Sandia National Laboratories

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Conceptual designs of pulsed-power accelerators for inertial fusion energy (IFE)

The IFE Accelerator Team

A large collaboration is developing a pulsed-power accelerator for IFE.

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Presentation outline

- Scope of this presentation
- Present state of the art: The Z accelerator
- Strategy for the development of next-generation machines
- Approach
- Two conceptual designs
- Linear transformer drivers (LTDs)
- LTD development
- Transmission-line impedance transformers
- Vacuum insulator stack and magnetically insulated transmission lines (MITLs)
- Standoff concept for IFE
- Publications
- Summary

We have been funded by the National Nuclear Security Administration (NNSA) to develop *single-shot* accelerators.

- Hence *this* presentation will present *conceptual* designs of next-generation accelerators that are designed to operate at a repetition rate of one shot per day.

- In the *subsequent* presentation, Mike Cuneo will outline how such accelerators would be adapted to operate at higher repetition rates (~0.1 Hz), and produce inertial fusion energy (IFE).

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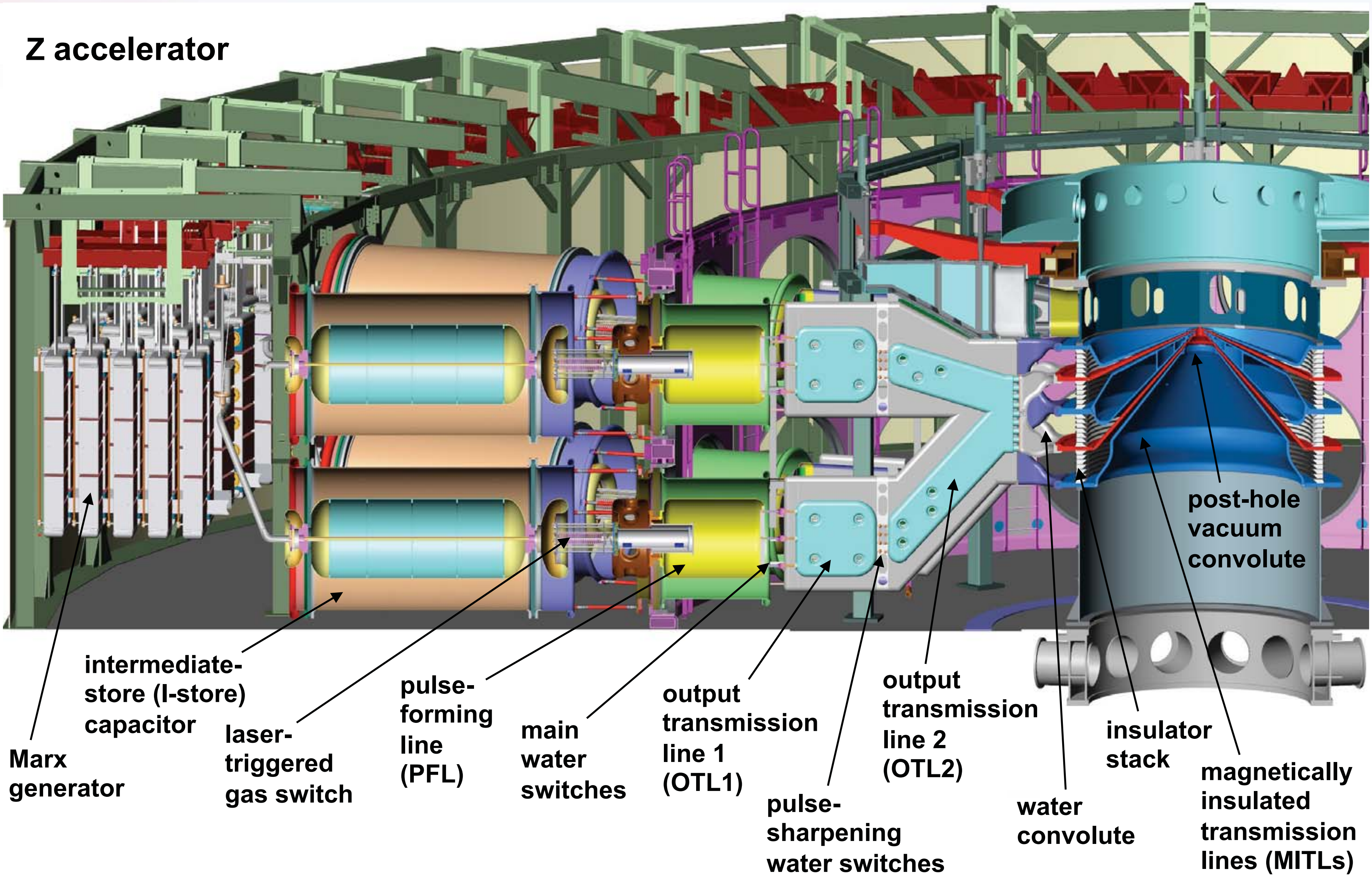
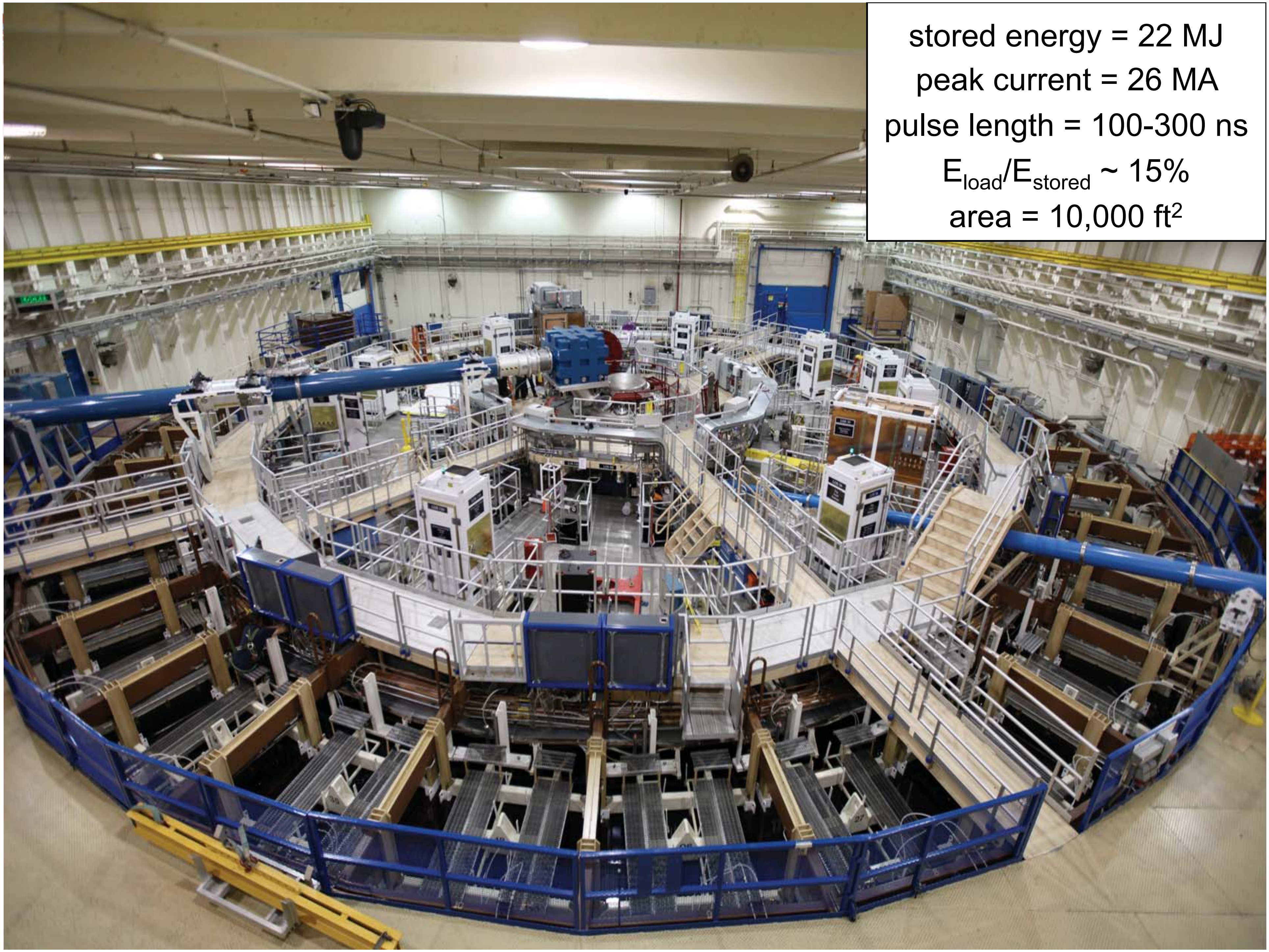
The Z pulsed-power accelerator is a megajoule-class target-physics platform.





stored energy = 22 MJ

peak current = 26 MA

pulse length = 100-300 ns

$E_{load}/E_{stored} \sim 15\%$

area = 10,000 ft^2

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We intend to develop the cleanest and most efficient possible architecture for next-generation accelerators.

- A **clean** architecture is easier to model, maintain, and troubleshoot.

- An **efficient** architecture minimizes costs, wasted energy, and self-inflicted damage to the accelerator.

Our strategy for achieving both a clean and efficient design is to use **impedance matching.**

This approach minimizes electromagnetic-power reflections within the accelerator-load system.

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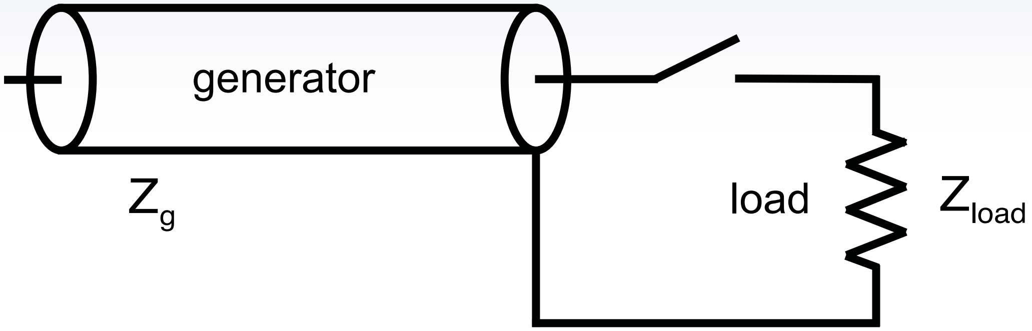
We begin by considering the simplest possible accelerator: a transmission-line pulse generator.



We assume:

- The system of pulse generators that drive the accelerator can be modeled as a single lossless transmission line with constant impedance Z_g.
- The generator impedance is matched to that of the load; i.e., $Z_g = Z_{load}$.

Under these conditions:

- The peak power delivered to the load is maximized.
- We have 6 equations and 9 variables.
- To achieve fusion would require certain values of I_{load}, τ_{load}, and Z_{load}.
- These in turn would determine the machine parameters P_g, E_g, V_g, L_g, C_g, and Z_g.

$$Z_g = Z_{load}$$

$$Z_g = \sqrt{\frac{L_g}{C_g}}$$

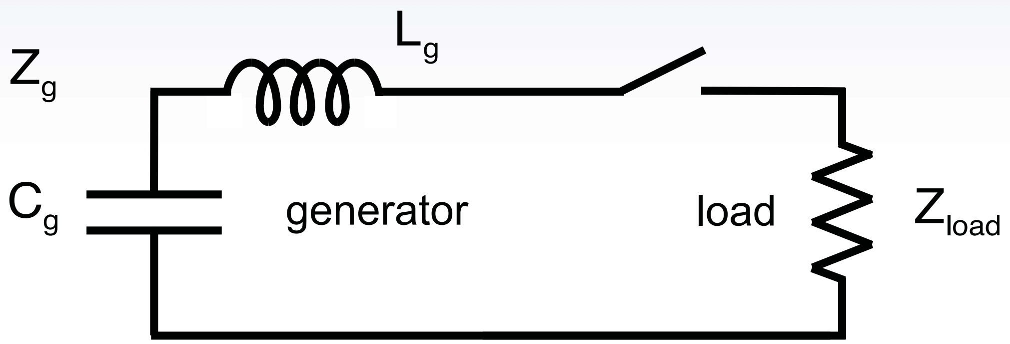
$$I_{load} = \sqrt{\frac{P_g}{Z_{load}}}$$

$$\tau_{load} = 2\sqrt{L_g C_g}$$

$$P_g = 0.25\frac{V_g^2}{\sqrt{L_g/C_g}}$$

$$E_g = \frac{1}{2}C_g V_g^2$$

It presently appears that an LC drive circuit will be more practical.



We assume:

- The system of pulse generators that drive the accelerator can be modeled as a single lossless LC circuit.
- The generator impedance is matched to that of the load; i.e., $Z_g = Z_{load}$.

Under these conditions:

- The peak power delivered to the load is maximized.
- We have 6 equations and 9 variables.
- To achieve fusion would require certain values of I_{load}, τ_{load}, and Z_{load}.
- These in turn would determine the machine parameters P_g, E_g, V_g, L_g, C_g, and Z_g.

$$Z_g = Z_{load}$$

$$Z_g = 1.1\sqrt{\frac{L_g}{C_g}}$$

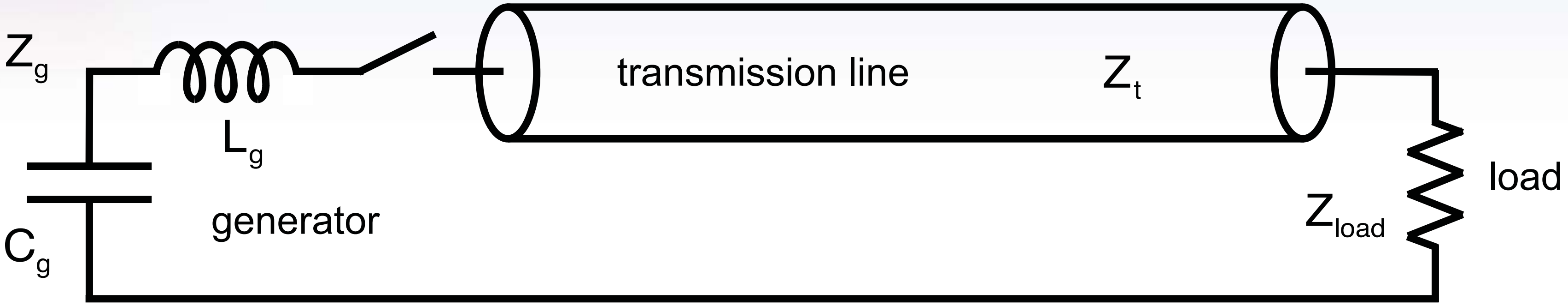
$$I_{load} = \sqrt{\frac{P_g}{Z_{load}}}$$

$$\tau_{load} = 2\sqrt{L_g C_g}$$

$$P_g = 0.30\frac{V_g^2}{\sqrt{L_g / C_g}}$$

$$E_g = \frac{1}{2}C_g V_g^2$$

Geometric constraints require that a system of transmission lines connect the LC drivers to the load.



We assume:

- The transmission-line system can be modeled as a single lossless line with constant impedance Z_t.
- The generator impedance Z_g is matched to that of the transmission-line system Z_t, which in turn is matched to the load Z_{load}.
- Hence $Z_g = Z_t = Z_{load}$.

Under these conditions:

- The peak power delivered to the load is maximized.
- We have essentially the same set of equations as before.

$$Z_g = Z_t = Z_{load}$$

$$Z_g = 1.1\sqrt{\frac{L_g}{C_g}}$$

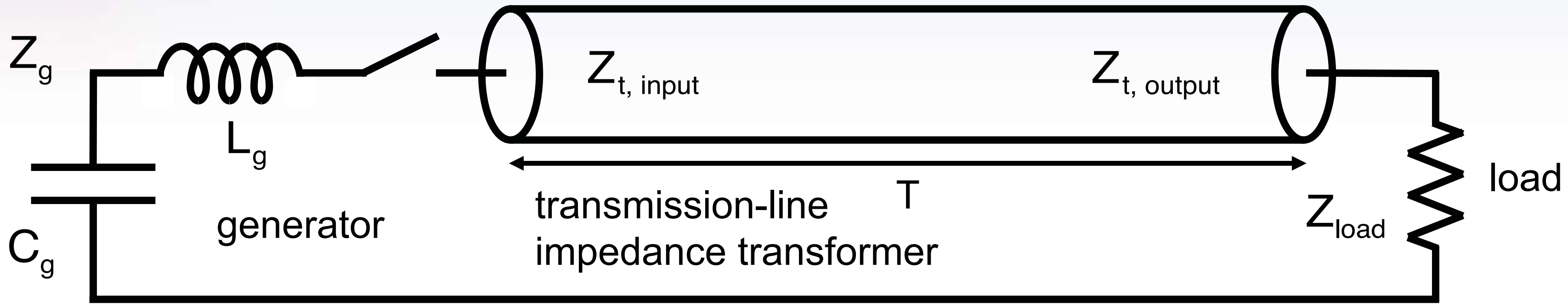
$$I_{load} = \sqrt{\frac{P_g}{Z_{load}}}$$

$$\tau_{load} = 2\sqrt{L_g C_g}$$

$$P_g = 0.30\frac{V_g^2}{\sqrt{L_g / C_g}}$$

$$E_g = \frac{1}{2}C_g V_g^2$$

It is likely that the optimum generator impedance will not be the same as the optimum load impedance.



