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Sirius I: prototype of a prime-power source for future 1 - 10 GJ fusion-yield experiments

K. R. LeChien, W. A. Stygar, M. G. Anderson, D. A. Max, R. M. Anaya, C. B. Beatty, A. D. White, J. J. Trueblood, A. M. Benson, R. E. Beverly, R. S. Chaffee, J. E. Cortes, W. A. Drews, R. K. Hicks, F. A. Howland, D. B. Norton, R. D. Speer, J. A. Watson

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FULL TECHNICAL LDRD REPORT

LDRD project title: Sirius I: prototype of a prime-power source for future 1 – 10 GJ fusion-yield experiments

LDRD Principal Investigators: K. R. LeChien,[1] W. A. Stygar,[1] and M. G. Anderson[1]

LDRD Team: D. A. Max,[2] R. M. Anaya,[1] C. B. Beatty,[1] A. D. White,[1] J. J. Trueblood,[1] A. M. Benson,[3] R. E. Beverly,[4] R. S. Chaffee,[1] J. E. Cortes,[1] W. A. Drews,[3] R. K. Hicks,[1] F. A. Howland,[1] D. B. Norton,[1] R. D. Speer,[1] and J. A. Watson[1]

[1]*Lawrence Livermore National Laboratory, Livermore, California 94550, USA*
[2]*Mission Support and Test Services, North Las Vegas, Nevada 89030, USA*
[3]*General Atomics Energy Group, Poway, California 92064, USA*
[4]*R. E. Beverly and Associates, Lewis Center, Ohio 43035, USA*

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Abstract

We have designed, assembled, and tested a prototype coaxial impedance-matched Marx generator (IMG). An IMG is a pulsed-power device that achieves electromagnetic-power amplification by triggered emission of radiation. Hence an IMG is a pulsed-power analog of a laser, with an energy efficiency of 90%. We have demonstrated that the prototype performs as predicted theoretically, thereby proving the IMG concept. We propose that a system of IMGs drive a next-generation pulsed-power accelerator that delivers 90 MA to a physics load. Such a machine would attain thermonuclear-fusion yields as high as 1 – 10 GJ, and revolutionize high-energy-density-physics experiments in support of the national-security mission.

Background and Research Objectives

NIF has recently achieved a 1-MJ thermonuclear-fusion yield, clearly a stunning and historic success. Proposed upgrades to NIF would achieve as much as 10 MJ. NIF targets that realize 1 – 10 MJ fusion yields would support unprecedented high-energy-density-physics (HEDP) experiments.

As demonstrated by Hammer, LeChien, Raman, Meezan, Grim, Edwards, and colleagues [1,2], we could expand immensely applications of HEDP experiments by developing a platform that increases fusion yields by a factor of 1000, to 1 – 10 GJ. It appears possible to realize such yields with a pulsed-power accelerator that delivers 75 MA to a physics load [1,2].

Motivated by these observations, we have developed a conceptual design of a next-generation pulsed-power accelerator that generates a peak electrical power of 700 TW, and delivers as much as 90 MA to a physics load. We refer to the machine as Sirius, after the brightest star in the night sky. The conceptual design of Sirius is illustrated by Fig. 1.

