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Conceptual designs of next-generation pulsed-power accelerators

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Sandia National Laboratories

Designing new machines is a large team effort.

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Outline

- Pulsed-power technology
- Present state of the art of pulsed power: the Z accelerator
- Proposed architecture for the design of next-generation machines
- Proposed requirements for machines optimized for material-physics experiments
- Thor: a megabar-class accelerator
- Neptune: a 10-megabar-class accelerator
- Proposed requirements for machines optimized for fusion experiments
- Z 300: a thermonuclear-ignition accelerator
- Z 800: a high-yield-fusion accelerator
- Linear transformer drivers (LTDs): the prime power source of Z 300 and Z 800
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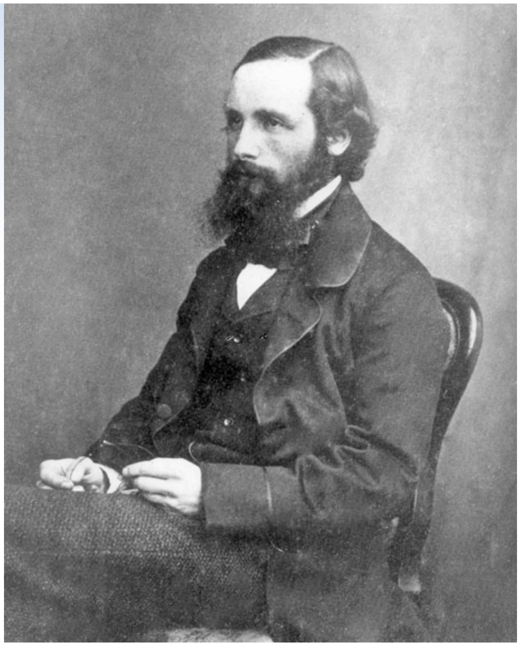
Pulsed power is an amazing technology.

Pulsed-power accelerators:

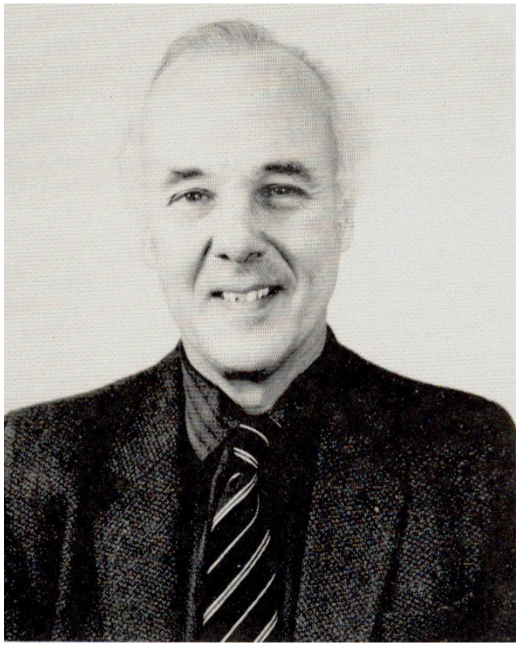
- Serve as precision scientific instruments.
- Deliver megajoules of energy to milligrams of matter on a time scale of nanoseconds.
- Achieve extreme states of matter over macroscopic volumes.
- Drive a wide variety of high-energy-density-physics experiments in support of the U.S. national-security mission.

Michael Faraday



James Clerk Maxwell

Erwin Otto Marx

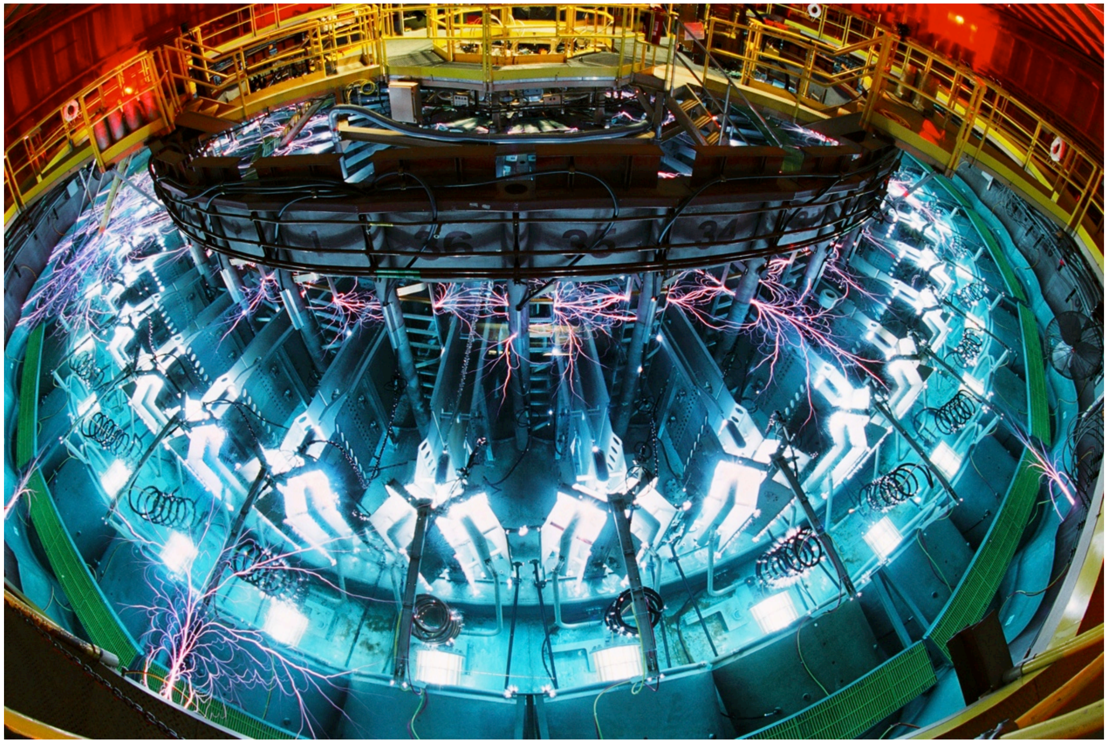


J. C. “Charlie” Martin

Pulsed-power experiments presently deliver the following:

- Kinetic energy per atom: 1 MeV.
- Implosion velocities: 60 cm/μs.
- Shock velocities: 30 km/s.
- Temperatures: 3 keV.
- Magnetic pressures: 5 Mbar.
- Energy radiated in K-shell x rays: 400 kJ.
- Energy radiated in thermal x rays: 2 MJ.
- Power radiated in thermal x rays: 330 TW.

100-ps x-ray image of a 280-TW z pinch at stagnation (Deeney, Douglas, Spielman, and colleagues, PRL, 1998)



20-TW Saturn accelerator (Bloomquist, Corcoran, Spielman, and colleagues)

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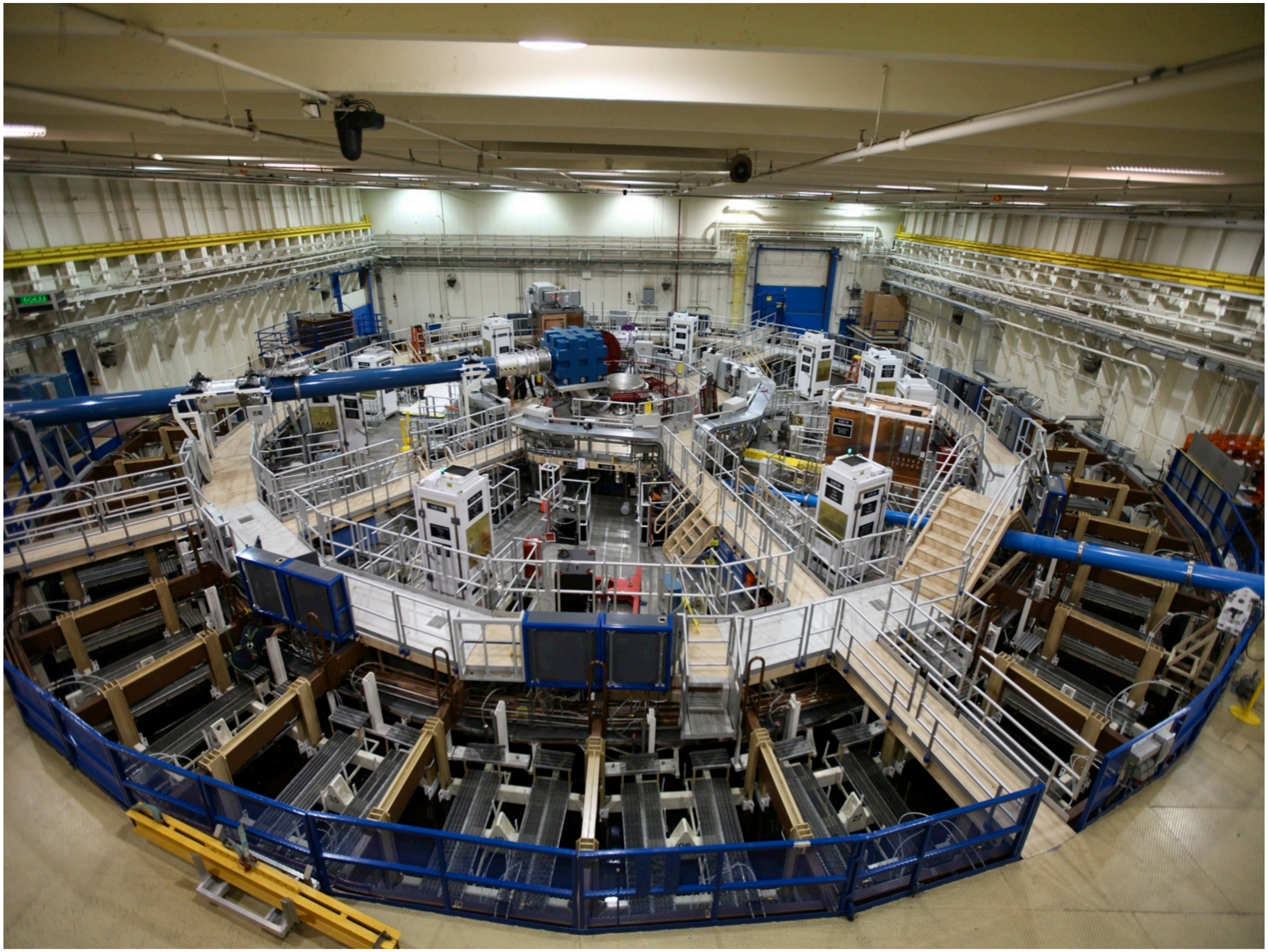
Sandia's Z accelerator is presently the world's largest and most powerful pulsed-power machine.

E_{stored} = 20 MJ	V_{stack} = 4 MV	I_{load} = 26 MA	$E_{radiated}$ = 2.2 MJ
$P_{electrical}$ = 80 TW	L_{vacuum} = 12 nH	$\tau_{implosion}$ = 130 ns	diameter = 33 m

- Since 1997 we have conducted, on average, 160 Z shots each year.
- To date, 2800 Z shots have been conducted altogether.

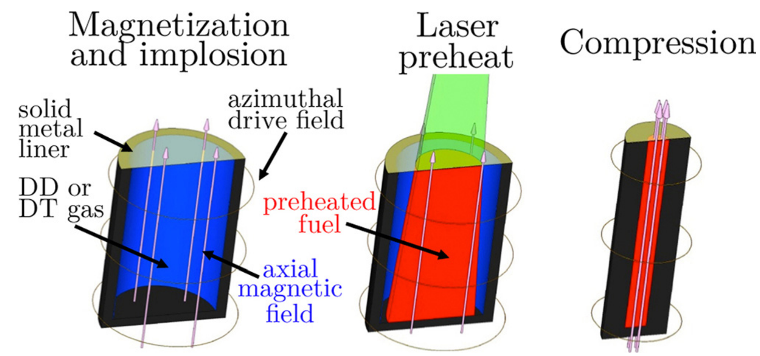


Z drives a wide variety of experiments in support of the U.S. national-security mission.

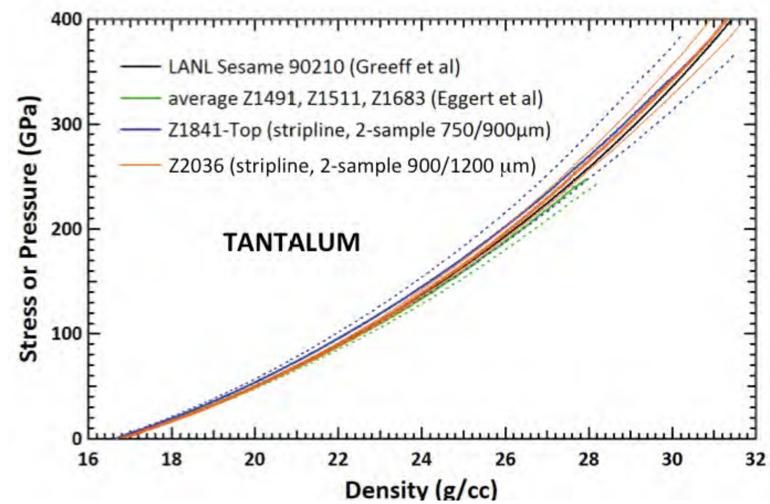
- Inertial confinement fusion
- Radiation physics
- Material physics
- Laboratory astrophysics

Results of experiments conducted on Z have been published in over 500 peer-reviewed journal articles.

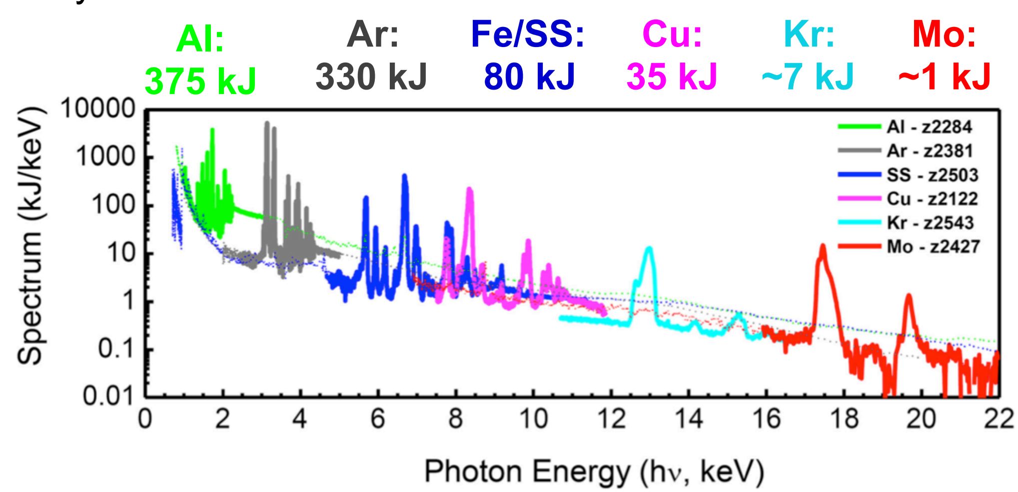
magnetized liner fusion (MagLIF) concept



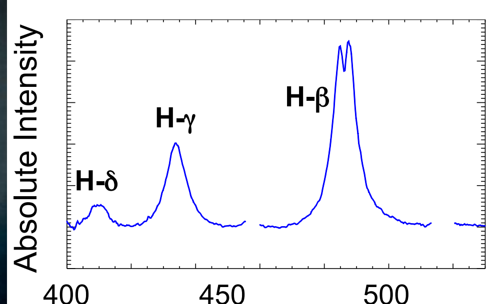
quasi-isentrope of tantalum to 4 Mbar



K-shell x-ray sources



white-dwarf line shapes



Z's success naturally leads to the question: How do we advance to the next level?

How do we design next-generation pulsed-power accelerators?

- How do we design machines for material-physics experiments?
- How do we achieve thermonuclear ignition and high-yield fusion?
- How do we make the new machines robust, reliable, and safe?

In other words:

How do we design accelerators that will serve as a suitable legacy from us to the next generation of high-energy-density scientists?

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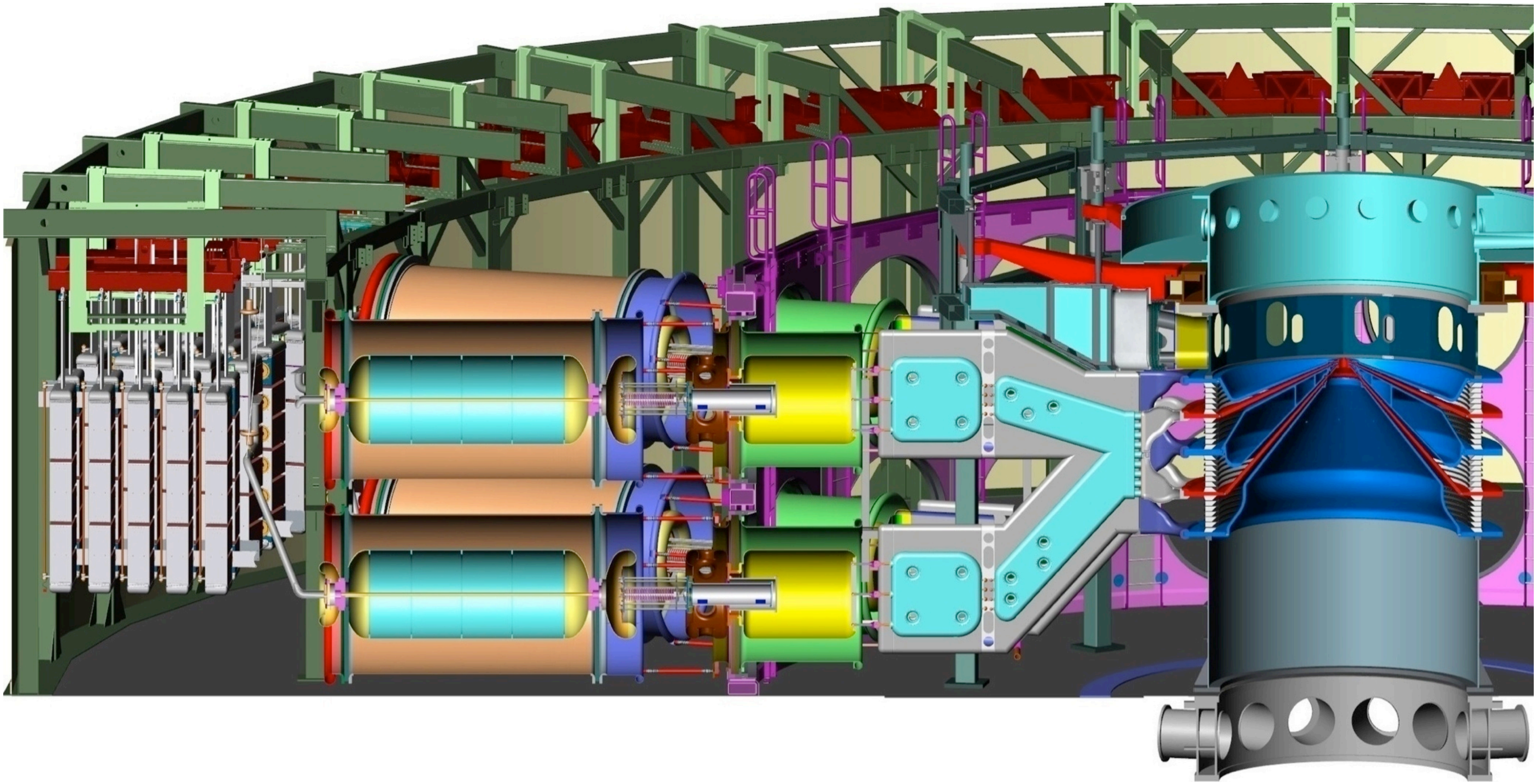
Each of Z's 36 modules includes four stages of electrical pulse compression.

