High Power Test of Ultra-Short High Gradient Cavities by RF Pulse Compression

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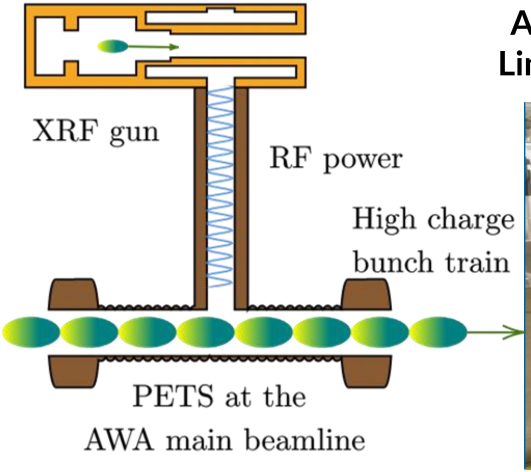
AAC 2026

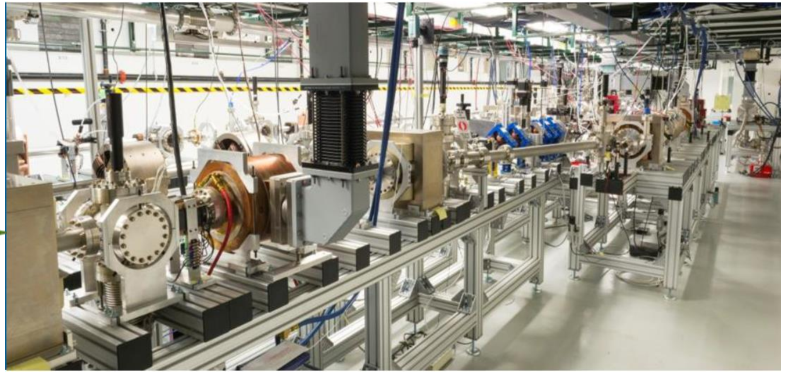
July 28th, 2026

Higher Brightness through High Gradient

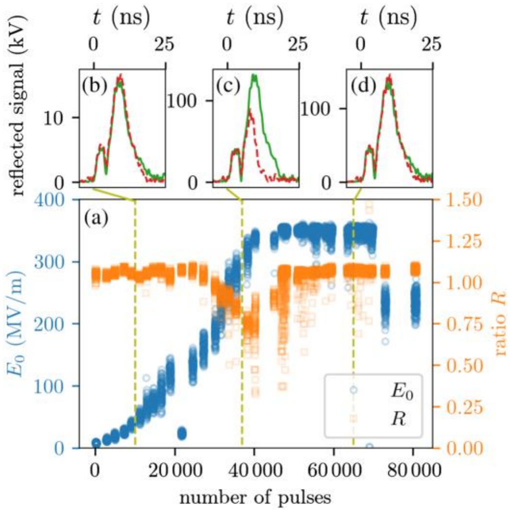
Previous work at Argonne Wakefield Accelerator (AWA) used ultrashort (<20 ns) RF pulses to achieve surface fields <400 MV/m for a 10X improvement in beam brightness and very low dark current.



AWA Approach: Requires Stand Alone High-Charge Linac and Power Extraction Transfer Structure (PETS)



Ultrashort RF Pulses



Increased Surface Fields

Tan et al., *PRAB 25*, 2022.

RF pulse compression, a SLAC expertise, provides similar high peak power.

Compressed Ultrashort Pulse Injector Demonstrator

Developing higher brightness photo-injectors is a crucial R&D focus for increasing our facilities' scientific reach

- One method to enable higher brightness beams is by increasing the electric field on cathode
- Ultrashort RF pulses (<20ns) can produce these higher cathode fields with fewer breakdowns
- We can utilize a novel ultrashort RF pulse compression network within TID to test this concept directly

Goal within two years is to design, build and test a RF gun cavity powered by an RF pulse compression network

- Simulations of a full photoinjector show an order of magnitude increase in hard x-ray (40 keV) performance
- High power testing of cavities with pulse compression has demonstrated cathode gradients of 400 MV/m.

RF Pulse Compression → **Higher Cathode Field** → **Higher Brightness** → **Greater Science Reach**

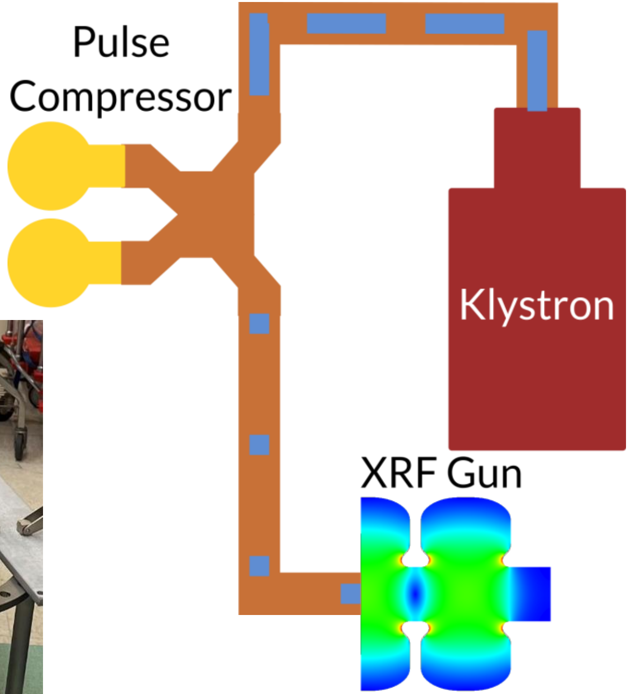
X. Wang, P. Musumeci, E. Lessner, and J. Goldstein, 2016.

