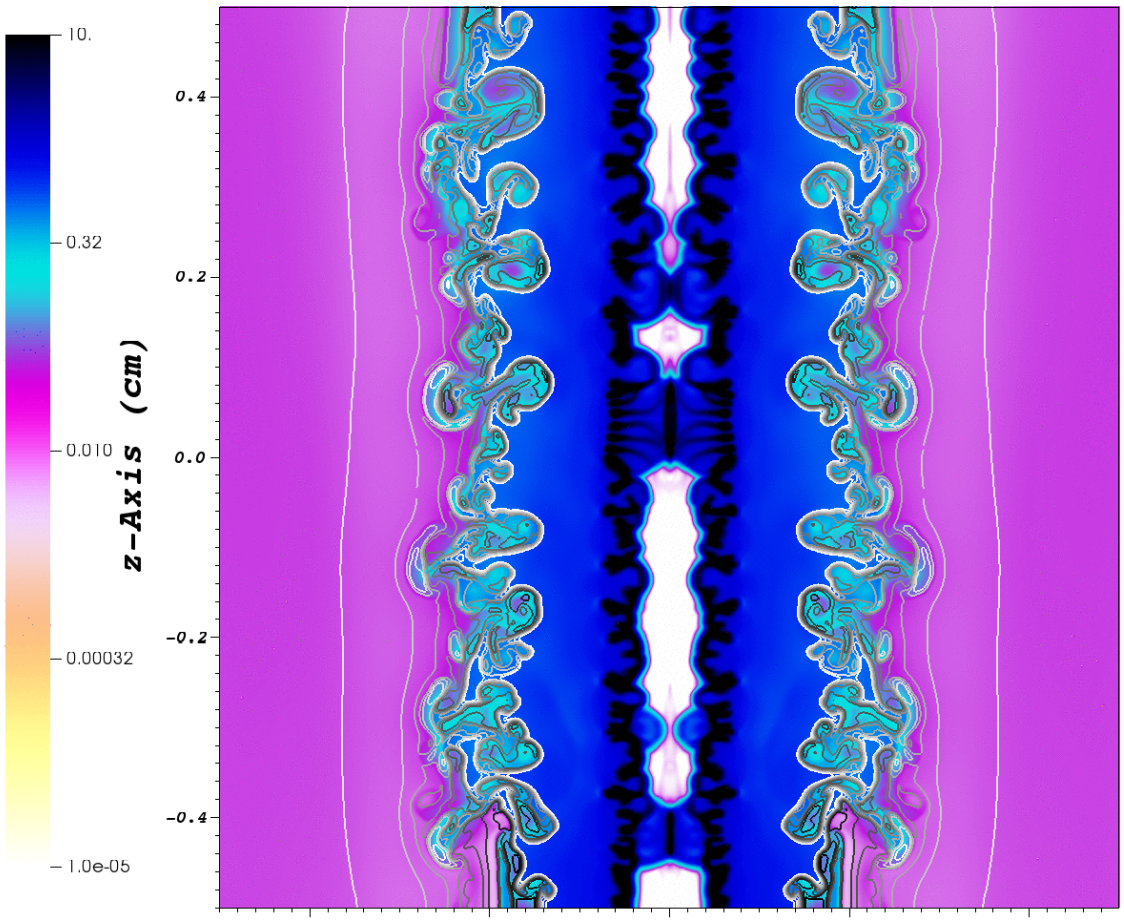
You'll also hear about "modes" $m = 0, 1$ etc.





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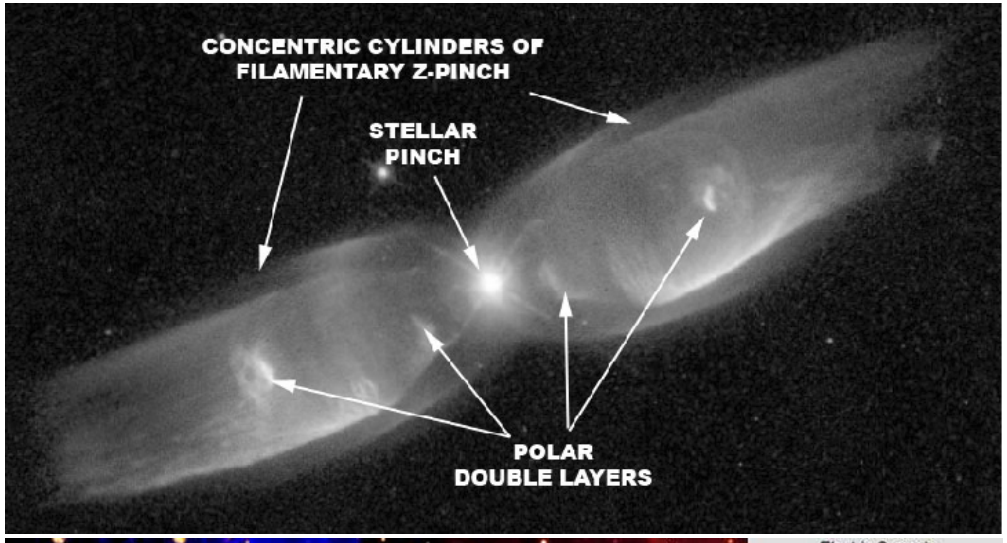
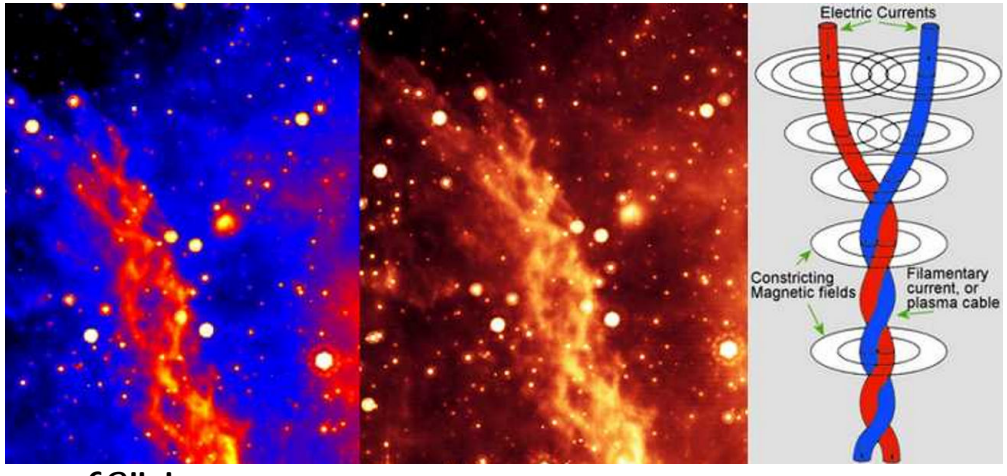
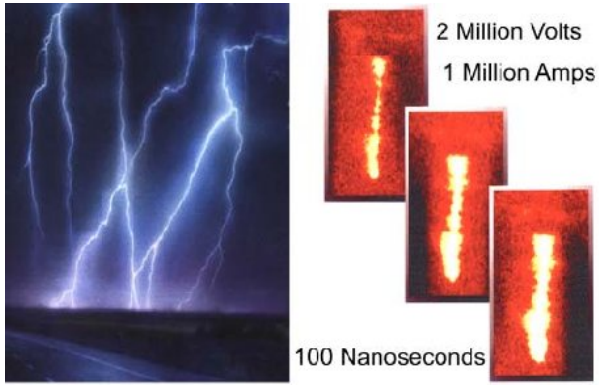
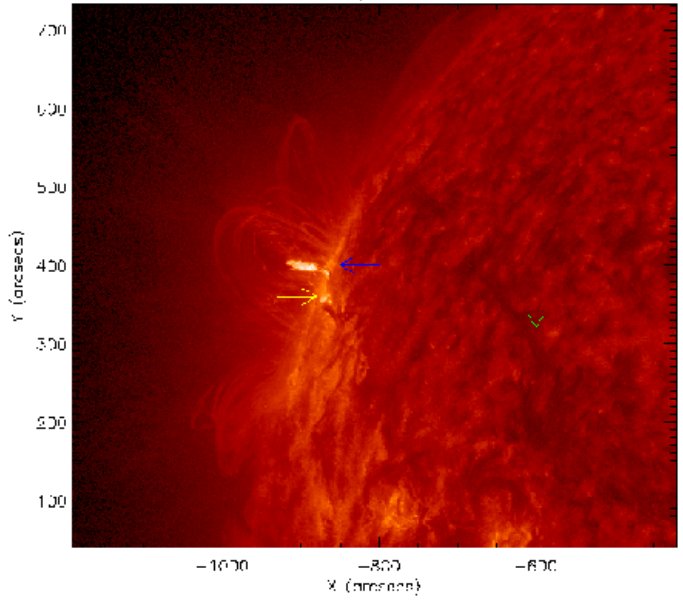
The pinch effect in the wild is observed across a wide range of scales









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1. $\nabla p = \mathbf{J} \times \mathbf{B}$

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3. If a Z-pinch plasma is ionized and quasineutral, the Bennett condition is satisfied if in a steady state

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5. They can occur when nature feels like generating an electrical discharge: lightning, solar flares, jets...

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How do you make Z-pinches?

Recipe

SERVINGS: 1 PREP TIME: 20min-2yr COOK TIME: 100-5000 ns

Z-Pinch Plasma

INGREDIENTS

DIRECTIONS

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Gas or solid

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Material to be ionized into plasma

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Z-Pinch Plasma

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More than just a *pinch*, be generous!

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Z-Pinch Plasma

INGREDIENTS	DIRECTIONS
Gas or solid	Material to be ionized into plasma
Current	More than just a *pinch*, be generous!
Magnetic field	Conveniently provided by the current

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- Vacuum-filled metal cavity containing a pair of electrodes (assume perfectly conducting), therefore inductance (L) is the only thing limiting the discharge

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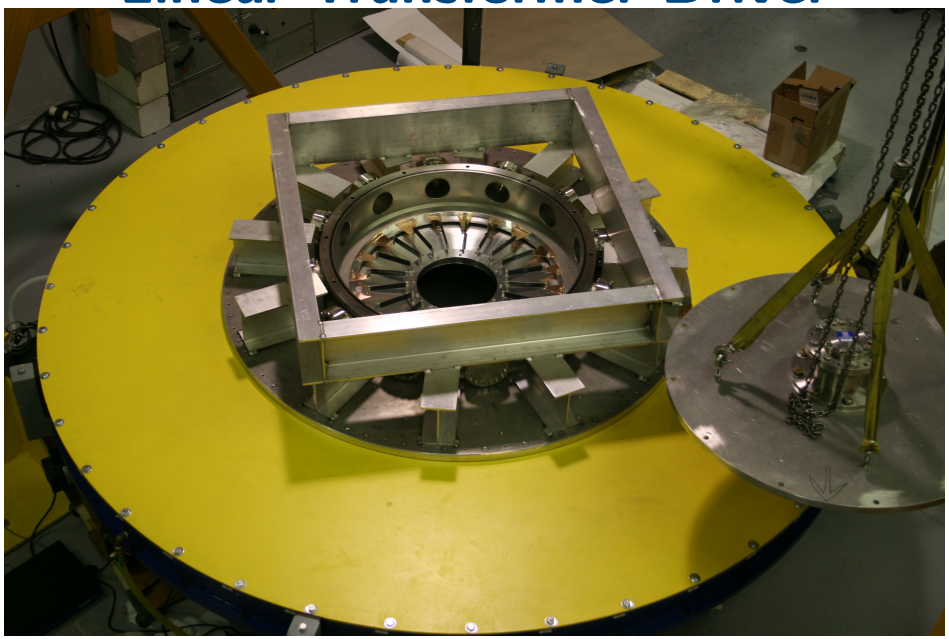
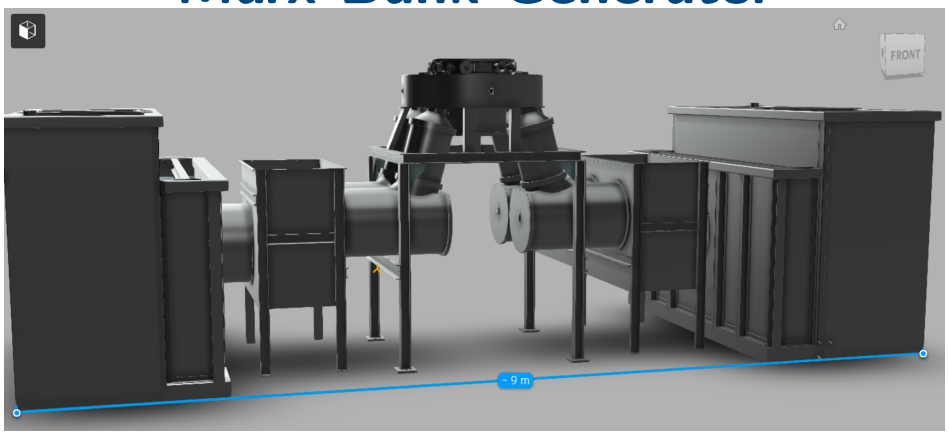
- *https* : *//hrhasson.github.io/McBride_LTD_Writeup.pdf*

