Machine Development R&D Overview

Advisory Board Meeting, FY25 Q1

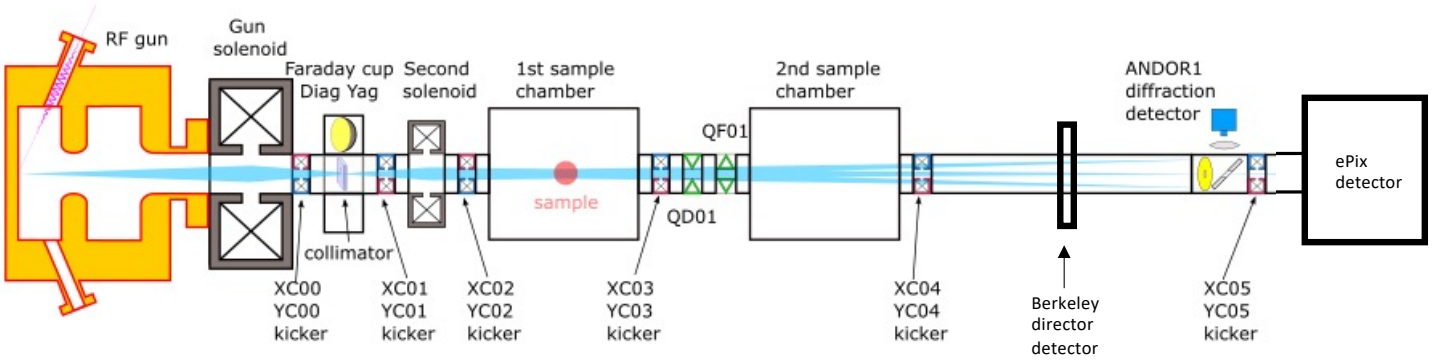
Joel England / Test Facilities / MeV-UED

Nov 18, 2024

SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University | U.S. DEPARTMENT OF ENERGY

ASTA MeV-UED Facility



S. Weathersby, et al., Rev. Sci. Instr. 86, 073702 (2015), X. Shen et al., Struct. Dyn. 6 054305 (2019)

***q*-resolution**	***time-resolution***
< 0.17 Å^{-1} FWHM	<150 fs FWHM

L. Le Guyader et al., Struct Dyn. 4 (4), 044020 (2017)

J. Yang et al., Science 368, 885 (2020)

stable over multi-day operation
(typical 5 days continuous 24 hr/day)

Current beam parameters

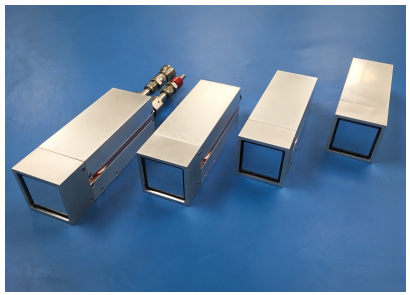
Parameters	Values
rep. rate	360 – 1080 Hz
beam energy	2.3 - 4.2 MeV
q-range	12 Å^{-1}
bunch charge	10^2-10^6
emittance	0.3 - 20 nm
bunch length	<120 fs FWHM

Detectors

Andor EMCCD + P43 Phosphor

Parameters	Values
phosphor thickness	50-100 µm
frame rate	26 fps
point spread function	85 µm RMS
pixel size	13x13 µm
resolution	1024 x 1024
pixel well depth	$80x10^3$

LCLS ePix10k Direct Detector*



Parameters	Values
sensor thickness	500 µm
frame rate	360 Hz (→ 1080 Hz)†
pixel size	100 x 100 µm
SNR (high gain)	> 100
dynamic range	245 eV – 88 MeV

