

# Future Light Sources 2023

67th ICFA  
Advanced  
Beam Dynamics  
Workshop  
FLS 2023

28 August – 1 September 2023  
Swiss Museum of Transport  
Lucerne, Switzerland  
[www.fls23.ch](http://www.fls23.ch)



清華大學  
Tsinghua University

## An ultra-high vacuum, high-gradient rf gun and advanced photocathode studies

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Tsinghua University  
2023/8/31

# Acknowledgement



清華大學  
Tsinghua University

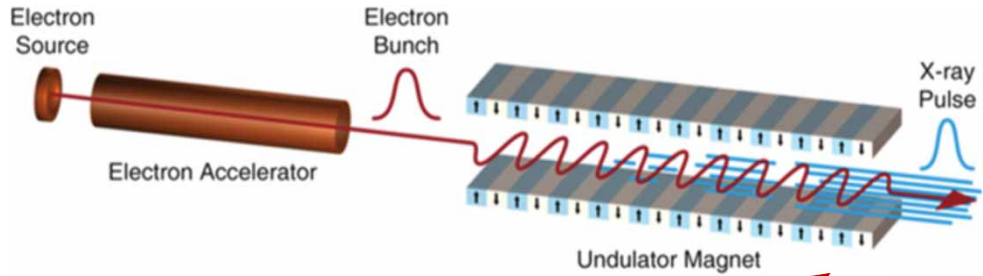
- **Collaboration and stimulating discussions with many colleagues**
- **Colleagues at Tsinghua:** C. X. Tang, H. B. Chen, W. H. Huang, Y. C. Du, L. X. Yan, L. M. Zheng, J. R. Shi, H. Zha etc.
- **Postdocs and PhD students:** P. W. Huang, Z. C. Dong, Y. M. Tan, Y. A. Wang, X. Y. Zhang, Y. N. Yang, P. Lv, Z. Y. Wang, B. T. Song etc.
- **Funding by Tsinghua University Initiative Scientific Research Program, NSFC, and MOST**

# Outline

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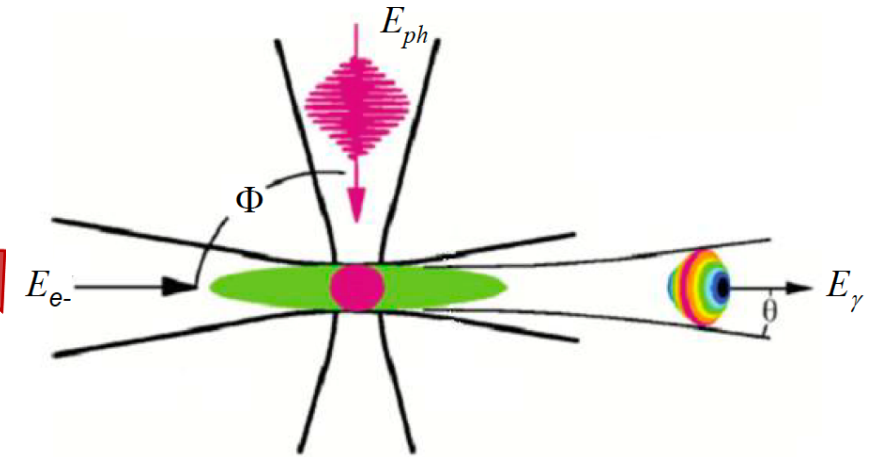
- **Introduction**
  - **Gun design and commissioning**
  - **Cathodes and beam studies**
  - **Summary and outlook**
-

## Free-electron lasers



Rev. Mod. Phys. 88, 015006 (2015)

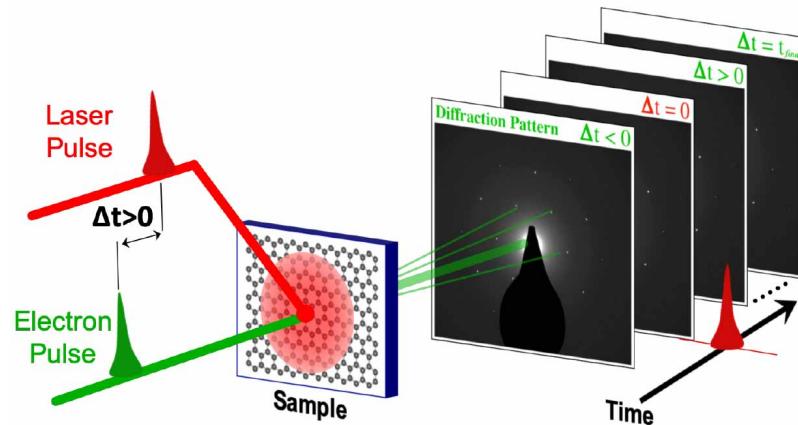
## Inverse Compton scattering



Science 274, 236 (1996)

high-brightness,  
ultrashort e-beams

## Ultrafast electron diffraction

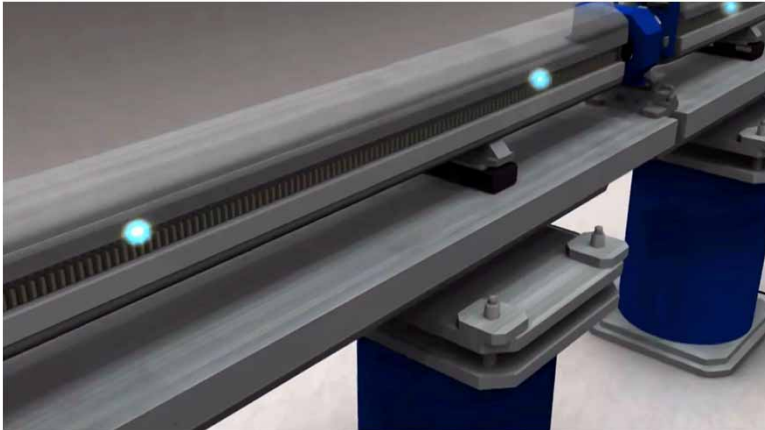


Other applications:

ERL, spin-polarized sources,  
electron cooling

Rev. Mod. Phys. 94, 045004 (2022)

## XFEL: $\sim 0.1$ $\mu\text{m-rad}$

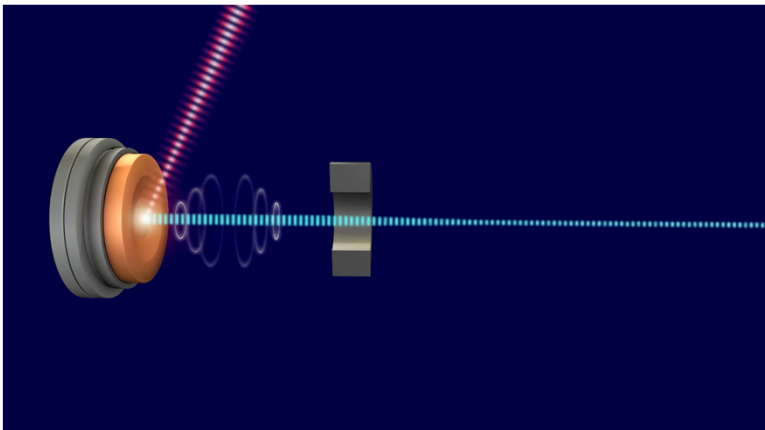


- Low normalized emittance
- High current (kAmp)
- Beam charge ranging from 10 pC - 1 nC

$$\frac{\epsilon_n}{\gamma_0} \leq \frac{\lambda}{4\pi}$$

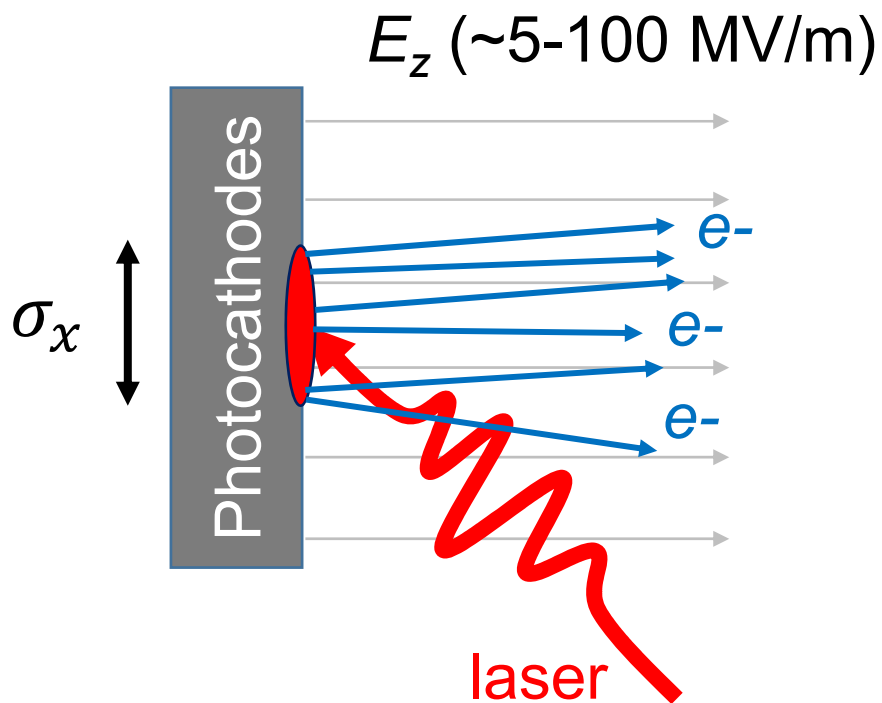
$$\rho = \left[ \frac{1}{16 I_A} \frac{I_e K_0^2 [\text{JJ}]^2}{\gamma_0^3 \sigma_x^2 k_u^2} \right]^{1/3}$$

