



## SLAC MeV-UED Upgrade Plans and R&D

Robert Joel England, SLAC National Accelerator Laboratory

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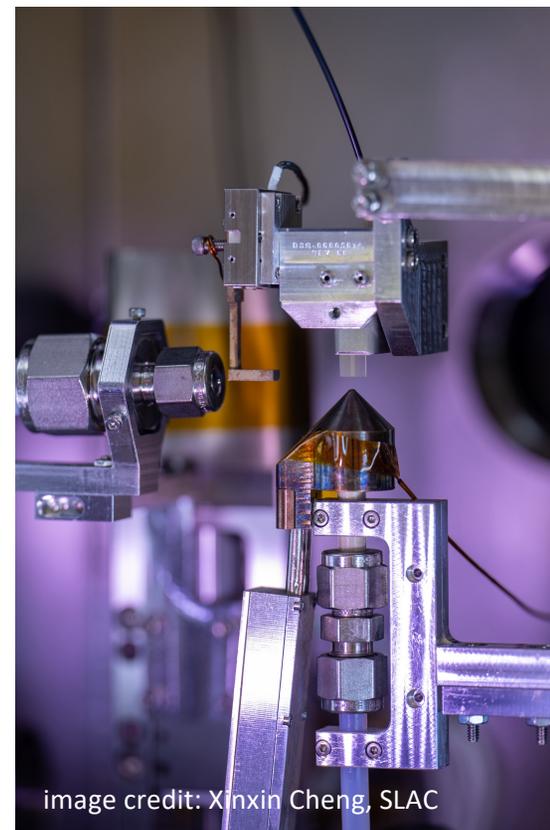


image credit: Xinxin Cheng, SLAC

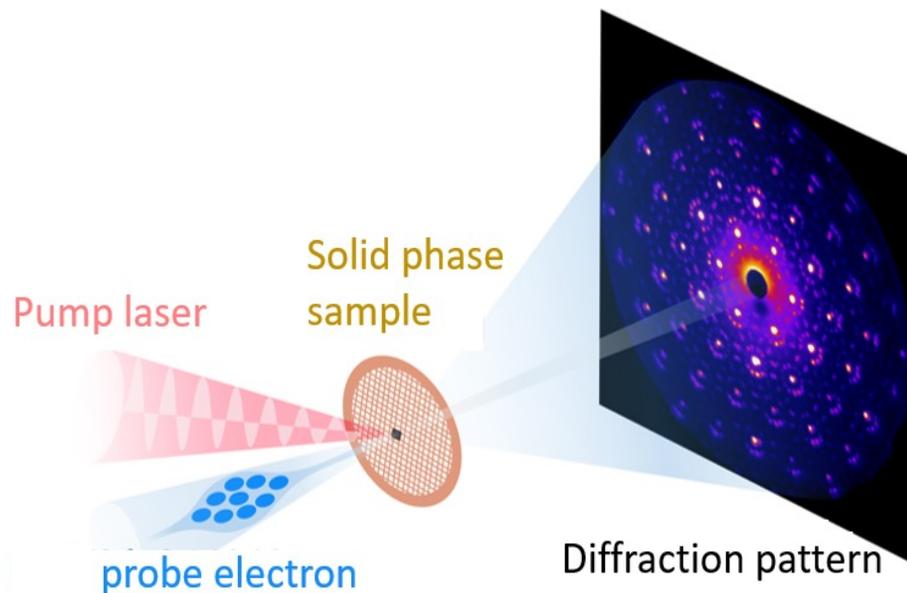
Aug 27-29, 2025

Frontiers in Ultrafast Scattering of Electrons (FUSE) Workshop 2025

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# Ultrafast Electron Diffraction

UED enables measurement of dynamic processes with unprecedented spatial ( $\text{\AA}$ ) and temporal (fs) resolution to visualize the ultrafast and ultrasmall



## Dynamic Processes

**Solid-state:** nano-scale, 2D materials, diffuse scattering, strongly correlated systems, functional materials

**Gas-phase:** sequential double-dissociation, roaming reaction, ring opening

**Liquid-phase:** photochemistry, photosynthesis, DNA photodamage

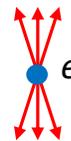
Current user run 5 focused on solid state  
Upcoming user run 6 will focus on gas and liquid phase dynamics

# Benefits of MeV vs. keV Electrons

## Space charge effects

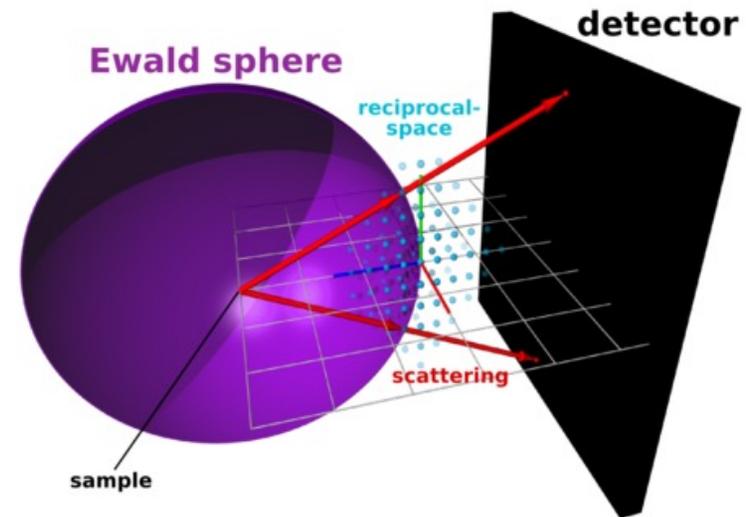
Coulomb repulsion is reduced at higher energy, allowing for higher charge density (and thus shorter bunches)

$$F_{sc} \propto \frac{1}{\gamma^3}$$



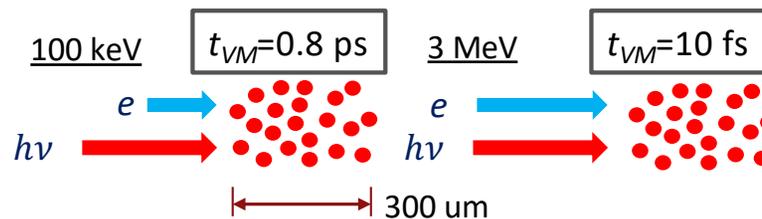
## Larger Ewald Sphere

Due to reduced DeBroglie wavelength, Ewald sphere is “flatter” at MeV energies, encompassing more diffraction peaks.