There are two main types of driver

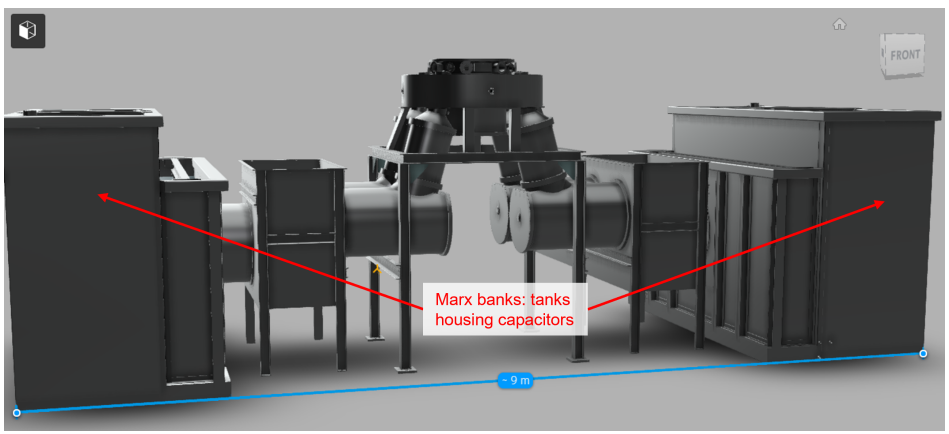
Linear Transformer Driver

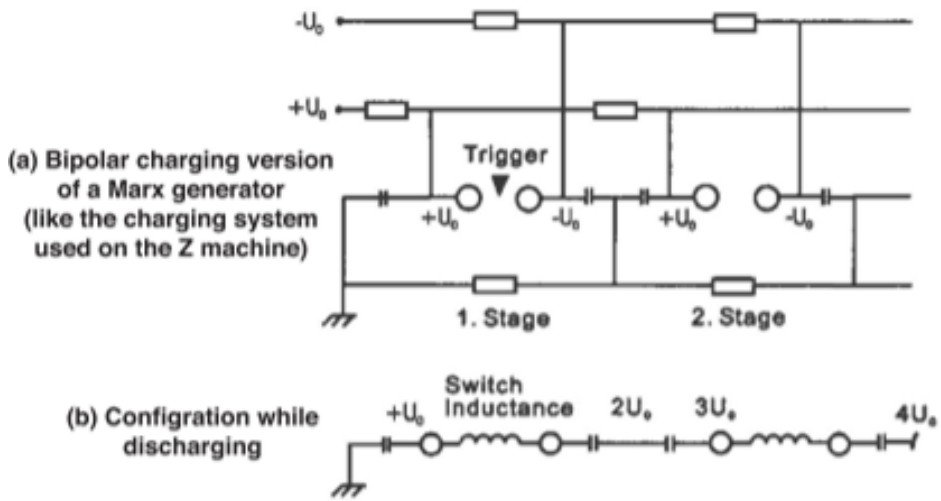


Marx Bank Generator



Marx Bank Generators





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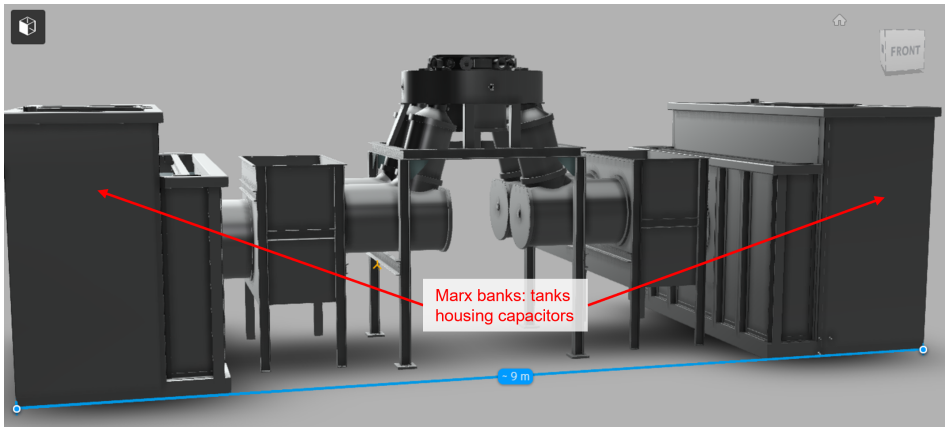
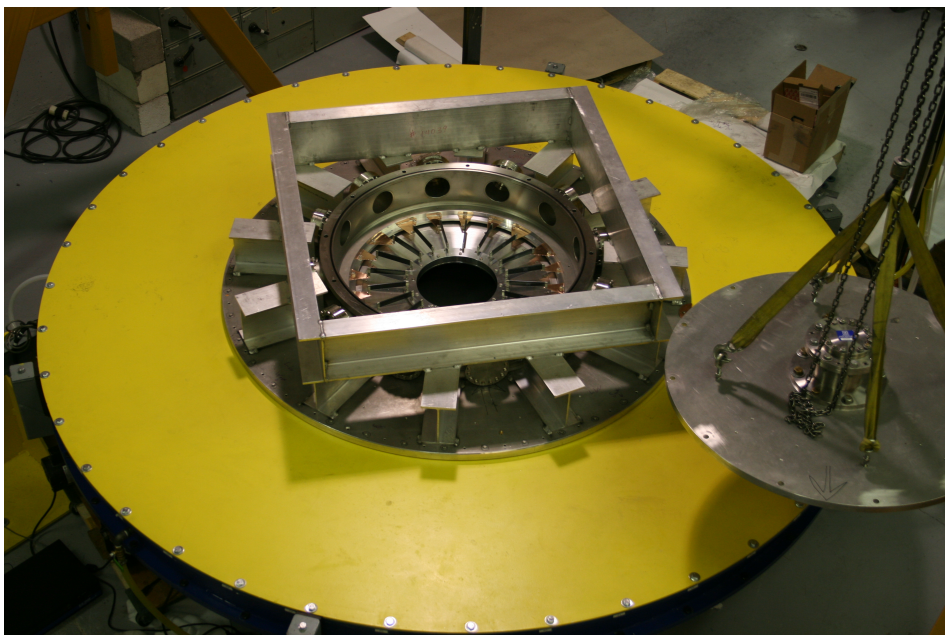
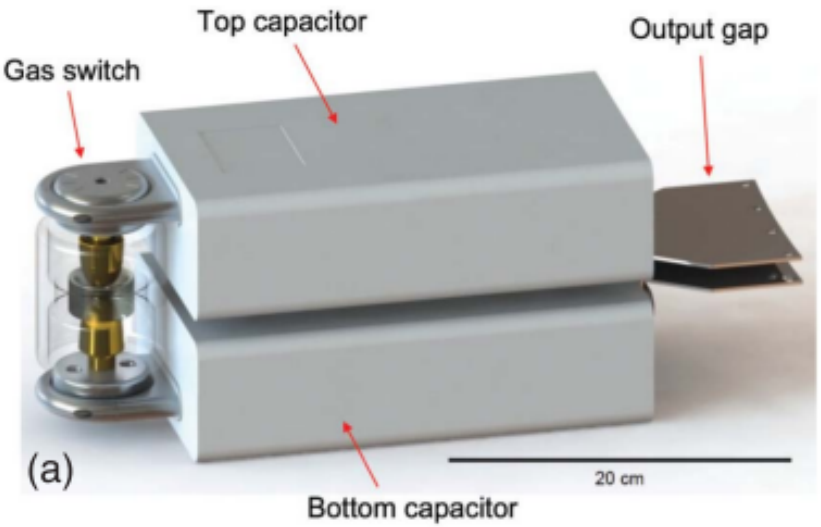
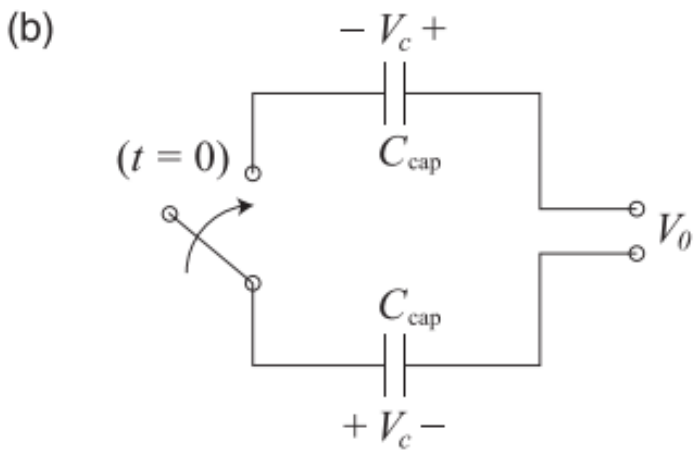


Linear Transformer Drivers







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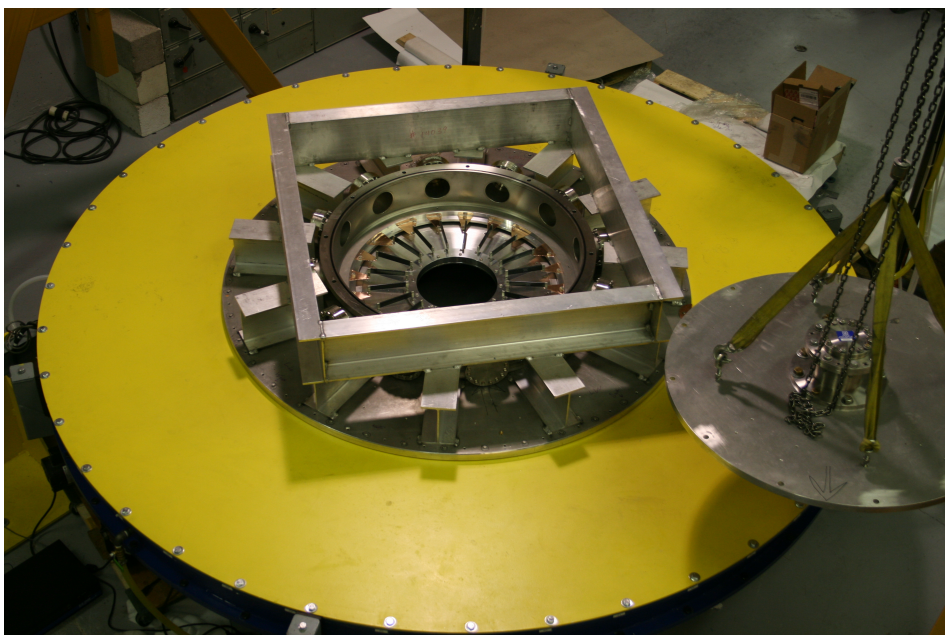

