SAND2017-10294C

Sandia National Laboratories

11-15 September 2017

Conceptual design of a 960-TW pulsed-power accelerator optimized for ICF research

10th International Conference on Inertial Fusion Sciences and Applications (Saint Malo, France)

Sandia National Laboratories

Developing a new accelerator is a large team effort.

Sandia National Laboratories

CSI Technologies, Inc.

GENERAL ATOMICS ELECTROMAGNETICS

Idaho State University

Lawrence Livermore National Laboratory

NNSA National Nuclear Security Administration

NWL

TECHSOURCE™ Science and Engineering Consultants

UNIVERSITY OF MICHIGAN

UR LLE

Voss Scientific

W. Stygar, K. Austin, T. Awe, J. Bailey, J. Benage, E. Breden, G. Brent, J. Brown, J. Calhoun, M. Campbell, R. Clark, R. Cooper, M. Cuneo, J. Edwards, J. Ennis, R. Gilgenbach, M. Gomez, P. Gourdain, G. Greiser, F. Gruner, J. Hammer, M. Herrmann, M. Hess, 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. McBride, 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, D. Sinars, S. Slutz, R. Spielman, B. Stoltzfus, C. Verdon, R. Vesey, E. Waisman, E. Weinbrecht, D. Welch, A. White, and M. Wisher.

Outline

- Pulsed-power technology.
- Present state of the art: the Z accelerator.
- Unified approach to the design of next-generation machines.
- Three next-generation-accelerator concepts.
- 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.
- Technical foundation for Jupiter.
- Summary.

Outline

- Pulsed-power technology.
- Present state of the art: the Z accelerator.
- Unified approach to the design of next-generation machines.
- Three next-generation-accelerator concepts.
- 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.
- Technical foundation for Jupiter.
- Summary.

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.

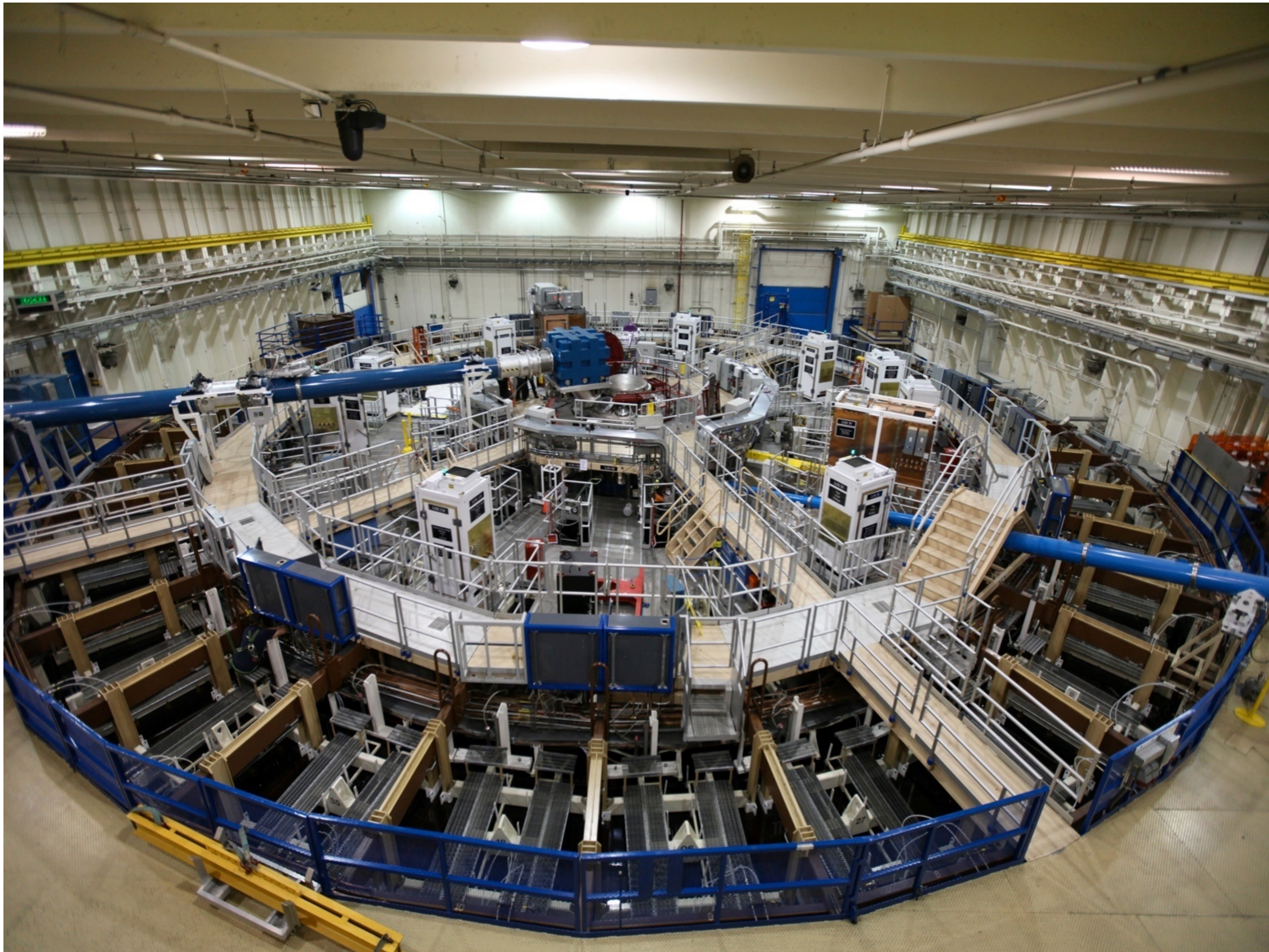
Outline

- Pulsed-power technology.
- Present state of the art: the Z accelerator.
- Unified approach to the design of next-generation machines.
- Three next-generation-accelerator concepts.
- 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.
- Technical foundation for Jupiter.
- Summary.

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} = 25 MA	$E_{radiated}$ = 2.3 MJ
$P_{electrical}$ = 85 TW	L_{vacuum} = 12 nH	$\tau_{implosion}$ = 130 ns	diameter = 33 m

- Since 1996 we have conducted, on average, 150 Z shots each year.
- To date, we have conducted more than 3100 shots altogether.
- Z shots drive a wide variety of experiments in support of the U.S. national-security mission.

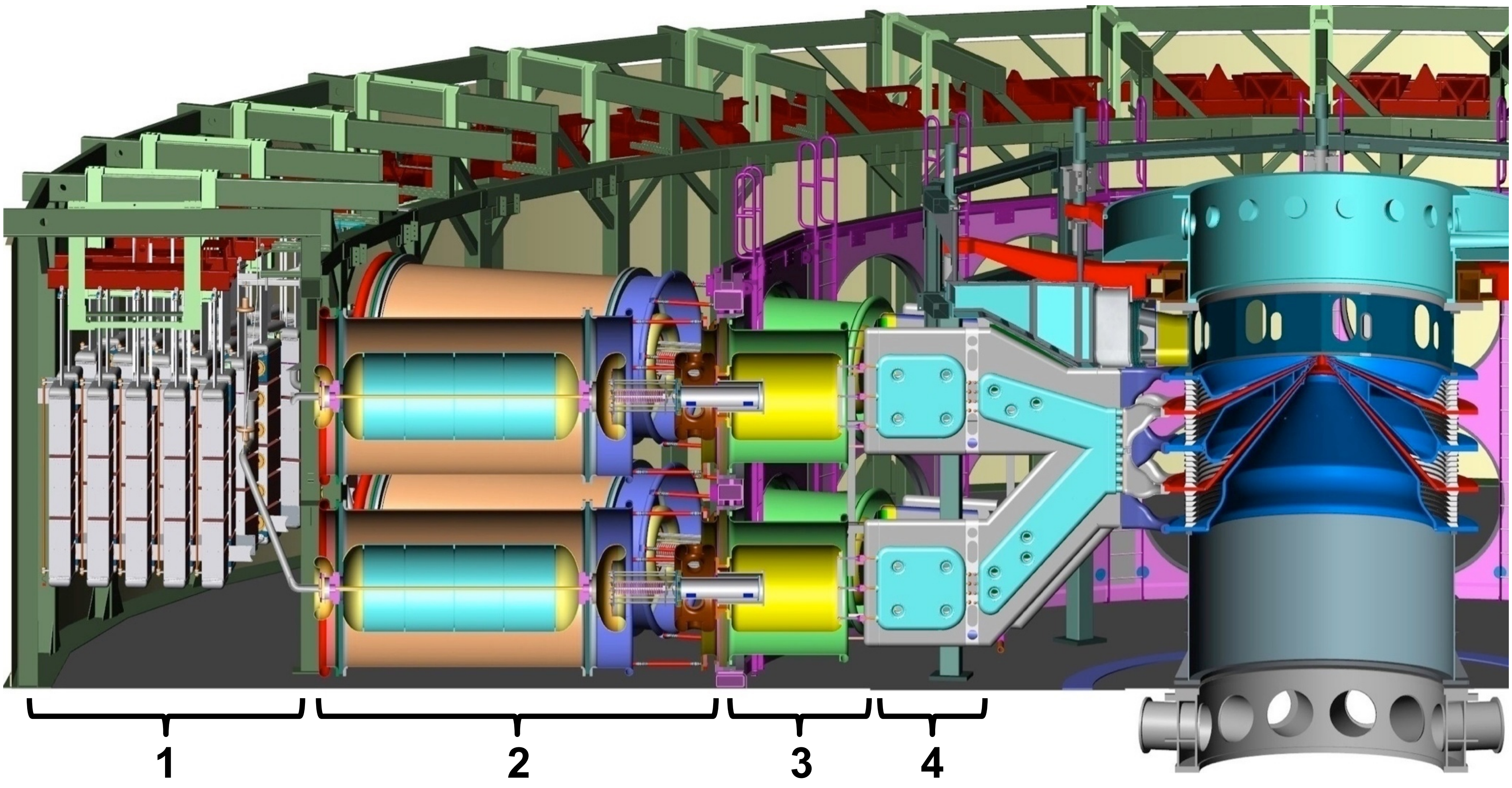


Outline

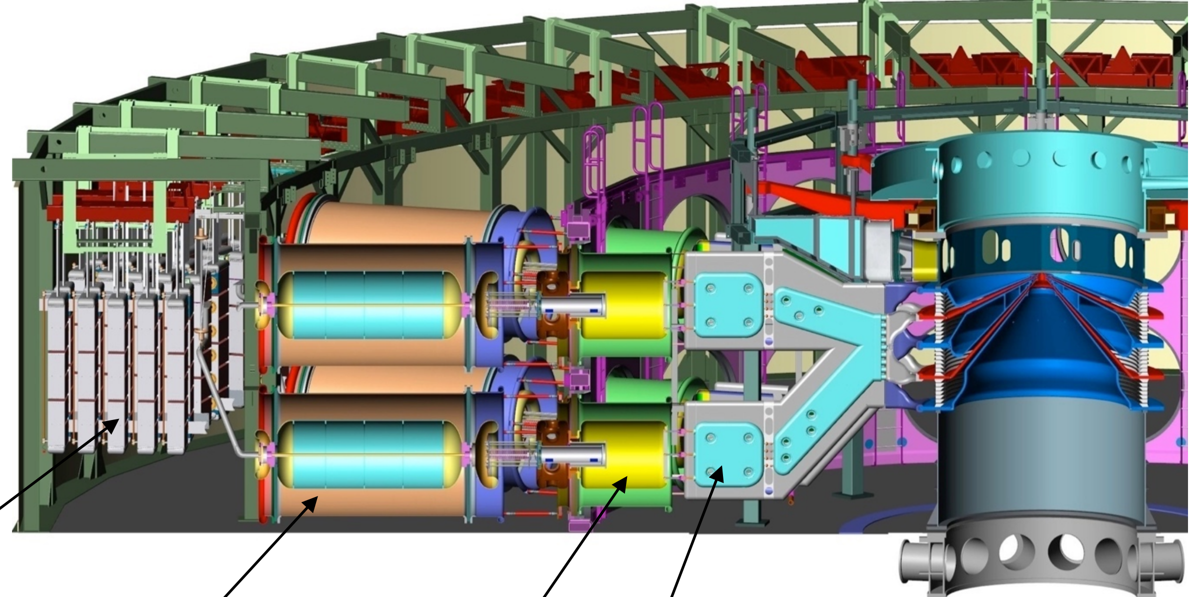
- Pulsed-power technology.
- Present state of the art: the Z accelerator.
- Unified approach to the design of next-generation machines.
- Three next-generation-accelerator concepts.
- Jupiter: a high-yield thermonuclear-fusion accelerator.
- Prime-power source: impedance-matched Marx generators (IMGs).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