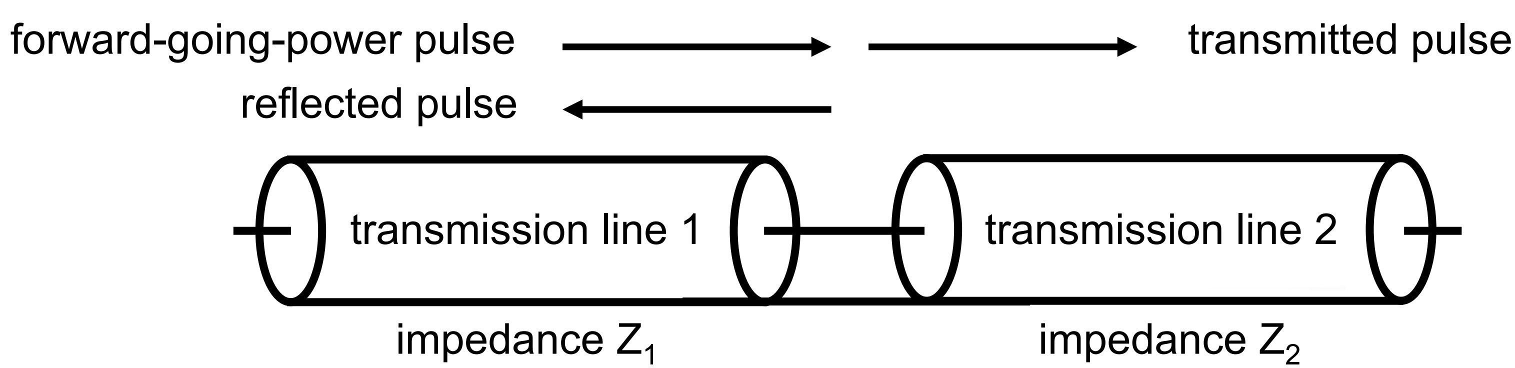
- These introduce impedance mismatches, which create reflections of the power pulse.
- The reflections damage hardware, reduce efficiency, and complicate efforts to model a Z shot.



We propose to base the designs of next-generation machines on a *new* architecture.

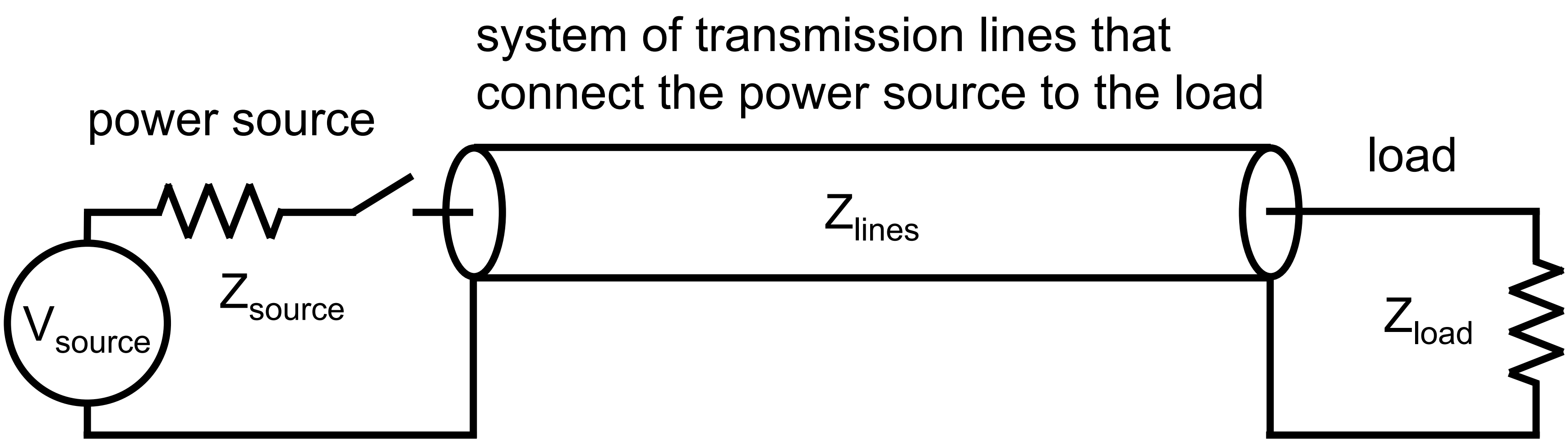
The architecture is based on two concepts: Single-stage electrical-pulse compression and impedance matching.

- We propose to go from DC-charged capacitors to the requisite 100-ns power pulse in a single step (as proposed by Dillon McDaniel and Rick Spielman).
  - This eliminates the need for pulse-compression hardware.
  - This in turn simplifies the machine design, increases efficiency, improves component lifetime, and facilitates simulations of an accelerator shot.
- We propose to use impedance matching throughout.
  - When power flows from one transmission line to another, the reflected power is zero (and the power-coupling efficiency is maximized) when $Z_1 = Z_2$.



The new architecture is illustrated by the following idealized circuit model.

- Single-stage electrical-pulse compression is achieved by a single set of switches in the power source.
- $Z_{source} = Z_{lines} = Z_{load}$.

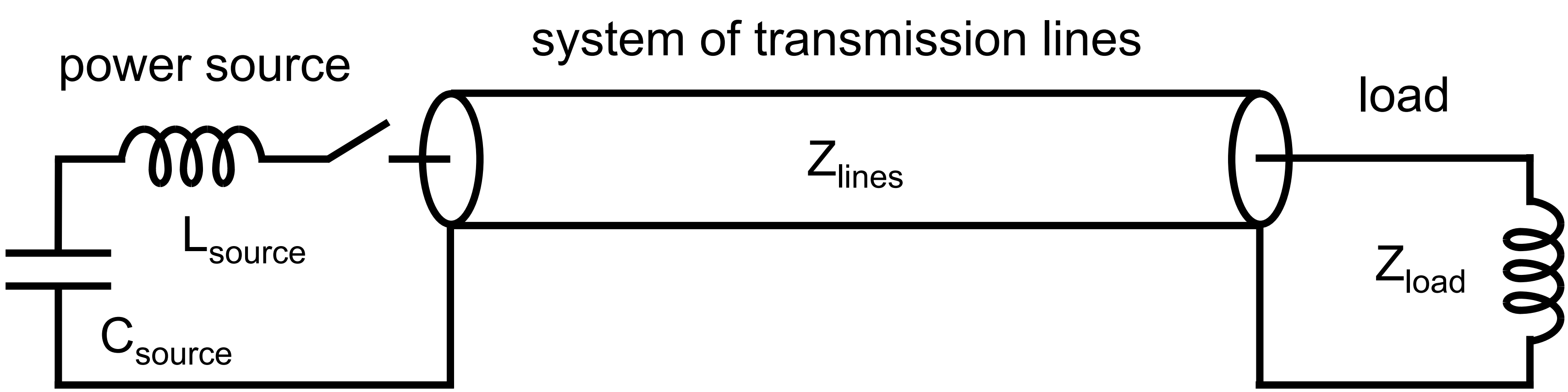


We will consider power sources that can be modeled as LC circuits, and loads that are primarily inductive.

- $Z_{source} = 1.1\sqrt{\frac{L_{source}}{C_{source}}}$

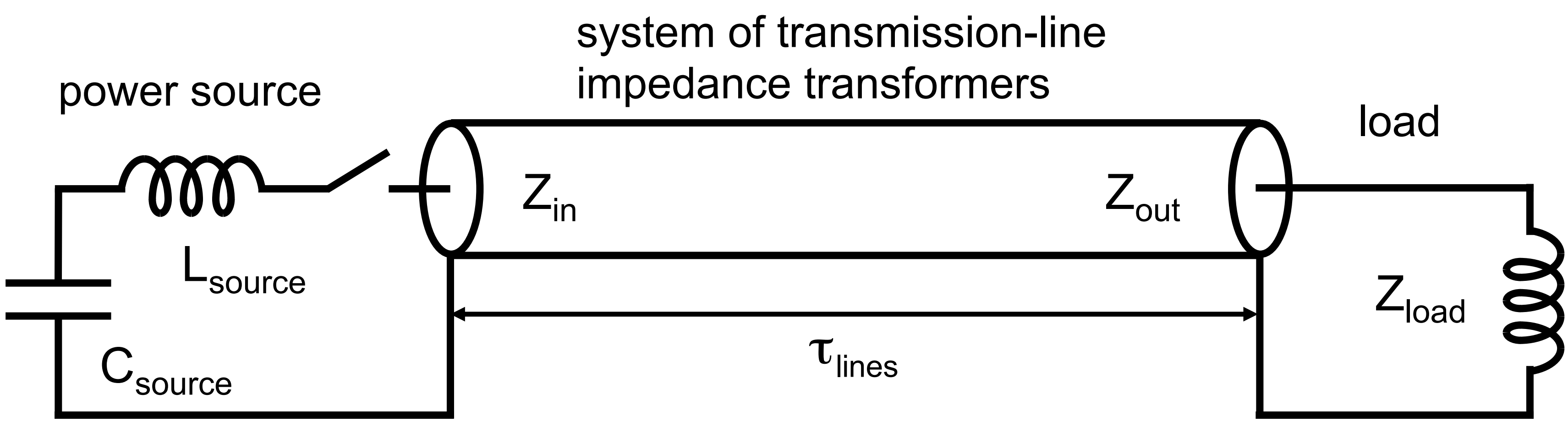
- $Z_{load} = \frac{k\,L_{load}}{\sqrt{L_{source}C_{source}}}$ (k = 0.87 maximizes peak load power; k= 0.55, peak load current.)

- $Z_{source} = Z_{lines} = Z_{load}$.



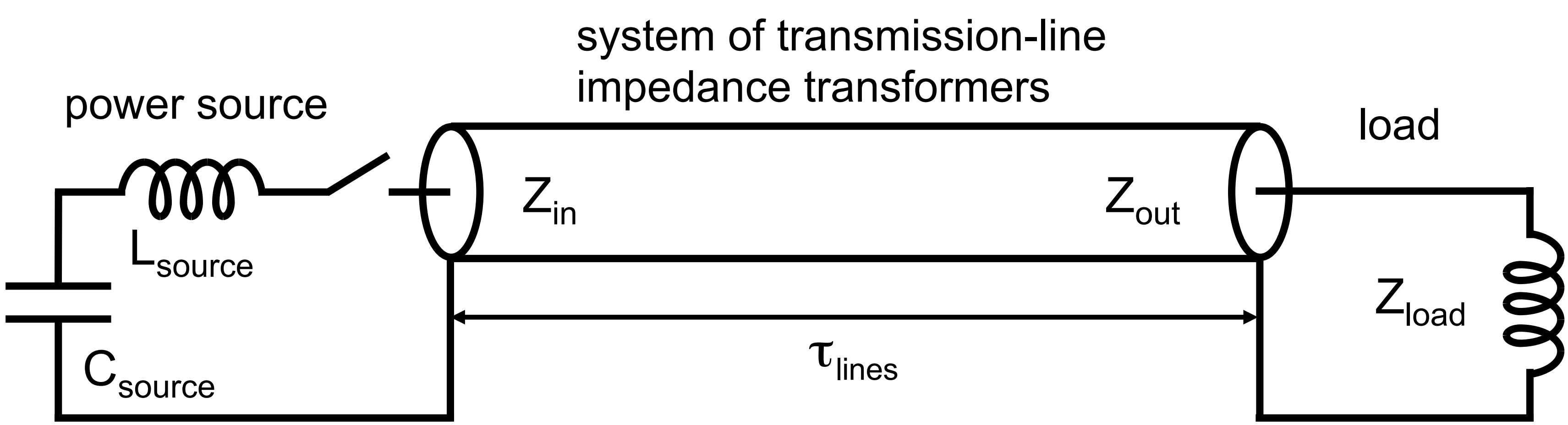
When the source and load have different impedances, we connect the two with an impedance transformer.

- $Z_{source} = 1.1\sqrt{\frac{L_{source}}{C_{source}}}$
- $Z_{load} = \frac{k}{\sqrt{L_{source} C_{source}}}$ (k = 0.87 maximizes peak load power; k= 0.55, peak load current.)
- $Z_{in} = Z_{source}; \quad Z_{out} = Z_{load}$
- $\tau_{lines} >> \left[\ln\left(\frac{Z_{out}}{Z_{in}}\right)\right]^2 \sqrt{L_{source} C_{source}}$



We will outline today conceptual designs of four pulsed-power accelerators: Thor, Neptune, Z 300, and Z 800.

- At a high level, all four machines can be described by the following circuit model.
- Thor and Neptune use transmission lines with a constant impedance.
  - For these two machines, $Z_{source} = Z_{in} = Z_{out} = Z_{load}$.
- Z 300 and Z 800 use transmission-line impedance transformers.
  - For these two machines, $Z_{source} = Z_{in} \neq Z_{out} = Z_{load}$.
  - $\tau_{lines} >> \left[\ln\left(\frac{Z_{out}}{Z_{in}}\right)\right]^2 \sqrt{L_{source} C_{source}}$



Lewis and Wells discuss the use of transmission-line impedance transformers to connect a power source to a load when the two have different impedances (1959).

MILLIMICROSECOND PULSE TECHNIQUES

(Second Edition)

By

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THE principle of impedance matching (FANO [301]) is widely applied when it is desired to transmit maximum power from a generator into a load. In the simplest case the internal impedance of the generator, Z_1 say, and the impedance of the load, Z_2 say, are both pure resistances. It is easily shown that, for a given generator e.m.f., the power dissipated in the load is a maximum when $Z_1 = Z_2$. The two impedances are different in general and a transformer is accordingly inserted.

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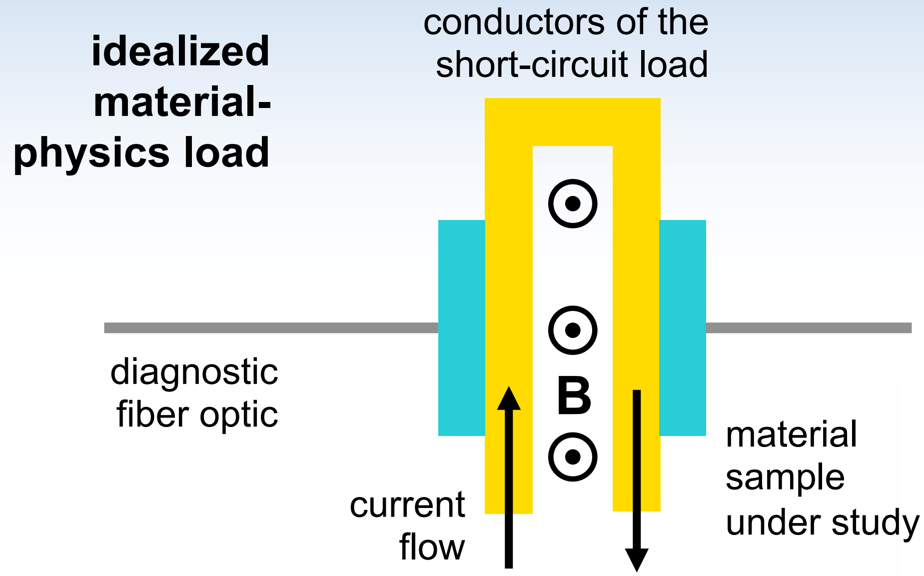
Pulsed-power accelerators are used to drive a wide variety of material-physics experiments.

