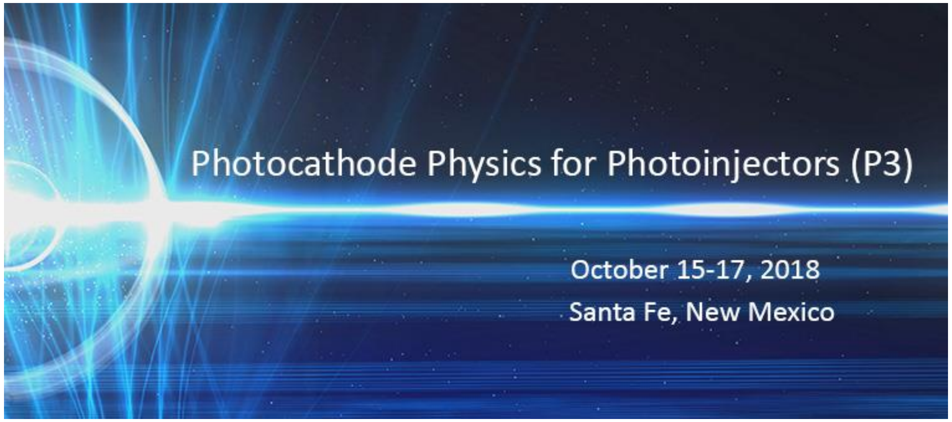


Photocathode requirements and challenges for ultrafast electron scattering

Renkai Li

Oct 15, 2018, Santa Fe, NM

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Outline

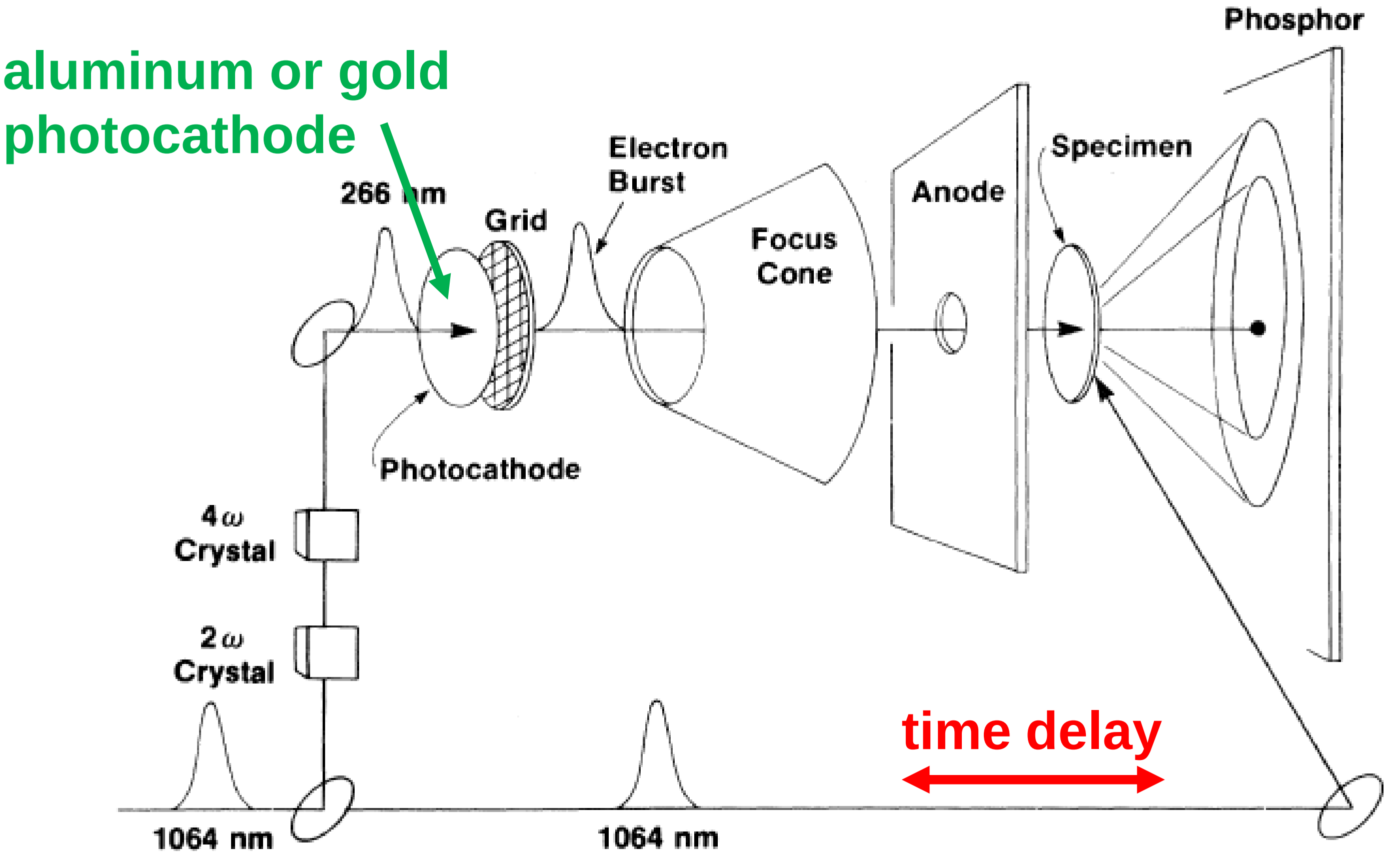
SLAC

- Introduction and status of UED
- Photocathode requirements and challenges for UES
  - UED: single-shot, high rep-rate
  - UEM: extremely low emittance in SRF
  - fs EELS: pushing the longitudinal emittance
- Summary and outlook

UED – ultrafast electron diffraction

G. Mourou and S. Williamson, APL 41, 44 (1982)

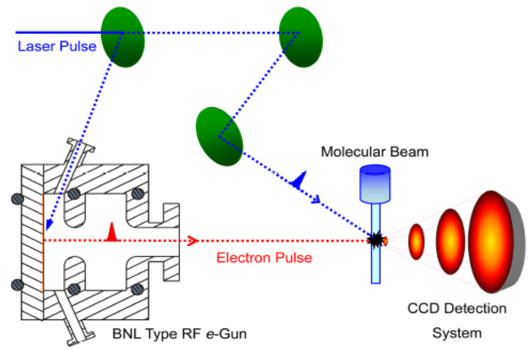
S. Williamson, G. Mourou and J. C. M. Li, PRL 52, 2364 (1984)



Science outcome: See e.g. M. Chergui and A. H. Zewail, *ChemPhysChem* **10**, 28 (2009); R. J D. Miller, *Science.* **343**, 1108 (2014) and etc.