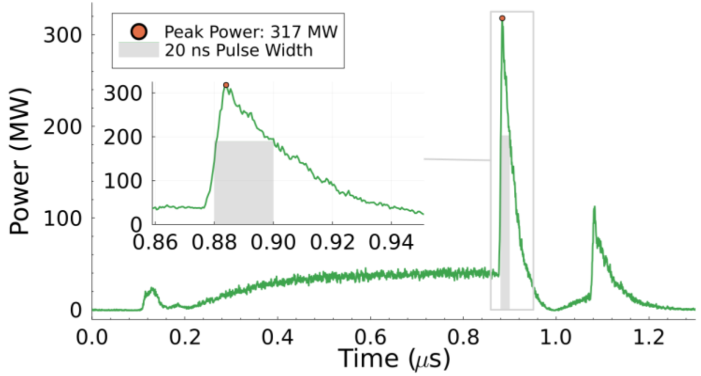
RF Pulse Compression

Utilizing a compact SLAC Energy Development (SLED) by filling a high Q resonator with energy over several μs

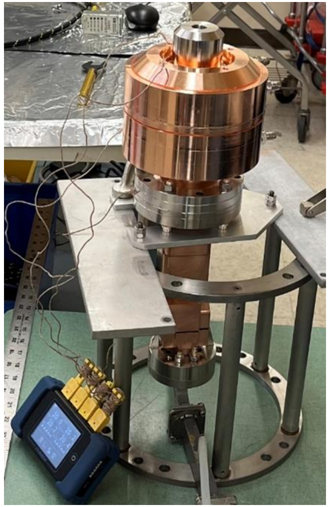
This energy is then released over a much shorter interval by flipping the RF phase, resulting in a net power gain of 6-8X

Our work is based on systems used for the TCAV project





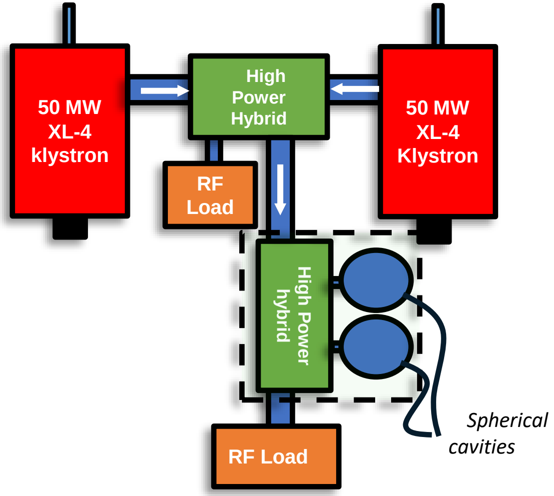
Pulse from recent work

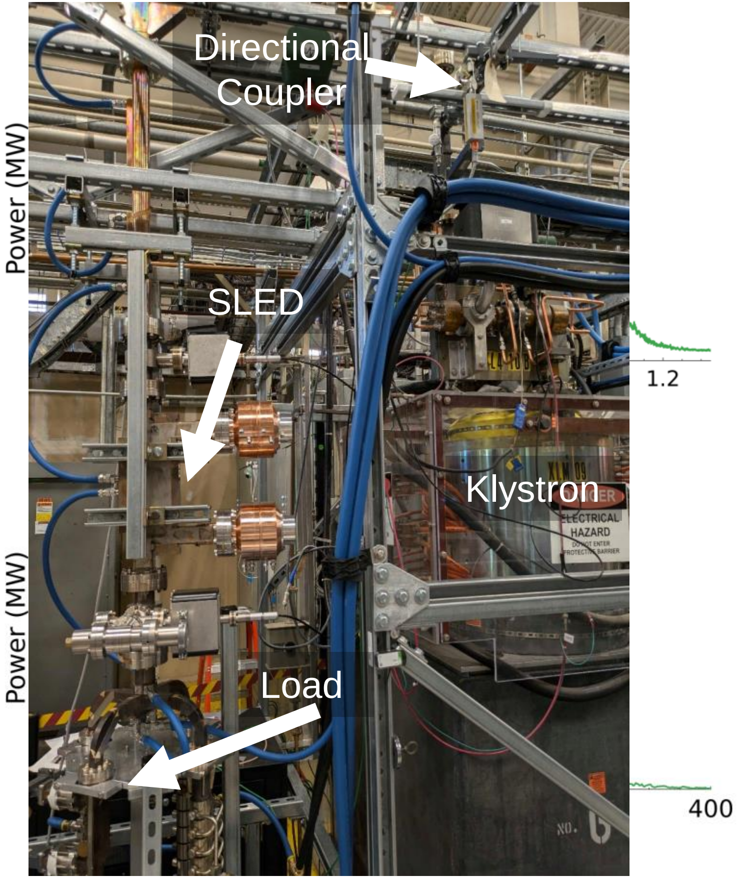


SLED Cavity

Franzi et al., *PRAB* 19, 2016
Wang et al., *PRAB* 20, 2017
A. Dhar et al., arXiv (2026)

