Photocathode sources studies for UED/UEM at Tsinghua University

Renkai Li
Tsinghua University

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- **Colleagues at Tsinghua**: C. X. Tang, H. B. Chen, W. H. Huang, Y. C. Du, L. X. Yan, L. M. Zheng, J. R. Shi, H. Zha etc.
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Outline

- Introduction
- Cathode preparation
- Ultra-high vacuum rf gun
- 200 kV DC gun
- Summary and outlook

Ultrafast electron and X-ray probes

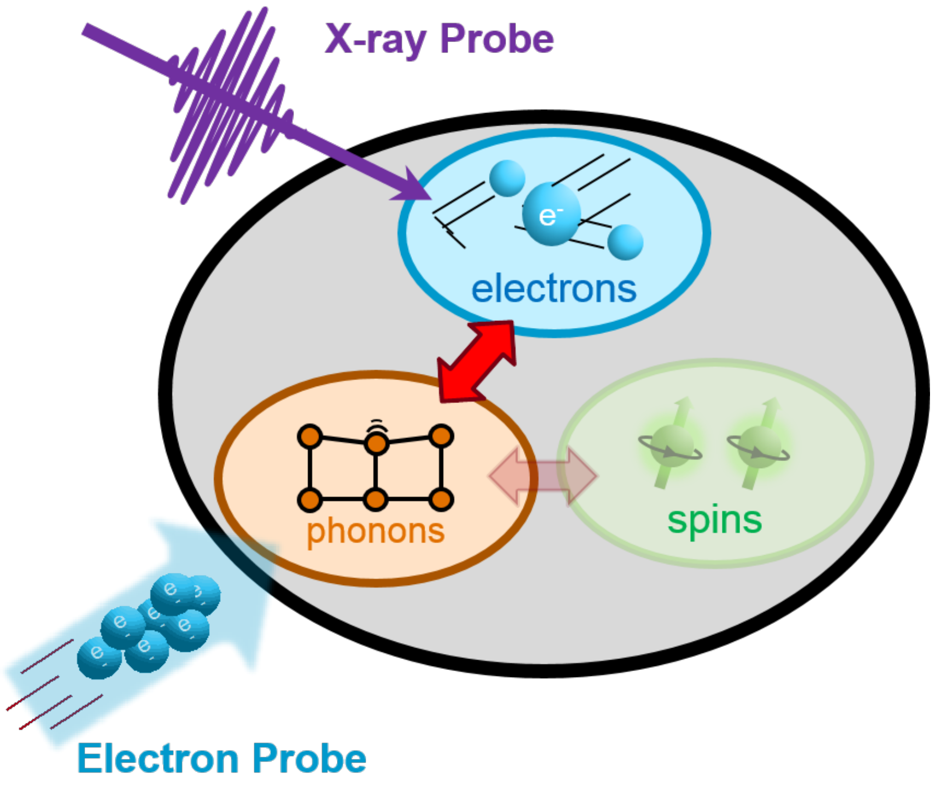
Ultrasmall:

short wavelength

Ultrafast:

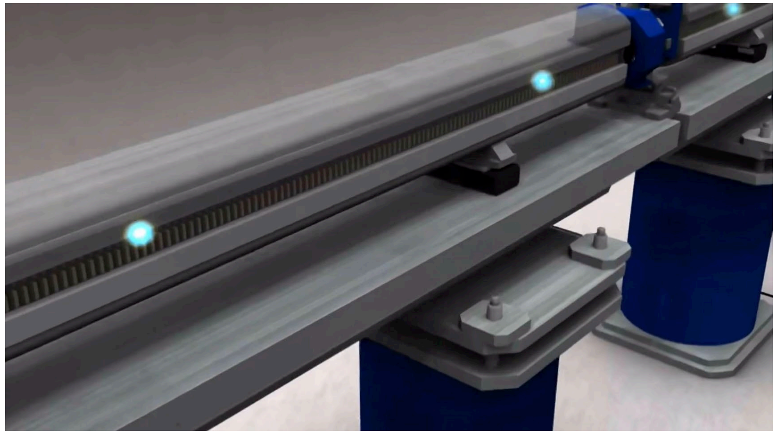
short pulse duration

XFEL and UES are complementary tools towards a complete picture of dynamics



Beam quality and brightness requirements

XFEL: ～0.1 um-rad



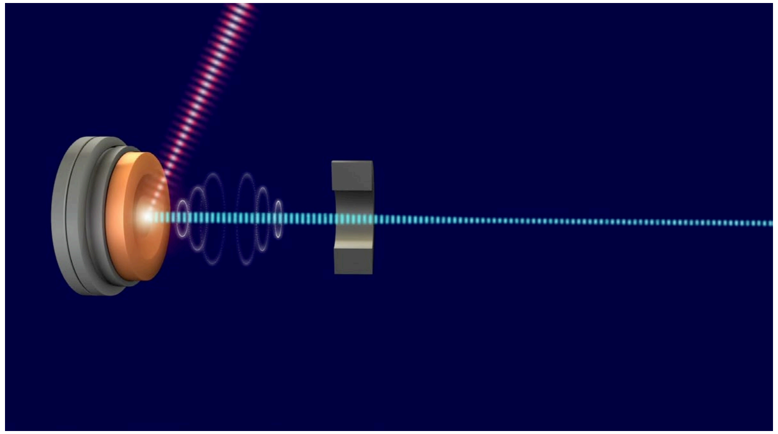
– Low normalized emittance

– High current (kAmp)

– Beam charge ranging from 10 pC - 1 nC

$$\frac{\epsilon_n}{\gamma_0} \leqslant \frac{\lambda}{4\pi} \qquad \rho = \left[\frac{1}{16}\frac{I_e}{I_A}\frac{K_0^2[\mathrm{JJ}]^2}{\gamma_0^3\sigma_x^2k_u^2}\right]^{1/3}$$

UED: ～0.01 um-rad

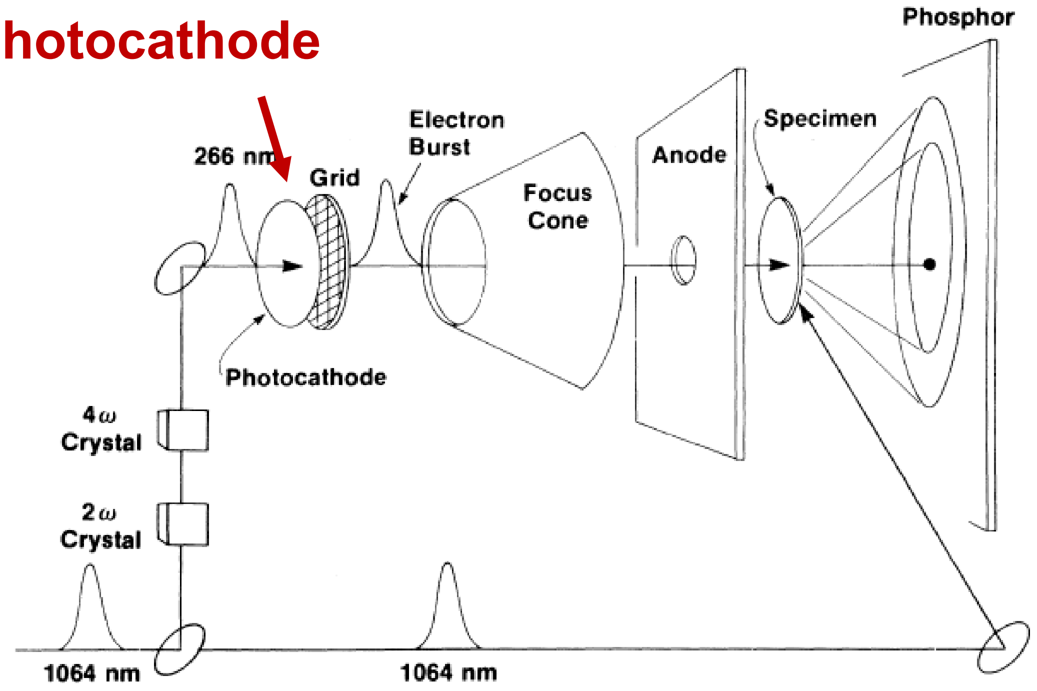


$$\boldsymbol{B}_{6\mathrm{D}} \propto \frac{N}{(\sigma_x \cdot \gamma\sigma_{x'})^2 \cdot \sigma_t \cdot \sigma_\gamma} \cdot f_{\mathrm{rep}}$$

- N: signal level
- f_{rep}: rep. rate, depends on samples and processes
- σ_x: sample size 10s of μm or less
- $\gamma\sigma_{x'}$: *q*-resolution $1\ mrad$ or smaller
- σ_t: bunch length 100 to few fs
- σ_γ: energy spread 10^{-3} or smaller

UED – ultrafast electron diffraction

photocathode

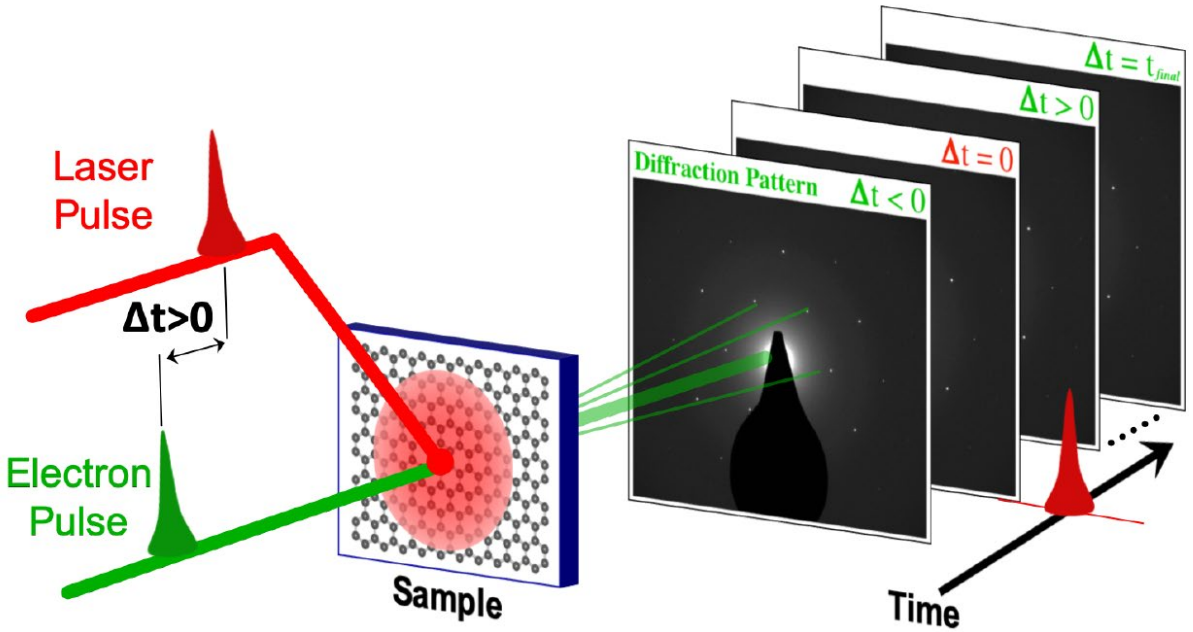


First UED instrument and demonstration:
- Mourou and Williamson, APL 41, 44 (1982)
- Williamson, Mourou and Li, PRL 52, 2364 (1984)

Science results from keV UED:
- Chergui and Zewail, ChemPhysChem 10, 28 (2009)
- Miller, Science 343, 1108 (2014) and many others