We assume:

- The transmission-line system serves as an impedance transformer.
- The line impedance Z_t is a function of position, and gradually transforms from the generator impedance Z_g to the load impedance Z_{load}.
- The voltage pulse width τ_{load} << T, the one-way transit time of the transmission line.

Under these conditions:

- The power-transport efficiency of the transformer is maximized.
- The peak power delivered to the load is maximized.

$$Z_g = Z_{t,\ input} \qquad Z_{t,\ output} = Z_{load}$$

$$Z_g = 1.1\sqrt{\frac{L_g}{C_g}}$$

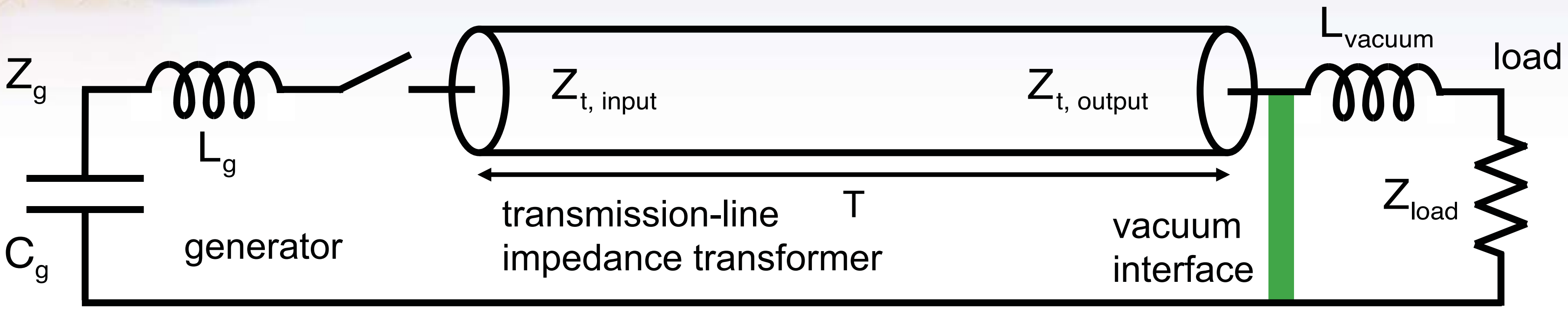
$$I_{load} = \sqrt{\frac{P_g}{Z_{load}}}$$

$$\tau_{load} = 2\sqrt{L_g C_g} << T$$

$$P_g = 0.30\frac{V_g^2}{\sqrt{L_g / C_g}}$$

$$E_g = \frac{1}{2} C_g V_g^2$$

The load will operate under vacuum, which requires an inductive connection to the accelerator.



- L_{vacuum} is the inductance of the connection from the vacuum interface to the load.
- We have 8 equations and 13 unknowns.
- We would specify I_{load}, τ_{load}, Z_{load}, Z_g, and L_{vacuum}.
- These in turn would determine the other 8 machine parameters, such as P_g and E_g.

$$Z_g = 1.1\sqrt{\frac{L_g}{C_g}} = Z_{t,\ input}$$

$$Z_{t,\ output} \sim \frac{L_{vacuum}}{\tau_{load}} + Z_{load}$$

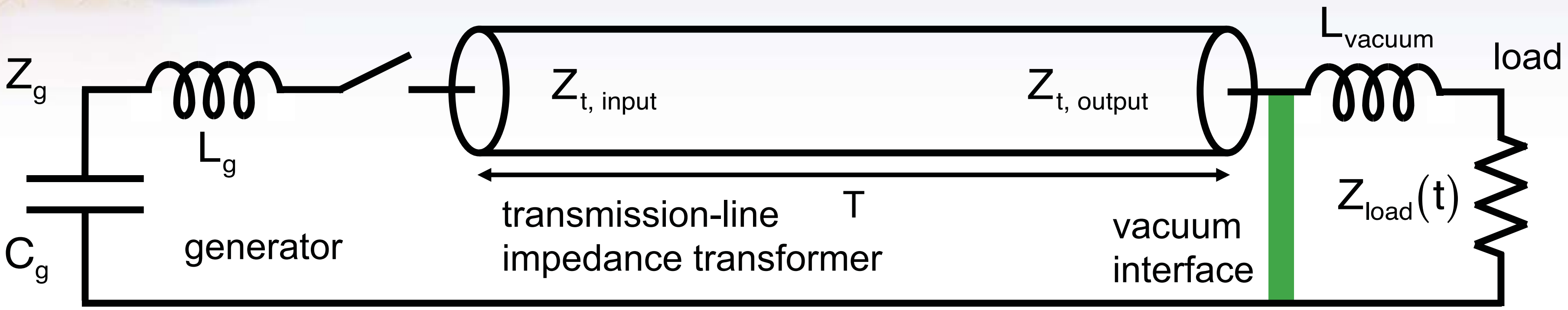
$$I_{load} \sim \sqrt{\frac{P_g}{Z_{t,\ output}}}$$

$$\tau_{load} \sim 2\sqrt{L_g C_g} << T$$

$$P_g \sim 0.3\frac{V_g^2}{\sqrt{L_g / C_g}}$$

$$E_g = \frac{1}{2}C_g V_g^2$$

The load impedance will be time dependent.



- The load geometry will vary substantially on the time scale of the power pulse, hence the load impedance will be a function of time.
- An *approximate* model of such a coupled accelerator-load system is given by 8 equations and 13 unknowns.
- The requirements of an optimized system design are best determined *numerically*.

This is a circuit diagram of our new accelerator architecture, which has four principal components.

$$Z_g = 1.1\sqrt{\frac{L_g}{C_g}} = Z_{t,\ input}$$

$$Z_{t,\ output} \sim \frac{L_{vacuum}}{\tau_{load}} + Z_{load}$$

$$I_{load} \sim \sqrt{\frac{P_g}{Z_{t,\ output}}}$$

$$\tau_{load} \sim 2\sqrt{L_g C_g} << T$$

$$P_g \sim 0.3\frac{V_g^2}{\sqrt{L_g / C_g}}$$

$$E_g = \frac{1}{2} C_g V_g^2$$

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We could build a 300-TW LTD-driven accelerator that fits within the existing Z building.

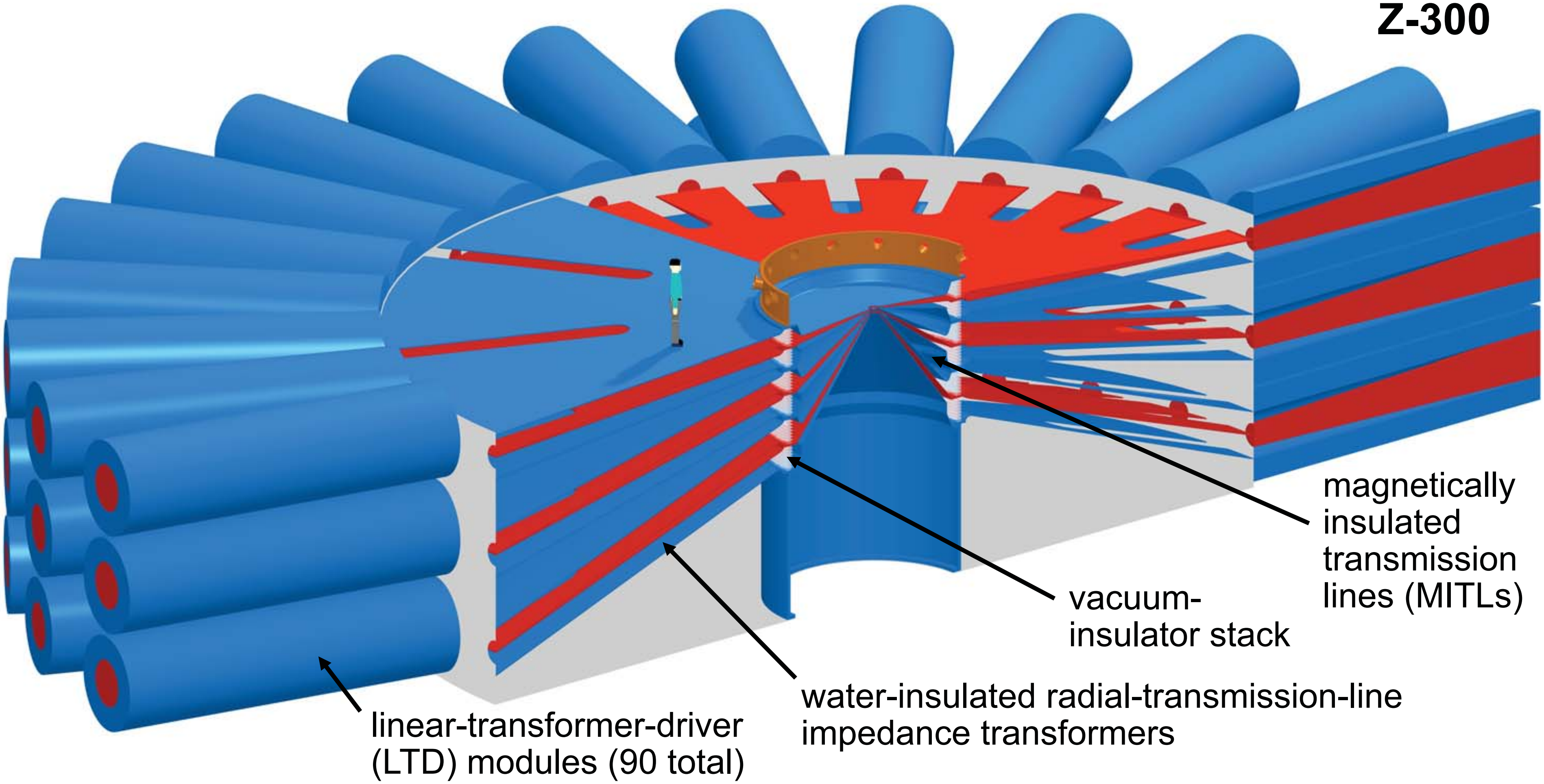
P_g = 300 TW
E_g = 47 MJ

V_{stack} = 6 MV
L_{vacuum} = 14 nH

I_{load} = 50 MA
$\tau_{implosion}$ = 130 ns

$E_{radiated}$ = 11 MJ
diameter = 35 m

η_{x-ray} = 23%



This would be the first LTD-driven machine that generates > 10 TW.

Without constraining ourselves to the Z building, we could build a 2000-TW accelerator.

P_g = 2000 TW
E_g = 360 MJ

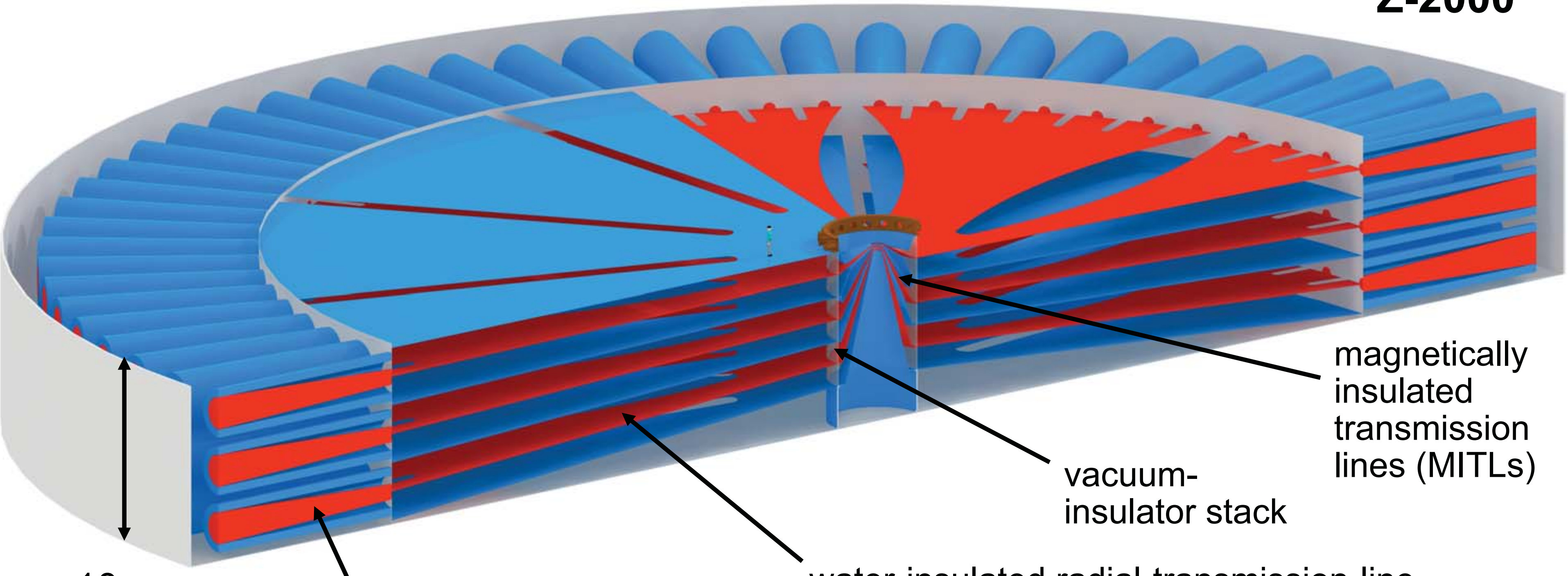
V_{stack} = 24 MV
L_{vacuum} = 25 nH

I_{load} = 100 MA
$\tau_{implosion}$ = 130 ns

$E_{radiated}$ = 44 MJ
diameter = 104 m

η_{x-ray} = 12%

Z-2000



magnetically insulated transmission lines (MITLs)

vacuum-insulator stack

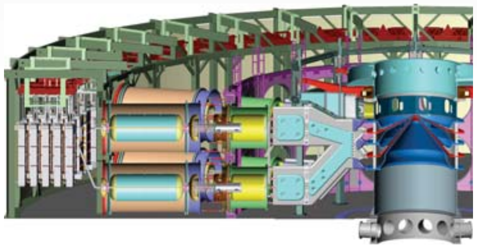
10 m

water-insulated radial-transmission-line impedance transformers

linear-transformer-driver (LTD) modules (210 total)

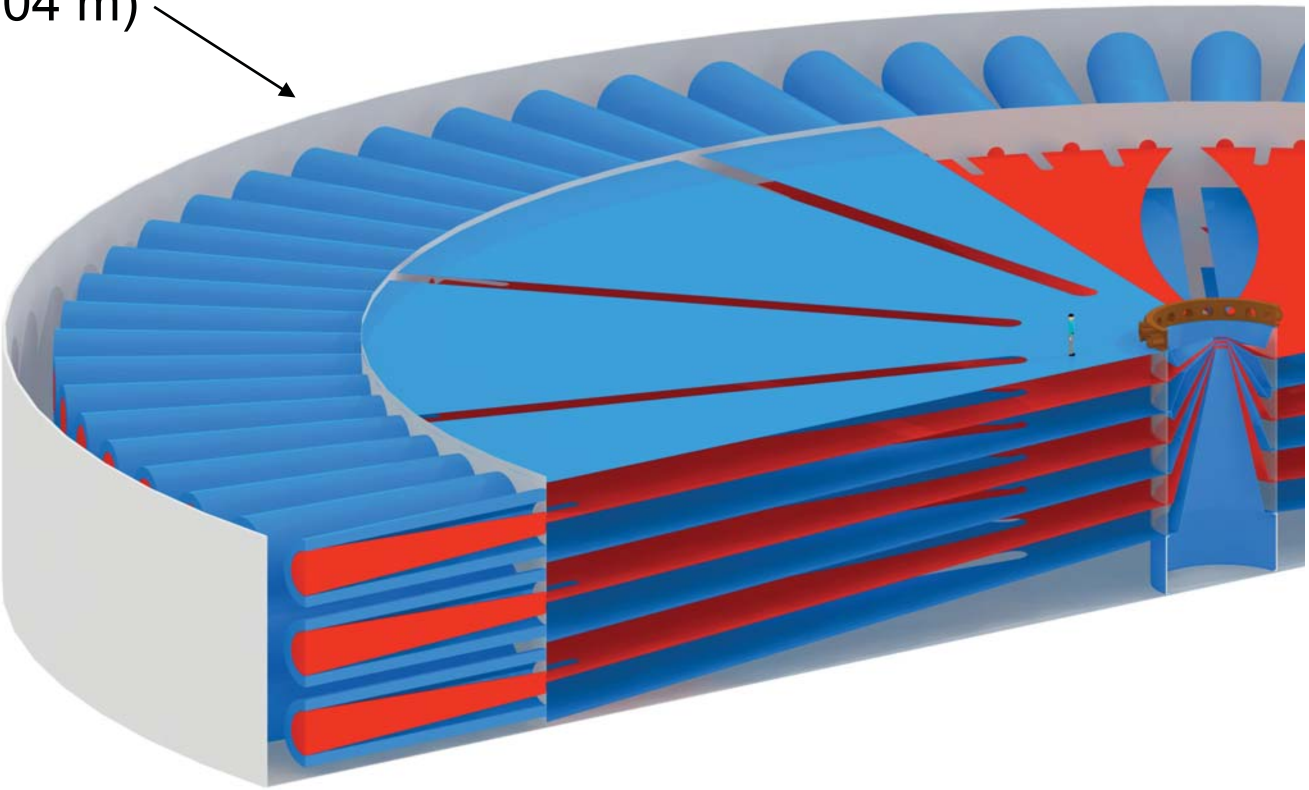
This accelerator would deliver a fusion yield > 1000 MJ.