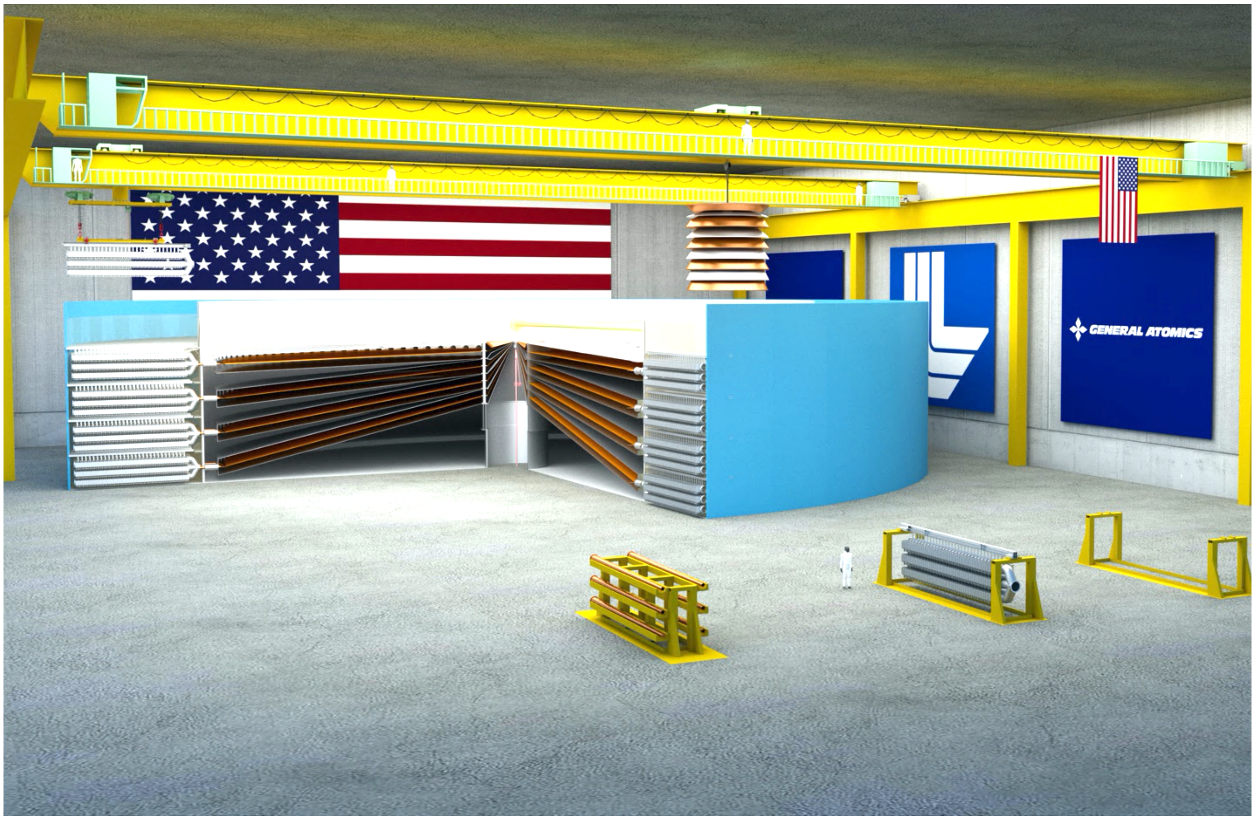

Fig. 1. Conceptual design of the 74-m-diameter 90-MA 700-TW Sirius accelerator.

The prime-power source of Sirius is a system of impedance-matched Marx generators (IMGs). The IMG concept was invented in 2017 [3]. Sirius is powered by 480 IMG triplets; a single triplet is illustrated by Fig. 2. The IMG concept was developed to overcome significant shortcomings of other candidate prime-power sources, such as conventional Marx generators and linear-transformer drivers.

Reference [3] presents analytic calculations and circuit simulations that illustrate the IMG concept. The fundamental building block of an IMG is a brick, which consists of two capacitors connected electrically in series with a single switch. An IMG comprises a single stage or several stages distributed axially and connected in series. Each stage is powered by a single brick or several bricks distributed azimuthally around the stage and connected in parallel. The stages of a multistage IMG drive an internal axial transmission line. The wave impedance of the internal line is a function of distance along the axial dimension of the line; the line's spatial impedance profile is matched to that of the stages that drive the line.

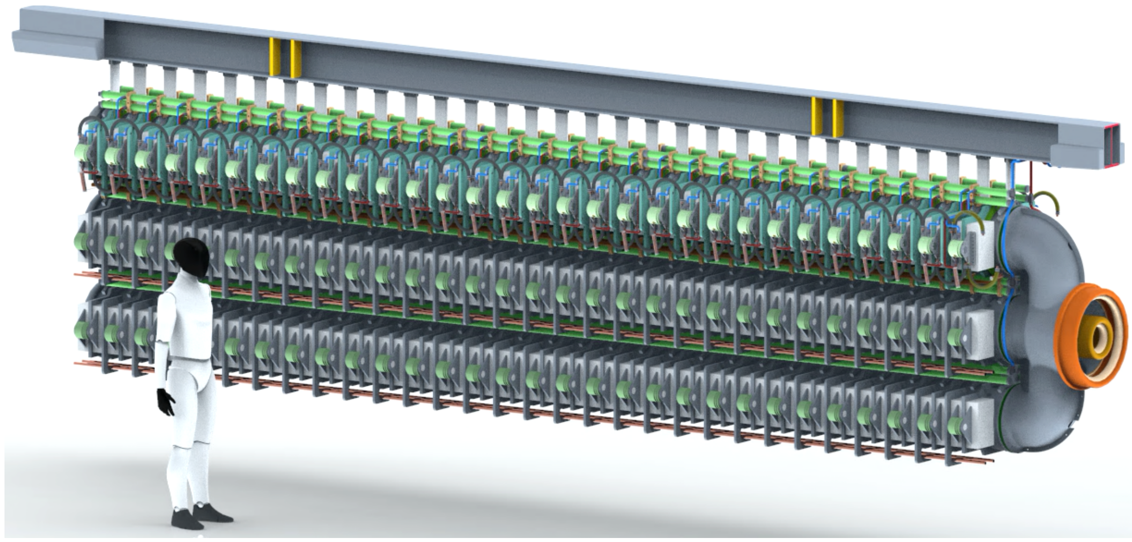

Fig. 2. Triplet of Sirius IMGs. Each triplet generates a peak electrical power of 1.4 TW.

