65th ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e+e- Colliders (eeFACT2022)

2022/09/15 WG6: Injection (parallel)

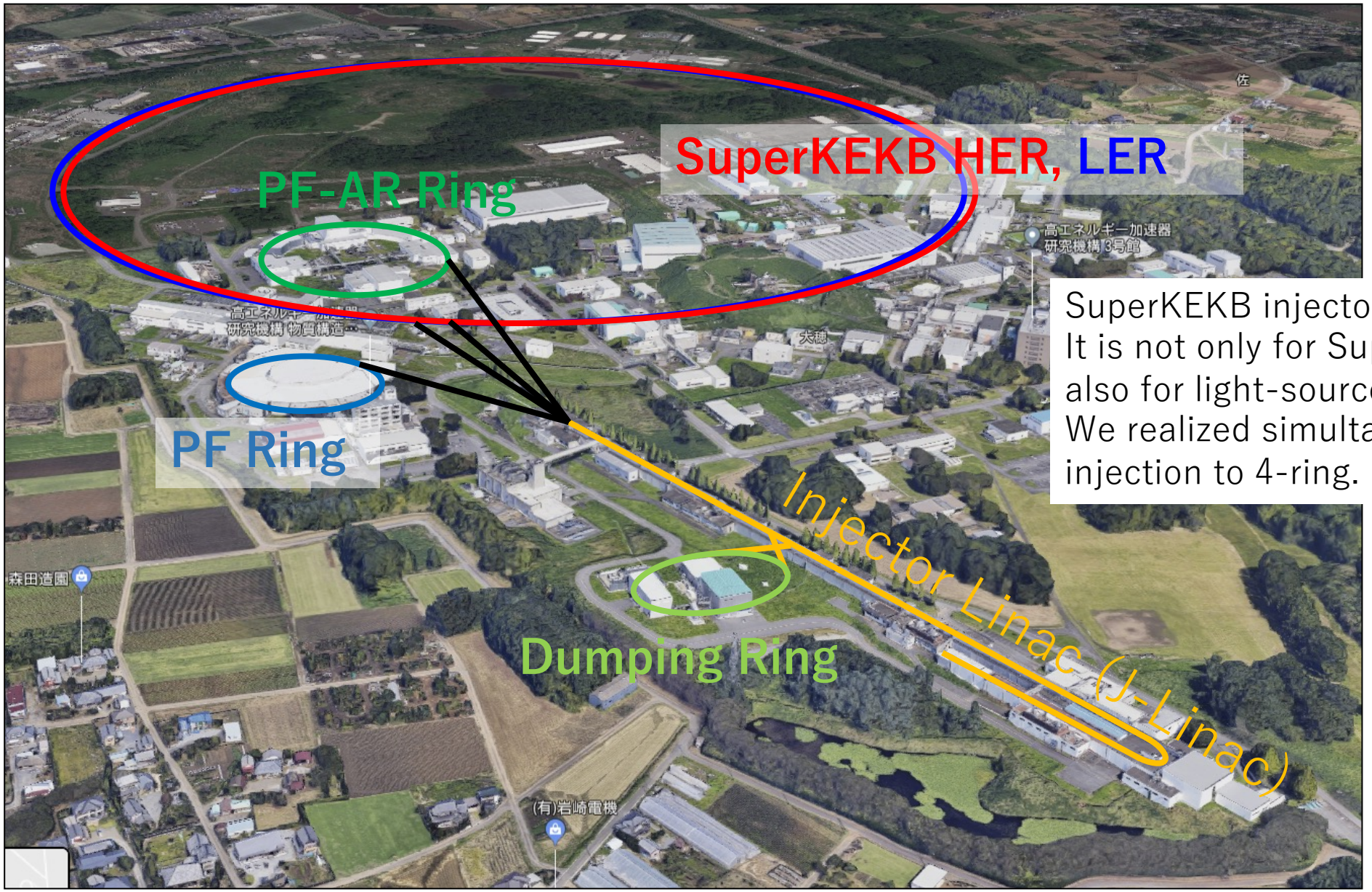
KEK e+/e- Injector Linac

Takuya Natsui

KEK

Introduction of KEK LINAC

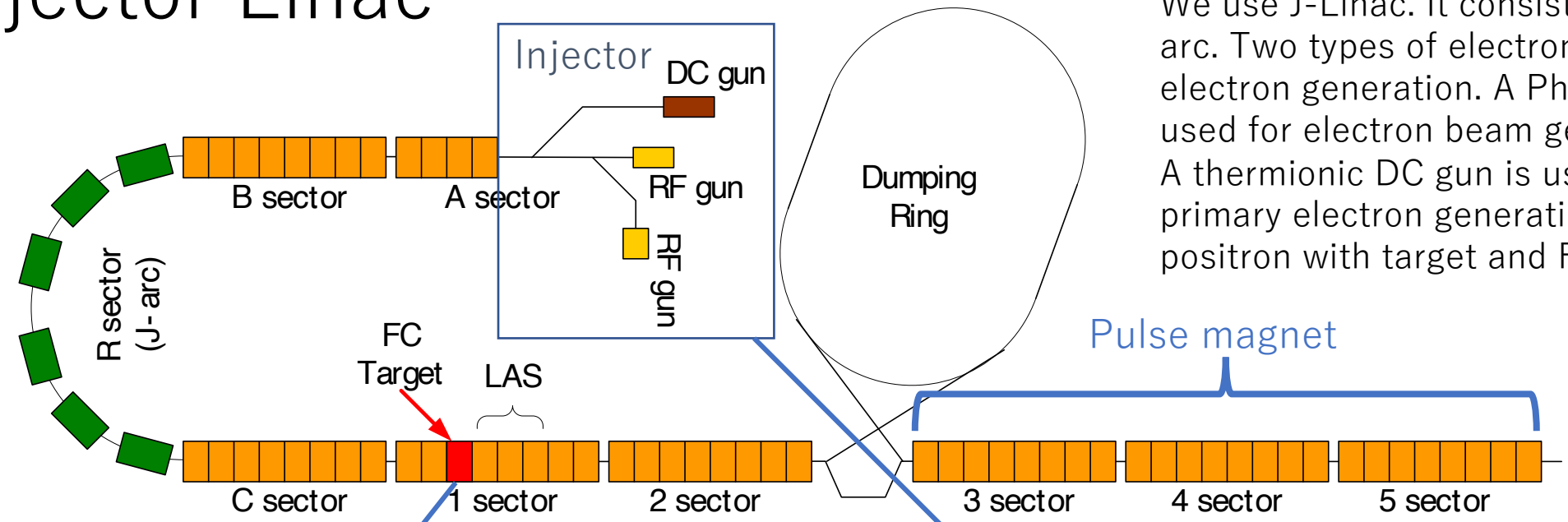
KEK Linac and 5-rings

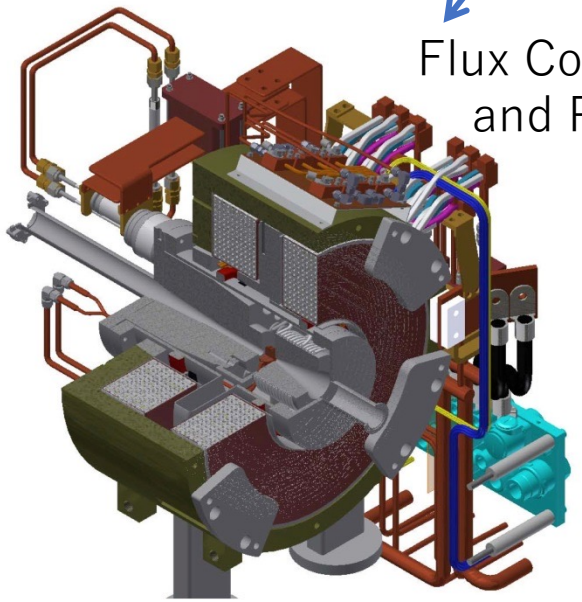


SuperKEKB injector is called J-Linac.
It is not only for SuperKEKB rings but also for light-source rings.
We realized simultaneous top-up injection to 4-ring.

Injector Linac

This is a brief introduction to an injector linac. We use J-Linac. It consists of 8 sectors and J-arc. Two types of electron guns are used for electron generation. A Photocathode RF gun is used for electron beam generation.
A thermionic DC gun is used for positron primary electron generation. It is converted to positron with target and Flux Concentrator.





Flux Concentrator (FC)
and Positron Target

Thermionic DC Gun

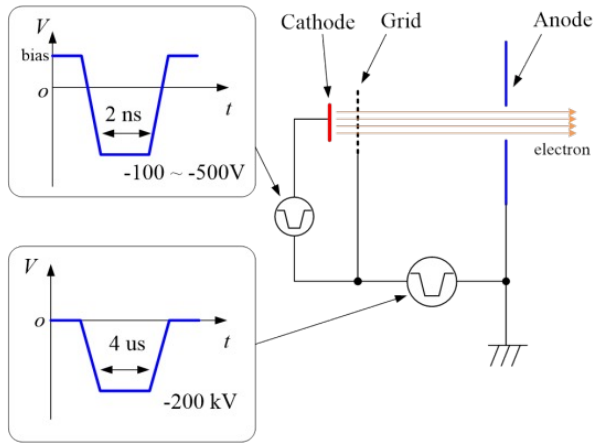
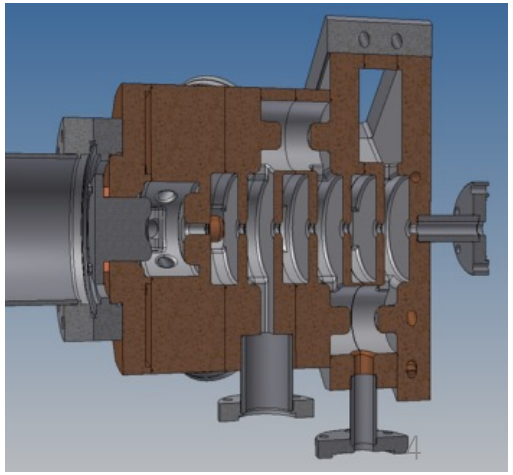
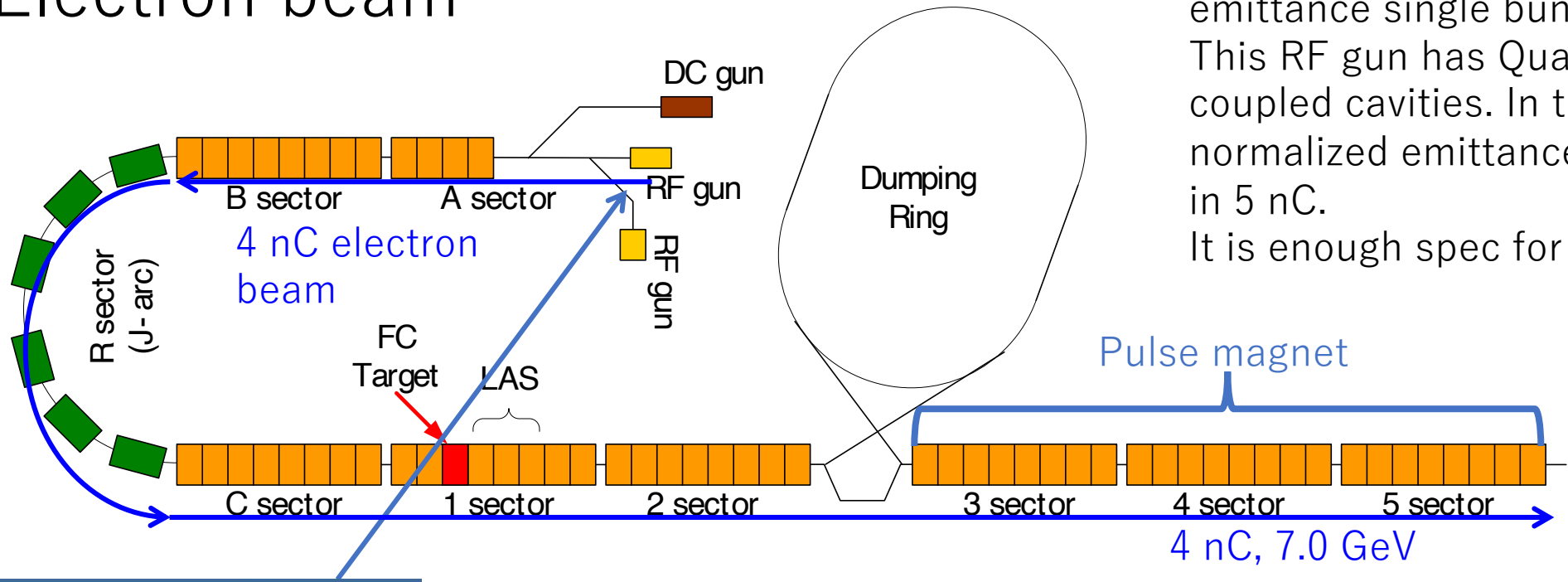


