

Development of ultrahigh power compact x-band pulse compressor

A. Dhar[✉],* M. A. K. Othman[✉], and V. A. Dolgashev[✉]

SLAC National Accelerator Laboratory, Menlo Park, California, USA



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We demonstrate a new 11.424 GHz SLED-type rf pulse compressor for powering high-gradient x-band photoinjectors with pulse lengths around 20 ns. rf pulse compression provides a practical path to higher peak power at the cost of pulse length for various applications such as rf deflectors for electron beam diagnostics on free-electron lasers. Our new compact pulse compressor uses spherical cavities supporting axially symmetric TE modes which have minimal electric fields on the cavity surfaces, intended to improve high-power robustness as compared to existing compact spherical SLEDs which use a TE dipole mode. We present the design of this pulse compressor composed of two spherical cavities and a waveguide hybrid. The two cavities and hybrid have TE_{01} circular waveguide ports. This pulse compressor was built and high power tested at SLAC. These tests demonstrated a peak power of 317 MW by compressing 52 MW, 1 μ s pulses generated by a SLAC XL-4 klystron representing, to our knowledge, the highest peak power achieved from a single-stage compact SLED rf pulse compressor at x-band. The full width at half maximum of this compressed pulse was (27.1 ± 1.1) ns. We conjecture that this development demonstrates a viable route to reaching the high-gradient, short pulse regime for accelerating structures and rf photoinjectors.

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I. INTRODUCTION

The performance of modern free-electron lasers such as the SLAC Linac Coherent Light Source (LCLS) is driven by the brightness of the electron beam, which improves with reduction in beam transverse emittance. Among the approaches for reducing the transverse emittance is increasing the electric field on the cathode surface at the time of emission to mitigate space-charge forces through rapid acceleration [1]. A major obstacle to increasing cathode fields is rf breakdown, which disrupts rf pulses and damages the cavity. The probability of rf breakdown reduces with decreasing pulse length [2]. Recently, the Argonne Wakefield Accelerator successfully achieved this increased electric field in a photoinjector by using ultrashort (< 20 ns) rf pulses with high peak power to generate cathode surface fields up to 400 MV/m [3,4].

In order to create such short-pulse electric fields in rf cavities, they need to be powered by multi-MW rf sources with very short pulse lengths (< 20 ns) [5]. Because klystrons capable of supplying such short, multi-MW pulses are not available, rf pulse compression

provides a practical path to higher peak power at the cost of pulse length. One type of rf pulse compressor, the so-called SLAC Energy Development (SLED), was invented at SLAC [6]. SLED-type rf pulse compressors use low loss cavities fed by external waveguides to store energy. This energy is then rapidly discharged from the cavities, resulting in an increased peak power. The gain of the SLED is determined by the external quality factor of the low loss cavities, and the so-called charging time. During this charging time, the cavity is filled with rf energy from the klystron. This stored energy is then compressed and rapidly discharged by flipping the phase of the incoming rf pulse by 180° . This phase flip takes finite time (t_{flip}), which is limited by the overall bandwidth of the rf system, and impacts the compression gain of the SLED.

Over the years, SLAC has created numerous pulse compression systems for high-power rf applications, such as linear colliders [7]. More recently, SLAC built compact 11.424 GHz SLEDs to power x-band transverse deflectors for LCLS and LCLS-II [8–10]. Each of these compact SLEDs uses an overmoded spherical cavity operating with dipole TE_{114} modes. Other developments utilizing compact spherical cavities with dipole modes are two-stage pulse compressors. These pulse compressors have demonstrated peak powers up to 320 MW at x-band and 1.2 GW at S-band [11,12]. However, the dipole modes used in all of these spherical cavities have electric fields on the cavity walls which can cause rf breakdowns, potentially limiting the output power of these systems.

