Improving temporal and reciprocal space resolution of the SLAC MeV-UED instrument

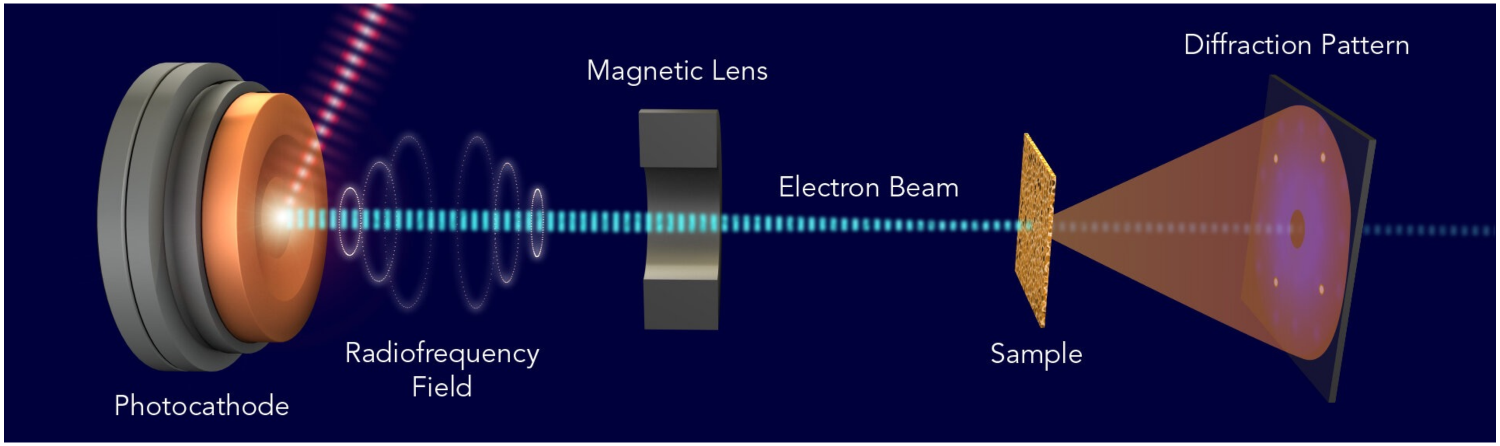
Tianzhe Xu

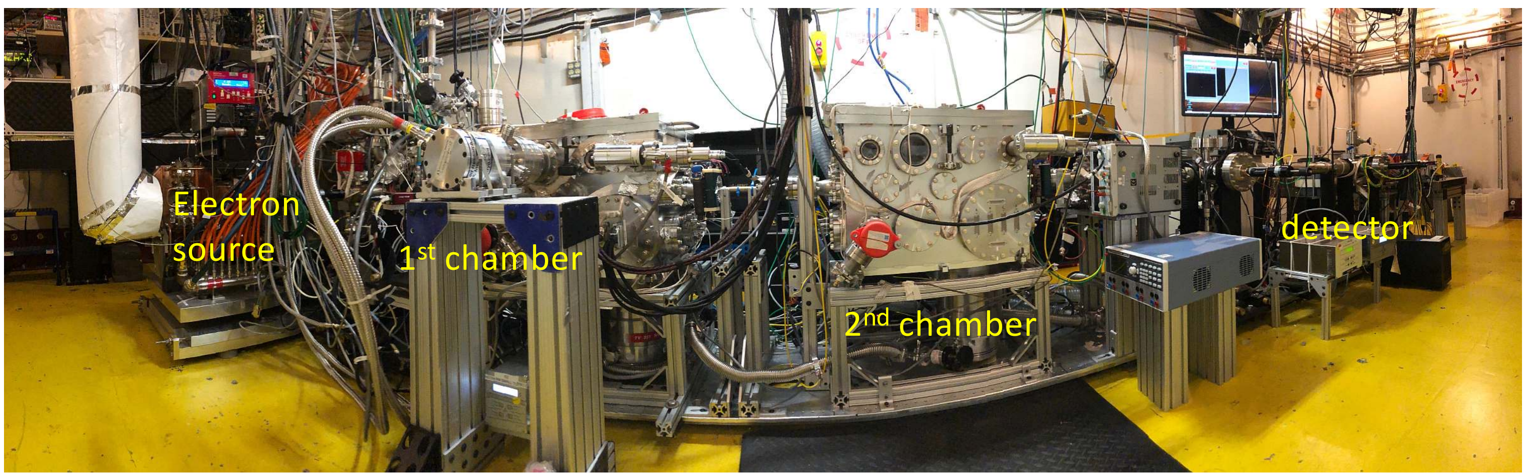
November 18, 2024

SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University | U.S. DEPARTMENT OF ENERGY

SLAC MeV-UED Instrument





Key capabilities

- 4.2 MeV electrons
- Transmission geometry (mono layers – 100's nm)
- 150 fs time resolution
- Multiple sample environments (solid/gas/liquid)
- Low damage (low current and small inelastic cross section)

Accelerator R&D for improving UED resolution

Temporal resolution

$$\tau_{\text{res}} = \sqrt{\tau_{\text{pump}}^2 + \tau_{\text{probe}}^2 + \tau_{\text{VM}}^2 + \tau_{\text{jitter}}^2}$$

Spatial and reciprocal space resolution

$$\Delta s = \frac{2\pi}{\lambda_e} \frac{\epsilon_n}{\sigma_x}$$

ϵ_n: beam emittance
σ_x: beam size

Beam and machine parameters

- Electron bunch duration
- Arrival time jitter, machine stability

- Emittance
- Detector resolution

R&D

- <u>Bunch compression</u>
  - RF based (1.4 cell gun or buncher)
  - Laser or THz based*
  - Magnetic compressor
- <u>Timing tool</u>