The 2000-TW machine would be a factor of three larger in diameter than Z.



80-TW ZR accelerator
(outer diameter = 33 m)

proposed 2000-TW accelerator
(outer diameter = 104 m)



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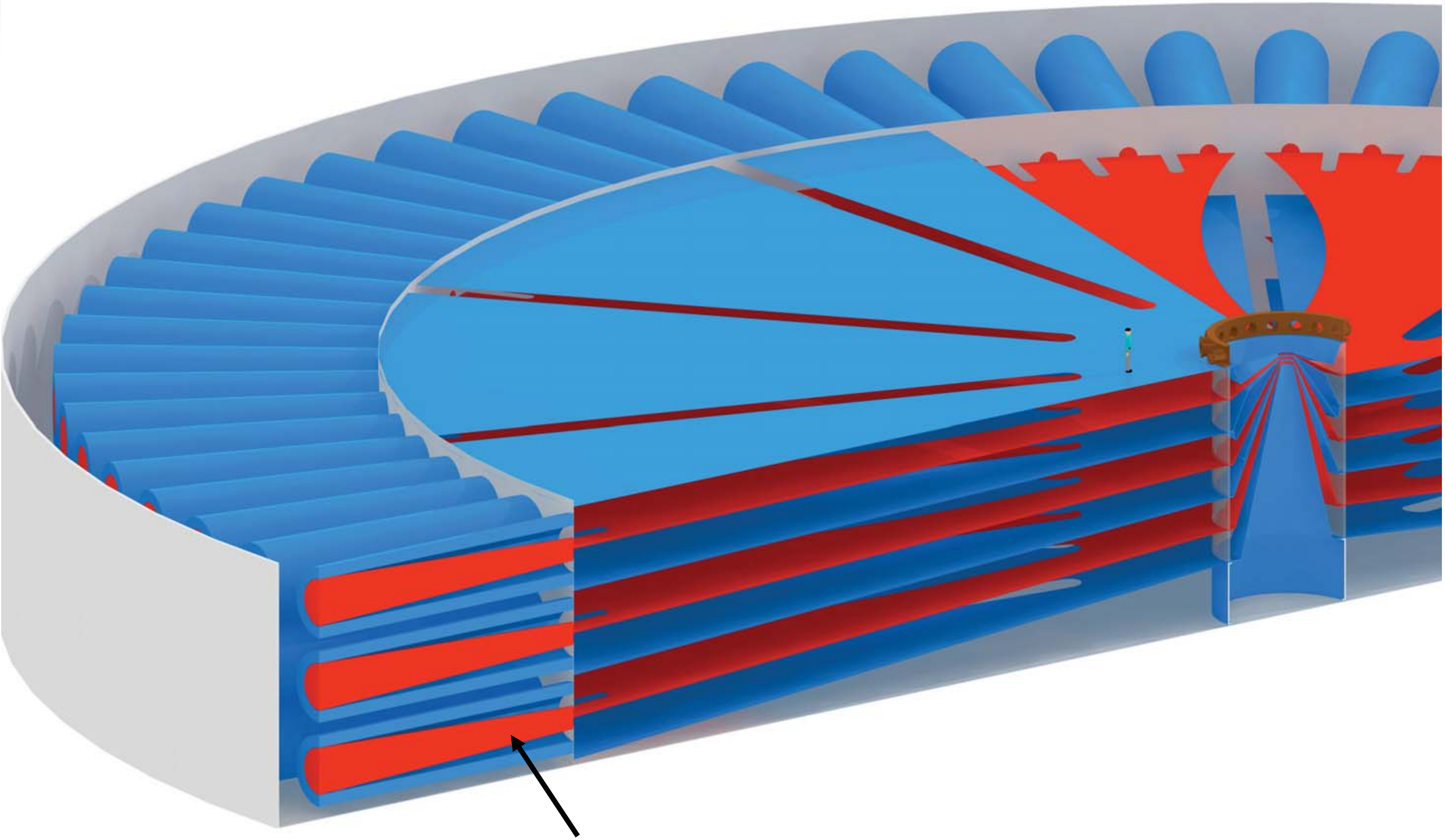
Both machines would be driven by linear-transformer-driver (LTD) modules.



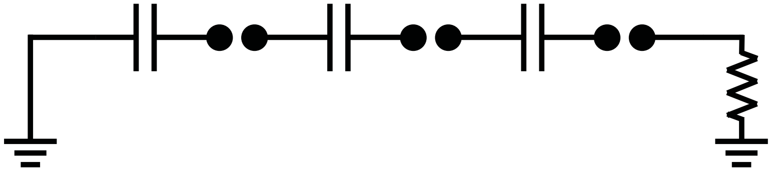
linear-transformer-driver (LTD) modules

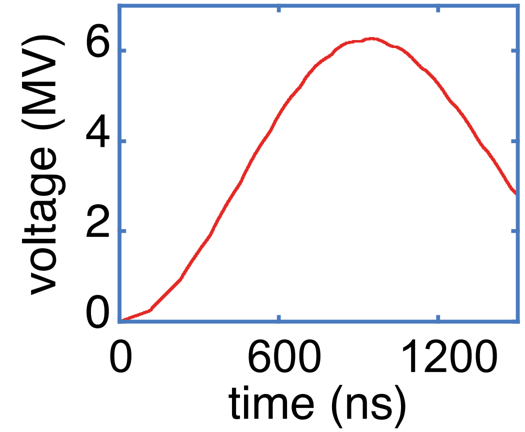
LTDs are the greatest advance in prime power generation since the invention of the Marx generator (1924).

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

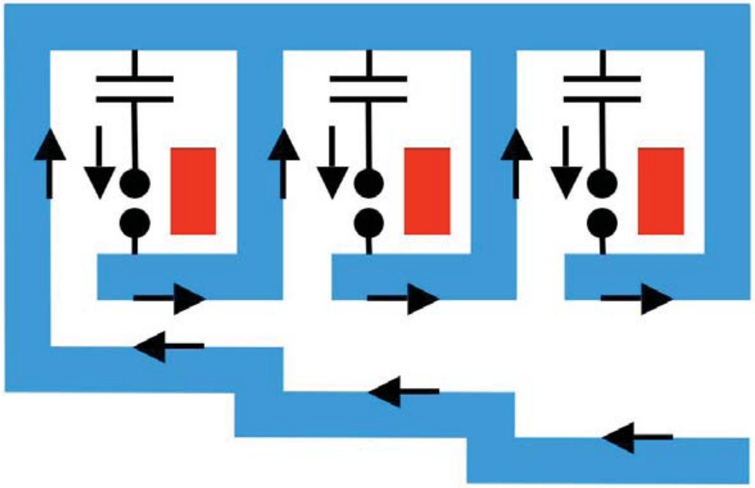


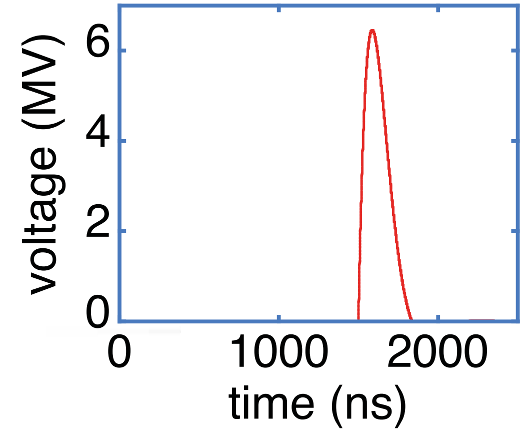


An LTD does this as an *induction voltage adder* (IVA), in which each of the adder's cavities is driven by LC circuits that are *contained within the cavity*:

LTD

$2\sqrt{LC} = 140$ ns





Our LTDs produce a pulse that is a factor of seven shorter than that of a Z Marx generator.

- A Marx generator and an LTD both consist of a large number LC circuits connected together.
- The minimum pulse width that can be produced by a series-parallel combination of identical LC circuits is:

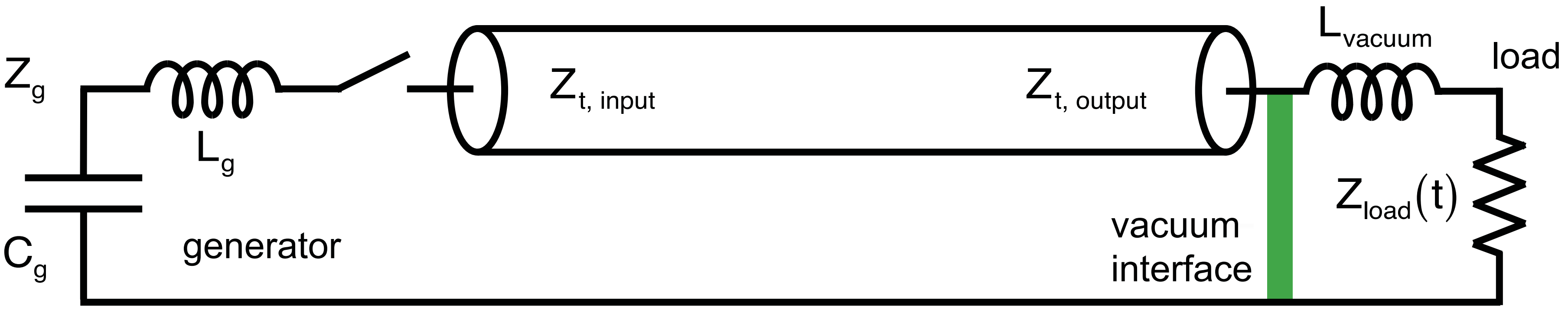
$$2\sqrt{LC} \quad ,$$

  independent of the number of circuits.
- The pulse width of a Z Marx generator is 1 μs ($L = 190$ nH, $C = 1300$ nF). If the desired pulse width is 140 ns, an accelerator driven by such Marxes would require a pulse-compression system.
- Pulse-compression hardware adds complexity and reduces efficiency.

LTDs are flexible: We can easily make the pulse width 140 ns ($L = 120$ nH, $C = 40$ nF), so no additional pulse compression would be required.

Our LTDs inherently have a longer lifetime than that of a Marx generator.

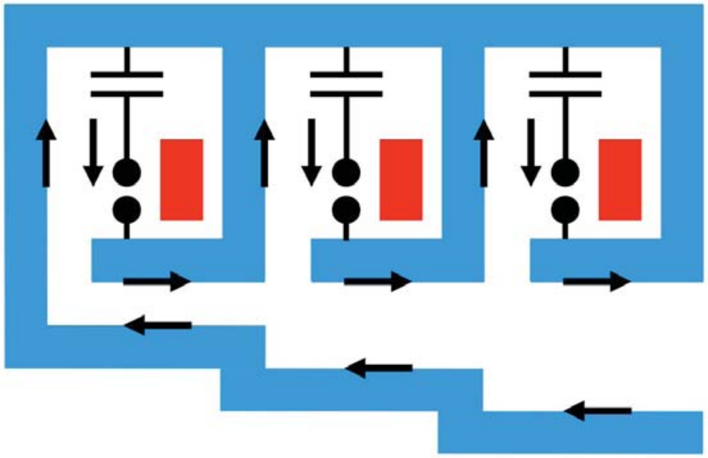
- The pulse width is reduced by reducing both the L and C of each LC circuit.
- Hence to achieve the energy stored that would be required, we need to increase the number of circuits.
- Each circuit includes a switch (which contributes most of the inductance). Consequently an LTD uses far more switches than a Marx generator.
- Since each LTD switch carries a *fraction* of the current and charge of a Marx switch, an LTD switch can be designed to achieve a longer life.

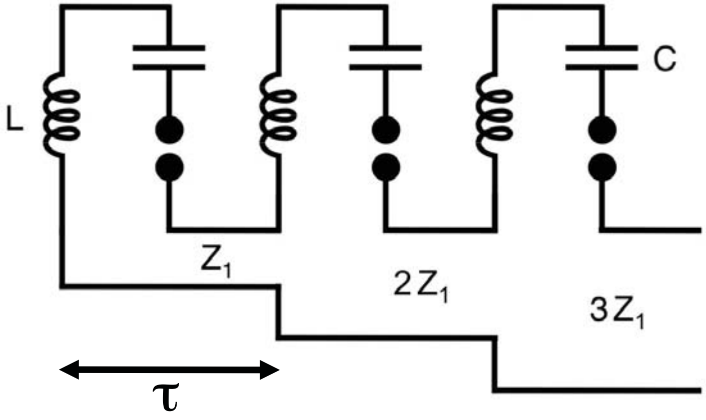


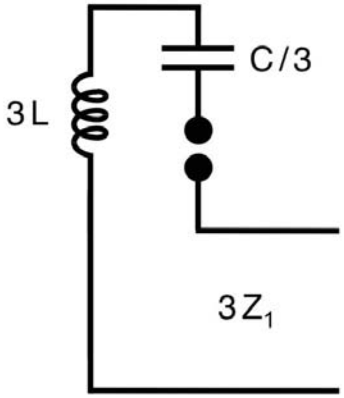
An entire LTD pulse generator consisting of n LTD cavities connected in series can be modeled as a single LC circuit.

When the switches of an LTD cavity close at time τ (the one-way transit time of a single cavity) after the closure of the switches in the previous cavity, then an entire n-cavity LTD pulse generator can be modeled as a *single LC circuit*:

- $L_g = nL$
- $C_g = \frac{C}{n}$



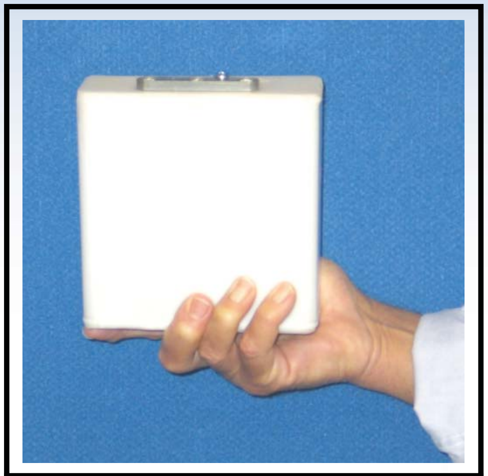




We could begin building the 2000-TW accelerator today.