*Contact author: adhar@slac.stanford.edu

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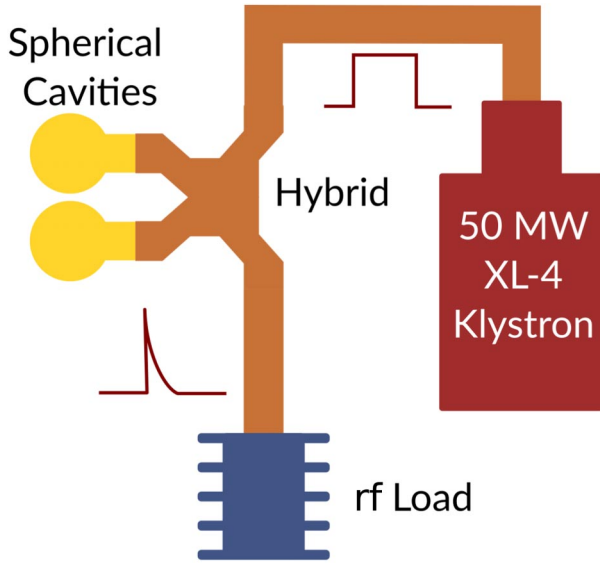


FIG. 1. Diagram of the experimental apparatus under test at SLAC. Power from the SLAC XL-4 50 MW klystron as square pulses is directed toward two spherical cavities connected through a waveguide hybrid. Power stored in these cavities is then compressed into short intense spikelike pulses via a flip in rf phase and is sent into a dry rf load for dissipation.

In order to increase peak output power while mitigating the risk of breakdown associated with high cavity surface electric fields, we have developed a new 11.424 GHz SLED, as shown in Fig. 1. This SLED uses two overmoded spherical cavities with an axially symmetric TE_{023} spherical cavity mode. The chosen mode minimizes the surface electric field in the main cavity body, reducing breakdown risk compared to the dipole mode of the aforementioned spherical cavities. The compression gain of this SLED is determined by the ratio between the internal and external quality factor of the cavities, known as the coupling factor (β). We chose the coupling factor of these cavities to be 25, allowing them to provide up to $6.5\times$ compression gain when powered by 50 MW 1 μ s pulses generated by a SLAC XL-4 klystron with a bandwidth of about 100 MHz [13].

The two spherical cavities of the SLED are connected through a previously designed waveguide hybrid with circular ports [14,15]. These ports operate with the TE_{01} circular waveguide mode. We have designed, built, and high-power tested this new SLED at SLAC, demonstrating peak rf power up to 317 MW. While higher peak powers have been reported using multistage pulse compression (up to 320 MW at x-band with a two-stage system [11] and 1.2 GW at S-band [12]), to our knowledge, this is the highest peak power achieved by a single-stage x-band SLED pulse compressor and is realized in a substantially more compact footprint than multistage systems.

II. DESIGN OF THE TE_{023} PULSE COMPRESSOR

A. Cavity mode selection and geometry

In the design of high-power pulse compression cavities, there are two crucial criteria to consider. These criteria are (i) a very high internal quality factor and (ii) sufficient spacing between the operating mode and neighboring parasitic modes that couple to the TE_{01} circular waveguide mode. One way to achieve these requirements is to use an overmoded spherical cavity. In high rf power applications, it is beneficial to use an axially (cylindrically) symmetric TE mode due to its low loss and minimal electric field on the cavity surface. For our purposes, we used the TE_{023} spherical mode, which has rotational symmetry about the Z axis to couple well to the TE_{01} circular waveguide mode, which has the same symmetry. The radius of the spherical cavity was then chosen to center this mode on 11.424 GHz. The external coupling into the cavity was set by an iris between a circular waveguide and the cavity. In this design, the circular waveguide diameter is 1.5 in. (38.1 mm), and the spherical cavity has an inner diameter of 4.037 in. (102.54 mm).

B. High-power rf simulations

The high power rf performance of this spherical cavity was simulated using Ansys High Frequency Structure Solver (HFSS) [16]. To evaluate the performance, we assumed an input rf power of 50 MW. These simulated fields (shown in Fig. 2) were used to evaluate the risk of vacuum rf breakdowns and material damage. We present high-power performance simulations of the optimized SLED spherical cavities to show the peak surface electric (E) field, peak surface magnetic (H) field, peak pulse surface heating, and a modified form of the Poynting vector [17–19].