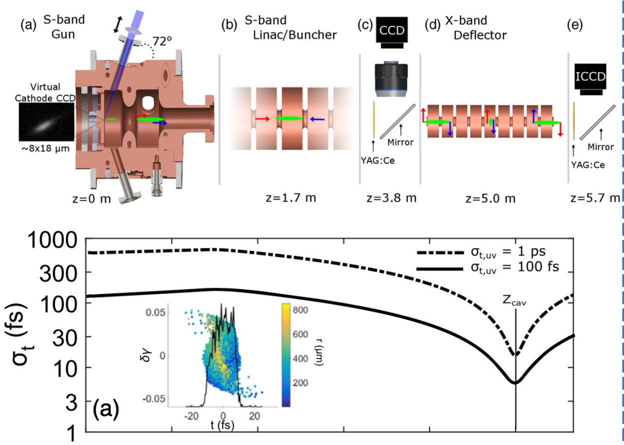
- <u>Reduce emittance</u>
  - Reduce cathode laser size
  - Reduce MTE*
  - Collimation
- <u>Angular magnification</u>

* Will NOT be discussed in detail in this talk

Temporal resolution

Bunch compression

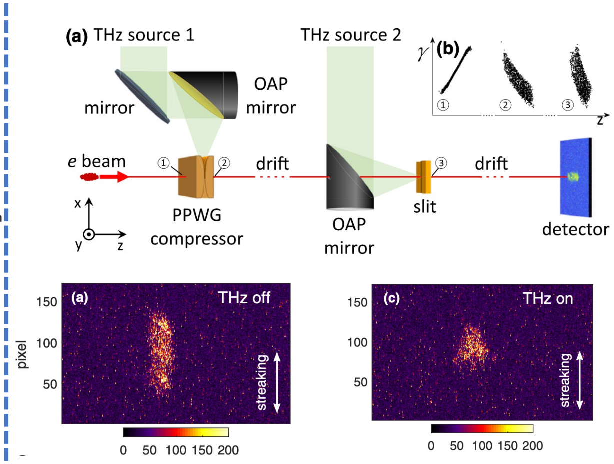
RF compression



J. Maxson et al, Phys. Rev. Lett. 118, 154802 (2017)

- Compression with linac/buncher, or a 1.4 cell gun
- Introduce additional jitter due to buncher phase variation

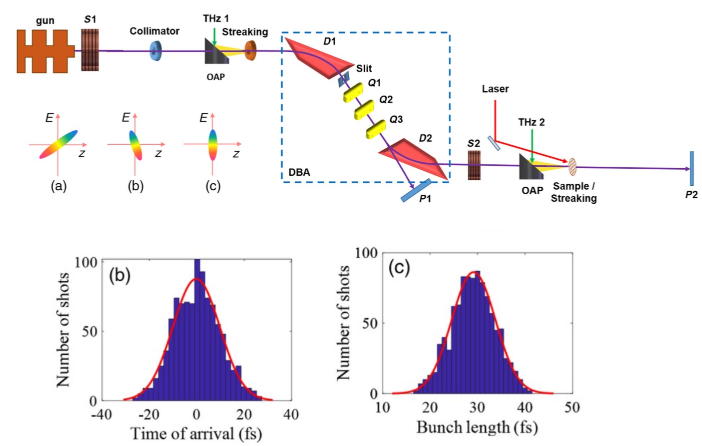
THz compression



E. Snively et al, Phys. Rev. Lett. 124, 054801 (2020)

- Phase-synchronous compression
- Experimental setup is nontrivial

Magnetic compression



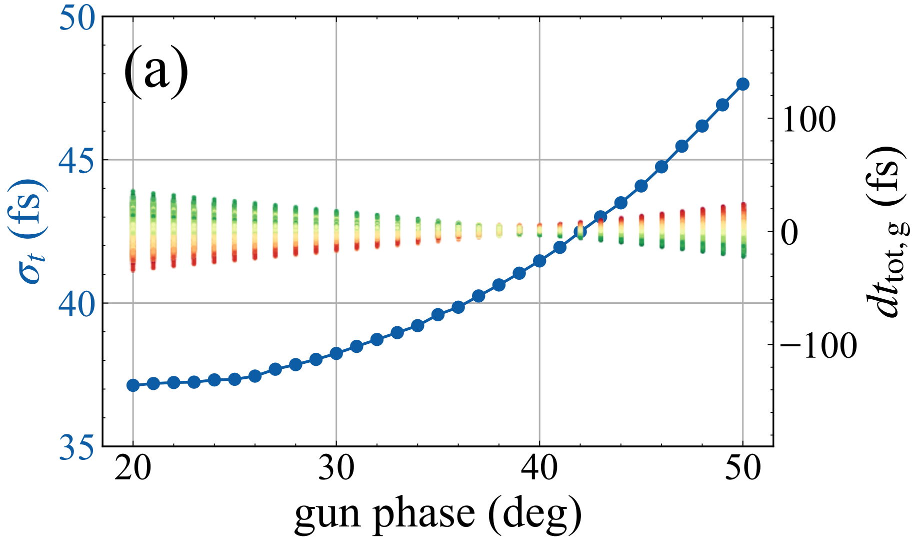
F. Qi et al, Phys. Rev. Lett. 124, 134803 (2020)

- Jitter-suppressed bunch compression
- Limited tunability.
- Need space.