## UED: $\sim 0.01$ $\mu\text{m-rad}$



$$B_{6D} \propto \frac{N \cdot f_{\text{rep}}}{(\sigma_x \cdot \gamma \sigma_{x'})^2 \cdot \sigma_t \cdot \sigma_\gamma}$$

← **signal level** (points to  $N$ )  
← **rep. rate, depends on samples and processes** (points to  $f_{\text{rep}}$ )  
← **sample size** (points to  $\sigma_x$ )  
10s of  $\mu\text{m}$  or less  
← **q-resolution** (points to  $\gamma \sigma_{x'}$ )  
1 mrad or smaller  
← **bunch length** (points to  $\sigma_t$ )  
100 to few fs  
← **energy spread** (points to  $\sigma_\gamma$ )  
10<sup>-3</sup> or smaller



**4D beam brightness**

$$B_{4D} \propto f_e \frac{N}{(\sigma_x \cdot \sqrt{\text{MTE}})^2}$$

Mean Transverse Energy  $\text{MTE} = \frac{1}{2} m v^2$

Preservation of the brightness  $f_e$

$B_{4D} \propto f_e \frac{E_z}{\text{MTE}}$  for pancake ( $A \gg 1$ ) beam, where aspect ratio  $A = \frac{\sigma_x m_e}{\sigma_t^2 E_z e}$   
PRL 102, 104801

$B_{4D} \propto f_e \frac{E_z^{3/2}}{\text{MTE}} \frac{\sigma_t}{\sigma_x^{1/2}}$  for cigar shape ( $A < 1$ ) beam  
PRAB 17, 024201



$E_z$ , Higher  
gradient

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

$f_e$ , Brightness  
preservation

Emittance compensation  
Beam shaping  
Aberration control  
Precise characterization

**Future  
electron  
sources**

**Lower MTE**

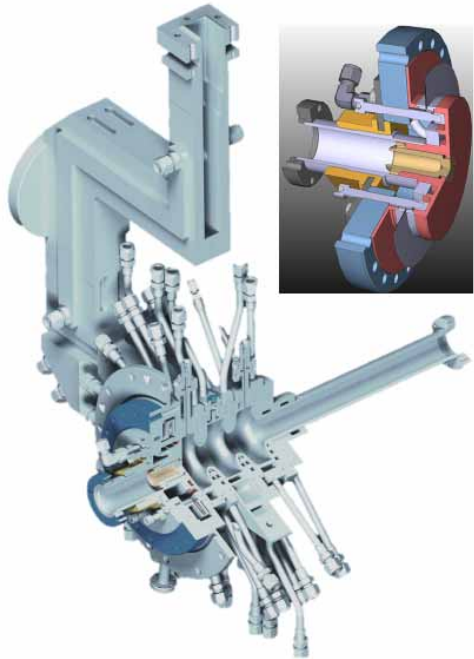
New cathode material  
Cooling  
Tuning laser wavelength  
Cathode by design

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

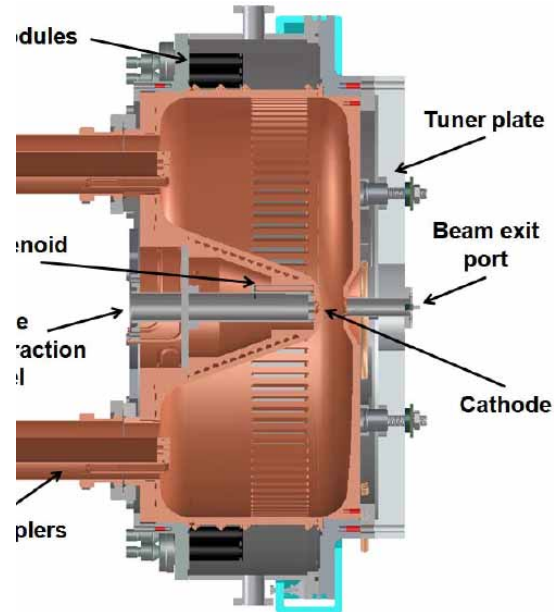


- What we are using now:
  - High  $E_z$  (20-100 MV/m) + high MTE (eg. Cu、 $\text{Cs}_2\text{Te}$ ,  $\sim 1$  mrad)
  - Low  $E_z$  ( $\sim 10$  MV/m) + low MTE (eg. multi-alkali antimony  $\ll \sim 0.5$  mrad)

