Development of 500kV DC electron guns and stable beam operation at KEK cERL

Seminaires du pole accelerateurs @IJCLab
Energy Recovery Linac Open Seminars
2025/1/16

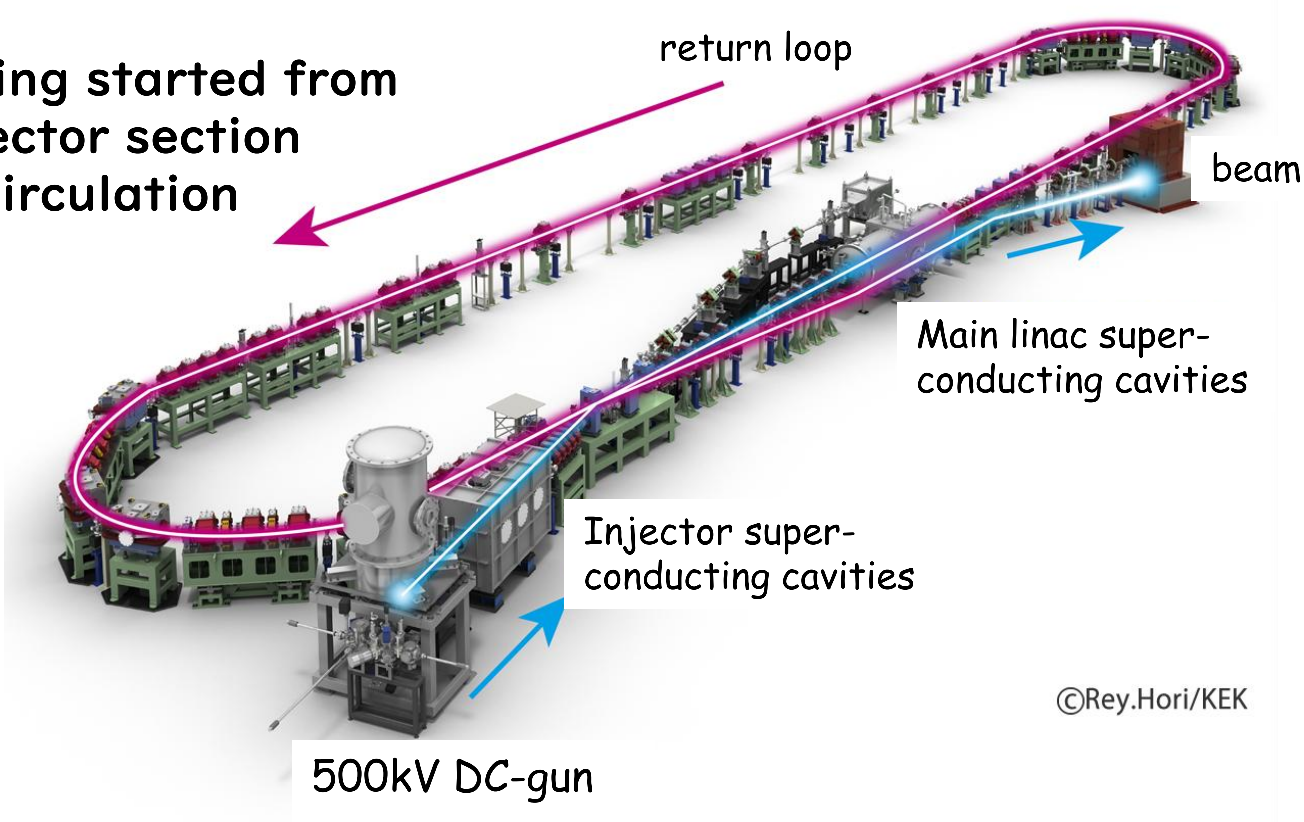
High Energy Accelerator Research Organization (KEK)
Masahiro Yamamoto
masahiro.yamamoto@kek.jp

Contents

Compact-ERL @ KEK

Proof of key technology at the Compact-ERL

The commissioning started from
Apr. 2013 :Injector section
Dec. 2013 :Recirculation



return loop

beam dump

Main linac super-conducting cavities

Injector super-conducting cavities

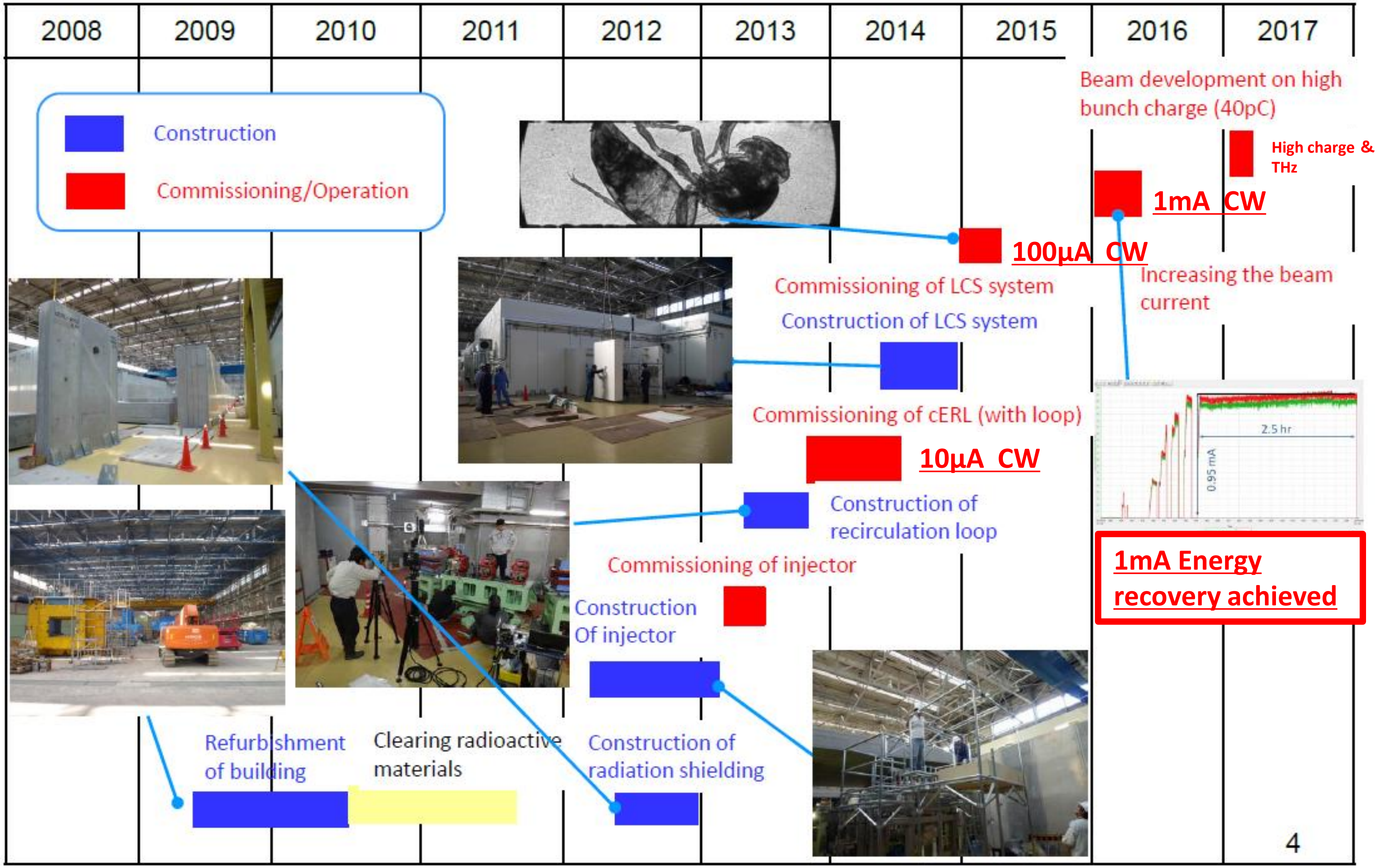
500kV DC-gun

©Rey.Hori/KEK

Electron Gun Technical Challenges:

- High rep. rate 1.3 GHz & high avarage current (7.7pC/bunch, 10 mA)
- Low emittance ($e_{n.rms}$: < 1 mm.mrad @77pC/bunch)
- Long cathode lifetime

cERL's history in the first 9 years (2009~2017)



2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017

🟦 Construction

🟥 Commissioning/Operation

Refurbishment of building

Clearing radioactive materials

Construction of radiation shielding

Construction Of injector

Commissioning of injector

Construction of recirculation loop

Commissioning of cERL (with loop)

10μA CW

Construction of LCS system

Commissioning of LCS system

100μA CW

Increasing the beam current

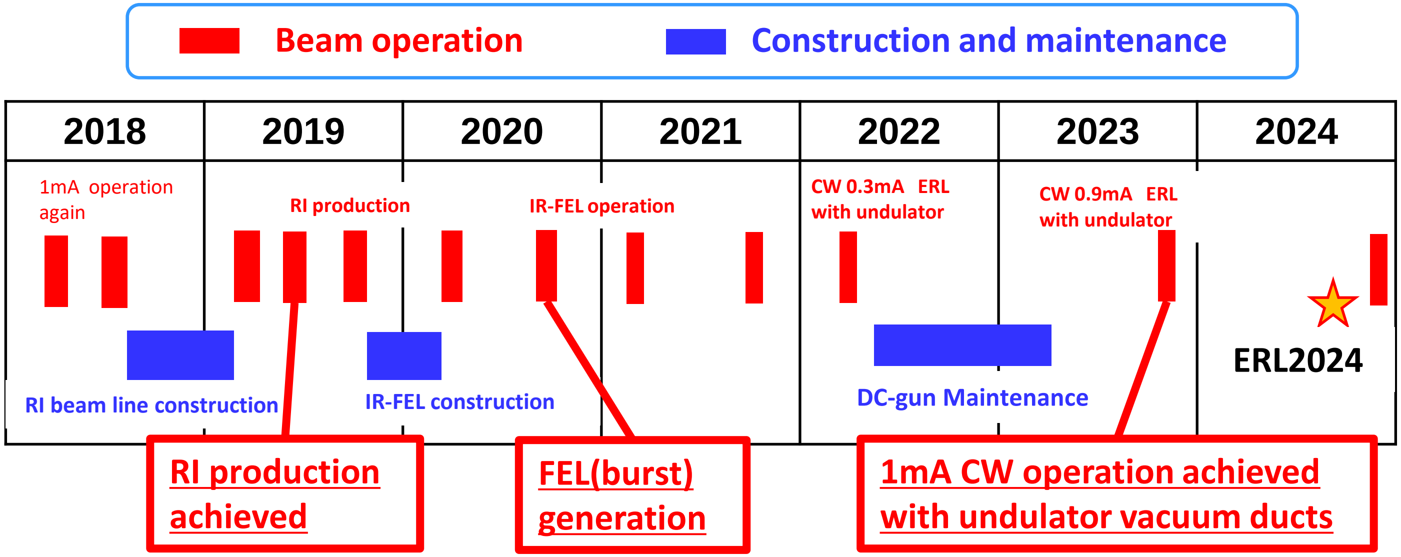
1mA CW

Beam development on high bunch charge (40pC)

High charge & THz

1mA Energy recovery achieved

cERL's history in the last 7 years (2018~2024)



🟥 Beam operation 🟦 Construction and maintenance

2018	2019	2020	2021	2022	2023	2024

1mA operation again

RI production

IR-FEL operation

CW 0.3mA ERL with undulator

CW 0.9mA ERL with undulator

ERL2024

RI beam line construction

IR-FEL construction

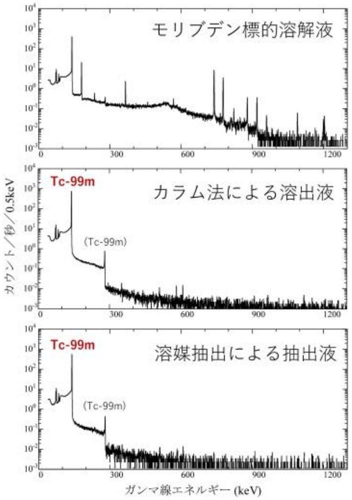
DC-gun Maintenance

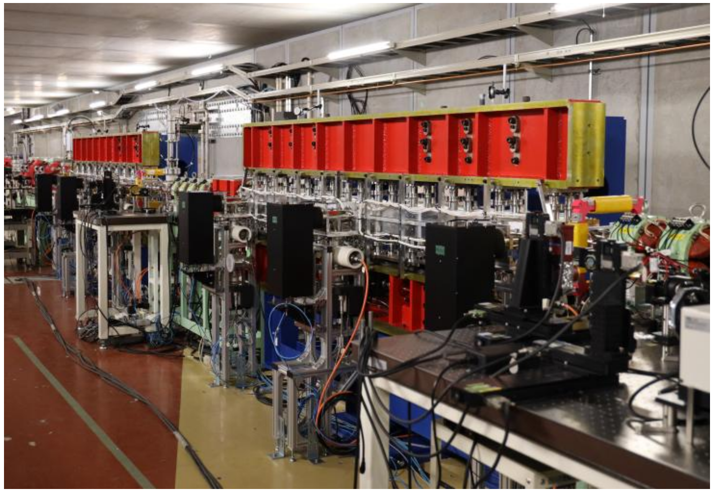
RI production achieved

FEL(burst) generation

1mA CW operation achieved with undulator vacuum ducts

RI Beamline for Mo-99 Production & Technetium Extraction Experiments





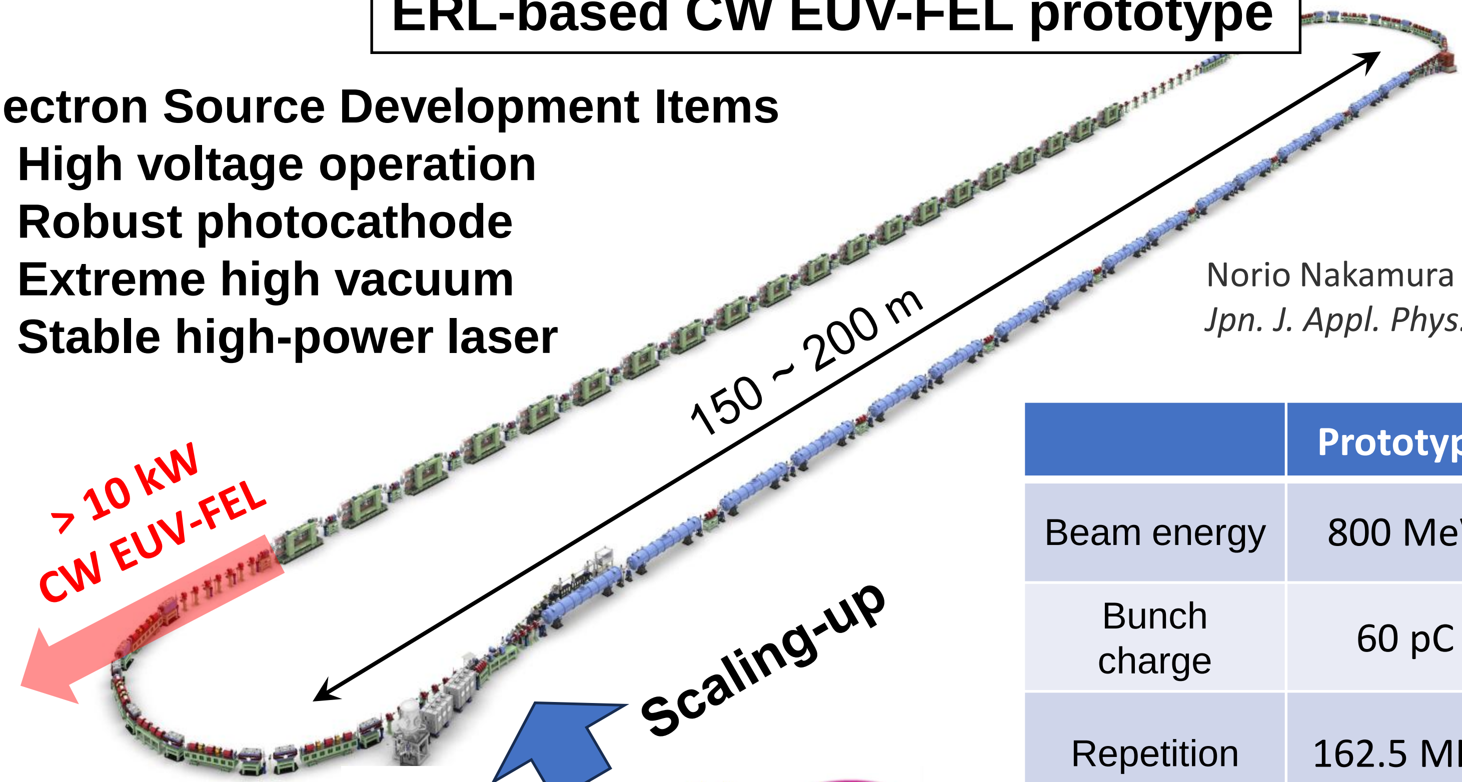
Introduction of undulators

What lies beyond cERL

ERL-based CW EUV-FEL prototype

Electron Source Development Items

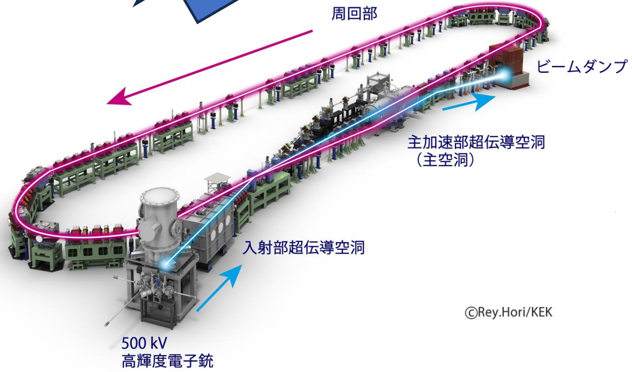
- **High voltage operation**
- **Robust photocathode**
- **Extreme high vacuum**
- **Stable high-power laser**



Norio Nakamura *et al.*,
Jpn. J. Appl. Phys. **62** SG0809 (2023)

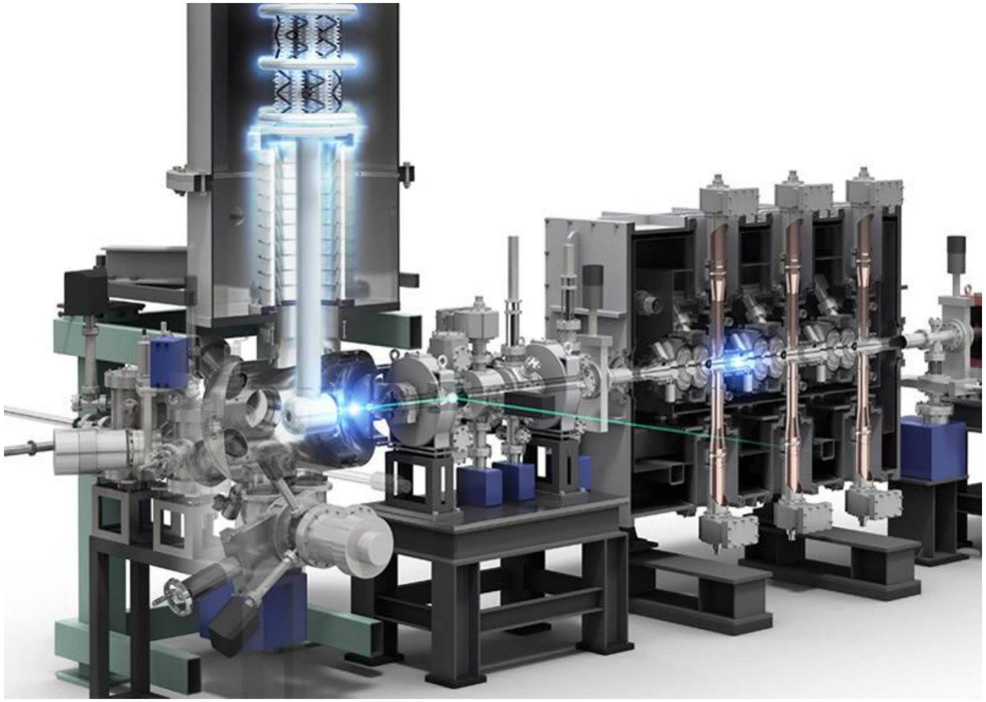
	Prototype	cERL(achieved)
Beam energy	800 MeV	17.5 MeV
Bunch charge	60 pC	0.8 pC (CW) 60 pC(burst)
Repetition	162.5 MHz	1.3 GHz 81.25 MHz
Average current	9.75 mA	1mA @0.8pC,1.3GHz
FEL wavelength	13.5 nm	20 µm
FEL power	> 10 kW	-