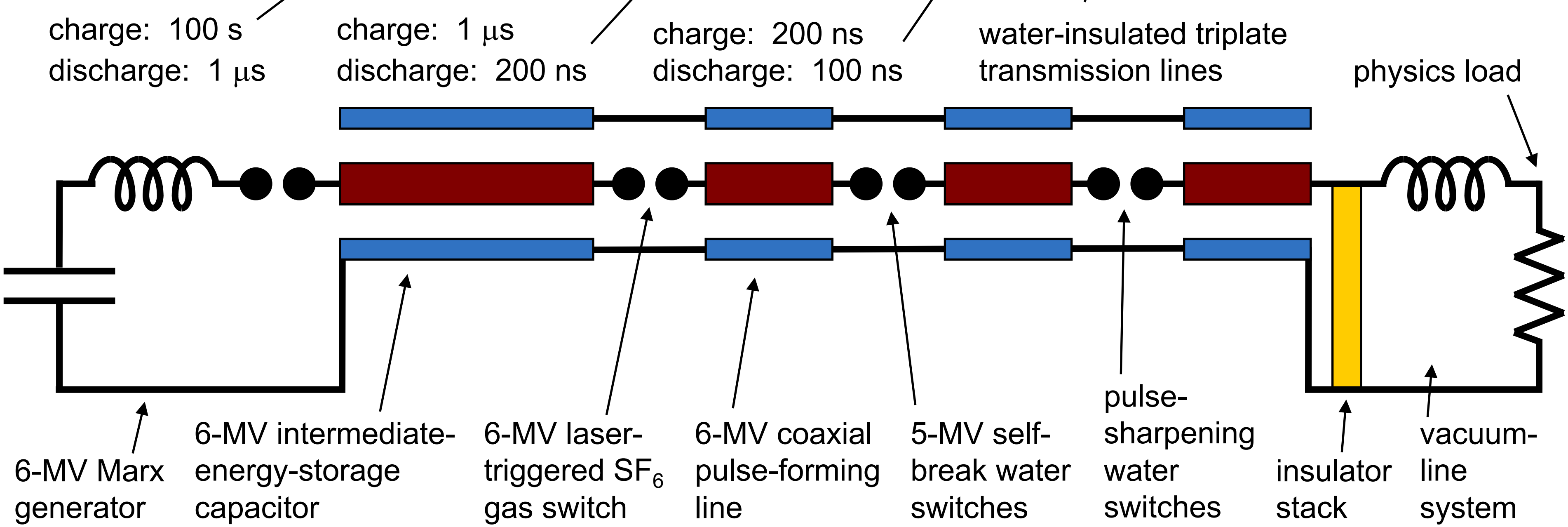
For decades, the community has designed pulsed-power machines with an architecture similar to that of Z.

- Experiments require a 100-ns pulse at the load; however, each Z Marx generates a 1-μs pulse.
- Hence 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.

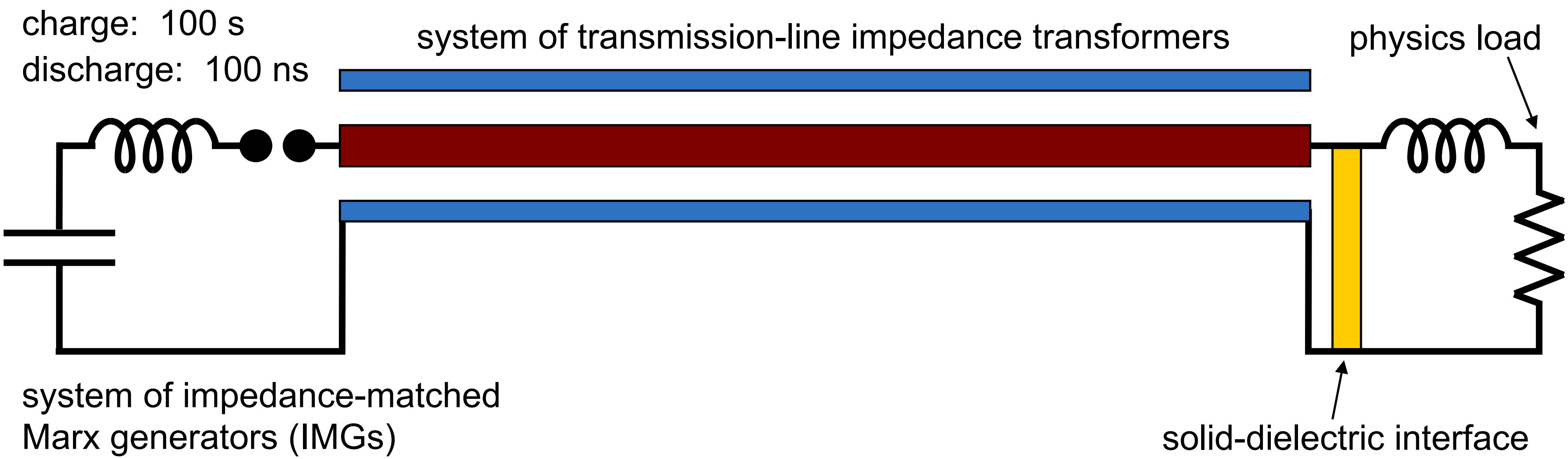




We propose *instead* to use a new unified approach to the design of next-generation accelerators.

The approach is based on six fundamental concepts:

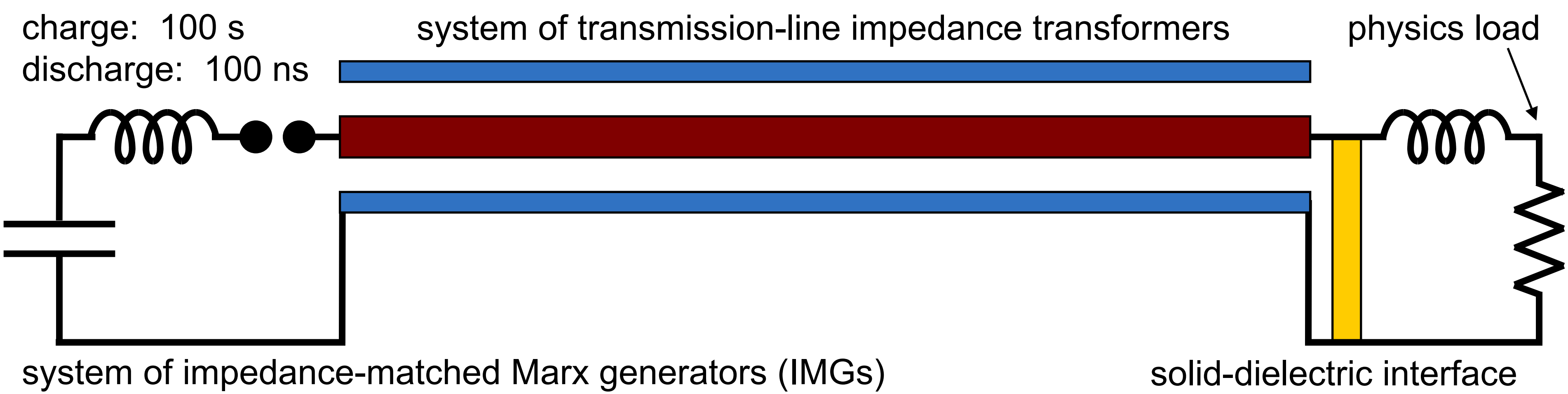
- Single-stage electrical-pulse compression.
- Low-voltage switching.
- Impedance matching.
- Transit-time-isolated prime power sources.
- Economies of scale.
- Engineered safety.



We have applied the new approach to the designs of three next-generation pulsed-power machines: Thor, Neptune, and Jupiter.

These accelerators

- Use DC-charged capacitors to generate a 100-ns 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 prime power sources that are transit-time isolated for at least 300 ns to facilitate shaping the current pulse at the load.
- 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).

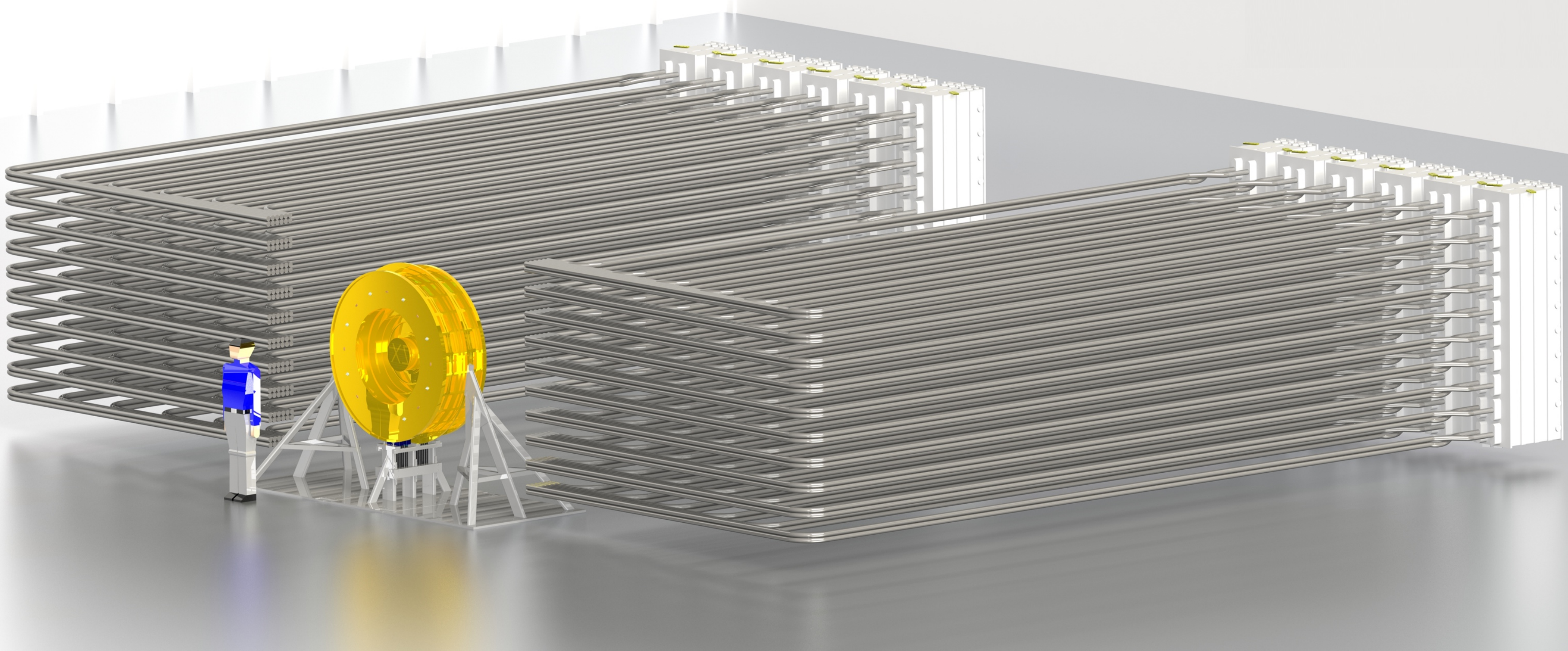


Outline

- Pulsed-power technology.
- Present state of the art: the Z accelerator.
- Unified approach to the design of next-generation machines.
- Three next-generation-accelerator concepts.
- 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.
- Technical foundation for Jupiter.
- Summary.