The peak surface E field on the cavity surface was calculated to compare with the expected breakdown criterion of 250 MV/m. This cavity mode has minimal electric field on the surface, so this is not a major concern. The peak surface H field was calculated to determine the estimated pulsed surface heating. This calculation was based on analysis that relates peak surface H field and pulse width to a temperature rise for a square rf pulse along a metal surface [20]. We use this approximation knowing that our input pulse is not square. The equation for 11.424 GHz is given as

$$\Delta T_{\text{pulse}} = 430 |H_{\text{peak}}|^2 \sqrt{t}, \quad (1)$$

where ΔT_{pulse} is in $^{\circ}\text{C}$, H_{peak} is in MA/m, and t is in μ s. The peak surface magnetic fields for a 1 μ s charging pulse induce a surface heating of 17.9 $^{\circ}\text{C}$, while the threshold for surface damage is 50 $^{\circ}\text{C}$ [21]. This surface heating

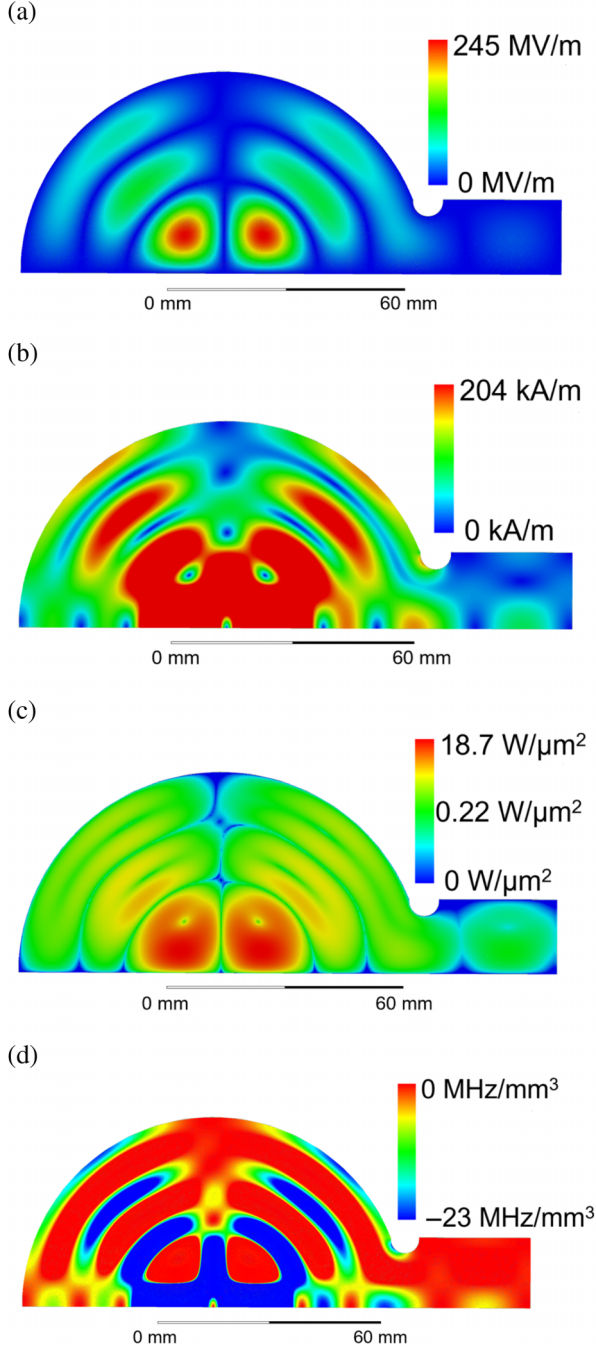


FIG. 2. (a) Volume rf electric fields, (b) volume rf magnetic fields, (c) volume modified Poynting vector, and (d) tuning sensitivity for a spherical cavity. A symmetric half of the cavity is shown. Fields are normalized to input power of 50 MW and a coupling factor of $\beta = 25$. The TE_{023} mode within the cavity is excited at 11.424 GHz. The electric field and modified Poynting vector are 0 on the cavity surface.

calculation is an overestimation given that our rf pulse in the cavity is not square.

As a further measurement of power flow, the Poynting vector magnitude along the surfaces was also evaluated.

TABLE I. Design parameters of rf pulse compressor operating at 11.424 GHz.