*See talk by Fuhao Ji in this review
†Upgrade to 1080 Hz in progress

Other MeV-UED facilities are coming online around the world

Country	Facility Name	Electron beam energy range (MeV)	Charge per pulse (fC)	Electrons per pulse	Bunch length (fs)	Repetition rate (Hz)	Start date
Germany	DESY - REGAE	2 - 5	<100 - 1000	10^4 - 10^6	7 - 30	50	2011
China	Tsinghua Thomson scattering X-ray source (TTX*)	2 - 4	10^4 - 10^5	10^8 - 10^9	1000 - 3000	5 - 10	2013
	SHINE**	0.75	1000 - 10^4	10^8 - 10^9	1000	10^6	2025
United States	SLAC MeV-UED	2 - 4	1 - 100	10^4 - 10^6	<150***	1 - 360	2014
	SLAC MeV-UED	2 - 3	1 - 100	10^4 - 10^6	<150***	1000	2024

* https://indico.cern.ch/event/577810/contributions/2479863/attachments/1424734/2185126/2017-CLIC_WS-Thomson_Scattering_X-ray_Source_at_Tsinghua_University.pdf

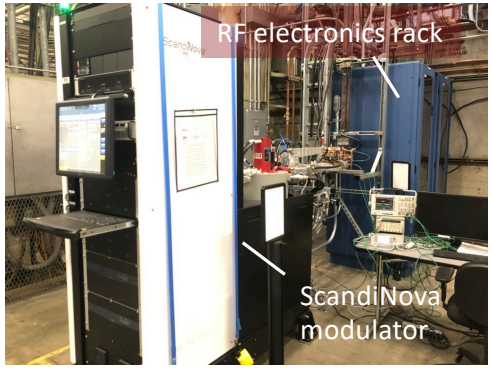
** http://linac2018.vrws.de/talks/mo2a01_talk.pdf (FEL Source)

*** Nominal. Beam charge dependent

Growing international interest in MeV-UED with new facilities coming online. Not a comprehensive listing. Other MeV-UED programs at BNL, Berkeley, UCLA, LANL, and Daresbury (UK).

System Upgrades → Toward kHz Pump-Probe

Upgrade to 1080 Hz Pump-Probe Acquisition Rate

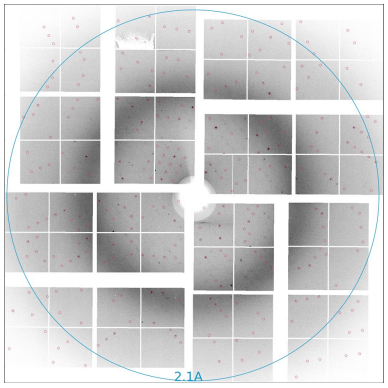


ScandiNova RF Klystron (S-band 2.856 GHz @ 1080 pps)

- Fully installed and in state of technical readiness; conditioned to full power on an RF load in 2022
- Commissioning test at 1 kHz in progress scheduled Oct-Nov 2024

Ti:Sapphire Coherent Legend Elite Duo + SPA

- Infrared laser upgrade completed in April 2021 (regen + single pass amp).
- Successfully operated through Run 4.



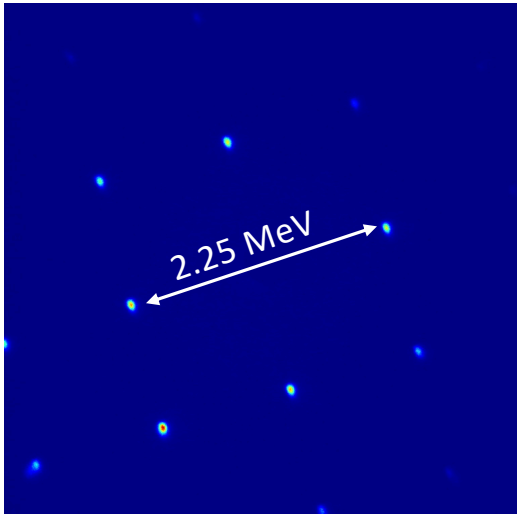
ePix Direct Electron Detector

- Existing 360 Hz version was tested in Run 3; R&D scheduled Nov 2024
- Upgrade components for 1 kHz ePix have been delivered; will include e-beam thru-hole
- Working with detector group to implement as an independent detector (anticipated install in FY25)
- Working with the LCLS detector group to balance commissioning with LCLS-II efforts