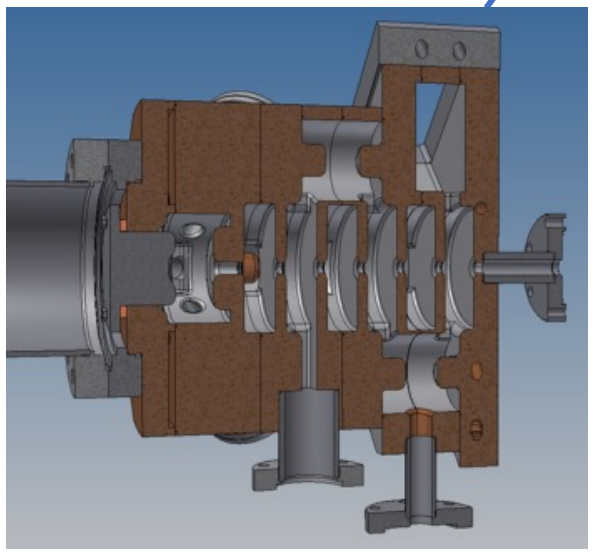
Photo cathode RF gun

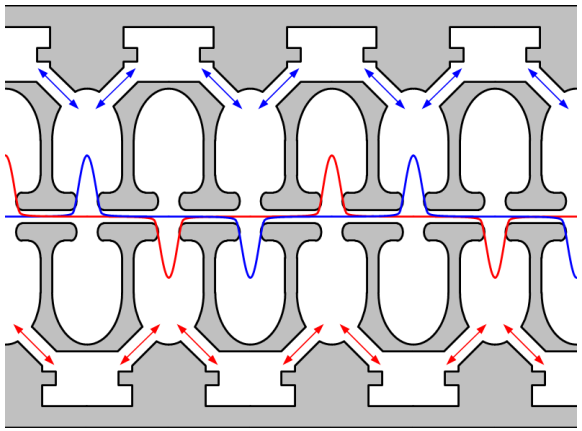


Electron beam

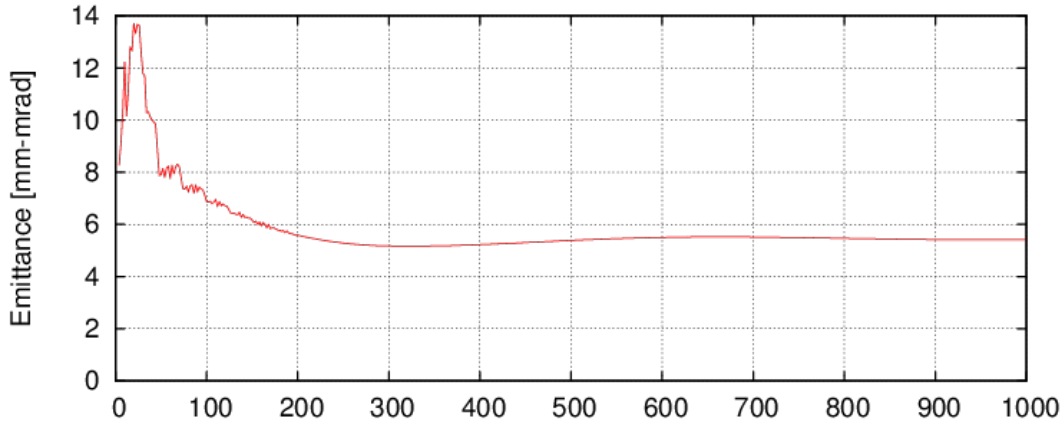
RF gun and laser system generates low emittance single bunch beam.
This RF gun has Quasi-traveling-wave side coupled cavities. In the simulation, normalized emittance is under 6 mm-mrad in 5 nC.
It is enough spec for SuperKEKB.





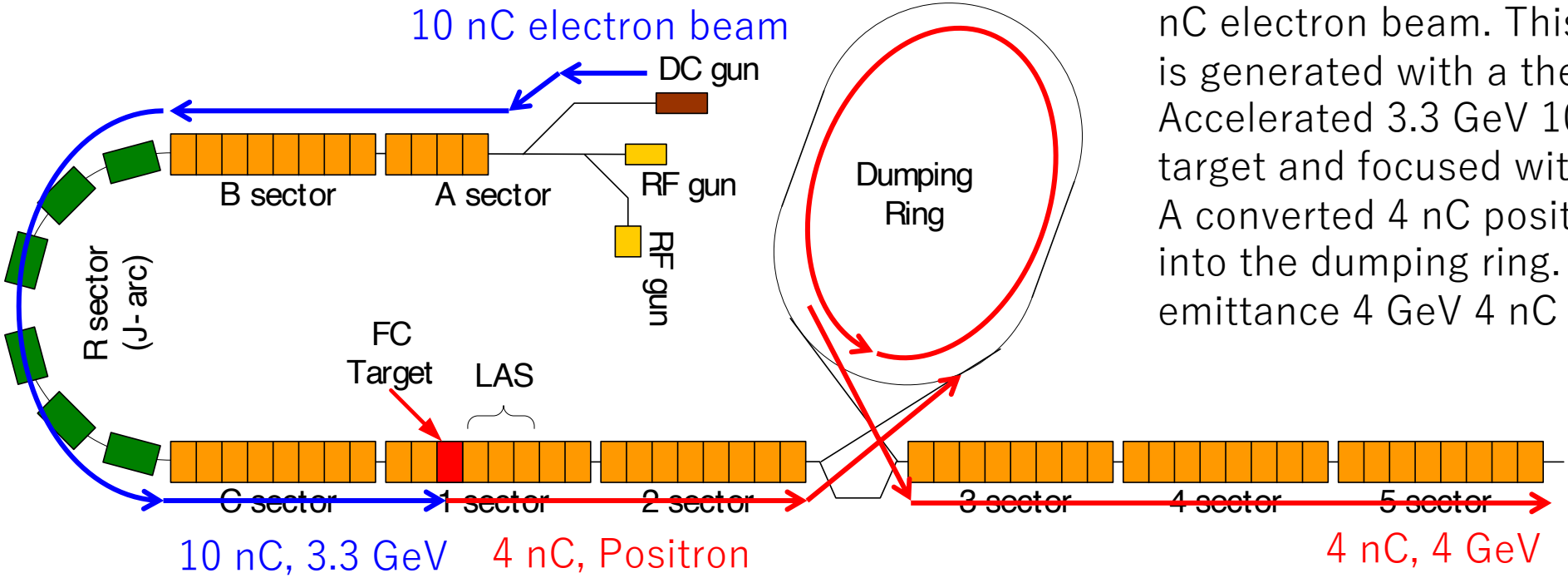


Quasi-traveling wave side coupled cavities

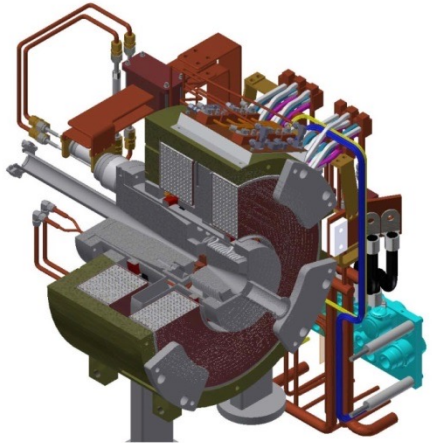


Emittance is 6 mm-mrad in simulation

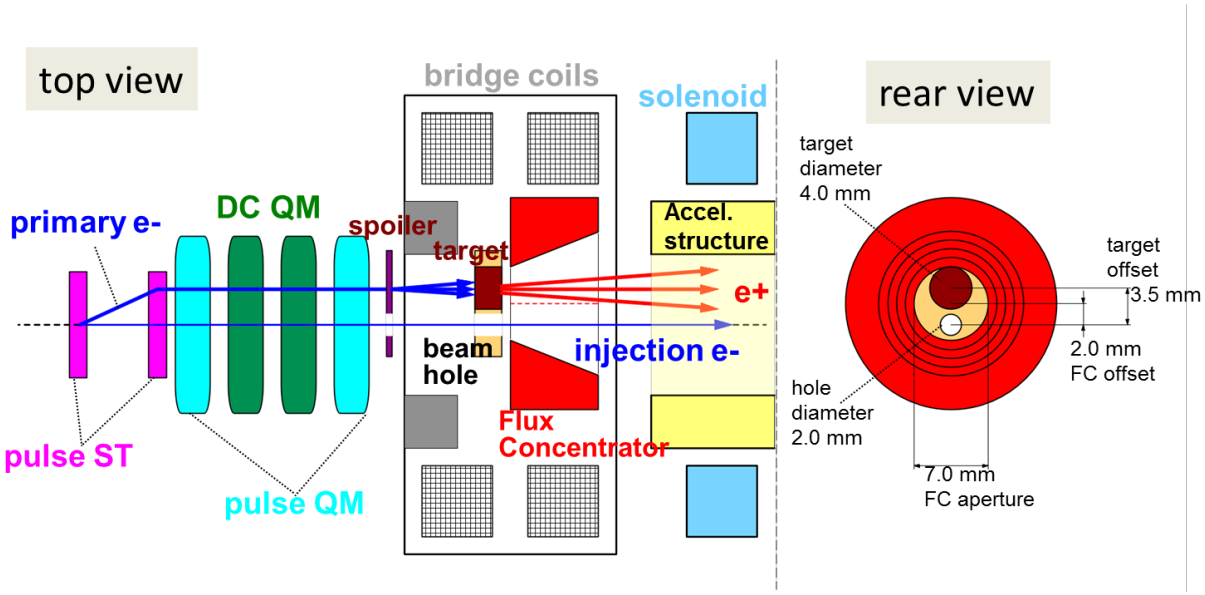
Positron beam



The positron beam is converted from a 10 nC electron beam. This 10 nC electron beam is generated with a thermionic DC gun. Accelerated 3.3 GeV 10 nC electron hit the target and focused with Flux Concentrator. A converted 4 nC positron beam is injected into the dumping ring. Finally, a low emittance 4 GeV 4 nC positron is generated.

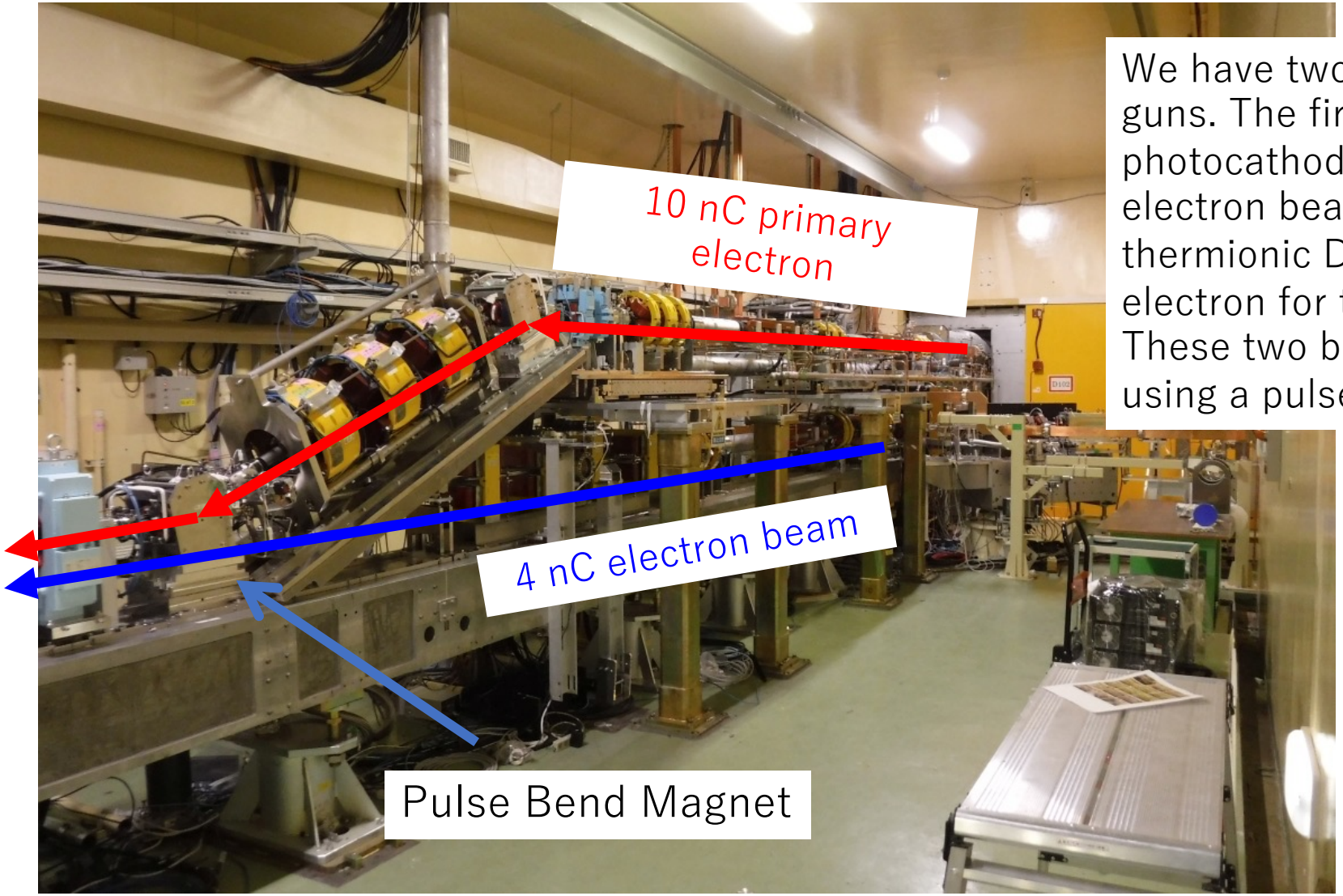


Flux Concentrator(FC), Positron target



Injector line

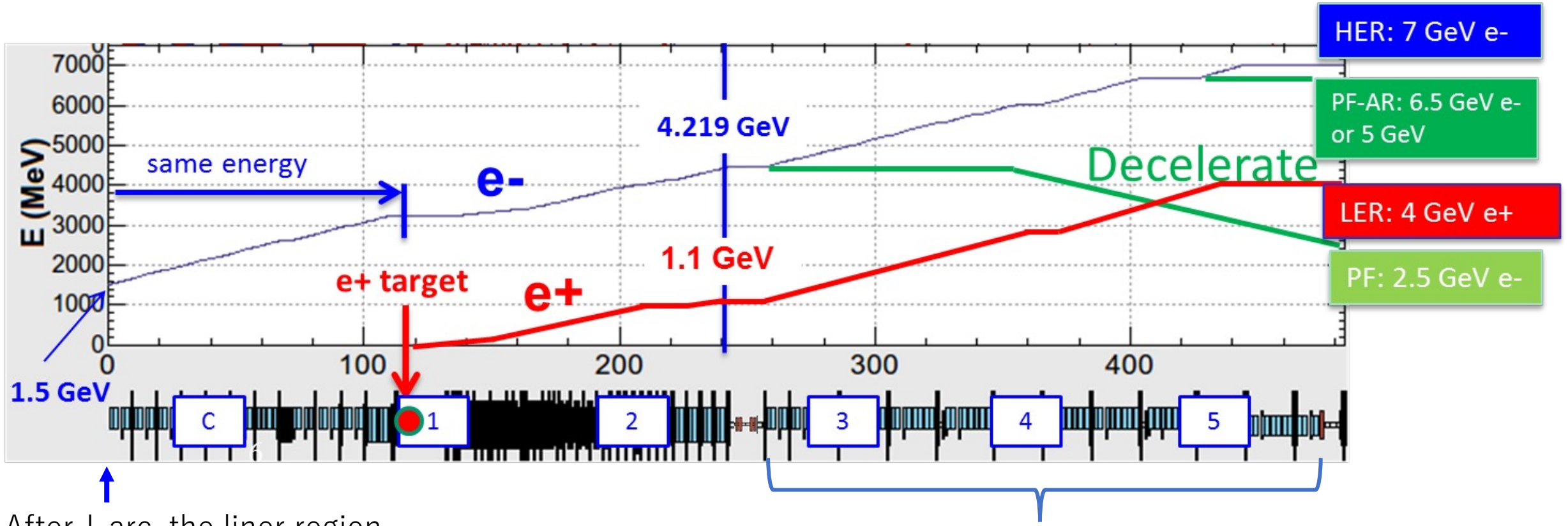
We have two lines in the injector sector for positron and electron beam.