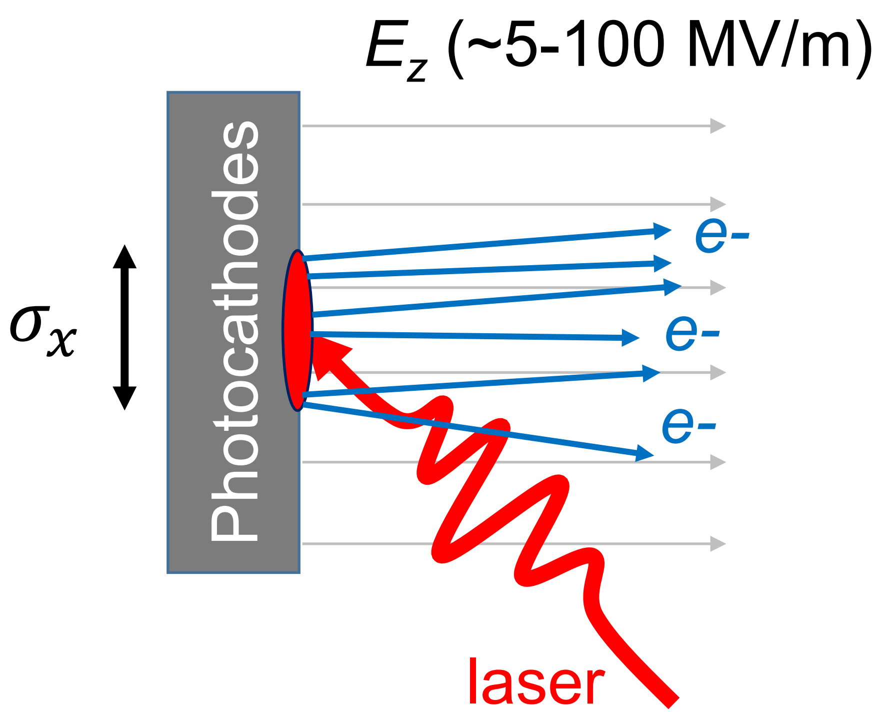
Pump-Probe technique

- non-equilibrium processes
- pump not limited to laser



Filippetto, Musumeci, Li et. al., RMP 94, 045004 (2022)

Photoemission sources and brightness



4D beam brightness

$$\mathcal{B}_{4D} \propto f_e \frac{N}{\left(\sigma_x \cdot \sqrt{\mathrm{MTE}}\right)^2}$$

Mean Transverse Energy $\mathrm{MTE} = \frac{1}{2}mv^2$

Preservation of the brightness f_e

$\mathcal{B}_{4D} \propto f_e \frac{E_z}{\mathrm{MTE}}$ for pancake (A>>1) beam, where aspect ratio $A = \frac{\sigma_x m_e}{\sigma_t^2 E_z e}$

PRL 102, 104801

$\mathcal{B}_{4D} \propto f_e \frac{E_z^{3/2}}{\mathrm{MTE}} \frac{\sigma_t}{\sigma_x^{1/2}}$ for cigar shape (A<1) beam

PRAB 17, 024201

Key aspects for brightness

E_z, Higher gradient

New materials
Surface processing
DC vs rf, higher frequency
Local enhancement

Future electron sources

f_e, Brightness preservation

Emittance compensation
Beam shaping
Aberration control
Precise characterization

Lower MTE

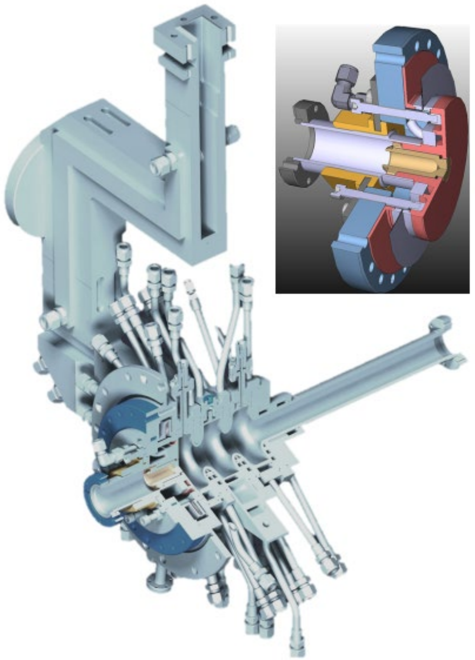
New cathode material
Cooling
Tuning laser wavelength
Cathode by design

- Courtesy of I. Bazarov
- P. Musumeci et al., NIMA 907, 209 (2018)

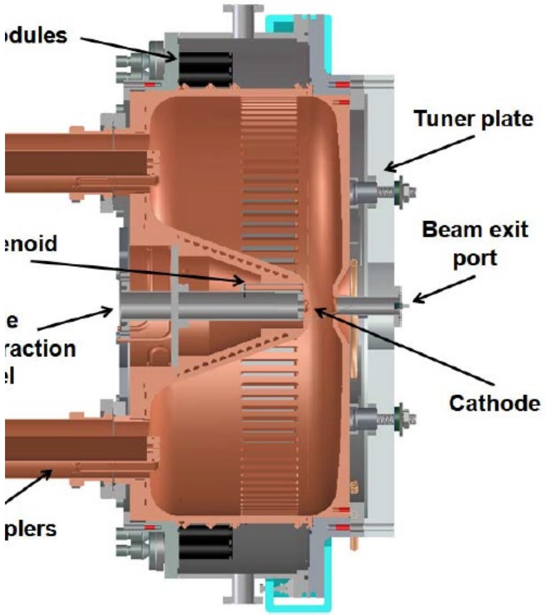
State-of-the-art sources

- **What we are using now:**
  - High E_z (20-100 MV/m) + high MTE (eg. Cu, Cs_2Te, ~1 mrad)
  - Low E_z (~10 MV/m) + low MTE (eg. multi-alkali antimony <~0.5 mrad)

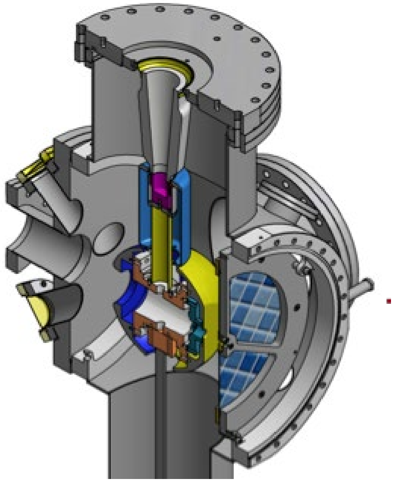
NC pulsed



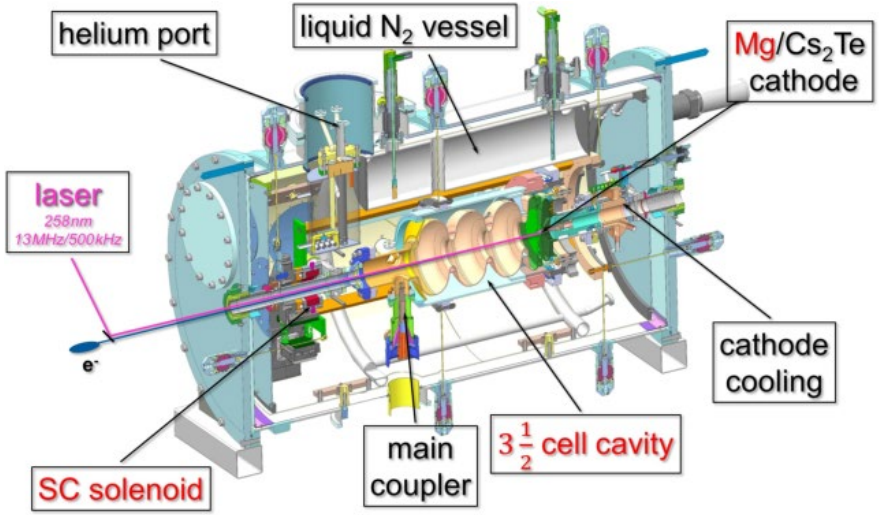
NC CW



DC

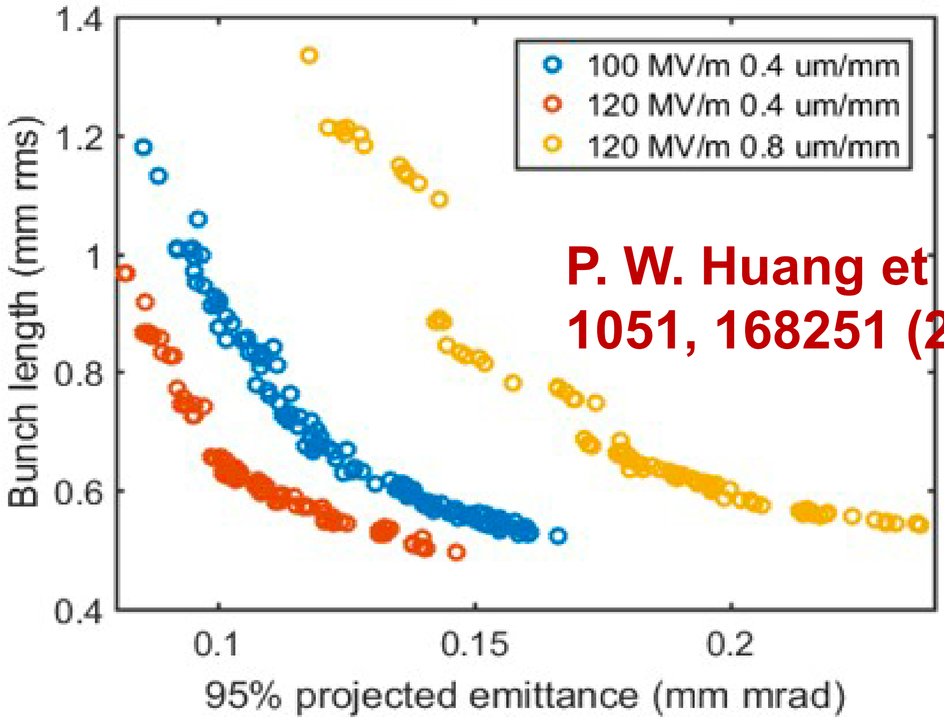


SRF

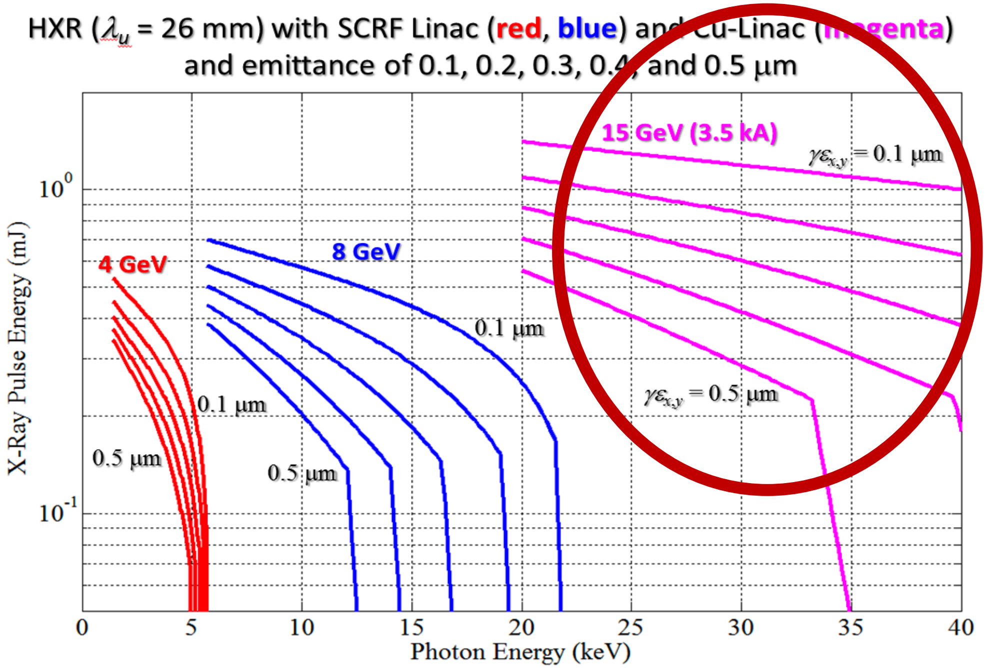


Photoemission sources towards the future

- **Highest possible E_z + Lowest possible MTE + high QE**
- **Operation considerations: long lifetime, visible light**
- **Recent efforts by the Cornell+UCLA, PITZ+INFN collaboration and others (see 2021 P3 workshop)**