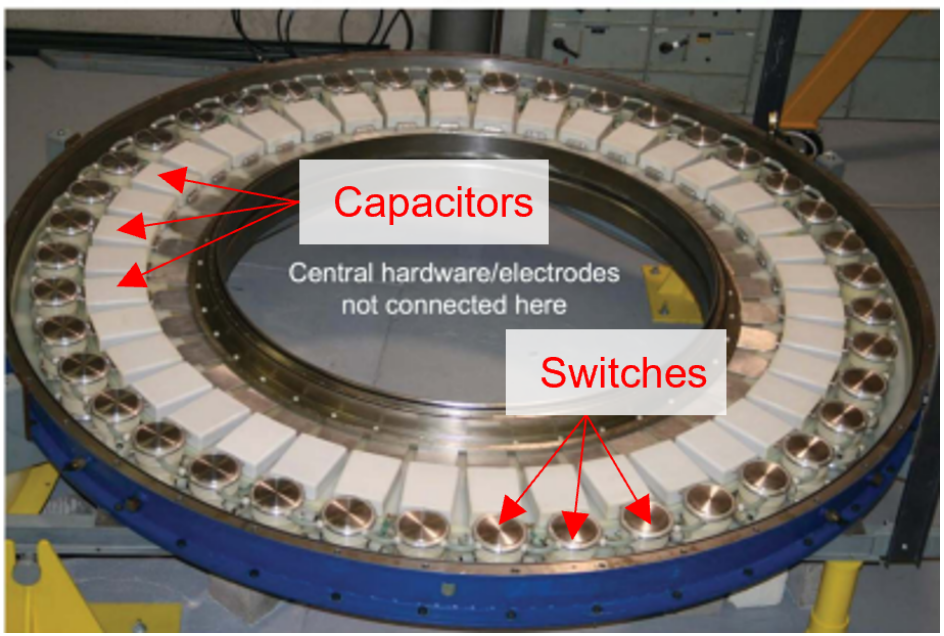

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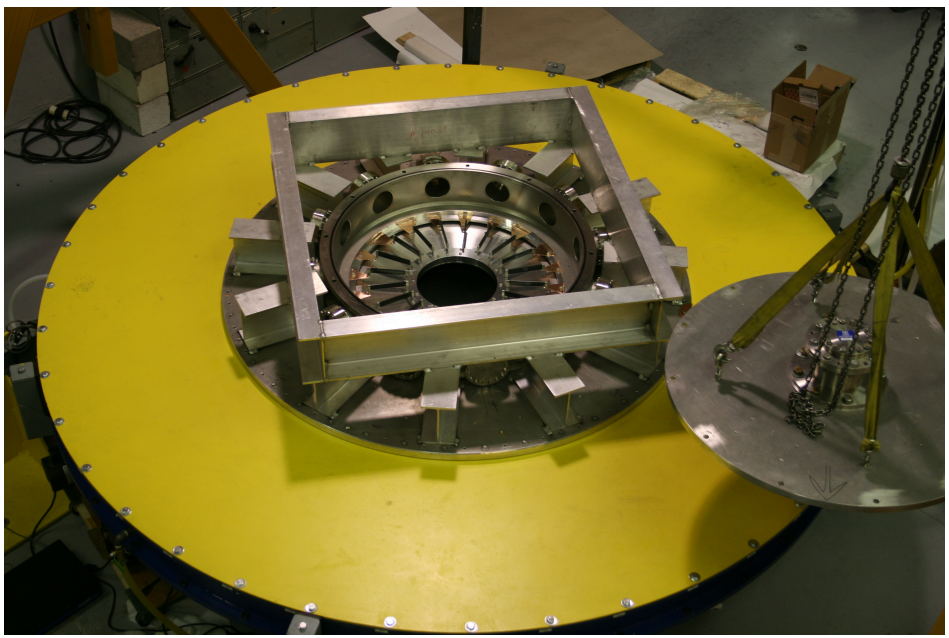
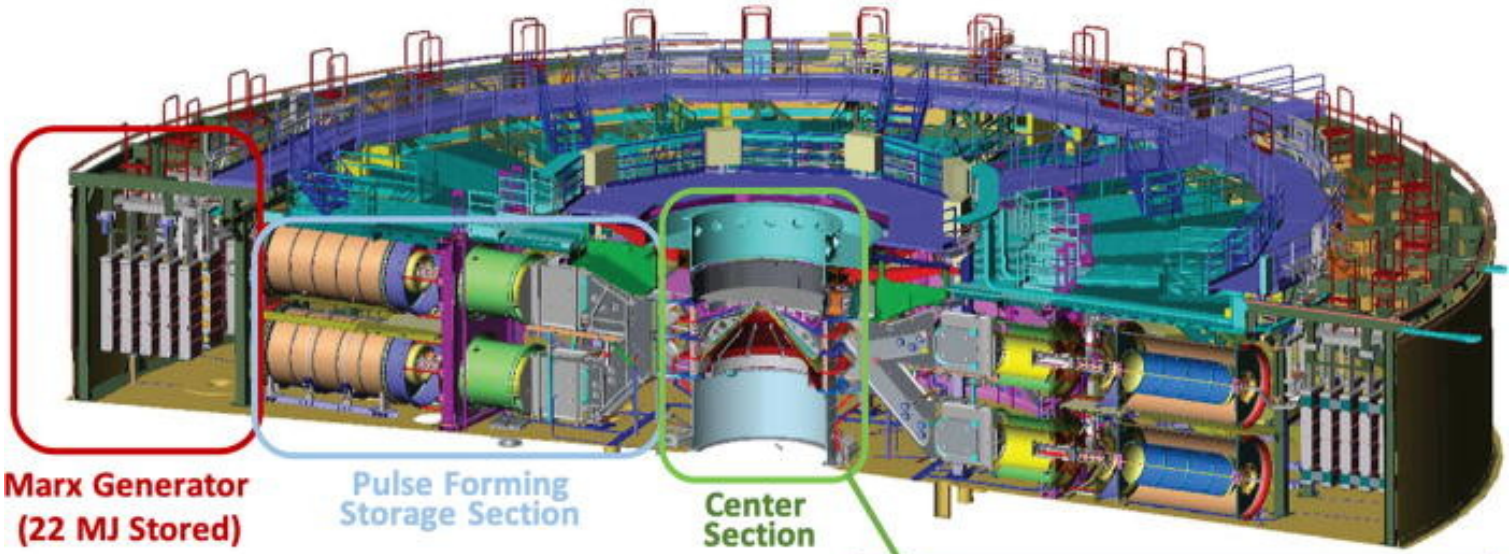
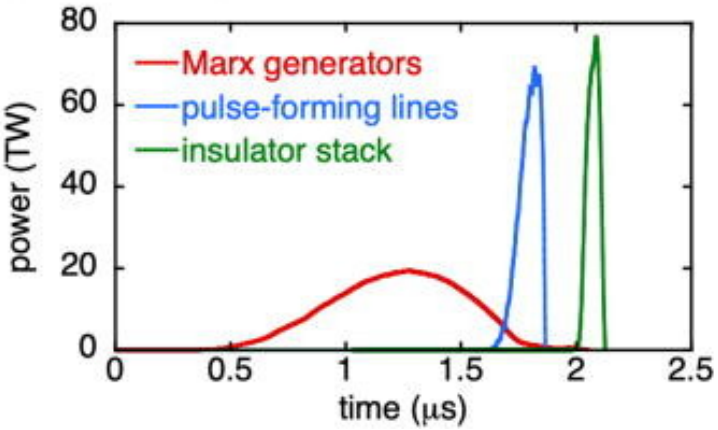


Pulsed power: it's how we make the current

Lots of energy + short time = high instantaneous power & high energy density plasma.

1. Capacitors charge slowly





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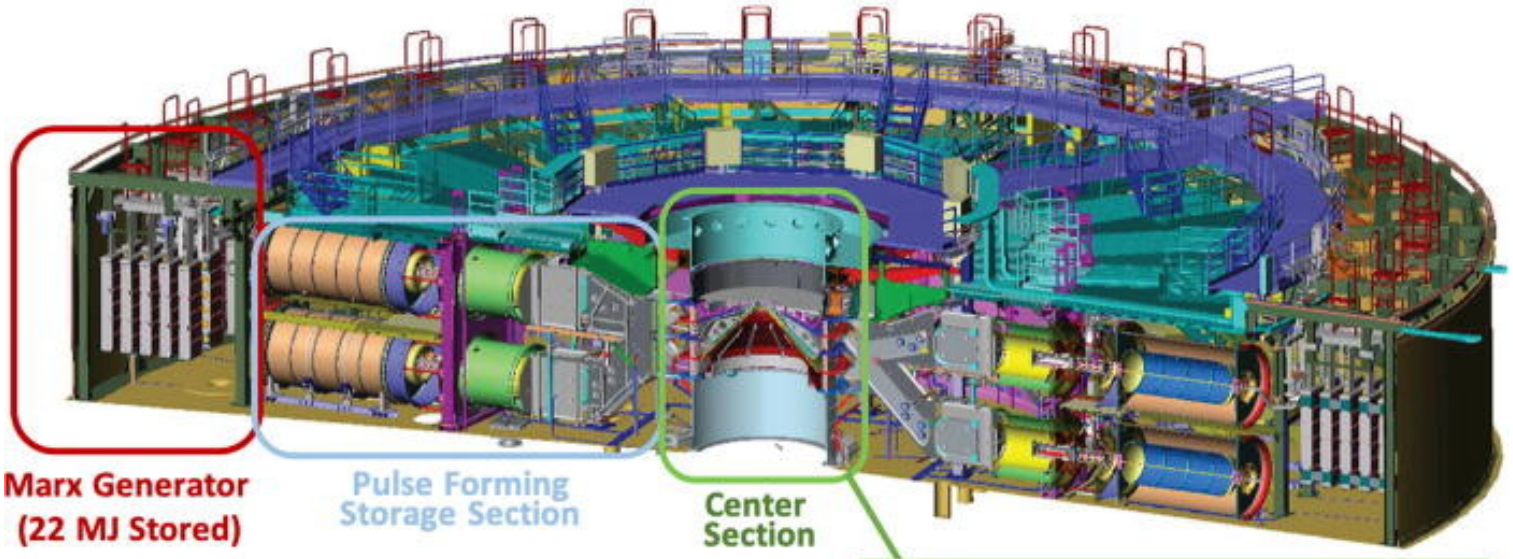

