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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. A brief overview of the Sirius designs, operations and results are provided here with more in-depth treatment with additional figures and tables provided in the companion PPC2023 conference presentation.**

Keywords*— impedance-matched Marx generator, next-generation pulsed-power accelerator, prime-power source, high-yield fusion, high energy-density physics experiments

I. Background and 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.

II. 700TW Sirius Concept

Motivated by the above work, we have developed a 700TW conceptual design (74m diameter) of a next-generation pulsed-power accelerator that delivers as much as 90 MA to a physics load. We refer to the machine as Sirius (shown in Figure 1), after the brightest star in the night sky. Sirius is powered by 480 IMG Triplets.

III. Sirius Impedance-matched Marx Generator

The prime-power source of Sirius is a system of impedance-matched Marx generators (IMGs). The IMG concept was invented in 2017 [3]. A 30-stage Sirius IMG "Triplet" is illustrated in Figure 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. Each IMG Triplet generates a peak electrical power of 1.4 TW.

A single IMG may be comprised of a single or multiple 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. Top, Side and Cross-sectional views of a 30-stage IMG is provided in Figure 3.

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 4 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.

IV. Marx Comparisons

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 [6-8], presently the world's largest and most powerful pulsed-power accelerator, is driven by 36 folded Marx

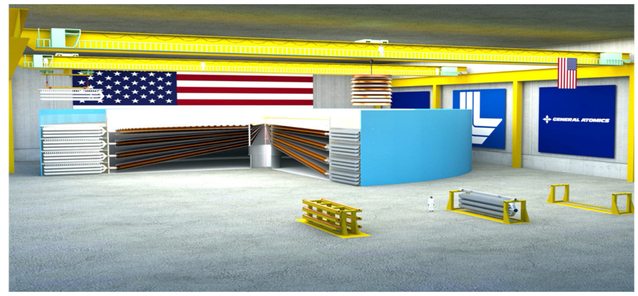

Fig. 1. 700TW Sirius Concept (74m diamter)

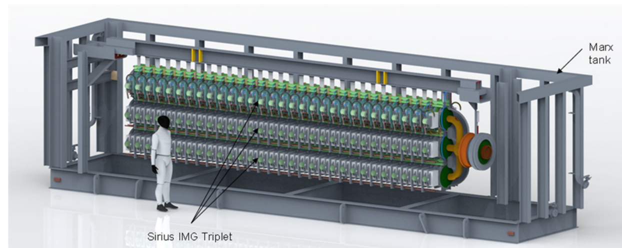

Fig. 2. 30-Stage Sirius IMG Triplet inside Marx tank (~10m long)

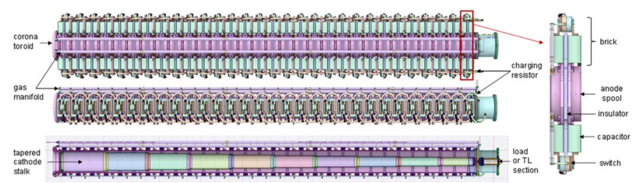

Fig. 3. Top, Side and Cross-sectional views of Single 30-Stage Sirius IMG (~8m long)

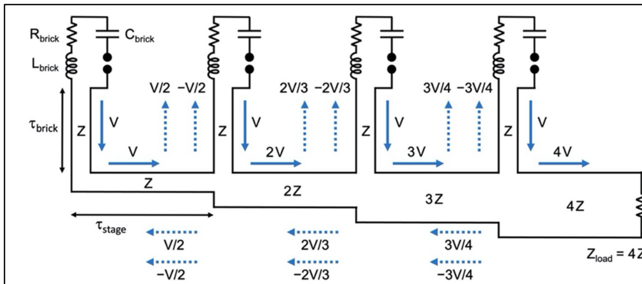

Fig. 4. Idealized four-stage IMG circuit with identified electromagnetic waves

TABLE I. Z-accelerator Marx and Sirius IMG Comparison

	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	160 nF
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

generators. Table I compares parameters of a Z-accelerator Marx with those of a Sirius IMG. As indicated in Table I, a Z Marx uses SF6 to insulate its gas switches; a Sirius IMG uses air. SF6 has 23,500 times the global warming potential of CO2 and is the most potent greenhouse gas ever reviewed by the Intergovernmental Panel on Climate Change. Since the mass density of SF6 is a factor of 5 greater than that of air, SF6 also presents an asphyxiation hazard to accelerator workers. Alternatives to SF6 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 [9]; 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 Figure 5, a Z Marx generates a much slower electrical-power pulse than a Sirius IMG. This is as expected since 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. 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.