Benefits with MeV electrons

- Tremendous advances with keV UEDs in the past decades
- ***Significant Benefits* with MeV *e-***



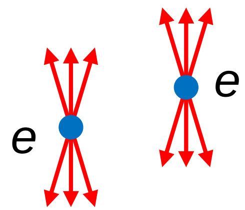
Active R&D field around the world!

X. J. Wang, Z. Wu, H. Ihee, PAC'03, 420-422 (2003).

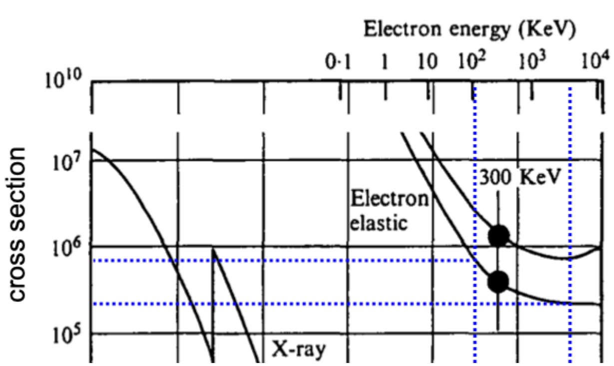
P. Musumeci and R. K. Li, ICFA BD Newsletter No. 59 (2012).

Space charge effects $\frac{1}{\beta^2\gamma^3}$

- ✓ Shorter bunch
- ✓ Higher charge



Penetration/multiple scattering

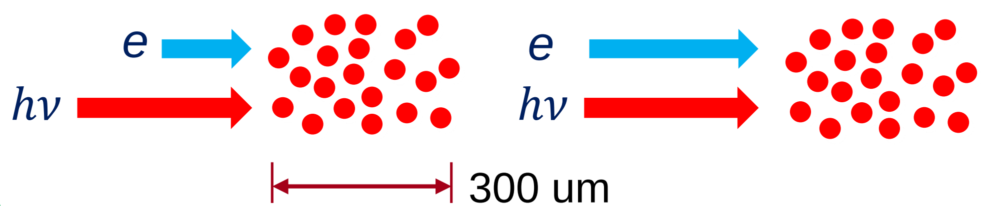


R. Henderson, Q Rev. Biophys. 28, 171 (1995)

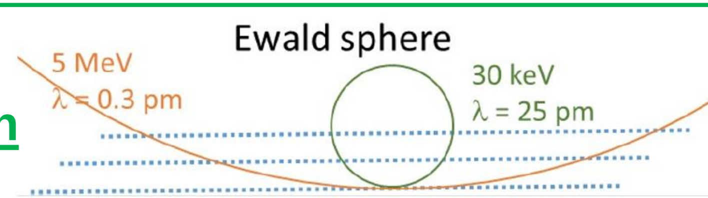
Velocity mismatch

100 keV t_{VM}=0.8 ps

3 MeV t_{VM}=10 fs

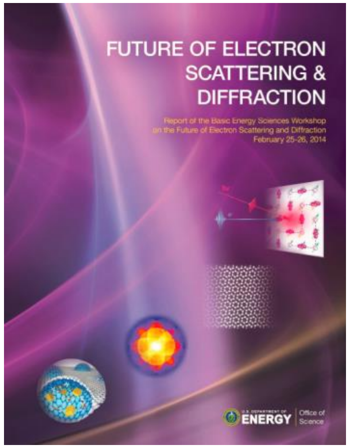


Shorter wavelength

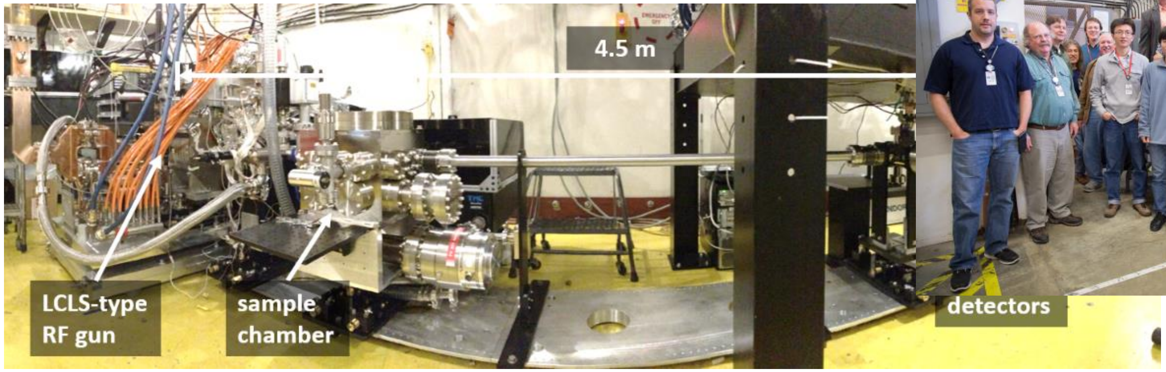


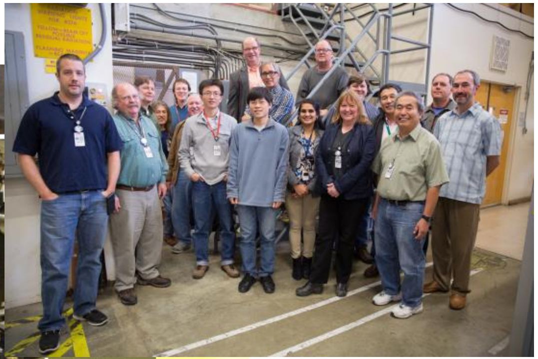
MeV UED at SLAC

SLAC



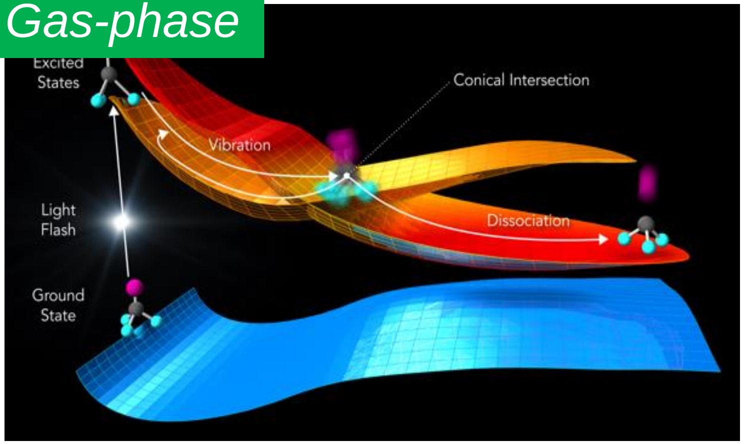
S. Weathersby et al., RSI **86**, 073702 (2015)





