Injector Overview

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on behalf of Injector Linac Group and Linac Commissioning Group

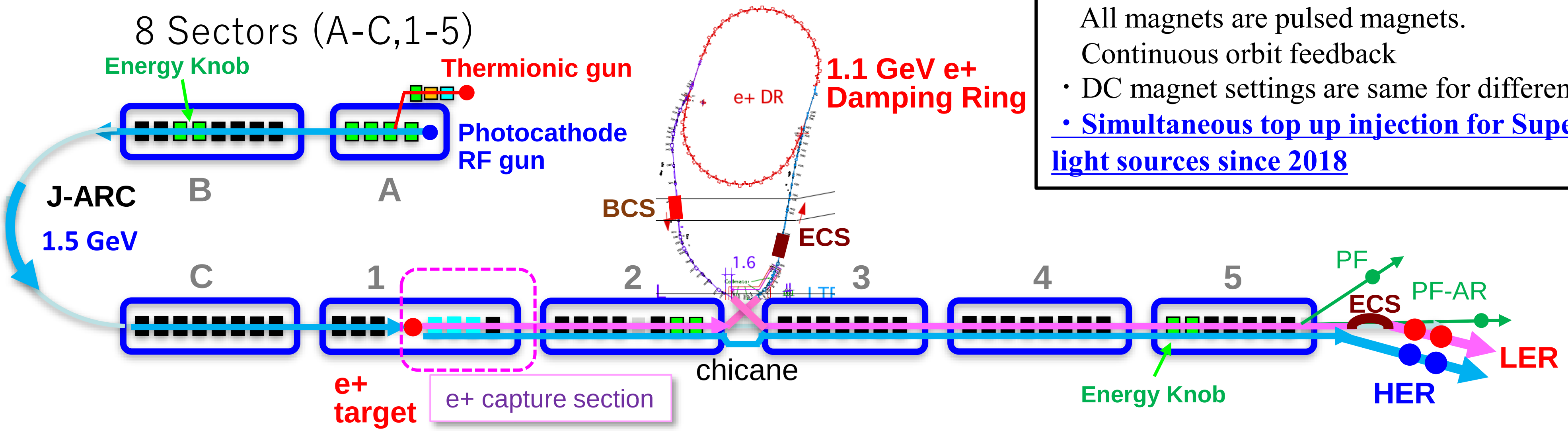
Contents

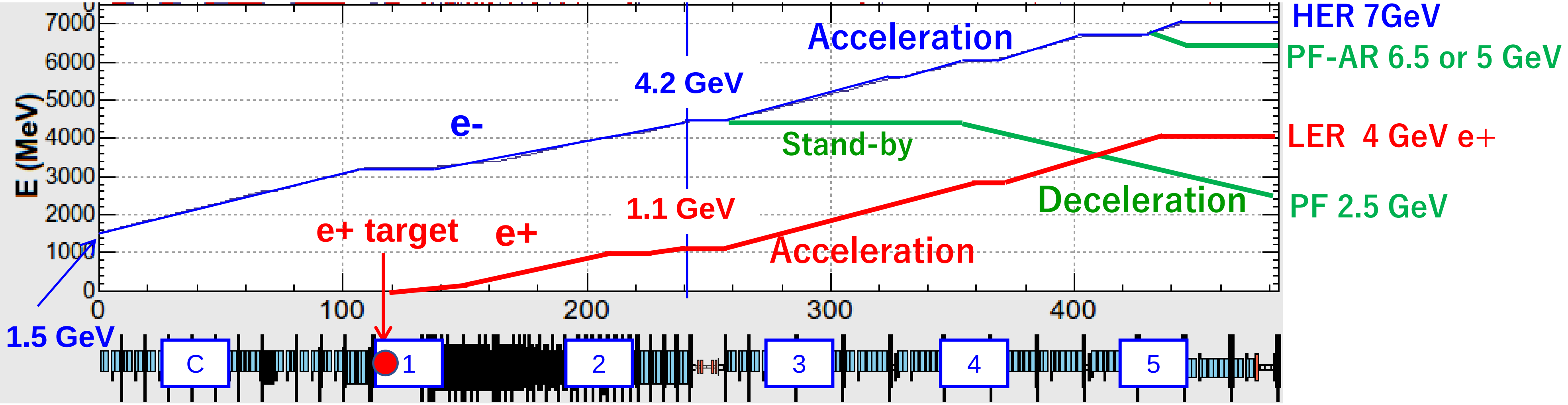
- Injector outline
- e- beam status and issue
- e+ beam status and issue
- Upgrade work and progress during LS1
- Summary

Injector Linac Layout

60 klystron units
240 accelerating structures (S-band 2-m-long)

- Two electron sources:
  RF gun: HER injection
  Thermionic DC gun: LER, PF, PF-AR
- Sector 3-5:
  All magnets are pulsed magnets.
  Continuous orbit feedback
- DC magnet settings are same for different beam mode
- **Simultaneous top up injection for SuperKEKB and light sources since 2018**



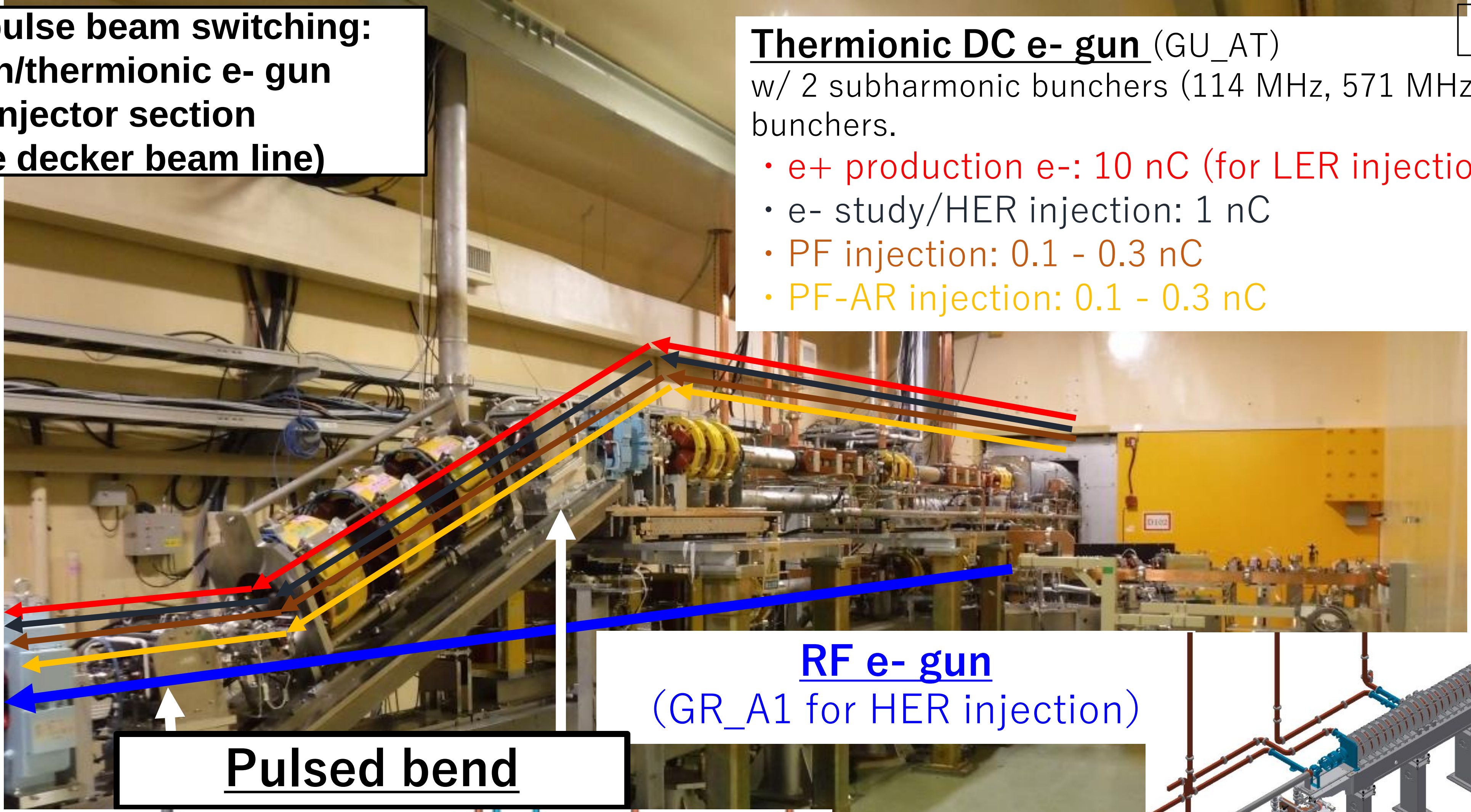


Beam energy variation for each beam mode along the beam line after J-ARC

Pulse to pulse beam switching: rf e- gun/thermionic e- gun In injector section (double decker beam line)

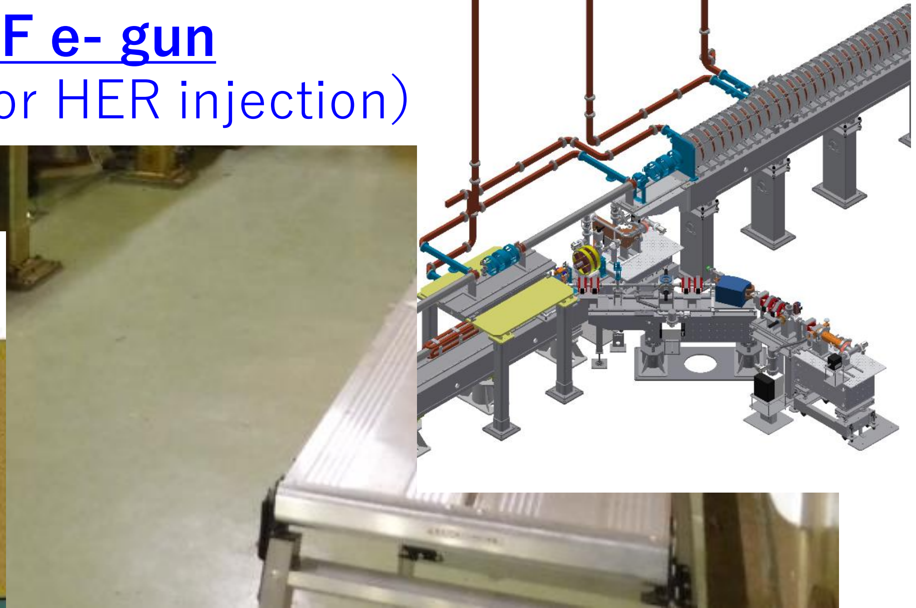
Thermionic DC e- gun (GU_AT)
w/ 2 subharmonic bunchers (114 MHz, 571 MHz) and 2 bunchers.

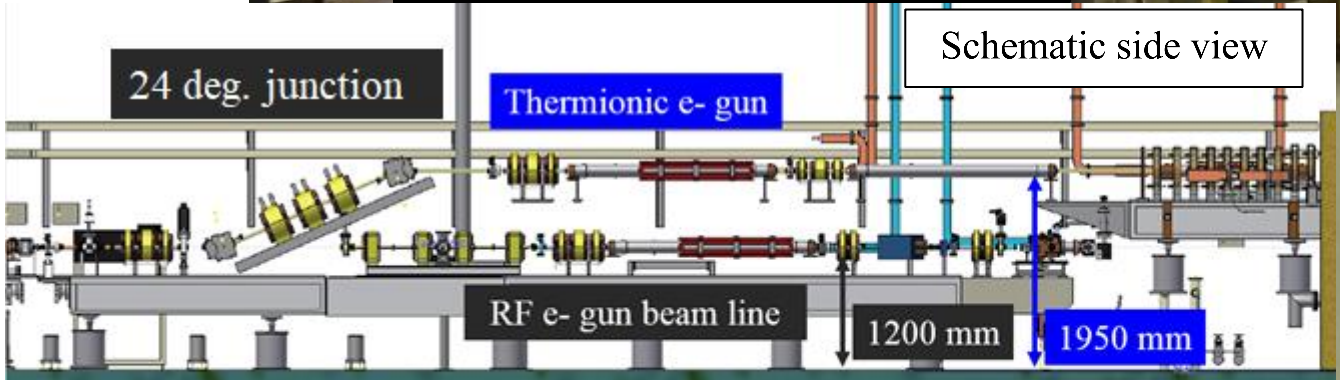
- e+ production e-: 10 nC (for LER injection)
- e- study/HER injection: 1 nC
- PF injection: 0.1 - 0.3 nC
- PF-AR injection: 0.1 - 0.3 nC



