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Sandia National Laboratories

18 - 22 June 2017

Conceptual design of a 900-TW pulsed-power accelerator driven by impedance-matched Marx generators

21st IEEE Pulsed Power Conference (Brighton, U.K.)

Sandia National Laboratories

Developing a new accelerator is a large team effort.

W. Stygar, K. Austin, T. Awe, J. Bailey, E. Breden, J. Calhoun, M. Campbell, R. Clark, R. Cooper, M. Cuneo, J. Edwards, J. Ennis, N. Frazier, M. Gomez, G. Greiser, F. Gruner, J. Hammer, M. Herrmann, B. Hutsel, C. Jennings, D. Jobe, O. Johns, B. Jones, M. Jones, P. Jones, K. Keilholtz, P. Knapp, G. Laity, D. Lamppa, K. LeChien, J. Leckbee, S. Lewis, D. Lucero, M. Martin, K. Matzen, M. Mazarakis, R. McKee, J. Moore, C. Mostrom, T. Mulville, D. Muron, K. Peterson, D. Pilkington, J. Porter, K. Raman, G. Rochau, D. Rose, M. Savage, M. Sceiford, P. Schmit, R. Schneider, B. Sims, D. Sinars, S. Slutz, R. Spielman, B. Stoltzfus, C. Verdon, R. Vesey, E. Waisman, E. Weinbrecht, D. Welch, and M. Wisher.

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Idaho State University

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TECHSOURCE™ Science and Engineering Consultants

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Voss Scientific

Outline

- Pulsed-power technology.
- Present state of the art: the Z accelerator.
- Unified approach to the design of next-generation machines.
- Jupiter: a high-yield thermonuclear-fusion accelerator.
- Prime-power source: impedance-matched Marx generators (IMGs).
- Power amplification by triggered emission of radiation.
- Idealized circuit model of Jupiter.
- Three types of *virtual* pulsed-power machines.
- Vacuum-power-flow experiments and facilities.
- Pulsed-power experiments and facilities.
- Publications.
- Summary.

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Pulsed-power accelerators deliver megajoules of energy to milligrams of matter on nanosecond time scales.

Such machines

- Achieve extreme states of matter over macroscopic volumes.
- Drive a wide variety of high-energy-density-physics experiments.

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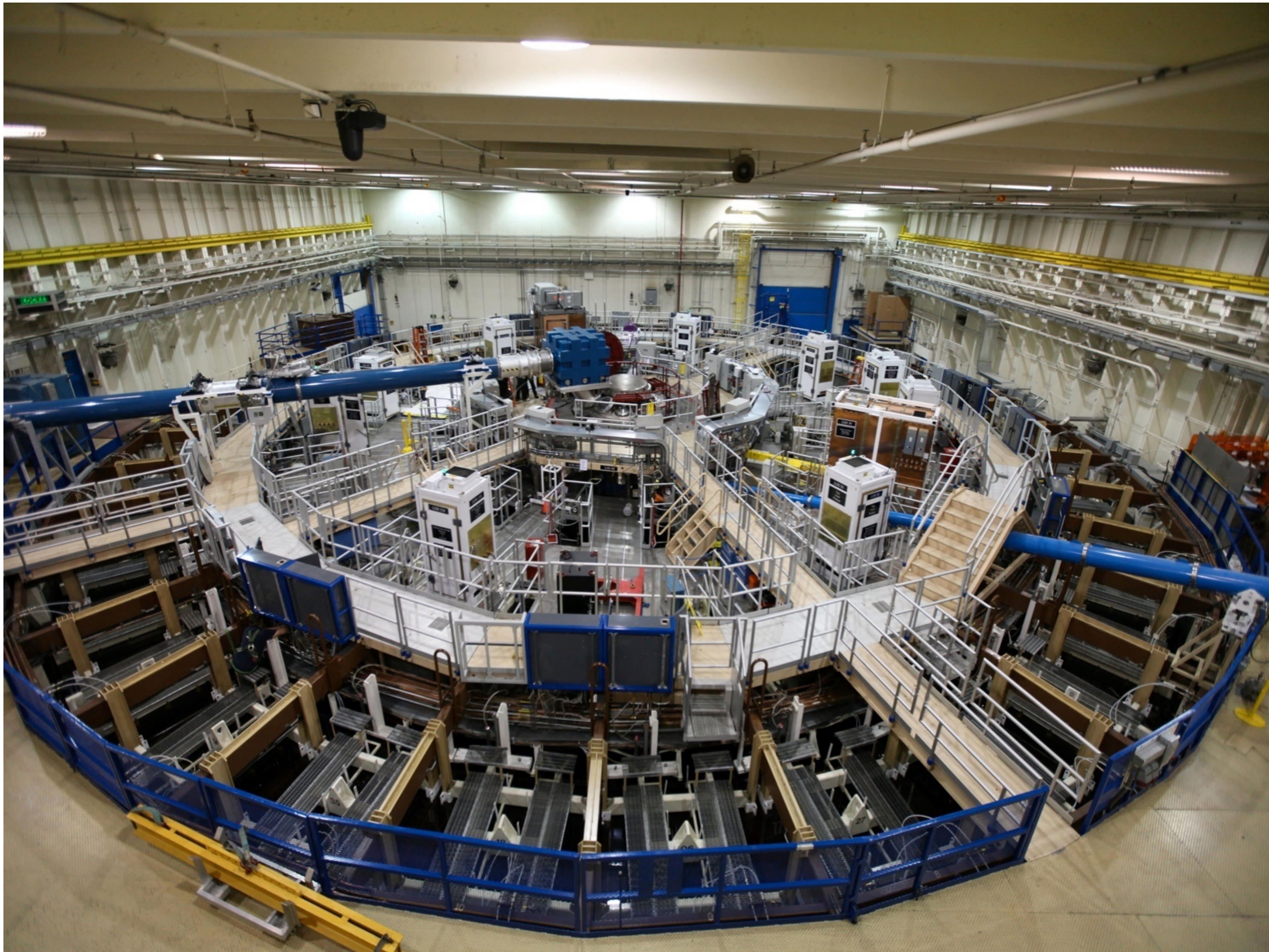
Sandia's Z accelerator is presently the world's largest and most powerful pulsed-power machine.

E_{stored} = 20 MJ	V_{stack} = 4 MV	I_{load} = 26 MA	$E_{radiated}$ = 2.3 MJ
$P_{electrical}$ = 85 TW	L_{vacuum} = 12 nH	$\tau_{implosion}$ = 130 ns	diameter = 33 m

- Since 1997 we have conducted, on average, 150 Z shots each year.
- To date, we have conducted 3000 shots altogether.
- Z shots drive a wide variety of experiments in support of the U.S. national-security mission.



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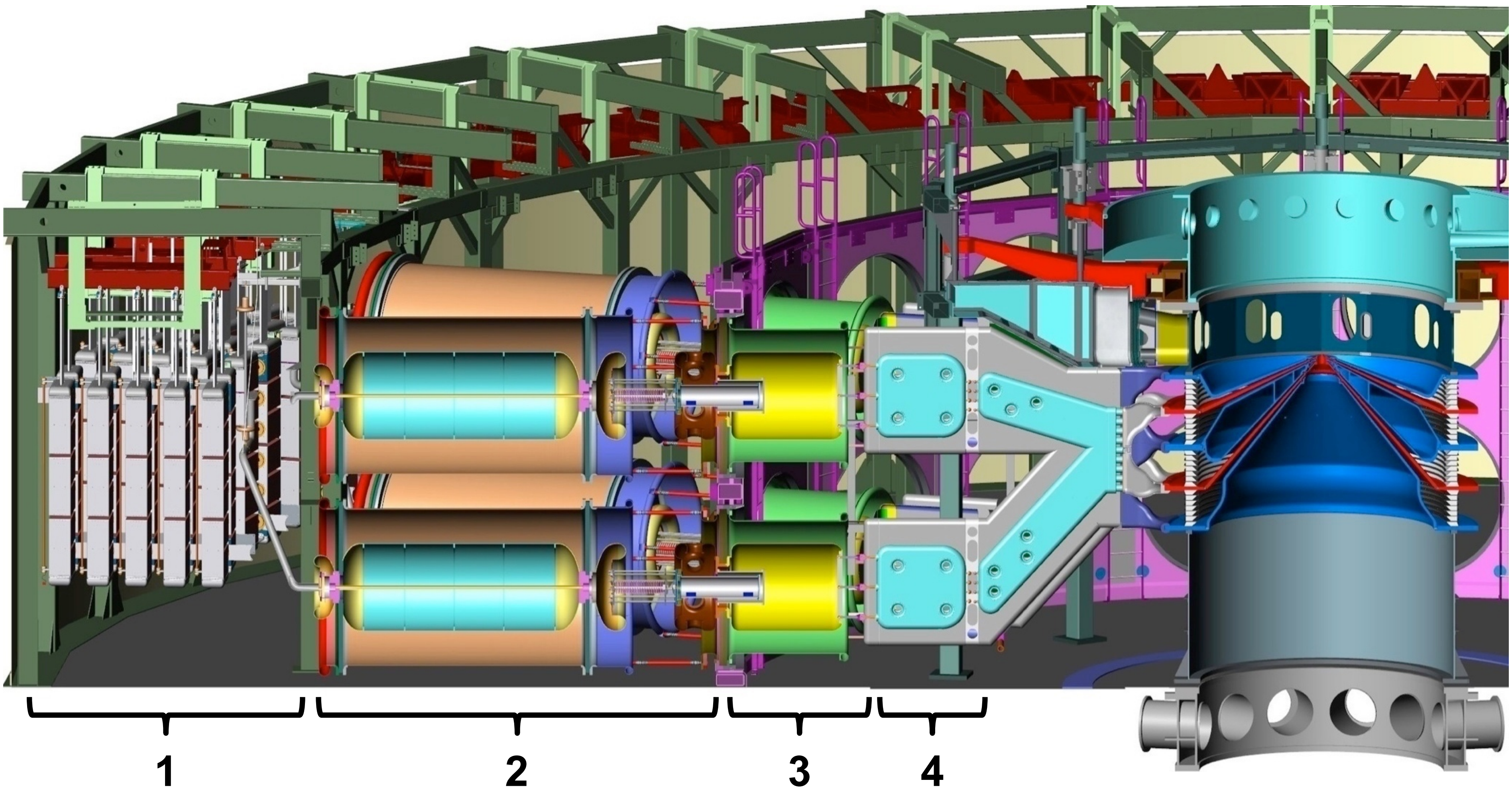
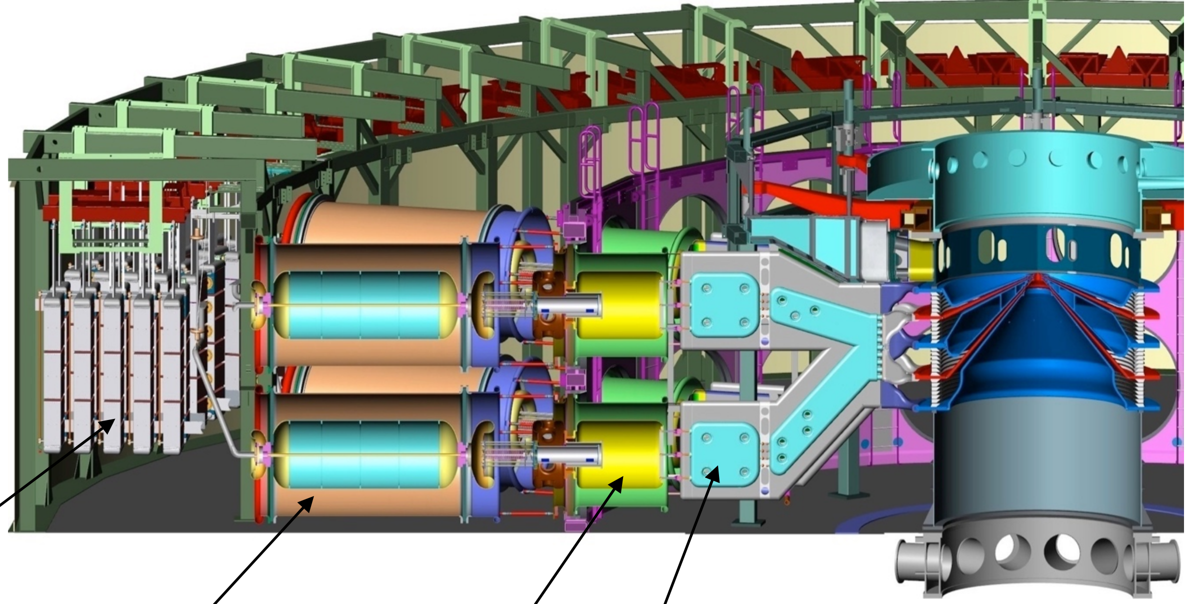
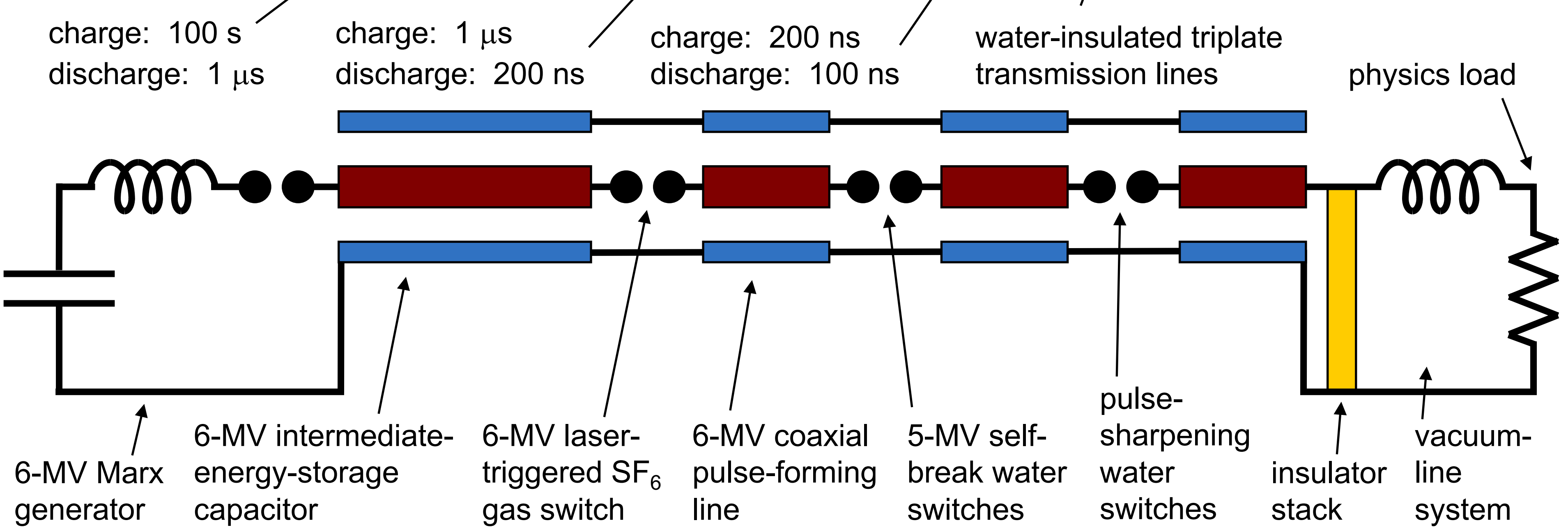
For decades, the community has designed pulsed-power accelerators with an architecture similar to that of Z.