The machine would require:

- 1,000,000 capacitors

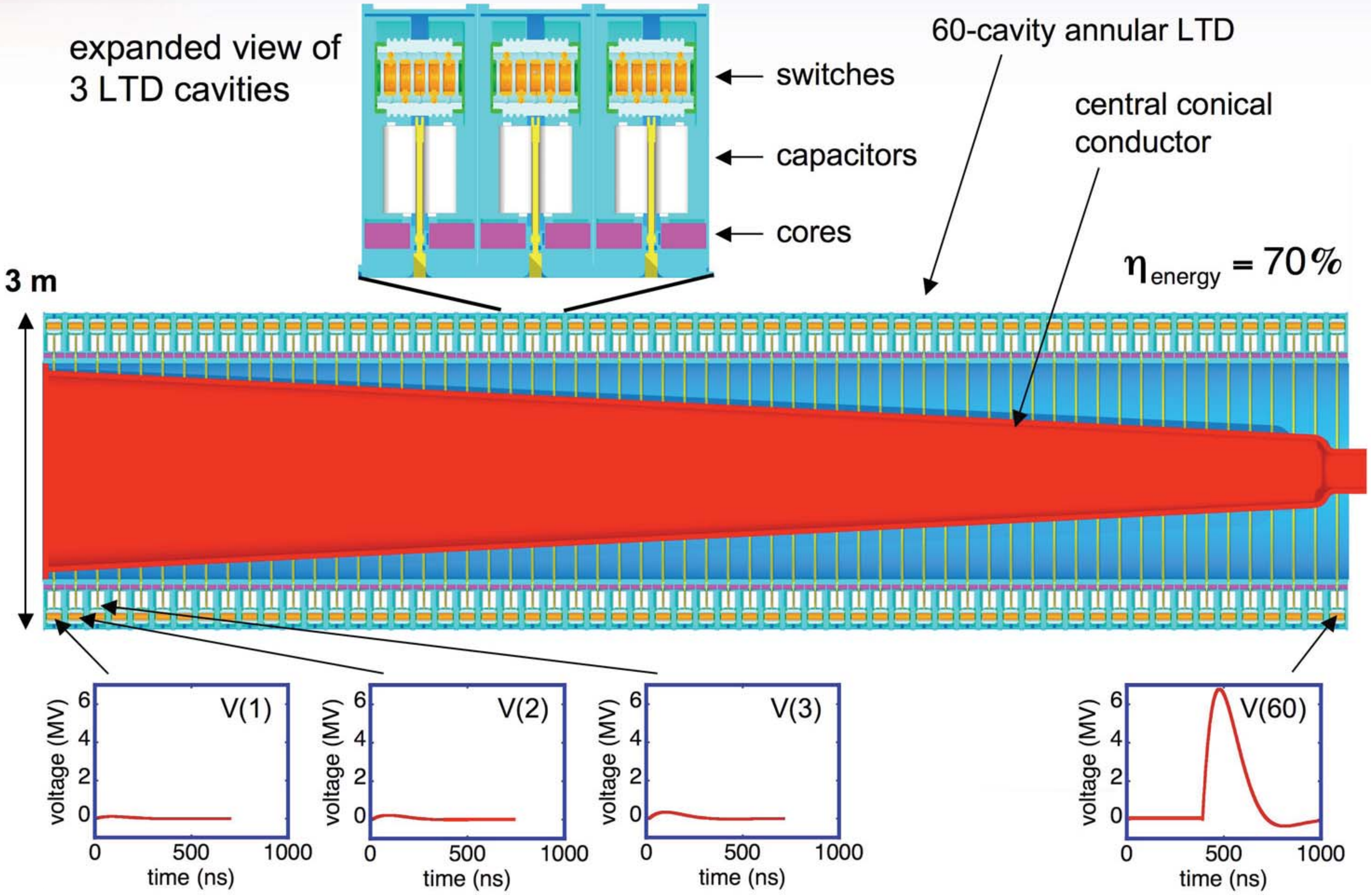


- 500,000 switches

- 25,000 magnetic cores

The rest of the machine would consist of water, plastic, and stainless steel.

Since an LTD module is impedance matched throughout, it generates a clean forward-going power pulse.



expanded view of 3 LTD cavities

switches

capacitors

cores

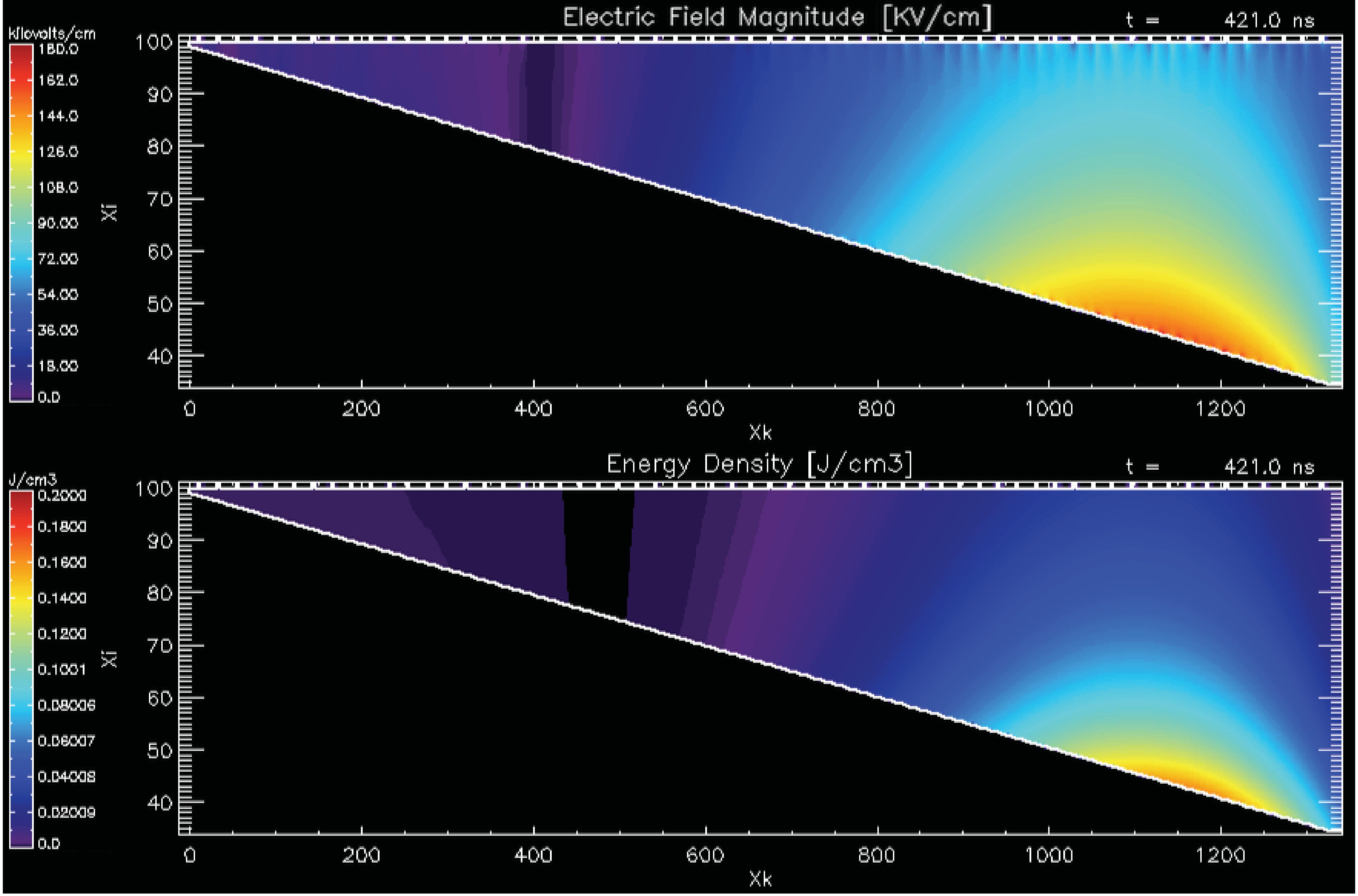
60-cavity annular LTD

central conical conductor

$\eta_{energy} = 70\%$

3 m

2D electromagnetic simulations confirms that a 60-cavity LTD module can generate a clean power pulse.



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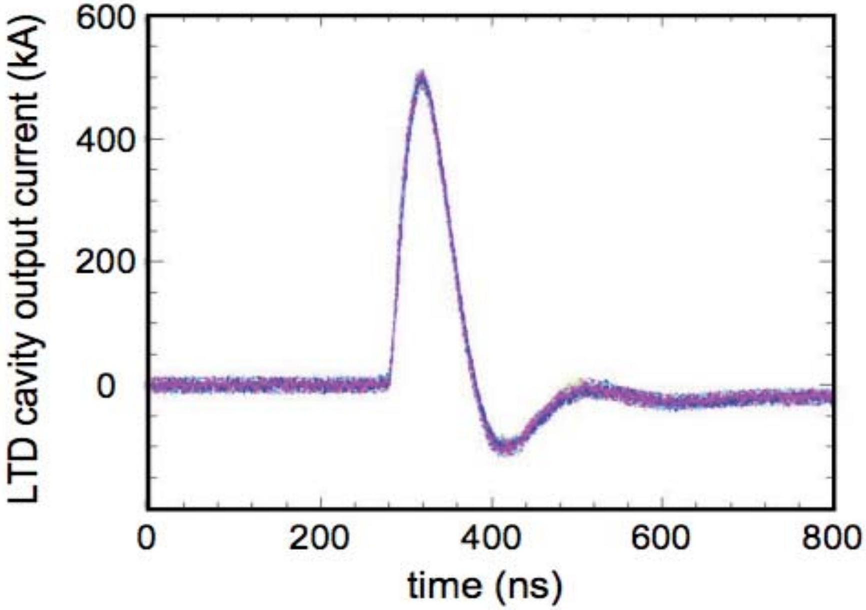
We have successfully tested a prototype 0.5-MA LTD cavity on over 12,000 shots.

The prototype LTD cavity includes
40 capacitors and 20 switches.



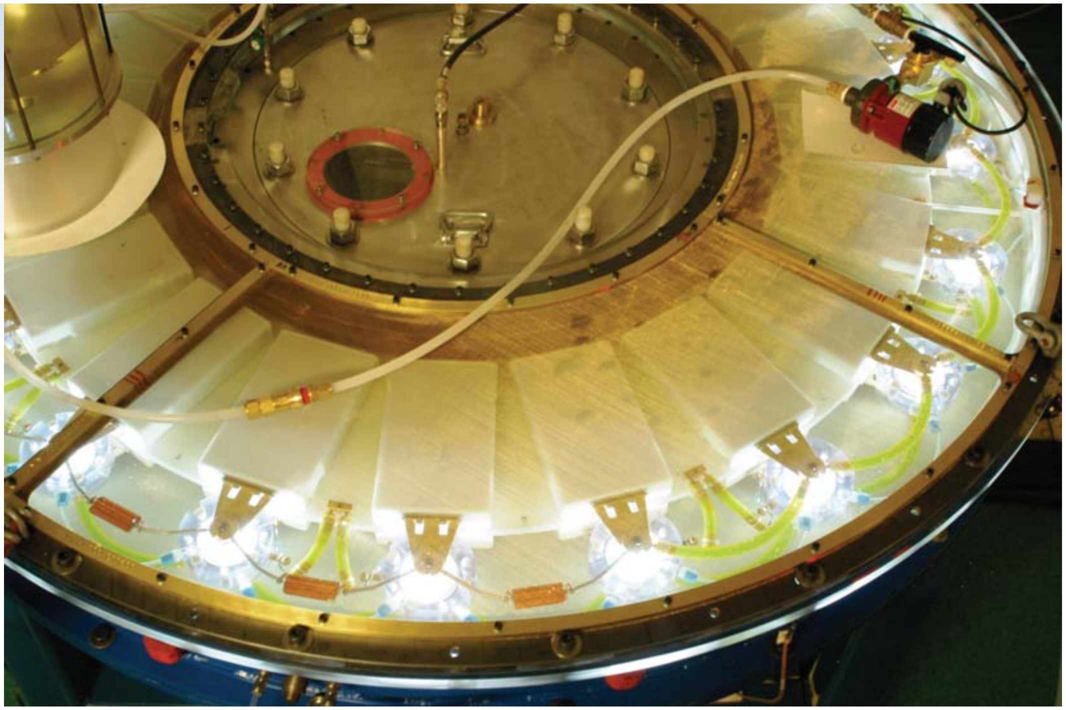
overlay of 200 consecutive shots of the prototype LTD module (170-kV charge)

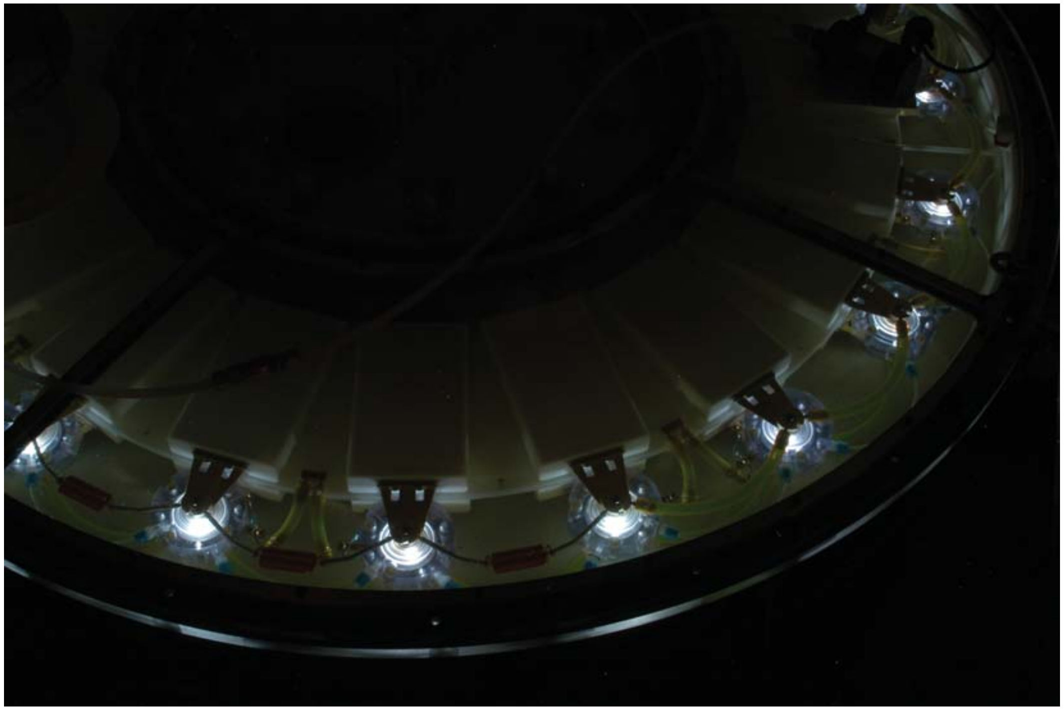
- timing jitter = 2 ns (1σ)
- voltage and current reproducibility = 0.3% (1σ)
- peak power = 0.05 TW
- output energy = 6 kJ
- electrical efficiency = 70%

The prototype cavity is now being used as an advanced LTD-component-test facility.