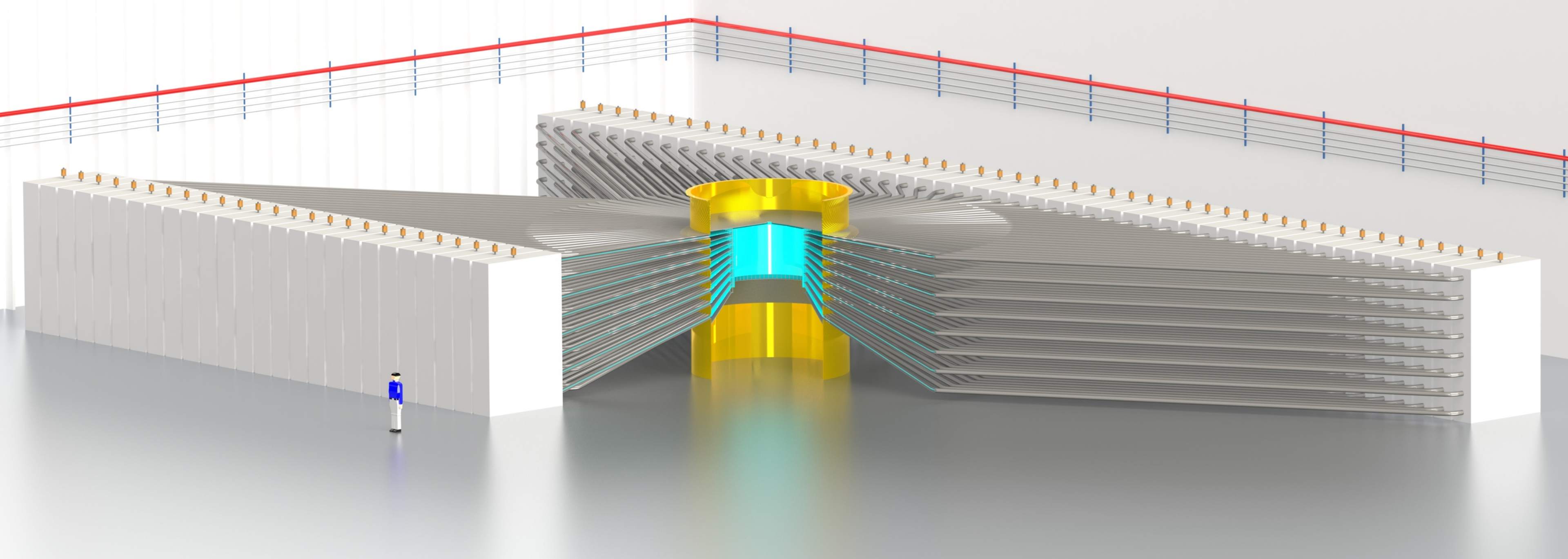
Thor stores 190 kJ of electrical energy, generates a peak electrical power of 1.2 TW, and delivers an arbitrary pressure-loading time history to a material-physics load.

Peak magnetic pressure: 0.2 TPa (2 Mbar).



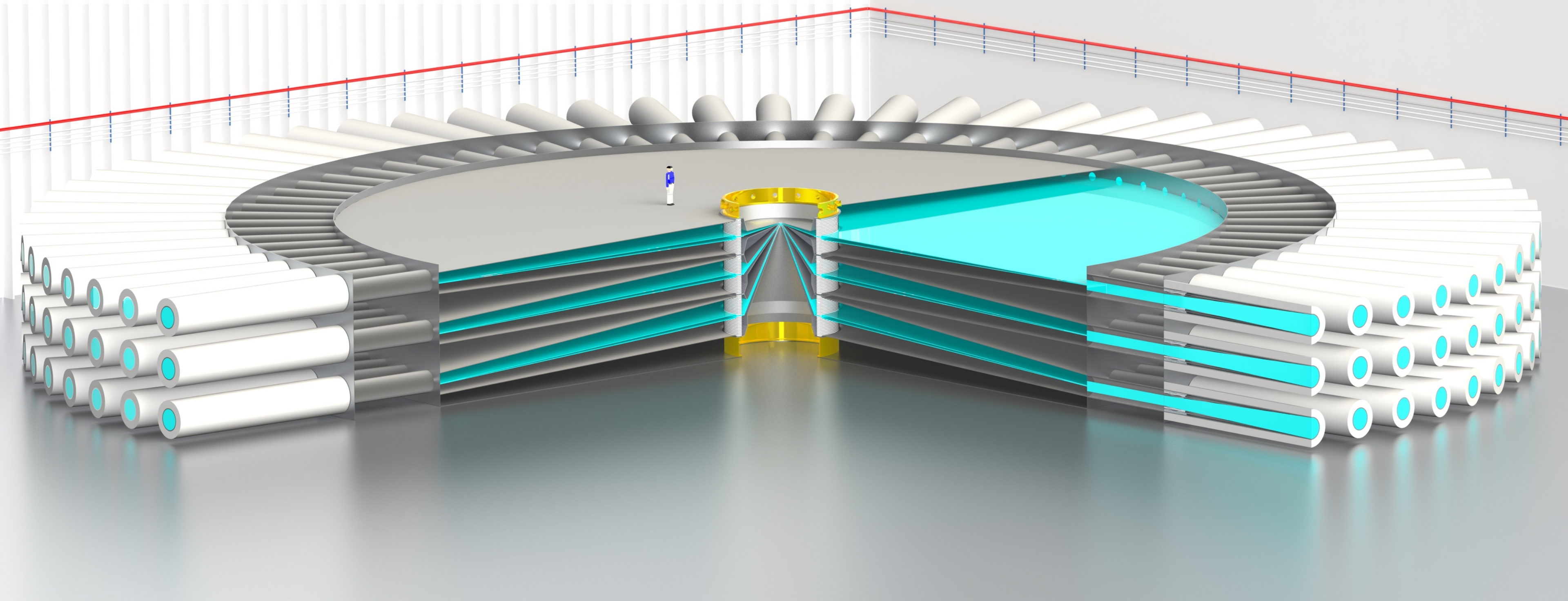
Neptune stores 11 MJ of electrical energy, generates a peak electrical power of 50 TW, and delivers an arbitrary pressure-loading time history to a material-physics load.

Peak magnetic pressure: 2 TPa (20 Mbar).



Jupiter stores 140 MJ of electrical energy, and generates a peak electrical power of 960 TW.

Peak current and energy delivered to the load: 67 MA and 9 MJ, respectively.

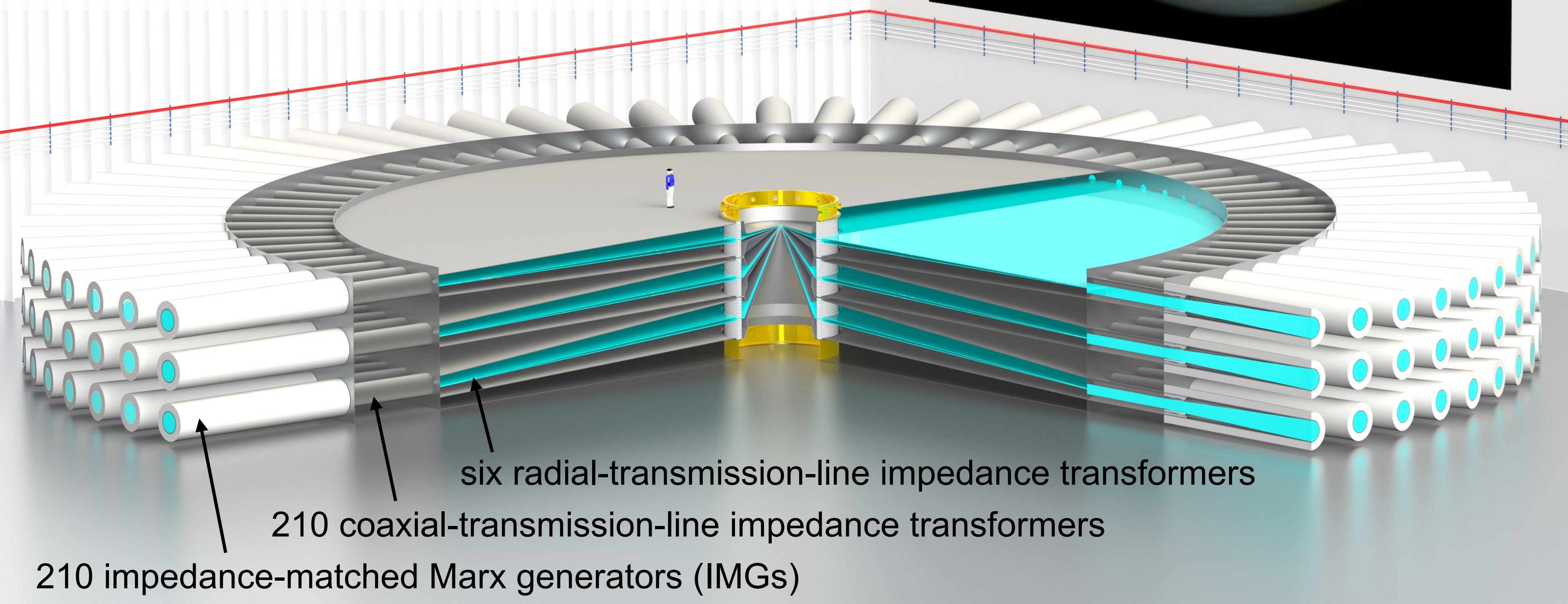


Outline

- Pulsed-power technology.
- Present state of the art: the Z accelerator.
- Unified approach to the design of next-generation machines.
- Three next-generation-accelerator concepts.
- 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.
- Technical foundation for Jupiter.
- Summary.

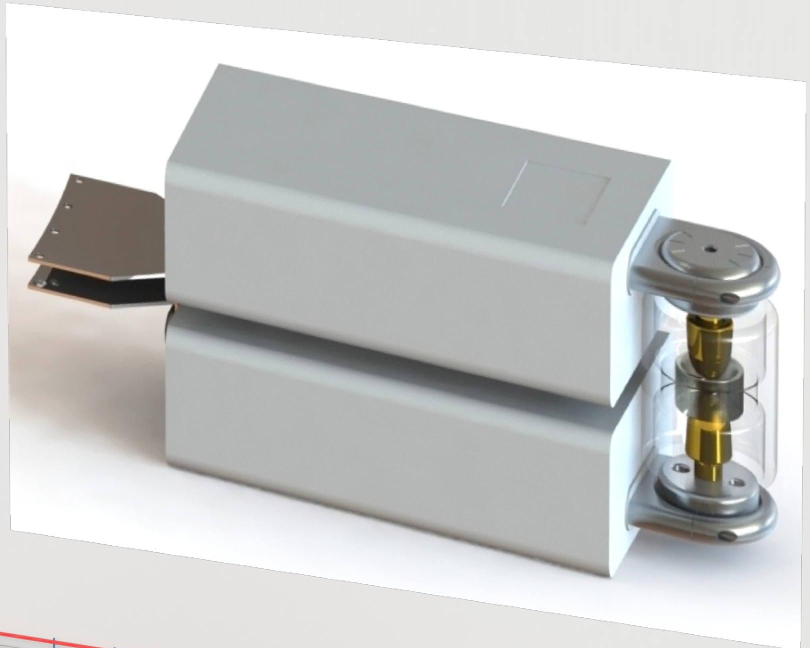
The conceptual design of Jupiter is optimized for ICF research.

