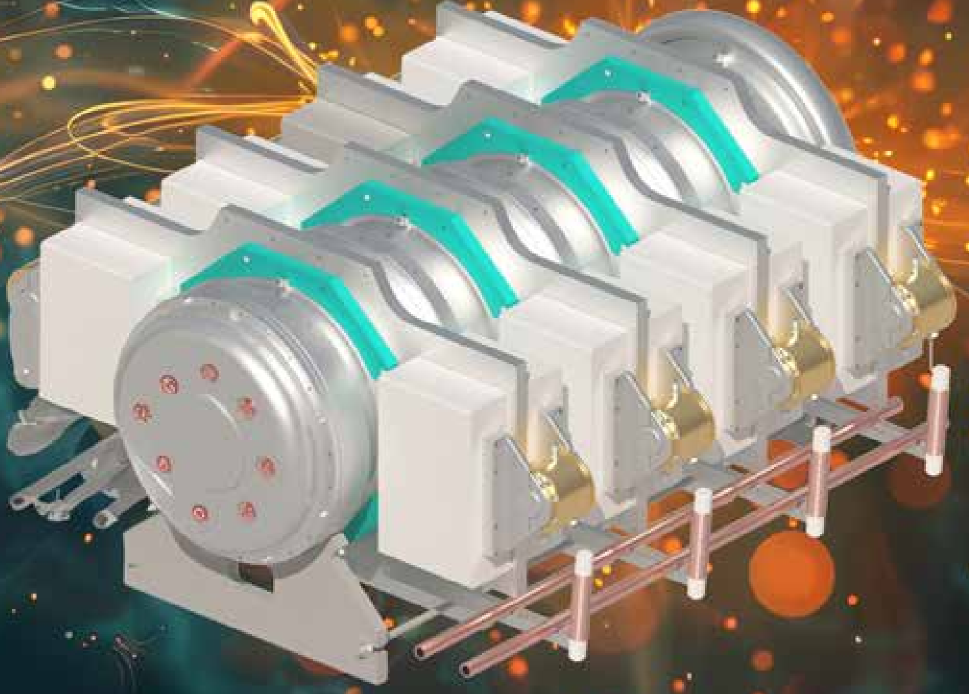
A New Era in PULSED POWER



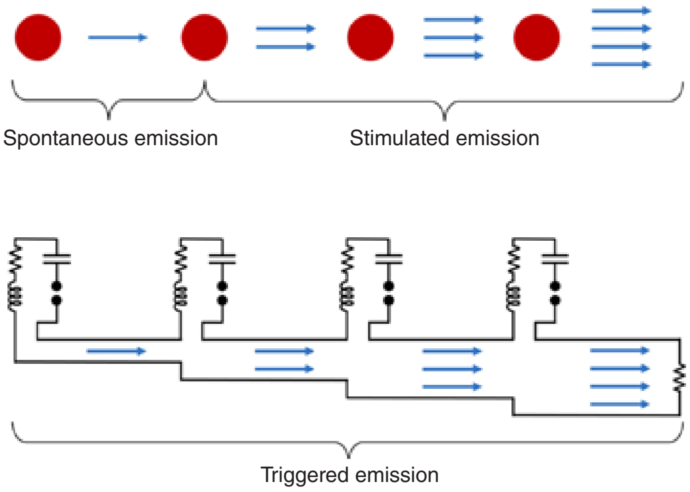
Sirius I, a four-stage impedance-matched Marx generator (IMG) prototype, is the first step toward a proposed future accelerator concept that would be powered by 120 IMG towers, each comprised of 12 vertically stacked 30-stage IMGs. If successful, the future accelerator would generate 700 terawatts of electrical power.

A team of engineers in the Laboratory's National Security Engineering Division (NSED) is exploring a new era in pulsed power by inventing and successfully demonstrating the impedance-matched Marx generator (IMG). The first major innovation in Marx generator design in more than 90 years, the IMG's simplicity and efficiency have the potential to improve both worker and environmental safety, extend component lifetimes, and enable pulsed-power machines in a fraction of the space, cost, and complexity of conventional designs. The technology could someday drive next-generation accelerators for a wide range of applications, including fusion energy and dynamic materials physics experiments, such as those currently conducted at the National Ignition Facility (NIF) and the Joint Actinide Shock Physics Experimental Research (JASPER) facility in Nevada, but with the potential of longer timescales than NIF and greater precision than JASPER.