Each stage of an IMG can be modeled as an *LCR* circuit; i.e., an oscillator. The capacitors of each stage are initially charged to high voltage; hence the oscillators are initially in an excited state. When the switches of the IMG stages are triggered sequentially to launch a coherent traveling wave along the IMG's internal axial transmission line, the IMG achieves electromagnetic-power amplification by triggered emission of radiation. Hence a multistage IMG is a pulsed-power analog of a laser. The power gain of an IMG is *n*, where *n* is the number of stages [3].

Figure 3 illustrates an idealized four-stage IMG, and the electromagnetic waves that flow within. As illustrated by the figure, all reflected waves cancel. All that remain are forward-going waves.

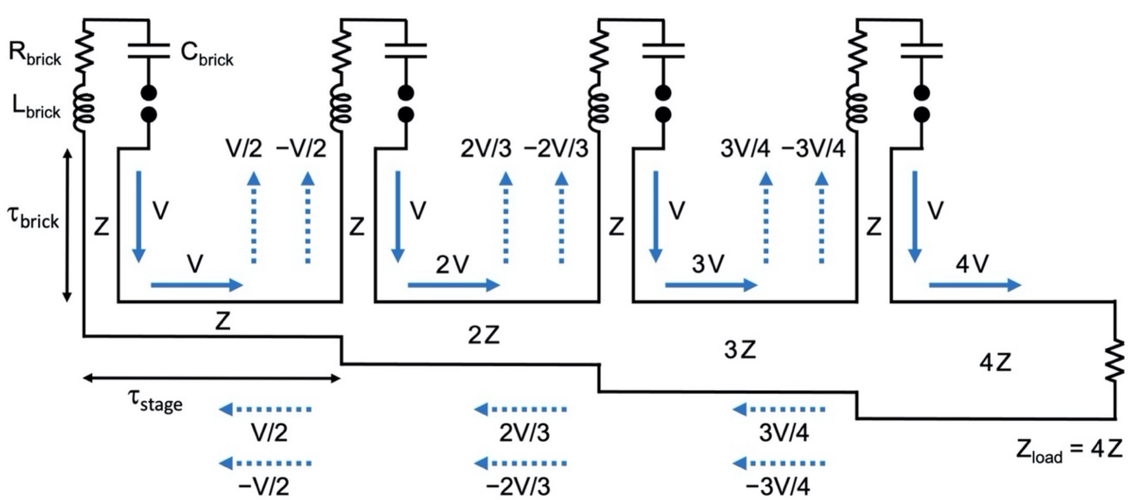

Fig. 3. Idealized four-stage IMG with four vertical and four horizontal transmission lines. The dotted arrows represent internal reflected electromagnetic waves, all of which cancel. All that remain are forward-going waves [3]. The illustration assumes each stage is triggered at time τ_{stage} after the stage located immediately upstream.

The principal objective of the LDRD was to demonstrate experimentally that a prototype IMG with an internal coaxial transmission line performs as predicted.

For completeness, we describe below conventional Marx generators and linear transformer drivers.

Conventional Marx generators

The conventional Marx generator was invented by E. O. Marx in 1924 [4]. One manifestation is the folded Marx concept developed by Martin [5]. Folded Marxes have been used by Sandia National Laboratories to drive pulsed-power accelerators since the 1970s. The Z machine, presently the world's largest and most powerful pulsed-power accelerator, is driven by 36 folded Marx generators.

Table I compares parameters of a Z-accelerator Marx with those of a Sirius IMG.

	Z Marx generator	Sirius IMG
switch insulating gas	SF_6	air
charge transfer per switch per shot	0.22 C	0.016 C
switch lifetime	~200 shots	~2000 shots
capacitance per capacitor	2.6 μF	0.16 μF
capacitor charge voltage	85 kV	100 kV
electrical energy stored per capacitor	9400 J	800 J
total stored energy	560 kJ	96 kJ
weight of a single capacitor	240 lbs.	23 lbs.
number of stages	30	30
LC time constant	820 ns	120 ns
peak electrical power	0.35 TW	0.47 TW

Table 1. Parameters of a Z Marx generator and Sirius IMG.

As indicated by the table, a Z Marx uses SF_6 to insulate its gas switches; a Sirius IMG uses air. SF_6 has 23,500 times the global warming potential of CO_2, and is the most potent greenhouse gas ever reviewed by the Intergovernmental Panel on Climate Change. Since the mass density of SF_6 is a factor of 5 greater than that of air, SF_6 also presents an asphyxiation hazard to accelerator workers.

Alternatives to SF_6 are presently being developed by the electrical-power industry; however, such a gas hasn't yet been successfully demonstrated by Sandia on the Z accelerator.