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%.

V. 4-Stage Sirius-I Prototype

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 IMG and is shown in Figure 6.

The Sirius-I IMG comprises four stages distributed axially and connected in series. Each stage is powered by two bricks located 180 degrees apart and connected in parallel. Under several accelerator-design constraints, using only two bricks per stage minimizes the diameters of the IMG's anode and cathode electrodes, which allows their fabrication by a larger number of machine shops. Using only two bricks per stage also facilitates sequential triggering of the IMG switches.

A transmission-line-circuit model is provided in Figure 7 for 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 resistive load.

Shown in Figure 8 is a 2D electric field plot within the IMG's three-electrode field-distortion gas switch when the potential difference across the switch is 200 kV. The electric field on the surface of each of the switch's two main electrodes is constant to +/-1% within a 1.2-cm radius.

VI. Accomplishments

Simulated and measured time histories of the electrical power delivered by the IMG to its resistive load are provided in Figure 9. The two histories agree 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%.

VII. Mission Impact

The LDRD has proven the IMG concept, which was invented in 2017 [3]. 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.

VIII. Conclusion

In conclusion, we have designed a 700TW Sirius accelerator concept that delivers as much as 90 MA to a physics load. A 30-stage Sirius IMG "Triplet" was developed to overcome significant shortcomings of other candidate prime-power sources. Each triplet generates a peak electrical power of 1.4 TW. To prove the IMG concept is an efficient, economical, and viable path towards a high yield fusion driver, we successfully designed, assembled, and demonstrated a prototype four-stage Sirius-I IMG. Finally, LLNL's ICF Program has graciously volunteered to support continued development of IMG technology. As such, provided in Figure 10 is our proposed Sirius IMG Facility conceptual design.

