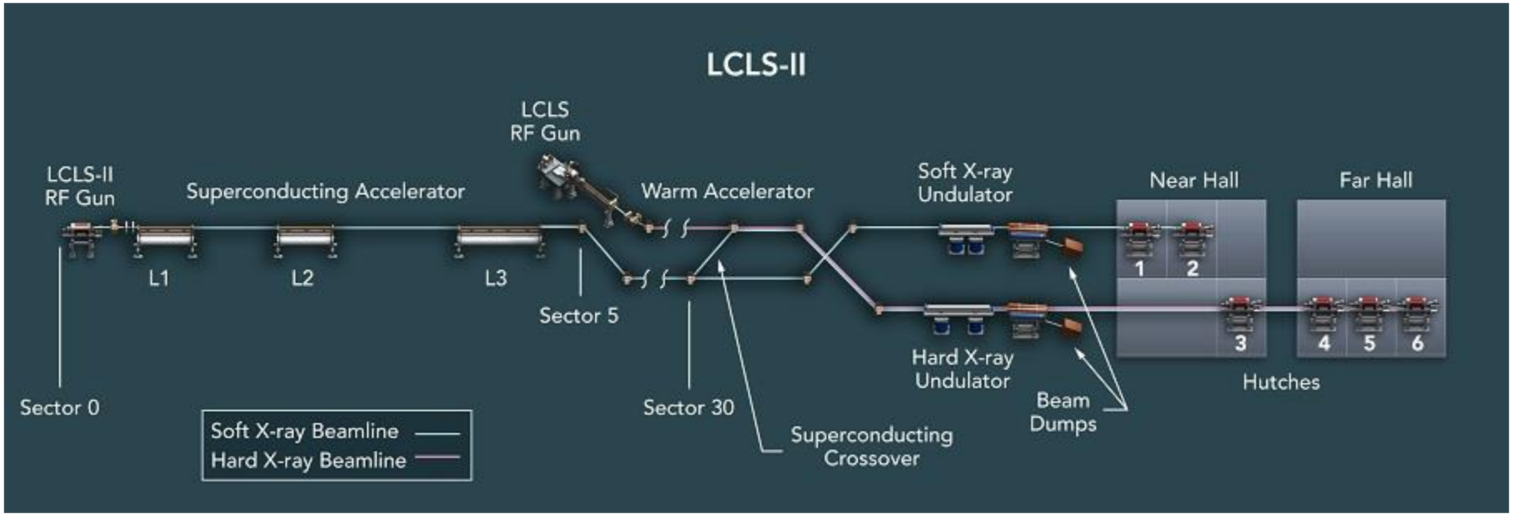
Review of experimental results from high brightness dc guns: Highlights in FEL applications

JAEA Nobuyuki Nishimori

Outline

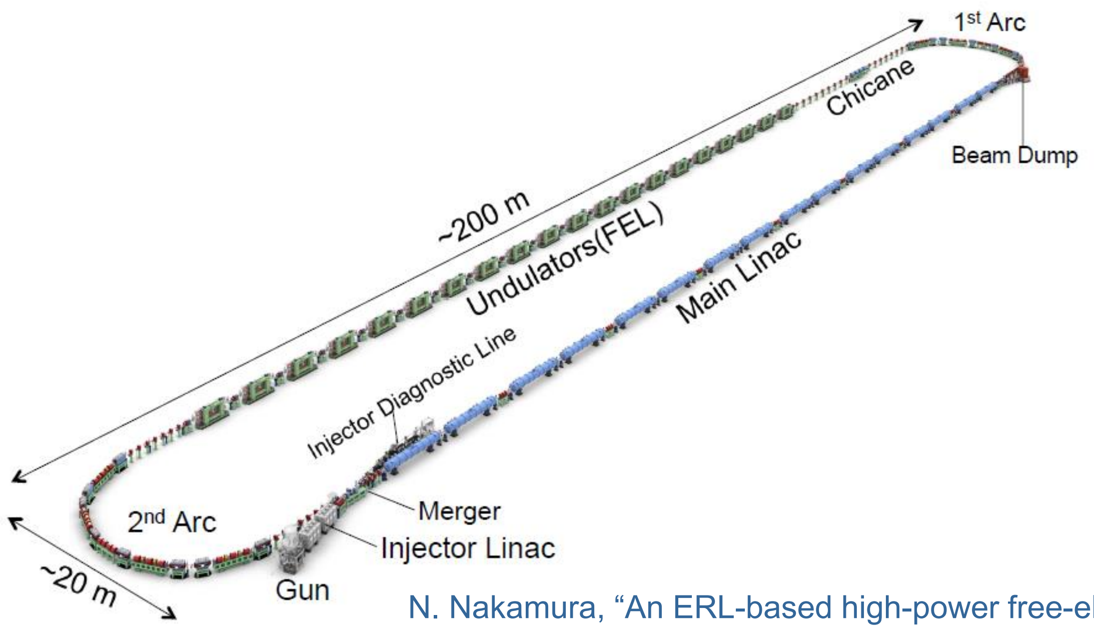
- Introduction
- The DC gun-based Cornell photoinjector
- High voltage DC gun at JAEA
- High gradient and high voltage DC guns at KEK and Cornell
- Summary

High repetition rate FEL



MHz XFEL

https://portal.slac.stanford.edu/sites/lcls_public/lcls_ii/Pages/design.aspx



10 kW FEL for EUV lithography

N. Nakamura, “An ERL-based high-power free-electron laser for EUV lithography”, 2015 EUVL Workshop

LCLS-II injector specifications

bunch charge	95 % ε_n (μm)	peak current (A)	average current (mA)
20 pC	0.25	5	0.02
100 pC	0.40	10	0.1
300 pC	0.60	30	0.3

- The Cornell photoinjector demonstrated cathode thermal emittance dominated beam satisfying LCLS-II specifications in 2015.

C. Gulliford et al., Appl. Phys. Lett. **106**, 094101 (2015).

- The Cornell photoinjector demonstrated average beam current of 75 mA much higher than LCLS-II specifications in 2013.

L. Cultrera et al., Appl. Phys. Lett. **103**, 103504 (2013);
B. Dunham et al., Appl. Phys. Lett. **102**, 034105 (2013).

- Reliability (long-term operational experience) is important especially for industrial application such as 10 kW EUV FEL for lithography.

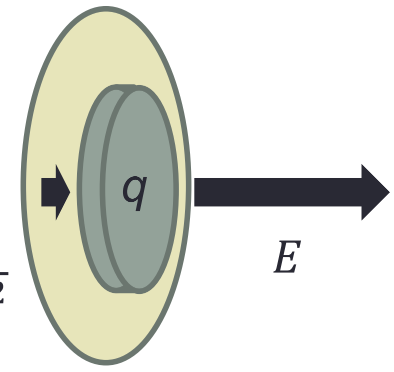
Cathode thermal emittance

I.V. Bazarov et al., Phys. Rev. Lett. **102**, 104801 (2009).

$$\varepsilon_{n,th} = \sigma_x \sqrt{\frac{MTE}{mc^2}} \geq \frac{1}{2}\sqrt{\frac{q}{\pi\varepsilon_0 E}}\sqrt{\frac{MTE}{mc^2}}$$

MTE: cathode mean transverse energy
σ_x: initial rms beam size
q: bunch charge
E: applied cathode field

$$E - \frac{q}{\varepsilon_0 \pi (2\sigma_x)^2}$$



D. Nguyen et al., “RF Linac for High-Gain FEL Photoinjectors”, LA-UR 14-23995

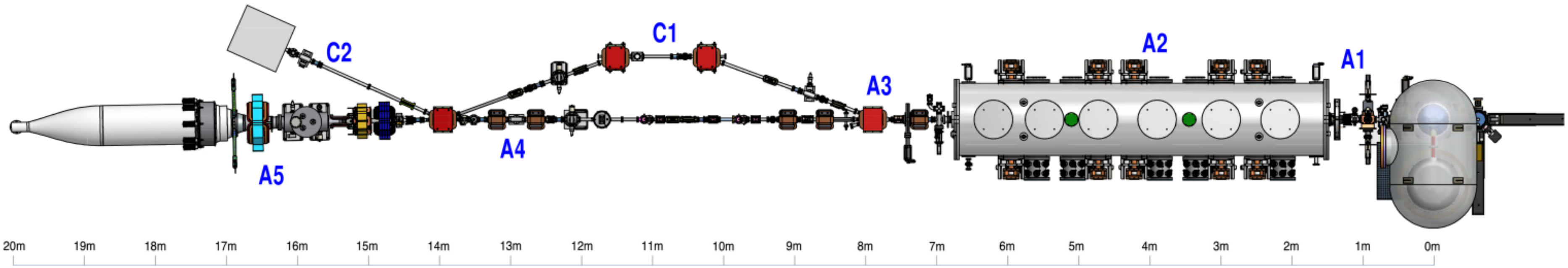
The applied cathode field *E* should be greater than image charge field $q/\varepsilon_0 \pi (2\sigma_x)^2$.

MTE = 140meV (corresponds to 0.5mrad) : NaKSb cathode
E = 4.3 MV/m: 400 kV DC gun

@Cornell

bunch charge	$\varepsilon_{n,th}$ (μm)	95 % ε_n (μm) LCLS-II specifications
20 pC	0.11	0.25
100 pC	0.24	0.40
300 pC	0.41	0.60

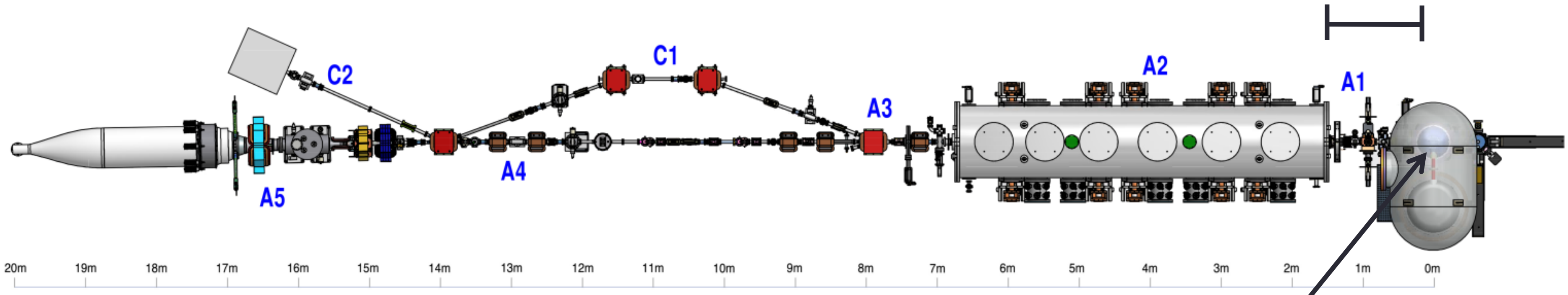
Cornell photoinjector



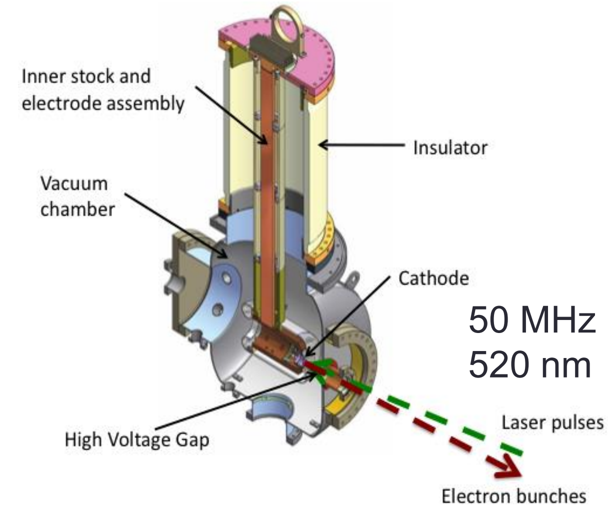
Courtesy of Adam Bartnik

Cornell photoinjector

400 kV DC Gun +
Bunching/Focusing



400 kV DC Gun

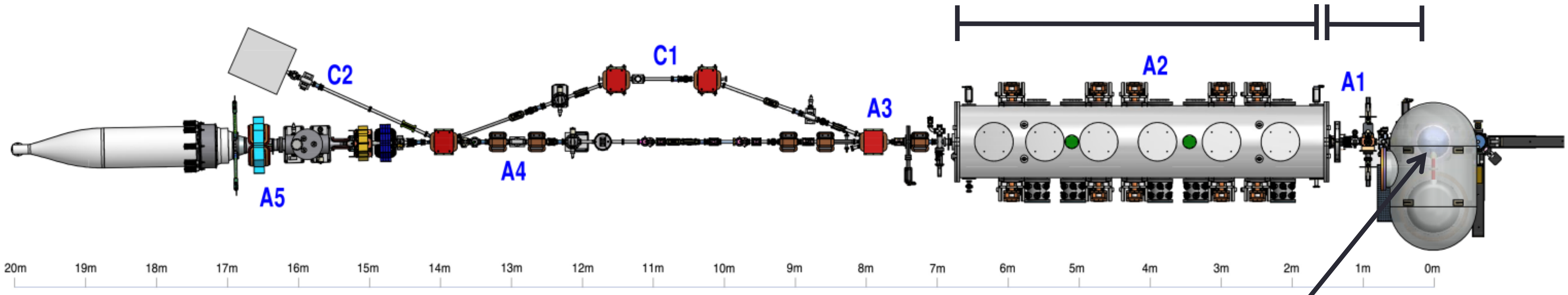


50 MHz
520 nm

Cornell photoinjector

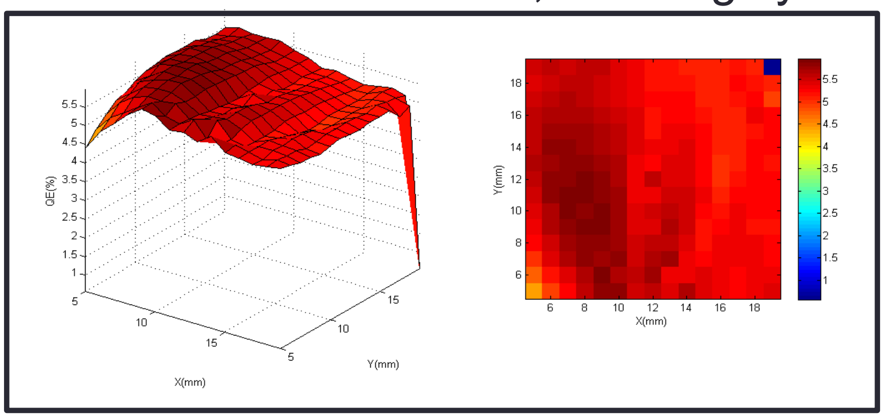
Short SRF Linac
5 – 15 MeV

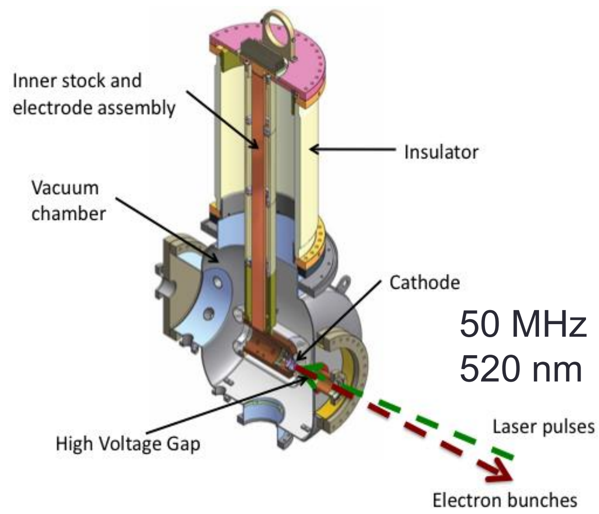
400 kV DC Gun +
Bunching/Focusing



400 kV DC Gun

NaKSb: MTE = 140 meV, QE roughly 5%

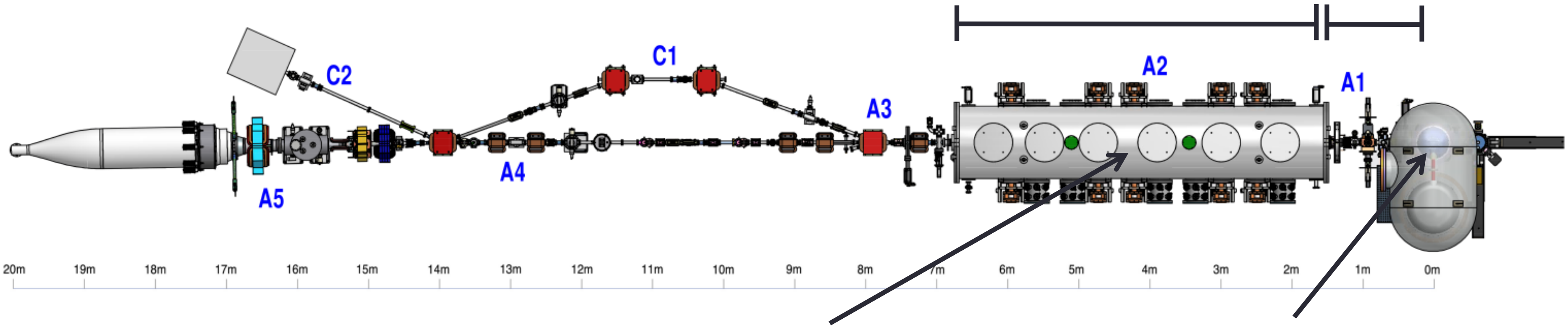




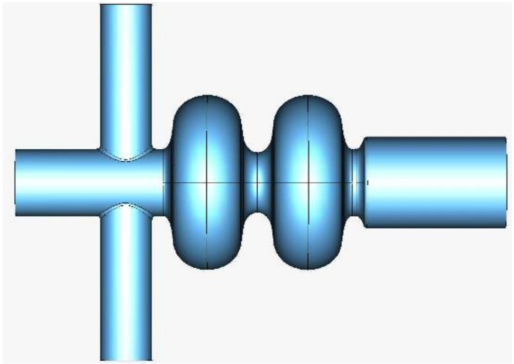
Cornell photoinjector

Short SRF Linac
5 – 15 MeV

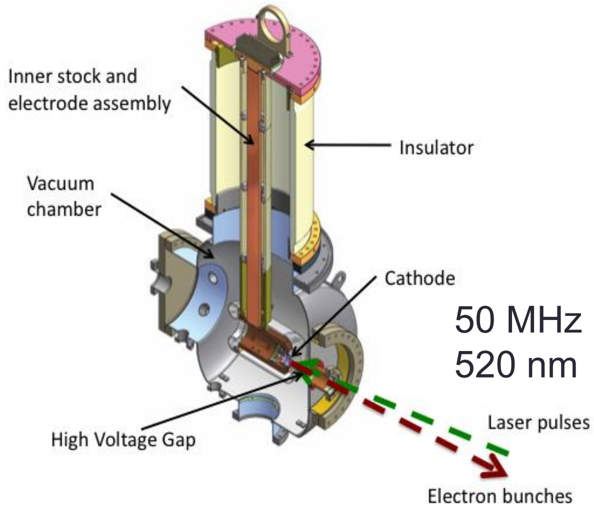
400 kV DC Gun +
Bunching/Focusing



Superconducting
RF Cavities (niobium)