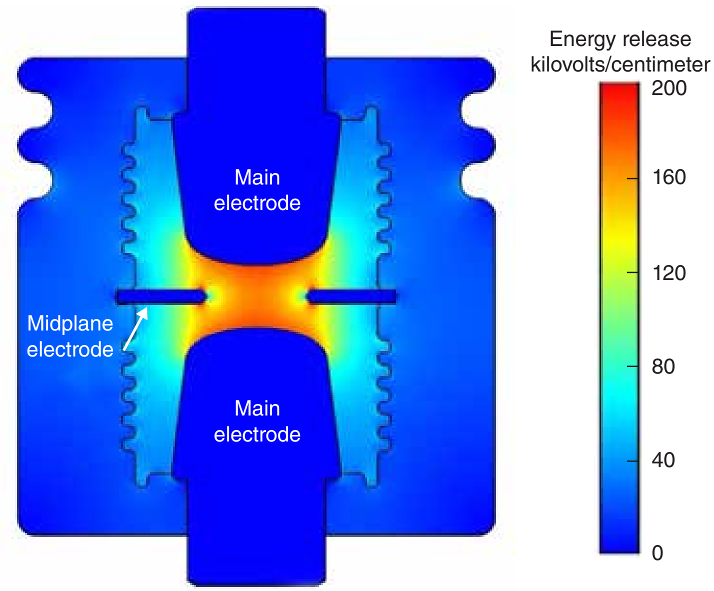
X Marx the Spot

A Marx generator is an electrical circuit that charges multiple capacitors in parallel and discharges them in a series, stacking voltages to generate a pulse. Despite being widely used for pulsed-power accelerators, the conventional design has not

(top) Particles (red dots) in a laser begin in an excited state and spontaneously emit photons, stimulating other particles to emit radiation (blue arrows), ultimately amplifying light. (bottom) The IMG's LC circuits begin in an excited state and are triggered sequentially to emit radiation, ultimately amplifying electromagnetic power.



(shown below) The IMG's three-electrode field-distortion gas switch, called a "brick," is filled with gas—in this case, pressurized dry air—and contains a midplane electrode equidistant from the two symmetrically charged main electrodes. A high-voltage pulse is applied to the midplane to generate arcs between the main electrodes, triggering the switch to close and releasing the energy stored by the two capacitors connected to the switch.



significantly changed from Erwin Marx's original 1924 concept aside from some optimization.

An IMG accounts for electromagnetic wave propagation, and instead stacks waves to generate a 100-nanosecond pulse that is 34 percent more powerful and up to eight times faster than state-of-the-art conventional Marx generators, while needing six times less stored energy. Its design consists of a linear array of LC circuits (each of which has inductance and capacitance) that are charged to high voltage and triggered sequentially to launch a coherent electromagnetic wave that propagates along the length of the IMG, stacking waves on top of each other the same way a laser stacks photons. "The IMG is a pulsed-power analog of a laser," says Bill Stygar, an NSED engineer who co-invented the technology. "Whereas a laser amplifies light through stimulated emission of radiation, an IMG amplifies electromagnetic power through triggered emission of radiation."

Stygar and a former Livermore employee introduced the IMG in *Physical Review Accelerators and Beams* in 2017, and the team received funding from the Laboratory Directed Research and Development program to build and demonstrate a four-stage prototype IMG in 2020. After three years of hard work, the team's prototype delivers 60 gigawatts of power to a load in approximately 100 nanoseconds, matching their theoretical predictions almost perfectly. "The IMG works as well as our simulations, which excited and surprised us because it was kind of a radical idea," says Stygar.

Keeping it Simple

Stygar "grew up" in the Marx generator world while working on Sandia National Laboratories' Z machine in New Mexico. Currently the world's most powerful pulsed-power machine, the Z accelerator and its contemporaries are powered by conventional Marx generators and use multiple stages of electrical pulse compression to deliver energy. Stygar's work was successful, but he also came to understand the complexities of operating and maintaining the machine and wondered if a new design would make a difference.

"The question I would ask myself was, 'If we were to start with a blank sheet of paper, how would we design a pulsed-power machine today?'" says Stygar. "With the IMG, we go from DC-charged capacitors to the power we need in a single step. We then transmit the power to the load. It's the simplest and cleanest thing you can possibly imagine."