We have two types of electron guns. The first one is a photocathode RF gun for HER electron beam. Another one is a thermionic DC gun for a primary electron for the LER positron beam. These two beam lines merged by using a pulse bending magnet.

Several energy beam generation on the same beamline.

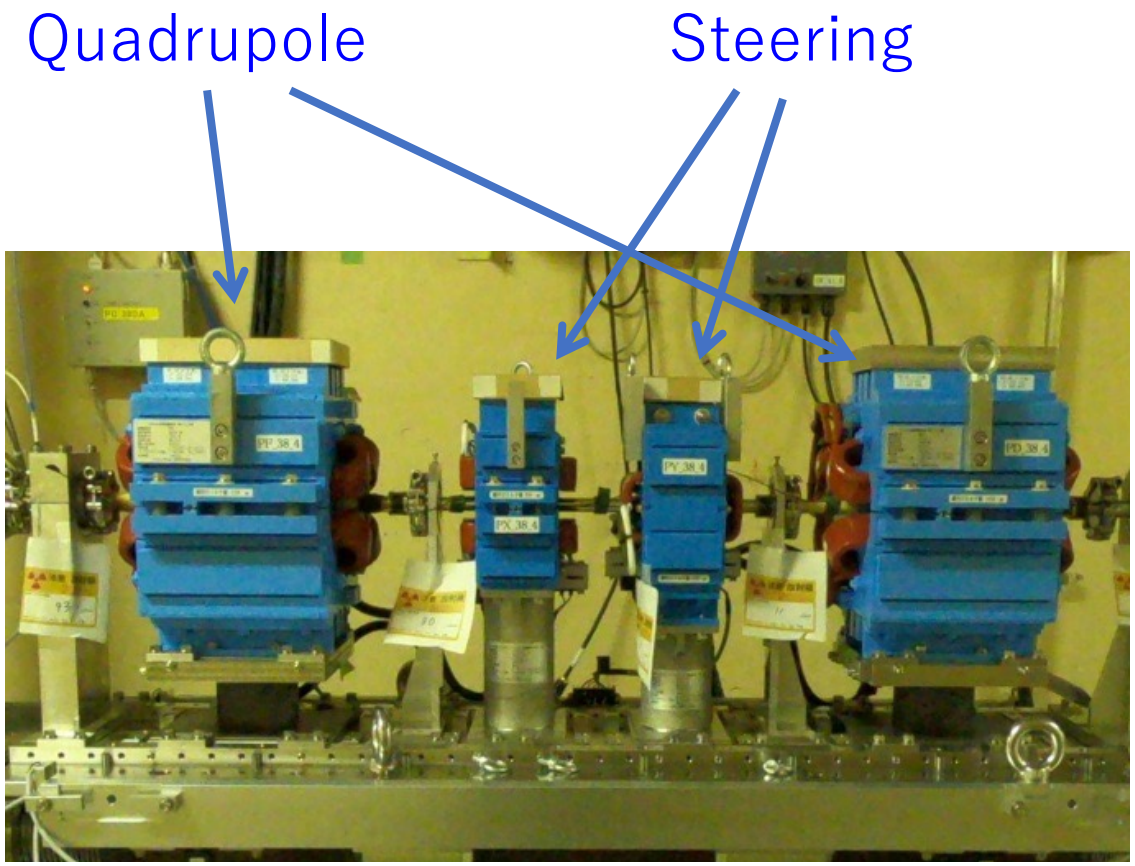
The KEK LINAC feeds beams to 4-rings, the beam parameters are totally different. Since the energy is split in the downstream part of the beamline, we must use different optics for each beam.
To achieve the simultaneous top-up injection, We use a pulsed magnet.



After J-arc, the liner region

We use pulse magnets
(quadrupole and steering magnet)

Pulse quadrupole magnet and steering magnet



Typical magnet set at 3-5 sector of LINAC

Quadrupole magnet

Parameter	spec
Reputation	50 pps
Max. Pulse Current	300 A
Max. Average Current	100 A
Max. Field Gradient	60 T/m
Bore diameter	20 mm

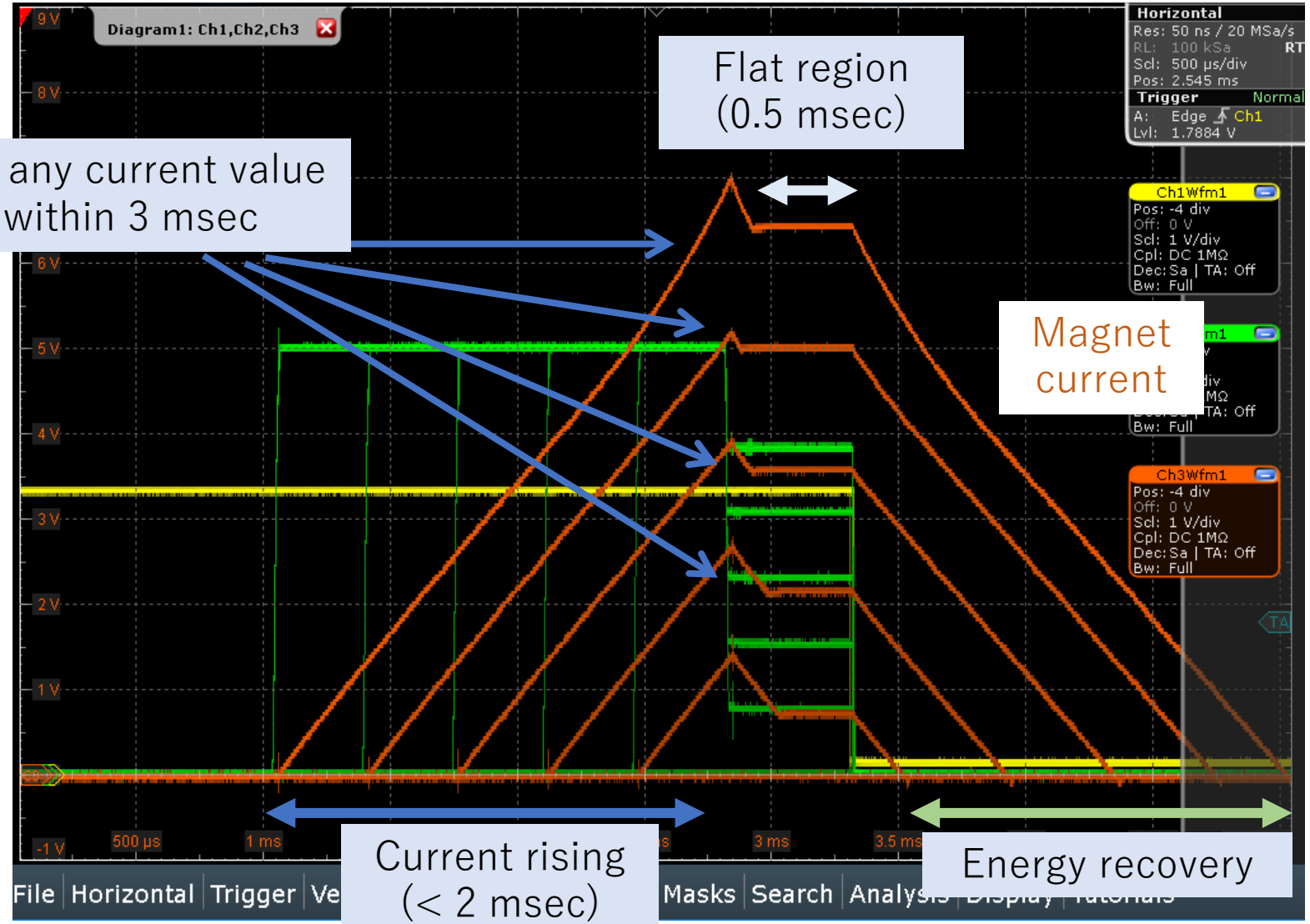
Steering magnet

Parameter	spec
Reputation	50 pps
Max. Pulse Current	10 A
Max. Field strength	44.3 mT
Pole gap	20 mm
Pole length	80 mm

Pulse Q magnet driver

Magnet driver

We developed a pulse magnet driver. The maximum current is 300 A at 50 pps. This is an energy recovery type. We can change optics at 50 pps by using the driver and magnets.



Pulse Q magnet current

Current beam status and commissioning

1. Electron beam for HER
2. Positron beam for LER

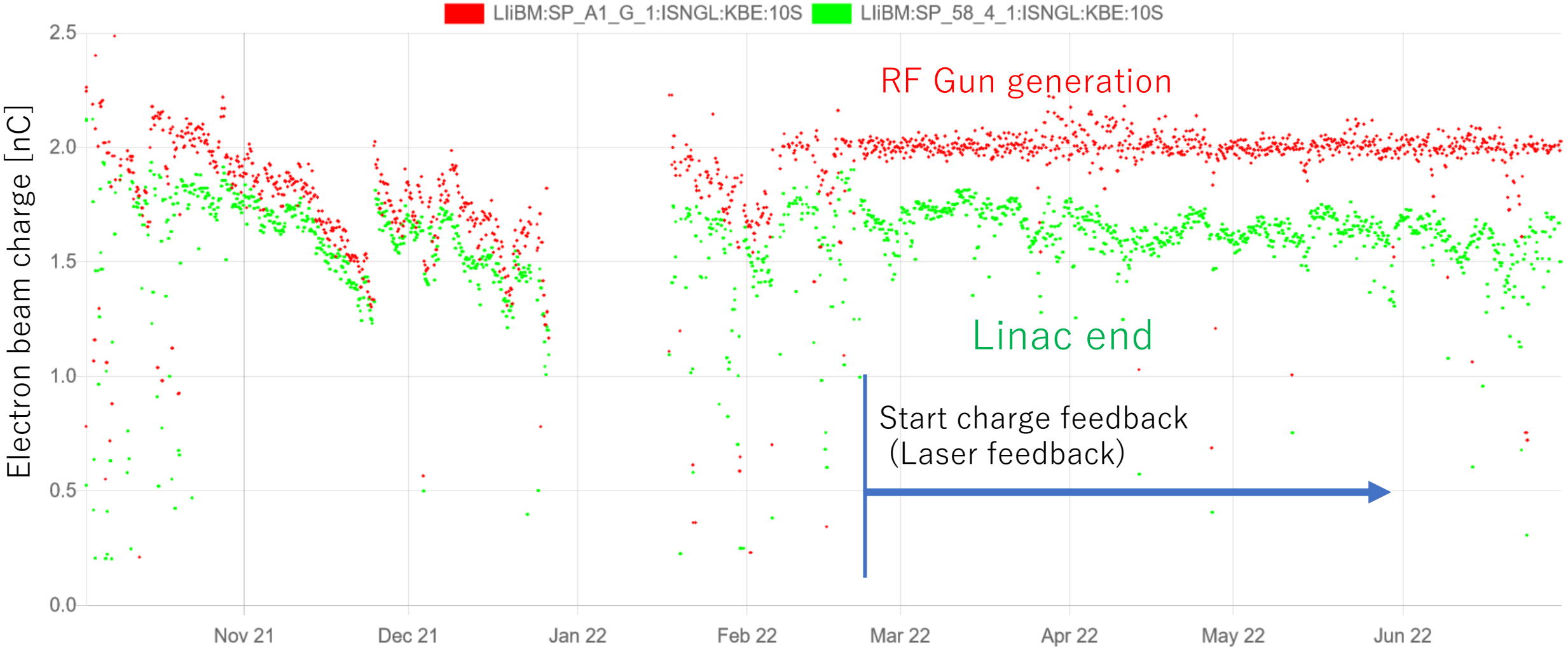
Linac beam status for SuperKEKB

	2022ab		Final goal	
Beam	e+	e-	e+	e-
Energy	4.0 GeV	7.0 GeV	4.0 GeV	7.0 GeV
Bunch charge 1st , 2nd [nC]	3.0 , 2.5	2.0 , 1.5	4.0, 4.0	4.0, 4.0
Normalized emmittance [mm-mrad]	120, 5 (Hor. , Ver.)	50-20, 50-20 (Hor. , Ver.)	100, 15 (Hor. , Ver.)	40, 20 (Hor. , Ver.)
Simultaneous top-up injection	4+1 rings (LER, HER, DR, PF, PF-AR)		4+1 rings (LER, HER, DR, PF, PF-AR)	

This is the beam status of the final goal and current status. The energy was set to require value. The beam charge is still not achieved. But it was almost enough in 2022b. Emittance was improved step by step. Simultaneous injection to 4 rings and dumping ring is already achieved.

History of electron beam charge injection to HER

One-year history except for the summer shutdown.