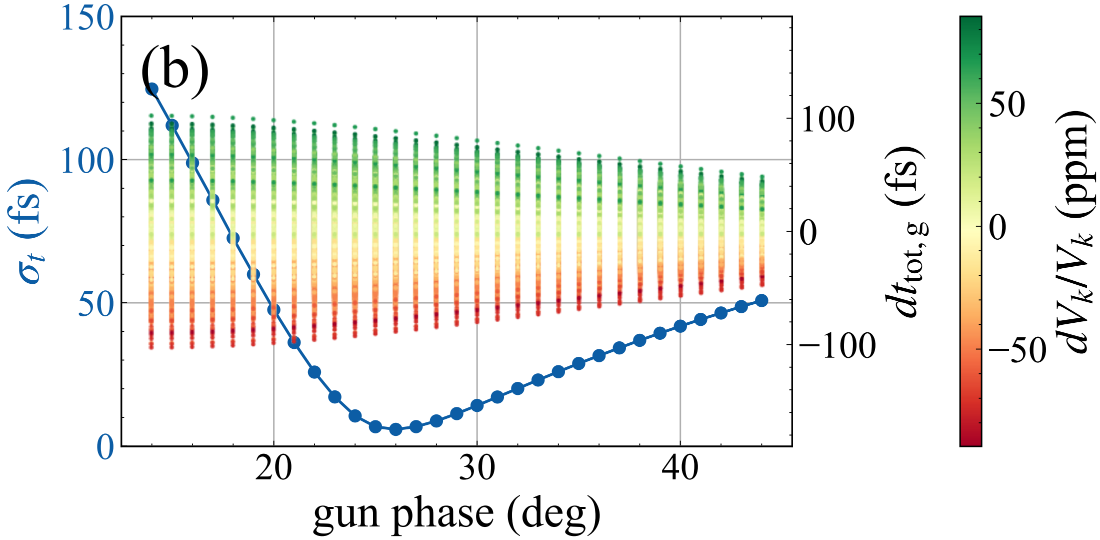
Performance of the 1.6 cell and 1.4 cell gun

- The current 1.6 cell gun produce smaller jitter, but is limited in producing shorter electron bunch.
- The 1.4 cell gun generates 5 fs electron bunch but suffers from larger jitter.

1.6 cell gun



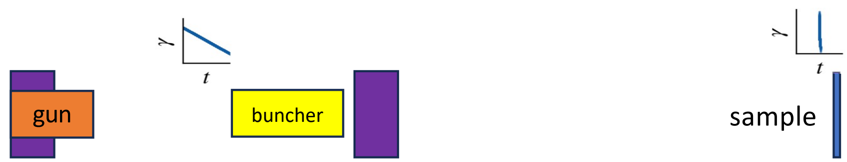
1.4 cell gun



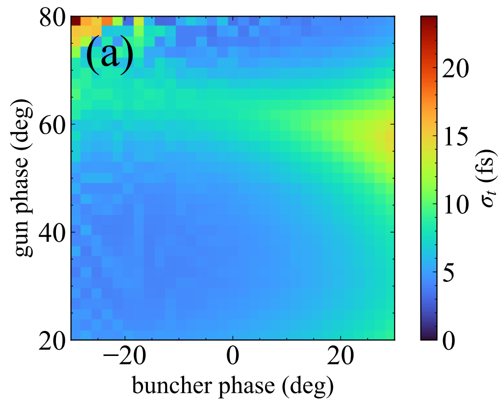
T. Xu et al, arXiv:2408.00937

RF compression with 1.6 cell gun + buncher

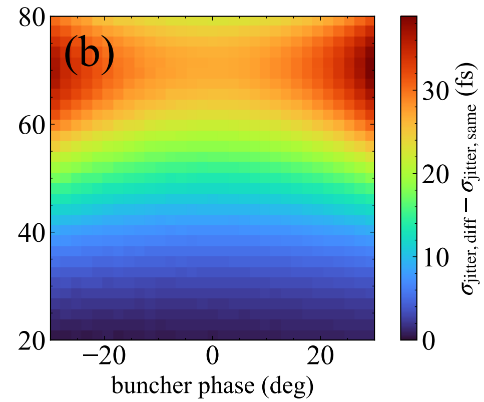
- Current 1.6 cell gun (90MV/m) + a 5 cell S band buncher with 25MV/m.
- Produce similar bunch duration (~5fs) as the 1.4 cell gun and similar timing jitter (around 18 fs rms).
- When gun and buncher are powered by same klystron, the reduction in timing jitter is only prominent at higher gun phases.