The facility is being used to develop next-generation LTD:

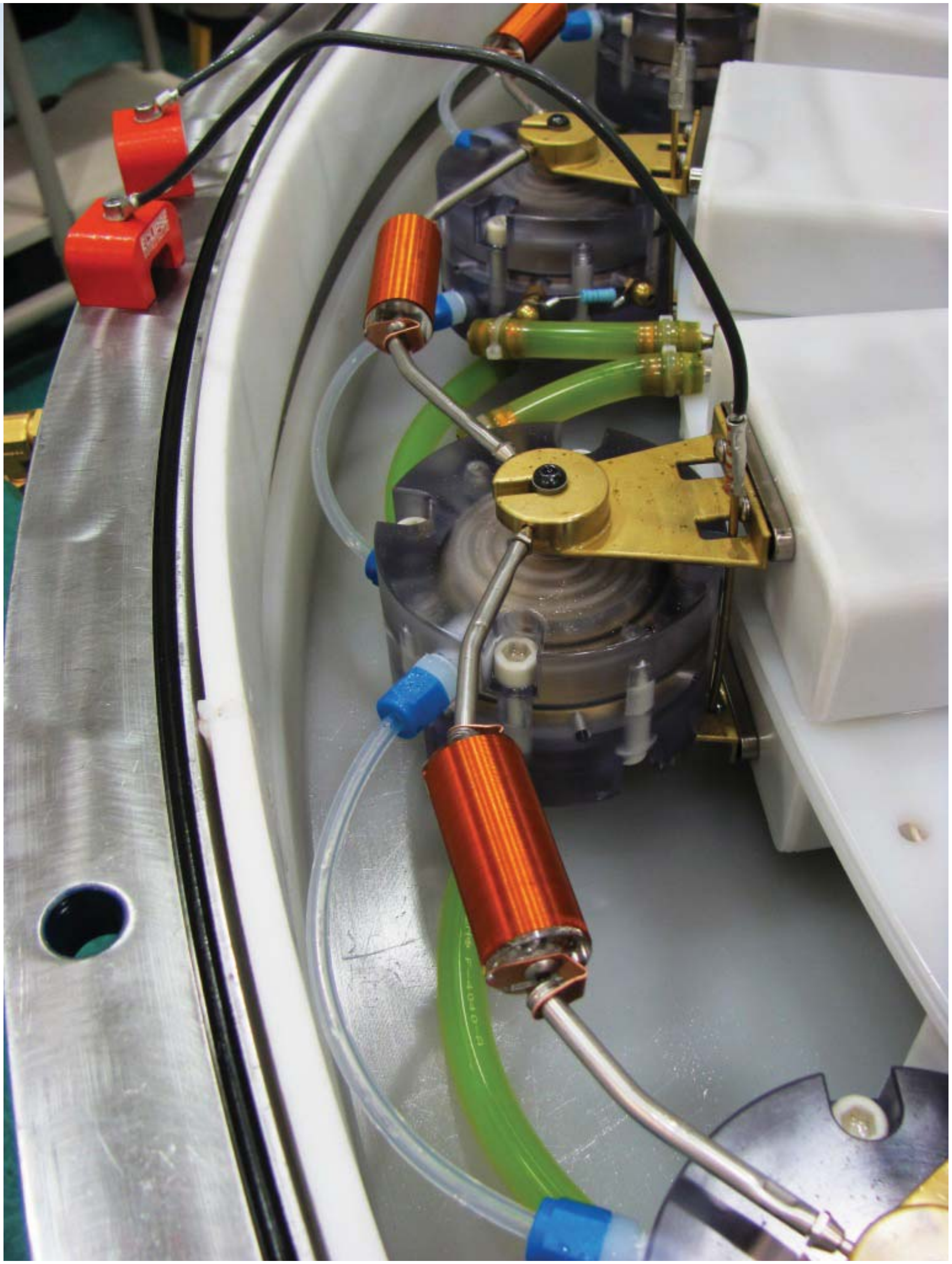
- Switches
- Capacitors
- Cores
- Inductors
- Resistors
- Insulators
- Cavity enclosures
- Circuit models
- 3D electromagnetic models





We have recently developed a next-generation LTD cavity.

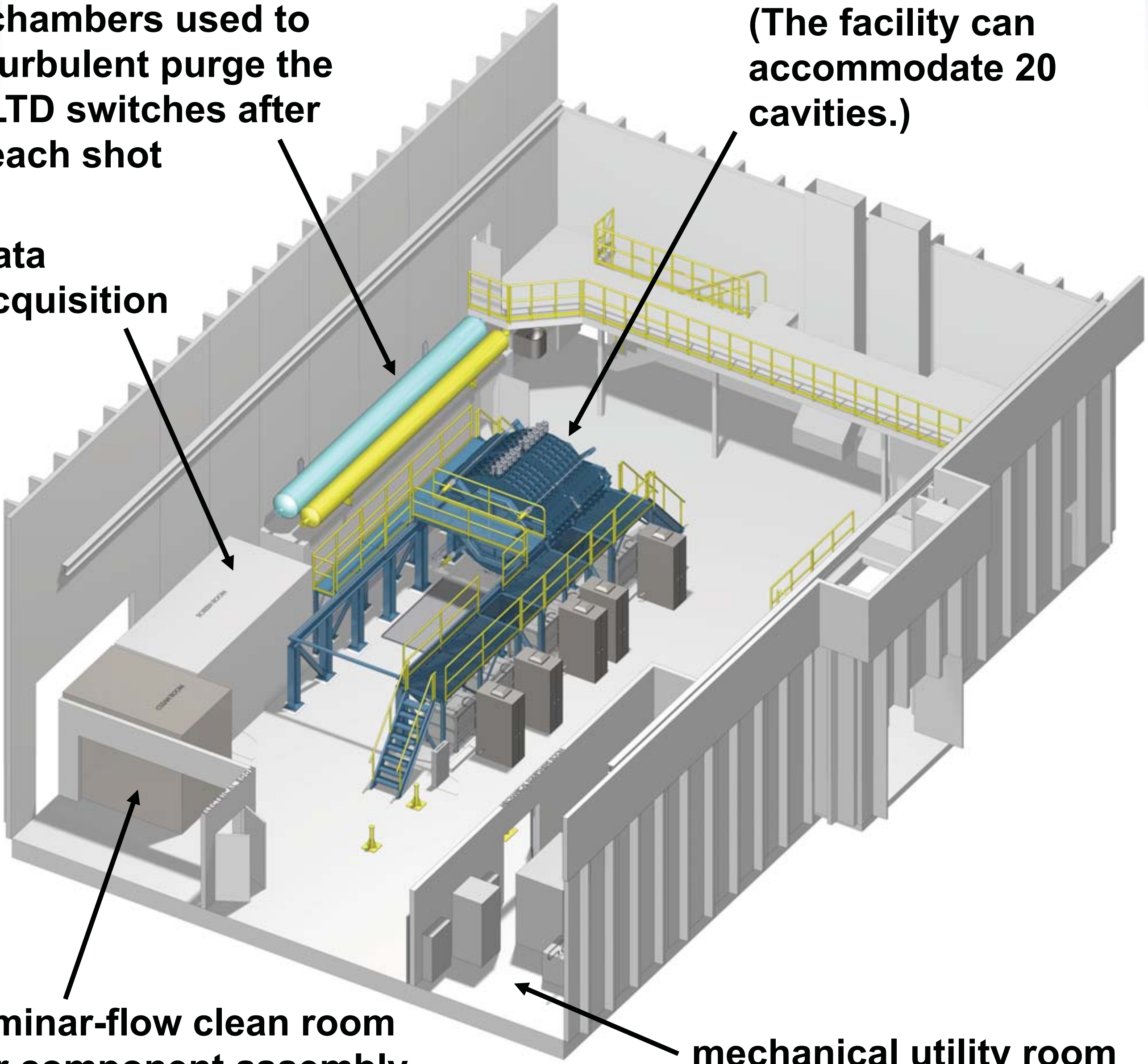
- The new cavity includes advanced switches, capacitors, and cores.
- We have increased the output current of an LTD cavity by 65%.



We are presently assembling Mykonos, which will be the world's first 1-TW LTD.

The Mykonos facility will be used to:

- Demonstrate current-pulse shaping.
- Demonstrate voltage addition.
- Demonstrate successful operation of a water-insulated inner-LTD transmisison line.
- Demonstrate successful coupling of an LTD module to a transmisison-line impedance transformer.
- Demostrate successful operation of an LTD module at the rate of one shot every 10 seconds.
- Measure random component failure rates and component lifetimes.



chambers used to turbulent purge the LTD switches after each shot

10-cavity LTD module
E_{stored} = 160 kJ
(The facility can accommodate 20 cavities.)

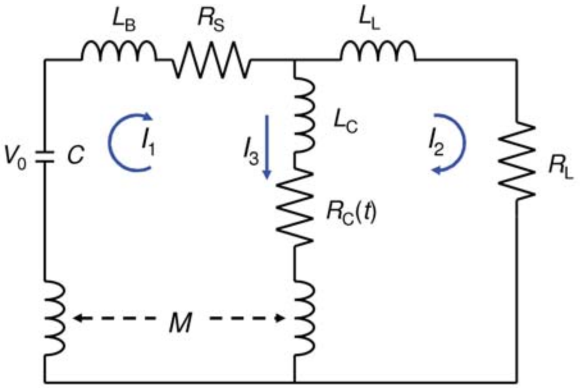
data acquisition

laminar-flow clean room for component assembly

mechanical utility room

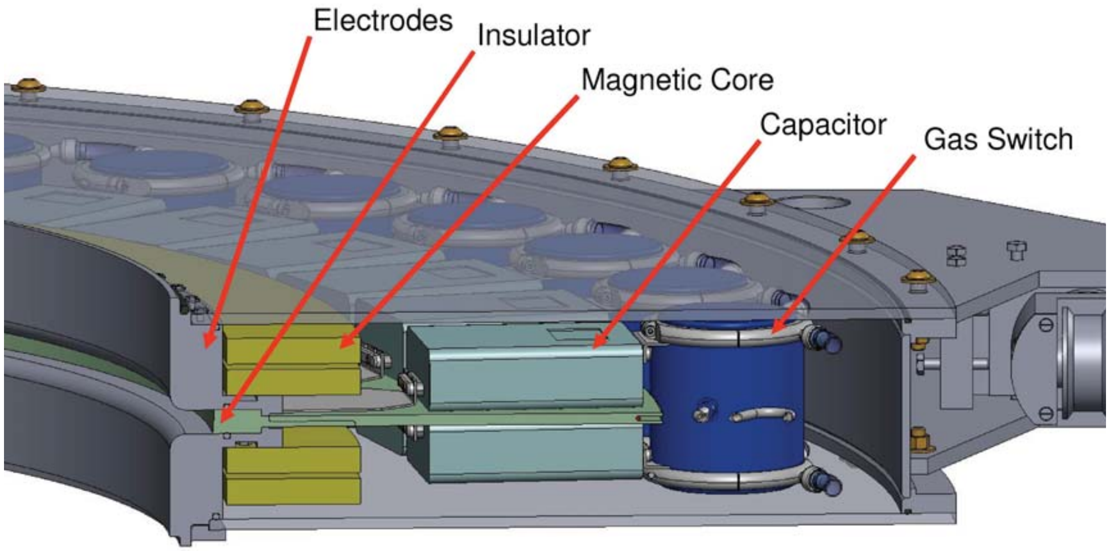

6

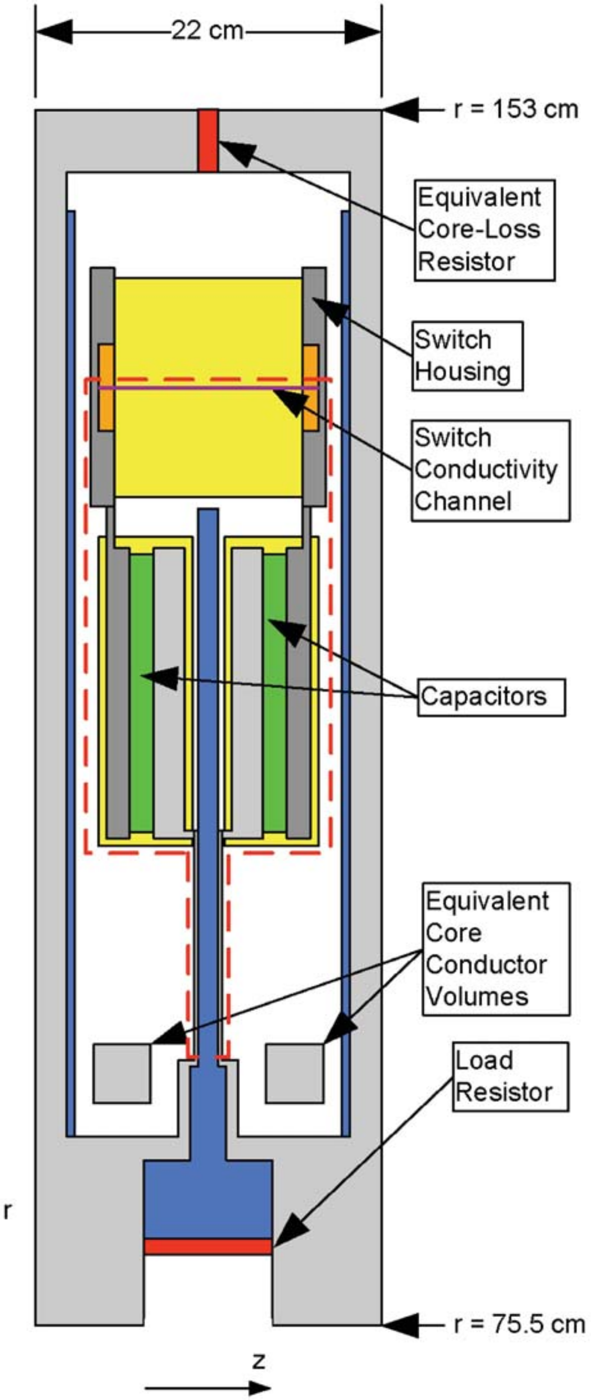
We have developed an advanced circuit model of an LTD cavity.



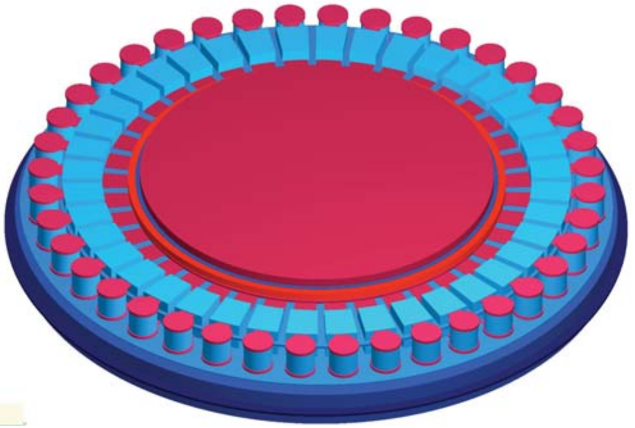
$$\frac{I_1}{C} + L_B \frac{d^2 I_1}{dt^2} + L_L \frac{d^2 I_2}{dt^2} + R_S \frac{dI_1}{dt} + R_L \frac{dI_2}{dt} - M \left(\frac{d^2 I_1}{dt^2} - \frac{d^2 I_2}{dt^2} \right) = 0,$$

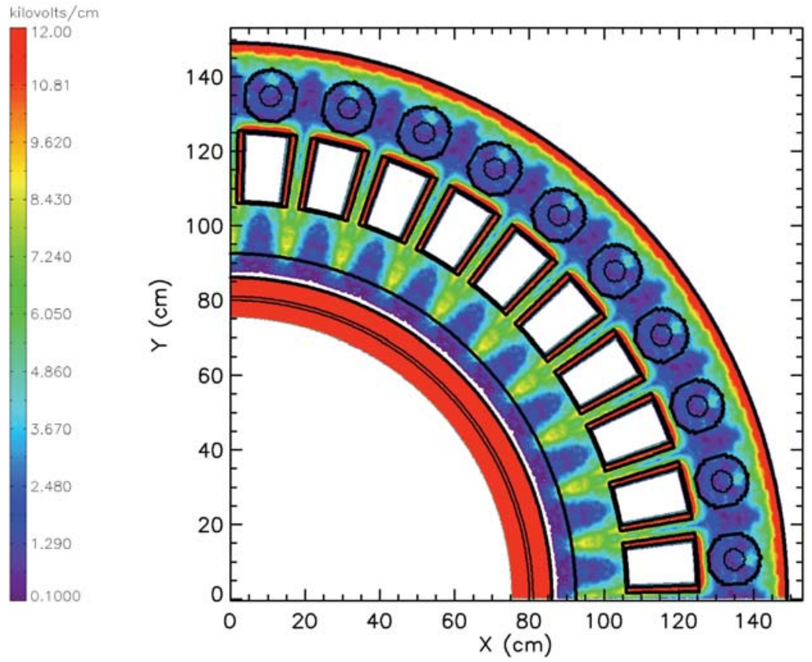
$$L_L \frac{dI_2}{dt} + R_L I_2 - (I_1 - I_2) R_C(t) + (M - L_C) \frac{dI_1}{dt} + L_C \frac{dI_2}{dt} = 0.$$