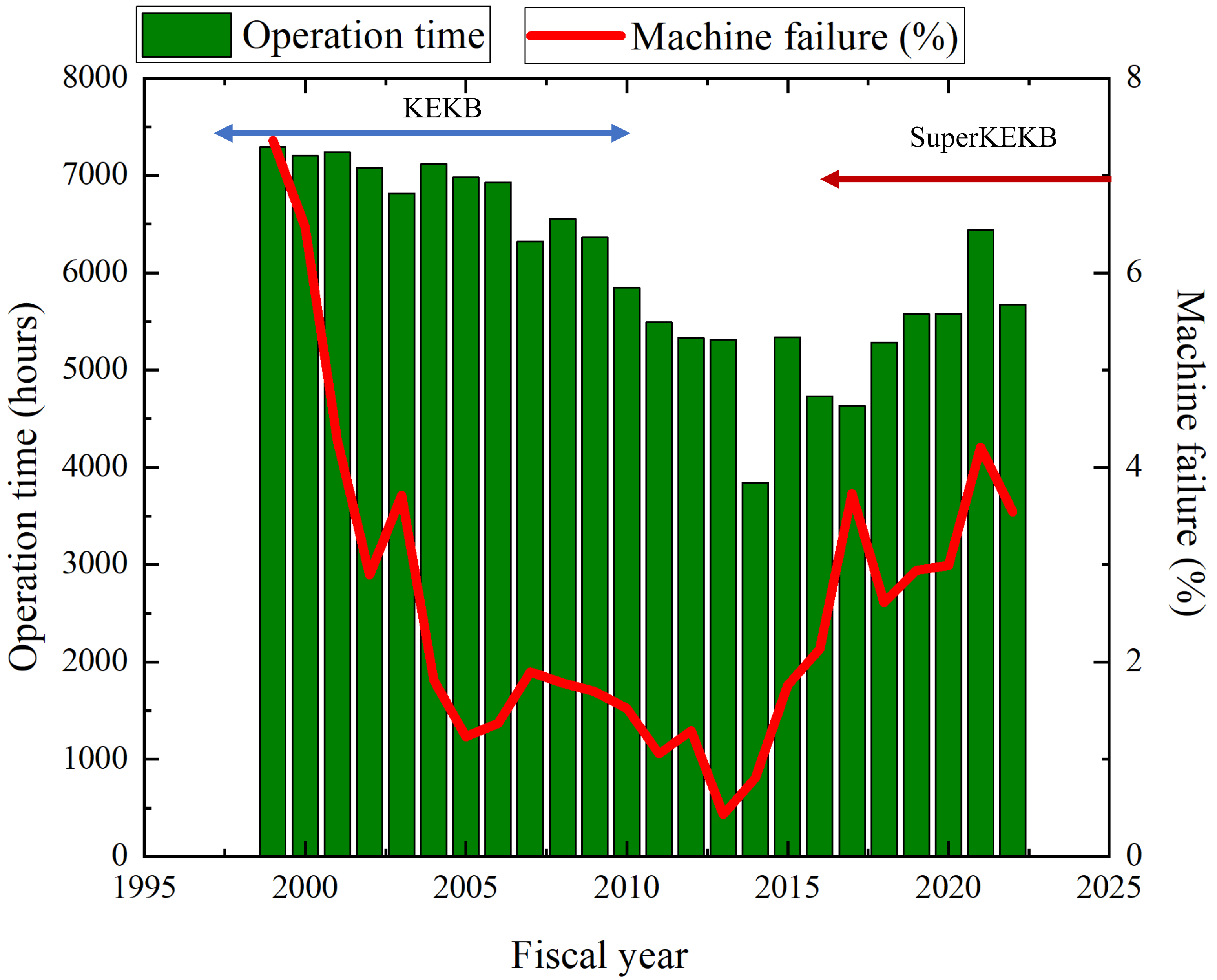
Pulsed bend

RF e- gun
(GR_A1 for HER injection)

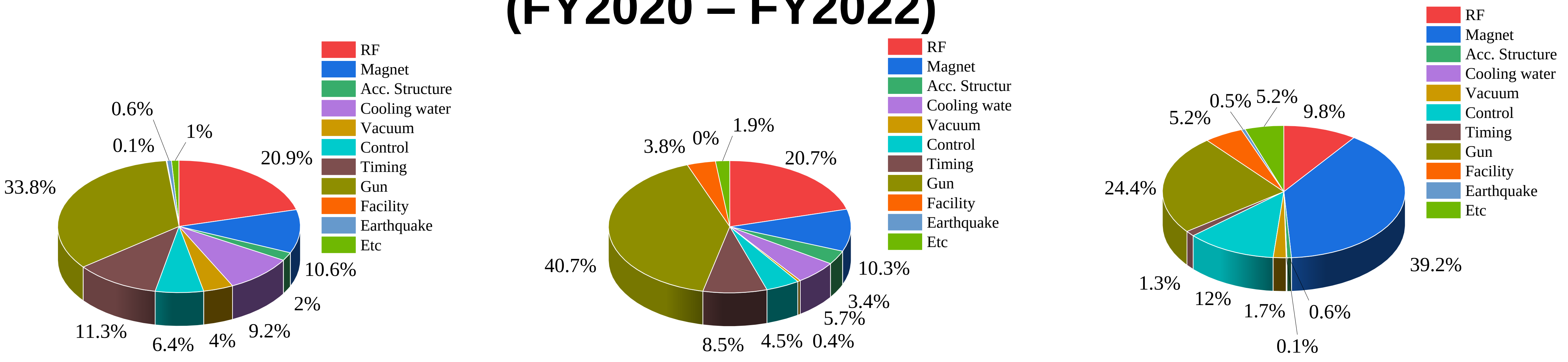




Injector operation statistics



Injector beam loss time statistics (FY2020 – FY2022)



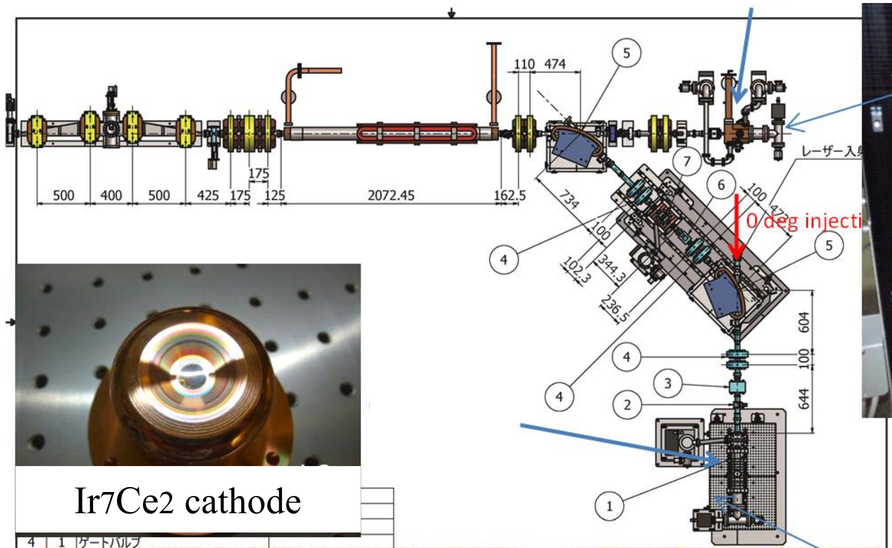
FY2020: 1.58% | FY2021: 1.83% | FY2022: 0.81%

- Beam operation could be interrupted by some different reasons. (RF, magnet powers supply, control software failure, …)
- Beam loss time ratio is less than 2%.
- Most beam loss time are caused by RF and e- gun related troubles.
- In FY2022, beam loss time is less than 1%.
  - In 2022b, 2022c, 2023a, SuperKEKB was not in operation because of LS1.
  - Linac klystron operation mode was changed from 50 Hz to 25 Hz.
- In FY2022, most of beam loss time are caused by magnet trouble.
  - Pulsed magnet controller problem.

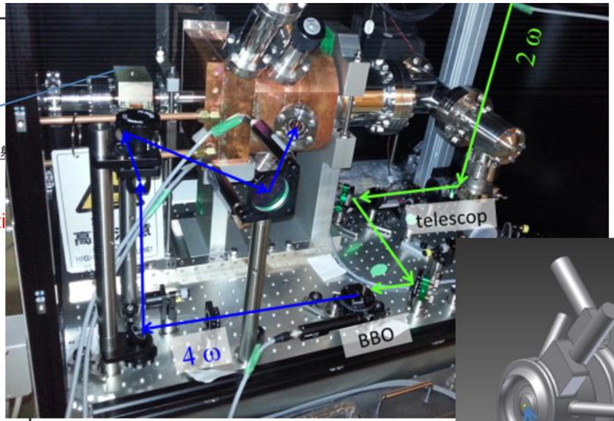
e- beam status and issue

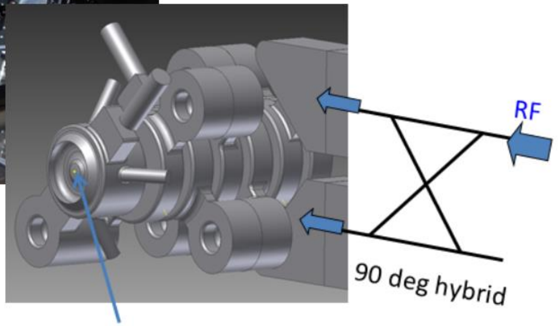
Low emittance photocathode rf e- gun

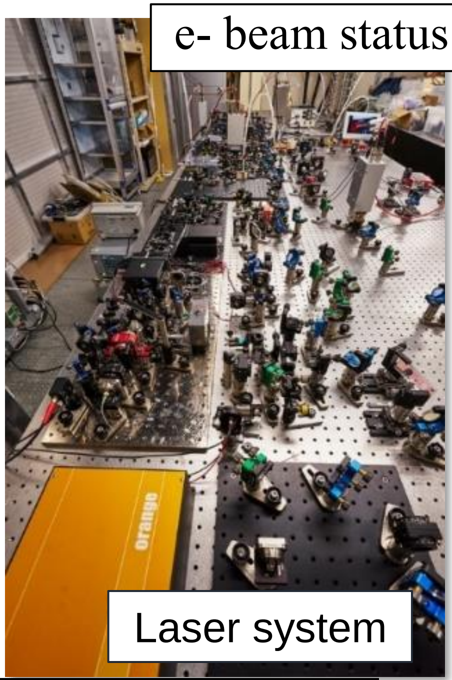
e- beam status



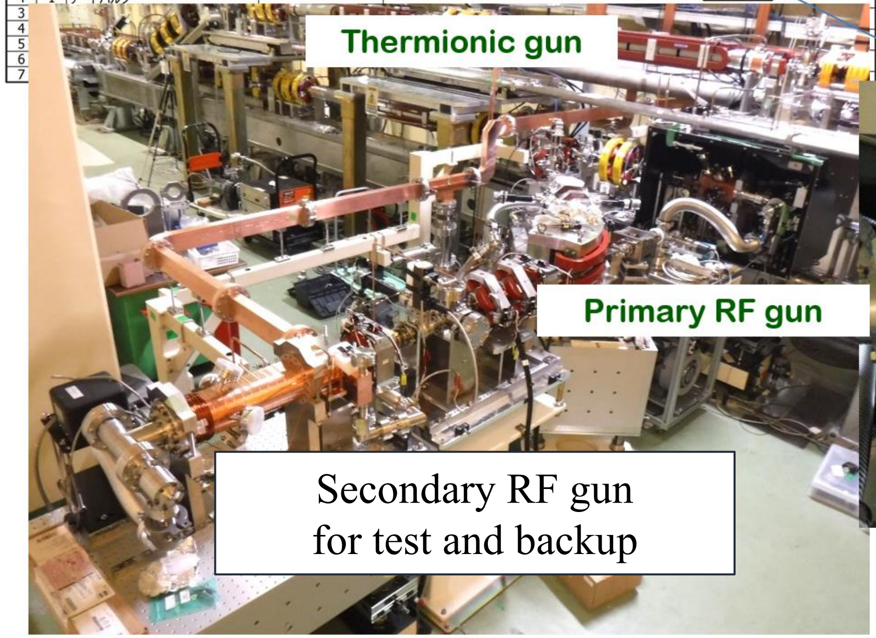
Ir7Ce2 cathode







Laser system

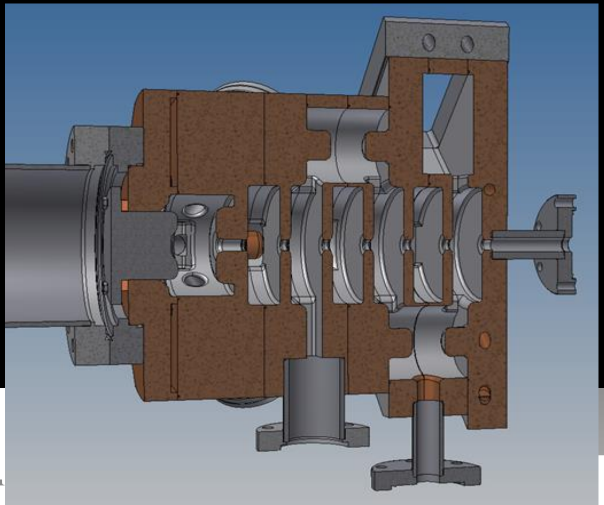


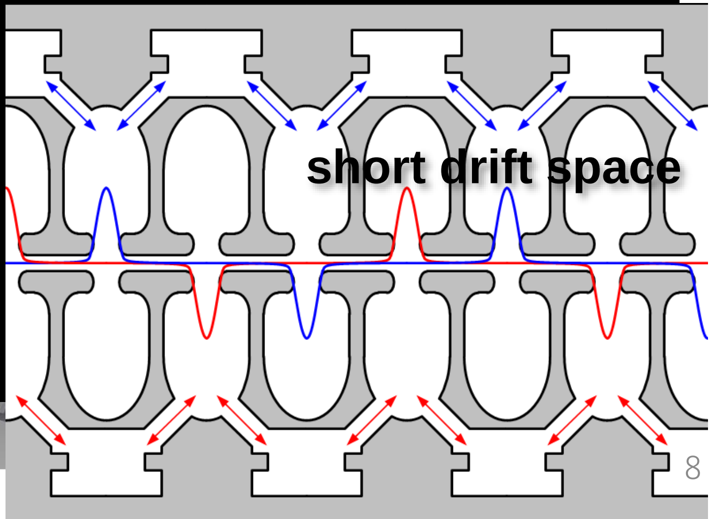
Thermionic gun

Primary RF gun

Secondary RF gun
for test and backup

- Photocathode: Ir_7Ce_2
- Cavity: QTWSC (Quasi Travelling Wave Side Coupler)
  - Strong focusing electric field