Compact-ERL
@KEK



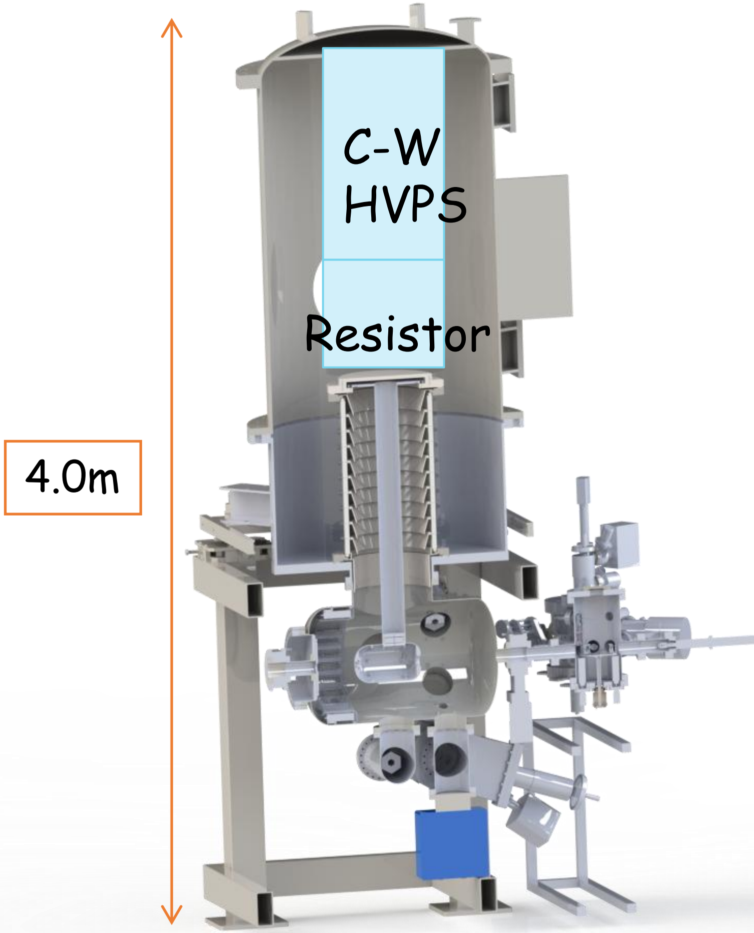
500 kV DC-gun development

- Technical Challenges (HV, Vacuum)
- Development of elemental technologies



500 kV DC gun (1)

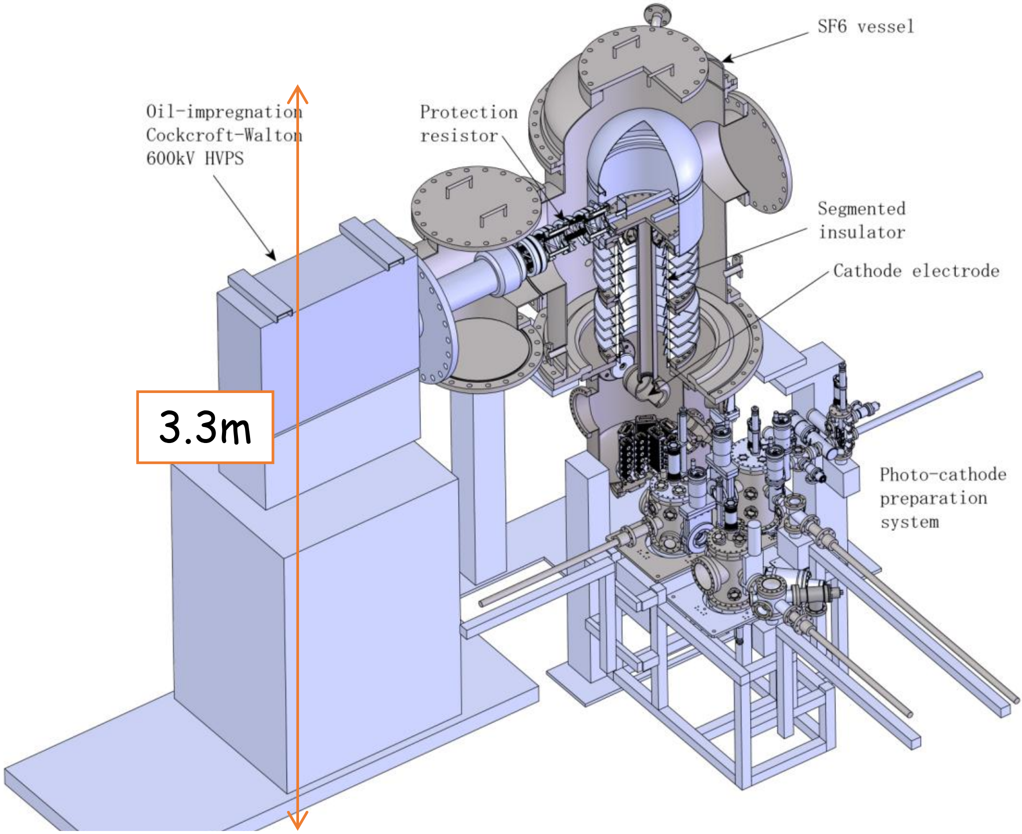
1st DC-Gun & preparation system



Developed at JAEA from 2007 ~
Installed compact-ERL at Oct. 2012.
Beam operation has been started from 2013 ~ at cERL

500 kV DC gun (2)

2nd DC-Gun & preparation system



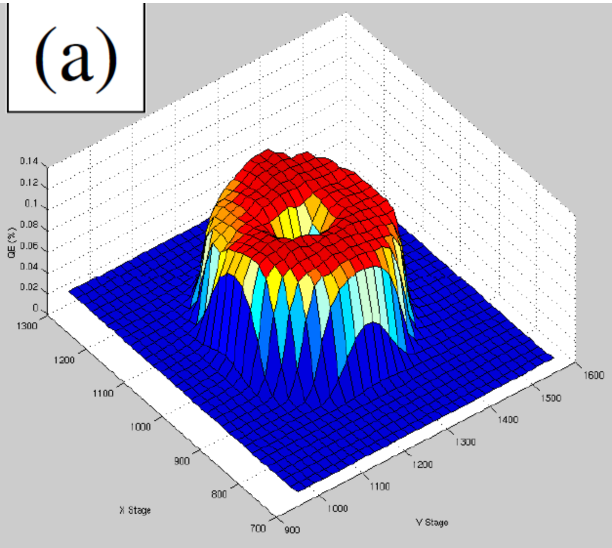
Developed at KEK from 2009 ~
Backup unit for the first DC-gun and R&D with a more challenging design.
Achieved stable applying of 500kV. Beam test started from 2015.
Since 2016, it has been suspended due to budgetary concerns.

https://accelconf.web.cern.ch/erl2015/talks/tuiblh1021_talk.pdf

Challenge 1: Extreme High Vacuum (XHV)

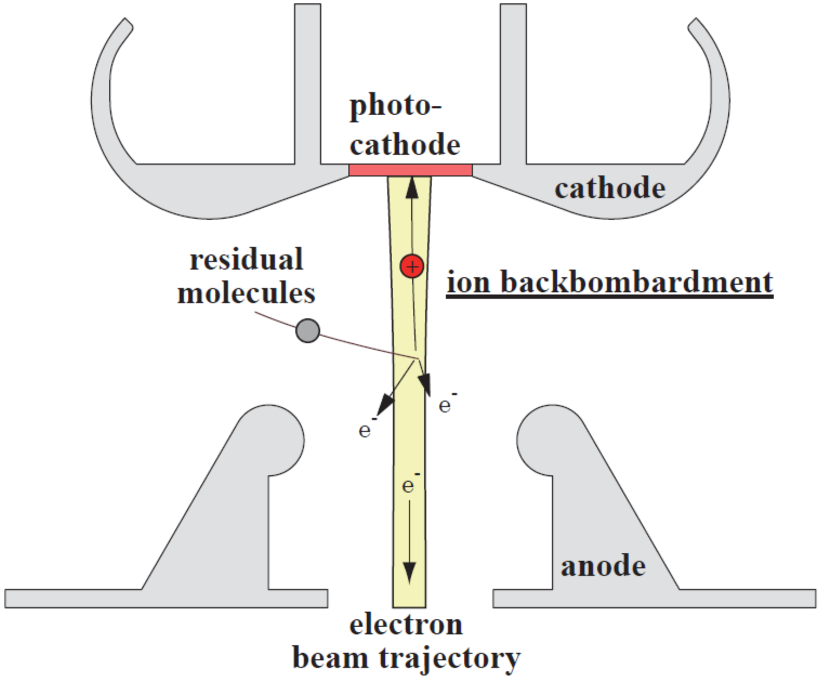
Cathode lifetime problem

Cathode surface degrade by ion back-bombardment.



Reference: C. K. Sinclair et al., Phys. Rev. STAB 10, (2007) 023501

Charge lifetime is limited ~1000 Coulomb for 10 mA operation under the pressure range of ~10^{-9} Pa.



Lifetime τ is defined as

$$\mathrm{QE}(t) = \mathrm{QE}_0 \cdot e^{-\frac{t}{\tau}}$$

Charge lifetime Q_τ is defined as

$$Q_\tau = \int_0^\tau I_{\mathrm{beam}}(t)dt$$

Vacuum design for 2nd DC-Gun

Simple formula of ultimate pressure

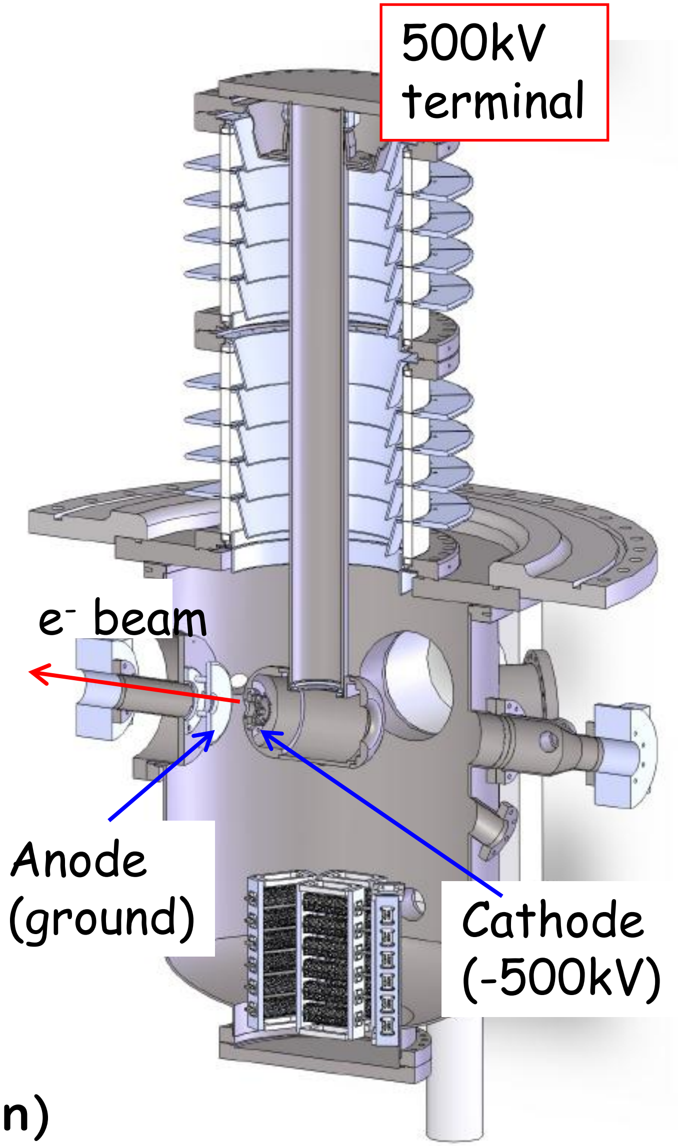
$$P\ [\mathrm{Pa}] = \frac{Q\ [\mathrm{Pa}\cdot\mathrm{m}^3/\mathrm{s}]}{S\ [\mathrm{m}^3/\mathrm{s}]}$$

- Ultra low outgassing material
  - Titanium chamber & electrodes
- High performance vacuum pumps
  - 4K bakeable cryopump
  - Massive NEG pumps (1～2x10^4 L/s)

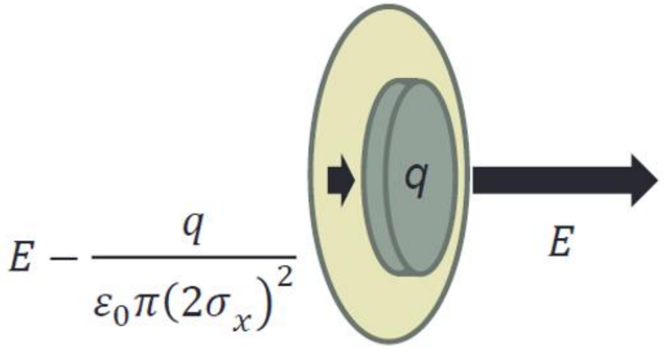
Goal

Ultimate pressure : ~1x10^{-10} Pa

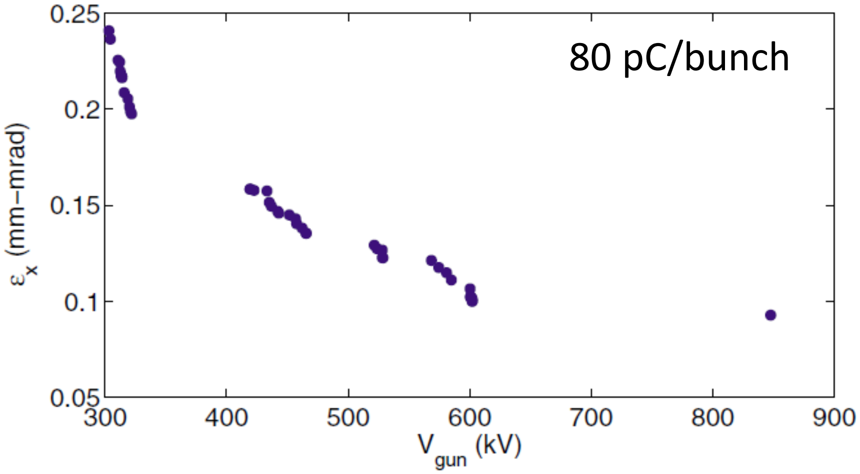
(during the gun operation)



Challenge 2: High Voltage & Field Gradient



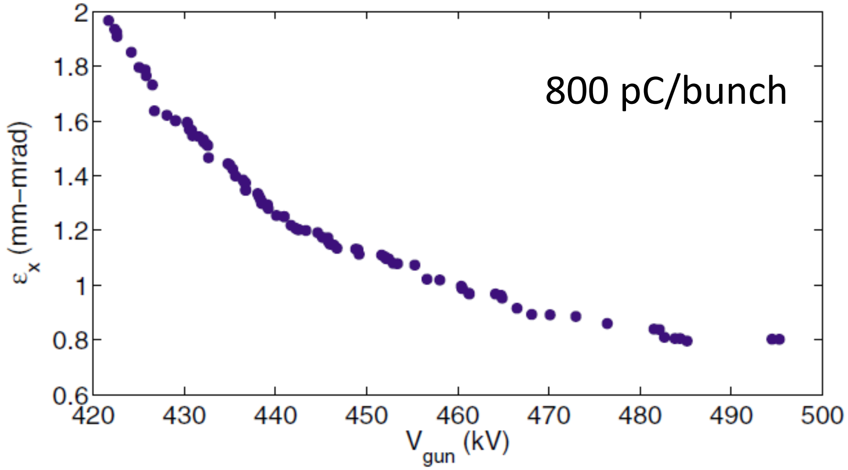
$$E - \frac{q}{\varepsilon_0 \pi (2\sigma_x)^2}$$



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

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

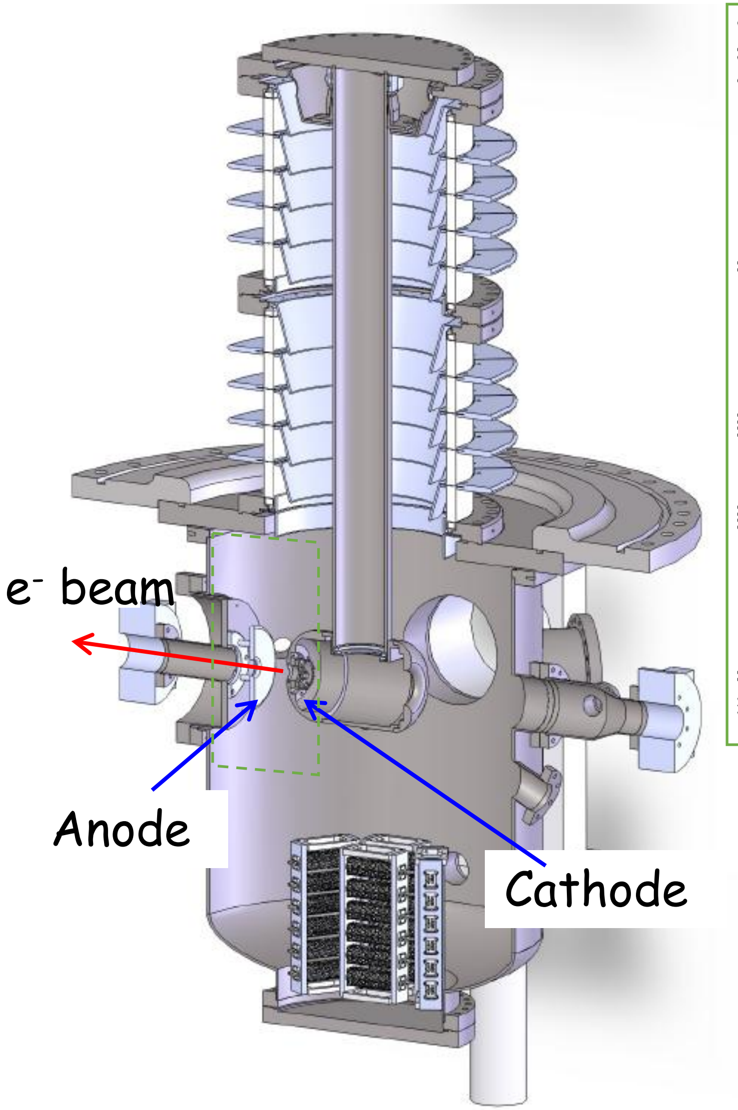
I.V. Bazarov et al., Phys. Rev. Lett. 102, 104801 (2009).
N. Nishimori, FEL2015 MOD01.