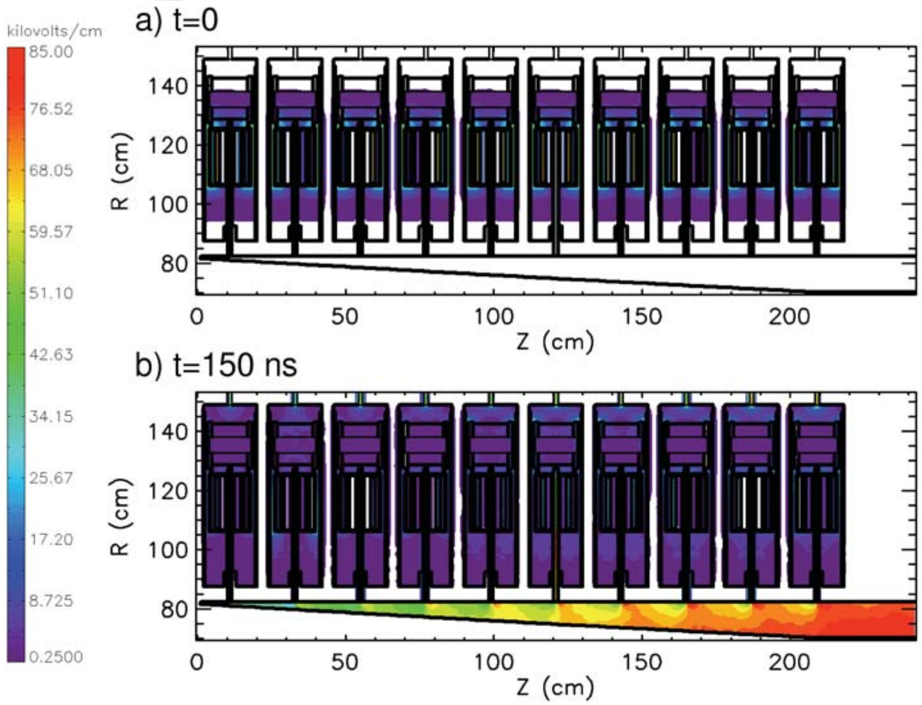


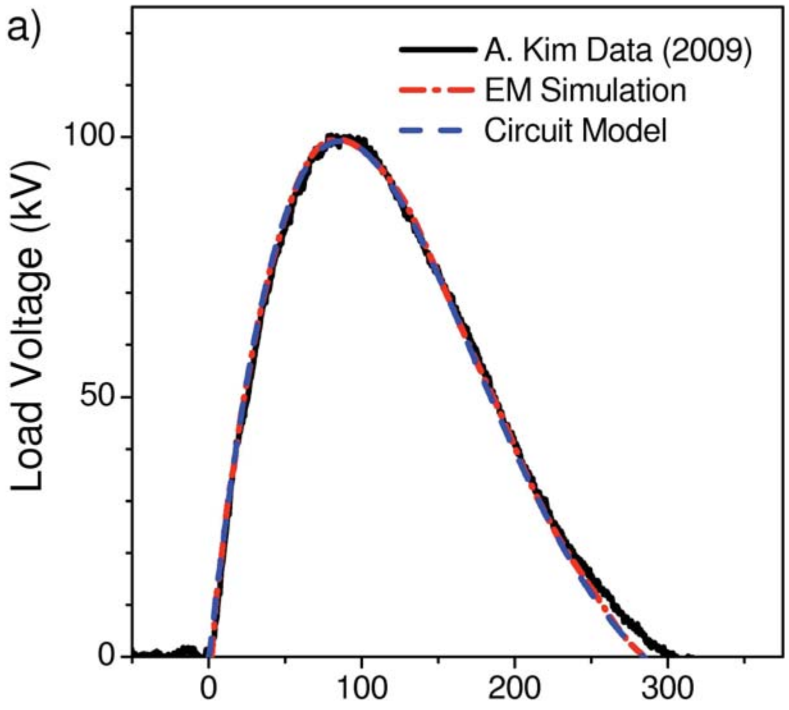


We have developed the first 3D electromagnetic model of an LTD module.









Presentation outline

- Scope of this presentation
- Present state of the art: The Z accelerator
- Strategy for the development of next-generation machines
- Approach
- Two conceptual designs
- Linear transformer drivers (LTDs)
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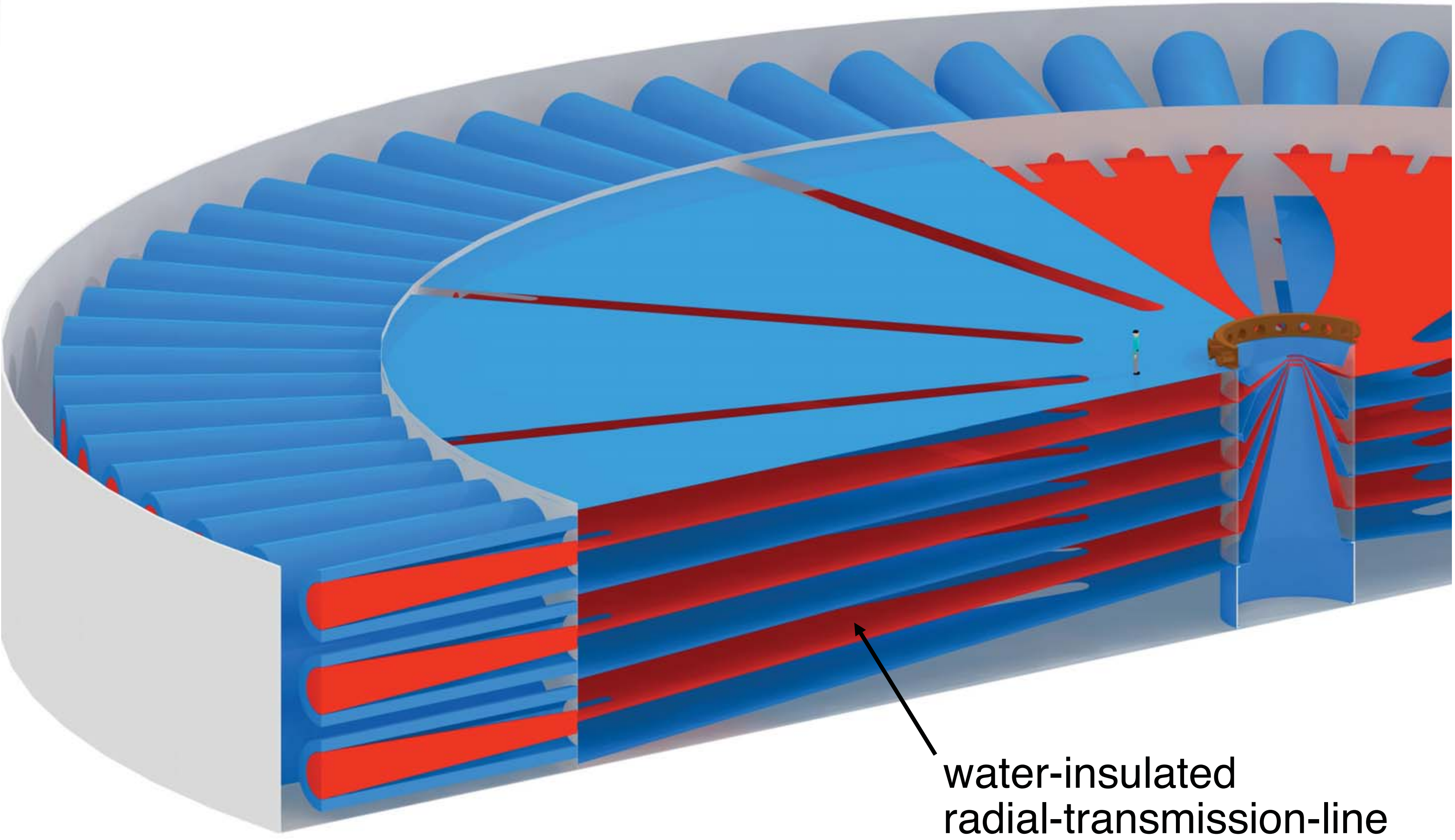
Transmission-line impedance transformers offer a *clean* and *efficient* method of combining the outputs of terawatt-level LTD modules to produce a petawatt-level pulse.

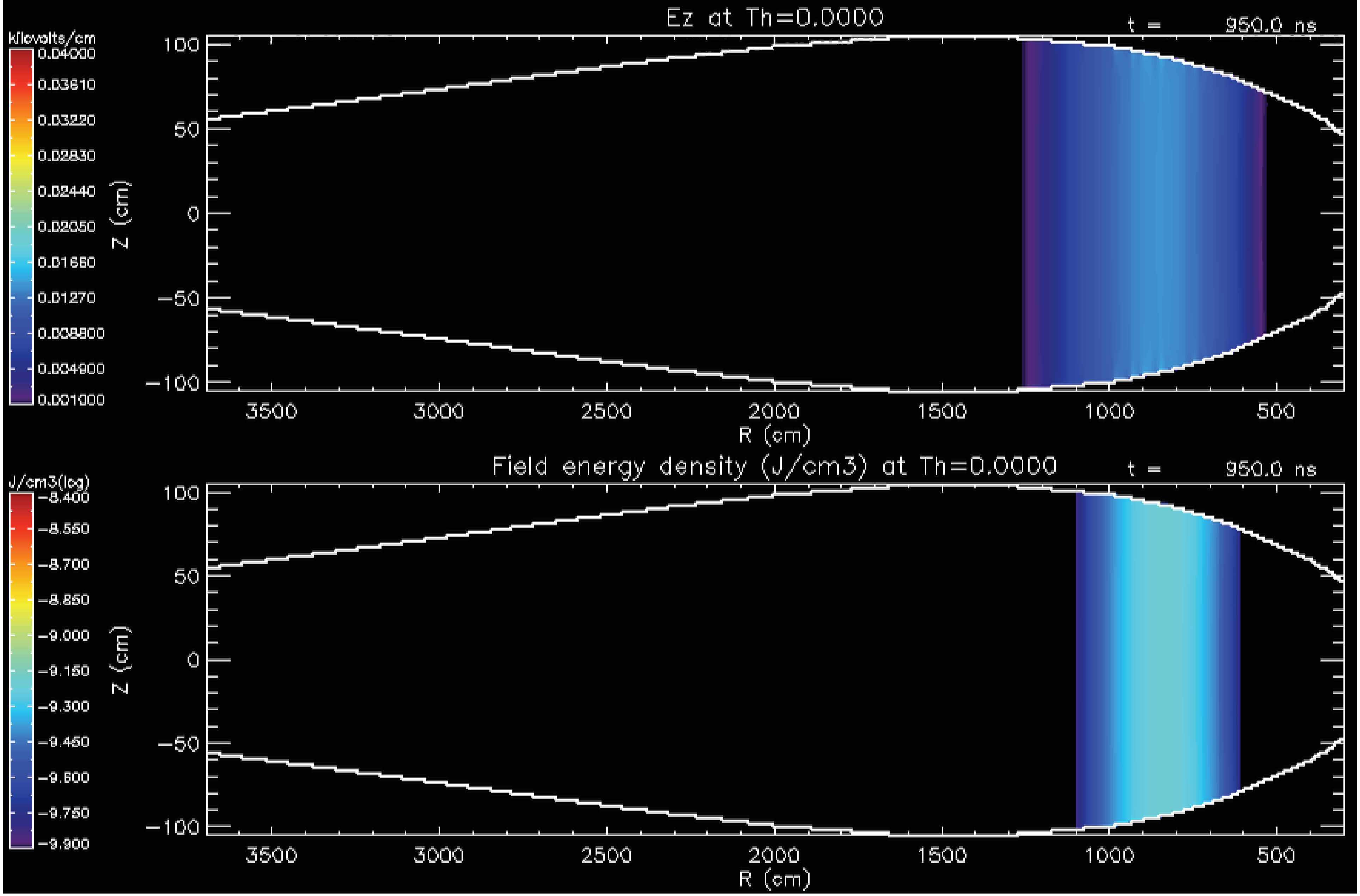


water-insulated
radial-transmission-line
impedance transformers

The radial transformers have the following characteristics:

- The *input impedance* of the transformers is matched to that of the LTD system.
- The *output impedance* is matched to that of the stack-MITL system.
- The *impedance is transformed in a gradual manner* from the input to output values to maximize the power-transport efficiency.
- The transformers serve as *high-pass filters* that sharpen the power pulse.
- The transformers *smooth azimuthal variations* in the forward-going pulse.
- The transformers allow the LTD modules to be fired at different times, to produce a desired current-pulse shape at the load.
- The transformers *shield external hardware* from EMP.

2D electromagnetic simulations confirm that an exponential transformer can be efficient.



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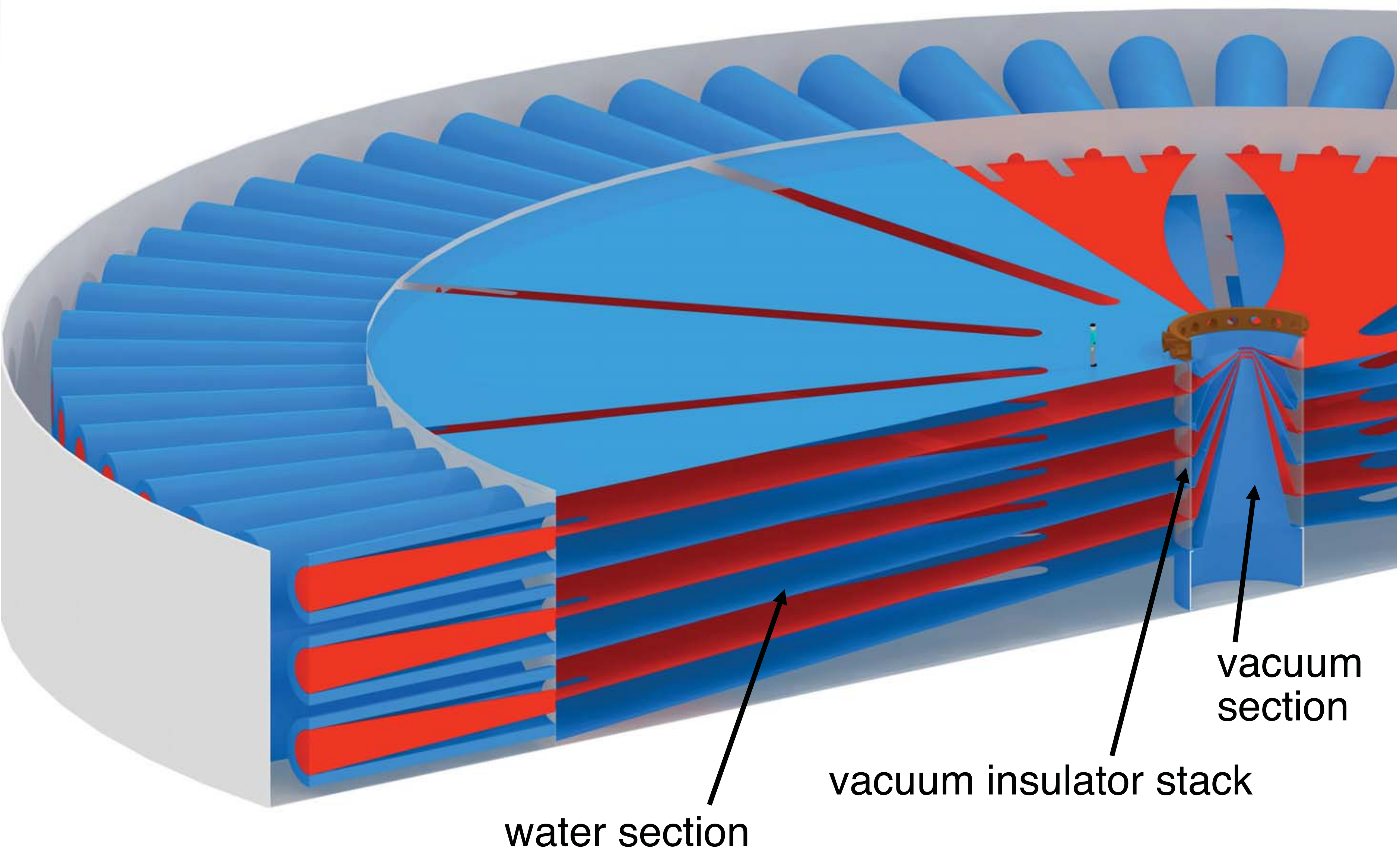
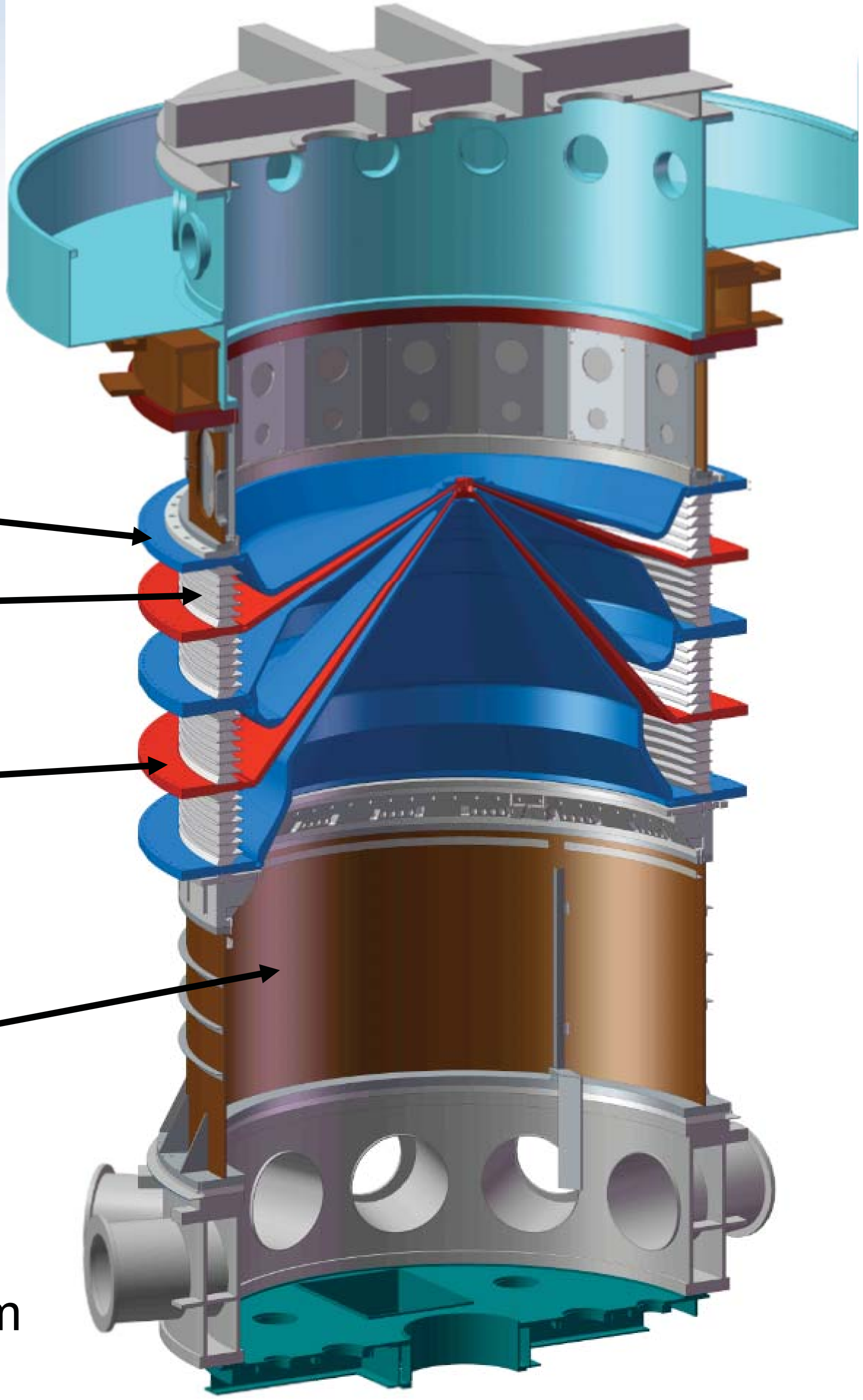
The accelerator's insulator stack servers as the hermetic interface between the vacuum and water sections.