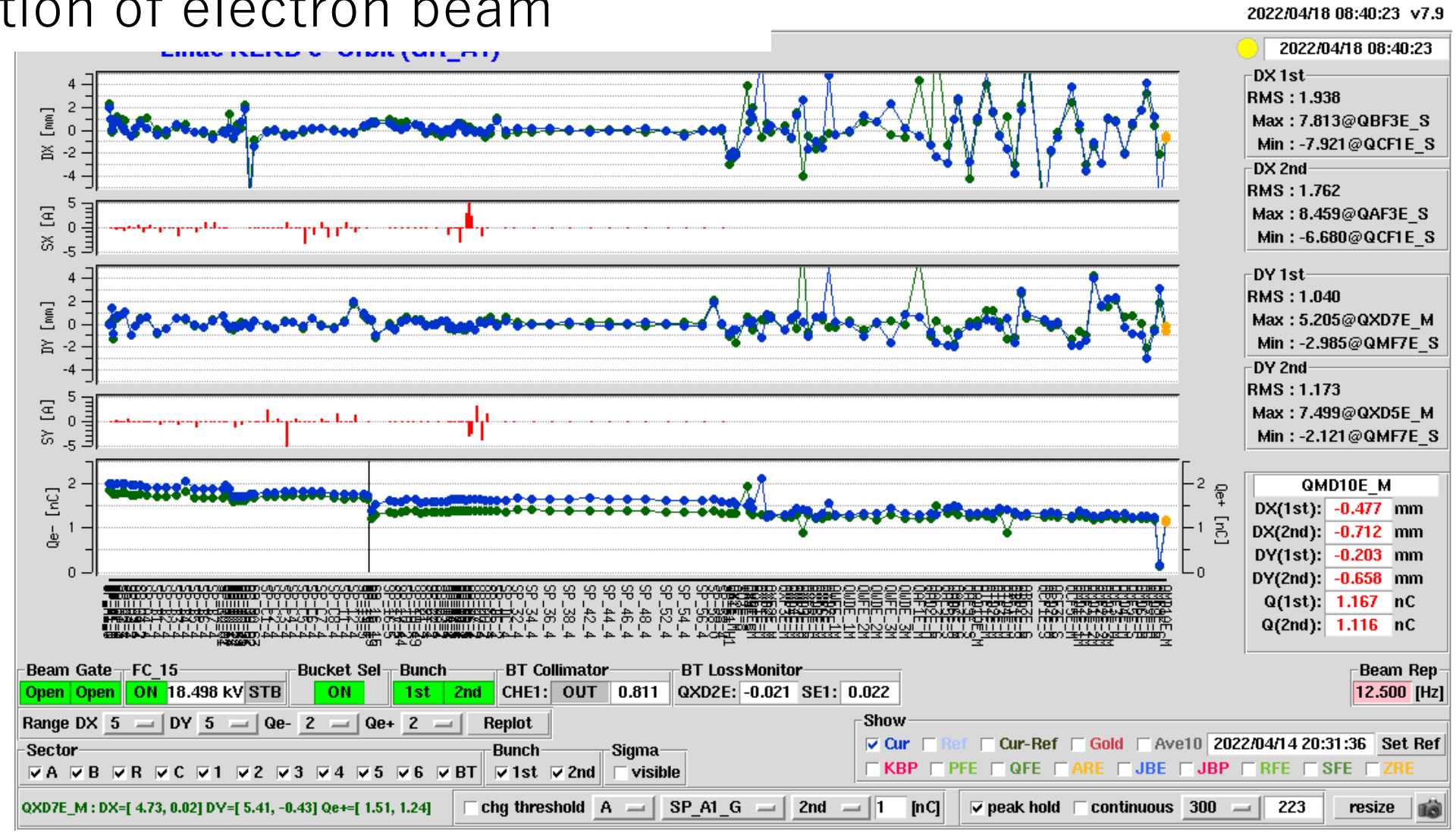
2022, stable 2 nC beam generation was achieved with a laser feedback system.
The amount of charge is almost enough current situation. But sometimes required to increase the charge. We have to increase the beam charge for the next SuperKEKB operation.

2 bunch operation of electron beam

Horizontal orbit

Vertical orbit

Charge

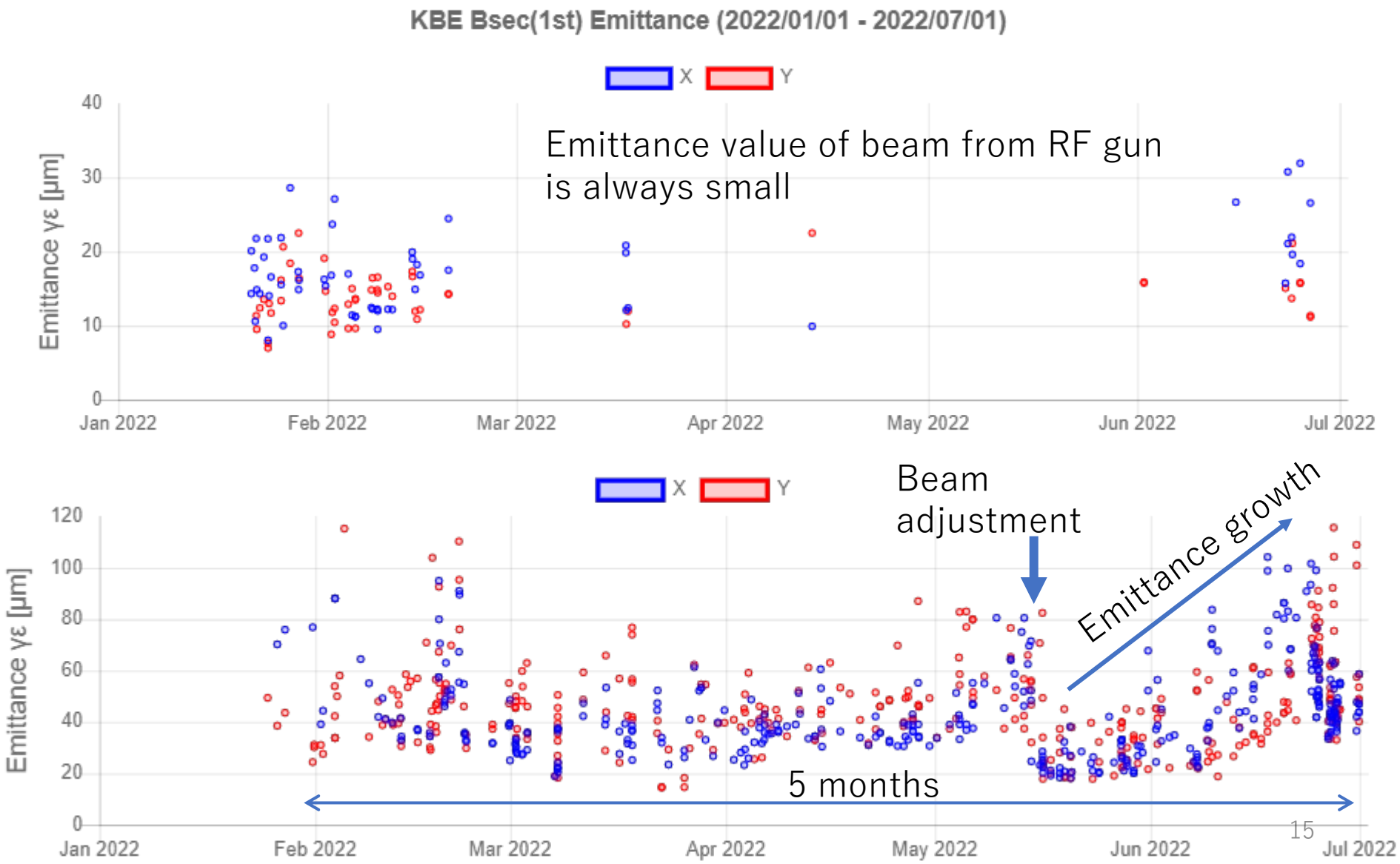


Sometimes we try 2-bunch operation.
But the injection rate is not so good. We use 1 bunch operation as usual.
Beam orbit seems good. But emittance value or energy spread is not so good, maybe.
2-bunch operation is one of the problems to be solved in the next operation term.

Long-term emittance value drifts due to emittance growth in Linac.

RF gun generation

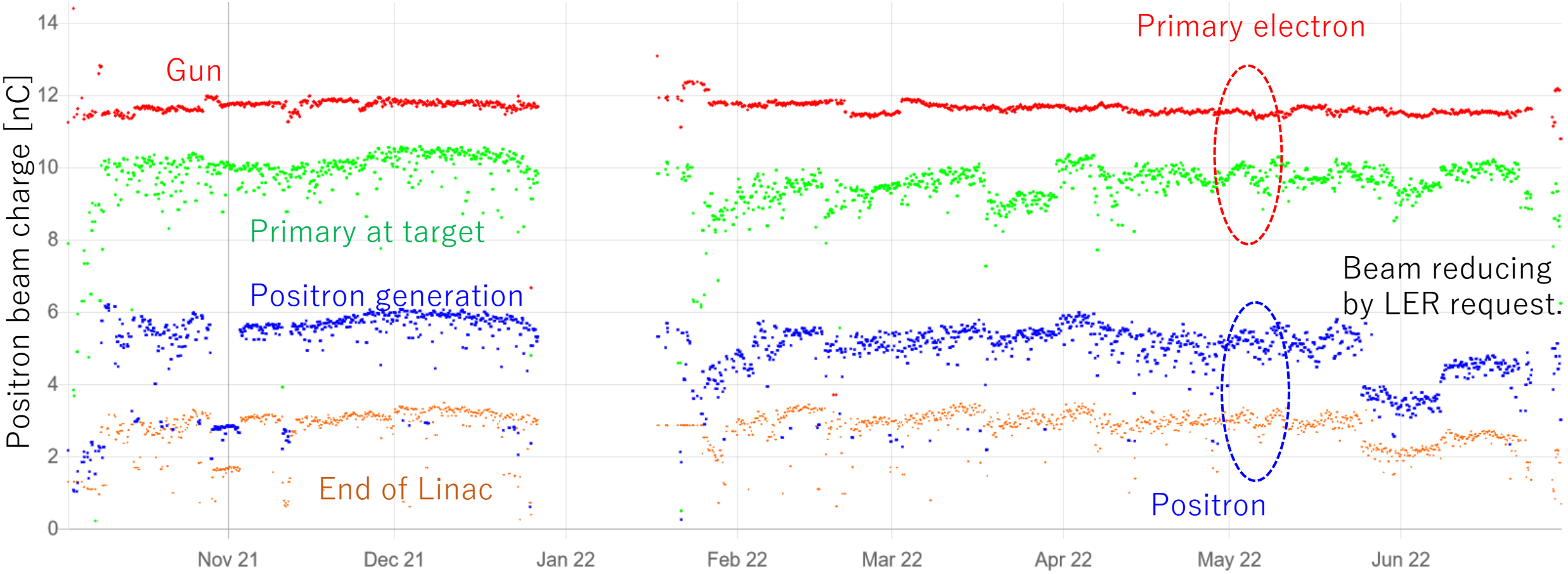
End of Linac



The measured emittance is meet the required value just after a beam adjustment. But the value increases gradually.