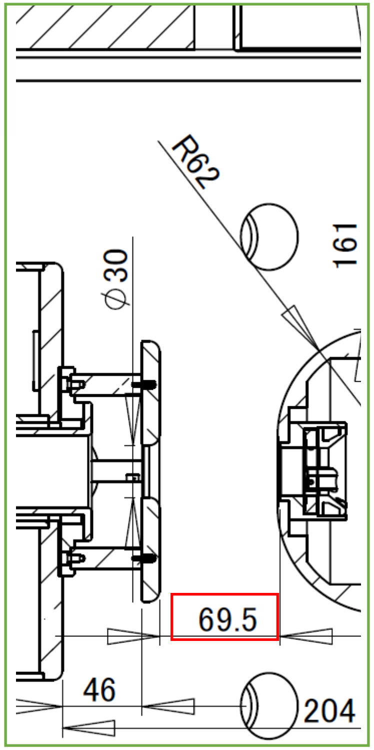


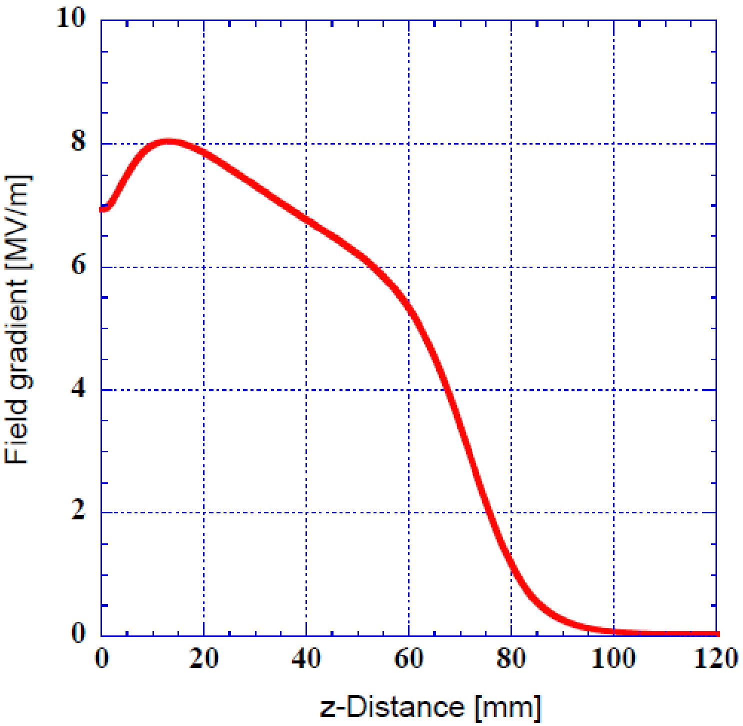
I. V. Bazarov and C. K. Sinclair, Phys. Rev. ST Accel. Beams **8**, 034202 (2005).

High voltage and high cathode field are essential to suppress emittance growth.

70 mm Gap Design for 2nd DC-Gun

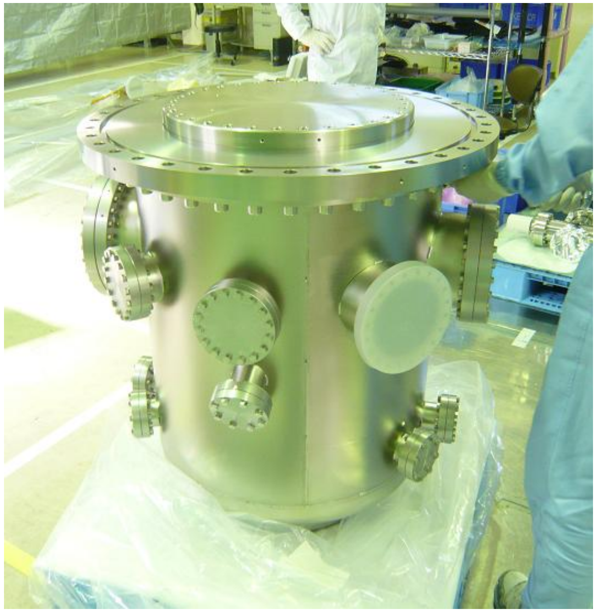






- ✓ 6.9 MV/m @ photocathode center (=E_{cath})
- ✓ 11.0 MV/m @ cathode ball surface

Fabrication of titanium gun chamber



Material

Chamber body:

*pure Titanium (JIS grade2)

Flanges :

*pure Titanium (JIS grade3) (Hv>180)

*6Al4V-Titanium alloy (Hv>330)

All base materials for flanges are forged.

Chemical polishing & Cleaning process

1. Degreasing wash.
2. Chemical polishing
3. Pure water rinse (HPR)
4. Nitric acid treatment
5. Pure water rinse (HPR) & wiping
6. Ultra pure water rinse (clean room)
7. Dry by N_2 blowing & package (clean room)

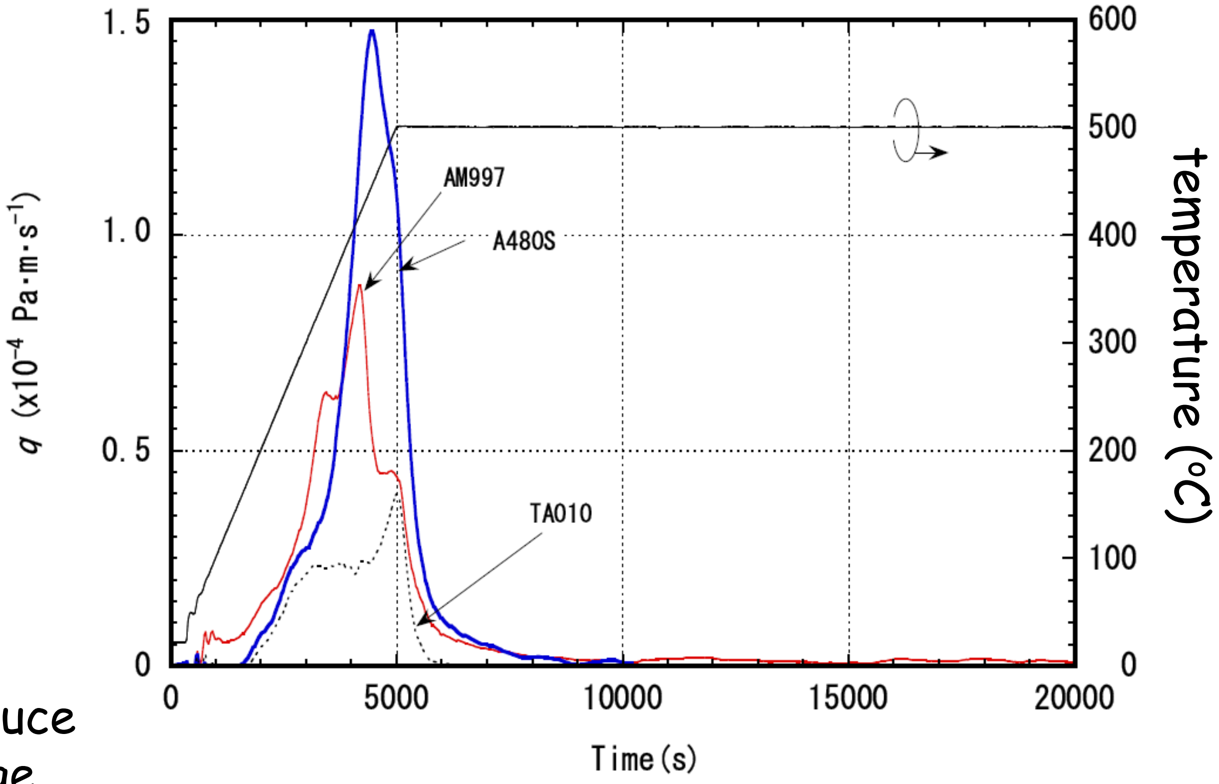
Material choice of insulator

Pure almina (Al_2O_3)

AM997
purity: >99.7%
grain size: ~3 um
A480S
purity: >99.7%
grain size: ~3 um

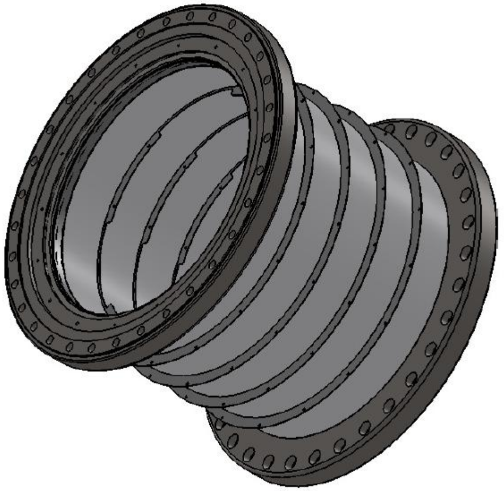
Almina based compound

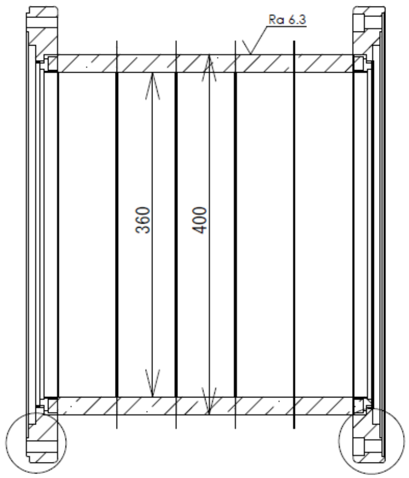
TA010
Al_2O_3 ~ 90%
Residuals: secret..
note: optimized to reduce creeping discharge.



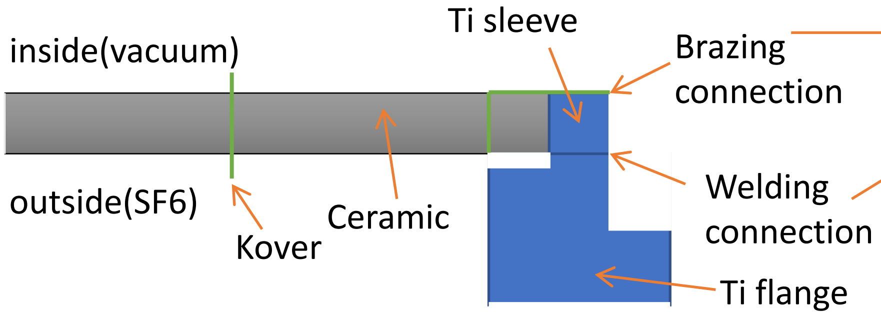
Samples are evaluated by thermal desorption spectroscopy.
TA010 is the most promising material for our DC-gun.

Structure of segmented insulator





Base ceramic: TA010 (Kyocera)
Flange: pure titanium (JIS-3)



inside(vacuum)

Ti sleeve

Brazing connection

outside(SF6)

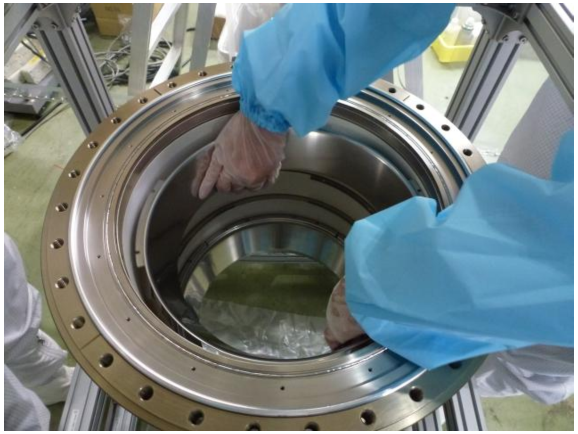
Kover

Ceramic

Welding connection

Ti flange

2nd 500kV DC-gun assembly



- All in-vacuum electrodes are made of pure titanium.
- All in-vacuum electrodes have no welding joint.
- All items were polished by buffing & chemical polishing, and washed by ultra pure water.

2nd 500kV DC-gun assembly

Clean hut size:
4m(L)x4m(W)x3.5m(H)

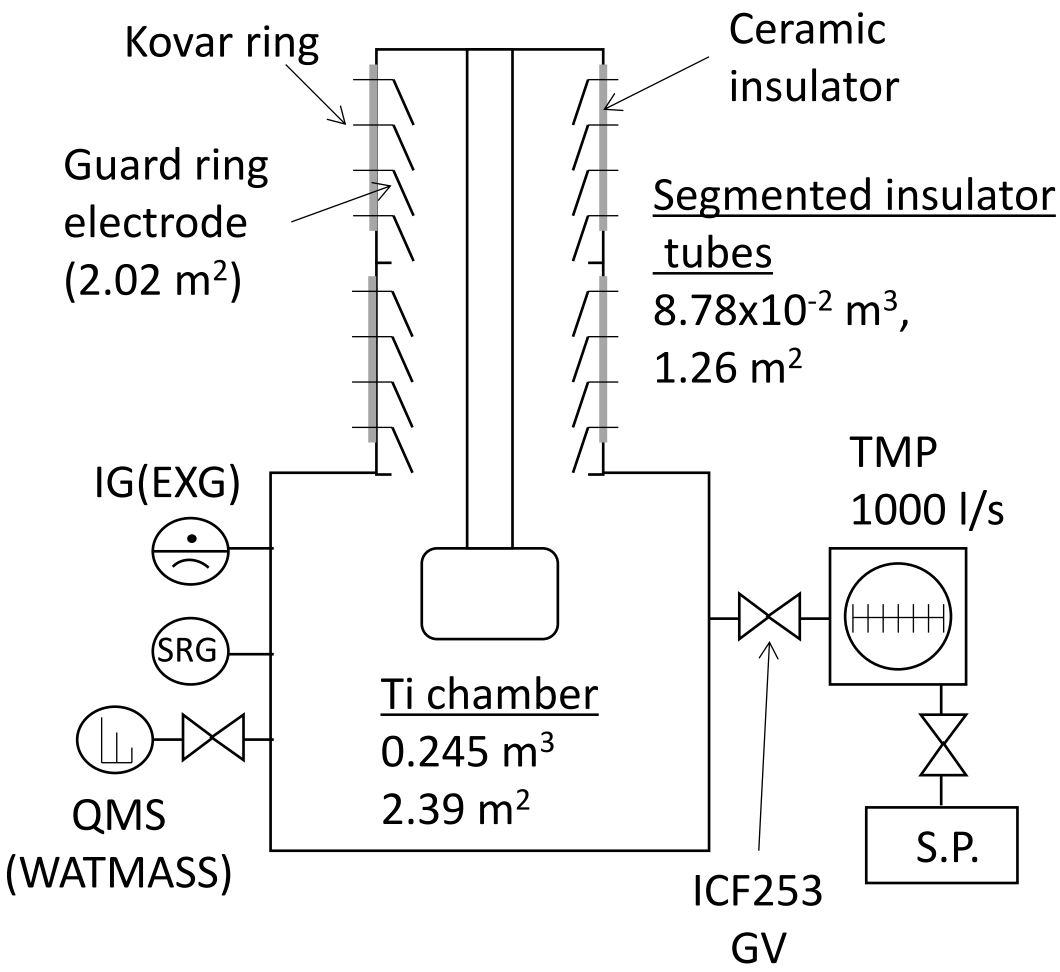
class ~10000

2nd 500kV DC-gun assembly

Ti electrodes (Cathode & Anode)

- Anodes and retarding electrodes are fixed insulated to ground.
- The purpose is to reduce the backflow of ions generated downstream.

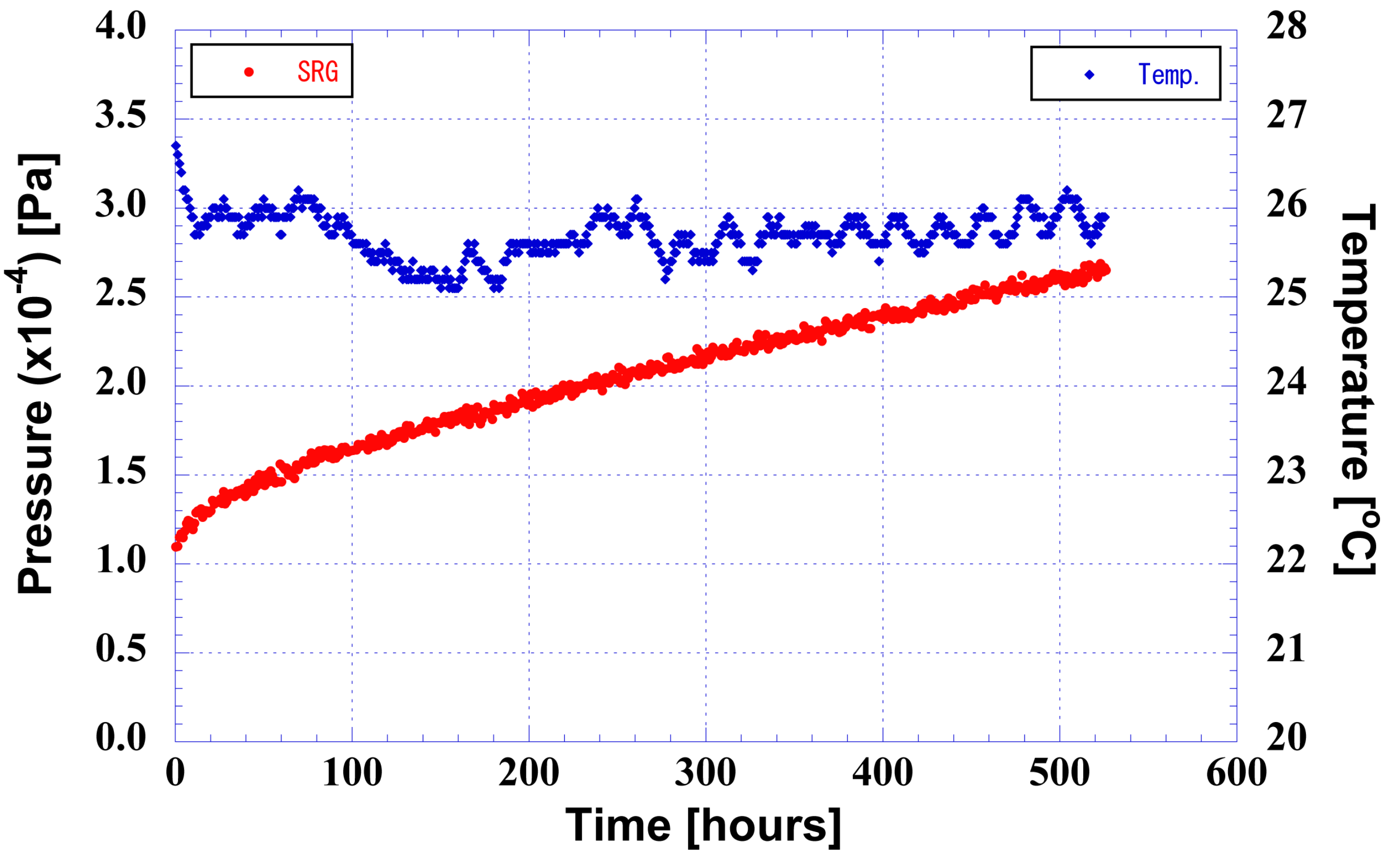
Outgassing rate measurement



150~200°C baking for 100 hours.

All components except main pump (NEGs, cryopump) were installed.

Outgassing rate measurement



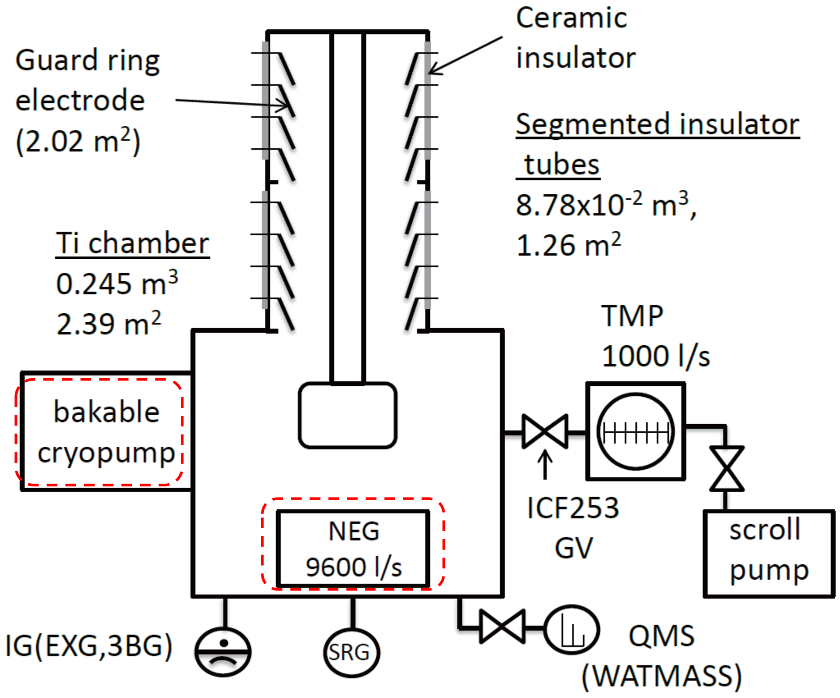
Outgassing rate was measured by rate of rise method using SRG.