Bunch duration for different phases



Difference in timing jitter for the same and different klystron configuration

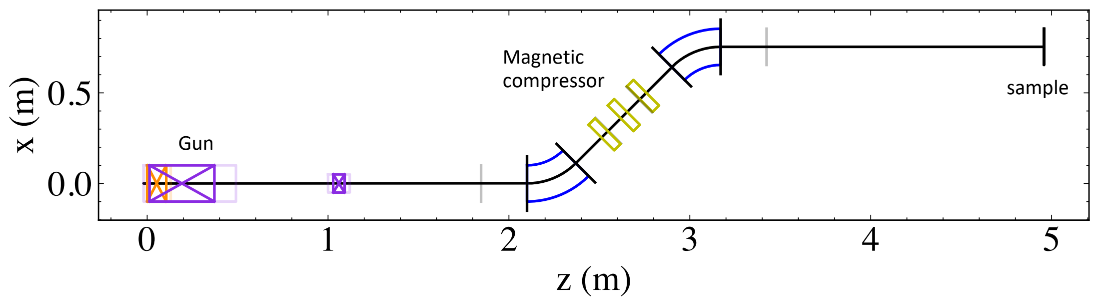


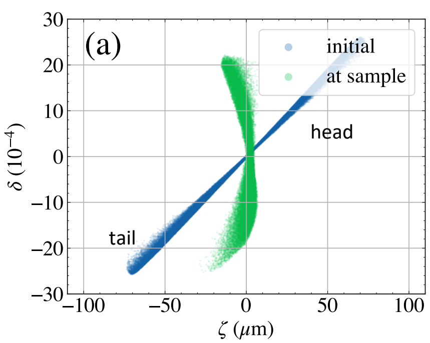
SLAC

Magnetic compressor

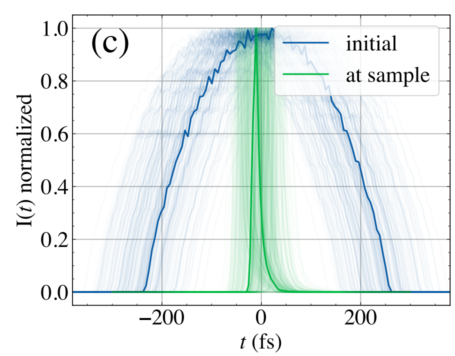
- Simultaneous reduction of bunch duration and jitter. Can be designed to fully eliminate jitter (need to consider gun design).
- Limited tunability in operation.
- Not compatible with current beamline/bunker. Need more space.

Layout of the MeV-UED beamline with a dogleg compressor





11.6 fs RMS when compressed



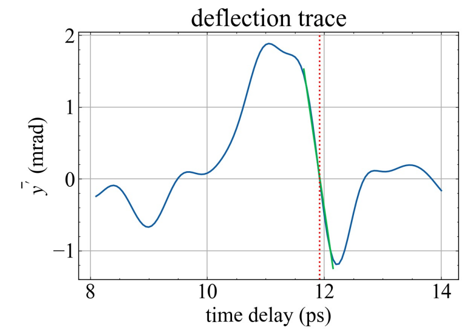
8 fs jitter at sample

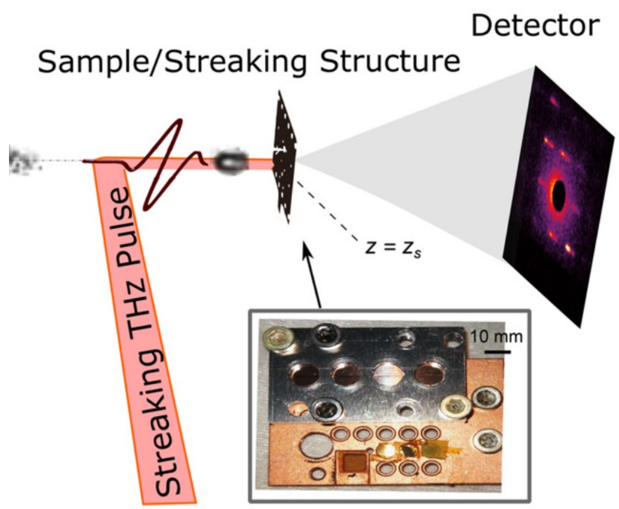
T. Xu et al, arXiv:2408.00936

SLAC

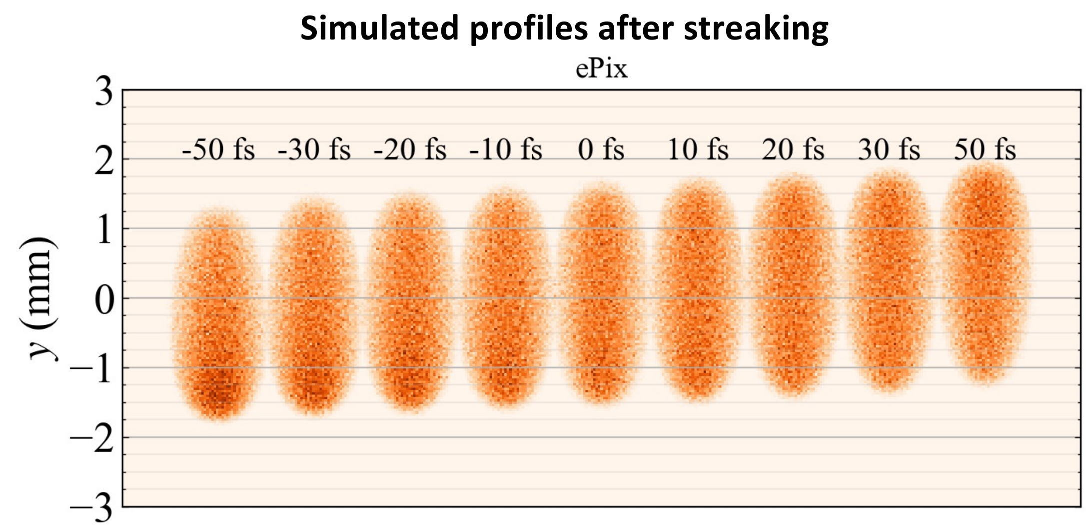
Timing tool

- THz based streaking structure to <u>measure and fully correct timing jitter.</u>
- <u>Non-evasive diagnostics</u> is possible when using a detector with thru-hole and placing the streaking structure downstream.
- Dedicated timing tool chamber to be installed.





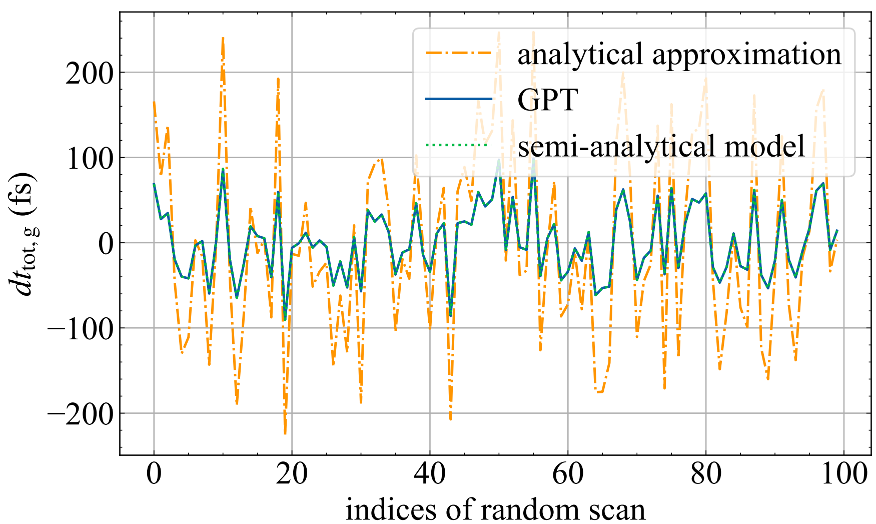
M. Othman et al, Struct. Dyn. 11, 024311 (2024)



