

## Century: Zap Energy's 100-kW-Scale Repetitive Sheared-Flow-Stabilized Z-Pinch System with Liquid Metal Cooling

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# Century: Zap Energy's 100-kW-Scale Repetitive Sheared-Flow-Stabilized Z-Pinch System with Liquid Metal Cooling

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**Abstract** — *Zap Energy is developing the sheared-flow-stabilized (SFS) Z-pinch concept for commercial applications. The SFS Z-pinch relies on plasma self-organization, in the sense that plasma dynamics play a critical role in confinement. Using plasma axial current for confinement and compression eliminates the need for external confinement or heating technologies. This compact magnetic confinement technology could, in turn, provide the basis for a cost-effective deuterium-tritium fusion power plant. In addition to a robust experimental program pushing plasma performance toward breakeven conditions, Zap Energy has parallel programs developing power handling systems suitable for future power plants. Technologies under development include high average power repetitive pulsed power, high duty cycle cathodes, and liquid metal wall systems. Century is the name of Zap Energy's first effort to integrate these three components into an operational system capable of firing nonreacting hydrogen SFS Z-pinch plasmas into a liquid metal-lined container at sustained repetition rates on the order of 0.1 Hz. The pulsed power driver and liquid metal heat exchanger are both designed to sustain input powers of 100 kW. Construction and initial operations with an interim ~10-kW liquid metal heat exchanger are described.*

**Keywords** — *Century, Z-pinch, alternative fusion concept, deuterium-tritium, compact fusion reactor, fusion power plant.*

**Note** — *Some figures may be in color only in the electronic version.*

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## I. INTRODUCTION

The sheared-flow-stabilized (SFS) Z-pinch approach to fusion energy<sup>[1,2]</sup> aims to improve the economic viability of fusion power by creating a system that can use the deuterium-tritium (DT) fuel cycle as advantageously as possible. Compared with typical magnetic and inertial confinement approaches, the SFS Z-pinch is intrinsically small in physical size, relatively low in technical complexity, and high in power density. The prototypical SFS Z-pinch plasma planned for

power plants is compact in length ( $\sim 0.5$  m), is thin in the radial dimension ( $\sim 0.15$  mm), and has high density ( $\sim 10^{26}$  m $^{-3}$ ). It is driven directly and efficiently by an electrical power supply without the need for external magnets, auxiliary heating, or inefficient conversion of the drive energy to other intermediate forms. The linear geometry of the SFS Z-pinch enables relatively straightforward engineering implementation of a liquid metal first wall and breeding blanket compared with other fusion approaches. Operating a DT fusion plasma within a liquid metal first wall and blanket has the potential to greatly reduce the engineering problems associated with first wall heat flux, neutron radiation damage, and activation.

Z-pinch fusion relies on the self-compression that occurs in a plasma column due to the passage of a strong unidirectional current and has a long history in controlled thermonuclear fusion research. Early promising results on the ZETA device in the late 1950s briefly made Z-pinch the front runner in fusion energy research.<sup>[3]</sup> However, progress in Z-pinch performance was short-lived because of the rampant plasma instabilities endemic to a static Z-pinch. By the 1960s, research on Z-pinch as systems for fusion energy was largely abandoned in favor of other approaches. This situation began to change in the 1990s with the proposal to stabilize Z-pinch plasmas via sheared flow.<sup>[4]</sup>

The SFS Z-pinch concept,<sup>[5]</sup> originally conceived at the University of Washington with Lawrence Livermore National Laboratory collaborators, is now being developed for commercial markets at Zap Energy. The Fusion Z-pinch Experiment (FuZE) and its successor FuZE-Q employ high power handling electrodes, flexible gas injection, and independently switched capacitor bank modules to tailor the discharge current and gas distribution to establish stabilizing

sheared flow and pinch current, Fig. 1.<sup>[2]</sup> Recent SFS Z-pinch experiments have demonstrated deuterium-deuterium fusion neutron production rates of  $5 \times 10^7$  neutrons/ $\mu$ s with simultaneous electron temperatures of 3 keV.<sup>[6]</sup>

Zap Energy pursues a parallel approach to developing fusion energy. A portion of the company works to improve fusion performance of SFS Z-pinch plasmas in devices like FuZE and FuZE-Q, while another part of the team works to validate the technologies needed for a power plant based on this plasma configuration.<sup>[1]</sup> The ability to rapidly fire Z-pinch plasmas between durable electrodes in a liquid metal-lined and -cooled vacuum chamber is key to the power plant design. The concept of plasma pinch fusion operating in a liquid metal environment appears in the literature during the 1970s.<sup>[7]</sup> Century represents the first integrated engineering test of high average power repetitive Z-pinch plasmas operating in a vacuum chamber protected and cooled by liquid metal.

## II. CENTURY

Century is Zap Energy's first vertical, liquid metal-lined and -cooled, high-repetition-rate Z-pinch plasma system. Effectively, it is a miniature mock-up of a future fusion power plant core based on the SFS Z-pinch paradigm.<sup>[1]</sup> The Century design point is 100 kW of average plasma drive power delivered as Z-pinch arcs at an  $\sim 0.1$ -Hz repetition rate. This design point is roughly 1% of the nominal plant power and repetition rate parameters that are expected to be on the order of 10 MW of plasma drive power at 10-Hz repetition rate.<sup>[1]</sup> However, it is important to note that the