- 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 *could* continue to build accelerators using this approach to machine design.

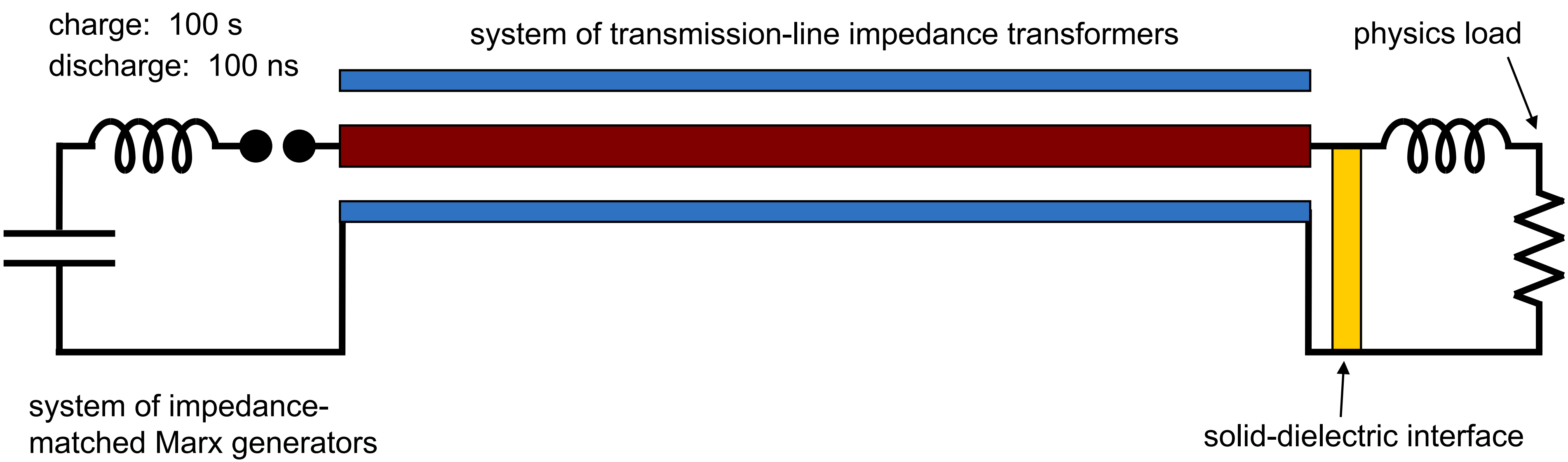




We propose *instead* to use a new unified approach to the design of next-generation accelerators.

The approach is based on six fundamental concepts:

- Single-stage electrical-pulse compression.
- Low-voltage switching.
- Impedance matching.
- Transit-time-isolated drive circuits.
- Economies of scale.
- Engineered safety.

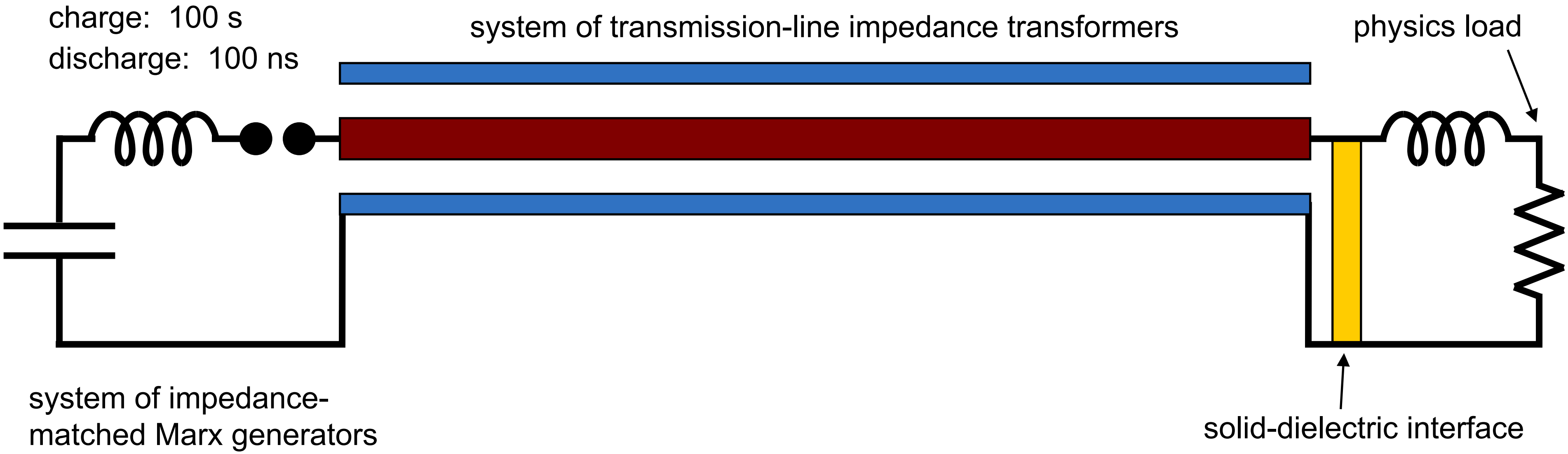


We have applied the new approach to the designs of several next-generation pulsed-power machines.

These accelerators

- Use DC-charged capacitors to generate a 100-ns electrical-power pulse in a single step.
- Use 200-kV gas switches to generate the power pulse (instead of 5- and 6-MV switches).
- Are impedance-matched throughout to maximize efficiency.
- Use drive circuits that are transit-time isolated for at least 300 ns to facilitate pulse shaping.
- Are powered by 10^2 – 10^5 identical "bricks" to provide economies of scale.
  - The rest of the machines consist of oil, water, plastic, and stainless steel.
- Do not use potentially lethal capacitors, SF_6 (or other asphyxiants or greenhouse gases), lead (or other neurotoxins), or high-power lasers (which present an eye hazard).

The following slides outline one of these next-generation accelerators.



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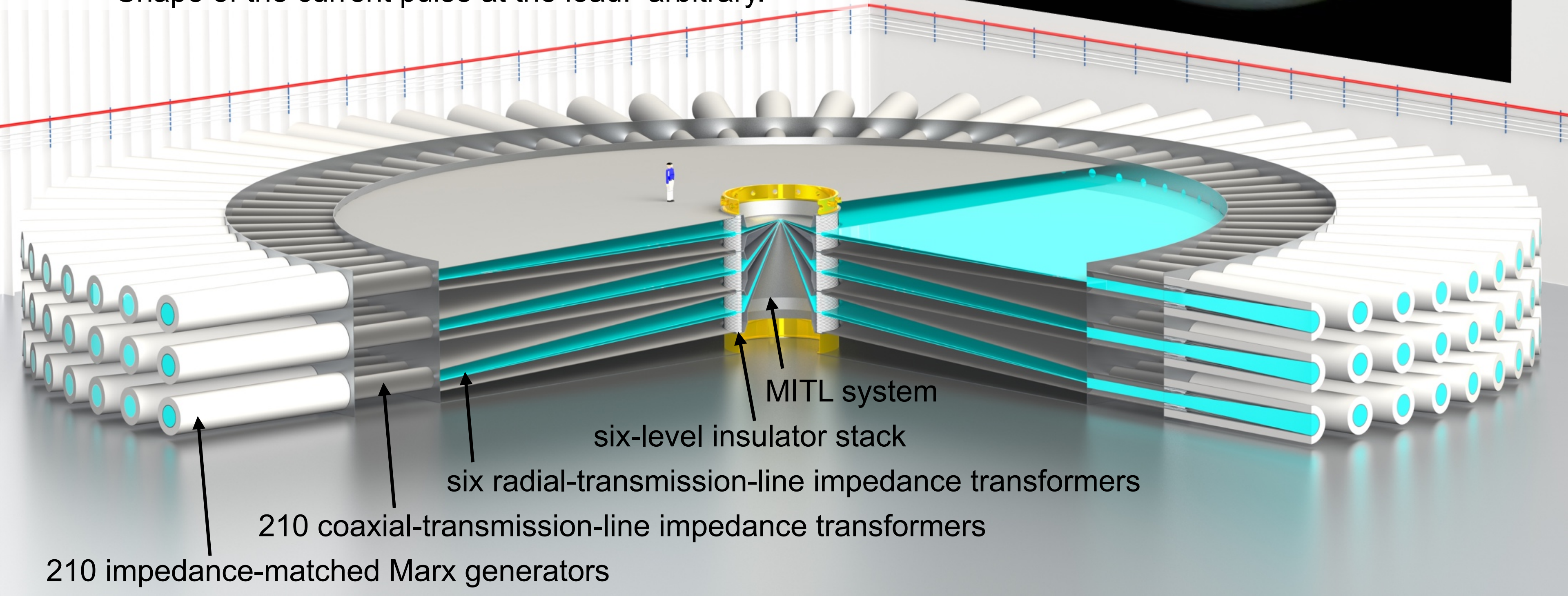
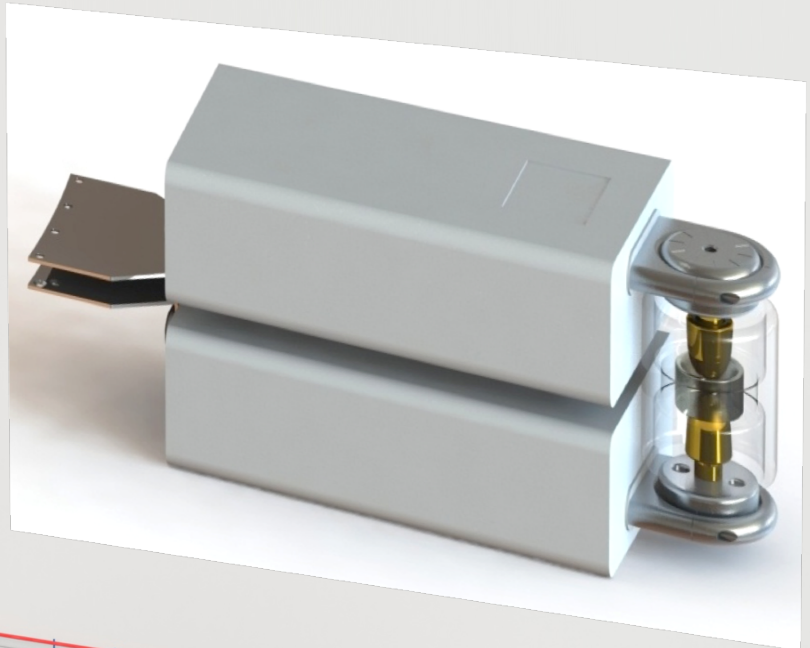
We have developed a conceptual design of an accelerator that is optimized for thermonuclear-fusion research.

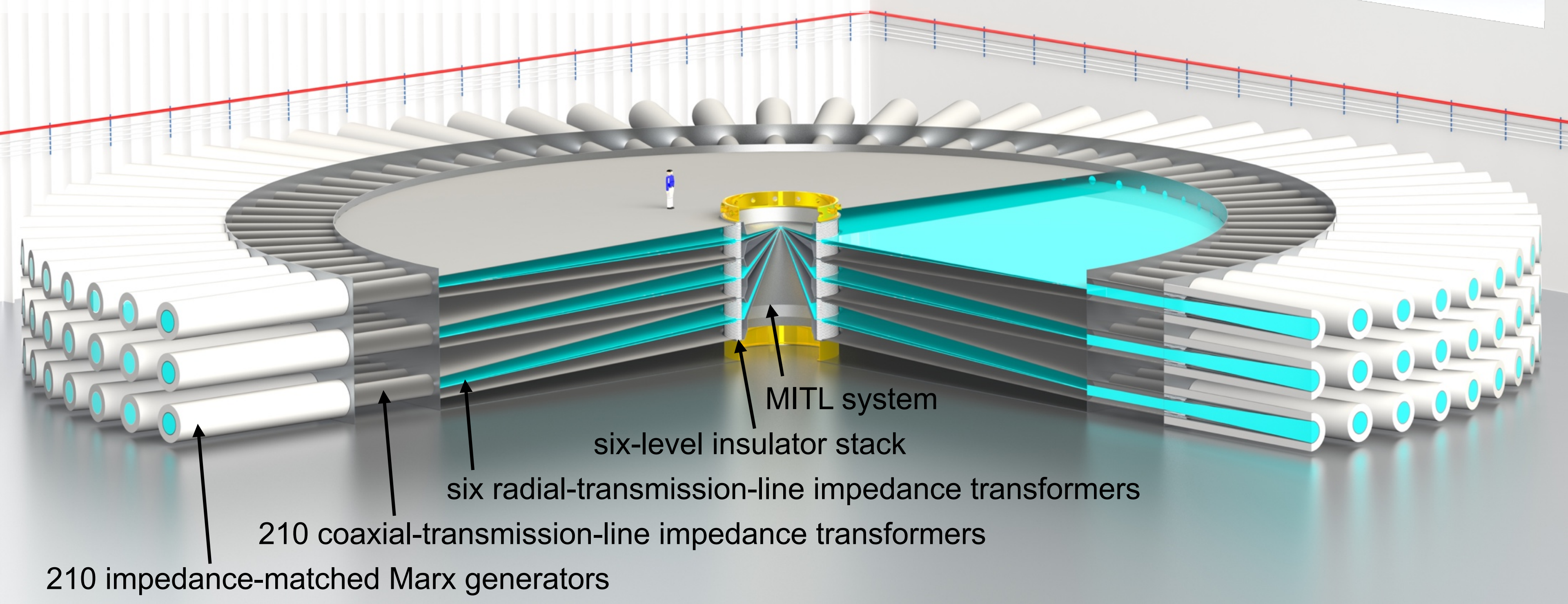
- We refer to the machine as Jupiter.
- Outer diameter: 72 m.
- Power source: 210 impedance-matched Marx generators (IMGs).
- Transit-time isolation between the IMGs: 300 ns.
- Energy storage: 141 MJ.
- Electrical power at the output of the IMGs: 960 TW.
- Shape of the current pulse at the load: arbitrary.