Cavity parameters		
Q_0	Q_l	β
82,000	3380	25
SLED parameters		
Pulse length	Charge time	t_{flip}
1 μs	> 250 ns	10 ns
High-power rf parameters at 50 MW		
H_{peak}	S_c	ΔT_{pulse}
204 kA/m	0.22 W/ μm^2	17.9 $^{\circ}\text{C}$

However, this magnitude was calculated in a specific fashion to compare with the empirical breakdown analysis of existing high-gradient accelerating structures. This modified Poynting vector was calculated as $S_c = |\text{Re}(S)| + 0.2|\text{Im}(S)|$, which was then evaluated against an established criterion for rf breakdowns [19]. This criterion is based on the established value of 5 W/ μm^2 for a 200 ns pulse. Further, using a scaling law developed for traveling wave structures, the criterion is 2.9 W/ μm^2 for a pulse length of 1 μs . Finally, we calculated the sensitivity of cavity frequency f to mechanical deformations using cavity perturbation theory [22]. This can be determined from the following equation

$$\frac{\Delta f}{f} \approx \frac{\iiint_{\Delta V} \mu |H_0|^2 - \epsilon |E_0|^2 dV}{U_0}, \quad (2)$$

where the integral of the difference in magnetic and electrical energy is taken over the relative perturbation in volume.

The TE_{023} mode in this cavity has an internal quality factor (Q_0) of 82,000. The coupler provides a coupling factor of 25 and loaded quality factor (Q_l) of 3380. Based on these parameters, the effective compression gain was evaluated for a range of charging times, determining that the maximum compression gain possible for this SLED should be between $6.5\times$ to $6.8\times$ depending on charging time ranging from 300 to 1500 ns. The design parameters for this cavity and SLED design are summarized in Table I.

III. FABRICATION AND COLD-TEST CHARACTERIZATION

A. Cavity tuning

The SLED cavities were fabricated out of OFE copper and brazed. After fabrication, each TE_{023} spherical cavity was tuned to ensure optimal rf pulse compression at 11.424 GHz. During the tuning process, the cavity was

filled with nitrogen gas and its temperature was monitored with thermocouples. The specific target frequency is determined by accounting for the relative change in frequency due to temperature and pressure of dry nitrogen. For a final operating target of 11.424 GHz in vacuum at 15 °C and a measurement temperature of 20 °C, our target frequency for tuning was 11.420 GHz. During the experiment, the temperature of each cavity was independently controlled by dedicated water chillers.

B. Parasitic-mode identification

The results of this tuning are shown in Fig. 3. After tuning both cavities, a parasitic mode remained approximately 5 MHz above the operating mode, within the bandwidth of the klystron. A fit to the measured reflection coefficient gives this parasitic mode a loaded quality factor of 57,380, compared to 3380 for the operating TE_{023} mode, suggesting weak external coupling. We identified through HFSS simulations that this parasitic mode couples to the TE_{21} quadrupole circular waveguide mode instead of the TE_{01} circular waveguide mode. Figure 4 compares the simulated field distributions of the two modes: the operating mode presents an azimuthally symmetric field in the circular waveguide port consistent with the TE_{01} mode, while the parasitic mode presents an asymmetric TE_{21} -like field. Because the hybrid powering the two spherical cavities uses mode conversion between the TE_{01} circular and TE_{10} rectangular waveguide modes with high mode purity, this TE_{21} -coupled parasitic mode is not driven appreciably. Therefore, we do not expect this parasitic mode to couple strongly during high-power testing.

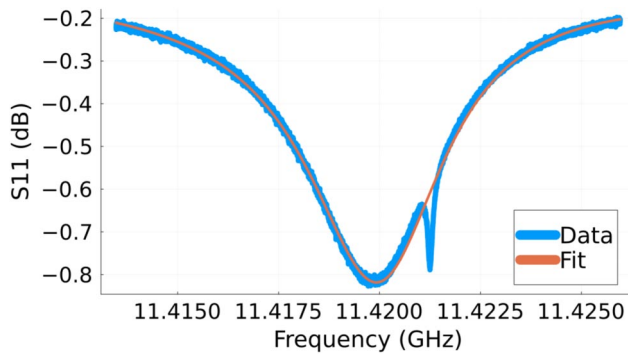


FIG. 3. Measurement of reflection coefficient for a spherical cavity after tuning. The cavity was tuned to 11.4201 GHz at 20 °C filled with dry nitrogen. Based on a fit to the data (orange), the internal quality factor was determined to be 71,854, with a coupling factor of 25.8. The internal quality factor is lower than the expected design value, but with the right coupling factor this would still be sufficient for pulse compression. Measurements after tuning (blue) show a small parasitic mode near the target frequency of 11.42 GHz. The parasitic mode seen here couples to the TE_{21} circular waveguide mode.