RF Pulse Compression Network at SLAC

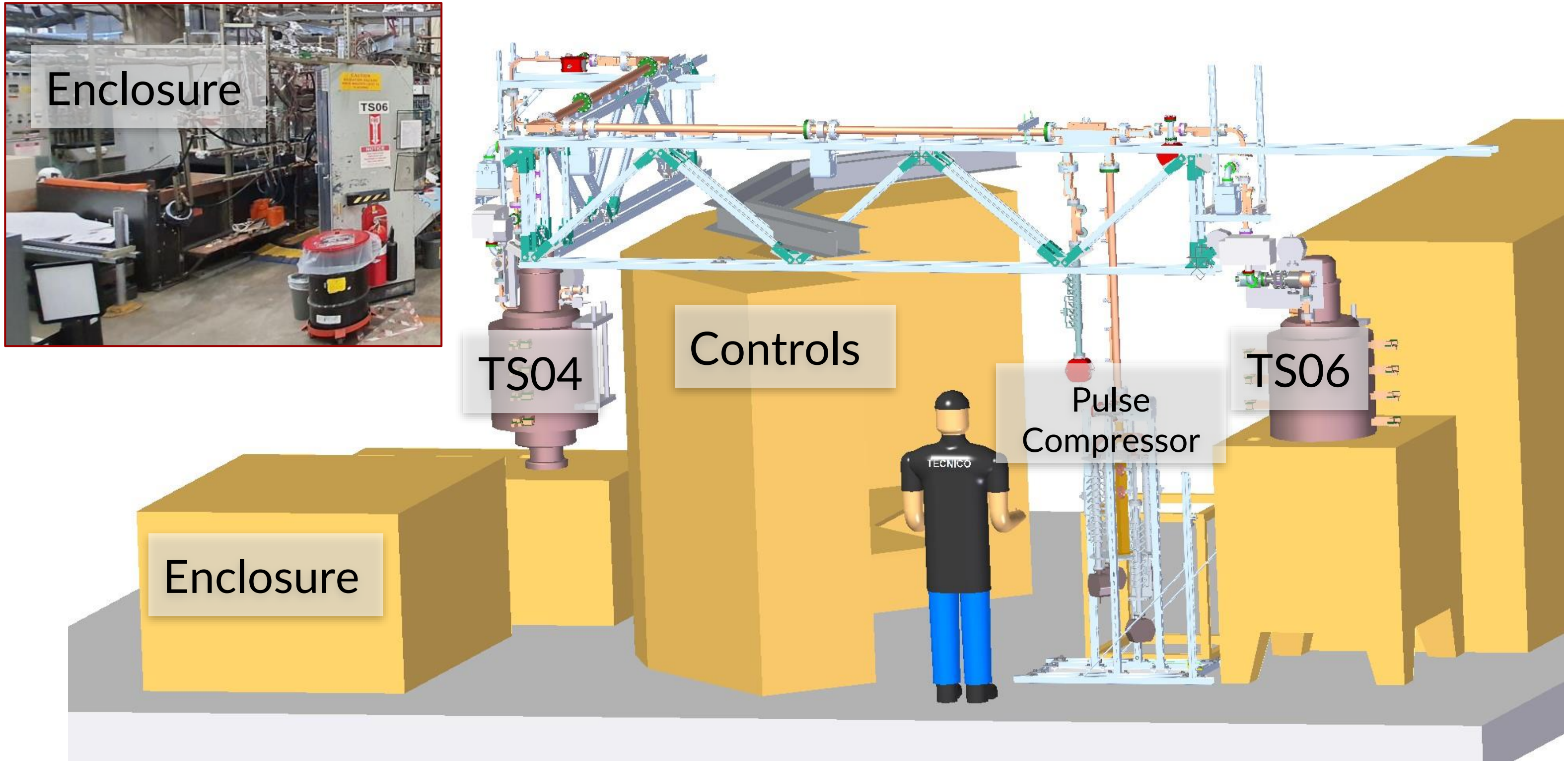




- SLAC-built RF pulse compression system recently used to compress pulses from 50 megawatts over 1 µs to 317 megawatts over 2 ns.
- Further development power combining two 50 MW klystrons has produced up to 510 MW.
- System used to high power test short-pulse gun cavities

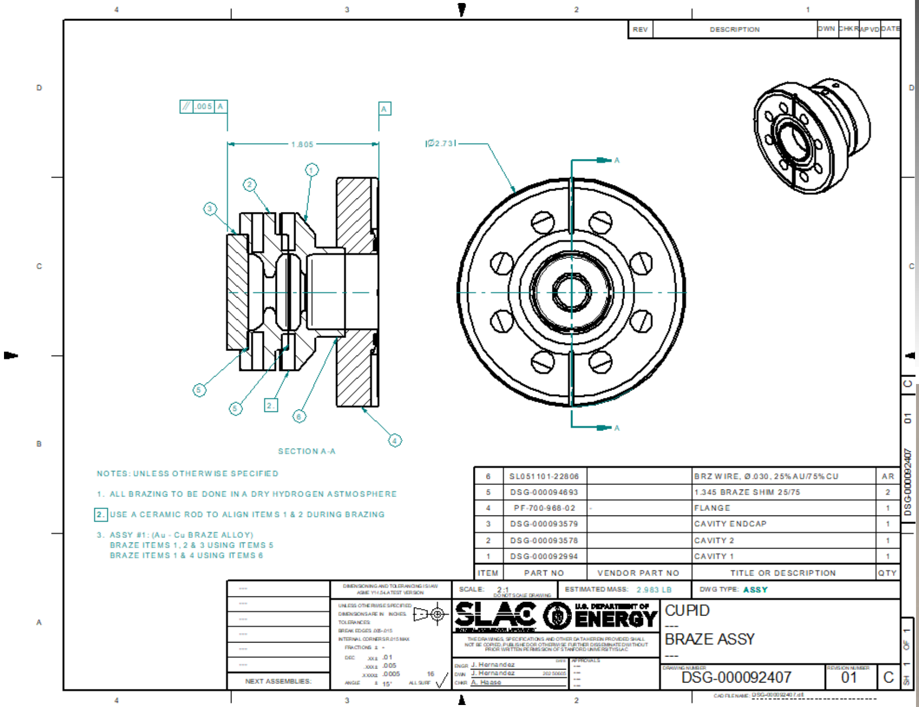
Capabilities for High Power Testing

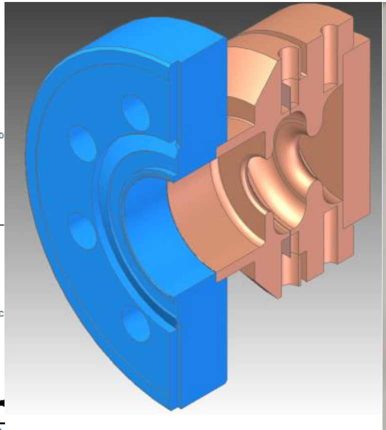
A lead-shielded radiation enclosure is available to house the gun cavity while under high power testing.