400 kV DC Gun

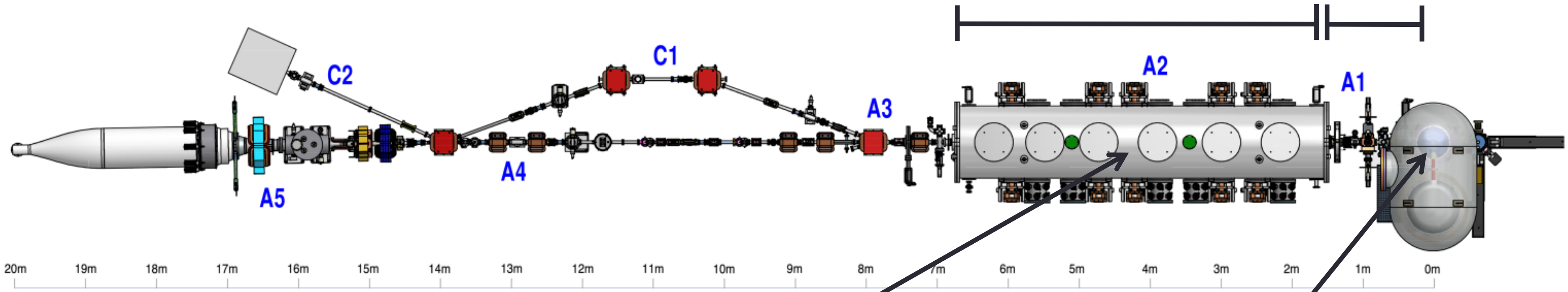


Courtesy of Adam Bartnik

Cornell photoinjector

Short SRF Linac
5 – 15 MeV

400 kV DC Gun +
Bunching/Focusing



Superconducting
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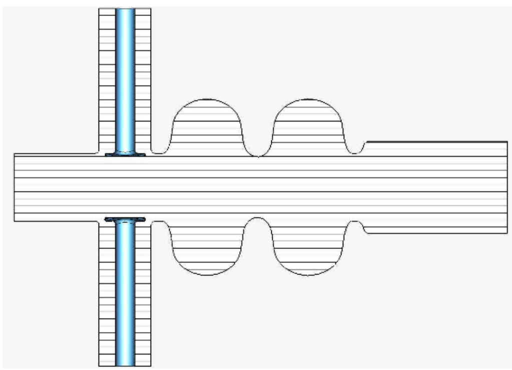
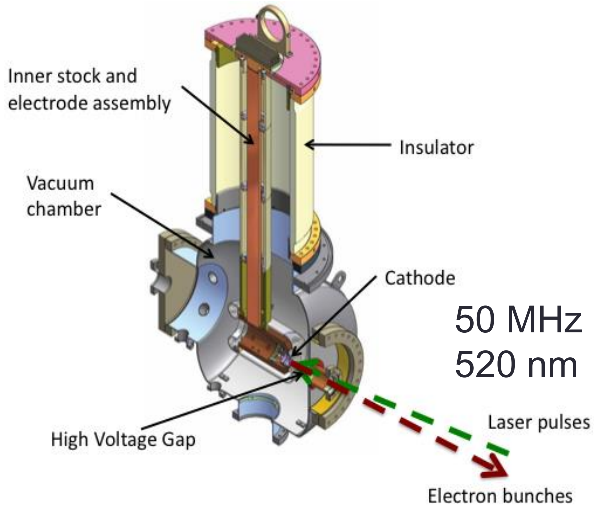


400 kV DC Gun



50 MHz
520 nm

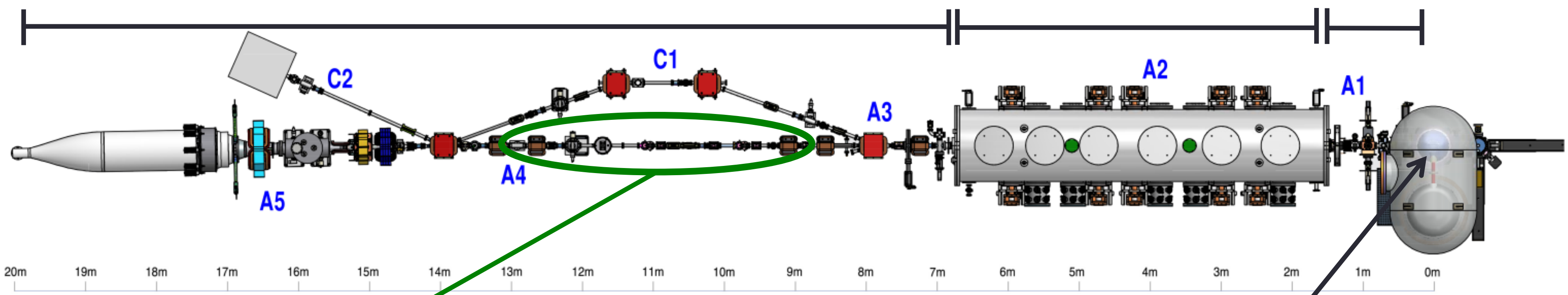
Courtesy of Adam Bartnik

Cornell photoinjector

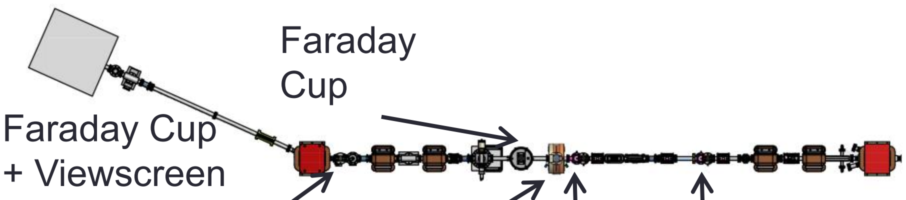
6 Dimensional Phase Space Diagnostics + High Power Beam Dump

Short SRF Linac
5 – 15 MeV

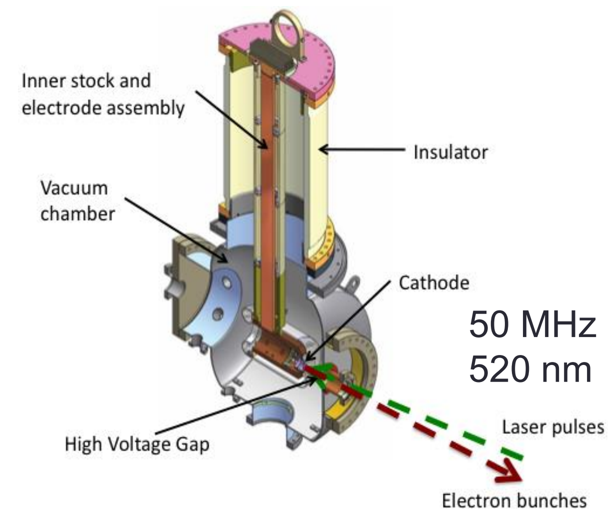
400 kV DC Gun +
Bunching/Focusing



Emittance Measurement System



400 kV DC Gun

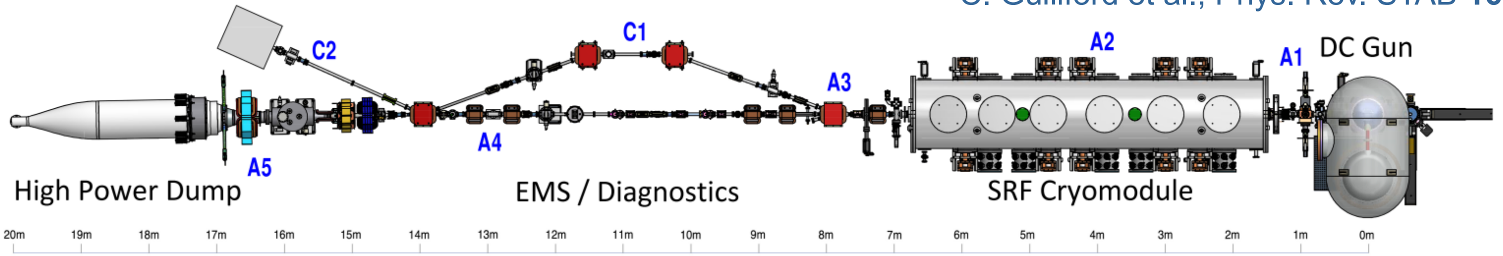


Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE)

Courtesy of Adam Bartnik

Beam based alignment with near-zero bunch charge

C. Gulliford et al., Phys. Rev. STAB **16**, 073401 (2013).

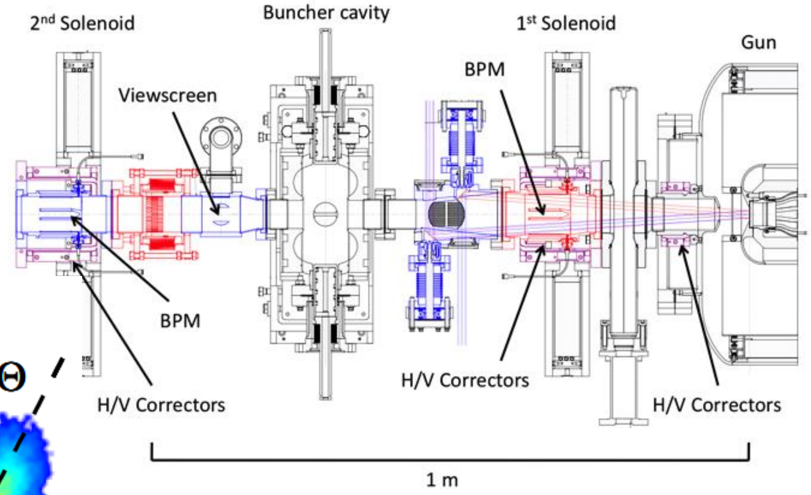


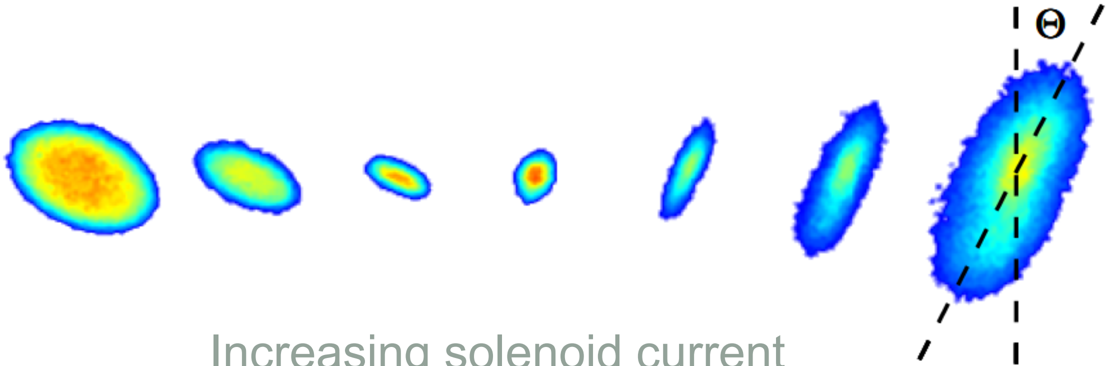
- Measured beam response of each injector component.
- Performed beam based alignment of gun, buncher, SRF cavities, and solenoids within 50 μm accuracy.
- Confirmed the emittance and beam sizes are reproduced by GPT simulations.
- Loaded optimum parameter set for each bunch charge and measured emittance and longitudinal profile.

Bunch charge	$\varepsilon_{n,x}$(100%)	$\varepsilon_{n,y}$(100%)
19 pC	0.33 μm	0.20 μm
77 pC	0.69 μm	0.40 μm
300 pC	1.36 μm	0.79 μm

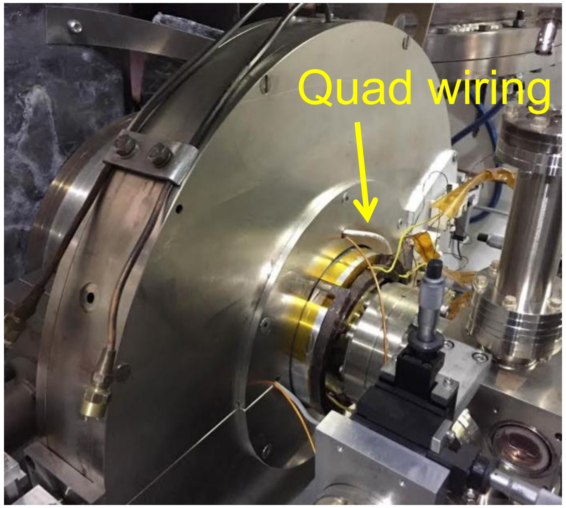
Origin of asymmetry

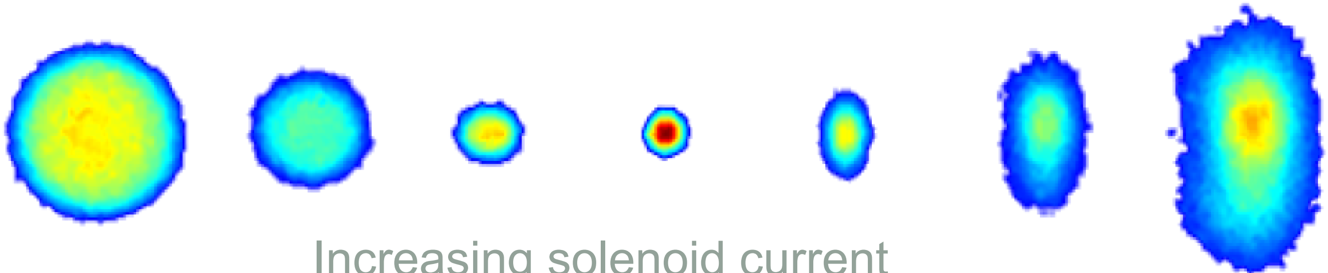
- Found a beam asymmetry after the first solenoid.
- Likely culprit: stray quad field in the solenoid.
- Mitigated with a correcting quadrupole coil.