P. W. Huang et al., NIMA 1051, 168251 (2023)



DOE BES Future Electron Source Workshop, 2016

Outline

- Introduction
- **Cathode preparation**
- Ultra-high vacuum rf gun
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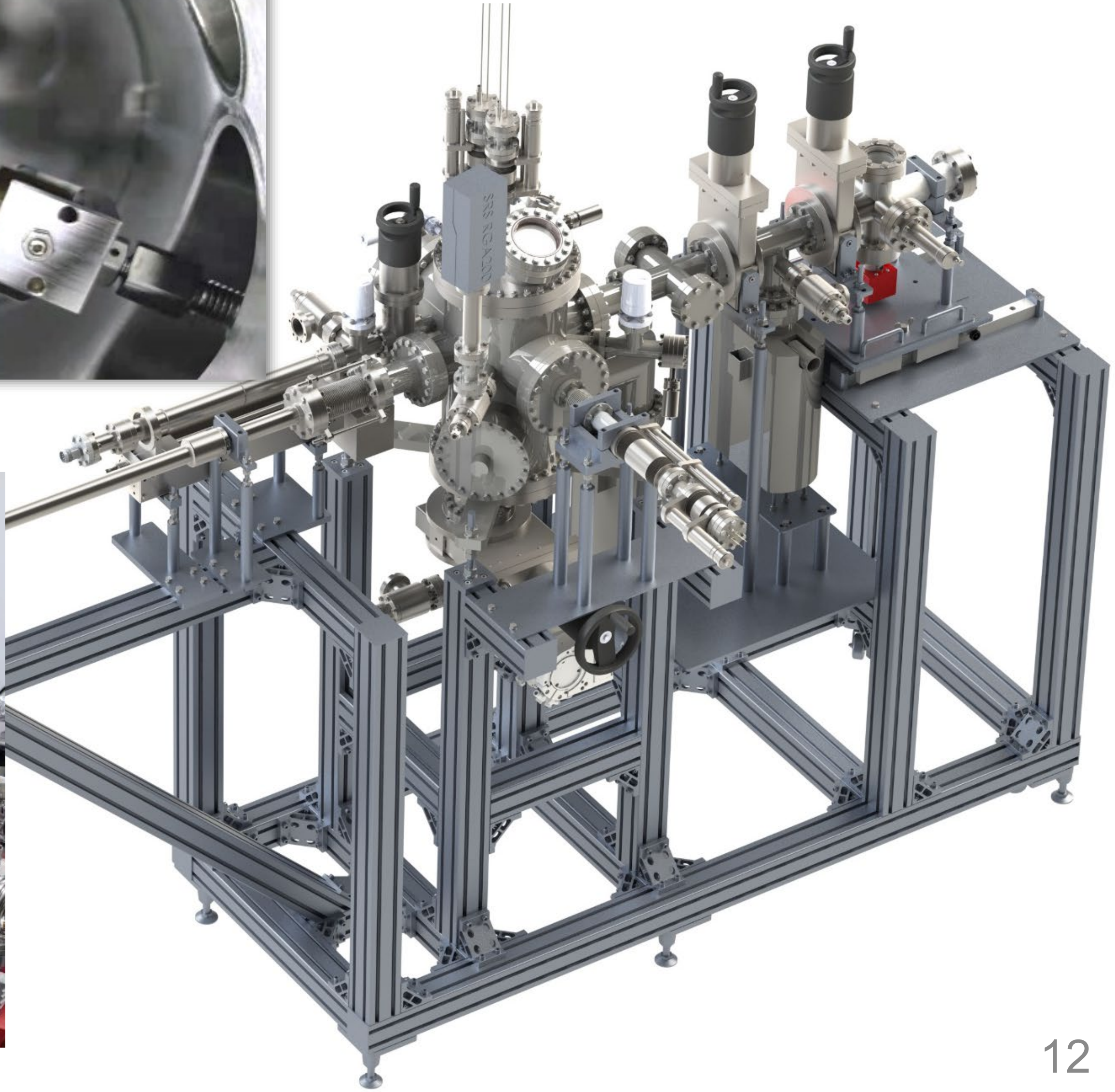
Photocathode deposition system

- **Efforts initiated in 2018**
- **Built and commissioned Cs_2Te and Alkali Antimony photocathodes deposition systems**
- **INFN-type cathode plug compatiable with many collaborators**

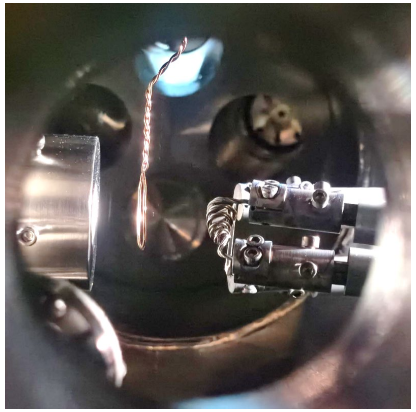


Cs_2Te deposition

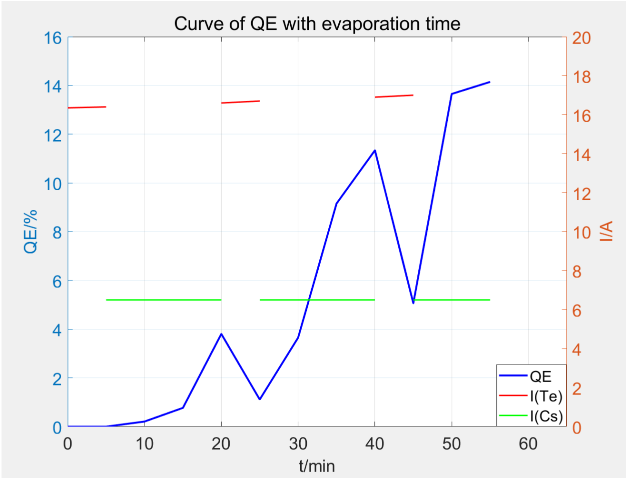
- **Carried out both sequential and co-deposition**
- **In sequential deposition, each layer of Te ~5.5 nm thick, with a total thickness of 15-20 nm for maximum QE**
- **Cathodes used in VHF and S-band gun**

Mo plug polished to 10 nm roughness

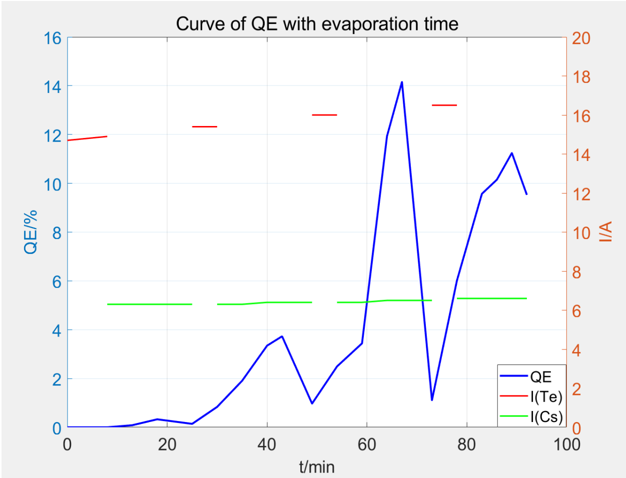
Te and Cs sources facing the plug



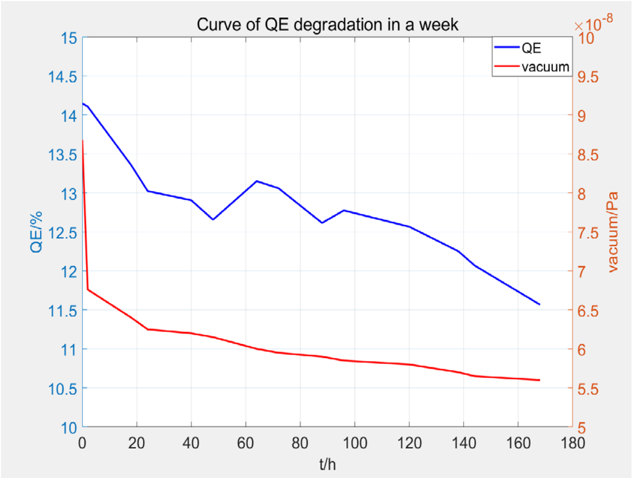
QE monitored by a picometer



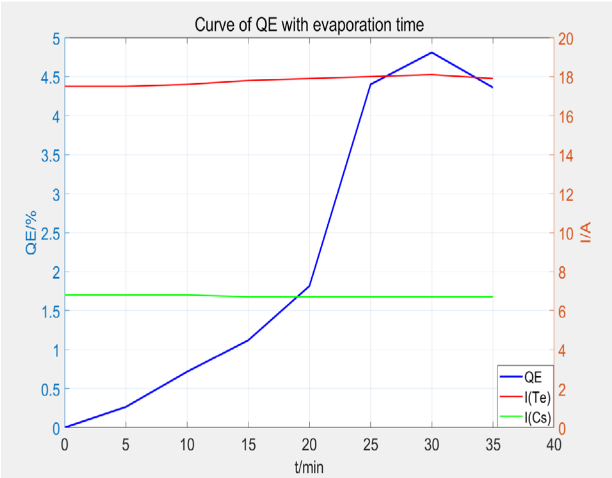
Sequential, 3 layers, max QE@3rd layer=14.1%



Sequential, 4 layers, QE@3rd layer=14.2%, QE@4th layer=11.2%



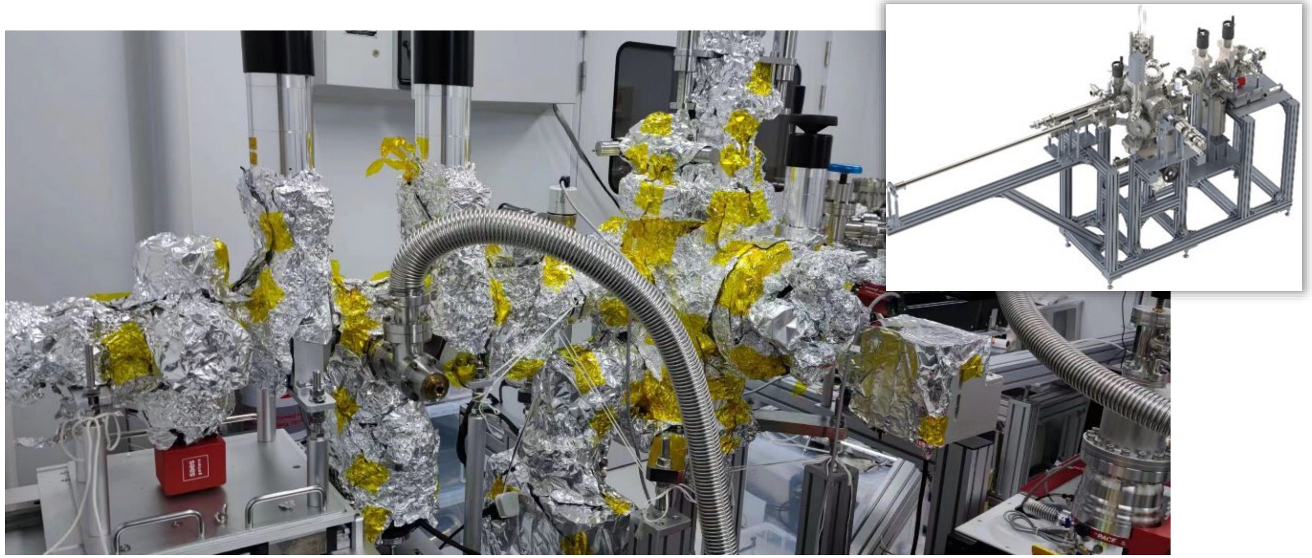
Sequential, 3 layers, monitored QE over a week, lifetime>1100 h



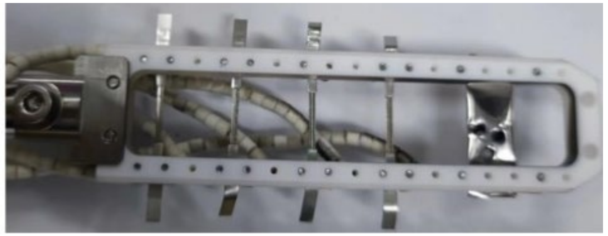
First attempt of co-deposition, QE>4%

Fabrication of Alkali Antimony etc.