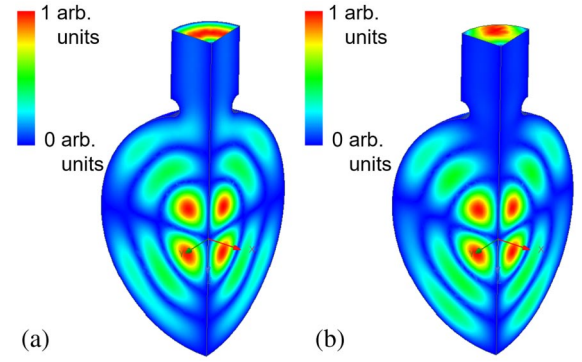


FIG. 4. HFSS-simulated electric field magnitude distributions comparing (a) the operating TE_{023} cavity mode and (b) the nearby parasitic mode. In the circular waveguide port (top), the operating mode exhibits the azimuthally symmetric field pattern characteristic of the TE_{01} circular waveguide mode, whereas the parasitic mode shows an asymmetric field pattern characteristic of the TE_{21} quadrupole circular waveguide mode. Because the hybrid drives the ports with high TE_{01} mode purity, the TE_{21} -coupled parasitic mode is not appreciably excited.

IV. HIGH-POWER EXPERIMENT

A. Experimental setup

Once tuned, the cavities were installed onto a waveguide hybrid with circular ports to form the SLED system. The rf pulses from the spherical cavities after the phase flip combine in the hybrid with the same amplitude and phase, and the combined power flows out of the hybrid. This SLED was then connected to the output of a SLAC XL-4 50 MW klystron. An overview of the assembled high-power test setup is shown in Fig. 5. The klystron output was directed through vacuum WR90 waveguide, and down toward the SLED and rf load. This load has a four way splitter to divide power between four stainless steel rf dry loads. One of the load tree's four arms had a directional coupler, allowing for measurements of the uncompressed power from the klystron and the compressed power from the SLED.

All relevant rf components were temperature stabilized via a cooling loop of house water, except for the cavities. Each cavity was connected to its own water chiller, allowing it to be independently tuned via temperature. The flexibility of this cooling circuit was vital to ensuring that both cavities remained tuned during operation.

B. Conditioning and rf diagnostics

In order to commission the pulse compression system, the SLED cavities were thermally detuned to perform initial conditioning at low power. This involved slowly increasing the output power of the klystron from 10 to 50 MW and pulse length from 100 ns to 1 μ s. During this progression, the vacuum was monitored for any sign of