Increasing solenoid current



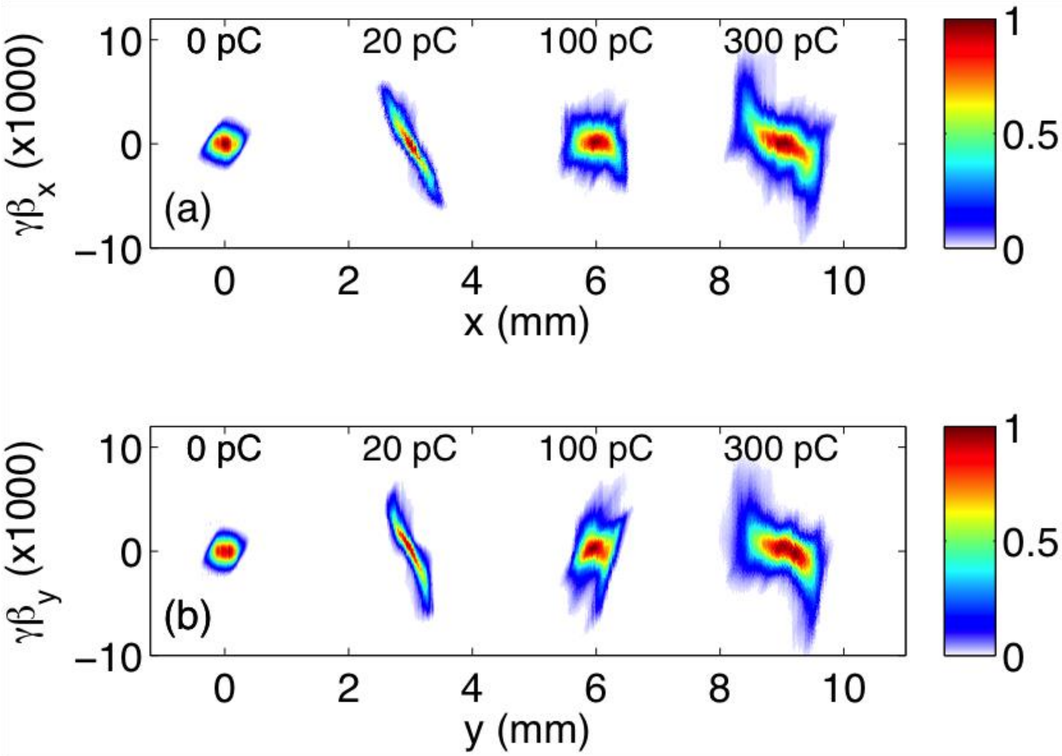


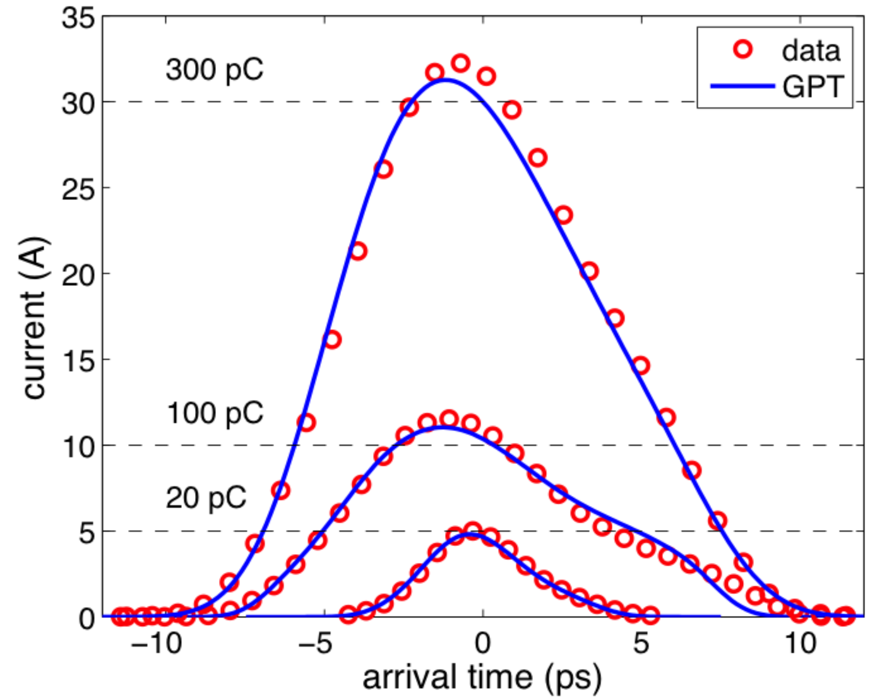
Increasing solenoid current

Courtesy of Adam Bartnik

Emittance and longitudinal profile measurements

C. Gulliford et al., Appl. Phys. Lett. **106**, 094101 (2015).

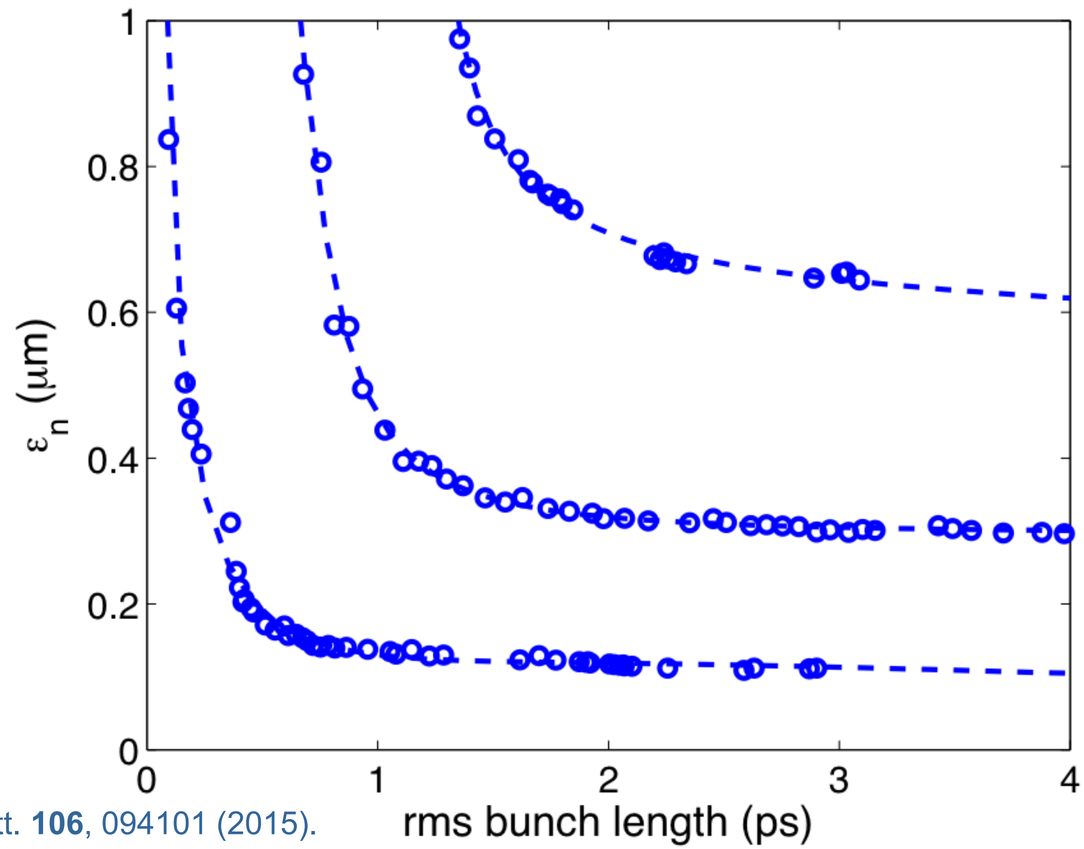




Q (pC)	I_{peak} Target (A)	I_{peak} (A)	ε_n Target (95%, μm)	ε_n (95%, μm)	$\varepsilon_{n,th} / \varepsilon_n$
20	5	**5**	0.25	**H: 0.18, V: 0.19**	**60%**
100	10	**11.5**	0.40	**H: 0.32, V: 0.30**	**80%**
300	30	**32**	0.60	**H: 0.62, V: 0.60**	**70%**

Courtesy of Adam Bartnik

Effects of the laser shape



C. Gulliford et al., Appl. Phys. Lett. **106**, 094101 (2015).

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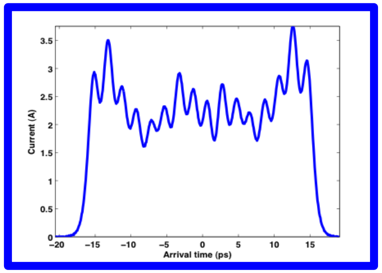
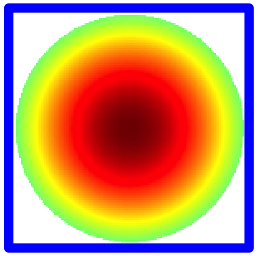
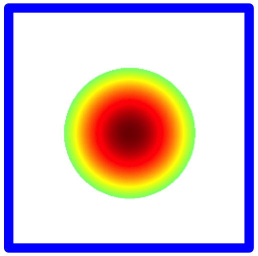
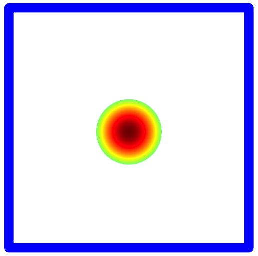
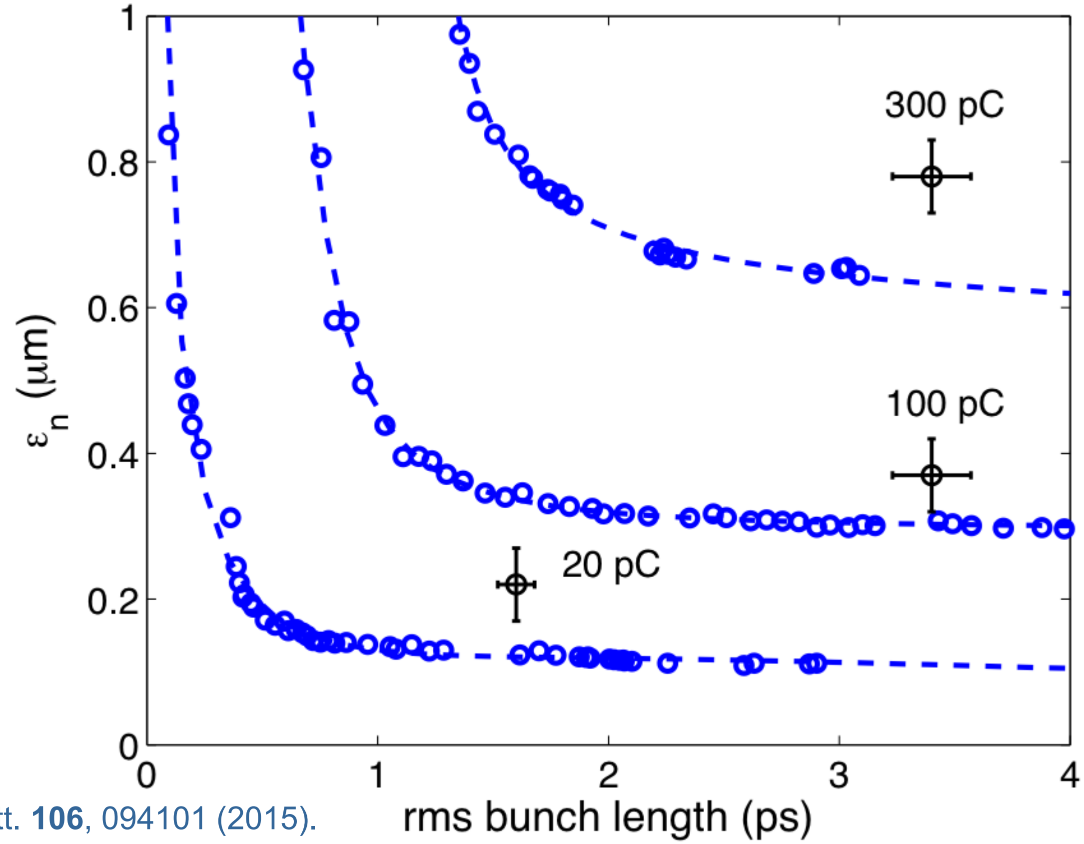


Ideal Shape









C. Gulliford et al., Appl. Phys. Lett. **106**, 094101 (2015).

Courtesy of Adam Bartnik

Effects of the laser shape

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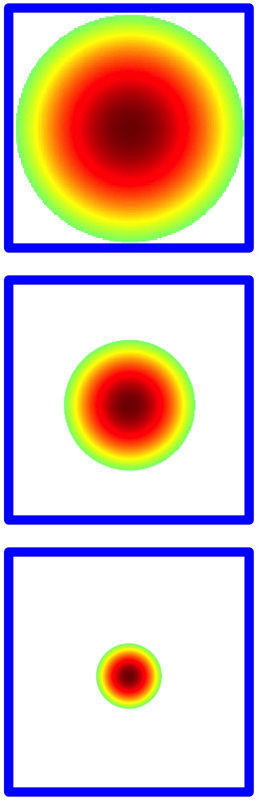

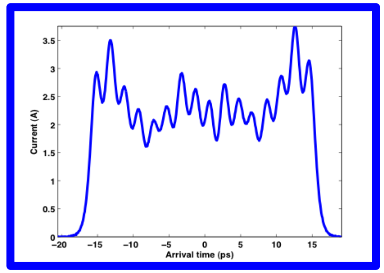

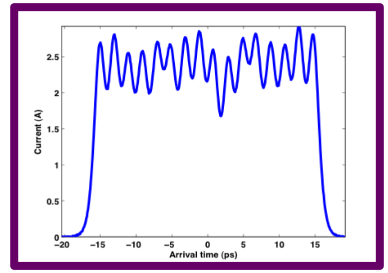

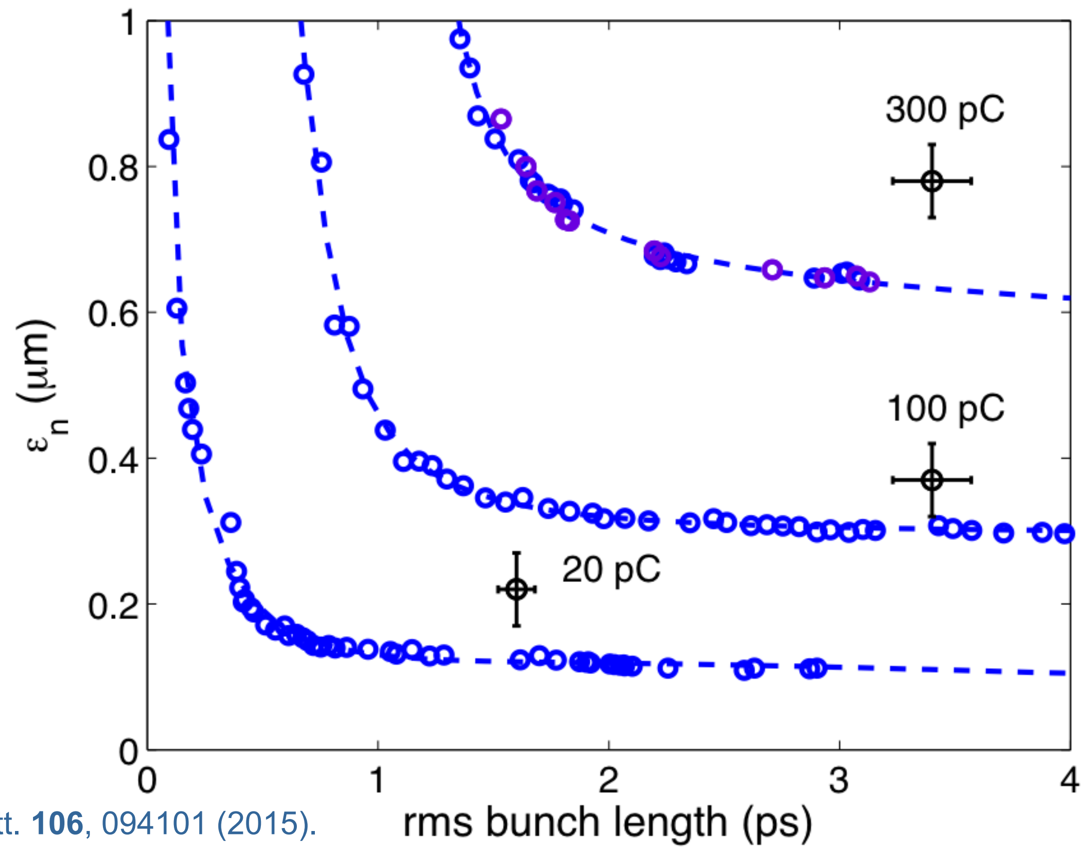

C. Gulliford et al., Appl. Phys. Lett. **106**, 094101 (2015).

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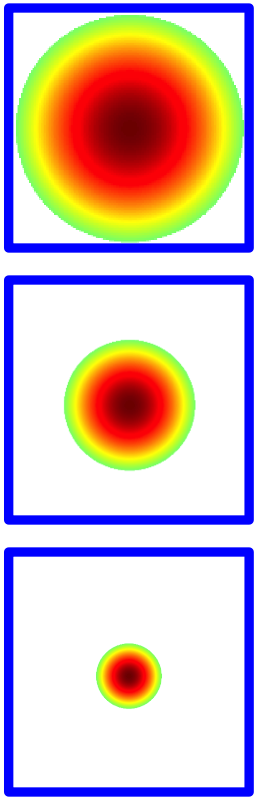
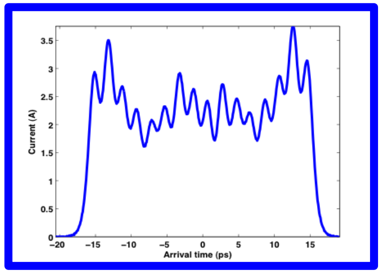
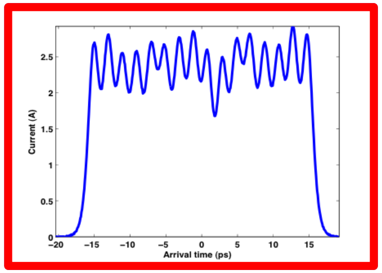
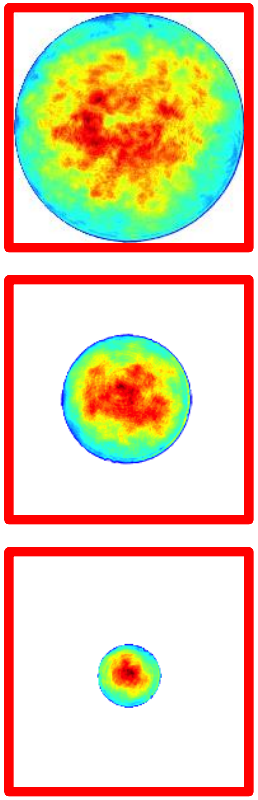
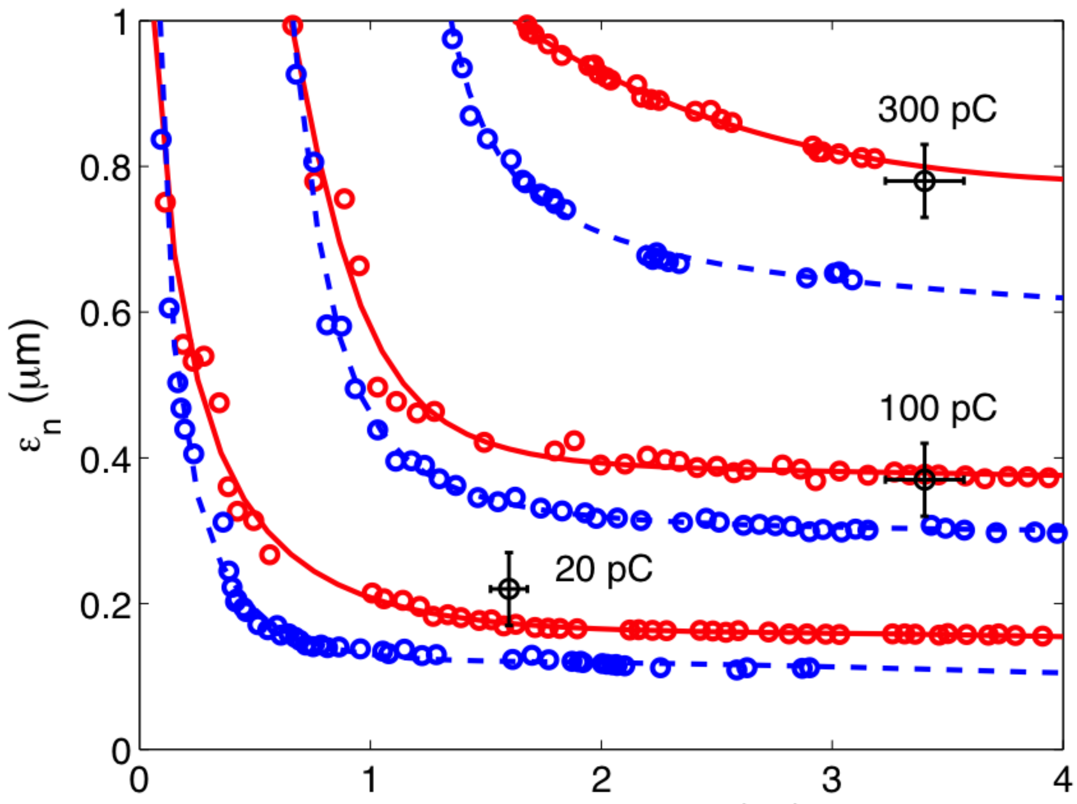