Single-shot

Gas-phase



Resolving ultrafast phase transitions - ***Science 360, 1451 (2018)***

Bond-breaking & nuclear wavepacket passing through conical intersections - ***Science 361, 64 (2018)***

30-40 experiments / yr

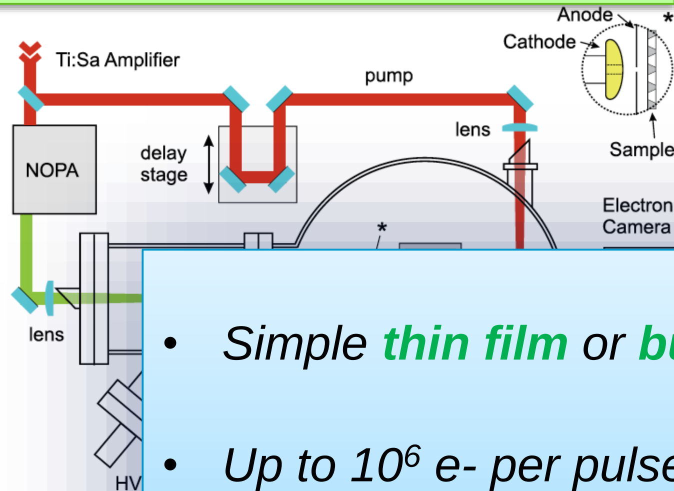
Solid state: nano-scale, 2D materials, diffuse scattering, strongly correlated system, functional material

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

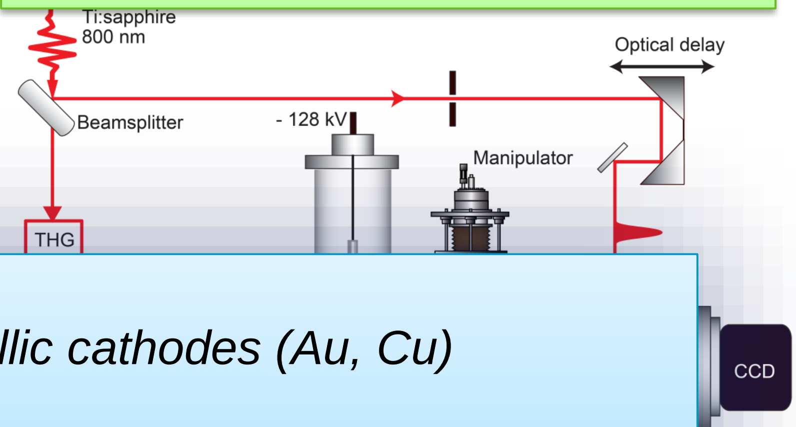
Liquid-phase: soon

State-of-the-art keV UEDs

L. Waldecker et al., JAP 117, 044903 (2015)



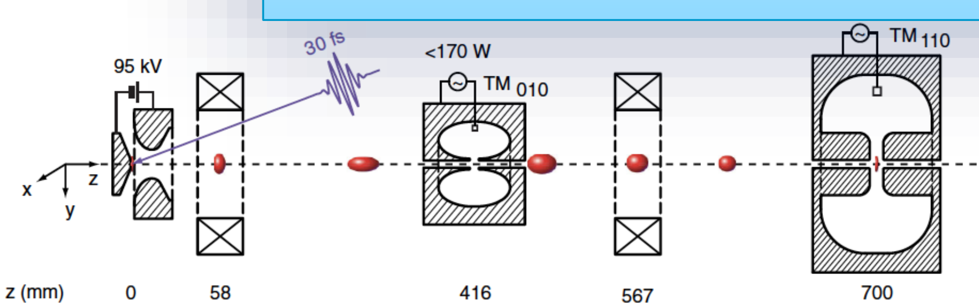
S. Ideta et al., Sci. Adv. 4, eaar3867 (2018)

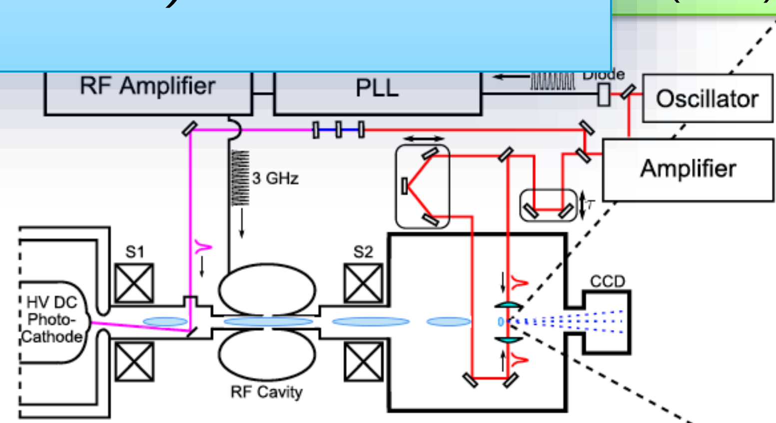


- *Simple **thin film** or **bulk** metallic cathodes (Au, Cu)*
- *Up to 10^6 e- per pulse w/ fs laser and ~100 um emission area*
- *Up to kHz rep-rate (allow samples to relax)*

T. van Oudh

01 (2012)