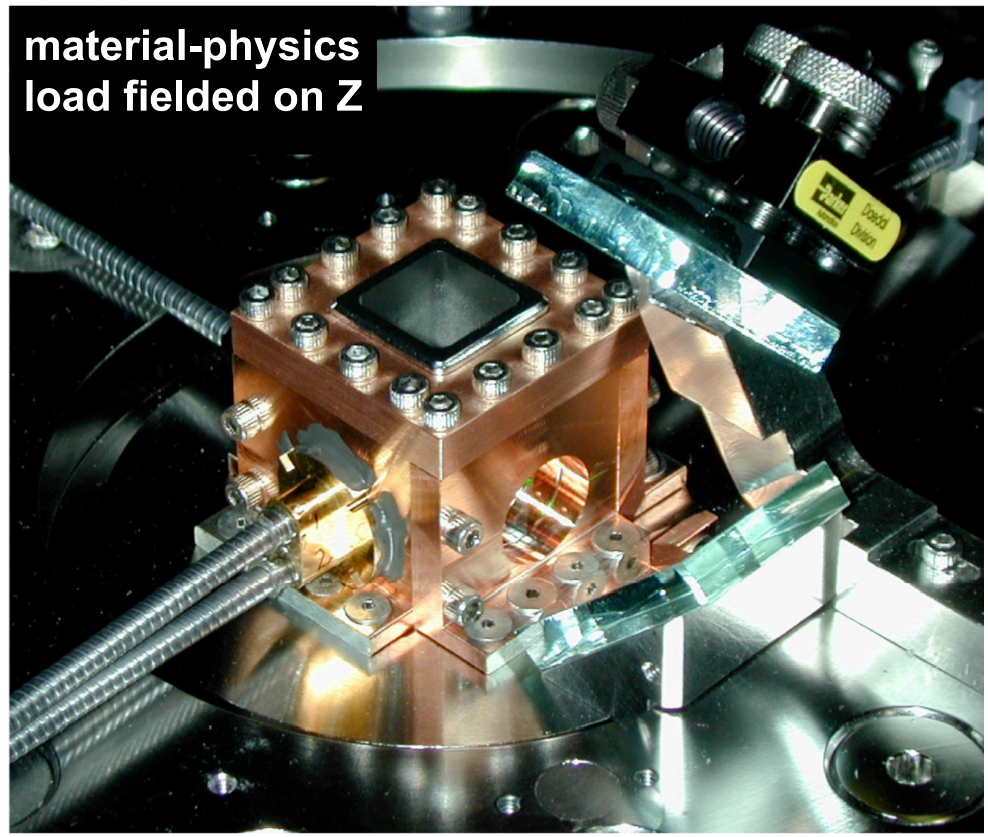
- This application is outlined in seminal publications by Reisman and colleagues (JAP, 2001) and Hall and co-workers (RSI, 2001).
- The magnetic pressure generated within a short-circuit load drives the experiment.

$$P_{magnetic} = \frac{\mu_0 I^2}{2 w^2}$$

I = current

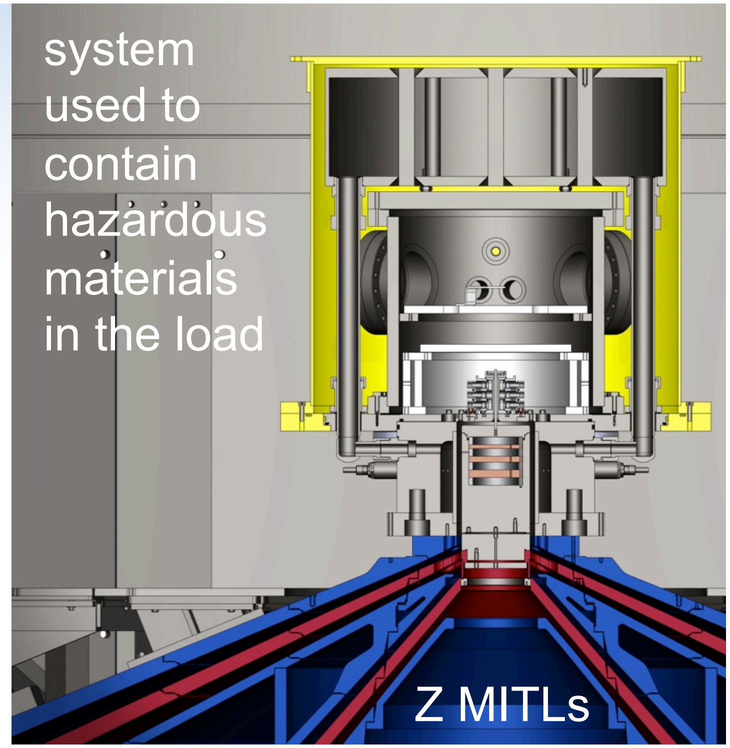
w = width of the conductor





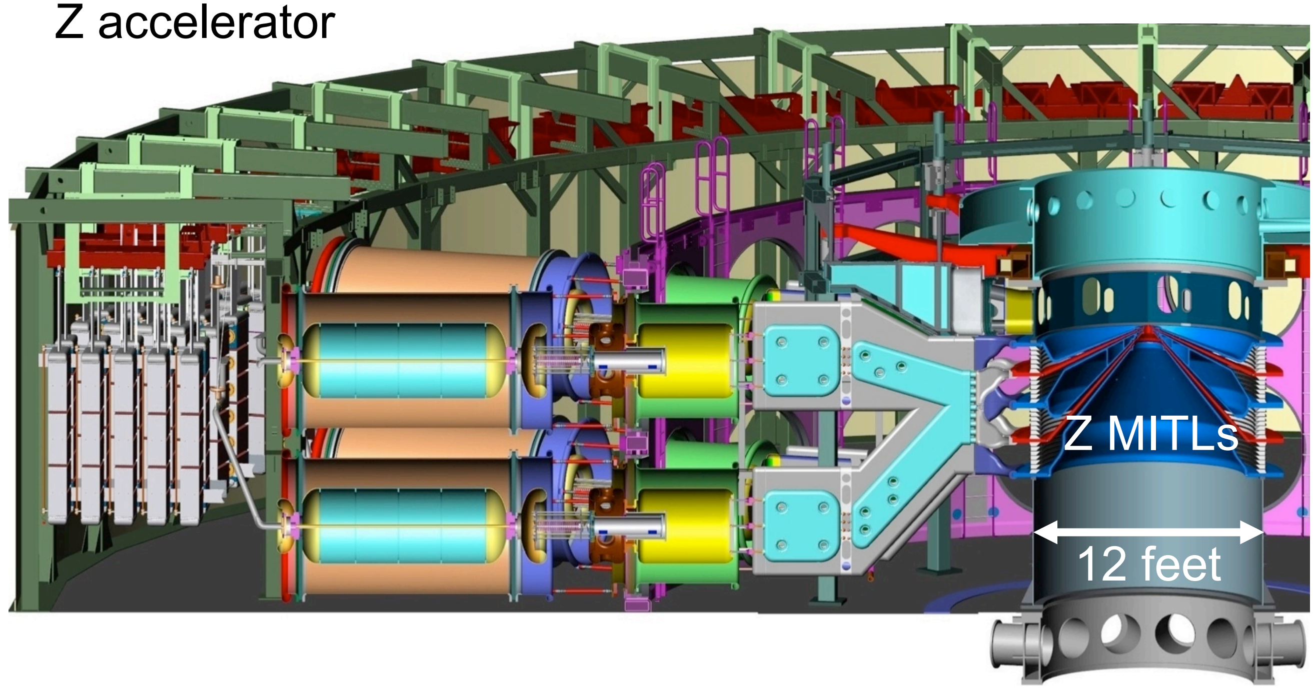
There is a need for accelerators that are *optimized* for material-physics experiments.

- Z was optimized to deliver a 100-ns current pulse to an imploding z-pinch load.
    - The resulting high voltage requires a 12-foot-diameter insulator stack.
    - However, a material-physics experiment requires a ~1000-ns current pulse, which generates much lower voltages.



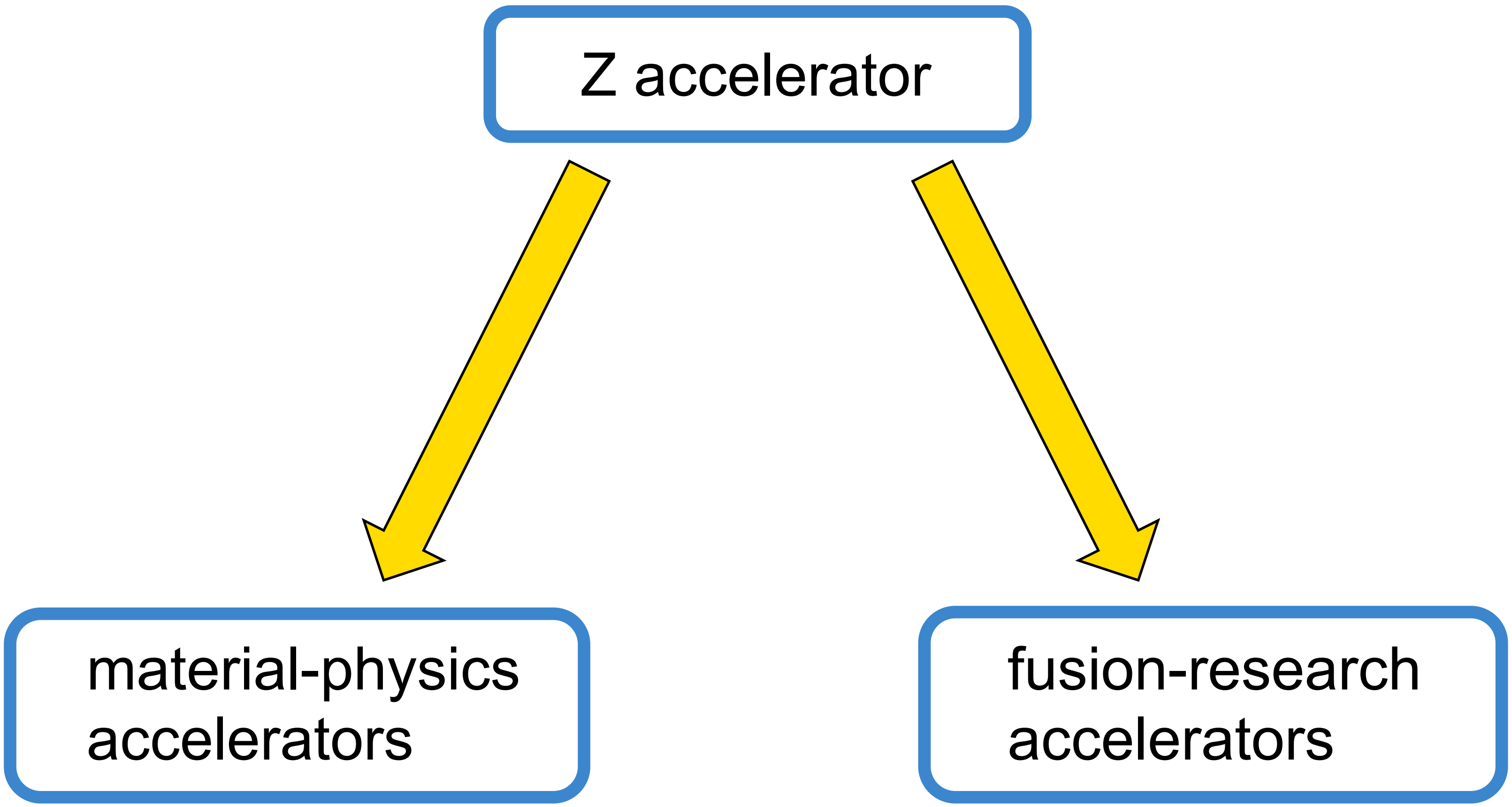
- Vacuum transmission lines (MITLs) deliver current to the load, so a containment system designed for hazardous materials must be open at t = 0.
    - It would be safer to have a containment system that is always closed.

Z accelerator



Instead of building one next-generation machine that tries to do everything, we propose to build two classes of machines.

- One will be optimized for material-physics experiments.
- The other, thermonuclear-fusion research.
- We are proposing a branch in the evolution of megampere-class accelerators.



We propose the following requirements for machines that are optimized for material-physics research.

- Pulse compression: From DC-charged capacitors to the requisite pulse in a single step.
- Impedance profile: Impedance matched throughout.
- Magnetic pressures: In excess of one megabar.
- Containment system: Passive, one that is closed at t = 0 and does not use explosives.
- Size of the containment system: The system should fit within a standard disposable container.
- Pulse shaping: The accelerators should be arbitrary waveform generators.
  - The machines should be designed to generate an arbitrary current-pulse shape at the load, and achieve a target shape with an accuracy better than 1%.
- Accelerator simulations: The accelerator designs should be simple enough to enable accurate simulations of a shot.
- Accelerator lifetime: The accelerators should use robust long-lifetime components.
- Engineered safety: The accelerators should not use potentially lethal energy-storage capacitors, SF_6 or any other asphyxiant or greenhouse gas, high-power lasers, or materials that include lead or other neurotoxins.

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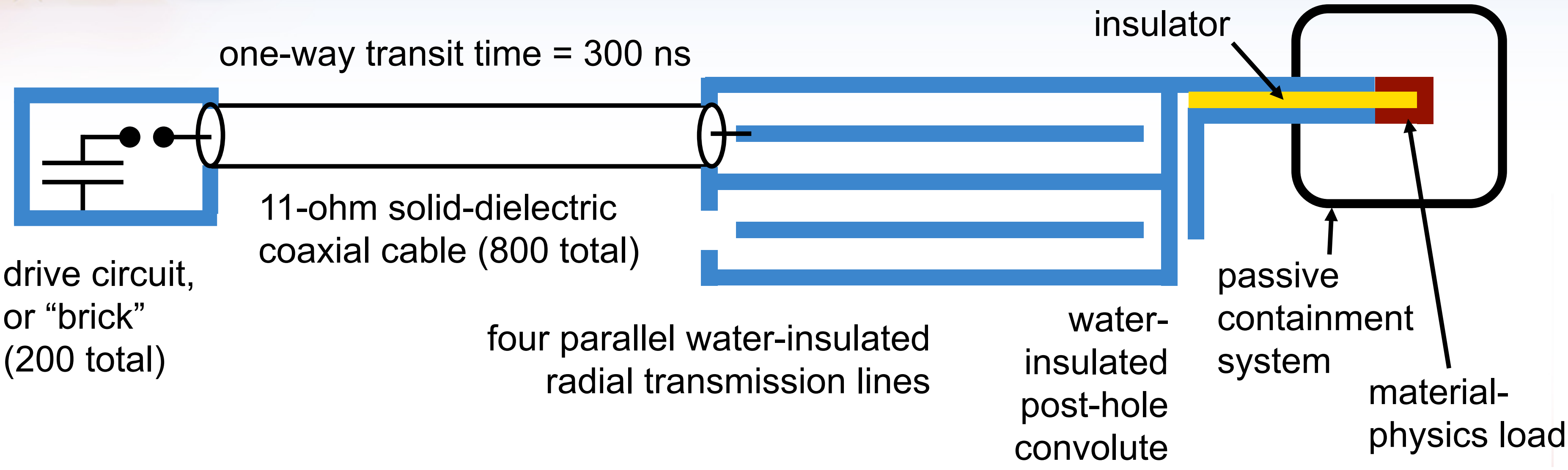
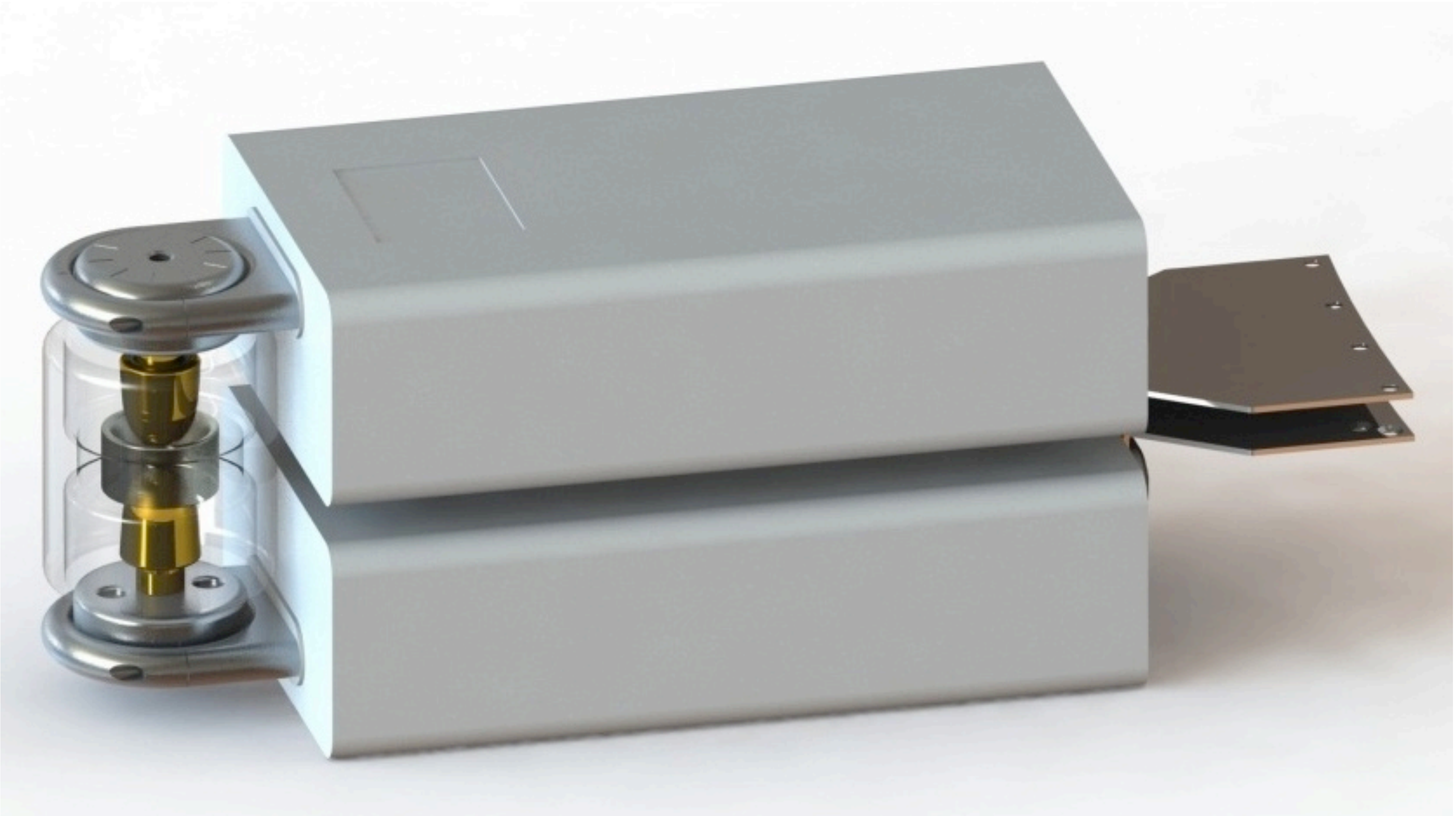
We have developed a conceptual design of Thor.