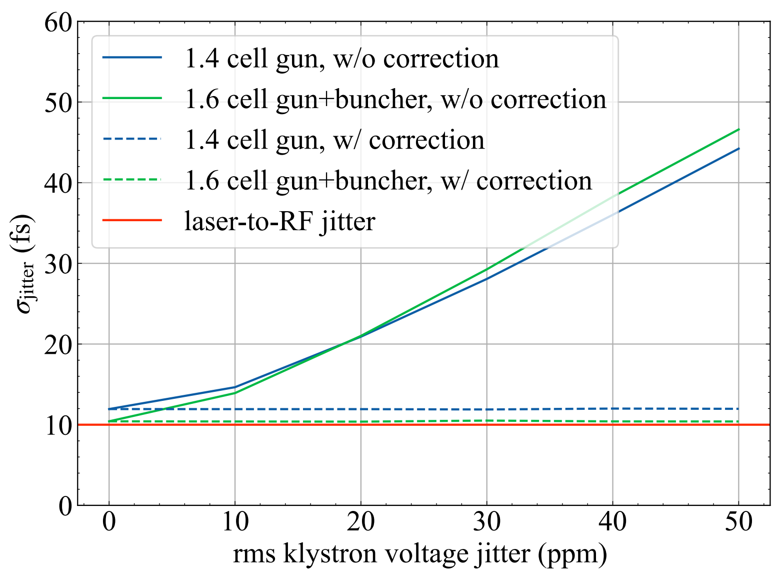
Online jitter correction from RF measurements

- Calculate arrival time jitter from shot-to-shot RF amplitude and phase measurements.
- Semi-analytical model based on single particle dynamics and differentiable solver.
- Can predict timing jitter induced by RF fluctuation. Laser-to-RF synchronization error can also be included if measurements available.

Benchmark of timing jitter obtained from different methods (simulation)



Comparison of jitter with and without correction



Summary on compression and temporal resolution

Duration, jitter, and temporal resolution are **FWHM** values

where we are right now

		τ_{ebeam}(fs)	τ_{jitter}(fs)	τ_{res}(fs) with 22 fs laser	τ_{res}(fs) with 60 fs laser	Charge (fC)	$\varepsilon_{nx}, \varepsilon_{ny}$ (nm)
RF	1.6 cell gun	118	14	120.8	133	10	20.6, 20.6
RF	1.4 cell gun	14.6	47.1	54	77.7	10	2.5, 2.5
RF	1.6 cell gun + RF buncher	7.8	42.4	48.4	73.9	10	21.7, 21.7
RF	1.4 cell gun + RF buncher	1.3	42.4	47.8	73.5	10	3.5, 3.5
magnetic	1.6 cell gun + dogleg	9	19	30	64	100	29, 27
magnetic	1.6 cell gun + dogleg (collimated)	11	19	31	64	10	6.1, 9.4

- RF-based compression
  - Capable of producing sub-10 fs electron bunch but also prone to jitter. Timing tool needed to improve overall temporal resolution.
  - Most realistic option for current bunker.
- Magnetic compressor
  - Suitable for gas phase UED with less stringent requirements on emittance.
  - Passive configuration compatible with MHz rep rate for future sources.
- At some point we'll need shorter pump laser (current 60 fs FWHM/26 fs RMS).

Reciprocal space resolution

Reciprocal space resolution

- <u>Improving emittance</u> is critical for simultaneously achieving smaller spatial resolution and reciprocal space resolution

at sample:

$$\Delta s = \frac{2\pi}{\lambda_e}\frac{\epsilon_n}{\sigma_x}$$

ϵ_n: beam emittance; σ_x: beam size

when detector PSF is small

$\approx$

measured at detector:

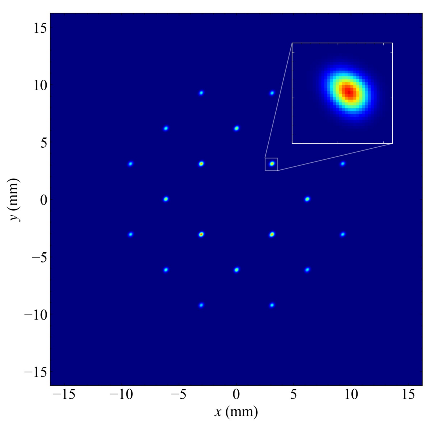
$$\Delta s = \frac{2\pi\beta\gamma}{\lambda_e}\frac{\sigma_x}{L}$$

σ_x: beam size at detector; L: drift length

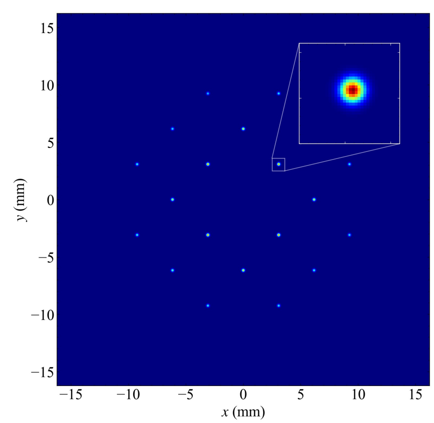
- At low emittance, we will be limited by <u>detector resolution.</u>

