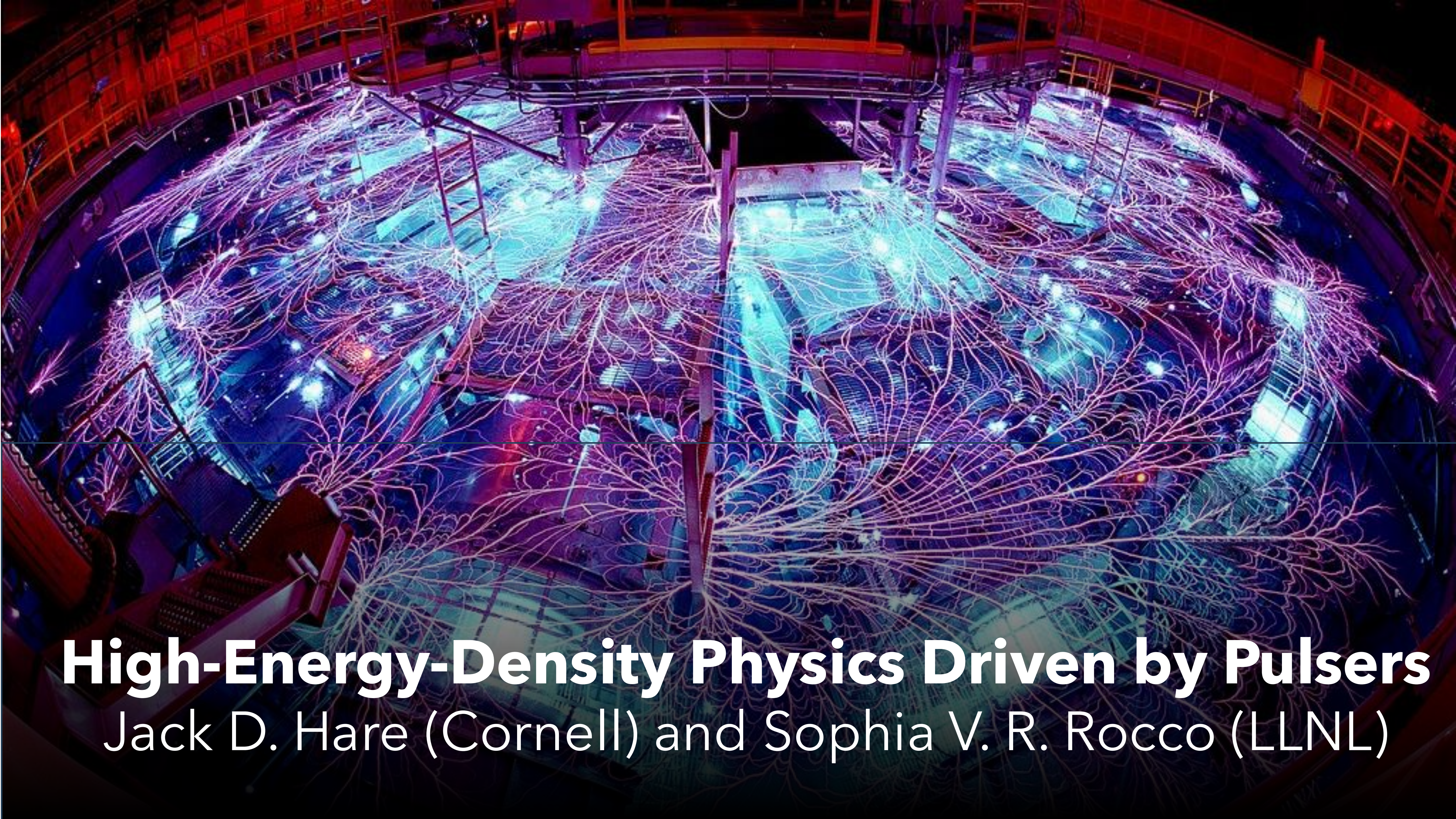

# High-Energy-Density Physics Driven by Pulsers

Jack D. Hare (Cornell) and Sophia V. R. Rocco (LLNL)

# Introduction: Jack Hare

- Undergrad at Cambridge University
- MA(!) in plasma physics at Princeton
- PhD at Imperial College London
- Postdocs at Imperial College and IPP Garching
- Assistant Professor at MIT 2021-2024
- Assistant Professor at Cornell from 2025
- Member of APS DPP Pride (LGBTQ+) [1]
- Outside of work: hiking, skiing, cycling, boardgames, TTRPGS

[1] engage.aps.org/dpp/programs/plasma-pride

jdhare@cornell.edu and rocco6@llnl.gov, SULI 2026

# Introduction: Sophia Rocco

- Undergrad at University of California, Santa Cruz (physics)
- PhD at Cornell University (plasma physics)
- Postdoc at Lawrence Livermore National Lab
- Now a staff scientist at LLNL
  - Dense plasma focus (DPF) for dynamic neutron radiography
  - Raman scattering thermometry on shock-compressed materials
  - Radiation testing for optically-initiated detonators
- Outside of work: climbing, crafting, dogs.

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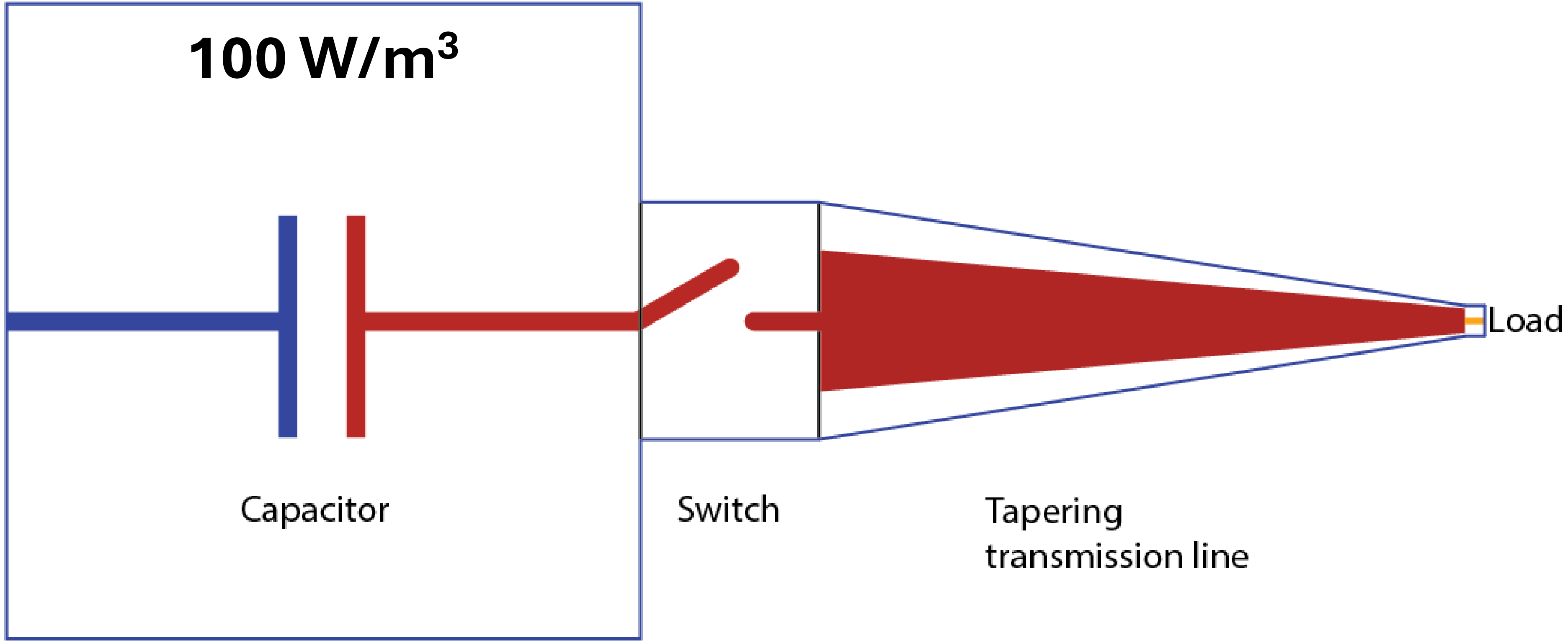
# Talk Outline

1. Pulsed Power: Marxs, LTDs, and IMGs
2. Z-pinches: Bennett pinch, thin shell, and rocket model
3. Applications: X-rays, neutrons, fusion, and lab astro

# Pulsed power compresses energy in time and space

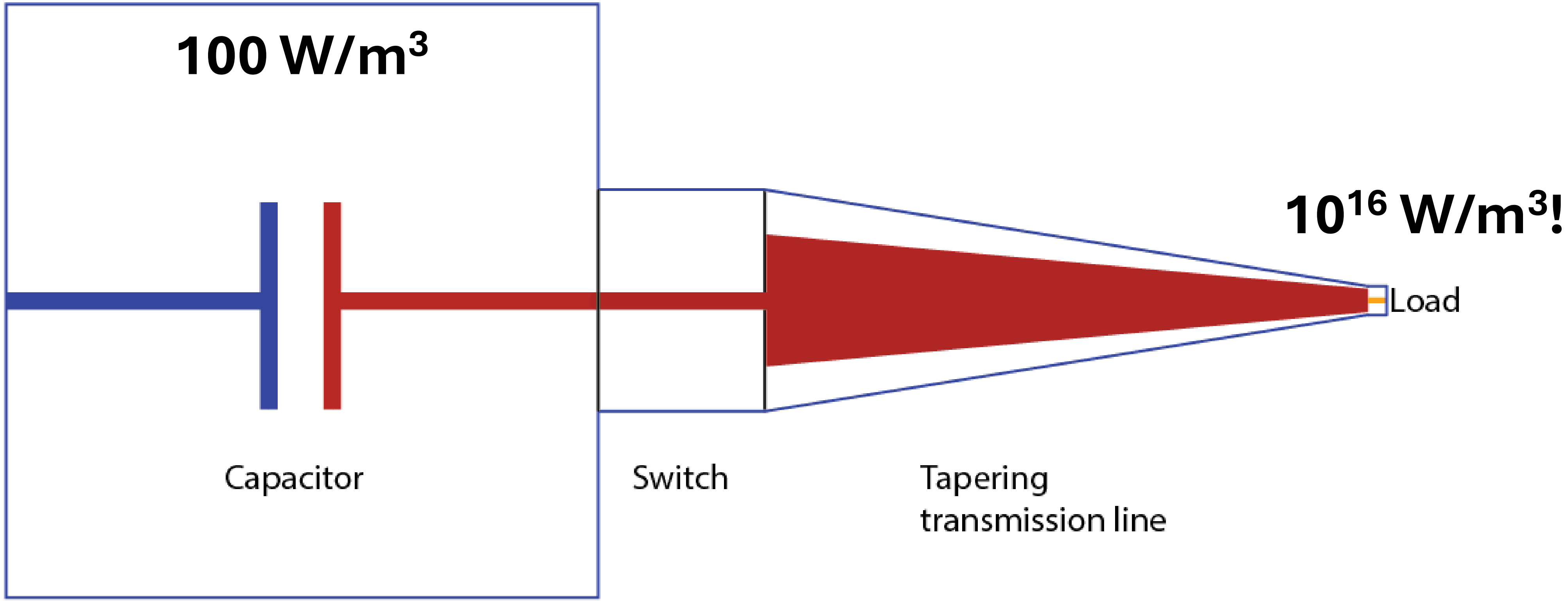
Charge: 10 kJ into 1 m$^3$ capacitors for 100 s