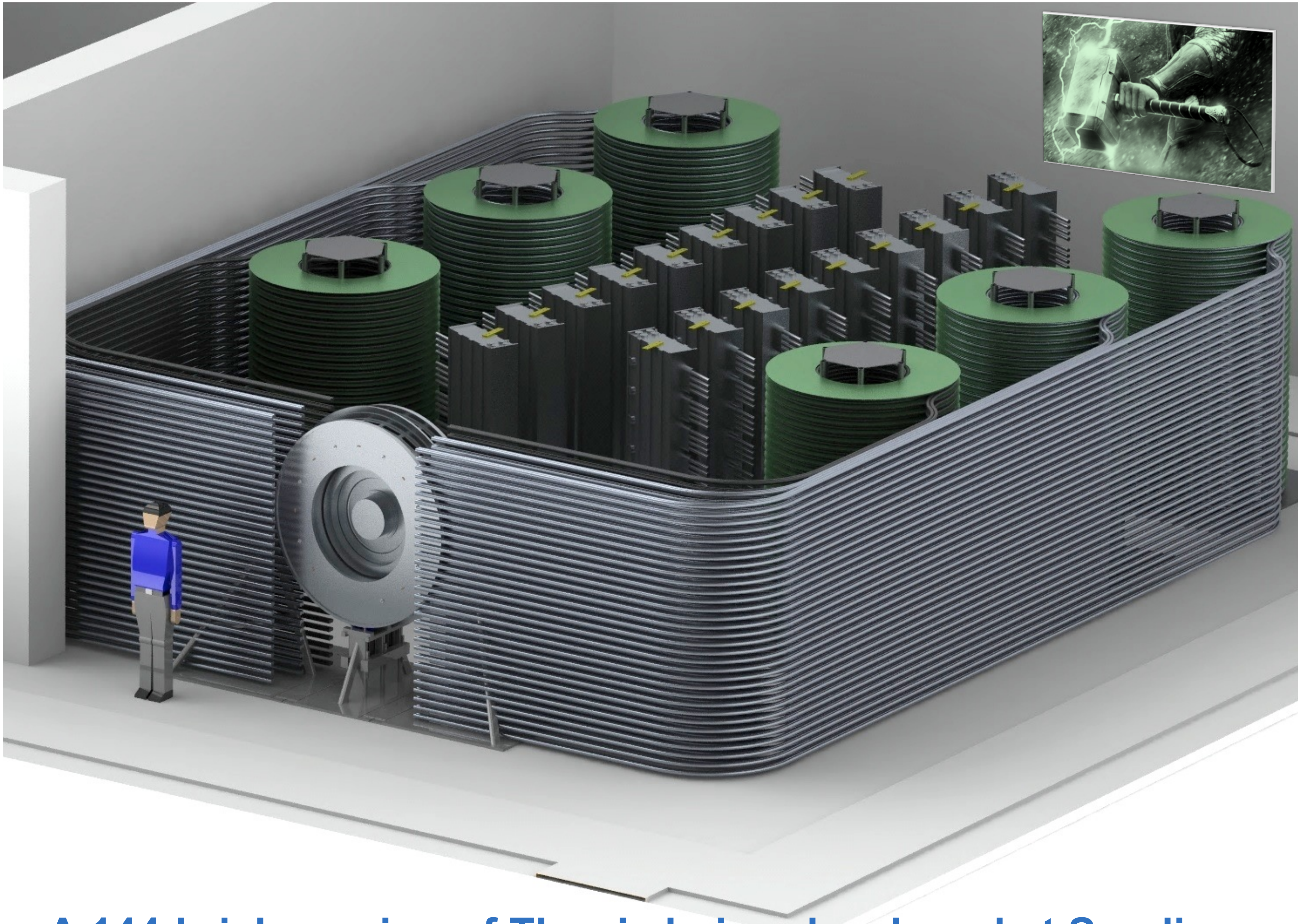


- Each of Thor’s 200 drive circuits is a single “brick”.
  - Each brick consists of two 80-nF capacitors in series with a 200-kV gas switch.
- Thor stores 160 kJ and generates 1 TW of peak electrical power.
- Thor uses single-stage electrical-pulse compression and is impedance matched throughout.
- The 200 switches are transit-time isolated from each other by 300-ns-long coaxial cables. Hence the current pulse at the load is a simple linear combination of 200 pulses.
- Thor does not use an explosive-driven containment system, potentially lethal energy-storage capacitors, SF_6 or any other asphyxiant or greenhouse gas, high-power lasers, or materials that include lead or other neurotoxins.

Each Thor brick stores 800 J and generates a peak electrical power of 5 GW.

Woodworth et al., PRSTAB (2009).
Woodworth et al., PRSTAB (2010).
Gruner et al., IEEE PPC (2013).
Wisher, Stoltzfus, and colleagues (manuscript in preparation).





A 144-brick version of Thor is being developed at Sandia.

We have developed an idealized circuit model of Thor.

- The circuit assumes Thor is driven by 200 bricks.
- Each brick drives four 11-ohm 300-ns coaxial cables.
- The 800 cables are connected to a system of water-insulated radial transmission lines.
- The water lines include a constant-impedance section and a water convolute.
- The idealized circuit assumes the characteristic inductance of the material-physics load is 1.8 nH.

L_{brick} = 160 nH

C_{brick} = 40 nF

R_{brick} = 0.3 Ω

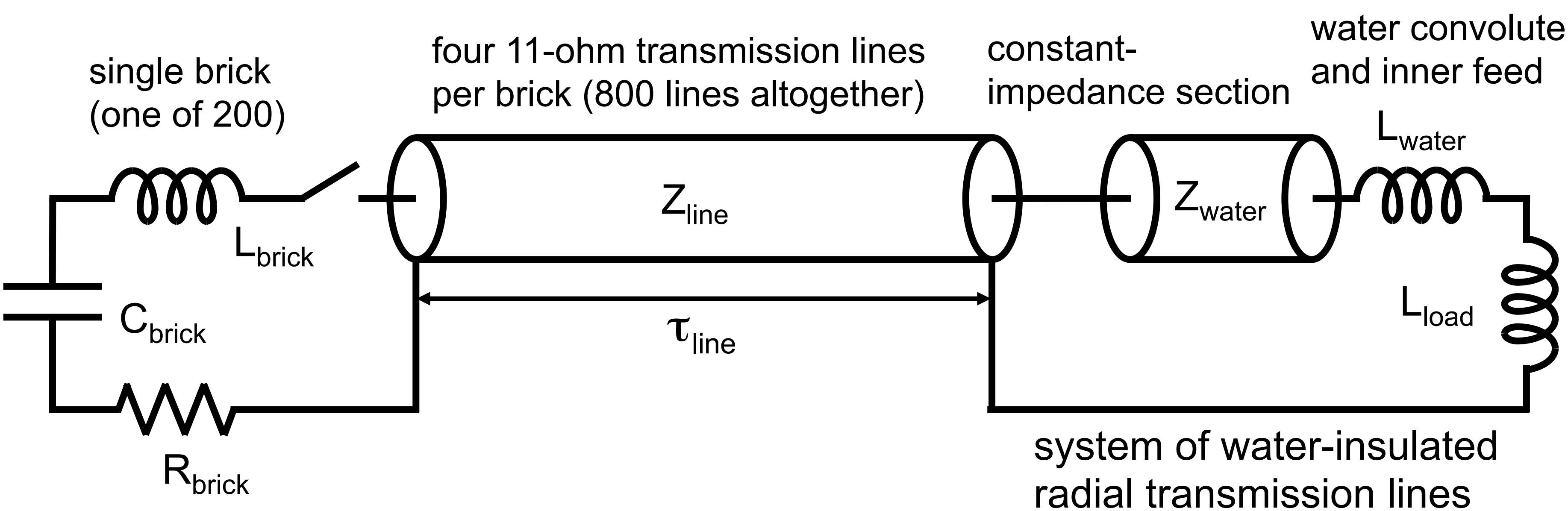
Z_{line} = 2.75 Ω

τ_{line} = 300 ns

Z_{water} = 0.01375 Ω

L_{water} = 1.1 nH

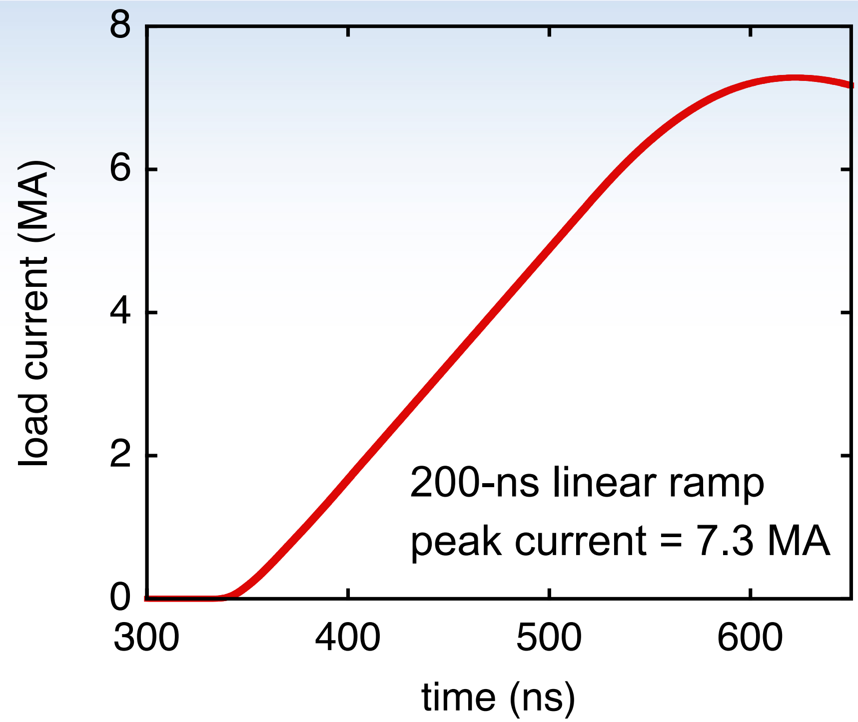
L_{load} = 1.8 nH

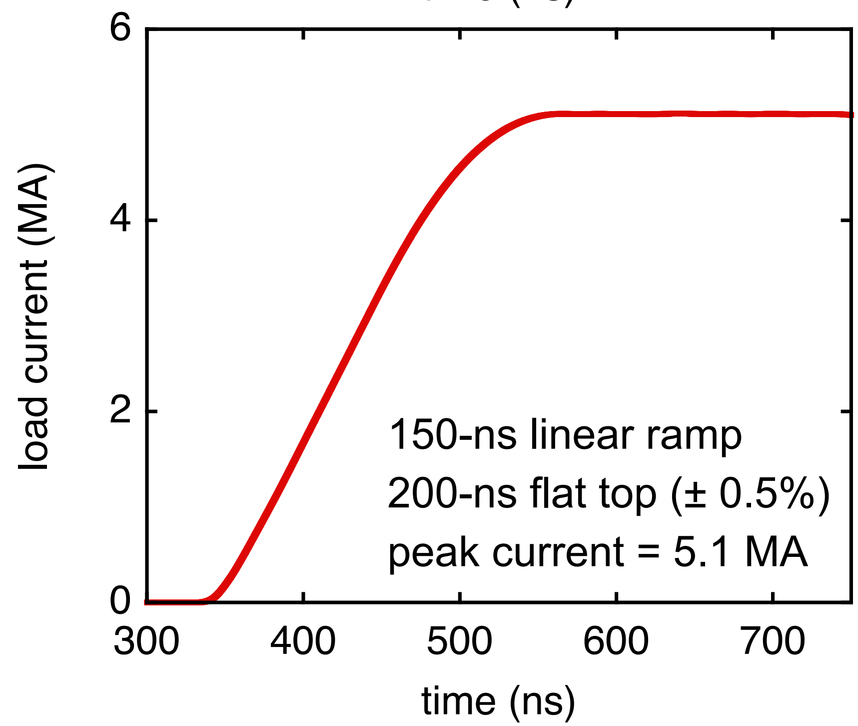


Thor can achieve a wide variety of current-pulse shapes.

Two examples are illustrated here.

- Thor can achieve a 200-ns linear ramp that peaks at 7.3 MA.
  - The magnetic pressure achieved across a 1.4-cm-wide conductor is 1.7 megabar.
- Thor can also achieve a 150-ns linear ramp followed by a 5.1-MA top that is flat to ± 0.5% over 200 ns.
  - The magnetic pressure achieved across a 1.4-cm-wide conductor is 0.8 megabar.





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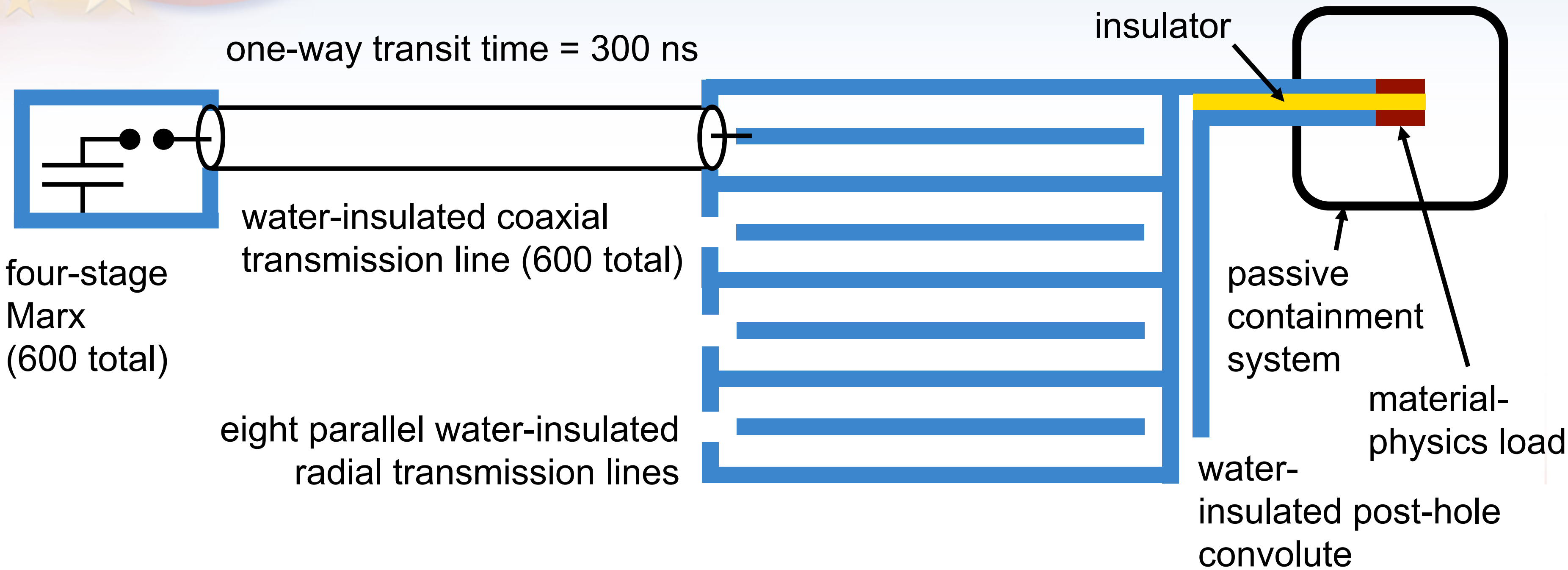
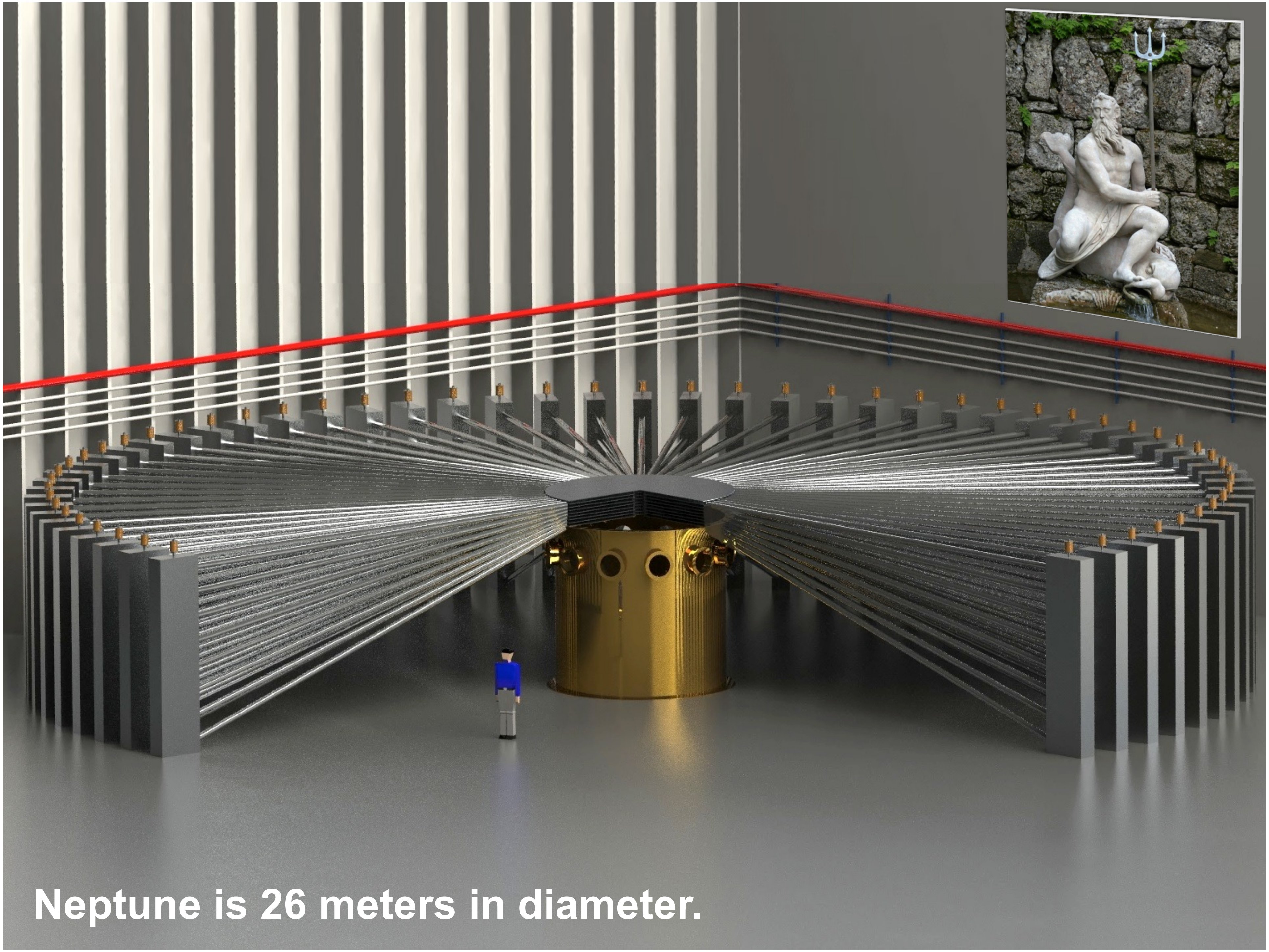
We have developed a conceptual design of Neptune.