Each of the 210 impedance-matched Marx generators (IMGs) includes 840 ”bricks.”

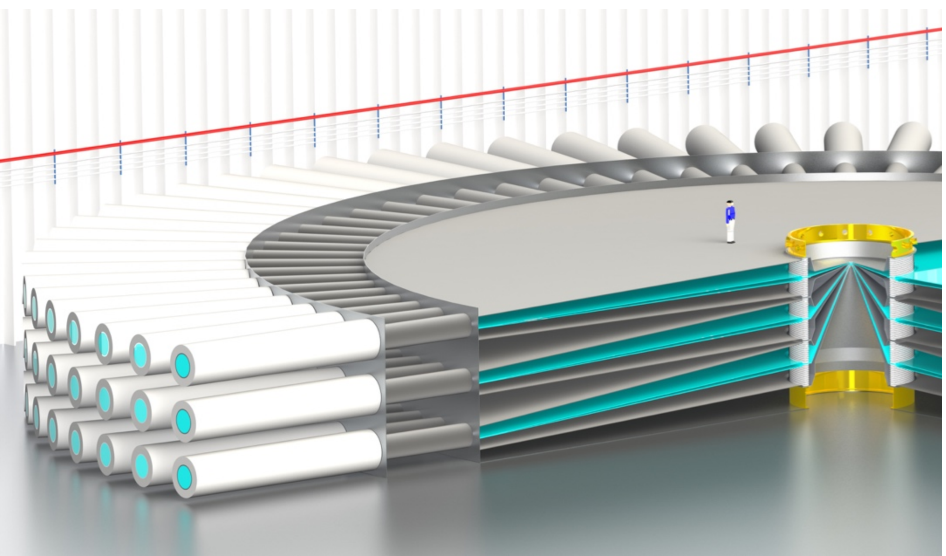
- A brick consists of two 100-kV 80-nF capacitors connected in series with a single 200-kV switch.
- Jupiter is powered by 176,400 bricks altogether.
- Economies of scale will reduce the cost per brick.
- The rest of the accelerator consists of oil, water, plastic, and stainless steel.

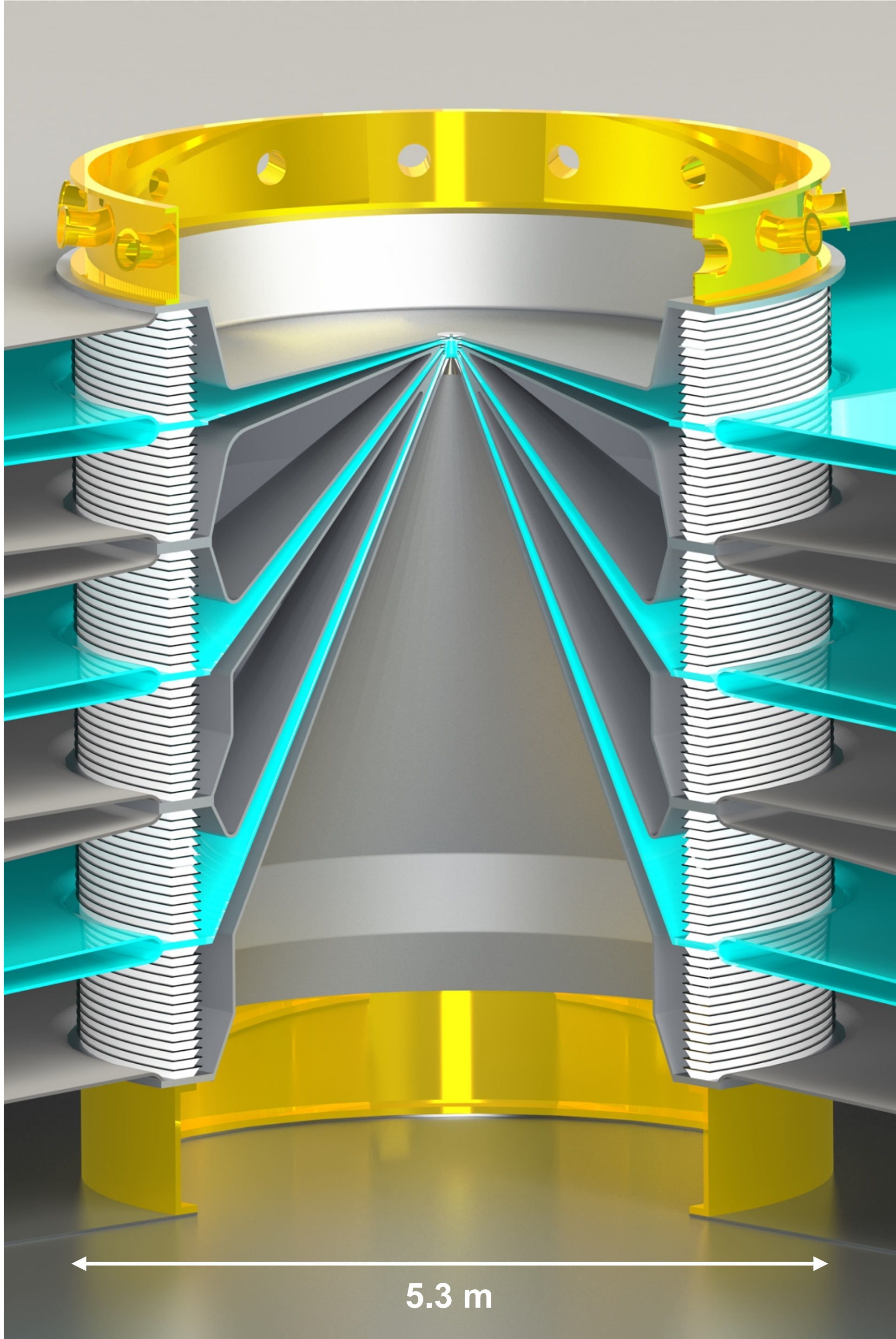




Jupiter drives a six-level centrally located vacuum section.

- Six 5.3-m-diameter insulator stacks serve as the water-vacuum interface.
- Six outer magnetically insulated transmission lines (MITLs) are connected in parallel at a 12-cm radius by a triple-post-hole convolute.
- The convolute sums the currents at the outputs of the six outer MITLs.
- A short single inner MITL delivers the combined current to the physics load.





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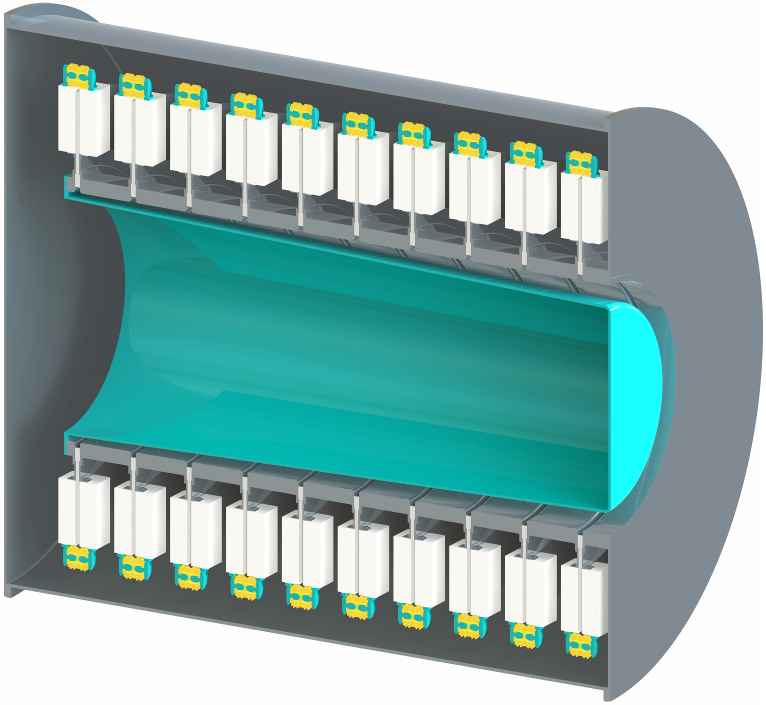
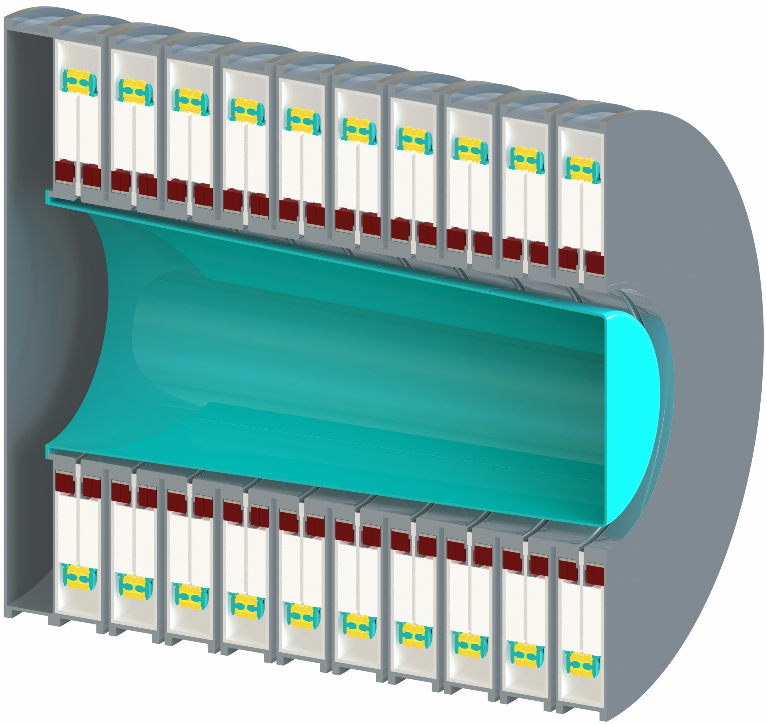
Jupiter is powered by impedance-matched Marx generators (IMGs).

- Each IMG module comprises 42 stages connected electrically in series.
- Each IMG stage is powered by 20 bricks distributed azimuthally within the stage and connected electrically in parallel.
- We are also considering the use of LTD modules as the prime-power source for Jupiter.
- We plan to build and evaluate prototype IMG and LTD modules in support of the Jupiter development effort.



10-stage IMG module with 20 bricks per stage



10-stage LTD module with 20 bricks per stage

Stygar, LeChien, Mazarakis et al., PRAB (2017).

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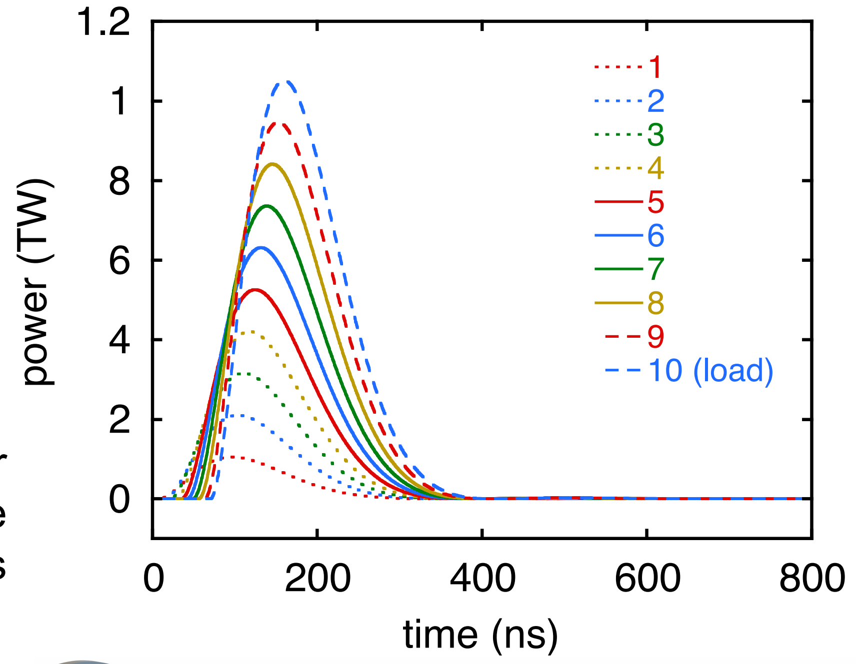
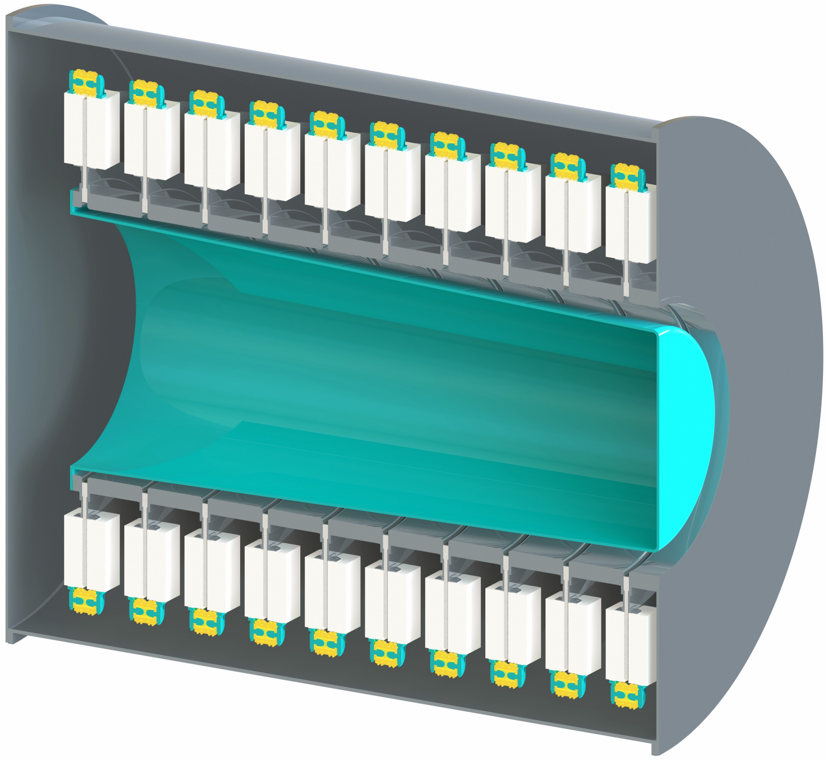
IMGs achieve power amplification by ***triggered*** emission of radiation.