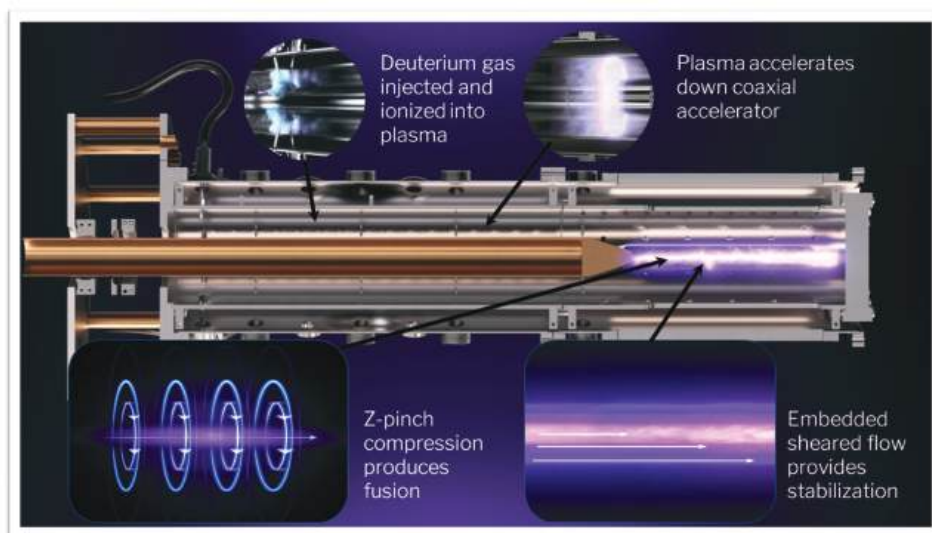


Fig. 1. Illustration of formation and fusion phases of a SFS Z-pinch as implemented in the FuZE and FuZE-Q devices.

~0.5-m-long plasma pinch region in Century matches the anticipated plant dimension.<sup>[1]</sup> Century's principal mission is system integration and testing at increasing power levels and operation durations. It is a platform for fusion system durability and longevity demonstration and development. The focus is on power handling and thermal-hydraulic systems. Neutronics is outside the scope of Century, and its plasmas are formed with hydrogen to prevent the production of substantial fusion neutron fluxes.

Century, Figs. 2 and 3, is named for its 100-kW average power handling capabilities. The system is powered by our second-generation 100-kW average power Z-pinch driver (100kWPS-02). 100kWPS-02 is composed of five identical containerized pulse forming network (PFN) modules that are each capable of sourcing 100 kA for a total of 0.5 MA in full operation. The pulse duration is ~100  $\mu$ s, and the nominal repetition rate is between 0.1 and 0.3 Hz. Forced convection

loop bismuth version two (FCLBi-02) sits on the ground level of the three-level Century platform and provides circulating liquid metal for the first phase of Century. FCLBi-02 has a bismuth-to-air, concentric tube in a tube heat exchanger capable of ~10 kW of cooling. In phase one, SFS Z-pinch plasmas fire between the wetted electrode plasma load version two (WEPL-02), which contains a prototype durable cathode, and liquid wall version one (LW-01), Fig. 3. Century construction began in June 2023, and phase one commissioning operations started in June 2024. Higher power phase 2 operations will be supported by the next-generation FCLBi-03 system starting in 2025. FCLBi-03 is much larger than FCLBi-02—see Fig. 2—and features a 100-kW duty liquid metal-to-air heat exchanger.

### III. HIGH AVERAGE POWER Z-PINCH DRIVER

The Z-pinch pulsed power driver is fundamental to the Century effort and has evolved through one complete iteration cycle. The 100-kW power supply version one (100kWPS-01), Fig. 4, was built as a precursor to Century's 100kWPS-02 to test the planned driver topology at repetition rates around 0.1 Hz. Traditional switches such as spark gaps or ignitrons are not viable for extended operations at this rate because of their limited lifetimes. Therefore, high-power semiconductor-based thyristors are used for switching in the 100kWPS-01 design. Other notable features include a Blumlein PFN topology and a transformer to increase the output current. The system is charged with a bank of high voltage power supplies providing peak charging powers of ~120 kW.

Testing 100kWPS-01 into resistive dummy loads and simple spark-gap-like arcs provided data for design and component selection refinement, as well as overall confidence in the topology. Figure 5 shows an example firing sequence for 100kWPS-01 at a repetition rate of about 0.1 Hz. The 3-s-long capacitor bank charging period at up to 120 kW is followed by

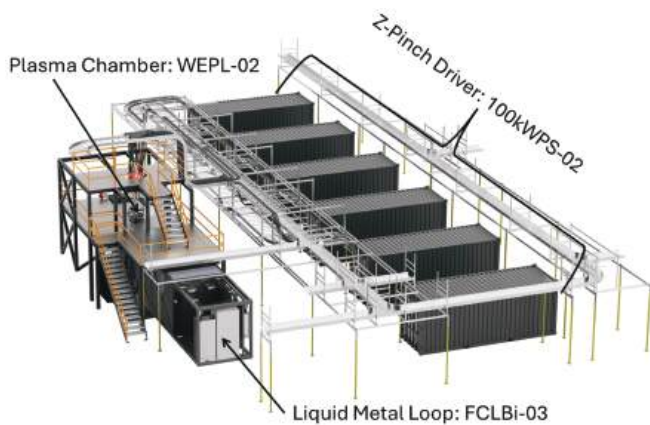


Fig. 2. Artist's conception of the overall Century system based on the engineering models of the components. At right are the five containerized units of the 100kWPS-02 plasma driver with a sixth charging supply container. At left is the Century platform, which houses the Z-pinch plasma chamber (WEPL-02) and liquid metal systems. The phase two liquid metal system FCLBi-03 is shown.



Fig. 3. Photograph of the Century platform in phase one configuration (left) and an illustration of major component locations (right).



Fig. 4. Panorama of the 100kWPS-01 enclosure interior.

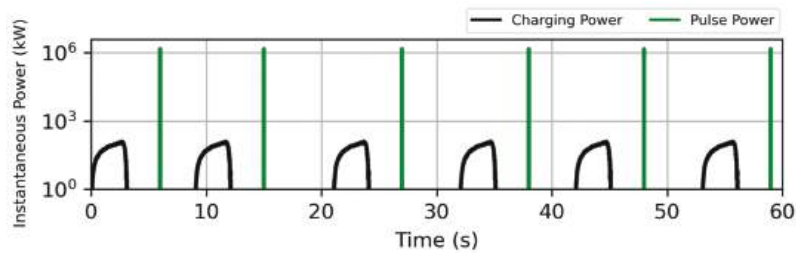


Fig. 5. Example charge/fire sequence for 100kWPS-01 operation at approximately 0.1 Hz.

the much shorter ~1-GW shot into a dummy load. The slightly uneven timing shown in Fig. 5 was rectified by full automation of the charge/fire sequence soon after these initial tests.