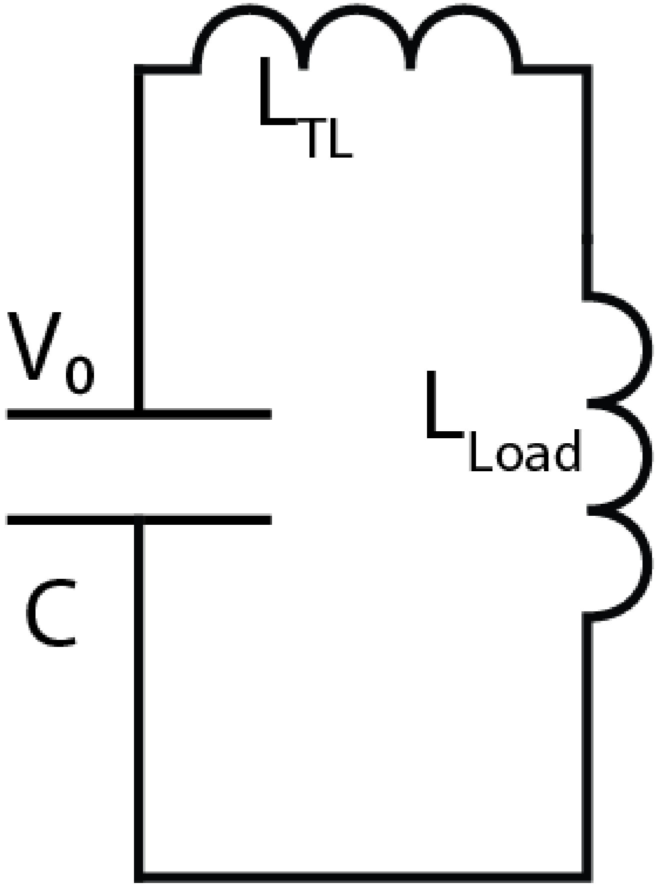
# Pulsed power compresses energy in time and space

Charge: 10 kJ into 1 $m^3$ capacitors for 100 s
Discharge into 1 $cm^3$ volumes in $10^{-6}$ s

$10^6$ compression in space, $10^8$ compression in time:



# Circuit model: LC circuit



- Simplest circuit for pulsed-power: LC
- Capacitor charged to $V_0$ stores energy in electric fields
- Switch closes, current flows through inductive transmission line to inductive load, $L = L_{TL} + L_{Load}$

$$I(t) = -\frac{2\tau}{\pi}\frac{V_0}{L}\sin\left(\frac{\pi}{2}\frac{t}{\tau}\right)$$

… where $\tau = \frac{\pi}{2}\sqrt{LC}$ is the time to reach peak current,

$$I_{peak} = -\frac{2\tau}{\pi}\frac{V_0}{L} = V_0\sqrt{\frac{C}{L}}$$

- Fast, intense current pulses require small $L$

# Getting to higher voltages: Marx generators

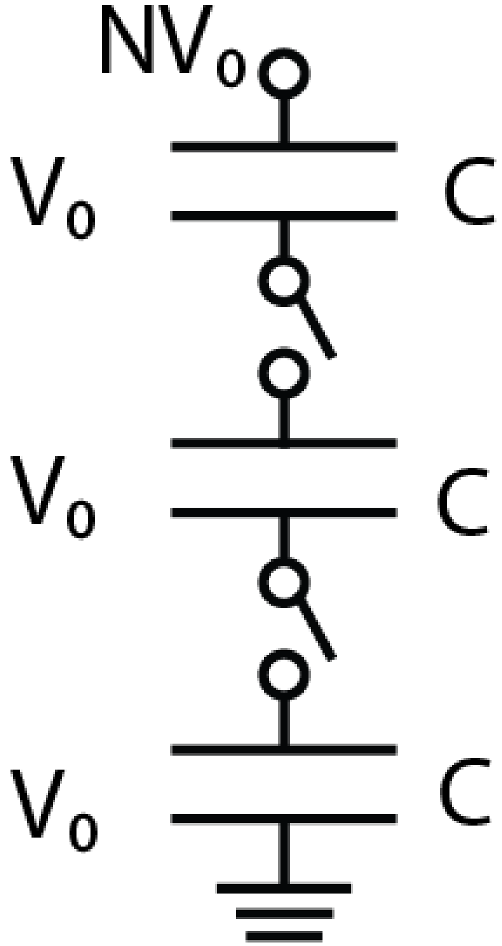
Capacitors are limited by materials to around 100 kV initial charge. For higher currents, we need higher voltage!

$$I_{peak} = -\frac{2\tau}{\pi}\frac{V_0}{L}$$

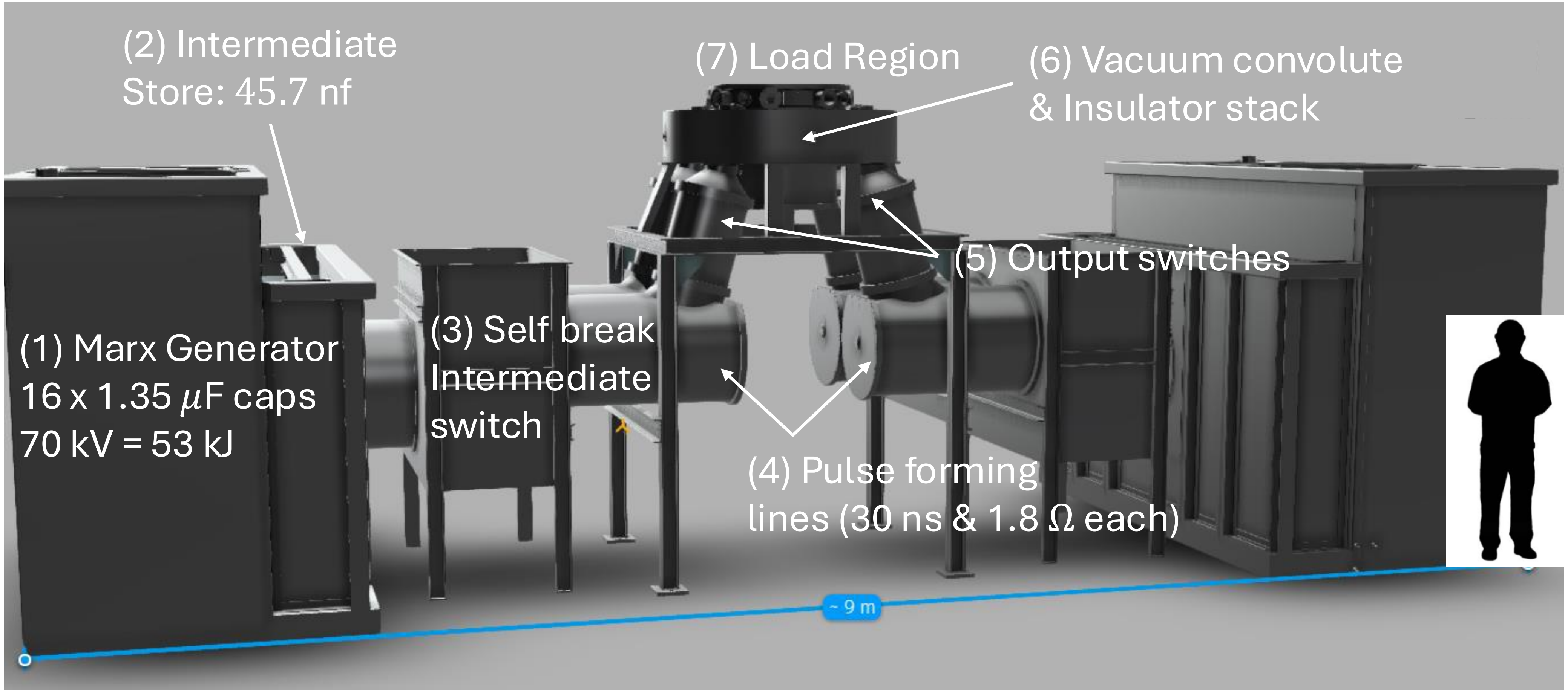
Solution: The Marx generator

- Charge $N$ capacitors to $V_0$ in **parallel**
- Close $N$ switches, connect capacitors in **series**
- Output voltage is $NV_0$

Issue: relatively long pulse length $\tau$, need compression



# A Marx Generator: COBRA (at Cornell)



COBRA: 1 TW, 1 MA, 100-220 ns rise time pulser
Produces high energy density plasmas. >7000 shots

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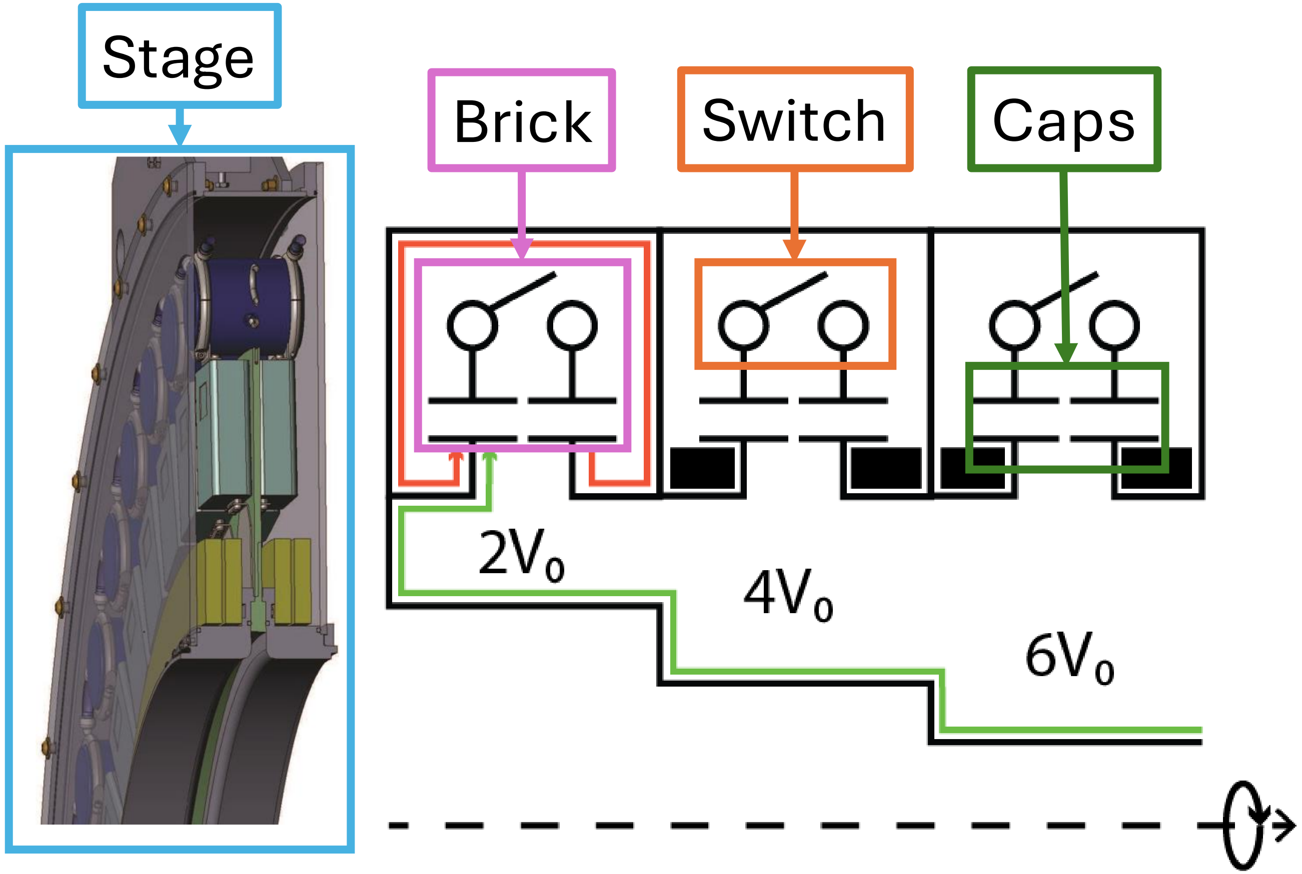
# Shorter pulses: LTDs