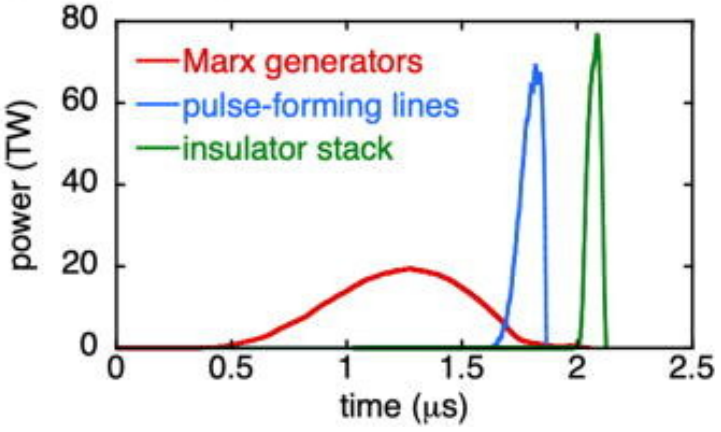

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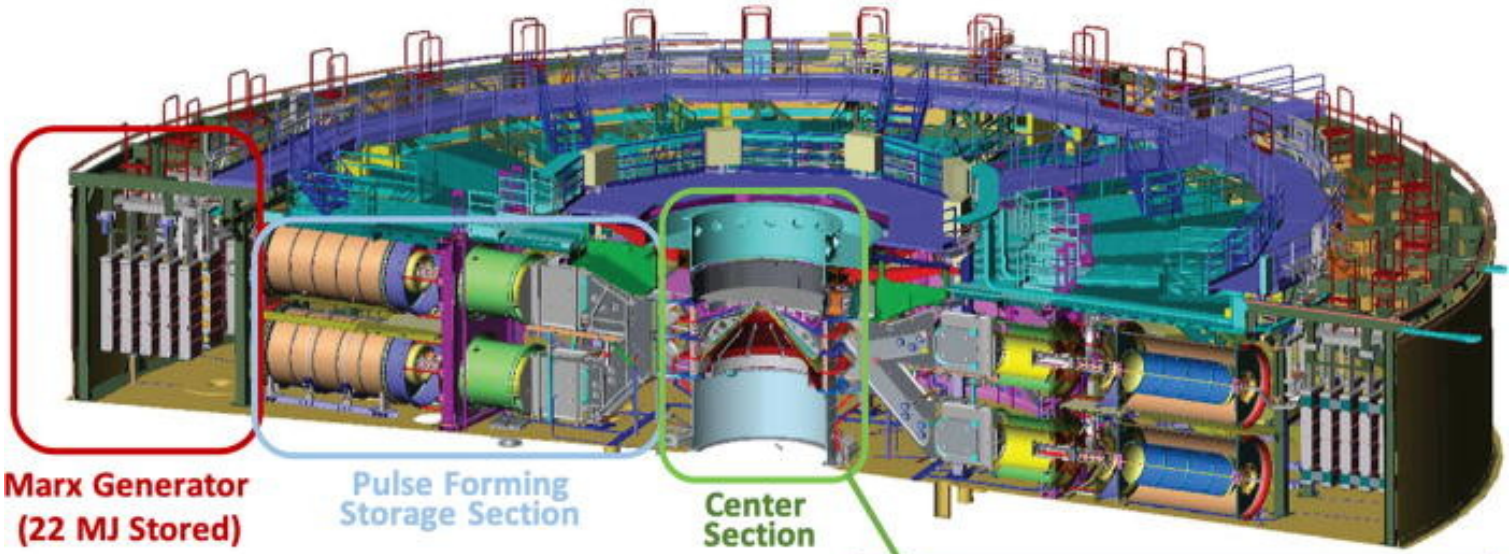
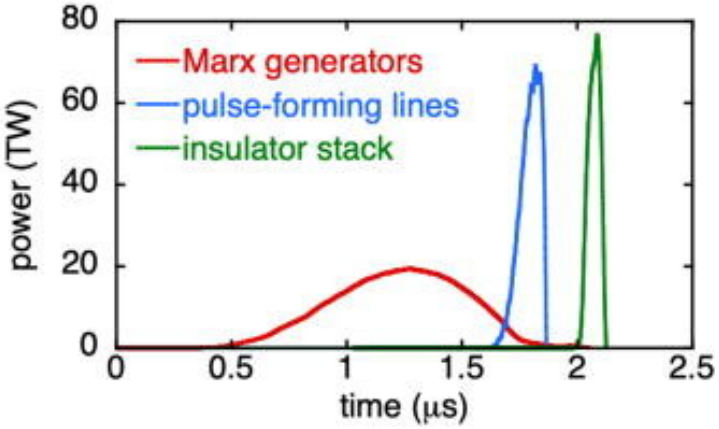
3. Energy discharged rapidly





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Pulsed power science is a rich field with a variety of applications

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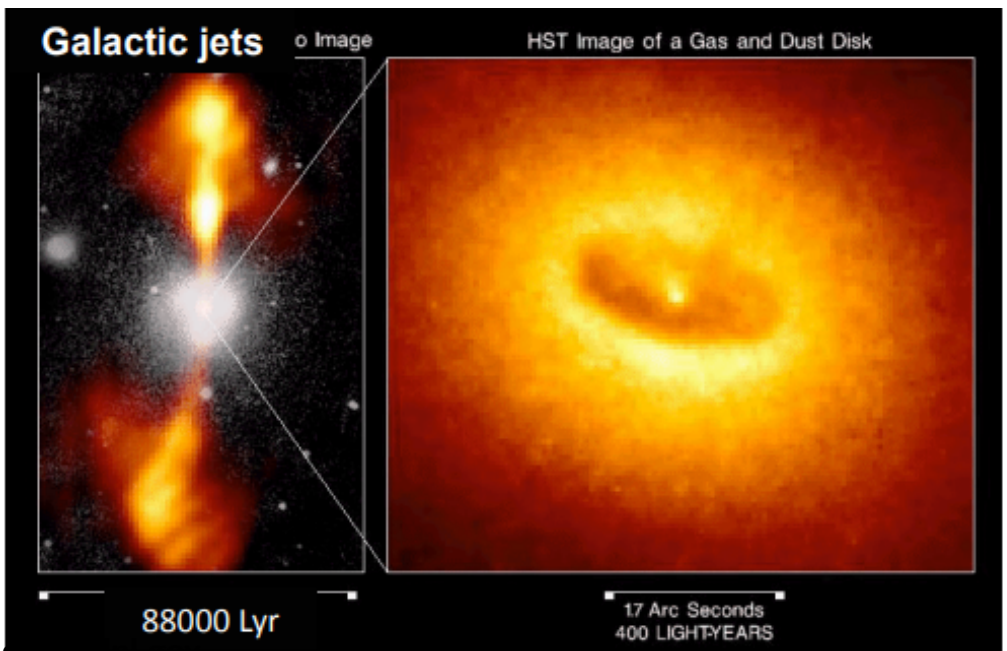
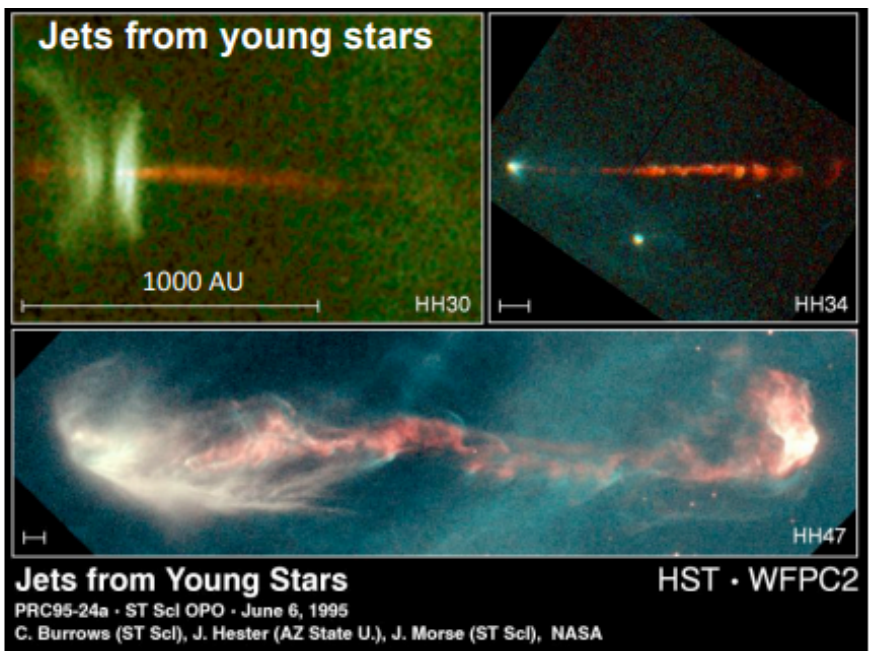
- Laboratory astrophysics: jets





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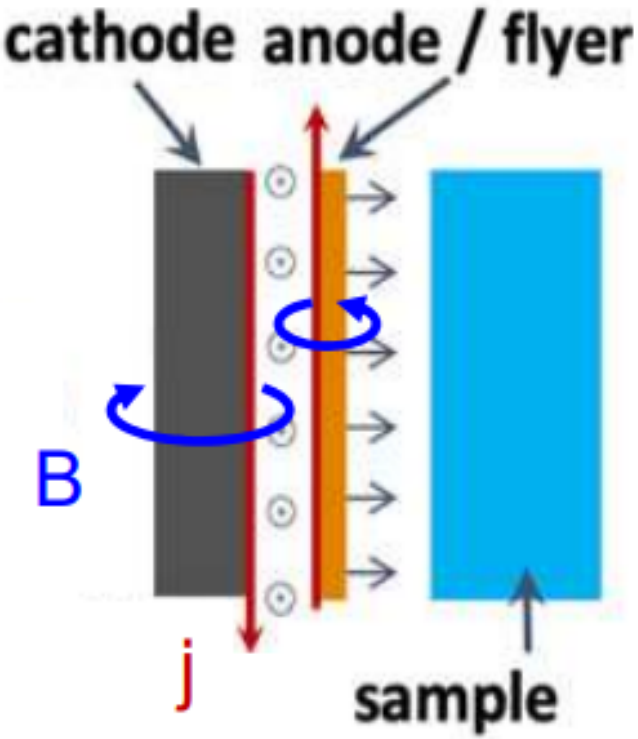
- Laboratory astrophysics: jets
- Material properties and equation of state



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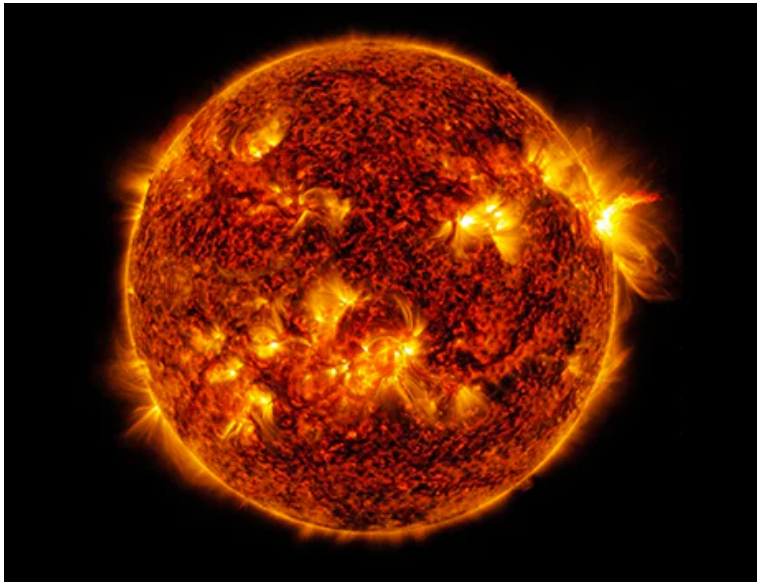