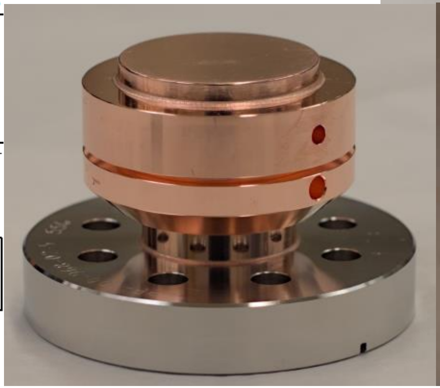


Mechanical Details of the Cavity and Assembly

Diffusion bonded assembly of 1.5 Cells







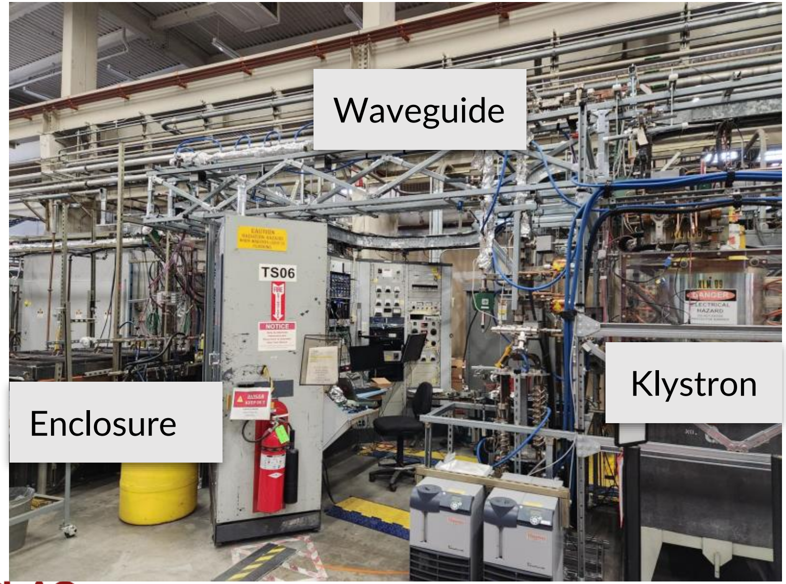
Installation for High Power Testing

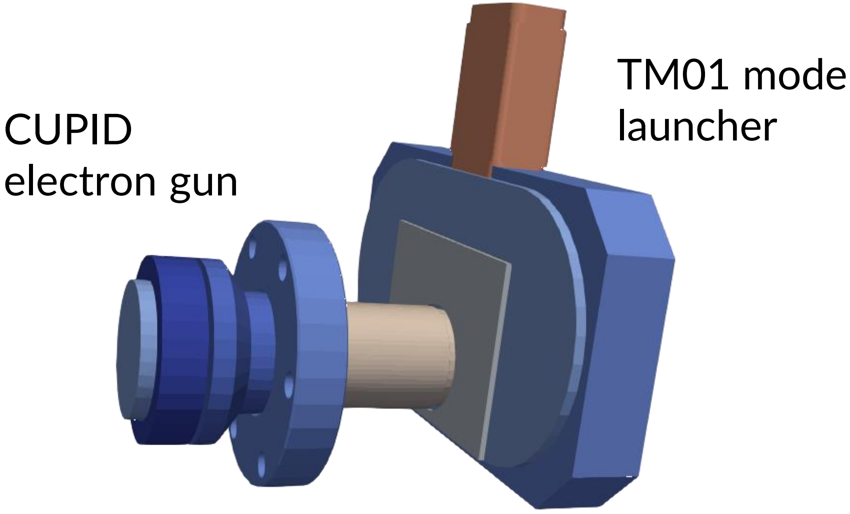
Waveguide is routed overhead and down into enclosure, building upon current scaffolding.

Waveguide hybrid is used to protect reflected power from going back to klystron.

Cavities are powered by TM01 mode launcher used for previous single cavity experiments