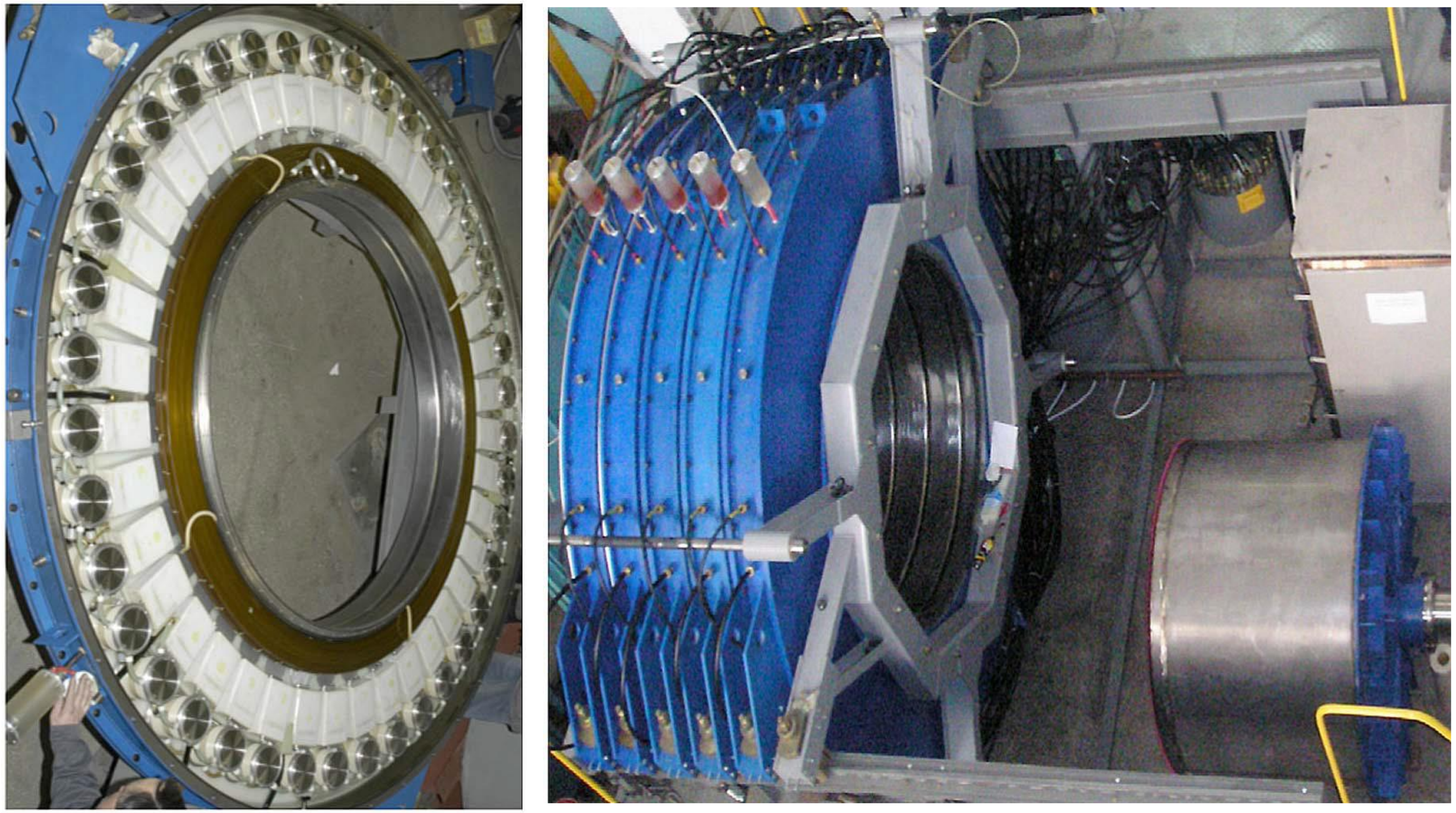
- Using many small capacitors and switches in parallel reduces $L$ and hence gives short rise time $\tau = \frac{\pi}{2}\sqrt{LC}$
- Shorter pulses, more intense conditions!

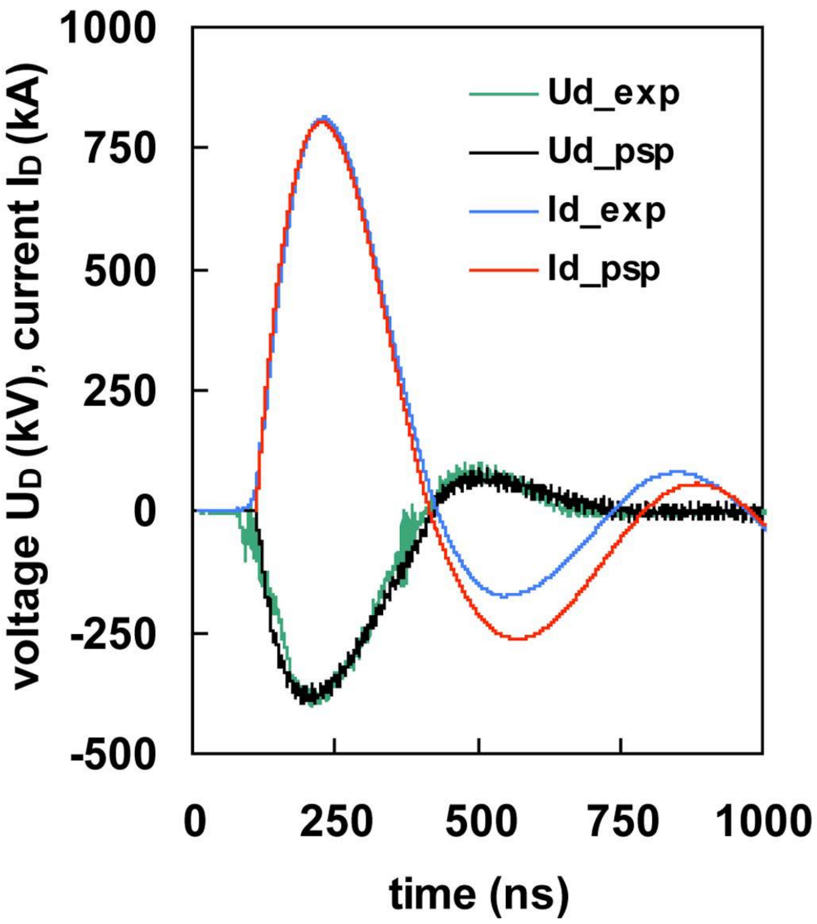


**Linear Transformer drivers** (bad name: use LTD) consist of:

- N Stages, with M bricks, each with a switch and two cap(acitor)s
- Parasitic current path in red choked by magnetic cores (high inductance)
- Forces current through load

# An LTD: Mykonos (at Sandia)

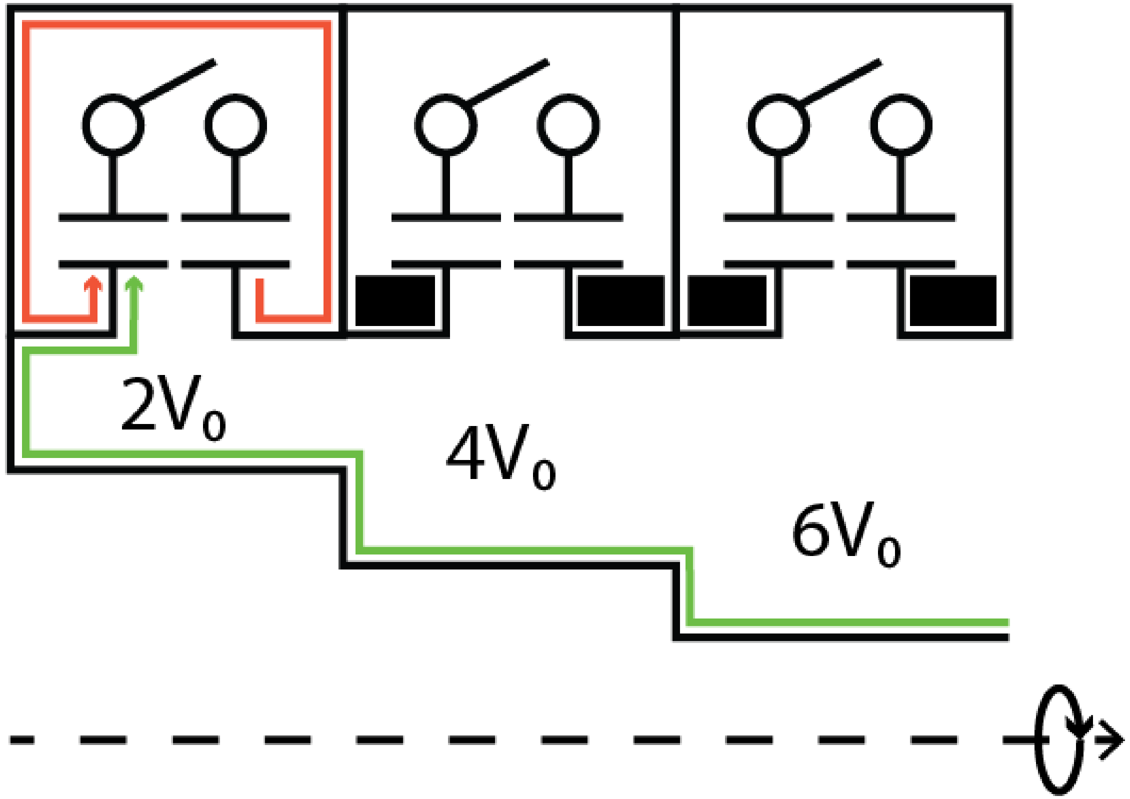




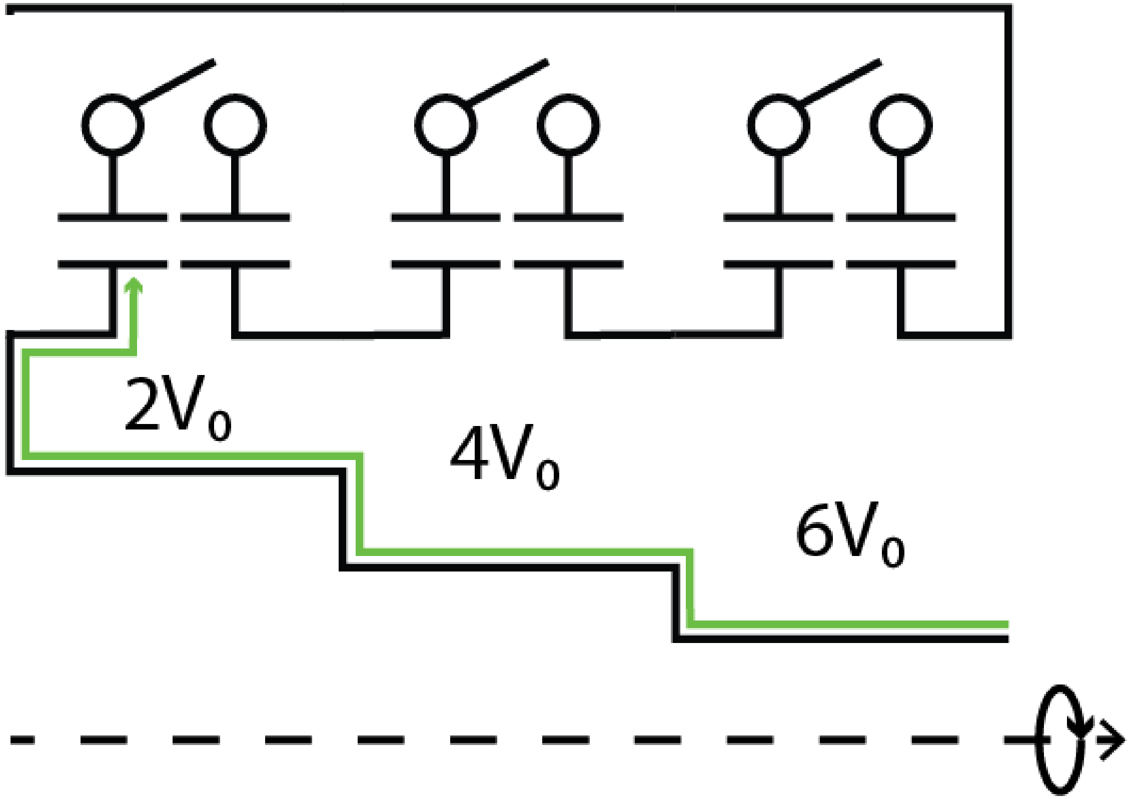
- 5 stage LTD – voltage stacks
- Rise time is inherently short (100 ns) without any compression