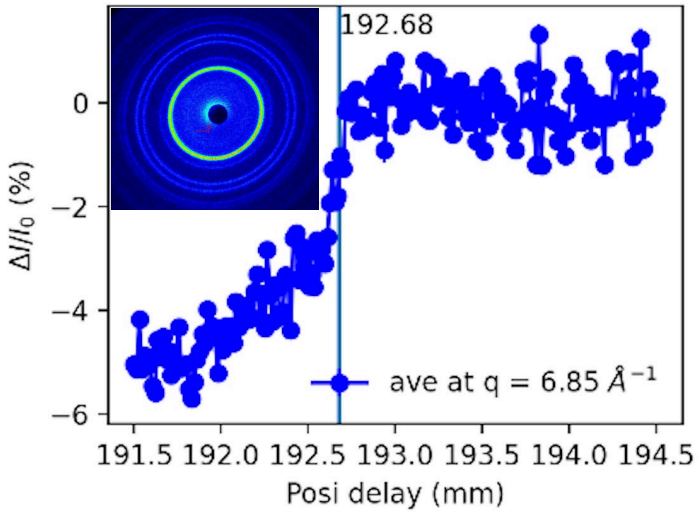
ASTA / MeV-UED: Near-Term (1-2 Year) R&D

Commissioning of kHz Pump-Probe (October 2024)

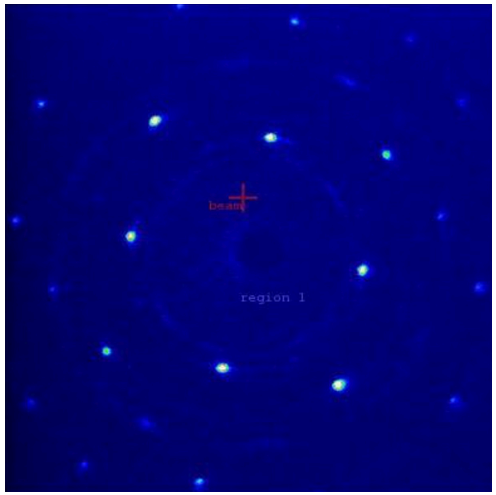
Si (static) energy calibration



Bi (pump-probe) time zero



Single xtal Au (pump-probe)



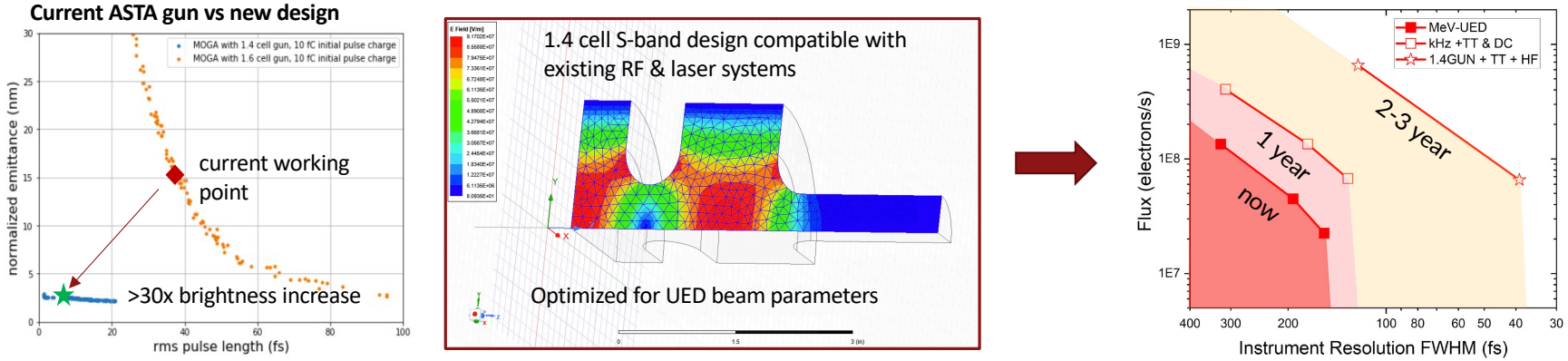
- Reduced electron energy (2.3-2.6 vs. 4.0 MeV at 360 Hz) due to lower peak power of system (negligible effect on time resolution, 35% reduction in q-range).
- Time resolution and stability are within Bismuth temporal response time (< 350 fs).
- Current plan is to **continue at 360 Hz into Run 5 with 1080 Hz available on as-requested basis**.
- Reconfiguring the system between rates requires a number of configuration changes, including retuning of the laser cavity to adjust for change in heat load.