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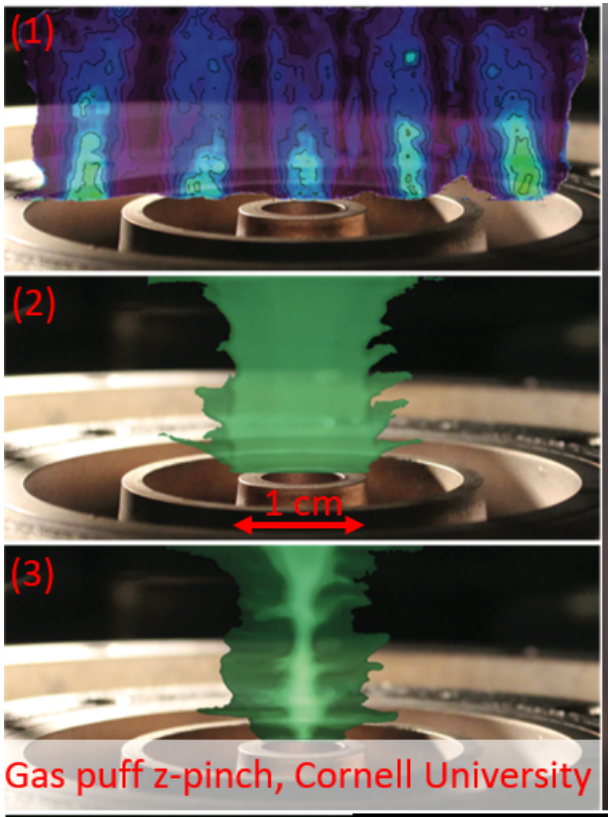
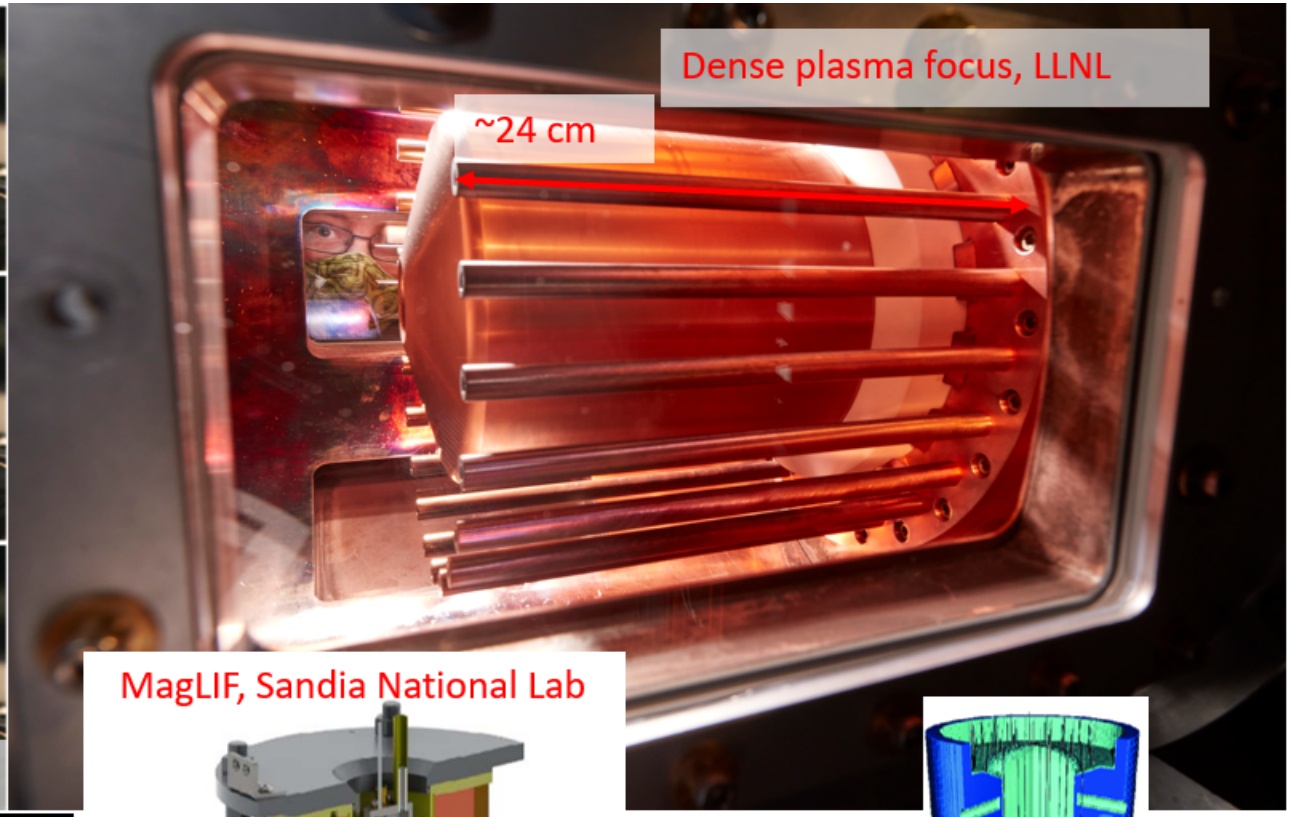
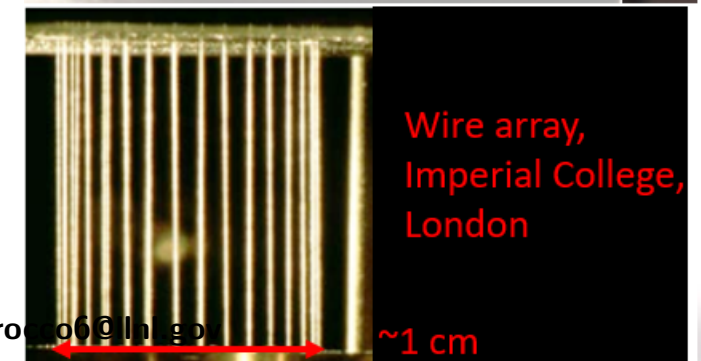
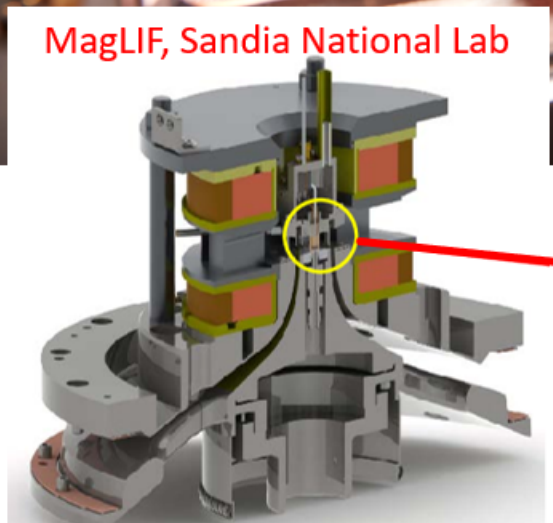
- Laboratory astrophysics: jets
- Material properties and equation of state
- Solar physics
- Stockpile stewardship
- Radiation sources: x-rays, UV, neutrons...

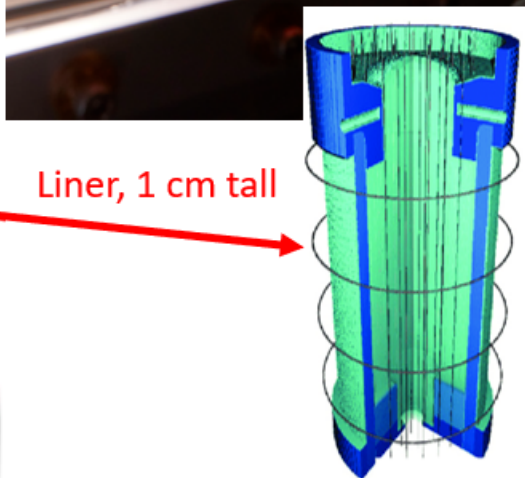
What configurations of Z-pinches are there?



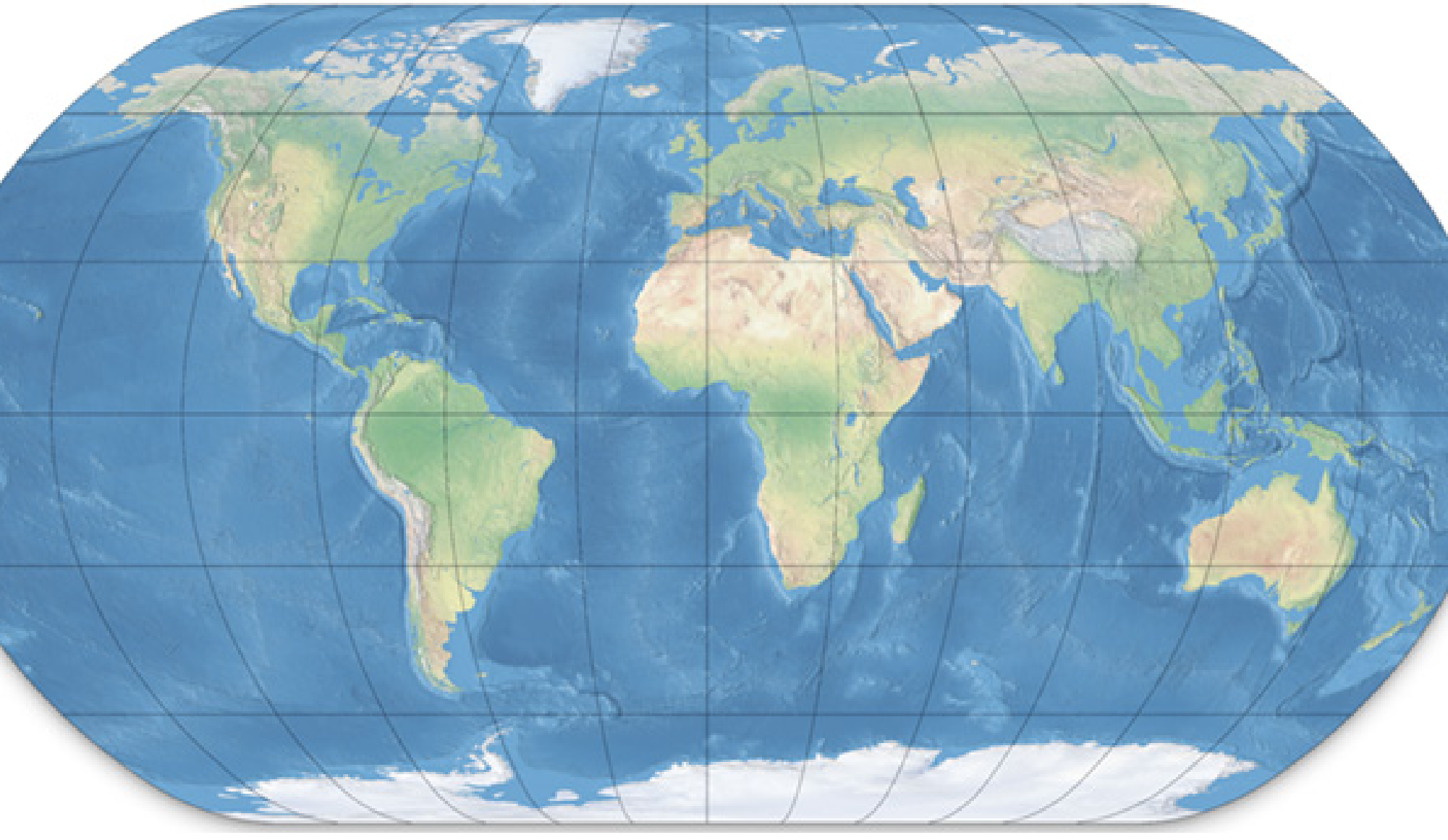








Where can you study z-pinches?



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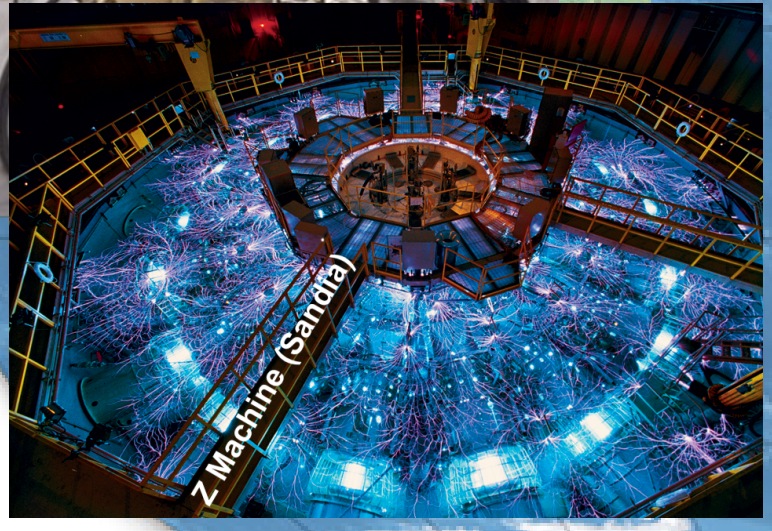

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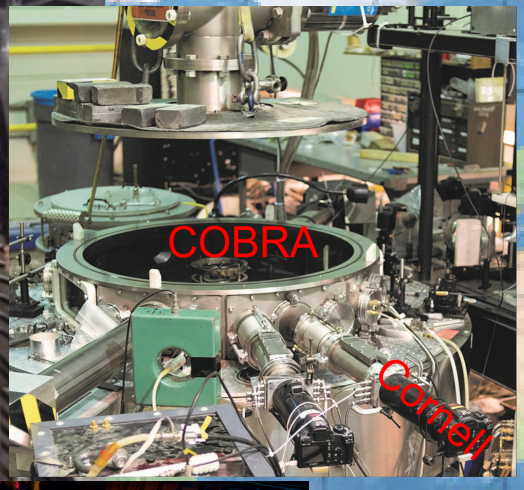

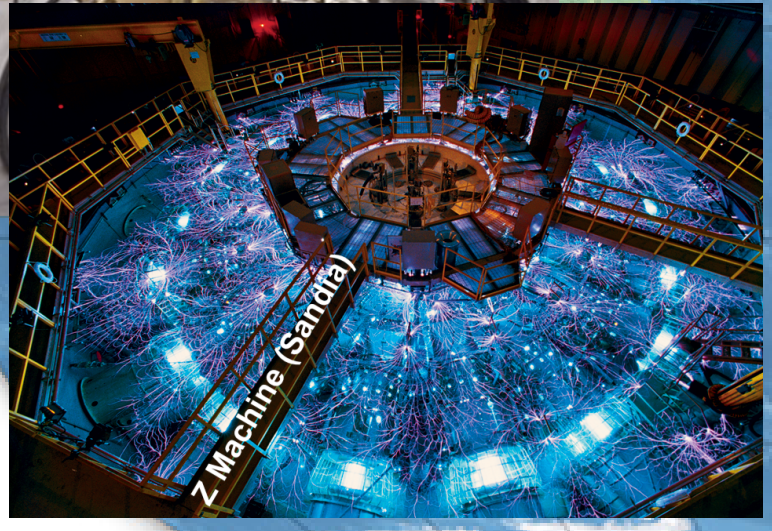

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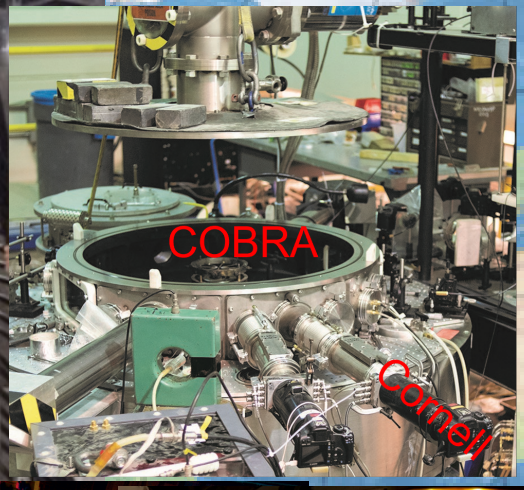