Most of the design features of 100kWPS-01 were carried forward into the 100kWPS-02 design. The largest change in the new iteration of the power supply was the containerization of the system into five identical steel shipping containers with custom side doors plus a sixth container for the charging supply bank, Figs. 2 and 6. The charging container houses a bank of parallel, high-voltage direct-current (DC) power

supplies capable of a combined average power in excess of 100 kW. The DC high-voltage power is distributed to five pulsed power containers via charging resistors and relays. Each of the five pulsed power containers has four PFNs grouped into two Blumlein pulse forming lines (BLs). The two BLs in each container feed into one transformer with a three-to-one voltage transformation ratio. The transformer increases the current output so that each of the five containers provides up to 100 kA for a total of 0.5 MA in full operation. Containerization of the circuits provides both a first step

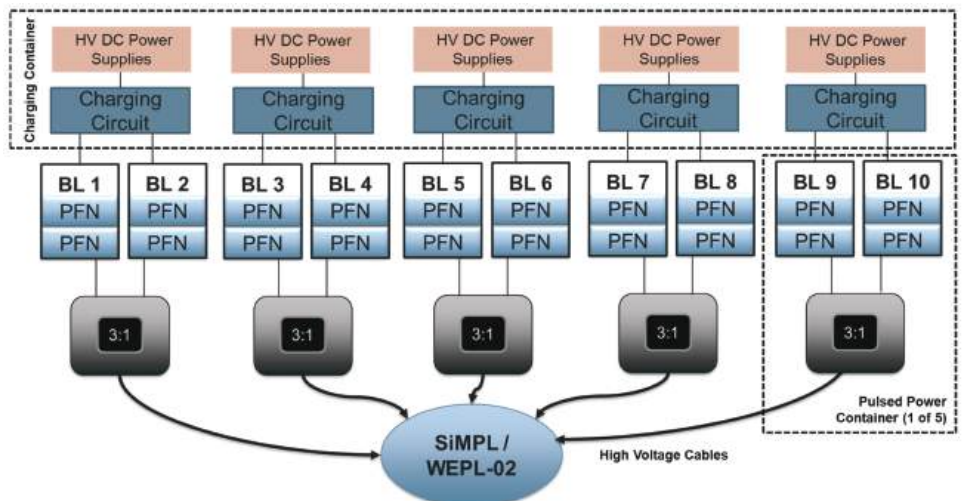


Fig. 6. Block diagram of the 100kWPS-02 repetitive Z-pinch plasma driver.

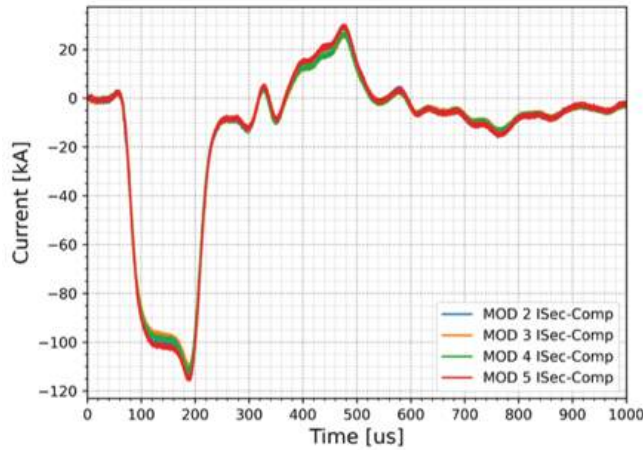


Fig. 7. Current traces for four out of five 100kWPS-02 modules undergoing single shot testing with their 40-mΩ resistive dummy loads.

toward industrializing the design and, because of the custom side doors, enhanced ergonomics for safety procedures and maintenance. Extensive tests of individual module performance were conducted on both a single-shot and repetitive basis using resistive dummy loads, Fig. 7, before connection to a plasma load.

#### IV. WETTED ELECTRODE PLASMA LOAD

WEPL-02 is Century’s SFS Z-pinch system, which generally replicates the geometry and plasma formation

techniques of FuZE-Q.<sup>[2]</sup> However, many other aspects of the design are novel and aimed at accommodating a prototype durable cathode and connection to a liquid metal-lined wall that serves as the anode. While the anode is a continuously renewed pool of liquid metal, heat and plasma fluxes result in cathode erosion that could limit the operational life of a basic solid SFS Z-pinch cathode to roughly 1 day in a power plant. WEPL-02 incorporates a mechanism to test the liquid metal surface strategy for electrode damage mitigation as a potential solution to the plant electrode erosion rate problem.<sup>[8]</sup>

WEPL-02 is oriented vertically, Fig. 8, instead of horizontally like FuZE-Q. The vertical orientation takes advantage of gravity in two ways. First, liquid metal drops will naturally trickle down to the tip of the plasma arc cathode, which is also referred to as the nose cone. Second, the liquid metal wall LW-01 relies on gravity to uniformly cascade liquid metal over a weir wall, Fig. 9. Note that LW-01 has liquid metal coverage limited to approximately half of the first wall area beneath the viewing port chamber. The copper-colored shaded region at the lower right of Fig. 8 corresponds to the liquid metal covered portion of the wall. The limited coverage provides a large gap between the liquid region and the viewing port plane to facilitate visual access during commissioning but limits heat rejection capacity. Future iterations of the liquid wall will have higher coverage. The overall WEPL-02 design also incorporates multiple

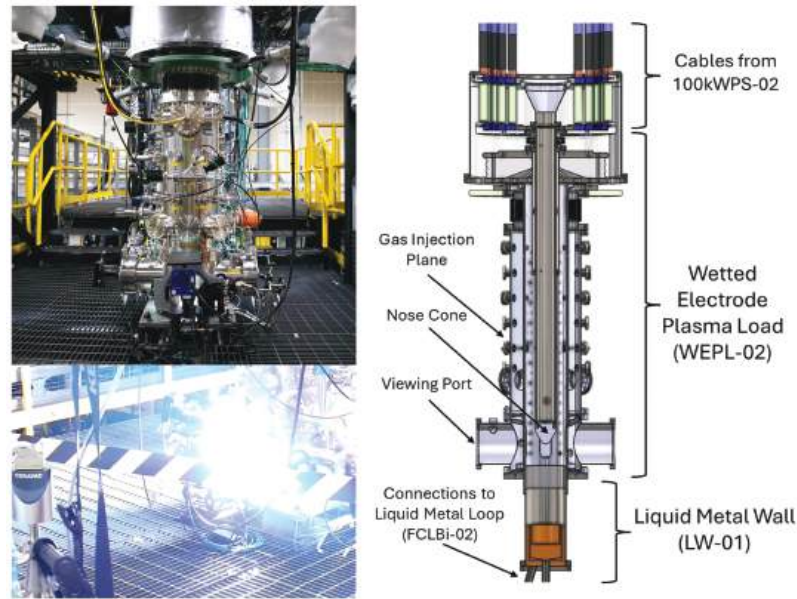


Fig. 8. Photograph of WEPL-02 from the middle level of the Century platform (upper left). Example image of the visible light plasma emission emerging from observation windows at the bottom of the WEPL-02 vacuum vessel during a shot (bottom left). Illustration showing a cross section of WEPL-02 and LW-01 with major features called out (right).