ASTA / MeV-UED: Near-Term (1-2 Year) R&D

Critical Mid-Term R&D goals identified from recent UED strategic planning efforts:

- Improve instrument time resolution towards 50 fs
- Increase electron flux to > 1e8 electrons/sec
- Improve tranverse emittance to reach Δq = 0.01 Å^{-1}

To meet future user requirements on electron flux, spot size, and time resolution, a new higher brightness, lower emittance electron source is needed



Mid-Term (1-2 Year) Goals / Milestones	Funding	Key Personnel/Responsibilities
Prototype Study of 1.4-cell S-band gun	TBD	LDRD In Preparation with UED & LCLS Accel Physics
Dedicated online (shot-to-shot) THz time-tool	prior DOE-BES	UED AD & LCLS team with Laser & Nanni Groups
Upgrade to kHz rep rate	prior DOE-BES	UED AD & LCLS team with TID Sensor Group
Utrafast studies & Q-resolution imaging	DOE-BES	UED AD Joint with LBNL & UCLA (FWP 100940)

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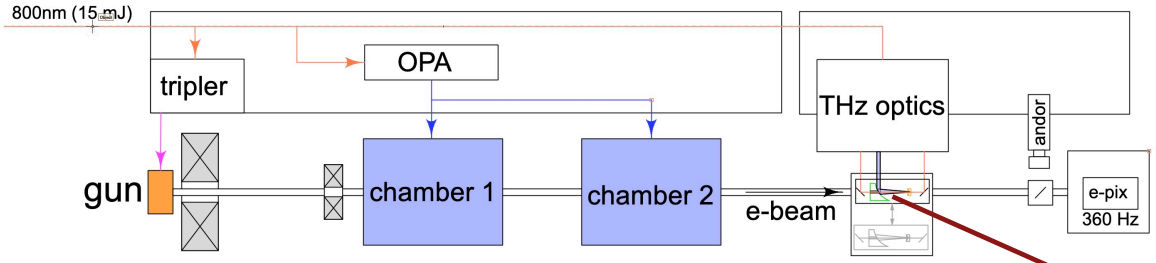
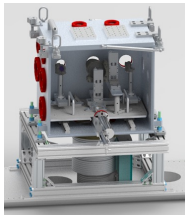
ASTA / MeV-UED: Near-Term (1-2 Year) R&D

Implementation of Dedicated THz Time-of-Arrival Diagnostic

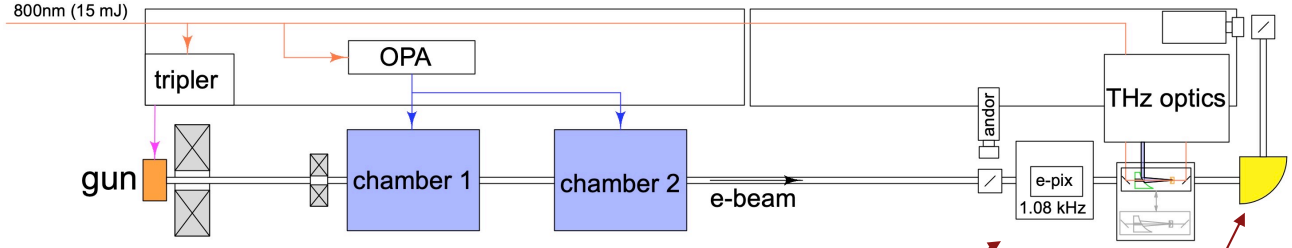
Phase I: Interruptive Diagnostic (anticipated install Dec 2024)