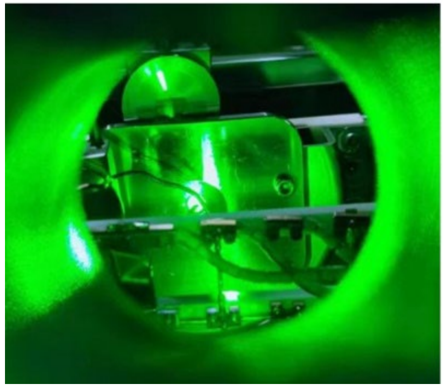
- **A newly commissioned deposition system for Alkali Antimony cathodes (Cs-Sb, K-Cs-Sb, etc.)**
- **Baseline vacuum 5.9e-9 Pa**
- **For preparation and study of QE, MTE versus deposition recipes**
- **Started fabrication of Cs-Sb and K-Cs-Sb**



	Sb	K	Cs
Plug temp.	110 ℃	60 ℃	60 ℃
Layer thickness	5 nm	\	\



Evaporation sources



- **So far has achieved Cs-Sb - 3%@405 nm and 0.1%@532 nm**
  K-Cs-Sb - 5%@405 nm and 1%@532 nm
- **Work in progress to improve the QE and reproducibility, and then testing in real guns**

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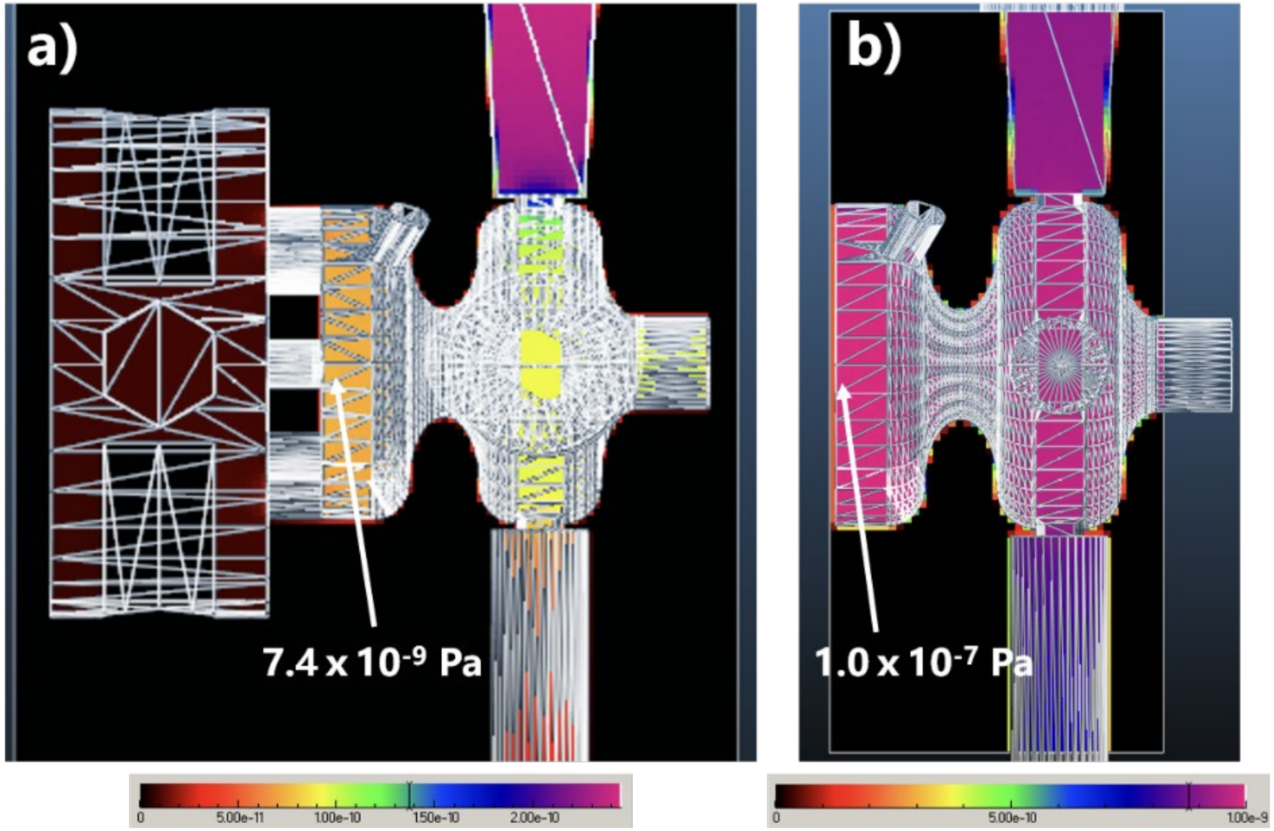
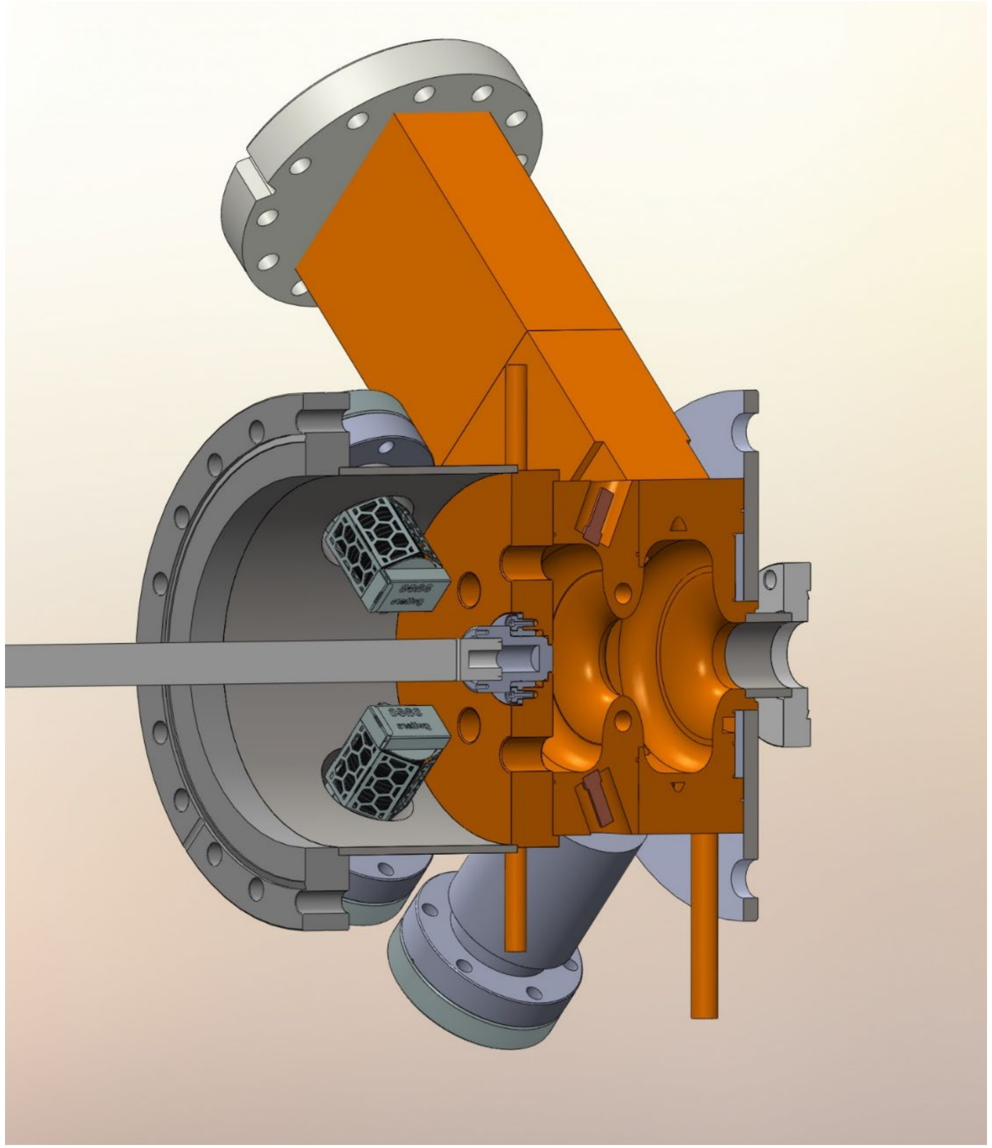
Ultrahigh vacuum gun design

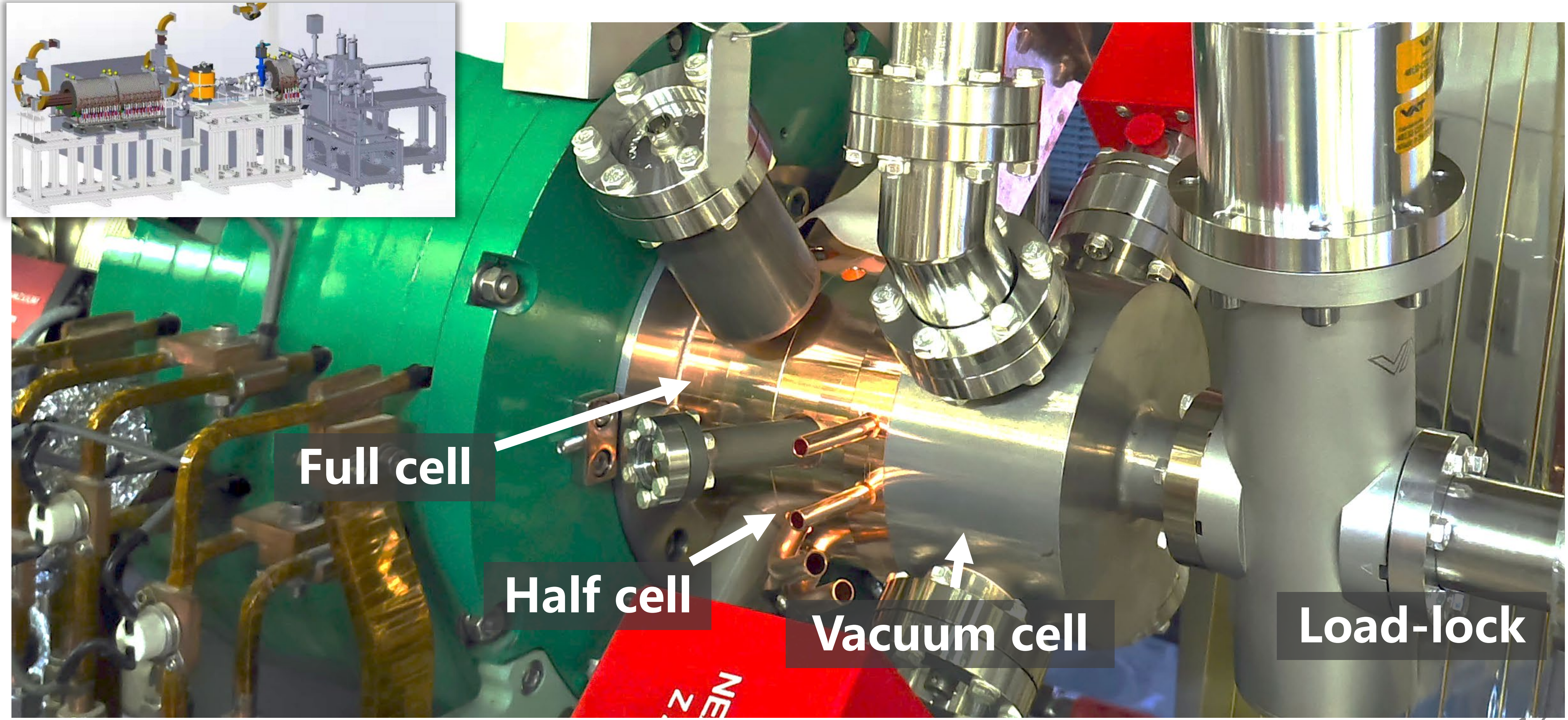
>10 fold improvement in vacuum at cathode surface