Measured Shape





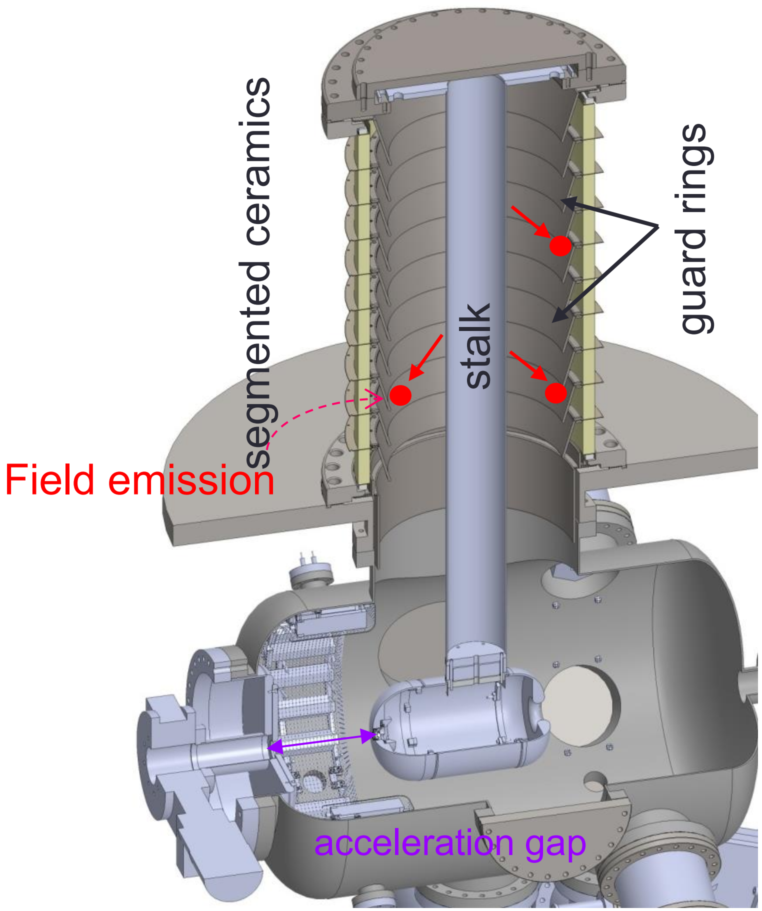
C. Gulliford et al., Appl. Phys. Lett. **106**, 094101 (2015).

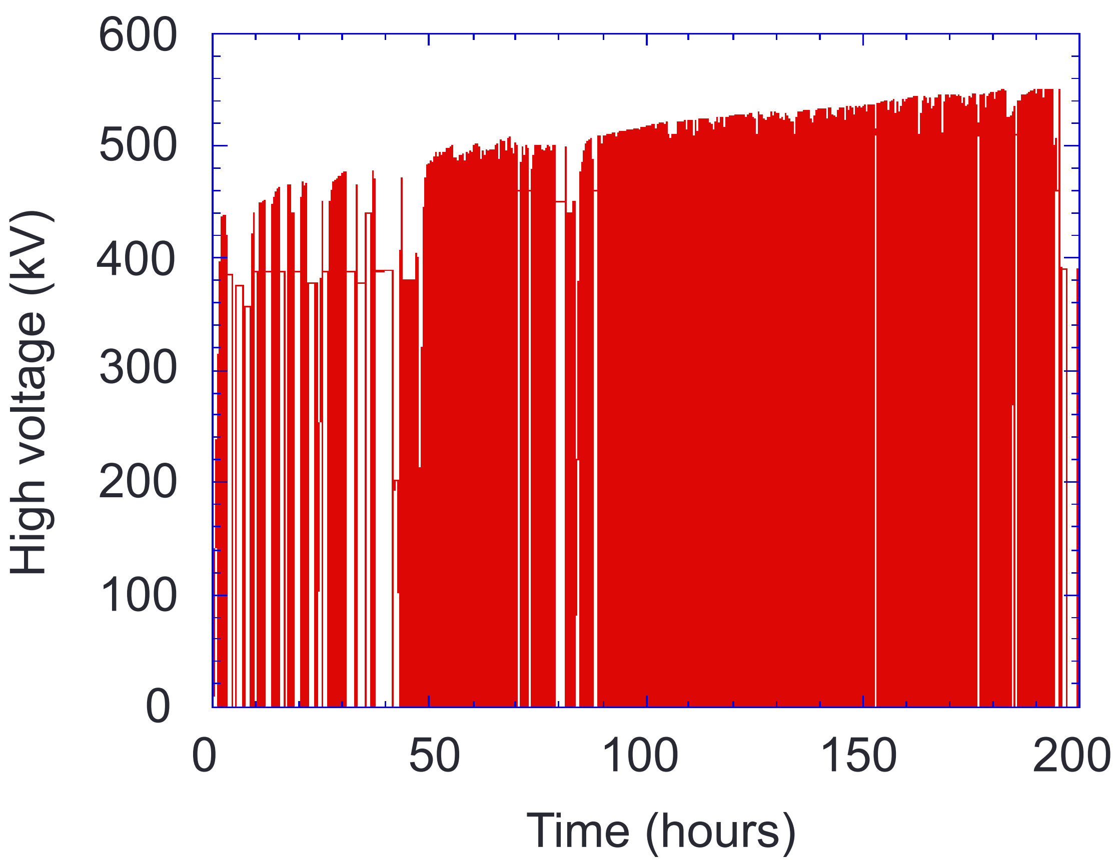
Courtesy of Adam Bartnik

Development of a 500 kV gun at JAEA

- a segmented insulator
- 160 mm acceleration gap

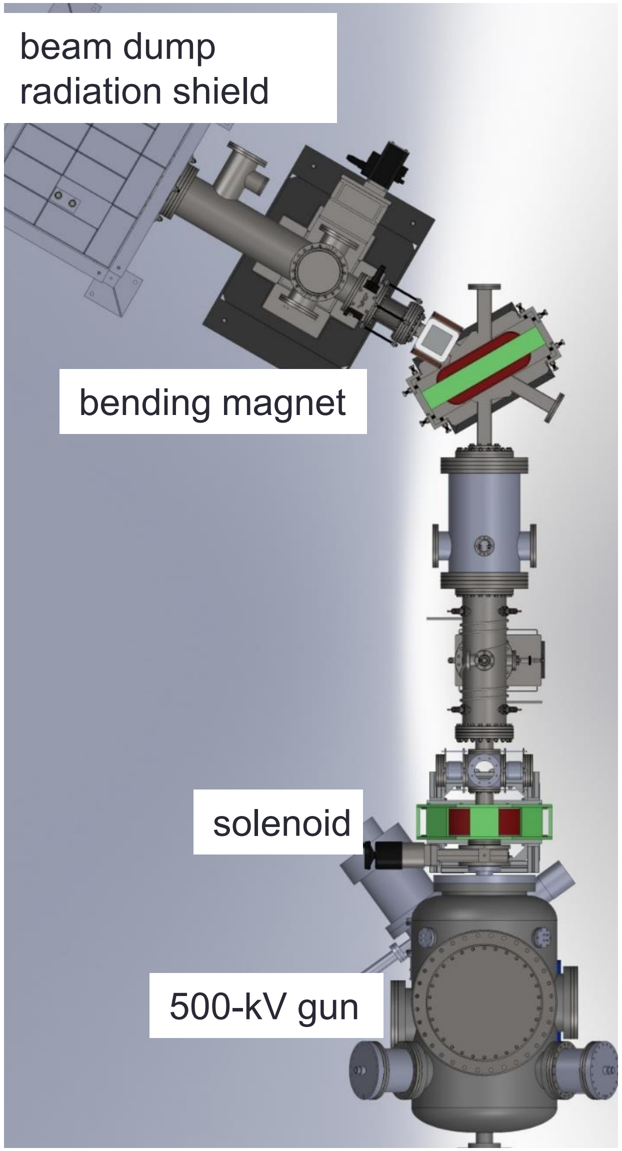
R. Nagai et al., RSI 81, 033304 (2010).
N. Nishimori et al., PRSTAB 17, 053401 (2014).

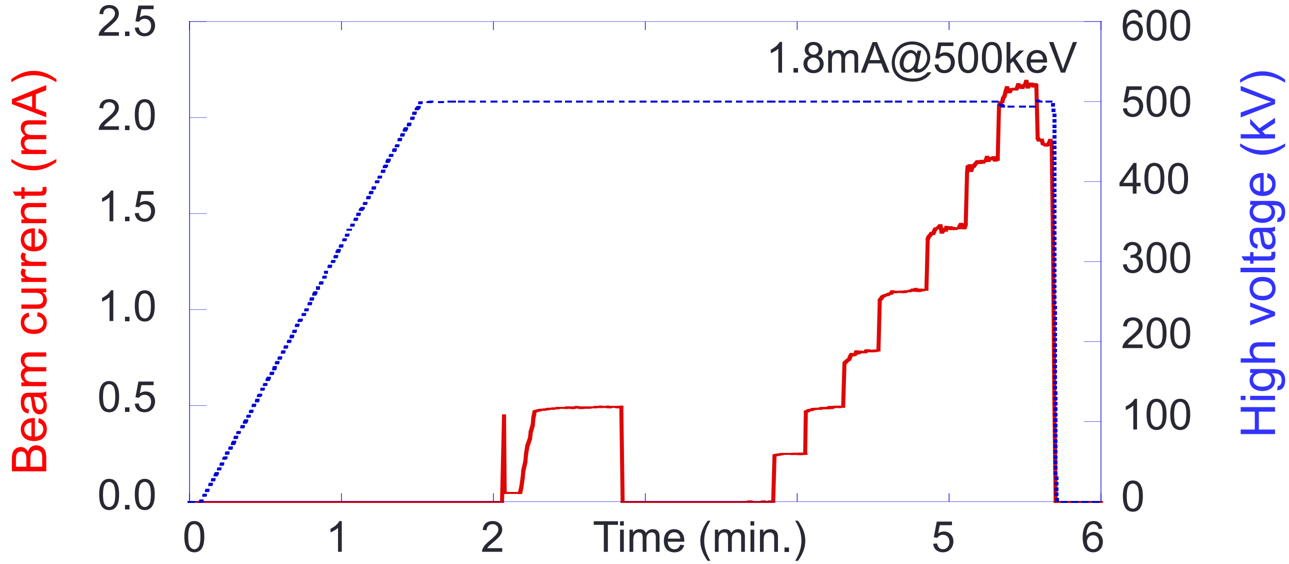


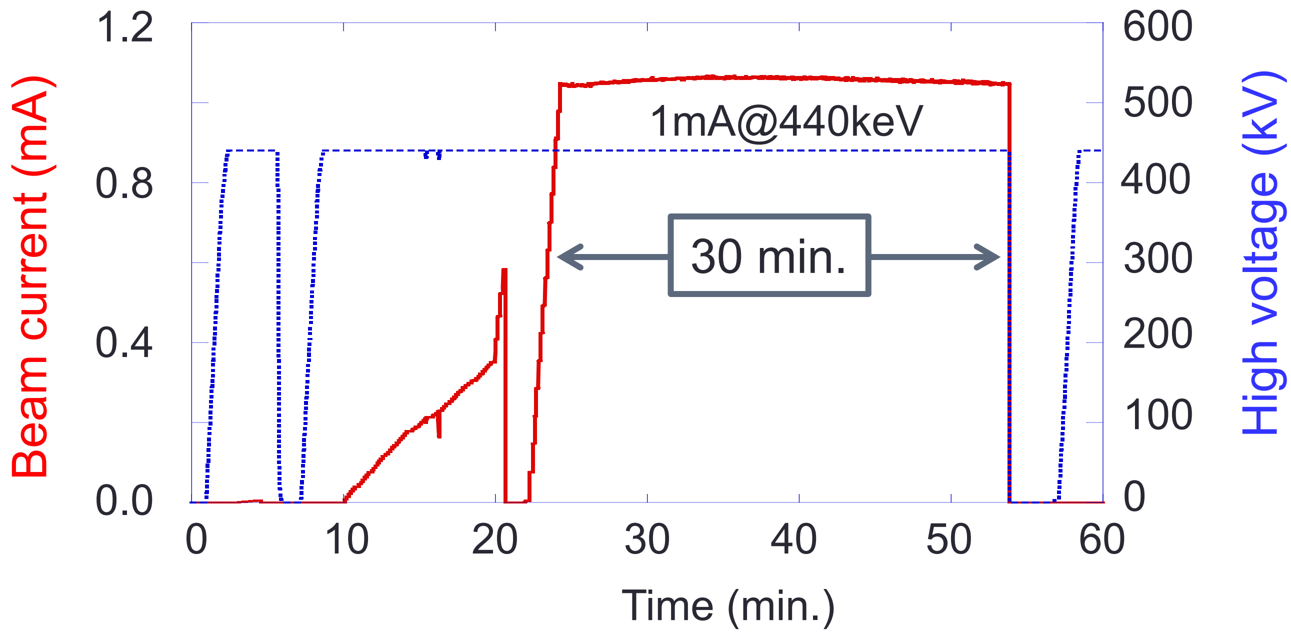


500keV beam generation

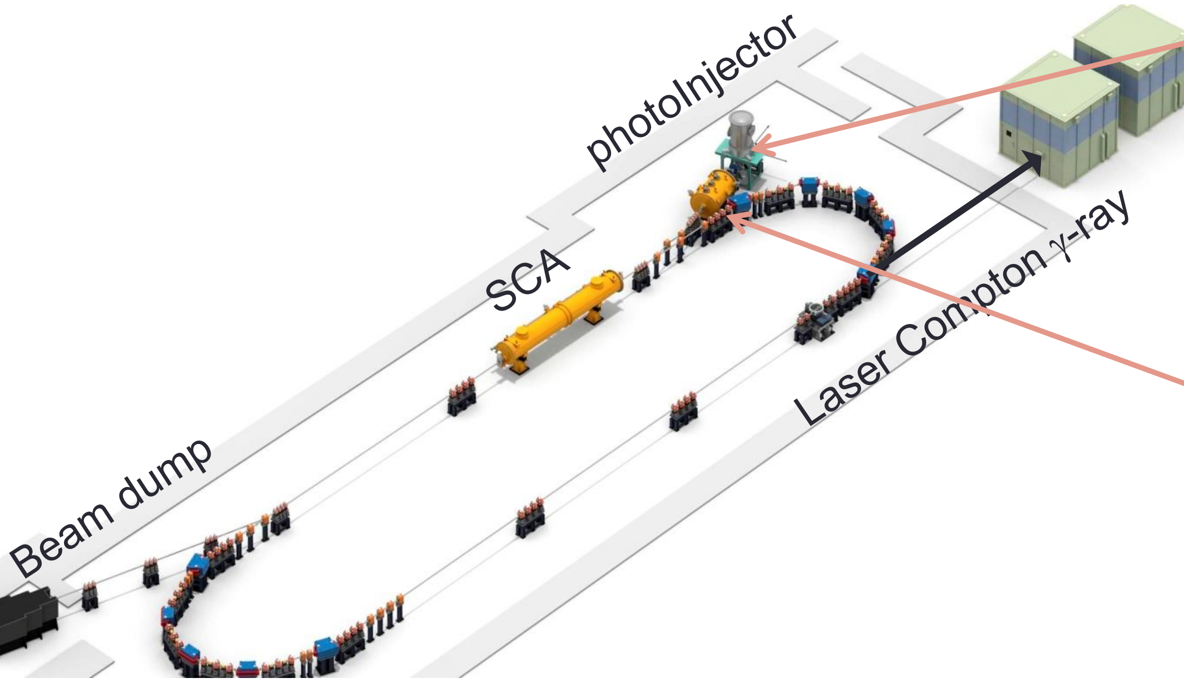
N. Nishimori et al., APL 102, 234103 (2013)

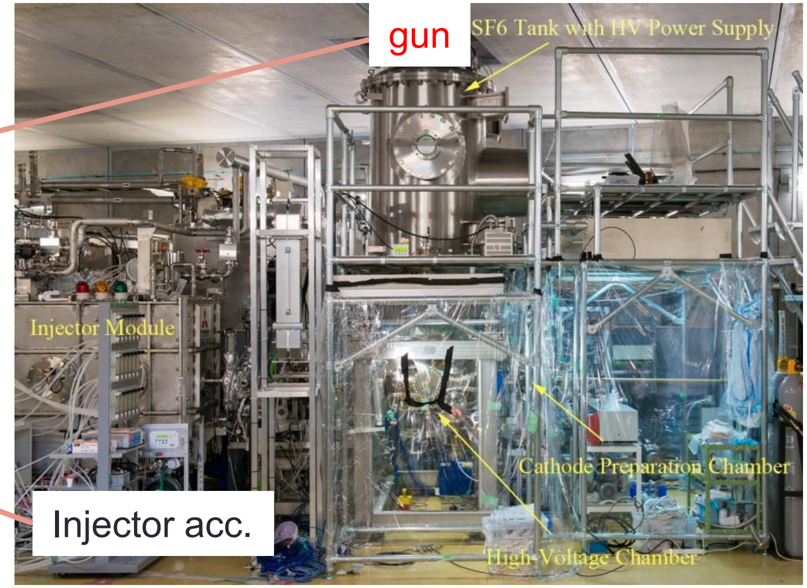




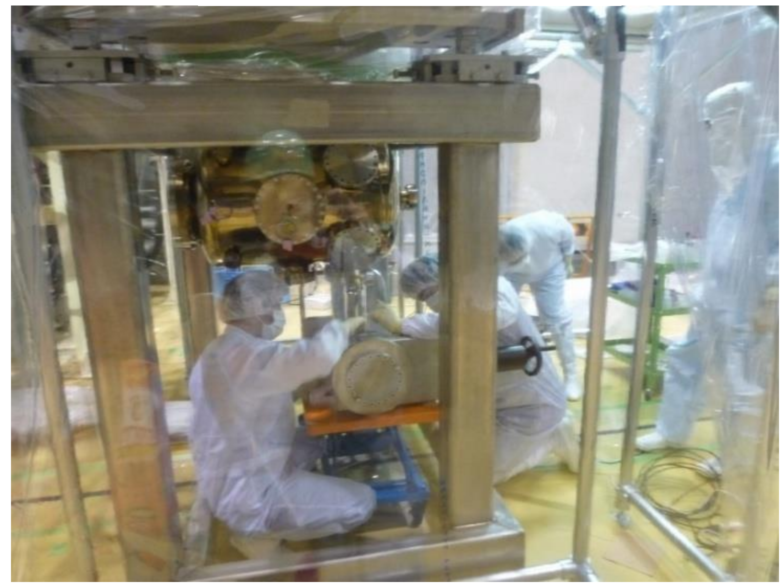


compact ERL (cERL) at KEK





Gun assembly at cERL



- ✓ Oct. 2012 Transport of gun from JAEA to cERL at KEK
- ✓ Jun. 2013 Injector commissioning 5MeV-0.3μA
- ✓ Mar. 2014 ERL loop commissioning 20MeV-4.5μA
- ✓ Mar. 2015 Laser Compton Scattering (LCS) 20MeV-80μA

Gun voltage is limited to 390kV at cERL.