- Faraday cup is installed to measure dark current emitted by cavity



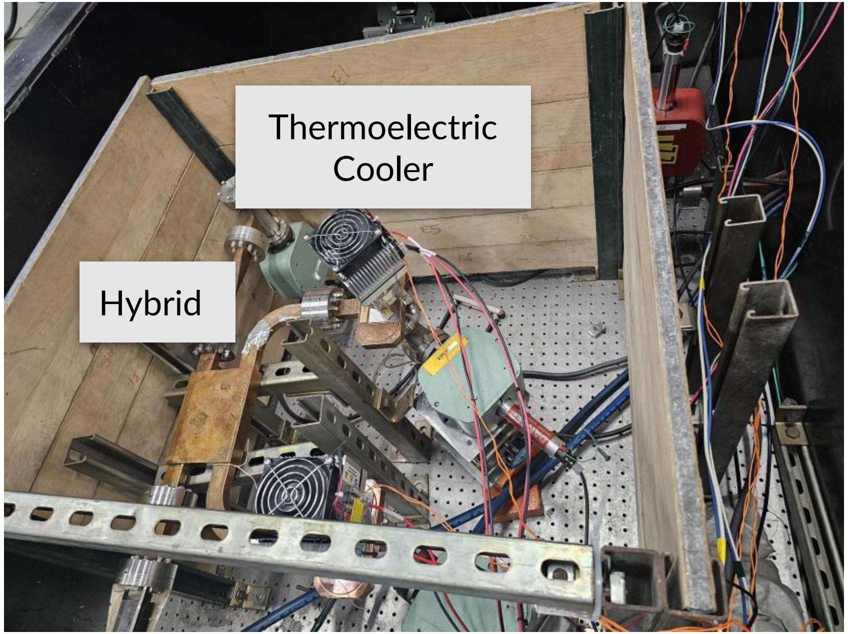


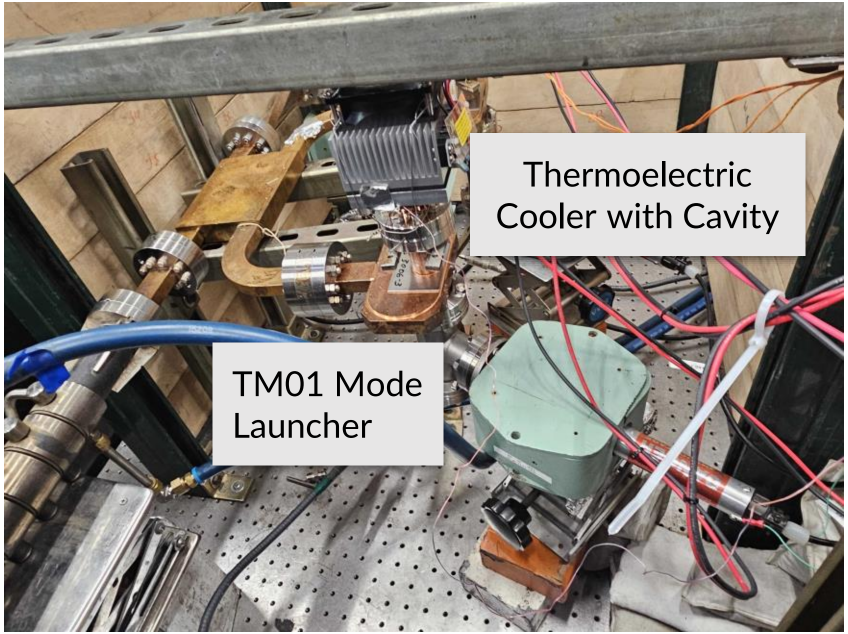
Installation for High Power Testing

Second hybrid is used to protect reflected power from going back to SLED, two cavities tested at once.

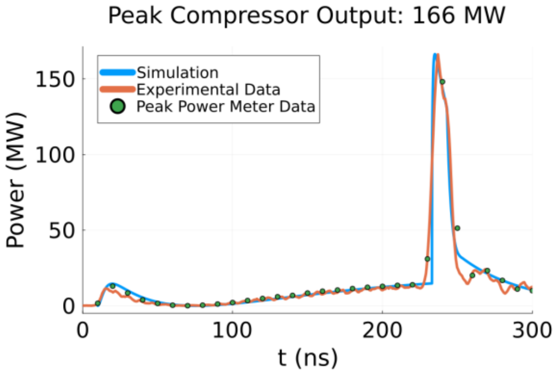
Cavities are attached to thermoelectric coolers for temperature stability up to 30 W average power

- Initially we would limit testing to 10 Hz to ensure both cavities remains in tune

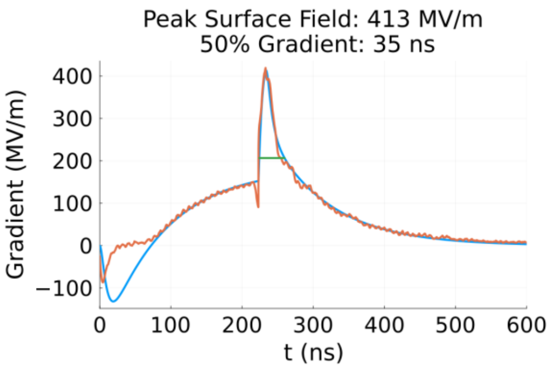




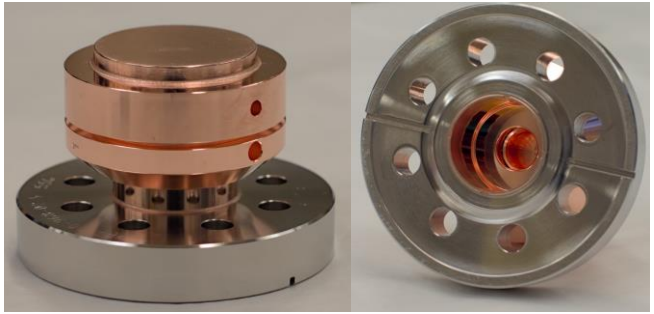
Demonstration of High Power Short Pulses at SLAC

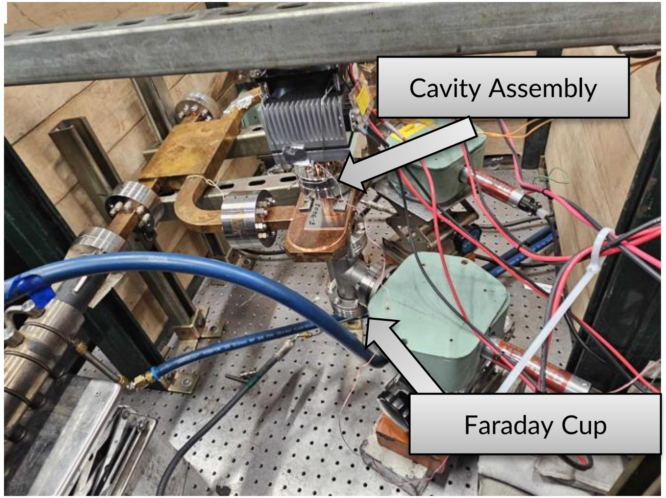


Compressed RF power into a single cavity



Surface field on cathode for single cavity


Fabricated test cavity after diffusion bonding



Test cavities installed in lead enclosure

- RF pulse compression system was used to compress pulses from 55 MW over 300 ns to 330 MW over 35 ns FWHM to power two test cavities in parallel.
- Based on cold test measurements and cavity simulations, surface fields in each cavity have reached 400 MV/m.
- In a full photo-injector, this could provide an output emittance of 90 nm for 100 pC bunch (more info in talk by W.H. Tan.