THz chamber design

Phase II: Shot-to-Shot Diagnostic

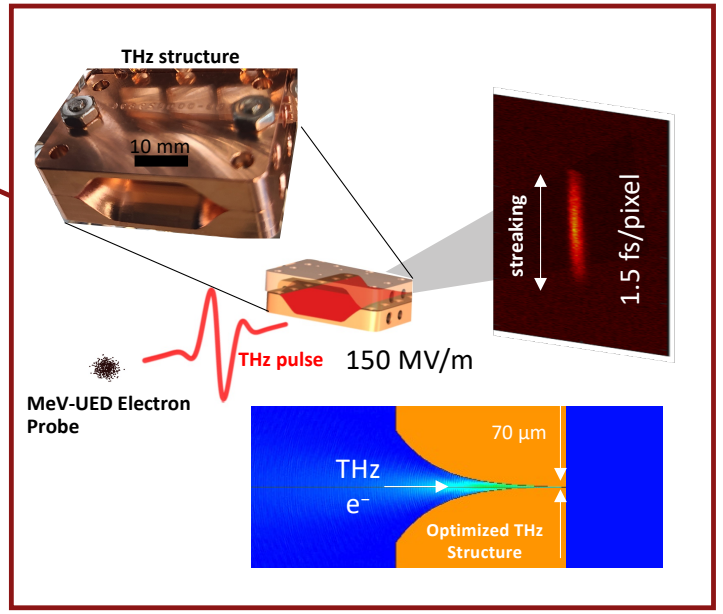


new ePix with thru-hole

spectrometer magnet

Proof of Principle demonstrated in prior runs:

- Enables simultaneous fs arrival time and bunch length measurement
- Developed in collaboration with Nanni group
- Robust performance under insert/remove actuation



M. Othman, et al., Efficient THz Time Stamping of Ultrafast Electron Probes, 47th IRMMW-THz Conference (2022).

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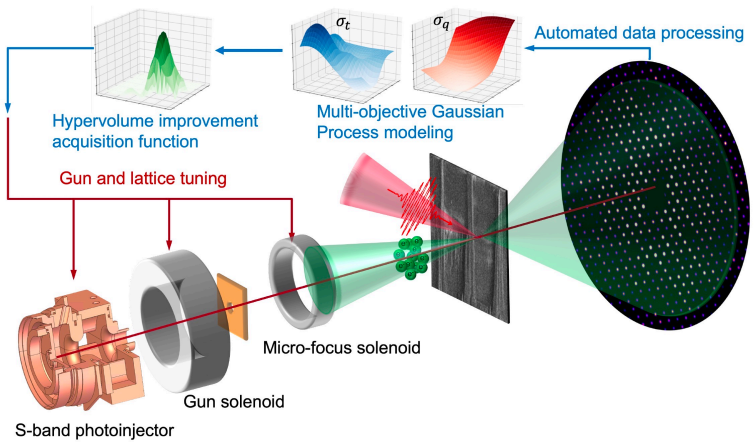
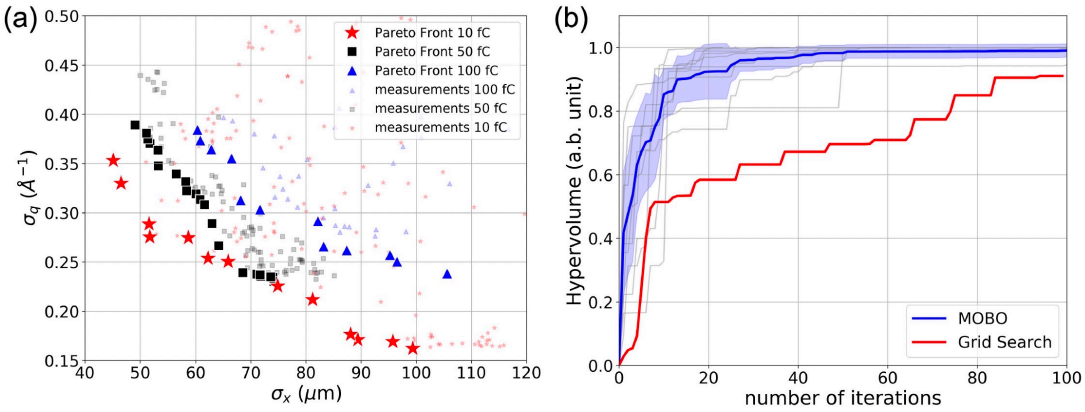
ASTA / MeV-UED: Near-Term (1-2 Year) R&D