# Higher efficiency: IMGs

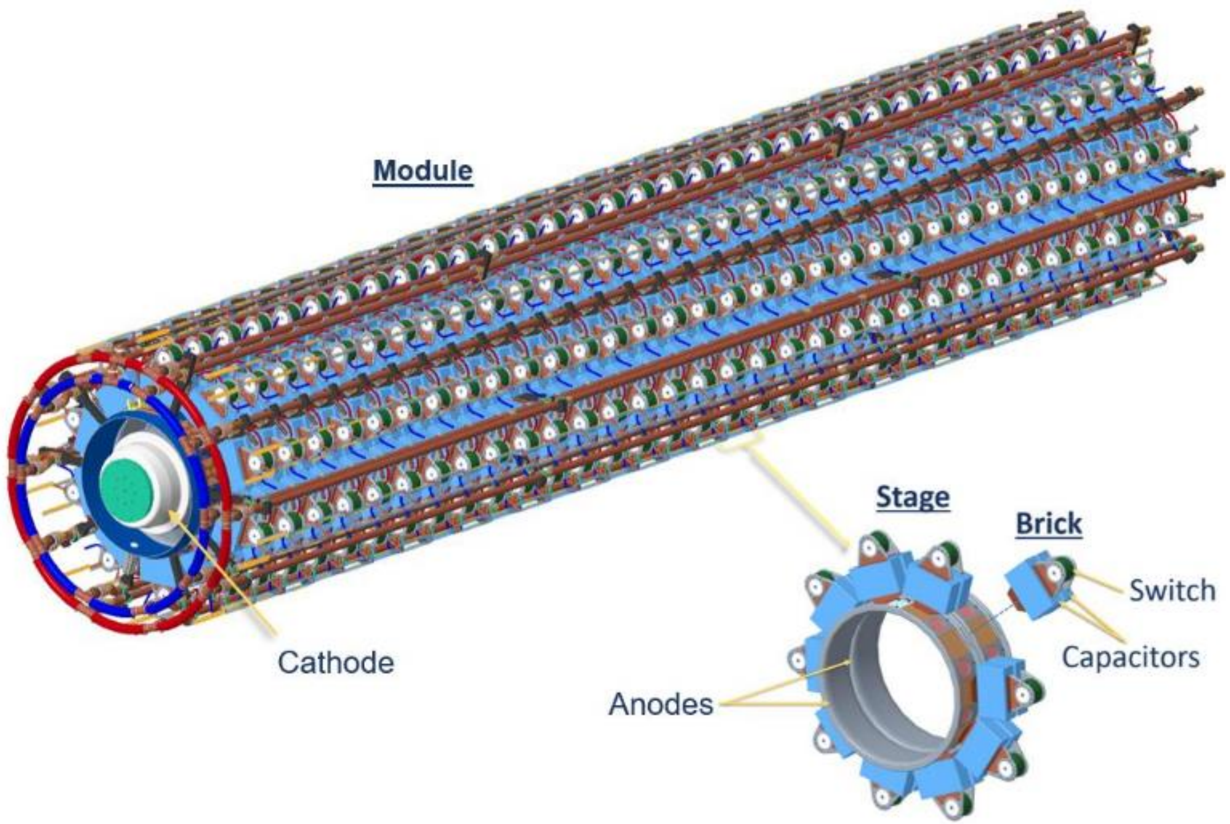
LTD:
Bricks enclosed in cavities
Ferrite cores choke parasitic current



Impedance-Matched Marx Generator:
All bricks share a cavity
No cores, no losses



# An IMG: Pacific Fusion



- Eventual goal: 156 modules, each with 32 stages, 10 bricks per stage
- Prototype: 9 stages: 1.1 MV, 80 ns rise time, 440 GW peak current

[pacificfusion.com/updates/validating-the-next-building-block-toward-affordable-fusion-power]

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# Talk Outline

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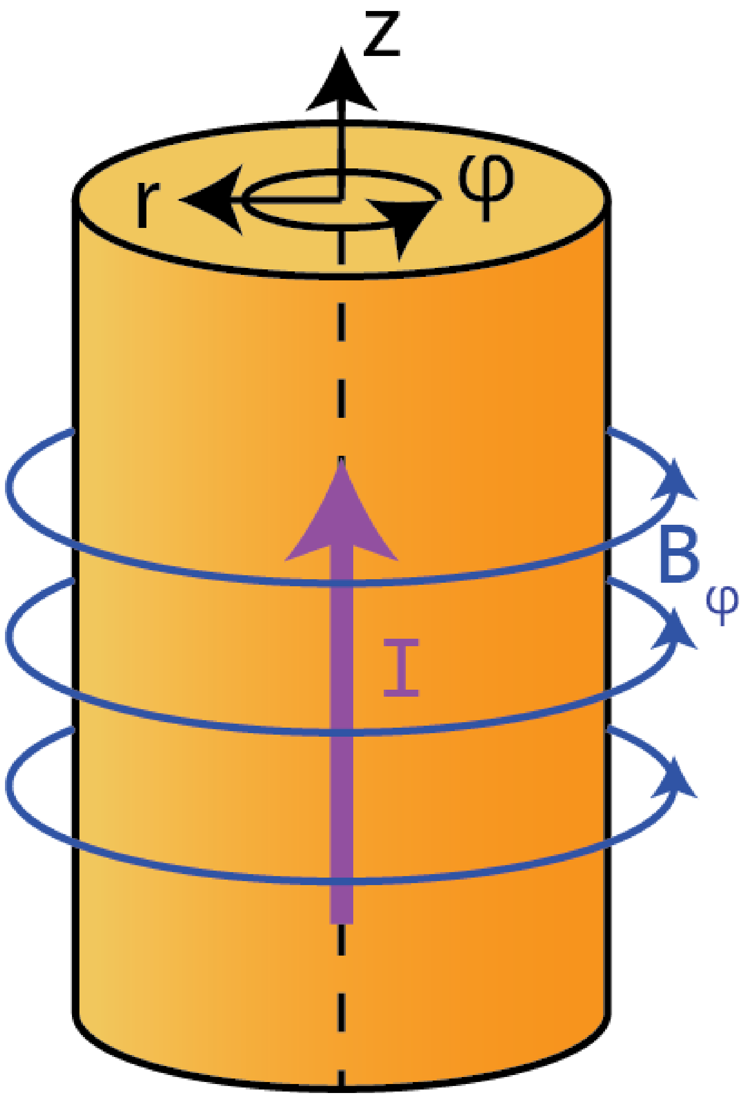
# So you’ve built a pulser. Now what?



- Simplest plasma load for a pulser: the z-pinch
- Start with a gas/wire and apply a current $I$ in $z$
- $I$ creates azimuthal magnetic field:

$$B_\phi = \mu_0 I/2\pi r$$

- Current and field combine via $\mathbf{J}\times\mathbf{B}$ force, compressing plasma radially inwards

$$F_r = -J_z B_\phi$$

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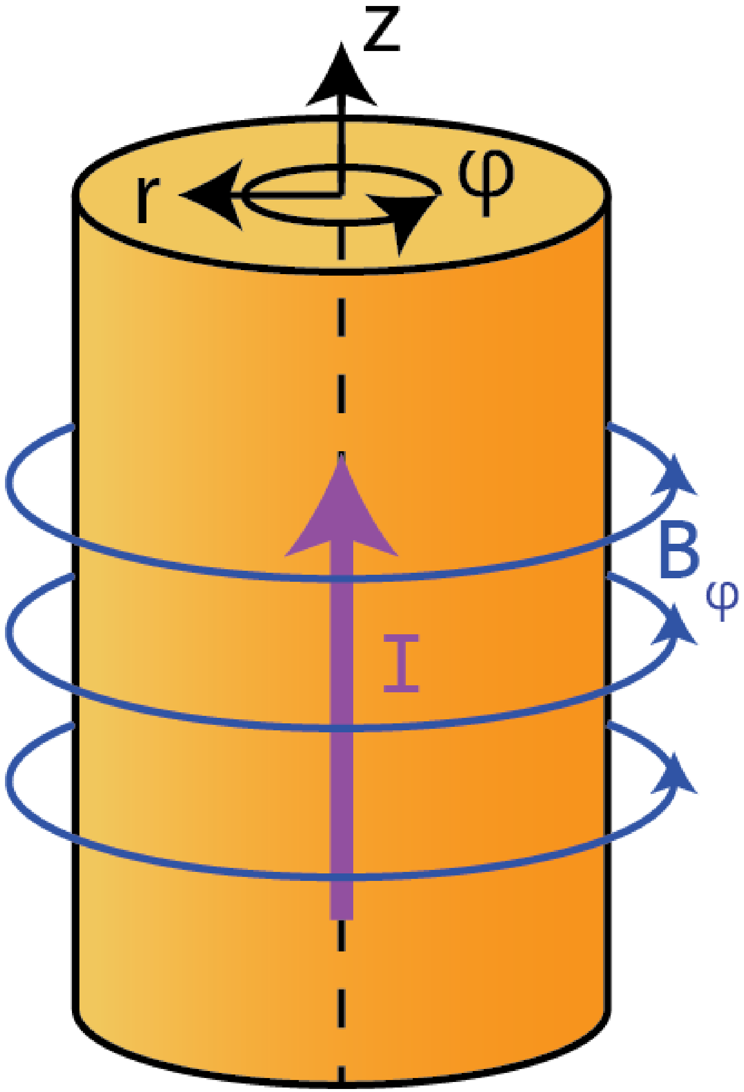
# The Bennett Pinch Relation



- As the plasma implodes, it passes through a series of equilibria given by MHD:

$$\nabla p = \mathbf{J} \times \mathbf{B} \rightarrow \frac{\partial p}{\partial r} = J_z B_\phi$$

- Integrating this gives Bennett pinch relationship:

$$N = \int 2\pi n \, dr \longrightarrow N K_B T = \frac{\mu_0 I^2}{8}$$

- For given current and linear density, we can determine temperature.
- Can we crank up $I$ and get to 10 keV/fusion?
- No! MHD instabilities (sausage and kink) disrupt pinch before it gets hot enough

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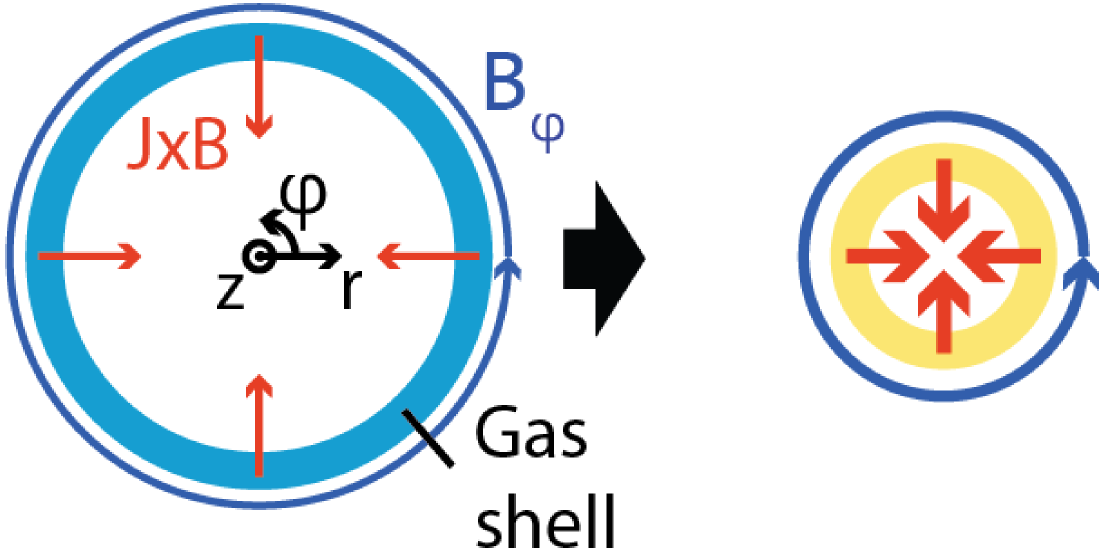
# Analytical model for a thin shell implosion