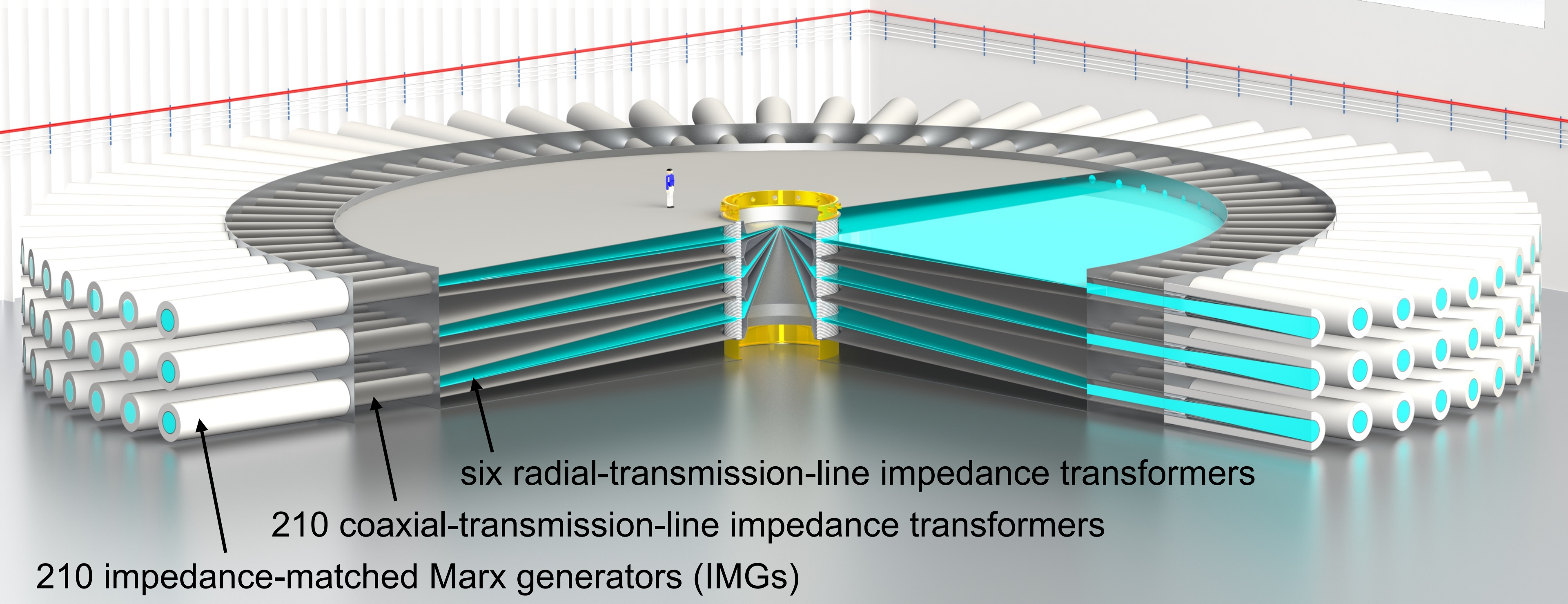
- Outer diameter: 72 m.
- Power source: 210 impedance-matched Marx generators (IMGs).
- Transit-time isolation between the IMGs: 300 ns.
- Shape of the current pulse at the load: arbitrary.



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

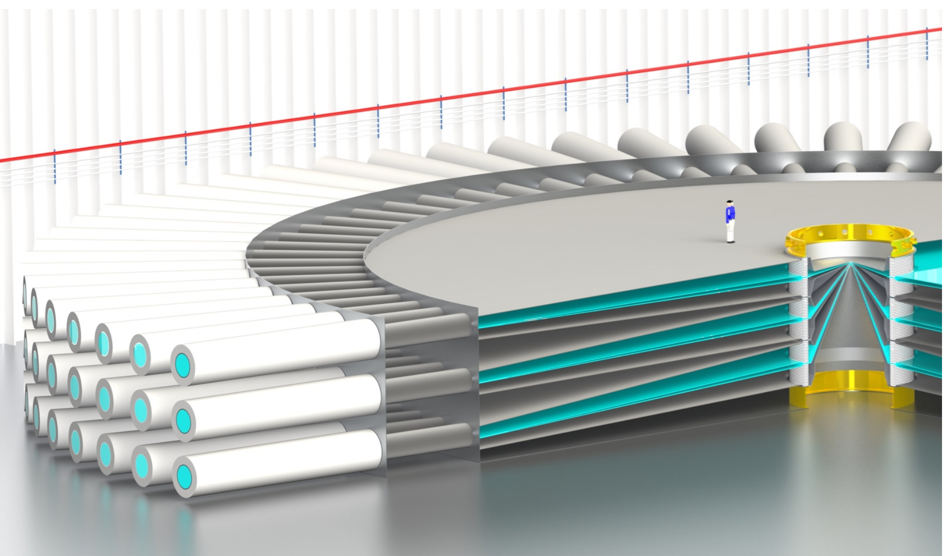
- A brick consists of two 80-nF 100-kV capacitors connected in series with a single 200-kV switch.
- Jupiter is powered by 176,400 bricks altogether.
- Economies of scale will reduce the cost per brick.
- The rest of the accelerator consists of oil, water, plastic, and stainless steel.

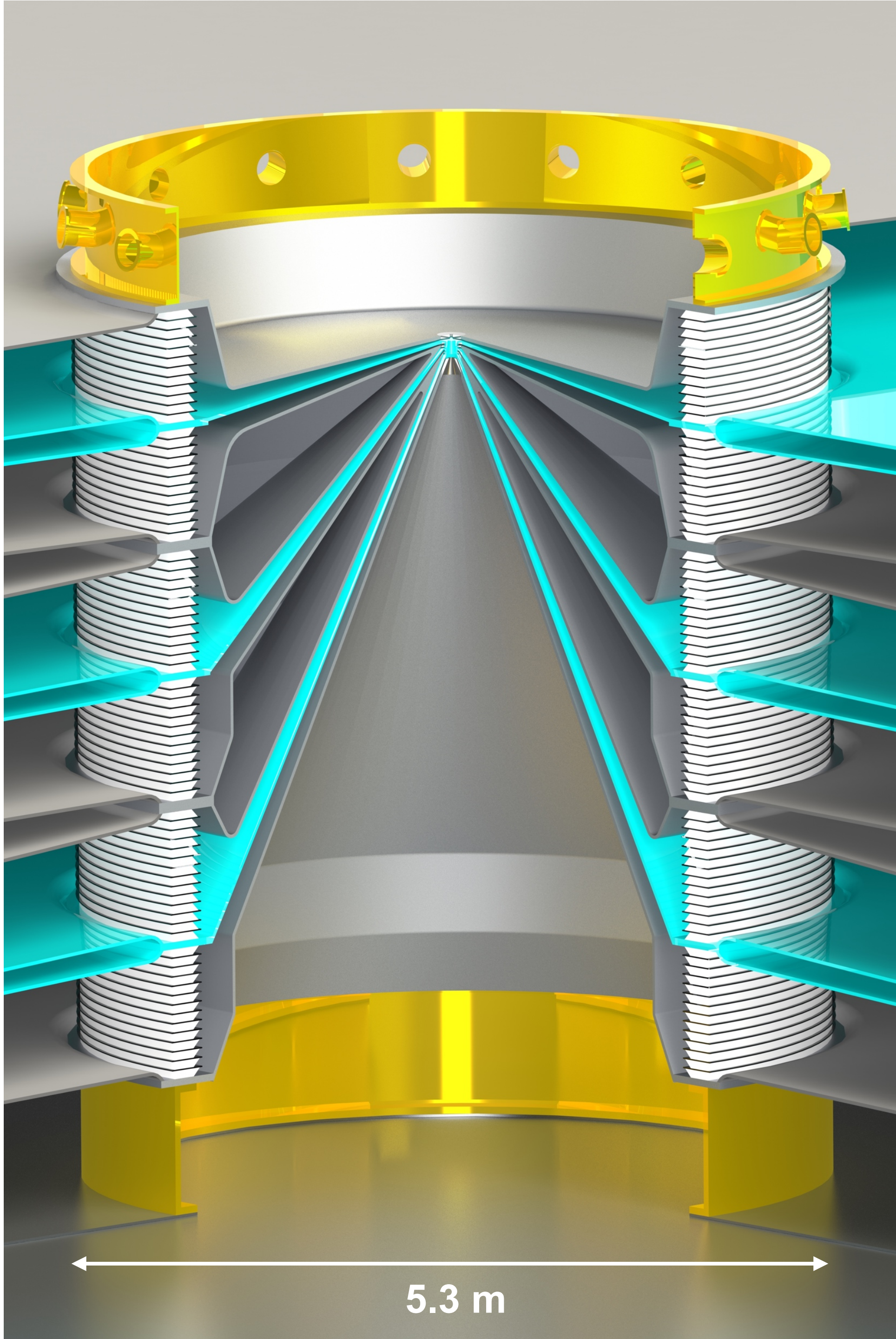




Jupiter drives a six-level centrally located vacuum section.