- Neptune is driven by 600 fast impedance-matched Marx generators.
- Each Marx consists of four bricks connected in series.
- Neptune stores 2.4 MJ and generates 14 TW of peak electrical power.
- Neptune uses single-stage pulse compression and is impedance matched throughout.
- The 600 Marxes are transit-time isolated from each other by 300-ns-long transmission lines. Hence the current pulse at the load is a simple linear combination of 600 pulses.
- Neptune does not use an explosive-driven containment system, potentially lethal energy-storage capacitors, SF_6 or any other asphyxiant or greenhouse gas, high-power lasers, or materials that include lead or other neurotoxins.


Neptune is 26 meters in diameter.

We have developed an idealized circuit model of Neptune.

- The circuit assumes Neptune is driven by 600 Marxes.
- Each Marx drives a 10-Ω water-insulated 300-ns coaxial transmission line.
- The 600 lines are connected to a system of water-insulated radial transmission lines.
- The water lines include a constant-impedance section and a water convolute.
- The idealized circuit assumes the characteristic inductance of the material-physics load is 1.8 nH.

L_{Marx} = 640 nH

C_{Marx} = 12.5 nF

R_{Marx} = 1.2 Ω

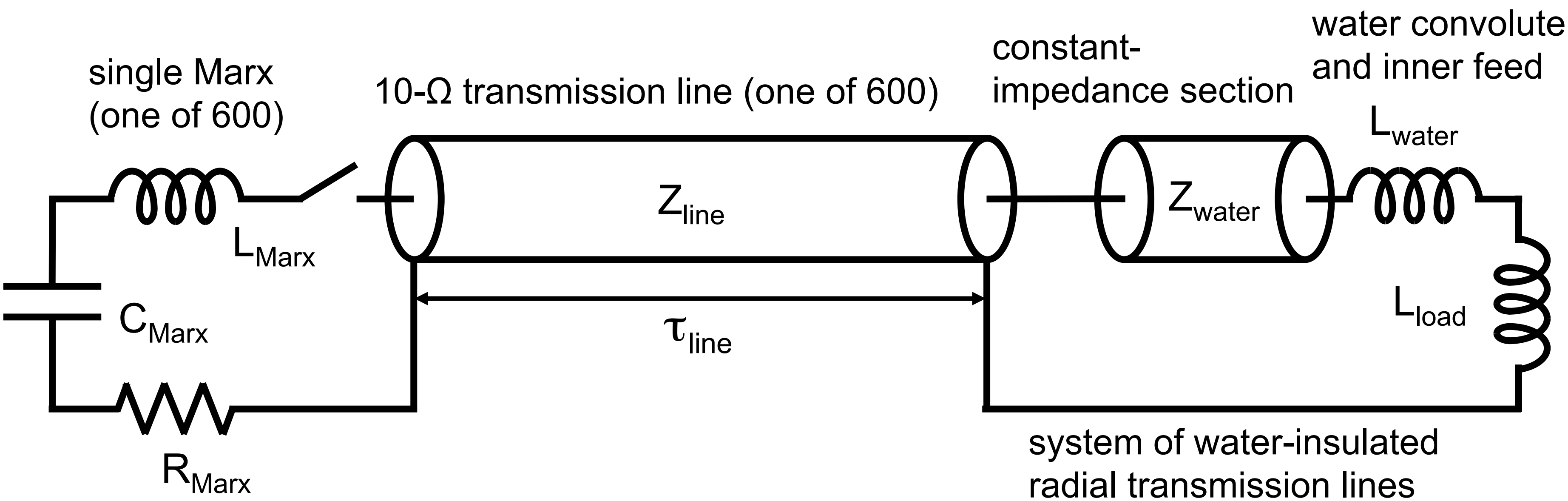
Z_{line} = 10 Ω

τ_{line} = 300 ns

Z_{water} = 0.0167 Ω

L_{water} = 2.2 nH

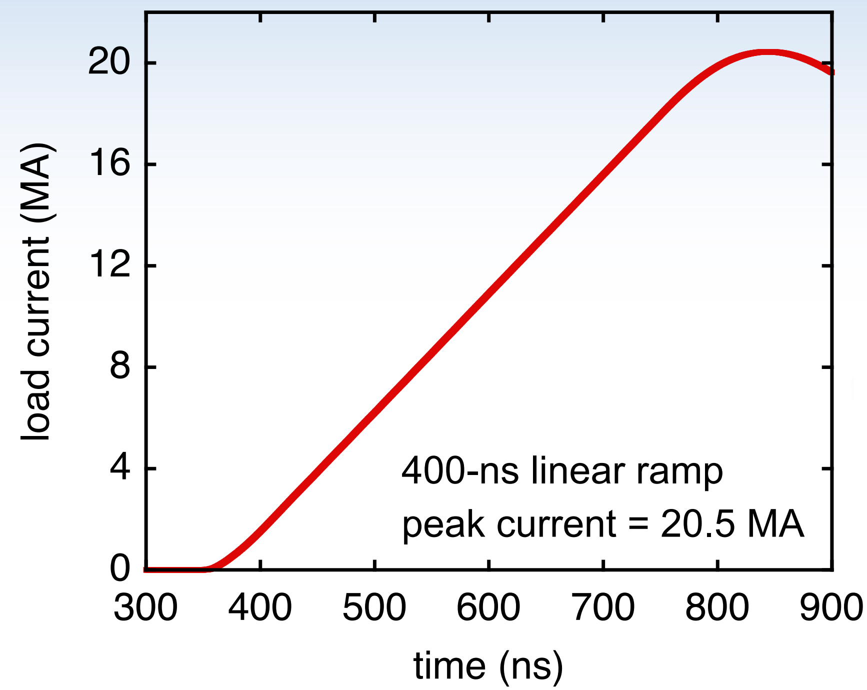
L_{load} = 1.8 nH

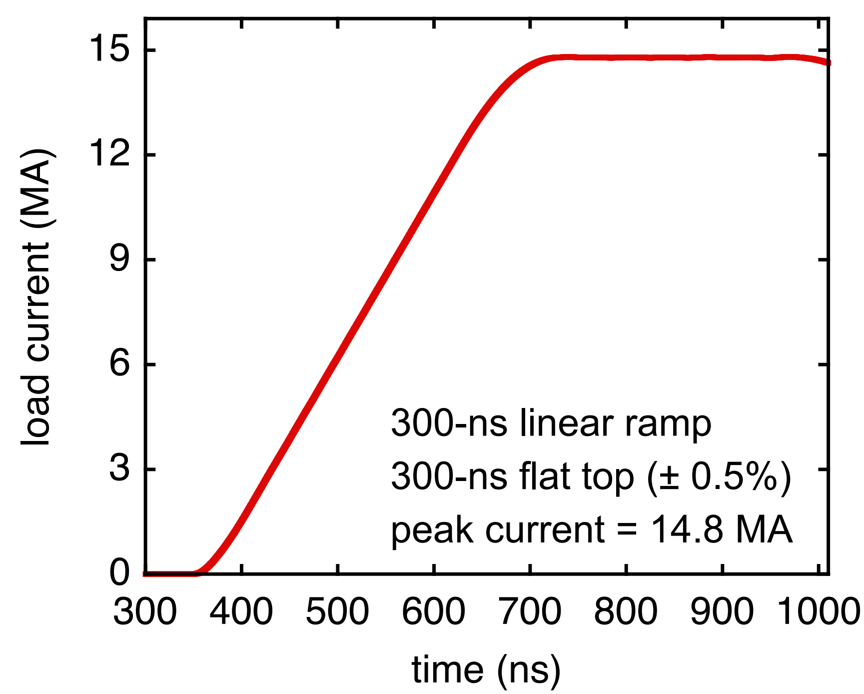


Neptune can achieve a wide variety of current-pulse shapes.

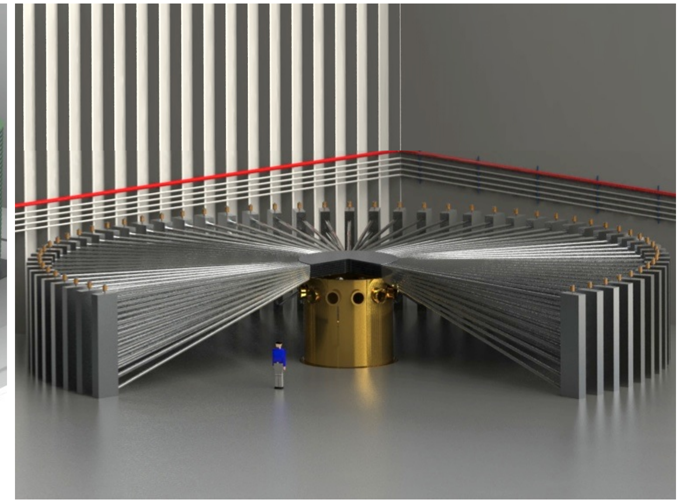
Two examples are illustrated here.

- Neptune can achieve a 400-ns linear ramp that peaks at 20.5 MA.
    - The magnetic pressure achieved across a 1.4-cm-wide conductor is 13 megabar.
- Neptune can also achieve a 300-ns linear ramp followed by a 14.8-MA-top that is flat to ± 0.5% over 300 ns.
    - The magnetic pressure achieved across a 1.4-cm-wide conductor is 7 megabar.





Both machines will enable interesting material-physics experiments.



parameter	Thor	Neptune
number of drive circuits	200 bricks	600 four-brick Marxes
stored energy	160 kJ	2.4 MJ
peak electrical power	1 TW	14 TW
peak load current	7 MA (200-ns rise)	20 MA (400-ns rise)
peak magnetic pressure across a 1.4-cm-wide conductor	**1.7 megabar**	**13 megabar**

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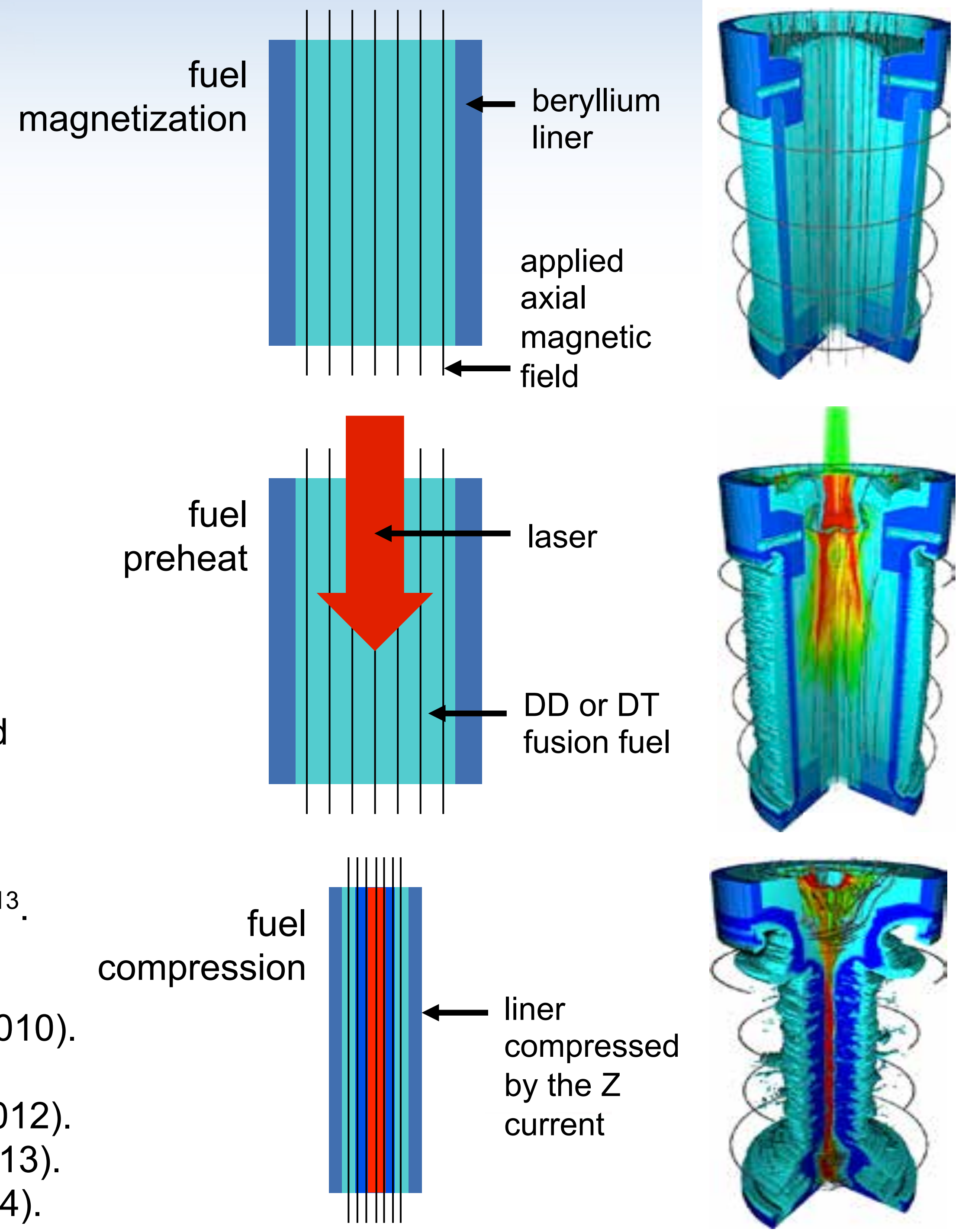
Sandia is conducting magnetized-liner-fusion (MagLIF) experiments on the Z machine.

- A beryllium liner contains DD or DT fusion fuel.
- The fuel is magnetized by an applied axial magnetic field.
- The fuel is preheated by a laser.
- The fuel is subsequently compressed by the Z-accelerator current.
- To date, the MagLIF concept has achieved DD neutron yields ~ 2×10^{13}.



Slutz, Herrmann, et al. Phys. Plasmas (2010).
Slutz and Vesey, Phys. Rev. Lett. (2012).
McBride, Slutz, et al., Phys. Rev. Lett. (2012).
Awe, McBride, et al., Phys. Rev. Lett. (2013).
Sefkow, Slutz, et al., Phys. Plasmas (2014).

There is a need for accelerators that achieve thermonuclear ignition and high-yield fusion.

- The U.S. conducted its last underground nuclear test 23 years ago (in 1992).
- Since then, the U.S. has not conducted thermonuclear-ignition or high-yield experiments, nor any weapon-effects testing.
- There will soon be no full-time scientists with direct experimental ignition or high-yield experience.
- It's clear the U.S. needs a thermonuclear-burn facility.

The second U.S. underground nuclear test was a 1-kiloton explosion detonated 20 m underground (1955).

Preparation for an underground test at the Nevada Test Site in the 1990s.

We propose that next-generation accelerators be developed that are optimized for thermonuclear-fusion research.

- Pulse compression: From DC charged capacitors to the requisite pulse in a single step.
- Impedance profile: Impedance matched throughout.
- The first such accelerator should be optimized to achieve thermonuclear ignition:
  - The fusion energy generated by this accelerator should exceed the electrical energy delivered to the accelerator's load.
- The subsequent accelerator should be optimized to achieve high-yield fusion:
  - The fusion energy generated by this accelerator should exceed the electrical energy stored by the accelerator's system of capacitors.
- Accelerator simulations: The accelerator designs should be simple enough to enable accurate circuit simulations of a shot.
- Accelerator lifetime: The accelerators should use robust long-lifetime components.
- Engineered safety: The accelerators should not use potentially lethal energy-storage capacitors, SF_6 or any other asphyxiant or greenhouse gas, high-power lasers, or materials that include lead or other neurotoxins.

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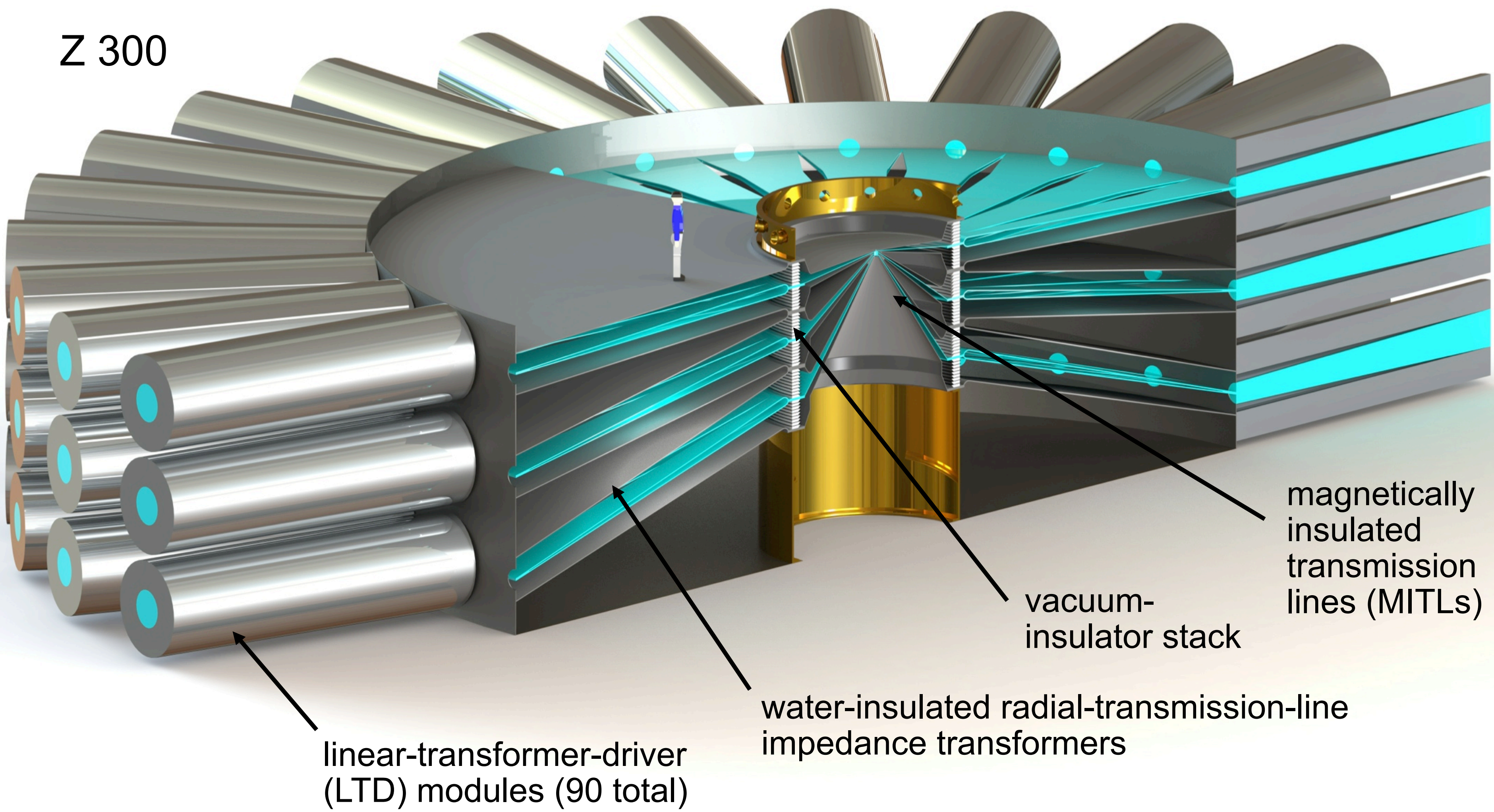
Z 300 will deliver 49 MA to a MagLIF load, and is expected to achieve thermonuclear ignition (i.e., a liner gain ~ 1).