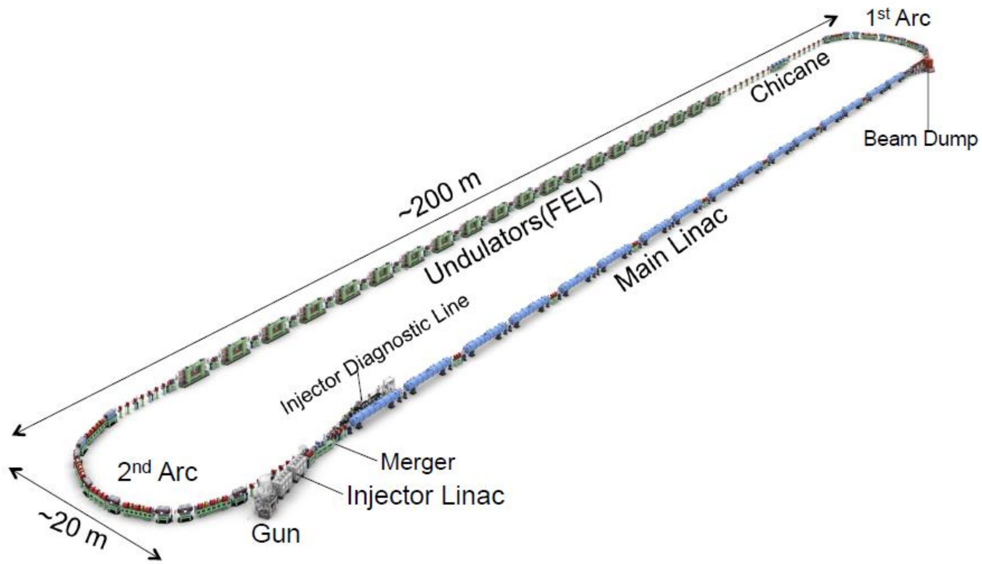
cERL
prototype for future ERL light sources: LCS, THz, and EUV FEL

N. Nakamura et al., "Design work of the ERL-FEL as the high intense EUV light source", Proc. of ERL2015 (2015).

10 kW EUV FEL injector specifications after merger

bunch charge	ε_n (μm)	peak current (A)	average current (mA)
60 pC	0.60	30	10

Reliability and high average current are important as well as brightness.

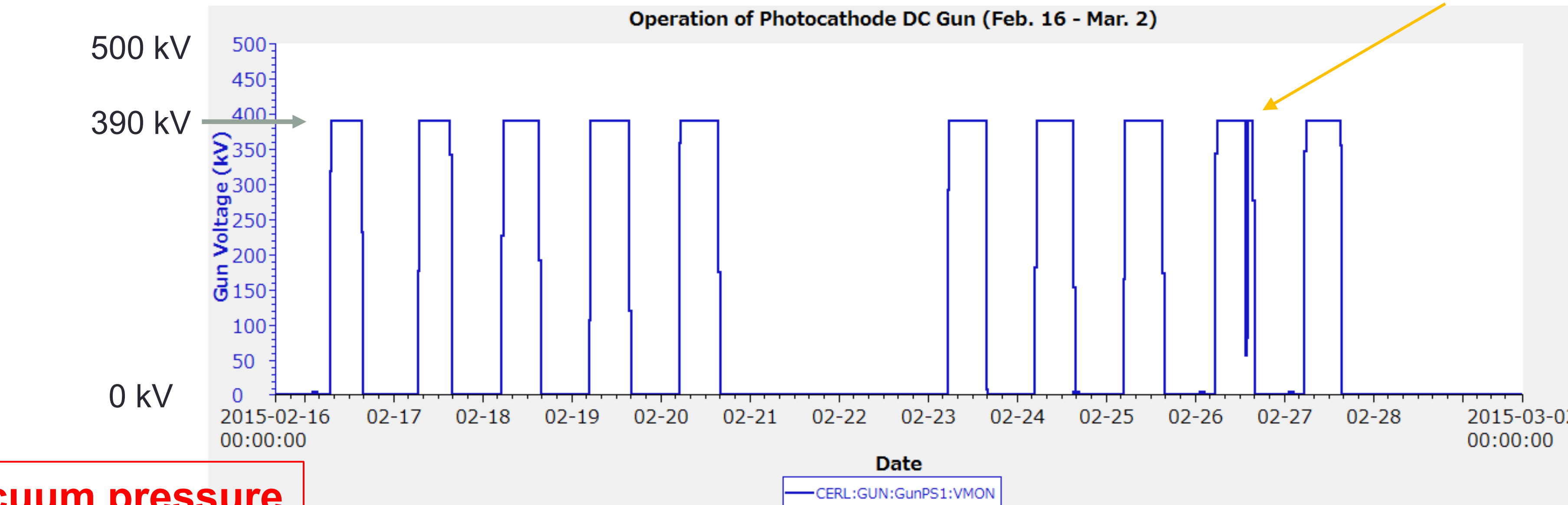


Gun operational status for two weeks

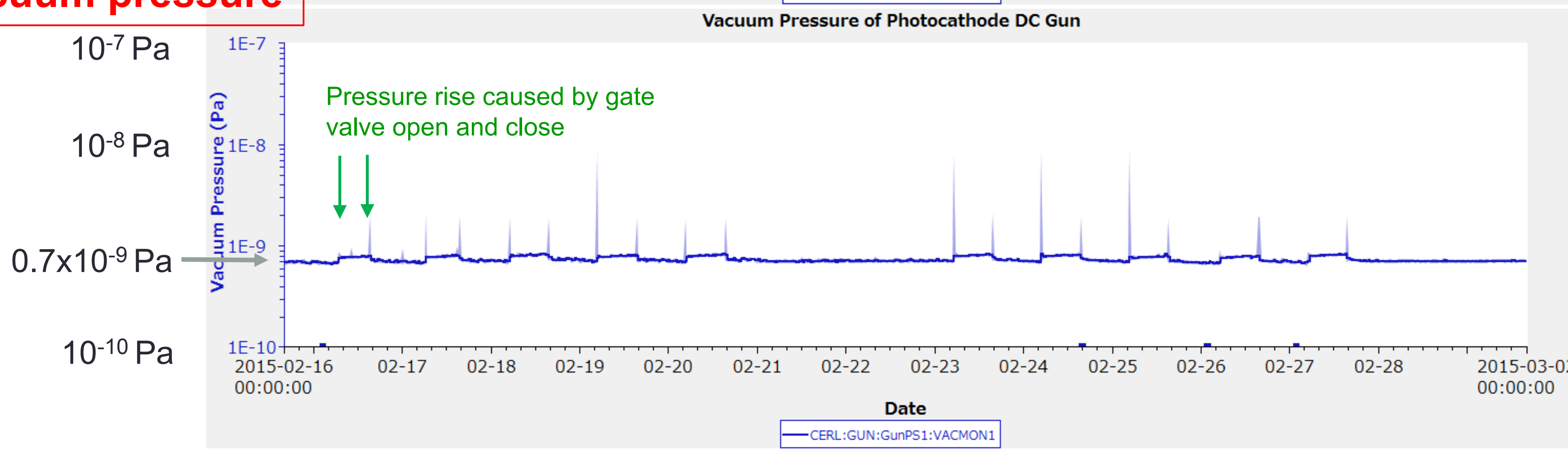
Gun HV

Stable operation

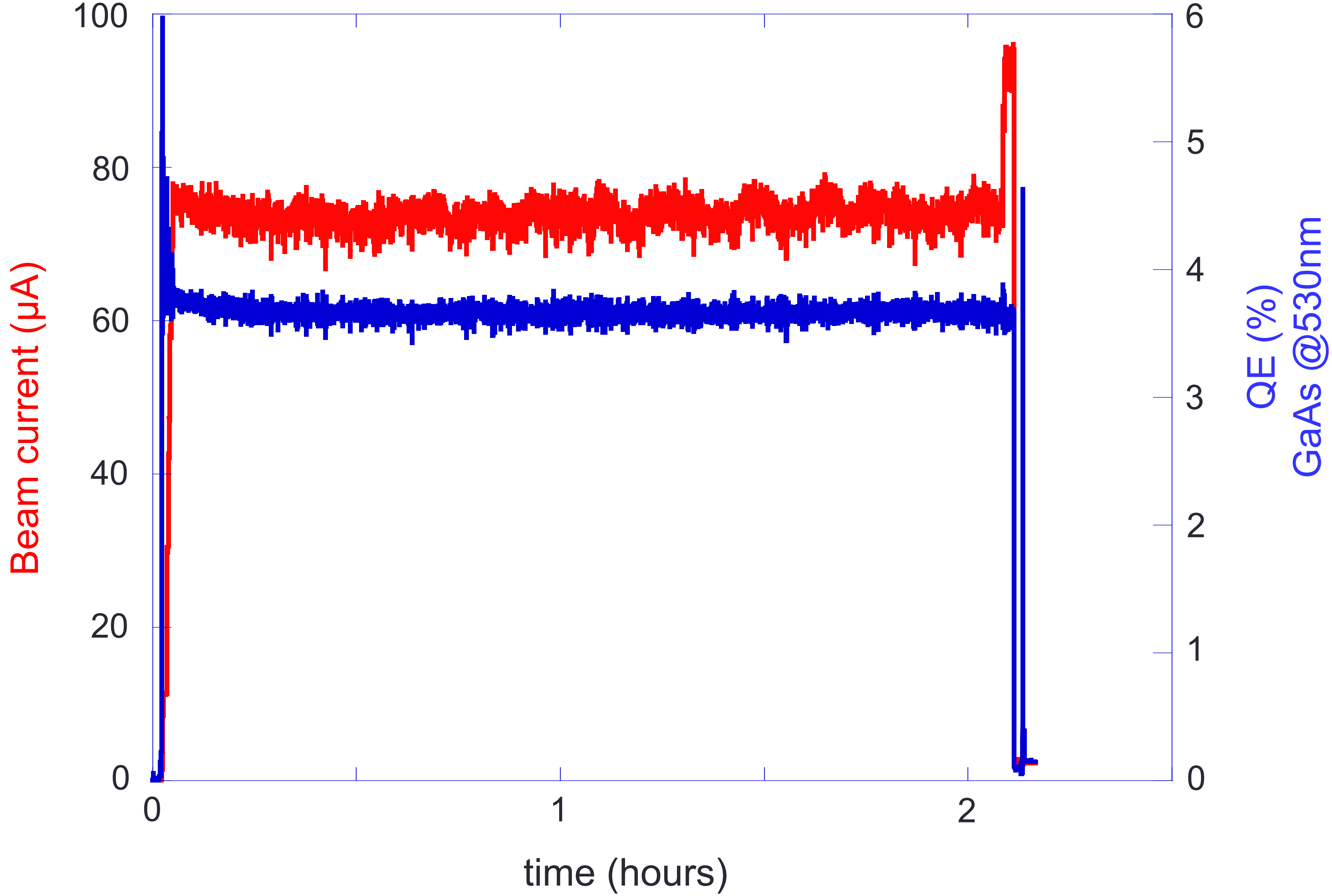
Interruption to enter the acceleration hall