Simulated Si diffraction pattern on Andor detector for a beam with difference emittances (solenoid tuned to minimize spot size on detector)

ε_n~14 nm



ε_n~1.4 nm

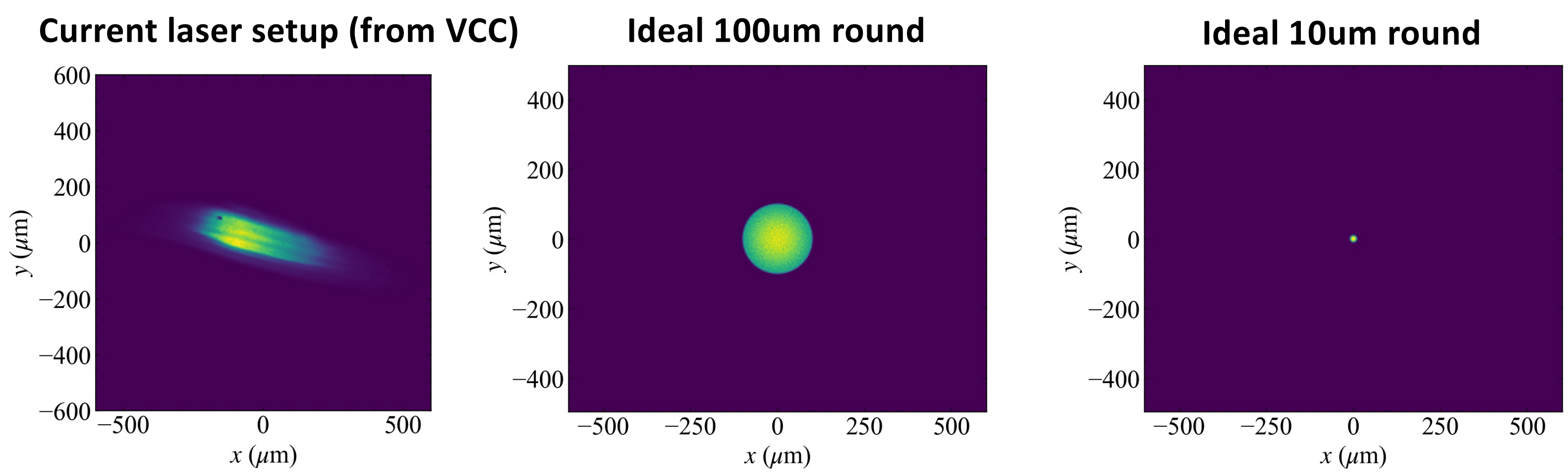


Why better emittance but similar q resolution?

The actual spot size on detector for the 1.4 nm case is smaller (10 μm), but detector PSF is 85 μm

Improving emittance with smaller cathode laser

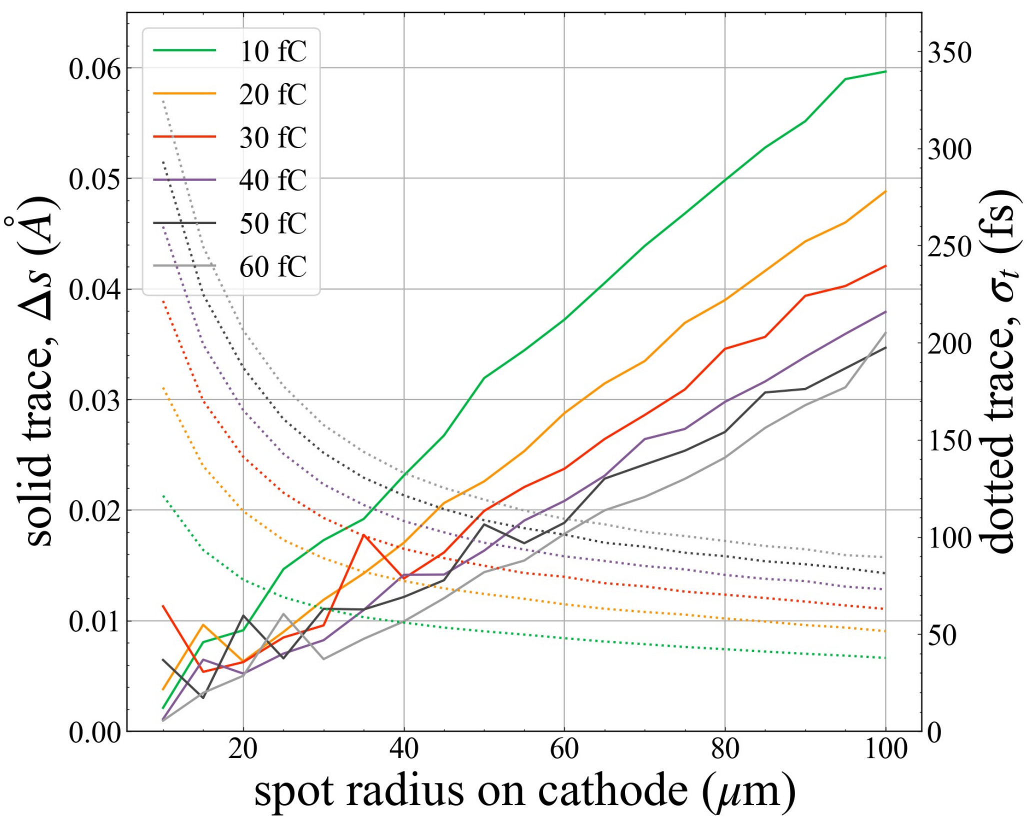
- Current laser setup use a pulse front tilt to minimize beam duration. Good for temporal resolution but also give larger emittance.