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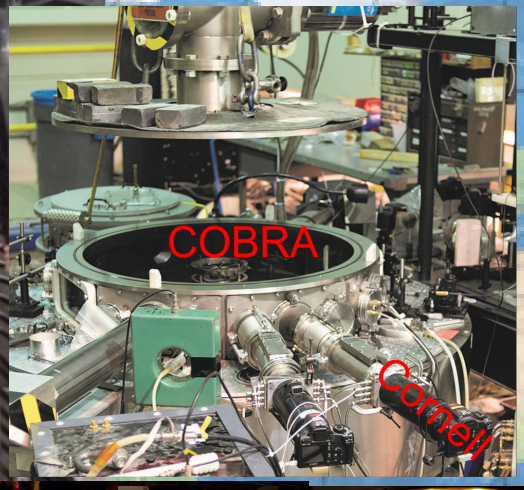

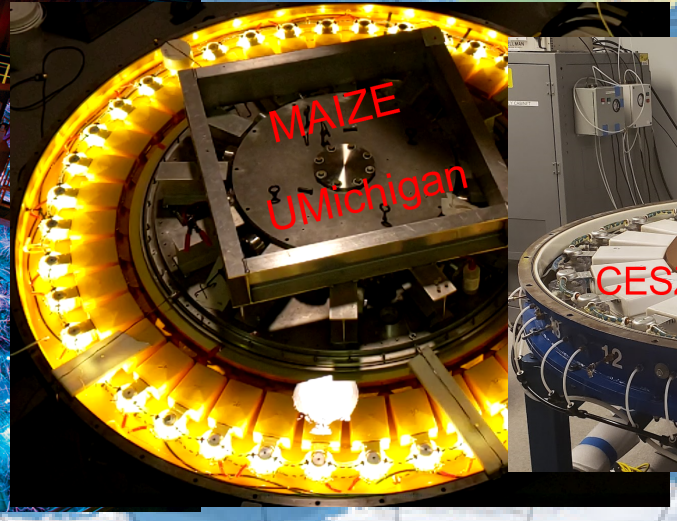

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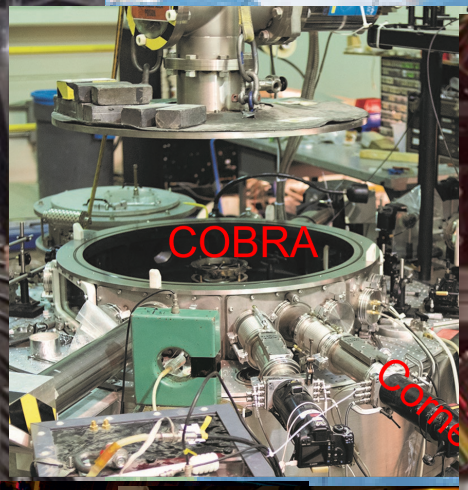

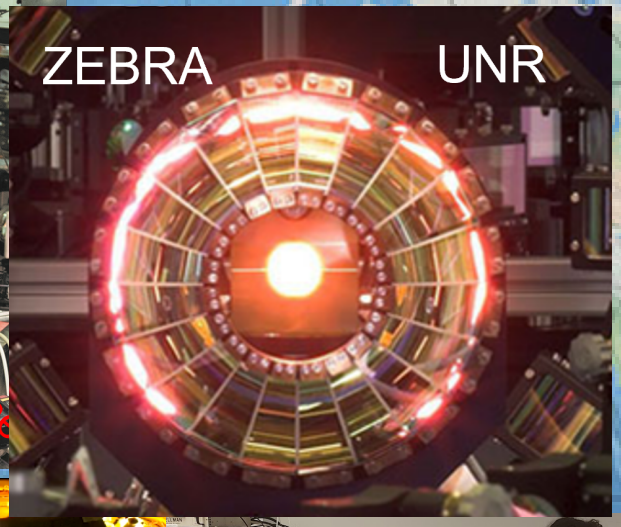

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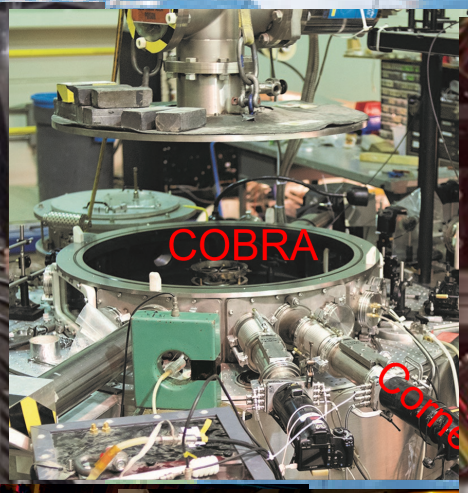

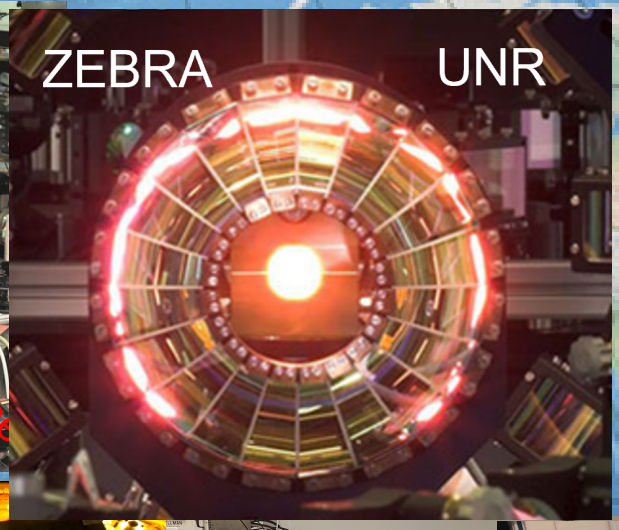

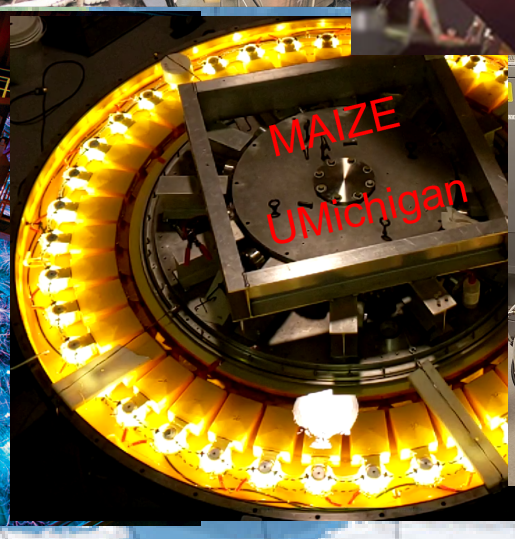

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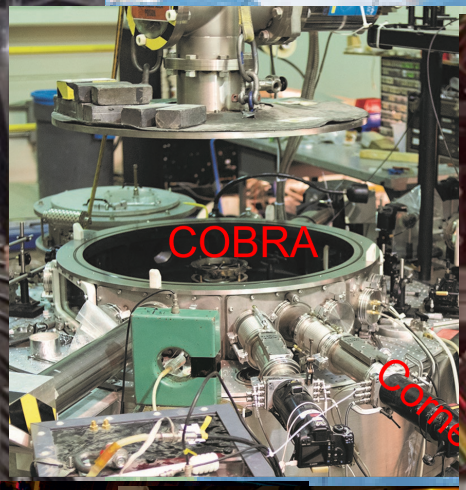

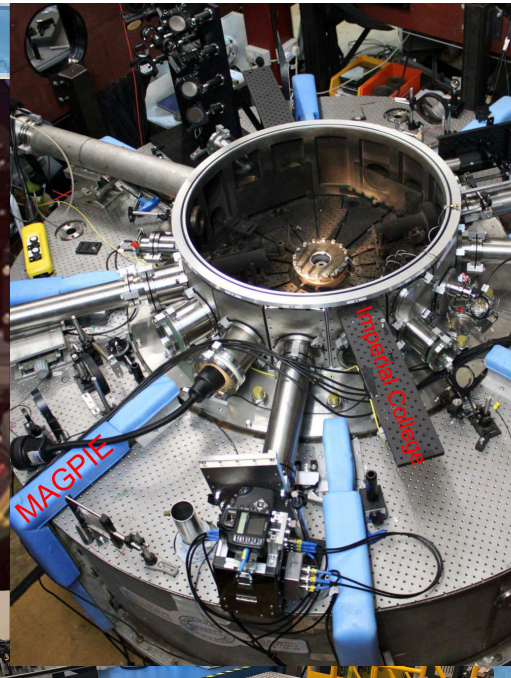

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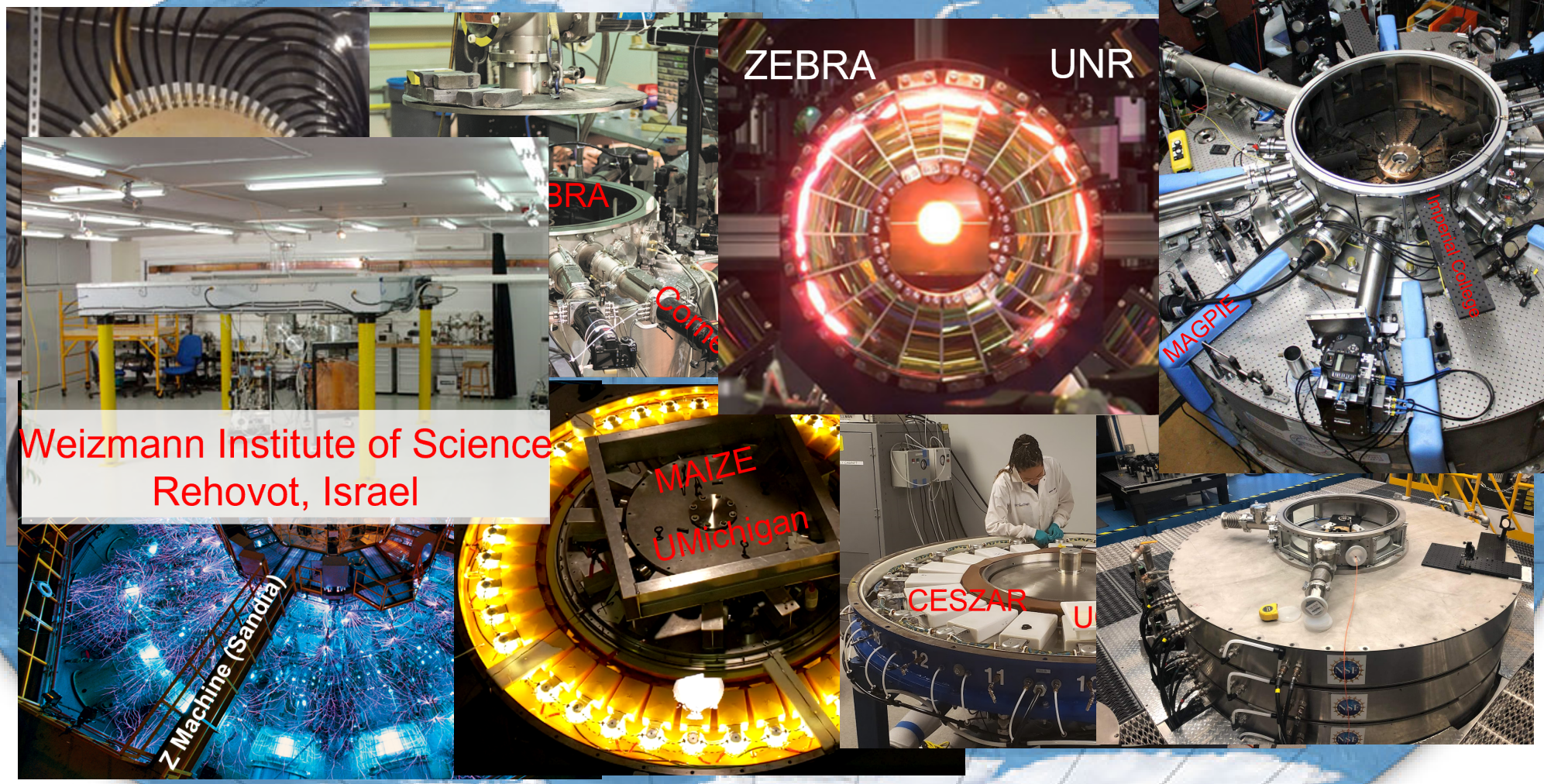

How can we apply z-pinches to fusion objectives?