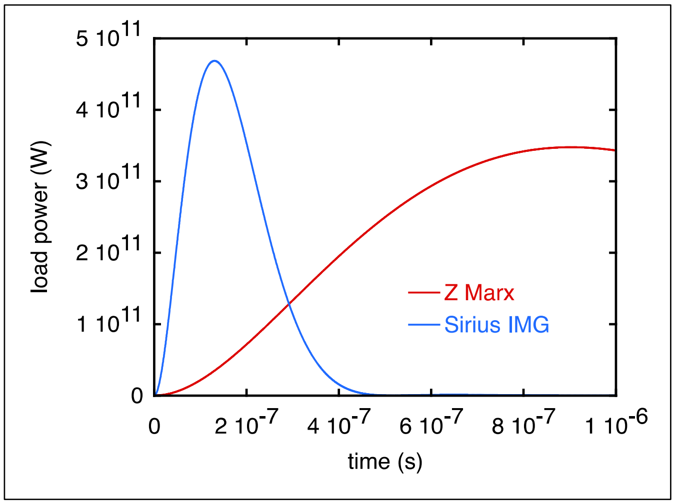

Fig. 5. Electromagnetic-power time histories of a Z Marx and Sirius IMG

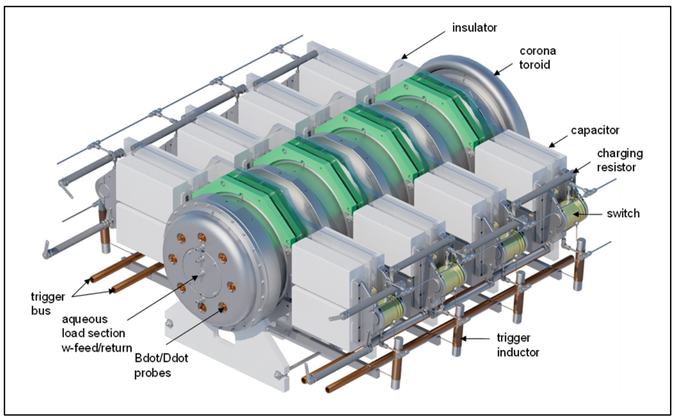

Fig. 6. Four-stage Sirius-I IMG prototype

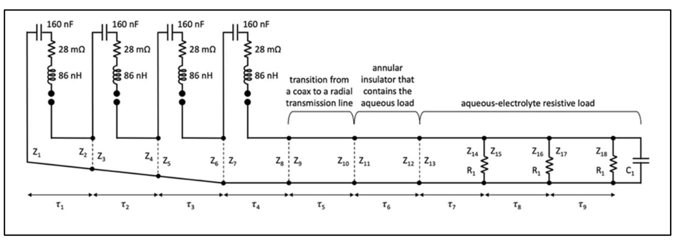

Fig. 7. Transmission-line-circuit model of the Sirius-I IMG

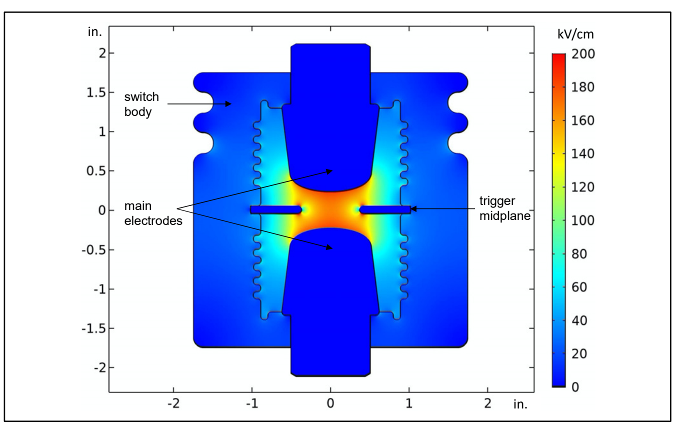

Fig. 8. 2D electric field within the IMG's three-electrode field-distortion gas switch when the potential difference across the switch is 200 kV

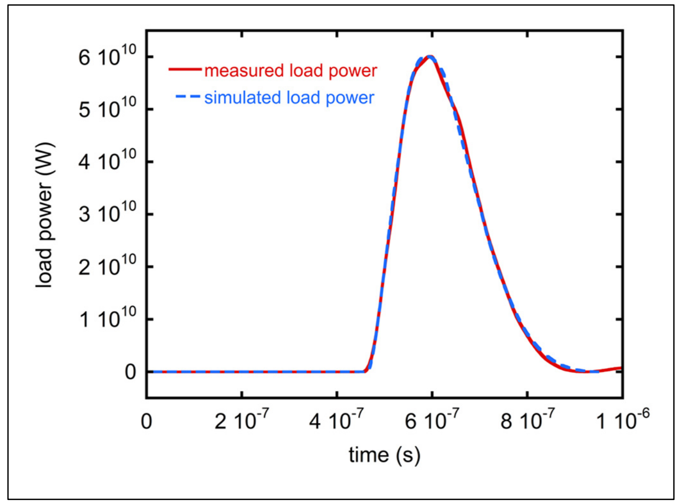

Fig. 9. Simulated and measured time histories of the electrical power delivered by the IMG to its resistive load

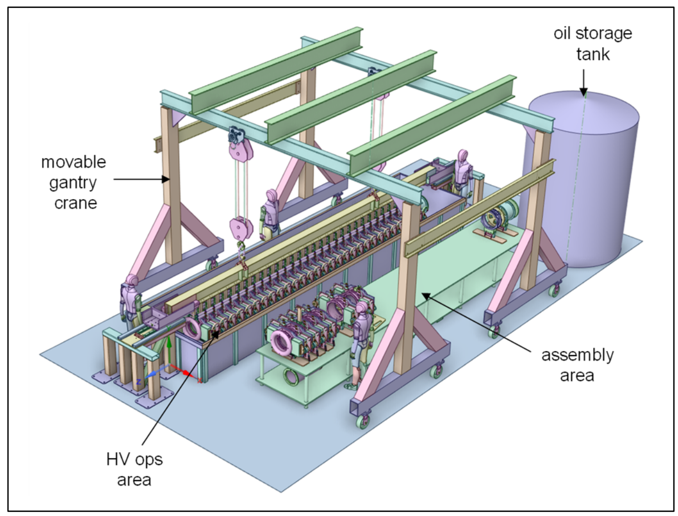

Fig. 10. Sirius IMG Facility conceptual design

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