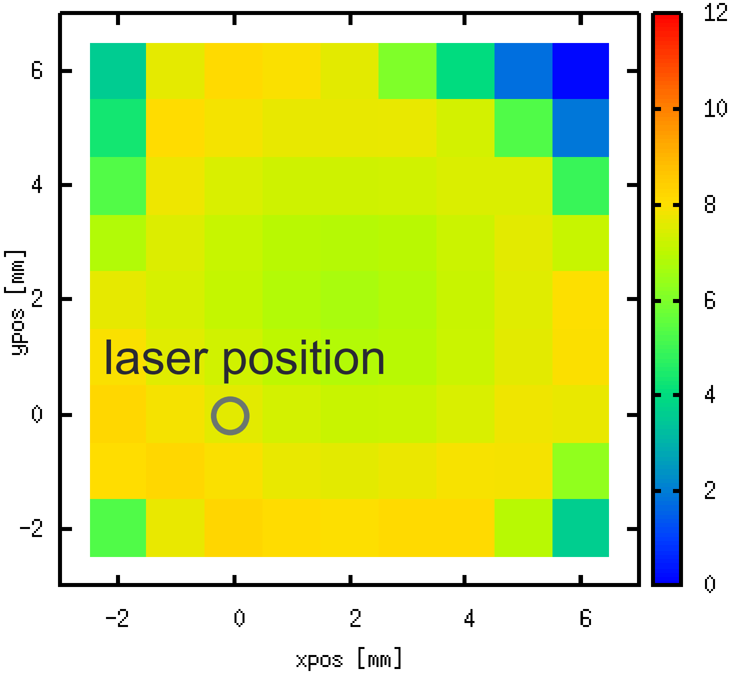
Vacuum pressure

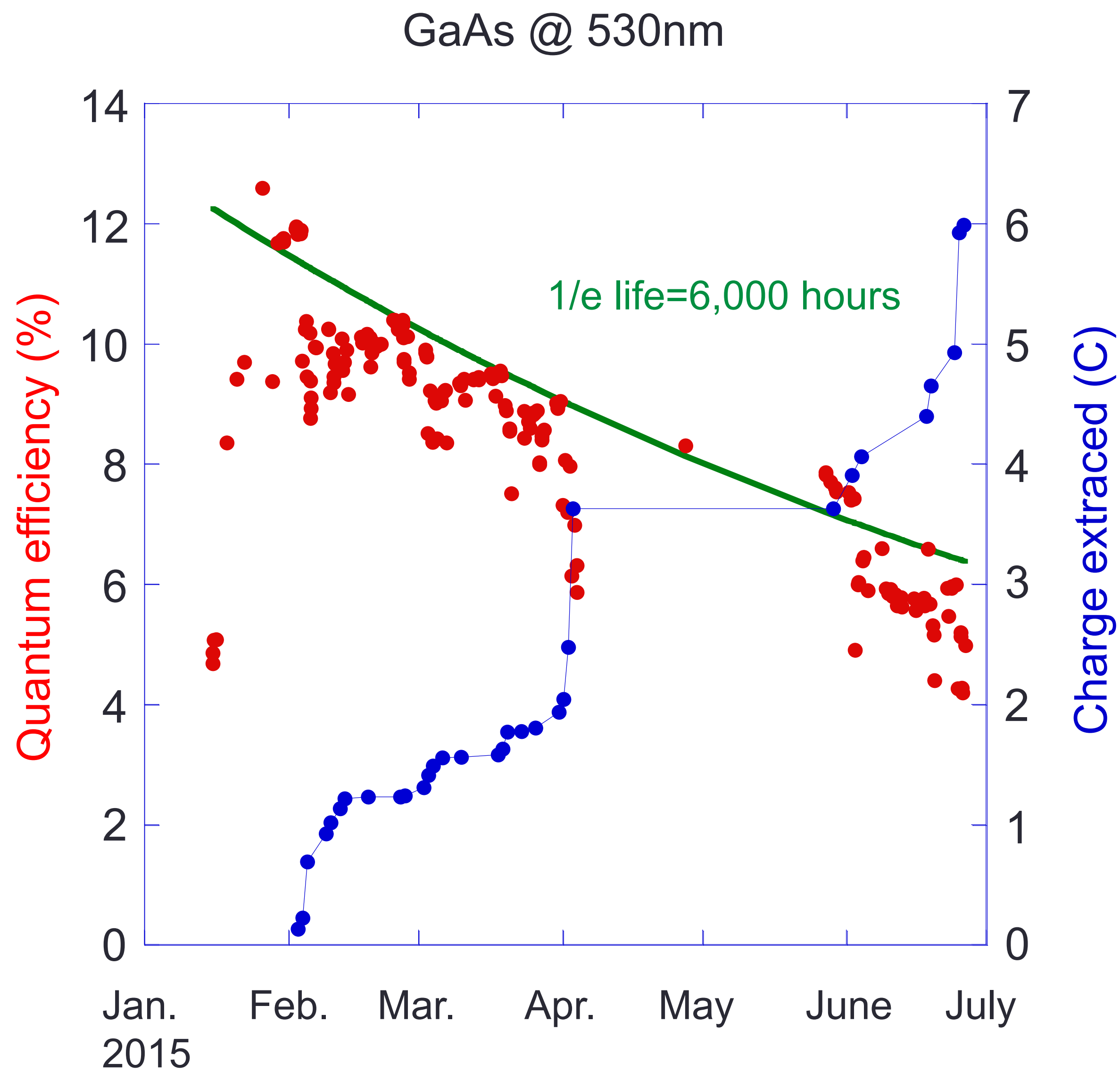


Gun operational status during LCS experiment

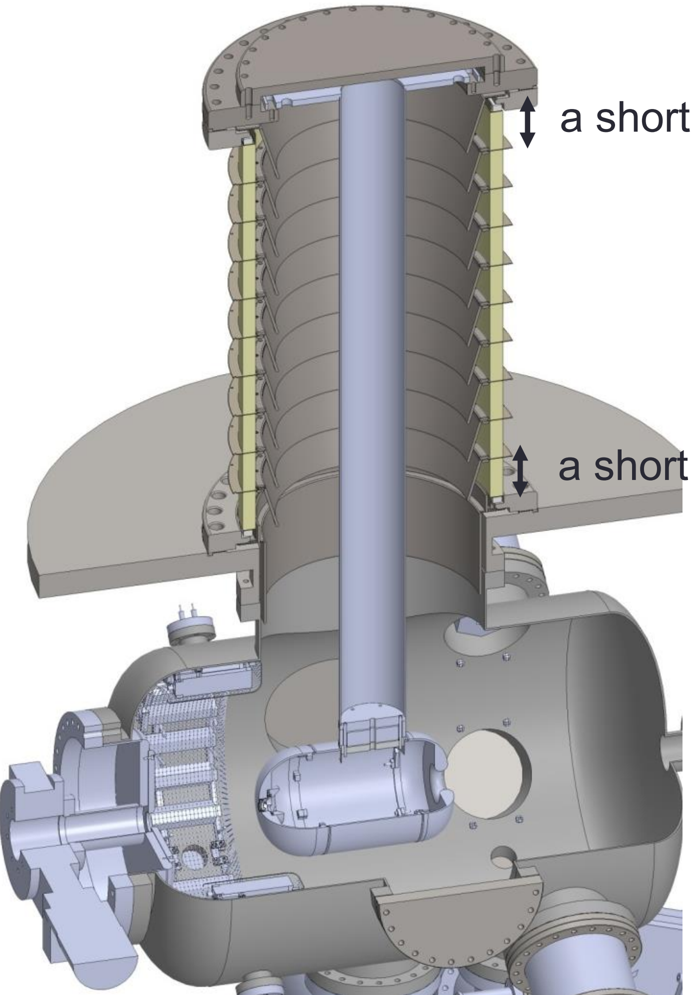


QE during the cERL operation





A Plan to 500kV operation at the cERL



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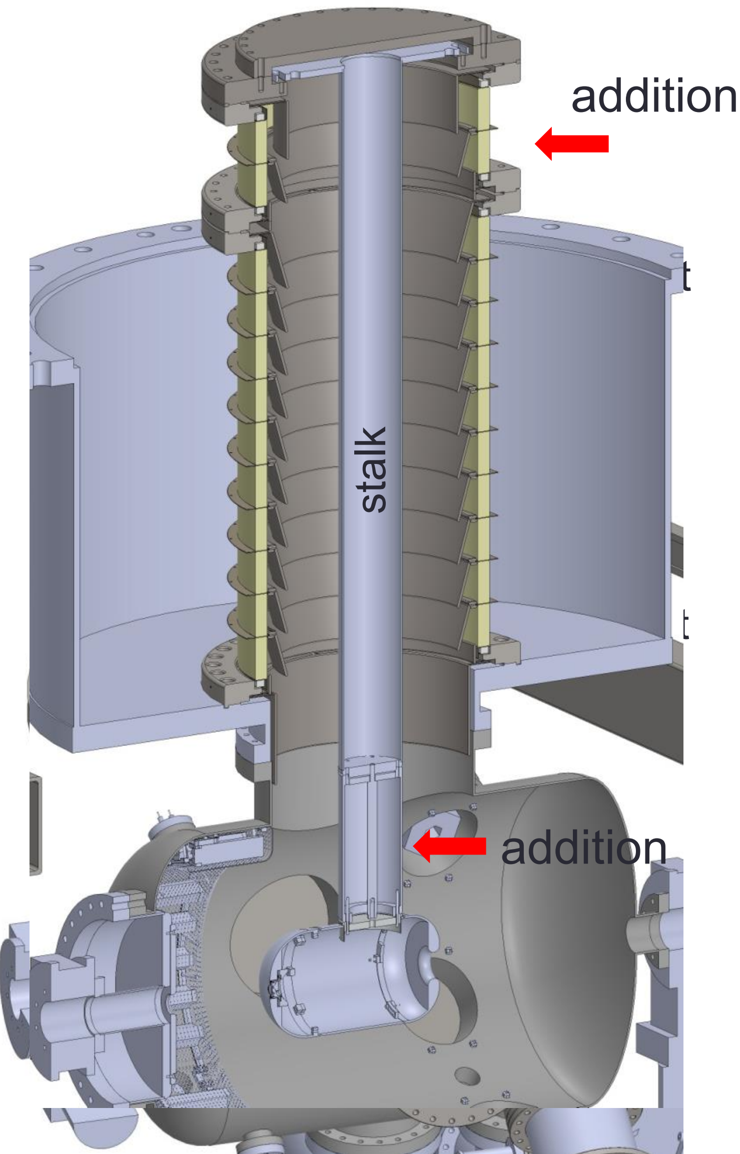

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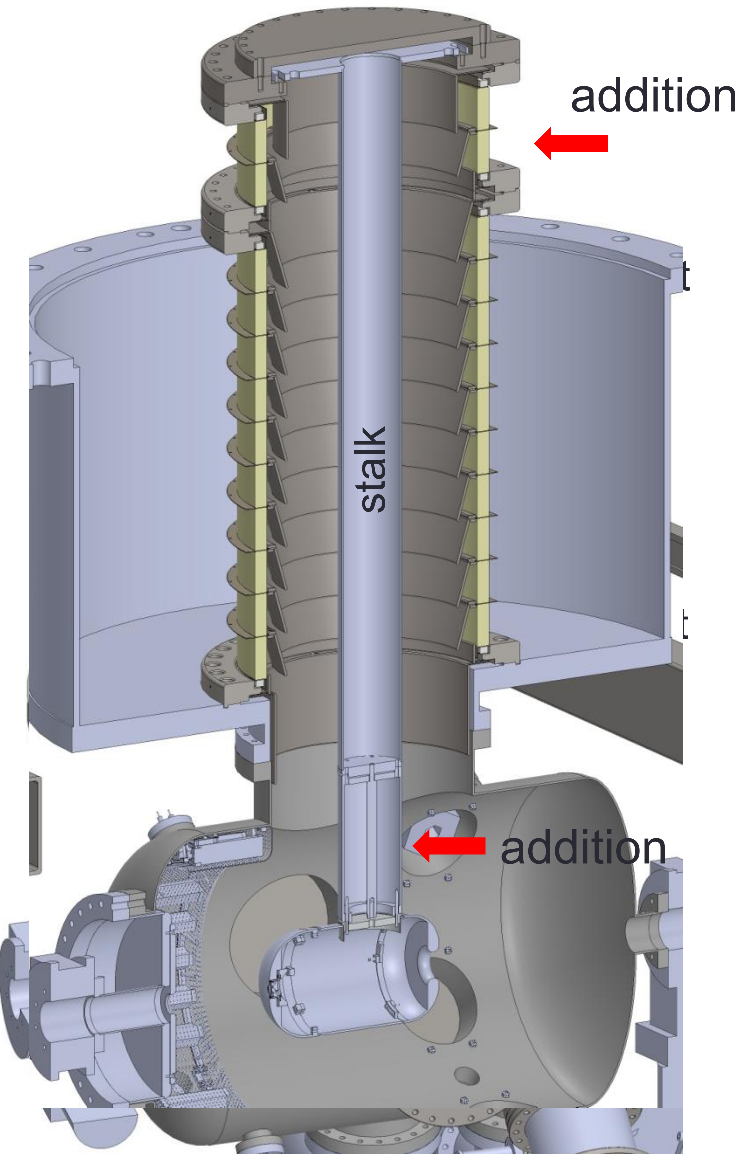
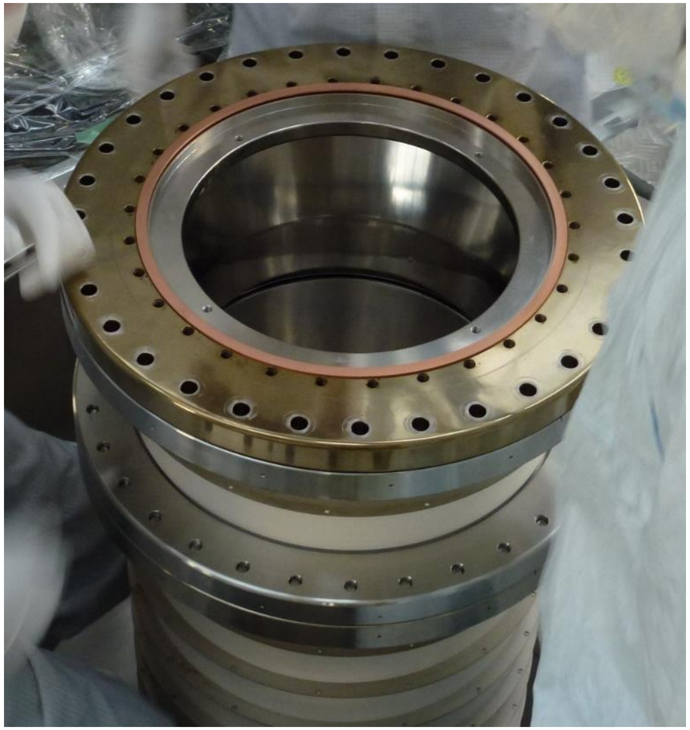
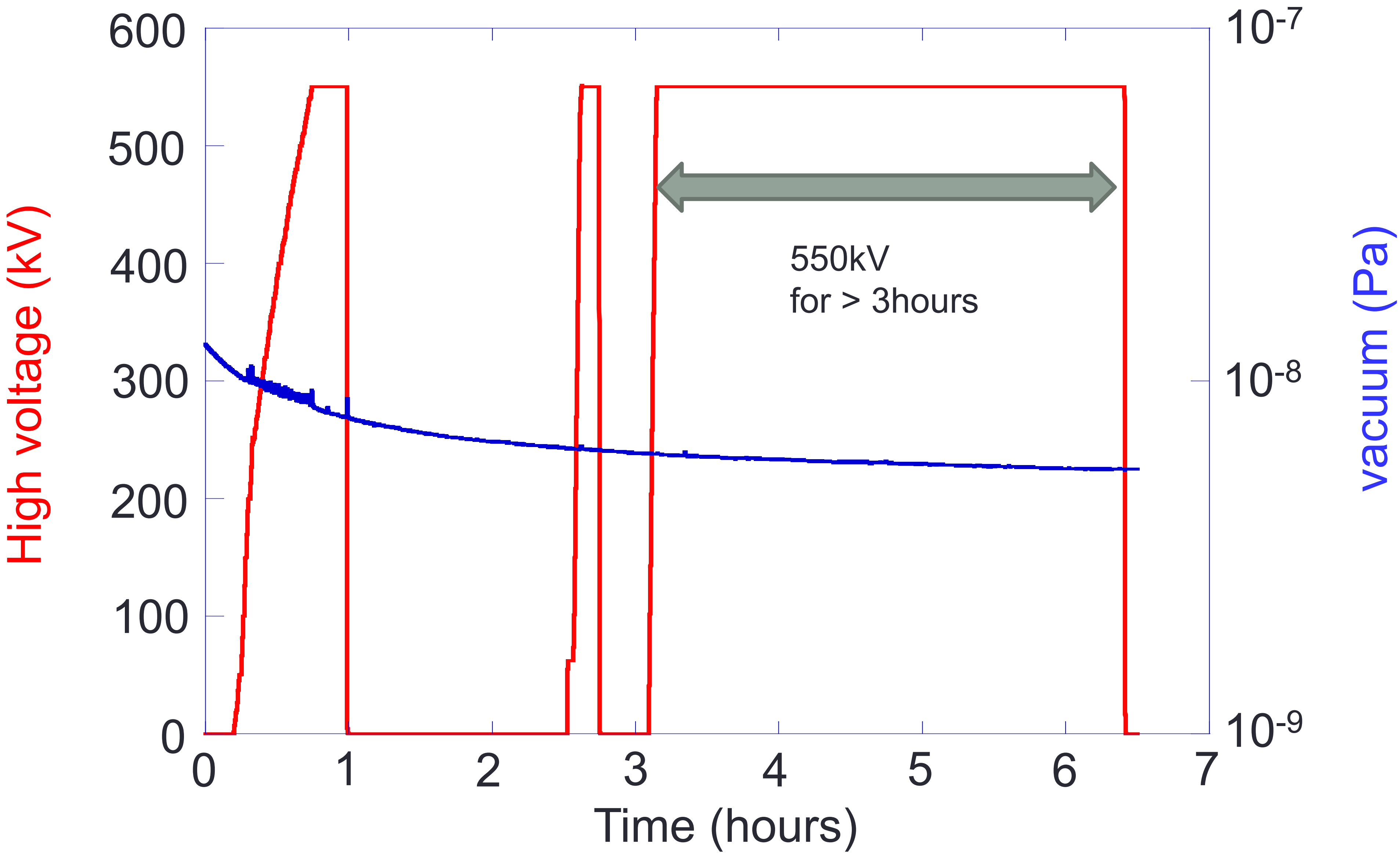




- Installed an additional ceramics in July 2015
- Performed HV test up to 550 kV without stalk
- Install a stalk in Sep. 2015
- Perform HV test with cathode electrode
- Perform beam generation in Nov. 2015

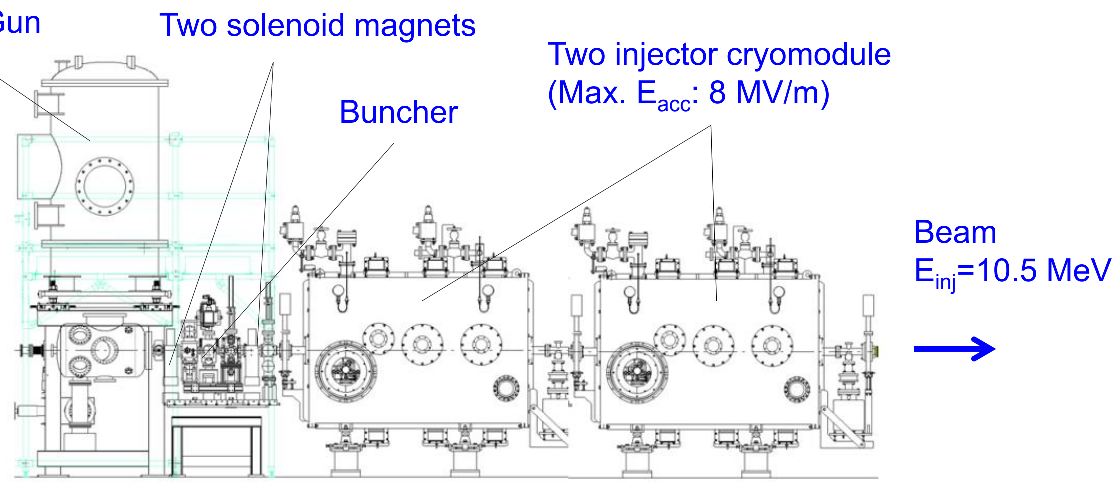
HV test with the additional insulator without stalk

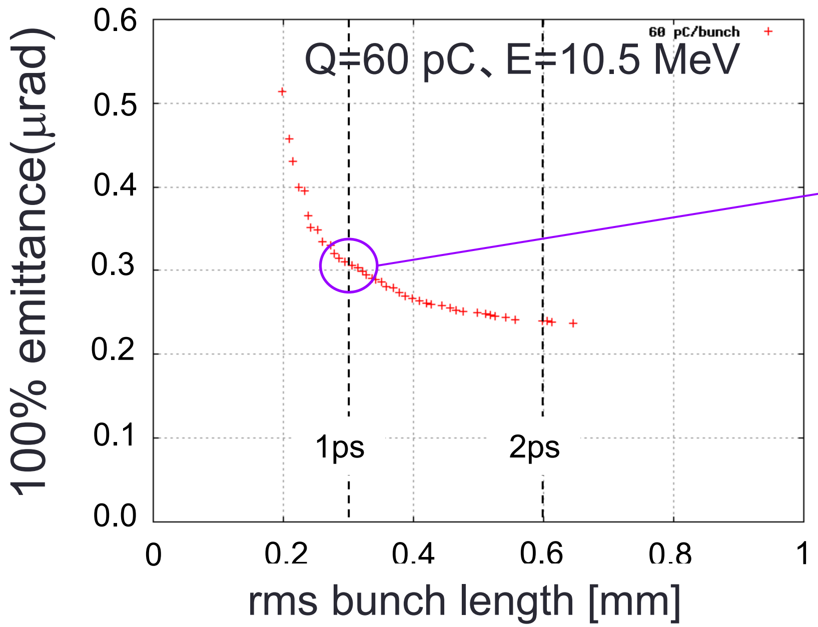


MOGA optimization for EUV FEL photoinjector

EUV FEL injector
(merger not included)