P. W. Huang et al., NIMA 1051, 168251 (2023)

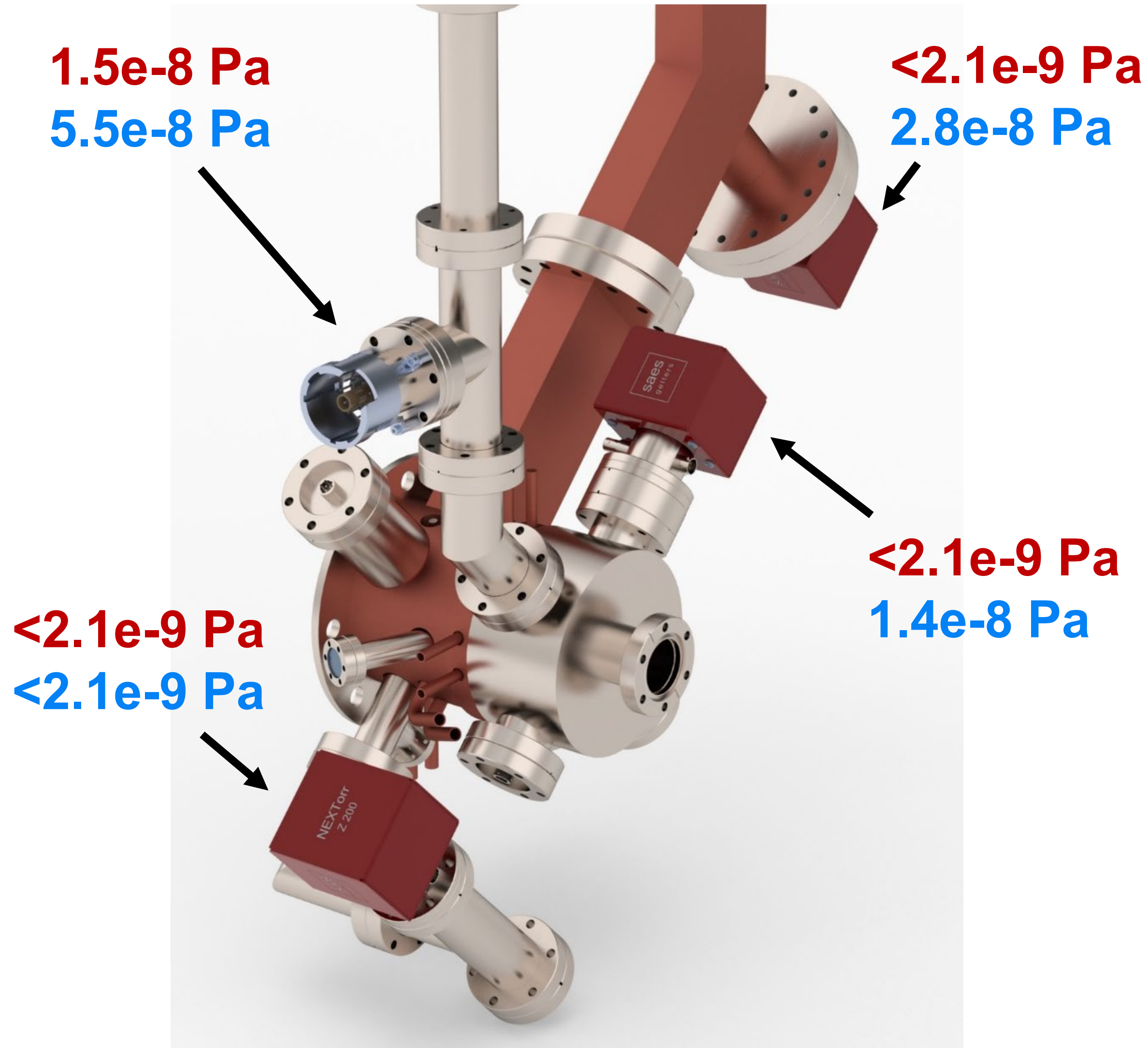


New gun installed



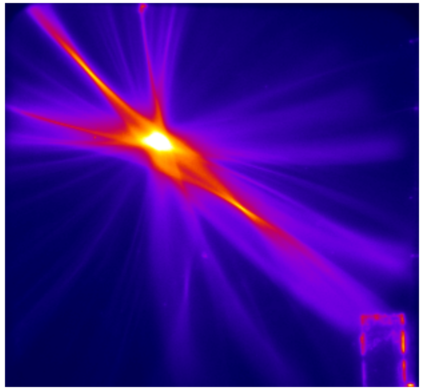
rf conditioning

Base/operation pressure

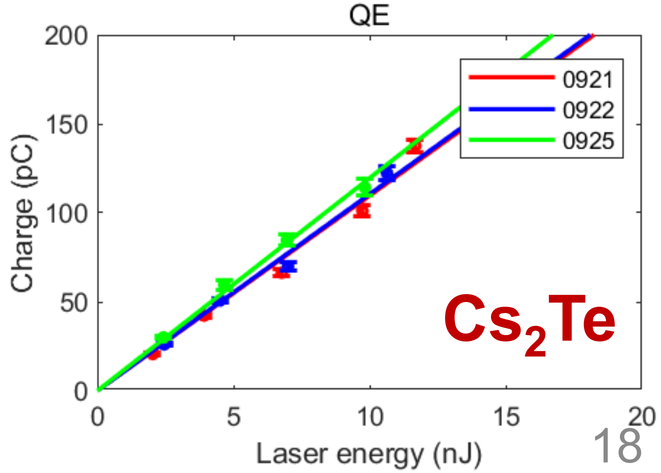


rf conditioning after 24 hrs

Dark current 0.5 nC @ E_z ~ 105 MV/m

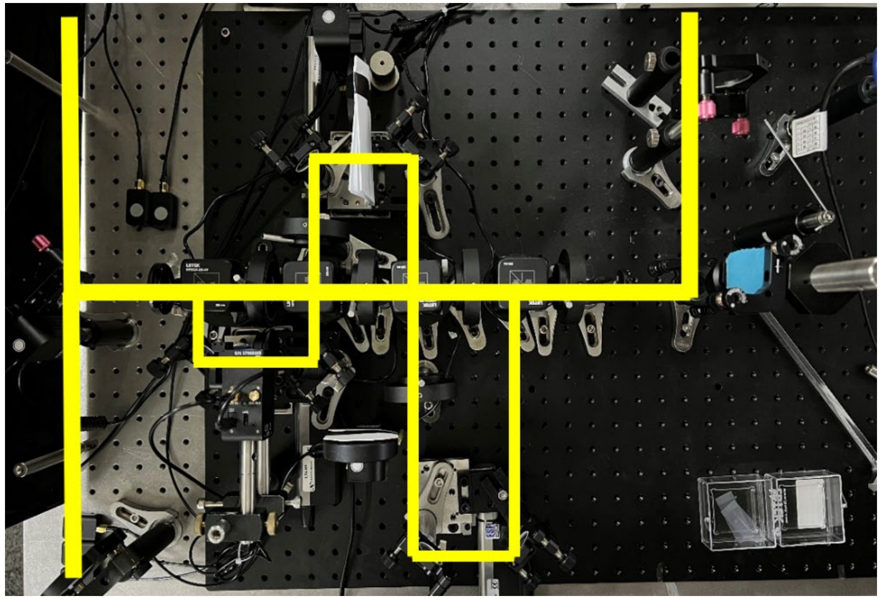


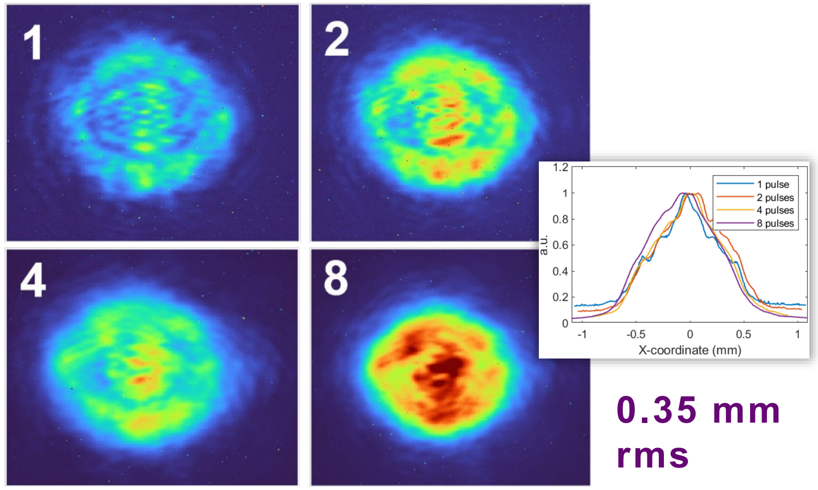
QE>~5% over a month



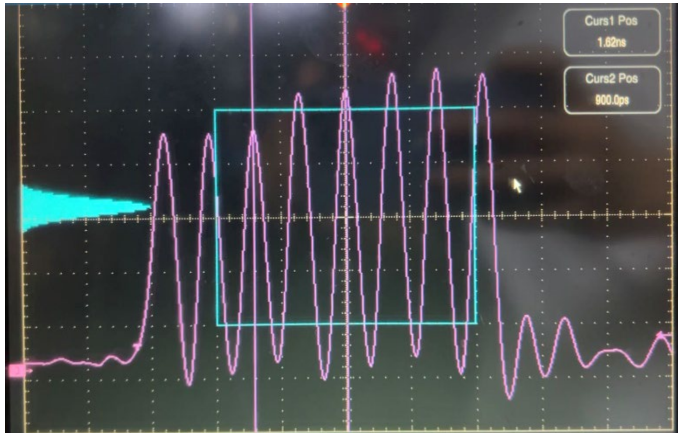
Every rf cycle operation

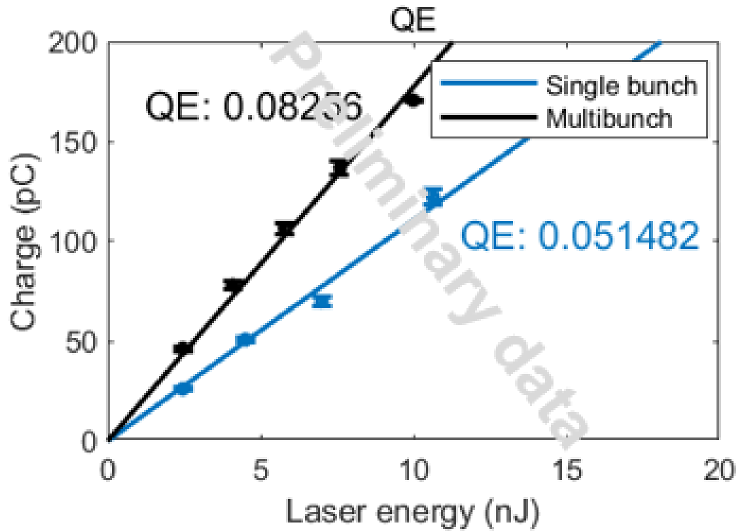
- For several applications, highest possible marco-pulse current is desirable
- Need to fill every rf cycle
- Laser pulse train generation (stacking or marco-pulse mode laser) and LLRF control
- Beam control supported by precise beam characterization
- Preliminary data shows QE differences for single versus multiple pulses, more systematic measurement underway