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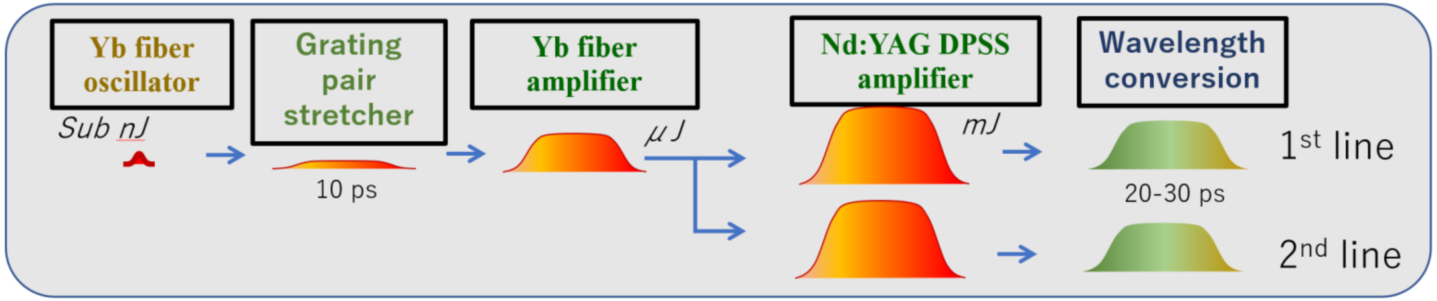
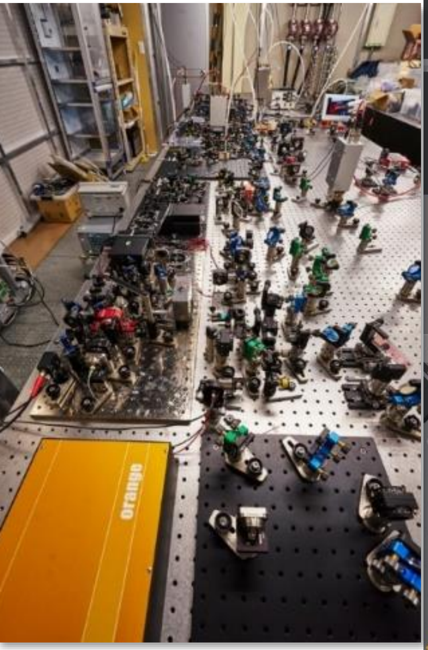
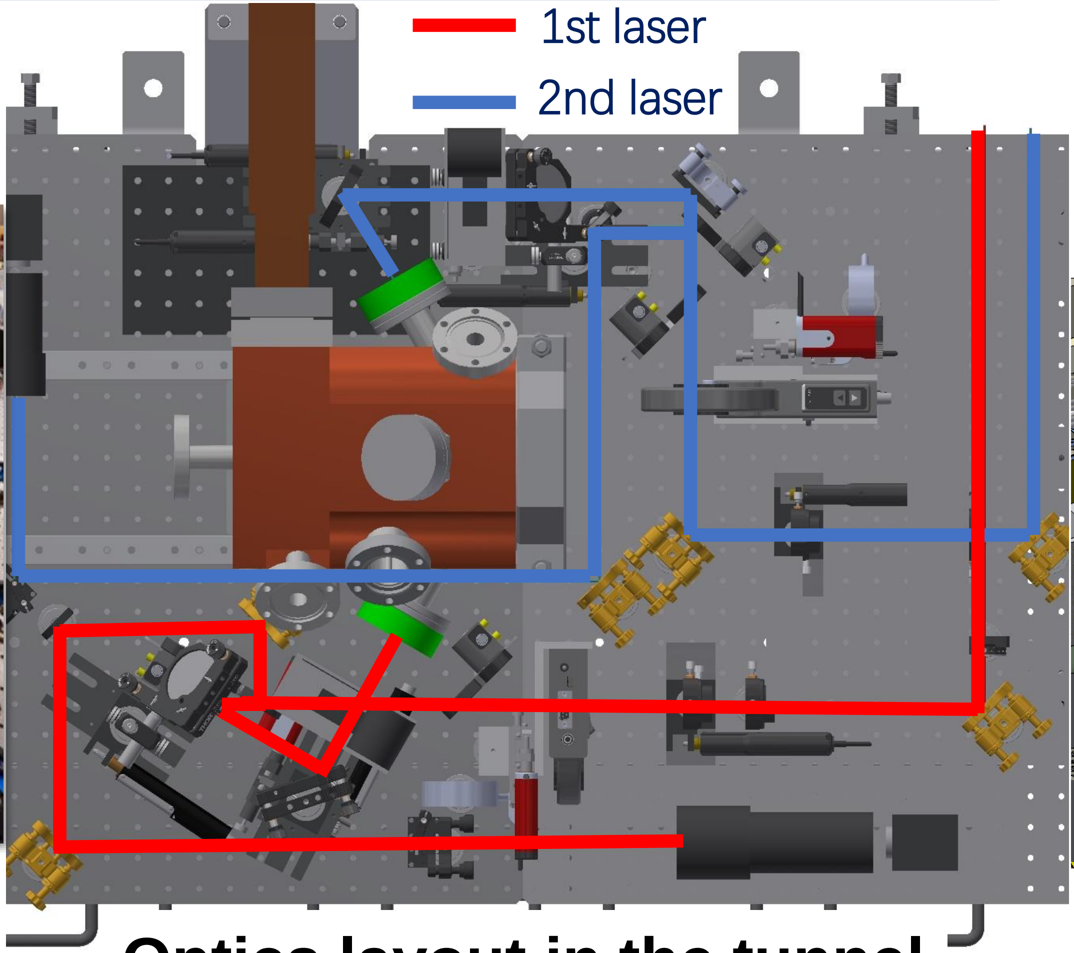
Hybrid laser system for rf e- gun

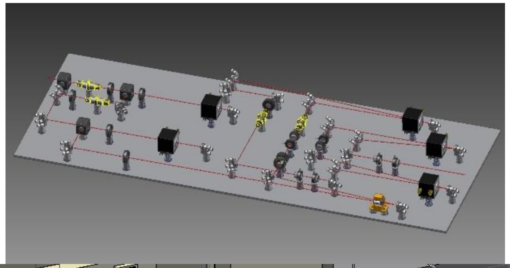
- Yb doped fiber and Nd:YAG DPSS module Amplifier

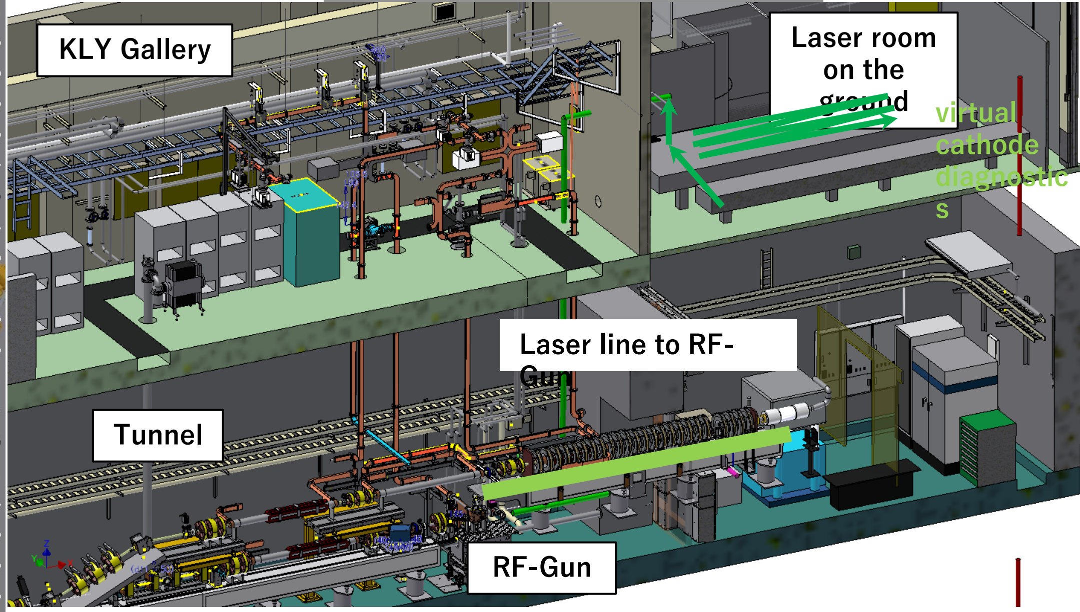


- **Output Power:**
- *ω (1064 nm): 30 mJ*
- *2ω (532 nm): 15 mJ*
- *4ω (266 nm): 1 mJ*









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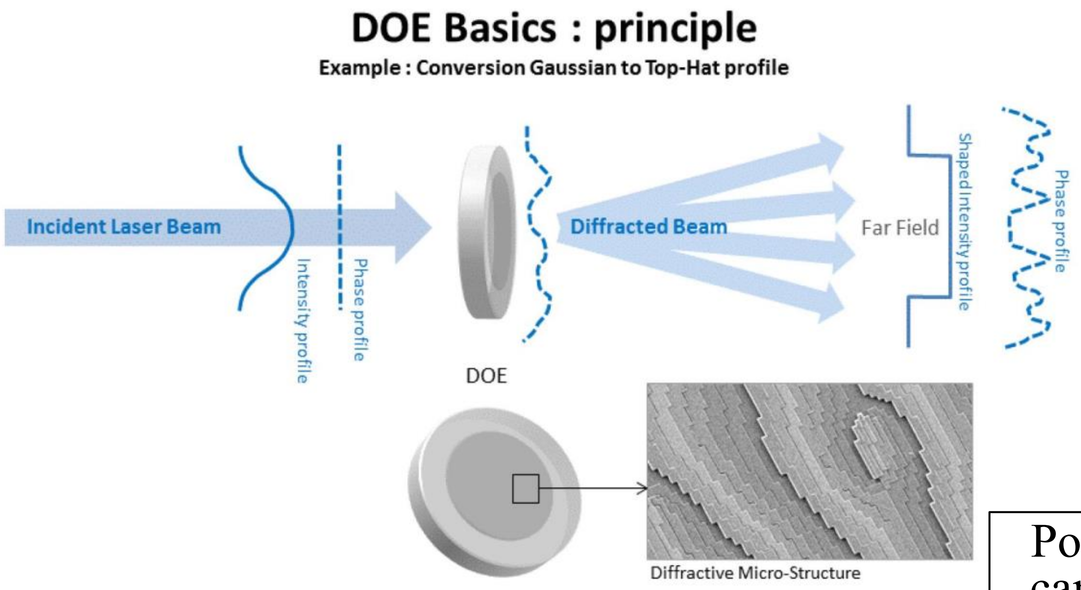
Optics layout in the tunnel

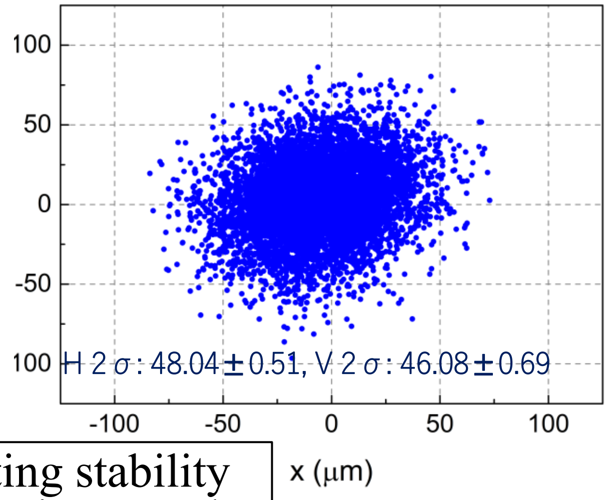
Laser transport line

DOE for reshaping of laser spatial distribution

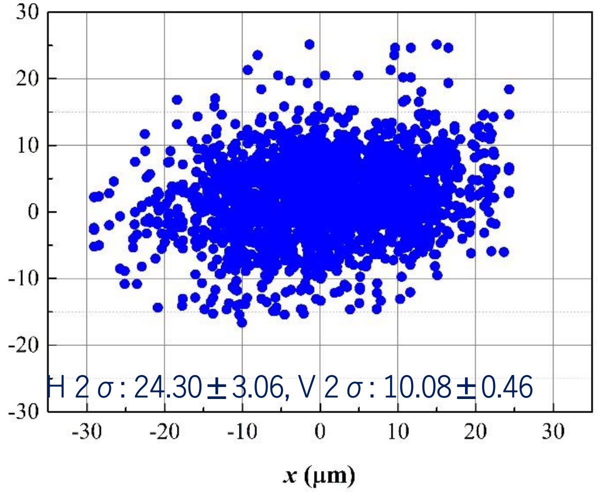
e- beam status



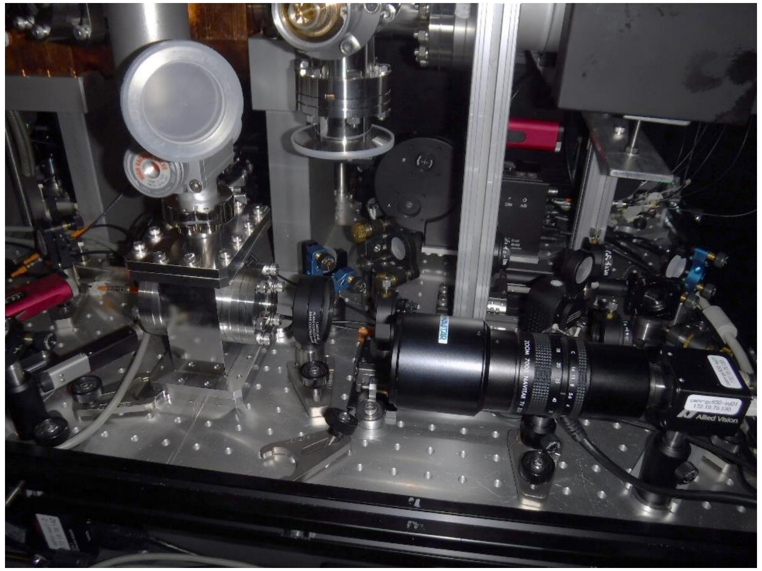
2019.06 without DOE & beam position sensor