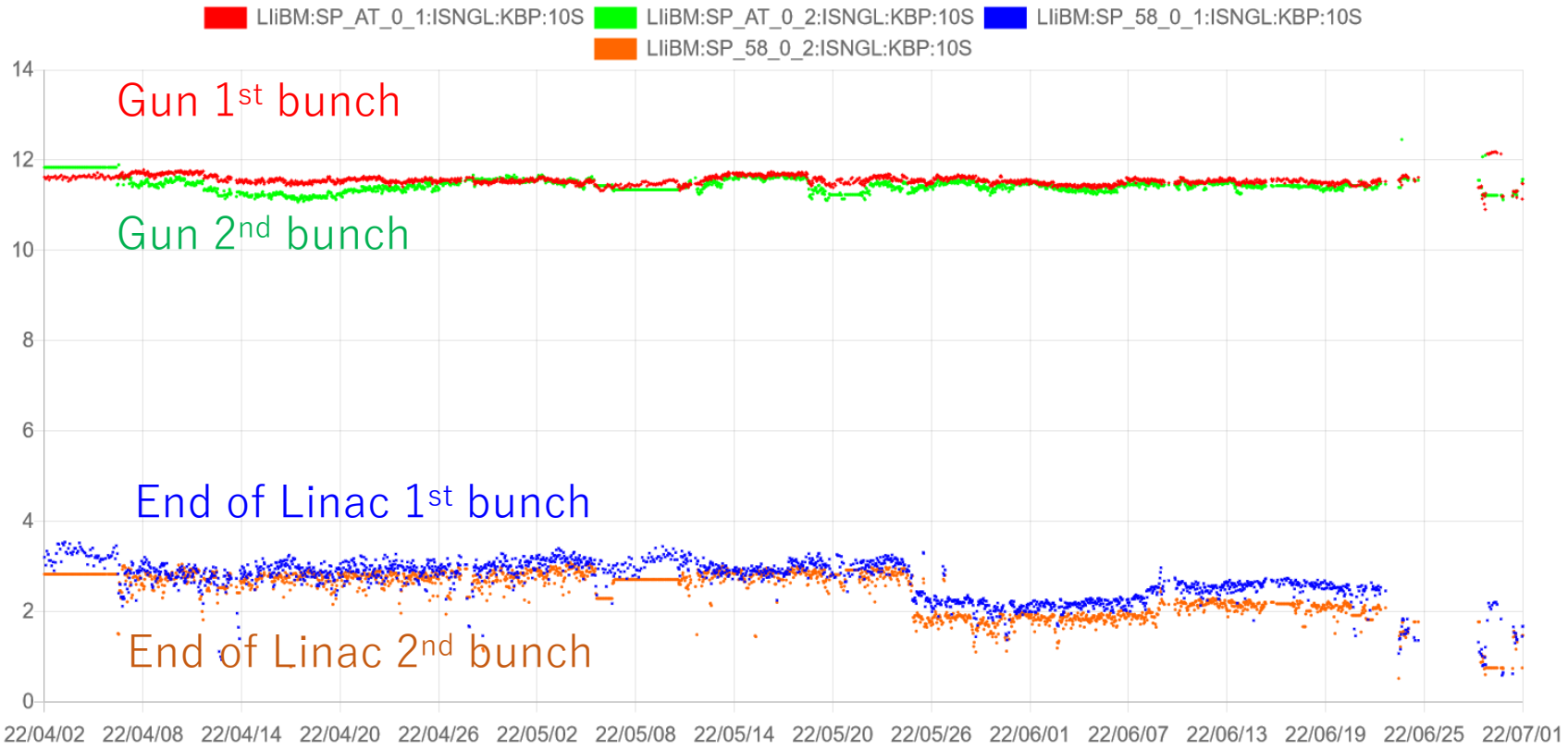
History of the positron beam generation

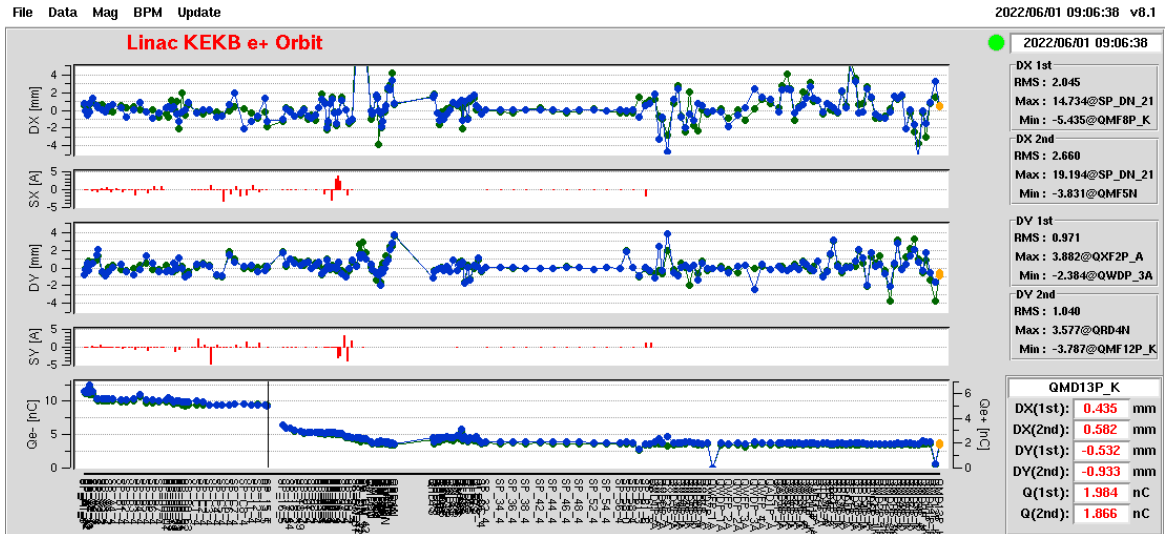
One-year history except for the summer shutdown.



We achieved a 3.5 positron beam generation. It is almost the target value.

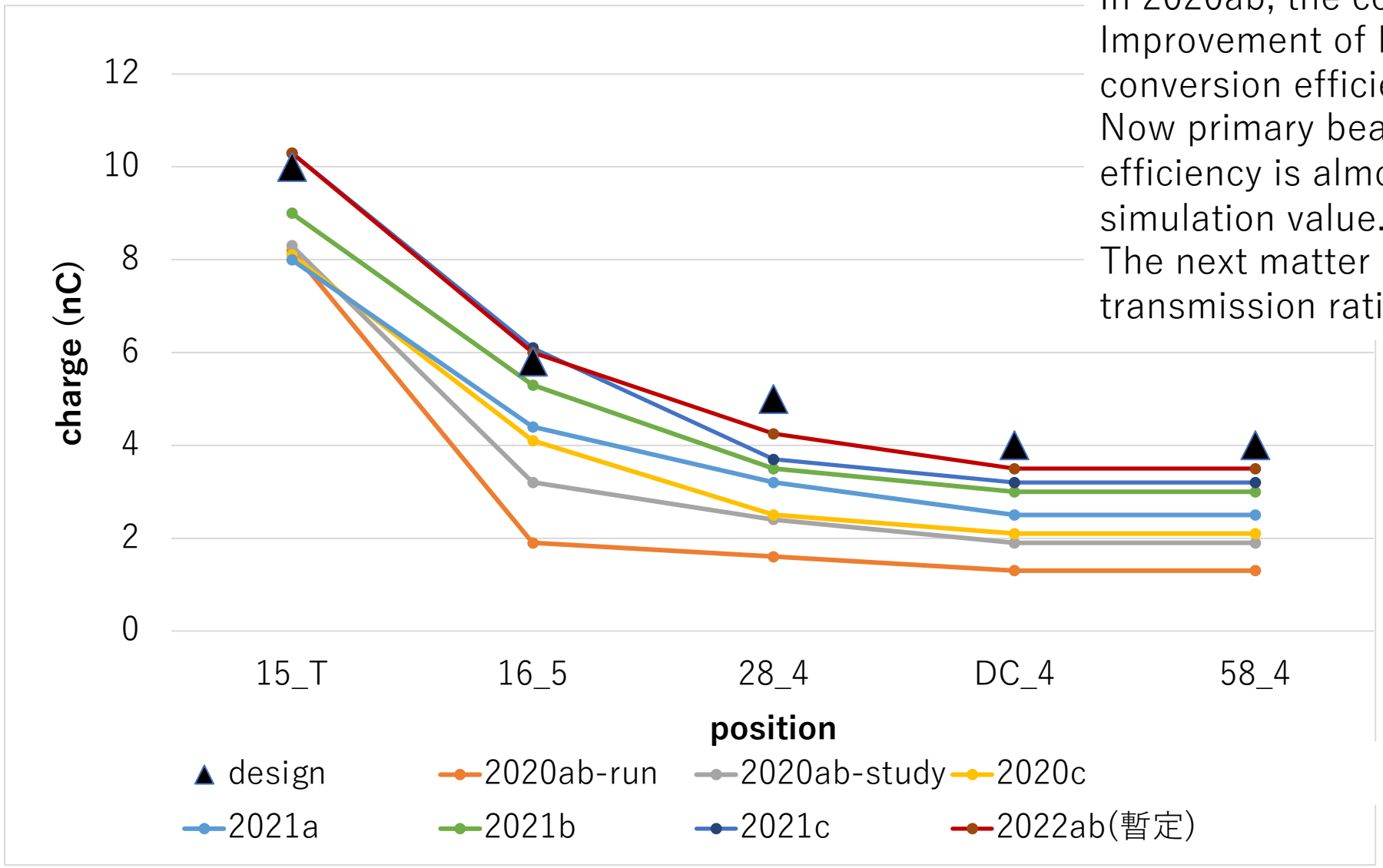
Two bunches operation history of KBP





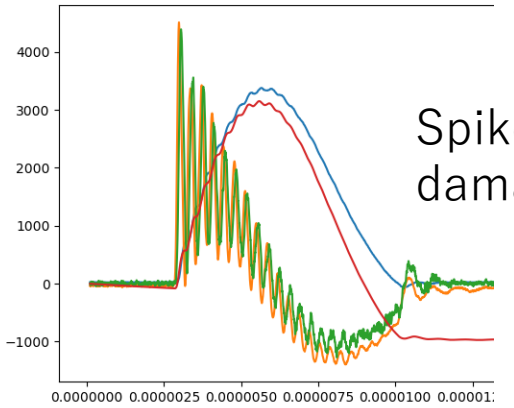
We succeeded in the two bunches operation for KBP.
2nd bunch charge is almost the same as 1st bunch charge.
We could maintain a stable two bunches injection to LER.

Long-term (a few years) charge history of positron(KBP) beam

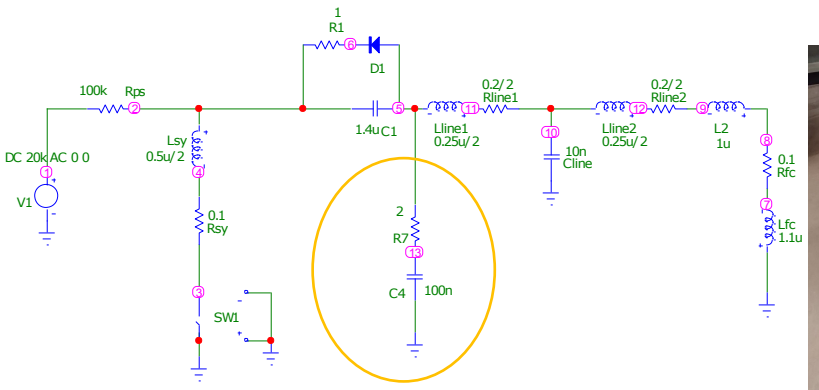


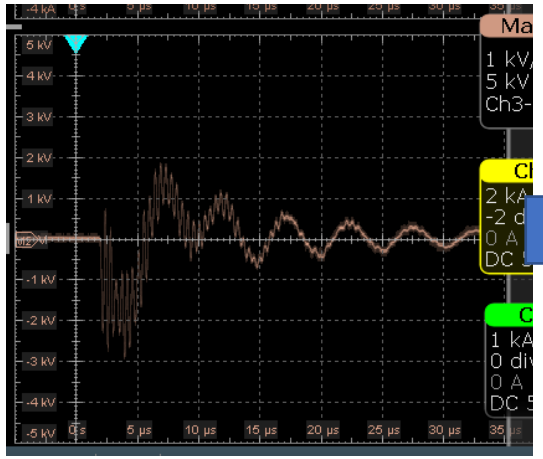
In 2020ab, the conversion efficiency is lower.
Improvement of FC was getting an increase in conversion efficiency.
Now primary beam is over 10 nC, conversion efficiency is almost the same as the simulation value.
The next matter is how to increase the transmission ratio.

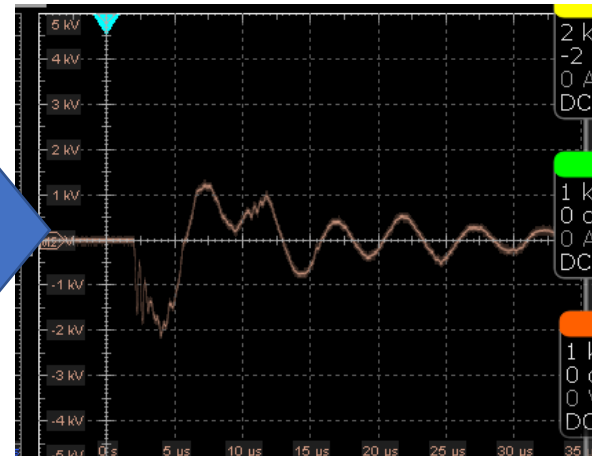
Flux concentrator (FC) improve for positron beam



Spike high voltage had been damaging to FC head

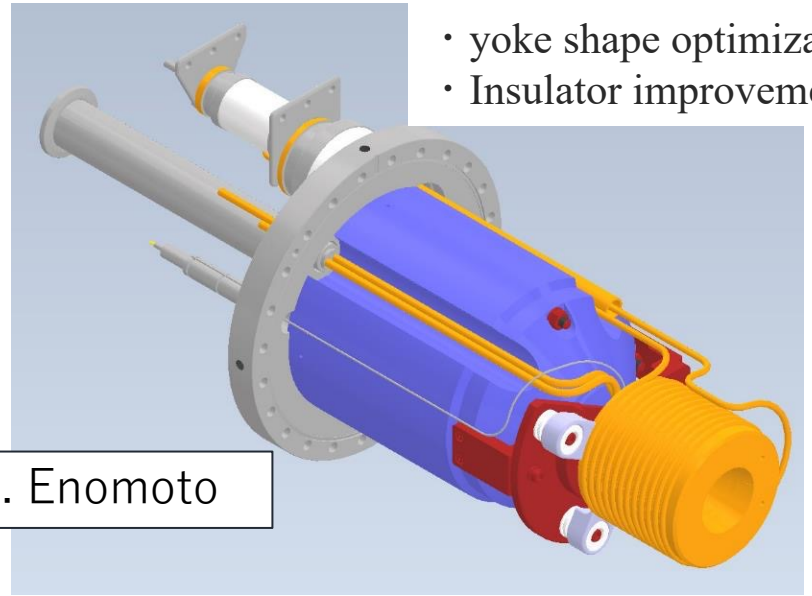






As a result of the circuit simulation, we found a modification of the modulator to reduce the spike voltage. A noise reduction circuit to the modulator was installed in 2021, enabling even more stable operation.

- yoke shape optimization
- Insulator improvement



Y. Enomoto

The new FC is very robust. It was installed in 2020. No breakdown from 2020c.