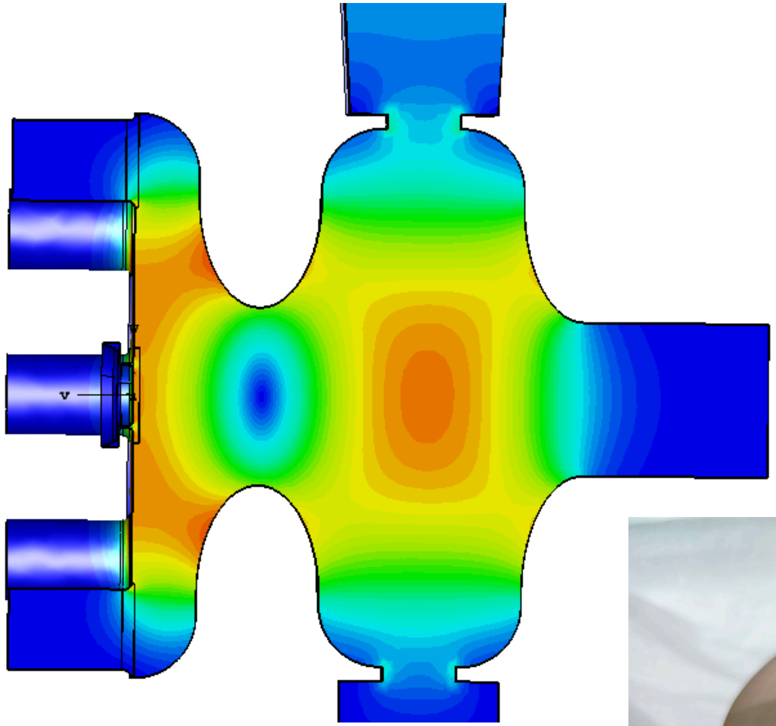


0.35 mm rms

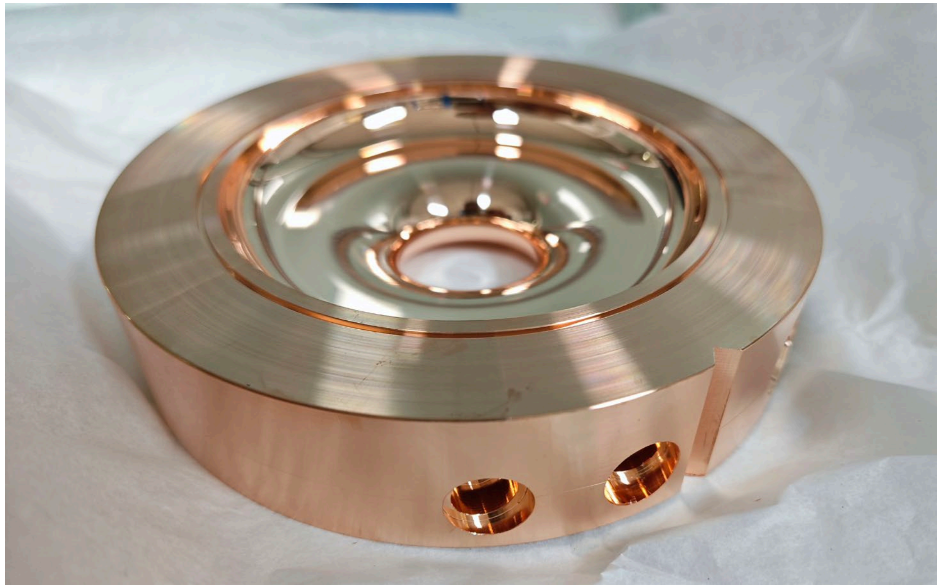


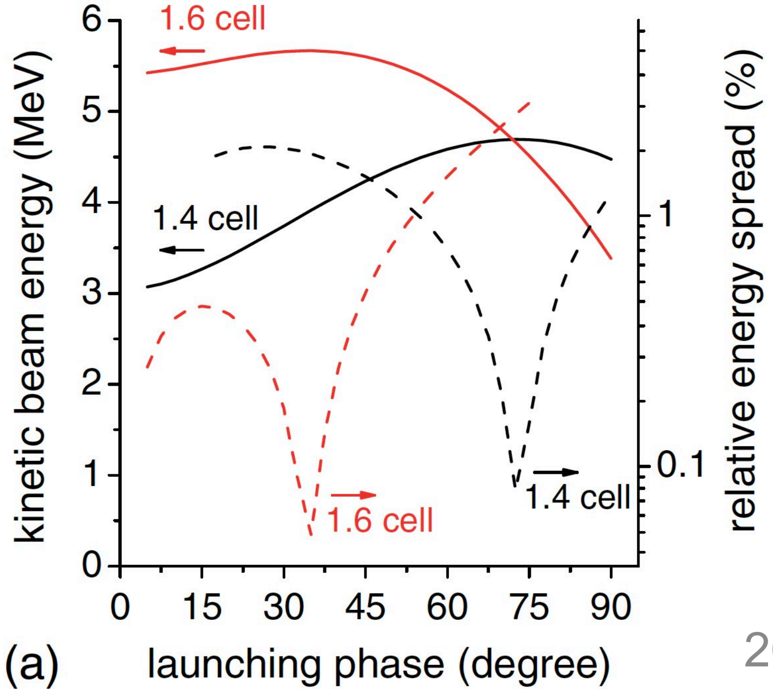


A New 1.4-cell gun under fabrication



- Launch field almost doubled, sin(30º)→sin(72º) (50% →95%), gain in beam brightness
- No laser-rf jitter-induced time-of-flight jitter (no rf compression)
- New gun ready for cold testing and then brazing





R. K. Li and P. Musumeci, PhysRevApplied 2, 024203 (2014)

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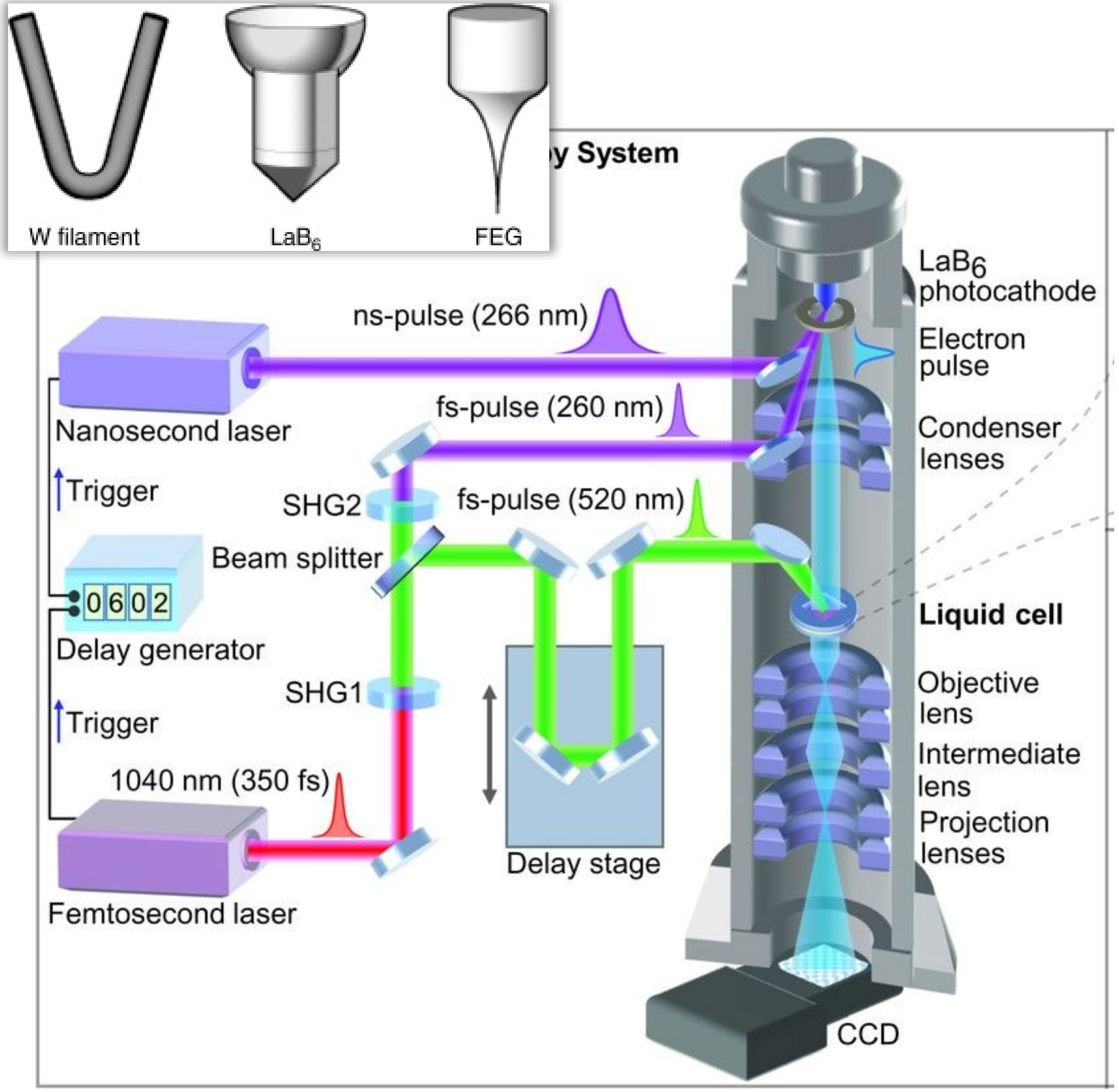
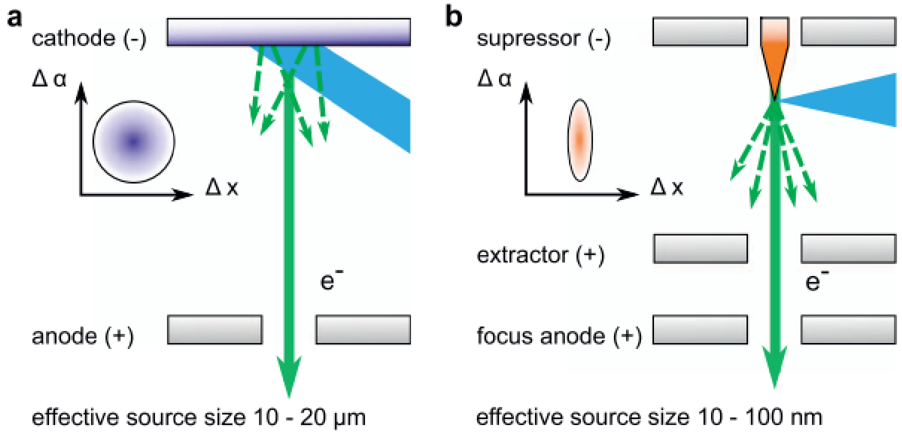
UEM and cathodes



Ji S, et al. Structural Dynamics, 4(5): 054303, 2017.
Feist A, et al. Ultramicroscopy, 176: 63-73, 2017.
Bach N, et al. Structural Dynamics, 6(1): 014301, 2019.

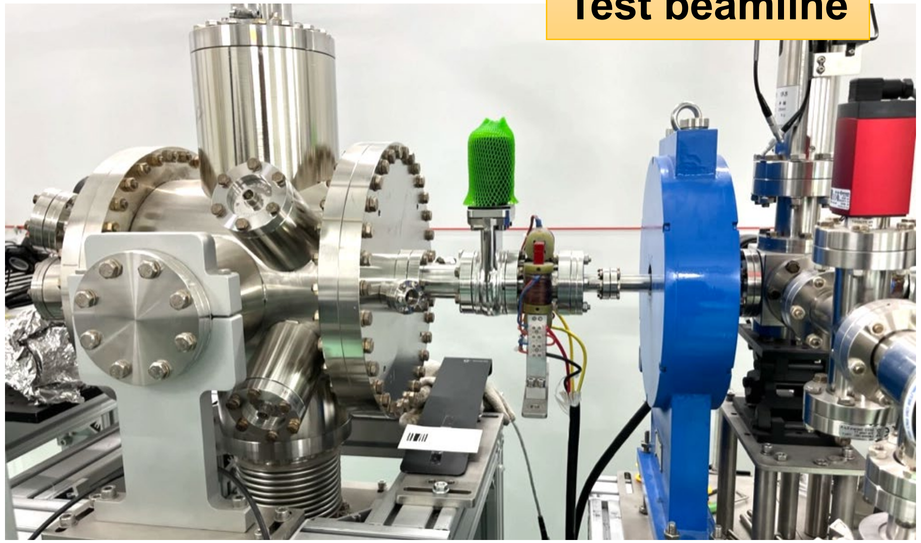


- **Most UEMs operate with photoemission from thermionic or field emission cathodes**
- **Single-shot (~10 nm, ~10ns) or stroboscopic (nm, 100s fs, eV) modes**
- **Exist unexplored parameter space**

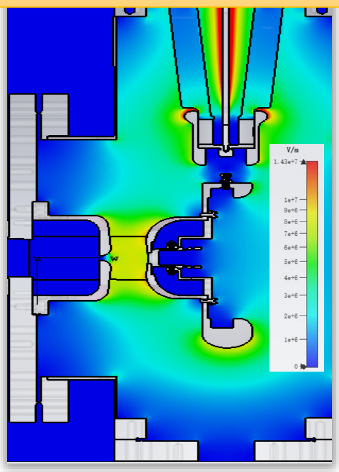
DC gun with cathode plug

- Compact 200 kV DC photocathode gun compatible with commercial TEM energies
- w/ INFN-type cathode plug and up to 7.5 MV/m extraction field
- Serve as a testbed of cathodes on ultra-flat, transparent substrate w/ front and back-illumination
- Now operates at 200 kV with low 10^{-8} Pa vacuum