Tuning Using Multi-Objective Bayesian Optimization (MOBA) Machine Learning





F. Ji, A. Edelen, R. Roussel, et al., *Nature Communications* (2024)

- Specific user run requirements on electron beams: pulse length, beam energy, beam spot size, q-resolution, pulse charge, energy spread, etc
- Currently optimizations rely on hand tuning by experienced operators, requiring ~1h for setting up the desired beam
- This experiment demonstrates trade-offs of key beam properties (pulse length, spot size, and q-resolution) that have a direct impact on the outcome and quality of scientific user experiments

*See talk by Fuhao Ji in this review

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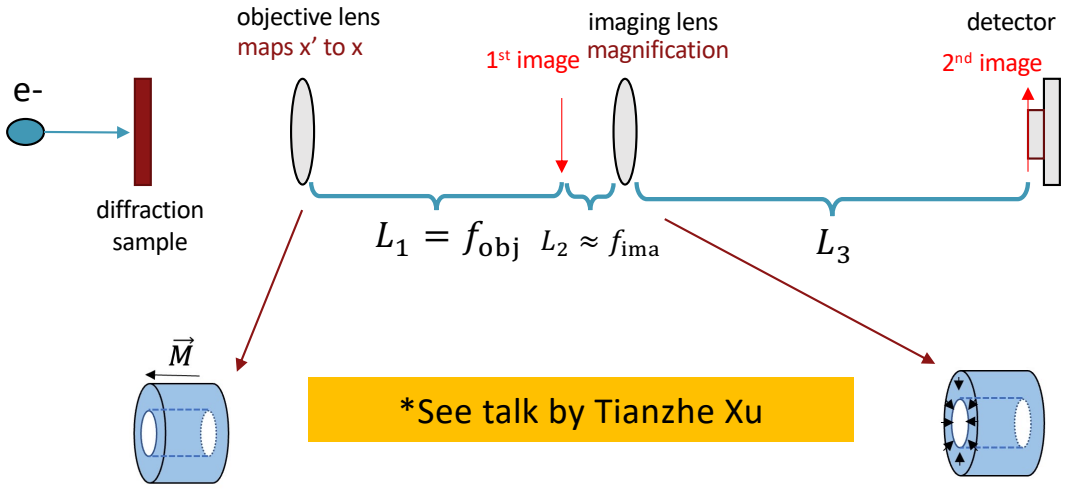
ASTA / MeV-UED: Near-Term (1-2 Year) R&D