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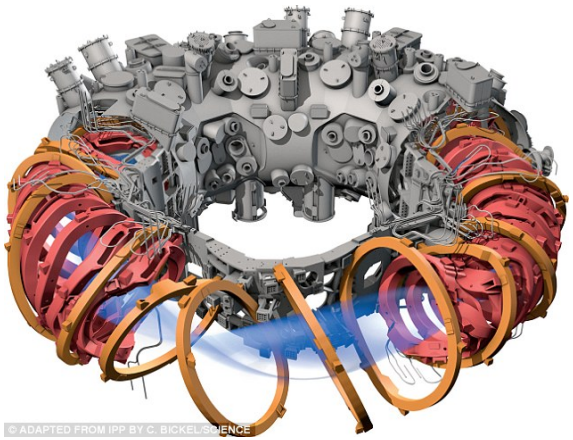

Tokamak, stellarator

$R \backsim 10$ m

$P \backsim 1$ bar

$\tau > 10$ s

$n_e \backsim 10^{15}/\text{cm}^3$

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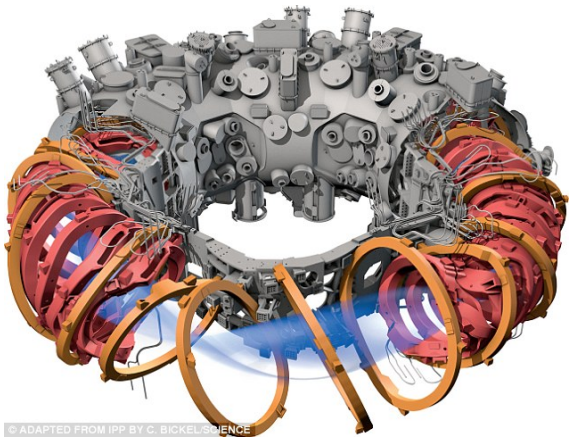

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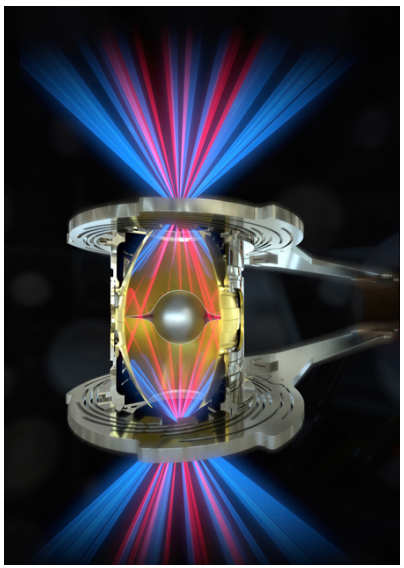

Direct and indirect drive

R $\backsim 10^{-5}$ m

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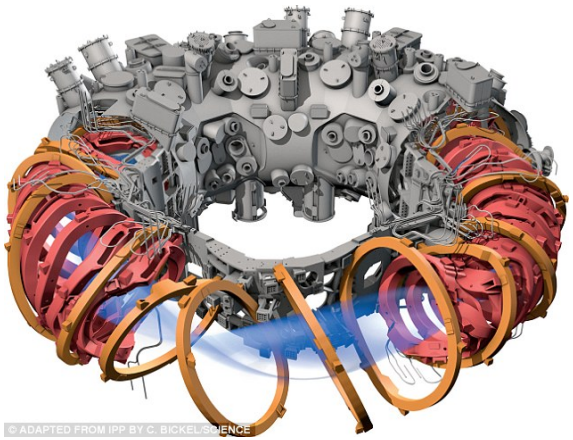

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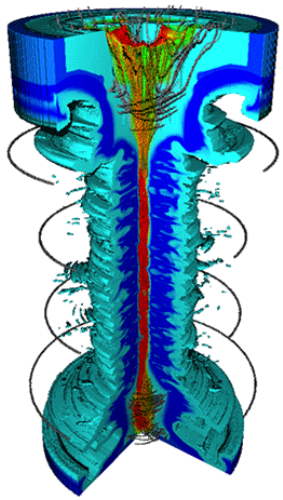


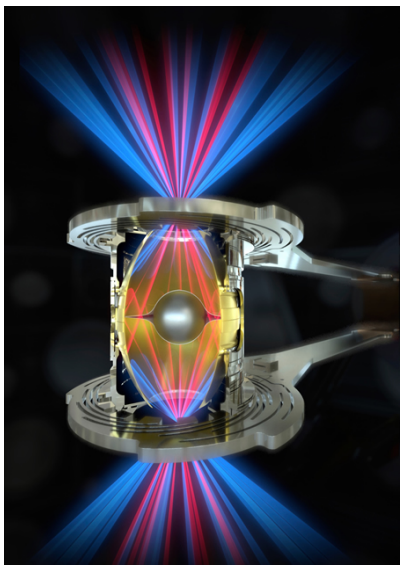
Magnetized Liner Inertial Fusion (MagLIF)

R $\backsim 10^{-3}$ m

P $\backsim 10^{9}$ bar

$\tau \backsim 10^{-9}$ s

$n_e \backsim 10^{20}/\text{cm}^3$



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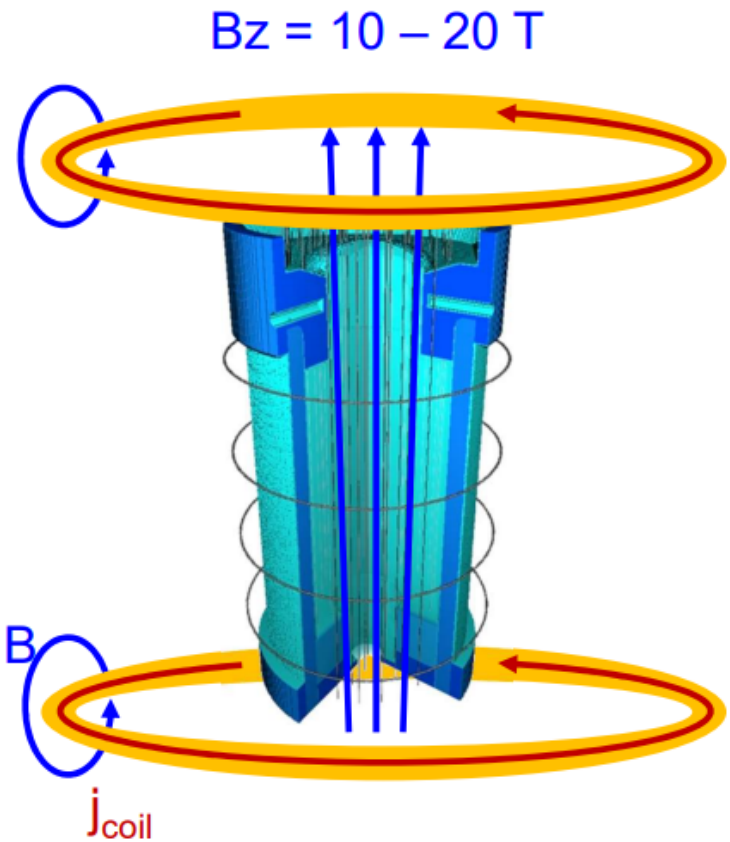
Magnetic Liner Inertial Fusion (MagLIF) is Sandia's current fusion platform



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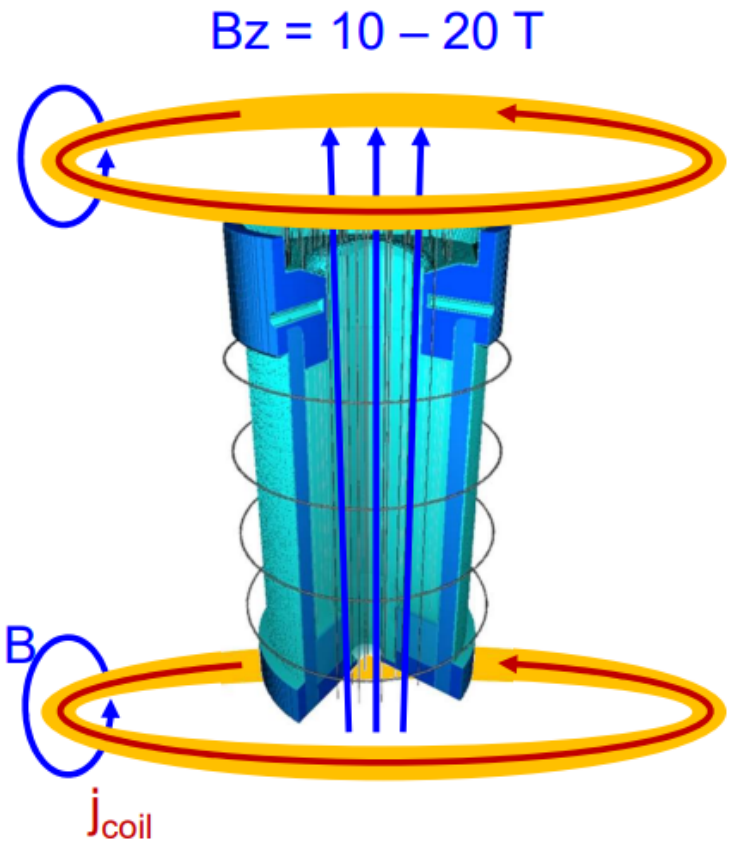
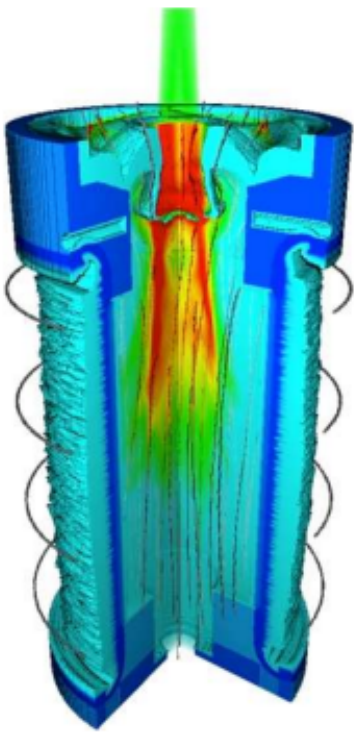


1.) Pre-magnetization

- A thin beryllium cylinder ('liner') is filled with deuterium gas
- A set of coils imposes an axial magnetic field that prevents conduction, which would cool the plasma