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



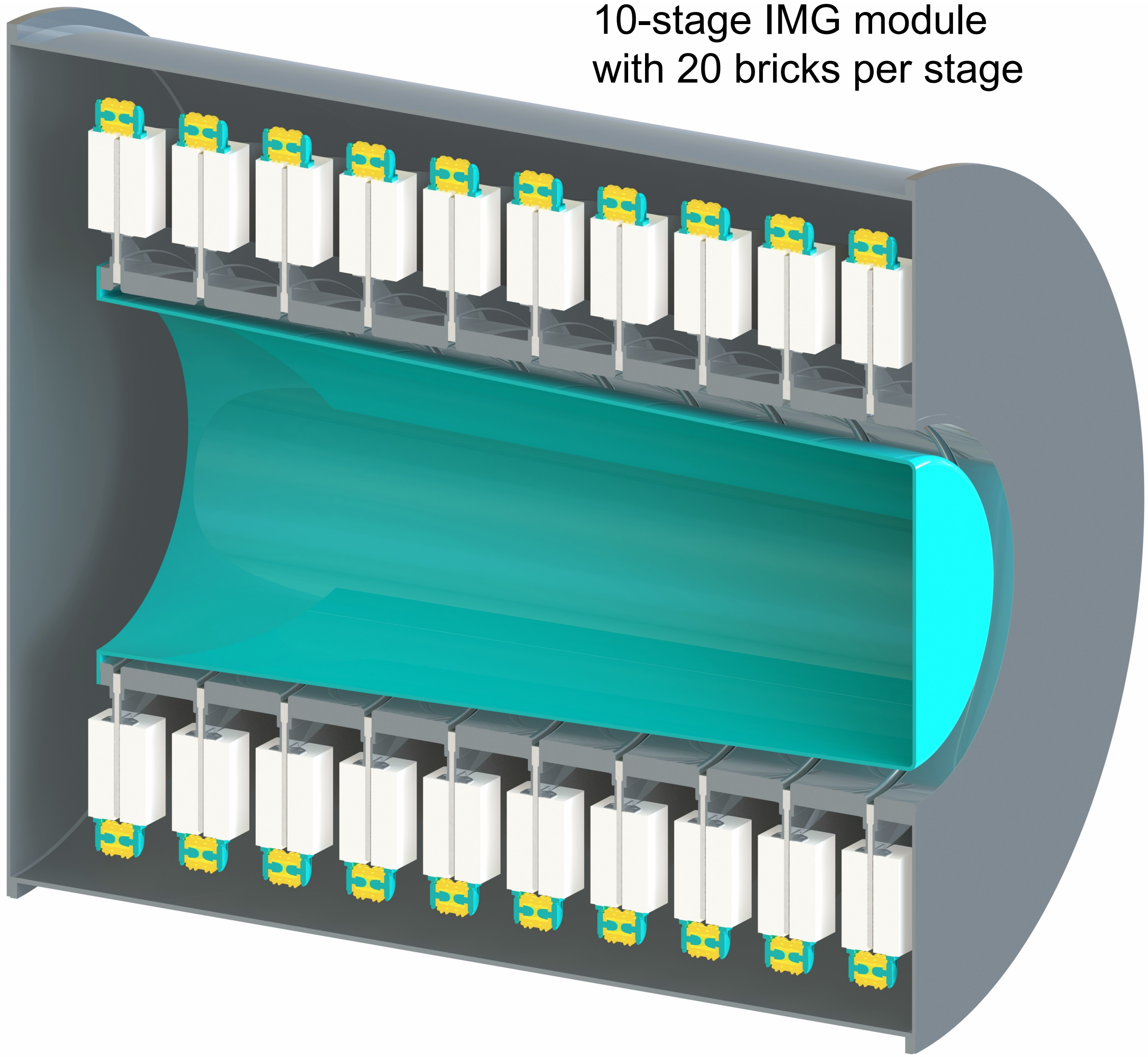


Outline

- Pulsed-power technology.
- Present state of the art: the Z accelerator.
- Unified approach to the design of next-generation machines.
- Three next-generation-accelerator concepts.
- 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.
- Technical foundation for Jupiter.
- Summary.

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 plan to build and evaluate prototype IMG modules in support of the Jupiter development effort.



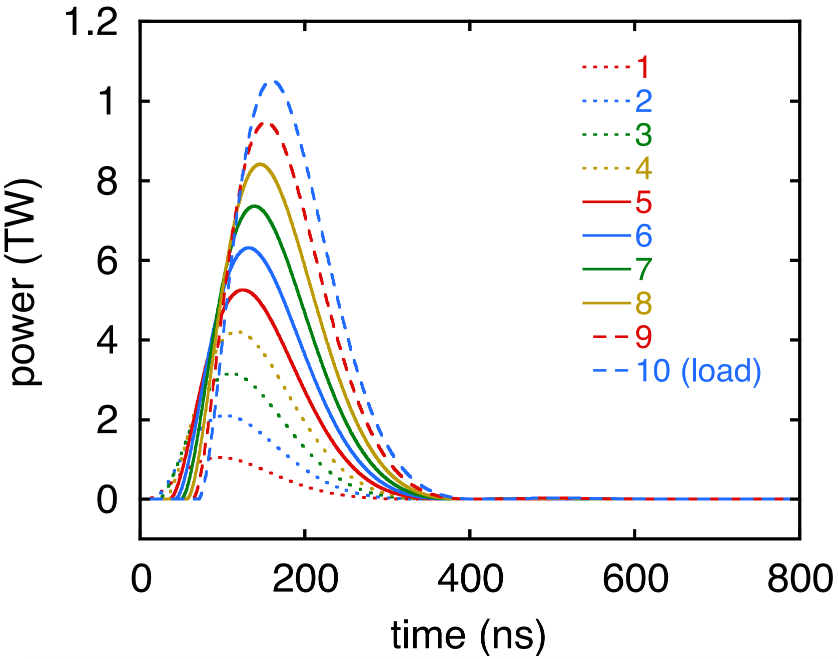
Stygar, LeChien, Mazarakis et al., PRAB (2017).

Outline

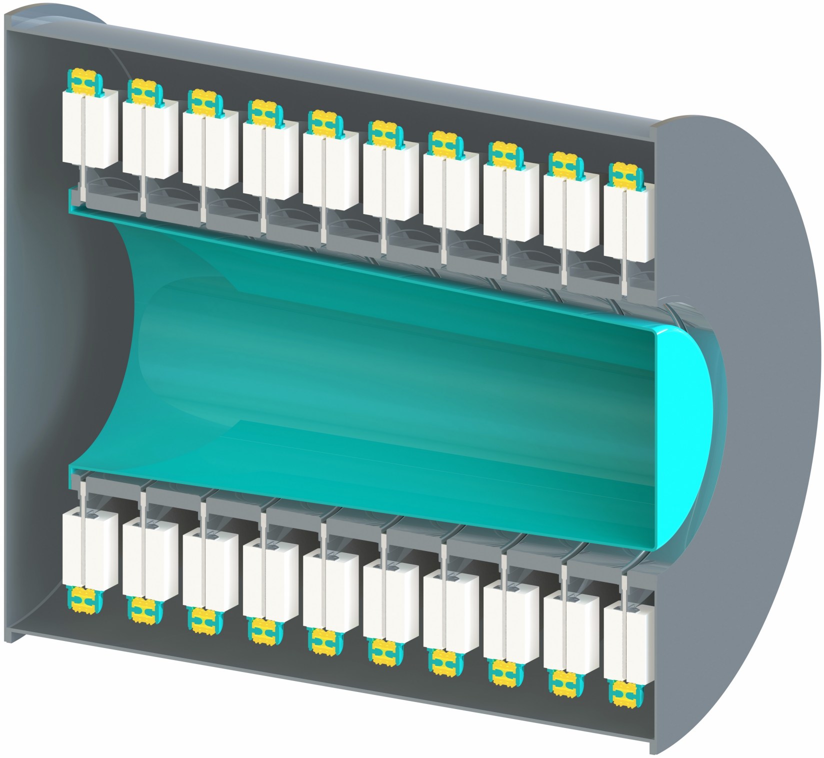
- Pulsed-power technology.
- Present state of the art: the Z accelerator.
- Unified approach to the design of next-generation machines.
- Three next-generation-accelerator concepts.
- Jupiter: a high-yield thermonuclear-fusion accelerator.
- Prime-power source: impedance-matched Marx generators (IMGs).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

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 ~ 80% - 90%.



power at the output of each of the 10 IMG stages



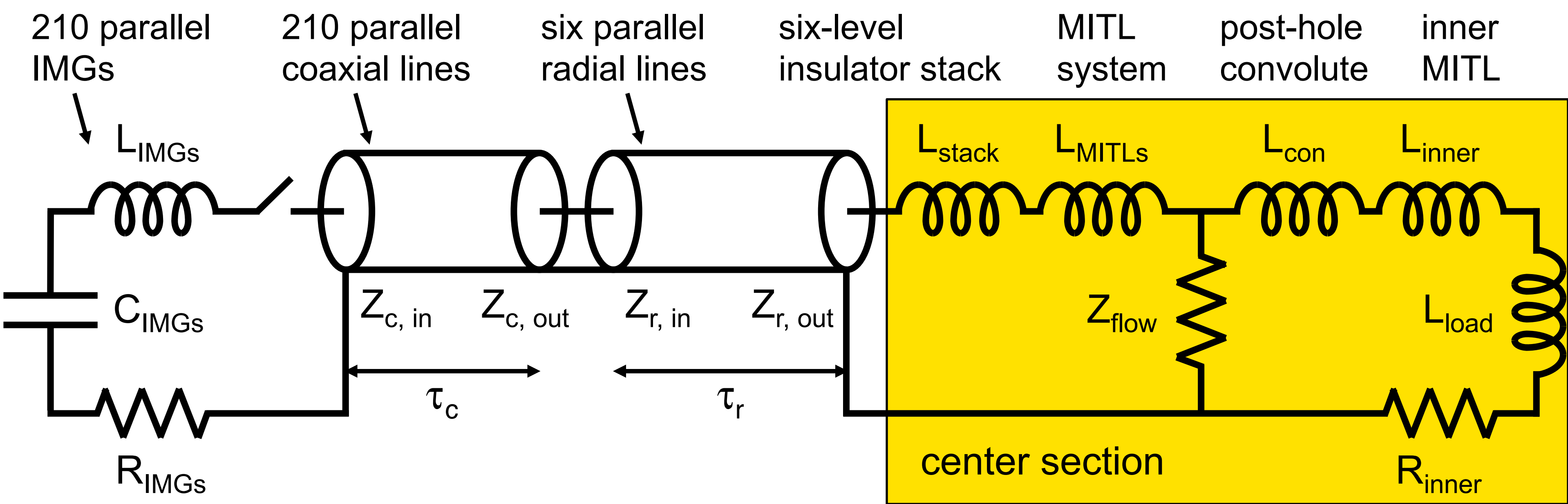
10-stage IMG module with 20 bricks per stage

Outline

- Pulsed-power technology.
- Present state of the art: the Z accelerator.
- Unified approach to the design of next-generation machines.
- Three next-generation-accelerator concepts.
- 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.
- Technical foundation for Jupiter.
- Summary.

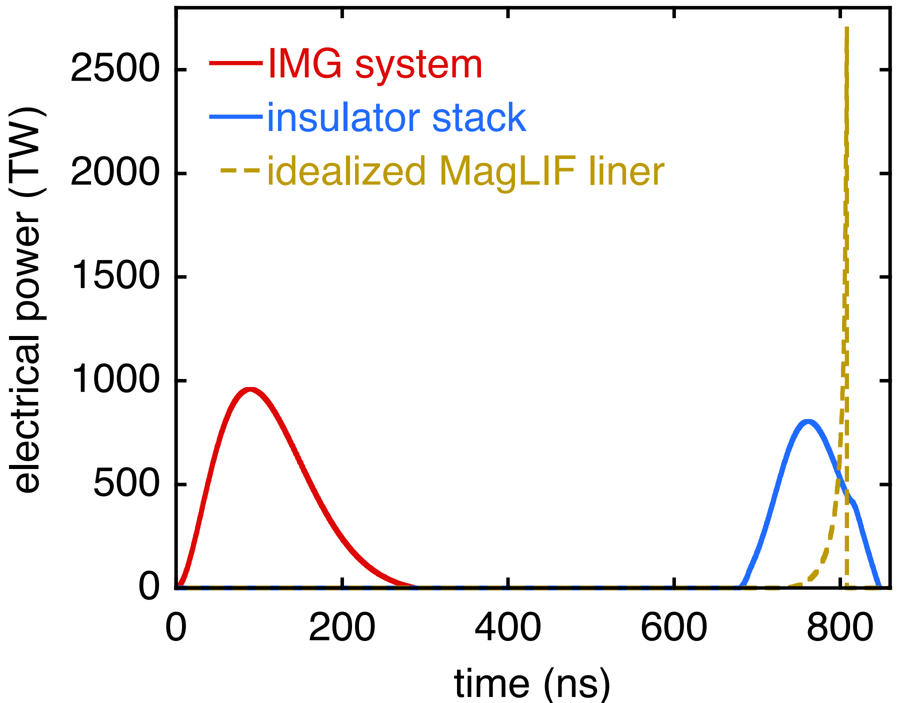
We have developed an idealized circuit model of Jupiter.