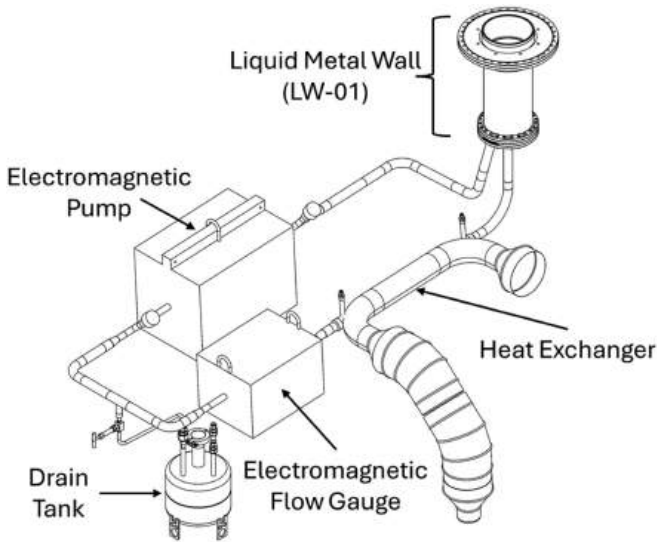


Fig. 9. Illustration of the FCLBi-02 liquid metal loop in Century phase one configuration with LW-01 attached.

design features to facilitate high-temperature operation since LW-01 operates at around 400°C.

At roughly the middle of WEPL-02 as seen in Fig. 8, there is a ring of gas injection valves that provide the hydrogen that is ionized and accelerated to form the SFS Z-pinch plasma. These valves passed several long-duration test stand trials at 0.1 Hz. Directly behind WEPL-02 (not visible in the photograph) is a large surge tank with multiple vacuum pumps sized to clear the plasma formation gas from the vessel between each plasma shot.

## V. LIQUID METAL LOOP AND WALL

Zap Energy's baseline power plant design uses the eutectic mixture of lead and lithium (Pb-Li) containing 87 at. % lead with 17 at. % lithium.<sup>[9]</sup> Molten Pb-Li is pumped into an annulus and allowed to cascade over the rim of a weir wall under gravity to form the first wall for the SFS Z-pinch plasma.<sup>[1]</sup> The pinch current terminates in the liquid metal at the bottom of the cavity. Studying the degree to which liquid wall material is entrained in the Z-pinch plasma is part of the Century program but was not investigated during phase one commissioning.

Our first-generation liquid wall LW-01 follows the general plant design concept and uses liquid bismuth as a proxy for Pb-Li because of its similar physical properties (e.g., melting and boiling points, specific heat, density, thermal and electrical conductivity) yet more favorable safety characteristics. Note also that LW-01 is designed only to coat a portion of the first wall and remove heat from the system. It is not designed to handle the ~1-m-

scale thicknesses of liquid metal that will be needed in a plant to capture fusion neutron flux.<sup>[1]</sup> Figure 9 shows Zap Energy's second-generation liquid bismuth loop FCLBi-02, which circulates ~7 L (70 kg) of bismuth. The loop circuit uses no mechanical connections and is entirely of welded construction to ensure fluid and vacuum leak tightness. Operation begins by pneumatically charging the preheated, suspended flow path loop from a drain tank at temperatures between 370°C to 420°C. An alternating-current, electromagnetic conduction pump is used to develop pressure in the flow path creating volumetric flow rates exceeding 5 gal/min.

Figure 10 illustrates the operation of the liquid metal wall LW-01. Before operations, the liquid metal loop and liquid wall vessel are charged with liquid bismuth up to the desired fill level. Figure 10 shows the static load of bismuth at the top right. Next, the loop circulating pump turns on, which raises liquid bismuth up the annulus between the vacuum vessel and weir wall while simultaneously drawing fluid down the central drain hole, which leads back to the loop. A steady-state liquid wall for plasma shots is achieved once liquid bismuth reaches the top of the weir wall and cascades over the rim in a continuous fall of fluid, bottom right in Fig. 10.

The vapor pressure of bismuth at 400°C is on the order of  $10^{-6}$  Torr.<sup>[10]</sup> As discussed below, this is well below the base pressure of Century during repetitive operation. The electrical resistivity of bismuth at 400°C is roughly  $135 \mu\Omega\text{-cm}$ ,<sup>[10]</sup> which is only slightly higher than the stainless steel vacuum vessel resistivity of  $\sim 100 \mu\Omega\text{-cm}$  at 400°C.<sup>[11]</sup> As expected, there was no obvious electrical difference observed between an arc fired with liquid bismuth in the LW-01 versus one fired into the emptied vessel.

FCLBi-02 and LW-01 underwent initial combined testing prior to installation on Century. The main validation test was 100 h of continuous liquid metal circulation through LW-01 while under vacuum. Multiday static immersion tests prior to the loop test showed negligible erosion of the liquid bismuth coated surfaces, as did the 100-h run itself. After this milestone, FCLBi-02 was fitted with a basic tube-in-tube air-cooled heat exchanger with a duty of ~10 kW. This provided a phase one heat rejection capability for Century in advance of the much larger FCLBi-03 system under construction for phase two.