The building blocks of an IMG are a series of "bricks"—LC circuits that each have two 100-kilovolt (kV) capacitors and a three-electrode field-distortion gas switch. For reference, the capacitors contain 10 percent of the stored energy of an iPhone battery but, unlike a battery, discharge their energy in 1 ten-millionth of a second. The capacitors are charged to opposite polarities to achieve a symmetric 200 kV difference in DC potential across the switch before it's triggered to release the stored energy. "We apply a 100-kV trigger pulse to the midplane electrode, which generates arcs that close the switch. We then trigger each switch sequentially to launch a wave that propagates along the length of the IMG's internal coaxial transmission line," says Stygar. "This generates multiple reflected waves within the IMG, but by design, they cancel and all that's left is the forward-going wave."

The canceled waves make the IMG inherently impedance-matched (where the electrical impedance in each direction is the same). This maximizes the electromagnetic power delivered to a load, which significantly improves efficiency and reduces the potential damage to components from voltage reversal. The design also only needs one stage to compress stored energy into a short, powerful pulse, meaning IMGs can be built with longer-lasting components—saving time, money, and labor on maintenance and repairs.

"The IMG is a much more compact and efficient way to generate power," says Michael Anderson, NSED lead for pulsed-power science. "The conventional Marx route offers about half the efficiency because it requires more pulse-forming lines and compression sections." The IMG's simplicity gives them an advantage over competing technologies such as the Linear

Transformer Drivers (LTDs) that inspired Stygar. LTDs also offer single-stage pulse compression and impedance matching and are a better alternative for rapid-fire multipulse devices but, unlike IMGs, require special components. "LTDs are similar in efficiency to IMGs, but LTDs require ferromagnetic cores to operate, which becomes expensive when building a large accelerator," says Anderson.

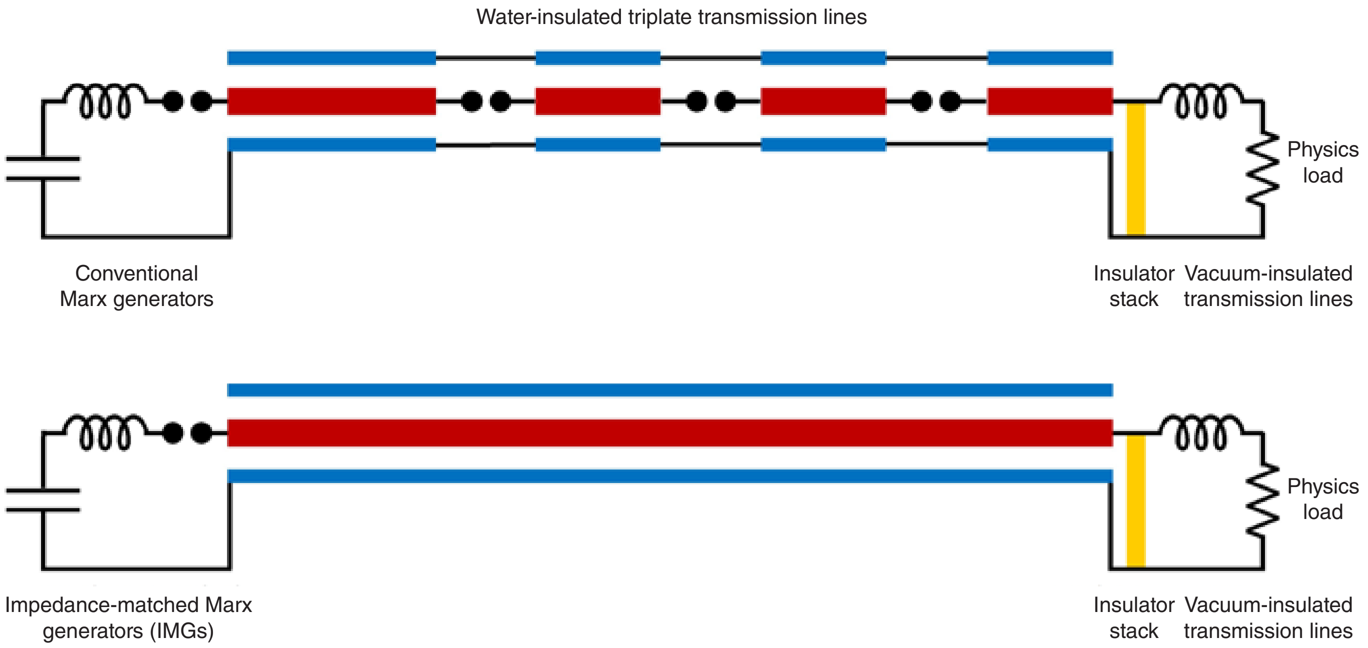
IMGs are also designed with safety in mind. Operating at lower voltages and storing less energy per capacitor not only reduces the likelihood of fatal accidents for workers but also eliminates the need for switches insulated with toxic and potent greenhouse gases like sulfur hexafluoride. Stygar says, "We believe our architecture is simpler, less expensive, more efficient, easier to operate and maintain, and safer for workers and the environment."