P_{LTDs} = 320 TW
E_{LTDs} = 47 MJ

V_{stack} = 7.7 MV
L_{vacuum} = 15 nH

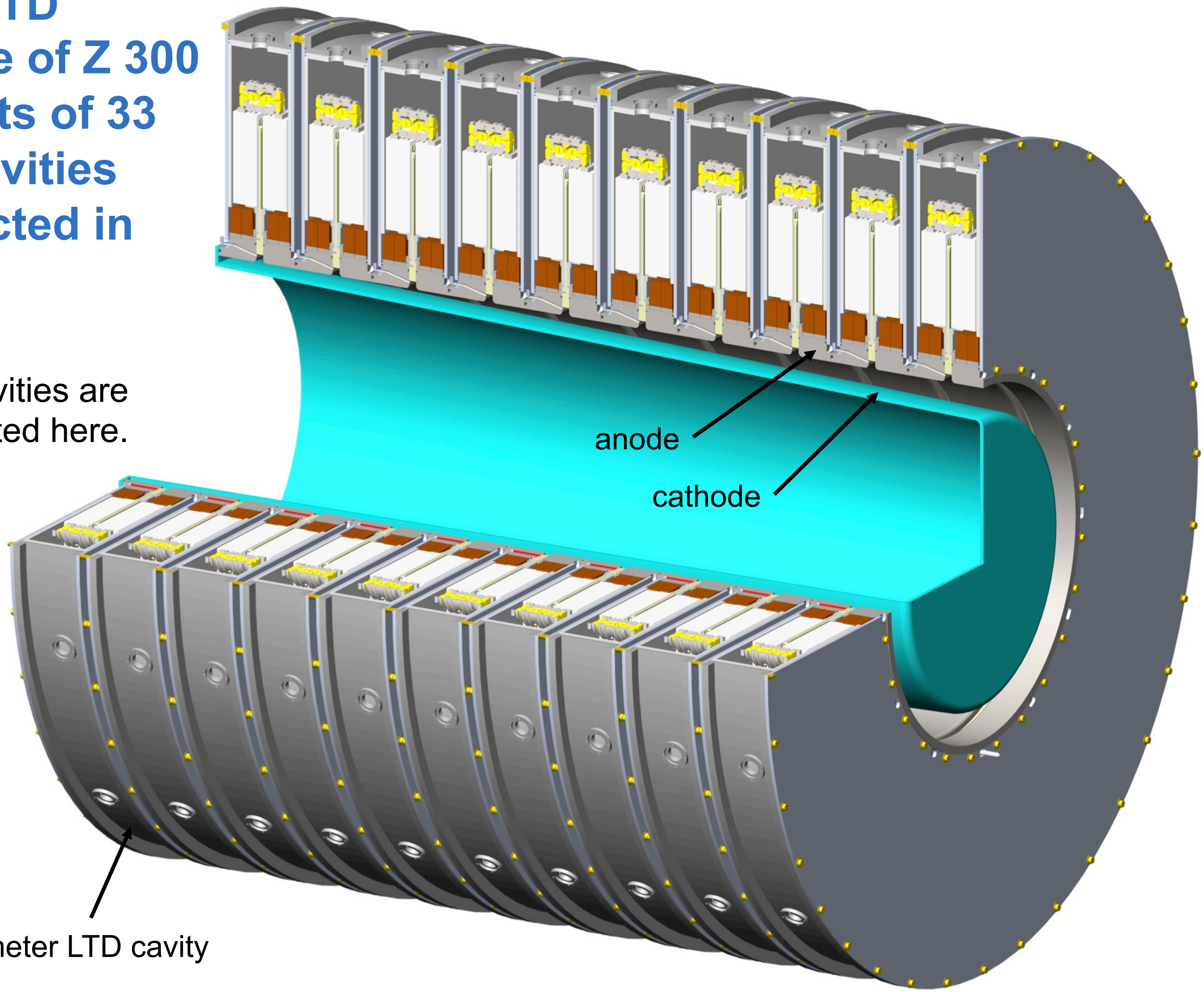
I_{load} = 49 MA
$\tau_{implosion}$ = 150 ns

diameter = 35 m
fusion yield ~ 5 MJ



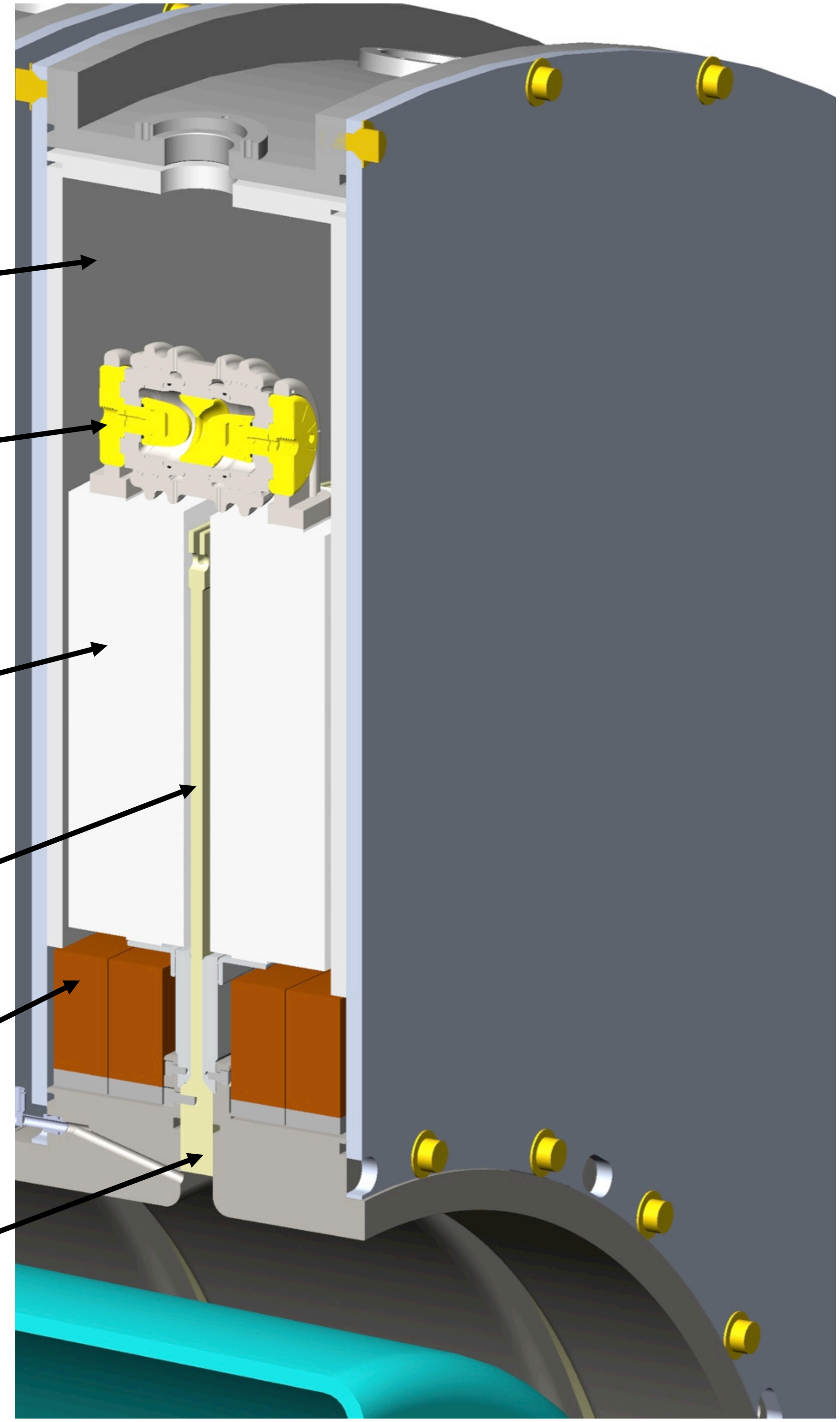
Each LTD module of Z 300 consists of 33 LTD cavities connected in series.

Ten cavities are illustrated here.



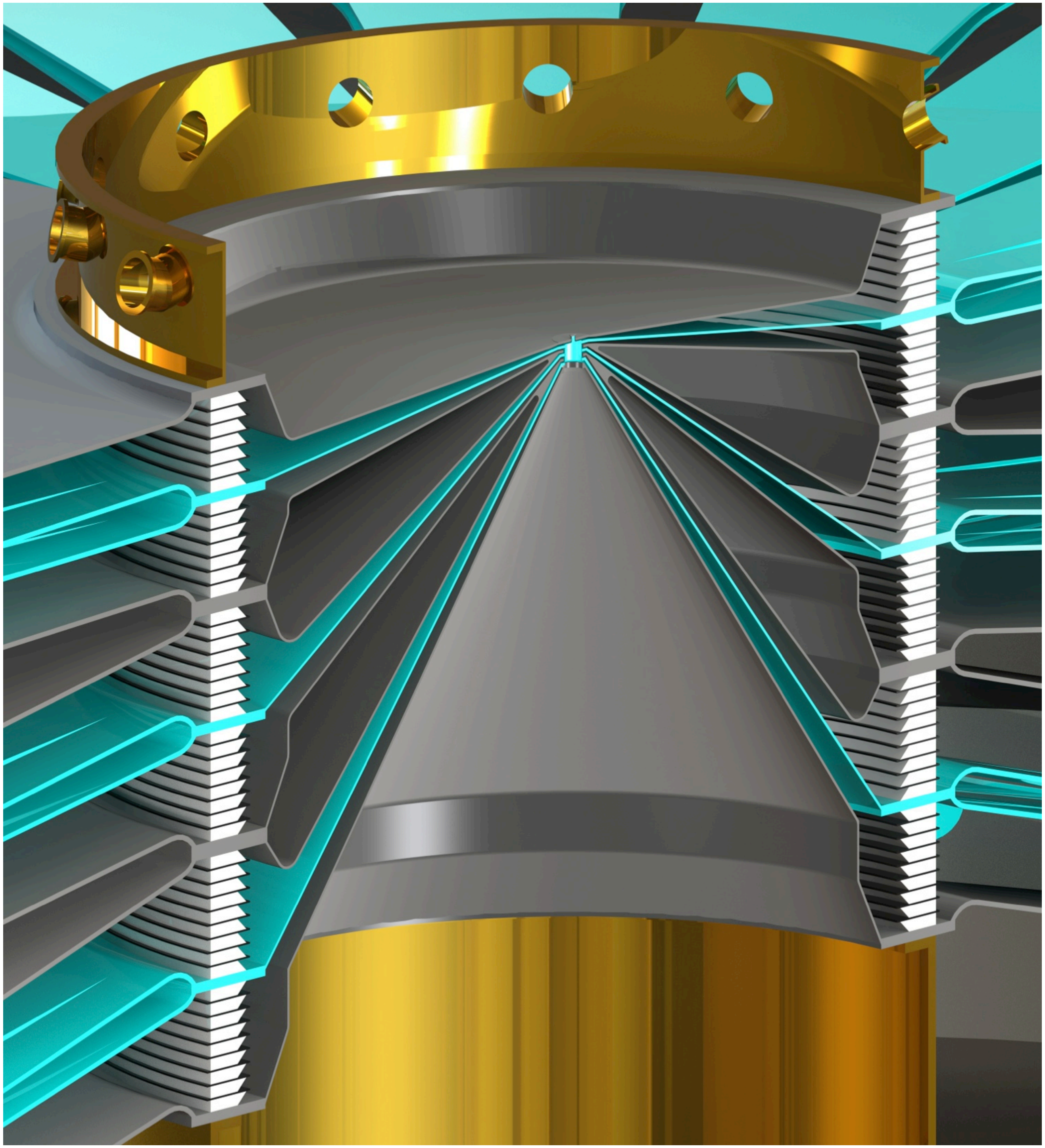
Each LTD cavity includes 20 LTD bricks.

- Each brick consists of two 80-nF capacitors in series with a 200-kV switch.
- Each brick is identical to the brick proposed for Thor.



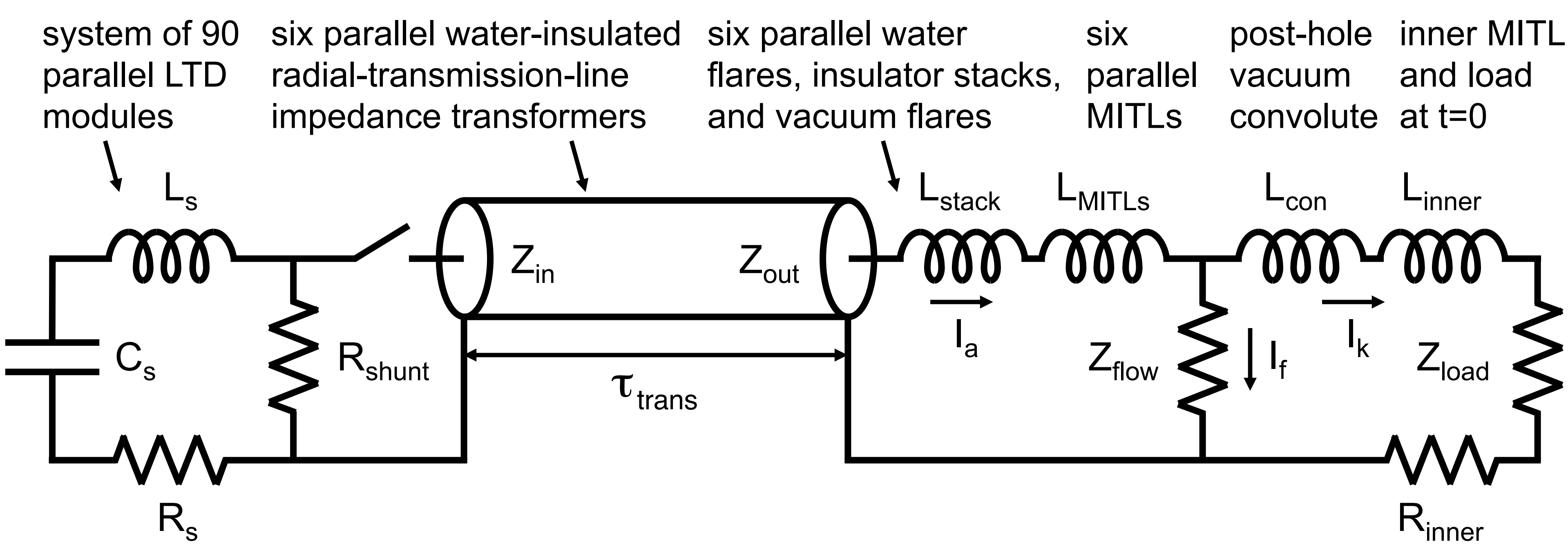
Z 300's water-insulated radial transmission-line impedance transformers drive a six-level center section.

- Six insulator stacks serve as the water-vacuum interface.
- Six magnetically insulated transmission lines (MITLs) are connected in parallel by a triple-post-hole convolute.
- A short single MITL connects the convolute to the load.



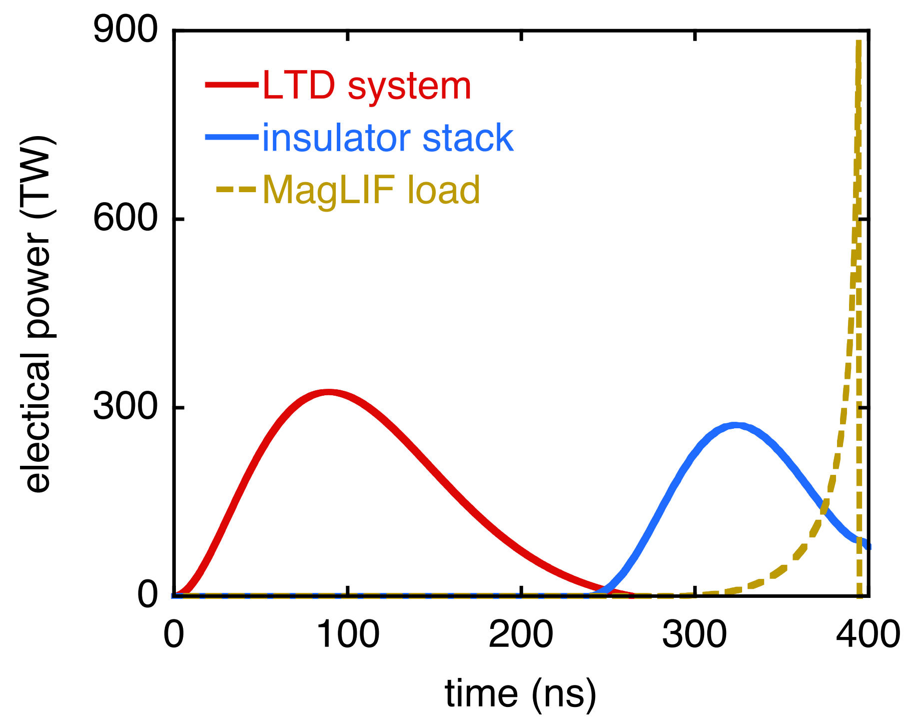
We have developed an idealized circuit model of Z 300.