2021.06 with DOE & beam position sensor



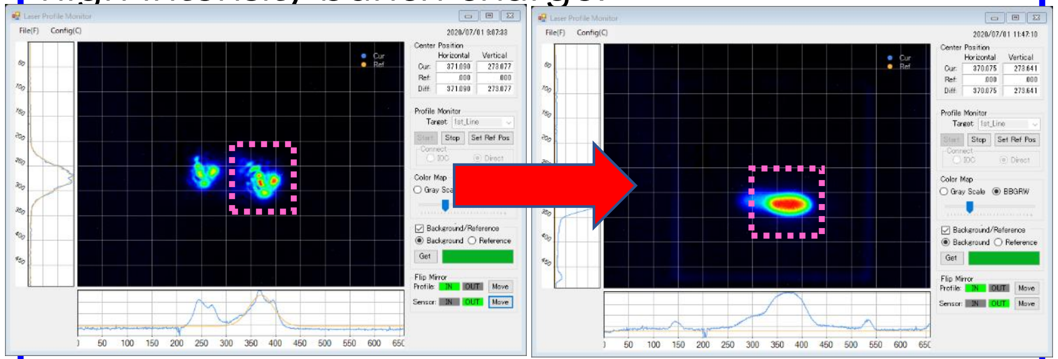
Pointing stability can be improved.



DOE is installed in vacuum chamber filled with Argon gas.

DOEs were replaced by new one (Φ8 mm from Φ6 mm) for high bunch charge operation.

DOE (diffractive optical element) were installed at 1st /2nd (in summer '20/'21) line laser: Laser beam homogenizer for low emittance beam with the high intensity bunch charge.

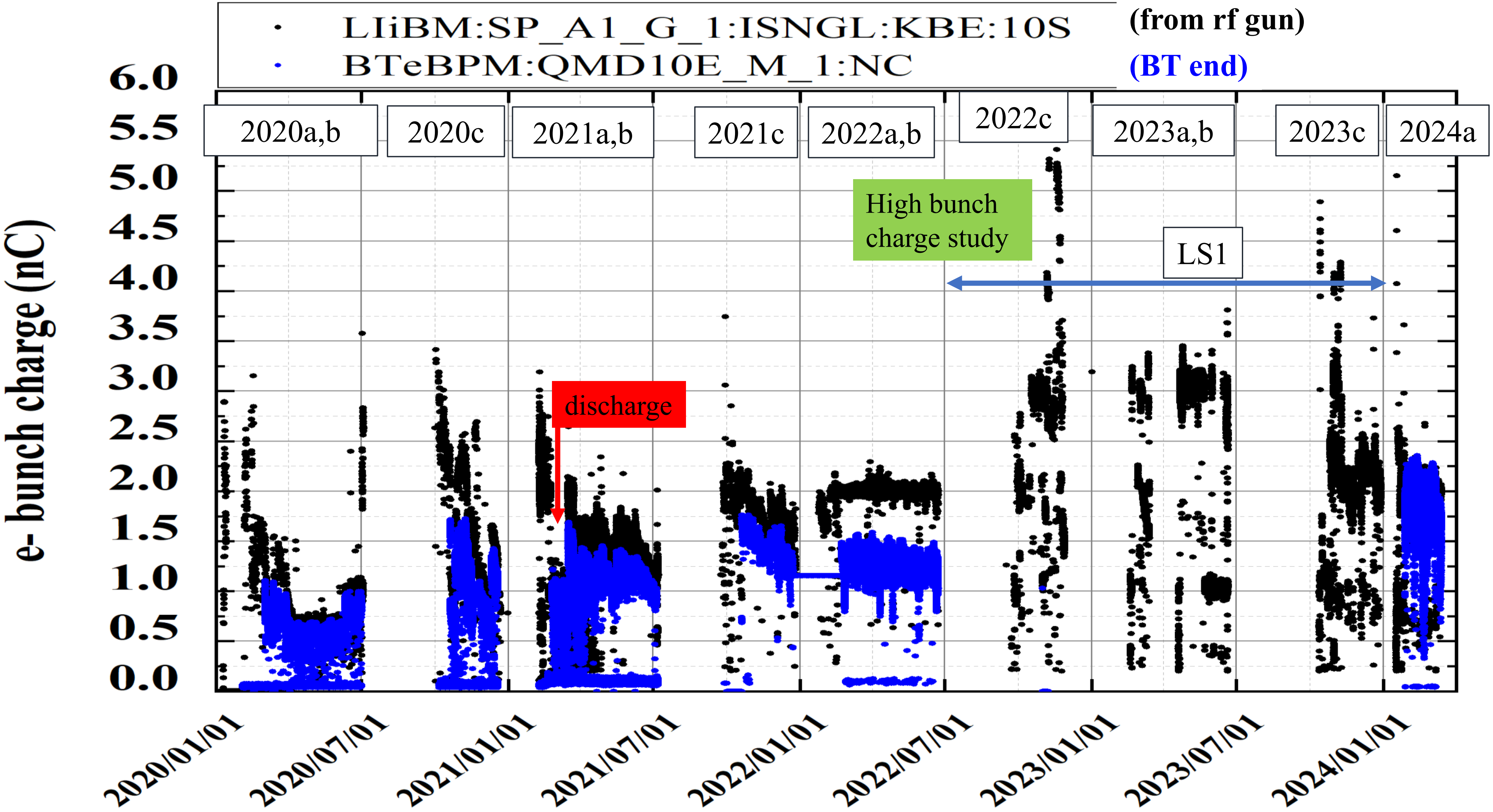


world first DOE application in UV laser

R. Zhang

e- bunch charge history (2020a to 2024a)

e- beam status



e- beam summary and issue

- Thermionic DC e- gun has worked fine for light source (PF, PF-AR) injection and e+ production primary e- beam (10 nC).
- Photocathode rf e- gun
  - Laser system and the new DOE (Φ8 mm) element have worked fine without any significant trouble.
- Increase of bunch charge
  - High bunch charge of 5 nC e- from gun was demonstrated w/ previous DOE (Φ6 mm).
  - Further high bunch charge e- beam study will be conducted w/ new DOE.
- Issue
  - Breakdown rate of rf gun cavity gradually increased. New cavity should be installed in the near future.
  - Best emittance at the linac end and BT1 (before Arc1) is almost satisfied the final goal while bunch charge (2 nC) is less than final goal (4 nC).
  - However, emittance at BT2 is increased due to ISR, CSR, and some other reasons.
  - Increase of 2nd bunch injection efficiency and improvement of its stability are important issues.
    - In this run 2024a, 2nd bunch emittance is improved. It is almost comparable to 1st bunch one. Two bunch injection will be tested soon.

Emittance measured on Mar. 10th, 2024

1st bunch @ BT1

Results of measurement

β_x @MW.1 m :	30.436	β_y @MW.1 m :	32.261
α_x @MW.1 :	-.333	α_y @MW.1 :	1.904
ε_x m :	2.4969E-9	ε_y m :	3.2477E-9
$\Delta\varepsilon_x$ m :	1.4147E-9	$\Delta\varepsilon_y$ m :	6.868E-10
$\gamma\varepsilon_x$ μm :	34.204	$\gamma\varepsilon_y$ μm :	44.489
$\Delta\gamma\varepsilon_x$ μm :	19.379	$\Delta\gamma\varepsilon_y$ μm :	9.408
Goodness x :	.728	Goodness y :	.858
Bmag x :	2.117	Bmag y :	1.094
ε Bmag x :	5.2866E-9	ε Bmag y :	3.5538E-9
$\gamma\varepsilon$ Bmag x :	72.419	$\gamma\varepsilon$ Bmag y :	48.683

2nd bunch @ BT1

Results of measurement

β_x @MW.1 m :	16.794	β_y @MW.1 m :	40.523
α_x @MW.1 :	-.089	α_y @MW.1 :	.743
ε_x m :	3.1429E-9	ε_y m :	1.7173E-9
$\Delta\varepsilon_x$ m :	6.056E-10	$\Delta\varepsilon_y$ m :	5.711E-10
$\gamma\varepsilon_x$ μm :	43.054	$\gamma\varepsilon_y$ μm :	23.525
$\Delta\gamma\varepsilon_x$ μm :	8.296	$\Delta\gamma\varepsilon_y$ μm :	7.824
Goodness x :	.973	Goodness y :	.376
Bmag x :	1.411	Bmag y :	1.993
ε Bmag x :	4.4340E-9	ε Bmag y :	3.4221E-9
$\gamma\varepsilon$ Bmag x :	60.740	$\gamma\varepsilon$ Bmag y :	46.879

e- emittance

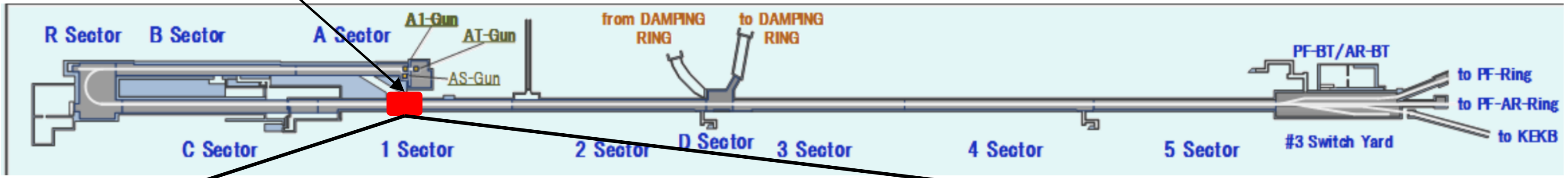
Measured $\varepsilon_{nx,nxy}$ (2 nC) : 20/20 μm (at BT1)

Goal: $\varepsilon_{nx,nxy}$ (4 nC) : 40/20 (H/V) μm

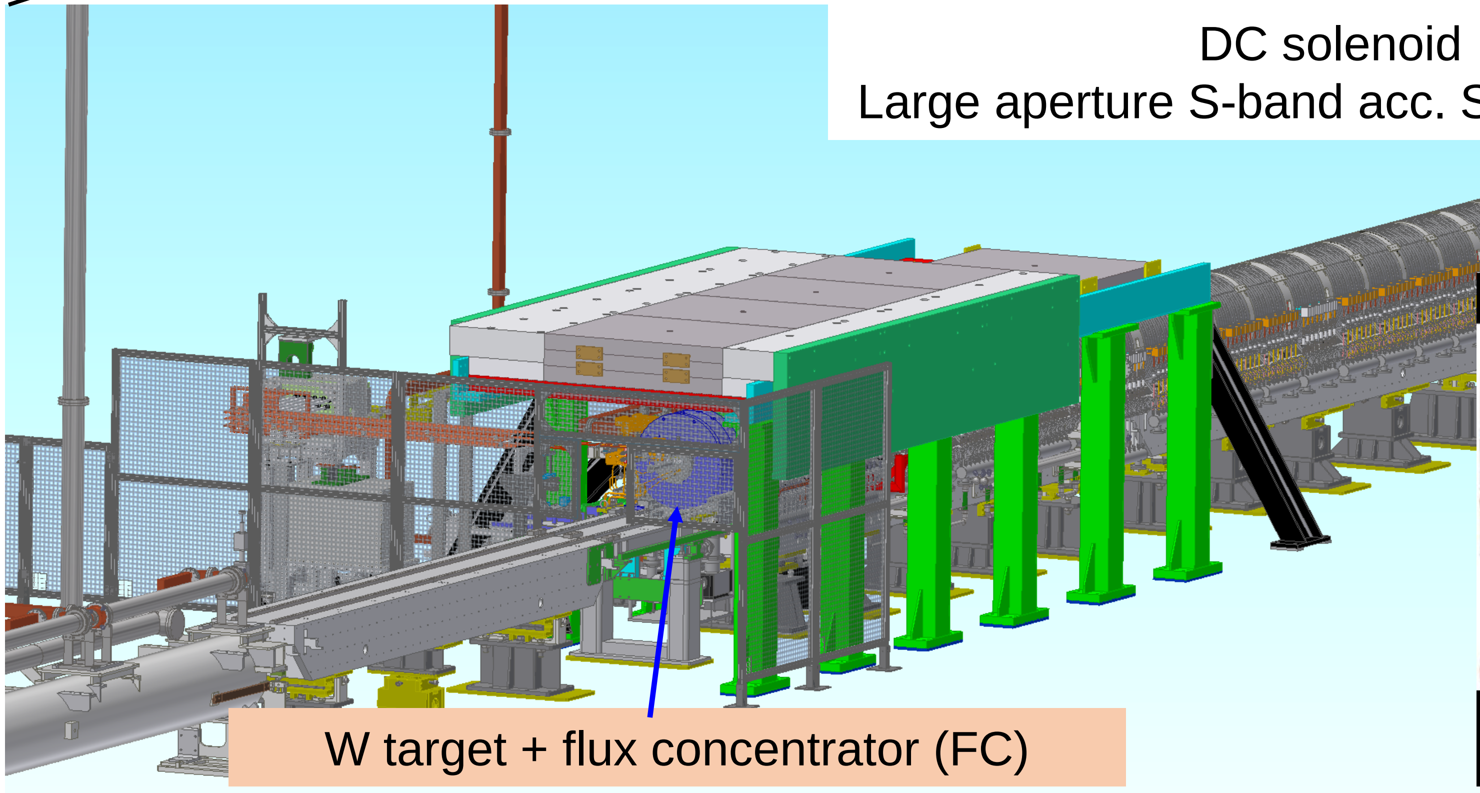
e+ beam status and issue

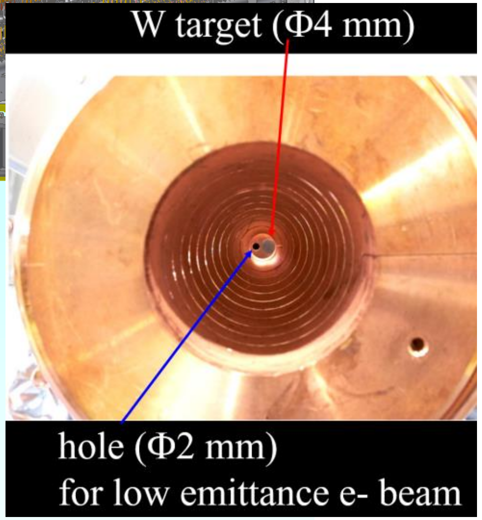
Positron source setup at Sector1

Positron target and capture section



DC solenoid
Large aperture S-band acc. Structures (x10)