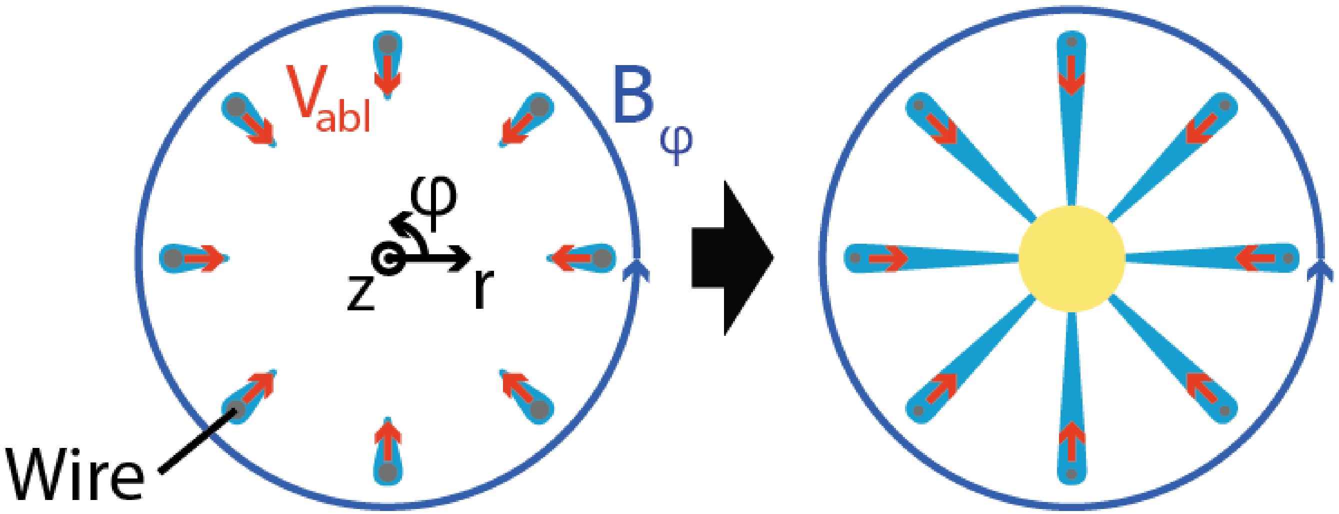


$$m_0 \frac{d^2 r}{dt^2} = -\frac{\mu_0 I(t)^2}{4\pi r}$$

- Start with a thin shell and rapidly compress to avoid instabilities
- Aka “Gas puff z-pinch”
- Analytical model: (Newton 2)
  Mass x acceleration = Force

- $\mathrm{F_r} \propto 1/r$, increases during implosion
- Implosion trajectory $r(t)$ depends on $I(t)$
- Fun project: add an LC circuit model and solve coupled ODEs in python!

# Analytical model for a wire array



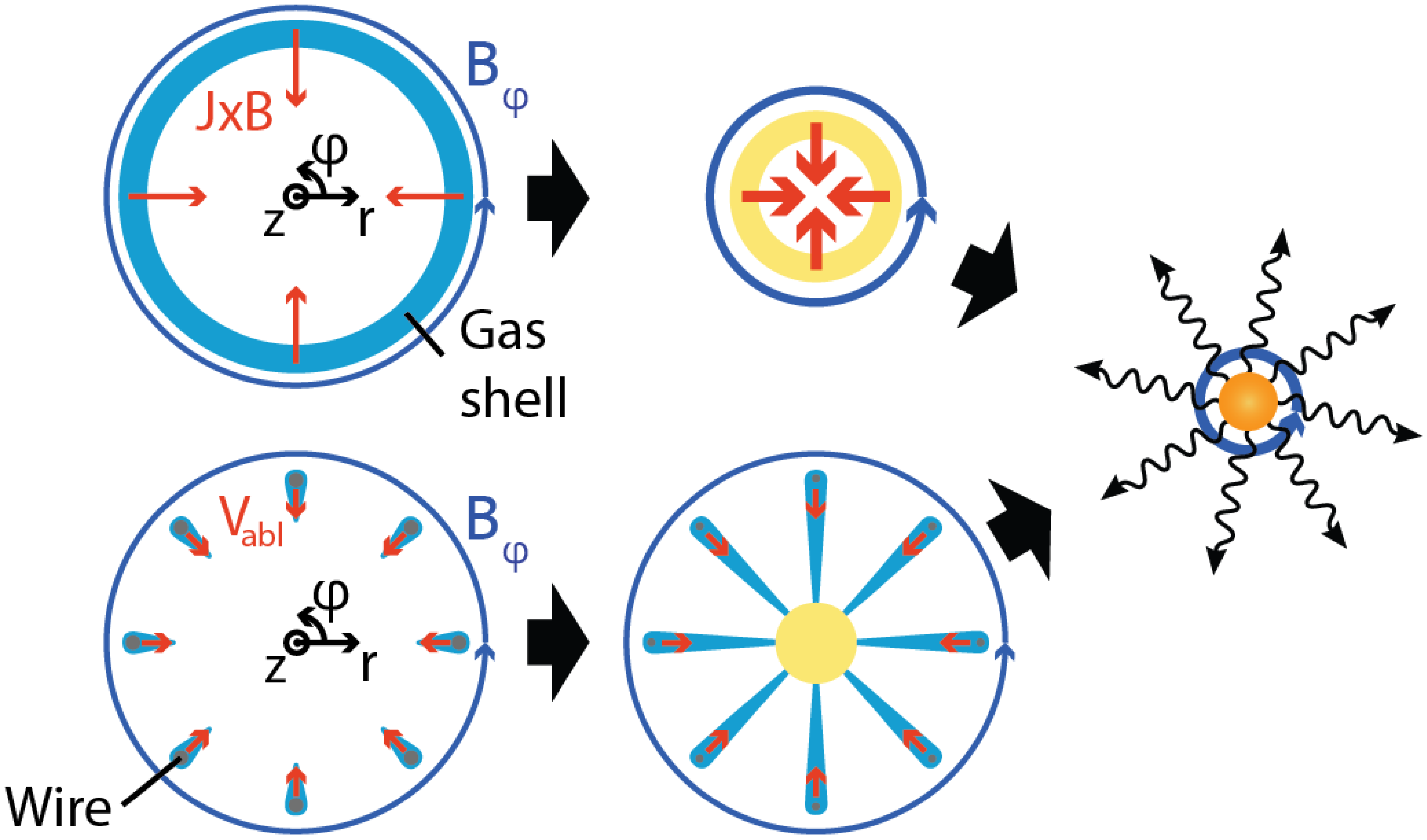
The Lebedev Rocket Model

$$V_{abl}\frac{dm}{dt} = -\frac{\mu_0 I(t)^2}{4\pi r_0}$$

Integrate: $\delta m(t) = \frac{\mu_0}{4\pi V_{abl} r_0}\int_0^t I(t')^2 dt'$

- Cylindrical array of thin wires
- Current heats and ablates plasma, which is accelerated by $\mathbf{J}\times\mathbf{B}$ force to $V_{abl}$
- Plasma collides on axis, heating and compressing
- Model mass ablation like a rocket: balance change in momentum with force
- Mass is ablated until wires are exhausted, causing the final implosion

# Gas puff and wire array z-pinches



- Gas puff or wire array, the intense current compresses plasma through magnetic fields
- The resulting plasma column is hot and dense, and so radiates X-rays
- Can also reach conditions to make some fusion neutrons (but not Q>1)
- Related concept: shear flow stabilized Z-pinch (Zap Energy)

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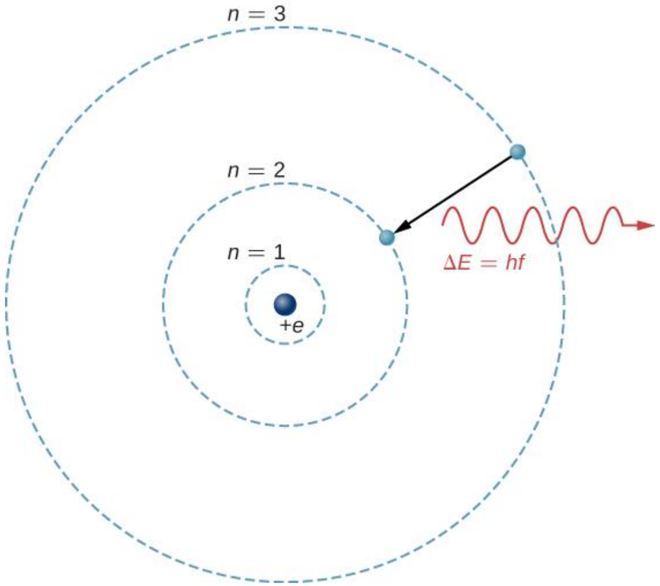
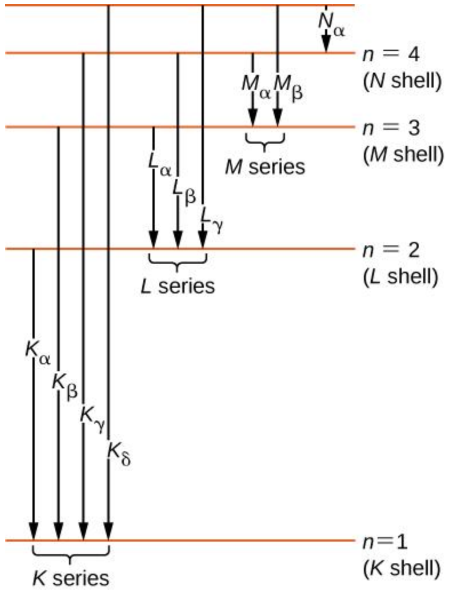
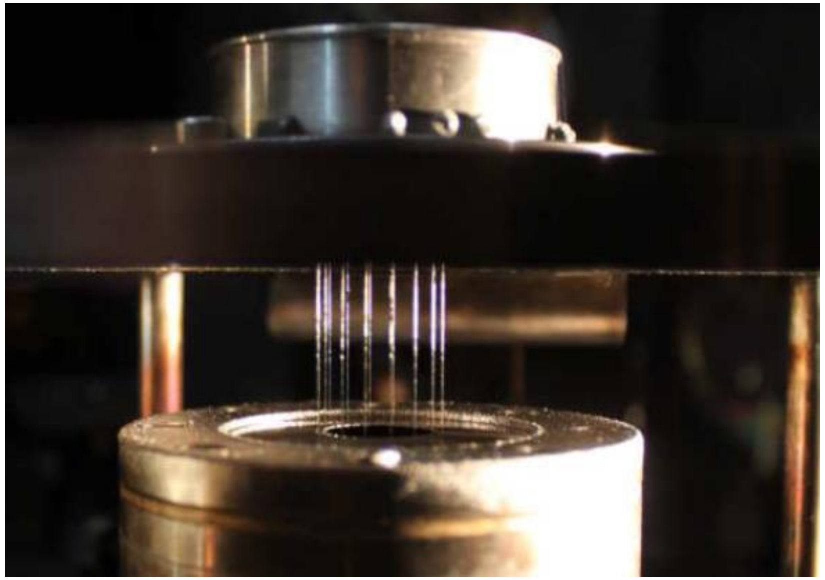
# X-ray basics





- X-rays: short wavelength photons (< 10 nm)
- Come in two flavors
  - Continuum/Bremsstrahlung: broadband, emitted when free electrons lose energy interacting with nuclei
  - Line radiation: localized at a specific wavelength, emitted when excited electrons transition to a lower-energy state ($E = \frac{hc}{\lambda}$)
- “K-shell” X-rays are line radiation emitted when electrons drop from the L-shell to the K-shell energy states