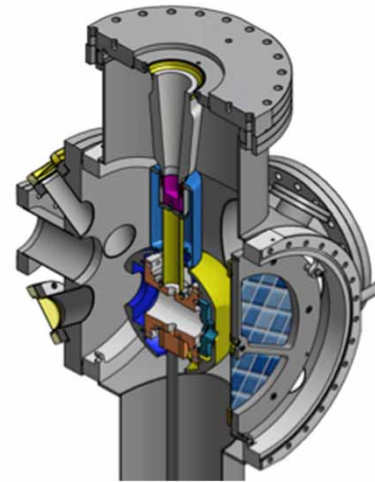
## NC pulsed



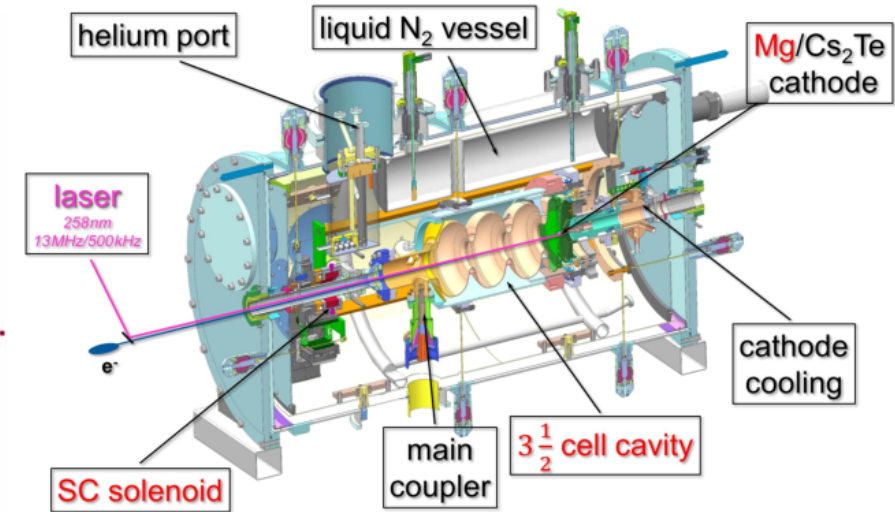
## NC CW



## DC



## SRF

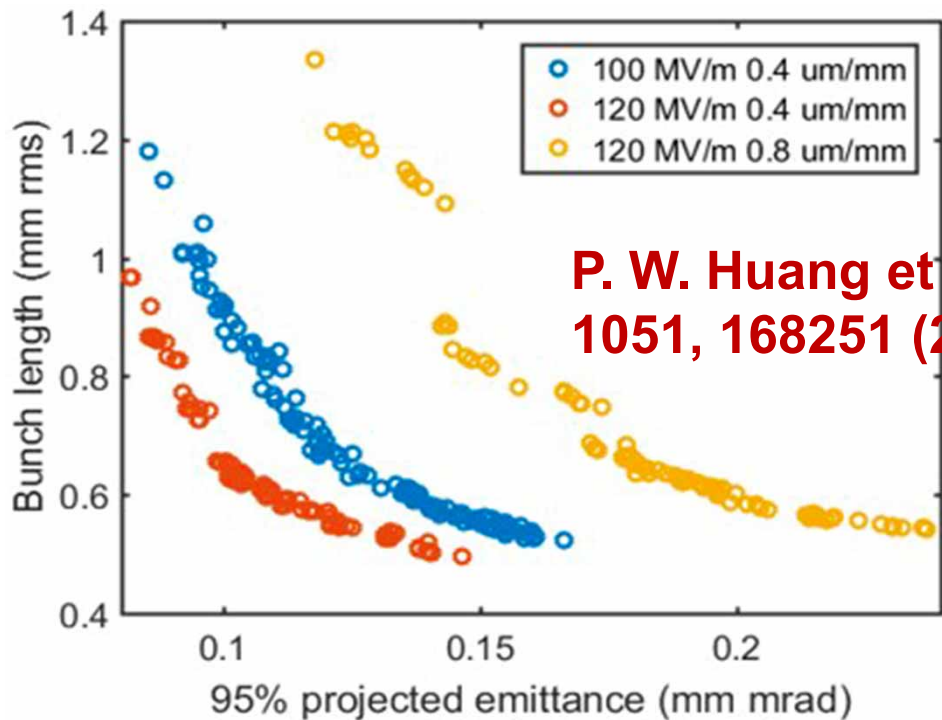




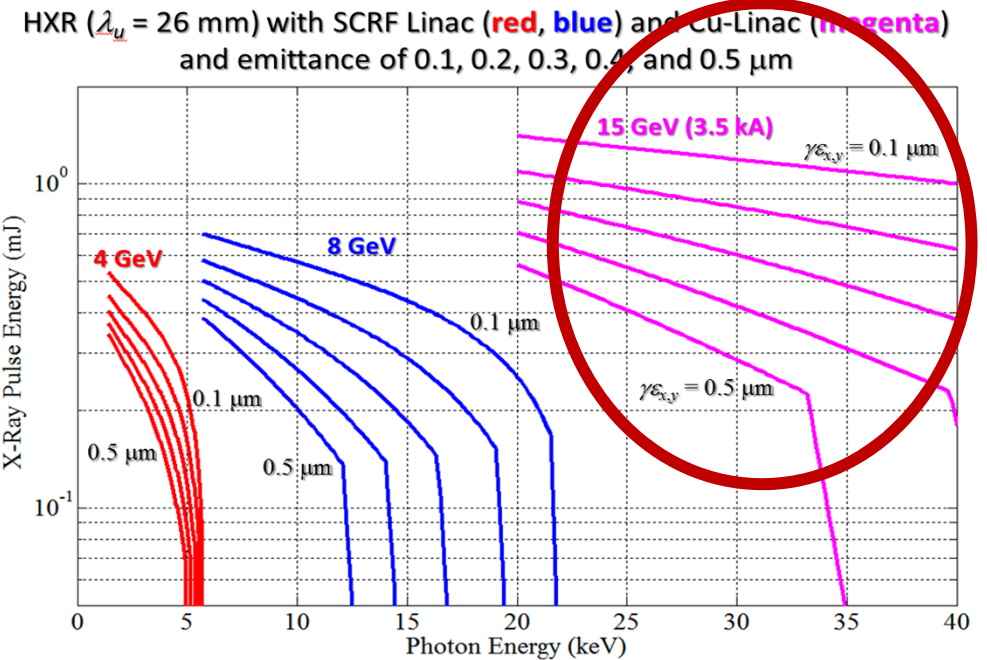


# Photoemission sources towards the future

- 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)