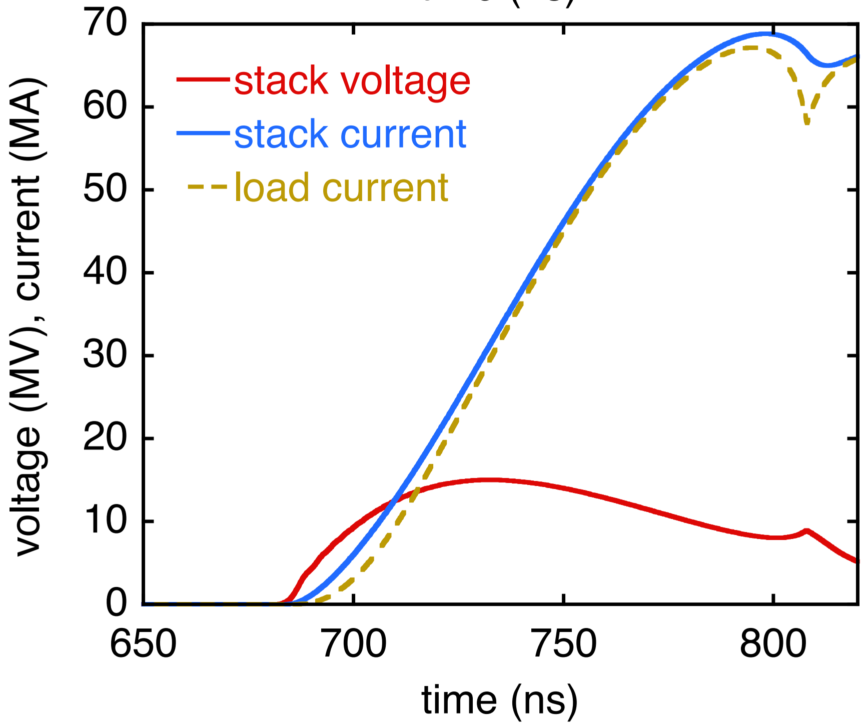
- Jupiter is powered by 210 IMG modules, which are electrically in parallel.
  - Each IMG module comprises 42 stages, which are connected in series.
  - Each IMG stage is powered by 20 bricks, which are connected in parallel.
- Each IMG module drives a water-insulated coaxial-transmission-line impedance 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 MJ.
- The thermonuclear-fusion yield predicted by 2D MHD simulations (Slutz and colleagues, POP, 2016) is 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).
Slutz et al., POP (2016).

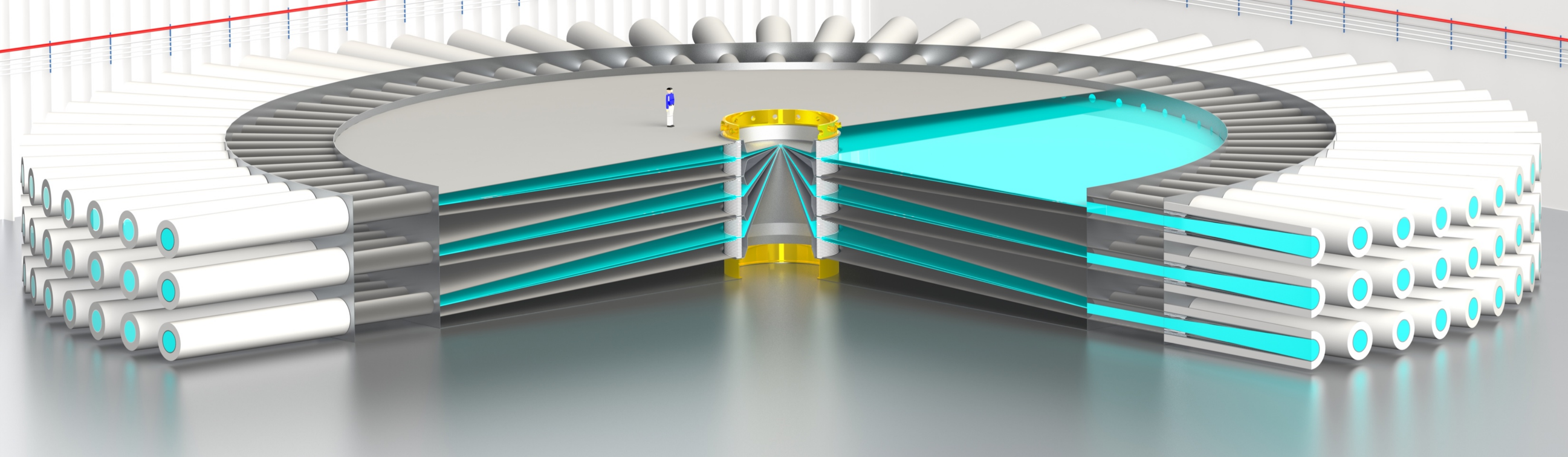
Outline

- Pulsed-power technology.
- Present state of the art: the Z accelerator.
- Unified approach to the design of next-generation machines.
- Three next-generation-accelerator concepts.
- 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.
- Technical foundation for Jupiter.
- Summary.

Fabricating and building a Jupiter-class accelerator will require a substantial effort.

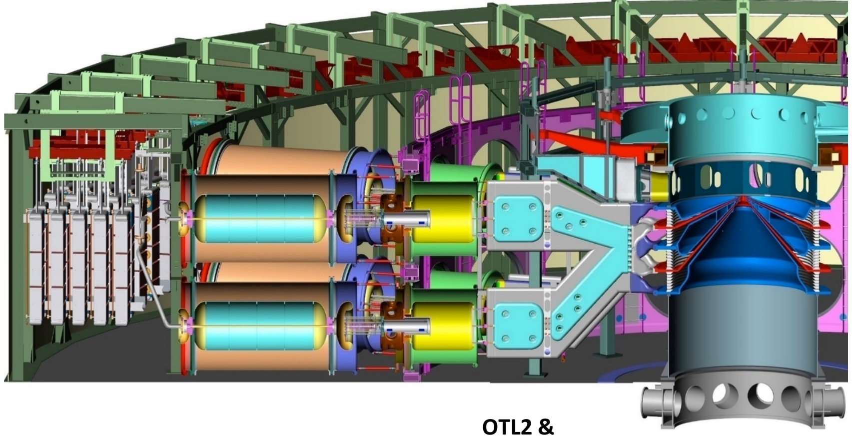
- Before cutting metal, and assembling hardware in a highbay, we will build three types of *virtual accelerators.*

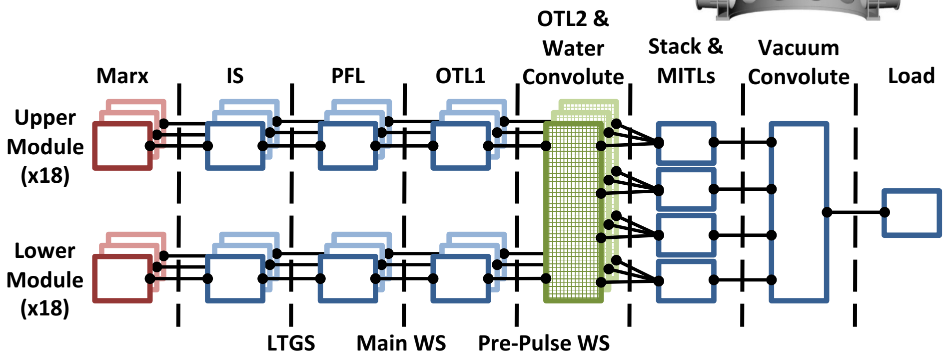
- The virtual machines will be used to conduct a large number of iterative *numerical accelerator experiments* to optimize the design of the machine.

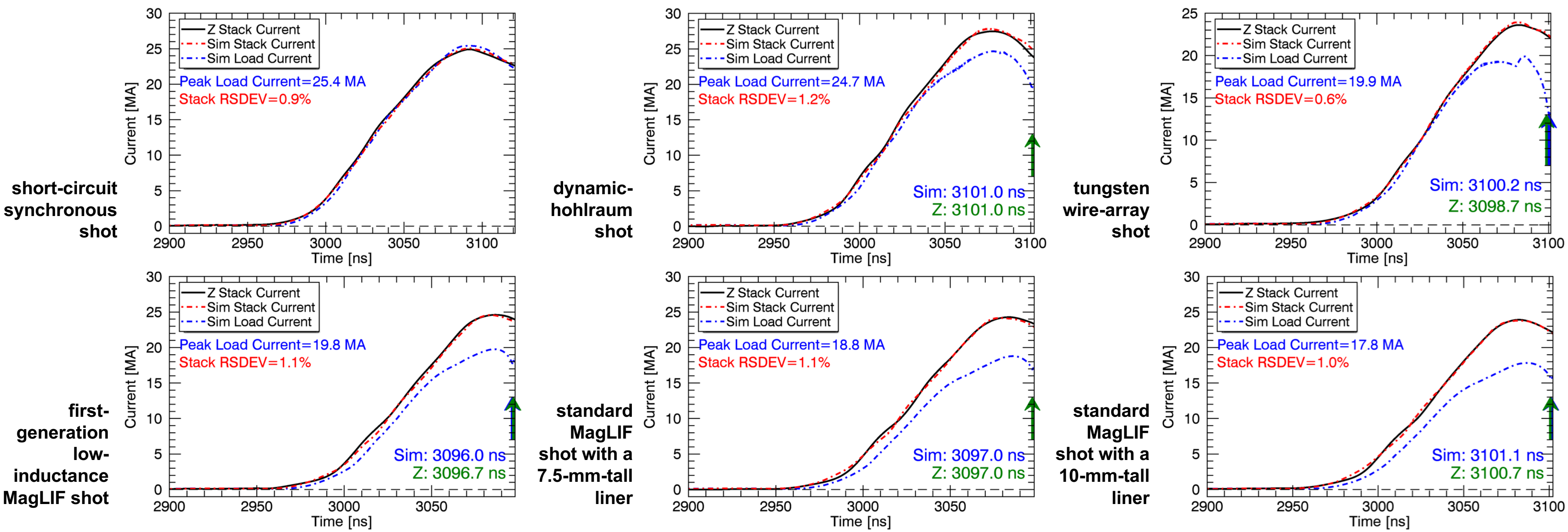


We will develop a physics-based transmission-line-circuit model of the entire Jupiter accelerator.

- The model will be used to conduct iterative *numerical accelerator experiments* to optimize the design of the machine.
- Brian Hutsel and colleagues have developed such a model of Z.
- The circuit model of Z is consistent with experiment to within 5%.