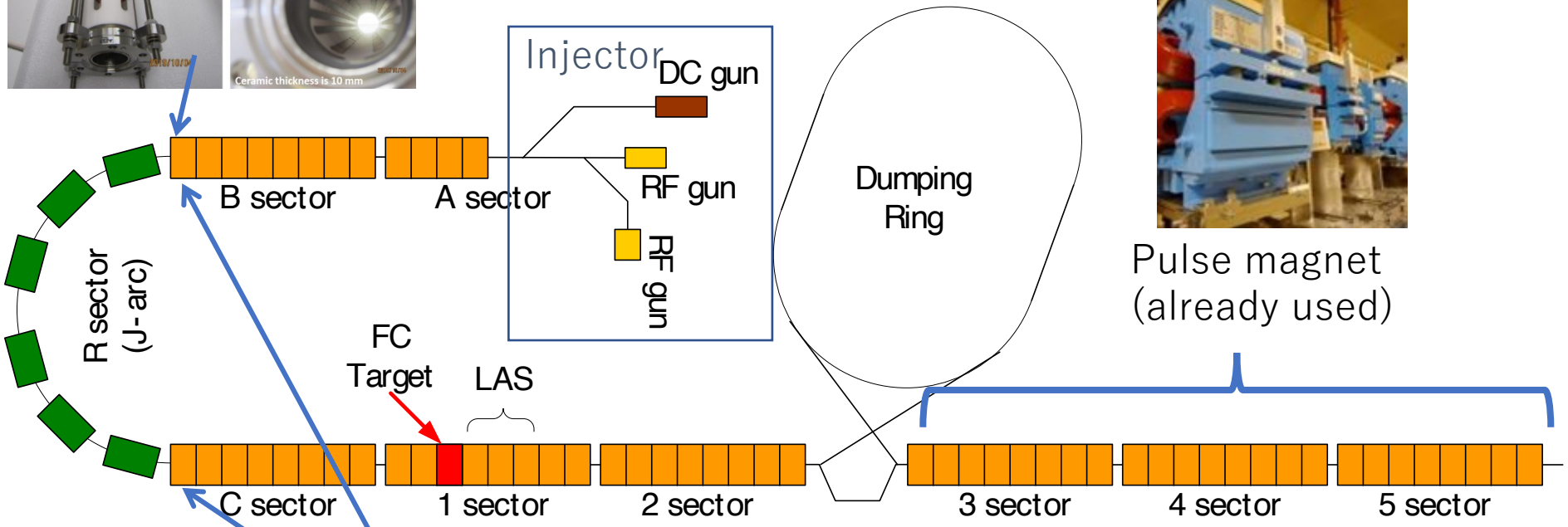
Linac Upgrade Plan 2022-2026

- Pulse magnet
- Girder Mover
- electron ECS
- RF gun
- Positron target and capture
- Acceleration structure
- High efficiency klystron

… and so on

Pulse magnet upgrade

Fast kicker



Pulse magnet
(already used)

New large pulse Q magnet and fast kicker

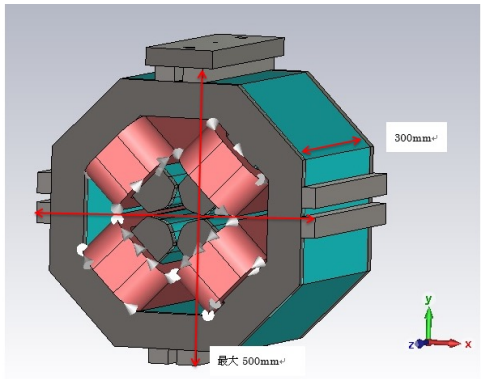
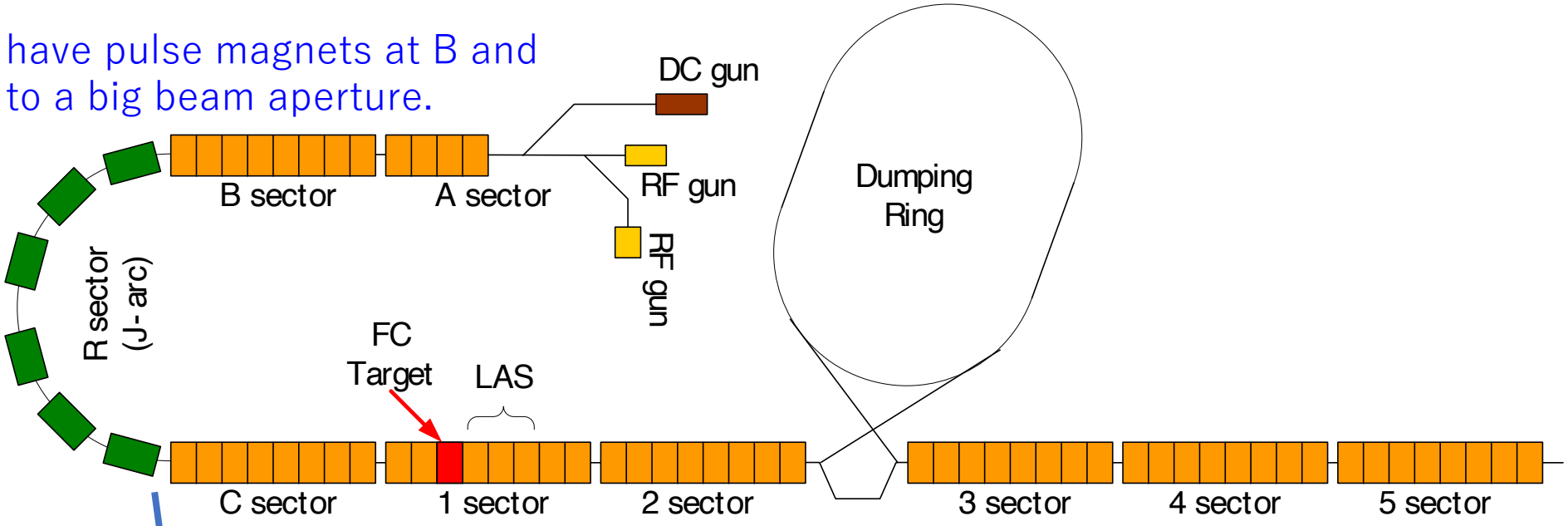
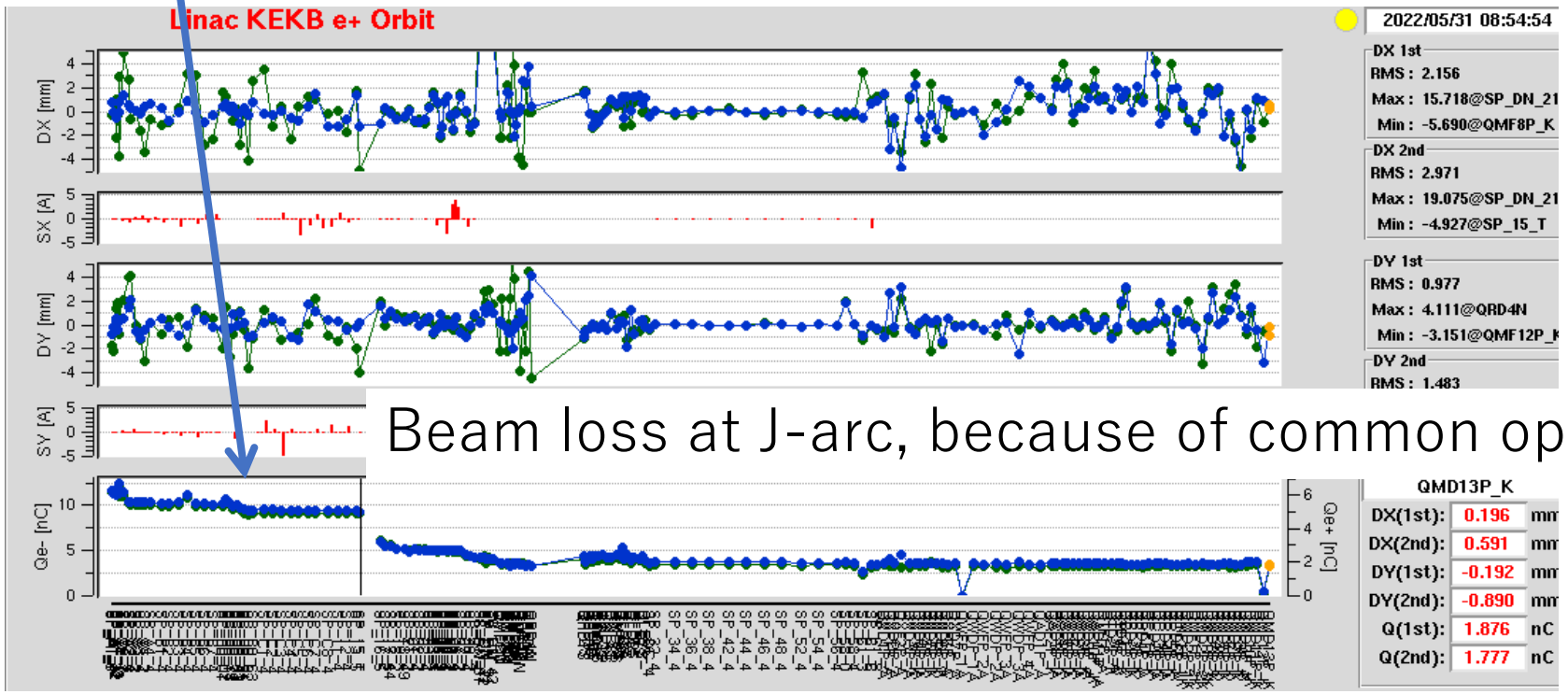


図1　外観形状案（参考図）パルス四極電磁石

We already use a pulse magnet in 3-5 sector.
But we need an additional pulse magnet at J-arc for matching with both beam of KBP and KBE

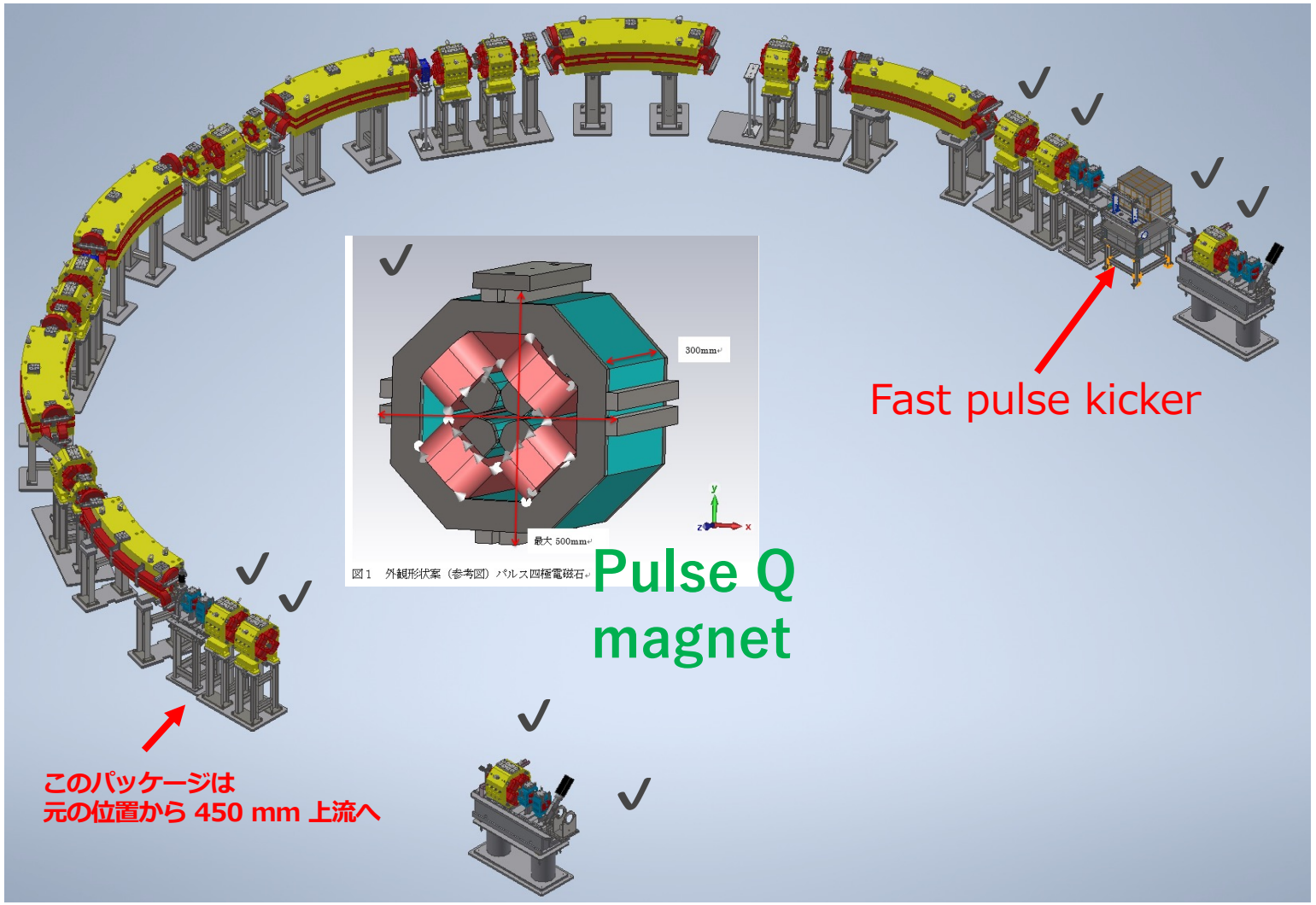
Now we don't have pulse magnets at B and C sectors due to a big beam aperture.