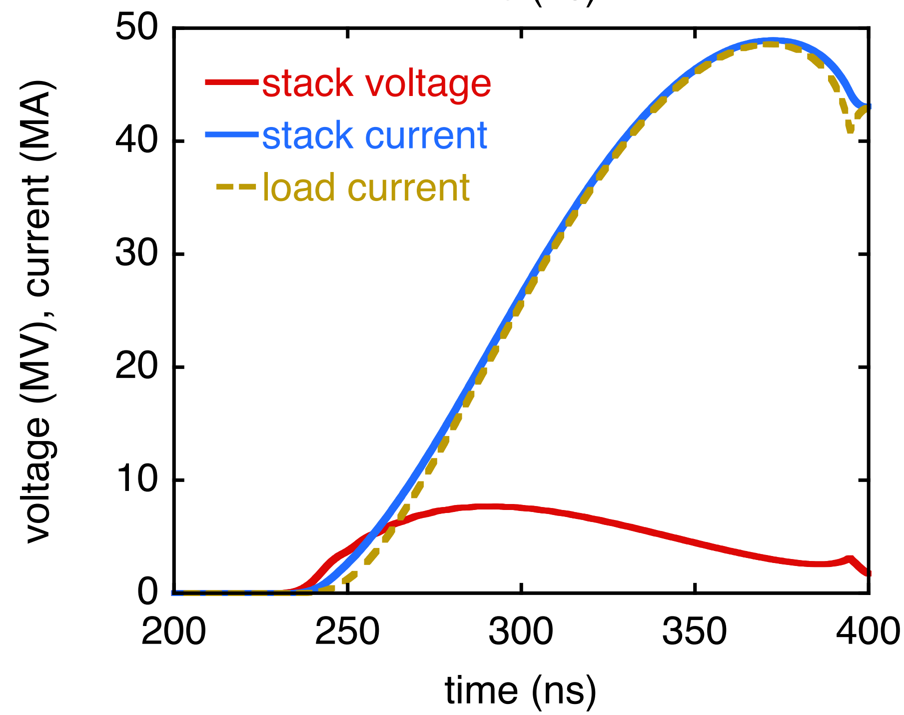
- Z 300 is powered by 90 33-cavity LTD modules.
- The LTD-module system drives radial transmission-line impedance transformers.
- The transformers, in turn, drive a centrally located vacuum section.
- The center section includes a six-level insulator stack, six-level system of magnetically insulated transmission lines (MITLs), a triple post-hole vacuum convolute, and the load.



Results of circuit simulations:

- Z-300's LTDs generate a peak electrical power of 320 TW.
- The peak power at the insulator stack is 270 TW.
- The peak power delivered to an idealized 0D MagLIF load is 900 TW.
- The peak load current is 49 MA.
- The electrical energy delivered to the load is 4.7 MJ.
- 2D magnetohydrodynamic simulations suggest the thermonuclear-fusion yield will be ~5 MJ.





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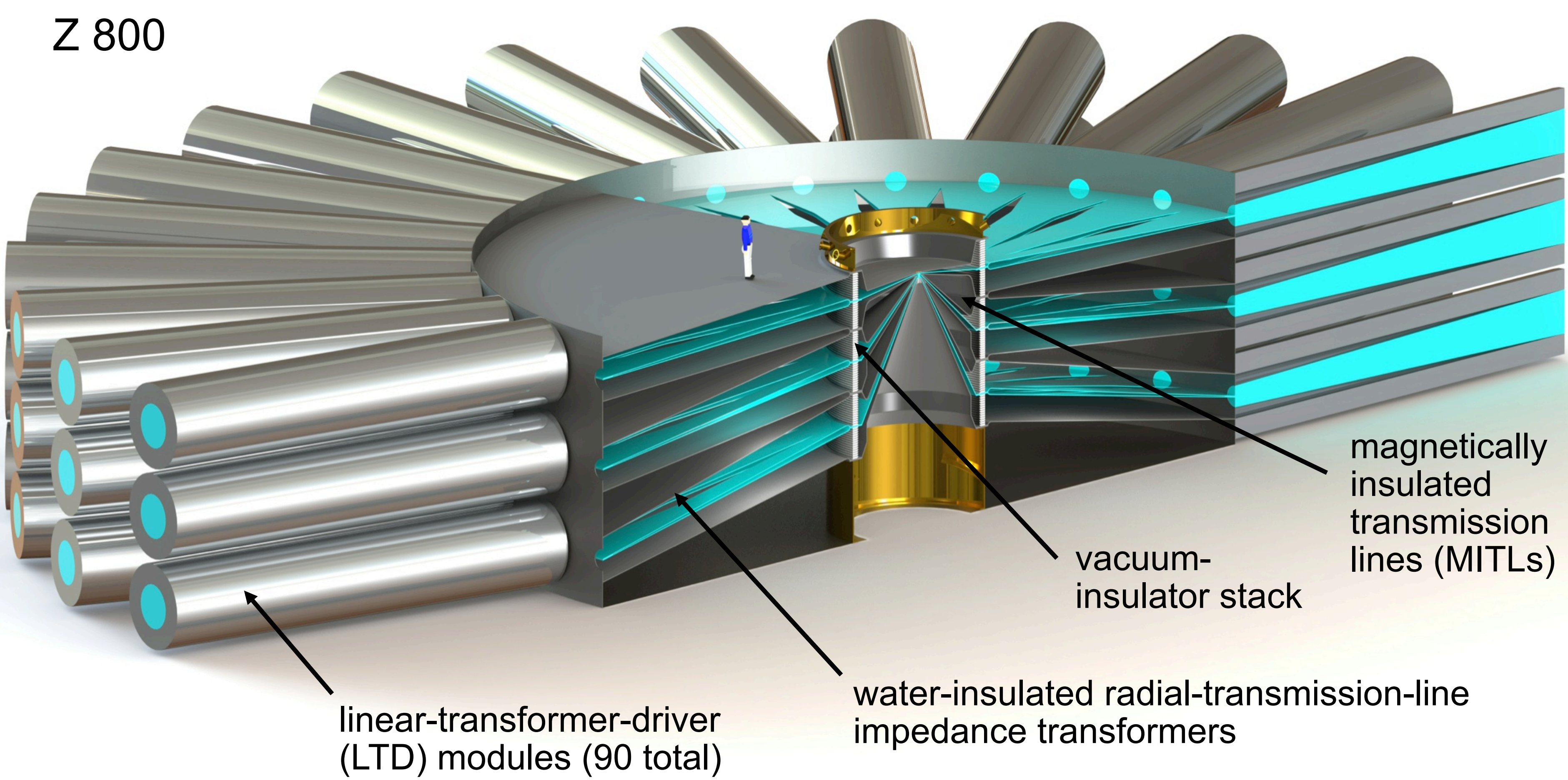
Z 800 will deliver 66 MA to a MagLIF load, and is expected to achieve machine breakeven.

P_{LTDs} = 890 TW
E_{LTDs} = 130 MJ

V_{stack} = 15 MV
L_{vacuum} = 20 nH

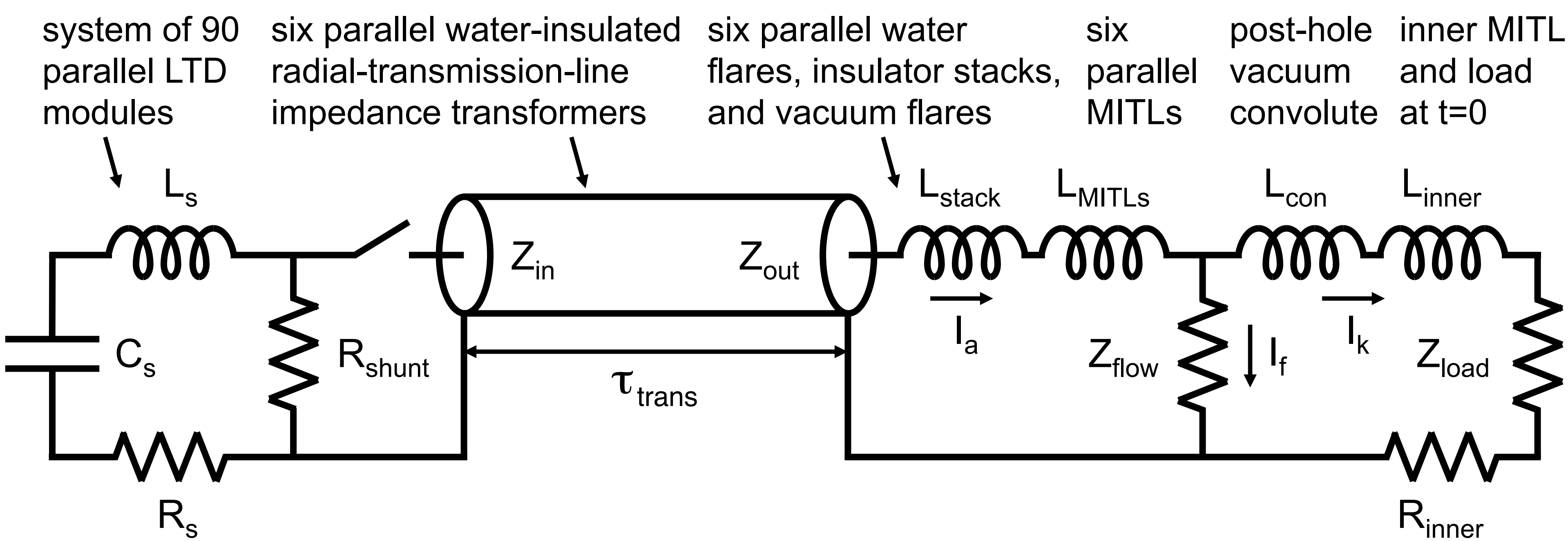
I_{load} = 66 MA
$\tau_{implosion}$ = 114 ns

diameter = 52 m
fusion yield ~ 500 MJ



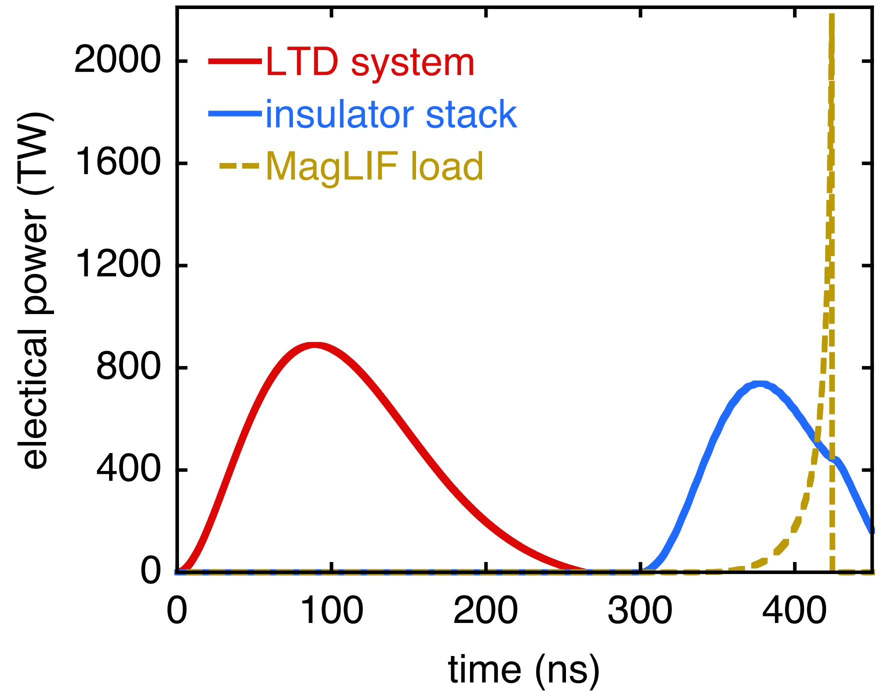
We have developed an idealized circuit model of Z 800.

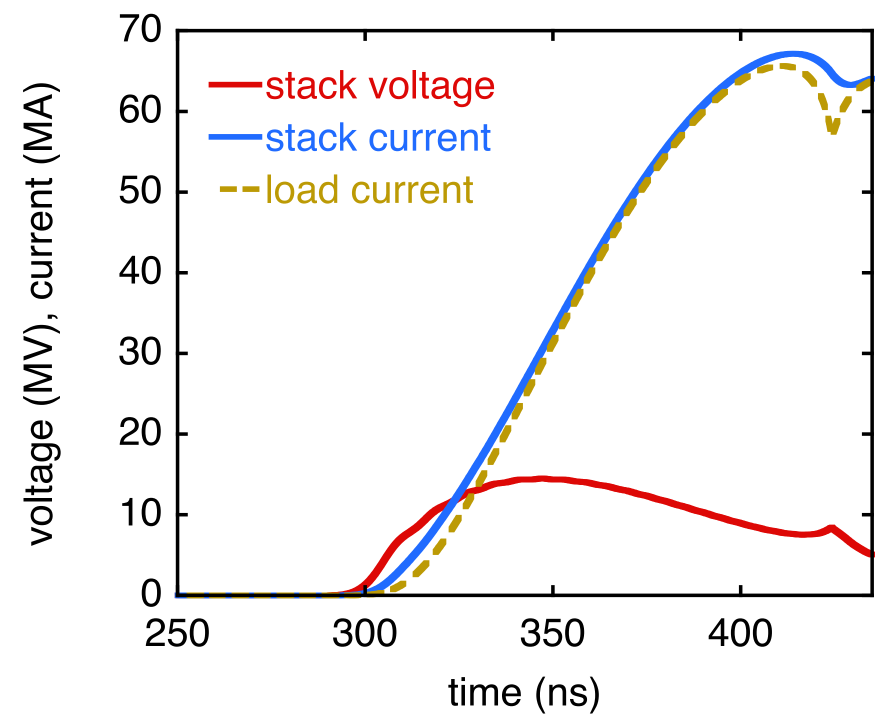
- Z 800 is powered by 90 60-cavity LTD modules.
- The LTD-module system drives radial transmission-line impedance transformers.
- The transformers, in turn, drive a centrally located vacuum section.
- The vacuum section includes a six-level insulator stack, six-level system of magnetically insulated transmission lines (MITLs), a triple post-hole vacuum convolute, and the load.



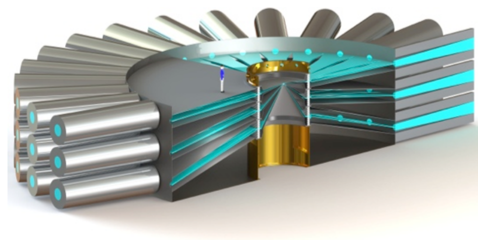
Results of circuit simulations:

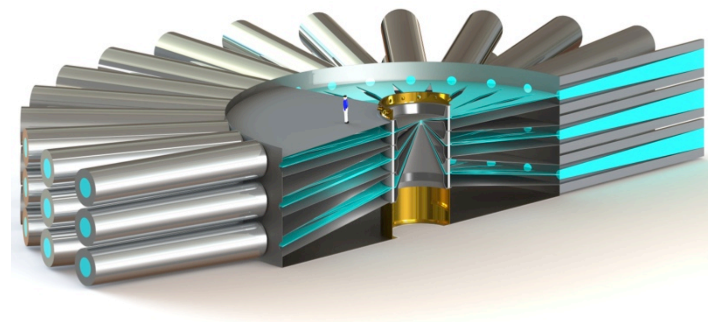
- Z-800’s LTDs generate a peak electrical power of 890 TW.
- The peak power at the insulator stack is 740 TW.
- The peak power delivered to an idealized 0D MagLIF load is 2200 TW.
- The peak load current is 66 MA.
- The electrical energy delivered to the load is 8.7 MJ.
- 2D magnetohydrodynamic simulations suggest the thermonuclear-fusion yield will be ~ 500 MJ.
- The fusion energy will exceed the electrical energy stored by Z-800’s system of capacitors (130 MJ).





Both machines will enable interesting fusion experiments.





parameter	Z 300	Z 800
accelerator diameter	35 m	52 m
stored energy	47 MJ	130 MJ
peak electrical power	320 TW	890 TW
peak load current	49 MA	66 MA
implosion time	150 ns	114 ns
energy delivered to the liner	4.7 MJ	8.7 MJ
DT-fusion yield (2D magnetohydrodynamic simulations)	**~ 5 MJ**	**~ 500 MJ**

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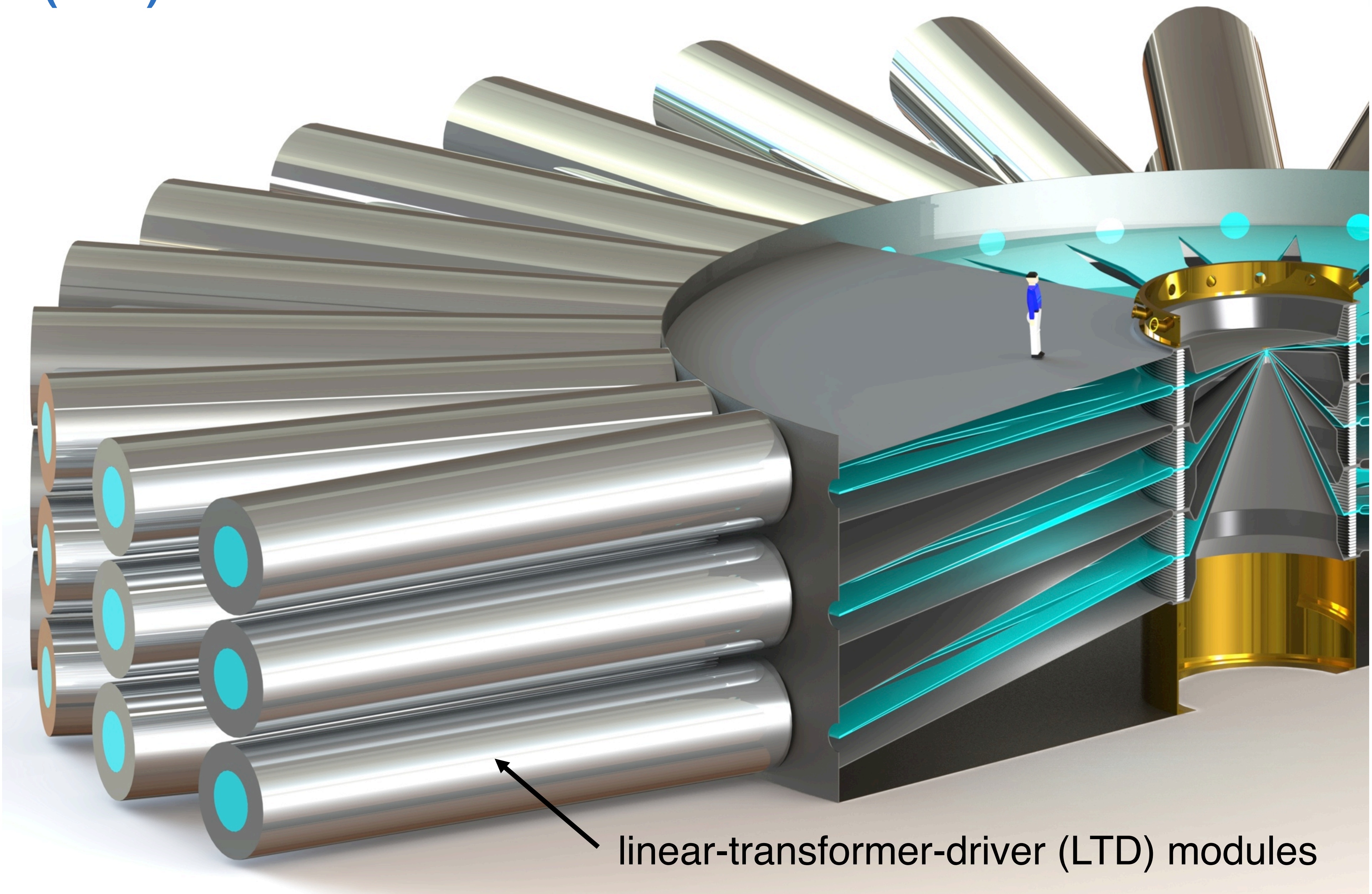
Z 300 and Z 800 are driven by linear-transformer-driver (LTD) modules.