N. Nakamura et al., Proc. of ERL2015, MOPCTH010





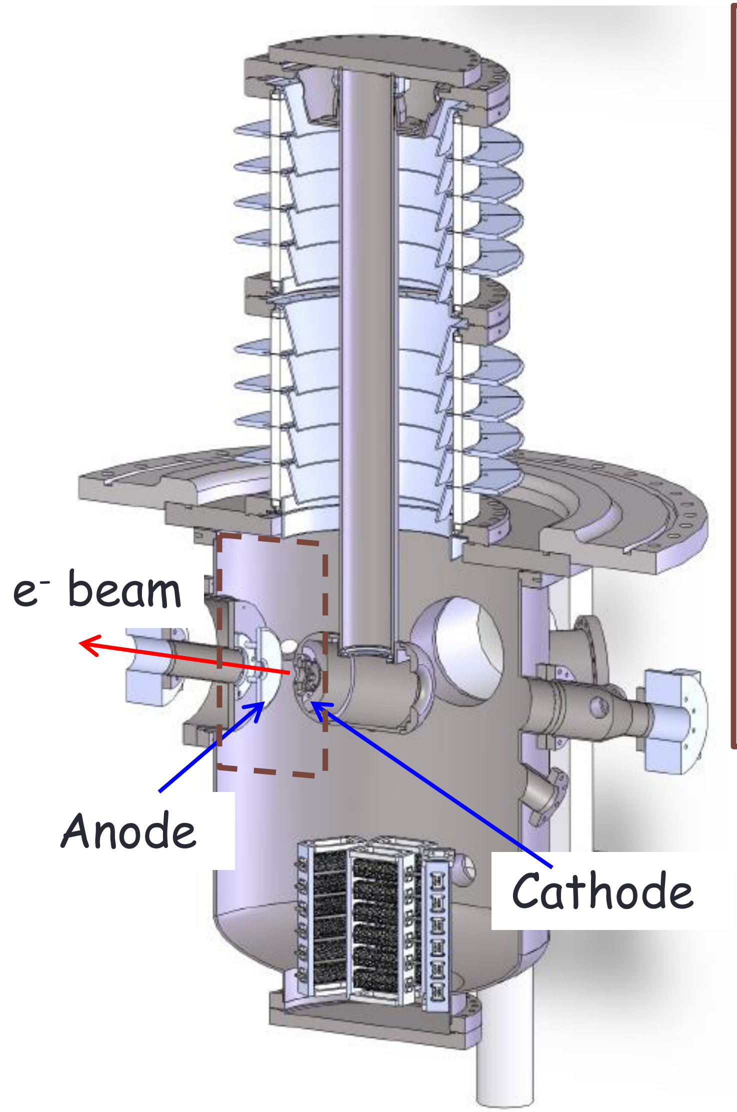
ε_n=0.30μm, 30A before merger

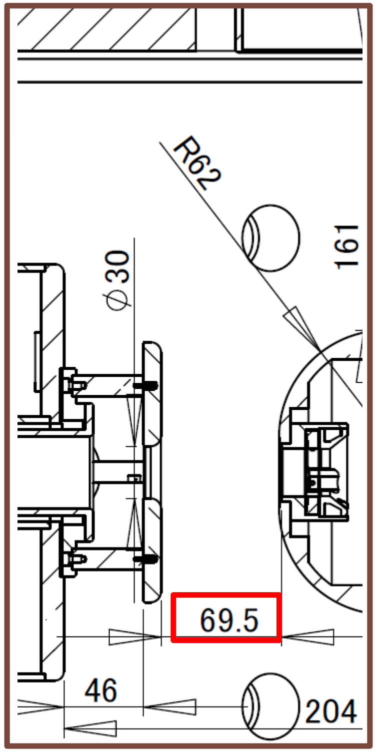
10 kW EUV FEL injector specifications after merger

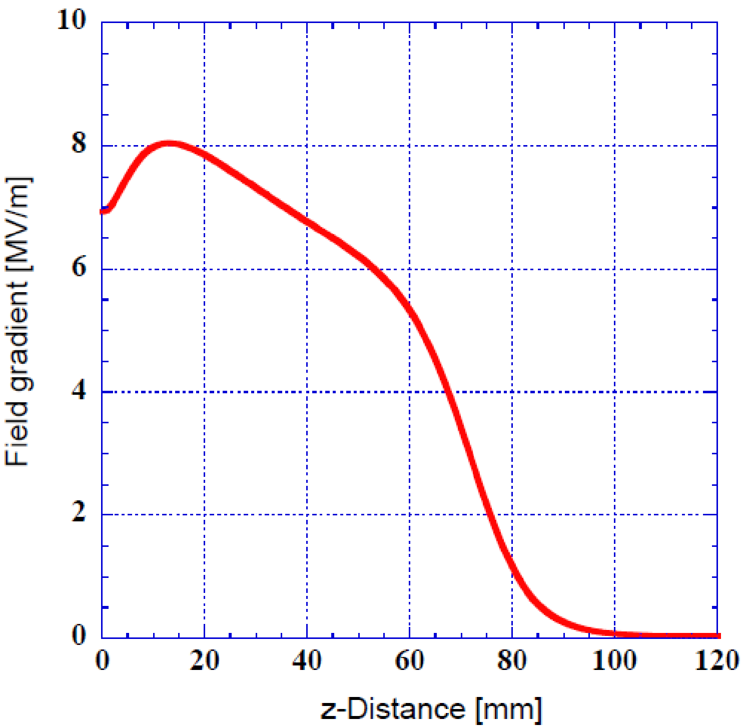
bunch charge	ε_n (μm)	peak current (A)
60 pC	0.60	30

Courtesy of Tsukasa Miyajima

70 mm gap 500 kV gun at KEK







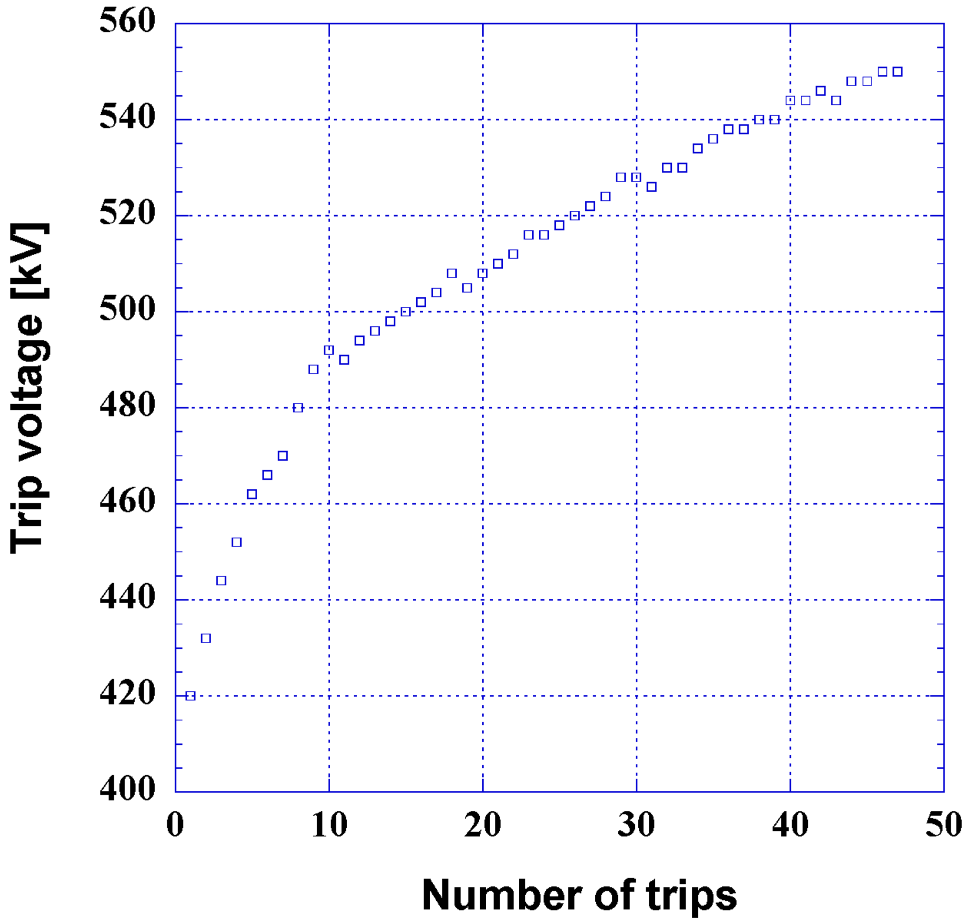
$$\varepsilon_{n,th} \geq \frac{1}{2}\sqrt{\frac{q}{\pi\varepsilon_0 E}}\sqrt{\frac{MTE}{mc^2}}$$

✓ 6.9 MV/m @ photocathode center (=E)
✓ 11.0 MV/m @ cathode ball surface

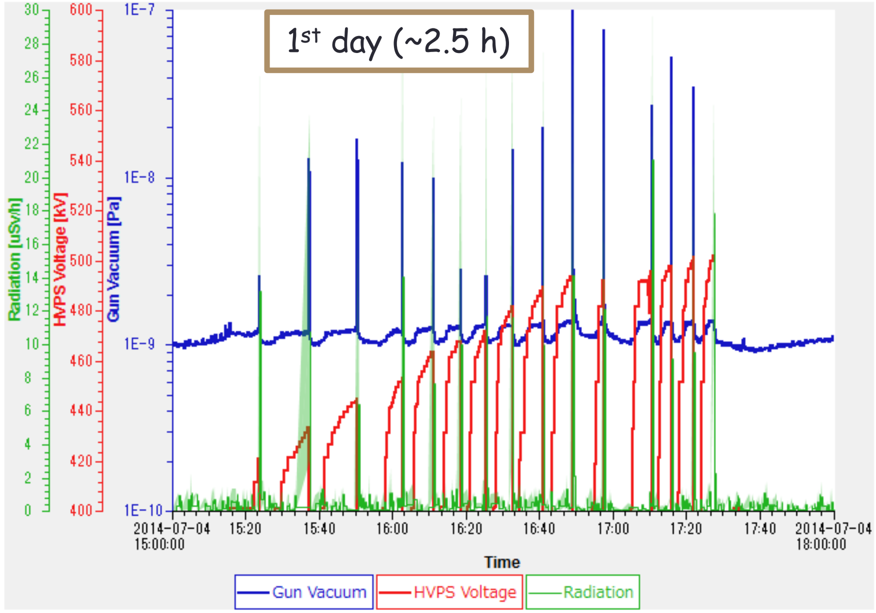
Courtesy of Masahiro Yamamoto

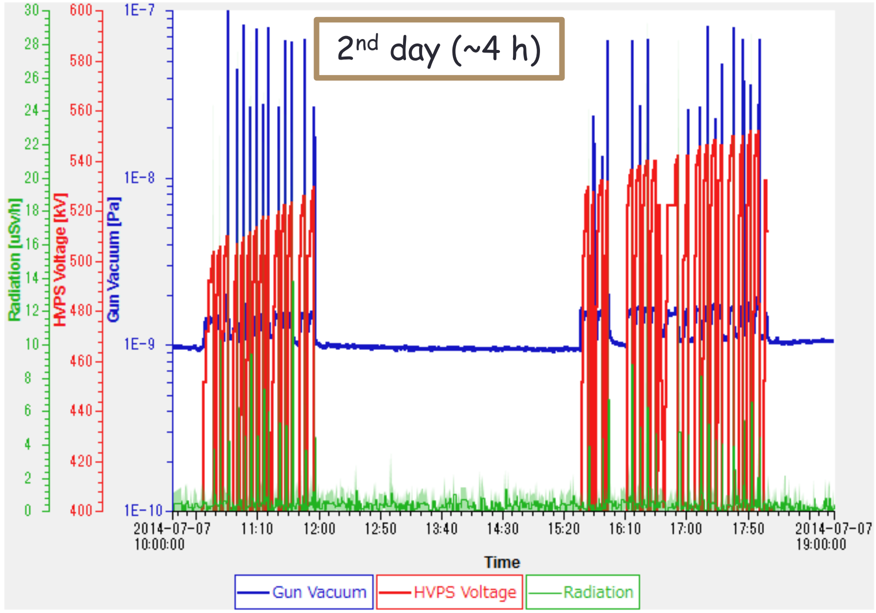
HV conditioning test

Reached 550kV in 48 trips / a short time (~7hs.)



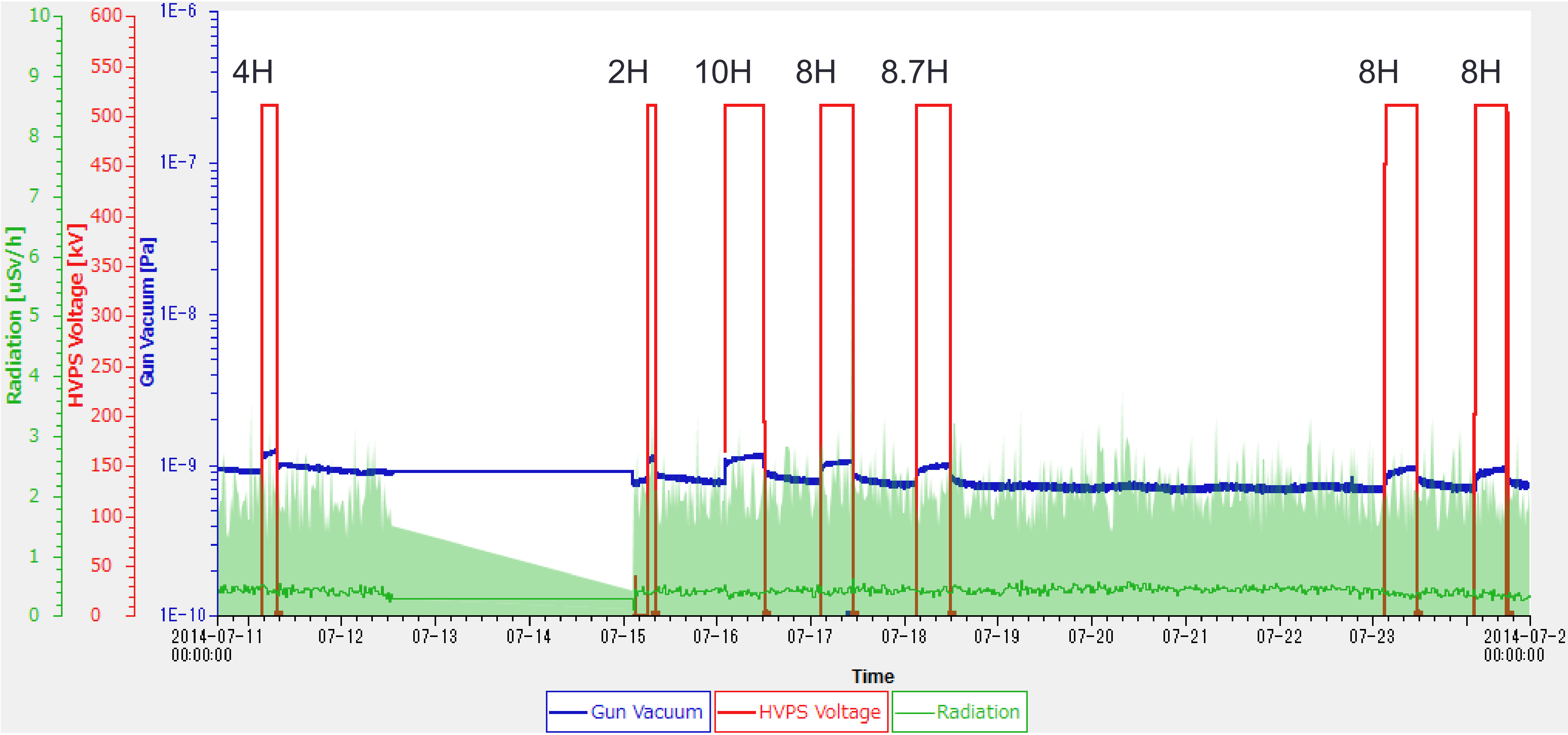
Vacuum pressure: ~4x10^{-10} Pa





Courtesy of Masahiro Yamamoto

HV holding test

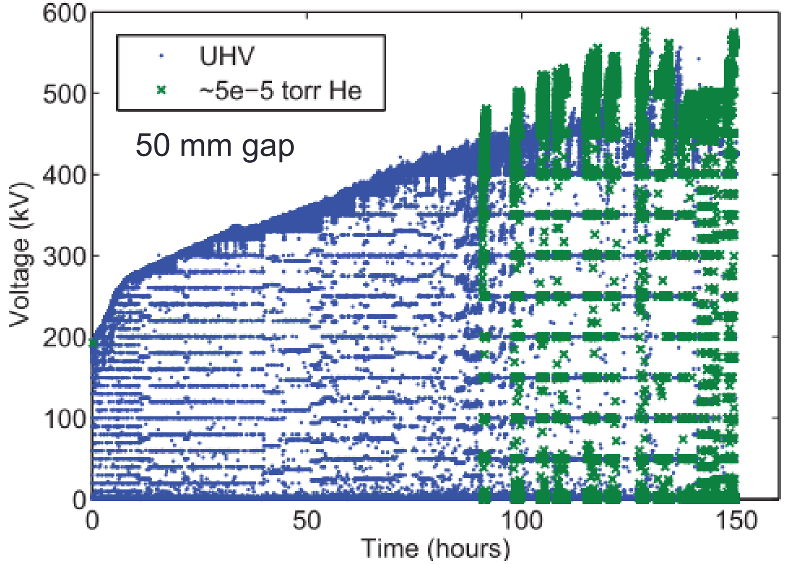


No breakdown happened during totally 50 hours of 500 kV-holding test.