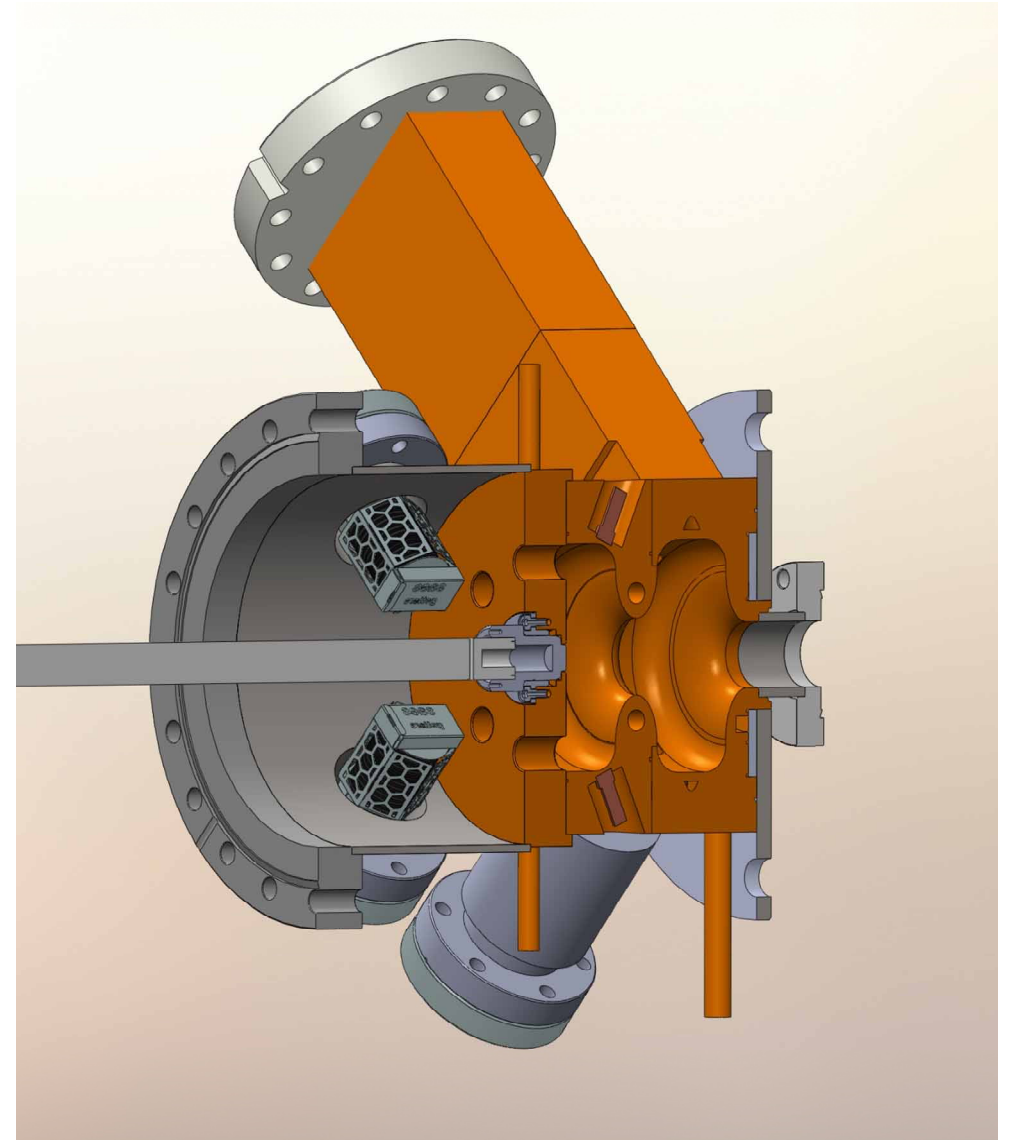
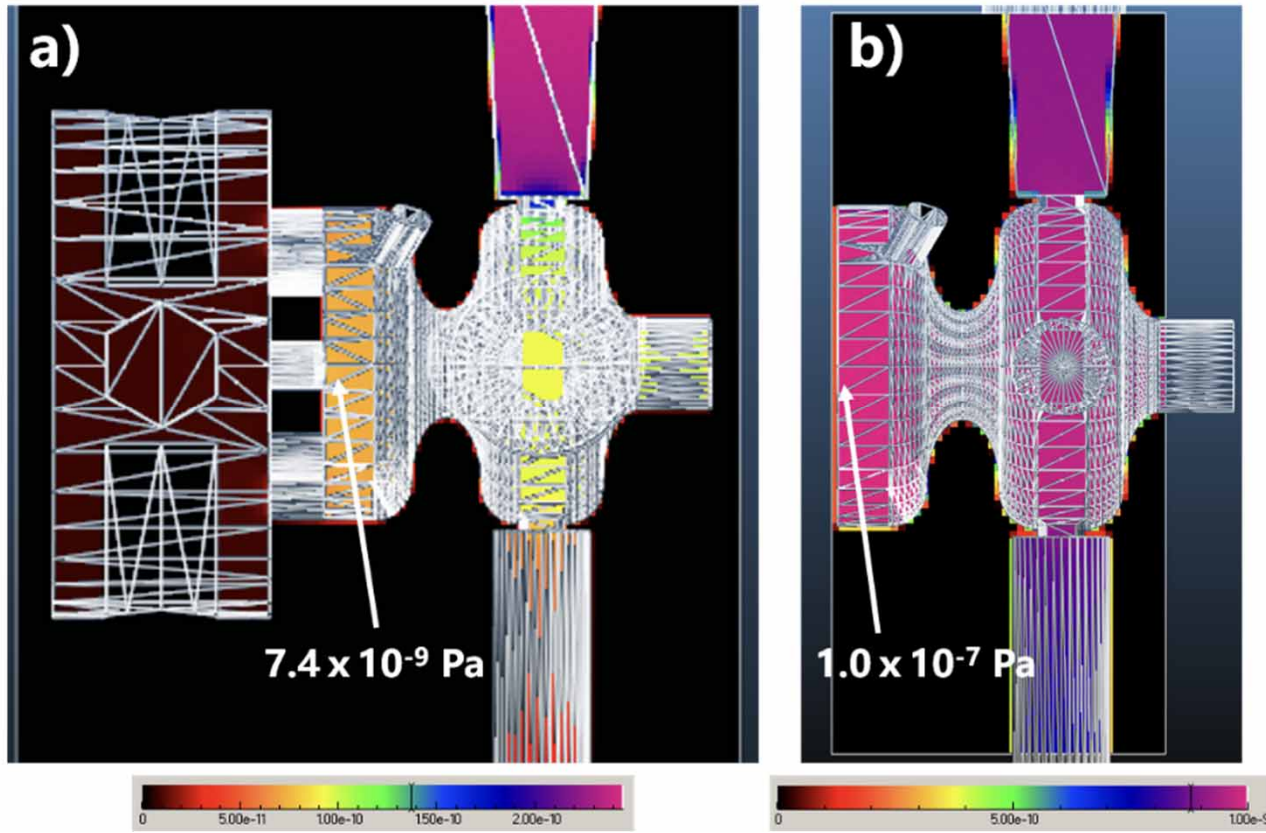
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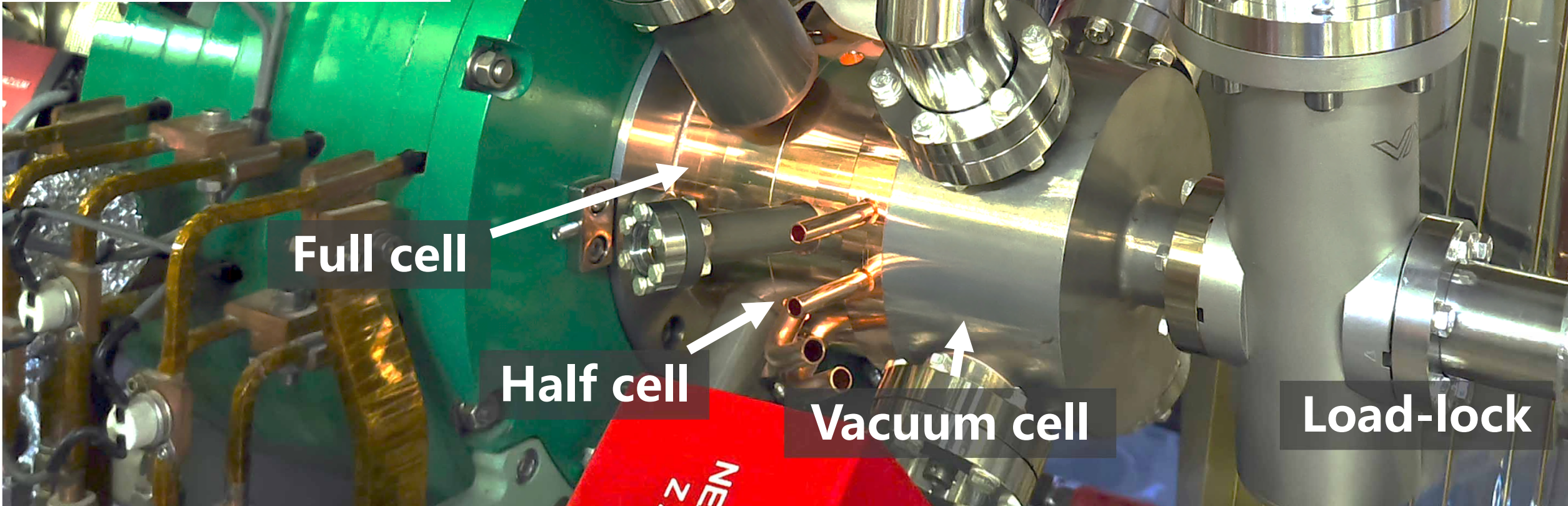
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**>10 fold improvement in vacuum  
at cathode surface**