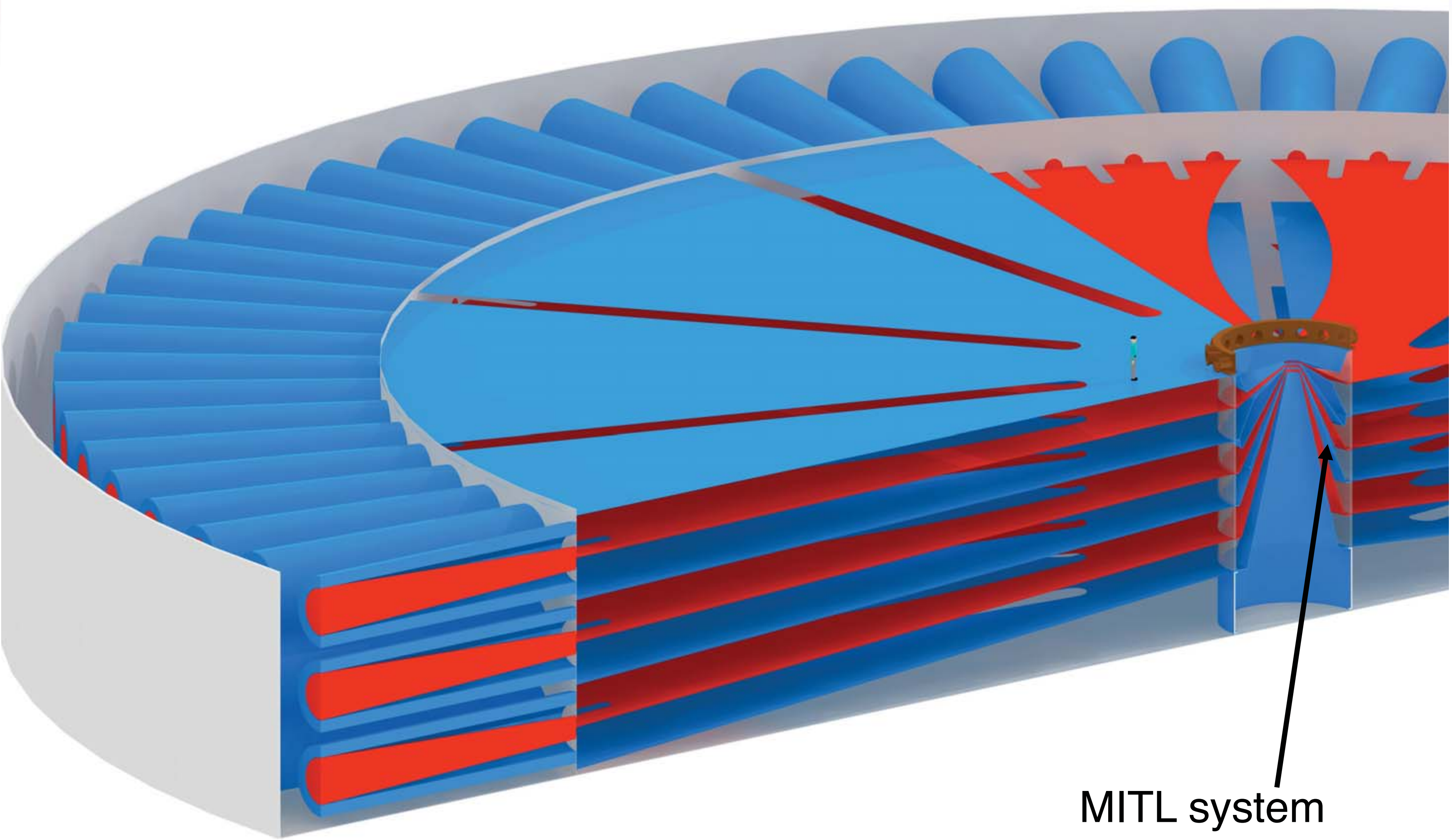


The stacks of the new machines would be *six*-level versions of the existing *four*-level Z-accelerator stack.



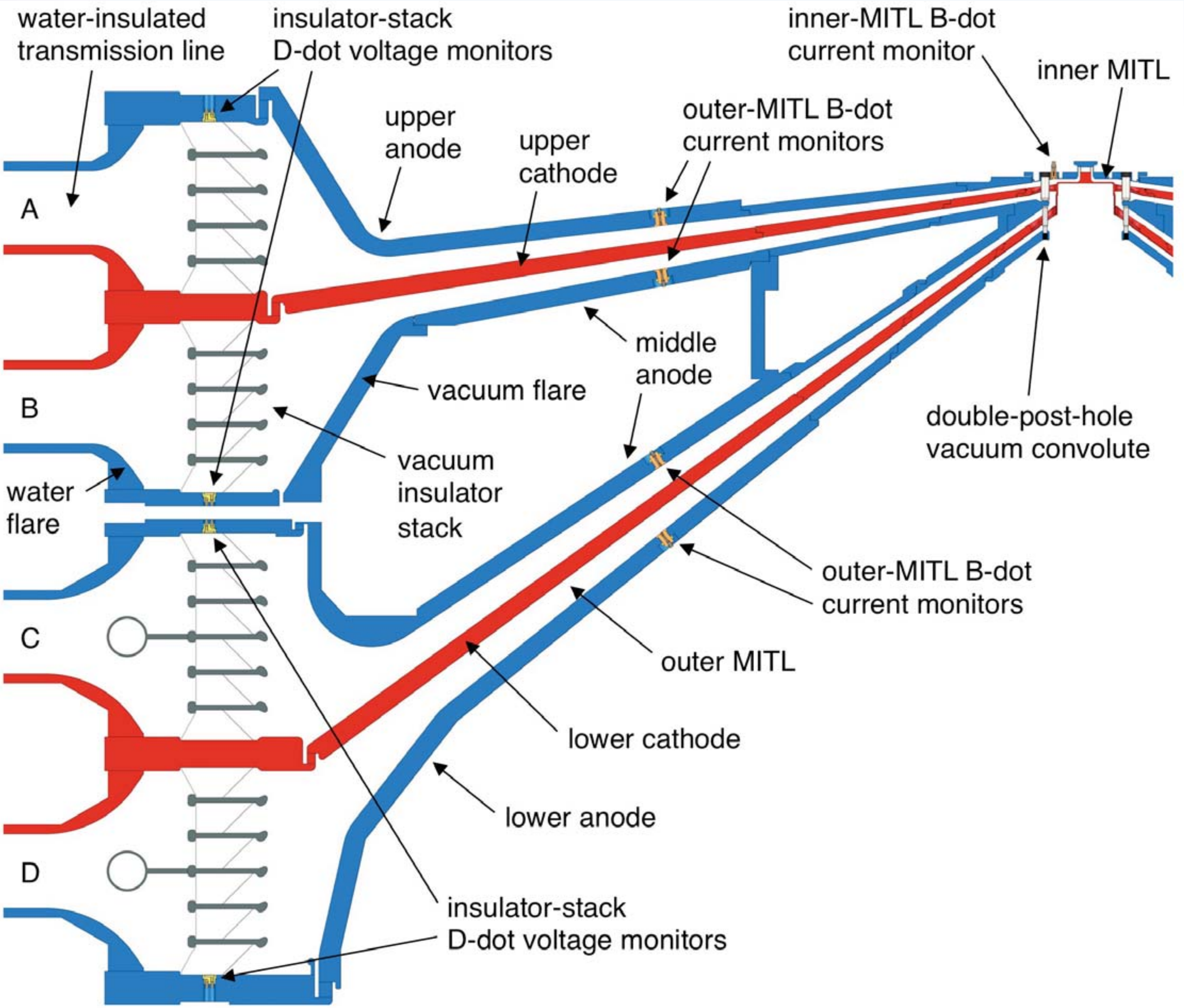
existing Z-accelerator stack-MITL system

A system of self magnetically insulated transmission lines (MITLs) transport the power pulse to the load.

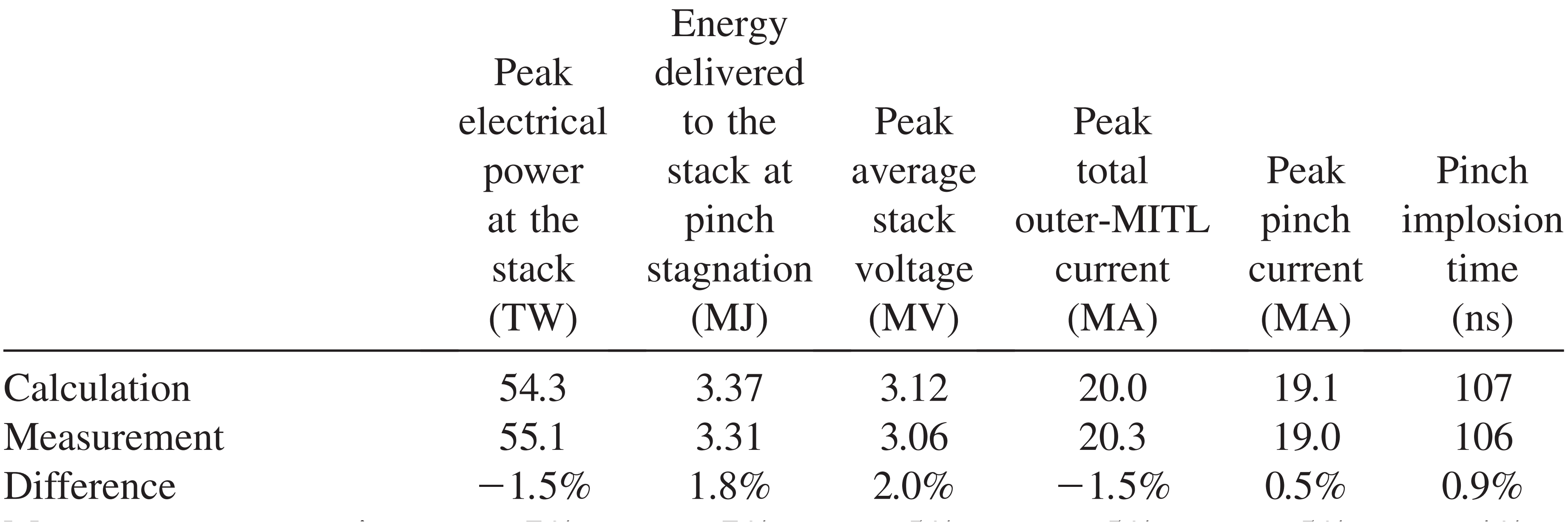


MITL system

The MITL systems of the new machines would be *six*-level versions of the *four*-level Z-accelerator system.



Our transmission-line circuit model of the stack-MITL system is consistent to within 5% with data taken on the original Z accelerator.



	Peak electrical power at the stack (TW)	Energy delivered to the stack at pinch stagnation (MJ)	Peak average stack voltage (MV)	Peak total outer-MITL current (MA)	Peak pinch current (MA)	Pinch implosion time (ns)
Calculation	54.3	3.37	3.12	20.0	19.1	107
Measurement	55.1	3.31	3.06	20.3	19.0	106
Difference	−1.5%	1.8%	2.0%	−1.5%	0.5%	0.9%