- An IMG is a pulsed-power analogue of a laser.
- The power gain of an *n*-stage IMG module is *n*.
- The maximum energy efficiency of an IMG is ~ 90%.

output power at each of the 10 IMG stages

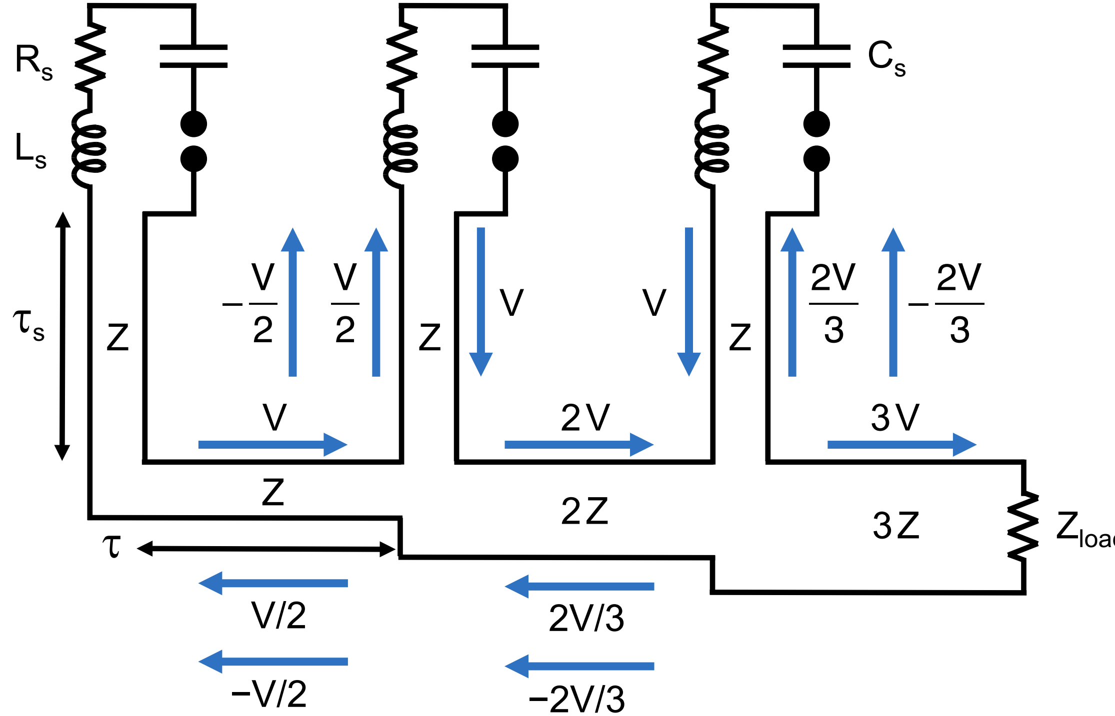


10-stage IMG module with 20 bricks per stage

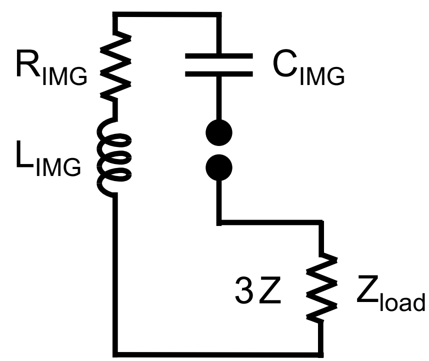


All the reflected and backward waves within an IMG cancel.

- The forward-going waves are all that are left.
- Hence a multi-stage IMG with multiple bricks per stage can be modeled as a single simple RLC circuit.



circuit model of a generalized 3-stage IMG



$$R_{IMG} = 3R_s$$

$$L_{IMG} = 3L_s$$

$$C_{IMG} = \frac{C_s}{3}$$

$$Z_{load} = 3Z$$

equivalent circuit model

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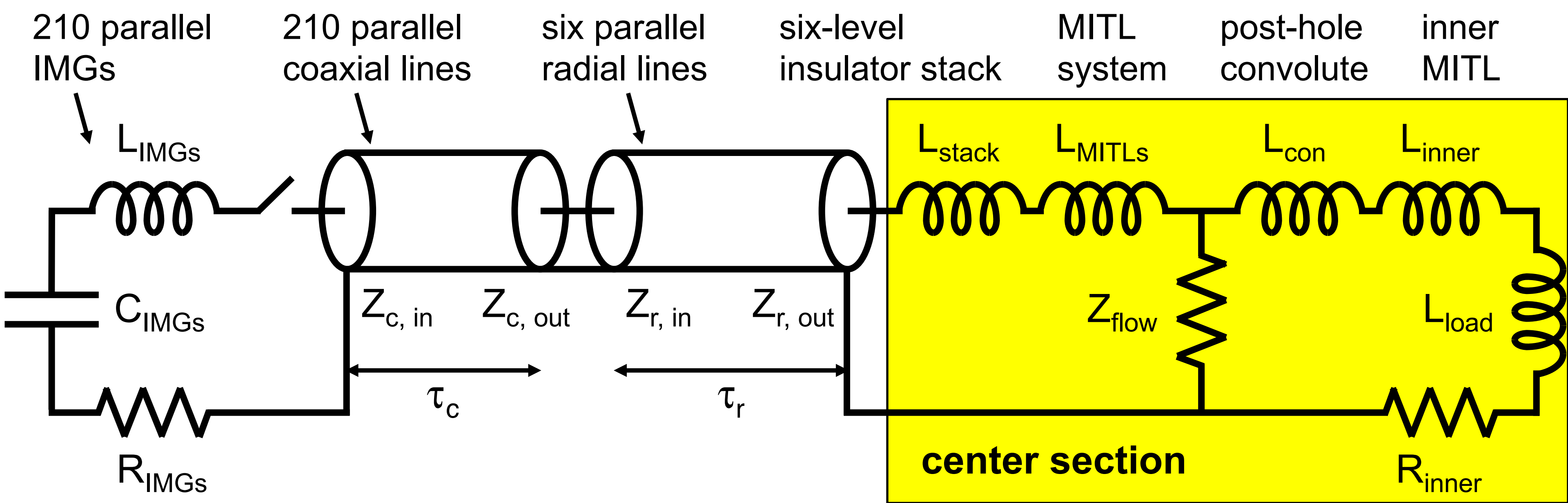
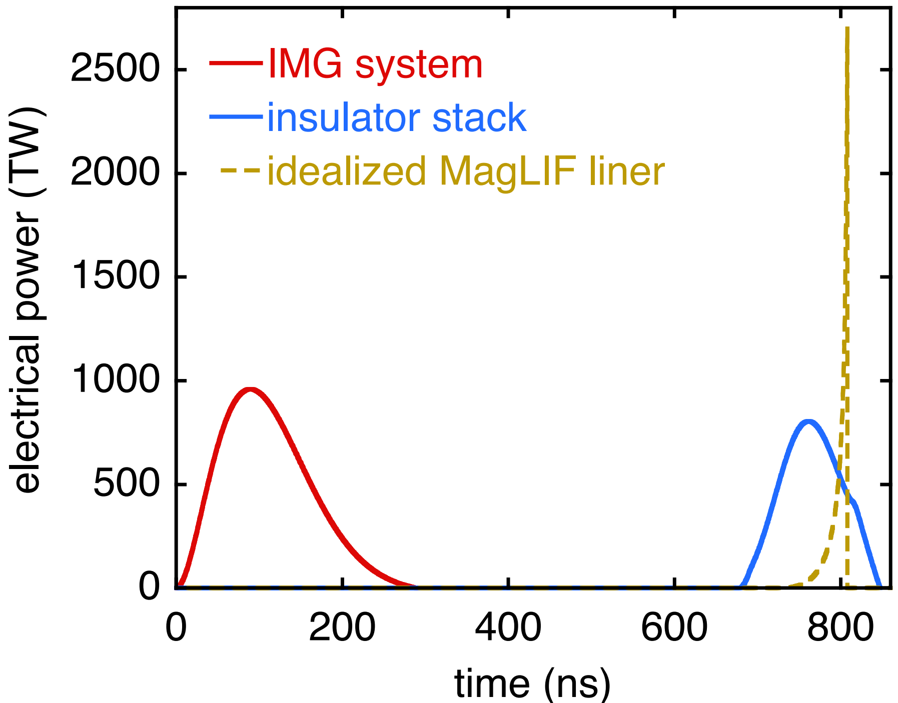
We have developed an idealized circuit model of Jupiter.

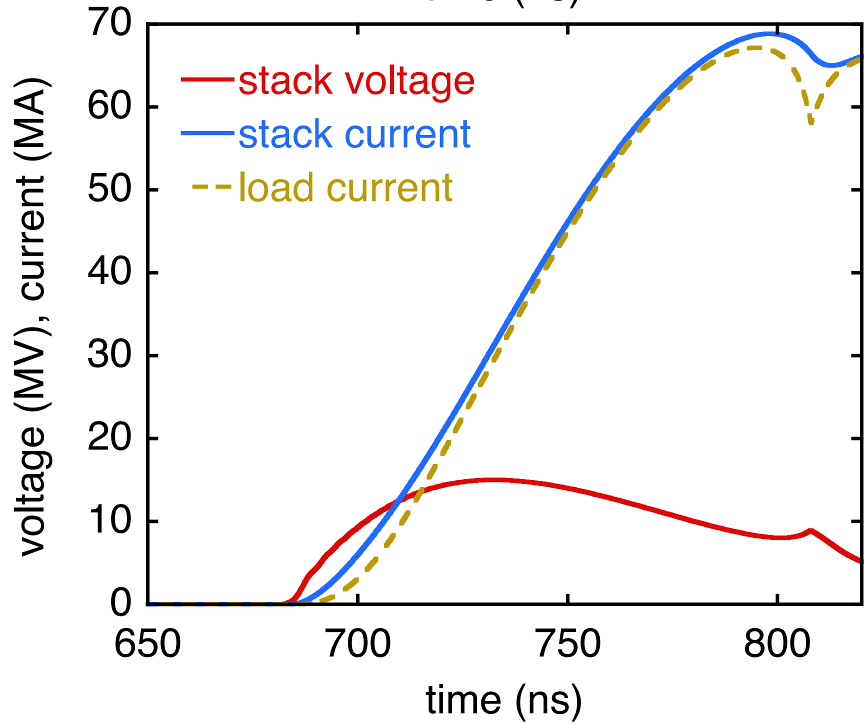
- Jupiter is powered by 210 IMG modules, which are electrically in parallel.
  - Each IMG module comprises 42 stages, which are connected in series.
  - Each IMG stage is powered by 20 bricks, which are connected in parallel.
- Each IMG module drives a water-insulated coaxial-transmission-line impedance transformer.
- The 210 coaxial lines couple the IMGs to six water-insulated radial-transmission-line impedance transformers.
- The radial transformers, in turn, drive a centrally located vacuum section.
- The center section includes a six-level insulator stack, six magnetically insulated transmission lines (MITLs), a triple-post-hole vacuum convolute, an inner MITL, and a physics load.



Results of circuit simulations:

- The peak electrical power at the output of the IMG system is 960 TW.
- The peak power at the insulator stack is 810 TW.
- The peak power delivered to an idealized magnetized-liner inertial-fusion (MagLIF) load is 2700 TW.
- The peak load current is 67 MA.
- The kinetic energy delivered to the load is 9.2 MJ.
- 2D magnetohydrodynamic (MHD) simulations by Slutz and colleagues suggest the thermonuclear-fusion yield will be as high as 7 GJ.