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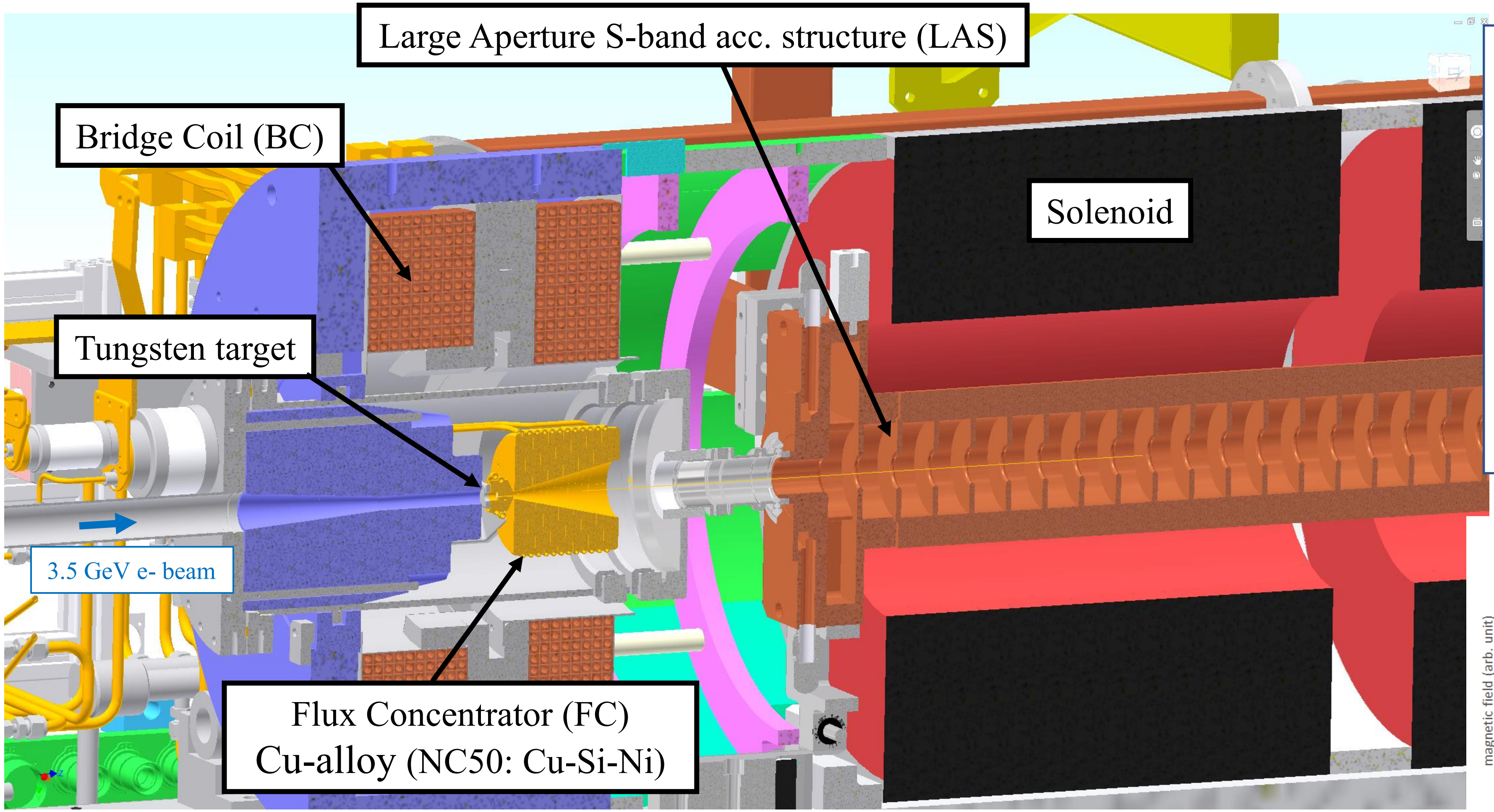
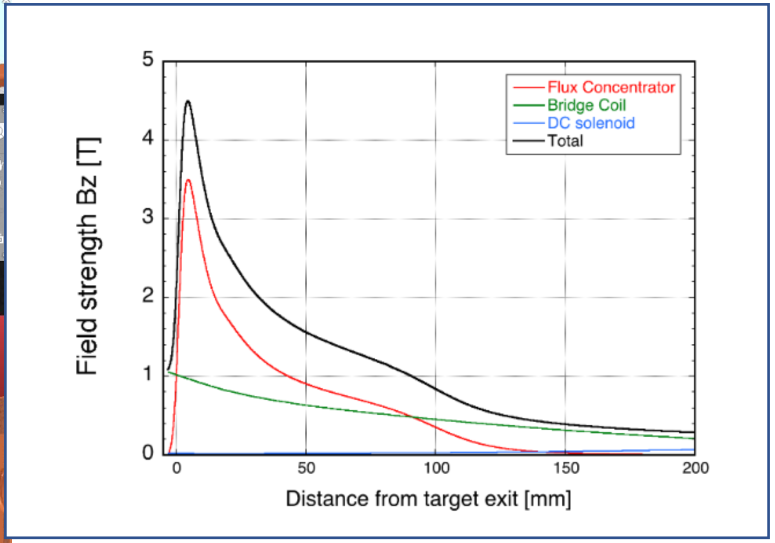
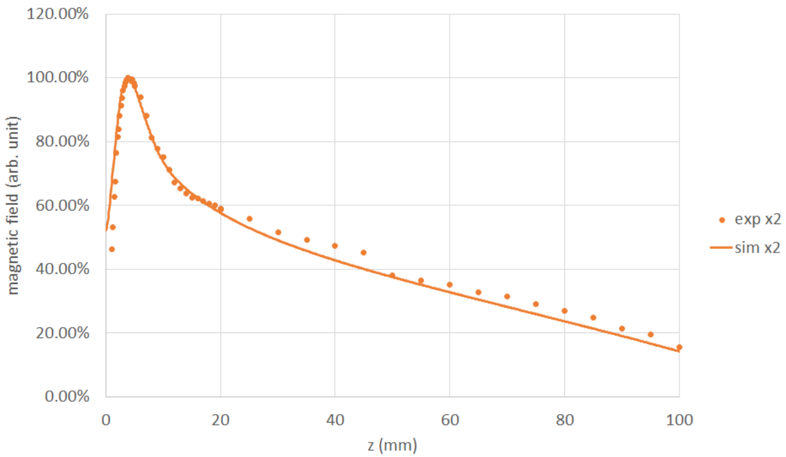
Positron Capture Section: Flux concentrator, bridge coil, solenoid







I_{FC}= 12 kA

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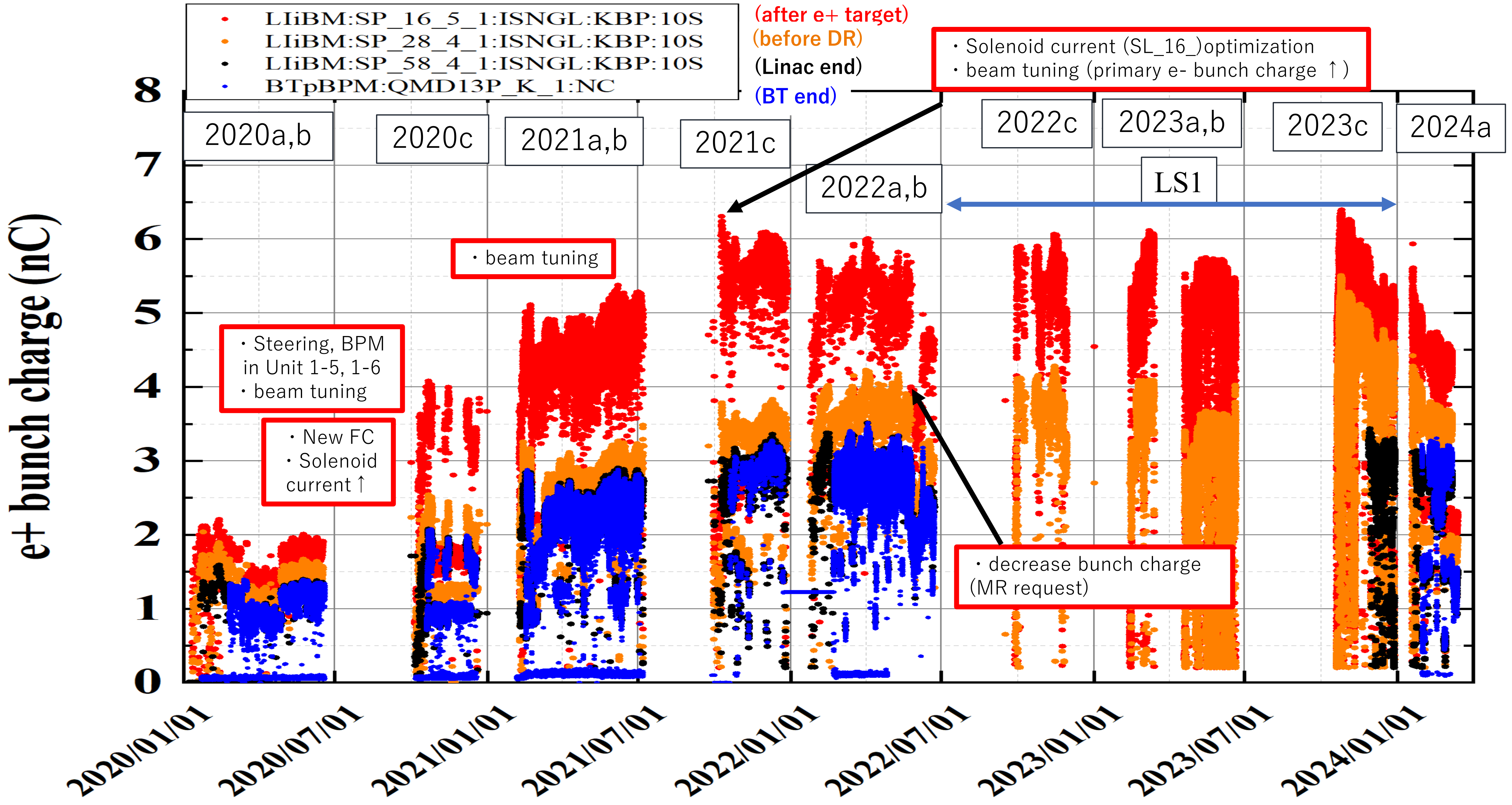
e+ bunch charge history (2020a to 2024a)

e+ beam status



e+ beam summary and issue

- e+ bunch charge is almost achieved (final target: 4 nC)
  - 3.5 nC at linac end and BT
  - Machine learning based automatic tuning can help to increase the e+ bunch charge at end of Sector2 (up to around 5.5 nC).
  - Measured e+ production efficiency (65%) is comparable to the simulation result (60%).
  - Flux concentrator operation has been very stable.