Total outgassing rate

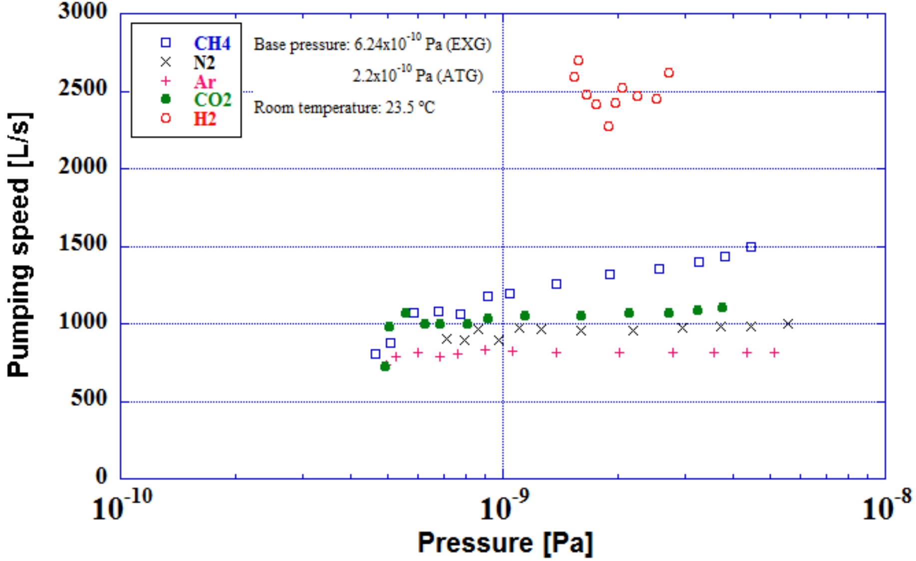
8.1×10^{-11} Pa m^3/s (H$_2$ equivalent)

2nd DC-Gun Main pump installation

(2014/Mar)



pumping speed of 4K bakable cryopump

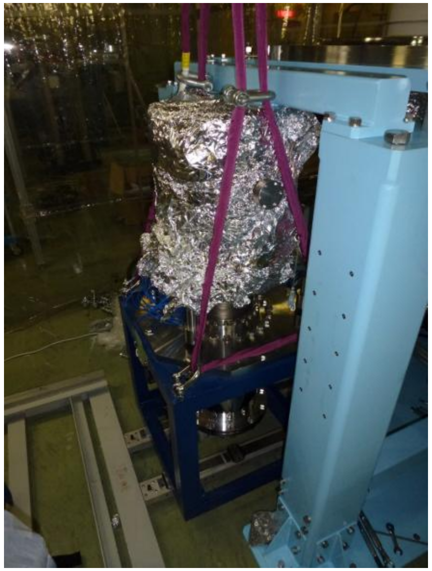


Main pump composition

1. Non Evaporable Getter (NEG)
   D400-2 x 24 = **9600 L/s (H_2)**
   = **4320 L/s (CO)**
   (catalog value)

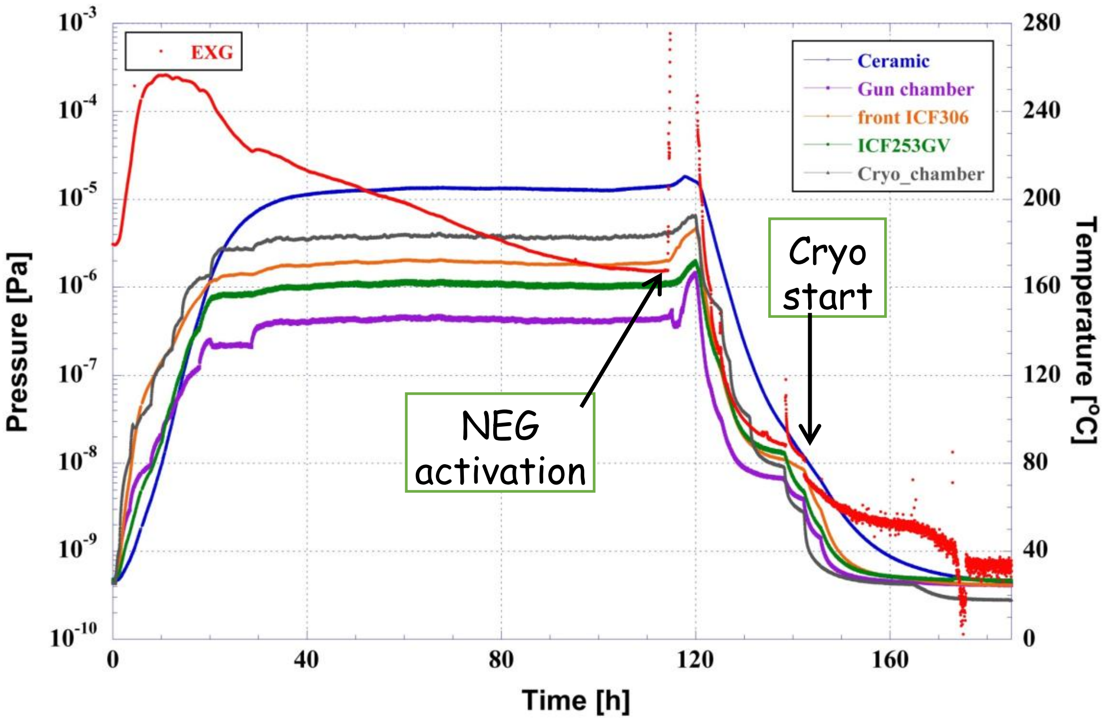
2. 4K bakable cryopump
   ~800 L/s (Ar), ~1000 L/s (N_2,CO_2), ~1200 L/s (CH_4) (measured values@1×10^{-9} Pa)

NEG pump set



4K bakable cryopump

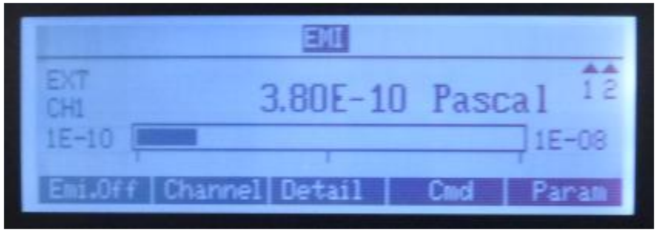
2nd DC-Gun Baking & RGA spectrum in XHV (2014/Mar~Apr)

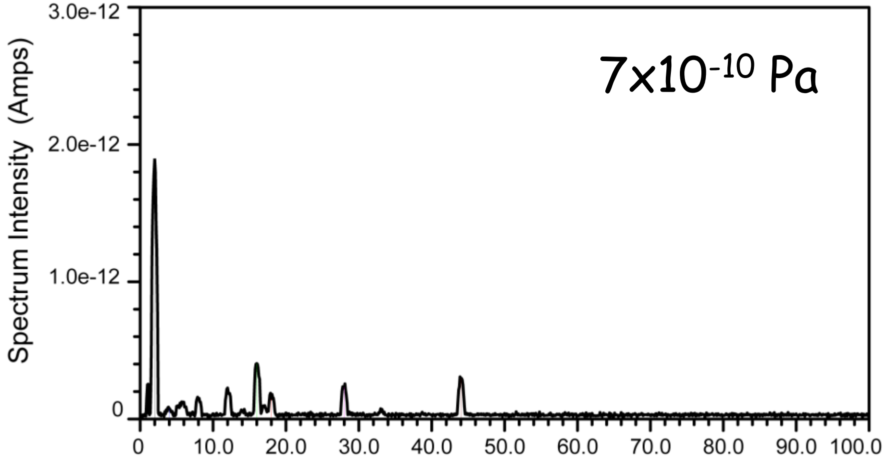


NEG activation

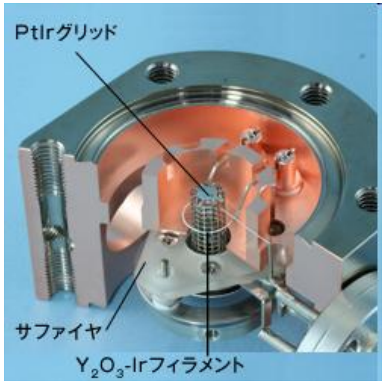
Cryo start

3B Gauge





7×10^{-10} Pa

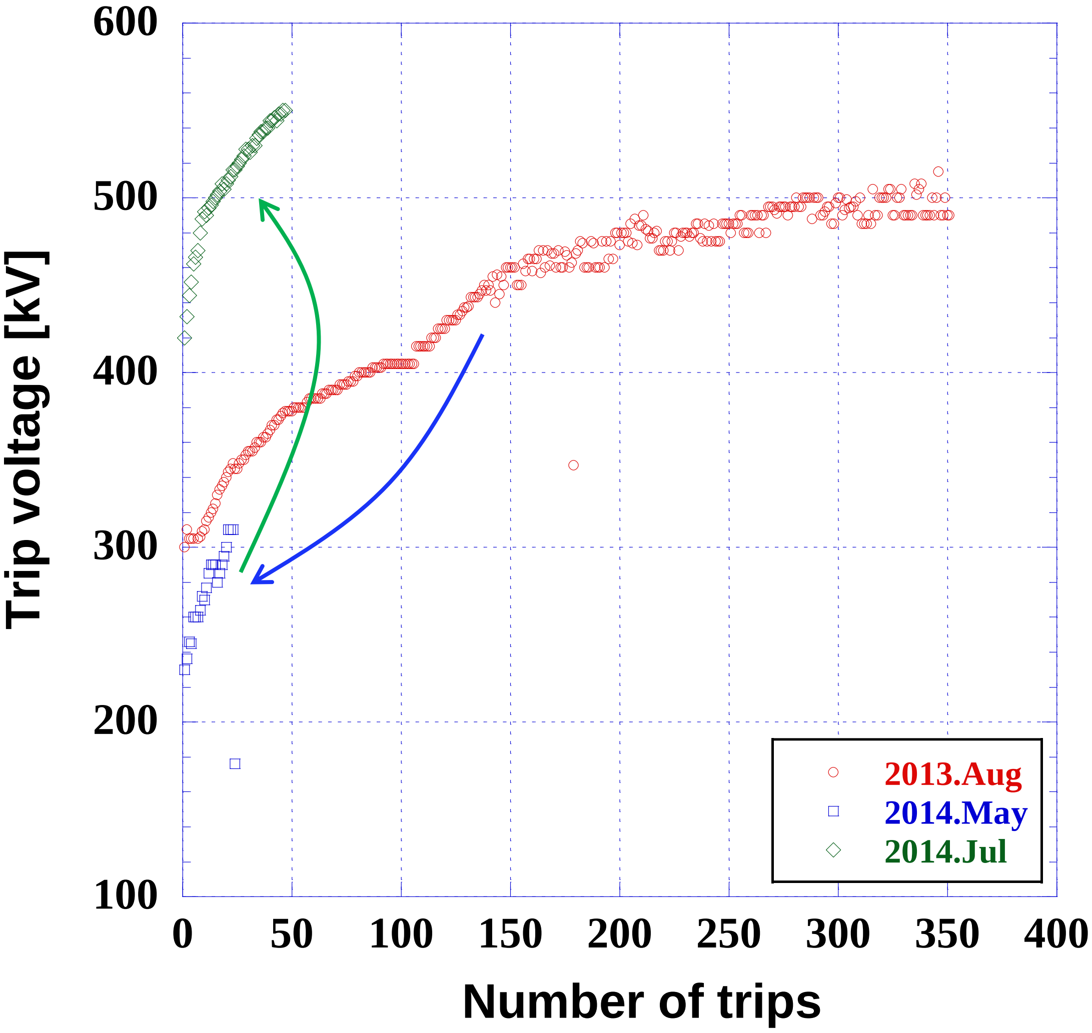


Special RGA ion source for XHV

http://www.vaclab.co.jp/product04.html

2nd DC-Gun HV conditioning history

(2013/Aug ~ 2014/Jul)



2013/Aug. HV Conditioning
(w/o main pump system)
reached 500 kV after ~300 trips

Main pump installation & baking.
XHV (~4x10^{-10} Pa) achieved.

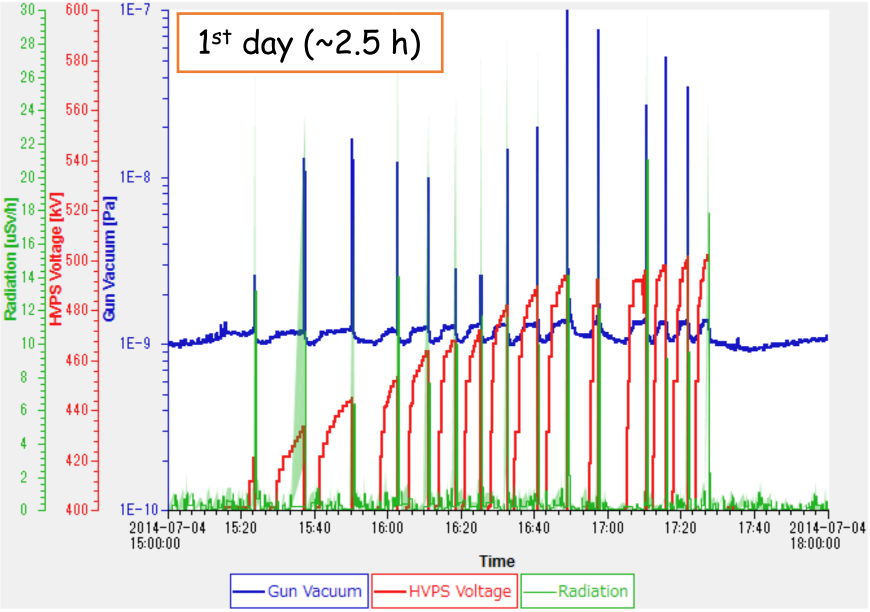
2014/May HV Conditioning
(FE source was generated after 24 trips)

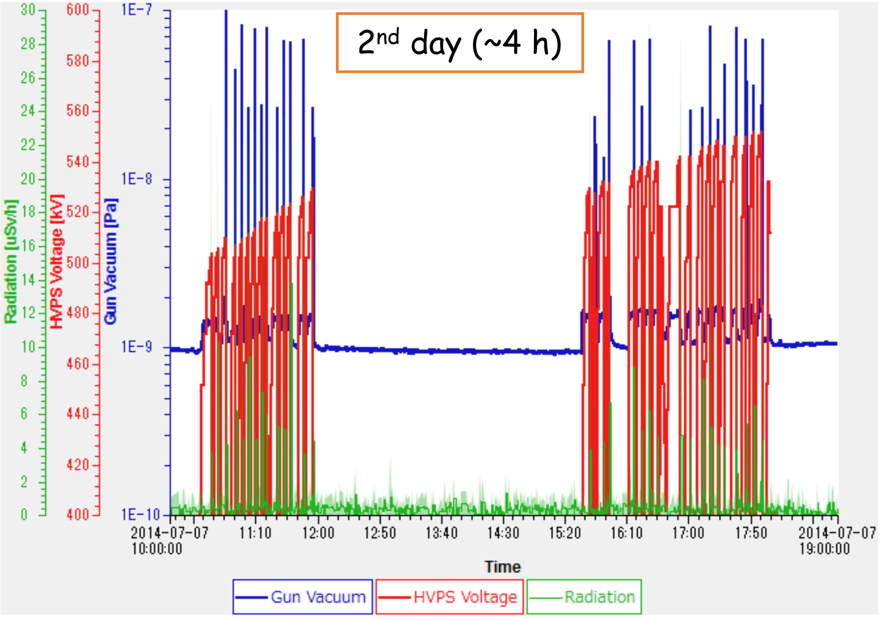
Took off electrode & eliminated dust on the cathode electrode. Set electrode and baking & rebuilt HV setup again.

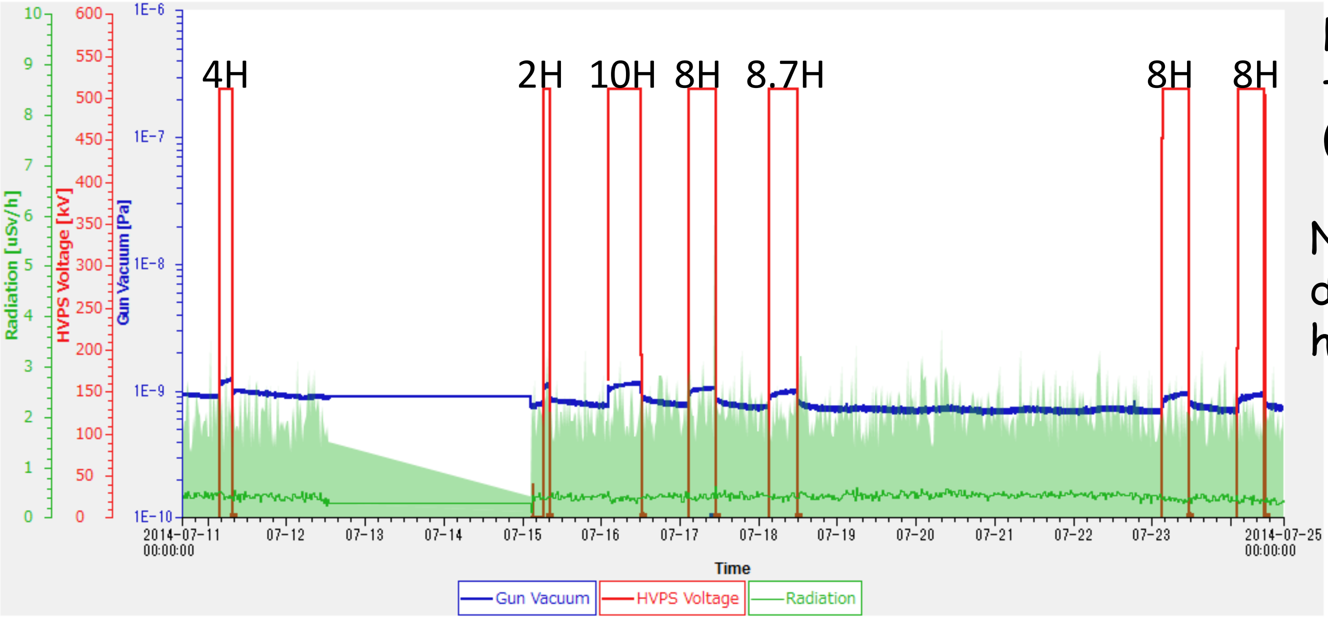
2014/Jul. HV Conditioning
(reached 550 kV after 48 trips)

2nd DC-Gun HV conditioning & holding test

(2014/Jul)





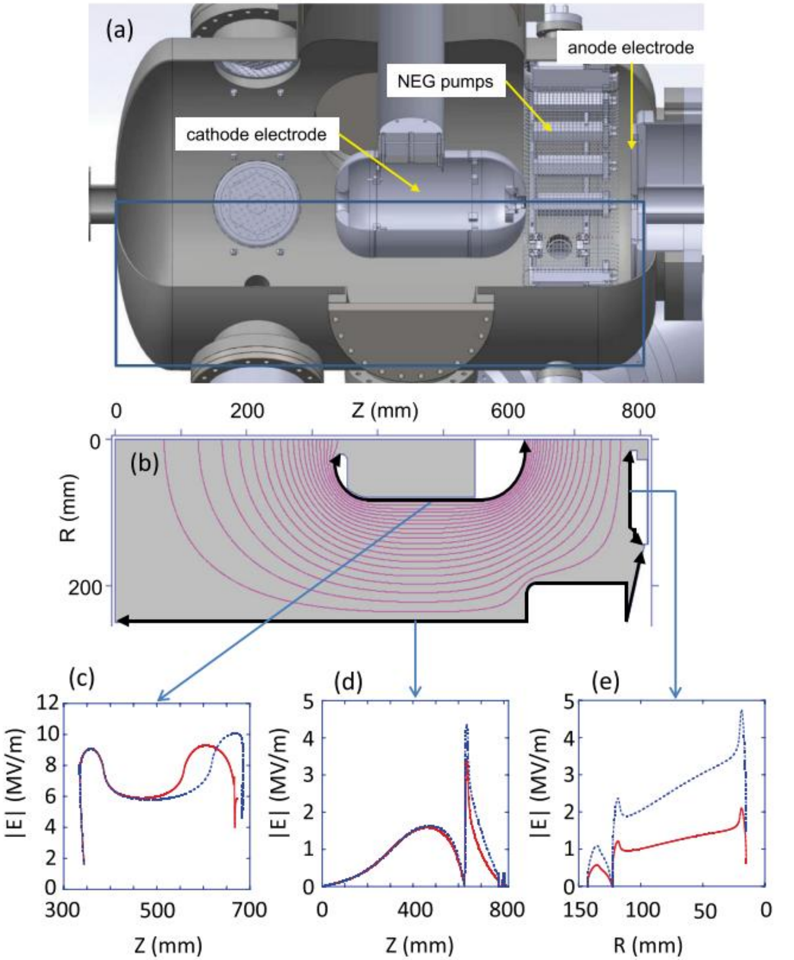


HV conditioning was finished in a short time (~7 hours).