In addition, each Z-Marx capacitor stores 9400 J and weighs 240 lbs. Such a capacitor presents a greater hazard to workers than a Sirius-IMG capacitor, which stores 800 J and weighs 23 lbs. (A capacitor discharge of 50 J is sufficient to cause a fatality [6]; hence both the Z-Marx and Sirius-IMG capacitors present a lethal hazard to workers. However, since a Sirius-IMG capacitor stores an order of magnitude less energy than that of a Z Marx, a Sirius capacitor requires less time to discharge to a safe energy, and is less likely to be fatal in an operational environment.) It appears a Sirius IMG is more consistent with the principles of engineered safety than a Z Marx.

Furthermore, as indicated by Fig. 4, a Z Marx generates a much slower electrical-power pulse than a Sirius IMG. This is as expected, since as indicated by Table I, the *LC* time constant of a Z Marx is a factor of 7 greater than that of a Sirius IMG. As a result, even though a Sirius IMG stores a factor of 6 less energy than a Z Marx, the peak power generated by a Sirius IMG is 35% greater.

The temporal width of the electromagnetic-power pulse generated by a Sirius IMG is – by design – sufficiently short for the pulse to be transported directly to, and used by, physics loads of interest, without additional stages of electrical-pulse compression.

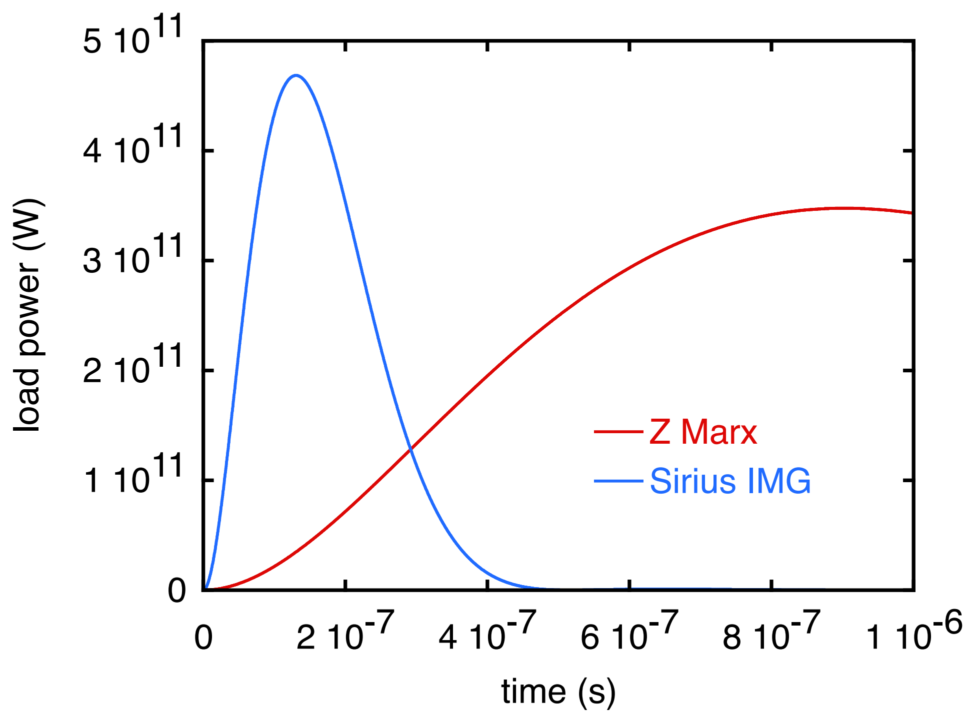

Fig. 4. Electromagnetic-power time histories of a Z Marx generator and Sirius IMG. A Sirius IMG stores a factor of 6 less energy than a Z Marx, and generates 35% more power.

In contrast to the power pulse generated by a Sirius IMG, a Z-Marx pulse requires additional stages of temporal compression before the pulse can be used to drive experiments of interest.

Each Z Marx is operated with the following pulse-compression hardware, much of which is illustrated by Fig. 5:

- 6-MV water-insulated intermediate-energy-storage (IS) capacitor.
    - Each IS capacitor is 1 m in diameter and 1.6-m long.
    - Each IS capacitor includes two 1-m-diameter polyurethane disks and associated hermetic seals to contain the water within the capacitor.
- 6-MV laser-triggered SF_6-insulated gas switch [7,8].
    - Each switch is 0.24 m in diameter and 0.42 m long.
- 5-MW ultraviolet (UV) laser that triggers the 6-MV gas switch.
    - It's clear a high-power UV laser presents an eye hazard to workers.
- Train of UV optics that transports the UV pulse from the laser to the 6-MV gas switch. Each train includes the following:
    - Laser tower within the Z-accelerator tank.
    - 6-MV SF_6-insulated laser-transport tube.
    - Remotely controlled UV-optics-alignment system.
- Closed-loop SF_6 processing system.
- 5-MV water-insulated pulse-forming transmission line (PFL).
    - Each PFL is 0.8 m in diameter and 0.8 m long.
- Set of 5-MV self-break water switches.
- Additional set of lower-voltage self-break water switches.