MagLIF publications:

Slutz et al., POP (2010).
Slutz and Vesey, PRL (2012).
McBride et al., PRL (2012).
Awe et al., PRL (2013).
McBride et al., POP (2013).
Awe et al., POP (2014).
Gomez et al., PRL (2014).
Schmit et al., PRL (2014).
Sefkow et al., POP (2014).
Gomez et al., POP (2015).
Hansen et al., POP (2015).
Harvey-Thompson et al., POP (2015).
Knapp et al., POP (2015).
McBride and Slutz, POP (2015).
McBride et al., POP (2016).
Awe et al., PRL (2016).
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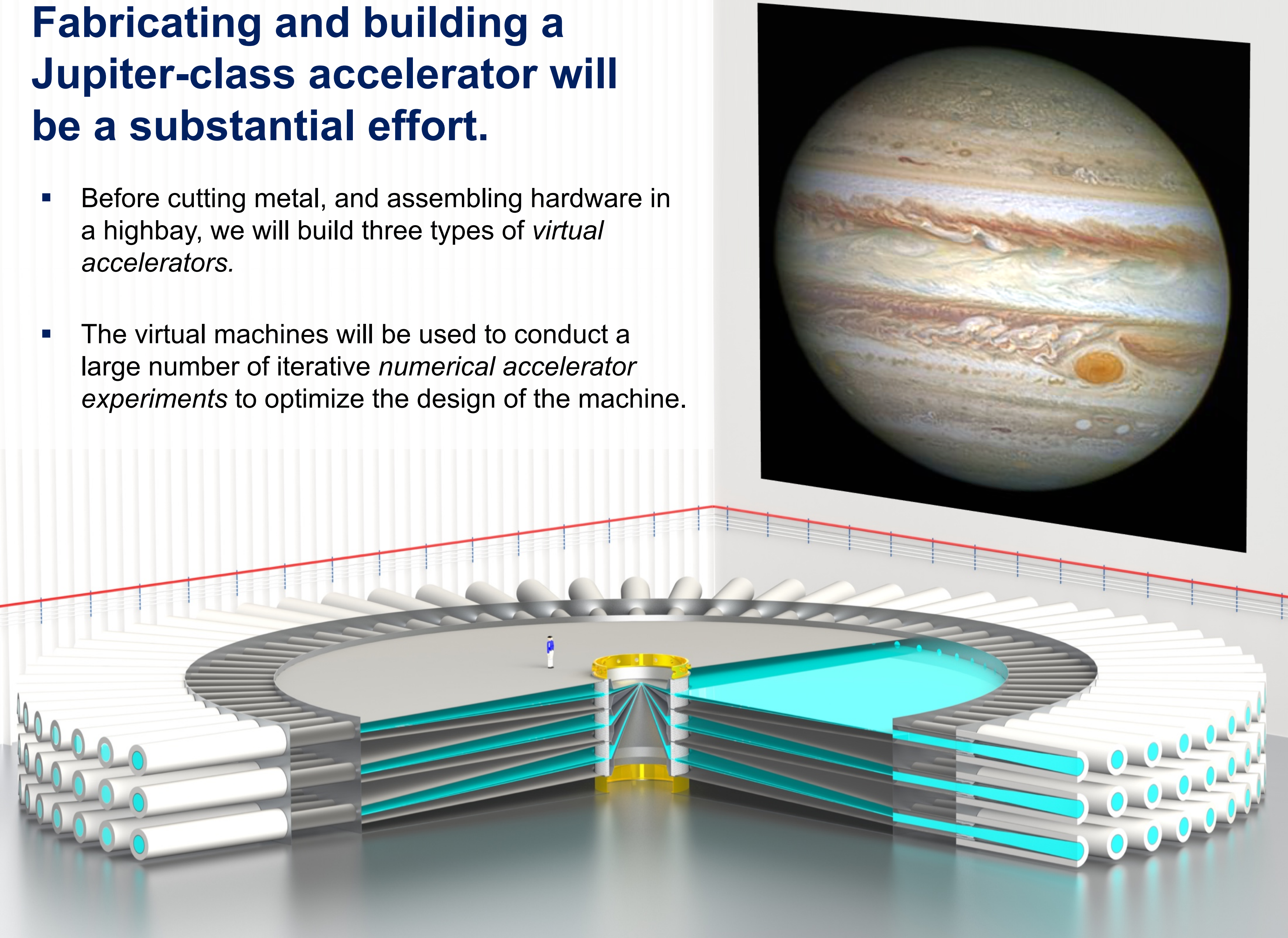
Fabricating and building a Jupiter-class accelerator will be a substantial effort.

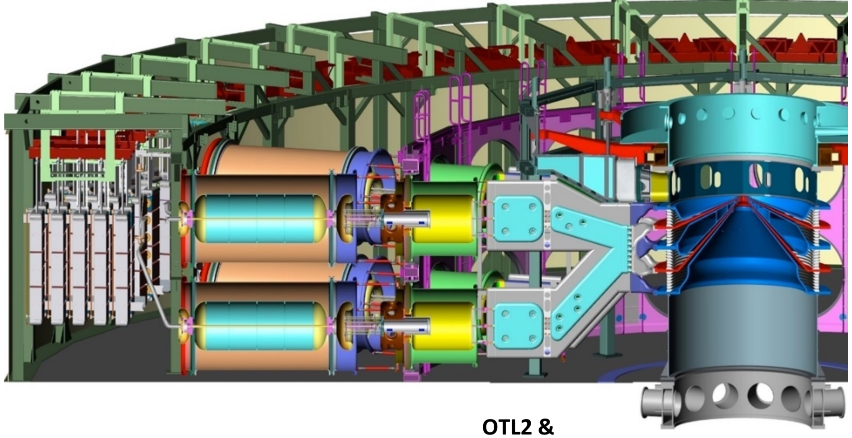
- Before cutting metal, and assembling hardware in a highbay, we will build three types of *virtual accelerators.*

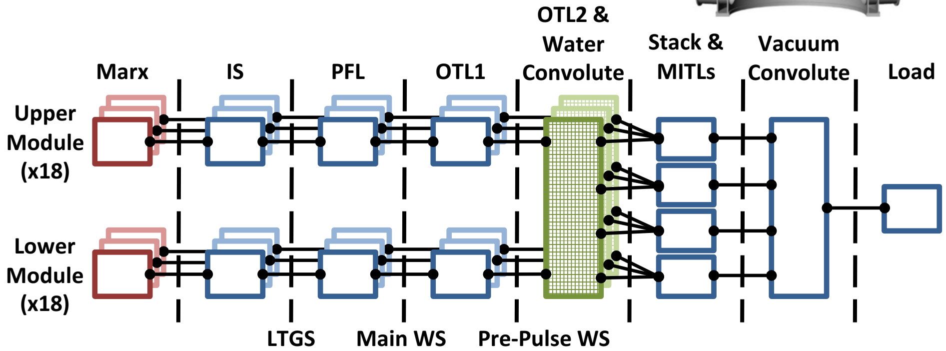
- The virtual machines will be used to conduct a large number of iterative *numerical accelerator experiments* to optimize the design of the machine.



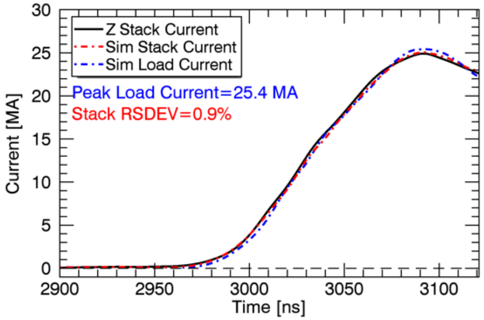
We will develop a physics-based transmission-line-circuit model of the entire Jupiter accelerator.

- The model will be used to conduct iterative *numerical accelerator experiments* to optimize the design of the accelerator.
- Brian Hutsel and colleagues have developed such a model of Z (Poster Session II, this conference).
- A circuit simulation of a Z shot is conducted on an office computer in 60 seconds.
- The circuit model of Z is consistent with experiment to within 5%.

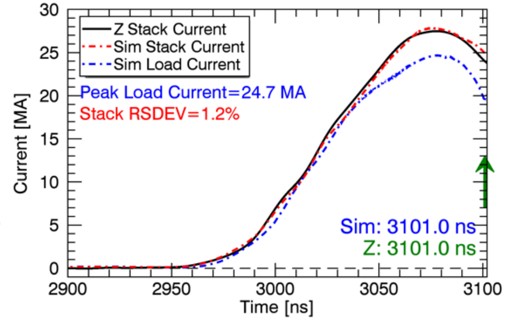




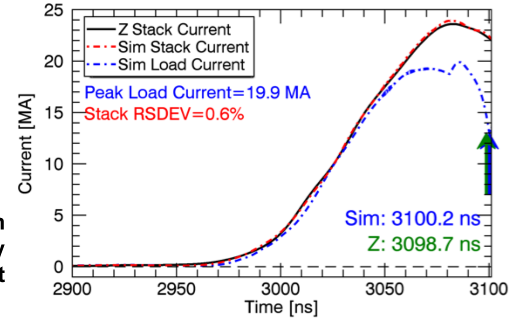
short-circuit synchronous shot



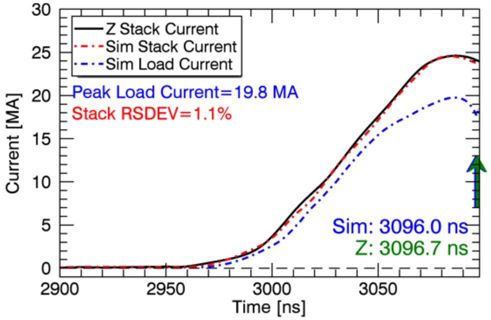
dynamic-hohlraum shot



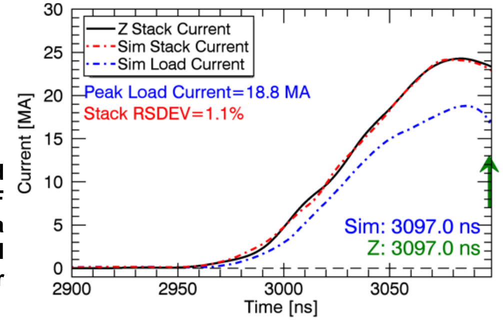
tungsten wire-array shot



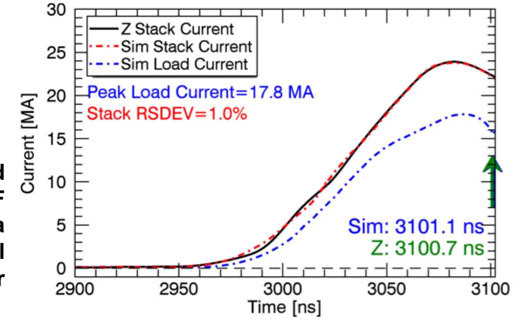
first-generation low-inductance MagLIF shot



standard MagLIF shot with a 7.5-mm-tall liner

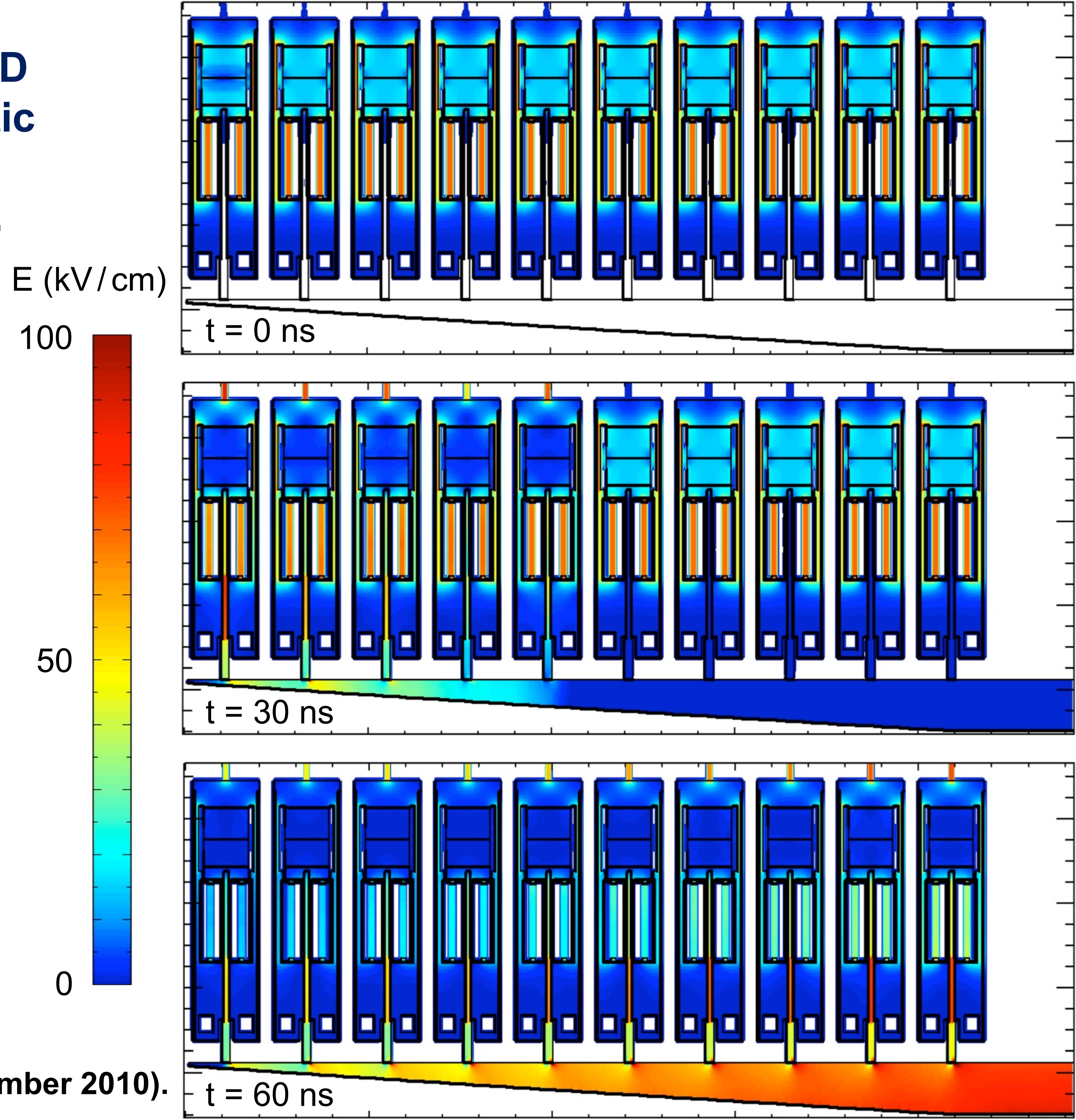


standard MagLIF shot with a 10-mm-tall liner



We will develop a 3D fully electromagnetic model of the entire Jupiter accelerator.