Guns and photocathodes for MeV UEDs

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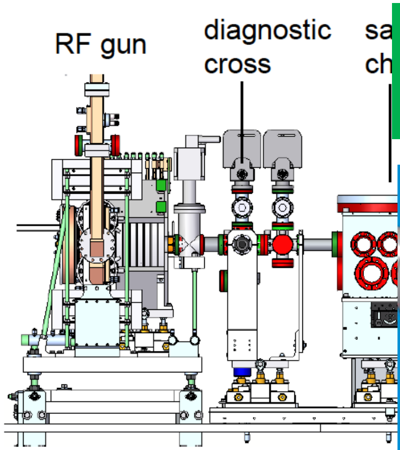
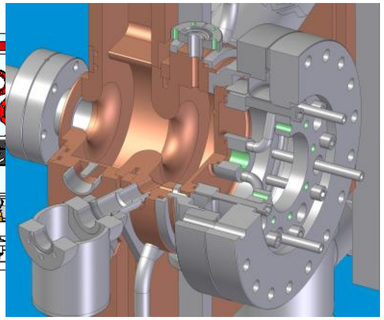
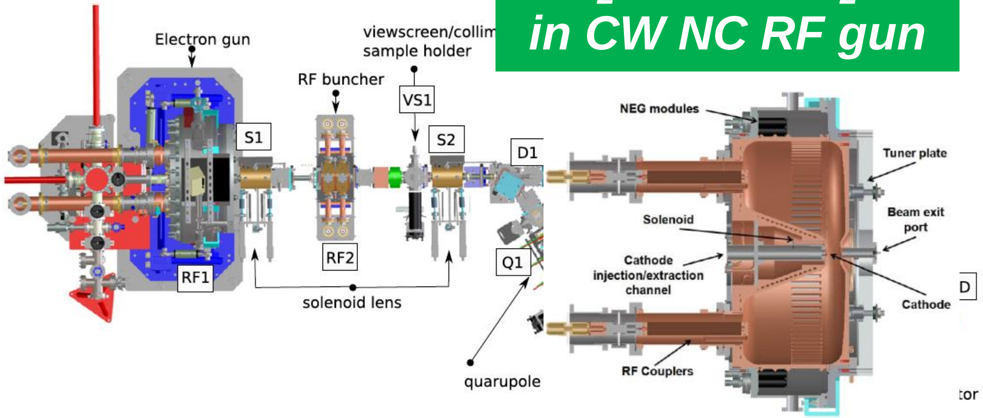
Cu cathode in pulsed RF gun

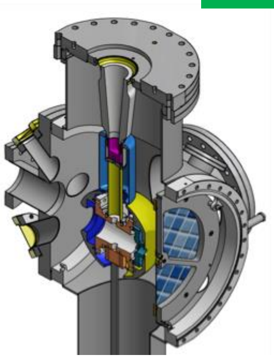


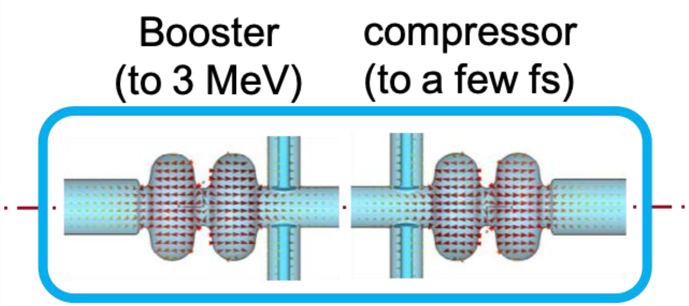


Cs_2Te or CsK_2Sb in CW NC RF gun

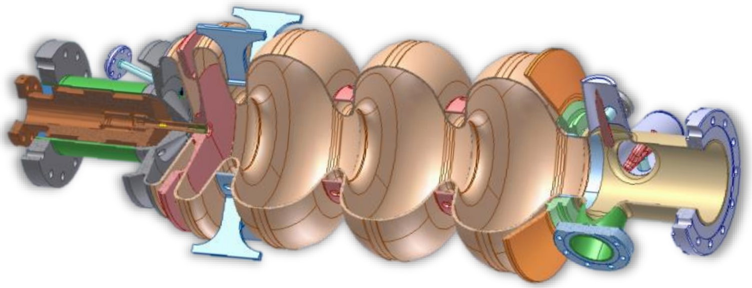


Cooled semiconductor cathodes in DC gun + booster





Metallic or semiconductor cathodes in SRF gun



Requirements for UED

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Signal level roughly scales *linearly* with beam brightness

$$\boldsymbol{B}_{\mathrm{6D}} \propto \frac{N}{(\sigma_x \cdot \gamma\sigma_{x'})^2 \cdot \sigma_t \cdot \sigma_\gamma} \cdot f_{\mathrm{rep}}$$

signal level (N)

rep. rate, depends on samples and processes (f_{rep})

sample size (σ_x): 10s of μm or less

q-resolution ($\gamma\sigma_{x'}$): 1 $mrad$ or smaller

bunch length (σ_t): 100 to few fs

energy spread (σ_γ): 10^{-3} or smaller

Processes	f_{rep}	Photocathodes
Irreversible, high-energy density	Single-shot	to reach highest $\boldsymbol{B}_{\mathrm{6D}}/f_{\mathrm{rep}}$
Reversible, relatively strong pump	Up to kHz	pulsed gun
Reversible, weak pump, gas/liquid flow, nano-diffraction	Up to MHz	CW gun

Requirements for UEM

Reaching atomic-level spatial resolution is the priority

$$\boldsymbol{B}_{6\mathrm{D}} \propto \frac{N}{(\sigma_x \cdot \gamma\sigma_{x'})^2 \cdot \sigma_t \cdot \sigma_\gamma} \cdot f_{\mathrm{rep}}$$

signal level (N)

rep. rate stroboscopic or single-shot (f_{rep})

illumination area $1\ \mu m$ or less (σ_x)

related to *contrast & Cs*, $1\ mrad$ or smaller ($\gamma\sigma_{x'}$)