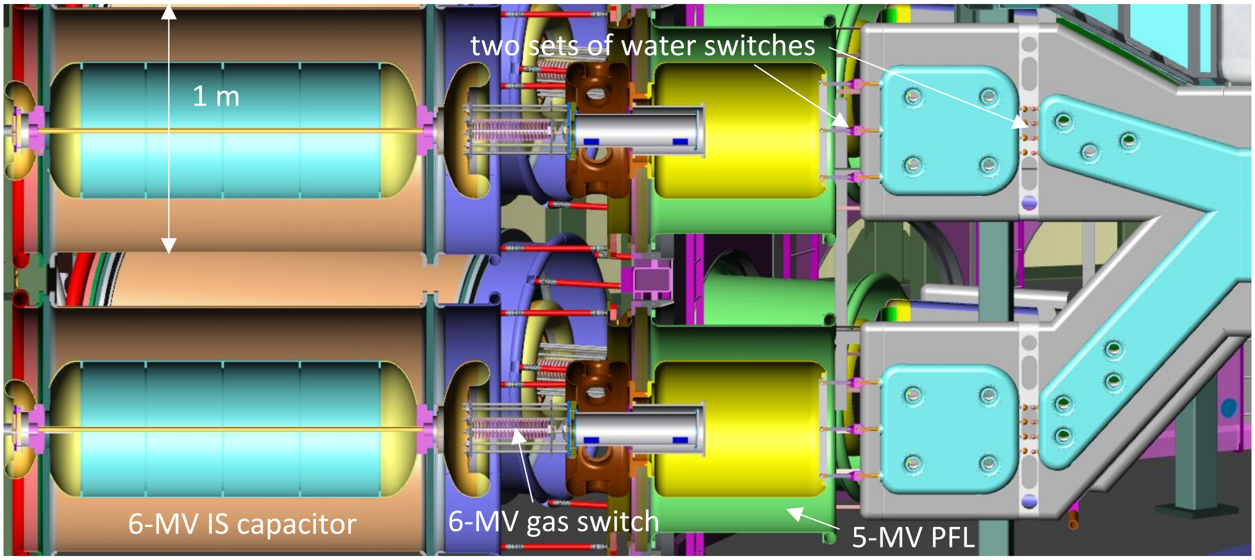

Fig. 5. Electrical-pulse-compression transmission lines and switches required by two Z Marx generators [9]. Each of the two intermediate-energy-storage (IS) capacitors is 1 m in diameter. None of the hardware illustrated here is required by a Sirius IMG.

A Sirius IMG requires none of the hardware described and illustrated above, and none of the associated hazards to workers and the environment.

Linear transformer drivers

In 1997, Koval'chuk and colleagues invented the linear-transformer-driver (LTD) concept as a prime-power source for next-generation pulsed-power accelerators [10]. For two decades thereafter, LTDs were leading candidates for the prime-power source of future machines. Like an IMG, an LTD is a pulsed-power analog of a laser.

An IMG is similar to, but simpler than, an LTD. Unlike an LTD, an IMG doesn't require the following [3]:

- Ferromagnetic cores.
- Circuitry that re-sets the cores after each shot.
- Two annular-disk metal cavity enclosures per stage.
- A cylindrical metal cavity enclosure per stage.

Reference [3] includes a more complete discussion of the differences between LTD and IMG pulse generators.

Unlike an LTD, an IMG doesn't require that its components be located within enclosed cavities. An IMG has an open architecture, which simplifies triggering of the IMG switches, and enables access to the IMG's high-voltage components for maintenance.

We estimate that using IMGs instead of LTDs as the prime-power source for a next-generation pulsed-power accelerator would reduce the cost of the machine by ~30%.

Scientific Approach and Accomplishments

To evaluate the IMG concept, we have designed, assembled, and tested a prototype four-stage IMG with an internal coaxial transmission line. We refer to the prototype as Sirius I, which is illustrated by Fig. 6.

As indicated by the figure, the Sirius-I IMG comprises four stages distributed axially and connected in series. Each stage is powered by 2 bricks located 180 degrees apart and connected in parallel. Reference [9] describes an accelerator concept that's powered by IMGs with 20 bricks per stage; reducing this to 2 reduces the diameters of the IMG's anode and cathode electrodes, which facilitates fabrication by a larger number of machine shops. Using only 2 bricks per stage also facilitates IMG maintenance and sequential triggering of the IMG switches.

Each of the eight Sirius-I bricks includes two pairs of 80-nF 100-kV capacitors and a single 200-kV switch. The capacitors were fabricated by CSI Technologies [11]. The two 80-nF capacitors of a pair are connected in parallel to form a 160-nF capacitor. Before an IMG shot, one capacitor pair of each brick is charged to +100 kV; the other, -100 kV. The two capacitor pairs are connected in series with the gas switch so that a potential difference of 200 kV appears across the switch.