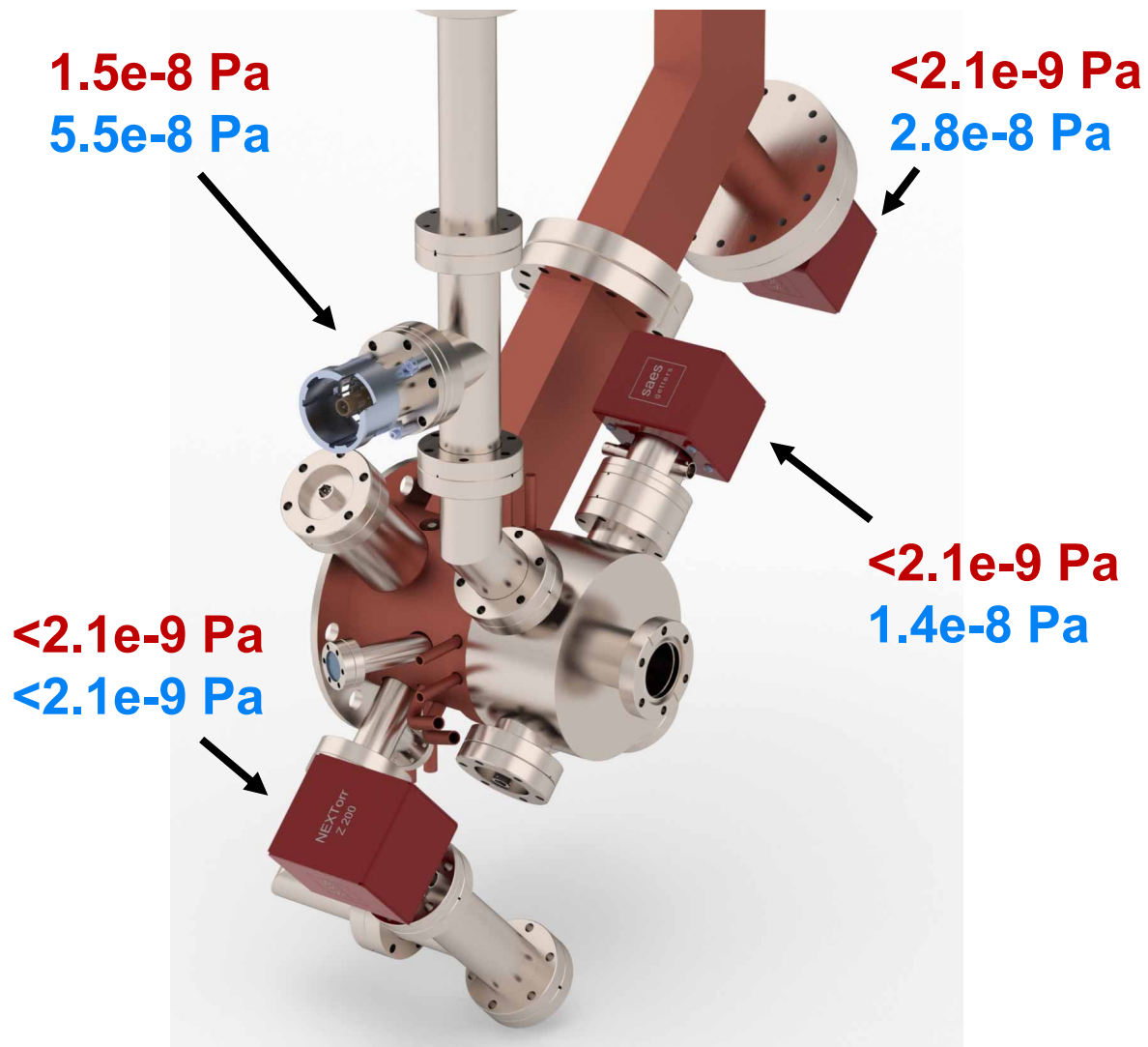


P. W. Huang et al., NIMA 1051, 168251 (2023)

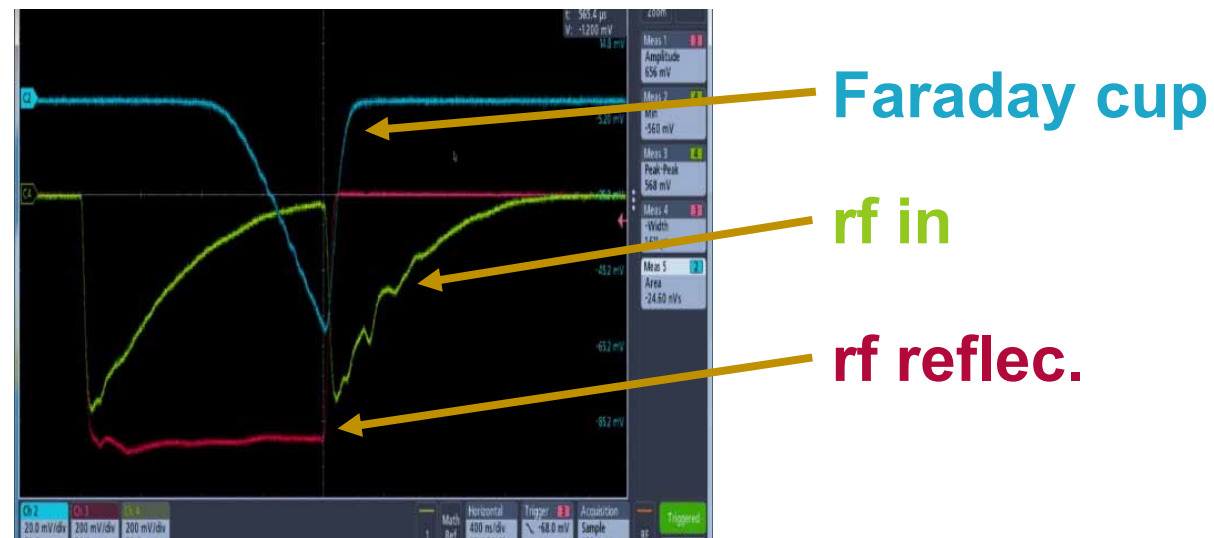




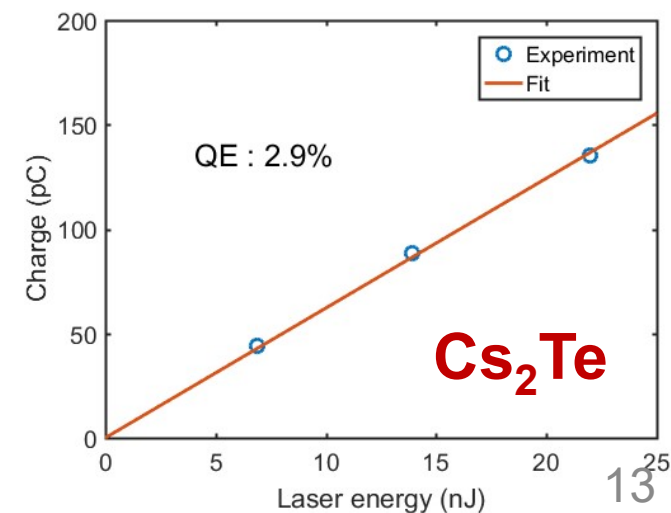
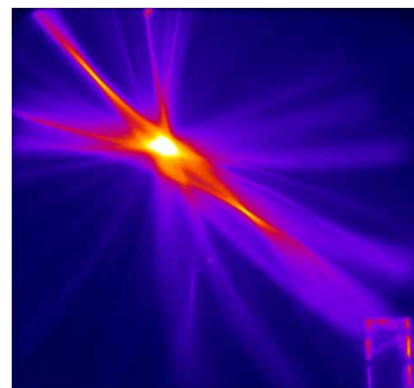
## Base/operation pressure



## rf conditioning after 24 hrs

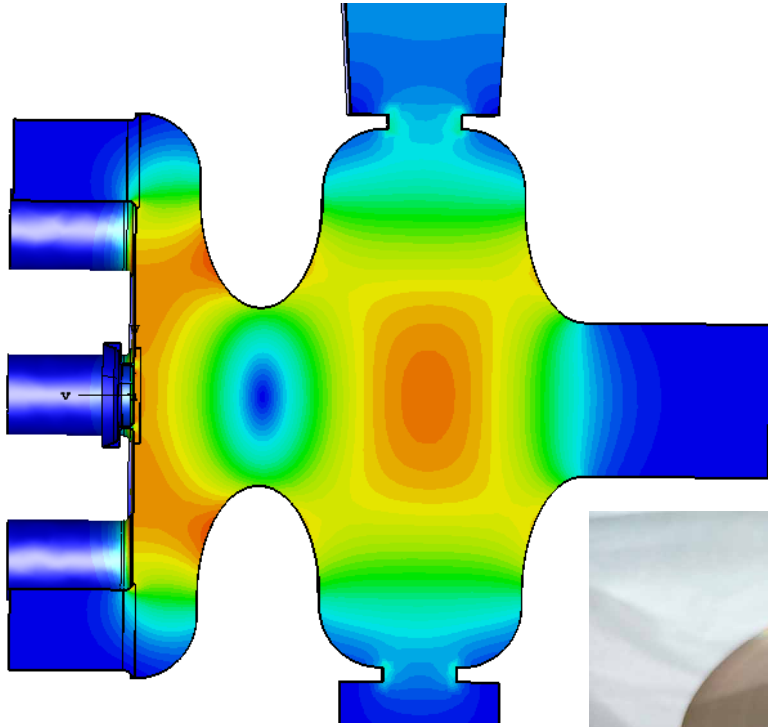


Dark current 0.5 nC @  
 $E_z \sim 105$  MV/m

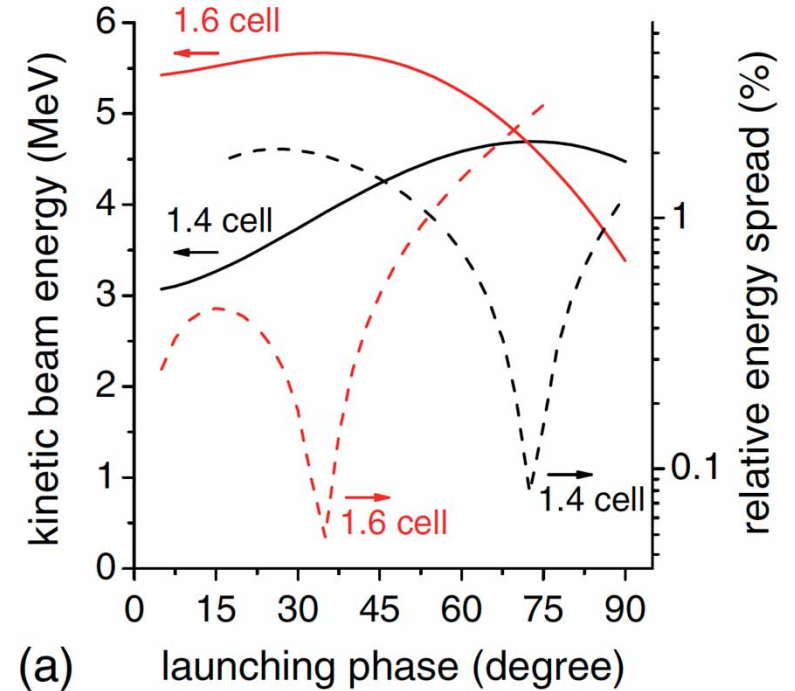
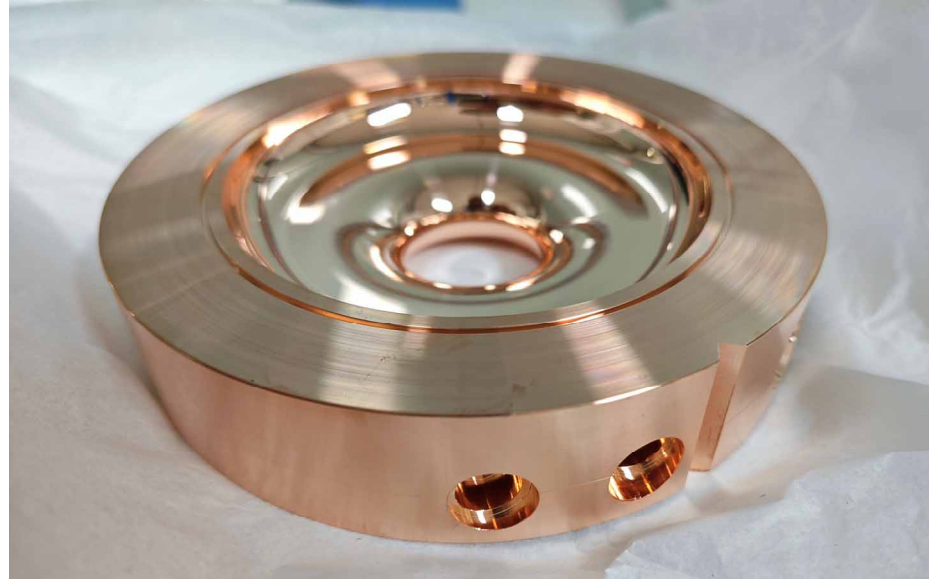