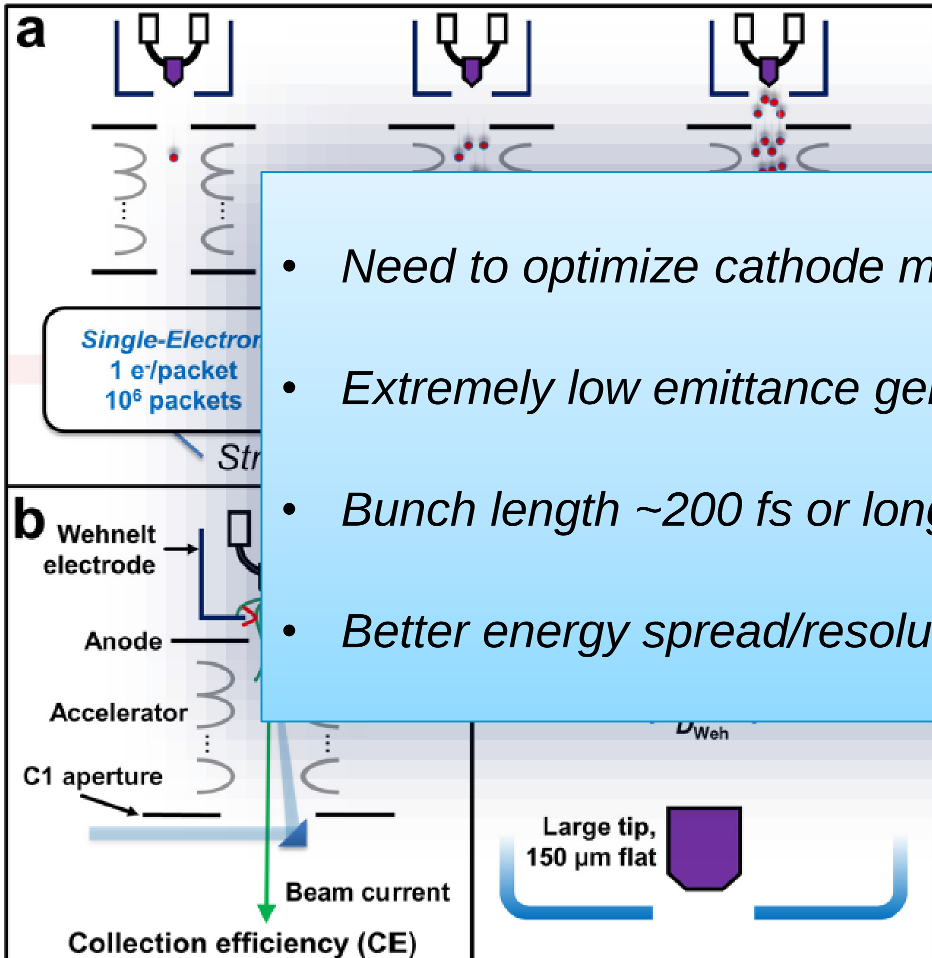
Somehow relaxed (σ_t)

related to *Cc* 10^{-5} level (σ_γ)

Operation mode	Beams
stroboscopic	200-300 kV UEM: ~1 e- per pulse, ϵ_n<1 nm-rad, 200 fs pulse MeV UEM: similar charge and ϵ_n, can reach 10 fs
single-shot	10^6-10^8 e- per pulse, similar ϵ_n

Cathodes for keV UEM

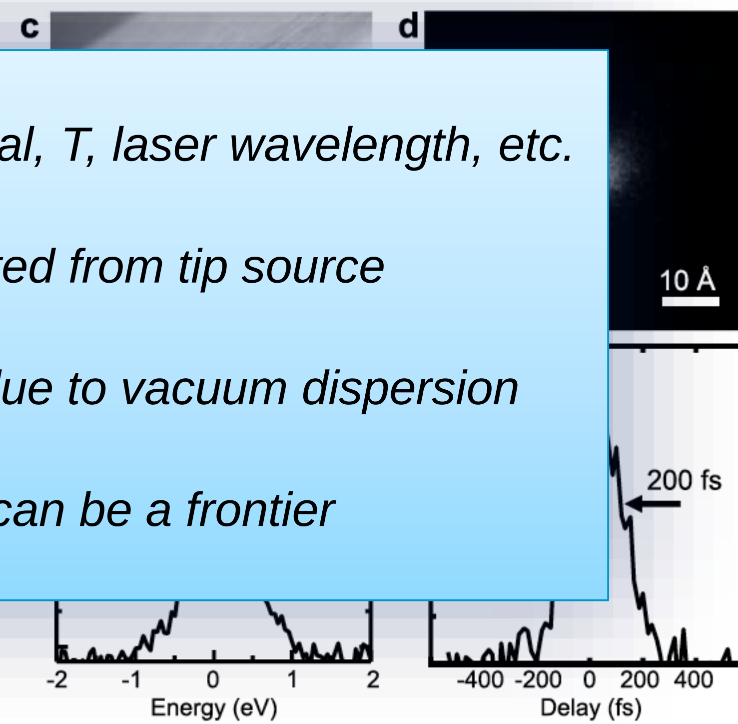
LaB_6 source in commercial TEMs



Kieft et al. Struct. Dyn. 2, 051101 (2015)

Tip field emission source

ZrO/W(100) tip emitter
0.5-1 V/m field, 1800 K

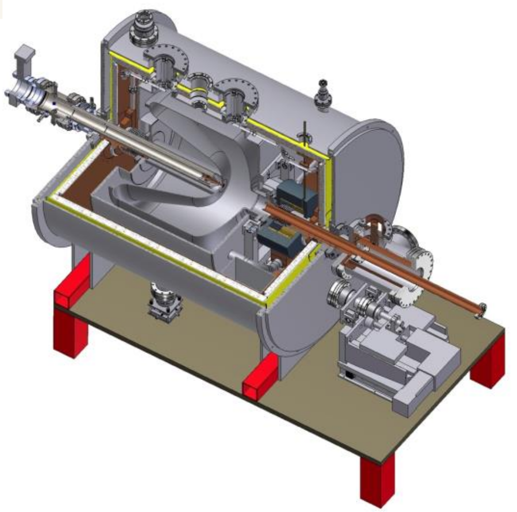


Stable operation >48 h

A. Feist et al. Ultramicroscopy 176, 63 (2017)

- *Need to optimize cathode material, T, laser wavelength, etc.*
- *Extremely low emittance generated from tip source*
- *Bunch length ~200 fs or longer due to vacuum dispersion*
- *Better energy spread/resolution can be a frontier*

Cathodes for MeV UEM



VHF SRF gun as a promising candidate for UEM w/ atomic spatial resolution

- Requires ϵ_n <1 nm-rad
  - e.g. <5 um spot size and 0.2 um/mm intrinsic emittance
- >1 pC charge in single-shot mode
  - 1 pC from few um spot: need high QE to avoid heating effect

Stability: toward 10^{-5} in amplitude

High gradient: up to 40 MV/m

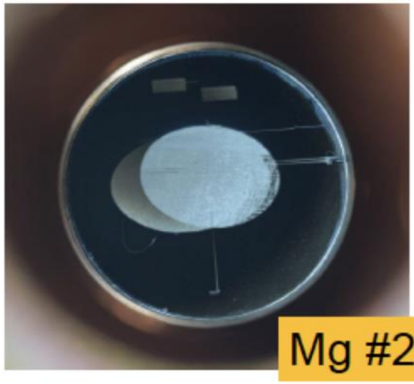
High beam energy: 4 MeV

Flexibility: ~100 ps bunch length

High rep-rate: up to 200 MHz

QWR geometry, 4.5 K operation

Challenges: gradient, cathode



Mg #214

Reliable operation of Mg cathode in SRF Gun II at ELBE HZDR

R. Xiang et al, THPMF039, IPAC2018.

Requirements for fs EELS

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Pushing the *longitudinal emittance* of photocathodes

$$\boldsymbol{B}_{6\mathrm{D}} \propto \frac{N}{(\sigma_x \cdot \gamma\sigma_{x'})^2 \cdot \sigma_t \cdot \sigma_\gamma} \cdot f_{\mathrm{rep}}$$