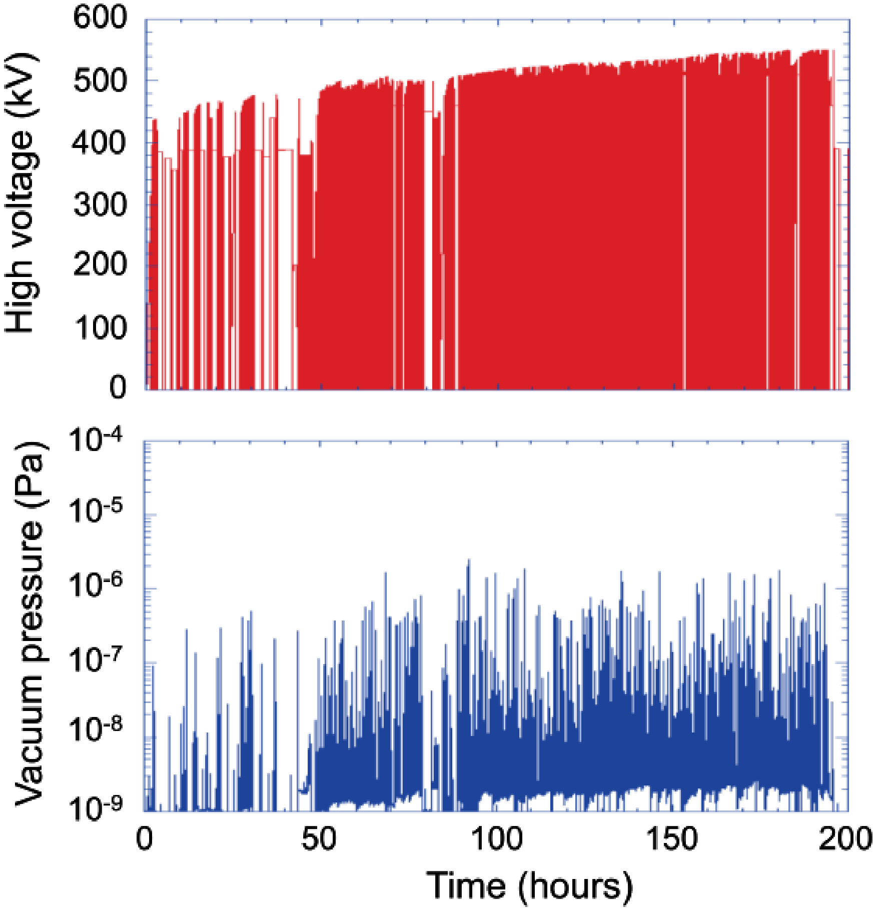
No breakdown occurred during 50 hours 500 kV-holding test.

1st DC-Gun HV conditioning history

160 mm cathode – anode gap

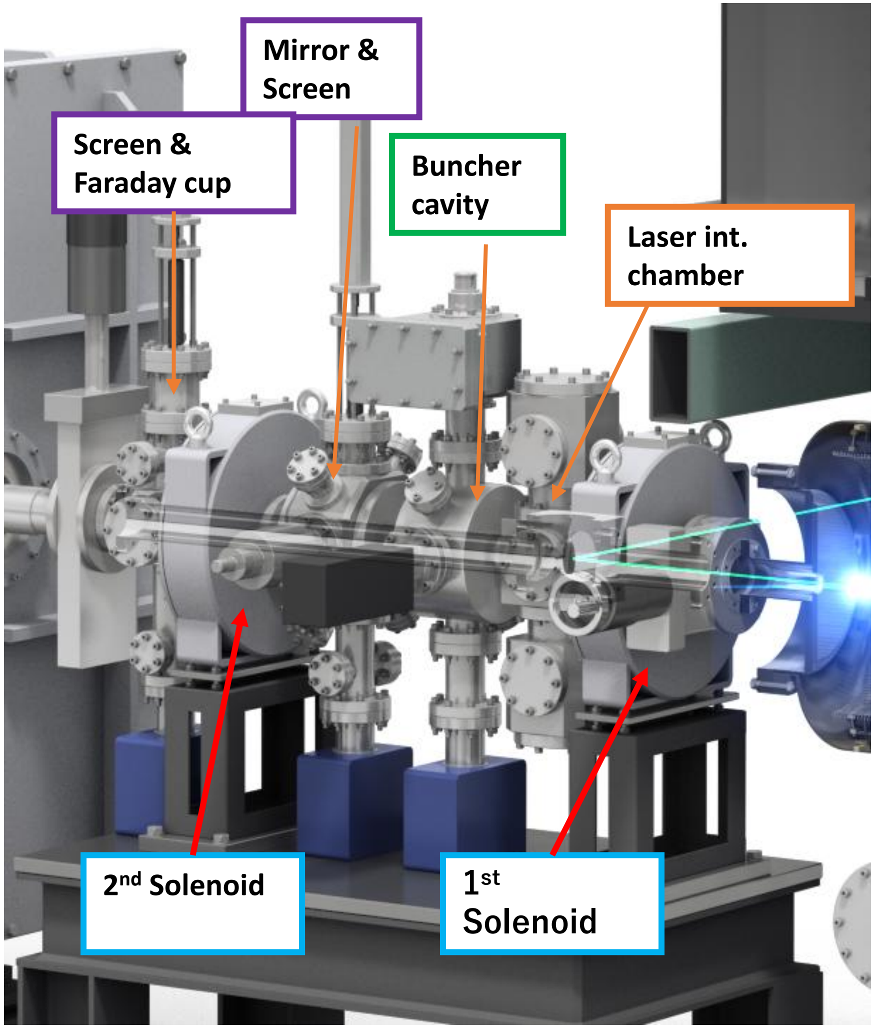


N. Nishimori et. al., Phys. Rev. ST Accel. Beams 17, 053401 (2014)



A longer conditioning time compared to 2nd DC-gun. Differences in electrode and chamber placement relationship and ceramic tube material.

Injection section



Number of devices inserted within a 1m section.

- 5 pairs of steering coils
- 2 solenoids
- 2 screen monitors
- Mirror for cathode observation
- Faraday cup for charge & QE measurement
- Laser introduction mirror
- 1.3 GHz normal-conducting buncher cavity

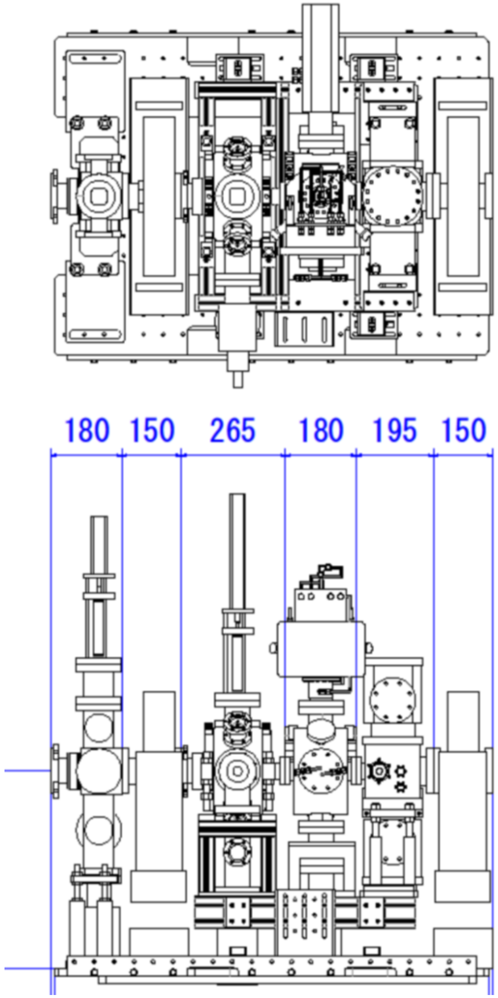
As vacuum system,

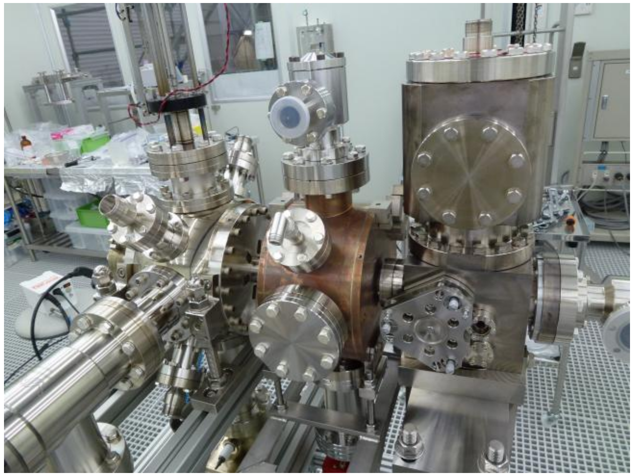
- Three ion pumps
- Five 400 L/s NEGs
- Two 2000 L/s NEGs
- Two extractor gauges

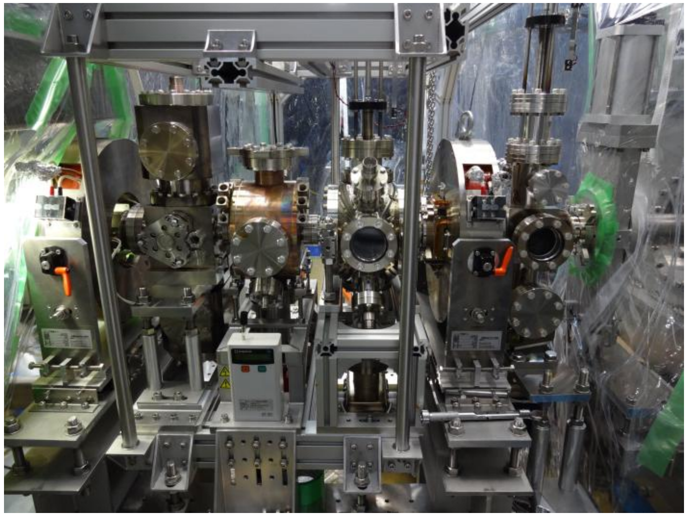
Keep good vacuum of 10^{-9} Pa level during CW operation.

Injection section

assembly works in clean condition





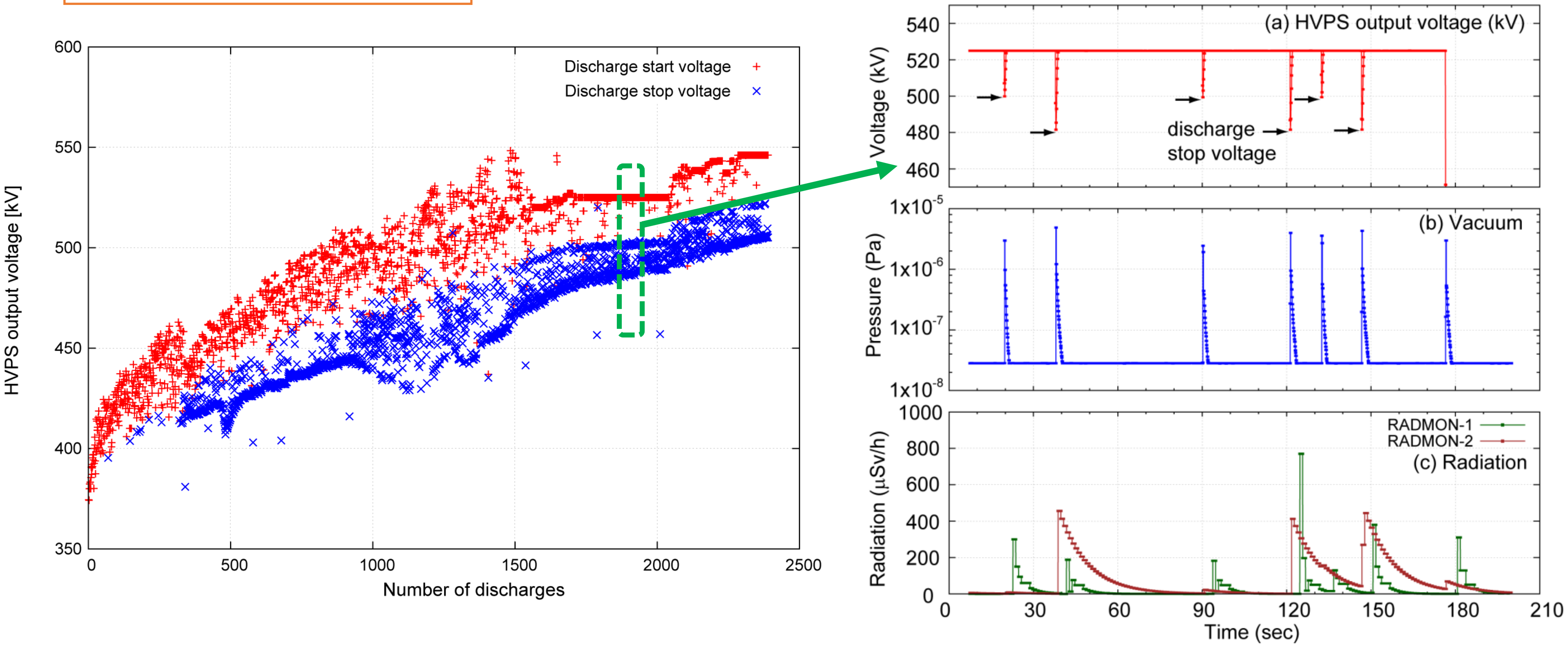


Dust removal & assembly in clean room.
Clean hut constructed on site to install these units.

HV conditioning for stable operation of DC-gun

HV conditioning for stable operation (1)

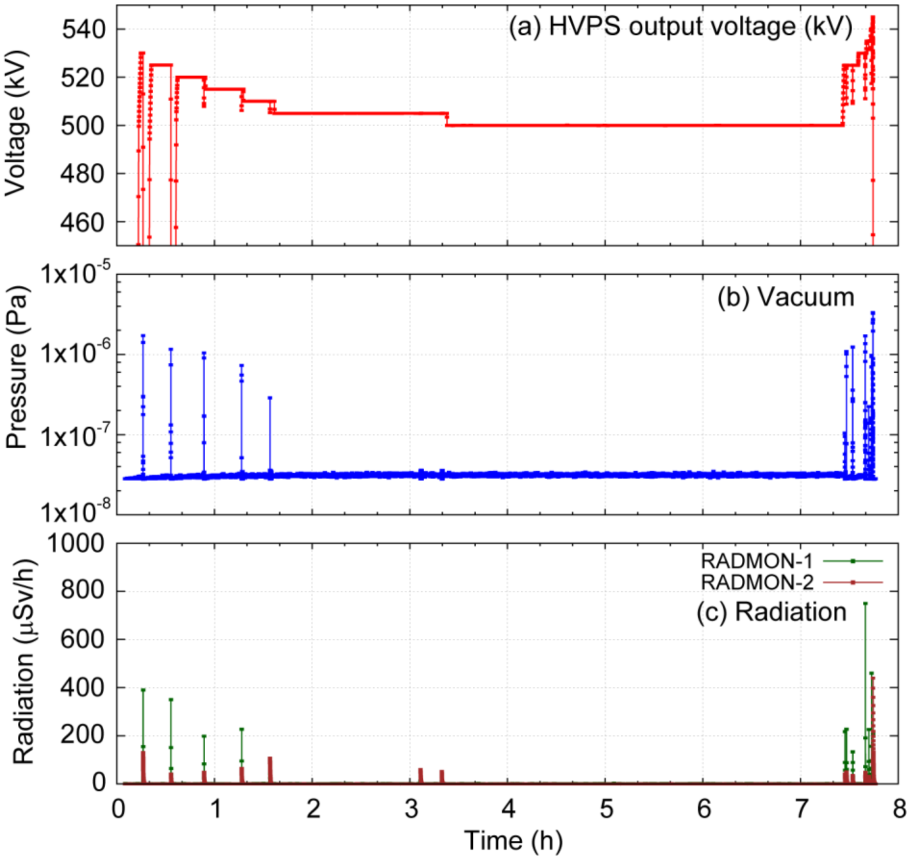
1st DC-Gun results

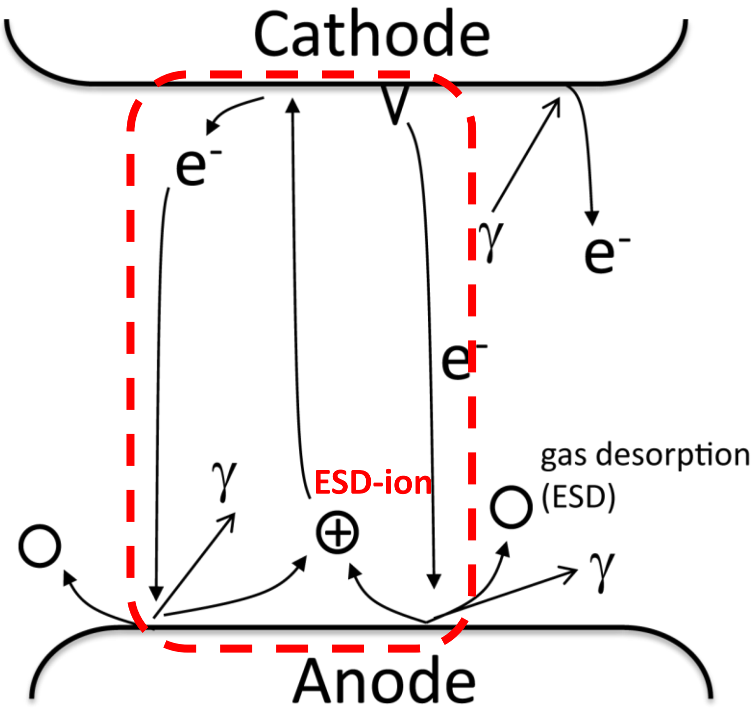


M. Yamamoto and N. Nishimori, Appl. Phys. Lett. 109, 014103 (2016)

- The discharge voltage gradually increased while repeating many discharges.
- The discharge stop voltage has an important meaning.