Magnetic Liner Inertial Fusion (MagLIF) is Sandia's current fusion platform

$E_{laser} = 1 - 2$ kJ



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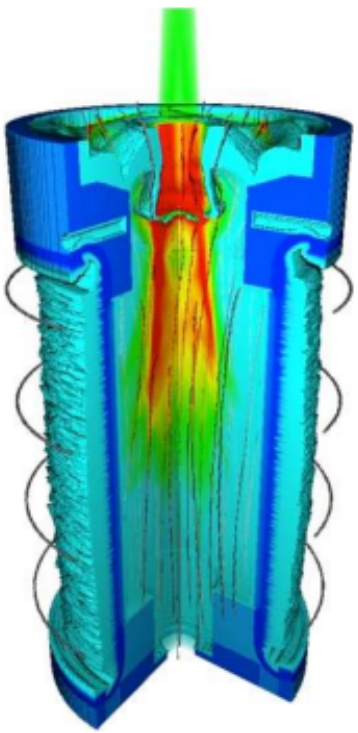
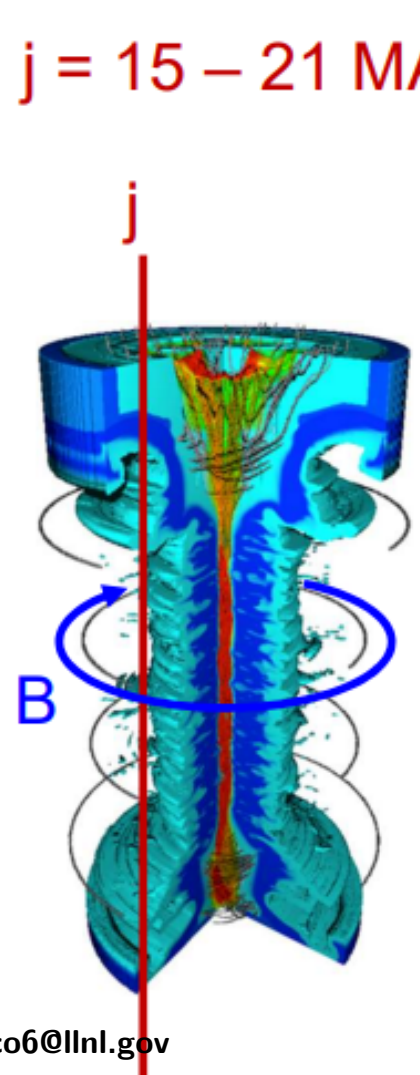


2.) Pre-heating the fusion fuel

- The Z-Beamlet laser heats the core of the fuel to about 200 eV (2 million K)
- This helps to reduce the implosion velocity and the final radius (convergence ratio) needed to get to fusion conditions

Magnetic Liner Inertial Fusion (MagLIF) is Sandia's current fusion platform



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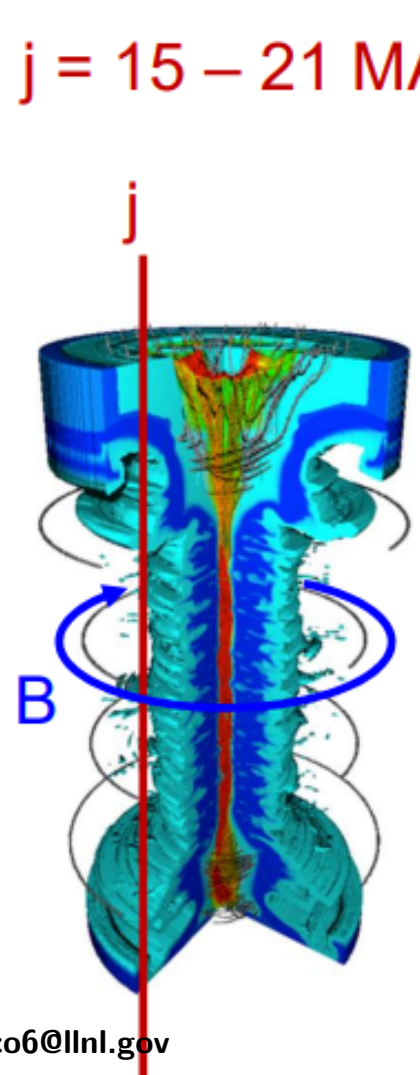
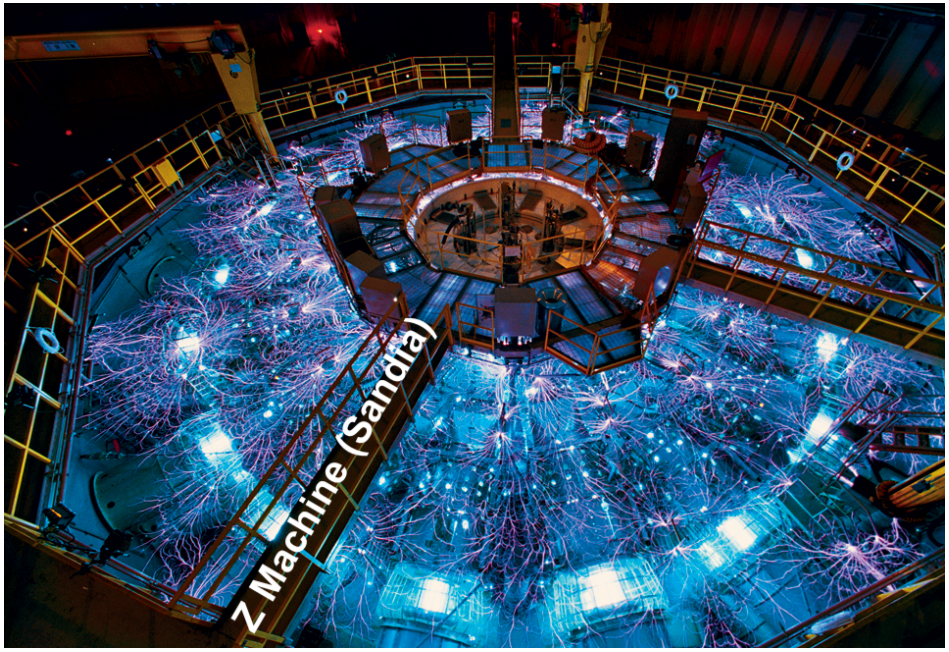


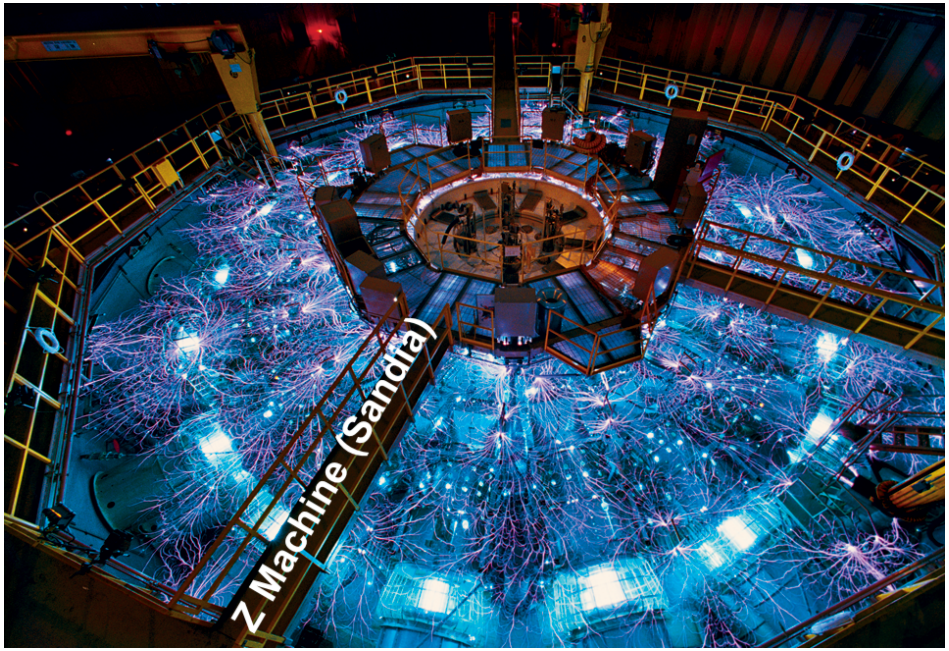
3.) Compress the whole shebang!

- The Z Machine fires, and the current runs through the liner, creating an azimuthal magnetic field
- Our friend the JxB force implodes the liner and fuel
- The stagnation column produces $\backsim 10^{13}$ neutrons from deuterium-deuterium fusion reactions

Z can fire once a day, tops.



Z can fire once a day, tops.



Smaller, higher repetition-rate machines and experiments are **essential** testbeds for MIF-related concepts.

Remember all those pulsed power devices that do z-pinch experiments?

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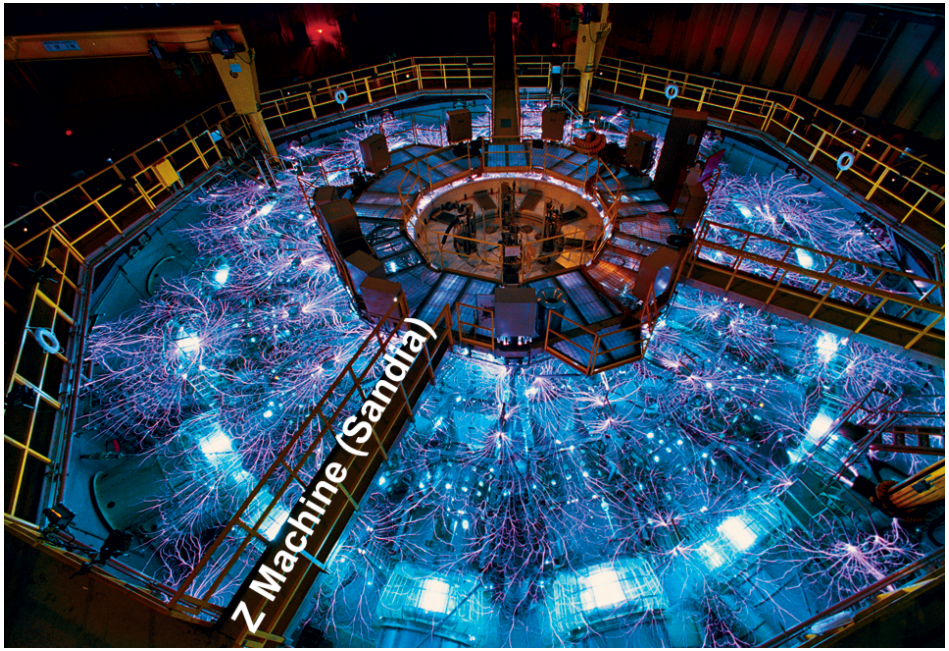
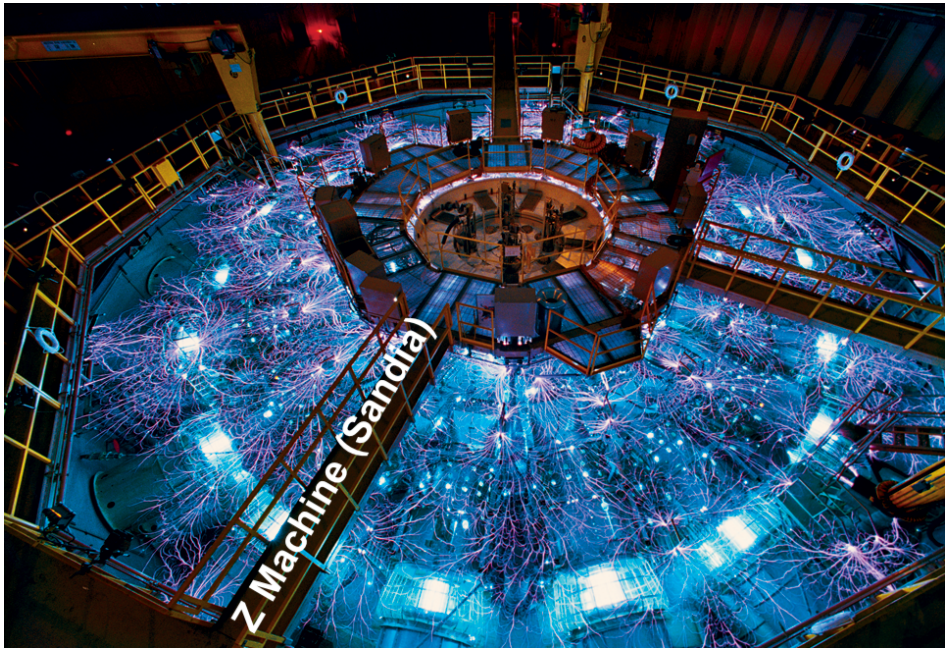


Smaller, higher repetition-rate machines and experiments are **essential** testbeds for MIF-related concepts.

Remember all those pulsed power devices that do z-pinch experiments?

- Fast diagnostic development
- Quick design and testing of new experiments/configurations
- Extra shot time to focus on specific aspects of tough questions facing MagLIF
  - Material mix
  - Laser plasma interactions
  - Field anisotropy

Z can fire once a day, tops.



Smaller, higher repetition-rate machines and experiments are **essential** testbeds for MIF-related concepts.

There's a ton of cool science to do in high energy density physics.

The national labs support the university labs and vice versa.

Raising a large-scale MIF experiment takes a village.

We hope you'll join us!