# A New 1.4-cell gun under fabrication



- Launch field almost doubled,  $\sin(30^\circ) \rightarrow \sin(72^\circ)$  (50%  $\rightarrow$  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



# Outline

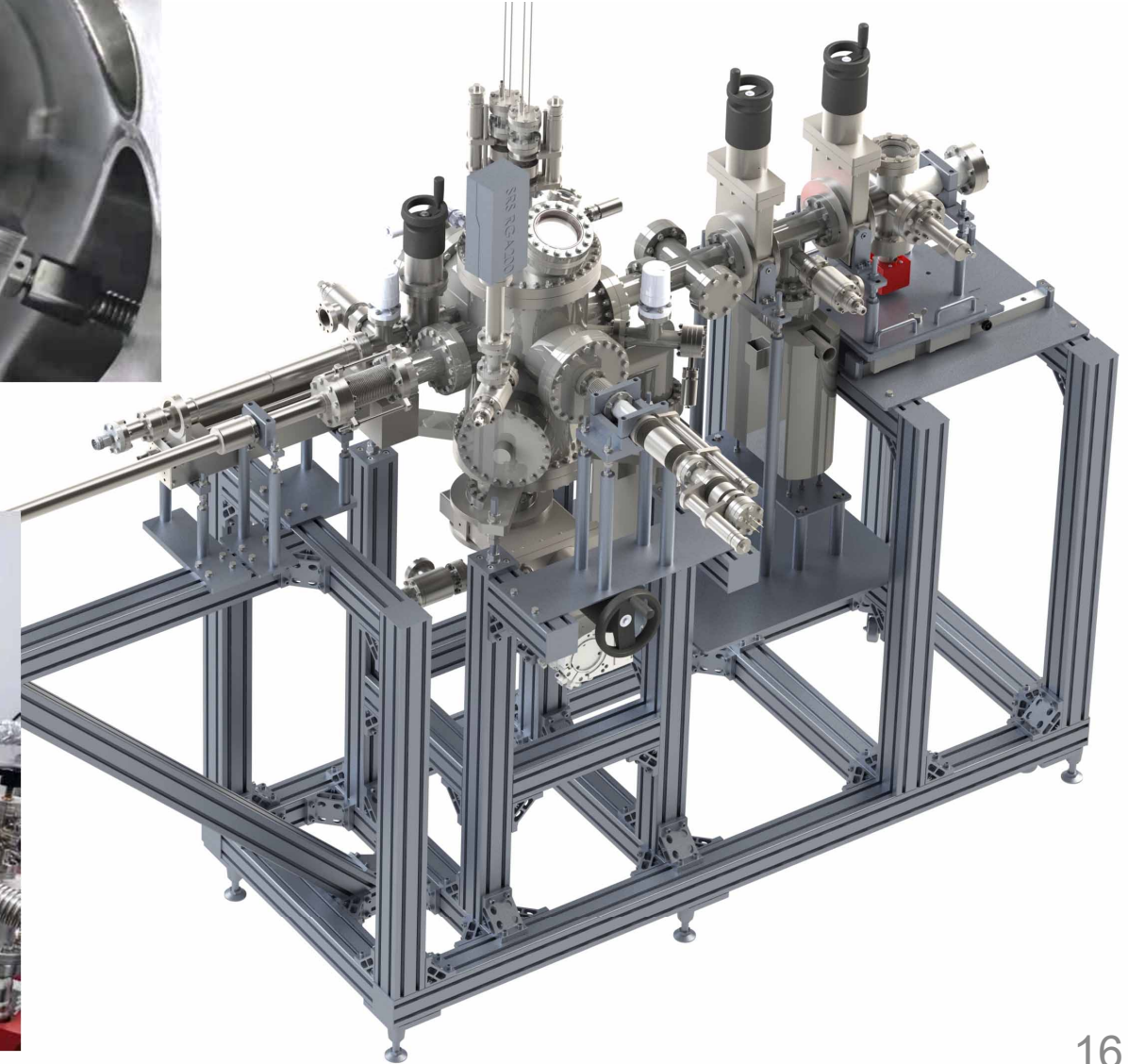
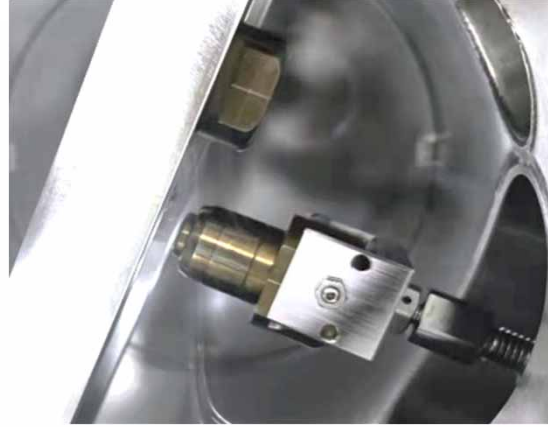
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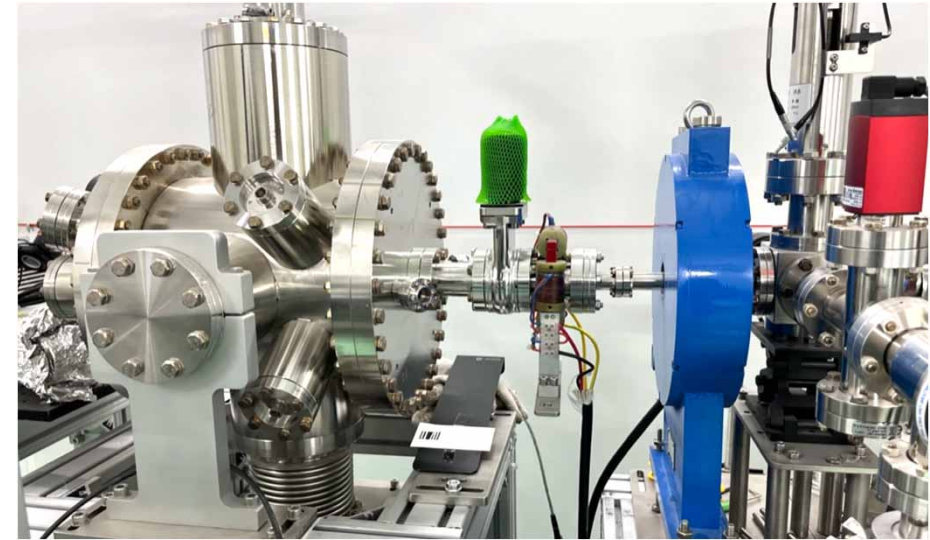
# Photocathode deposition system

- $\text{Cs}_2\text{Te}$  and multi-alkali photocathodes deposition systems
- INFN-type cathode plug compatible with many collaborators