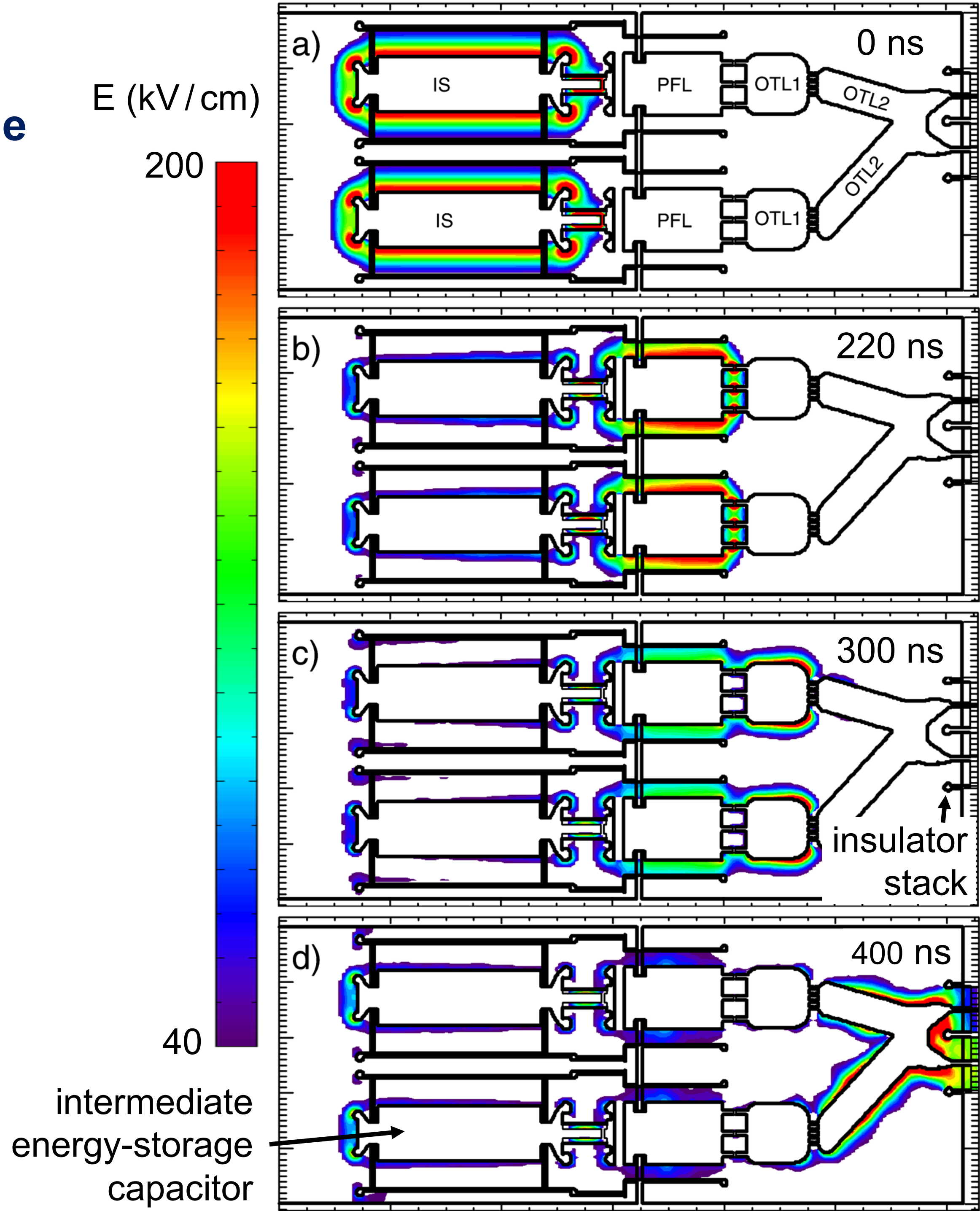
- Dave Rose, Dale Welch, and colleagues (Voss Scientific) have developed a 3D model of a 10-stage LTD module.
- These are 2D cross-sectional views of the 3D simulation.
- Simulation results agree with analytic and 2D calculations to within 2%.
- The simulations illustrate the flow of energy from the LTD capacitors to the load.
- The model is directly applicable to an IMG.



Rose et al, PRSTAB (September 2010).

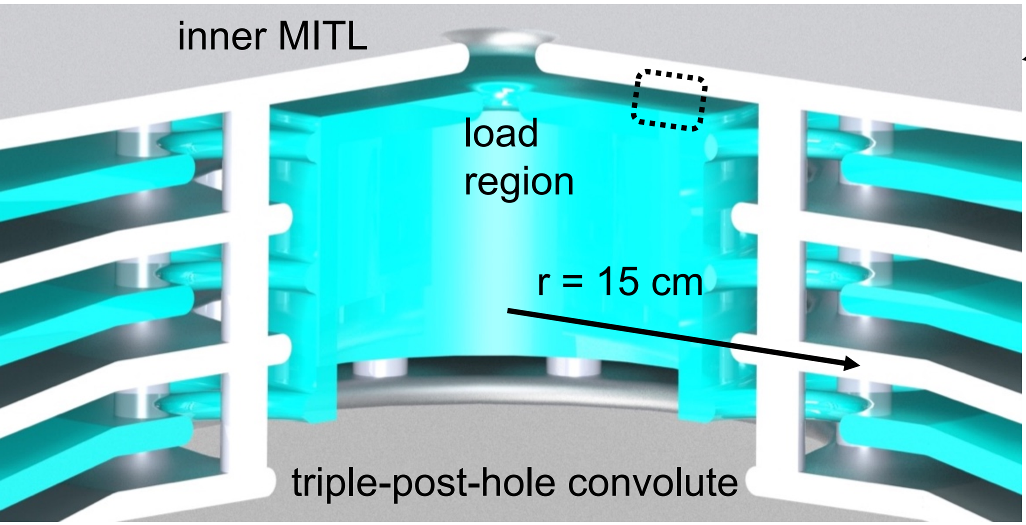
We will develop a 3D fully electromagnetic model of the entire Jupiter accelerator.

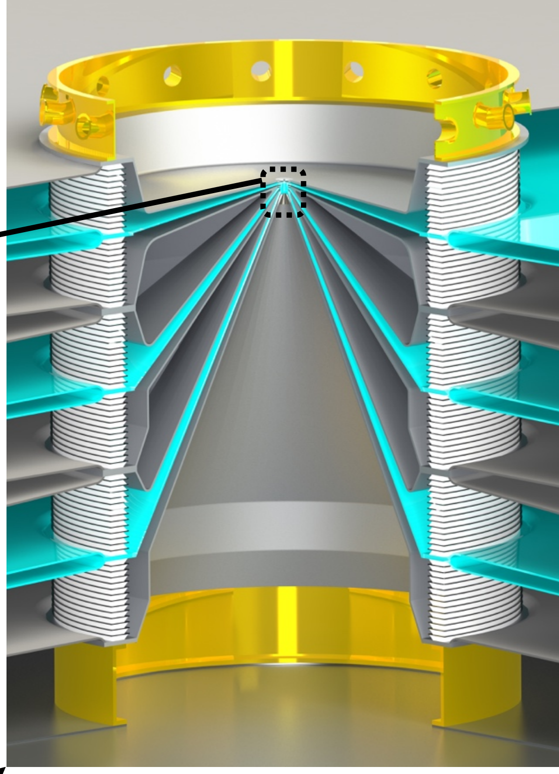
- Dave Rose, Dale Welch, and colleagues (Voss Scientific) have developed a 3D model of the entire water section of Z.
- These are 2D cross-sectional views of the 3D simulation.
- The simulations illustrate the flow of energy from Z's intermediate-store capacitors to the insulator stack.
- Simulation results agree with experiment to within ~5%.
- A 3D electromagnetic model of the entire Jupiter accelerator will be used to conduct iterative *numerical accelerator experiments*.
- The simulations will be used to optimize the design of Jupiter.

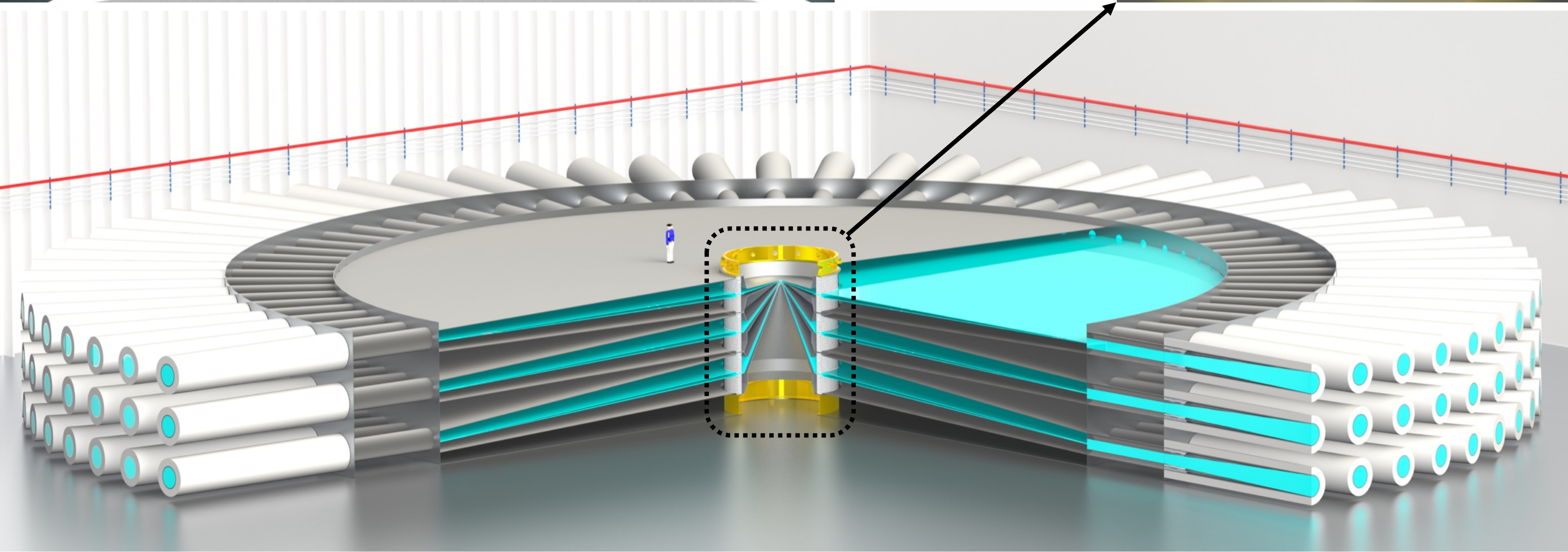


Rose et al., PRSTAB (January 2010).

We will develop a 3D fully electromagnetic, fully relativistic particle-in-cell (PIC) model of Jupiter’s MITL-convolute-load region.







A terawatt-class power pulse generates plasmas within a vacuum transmission line.

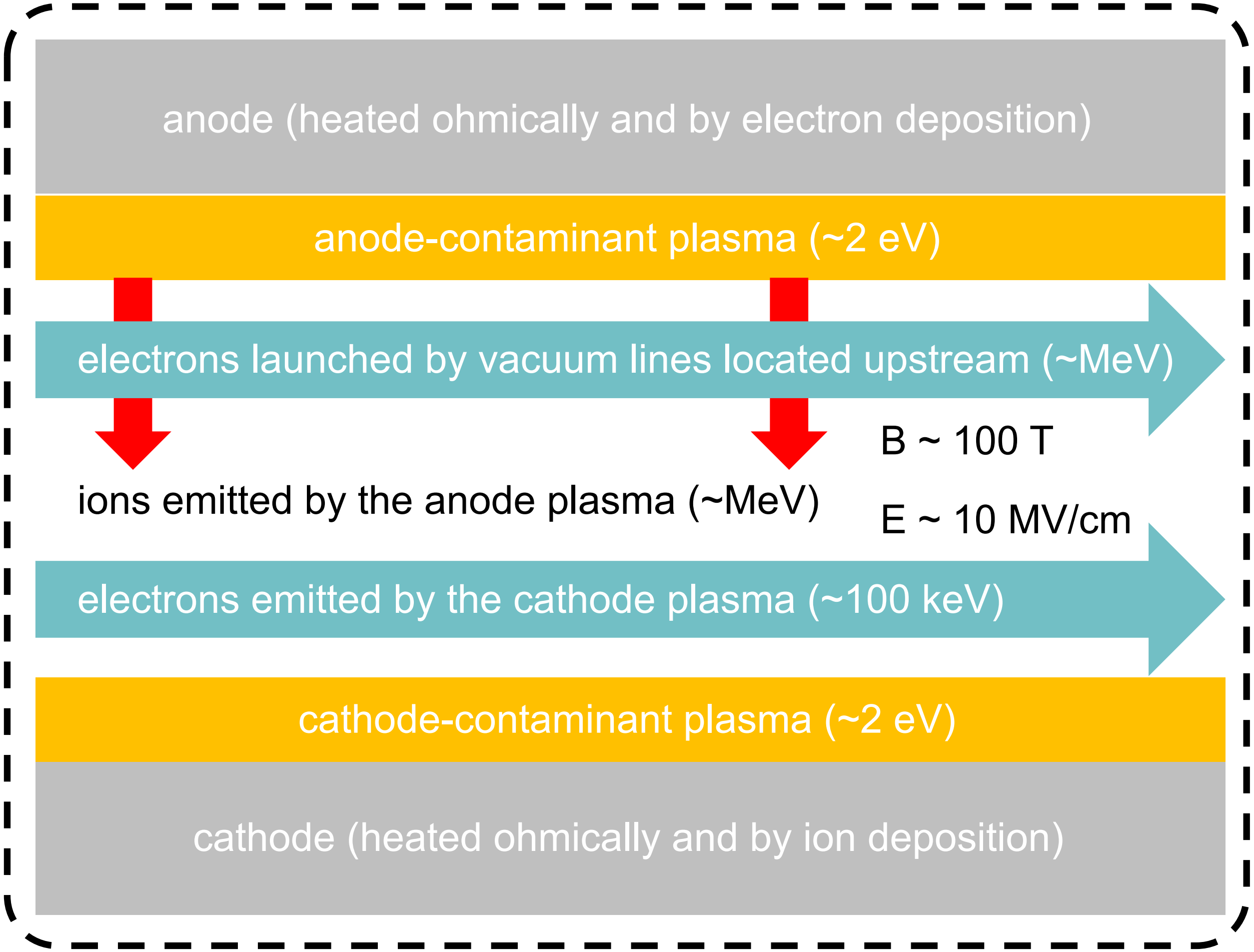
Such plasmas are

- Non-thermal.
- Non-neutral.
- Relativistic.
- Electromagnetic.
- Three-dimensional.