	RMS bunch duration (fs)	Emittance (nm)	Charge after collimator (fC)
Current setup	33	14	1.8
100 um spot radius	40	13	3
10 um spot radius	128	1.6	1

Effect of laser spot size and initial charge on resolution

With 200um collimator



There's a trade-off between temporal and reciprocal space resolution when we vary cathode laser sizes

SLAC

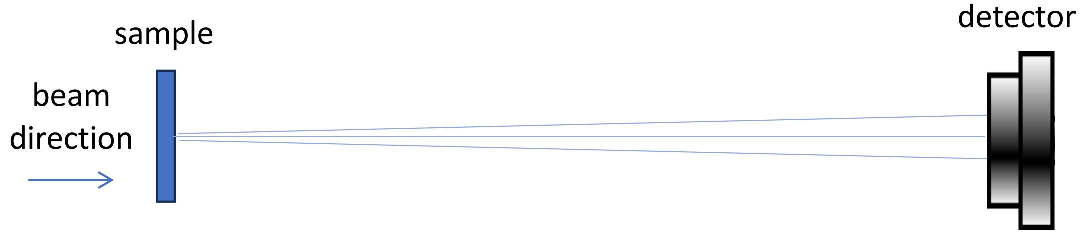
Here reciprocal space resolution is calculated with $\Delta s = \frac{2\pi}{\lambda_e}\frac{\varepsilon_n}{\sigma_x}$, assuming not limited by detector resolution (0.06 Å^{-1})

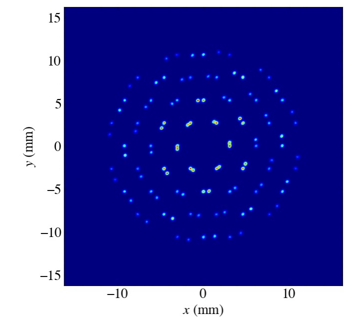
Overcoming detector limitation with magnetic lens

- Post-sample optics increase camera length. Improves reciprocal space resolution when limited by detector.
- Magnetic lens requirements (objective + eyepiece/projector)
  - Objective lens: there's an optimal focal length depending on total distance
  - Eyepiece: short focal length for high magnification

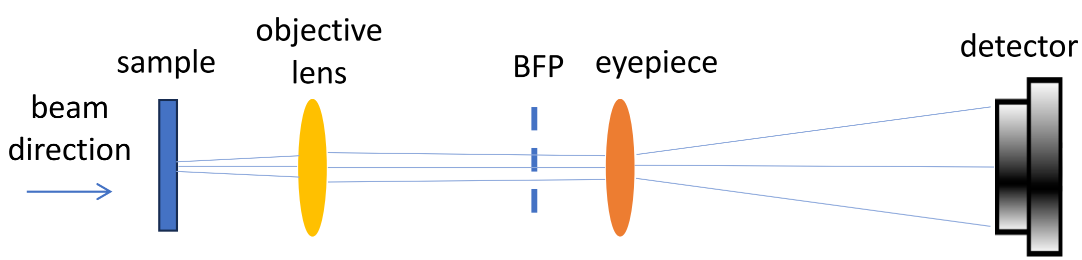
diffraction pattern

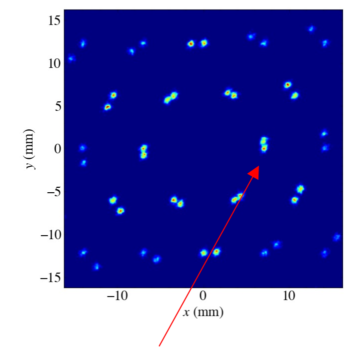
Without angular magnification

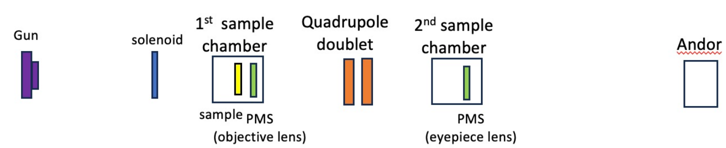




With angular magnification







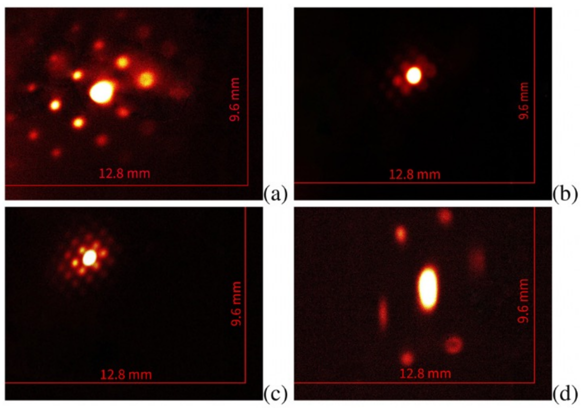
Magnification needed to resolve features in reciprocal space

SLAC

Strong focusing lens development (PMQ and PMS)

- Permanent Magnetic Quadrupoles (PMQ)
  - Existing setup from UCLA. Very short focal length (1.3cm) at high gradient.
  - Need a triplet for stigmatic imaging
- Permanent Magnetic Solenoids (PMS)
  - Short focal length (a few cms) with stigmatic focusing