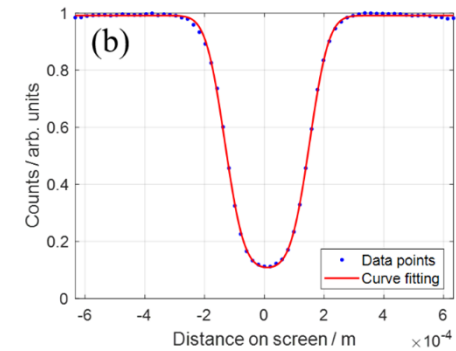
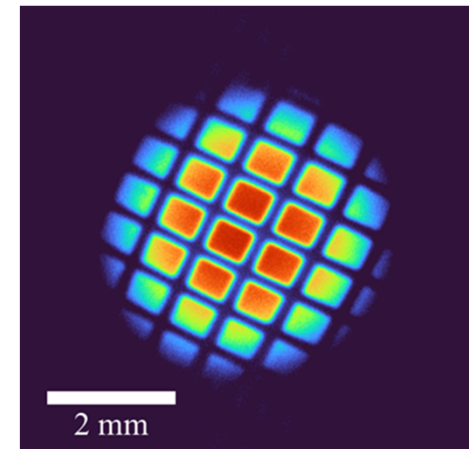
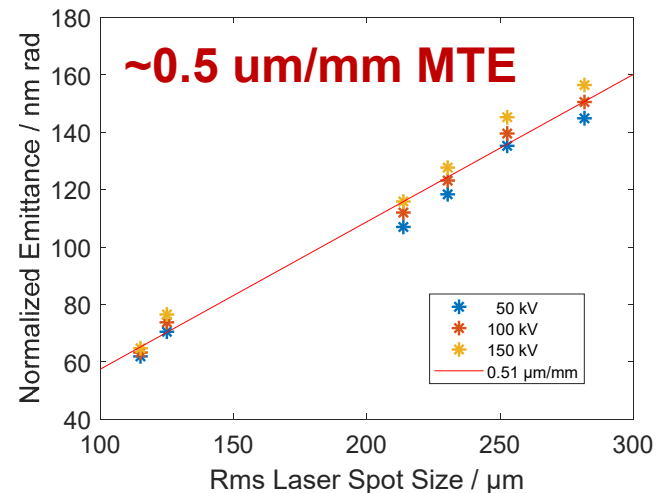
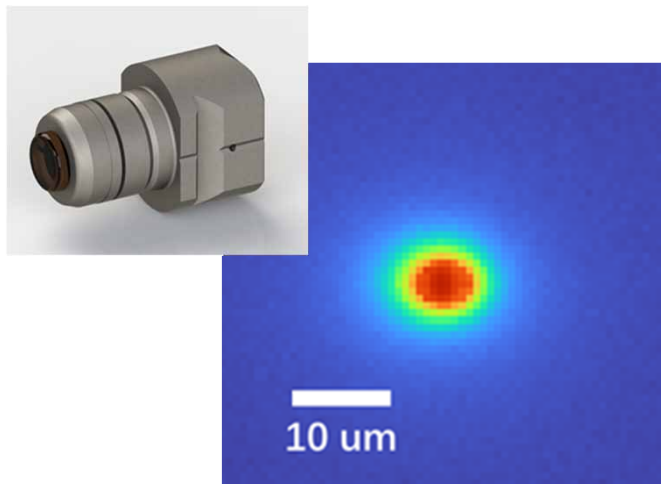




- Compact DC photocathode gun w/ INFN-type plug and up to 7.5 MV/m extraction field
- Back-illuminated plug w/  $\sim 3 \mu\text{m}$  emission area
- $\sim 0.5 \mu\text{m}/\text{mm}$  MTE from  $\sim 10 \text{ nm}$  thick Cu film
- Serve as a testbed w/ front/back illumination on ultra-flat, transparent substrate
- Plugs to be tested in rf gun

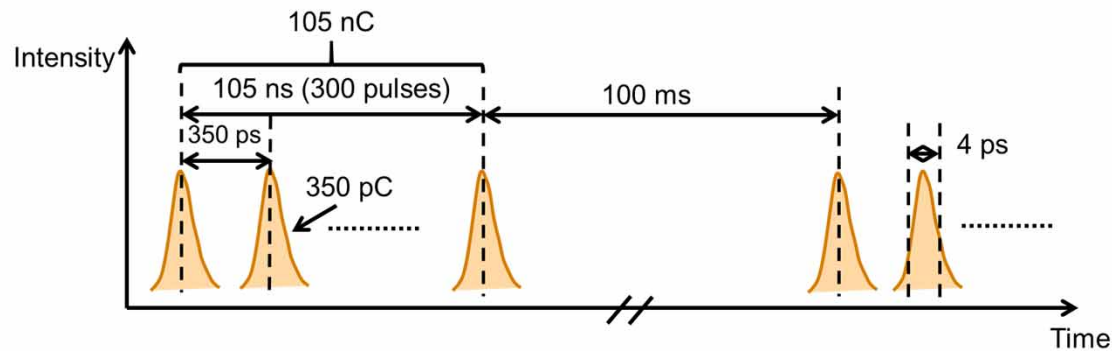


**< 2 nm-rad emittance measured w/ grid**

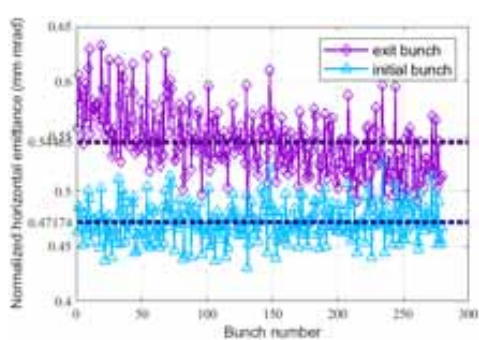


$$g(x) \propto \operatorname{erf}\left(\frac{x + Ma/2}{\sqrt{2}L\sigma_{x'}}\right) - \operatorname{erf}\left(\frac{x - Ma/2}{\sqrt{2}L\sigma_{x'}}\right)$$

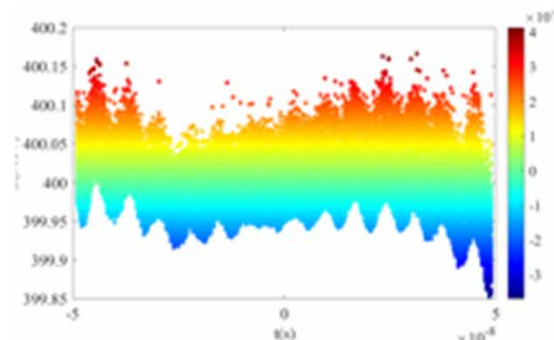
**Fill every rf cycle with an electron bunch  
(highest possible macro-pulse current)**