A simulation of such plasmas must account for the following:

- Cyclotron motion.
- Plasma oscillations.
- Collisions.
- Electromagnetic waves.

section of a “vacuum” transmission line at small radius

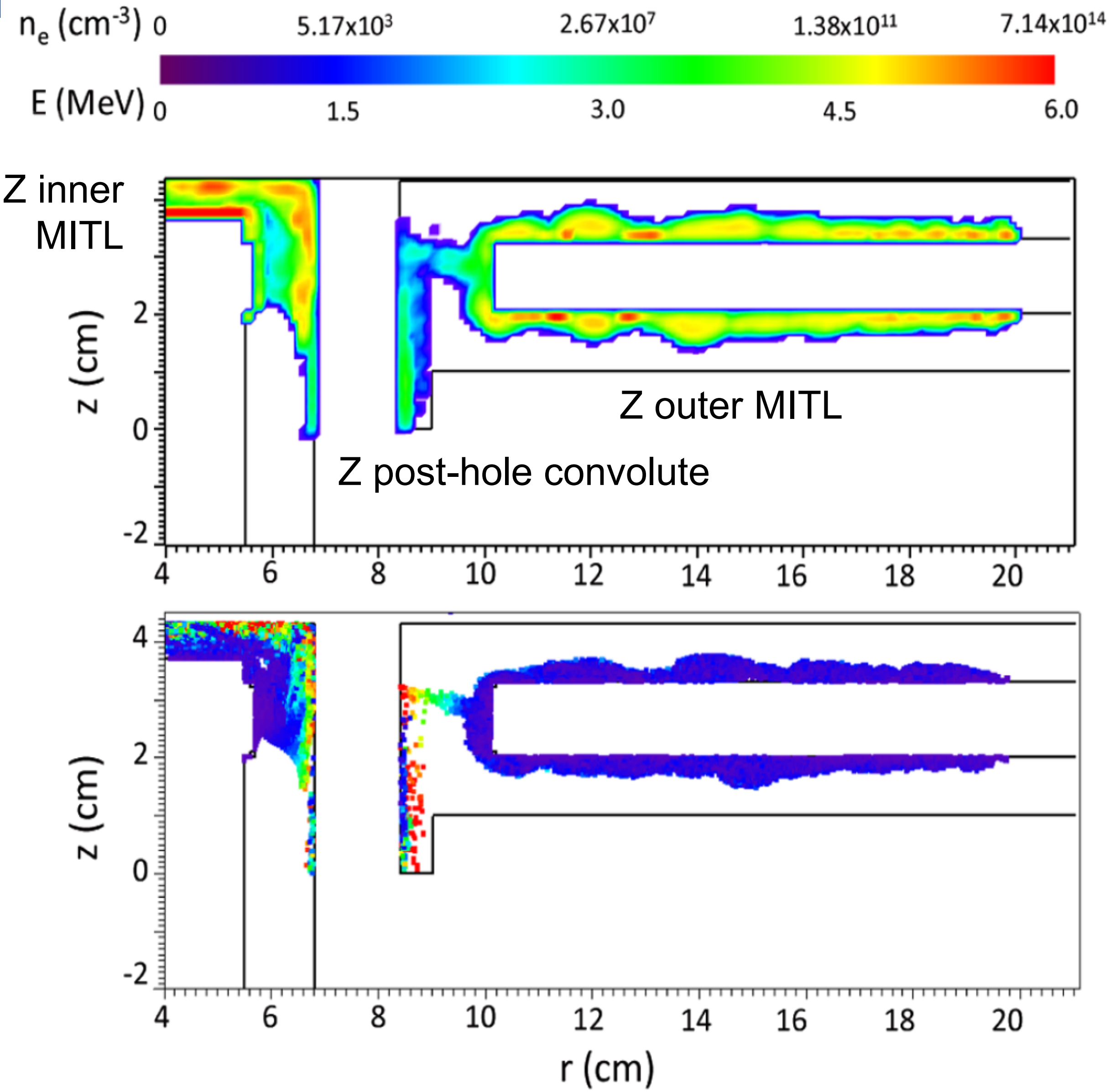


The only code that can presently model such plasmas is Chicago: the most advanced 3D particle-in-cell (PIC) code developed to date.

A Chicago model of Jupiter will be used to conduct numerical experiments.

- Chicago is being developed by Dale Welch, Dave Rose, and colleagues (Voss Scientific).
- Voss and Sandia have developed a 3D PIC model of the Z MITL-convolute-load system.
- The Chicago model of Z is consistent with experiment to within 5%.
- A 3D Chicago model of Jupiter's MITL-convolute-load system will be used to conduct iterative numerical experiments.
- The simulations will be used to optimize the design of Jupiter.

electron densities and energies within the MITL-convolute-load system of Z as simulated by a 3D Chicago calculation



Pointon et al., POP (2001).
Rose et al., PRSTAB (2008).
Madrid et al., PRSTAB (2013).
Rose et al, PRSTAB (2015).

Outline

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- Power amplification by triggered emission of radiation.
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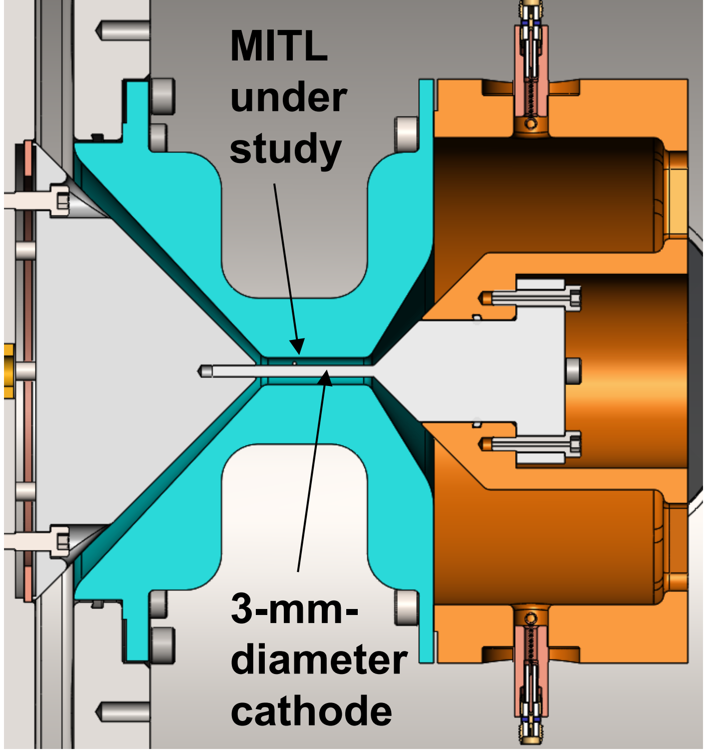
- Three types of *virtual* pulsed-power machines.
- Vacuum-power-flow experiments and facilities.
- Pulsed-power experiments and facilities.
- Publications.
- Summary.

We are conducting vacuum-power-flow experiments on Sandia's Mykonos Facility.

- The experiments are being led by Brian Hutsel as part of a three-year Sandia LDRD Project.
- The experiments are being designed to improve our understanding of fundamental vacuum-power-flow physics.
- The improved understanding will inform the design of next-generation accelerators such as Jupiter.
- Results are being compared to circuit (Hutsel) and PIC (Dave Rose, Dale Welch et al.) simulations.

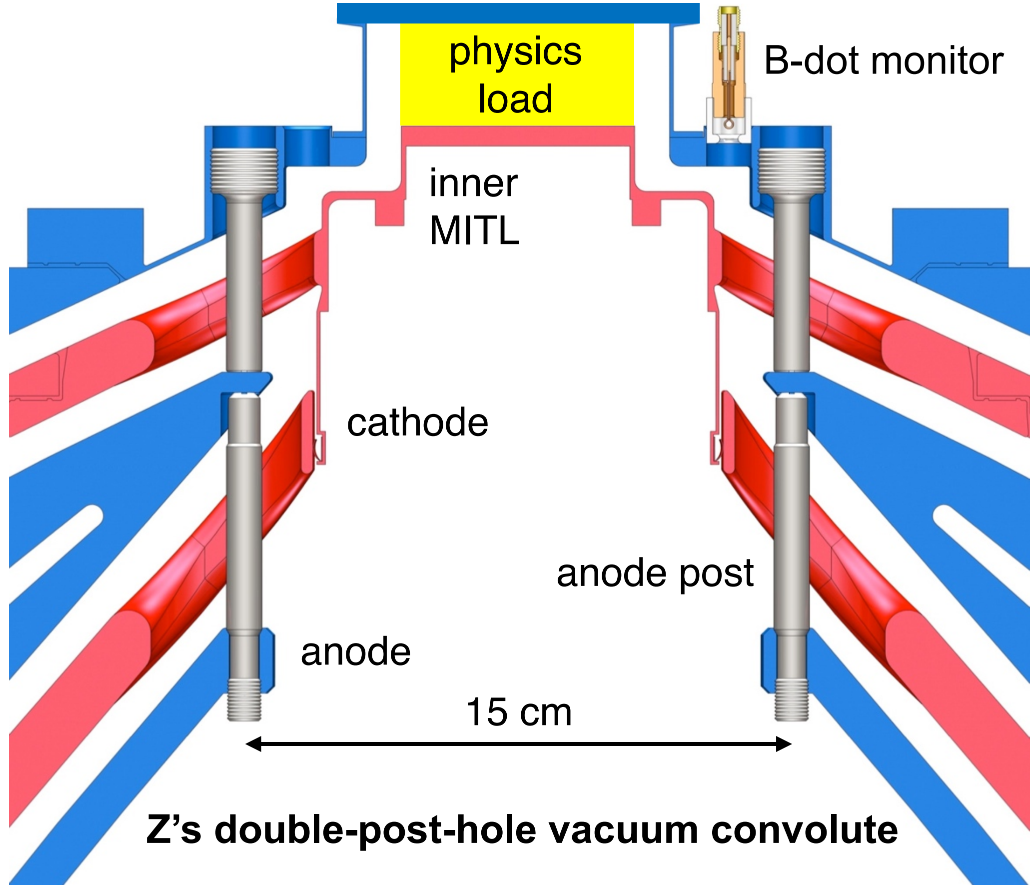


Mykonos Facility:

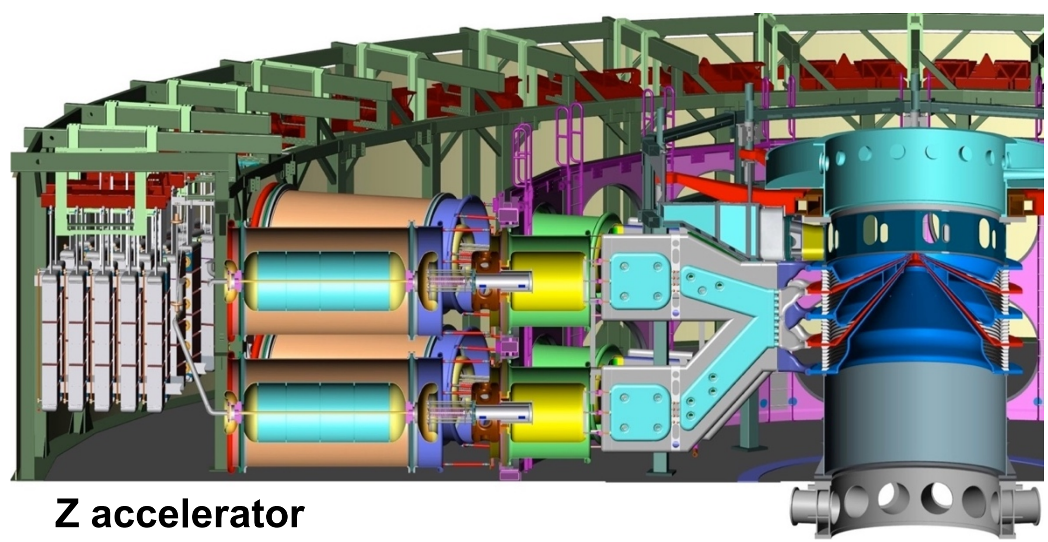
- Peak power = 220 GW.
- Peak voltage = 350 kV.
- Peak current = 700 kA.
- Rise time = 100 ns.
- MITL gaps = 1 - 4 mm.
- Peak E = 3.5 MV/cm.
- Peak B = 100 T.
- Peak E x B = 1.8 TW/cm^2.

We have established a Power Flow Physics & Spectroscopy Team.

- The Team is being led by George Laity and Mike Cuneo (Oral Session 11, this conference).
- The Team will conduct dedicated power-flow experiments on Sandia's Z accelerator.
- The experiments are being designed to improve our understanding of fundamental vacuum-power-flow physics.
- The improved understanding will inform the design of next-generation accelerators such as Jupiter.
- Diagnostics are being developed for the Z convolute, inner-MITL, and load regions.
- Results will be compared with circuit (Hutsel) and PIC (Rose, Welch, et al.) simulations.