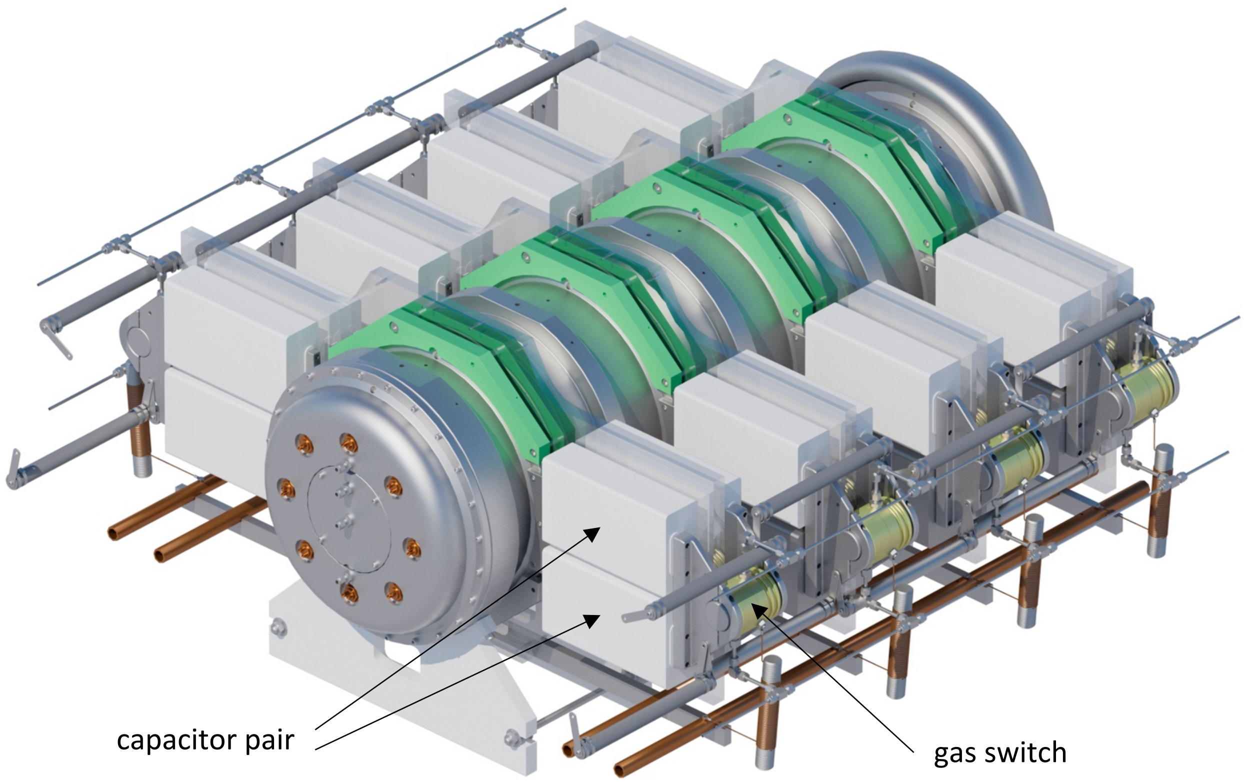

Fig. 6. Sirius I: a prototype four-stage IMG with an internal coaxial transmission line. The IMG is powered by eight bricks. Each brick comprises two capacitor pairs and a switch.

The IMG switch has a three-electrode field-distortion design, and is insulated with dry synthetic pressurized air. The switch was designed by the LDRD Team, and is the most advanced 200-kV gas switch developed to date. The specifications that define the switch design are listed by Ref. [11]. A 2D plot of the electric field within the switch is presented by Fig. 7.

As suggested by Fig. 7, the switch's midplane electrode is equidistant from the switch's two main electrodes, and the switch is symmetric about the midplane. The switch is charged in a balanced manner so that before a shot, the midplane is at a potential of 0 V. The switch is triggered by applying a fast-rising high-voltage pulse to its midplane. The pulse distorts the electric field within the switch, which launches ionized streamers that cause the switch to close.

The IMG's eight switches are triggered by a novel 50-ohm 100-kV switch-trigger pulse generator with an all-solid-state front end [13]. The generator was developed by R. E. Beverly and Associates; the development was funded in part by the LDRD. The generator is connected to the switches by a new traveling-wave triggering circuit that was developed by the LDRD Team. The circuit allows one pulse generator to trigger at least eight switches.

The IMG's four stages drive an internal coaxial transmission line with a conical center conductor. The coaxial line is insulated with MIVOLT DFK oil [14]. Unlike a mineral oil (such as Shell Diala or Mobil Univolt), MIVOLT DFK is a synthetic ester and is biodegradable. In addition, MIVOLT DFK has a relative permittivity of 3.2, substantially higher than the 2.2 of a mineral oil. The higher permittivity allows the use of larger anode-cathode gaps between the inner and outer conductors of the IMG's internal coaxial transmission line.