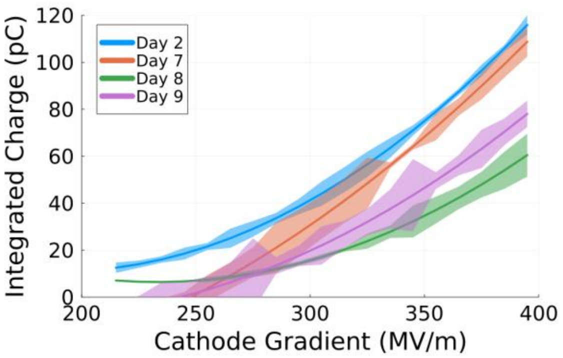
Dark Current Charge Quantification

Data from one faraday cup collected over 7 days, with a total of over 295997 pulses in that time

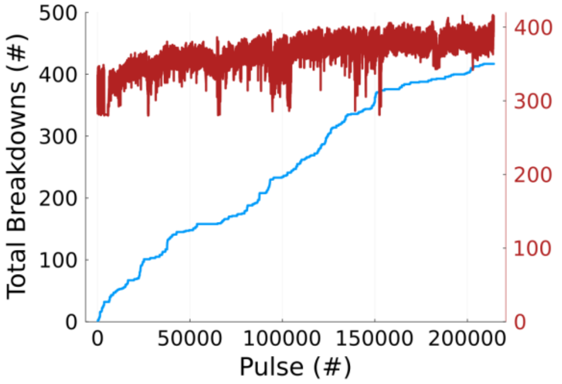
- Emission rose on final day due to aggressive conditioning to reach 400 MV/m

Dark current approximately follows $E^{2.6}$ scaling, fit based on normalized data and fall time

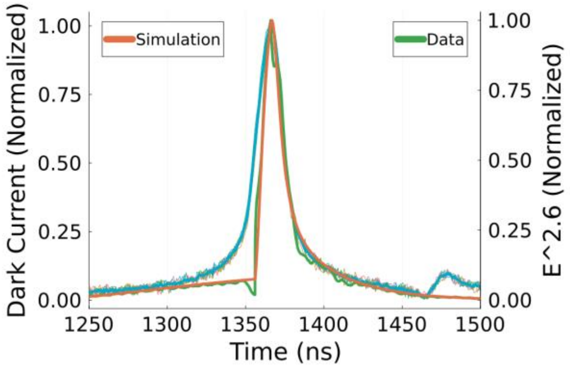
- Time response of faraday cup seems too slow for rise time, more studies required to understand this temporal response accounting for capture, emission physics, and instrumentation



Dark Current Charge versus Cathode Gradient per Day



Breakdown Summary over 7 Days



Dark Current Pulse versus Normalized Cathode Gradient

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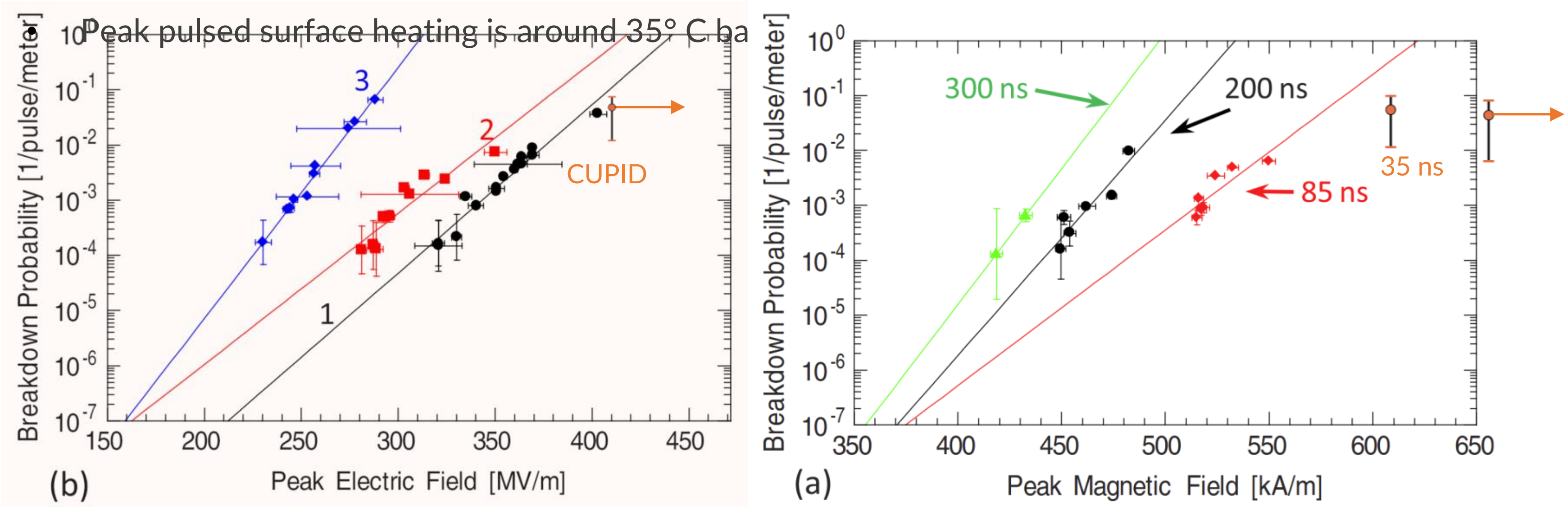
Breakdown Statistics Estimate

Comparing breakdown rate to peak H field shows current rate around 0.05 between 600 to 700 kA/m

This sets an upper bound on attainable breakdown rate compared with previous single cell tests at SLAC

- For comparison, these previous measurements used 10^7 pulses, whereas we are at 3×10^5 pulses
- Peak pulsed surface heating is around 35° C ba



https://pubs.aip.org/aip/apl/article/97/17/171501/121358/Geometric-dependence-of-radio-frequency-breakdown

Comparison to Other Photo-guns

Assuming the following:

- Dark current charge of 60 pC
- 120 Hz rep rate
- Average dark current becomes 7.2 nA,

However, these values were collected with a solenoid to maximize dark current on Faraday cup, so average dark current may be higher in operational conditions

Table 1
Main parameters for the state of the art RF guns.