- Issue
  - Emittance at linac end and BT1 (before Arc1) are almost satisfied the final goal.
  - However, emittance at BT2 is increased. It could be caused by some magnetic errors.
    (“Injection” report by T. Yoshimoto san)
  - Horizontal emittance after DR is larger than design value. Low emittance DR optics will be tested after LS1.

e+ emittance

Measured $\varepsilon_{nx,nxy}$ (3 nC) : 103.5/4.7 μm (at BT1)

Goal: $\varepsilon_{nx,nxy}$ (4 nC) : 100/15 (H/V) μm

Upgrade work and progress during LS1

Upgrade work and progress during LS1

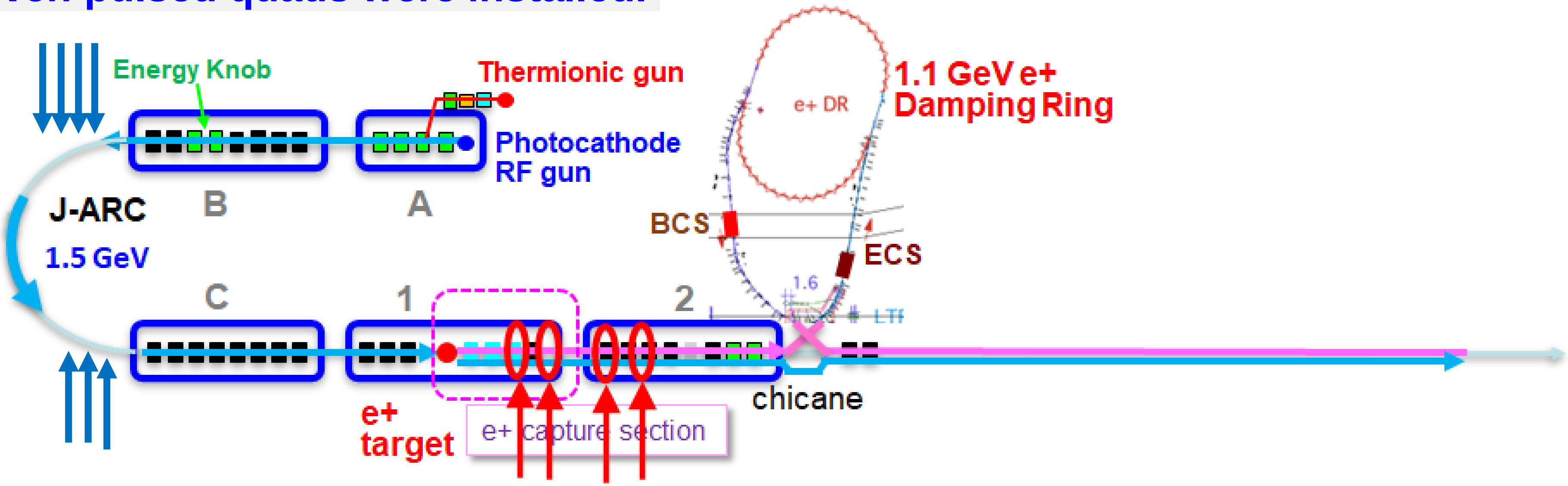
- Pulsed Quads
  - at J-ARC
  - at Sector1, 2
  - Control software upgrade
- Fast kicker for 2nd bunch orbit control (J-ARC, linac end, e- BT)
- New accelerating structure
- Automatic beam tuning

Upgrade during LS1

Pulsed Quads at J-ARC and Sector1, 2

- Additional pulsed quads at J-ARC and Sector1, 2 were installed in 2023 summer maintenance.
  - J-ARC: dedicated beam matching for each injection beam (HER/LER/PF/PF-AR)
  - Sector1, 2: low beta optics for HER injection beam (mitigate emittance growth)
- At J-ARC, newly designed pulsed quad (K. Yokoyama) and pulsed power supply driver (T. Natsui) were installed in the 2023 summer maintenance.

Seven pulsed quads were installed.



Four DC quads were replaced by pulsed one.

Pulsed magnet control system (1)

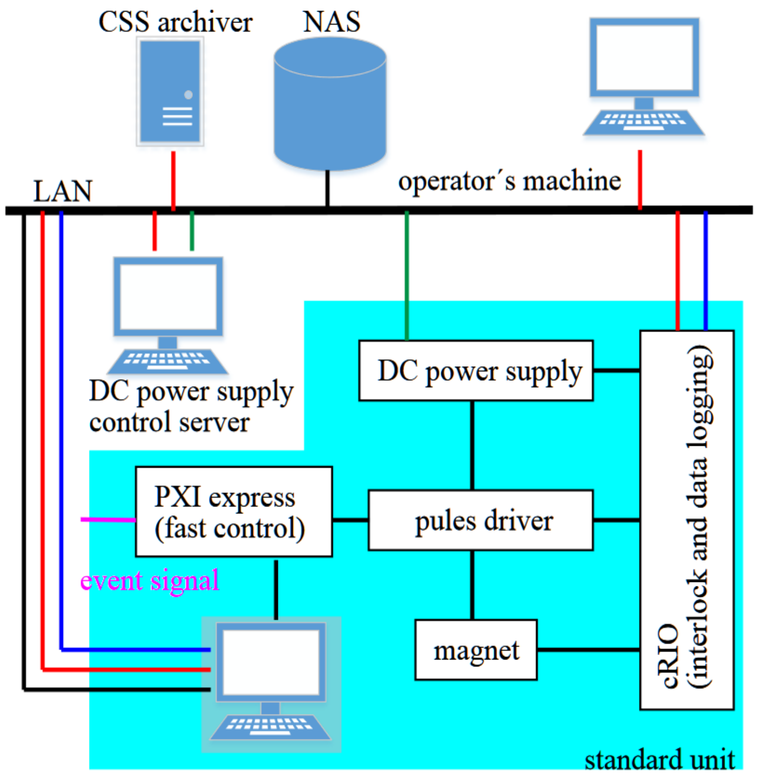
Upgrade during LS1

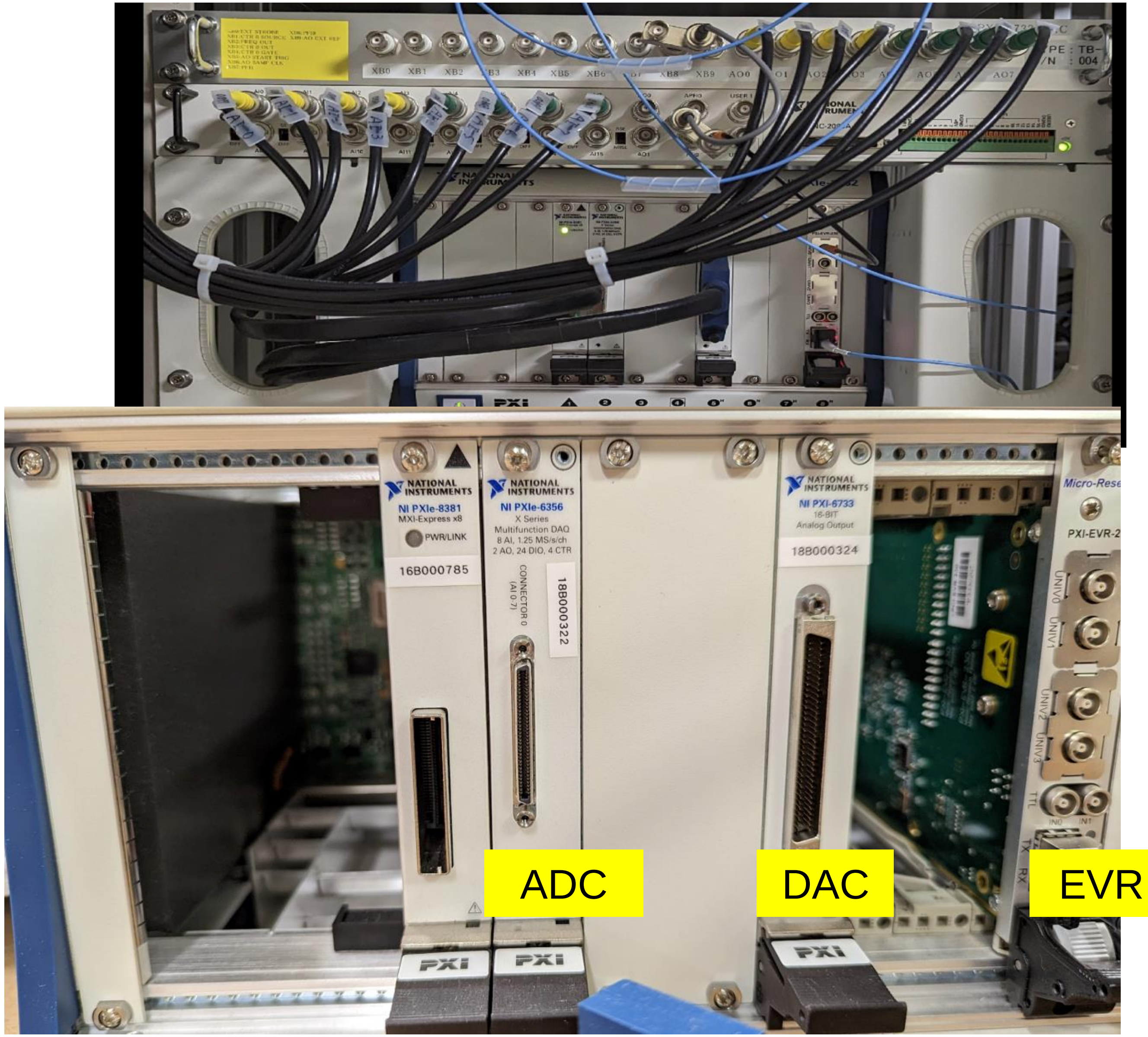
=== PXI-based controller ===

- PCIe-8381 & PXIe-8381, PXI Remote Control Module
- PXI 6733 DAC
- PXIe 6356 ADC
- MRF EVR-230

=== cRIO ===

- Interlock system
- Data logging





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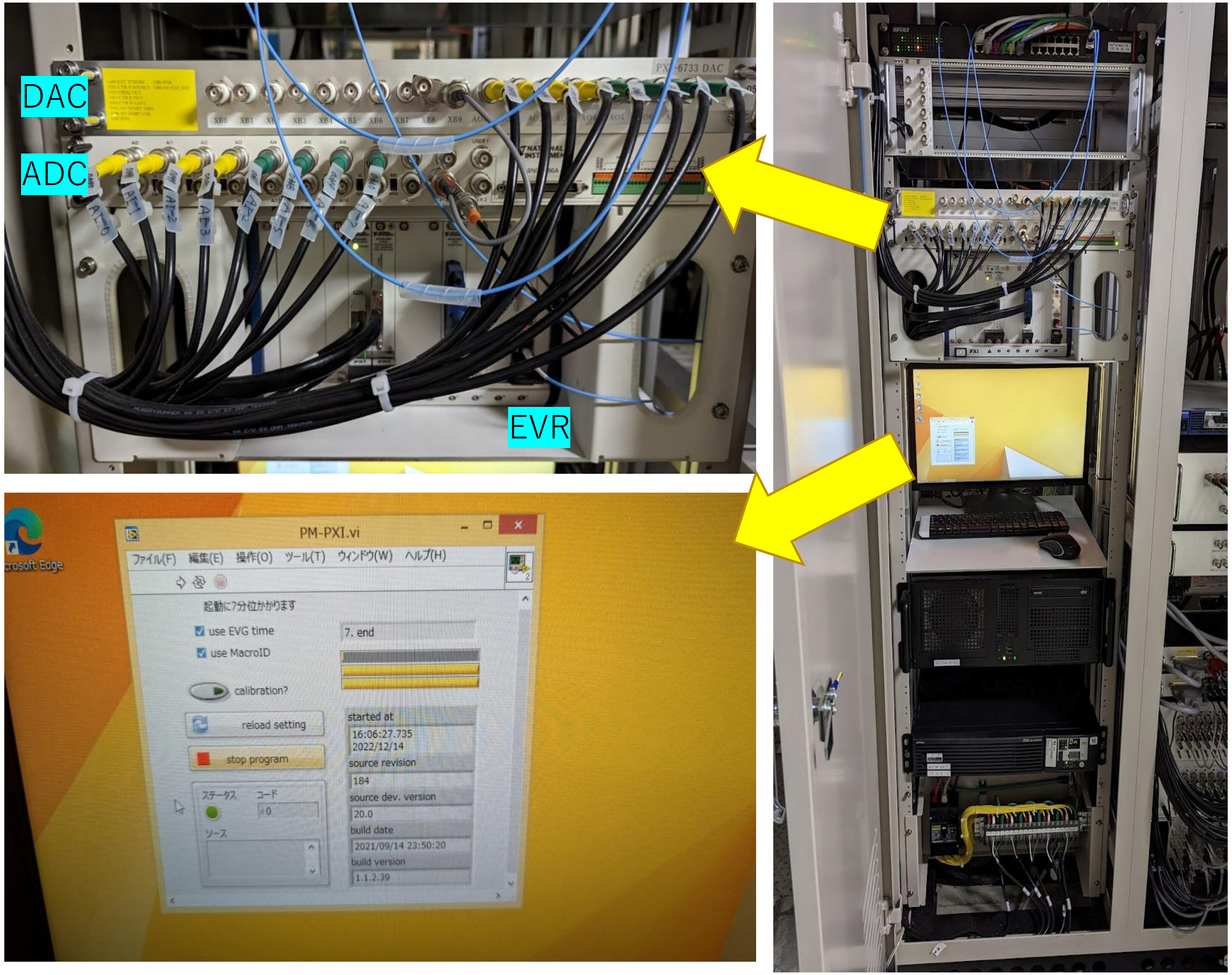
Pulsed magnet control system (2)

- Windows/LabVIEW/PXI system
  - Started since 2017
  - Sometimes control PC or LabVIEW program freeze.
  - It takes 20 minutes for restarting system. (Large # of variable should be initialized in LabVIEW software)
- Development history
  - Decided to migrate to Linux/EPICS IOC (2022/12)
  - NI DAC&ADC driver (2023/02)
  - EVR driver (2023/03)
  - EPICS IOC (2023/04)
  - OPI & Monitoring (2023/05)
  - Experiment (2023/06)
  - Revision (2023/07)
  - Stability test (2023/07)
- 8 of 17 control system were replaced by new software since 2023c.
  - They have worked well w/o trouble.
  - In this summer maintenance, remaining system also will be replaced by new one.