1 *e*- per pulse to control space charge (N)

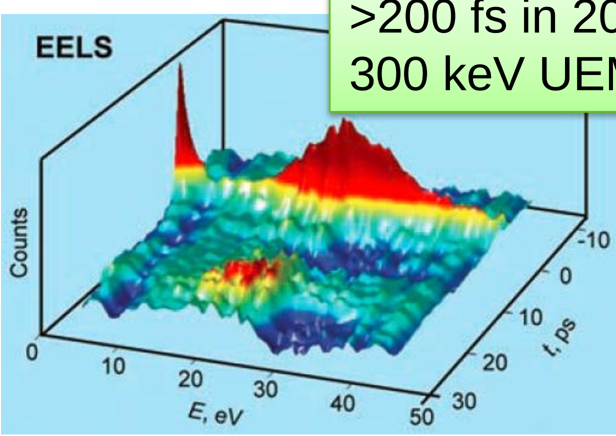
rep. rate (f_{rep})

Probe size nm level (σ_x)

related to *spectrometer resolution, < 1 mrad* ($\gamma\sigma_{x'}$)

Towards 10 fs (σ_t)

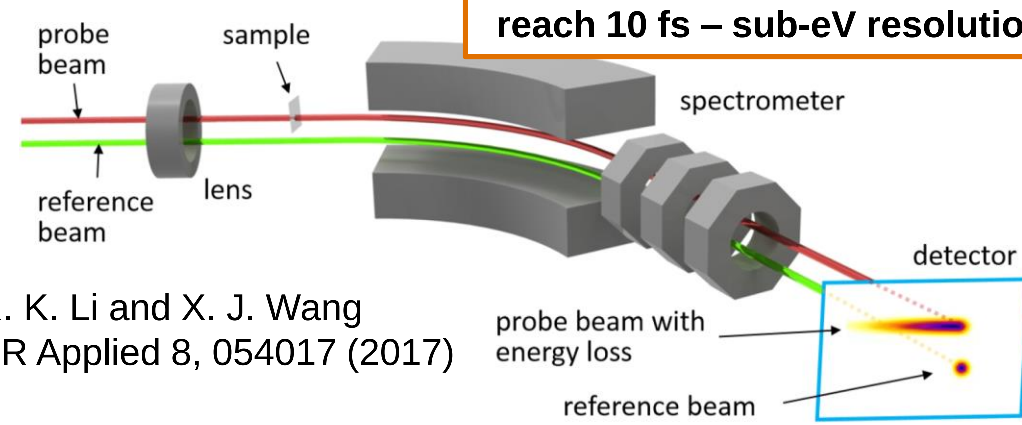
Stay effectively at sub-eV level (σ_γ)



>200 fs in 200-300 keV UEMs

F. Carbone et al., Science 325, 181 (2009)

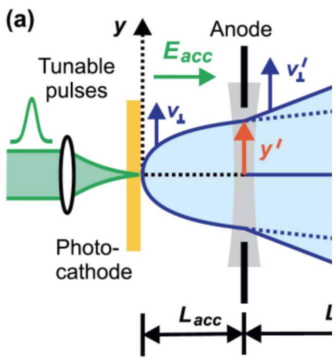
w/ 'reference beam' technique to reach 10 fs – sub-eV resolutions



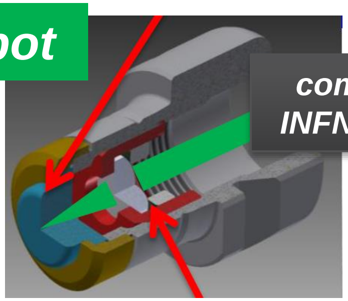
R. K. Li and X. J. Wang
PR Applied 8, 054017 (2017)

Sub-nm-rad emittance from small emission area

tight focus to um spot



P. Baum et al., PNAS 107, 19714 (2010).



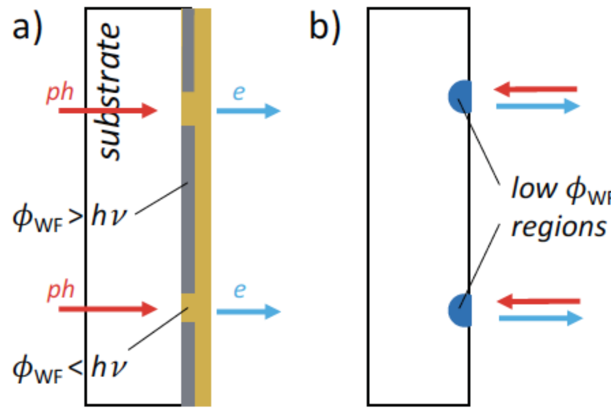
compatible with INFN plug, cooled

Courtesy of L. Cultrera

Transparent SC substrate

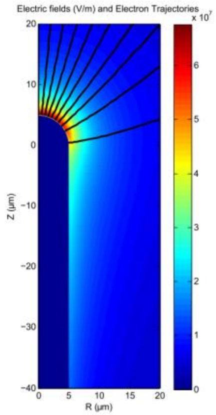
R. Inagaki et al., IPAC'14, MOPRI035

Sub-um flat cathode

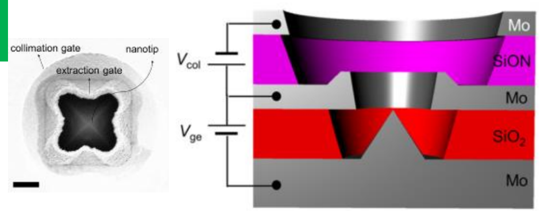


R. K. Li and X. J. Wang, PR Applied 8, 054017 (2017)

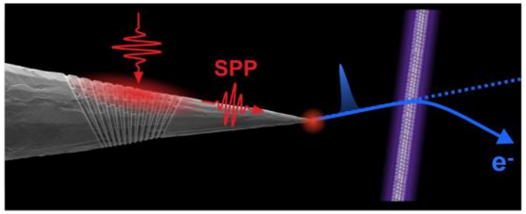
Tip sources



Courtesy of J. Maxson



C. Lee et al., APL 113, 013505 (2018)



M. Muller et al., ACS Photonics 3, 611 (2016)

- Minimize spot size × divergence
- Control MTF with T, λ, E, etc.
- Laser heating
- Surface contamination