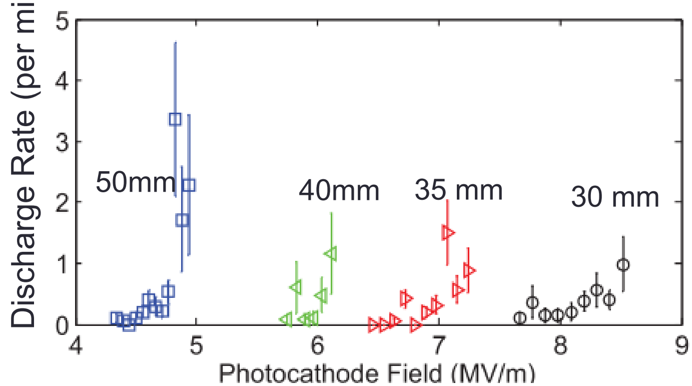
Courtesy of Masahiro Yamamoto

Variable gap segmented insulator gun at Cornell

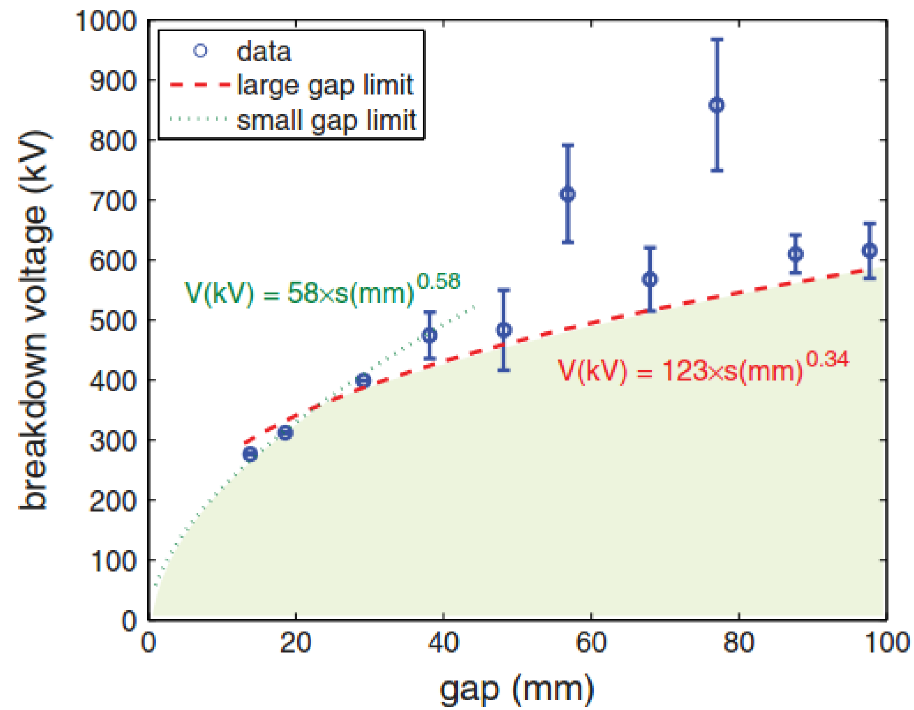
J. Maxson et al., RSI **85**, 093306 (2014)



Stability test with various gaps:

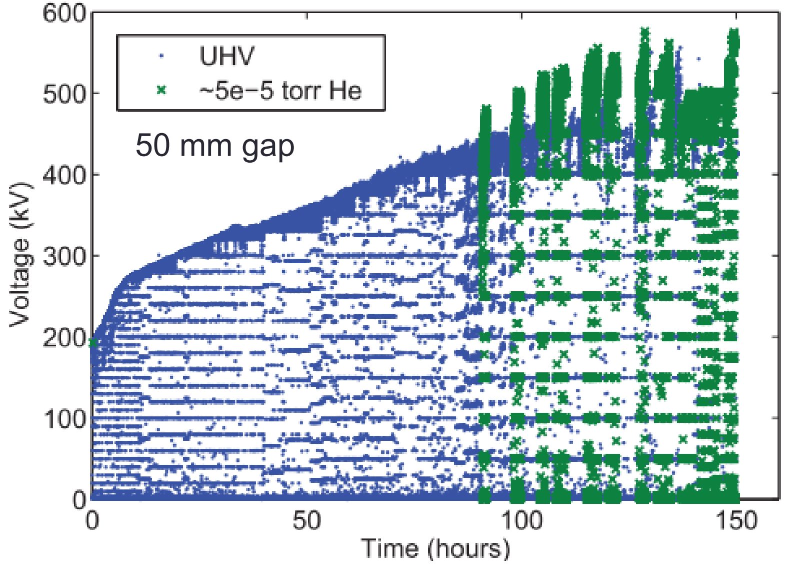


P. Slade, *The Vacuum Interrupter*, CRC Press, 2008

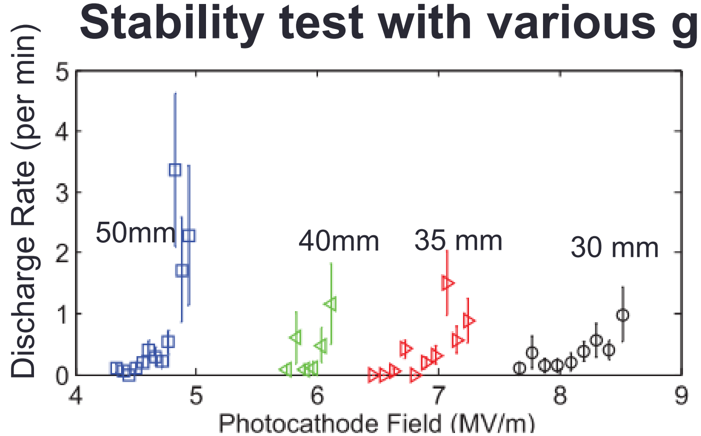


Variable gap segmented insulator gun at Cornell

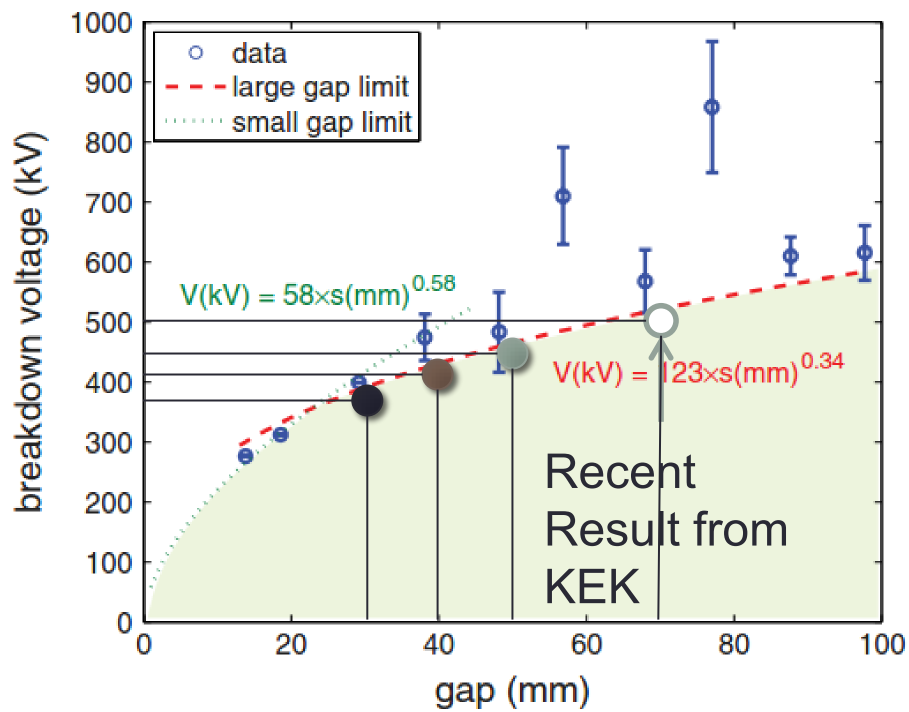
J. Maxson et al., RSI **85**, 093306 (2014)



Stability test with various gaps:



P. Slade, *The Vacuum Interrupter*, CRC Press, 2008



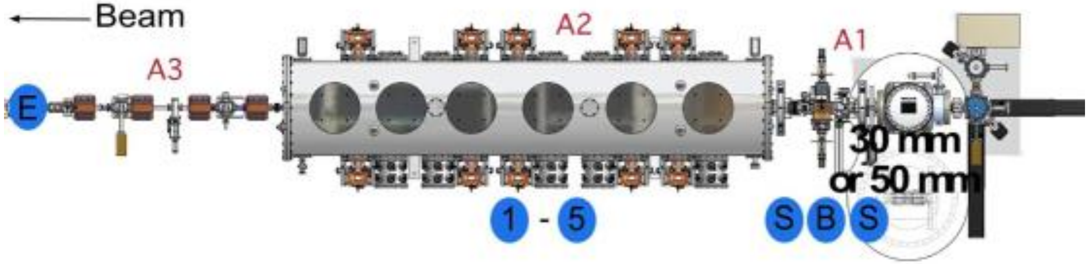
- Surprisingly good agreement between different HV systems.
- But what configuration is best for the beam emittance? –Turn to simulations.

Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE)

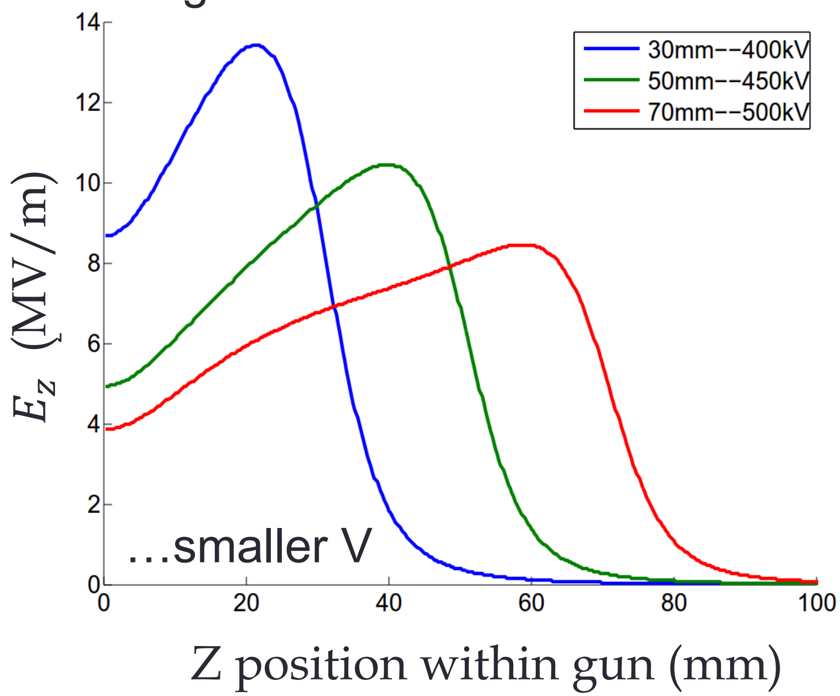
Courtesy of Jared Maxson

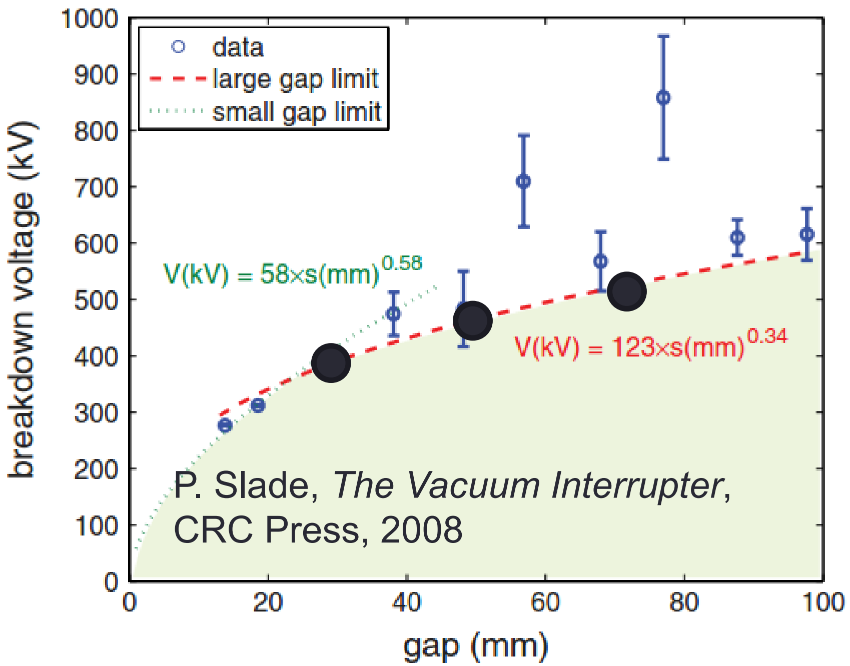
MOGA optimizations with various gaps

- Choose 3 Cornell style guns as the injector source→ use MOGA
  - 500 kV: 70mm
  - 450 kV: 50 mm
  - 400 kV: 30 mm



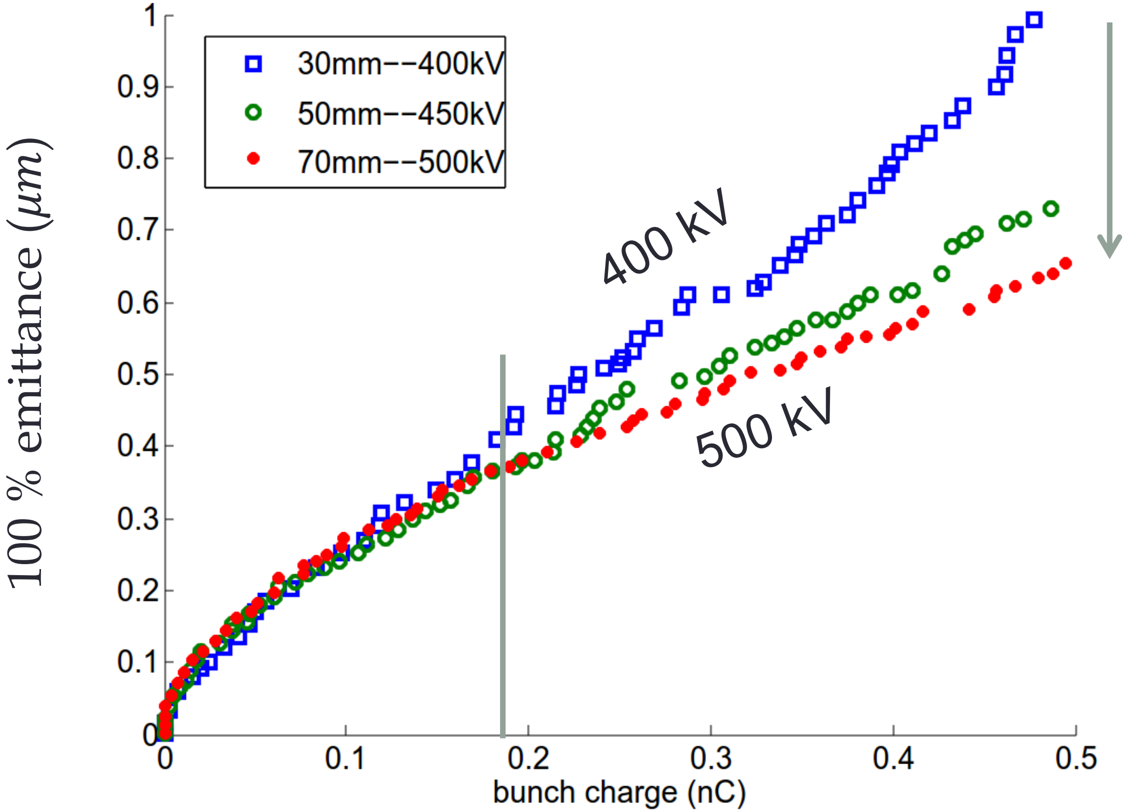
larger field…

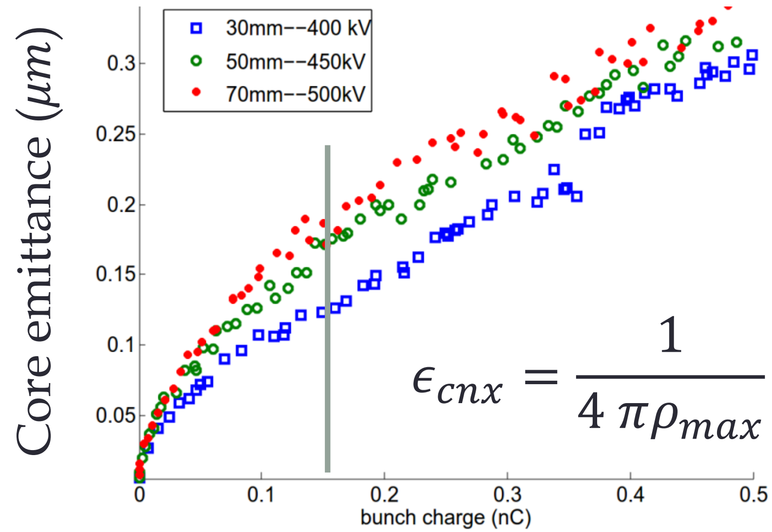




Emittance vs. bunch charge with various gaps

Approaching thermal emittance!





$$\epsilon_{cnx} = \frac{1}{4\,\pi\rho_{max}}$$

Summary

- The DC gun-based Cornell photoinjector demonstrated cathode emittance dominated beam satisfying LCLS-II specifications with a 400 kV gun.
- Higher voltage and higher gradient gun developments with segmented insulators are in progress at JAEA/KEK and Cornell University to go beyond the Cornell photoinjector.
  - 500 keV beam generation from JAEA gun with 160 mm gap
  - 50 hours holding at 500kV with 70 mm gap at KEK gun
  - Experimental and numerical studies with 20-50 mm gaps at Cornell gun
- Gun operational experience for users is accumulated at the cERL.

Acknowledgements

We acknowledge Adam Bartnik, Colwyn Gulliford, Jared Maxson, Bruce Dunham, and Ivan Bazarov at Cornell University for useful discussion on the Cornell photoinjector developments.

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