## VI. TESTING HIGH-REPETITION-RATE PLASMA PRODUCTION

Several of Century's other subsystems were tested individually prior to integration while major construction of the

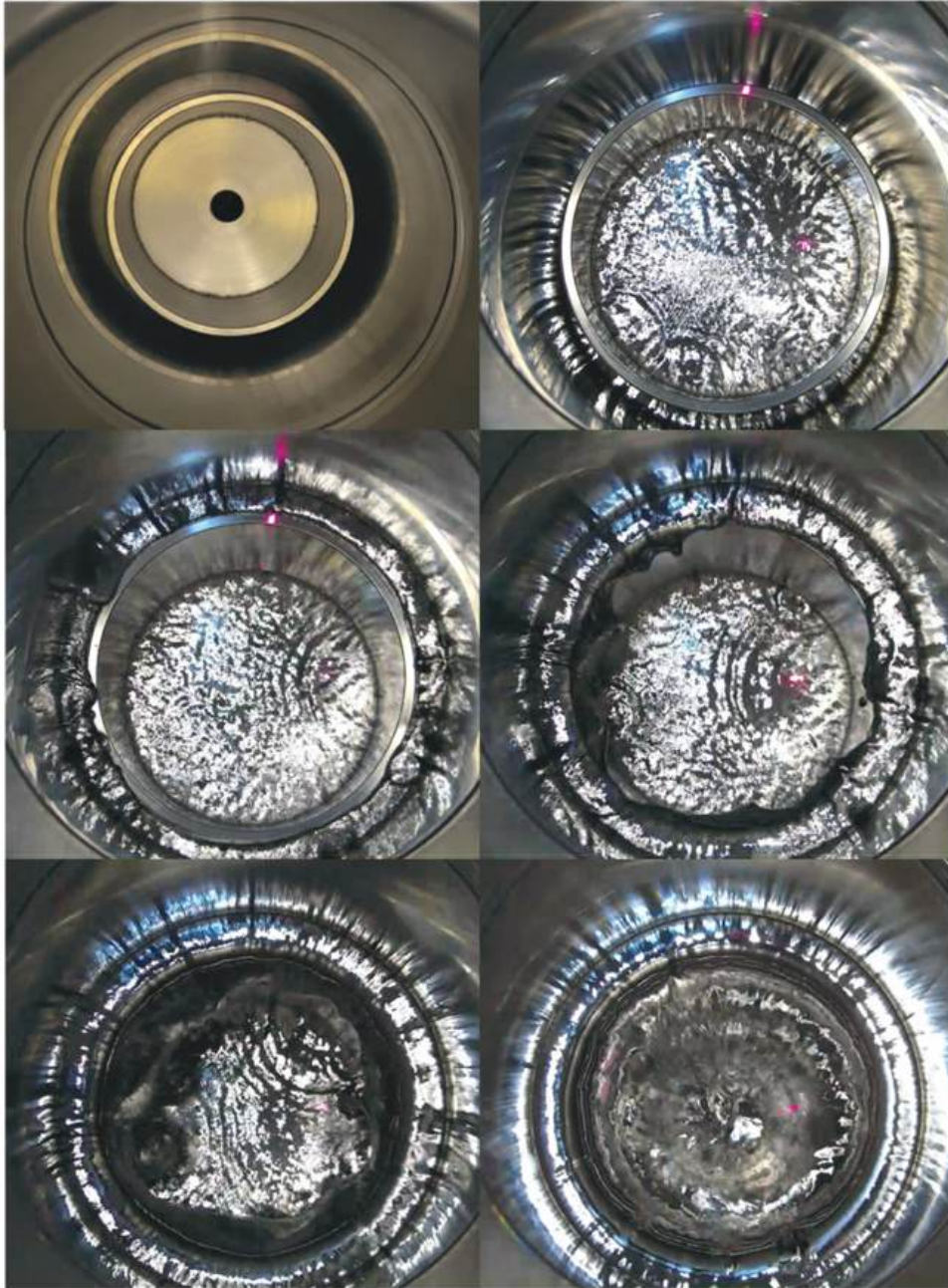


Fig. 10. Views of the liquid metal wall used in phase one of Century taken from above. The outer vacuum boundary wall, inner weir wall, and central drain hole are shown in the top left frame in their unfilled dry condition. Formation of the liquid metal wall is shown starting from the top right frame and proceeds left to right down the rows.

platform was ongoing. Foremost among these tests was firing 100kWPS-02 with a plasma pinch load. Its initial testing was into a fixed load built from passive electrical components that cannot fully replicate the dynamic impedance of a plasma arc. The simple modular plasma load (SiMPL) Z-pinch device provided a realistic plasma load for testing 100kWPS-02. SiMPL is a SFS Z-pinch system with the same length and similar geometry as FuZE-Q, but with half the diameter, Fig. 11. In addition, it has modular

sections for easy reconfigurability. The stainless steel wall of SiMPL does double duty as both the outer electrode/anode and vacuum vessel. The magnetic (B-dot) probes along the length of the device do not penetrate into the vacuum, and no seals are required. Instead, pockets are cut into the vacuum vessel wall to create a locally thin wall of stainless steel that allows measurable field to leak out. Finally, the entire system, including vacuum pumps and the instrumentation and control cabinets, is palletized to

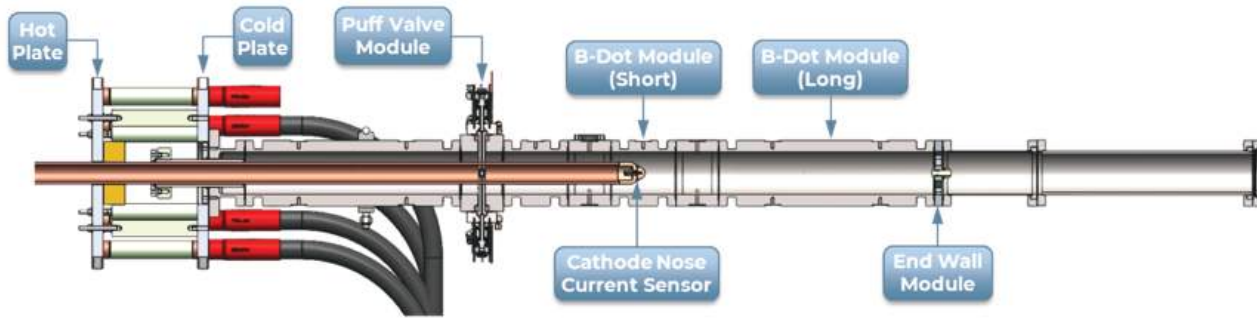


Fig. 11. Cross section of the SiMPL SFS Z-pinch plasma device with callouts of major features.

facilitate easy relocation for testing different plasma drivers, Fig. 12.