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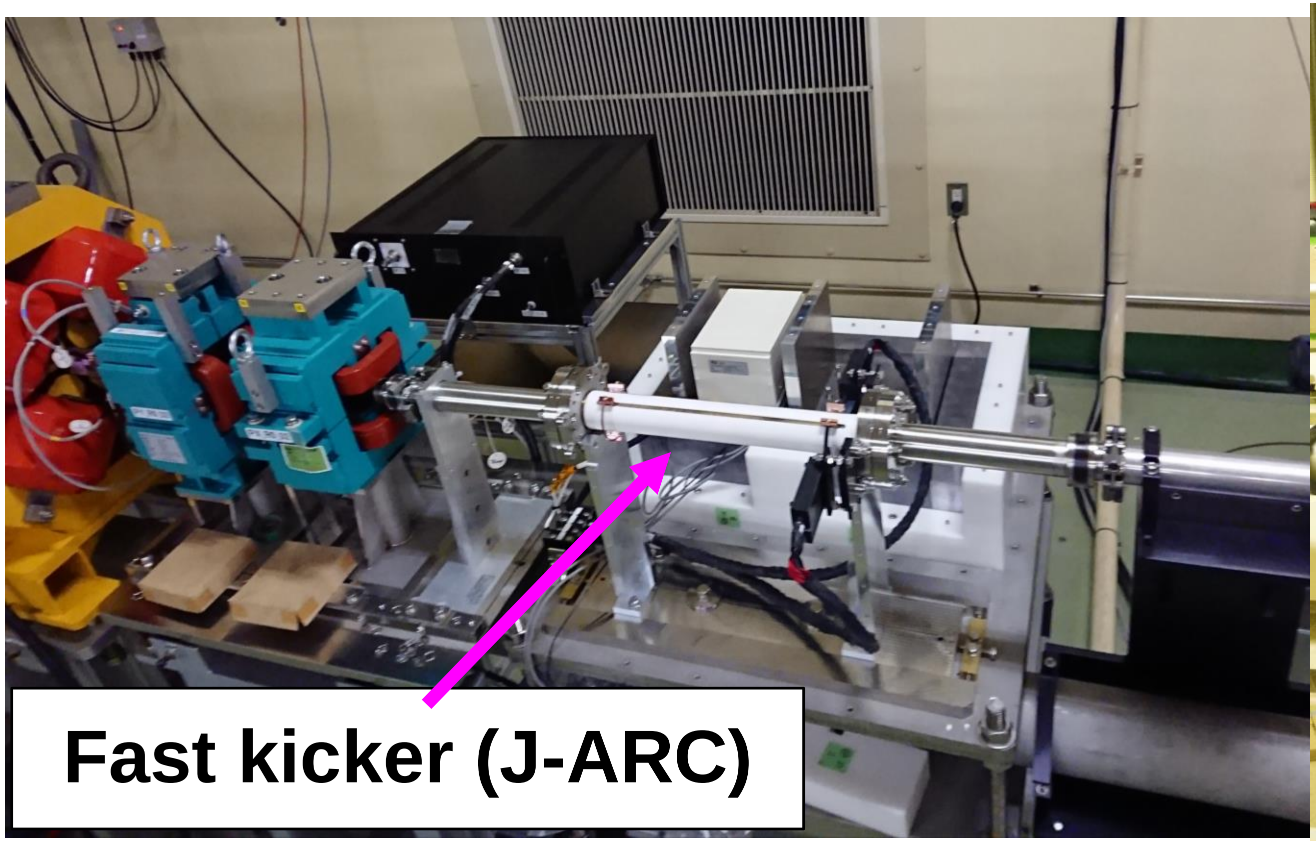
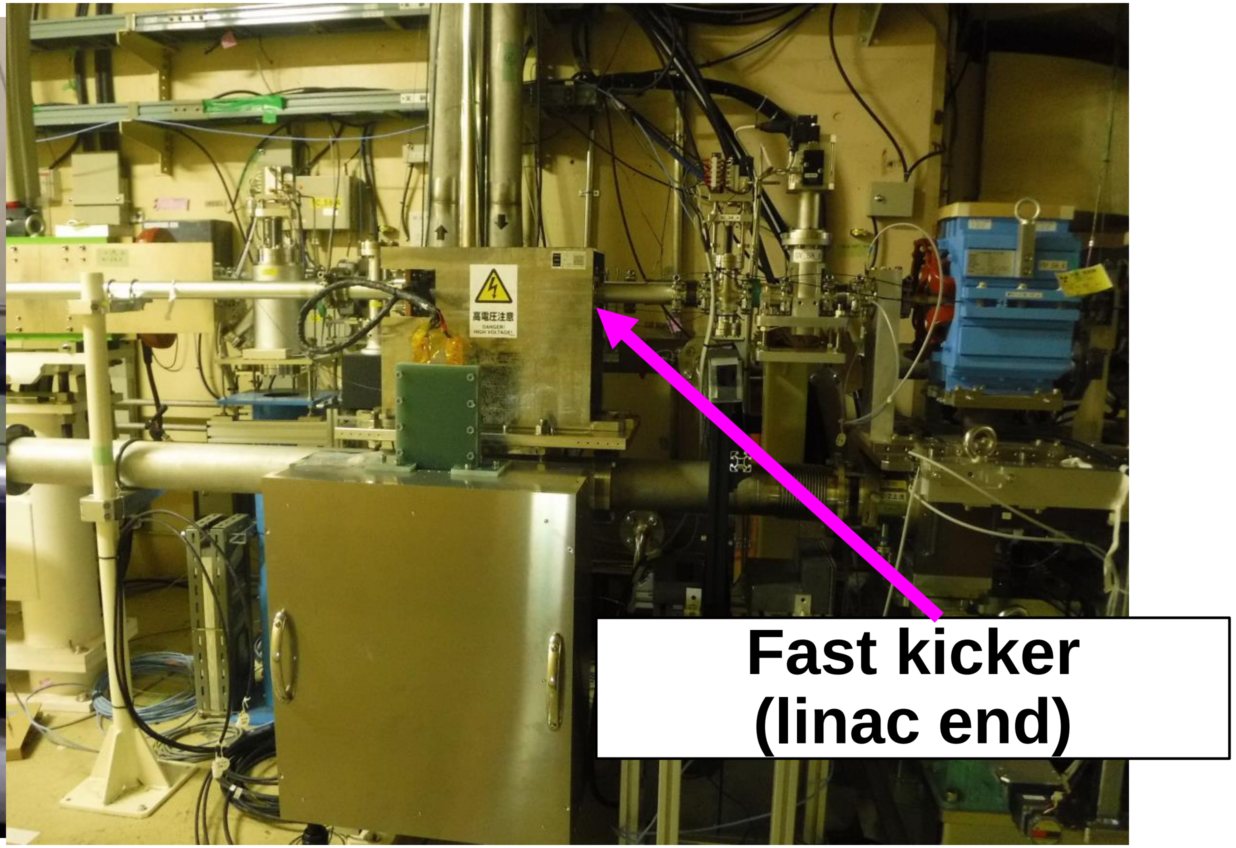
Fast kicker for 2nd bunch orbit correction

- Based on "ceramics chamber with integrated pulsed magnet" developed by C. Mitsuda (PF)
- J-ARC ('22 summer), end of linac and e- BT ('23 summer/winter) for 2nd bunch orbit correction
- It could help to increase the injection efficiency of e- 2nd bunch.





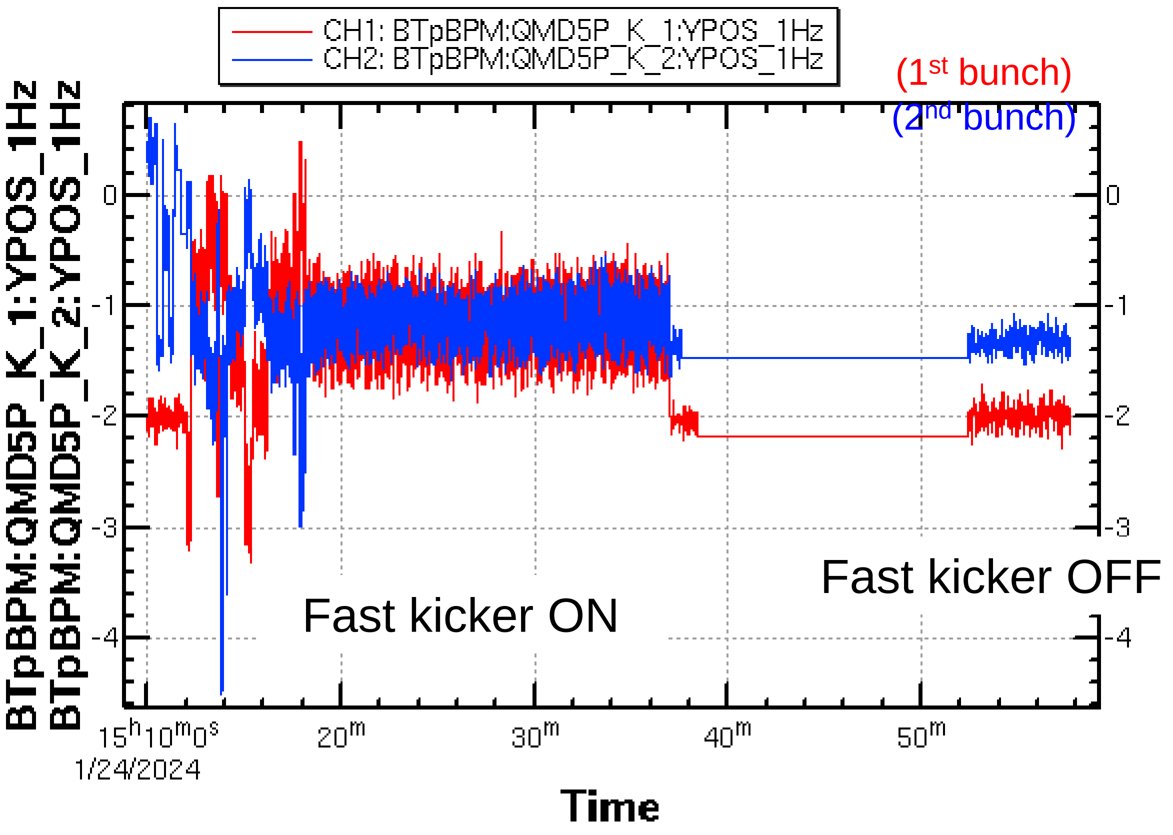
PF (Mitsuda, Shinohara, Naito), Linac (Kamitani, Okayasu, Y. Enomoto, Natsui)

e+ beam test w/ fast kicker (linac end)

Upgrade during LS1

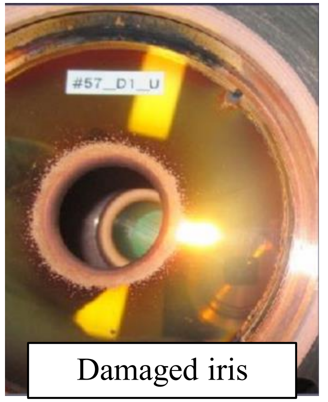
- Fast kicker can correct the 2nd bunch beam position and reduce the orbit difference (1st and 2nd bunch).
- However, it increase the beam position jitter. It should be corrected for beam operation.

e+ BT vertical beam position at BPM QMD5P



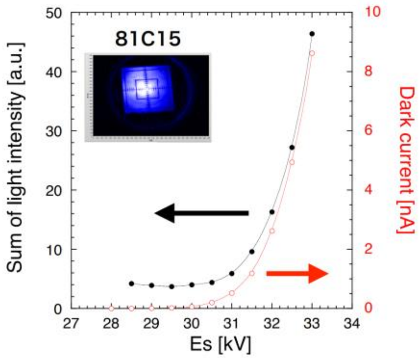
New accelerating structure

Upgrade during LS1

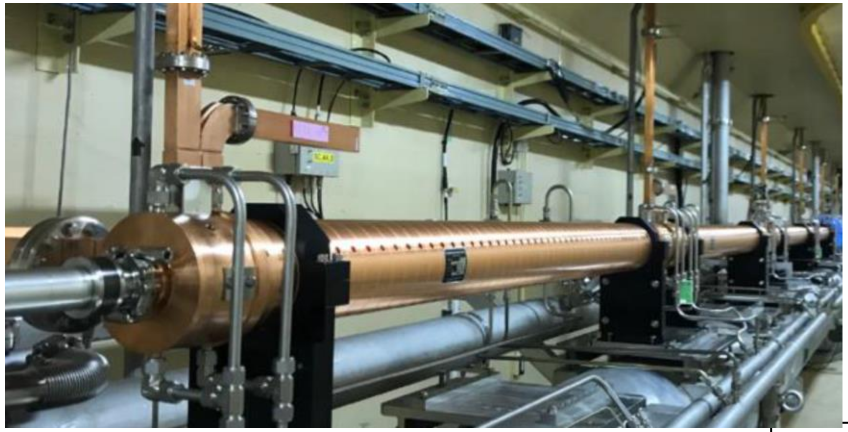


Damaged iris

- Mitigation of accelerating structure failures
  - Originally designed for 8 MeV/m (PF injector), but used at 20 MeV/m (KEKB upgrade)
  - Degradation is leading to high field emission rate and discharges.
  - Water leaks, field emission , discharge in waveguide, and so on (29 of 60 units have some problems)
  - Not only future Υ(6S) but even Υ(4S) could be suffered

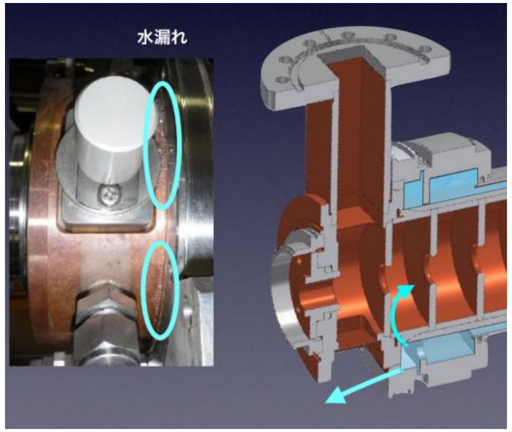


- 5-year upgrade plan to fabricate and install new accelerator structures (FY2018 – FY2022)
  - 4 units (16 acc. structures) have been replaced by new one.
  - New acc. structure: acc. gain ↑7%, surface field ↓20% (reduce breakdown)
  - New pulse compressor (SCPC) was also developed and installed in Unit#44.