HV conditioning for stable operation (2)

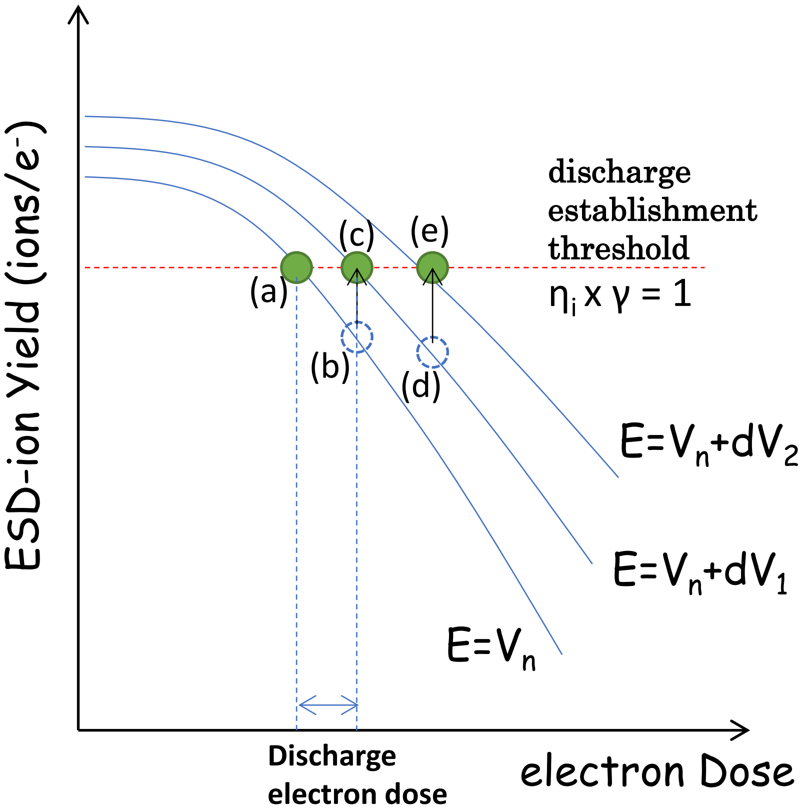


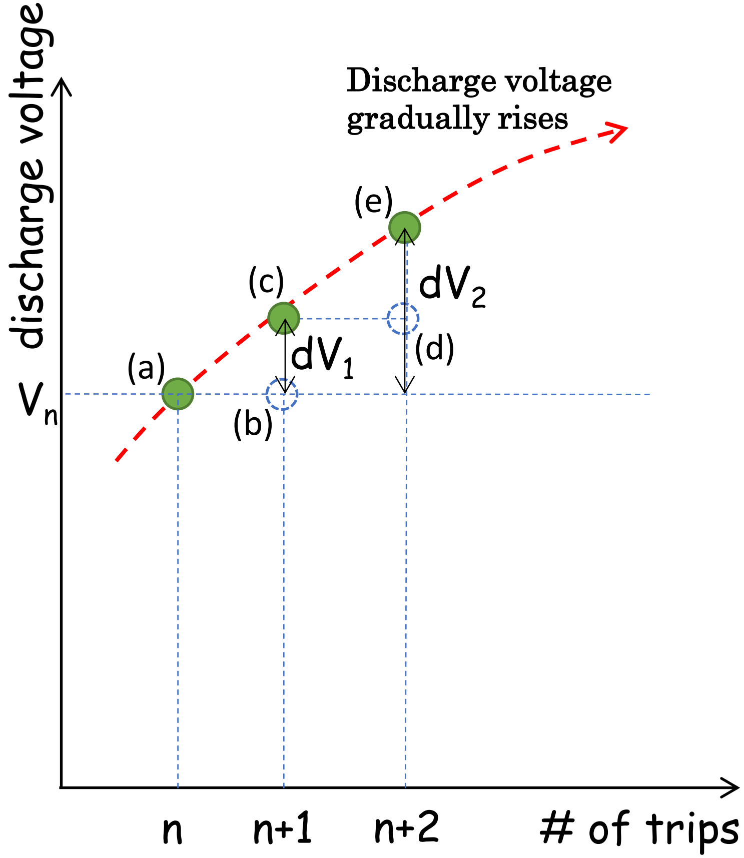


- The discharge stop voltage after HV conditioning is about 502 kV.
- Discharge occurs above 505 kV. The higher the voltage, the higher the discharge frequency.
- No discharge occurs at 500 kV.

ESD-ions may form a discharge circuit.

HV conditioning for stable operation (3)

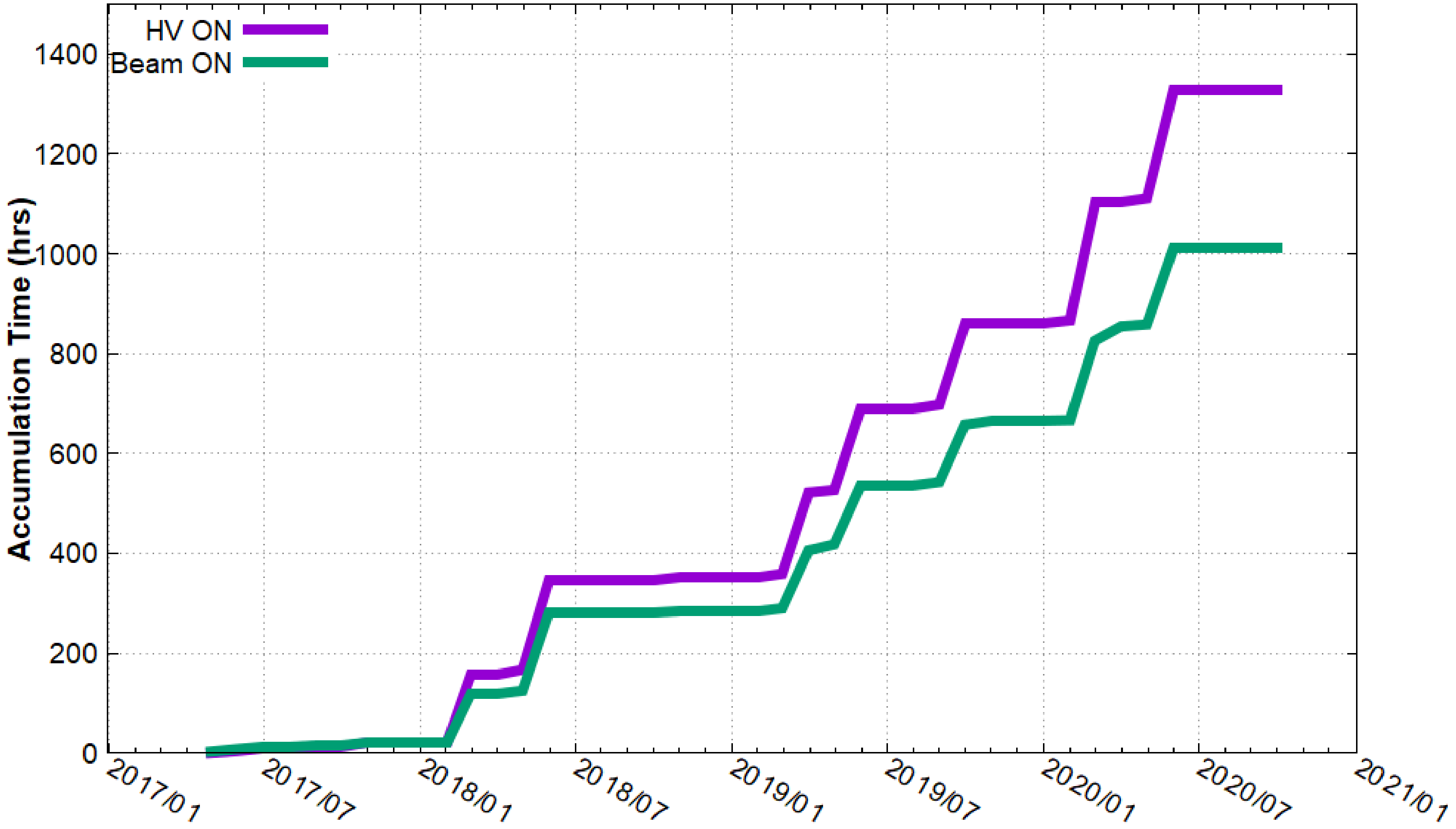




- The discharge establishment threshold is defined as the product of the yield of ESD-ion and the ratio of SE by ion impact becomes 1.
- ESD-ion yield is decrease by discharge electron impact dose.

According to this mechanism, the discharge does not occur below the discharge stop voltage. (Discharge establishment threshold ≅ Discharge stop voltage)

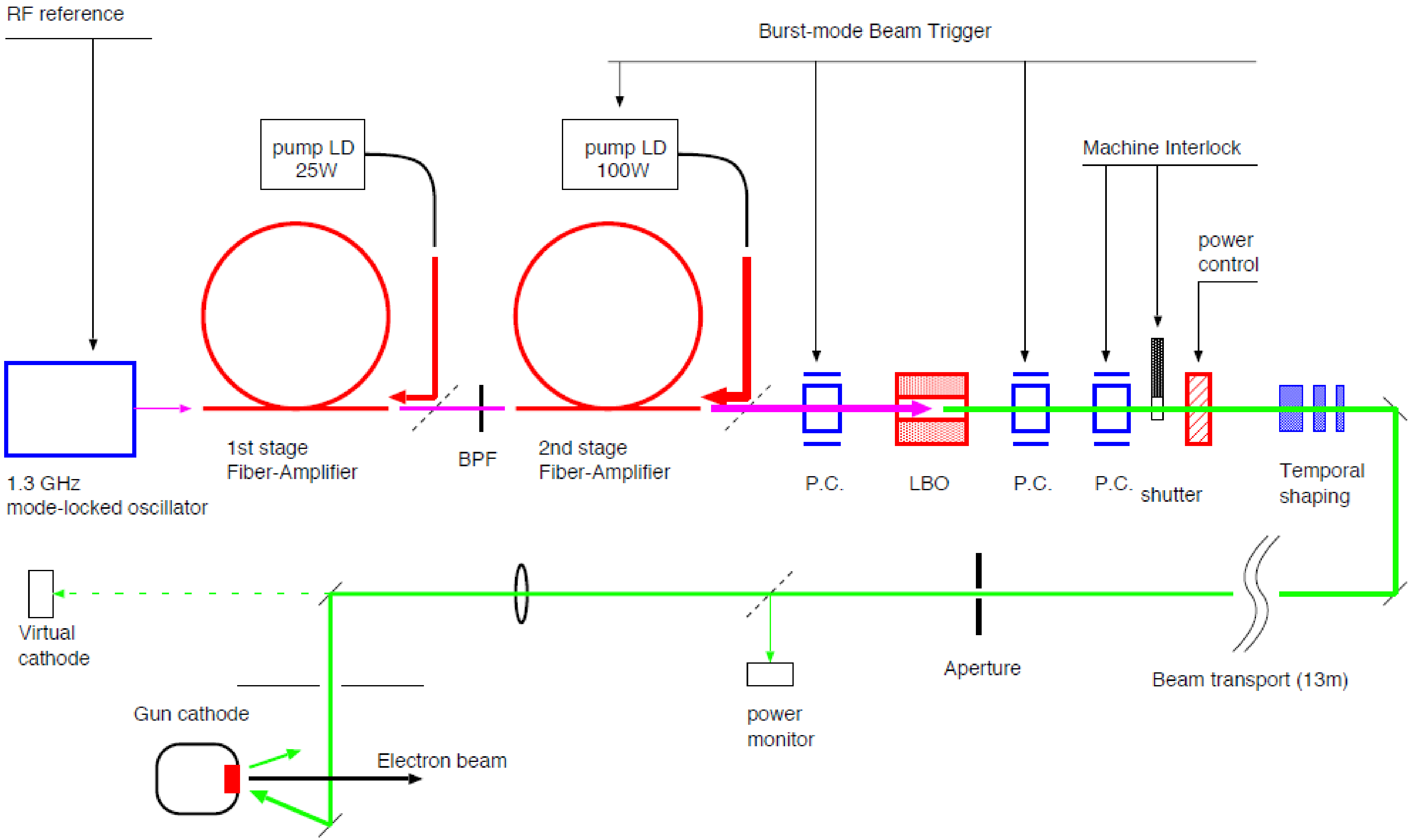
500 kV gun operation history



- 500 kV operation of the electron gun started in May 2017.
- **No discharge interruption** caused by the electron gun itself.
- Long-term stability is demonstrated at an operating voltage lower than "**the discharge stop voltage**" observed in HV conditioning.

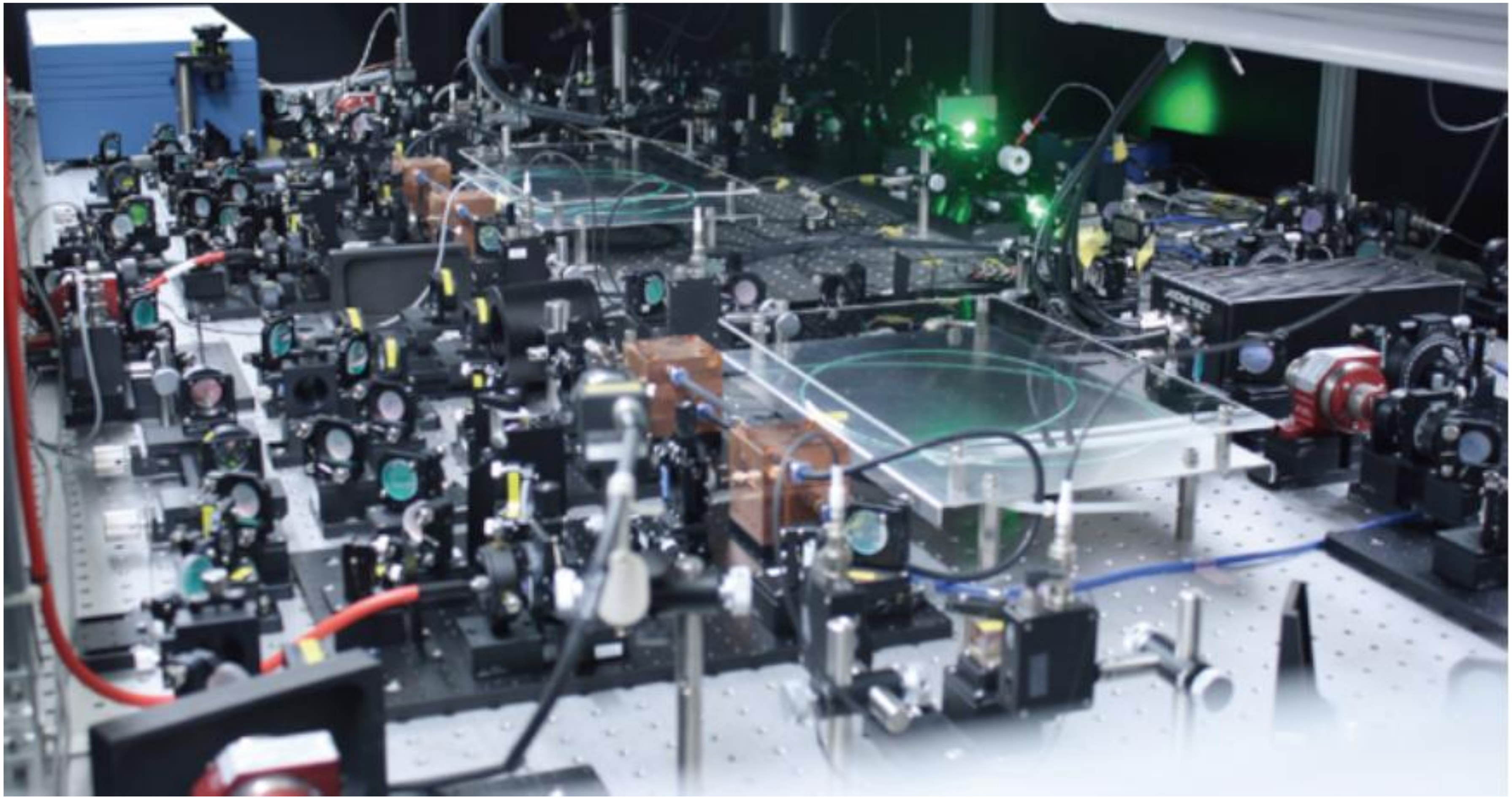
Beam tuning for CW operation

Drive Laser system



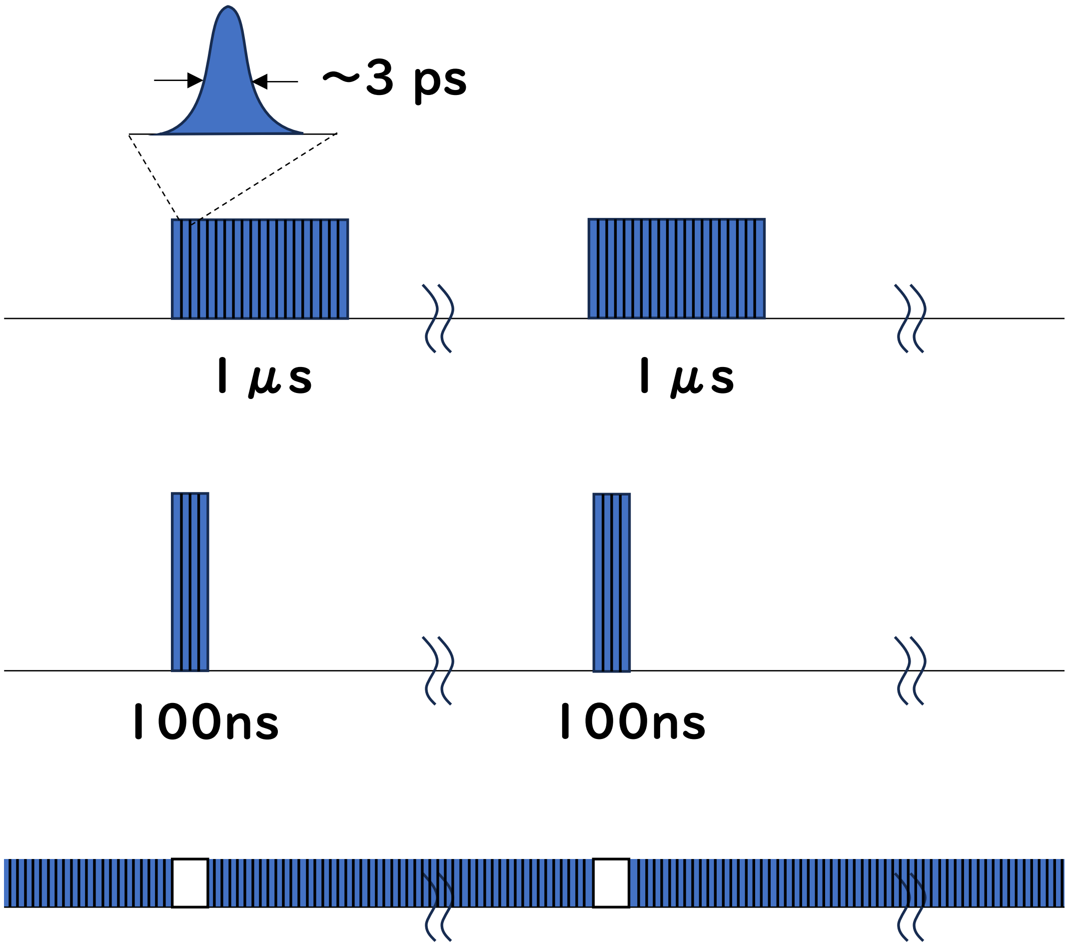
http://pfwww.kek.jp/ERLoffice/cERL_miniWorkshop/presen/1_Yhonda.pdf

Drive Laser system



http://pfwww.kek.jp/ERLoffice/cERL_miniWorkshop/presen/1_Yhonda.pdf

Laser operation modes


Rep. 1.3 GHz

~3 ps

1 μs burst, 5 Hz
for low bunch charge
(<5 pC/bunch)

1 μs

1 μs

100 ns burst, 5 Hz
for high bunch charge
(>5 pC/bunch)

100ns

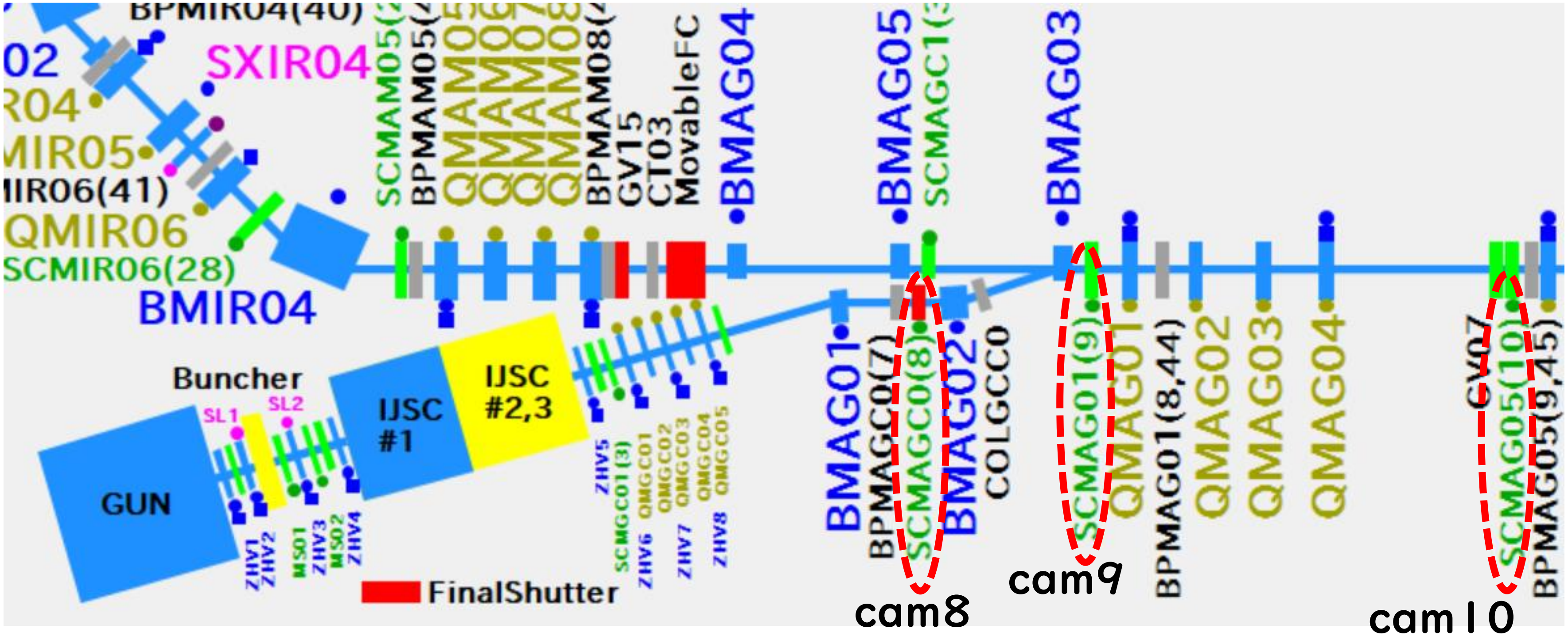
100ns

CW mode

Charge-up and discharge of the screen monitor occurs at more than 100 nA as an average current. To avoid this, the burst width is switched.