Beam loss at J-arc, because of common optics

8 large pulse magnets will be installed at entrance and exit of J-arc



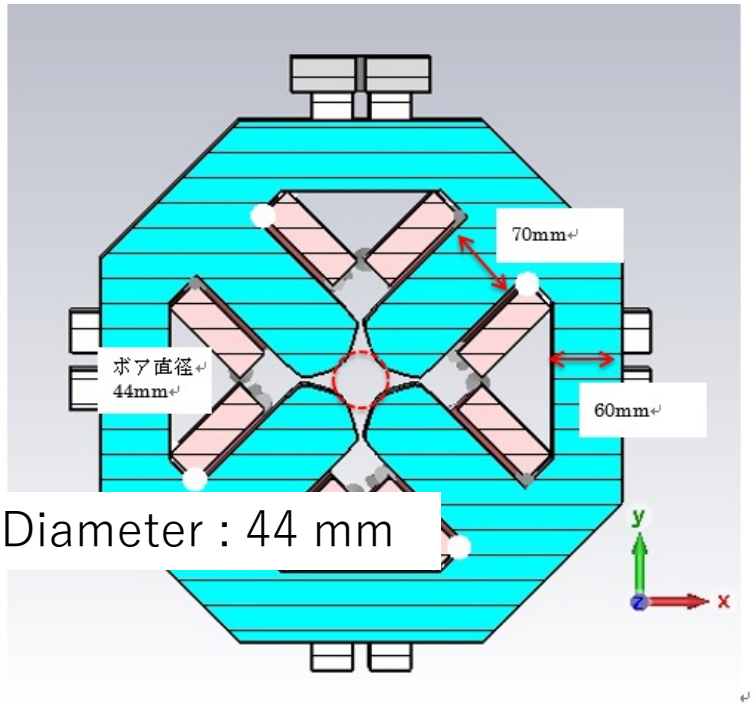
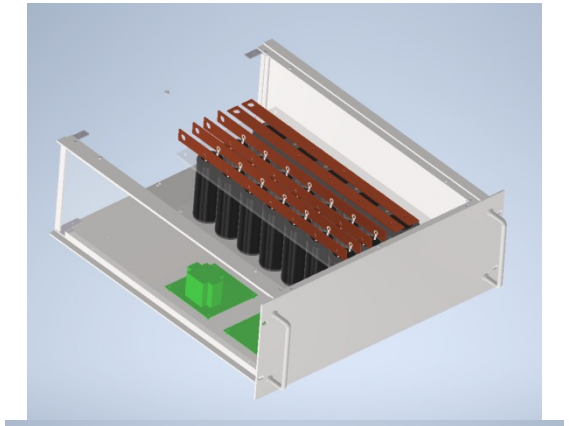


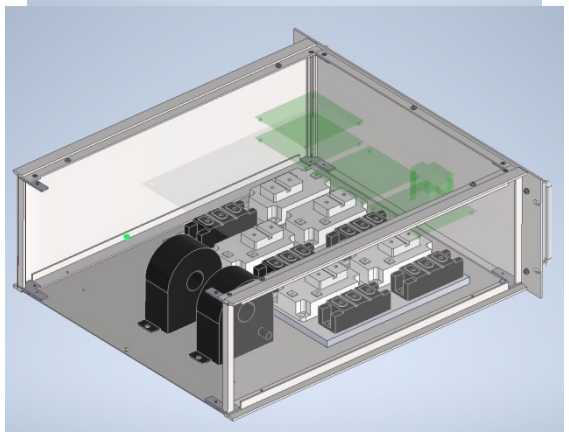
図２　断面形状（参考図）パルス四極電磁石

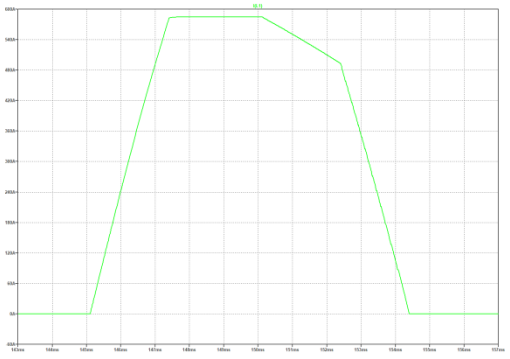
The new pulse Q magnet has a large aperture for positron primary

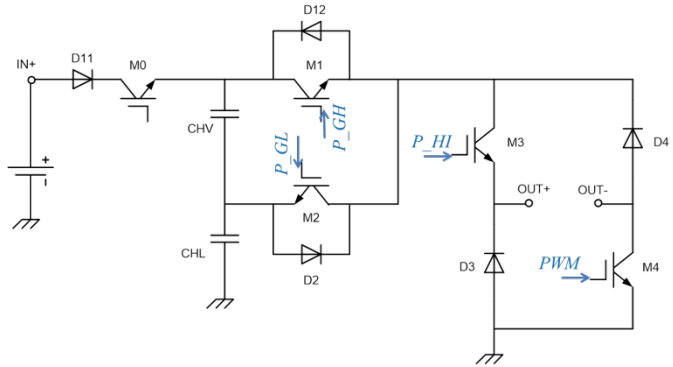
A new pulse magnet driver is also developing.

	3-5 sector type	New driver
Max Voltage [V]	230	400
Max Current [A]	330	600
Magnet inductance [mH]	1	1.5
Control method	I_D-V_{GE} analog control	PWM

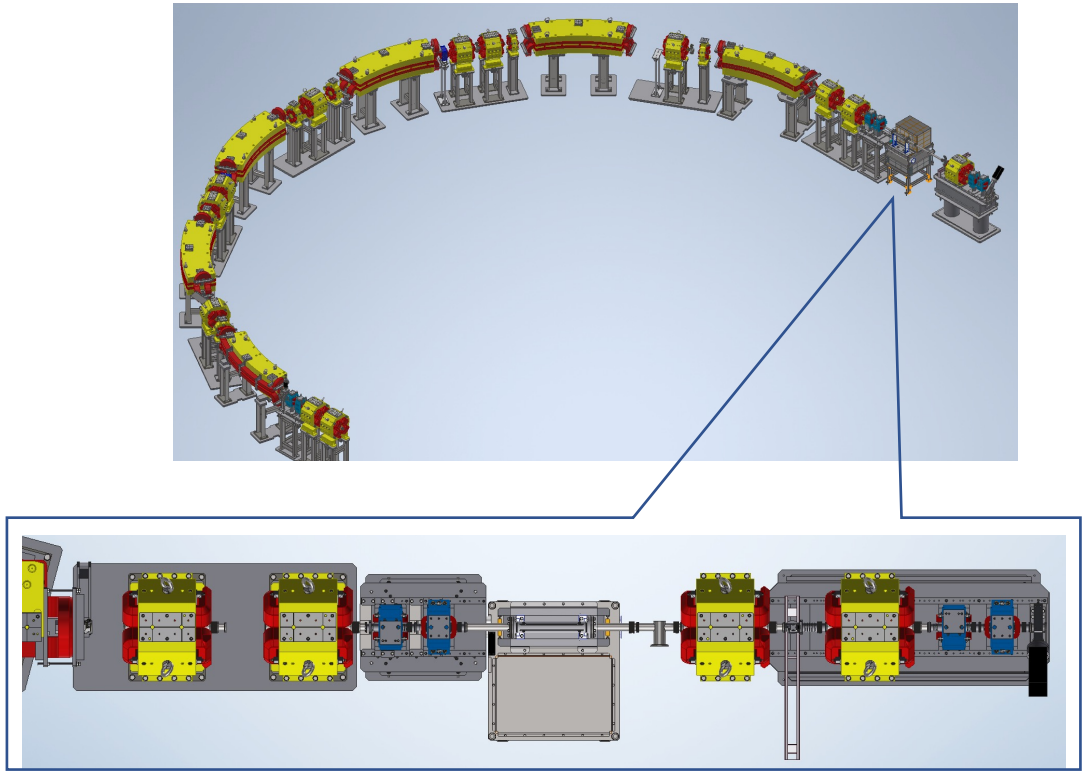


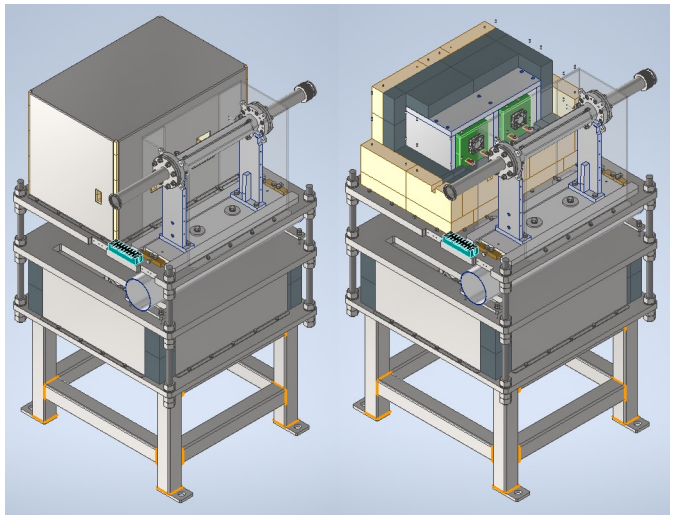






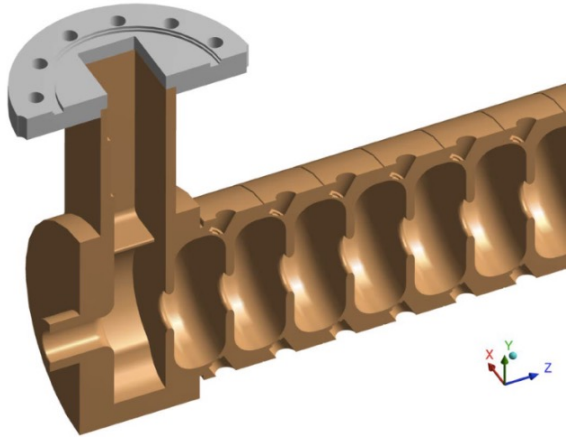
Fast kicker for 2nd bunch





Fast kicker affects only 2nd bunch. Pulse raising time must be under 96 ns. The fast kicker will be tested next operation term.

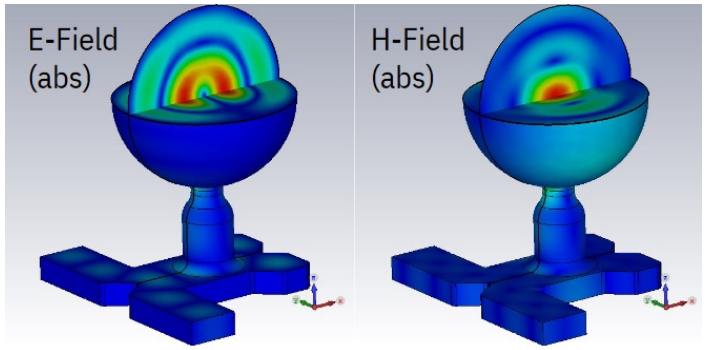
New acceleration structure

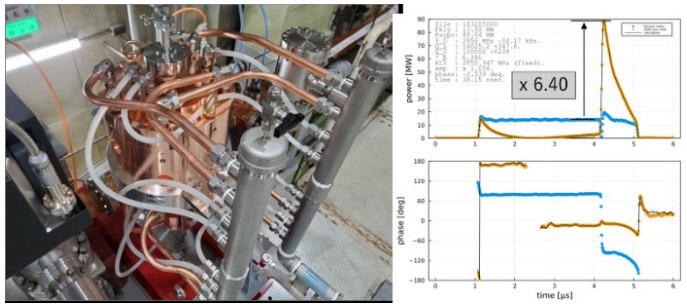


The old acceleration tube must be replaced.

New structures have higher accelerating gradient and lower surface electric field.
We will replace it with a new accelerating structure to reach a collision at the higher energy resonance of (6S).

New accelerating structure is high quality

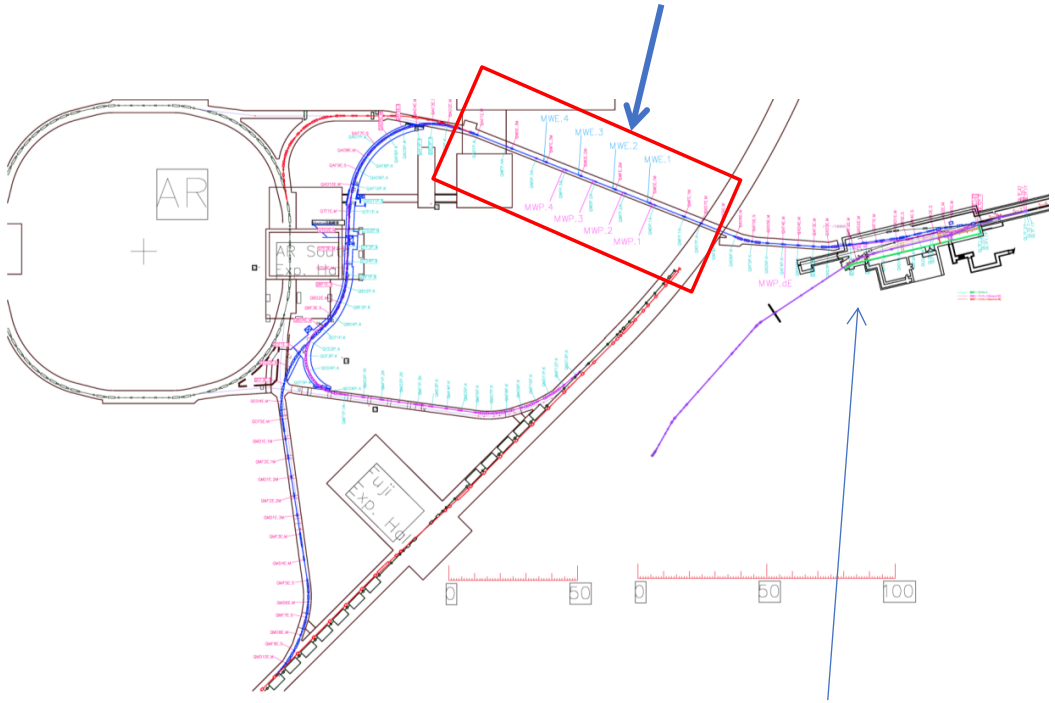




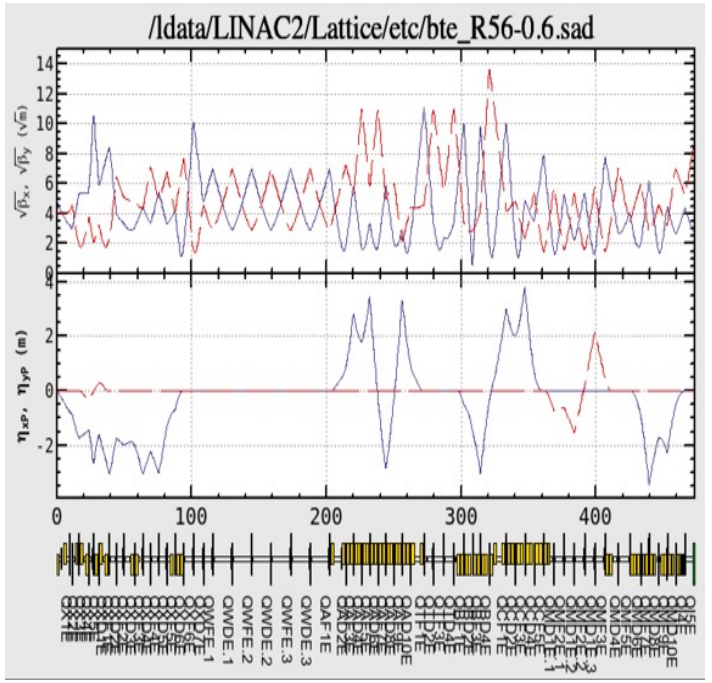
A new pulse compression system was also developed.