Z's double-post-hole vacuum convolute


Z accelerator

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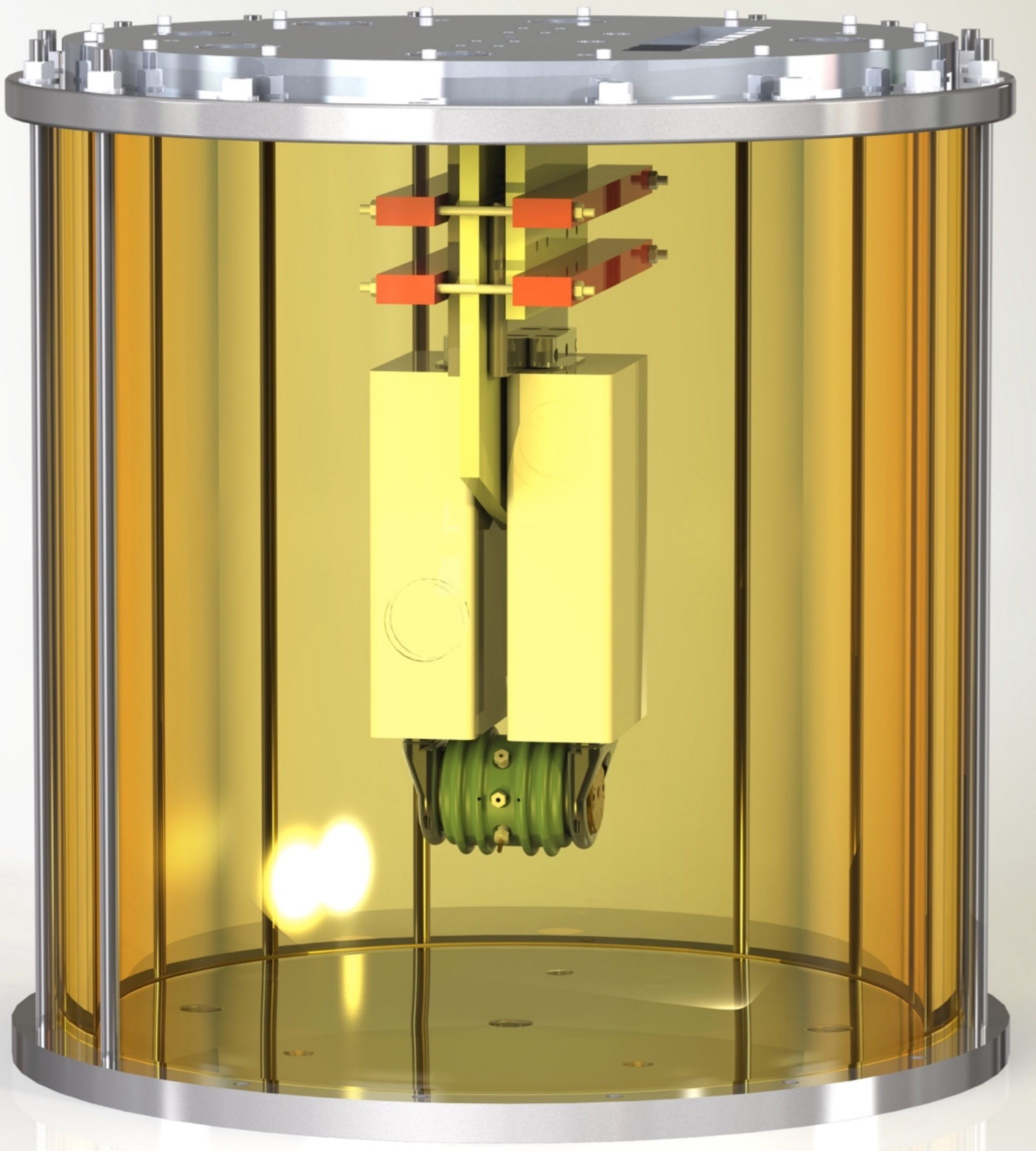
We have developed a 5-GW 100-ns brick.

- Matt Wisher and colleagues (Poster Session I, this conference) developed the brick at Sandia's Single-Brick-Test Facility.
- The facility conducts a shot every 30 seconds.
- Wisher and coworkers are building a second such facility.

parameter	achieved
peak electrical power	5 GW
power variation	5% (1σ)
switch prefire rate	< 0.1%
lifetime	> 3,000 shots

Sandia's Single-Brick-Test Facility



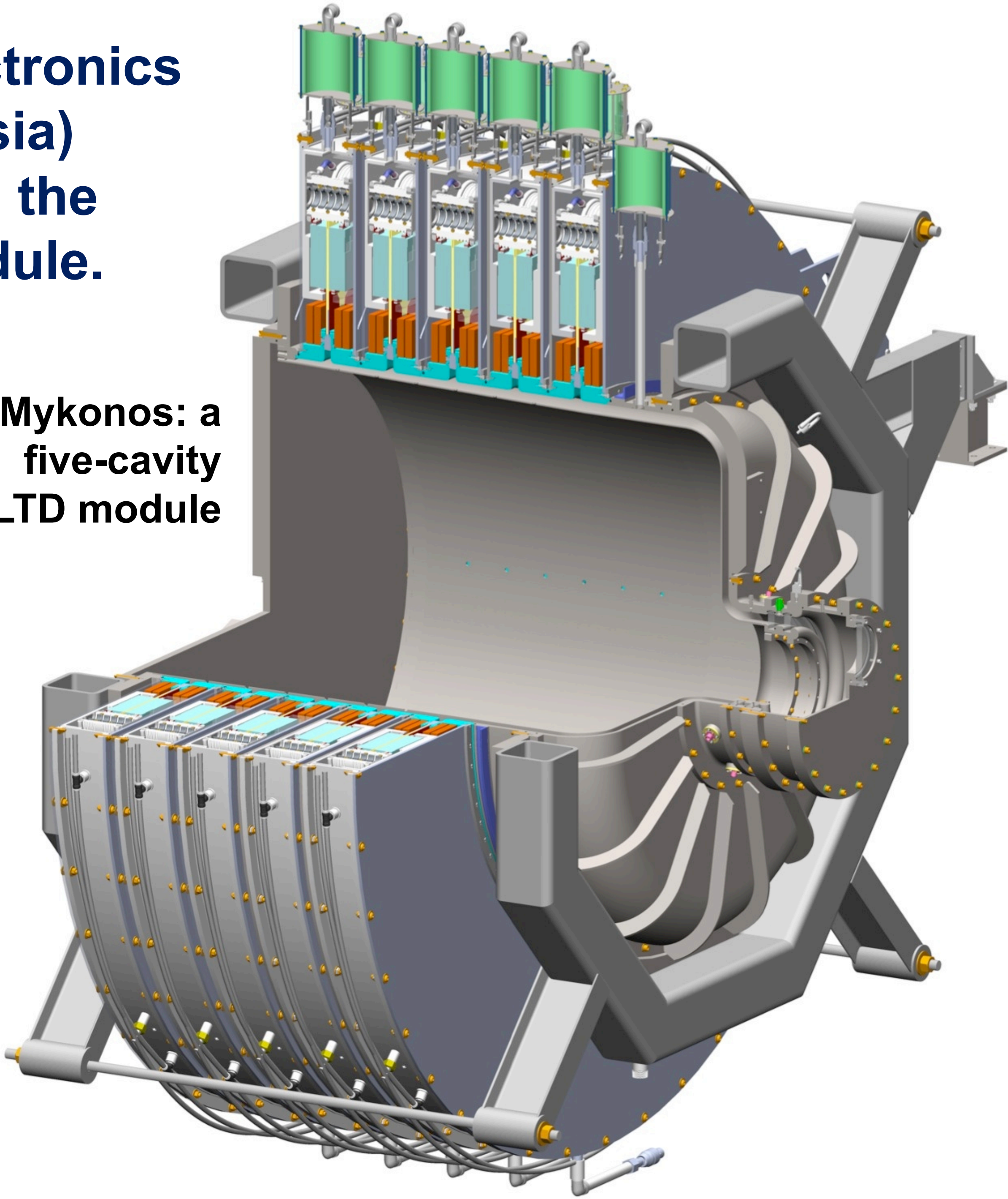
We have developed a 2-m-diameter 79-GW LTD cavity.

- Brian Stoltzfus and colleagues developed the cavity at Sandia's Single-Cavity-Test Facility.
- Matt Wisher and colleagues are presently building a next-generation LTD cavity with 5th-generation components.
- Much of this technology is directly applicable to the development of an IMG.
- We will soon build prototype *three-stage* LTD and IMG modules.

parameter	achieved
peak electrical power	79 GW
output power variation	1% (1σ)
cavity diameter	2 m
switch prefire rate	< 0.1%
lifetime	> 2000 shots

The High-Current Electronics Institute (Tomsk, Russia) and Sandia developed the 220-GW Mykonos module.

- The Mykonos module was the first to drive an internal water-insulated transmission line, as assumed by Jupiter.
- At a charge voltage of 70 kV, Mykonos generates 220 GW.
- At a charge voltage of 90 kV, Mykonos will generate 400 GW.
- Much of this technology is directly applicable to the development of an IMG.



Mykonos: a five-cavity LTD module

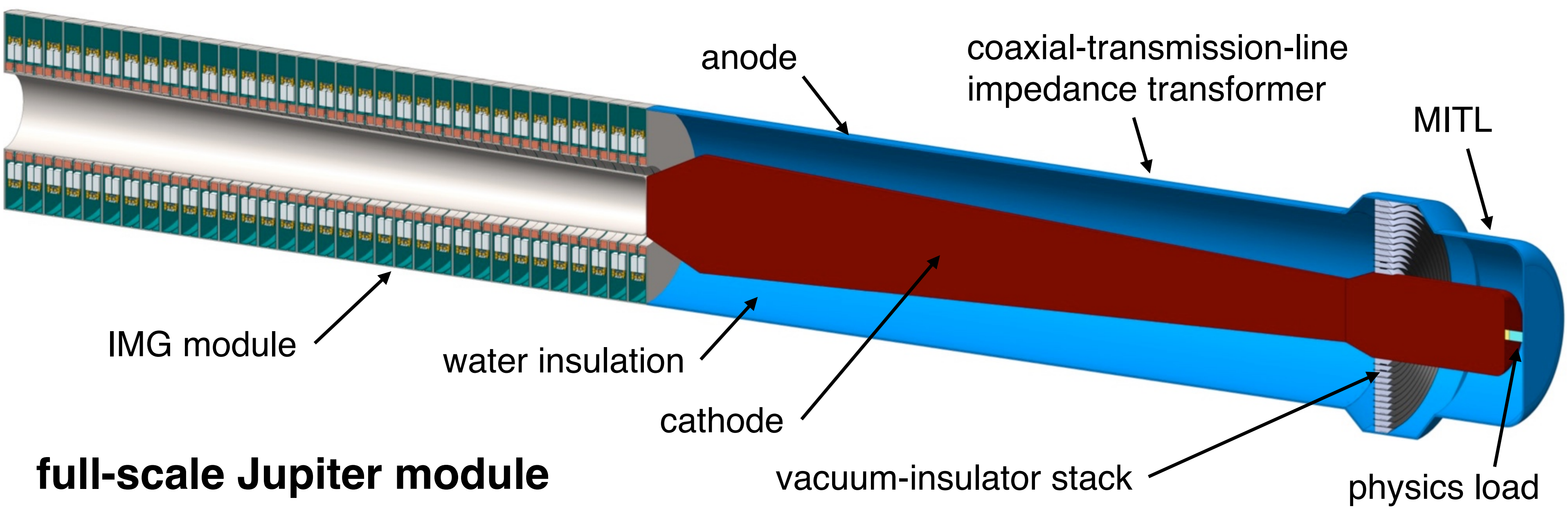
Kim et al., PRSTAB (2009).
Mazarakis et al., PRSTAB (2009).
Woodworth et al., PRSTAB (2009).
LeChien et al., IEEE PPC (2009).

We propose to build and test a full-scale (1/210)th sector of Jupiter.

The Jupiter module would generate 4.6 TW and comprise four principal components:

- A full-scale full-power 42-stage water-insulated IMG.
- A water-insulated coaxial-transmission-line impedance transformer.
- A full-voltage vacuum-insulator stack.
- A MITL section that includes a physics load.

The module would operate at the full Jupiter voltage, and test everything from the IMG module to the vacuum insulator stack.



full-scale Jupiter module

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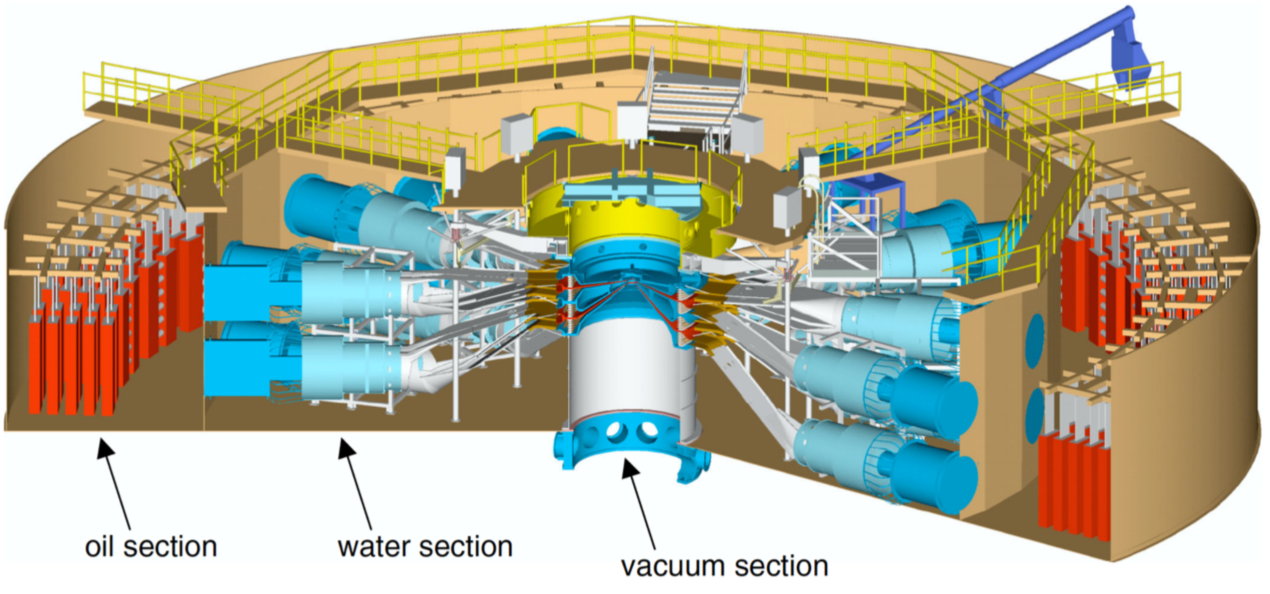
We have been establishing a technical foundation for Jupiter since 1996.

- The foundation is summarized by 50 peer-reviewed-journal articles.
- This effort began with the design, assembly, and commissioning of the original Z accelerator.
  - The Z machine generated a peak electrical power of 55 TW, and delivered 20 MA and 2 MJ to a physics load.
  - Z met its 20-MA load-current objective on its 9th shot.
  - Z met its 1.5-MJ x ray-yield objective on its 26th shot.

We propose to use the same methodology to design Jupiter as we applied to the design of the original Z machine.



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Summary

- We have developed a new unified approach to the design of next-generation pulsed-power accelerators.
- We have applied the approach to the design of Jupiter: an accelerator that is optimized for high-yield thermonuclear-fusion experiments.
- The design is a *point conceptual* design that generates a peak electrical power of 960 TW, and delivers 67 MA and 9.2 MJ in 100-ns to an ICF load.
- The *optimized final engineering* design of Jupiter will be informed by a large number of iterative numerical experiments.
- The final design will also be informed by the results of a large number of iterative laboratory experiments, including those conducted with a prototype full-scale Jupiter module.
- We have been establishing a technical foundation for Jupiter since 1996.
- The foundation includes 50 peer-reviewed scientific journals.