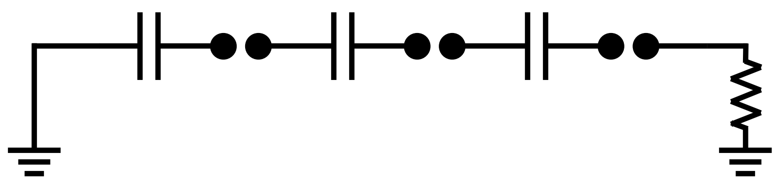


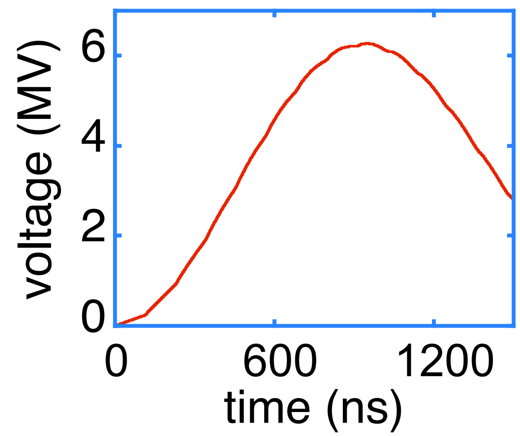
LTDs are the greatest advance in prime power generation since the invention of the Marx generator (1924).

A Marx generator and an LTD both charge capacitors in parallel and discharge them in series. A Marx does this as a large LC circuit:

Marx generator

$2\sqrt{LC} = 1000$ ns

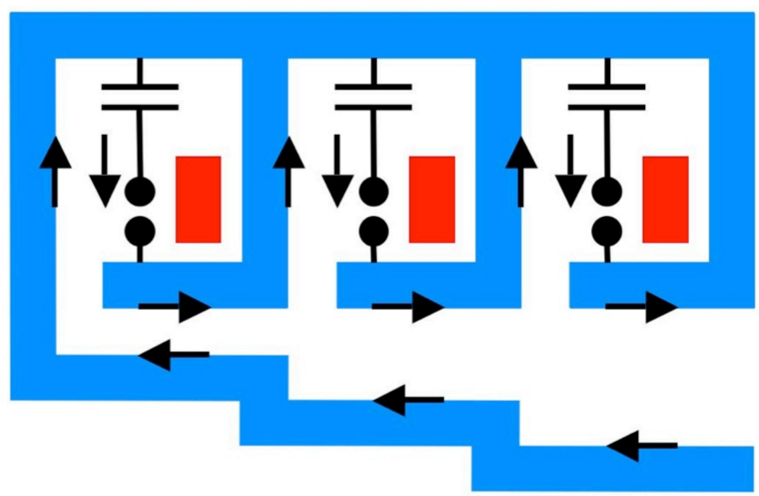


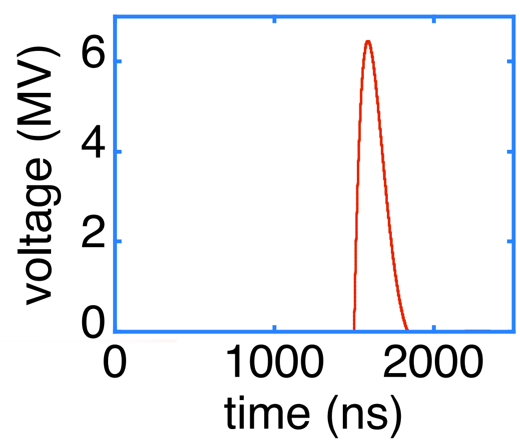


An LTD does this as an *induction voltage adder* (IVA), in which each of the adder's cavities is driven by LC circuits that are *contained within the cavity*:

3-cavity LTD module

$2\sqrt{LC} = 140$ ns





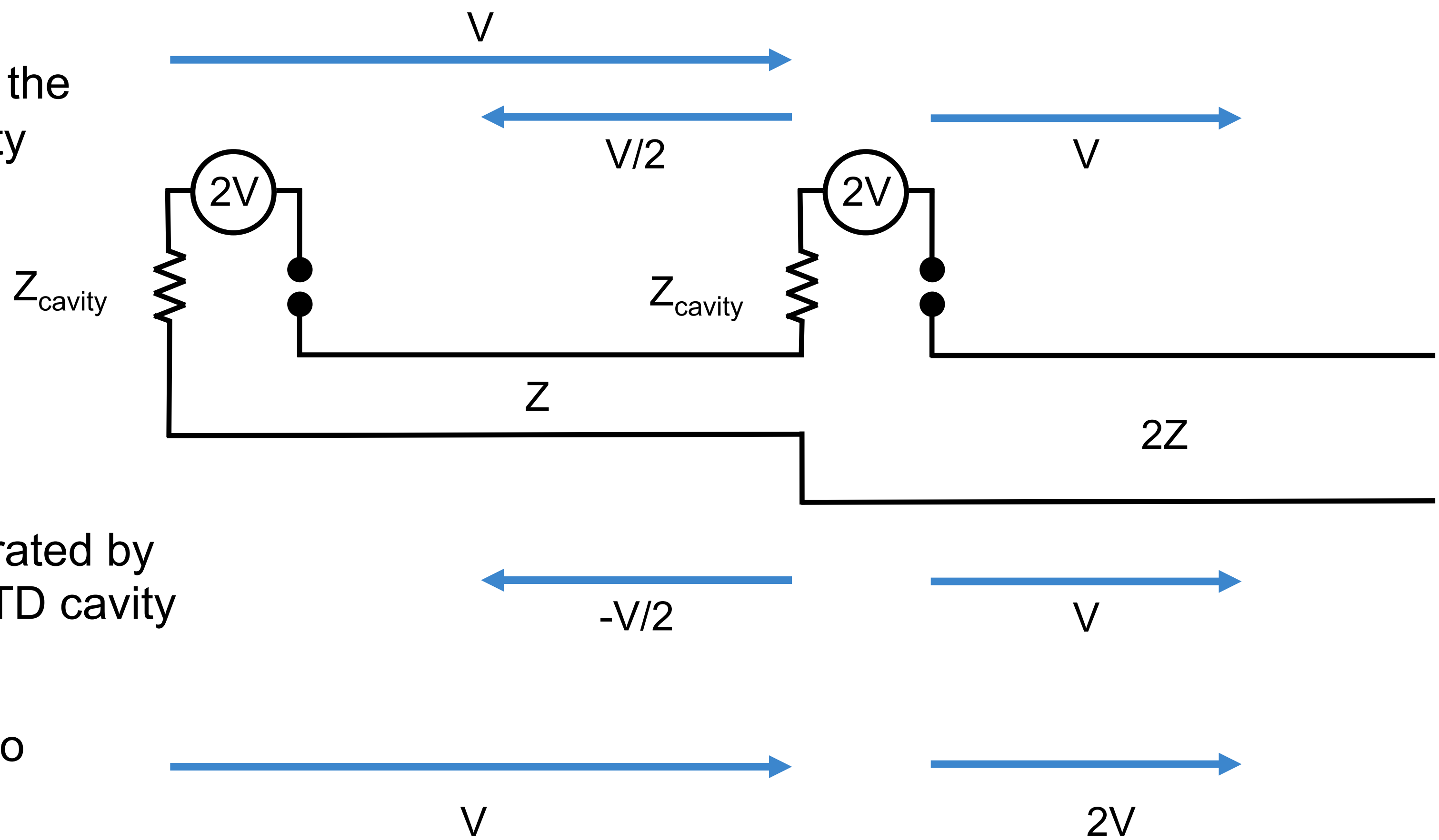
The backward waves launched in an LTD module cancel; the forward-going waves are all that are left.

When $Z_{cavity} = Z$, the voltage at the nth cavity of an LTD module is given by nV:

voltage generated by the first LTD cavity

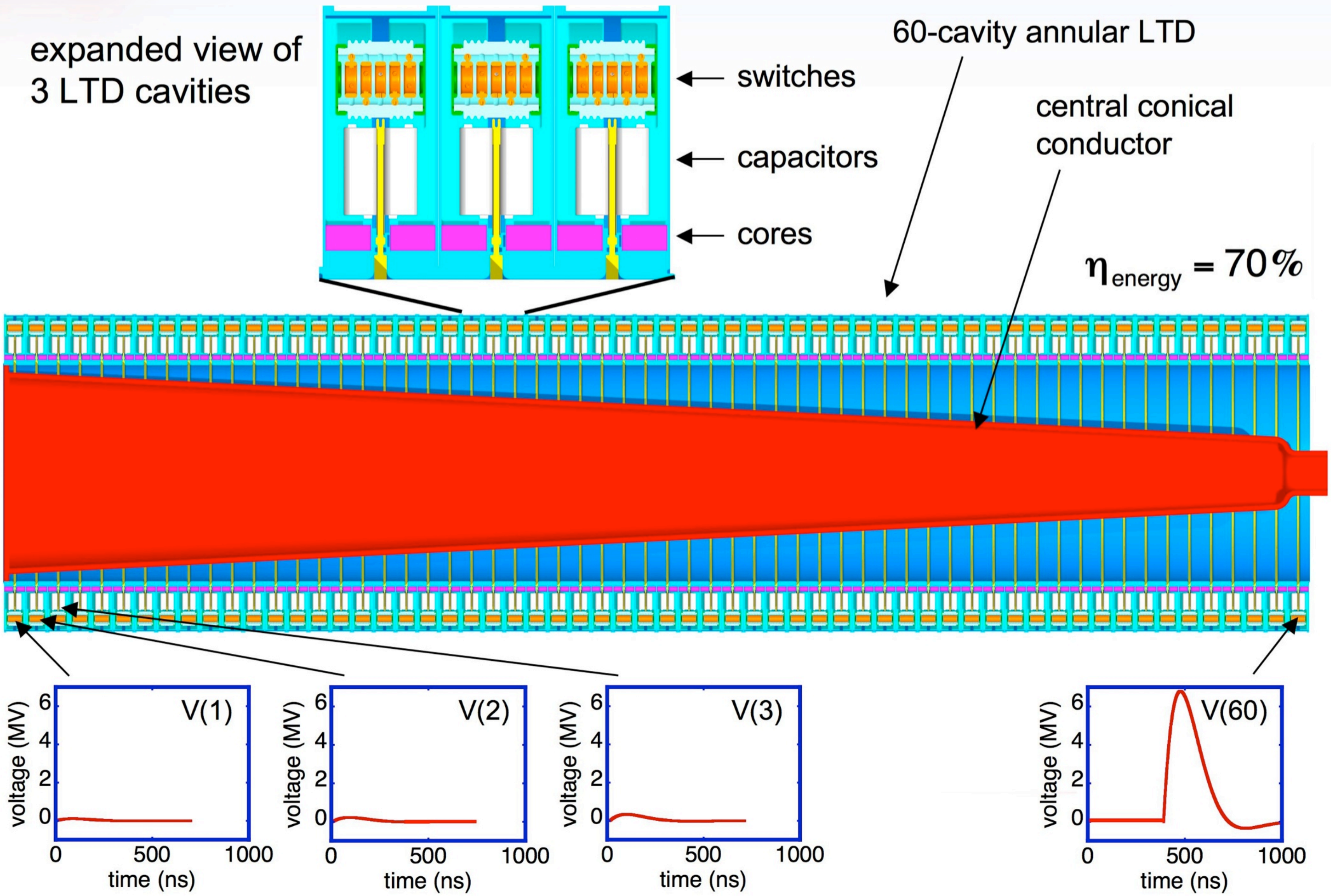
voltage generated by the second LTD cavity

sum of the two voltages



The backward waves cancel even when $Z_{cavity} \neq Z$.

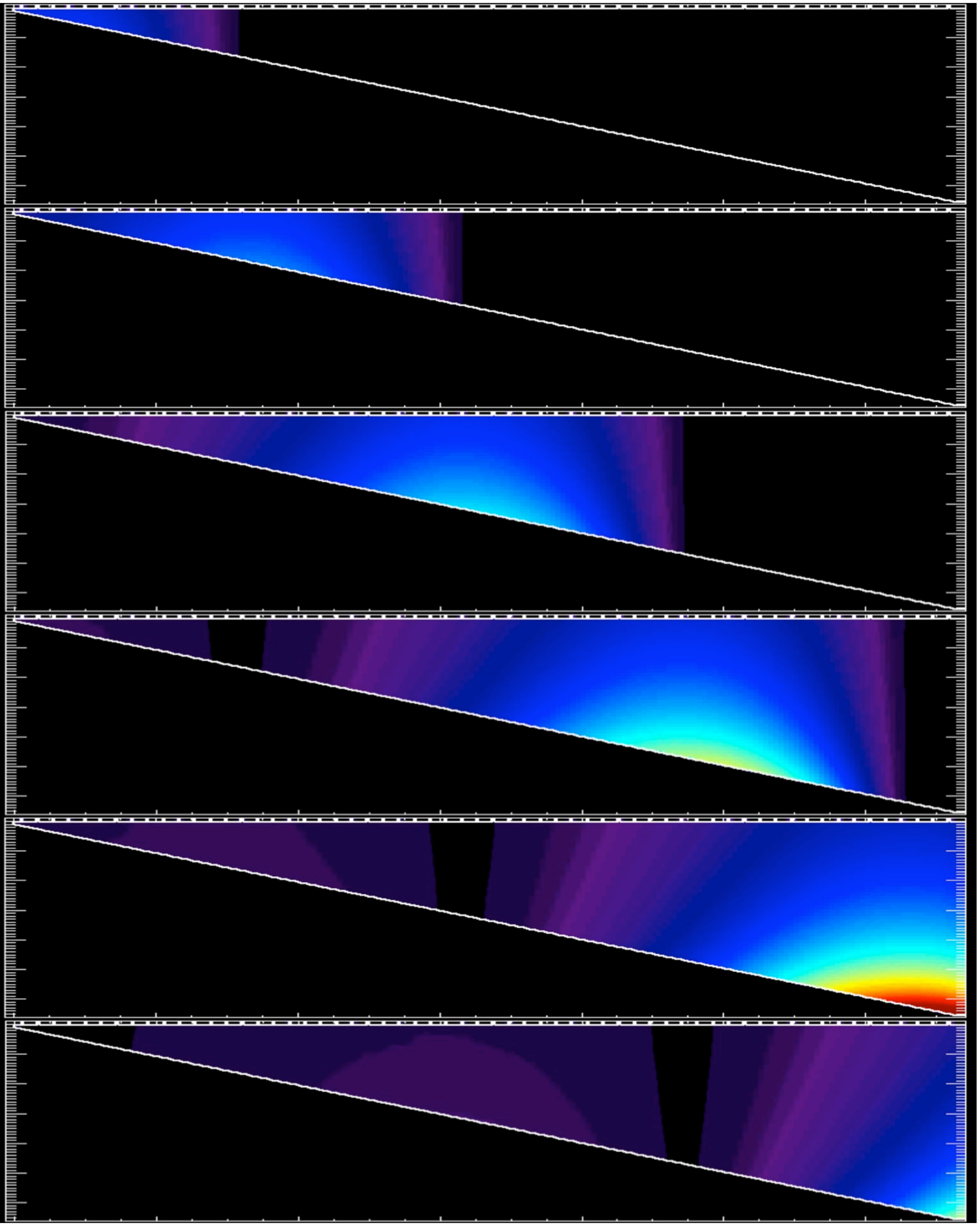
An LTD module is an electromagnetic analogue to a laser: Power amplification is achieved by *triggered* emission of radiation.



2D electromagnetic LSP simulations confirms that a 60-cavity LTD module generates a clean electrical-power pulse.

Calculations agree to within 1%:

- Analytic model: 6.49 TW.
- 1D circuit: 6.49 TW.
- 2D LSP simulation: 6.38 TW.



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Summary

- We propose to use a new architecture for the design of next-generation pulsed-power accelerators.
- The architecture is based on two concepts: single-stage electrical-pulse compression and impedance matching.
- We have applied the architecture to *conceptual* designs of two machines optimized for material-physics experiments:
  - Thor will deliver 7 MA to a load, and achieve magnetic pressures as high as 1.7 megabars (across a 1.4-cm-wide planar conductor).
  - Neptune will deliver 20 MA to a load, and achieve magnetic pressures as high as 13 megabars (across a 1.4-cm-wide conductor).
- We have also developed *conceptual* designs of two machines optimized for thermonuclear-fusion research:
  - Z 300 will deliver 49 MA to a MagLIF load, and is expected to achieve a fusion yield of 5 MJ. (The electrical energy delivered to the liner will be 4.7 MJ.)
  - Z 800 will deliver 66 MA to a load, and is expected to achieve a fusion yield of 500 MJ. (The electrical energy stored in the capacitors will be 130 MJ.)
- We are ready to begin developing *initial* designs of these four accelerators.