In April 2024, 100kWPS-02 achieved full operational status by firing 50 shots at 0.1 Hz into SiMPL. The results validated the performance of 100kWPS-02 with a live SFS Z-pinch load at peak currents more than 200 kA and provided an opportunity to benchmark thermal loads and erosion rates against calculated expectations. Data from a thermocouple in the nose cone showed good agreement with the anticipated heating.

The removable tungsten-copper nose cone inserts on SiMPL, Fig. 13, allowed for a direct measurement of arc erosion mass loss per coulomb of charge, which is a common metric of electrode erosion.<sup>[8]</sup> Taking examples from the literature, erosion rates measured for vacuum arc discharges with a copper electrode are 0.115 mg/C at 80 A<sup>[12]</sup> and 7 mg/C at 40k A.<sup>[13]</sup> Tungsten erosion rates are the same order of magnitude as the copper rates under similar conditions.<sup>[8]</sup> Weighing unexposed and exposed SiMPL nose cone tips on two separate precision scales indicated a mass loss of ~860 mg from the exposed sample. The total charge delivered to SiMPL was calculated at ~2500 C by integrating the hot plate current measurement over the 50 shots of the run. Combining

these results yields an erosion rate of 0.34 mg/C for the tungsten-copper composite SiMPL nose cone assuming all current delivered to the hot plate exits the nose cone. This value is the same order of magnitude as erosion rates measured for 80-A copper electrode vacuum arc discharges noted above, which may indicate that the SFS Z-pinch arc generates relatively low erosion rates. Alternatively, it may indicate that significant current is exciting the inner electrode at locations other than the nose cone. A nose cone current sensor, Fig. 11, is under development to help resolve this ambiguity.

## VII. CENTURY COMMISSIONING RUNS

Initial Century commissioning runs started immediately after phase one major construction finished in June 2024. These runs focused on system checkout and integrated testing at low power. Plasma pinches were formed with hydrogen, and there was circulating liquid metal in LW-01 for all the cases described. Three successful 1080 shot continuous runs at 0.1 Hz (3-h total duration) occurred between June and October 2024. All Century systems except liquid metal supply to the nose cone tip

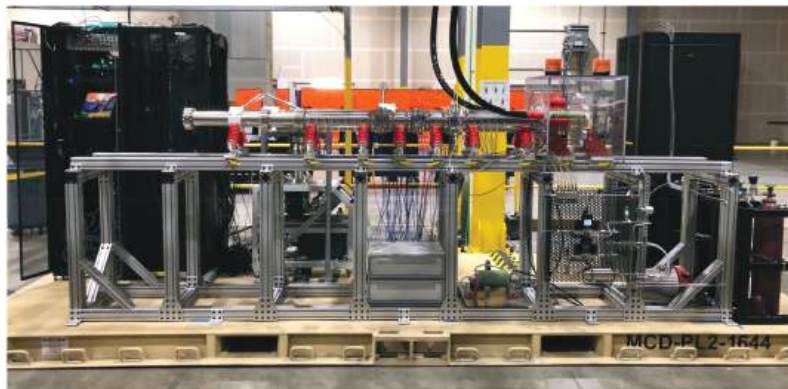


Fig. 12. Photograph of the palletized SiMPL system in operational configuration.



Fig. 13. SiMPL cathode nose cone tip inserts composed of tungsten-copper 10W3 (75% W/25% Cu) composite. Unused and pristine spare part, left. Identical unit after exposure to 50 repetitive high-power SFS Z-pinch plasma shots in SiMPL, right.

were operational for the initial run in June, which we will designate Run 1. Both runs in October, which we will designate Runs 2 and 3 in chronological order, utilized all systems including liquid metal supply to the nose cone. Thus, in Runs 2 and 3, the main pinch current was conducted between two renewable liquid metal electrodes: the liquid metal coated cathode above and flowing liquid wall anode below. The best shot stability was obtained during Run 3, and Fig. 14 shows the high reproducibility of shot-to-shot energy delivery during those 1080 shots. The average power delivered to the WEPL-02 system over the period of 3 h was ~1.4 kW.

Runs 1 and 2 had several shots that broke down later than desired; see Fig. 15 for an illustration of normal breakdown time. This issue was resolved by Run 3 through tuning of the WEPL-02 gas injection system and other Century parameters. Figure 15 shows current and voltage traces for a selected shot during Run 3. The traces are typical of the shots at this low initial power setting where 100kWPS-02 operated at a fraction of its full voltage and current capability. Even at these reduced settings, the current reaches ~125 kA with a corresponding peak power of ~150 MW.

The 100kWPS-02 driver performed reliably through all three runs, as did the WEPL-02 gas injection system. The WEPL-02 vacuum system was able to clear the injected hydrogen gas load and successfully recovered  $\sim 10^{-4}$  Torr vacuum in the 10s between each shot. As testing progressed, vacuum vessel windows became increasingly coated with condensed metal vapor and droplets, diminishing the quality of camera views. Figure 16 shows example imagery of Z-pinch plasma formation on the Century bismuth coated nose cone taken early in the run before material accumulated on the window's inner surface. The nose cone is at the top of the image, and a row of liquid bismuth introduction holes is visible just above the bismuth drop clinging to the bottom surface. The images were taken through the viewing port called out in Fig. 8. Images like these verified that the Z-pinch plasmas made in