## Reduced velocity mismatch

Reduced e- velocity mismatch compared to speed-of-light pump laser improves temporal resolution



# Q-Resolution: High-Brightness Beams

$$\epsilon_n = \sigma_x \cdot \gamma \beta \sigma_{x'}$$

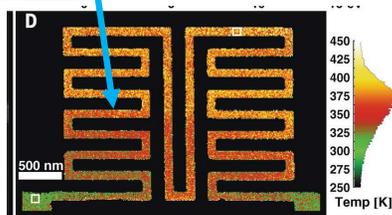
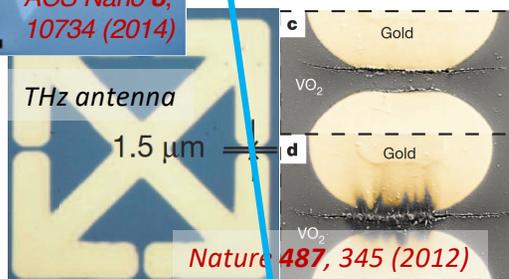
e.g. 0.1 nm-rad = 0.4  $\mu\text{m} \times 0.25$  mrad

$$\Delta q = \frac{2\pi}{\lambda_e} \cdot \sigma_{x'}$$

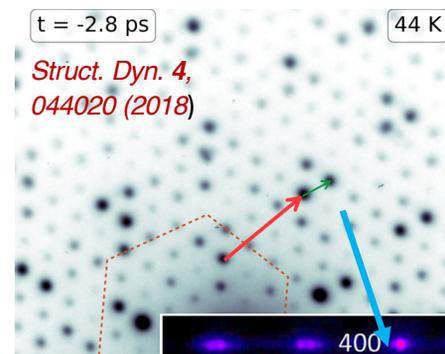
e.g.  $\Delta q = 0.07 \text{ \AA}^{-1}$  w/  $\gamma \sigma_{x'} = 0.25$  mrad



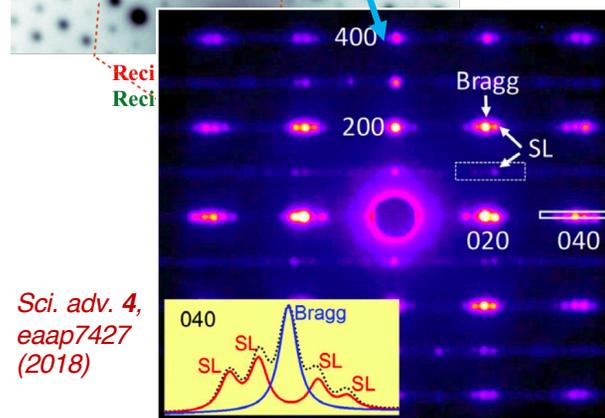
**Probe size:**  
10s of  $\mu\text{m}$  to  $\mu\text{m}$  to nm



*Science* **347** (6222), 629 (2015)

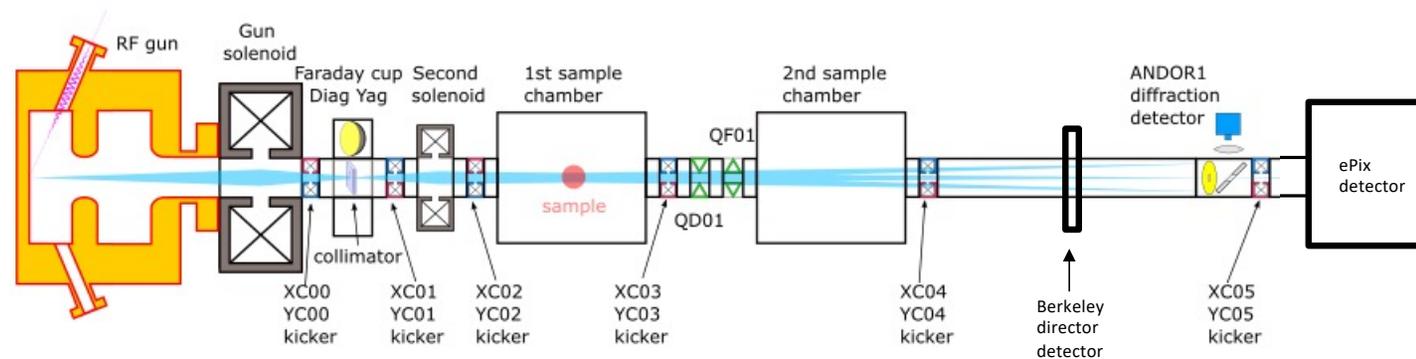


**Q-resolution:**  
need to improve by a few times



*Sci. adv.* **4**, eaap7427 (2018)

# ASTA UED Experimental Area



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

## Current beam parameters

Parameters	Values
rep. rate	single shot to 1080 Hz
beam energy	3 to 3.7 MeV
q-range	10-12 $\text{\AA}^{-1}$
bunch charge	$10^2$ - $10^6$
emittance	0.3 - 20 nm
bunch length	<120 fs FWHM

### q-resolution

< 0.17  $\text{\AA}^{-1}$  FWHM

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

### time-resolution

<150 fs FWHM

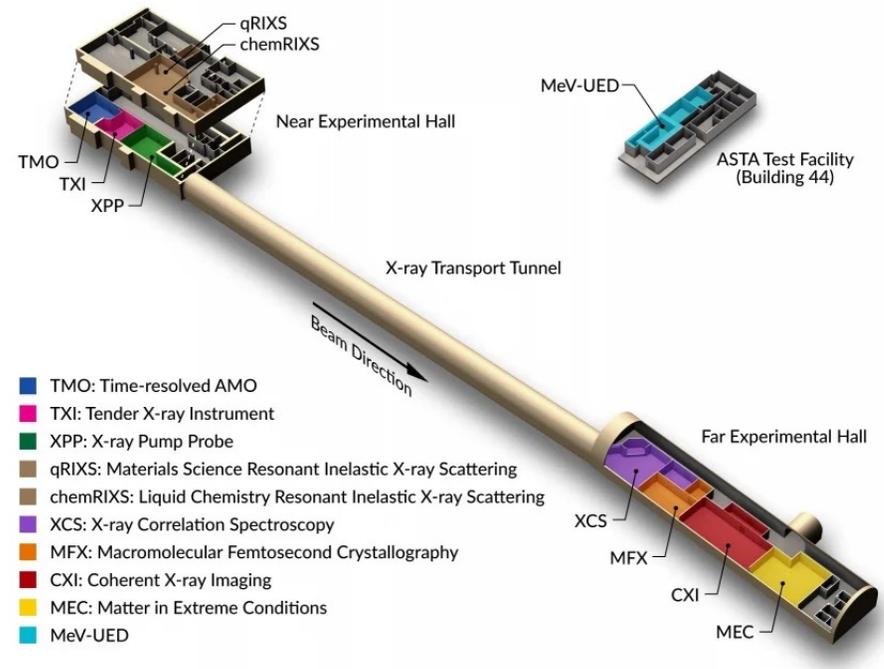
J. Yang et al., Science 368, 885 (2020)

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

# MeV-UED: Transition to a User Facility

- Leveraging the strengths of LCLS, MeV-UED became a user facility in 2019
- 4 user runs fielded; Run 5 currently underway
- Modeled operations to focus on science delivery on the big stage
- Large part of MeV-UED publications are classified as DOE defined high impact journals publications.