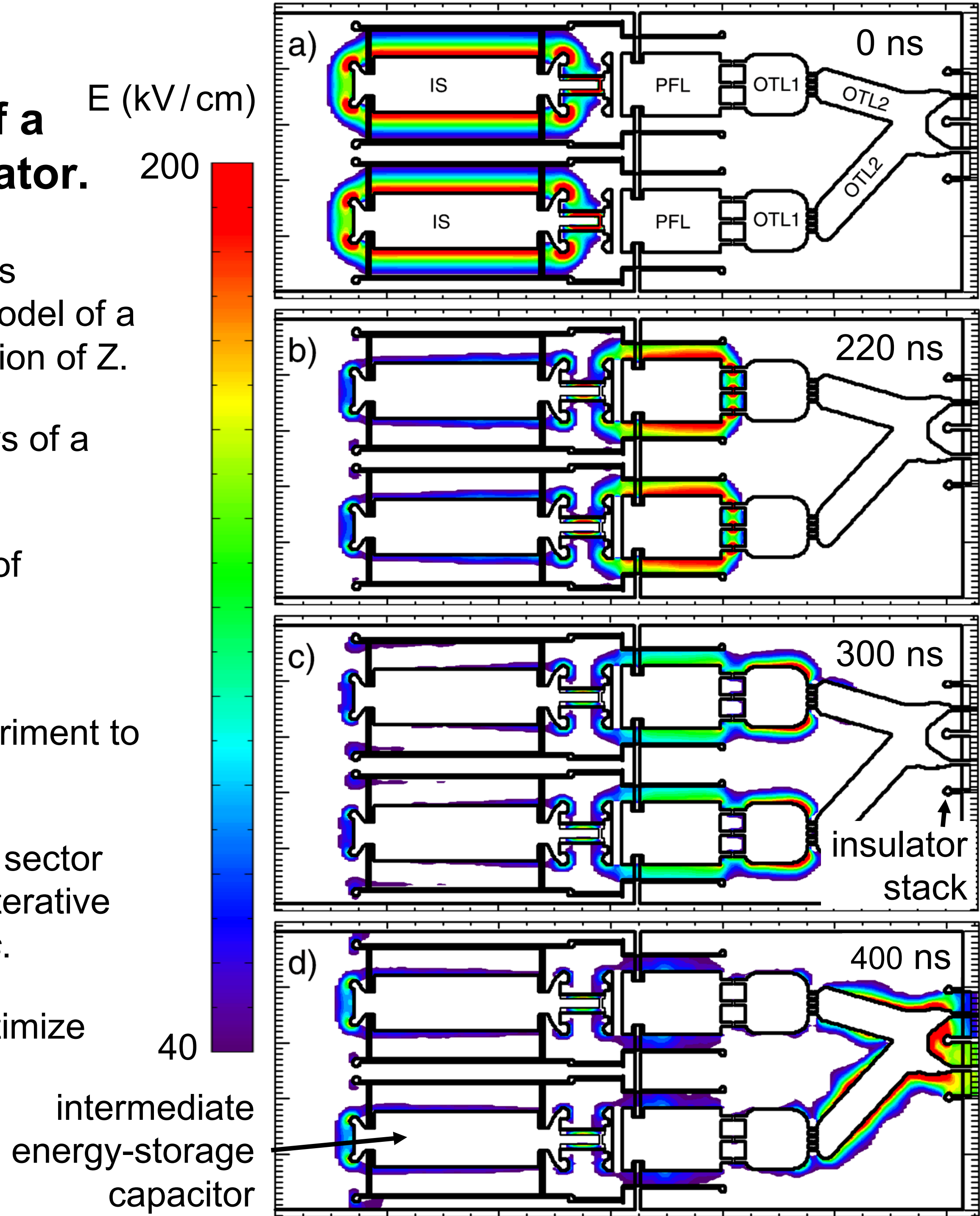




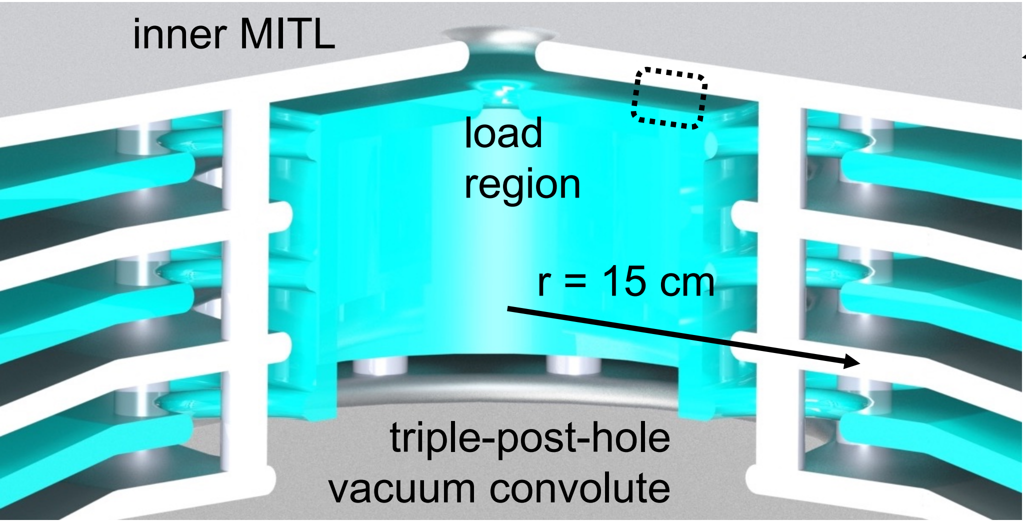
We will develop a fully electromagnetic 3D model of a sector of the Jupiter accelerator.

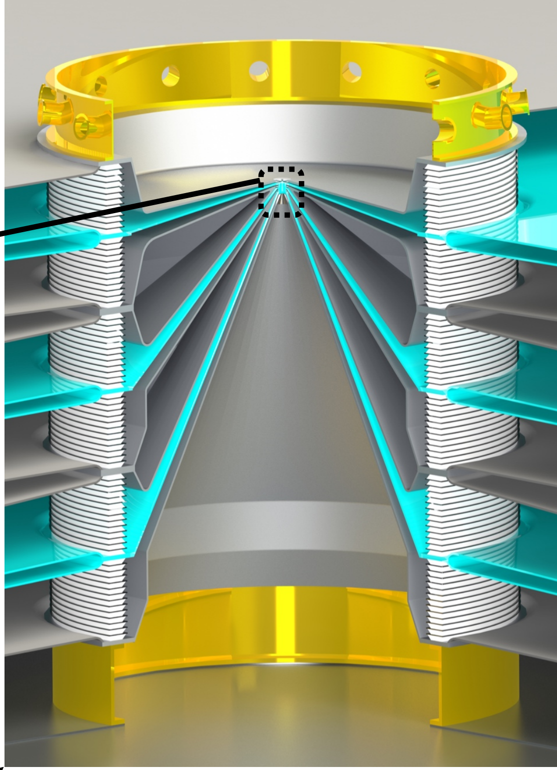
- Rose, Welch, and colleagues (Voss Scientific) have developed a 3D model of a 20-degree sector of the water section of Z.
- These are 2D cross-sectional views of a 3D simulation.
- The simulations illustrate the flow of energy from Z's intermediate-store capacitors to the insulator stack.
- Simulation results agree with experiment to within ~5%.
- An electromagnetic 3D model of a sector of Jupiter will be used to conduct iterative *numerical accelerator experiments*.
- The simulations will be used to optimize the design of Jupiter.

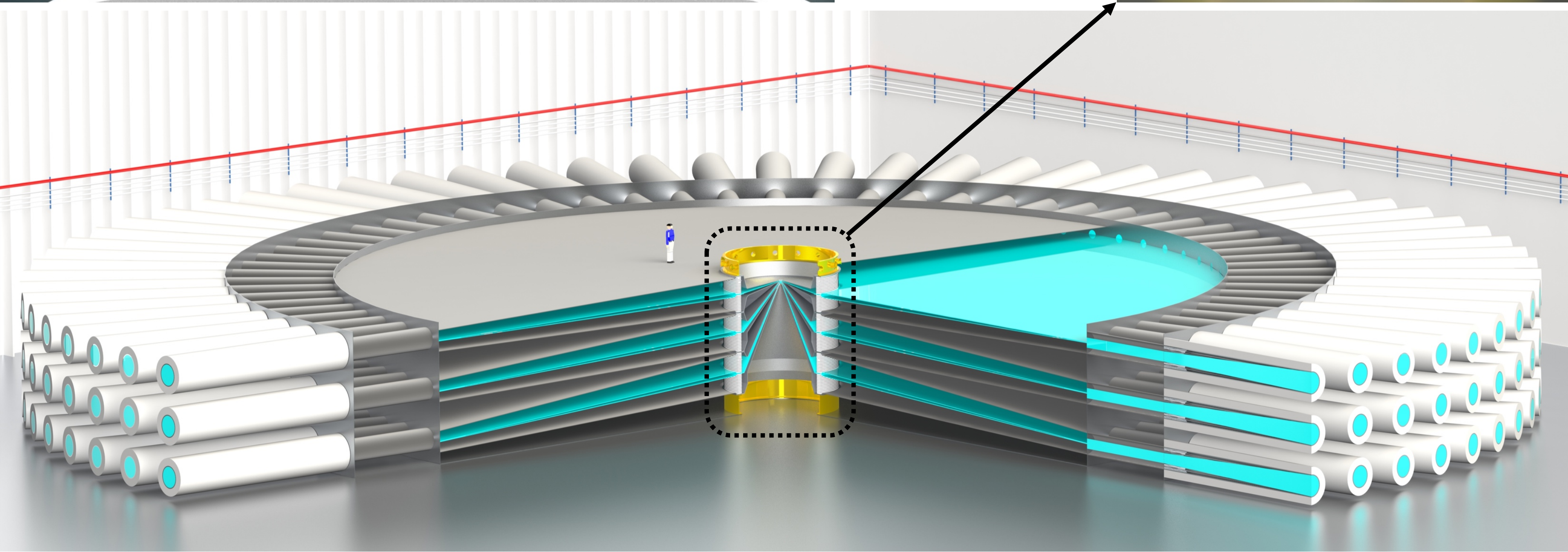
Rose et al., PRSTAB (January 2010).