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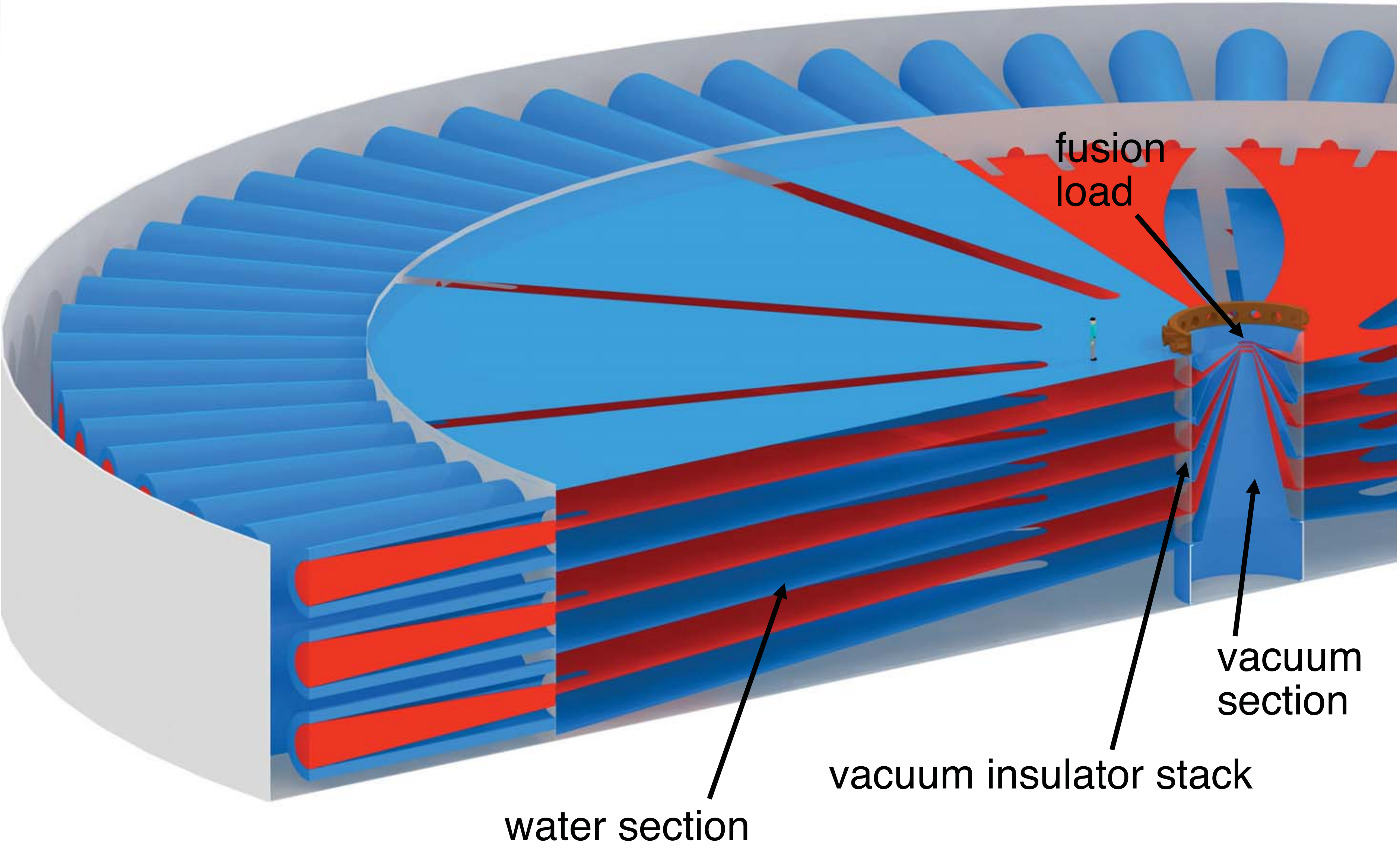
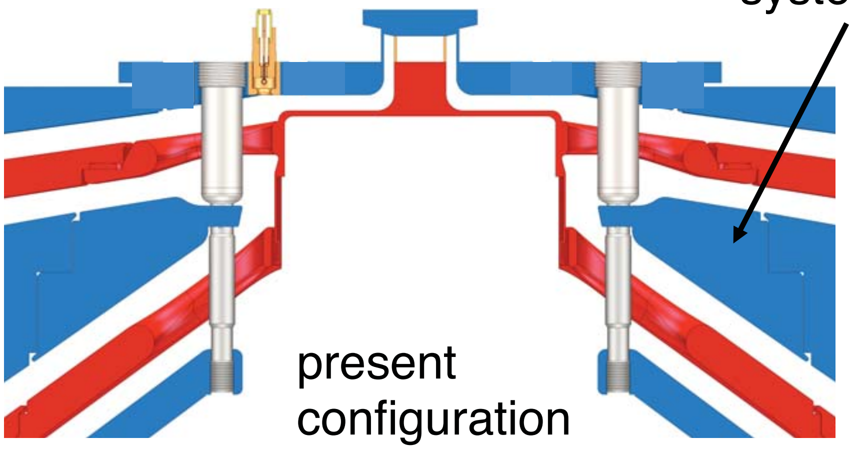
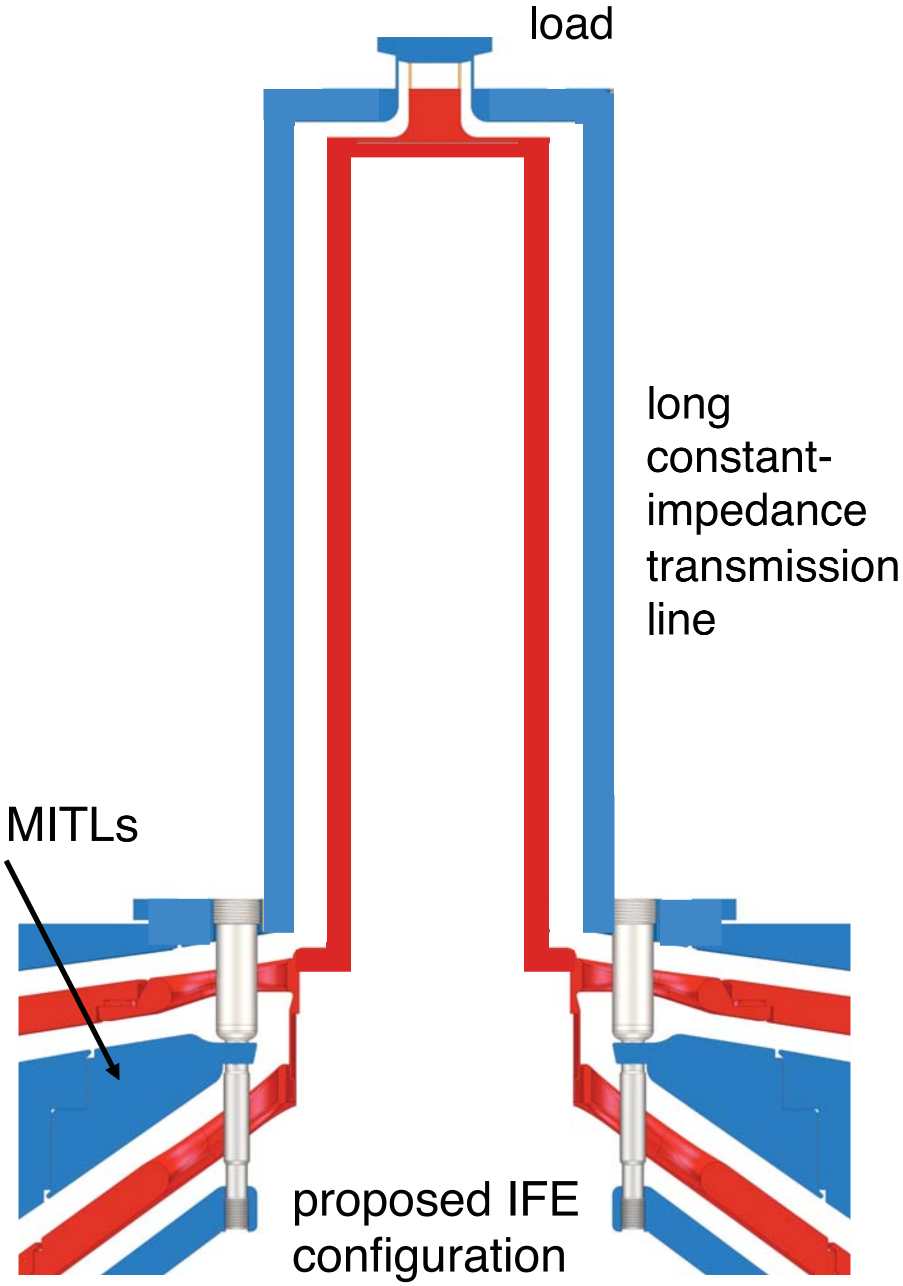
It would be challenging to build part of the power plant in the middle of the accelerator.



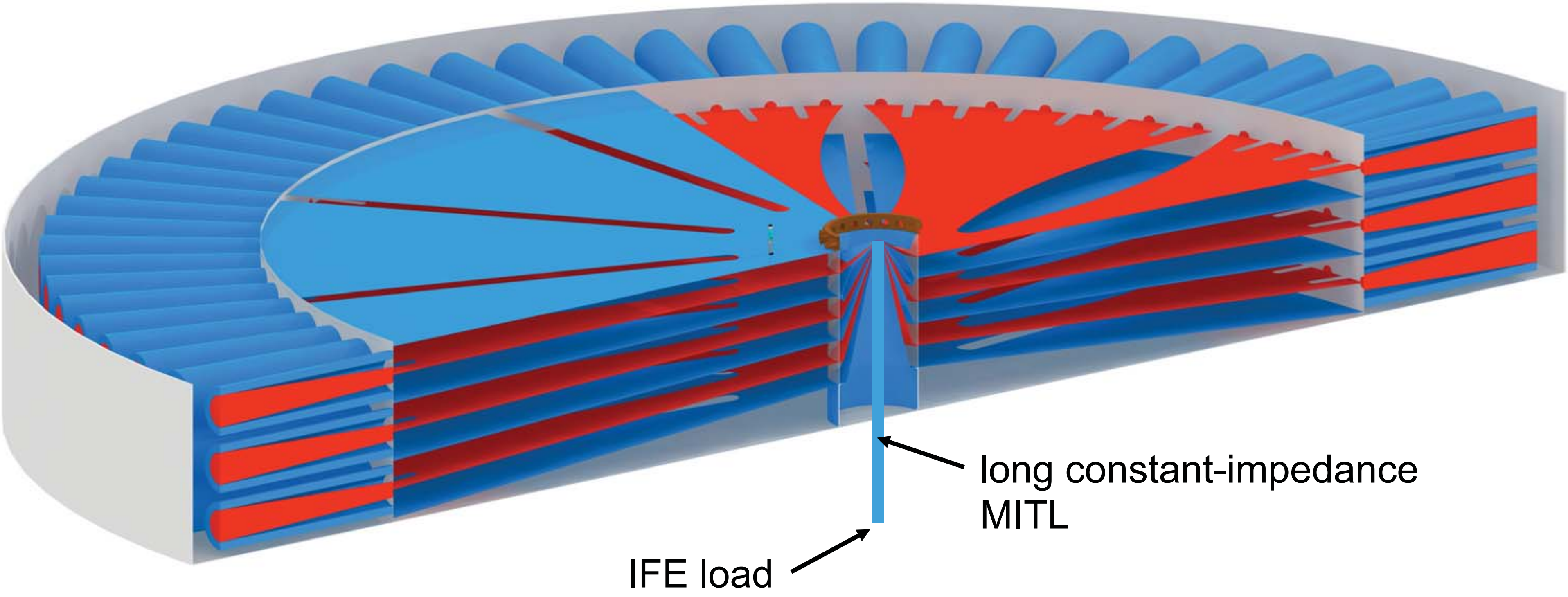
We have recently developed a new standoff concept for IFE.

- The accelerator would be designed to drive a long transmission line, which in turn would be designed to drive the load.
- The length of the line would be sufficient to transit-time isolate the load from the accelerator.
- The line would provide the standoff required to protect the accelerator from the fusion energy generated by the load.





The concept provides distance between the fusion event and the accelerator.



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We are documenting our work in peer-reviewed journal articles.

- Physical Review Special Topics - Accelerators and Beams (PRSTAB) is one of the world’s premier journals on accelerator physics.
- PRSTAB is sponsored by Argonne, Brookhaven, CERN, Fermilab, LBNL, Princeton Plasma Physics Lab, SLAC, and other top accelerator laboratories.
- Since its inception 14 years ago, the journal has published 54 papers in its section titled “Pulsed Power Accelerators, Technology, and Dynamics”.
- 32 of these papers (i.e., 59%) have been co-authored by Sandia’s Pulsed Power Sciences Center (1600).

Physical Review Special Topics–

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We could begin building a 2000-TW accelerator today.

- At a high level, the accelerator would consist of a large number of identical LC circuits, and a system of transmission lines that connect these circuits to a load.

- The *time constant* of each LC circuit would be determined by the current-pulse width needed to achieve inertial fusion energy (IFE).

- The *number* of LC circuits would be determined by the peak current needed to achieve IFE.

- Distributing the electrical power produced by the accelerator over a large number of LC circuits would increase the lifetime of each circuit.

- Using a large number of LC circuits would reduce costs through economies of scale.

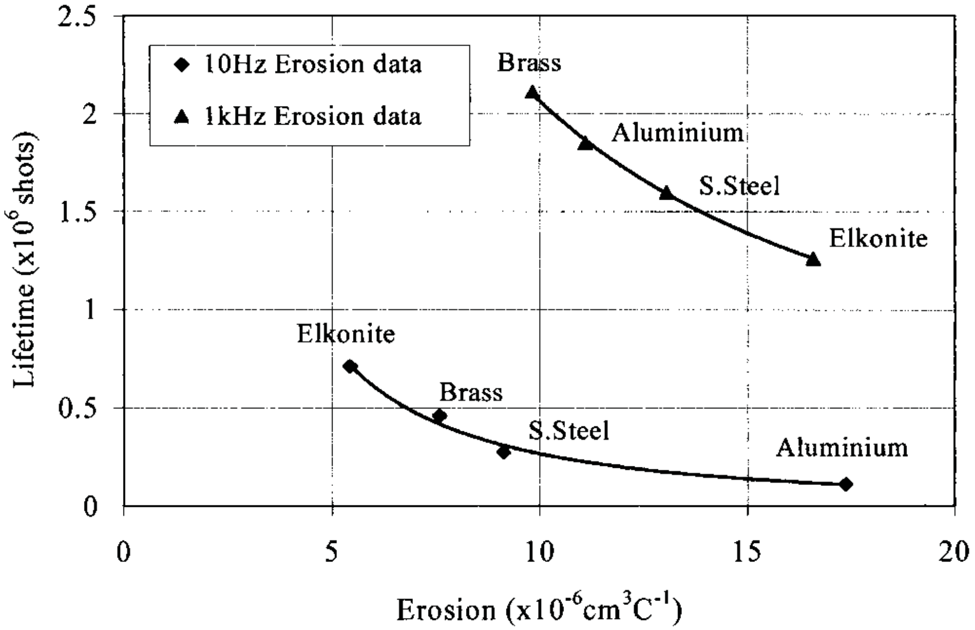
Our next speaker is Michael Cuneo, who is the Manager of the Radiation and Fusion Experiments Department at Sandia Labs.

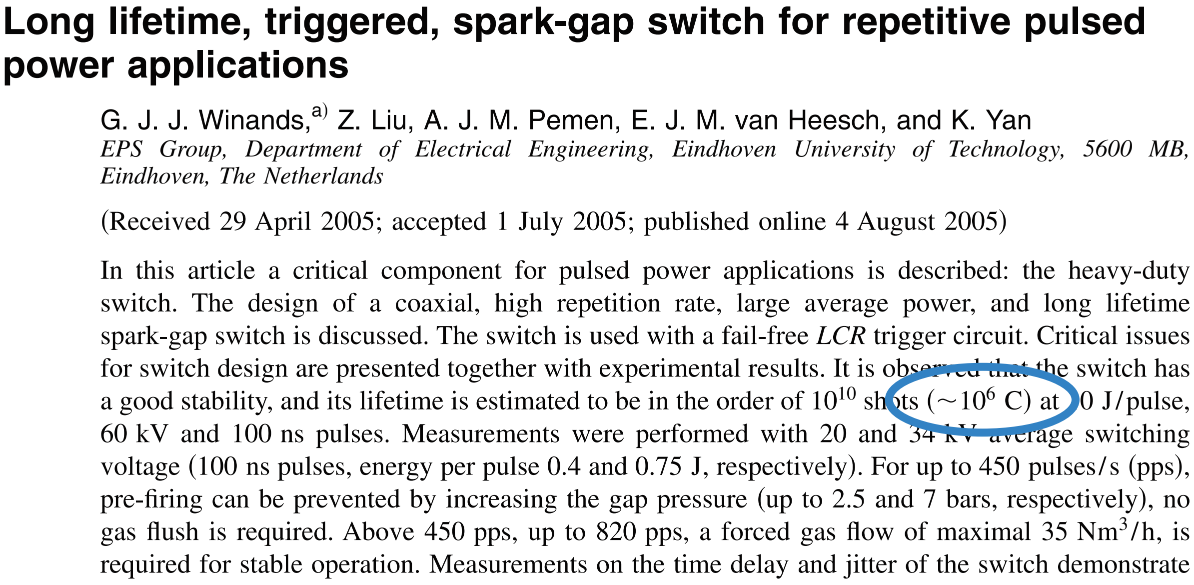
Back-up slide

It appears we can develop a switch that last 3 x 10^6 shots.

- Approximately one atom of electrode material is eroded per electron.
- For brass, the erosion rate is ~8 x 10^{-6} cm^3/C.
- To last 3 x 10^6 shots, each LTD switch would need to transfer 1.5 x 10^4 C.
- Hence each switch would need to be designed to continue working after losing 0.12 cm^3 of electrode material from each electrode.
- Our present LTD switches may have a lifetime ~10^3 C.
- Switch lifetimes of 10^4-10^6 C have been *inferred* in the literature.

Koutsoubis and MacGregor, J. Phys. D. 22, 1093 (2000).





Long lifetime, triggered, spark-gap switch for repetitive pulsed power applications

G. J. J. Winands,[a)] Z. Liu, A. J. M. Pemen, E. J. M. van Heesch, and K. Yan
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In this article a critical component for pulsed power applications is described: the heavy-duty switch. The design of a coaxial, high repetition rate, large average power, and long lifetime spark-gap switch is discussed. The switch is used with a fail-free *LCR* trigger circuit. Critical issues for switch design are presented together with experimental results. It is observed that the switch has a good stability, and its lifetime is estimated to be in the order of 10^{10} shots (~10^6 C) at 0 J/pulse, 60 kV and 100 ns pulses. Measurements were performed with 20 and 34 kV average switching voltage (100 ns pulses, energy per pulse 0.4 and 0.75 J, respectively). For up to 450 pulses/s (pps), pre-firing can be prevented by increasing the gap pressure (up to 2.5 and 7 bars, respectively), no gas flush is required. Above 450 pps, up to 820 pps, a forced gas flow of maximal 35 Nm^3/h, is required for stable operation. Measurements on the time delay and jitter of the switch demonstrate