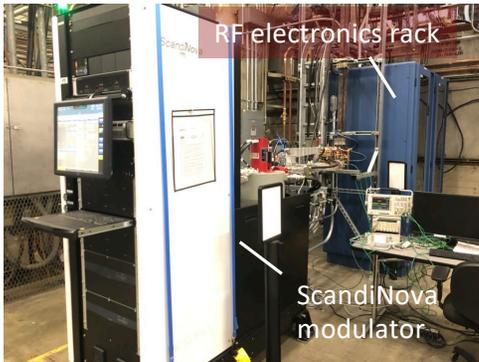
[https://oraweb.slac.stanford.edu/apex/slacprod/slacesaf.pubs\\_ued](https://oraweb.slac.stanford.edu/apex/slacprod/slacesaf.pubs_ued)



With the strong support of DOE-BES, the MeV-UED facility has produced high user science output since 2016, including 9 PhD theses and 37 pubs in high-impact journals (IF > 7).

# System Upgrades → Toward kHz Pump-Probe

## Upgrade to 1080 Hz Pump-Probe Acquisition Rate

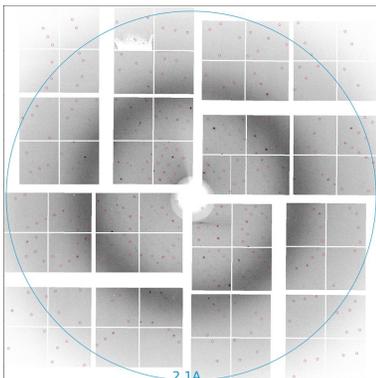


### ScandiNova RF Klystron (S-band 2.856 GHz @ 1080 pps)

- Commissioned at 360 Hz for user experiments in March 2024
- On offer with 1080 Hz rate for user experiments since January 2025
- Funded by DOE BES R&D under prior FWPs 100206, 100713

### Ti:Sapphire Coherent Legend Elite Duo + SPA

- Infrared laser upgrade completed in April 2021 (regen + single pass amp).
- Successfully operated through Run 5.

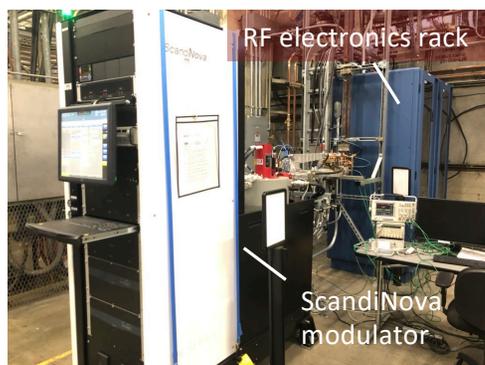


### ePix Direct Electron Detector

- Existing 360 Hz version now on offer in Run 5
- Upgraded version for 1080 Hz completed; will include e-beam thru-hole
- Built as an independent detector (commissioning planned in Run 6)
- Working with the LCLS detector group to balance commissioning with LCLS-II efforts

# MeV-UED 1080 Hz Operations: A New Regime of Sensitivity

- **Upgrade: New ScandiNova RF Klystron (S-band 2.856 GHz)**



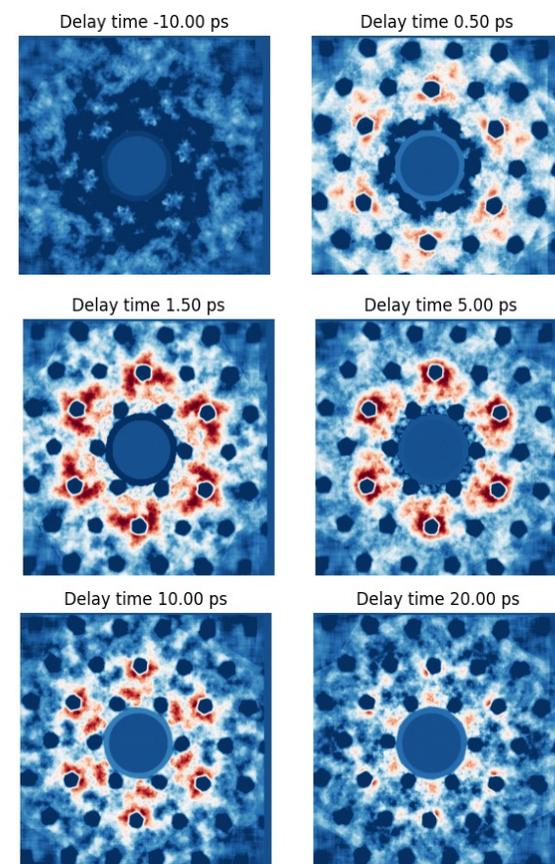
- Fully installed and in state of technical readiness; conditioned to full power on an RF load in 2022
- Commissioned for 360 Hz operation in April 2024
- Commissioned for 1080 Hz operation October 2024
- First User operation January 2025

## Science Enabled: Diffuse scattering in atomically thin materials

- First measurements by a user team comprising research groups of Archana Raja (LBNL), Fang Liu (Stanford) and Tony F. Heinz (Stanford/SLAC)
- Measured diffuse scattering intensity on the picosecond scale in MoS<sub>2</sub> monolayers, corresponding to k-resolved phonon emission during the heating of the sample
- Changes in diffuse scattering at <1% of changes in Bragg diffraction and enabled by the 3x increase in electron flux at 1080 Hz



SLAC

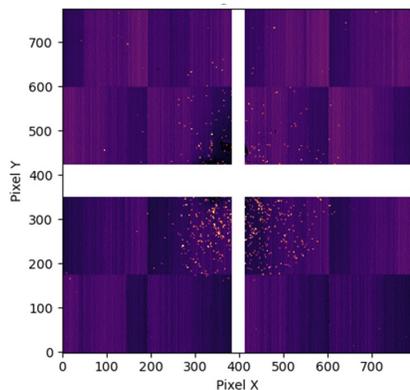
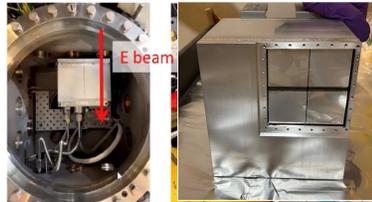
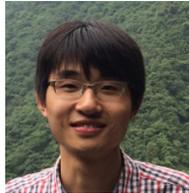


Time & k resolved phonon scattering in MoS<sub>2</sub> following laser excitation at 660 nm.