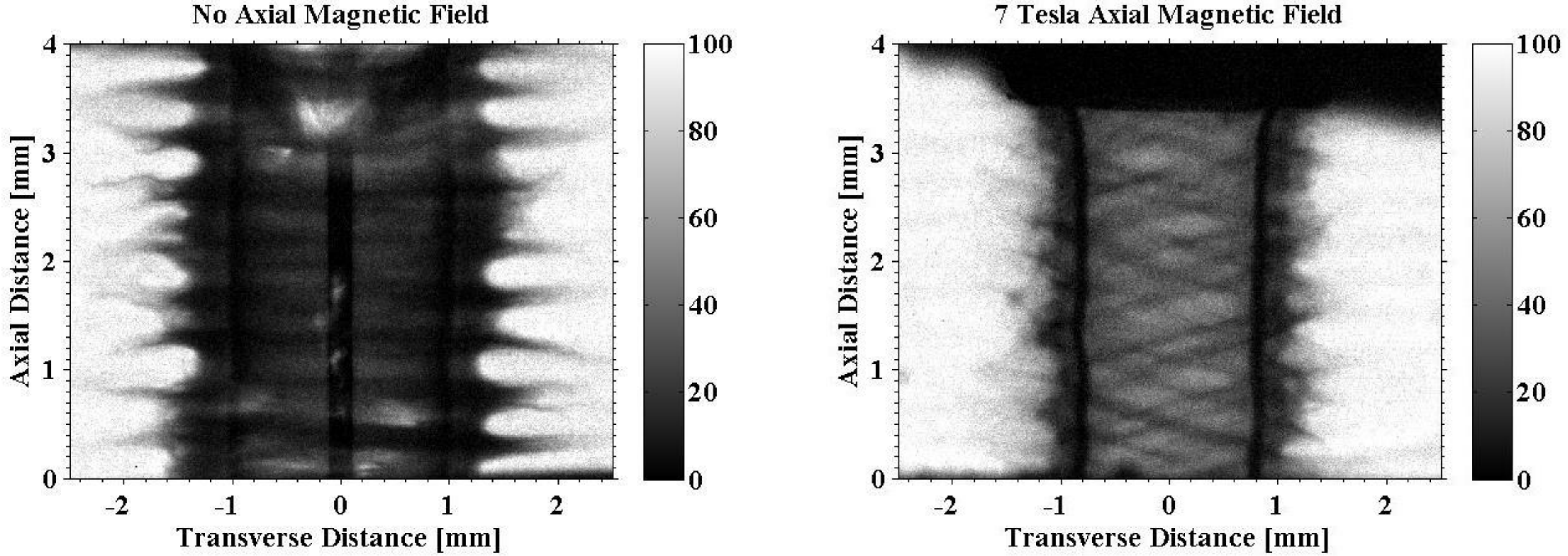
# Pulsed power for X-ray production



Wire array Z-pinch (Imperial College)

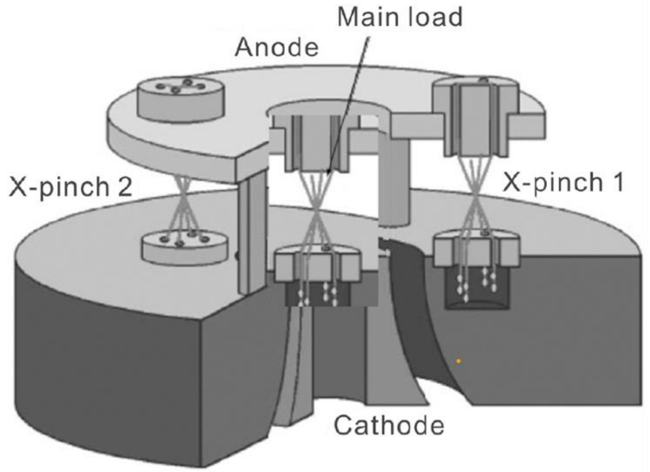
- Wire material (in wire arrays) or gas species (in gas puff Z-pinches) determines the X-ray characteristics
  - Source size
  - Wavelength/energy
  - Brightness
  - Duration of source
- Aluminum, molybdenum, copper, tungsten, deuterium fiber, DT (gas), argon, neon, krypton, xenon, etc. etc.

# X-ray radiography of other plasmas!



https://phys.org/news/2014-01-fusion-instabilities-lessened-unexpected-effect.html

Short bursts of X-rays from pulsed-power-driven plasmas can perform X-ray radiography on dynamic systems, like other Z-pinch plasmas!



https://www.sciencedirect.com/science/article/pii/S2468080X18300669

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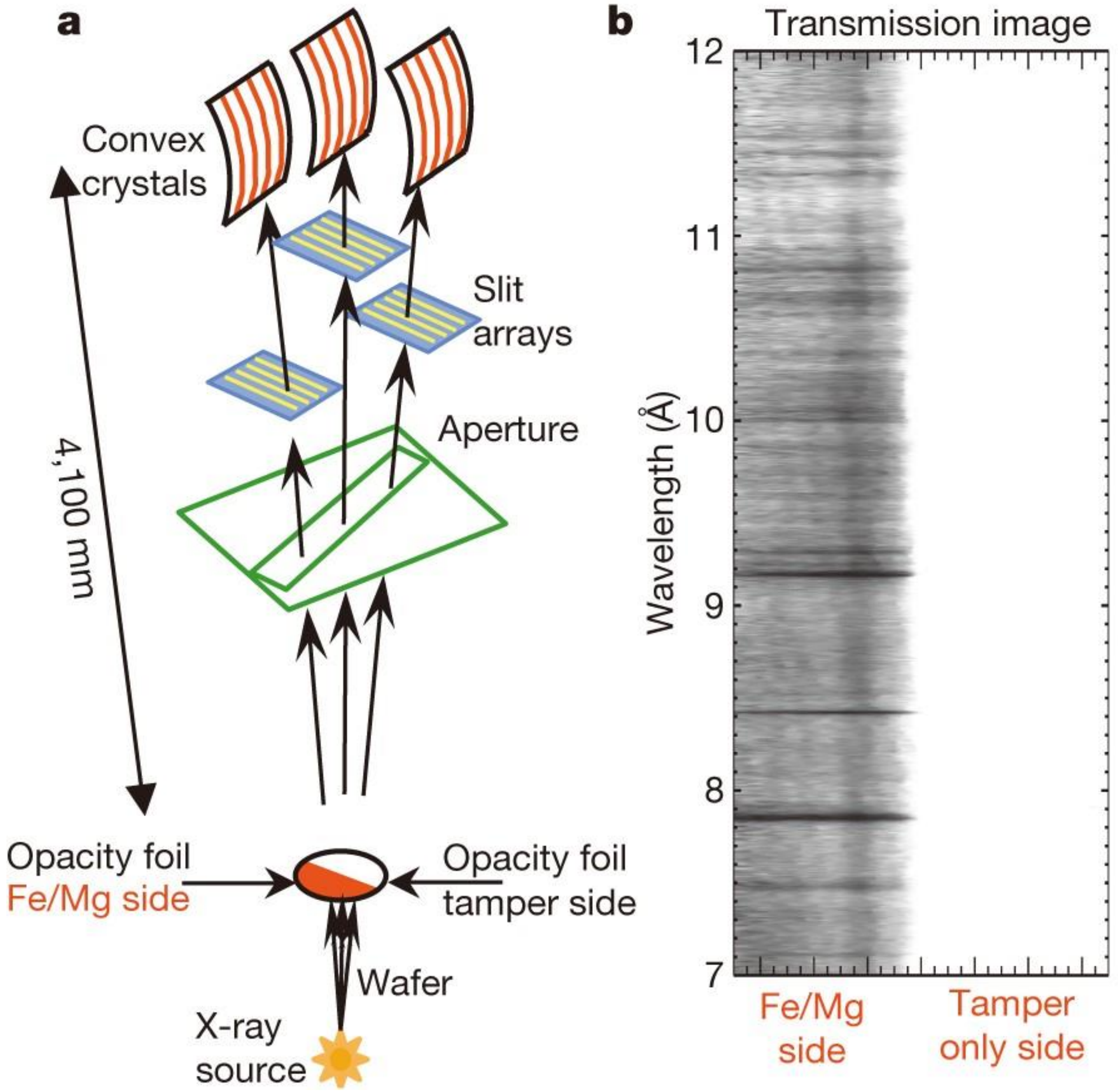
# X-rays for opacity measurements

- A “backlighter” (Z-pinch, X-pinch) produces X-rays of a known energy
- X-rays hit a sample
- The sample is opaque to some energies and transparent to others
- By measuring what energies made it through to the detector on the other side of the sample, the sample density and temperature can be determined or at least bounded
- Experimentally-validated opacities are used in codes that model solar behavior, inertial confinement plasmas, etc.



https://www.nature.com/articles/nature14048/

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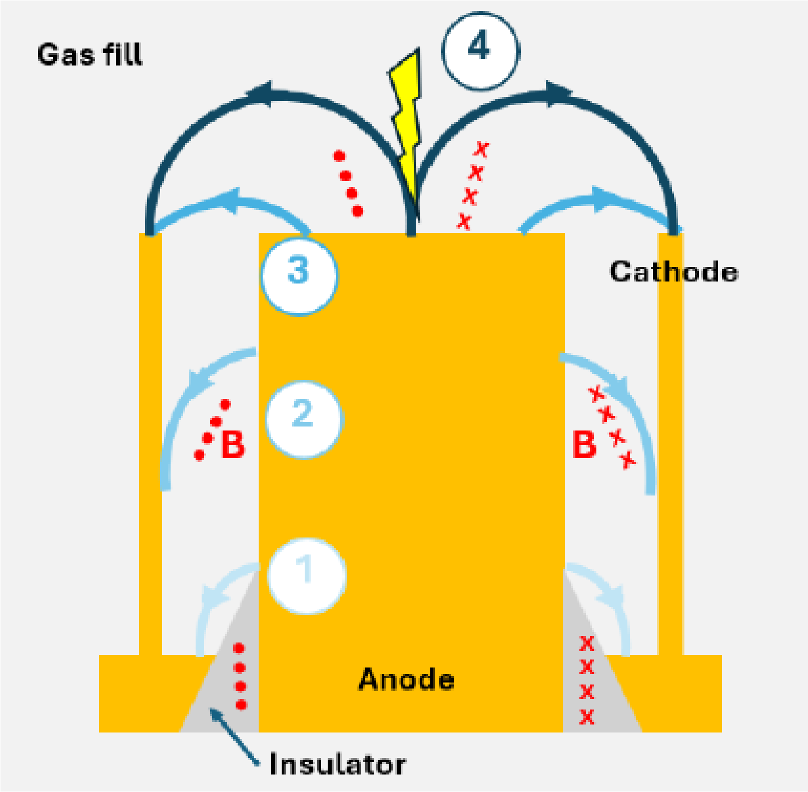
# Pulsed power for making neutrons

- Deuterium (D) or deuterium and tritium (T) gas or fibers
  - Gas puff, dense plasma focus (DPF), even wire (fiber) arrays!

$$\mathrm{D}+\mathrm{D} \rightarrow {}^{3}\mathrm{He}+\mathrm{n} \quad (50\%\ \text{probability})$$

$$\mathrm{D}+\mathrm{D} \rightarrow {}^{4}\mathrm{He}+\mathrm{p} \quad (50\%\ \text{probability})$$

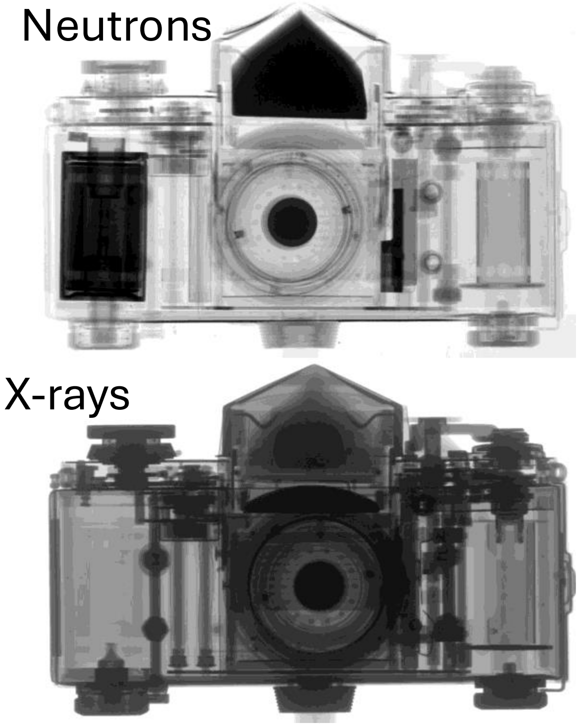
$$\mathrm{D}+\mathrm{T} \rightarrow {}^{4}\mathrm{He}+\mathrm{n}$$