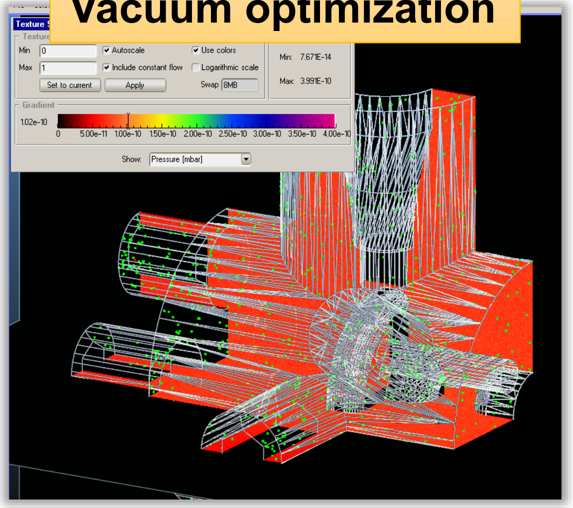
Test beamline



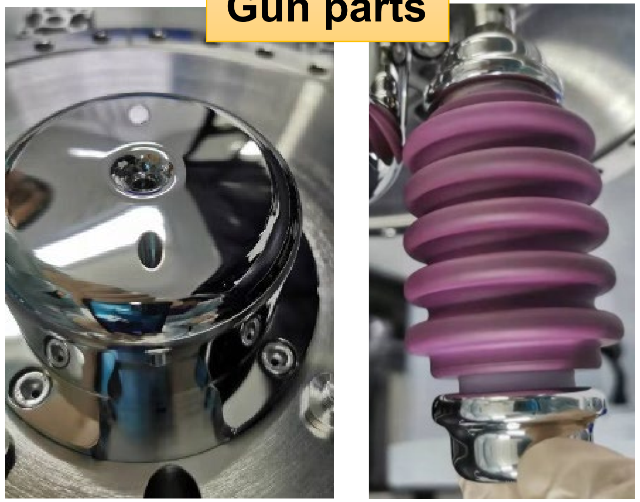
Field optimization



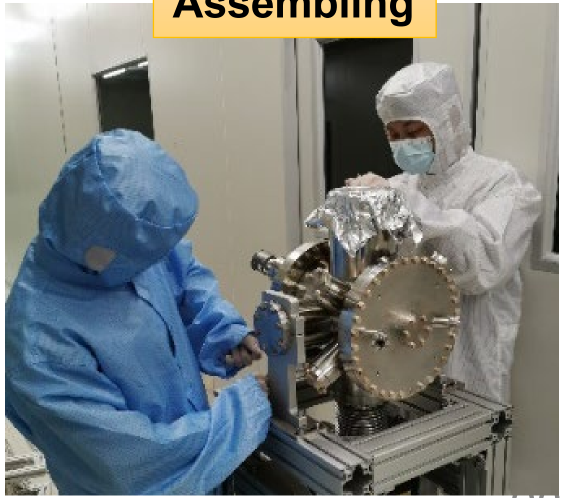
Vacuum optimization



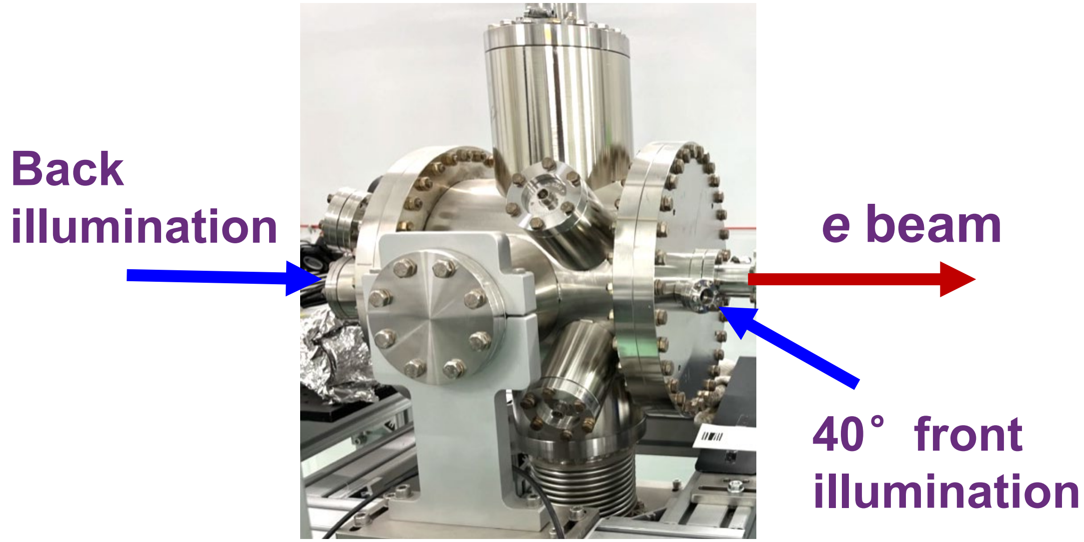
Gun parts



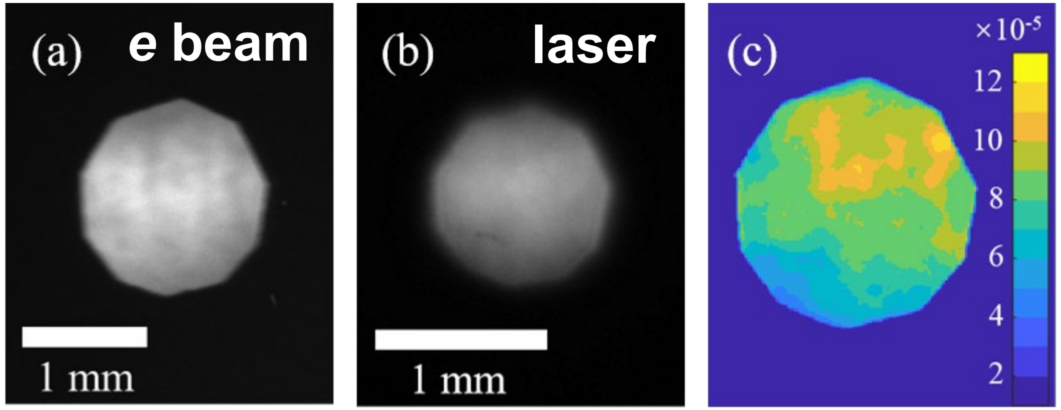
Assembling



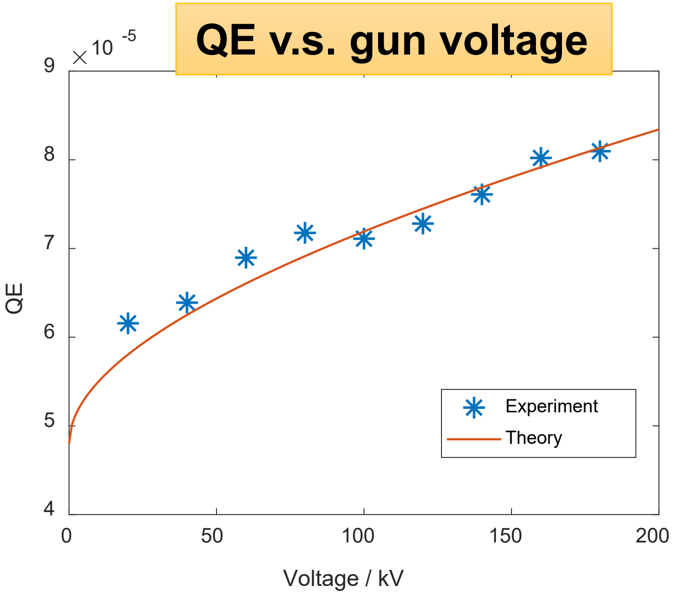
Front-illumination - QE

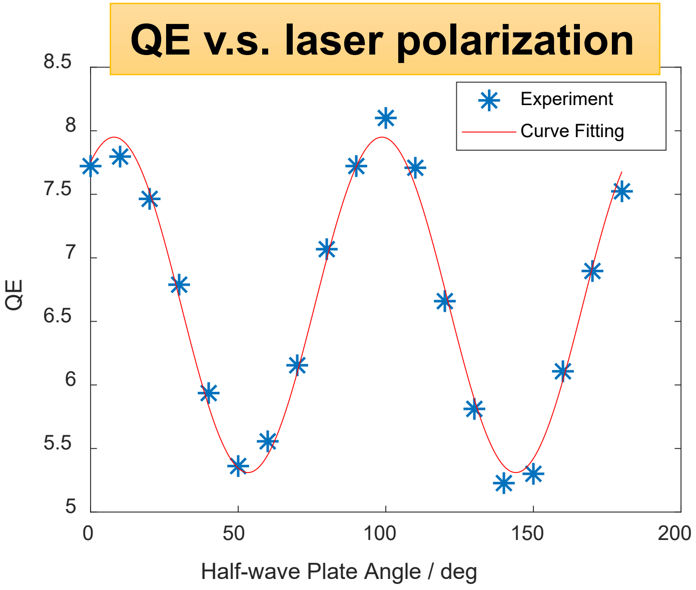


QE map by comparing e-beam and VCC images



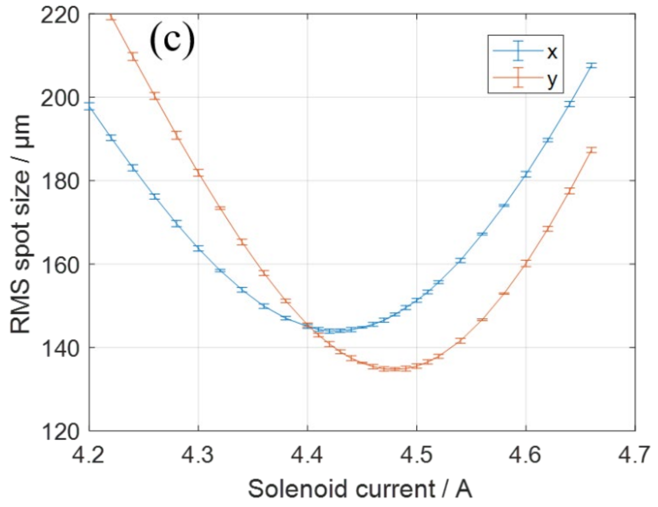
- 100 ns, 266 nm, 20 kHz laser
- 10 nm thick Cu film on UV grade quartz substrate
- QE varies from 6-8×10^{-5} for different gun gradient
- Polarization dependent QE variation (35% drop)





Front-illumination - MTE

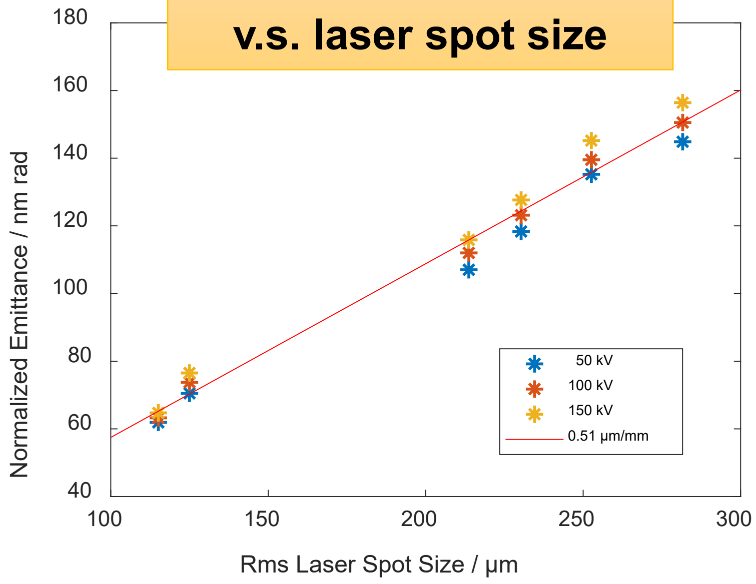
- **Emittance measured with solenoid scan**
- **Emittance varies between 60-160 nm-rad, not limited by beam profile PSF**
- **Measured $\varepsilon_{thermal}$ ~0.5 μm/mm**
- **Work function fitted to be ~4.32 eV**



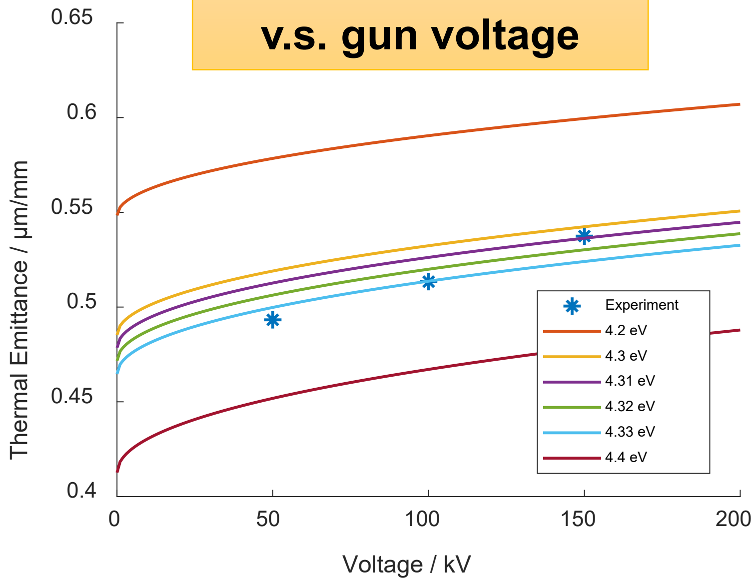
Solenoid scan

measured beam size w/ fitting, 280 μm rms laser spot size and 50 kV gun voltage

Norm. beam emittance v.s. laser spot size



Thermal emittance v.s. gun voltage

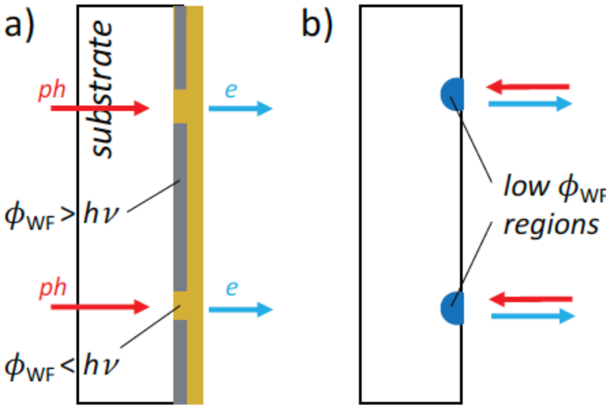


Voltage/kV	$\varepsilon_{thermal}$/μm/mm
50	0.493
100	0.513
150	0.537

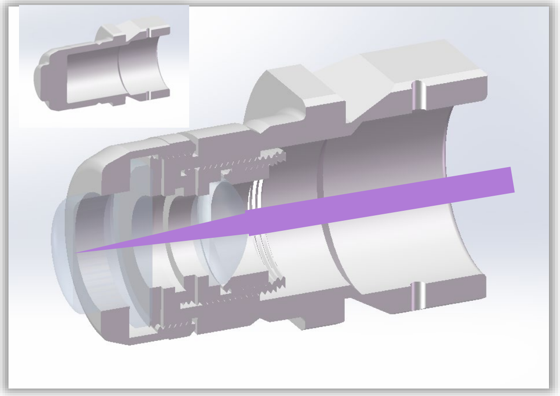
D. H. Dowell and J. F. Schmerge, PRST-AB. 12, 1 (2009).
D. H. Dowell et al, PRST-AB. 9, 1 (2006).