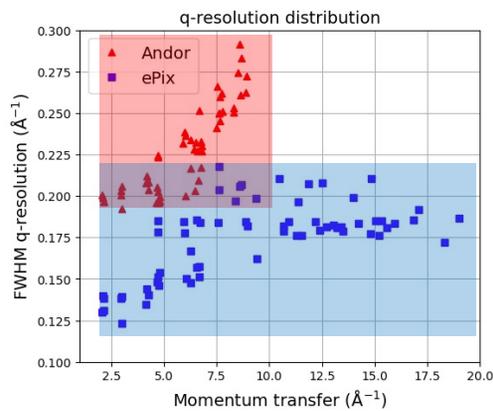
# Detector and Micro-Aperture Studies

## ePix10k Detector Deployment at UED Lead: Fuhao Ji

- Electron counting at 360 Hz
- Increased  $q$  range and resolution using hit-finding algorithm
- First user deployment in run 5 (January 2025)
- 1080 Hz version ready for commissioning in Run 6



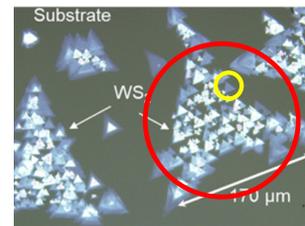
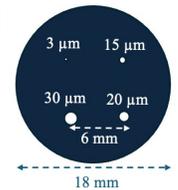
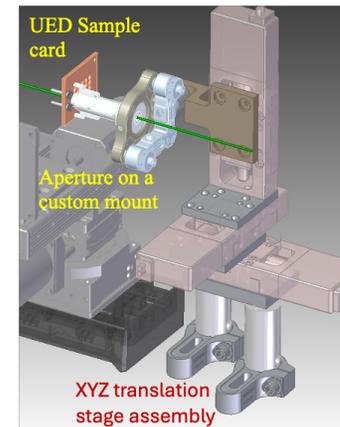
Single-shot readout from ePix



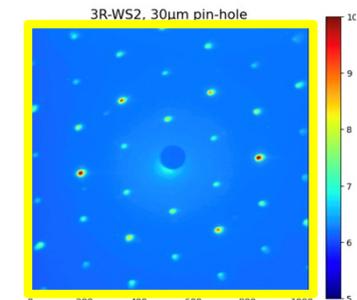
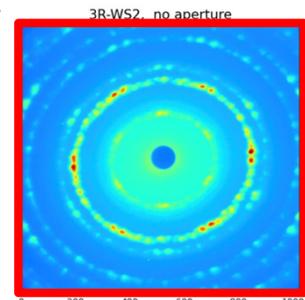
Comparison ePix vs current Andor CCD

## Selected Area Electron Diffraction (SAED) Lead: Sharon Philip

- Micro scale apertures allow in-homogenous samples to be studied



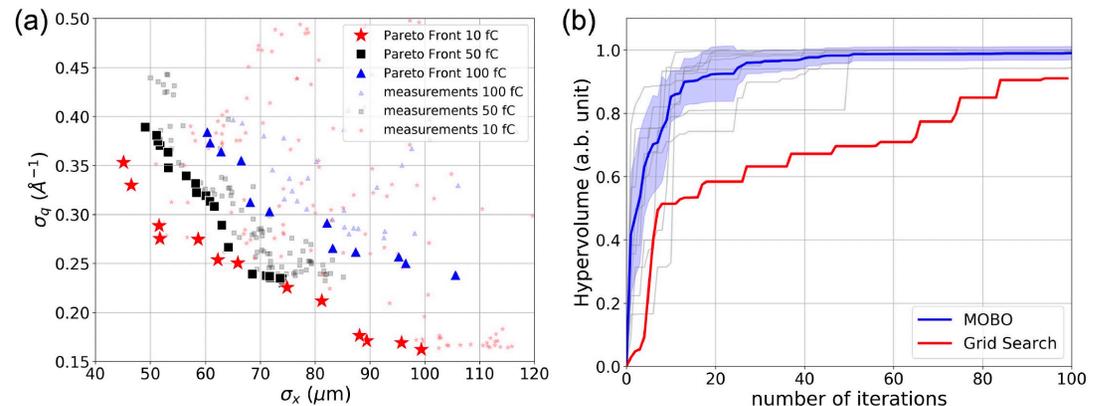
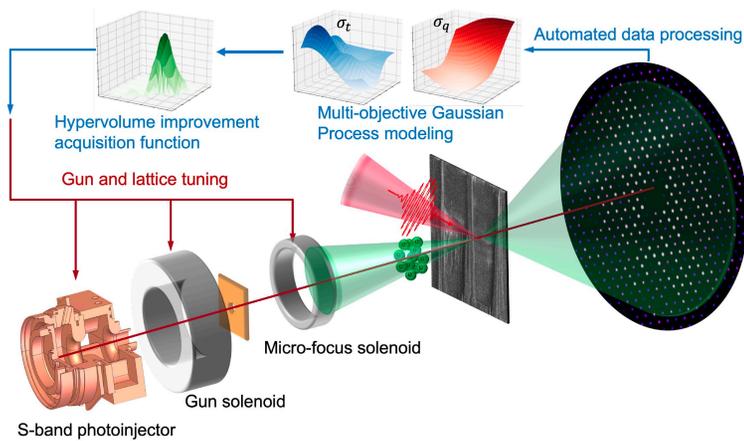
WS2 flake with relative probe regions illustrated.



Diffraction patterns from WS2 flake without aperture (left) and with 30 μm aperture inserted (right).

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

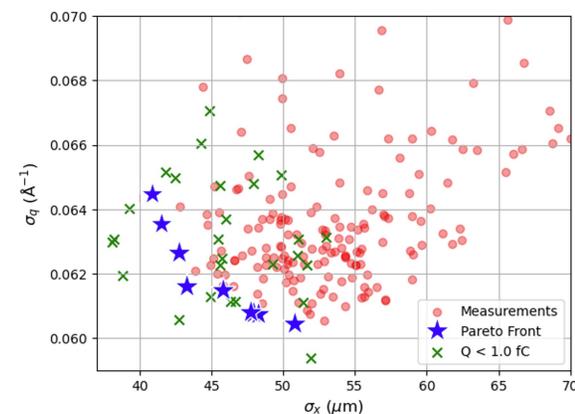
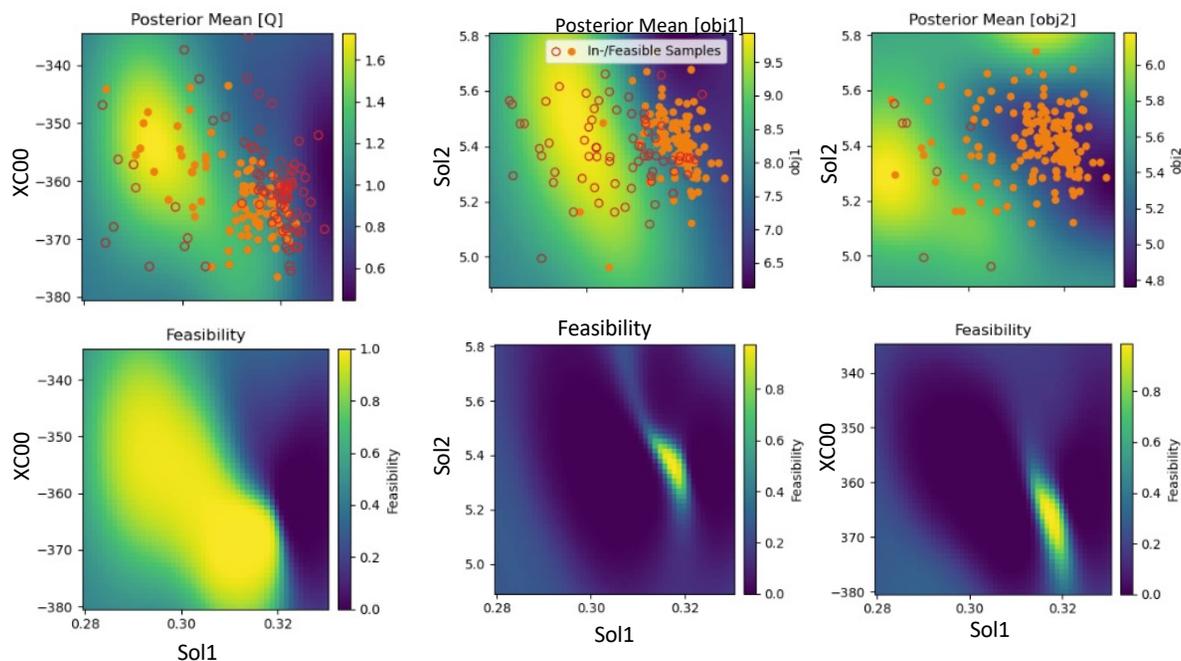
## Tuning Using Multi-Objective Bayesian Optimization (MOBO) Machine Learning