Layout of components

(DC-gun to Merger section)



Symbols for Magnet

SL.. -> Solenoid

▬ BM.. -> Bend

QM.. -> Quadrupole

● ZH.. -> Horizontal steering

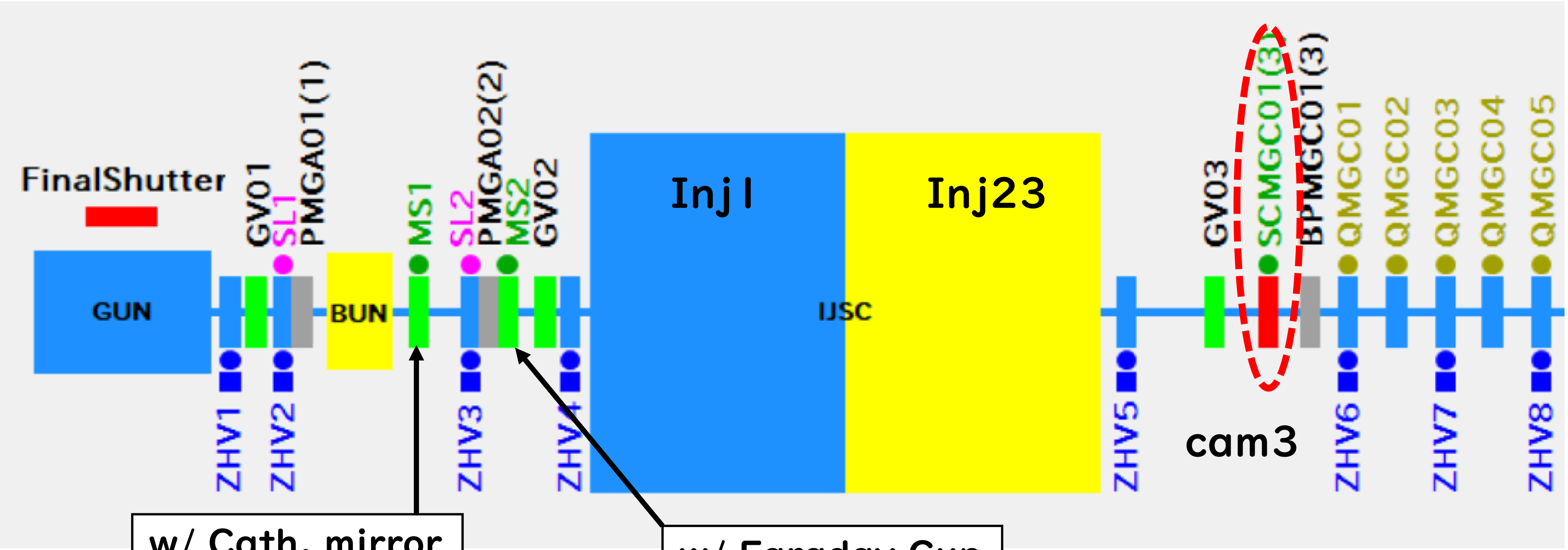
■ ZV.. -> Vertical steering

MS.., SCM.. : Screen Monitor

Red: Inserted (Closed) state

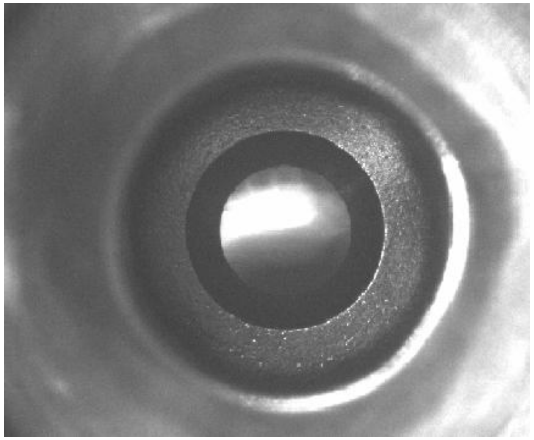
Green: Open state

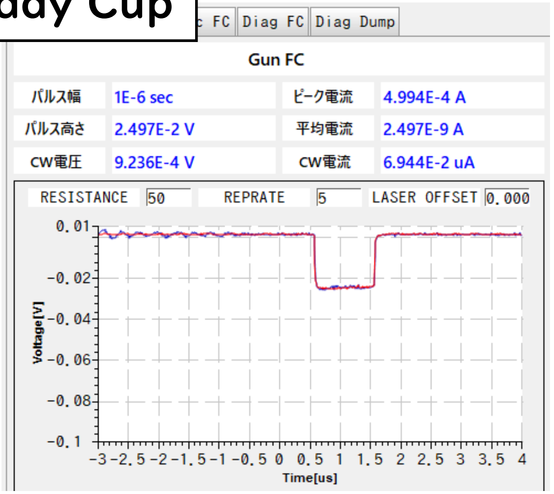
Layout of Injector section



w/ Cath. mirror

w/ Faraday Cup





Gun FC

パルス幅	1E-6 sec	ピーク電流	4.994E-4 A
パルス高さ	2.497E-2 V	平均電流	2.497E-9 A
CW電圧	9.236E-4 V	CW電流	6.944E-2 uA

RESISTANCE 50
REPRATE 5
LASER OFFSET 0.000

Typical beam adjustment flow
(up to the merger)

1. Bunch charge measurement and cathode QE map measurement using FC.
2. Adjustment through the solenoid center.
3. Coarse tuning of acceleration phase of injection cavity Inj1 by Cam3.
4. Fine tuning of acceleration phase and amplitude of injection cavity Inj1 by Cam8.
5. Coarse adjustment of buncher phase by Cam2.
6. Fine tune of buncher phase at Cam8.
7. Adjustment of cavity centering by phase scan of Inj1 with Cam3.

Typical beam adjustment flow
(up to the merger)

8. Coarse adjustment of acceleration phase of Inj23 by Cam3.

9. Fine tune of acceleration phase and amplitude of Inj23 by Cam8.

10. Adjustment of cavity centering by phase scan of Inj23 with Cam3

11. Repeat centering adjustment of Inj1 and Inj23 phase scan with Cam3.

12. Dispersion adjustment at the merge with Cam9, 10 by Inj. amplitude scan.

13. Optics matching by adjusting 5 series Q magnets.

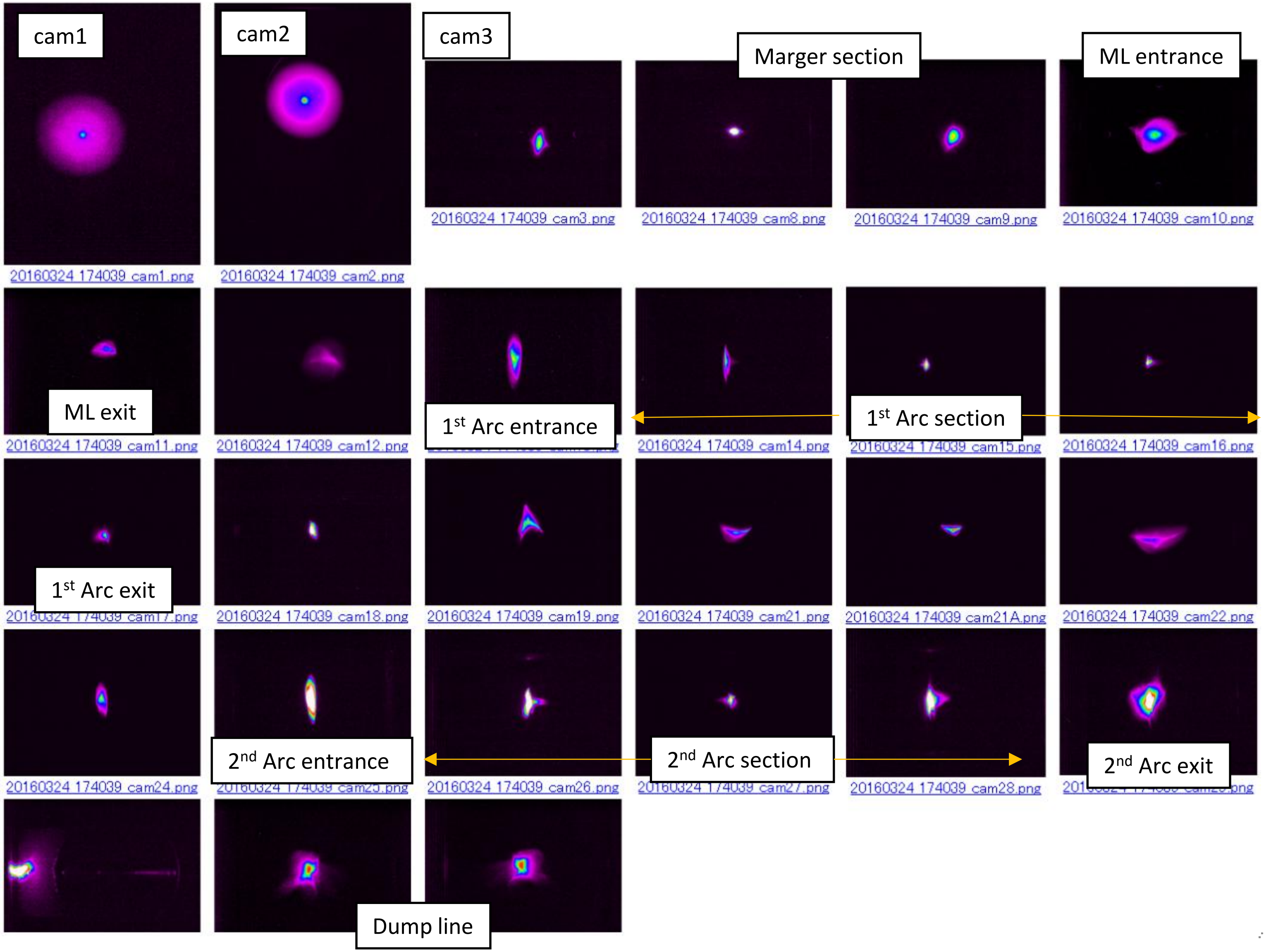
14. To the adjustment of the circular section (acceleration phase and amplitude adjustment of ML...)

The tuning up to the marger section takes approximately 2-3 days.

Typical beam adjustment

(up to the main dump)

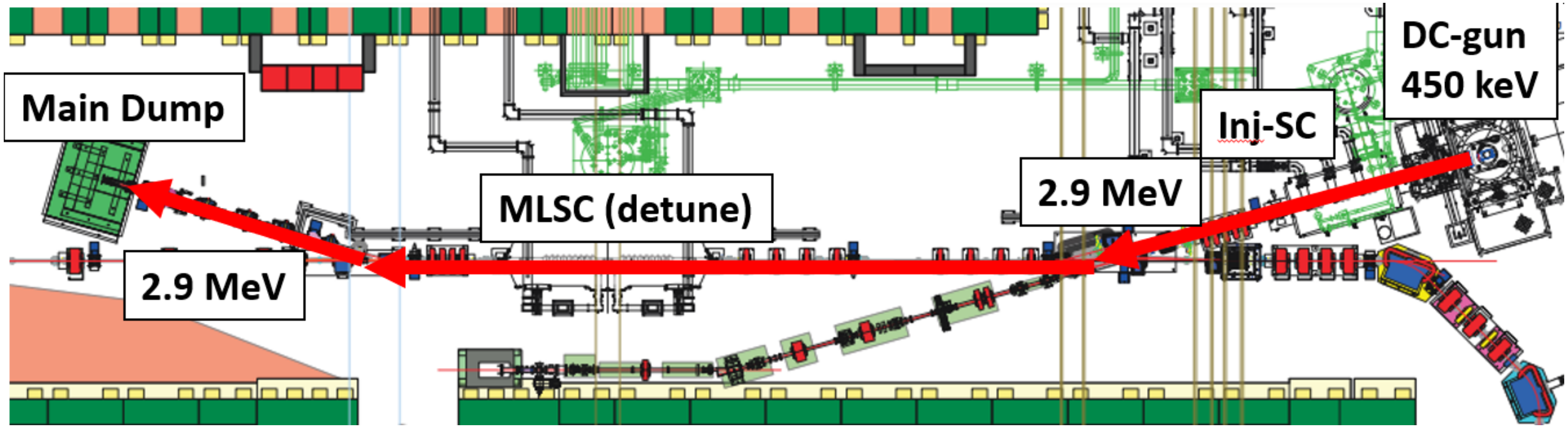
Typical example of All screen capture after adjusting the circulation



Preparation for
10 mA CW-beam operation

First phase of 10mA CW operation

Demonstration of 1mA CW operation with direct beam dump transport in November 2023



From experience with 1mA CW beam circulation,

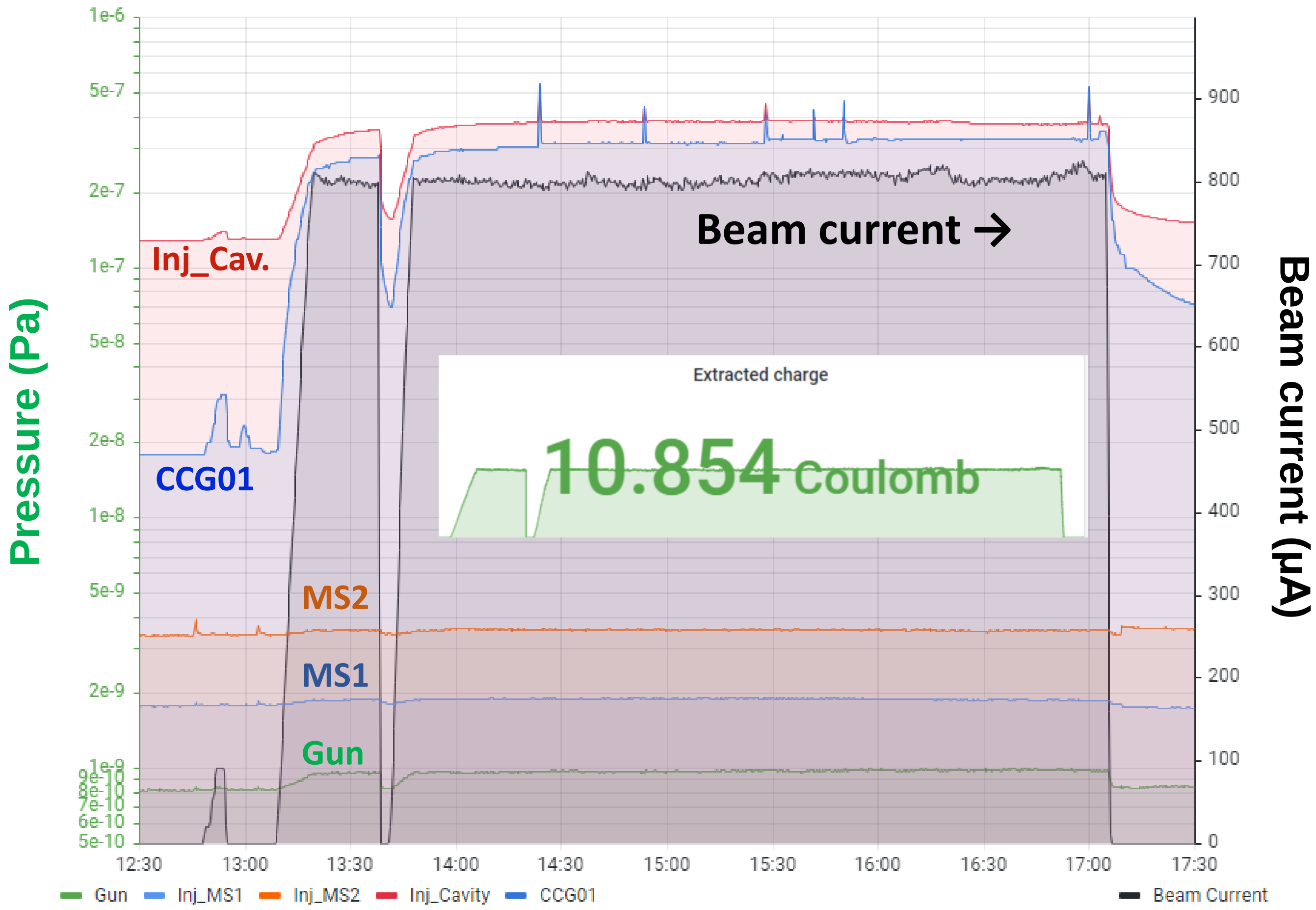
- Difficulty in suppressing beam loss around undulator section.
- Allowable beam loss with the current radiation shield is low.

On the other hand, The following issues need to be addressed in the early stage of 10 mA operation.

- Develop a robust cathode and evaluate its lifetime.
- Investigate beam stability (intensity, position, energy) including injector.
- Identify problems in high-current beam operation.