From Prediction to Prototype

The IMG's promise begins at the Laboratory with a four-stage prototype named "Sirius I," which sits in a tank of biodegradable oil that provides high-voltage insulation. When Sirius I fires into an impedance-matched aqueous load, a series of magnetic and electrical field probes record results, and other diagnostics measure the load's temperature, flow rate, and electrical conductivity. The team fires the prototype as often as possible to continually improve the design and test component lifetimes. "Every shot tests eight switches and 16 capacitors, so when we've conducted 100 shots, we've actually conducted 800 switch shots and 1,600 capacitor shots," says Stygar. "Since our latest component upgrades, we haven't had a single capacitor failure, switch flashover, or pre-fire, which is great news."

Getting to this point required innovation and team effort. NSED technologists Rick Anaya and Don Max were instrumental in upgrading components as they built and tested the first design. "We now have completely different switches that are bigger and have higher capacities than the original to handle the pressures and current," says Max. Flowing oil between the anode–cathode

The Pulsed Power group (from left)—Jacob Trueblood, Bill Stygar, Michael Anderson, Don Max, David Norton, Rick Anaya, and Cuyler Beatty—pose with the prototype four-stage IMG.



Compared with a conventional Marx generator–based accelerator (top diagram) that requires four stages of pulse compression to transmit power to a load, the IMG (bottom diagram) only needs one stage of pulse compression. Each pair of black dots represents a set of switches.

gap of the IMG's internal transmission line, which both prevents breakdown between components during shots and flushes out streamers (unwanted electrically conducting channels in the insulating oil) before the next shot, solved another issue identified by the team.

"After Rick [Anaya] implemented that oil flow manifold design, a lot of the heartaches and breakdowns went away," says Anderson. "This oil also has a much higher breakdown voltage, so high-voltage and grounded parts can be brought closer together and the total inductance of the system can be decreased to make it 'sportier' and more compact." Other upgrades include materials, capacitors, trigger generators, and insulator guards. NSED applied physicist and electrical engineer Cuyler Beatty dramatically improved performance with a new aqueous load made of soapy water and an accompanying recirculation system. "Thermal runaway plagued these aqueous loads because there was really no way to cool them," says Beatty. "We've solved this with improved recirculation, which helps give us more control over the thermal properties."

A Powerful Future

The four-stage prototype is the first step toward greater things. The next step is building and rigorously testing a 30-stage version—capable of producing 7.5 times more power—before moving on to increasingly larger designs. The team dreams of someday building a 78-meter-diameter accelerator powered by 1,440 IMGs that they believe could achieve as much as 10 gigajoules of fusion energy in a fraction of the size and cost of a similar machine built with conventional Marx architecture. "Lawrence Livermore and Sandia hope to build a next-generation machine, and IMGs are one of the architectures under consideration," says Anderson. "The goal is to produce pulses that are much greater than what has been done in the past."

The team is exploring other applications, including efficient creation of relativistic high-energy-density plasmas and charged particle beams for fusion energy, lightning-electromagnetic pulses, and combined radiation effects environments for research and development. In all cases, IMGs' simplicity makes them an attractive, efficient, low-cost, and potentially revolutionary option for generating energy. "The possibilities are kind of endless," says Beatty. "To be involved at this level, on this type of device, which can have so many different applications, is incredible and a real honor."

— Noah Pflueger-Peters

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