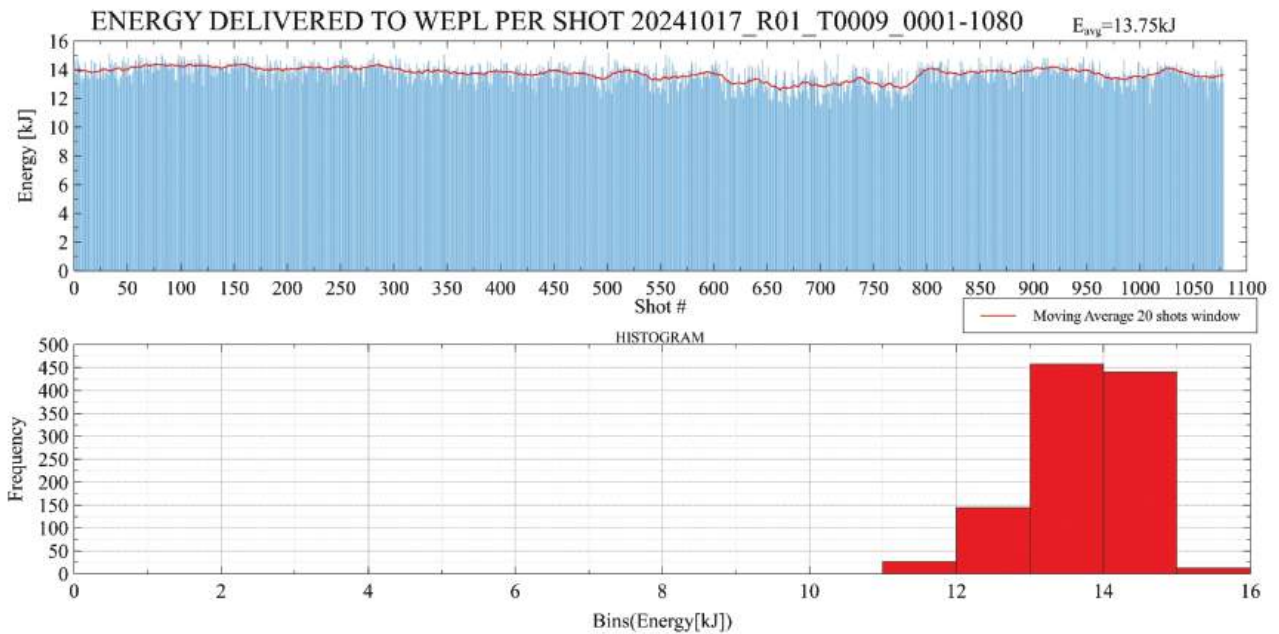


Fig. 14. Energy delivered to the Century system by 100kWPS-02 for each shot during Run 3 in October 2024, top. Histogram of delivered shot energies showing a tight grouping around 14 kJ, bottom. The overall average power delivered during the sequence was ~1.4 kW.

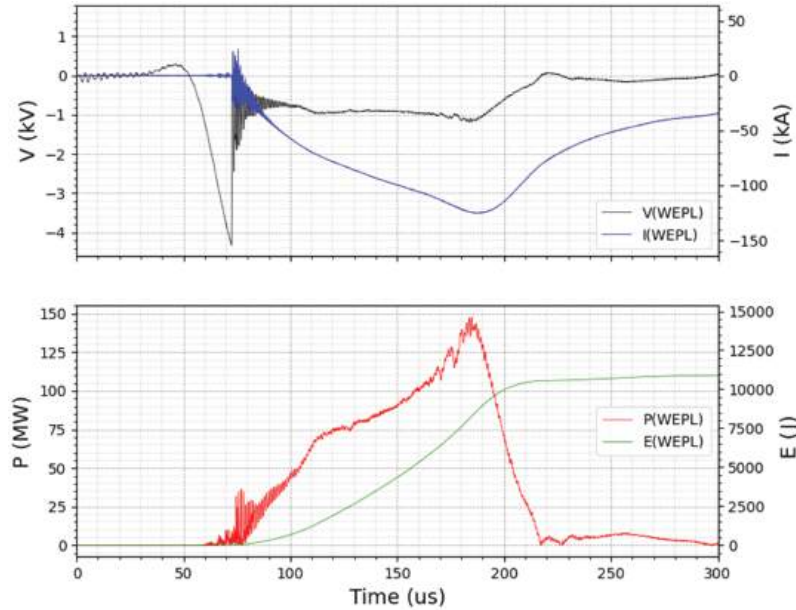


Fig. 15. Voltage and current traces for a typical shot in Century Run 3 during October 2024, top. Plasma breakdown occurs at about  $t = 70 \mu\text{s}$ . Corresponding instantaneous power and integrated energy as a function of time, bottom.

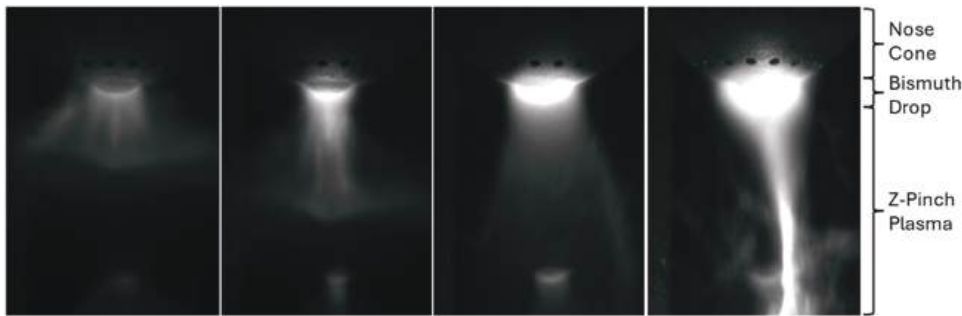


Fig. 16. Sequential monochrome visible light fast camera images of plasma pinch formation on a bismuth drop clinging to the bottom of Century's stainless steel nose cone. Taken at a 500-kHz frame rate.

Century were qualitatively like those produced in the FuZE series devices.<sup>[2]</sup>

Thermocouples were placed throughout the parts of Century that require preheating for liquid bismuth handling or were expected to experience significant heating by the plasma. This was particularly true of FCLBi-02 and LW-01. The temperature of components in the liquid loop and wall was generally maintained by a proportional-integral-derivative (PID) control loop between the heaters and thermocouples. In order to measure the temperature rise solely due to pulsed power heating via the plasma arcs, the system was allowed to settle to a steady-state temperature of  $374^\circ\text{C}$  prior to the start of the Run 1, PID control was disabled, and the heaters were placed at the steady-state duty cycle required to maintain that temperature. The subsequent gradual temperature rise from  $374^\circ\text{C}$  to  $401^\circ\text{C}$  observed during Run 1 was therefore due to plasma heat input into the bismuth, Fig. 17.