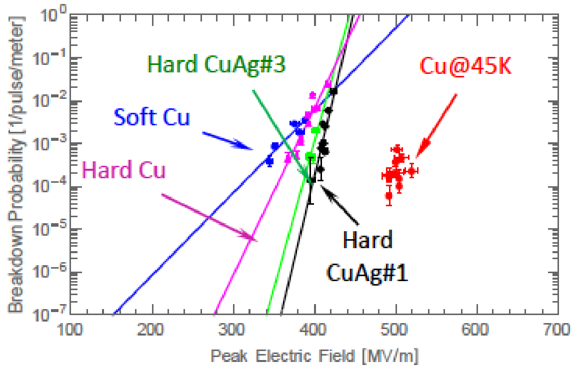
Cathodes in extremely high fields

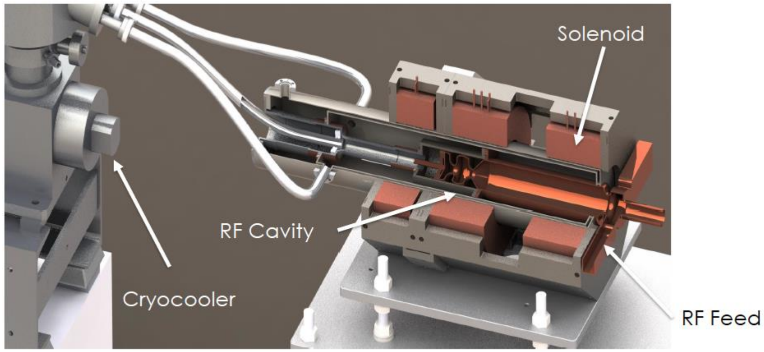
$$\mathcal{B}_{\mathrm{4D}} \propto \frac{E_z}{\mathrm{MTE}}$$ for pancake beam
Bazarov et al., PRL 102, 104801 (2009)

$$\propto \frac{E_z^{3/2}}{\mathrm{MTE}} \frac{\sigma_t}{\sigma_x^{1/2}}$$ for cigar beam
Filippetto et al., PRAB 17, 024201 (2014)

>250 MV/m field with cryo-cooled Cu gun

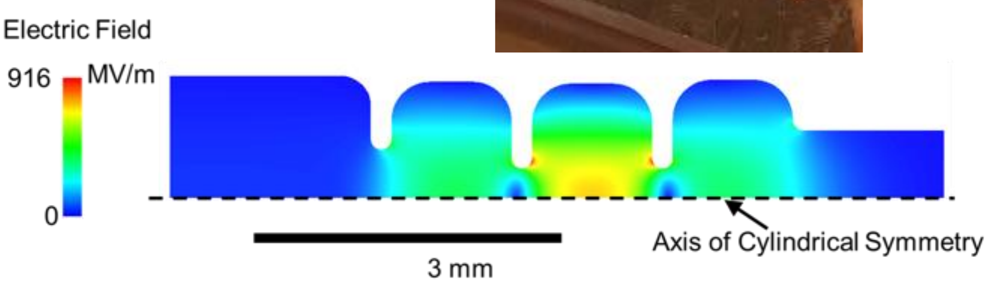
Courtesy of A. Cahill, J. B. Rosenzweig, et al.





GV/m field in THz gun

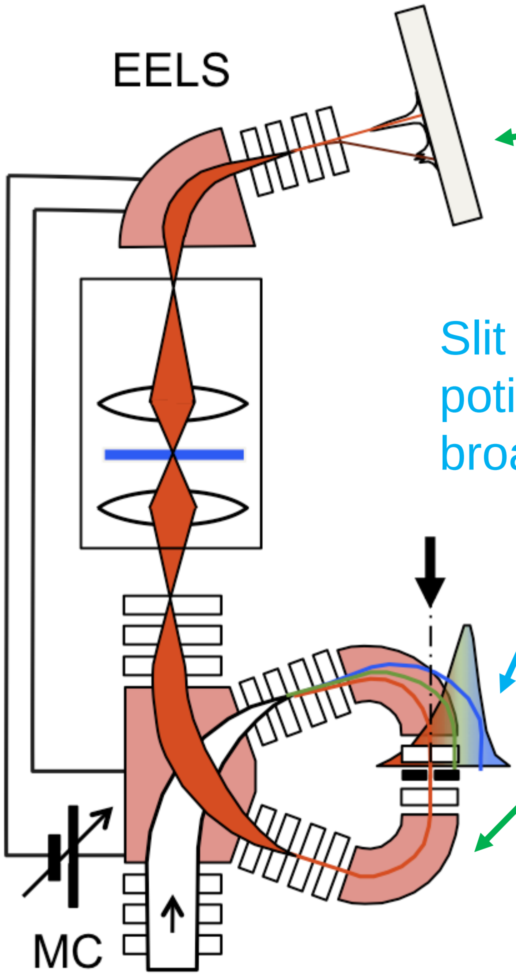
Courtesy of E. A. Nanni



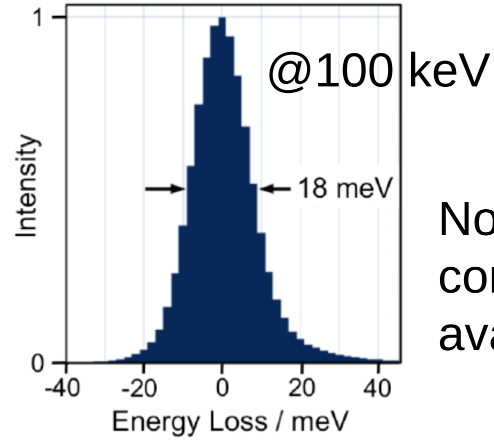
- Need compatible cathodes
- Can they survive?
- Modified MTF due to fields, surface morphology, etc.