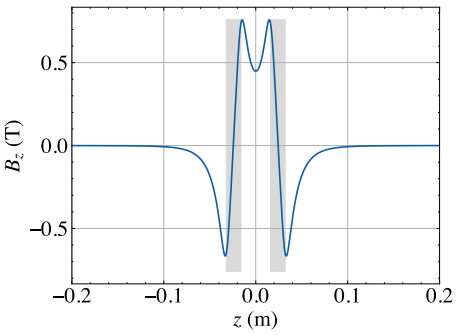
Q-resolution imaging and magnification with permanent magnet solenoids (PMS)



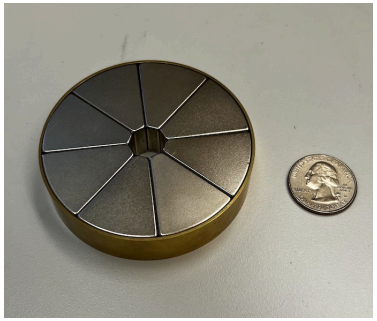
*See talk by Tianzhe Xu

Axially magnetized PMS (in hand)

simulated field profile of imaging lens

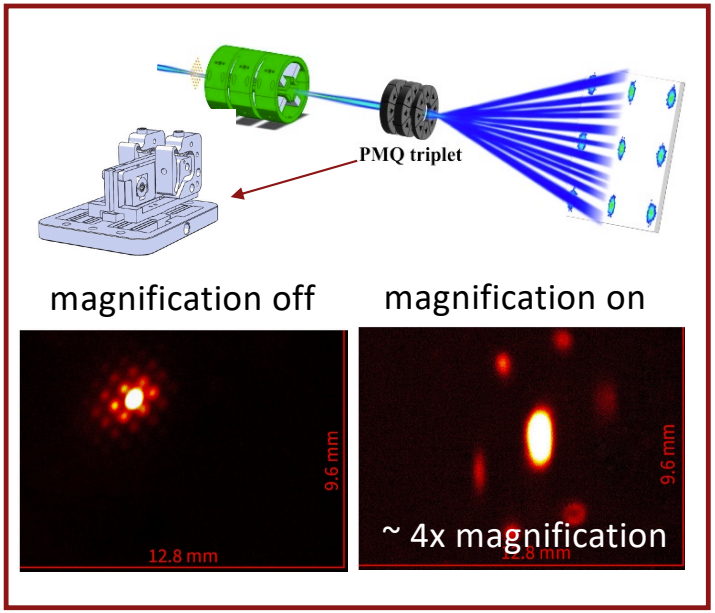


Radially magnetized PMS (designed, delivered April 2024)



Q-range magnification demonstrated (Nov 2023):

- Enables resolution of small or closely spaced diffraction features
- Tested in collaboration with UCLA group
- Up to 4x magnification demonstrated using 8.1 MeV electrons on Au sample



Demonstration at UCLA Pegasus beamline on Au sample at 8.2 MeV, *Struct. Dyn.* **11**, 024302 (2024)

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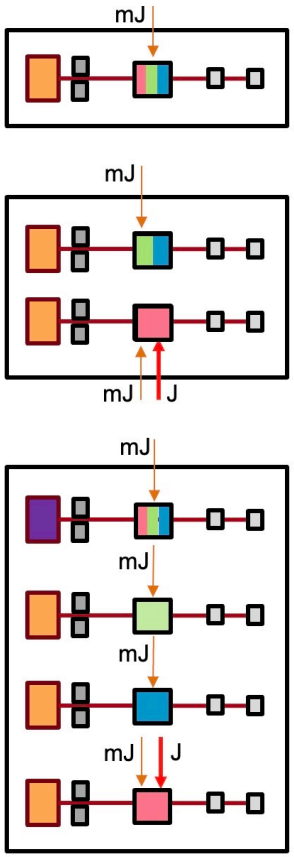
ASTA / MeV-UED: Long-Term (5-10 Year) Roadmap*



Near Term

Long Term

Single Multipurpose Beamline (1-2 years)

Solid → Gas → Liquid, Bio

Improved temporal and q-resolution:

- Single shot THz streaking diagnostic
- Single electron detection for high SNR
- High repetition **RF** operation (**kHz**)
- Development of new 1.4 cell gun prototype

Additional Beamline (3-5 years)

- Testing/commissioning of 1.4 cell gun
- Gun R&D → User operations
- Two lines (Gas + Liquid/Bio) & (Solid + MEC)
- Increased R&D and User capacity

UED Farm (5-10 years)

- Dedicated instruments for Solid/Liquid/Gas
- Dedicated lasers: IR, TW/Joule-class, THz
- Diversified beam lines for User + R&D
- **SRF** or APEX-like **VHF** gun (**kHz** → **MHz**)

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*R. J. England, A. Reid, X. Shen, M. P. Minitti, *White Paper: Expansion of MeV UED Facility at SLAC, March 23, 2022*

MeV-UED Workshop – Initial Thoughts

- Aiming for Late Spring-Early Summer 2025 (TBD)
- Option to combine with next Advisory Board Meeting
- Attendance: combination of UED science users, accelerator science and instrument technology communities
- Location: SLAC or nearby Bay Area venue (TBD)
- 2-3 days, split between material science, chemistry, and instrument development
- Goals: invite broader community to discuss future needs and directions for MeV-UED science and **evaluate plans for a 2nd MeV-UED beamline at SLAC**
- Recurrence: every 2 years; possible rotation between institutions
- Outputs: Workshop report, proceedings and/or archive of presentations

Feedback and recommendations welcomed!

Summary of Instrument R&D Priorities

R&D Activity	Status	Covered in this Review
ePix 360 Hz development	Current – hdwr under test	Fuhao Ji
ePix 1080 Hz development	Current – under construction	Joel England
kHz RF upgrade	Current – commissioned	Joel England
AI/ML Optimization & Tuning	Current – ongoing project	Fuhao Ji
Q-range Magnification	Current – ongoing project	Tianzhe Xu
Pump laser UV extension	Current – ongoing project	Yusong Liu
Cathode laser focus (Q-resolution)	Current – planned in FY25	Tianzhe Xu
Time-Tool Phase 1 (destructive)	Current – planned in FY25	Joel England
Time-Tool Phase 2 (nondestructive)	Planned (1-2 years)	Joel England
High-Brightness Gun R&D	Design study – future expansion	Fuhao Ji
RF & Magnet Compressor R&D	Design study – future expansion	Tianzhe Xu

Summary & Conclusions

- Critical needs identified from UED strategic planning efforts and user feedback:
  - Improved electron source performance to achieve ≤0.01 $Å^{-1}$ momentum resolution, ≤50 fs temporal resolution, and ≥1e8 e-/sec flux imply need for higher beam brightness
  - Increase user support capacity with diversified beamlines for solid, liquid, gas phase, and MEC experiments and more efficient R&D development

- Machine development R&D to meet the above needs:
  - Near-Term (1-2 years): upgrade existing beamline with shot-to-shot THz TOA and kHz RF and detector rep rates
  - Mid-Term (3-5 years): additional user beamline based on optimized 1.4 cell S-band gun for improved beam brightness
  - Long-Term (5-10 years): multi-beamline facility using combination of S-band and SRF or VHF sources (leveraging LCLS-II-HE gun development)

- Broader interests/impact of MeV-UED R&D:
  - Continuing R&D needed to keep MeV-UED capabilities at the technical forefront
  - Other MeV-UED facilities coming online at DESY REGGAE, Tsinghua TTX, SHINE, BNL
  - MeV-UED directly complements LCLS-II HE (sensitivity nuclear and electronic distributions, low energy deposition, and high cross section)

- Synergy and Collaboration:
  - Seeking methods and techniques to maintain MeV-UED as a prominent pump-probe technique.
  - Strong synergy with other SLAC programs leveraging LCLS injector, laser, and detector development.

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MEV-UED INSTRUMENT

Questions?

Test Facilities Operations Review

Nov 15, 2024