PMQ

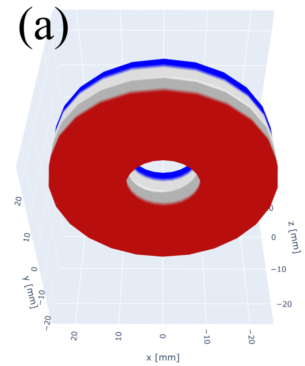


Proof-of-principle experiment demonstrated at UCLA for angular magnification

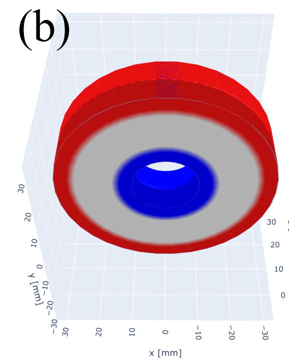
Denham et al, Struct. Dyn. 11, 024302 (2024)

PMS

Axially magnetized PMS

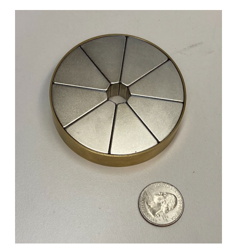


Radially magnetized PMS



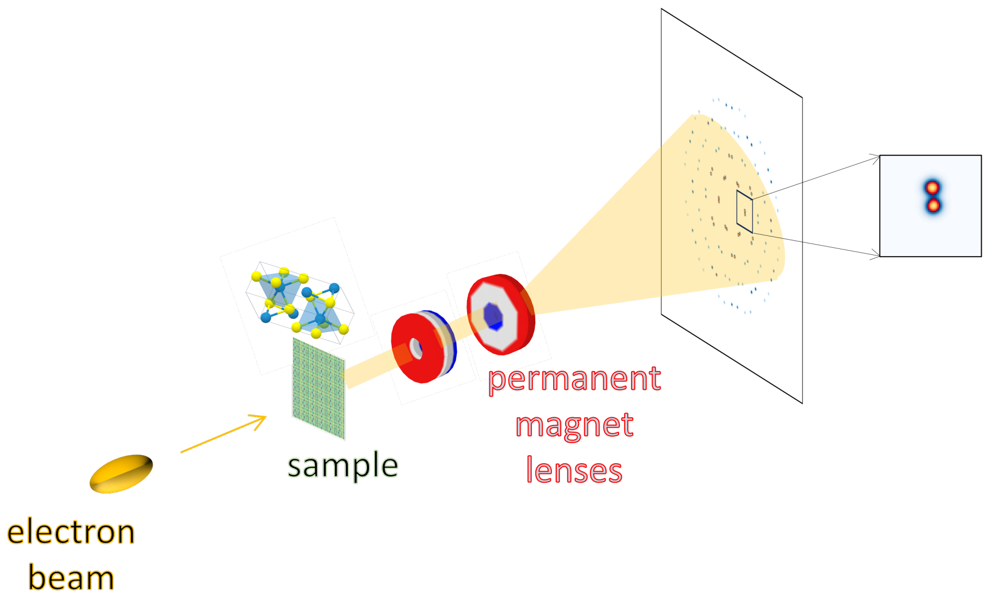
An off-the-shelf axial PMS

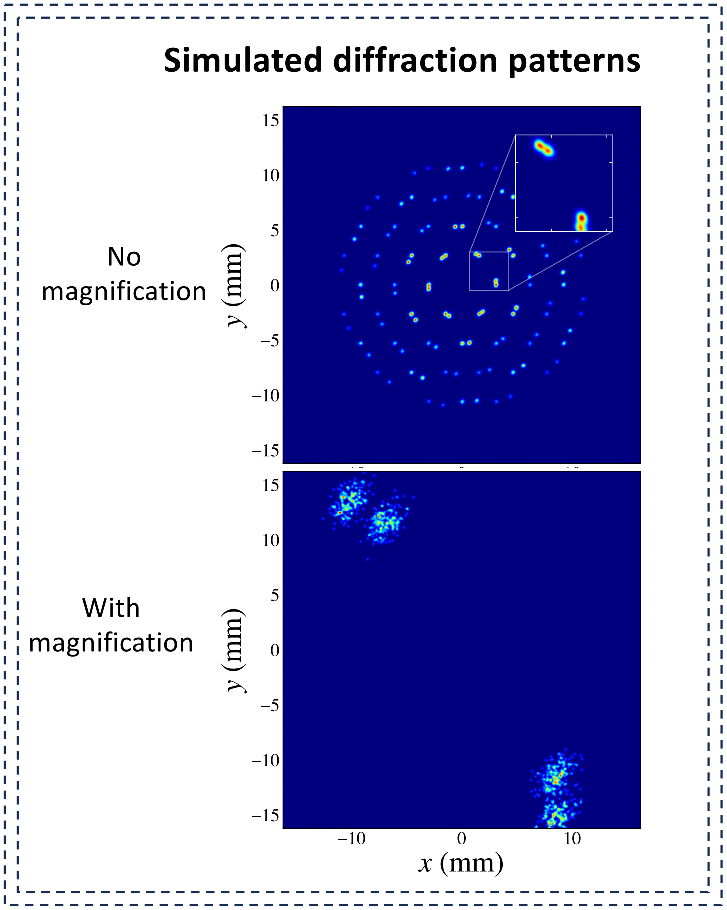
Custom-built radial PMS



Angular magnification

- A weak PMS (objective lens) combined with a strong PMS (eyepiece) for angular magnification.
- Magnification of 10 expected compared with drift.





Conclusions

- Various schemes are being developed to improve the resolution of the SLAC MeV-UED instrument, with focus on practical implementation for current beamline.
- A few important aspects not mentioned: electron flux, machine stability, ease of operation.
- Temporal resolution
  - **New 1.4 cell gun for RF-based compression.** Sub-10 fs electron bunch with 2nm emittance.
  - **Timing tool** for jitter correction and further improvement of temporal resolution
- Reciprocal space resolution
  - **Reducing cathode laser spot size** is a straightforward route to improve intrinsic emittance
  - At low emittance, **angular magnification** is need to overcome detector resolution.

Thanks for your attention!