Similarly, the nose cone experienced a combination of plasma and resistive heating from the commissioning run shots. During Run 1, the liquid metal coating system for the nose cone was not in operation. Although the nose cone was not internally preheated, it still reached an initial temperature around  $200^\circ\text{C}$  due to radiative heating from the liquid metal wall below it as seen in Fig. 18. Over the course of Run 1, the nose cone temperature rose to  $\sim 360^\circ\text{C}$ . Runs 2 and 3 had liquid metal coating on the nose cone.

Figure 19 illustrates cathode nose cone damage and damage mitigation in Century. Weighing the nose cones to determine mass loss and estimate erosion rates, as was done on SiMPL, was not possible after the Century commissioning runs because of solidified bismuth within the nose cone structure. However, liquid metal protection of the nose cone tip makes a clear qualitative reduction in the erosion of the stainless steel substrate; see the difference between Figs. 19b,

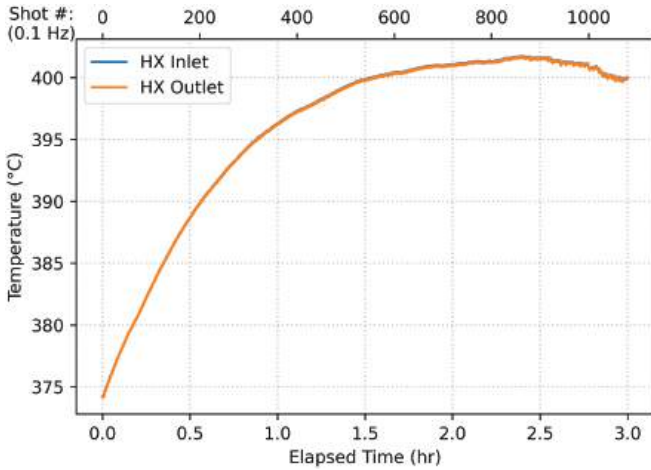


Fig. 17. Temperature rise in the liquid bismuth due to plasma heating during Run 1 as measured by thermocouples on either side of the FCLBi-02 heat exchanger (HX). Note that traces overlap in this case since the heat exchanger air blower was left off.

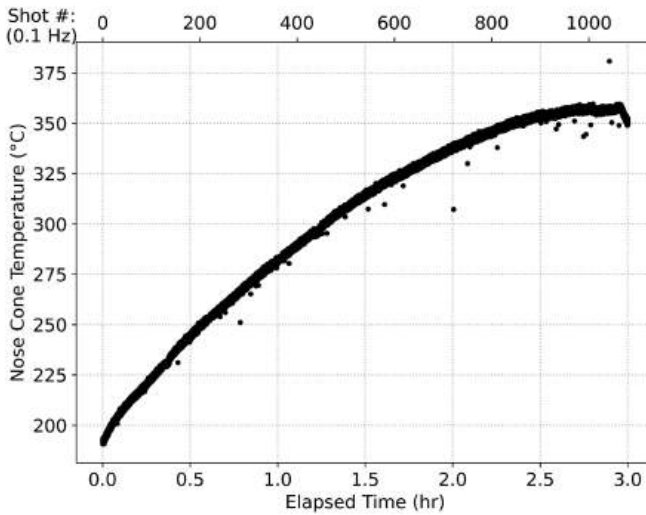


Fig. 18. Temperature rise in the WEPL-02 nose cone due to plasma and resistive heating during Run 1 as measured by a thermocouple embedded in the nose cone body.

c. Whereas the largely unprotected nose cone’s surface is deeply pitted and roughened (b), the nose cone nearly always run with liquid metal protection shows much less obvious surface degradation (c). For example, the top row of liquid metal introduction holes on the protected sample (c) retain their original edges (a) much better than the unprotected nose cone (b). Note that the central hole and first ring of liquid bismuth introduction holes are present in (c) but are filled with solidified bismuth. The degree to which the solid substrate can be protected by a liquid metal coating will ultimately determine the cathode nose cone lifetime in a repetitive Z-pinch plasma system.<sup>[8]</sup> Liquid metal nose cone protection system development will continue in the next phases of Century.

VIII. SUMMARY

Zap Energy is laying foundations for future fusion power plants based on SFS Z-pinch plasmas with the construction and commissioning of the Century system. Century integrates a liquid metal-lined and -cooled plasma chamber with high-repetition-rate Z-pinch plasmas for the first time. The success of multiple continuous 1080 shot, 0.1-Hz commissioning runs validates the engineering fundamentals of the design. Next steps include gaining experience with the liquid metal tipped cathode system and steady increase of the average power level from ~1.4 kW in the initial commissioning run toward the full 100-kW design point.

Century is planned as a precursor to follow on projects with even higher average power levels and liquid metal surfaces testing targeted plant materials. The planned immediate successor to Century is called Millennium and will operate at 1000-kW input power. Demonstration of single-shot high-fusion-gain plasma performance in the SFS Z-pinch combined with the engineering experience acquired through these high average power platforms will open the pathway to implementing

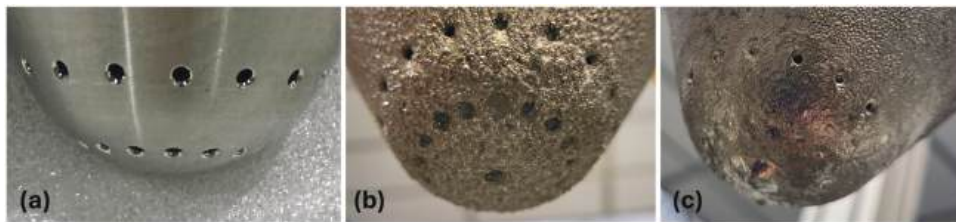


Fig. 19. Century cathode nose cones. (a) Unused and pristine part. (b) Identical unit after exposure to 2452 plasma shots without liquid metal coating mixed with an additional 651 shots with coating. (c) Identical unit after exposure to 16 plasma shots without liquid metal coating plus 3921 shots with coating.

simple and flexible DT fusion power core designs. Their compact plasma geometry, absence of external magnets, and use of a liquid first wall and blanket to address high first wall heat flux and DT neutron damage issues are all attractive features for end product economics.

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## Author Contributions

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