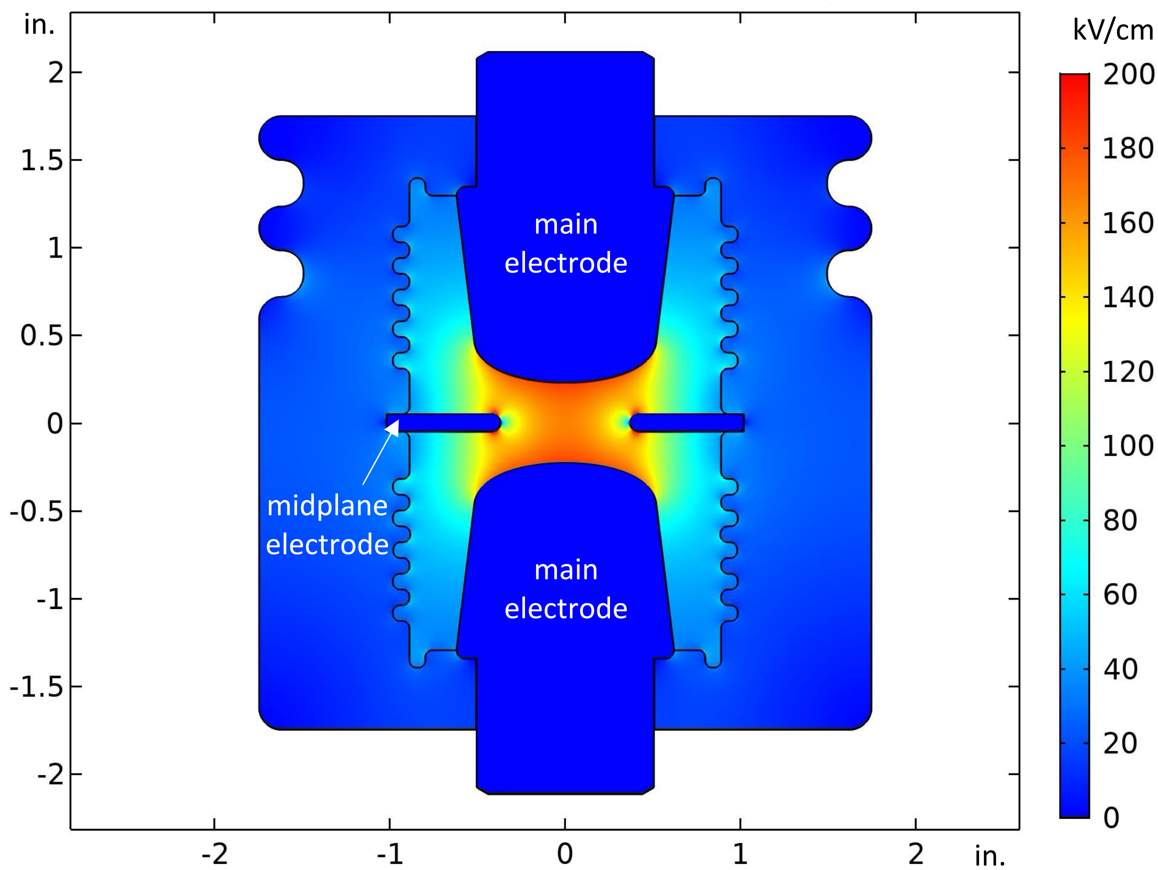

Fig. 7. 2D electric field within the IMG's three-electrode field-distortion gas switch when the potential difference across the switch is 200 kV. The field on the surface of each of the switch's two main electrodes is constant to ± 1% within a 1.2-cm radius.

The IMG's coaxial transmission line is terminated by a 4-ohm aqueous-electrolyte resistive load. The aqueous solution is recirculated and cooled by a prototype aqueous-electrolyte recirculation and control system [15]. The prototype was developed by R. E. Beverly and Associates; the development was funded in part by the LDRD.

To simulate the performance of the Sirius-I IMG, we developed the transmission-line-circuit model illustrated by Fig. 8. The two bricks of each IMG stage are modeled as a single *LCR* circuit. The simulated time history of the electrical power delivered by the IMG to its load is plotted by Fig. 9; the measured time history is also plotted. The simulated and measured histories agree to within experimental uncertainties. The agreement proves the IMG concept, and demonstrates that the objectives of the LDRD were fulfilled. The simulated and measured IMG energy efficiencies are both 90%.