F. Ji, A. Edelen, R. Roussel, et al., *Nature Communications* **15**, 4726 (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  $\sim 1\text{h}$  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

# Two-stage constrained Bayesian active learning



Stage	Random	CBE	MOBO-post CBE
$\rho$ ( $Q \geq 1.0$ fC)	57.7%	63.3%	81.6%

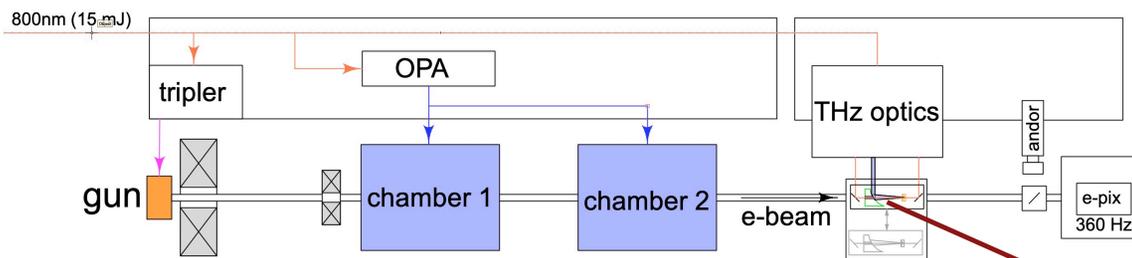
*Proc. NAPAC'25, MOP094, Sacramento, CA, USA, Aug. 2025*

- Bayesian exploration (CBE-MOBO) with minimum beam charge constraint automates steering through collimator to improve valid data efficiency.
- Requires minimal human inputs and can learn feasible region in multi-dimensional input space.
- Strategically proposes next observation point to improve data efficiency.

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

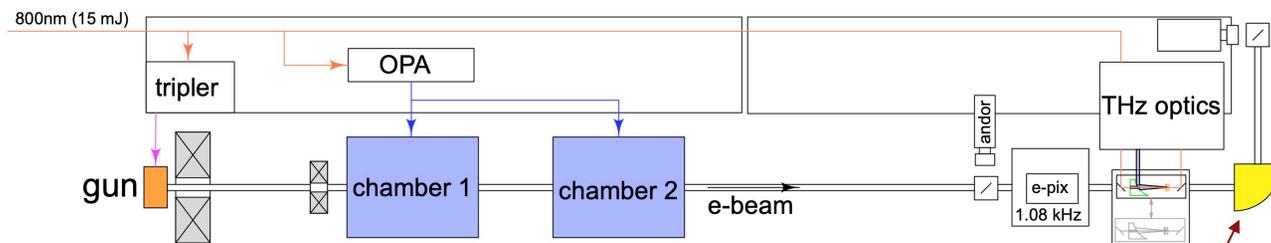
## Implementation of Dedicated THz Time-of-Arrival Diagnostic