DPF

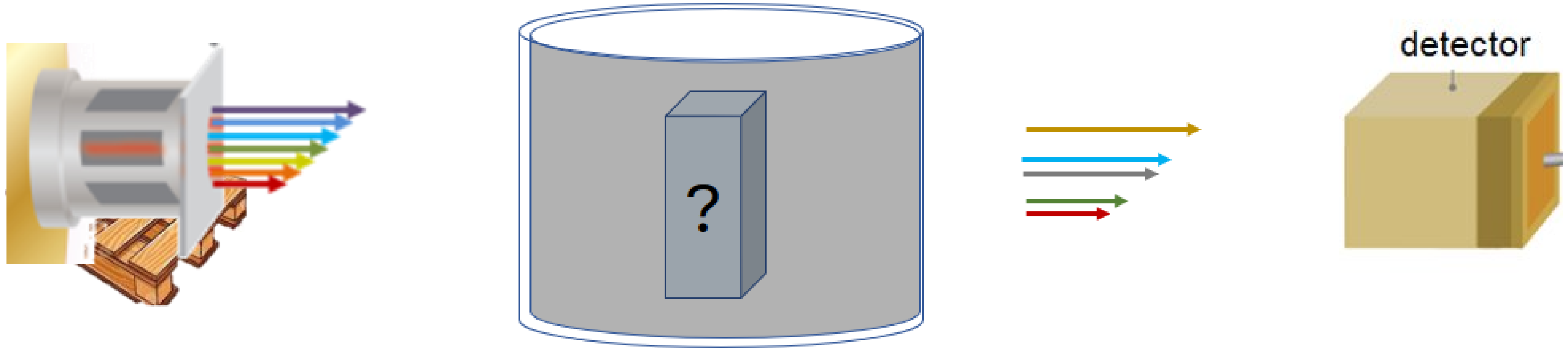
# Neutrons for non-destructive analysis

- Neutron radiography
  - Neutral particles—less interaction with high-Z materials (like metal)
  - More interaction with hydrogenous materials (plastic, water, oil)
  - Complementary to X-ray radiography
  - Fast pulsed power sources can perform dynamic neutron radiography
- Neutron resonance transmission analysis (NRTA)
  - Measuring the absorption of neutrons in an unknown material
  - Determine what is in a box without opening it



psi.ch

Canonical object:



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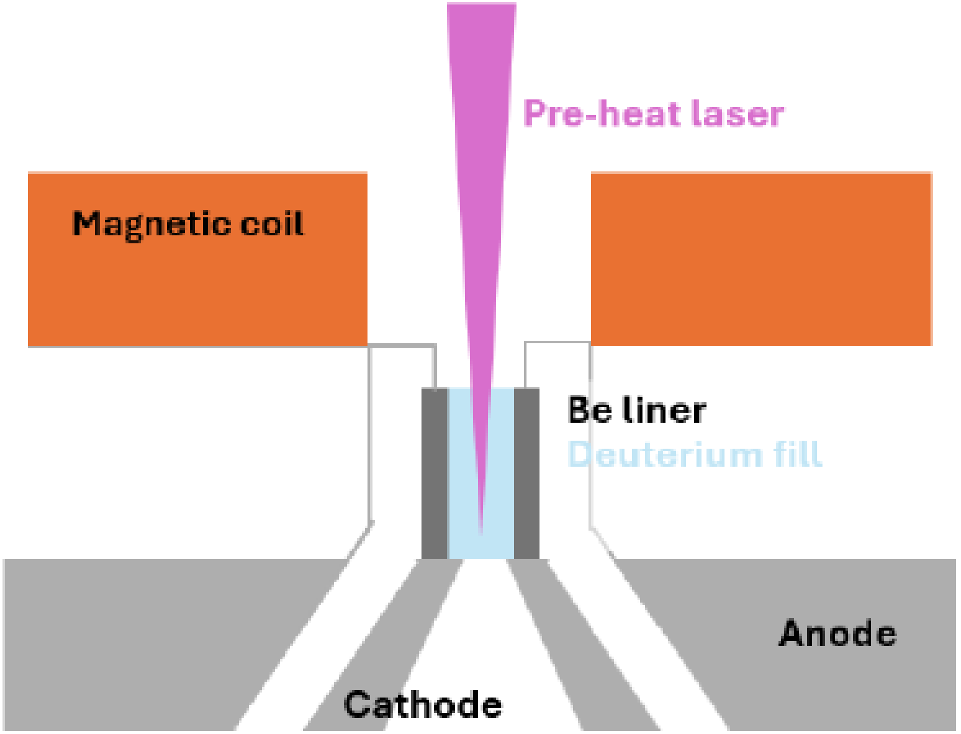
# Z-pinch neutrons for power!

## Magnetized liner inertial fusion (MagLIF): Z Machine at Sandia National Lab

- A beryllium liner is imploded with a pulsed power driver
- The liner compresses DT fuel inside
- The fuel is pre-heated with a laser
- External magnetic field coils trap alpha particles to maintain heating
- Neutrons emitted at peak compression



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# Pulsed Power for Lab Astrophysics

- Astrophysical-scale phenomenon (shocks, jets, accretion disks) can be explored in the lab
  - Rewriting governing equations in dimensionless form shows that systems with the same initial conditions evolve in a similar manner
  - Dimensionless parameters
    - Mach number $M = \frac{V}{C_s}$
    - Reynolds number $Re = \frac{\rho v L}{\mu}$
    - Plasma beta: $\beta = \frac{P_{thermal}}{P_{magnetic}}$

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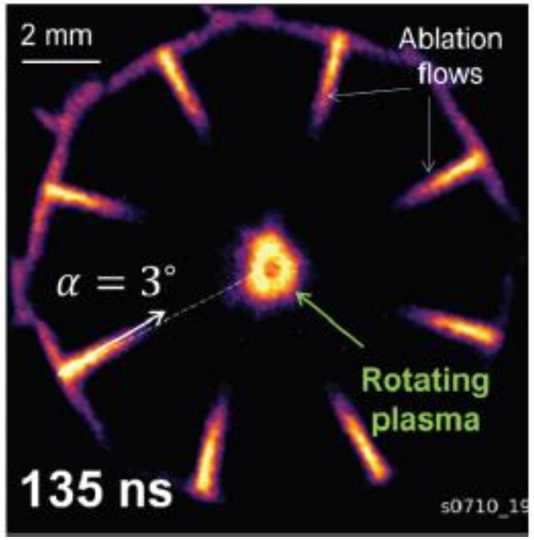
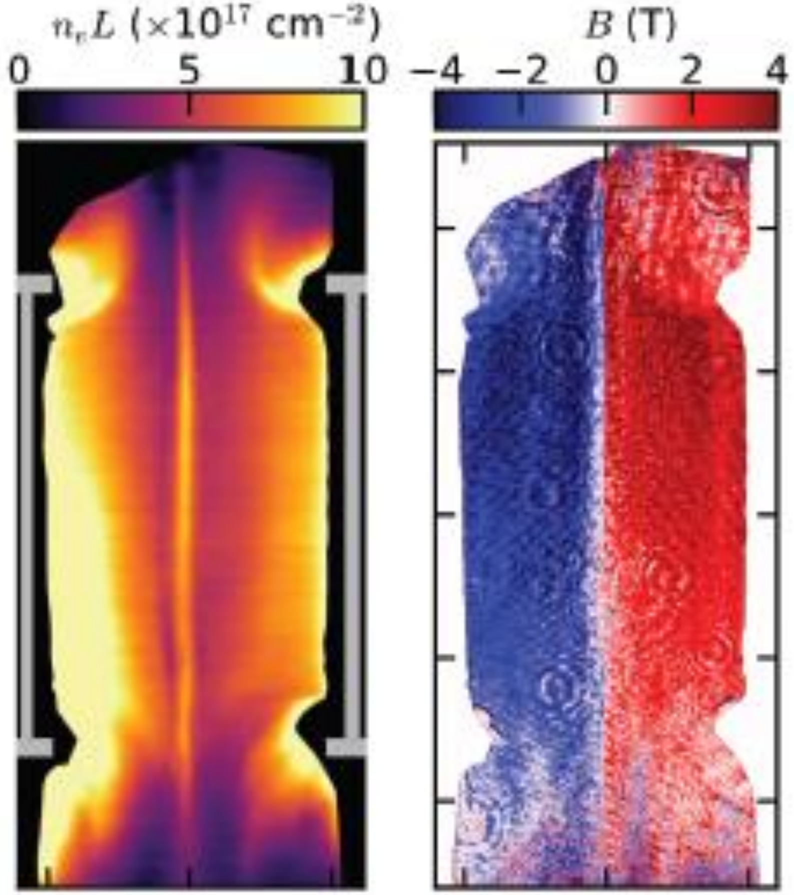
# Astrophysical jets in the lab



- Astrophysical jets are found in objects with accretion disks: black holes, young stellar objects, etc.
- Accretion disks show accretion rates far higher than can be explained by classical viscous dissipation of the angular momentum, suggesting other forces at play
- Top left: a jet launched inside a conical wire array (laser shadowgraph imaging)
- Bottom left: optical self-emission imaging of a rotating plasma inside an imploding wire array (accretion disk!)
    - Rotating disks can be created by twisting conical wire arrays, adding a radial magnetic field component with twisted electrodes, or offsetting return posts

# Magnetic reconnection

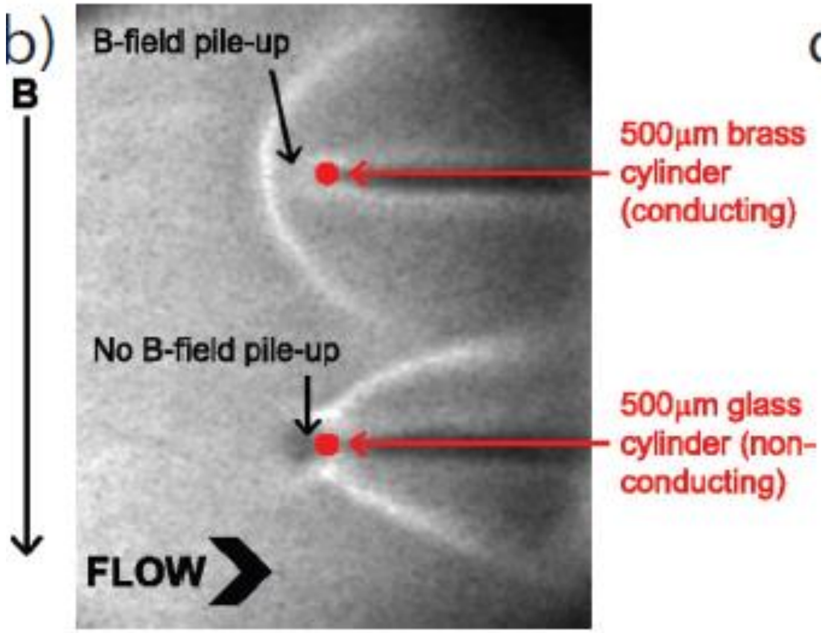
- Anti-parallel B fields in a plasma generate a sheet of intense electric current through Ampere’s law ($\nabla \times B = \mu_0 J$).
- The frozen-in condition of ideal MHD is broken, allowing the magnetic field lines to break and reconnect.
- The magnetic energy is dissipated as heat.
- Reconnection changes magnetic topology (in solar flares which result in coronal mass ejections) and converts magnetic energy to thermal and kinetic energy.
- Exploding wire arrays create a reconnection region

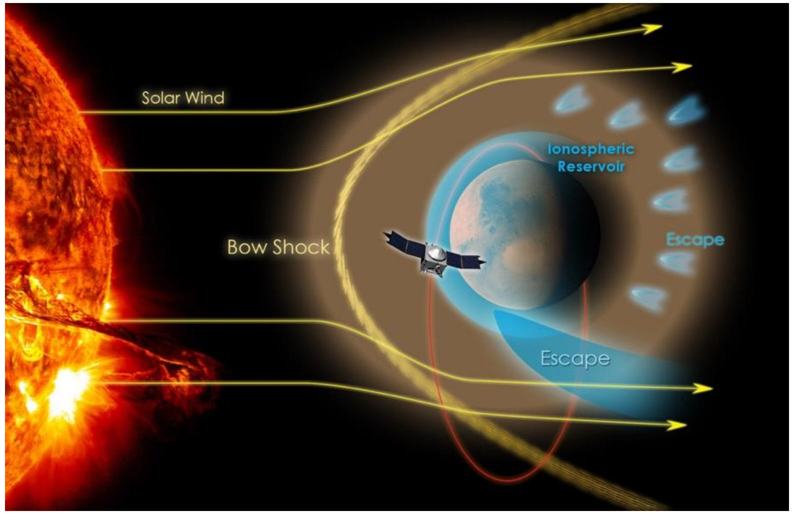


A reconnecting layer is formed between two exploding wire arrays (left: density. Right: B field).