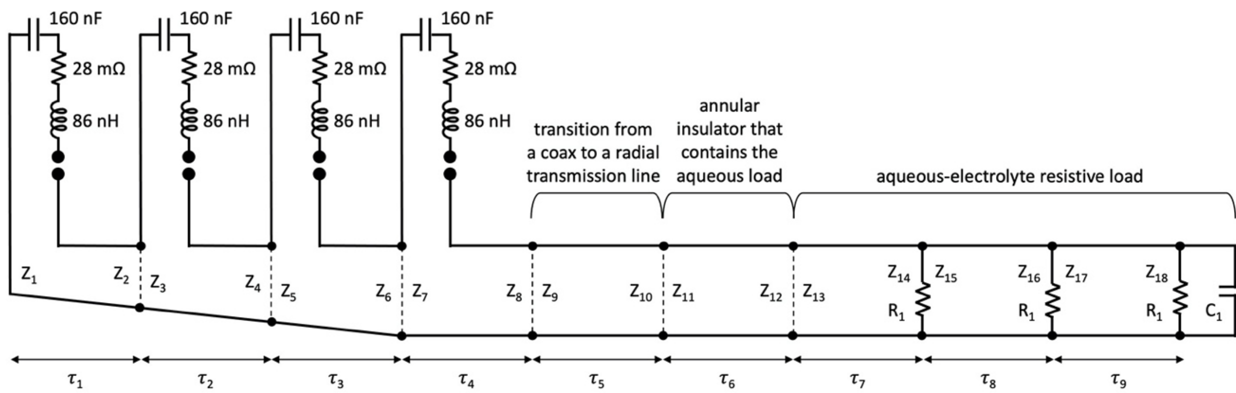

Fig. 8. Transmission-line-circuit model of the Sirius-I IMG. The two bricks of each IMG stage are modeled as a single *LCR* circuit. Nine transmission-line segments connect the IMG's four stages to the aqueous-electrolyte resistive load.

The peak power delivered by the IMG to its load is 60 GW. A single Sirius-I brick generates a peak power of 7.5 GW, which is more than twice the 3.3 GW generated by the largest nuclear power plant in the United States. (Of course, the brick generates power for only ~10^{-7} s.)

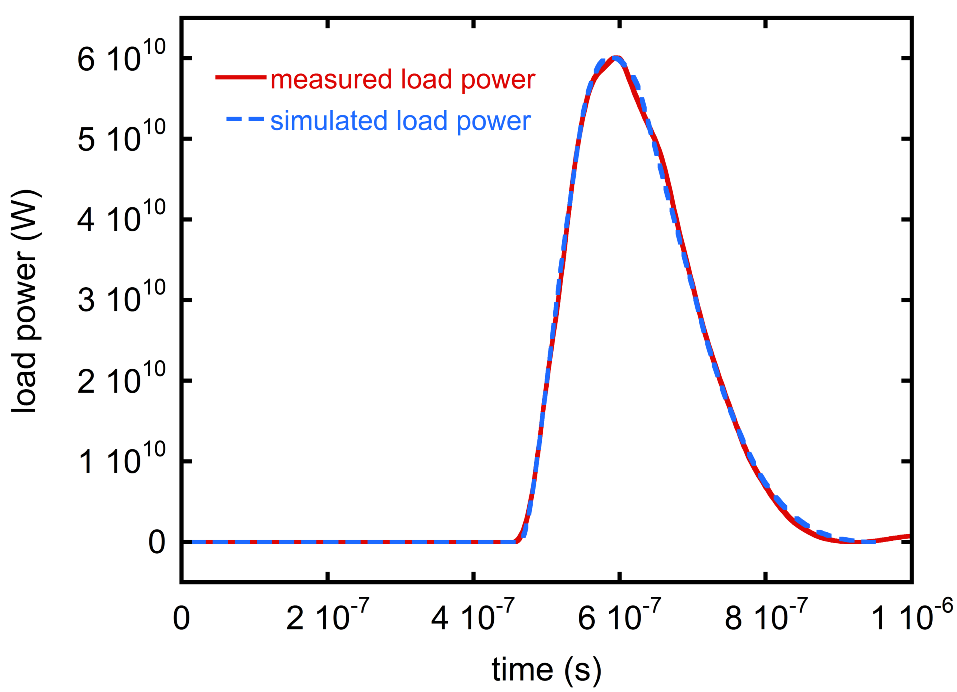

Fig. 9. Simulated and measured time histories of the electrical power delivered by the IMG to its resistive load. The two histories agree to within experimental uncertainties. The agreement proves the IMG concept, and demonstrates that the LDRD objectives were fulfilled. The simulated and measured IMG energy efficiencies are both 90%.

Mission Impact

The LDRD has proven the IMG concept, which was invented in 2017. We propose that a system of IMGs drive a next-generation pulsed-power accelerator that delivers 90 MA to a physics load. Such a machine would achieve thermonuclear-fusion yields as high as 1 – 10 GJ, and revolutionize high-energy-density-physics experiments in support of the national-security mission.

Conclusion

LLNL's ICF Program has graciously volunteered to support continued development of IMG technology in FY 2023.

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Publications, Presentations, and Patents

The results summarized above will be included in a peer-reviewed journal article that we expect to publish in FY 2024.