### Phase I: Interruptive Diagnostic (installed Aug 2025)



THz chamber design

### Phase II: Shot-to-Shot Diagnostic

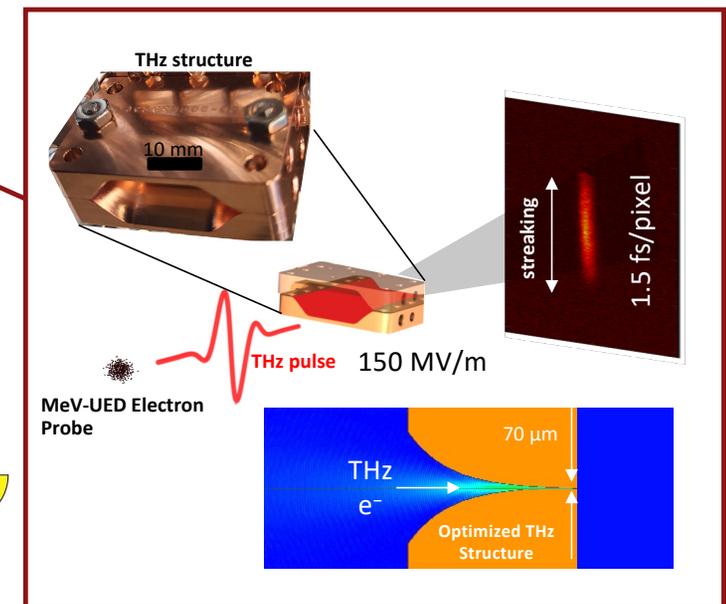


new ePix with thru-hole

spectrometer magnet

### Proof of Principle demonstrated in prior runs:

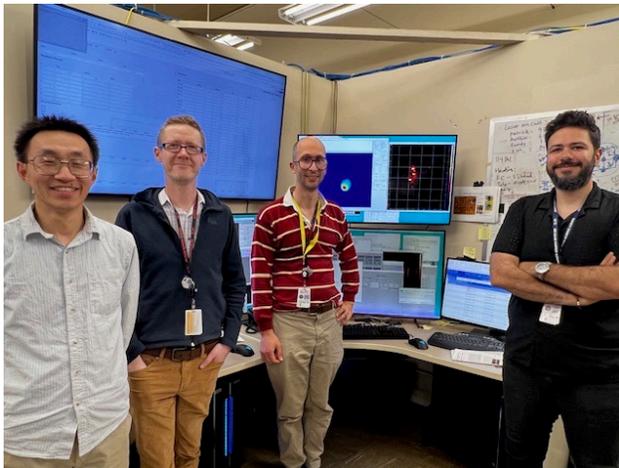
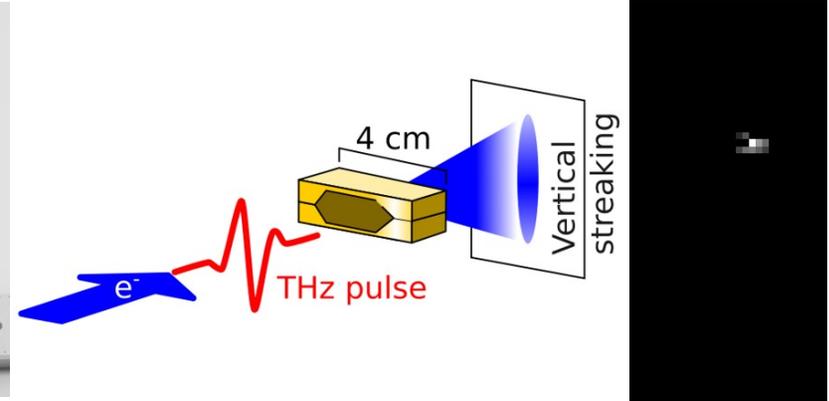
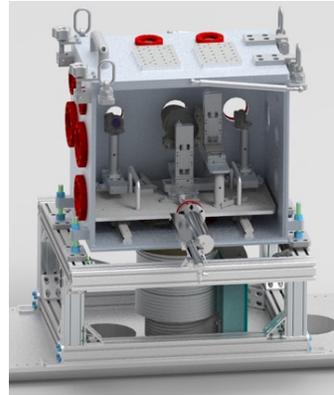
- Enables simultaneous fs arrival time and bunch length measurement
- Developed in collaboration with Nanni group
- Robust performance under insert/remove actuation



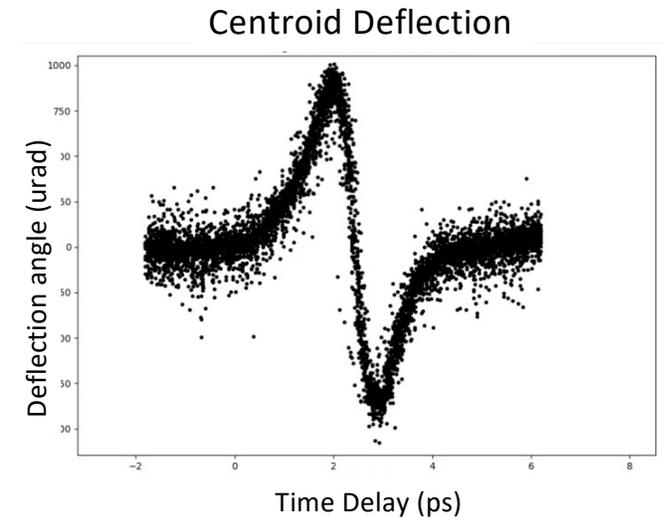
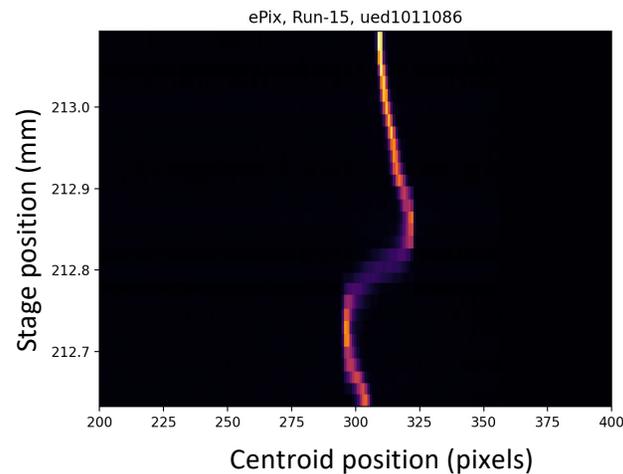
M. Othman, et al., Efficient THz Time Stamping of Ultrafast Electron Probes, 47<sup>th</sup> IRMMW-THz Conference (2022).

# Demonstration of New THz Chamber Diagnostic

- Time-tool chamber and dedicated THz optics fully installed (collaboration with Nanni group)
- Now a dedicated capability for future experiments
- First in-house R&D experiment with new setup Othman 1011086 June 4-6, Aug 19-20.
- Recently utilized in two R&D experiments 1011107 (Fuhao Ji), 1011057 (Xu)



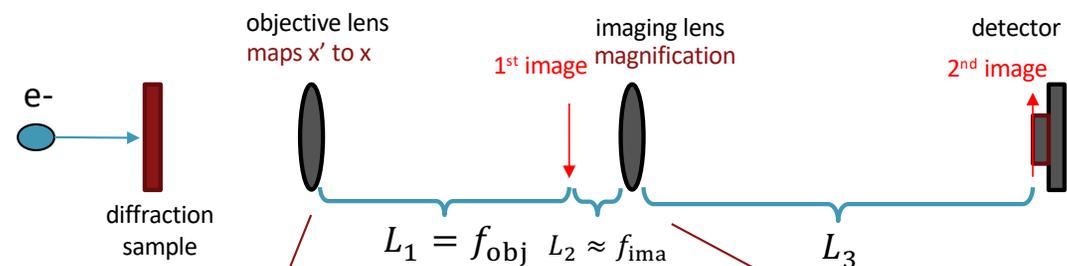
SLAC



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



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



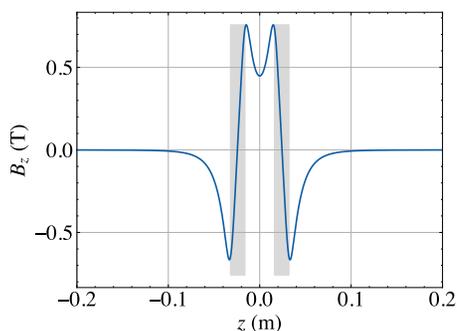
### Q-range magnification demonstrated (Nov 2023):

- 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

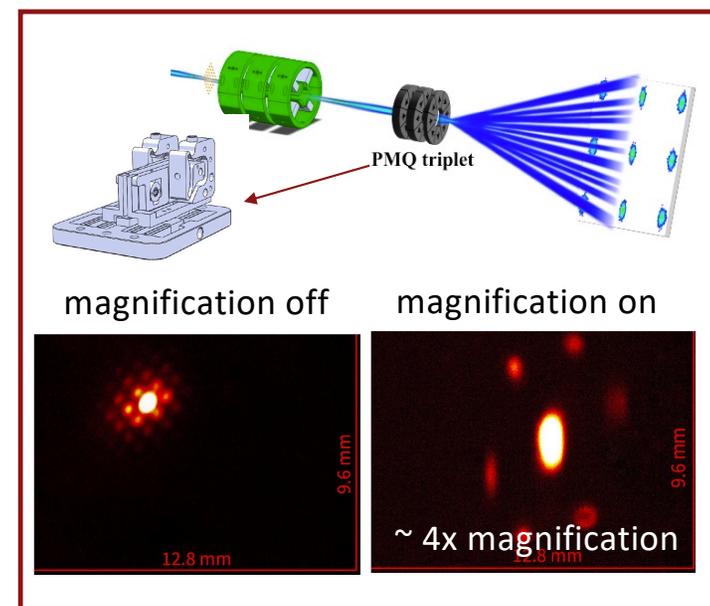
Axially magnetized PMS (in hand)



simulated field profile of imaging lens



Radially magnetized PMS (designed, delivered April 2024)