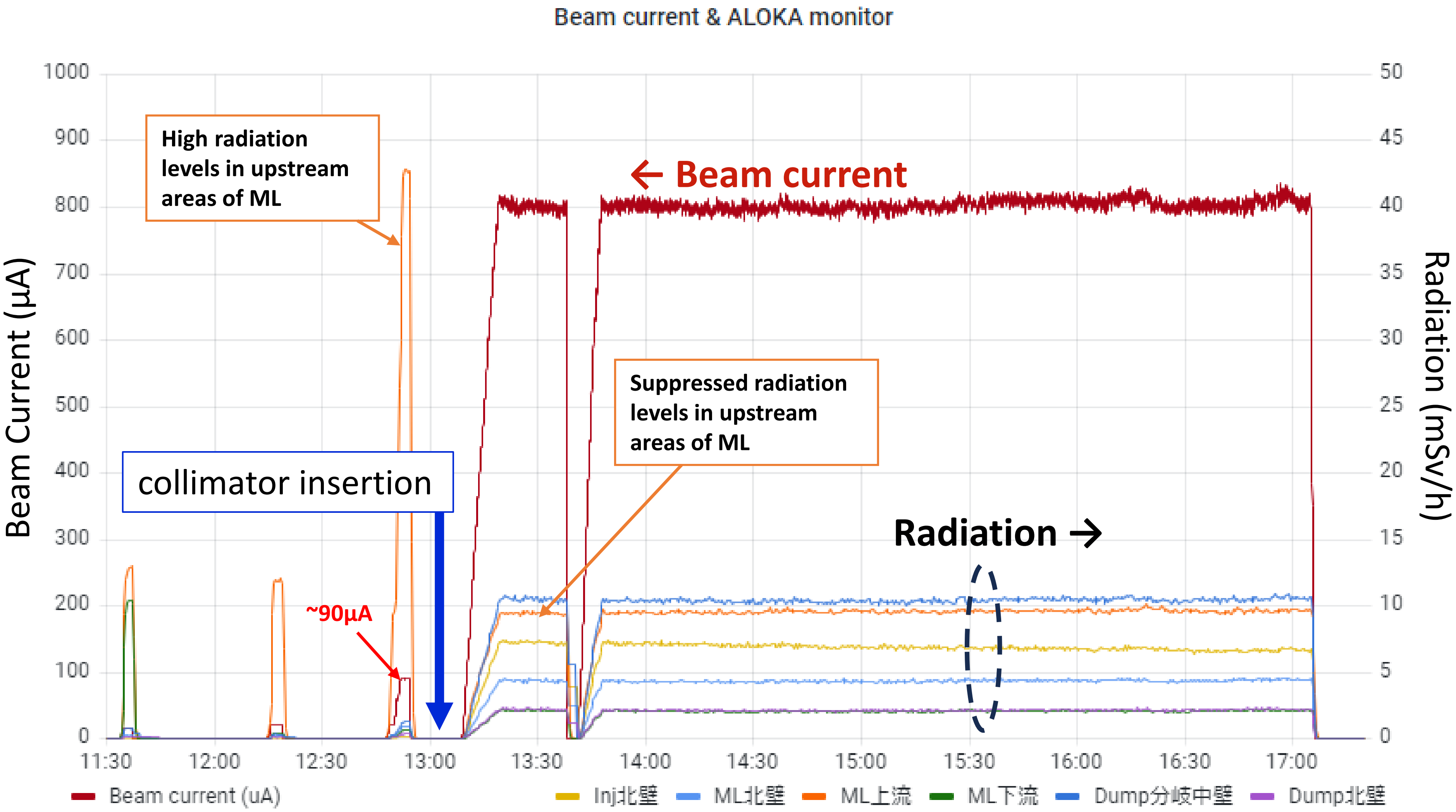
The first 10mA CW beam generation and acceleration will be tested in the main dump direct transport mode. (Call it “Phase-1 operation”).

Gun-Injector section vacuum history during CW beam operation



- About 4 hours of 800 uA CW beam operation was performed in the main dump direct transport mode.
- Collimators located after the injector cavities are the main outgassing source.
- Cathode QE decreases from 5.7% before the test to 5.6% after the test.

Beam loss distribution



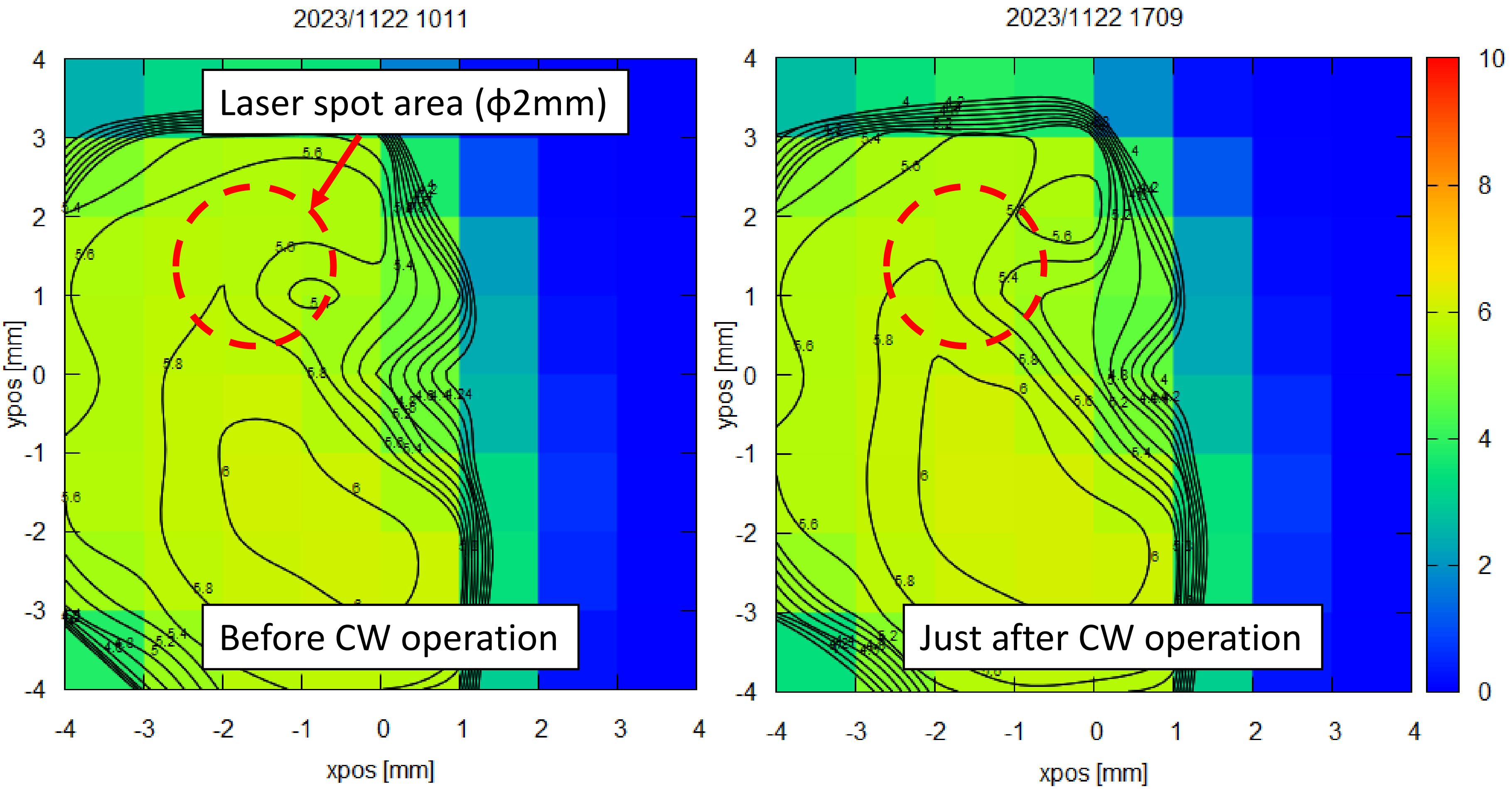
High radiation levels in upstream areas of ML

collimator insertion

Suppressed radiation levels in upstream areas of ML

- Without collimator insertion, the beam loss in the upstream of the ML could not be fully suppressed.

Cathode QE map @Gun



2023/1122 1011

2023/1122 1709

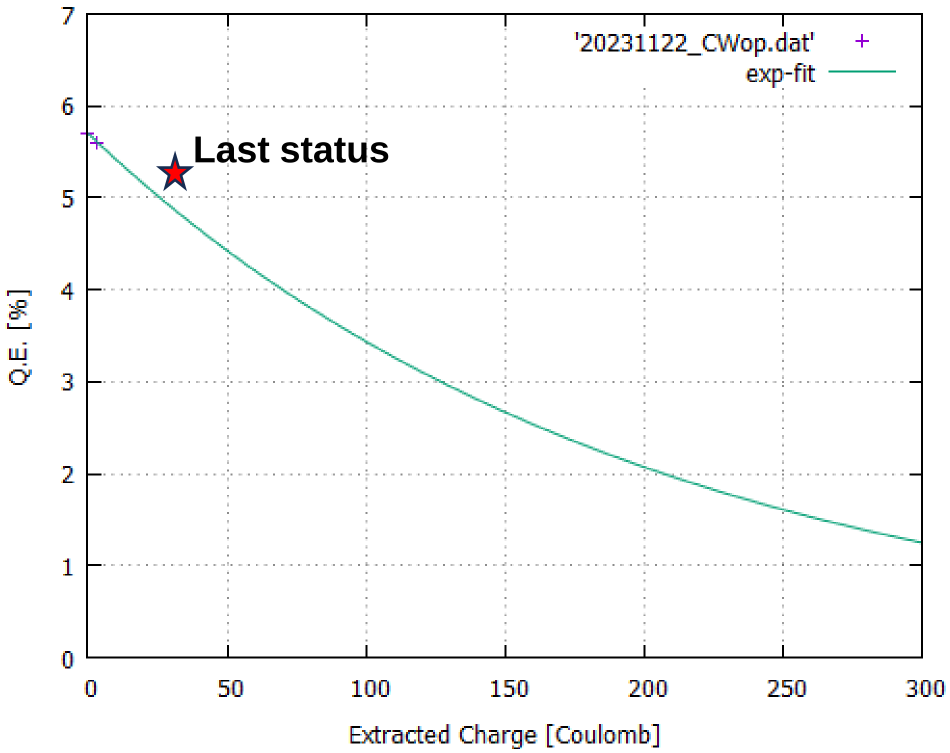
Laser spot area (ϕ2mm)

Before CW operation

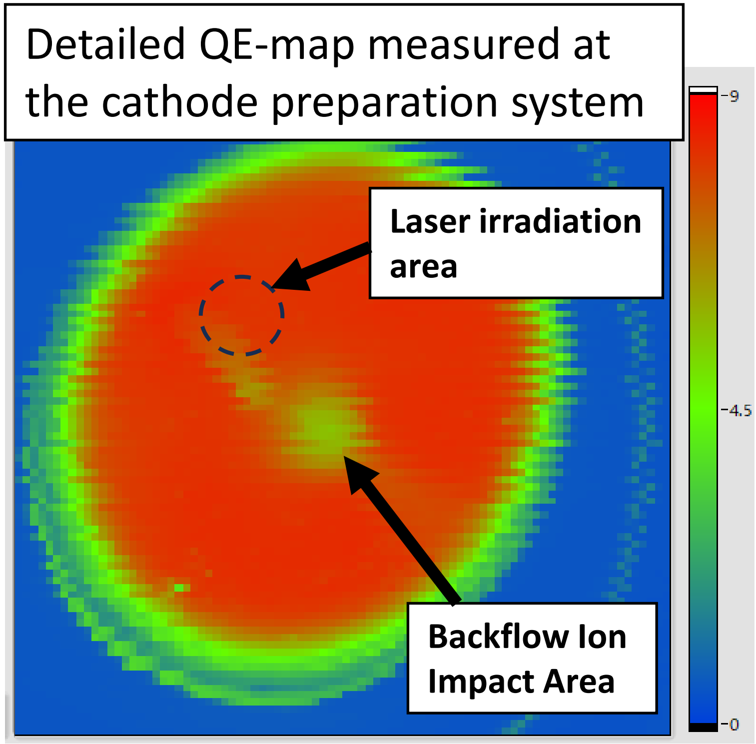
Just after CW operation

- QE at Laser irradiated position slightly decreased before and after CW operation.
- Amount of change from 5.7% to 5.6% at the (-1.5,1.5) position.
- Right area (x>1) is an area that cannot be irradiated by the laser.

Cathode lifetime estimation



Last status



Detailed QE-map measured at the cathode preparation system

Laser irradiation area

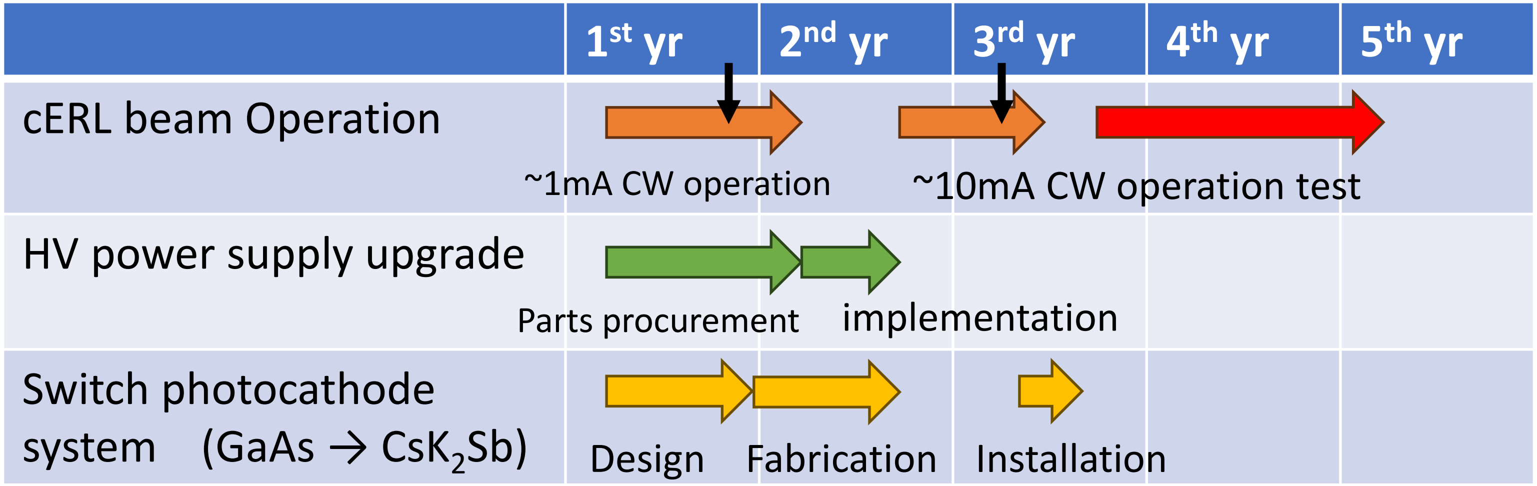
Backflow Ion Impact Area

- Although this is a rather rough evaluation, the photocathode lifetime for the amount of extracted charge is about 200 Coulomb.
- This is equivalent to the lifetime obtained in JLAB with GaAs photocathode.

Higher current beam operation requires a more robust photocathode.

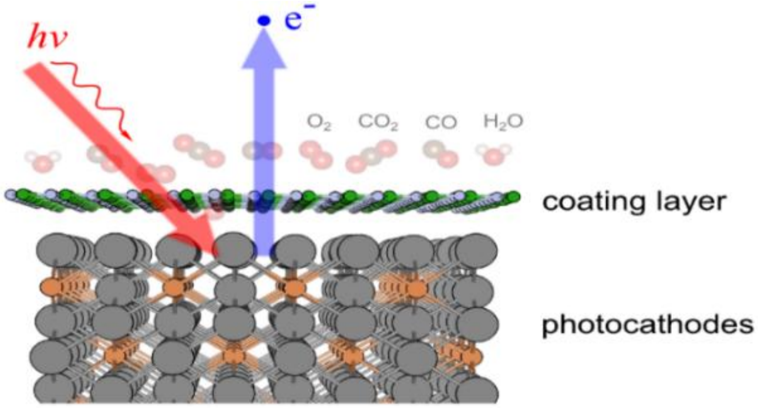
Future Plans

Phase-1 🟧 Phase-2 🟥 Facility inspection →



	1st yr	2nd yr	3rd yr	4th yr	5th yr
cERL beam Operation	~1mA CW operation		~10mA CW operation test		
HV power supply upgrade	Parts procurement	implementation			
Switch photocathode system (GaAs → CsK_2Sb)	Design	Fabrication	Installation		

Photocathode lifetime improvement



- The lifetime of NEA-GaAs is short in a high-current operation.
- Considering switching photocathode from NEA-GaAs to CsK_2Sb.
- Furthermore, R&D of photocathode protecting layer is underway in US-Japan collaboration. (LANL-Nagoya-KEK)

- L. Guo et al., "Graphene as reusable substrate for bialkali photocathodes", Appl. Phys. Lett. 116 251903 (2020).
- F. Liu et al., “Photoemission from Bialkali Photocathodes through an Atomically Thin Protection Layer”, ACS Appl. Mater. Interfaces 14 1710 (2022).

acknowledgements

Main collaborators in the development of the DC electron gun since 2009.

Y. Honda, X. Jin, **T. Uchiyama**, M. Kobayashi,
K. Satoh, H. Satoh, Y. Saito, **M. Yamamoto**
High Energy Accelerator Research Organization

N. Nishimori, R. Nagai, S. Matsuba, R. Hajima
National Institutes for Quantum Science and Technology

T. Miyajima
Sumitomo Heavy Industries, Ltd.

M. Kuriki,
Hiroshima Univ.

H. Kurisu
Yamaguchi Univ.

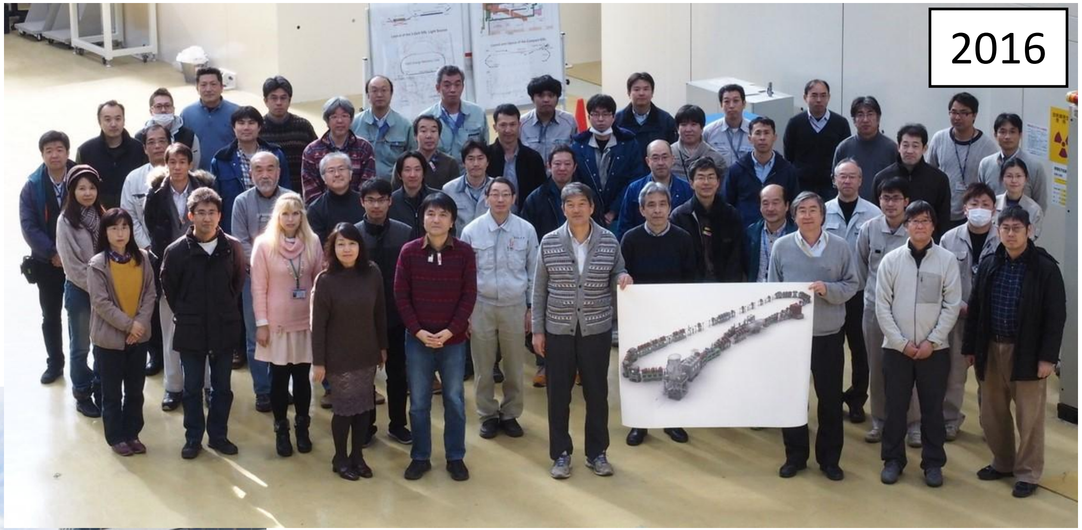
H. Yoshida
National Institute of Advanced Industrial Science and Technology

iCASA Innovation Center for Applied Superconducting Accelerators
応用超伝導加速器イノベーションセンター

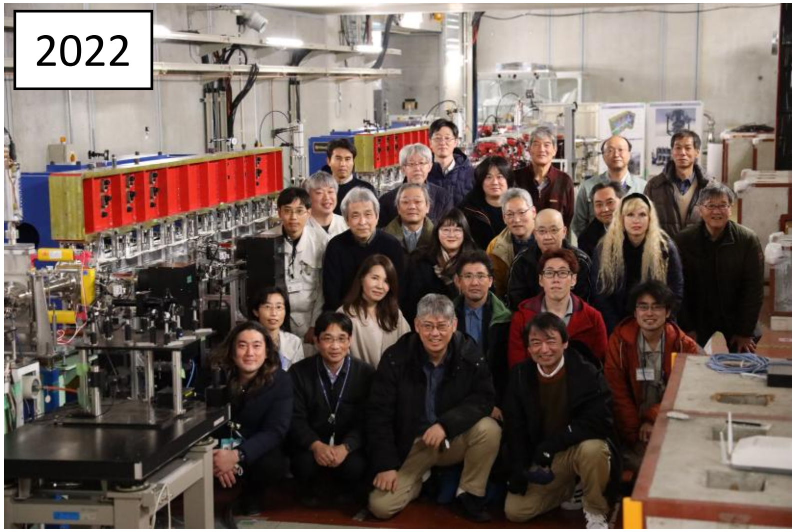
cERL compact ERL

Thank you for your attention


iCASA-cERL staffs 2024


2016

ERL2024 @KEK September,2024


2022