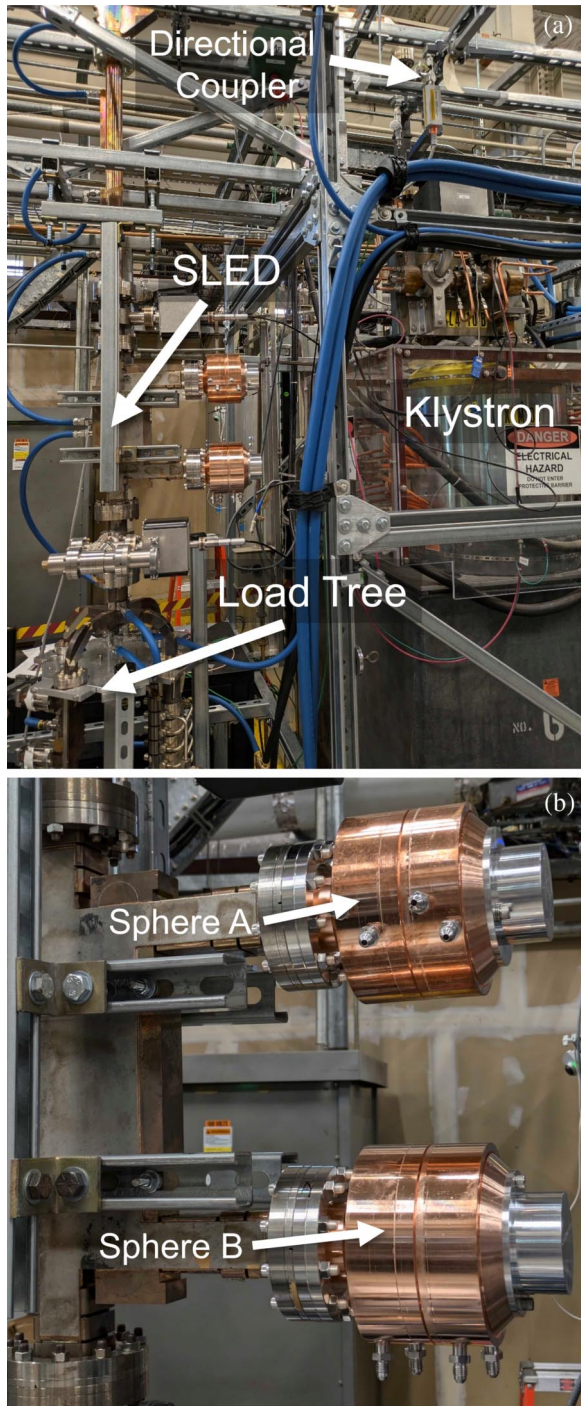


FIG. 5. (a) Overview of experimental apparatus at SLAC. Power from the SLAC XL-4 50 MW klystron is directed to the SLED and then a so-called load tree for dissipation. This load tree is a device which uses a four way splitter to divide power between four rf dry loads. (b) Closeup of the two SLED spherical cavities.

significant breakdowns or arcing to allow the waveguide network to condition. As a result, the system was able to operate with the klystron output power of 50 MW, 1 μ s pulse length, and 120 Hz repetition rate.

With the system conditioned, we characterized the compressed output using a dedicated set of rf diagnostics. For the measurement of rf power, we used calibrated peak power meters, fast digitizers to capture down-mixed rf signals, and crystal detectors. The peak power meters have a time resolution of 10 ns, while the digitizer has a resolution of 0.5 ns. To tap off power from the high-power waveguide circuit, we used two waveguide directional couplers: one after the klystron output, and another in an arm of the load tree. Each signal was routed to both a peak power meter and a down-mixer. All signals were then processed using LabVIEW software [23]. While the power meters provided calibrated measurements of forward power from the klystron, they did not have the temporal resolution required to resolve the peak of the compressed pulse. Thus we have calibrated the mixers against the power meters for our measurements of the peak compressed power. The mixers were calibrated by detuning the SLED and ensuring that a long rf pulse with a flattop measured out of the klystron and out of the SLED was equal in terms of power level on both the peak power meters and the digitizers.

V. RESULTS AND DISCUSSION

A. Peak power and compression gain

After initial conditioning and calibration, the SLED cavities were thermally tuned to resonance using chillers. At resonance, the compressed power was maximized and the reflected power back to the klystron was minimized. The system was then fully conditioned over 10 days to operate at 52 MW output power over 1 μ s at 120 Hz repetition rate. In order to compress the klystron pulse, its phase needs to be flipped by 180° after the SLED cavities are filled. This phase flip was realized with an arbitrary waveform generator and an rf mixer, which modulates the rf pulse at the klystron input. We monitored the phase flip via the down-mixed signals from the directional couplers, which were digitized and converted into amplitude and phase. This allowed us to confirm a phase flip of $(179.97 \pm 0.94)^\circ$ over a flip time (9.1 ± 1.5) ns and a full width at half maximum (FWHM) of (27.1 ± 1.1) ns for the compressed power measured over 10,000 pulses. An example of this amplitude and phase data is shown in Fig. 6.