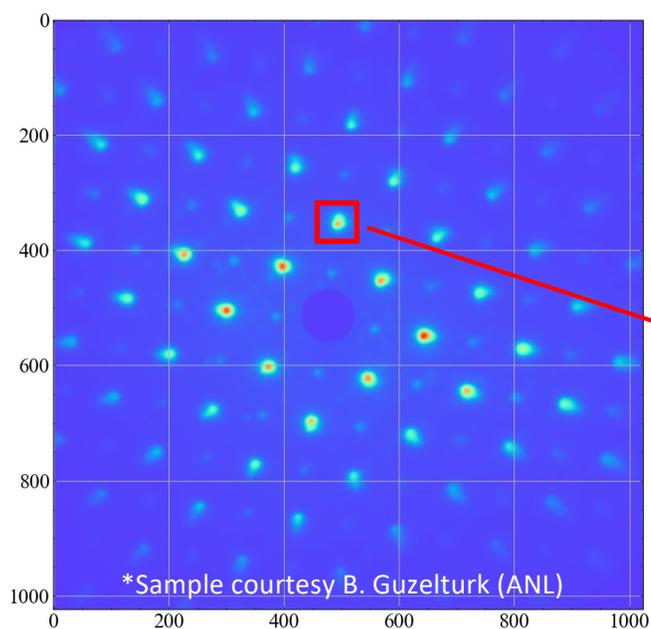


Q-magnification: P. Denham et al, *Struct. Dyn.* **11**, 024302 (2024)  
 Focusing study: T. Xu, et al., *Phys. Rev. Accel. Beams* **28**, 082401 (2025)

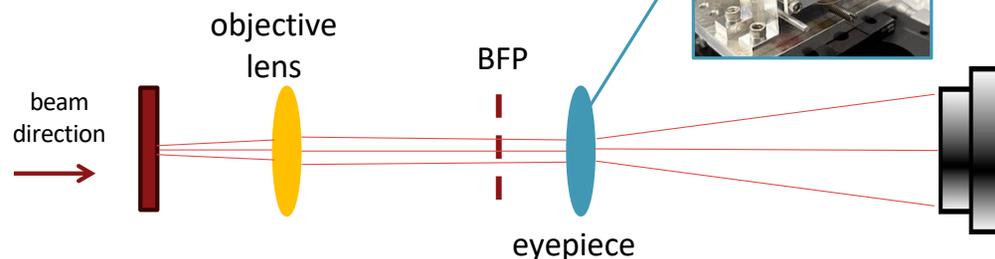
# Reciprocal space magnification



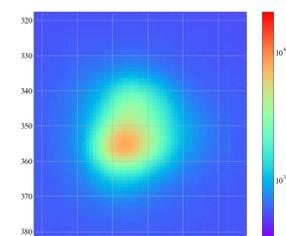
- Compact PMS magnet for reciprocal space magnification
- Experiment demonstrated **15x** magnification for PZO-STO bilayer sample.\*
- $\Delta s = 0.08 \text{ \AA}^{-1}$  resolution achieved with magnification.
- Results in preparation for submission to *Structure Dynamics*.
- Method to be used in upcoming R&D experiment 1011059 to observe q-resolution enhancement with cathode laser spot-size reduction



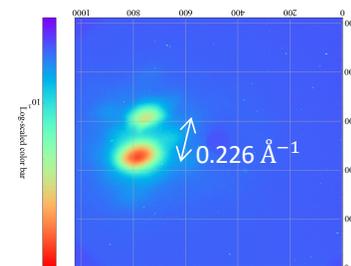
Diffraction with lenses



unmagnified



magnified



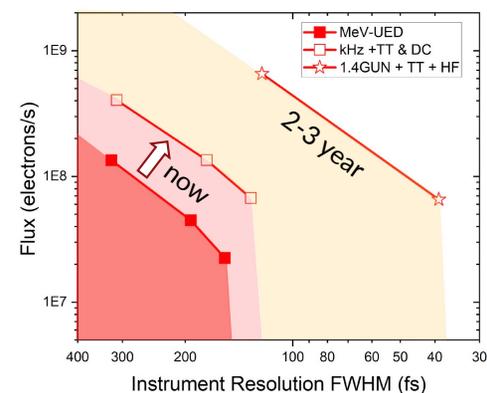
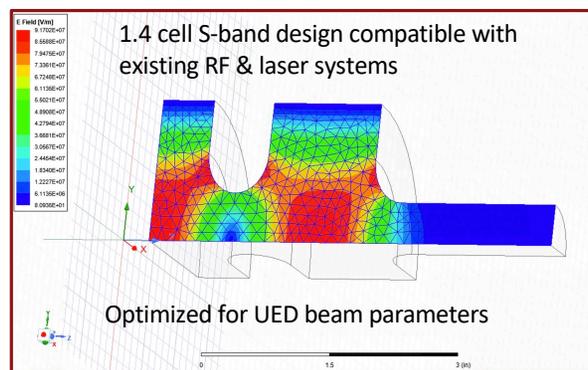
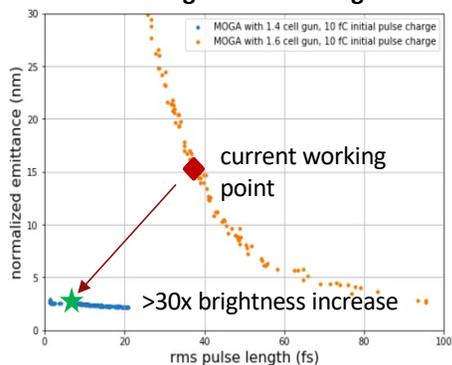
# ASTA / MeV-UED: Near-Term (1-2 Year) R&D

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 transverse emittance to reach  $\Delta q = 0.01 \text{ \AA}^{-1}$

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

Current ASTA gun vs new design

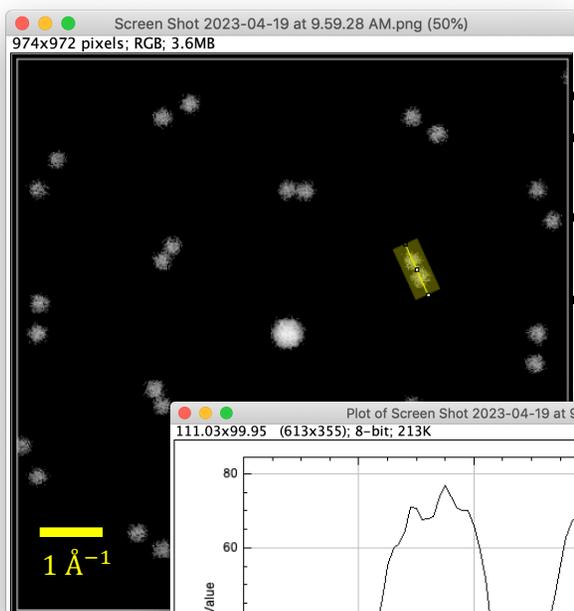


Mid-Term (1-2 Year) Goals / Milestones	Funding	Key Personnel/Responsibilities
Prototype Study of 1.4-cell S-band gun	LDRD	LDRD In Preparation with UED & LCLS Accel Physics
Dedicated online (shot-to-shot) THz time-tool	DOE-BES	UED AD & LCLS team with Laser & Nanni Groups
Upgrade of the ePix detector to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