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







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

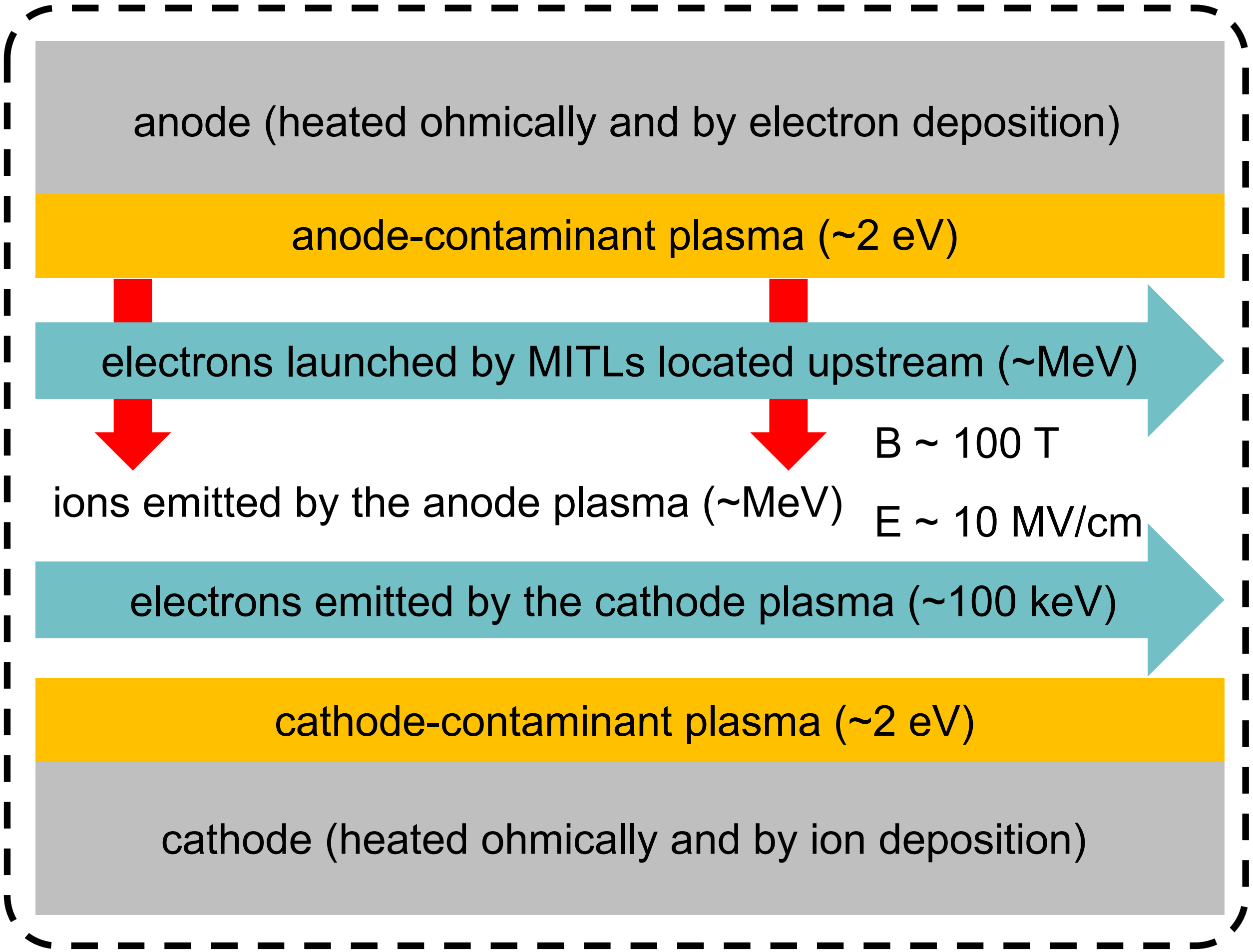
Such plasmas are

- 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



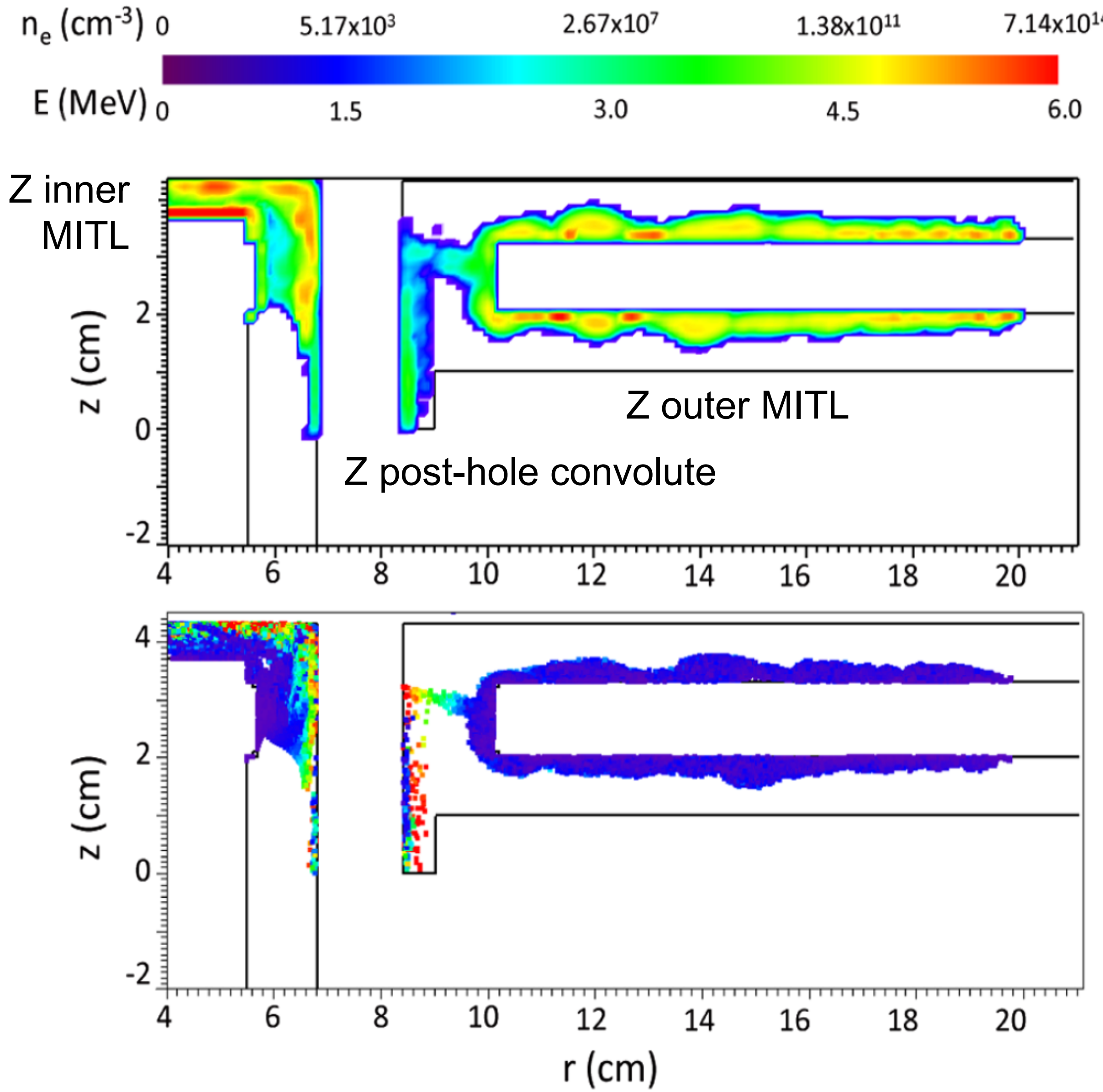
The only code that can presently model such plasmas is Chicago: the most advanced 3D particle-in-cell (PIC) code developed to date.

A 3D Chicago model of Jupiter will be used to conduct numerical experiments.

- Chicago is being developed by Welch, Rose, and colleagues (Voss Scientific).
- Voss and Sandia have developed a 3D Chicago model of the Z MITL-convolute-load system.
- The 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 optimize the design of Jupiter.

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

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



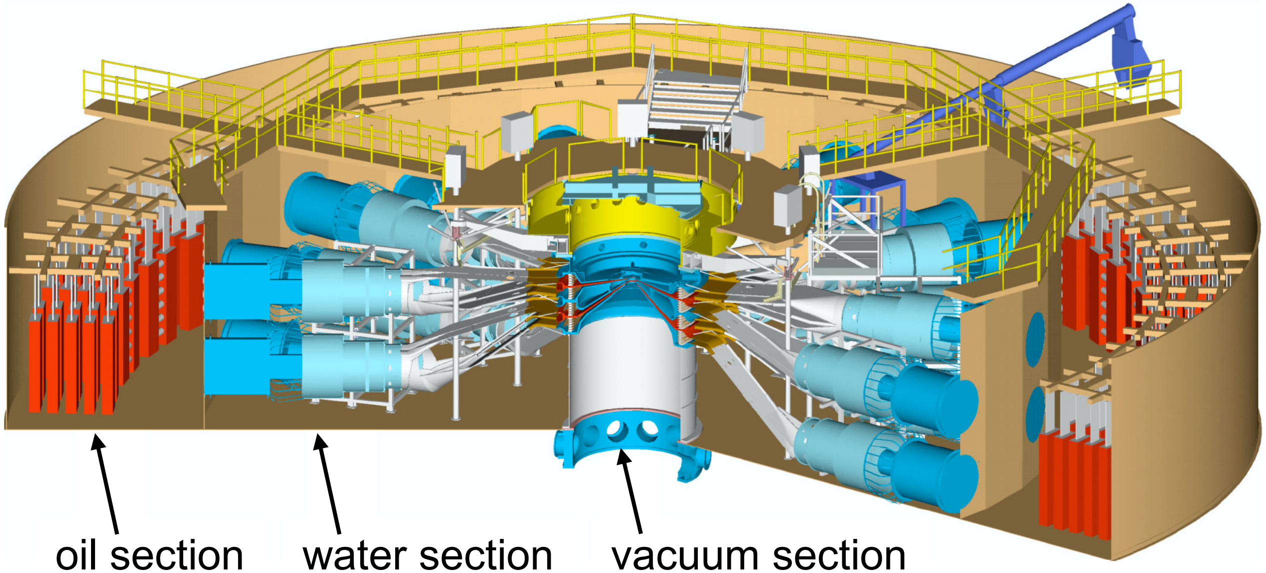
Outline

- Pulsed-power technology.
- Present state of the art: the Z accelerator.
- Unified approach to the design of next-generation machines.
- Three next-generation-accelerator concepts.
- 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.
- Technical foundation for Jupiter.
- Summary.

We have been establishing a technical foundation for Jupiter since 1995.

- The foundation is summarized by 50 peer-reviewed-journal articles.
- This effort began with the design, fabrication, assembly, and commissioning of the original 55-TW Z accelerator.
  - 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.
  - Z subsequently achieved a total radiated x-ray energy of 2 MJ, and a peak radiated x-ray power in excess of 200 TW.

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

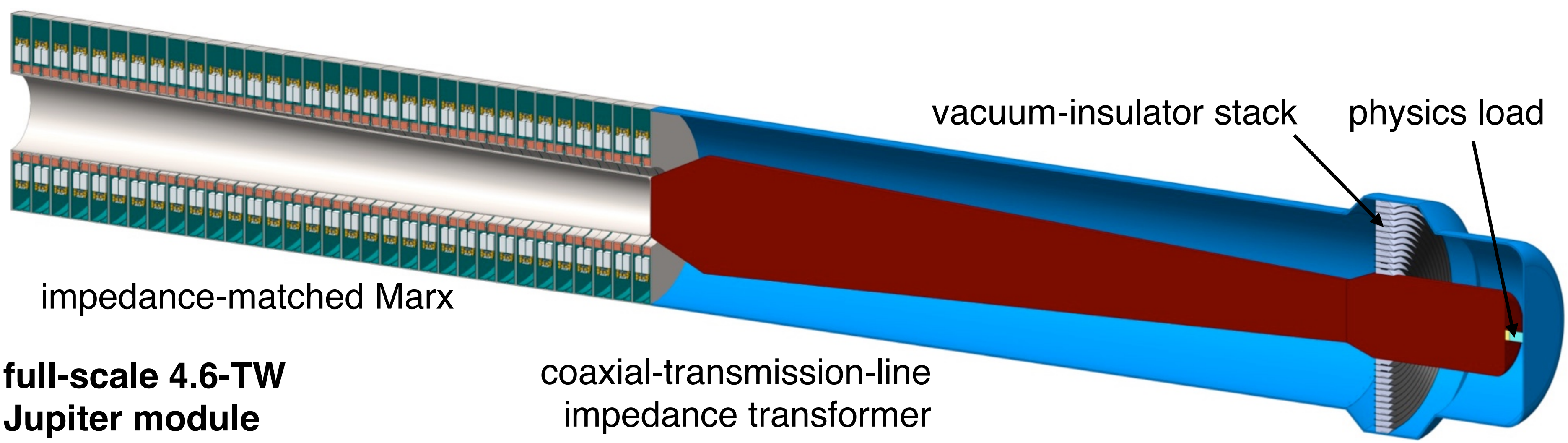


Outline

- Pulsed-power technology.
- Present state of the art: the Z accelerator.
- Unified approach to the design of next-generation machines.
- Three next-generation-accelerator concepts.
- 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.
- Technical foundation for Jupiter.
- Summary.

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 ICF experiments.
- The design is a *point conceptual* design that generates a peak electrical power of 960 TW, and delivers 67 MA and 9 MJ in 100-ns to an ICF load.
- The *optimized final engineering* design of Jupiter will be informed, in part, 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 1995.



full-scale 4.6-TW Jupiter module