Parameters	LCLS [7]	SwissFEL [8]
Cavity type	Normal conducting	Normal conducting
Operation mode	Short pulse	Short pulse
Cathode material	Cu	Cu (Cs_2Te)
Cathode assembly	Flat Cu backplane	Load-lock
RF frequency (MHz)	2856	2998
Cathode gradient (MV/m)	120	100
Beam energy (MeV)	6.0	7.1
Pulse length (μs)	2	1
Repetition rate (Hz)	120	100
Dark current (μA) in one RF bucket	~300[a]	~50[b]
Average dark current (nA)[d]	~72	~5

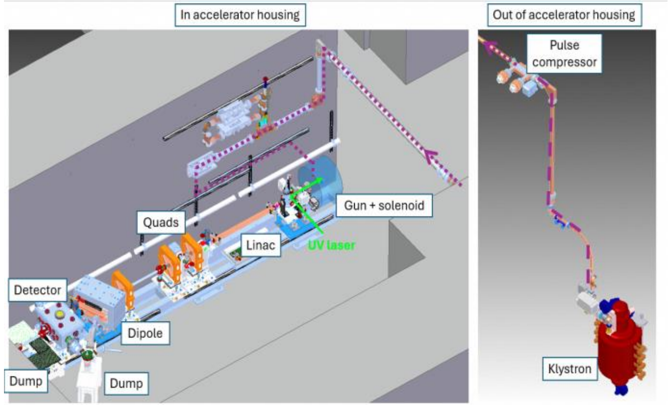
https://doi.org/10.1016/j.nima.2021.165546

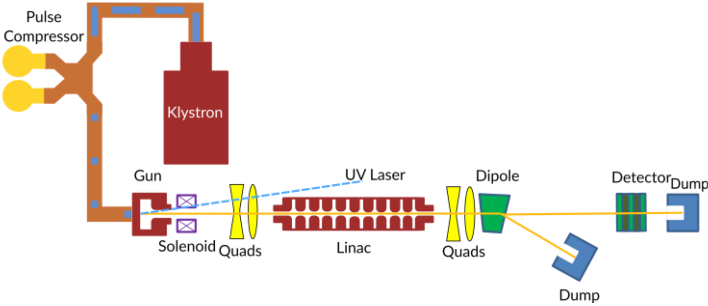
Phase II: Objectives and Resources

Based on our current design study, we would aim to build a photo-injector capable of <90 nm emittance, enabling a transformative improvement over existing performance at LCLS-I and UED.

This photoinjector would require the following key components:

- New RF gun cavities with integrated coupler (built at SLAC)
- UV laser for photoemitted electron bunch (repurposed at SLAC)
- Solenoid for focusing electron bunch (procurement)
- RF source: 50 MW X-band klystron (repurposed at SLAC)
- RF pulse compression system (built at SLAC)
- Low-level RF system to enable pulse compression (COTS plus SLAC development)
- Linac for emittance compensation out of the gun (repurposed at SLAC)
- Diagnostics for beam characterization (repurposed at SLAC)

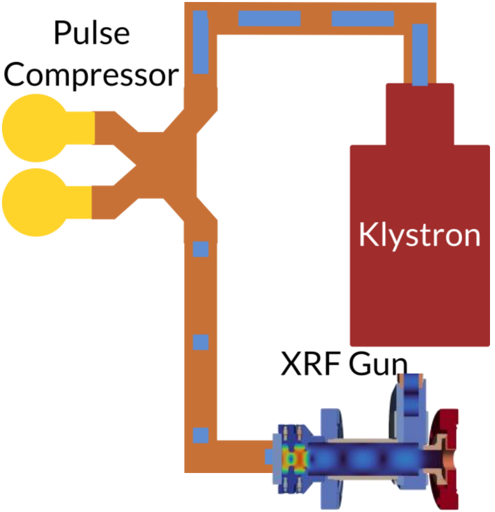


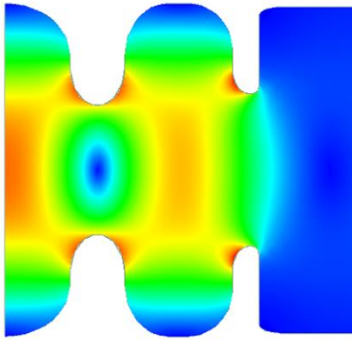


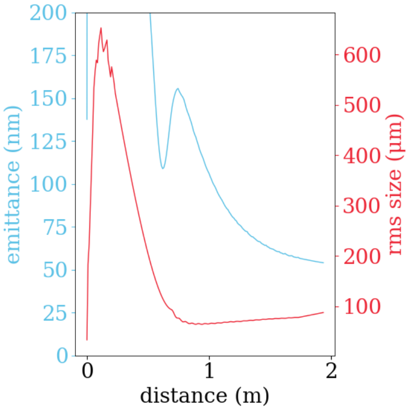
Could be sited at FACET-II or NLCTA

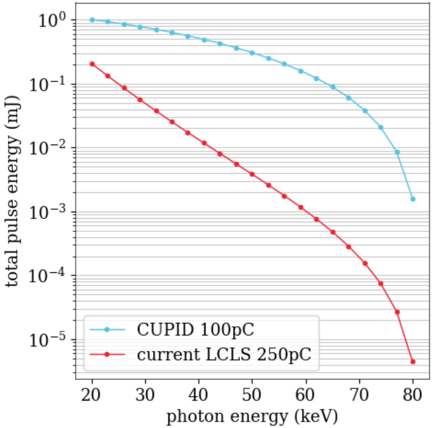
Major Takeaways

Using RF pulse compression can leverage existing SLAC expertise and infrastructure to generate brighter beams, which will dramatically advance the science reach of our facilities









RF Pulse Compression → **Higher Cathode Fields** → **Higher Brightness** → **Greater Science Reach**

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See Next Talk for more information on CUPID

Questions?