The compression gain for each pulse was evaluated by dividing the peak compressed power by the mean input forward power from the klystron immediately before the phase flip, accounting for uncertainty in the calibrated mixer measurement. With optimal tuning and phase-flip timing, we observed a compression factor of (6.1 ± 0.2) , which agrees well with the simulation prediction of 6.4. We also determined the pulse compression efficiency, defined as the total pulse energy out of the SLED divided by the total input pulse energy, to be $(86.6 \pm 0.2)\%$, which

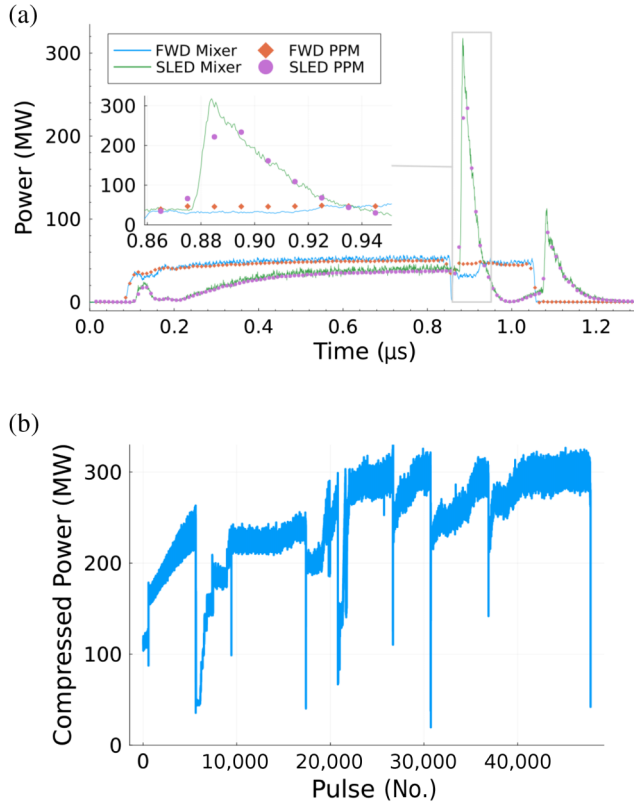


FIG. 6. (a) rf measurements of output pulses from the klystron and the SLED. The mean forward klystron power (blue) just before the phase flip is (52 ± 2) MW, and the peak compressed power (green) is (317 ± 8) MW, yielding a compression factor of (6.1 ± 0.2) . Dots denote data from peak power meters, and lines represent data from down-mixed signals. (b) Progression of compressed power as measured by calibrated mixers over the last 3 days of conditioning, with operation reaching an output power over 300 MW. Sharp drops in power were precipitated by vacuum interlock trips in other sections of the rf network, namely near the rectangular to circular waveguide mode converter out of the klystron.

agrees well with the theoretical expectation of 89%, considering the additional losses within the hybrid of $(2.2 \pm 0.2)\%$ caused by higher-order modes and rf dissipation.

B. Breakdown and vacuum behavior

We did not directly measure a breakdown rate in this experiment. Instead, we monitored vacuum pressure and reflected power as proxies for breakdown activity, advancing conditioning whenever vacuum levels remained stable. The rate of conditioning was primarily limited by vacuum activity in the waveguide mode converter connecting the output WR90 waveguide from the klystron to the circular waveguide feeding the SLED, rather than by activity in the SLED cavities themselves. Any breakdown within the cavities would have produced a corresponding loss of

transmitted power registered by the directional coupler in the load tree; we did not observe power loss consistent with breakdown originating in the cavities. The sharp drops in compressed power shown in Fig. 6(b) were each precipitated by vacuum interlock trips localized to the mode converter and other upstream sections of the rf network and were not associated with the SLED cavities. Following each trip, the affected section was reconditioned and full compressed power was recovered. These observations are consistent with the low surface electric field of the TE_{023} mode, which vanishes on the cavity wall, and support our expectation that the SLED cavities were not the breakdown-limiting element of the system. They also confirm our prediction that the parasitic mode observed in cold testing would not present any issues during high-power operation.

VI. CONCLUSION

We have built and experimentally demonstrated the performance of an ultrahigh peak power 11.424 GHz SLED-type rf pulse compressor. This SLED has achieved a peak compression gain of 6.1 with a compressed-pulse FWHM of (27.1 ± 1.1) ns and has generated peak output power up to (317 ± 8) MW, the highest peak power from a single-stage x-band SLED pulse compressor to our knowledge, and in a substantially smaller physical footprint than the two-stage pulse compressor that reached comparable power at the same frequency [11]. We conjecture that this development provides a viable route to reaching the high-gradient, short pulse regime for accelerating structures and rf photoinjectors [24]. Increasing the cathode gradient on photoinjectors has the potential to improve electron beam brightness, which translates to improved XFEL performance.

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DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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