meV energy resolution

MC+EELS change



Slit picks a tiny potion of a broad spectrum



Now sub-10-meV commercially available

ΔE (eV) @100 kV	**LaB_6**	**Schottky FEG**	**Cold FEG**
ΔE	1-2	0.3-0.7	0.2-0.7

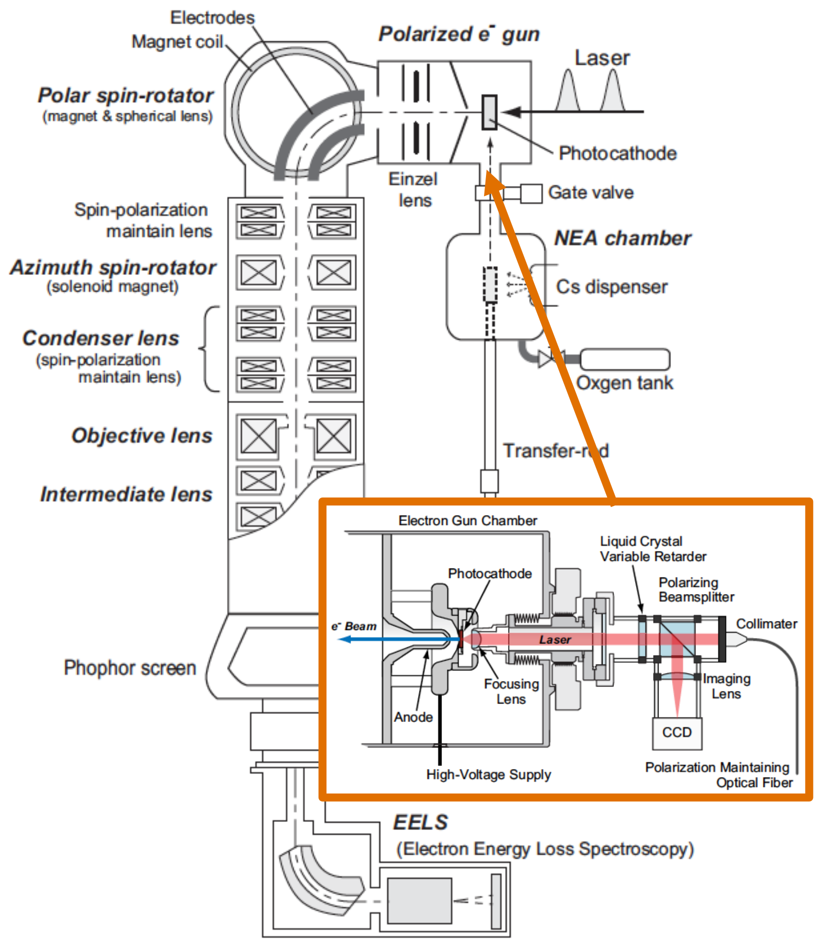
Reimer and Kohl, TEM, 2007

Cryogenic photocathodes will significantly advance ultra-resolution EELS!

O. L. Krivanek et al., J. Phys.: Conf. Ser. 522, 012023 (2014)

More cathode options for UED

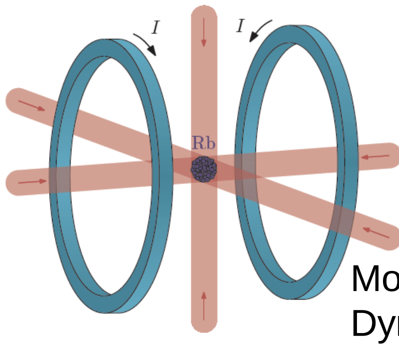
Spin-polarized TEM

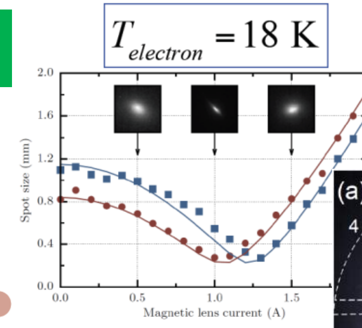


Kuwahara et al. APL 101, 033102 (2012)

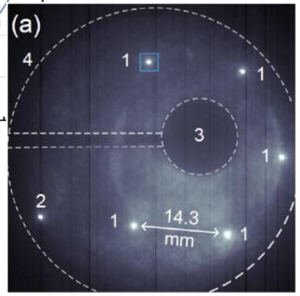
MOT source

Laser cooling & trapping



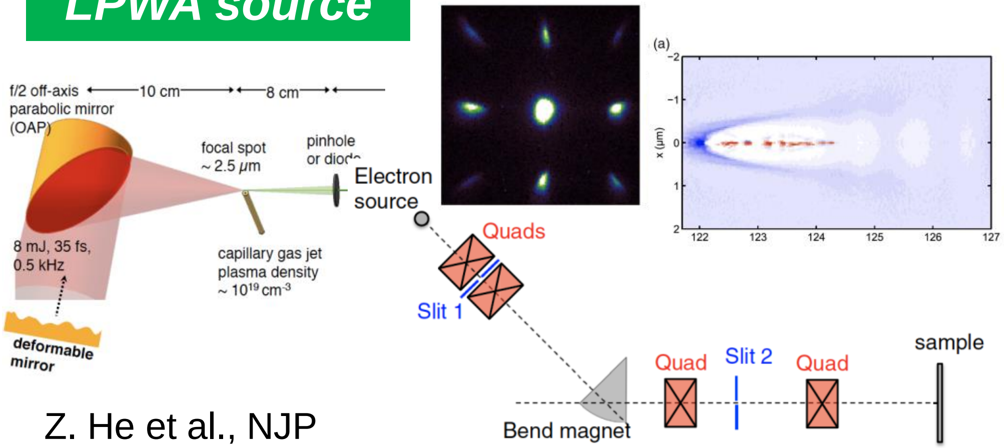


Graphite DP (13.2 keV)



Mourik et al., Struc. Dyn. 1, 034302 (2014).

LPWA source



Z. He et al., NJP 15, 05316 (2013)

J. Faure et al., PRAB 19, 021302 (2016)

Acknowledgement

- Helpful discussions with Pietro Musumeci, Daniele Filippetto, Jared Maxson, Theo Vecchione and many others
- SLAC UED/UEM team (X. J. Wang etc.) and collaborators
- Strong support from SLAC management. Technical support from SLAC AD, TID, and LCLS
- Work supported in part by the U.S. Department of Energy Contract No. DE-AC02-76SF00515 and the SLAC UED/UEM Initiative Program Development Fund.

Summary

- UES are demonstrated tools with transformative impacts, complementary and synergistic with XFEL
- Photocathode improvements will benefit UES

  A few near-term items on the wish-list: In extremely high launching field, in high gradient SRF gun, extremely small initial emittance, meV energy spread

- New capabilities will be enabled by new photocathodes

Thank you for your attention!

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1: Click “Insert” from menu and choose “Picture” to select image
2: Once image is inserted, right-click image and choose ‘Send to Back’