**Injector for a SSMB ring  
(train stretched to quasi-uniform over ~100 ns)**

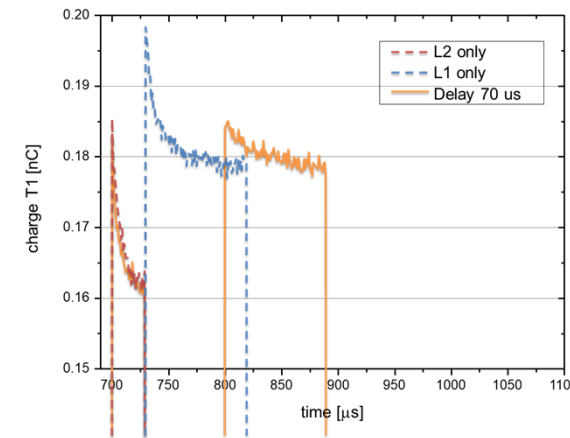


Bunch train emittance



Bunch train LPS

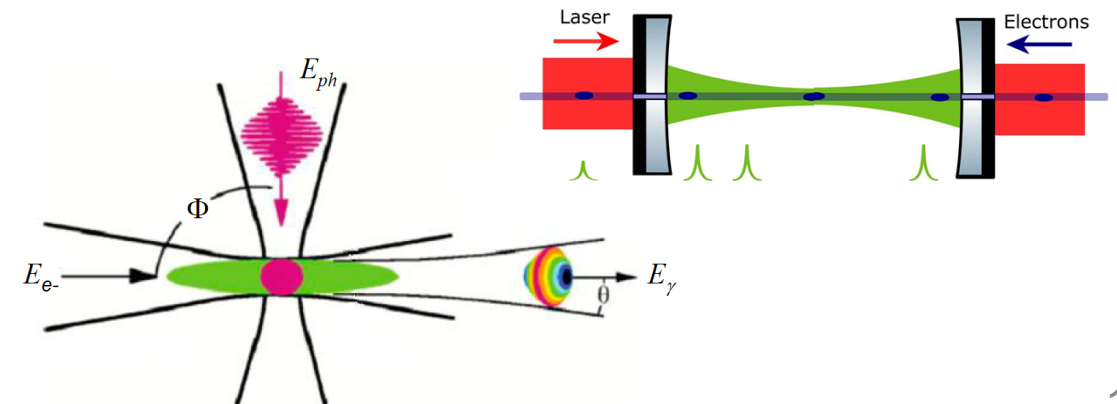
**Marco-pulse mode operation**



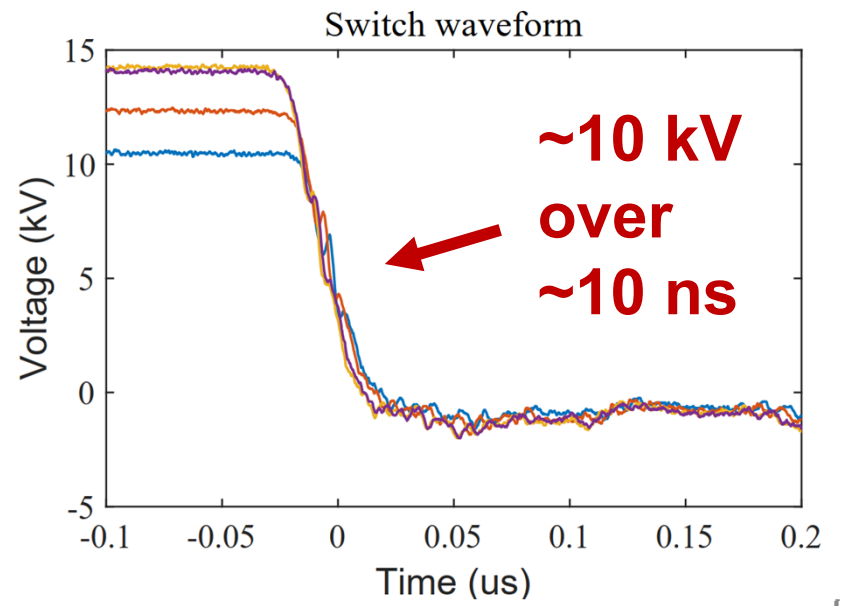
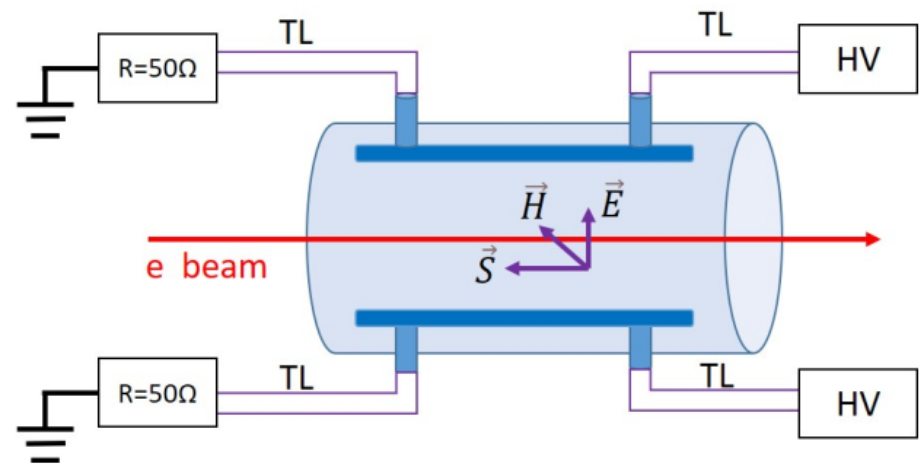
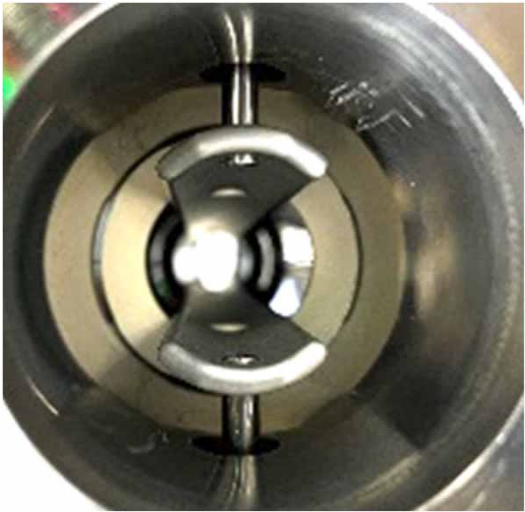
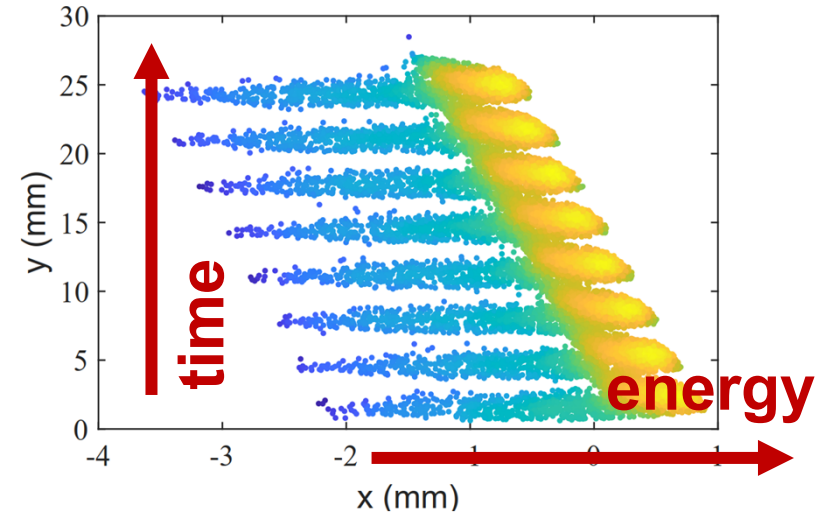
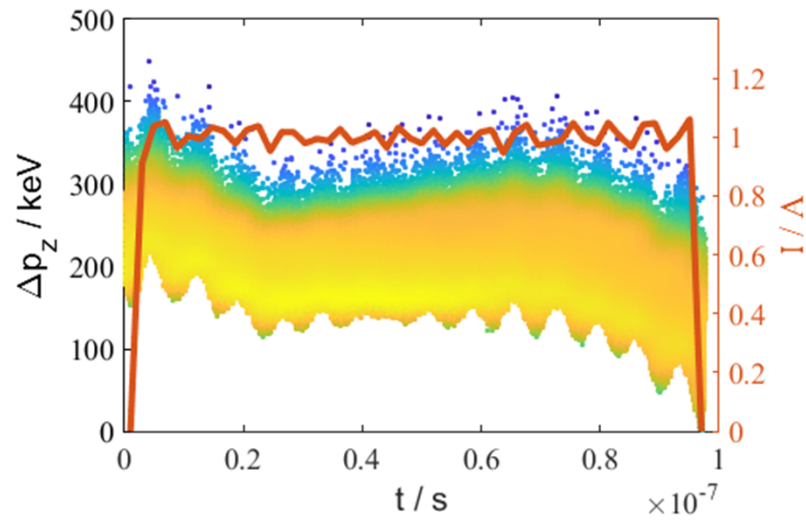
- bunch Q variation
- beam loading

Y. Chen's talk at  
2018 P3 workshop

**Inverse Compton scattering source  
(max # of ph. within up to us time window)**



## Bunch-by-bunch characterization of 350 ps spaced micro-pulse to guide injector emittance and beam-loading optimization

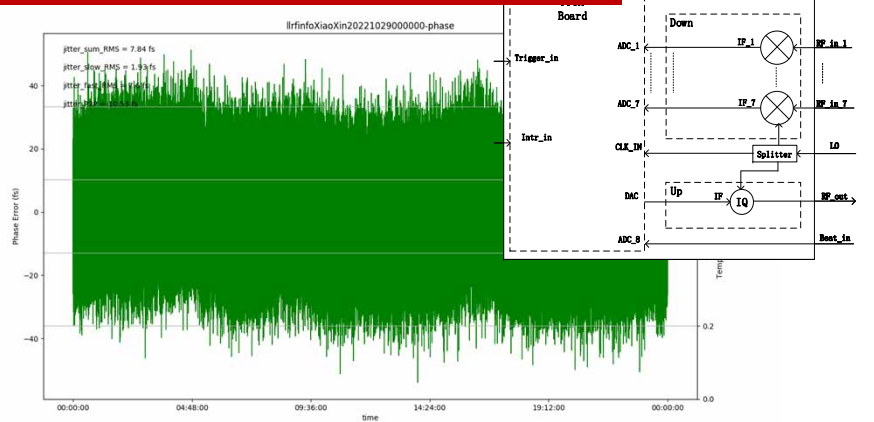


## <30 ppm solid-state modulator



- Student-run lab for high stability yet flexible, e-beam generation, control and applications

## 10 fs laser-to-rf timing





- **Combine highest possible  $E_z$  and lowest possible MTE**
- **Study in a real gun advanced photocathode materials and geometries**
- **Explore high macro-pulse current regimes with high stability, also push towards pm-rad and attosecond**

***Thank you for your attention!***