# Astrophysical shocks

Optical self-emission imaging of bow shocks around conducting and non-conducting obstacles.

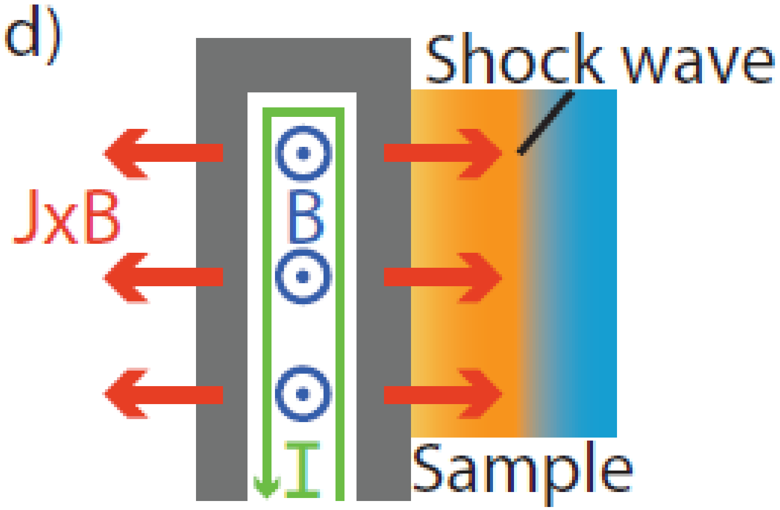




https://phys.org/news/2023-06-explores-magnetosheath-jets-mars.html

- Plasma flows carry magnetic field, sometimes faster than the magneto-sonic waves (pressure)
- Obstacles placed in these flows create shocks
  - Sudden change in density and advected magnetic field
  - Magnetic fields can't diffuse quickly through conductors, so the field 'piles up' on and drapes around obstacles
- Exploding wire arrays create outflows where obstacles can be placed

# Pulsed Power for Dynamic Compression



- Shock and compression experiments use a planar geometry
- Rising B field in the anode induces a current in a flyer plate or the sample itself
- JxB force accelerates the flyer and slams it into the sample, driving a shock and creating pressures up to the gigabar range
- Pressure, temperature, and density for material equation of state (EOS)
- Dynamic compression experiments benchmark EOS codes used to explore planetary formation, inertial confinement fusion, and stockpile stewardship

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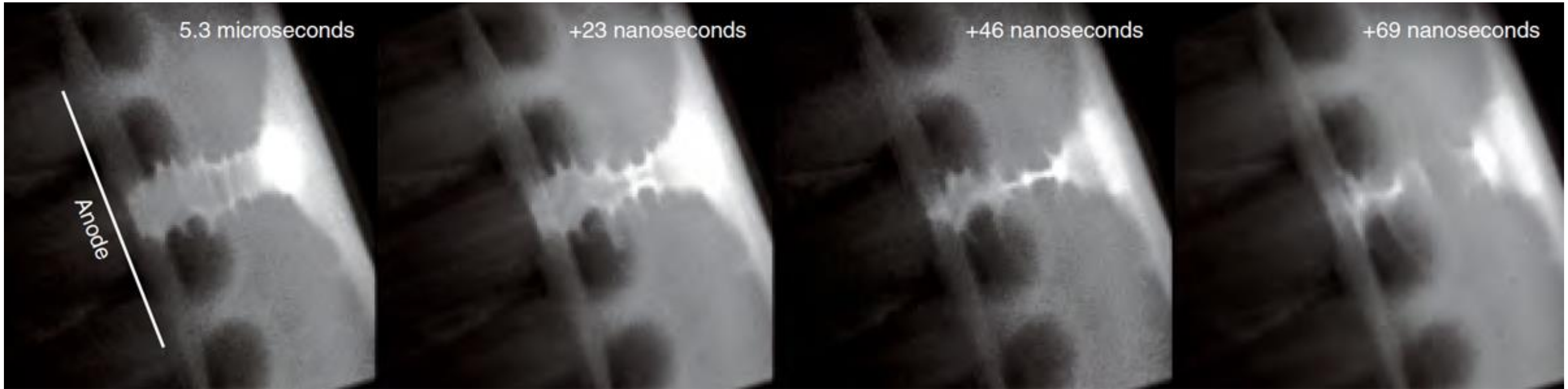
# Diagnostics for pulsed power plasmas

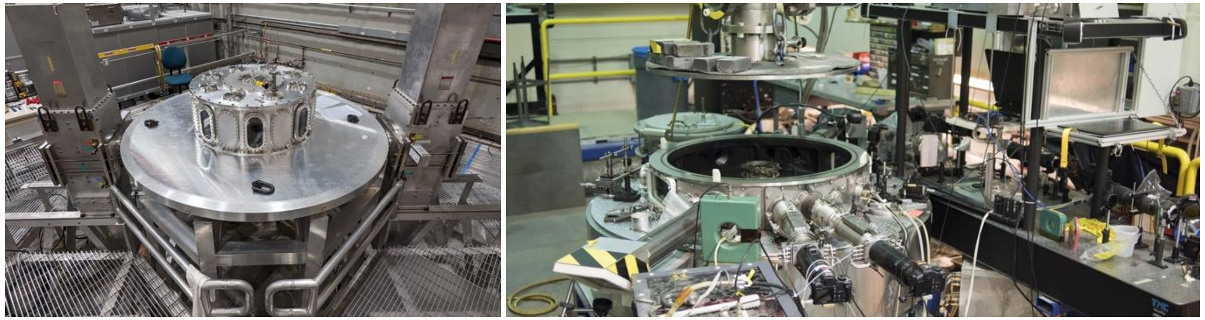
- University-scale facility plasmas have densities between $10^{17}$ and $10^{19}$ $cm^{-3}$, temperatures of 1 to 1,000 eV, flow velocities up to 200 kms–1 and magnetic fields up to 10 T.
- Good density for optical wavelengths: interferometry, Faraday rotation imaging, and Thomson scattering.
- Inductive probes can be placed directly in the plasma to measure the magnetic field and flow velocity (though they are perturbative due to supersonic flows)
- The plasmas are hot and dense enough to emit copious visible, XUV and X-ray radiation.
- The plasmas are also dense enough to be backlit by X-ray sources.



# Before we finish, a quick ad break

**Cornell Laboratory of Plasma Studies**

- Three pulsed-power facilities

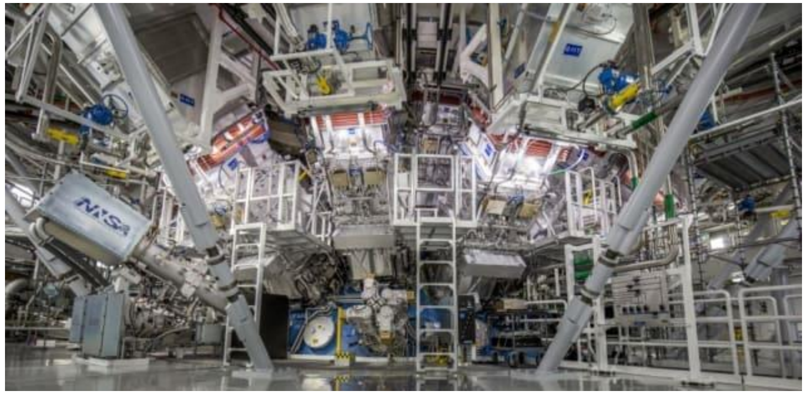


*puffin.ece.cornell.edu and lps.cornell.edu*

- Hands-on, student led projects from fusion to lab astro to pulsed-power to diagnostic development
- Beautiful (& affordable) upstate NY
- Looking for grad students: Apply by Dec 15th 2026

**Lawrence Livermore National Lab**

- Home to the National Ignition Facility, the world's most power laser and only Q>1 fusion device!



- Huge range of physics research
- Sunny California, close to SF
- Primarily looking for postdocs, but grad students can get involved through their university

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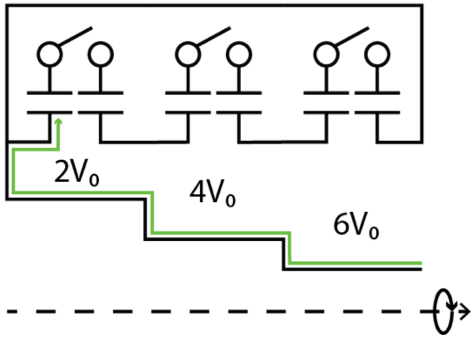
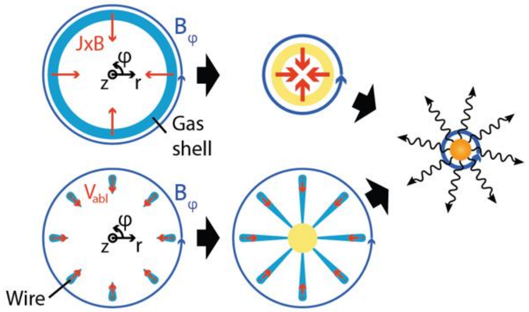
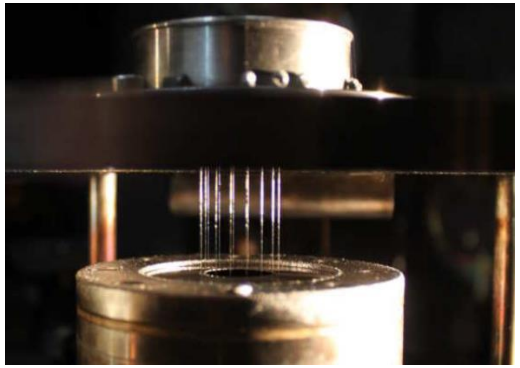
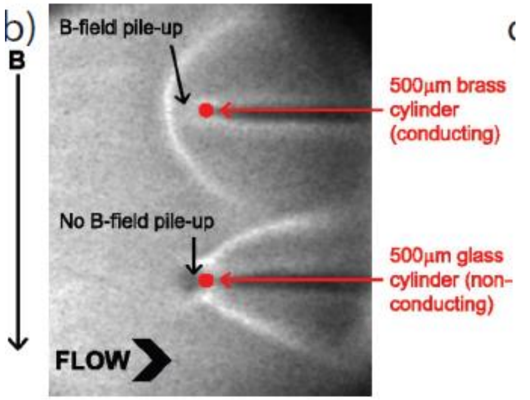
# Summary









- Pulsed power compresses electrical energy in space and time
- Various pulser architectures exist: Marx, LTDs, IMGs
- Standard load: the z-pinch, compress to high temperature and density
- Applications:
  - X-rays and neutrons for radiography
  - Path to fusion energy (MagLIF)
  - Laboratory astrophysics: learn about the Universe from the lab!

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