New S-band 2-m-long TW acc. structure

New pulse compressor
Spherical-Cavity Pulse Compressor (SCPC)



Colling water leakage

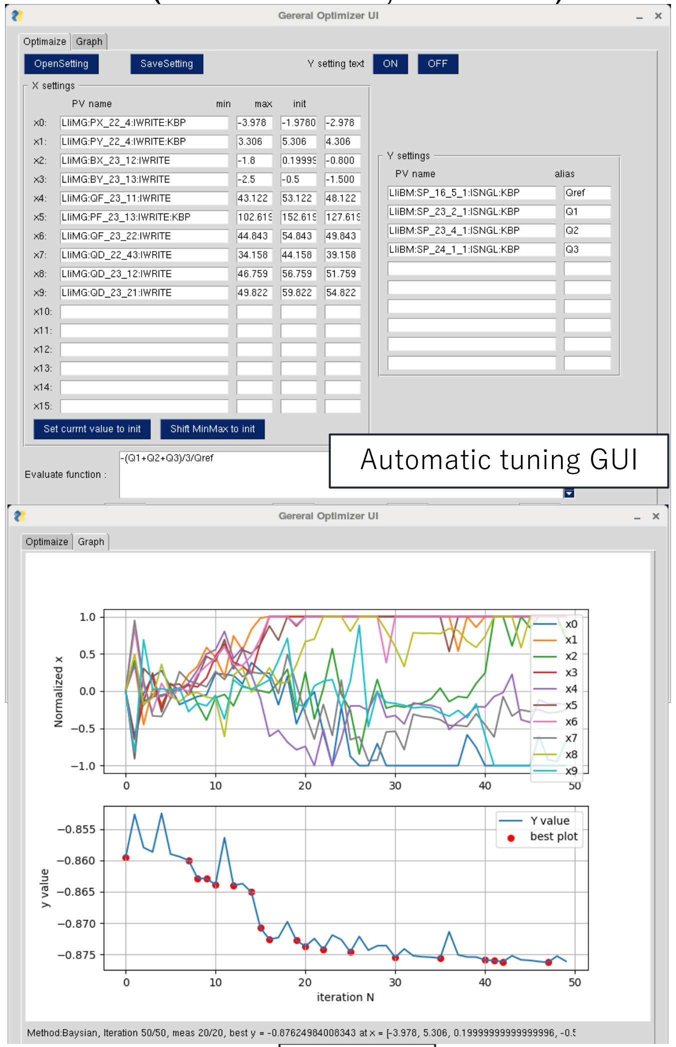
H. Ego

Automatic beam tuning

Upgrade during LS1

- Automatic beam tuning approach with machine learning is recent trend in accelerator operation.
- Bayesian Optimization approach is now under test by using the beam of injector Linac.
  - Implementation using GPyOpt Python library (T. Natsui) / In-house developed implementation (G. Mitsuka, S. Kato)

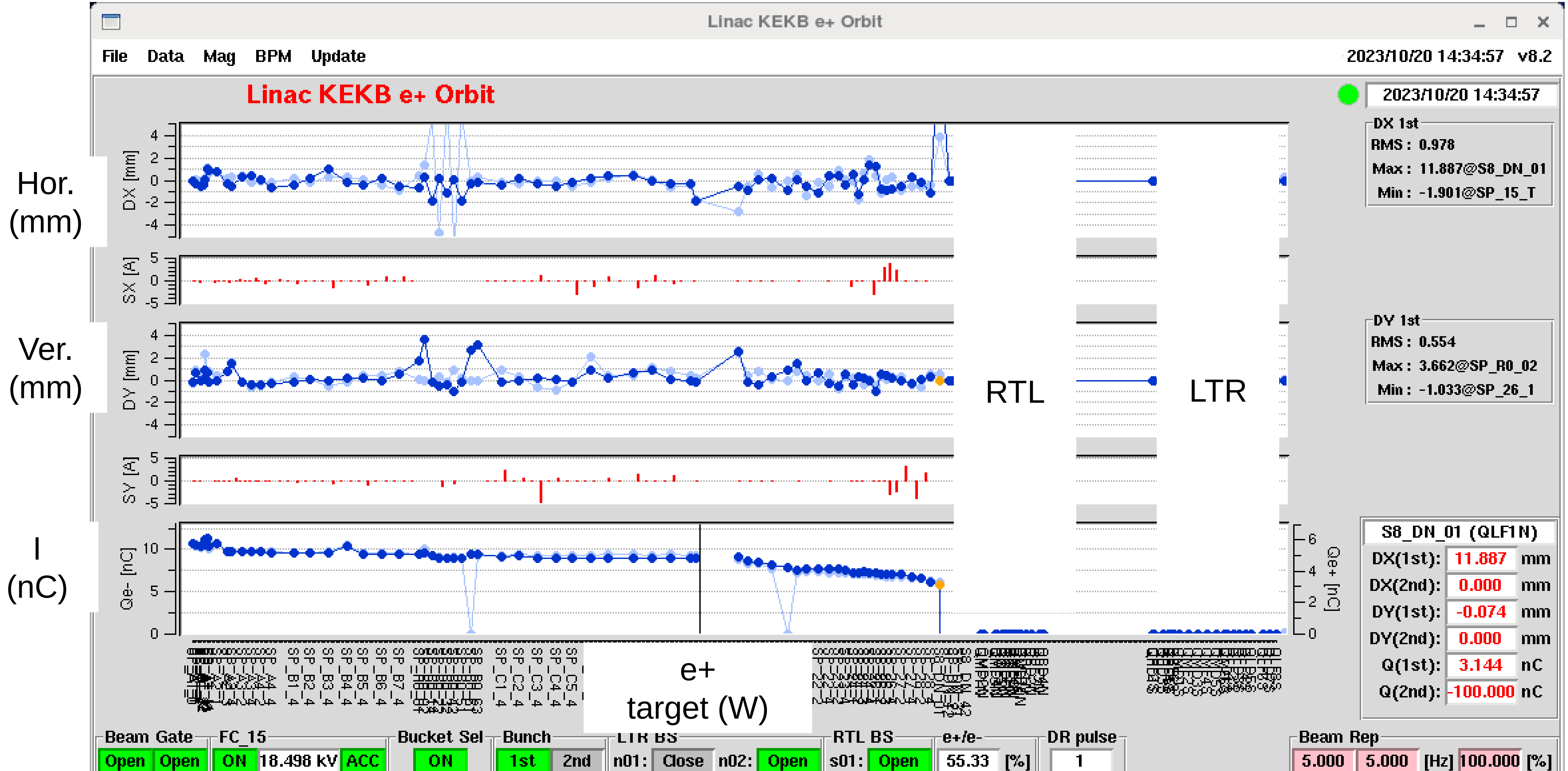
- Automatic beam tuning test started in 2022c.
- Both of Bayesian optimization and downhill simplex method are available.
- Preliminary test was started by using only 4 control variables (pulsed steering magnets) to improve e+ bunch charge.
- After continuous study and software improvement, the number of control variables increased to around 16.
- This automatic tuning is also applied to dispersion correction at J-ARC .
- Currently, any linac operators can easily used this automatic beam tuning software.



Automatic tuning GUI

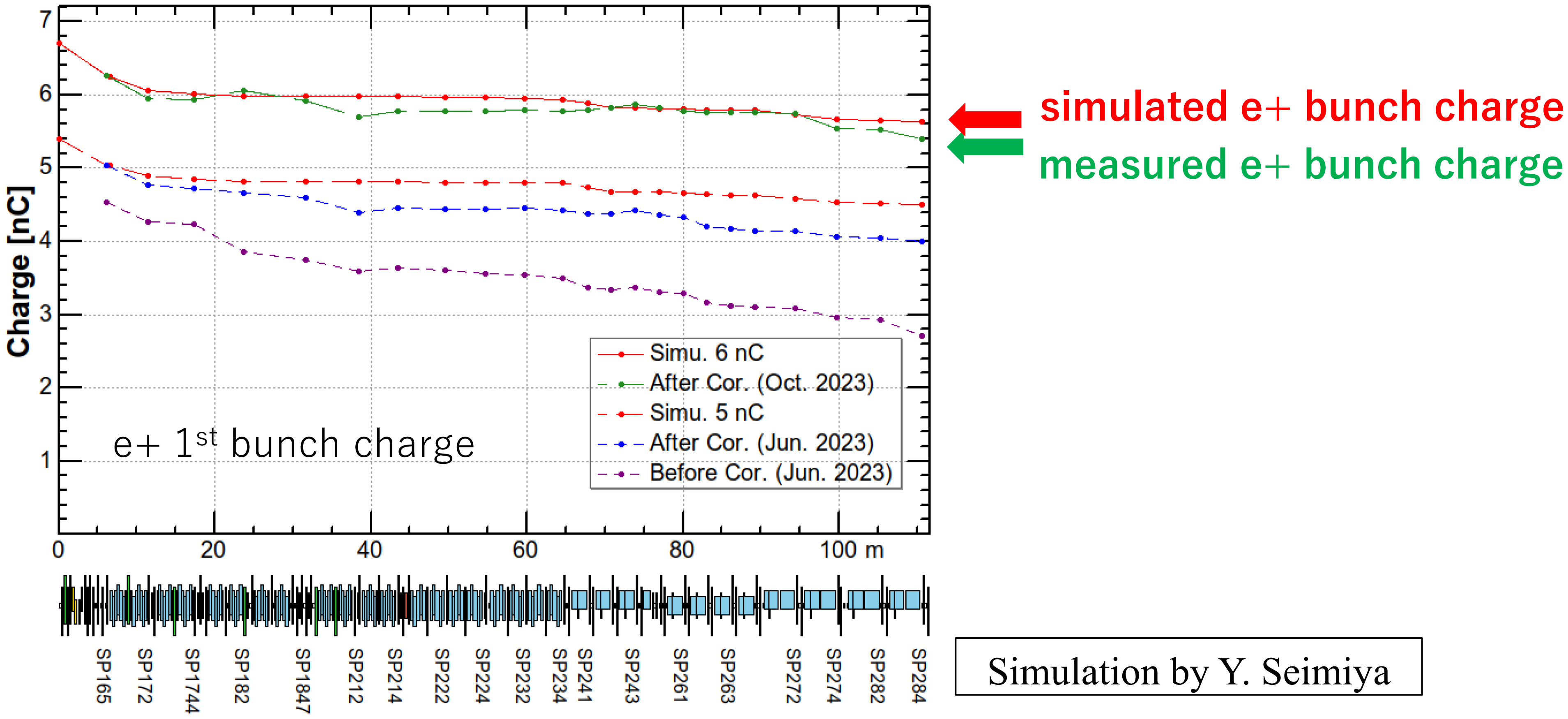
# of trial

Beam orbit and bunch charge during automatic tuning



Automatic tuning for increasing e+ bunch charge

- Measured data (Oct. 25the, 2023) of e+ bunch charge in Sector2 almost agree with the simulation result.
- Pulsed Quads at J-ARC (installed in 2023 summer) and automatic beam tuning software can help to increase the e+ bunch charge.



Simulation by Y. Seimiya

Summary

- Simultaneous top up injection has been successfully conducted.
- e- beam
  - Laser system has worked fine without any significant trouble.
  - New DOEs (Φ8 mm) have been installed at both of 1st and 2nd laser, and they have worked fine.
  - 5 nC from gun was demonstrated w/ previous DOE (Φ6 mm). Further beam study will be conducted w/ new DOE.
- e+ beam
  - e+ generation system (flux concentrator, power supply, DC solenoid) has worked fine.
  - e+ bunch charge of 3.5 nC at BT end are archived (final design 4 nC).
  - Machine learning based automatic tuning can help to increase the e+ bunch charge at end of Sector2 (up to around 5.5 nC).
- Upgrade work and progress during LS1
  - Pulsed quads at J-ARC and Sector1, 2 have been successfully installed and worked fine.
  - New control software for pulsed magnet
  - New accelerating structure
  - Fast kicker for 2nd bunch orbit correction (J-ARC, Linac end, e- BT)
  - Automatic beam tuning is deployed for daily operation.
- Issues
  - Emittance growth at end of BT for both of e- and e+ beam (Injection report)
  - Low e- injection efficiency of 2nd bunch so far. Fast kicker system could help to improve it.
  - Increase the e- bunch charge while keeping small emittance w/ new DOE.