Back-illumination

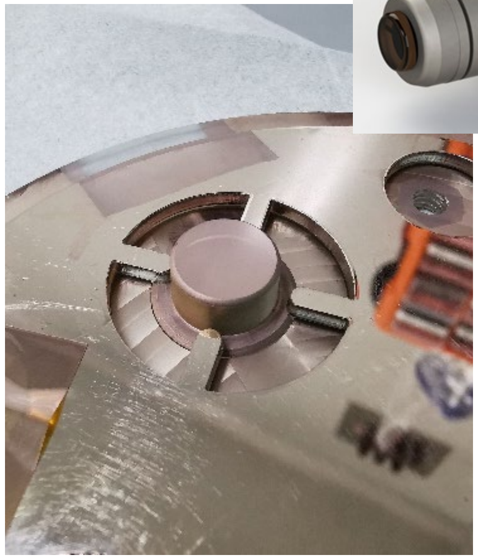
- **Back-illumination to allow small emission area and new geometries (similar schemes demonstrated in DC guns for UED, talk at 2018 P3)**
- **No front/normal incident mirrors close to the beam to minimize beamline length and avoid charging**
- **Measured minimal spot size ~2.9×3.6 μm rms**



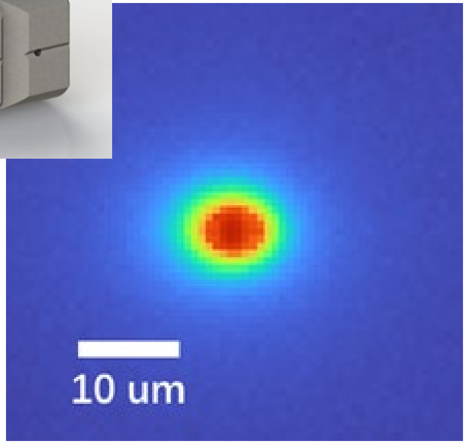
R. K. Li & X. J. Wang, PR Applied 8, 054017 (2017)



Back-illuminated plug w/ lens and transparent substrate

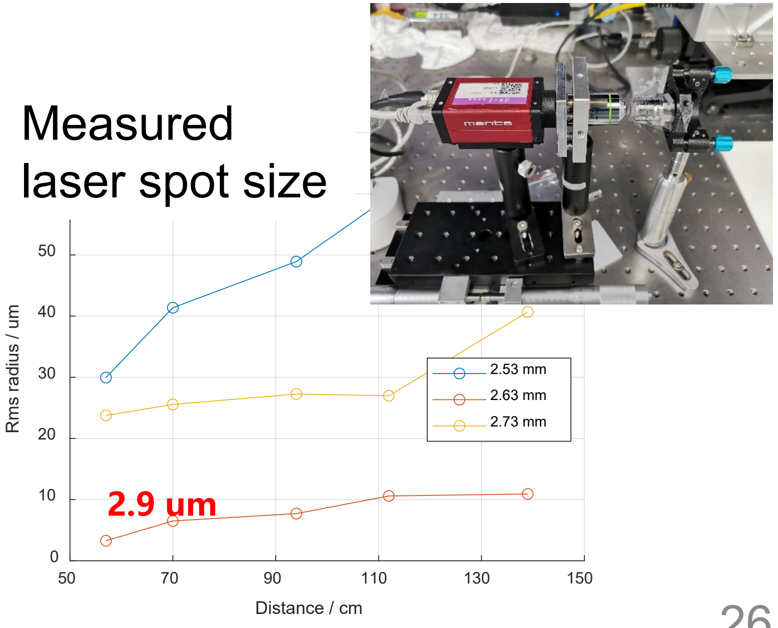


Substrate coated with Cu



Laser spot size measured at the plug surface

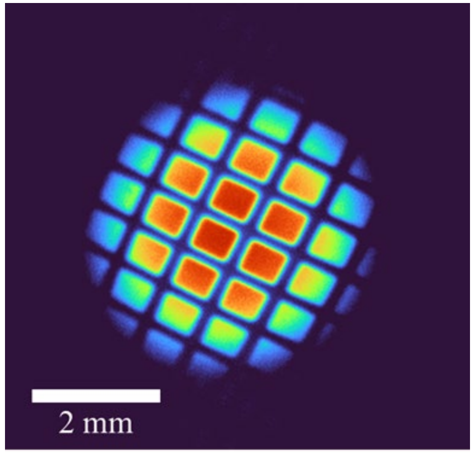
Measured laser spot size

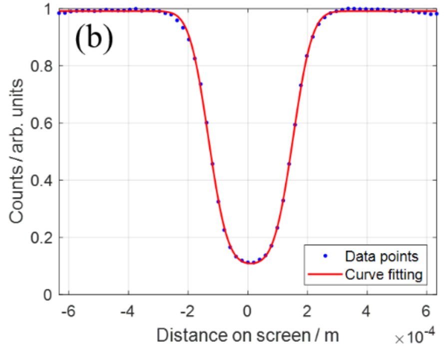


Back-illumination

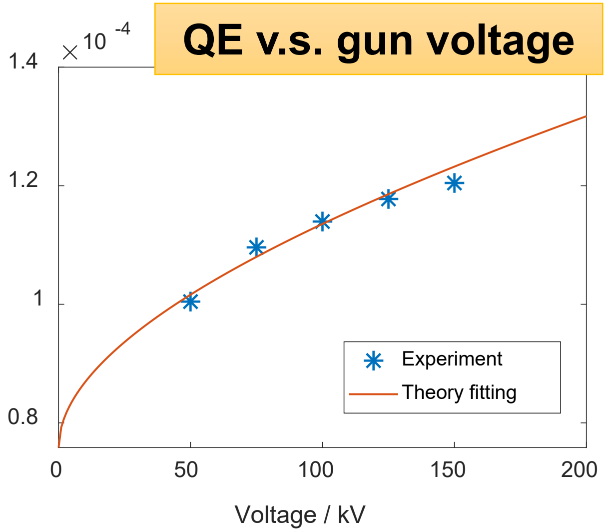
- At cathode center QE~1.2×10^{-4}, now looking into how far from laser damage threshold and the virtual cathode limit
- Measured <1.8 nm-rad beam emittance
- No dependence on laser power, indicating negligible heating or damaging effects
- Thermal emittance ~0.56 μm/mm

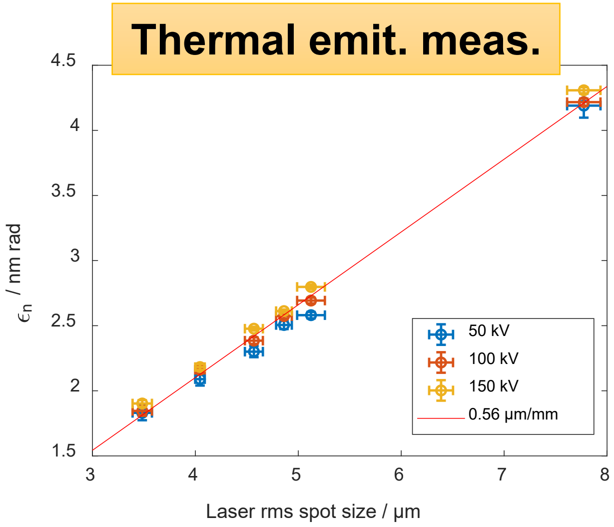
Grid method for very low emit. meas.

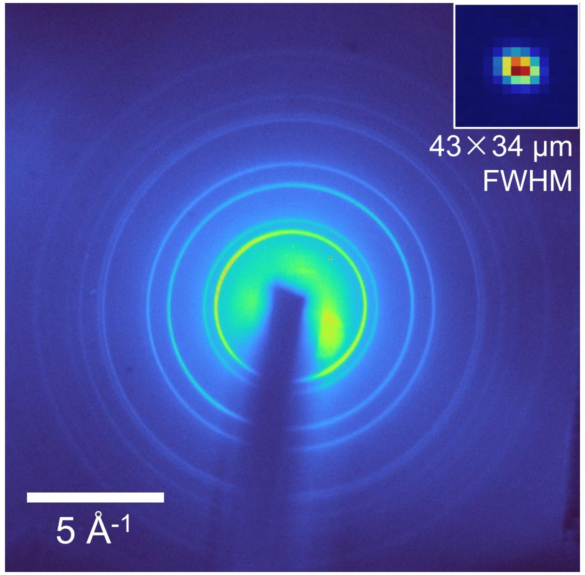




$$g(x) \propto \mathrm{erf}\left(\frac{x+Ma/2}{\sqrt{2}L\sigma_{x'}}\right) - \mathrm{erf}\left(\frac{x-Ma/2}{\sqrt{2}L\sigma_{x'}}\right),$$







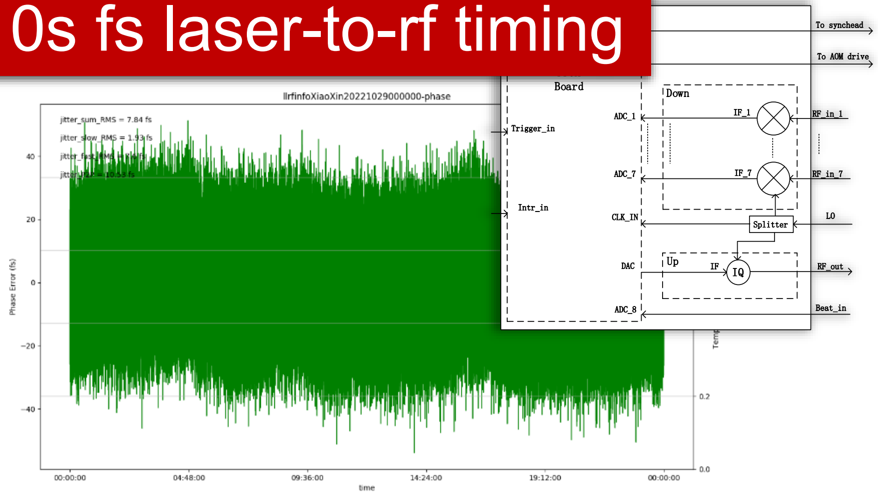
- DP of an Al film with 2 nm-rad beam
- Expected q-resolution ~10 times better, if not limited by the screen PSF

清華大學 Tsinghua University

New beamline for bright source and beam R&D

<30 ppm solid-state modulator

10s fs laser-to-rf timing



Y. Q. Jia, PhD thesis, Tsinghua University, 2023

High stability and flexibility beamline for photocathodes and e-beam studies

Summary and outlook

- Many exciting possibilities with photocathodes and sources
- Study in real gun environments advanced photocathode materials and geometries
- Explore high current density regimes with high stability, also push towards pm-rad and attosecond

Thank you for your attention!