Science Drivers for Hard X-ray Photons at LCLS

- Pushing to high energy photons enables larger penetration depth for complex sample environments
- Mesoscale measurements of material structure and damage mechanisms for programs of national interest
- Studying structural dynamics in disordered materials that cannot be measured in reciprocal space
- Core-level spectroscopy of heavier elements and nuclear resonances
- Reduced radiation damage for high repetition rate tracking of pumped dynamics


XFEL.EU WR-2024-002

WORKSHOP REPORT

Scientific Opportunities with very Hard XFEL Radiation

October 2024

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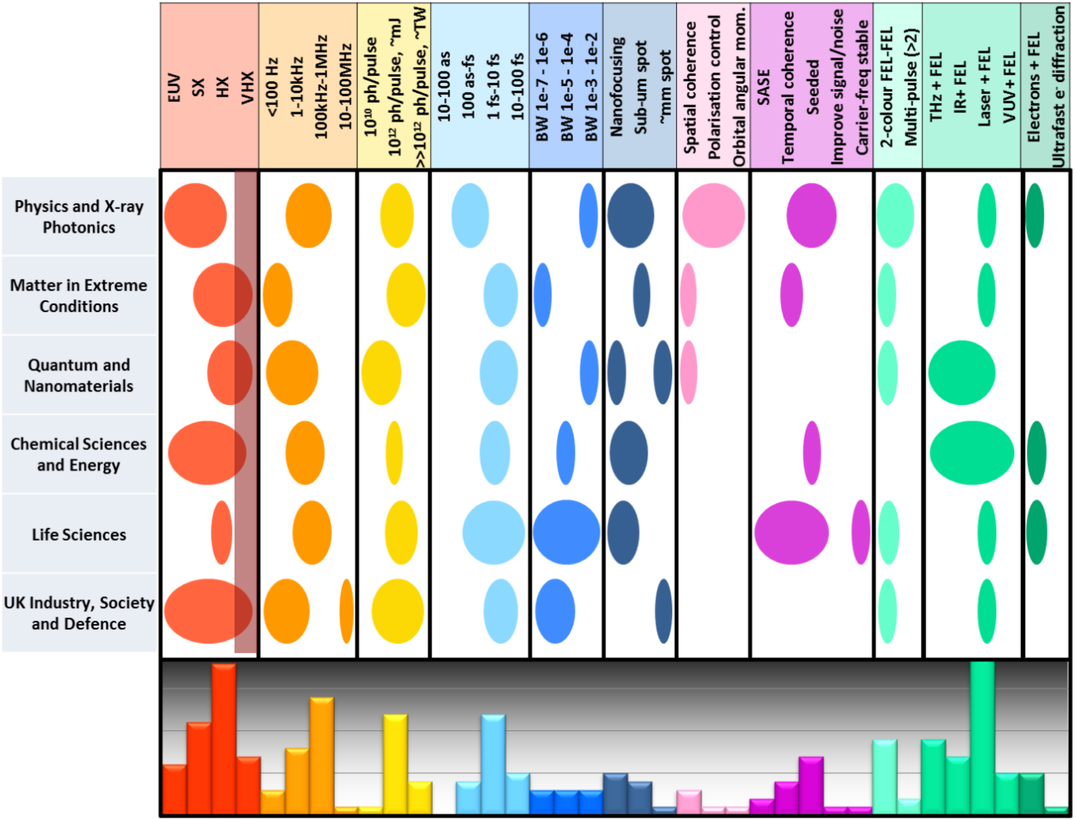
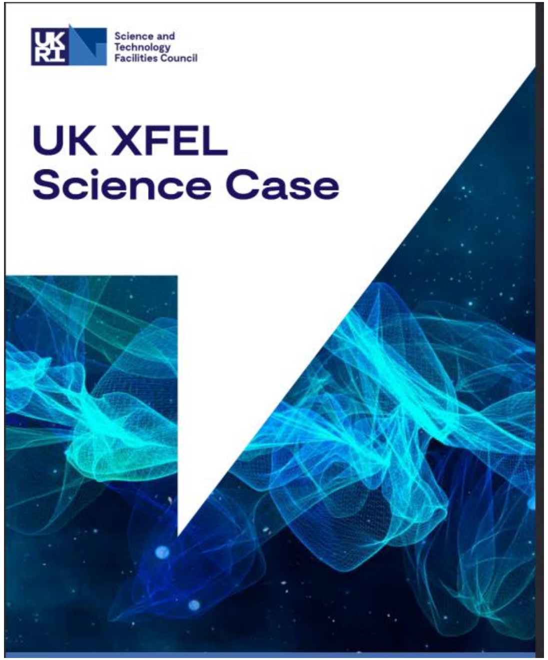
Benuzzi-Mounaix, A. et al. Scientific Opportunities with Very Hard XFEL Radiation. https://xfel.tind.io/record/3917 (2024) doi:10.22003/XFEL.EU-WR-2024-002.

Science Drivers for Hard X-ray Photons at LCLS





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Burnett, A., . et al. (2020). *UK-XFEL Science Case*. https://eprints.soton.ac.uk/451571/