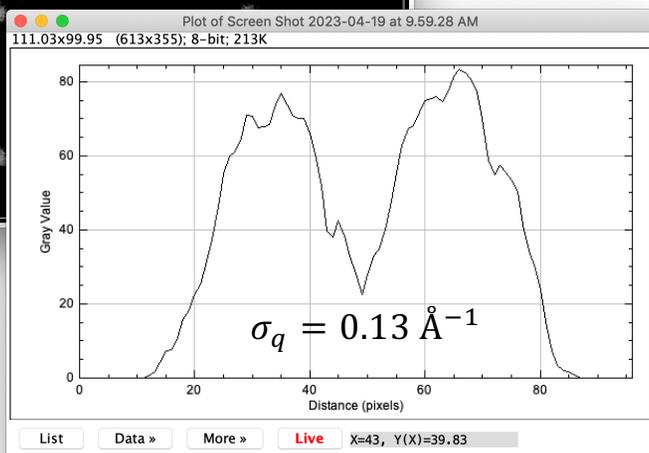
# ASTA / MeV-UED: Near-Term (1-2 Year) R&D

## Simulated q-resolution enhancement with high brightness gun design

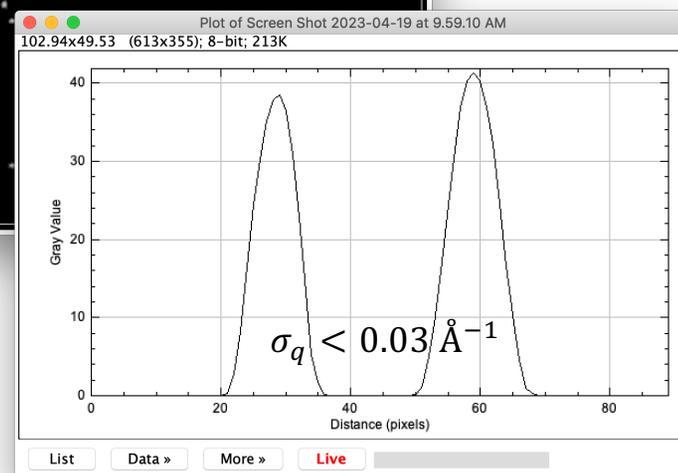
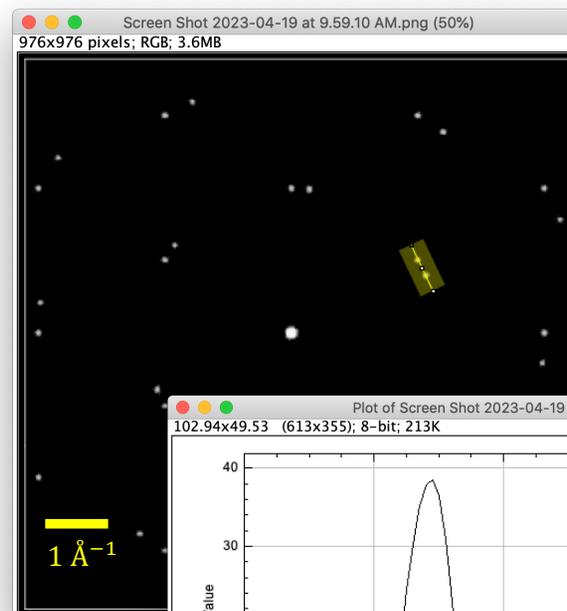
### Current ASTA 1.6 Cell Gun



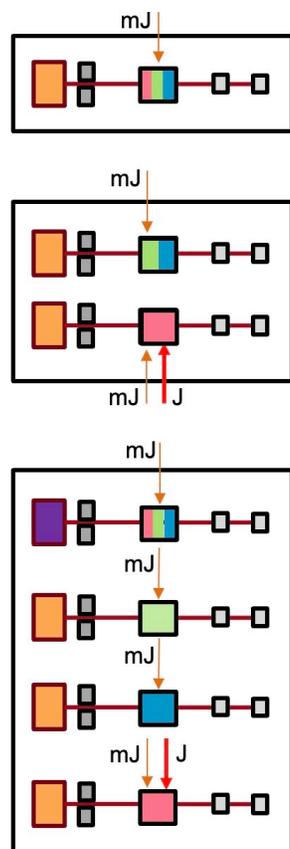
10 fC pulse charge (both cases)  
GPT simulation of 7 deg rotated WS<sub>2</sub> bilayer  
Detector resolution not included in simulation  
Results can be further improved with collimation



### Alternative 1.4 Cell Gun



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



Near Term

Long Term

## Single Multipurpose Beamline (current)

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 (1-3 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)

# Key Collaborations

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## **UED Machine Development:**

SLAC: Auralee Edelen, Ryan Roussel, Emilio Nanni, Mohamed Othman

Lawrence Berkeley National Lab (LNBL): Dan Wang, Wei Liu, Qing Ji

University of California Los Angeles (UCLA): Pietro Musumeci, Paul Denham, Victoria Guo

Science and Technology Facilities Council (STFC-UKRI): Julian McKenzie, Ben Hounsell, Tim Noakes

## **UED Instrument, Chemistry and Materials Science**

Aaron Lindenberg, Thomas Weinacht, Pedro Nunes, Martin Centurion, Siegfried Glenzer, Felix Allum, Barak Guzelturk

## **Broader Collaborations (beyond UED):**

National Tsing Hua University (Taiwan): Yenchieh Huang

Technion (Haifa, Israel): Levi Shachter, Ido Kaminer

Stanford University: Robert L. Byer, Olav Solgaard, Jelena Vuckovic, Shanhui Fan

Friedrik-Alexander-University (FAU, Erlangen): Peter Hommelhoff

Not an exhaustive list. Many important contributions to the success of the MeV-UED instrument with the strong support of DOE-BES. We welcome additional collaborations on all fronts!

# Summary & Conclusions

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- Critical needs identified from UED strategic planning efforts and user feedback:
  - Improved electron source performance to achieve  $\leq 0.01 \text{ \AA}^{-1}$  momentum resolution,  $\leq 50 \text{ fs}$  temporal resolution, and  $\geq 1e8 \text{ e-/sec}$  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.

# Acknowledgements

## The MeV-UED team



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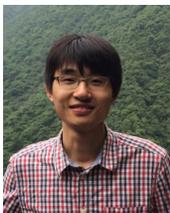
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Thank You!

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Questions?