Energy Compression System (ECS) for electron beam

Install accelerating structure in electron BT

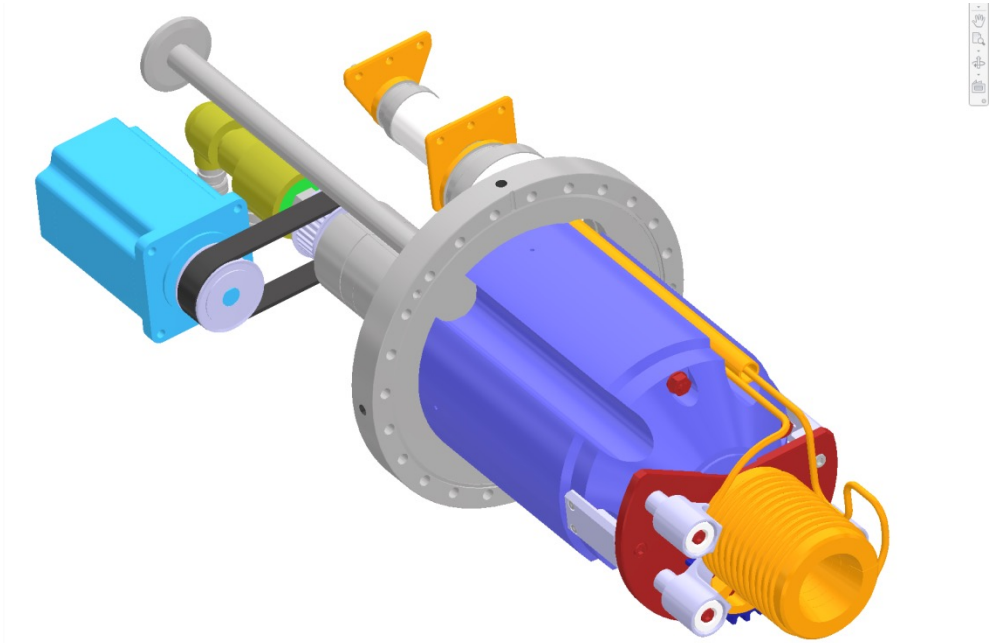


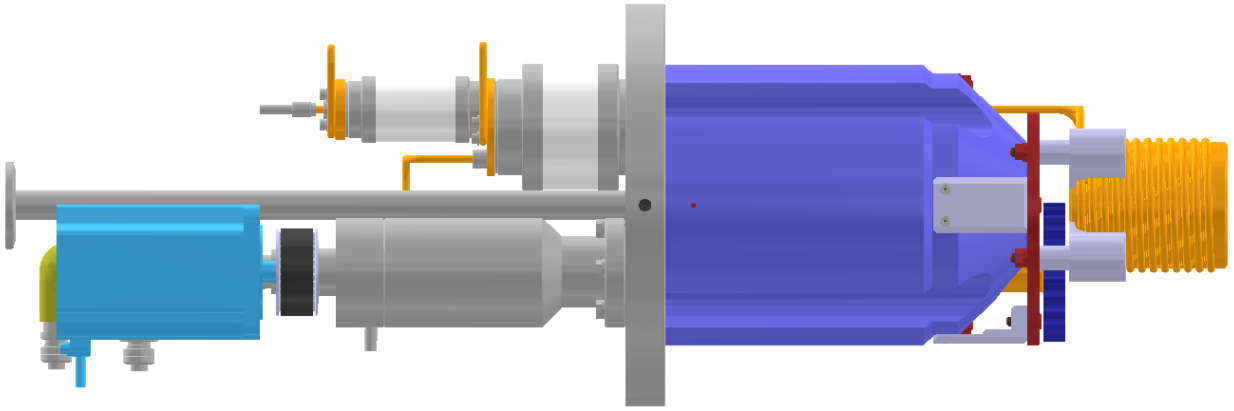
We make R56 in Arc0 of BTe

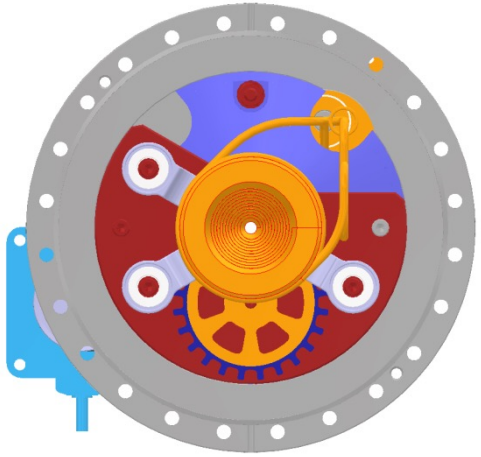


In the LINAC, we have ECS for only the positron beam. We will install accelerating structures in the electron BT line as ECS. We are currently preparing the acceleration unit.

New positron rotation target and FC

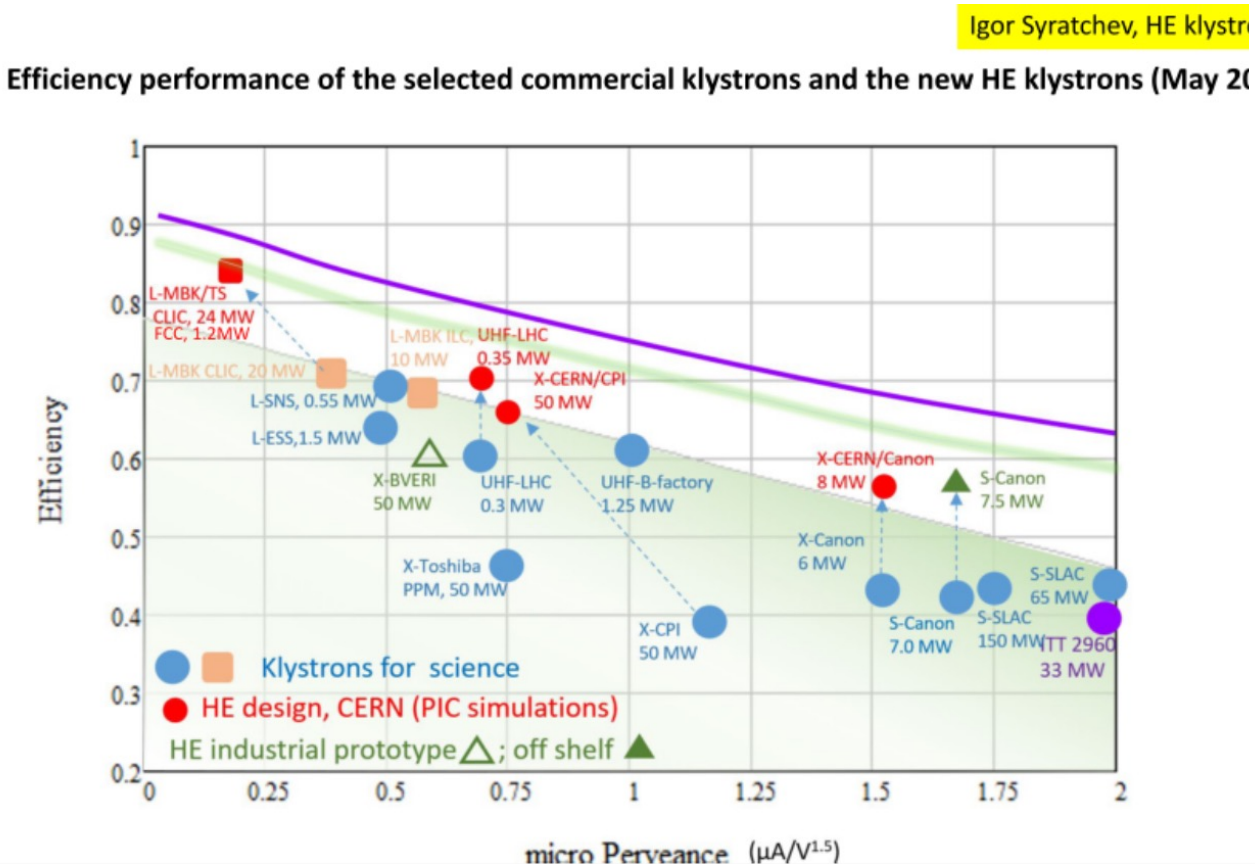






Rotation target is very nice system for not only positron beam but also electron beam.
That way, both beam orbits will be on the axis and big aperture for electron beam.

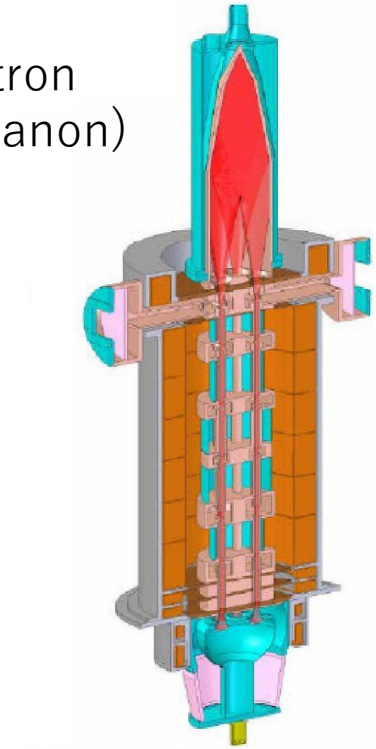
High efficiency klystron



Example of multi-beam klystron
1.3 GHz 10 MW, TOSHIBA(Canon)

Design parameters

Frequency	1300	MHz
Output Power	10	MW
Average Output Power	150	kW
Beam Voltage	115	kV
Beam Current	132	A
Efficiency	>65	%
RF Pulse Width	1.5	ms
Repetition Rate	10	pps
Saturation Gain	47	dB
Number of Beams	6	
Cathode Loading	<2.1	A/cm^2
Structure	6	cavities
RF Window	Pill Box WR-650	
Tube Length	2270	mm
Solenoid Power	<4	kW



THE TOSHIBA E3736 MULTI BEAM KLYSTRON
S. Miyake, A. Yano (Toshiba Electron Tubes & Devises Co., Ltd. , Japan)
S. Kazakov, A. Larionov, V. Teryaev (BINP, Russia)
Y. H. Chin (KEK, Japan)

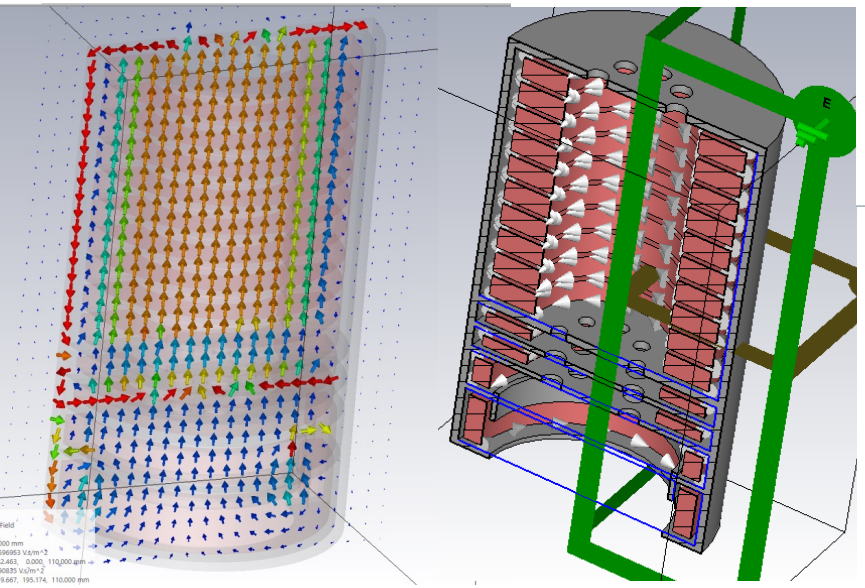
Klystron efficiency is related to perveance (A/V^1.5).
Efficiency [%] = 78-16*uPv (well known empirical formula)
Currently, we use the old type of the S-band 50 MW klystron, with an efficiency of 45 %.
One of the new high-power high-efficiency klystron candidates is the multi-beam klystron.

High efficiency klystron

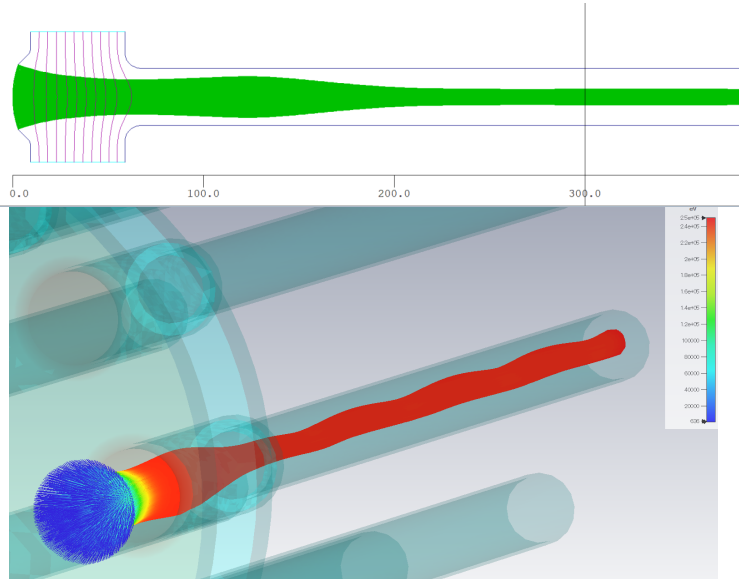
We are starting the design of a high-efficiency klystron for KEK LINAC.
It will be replaced with an old type klystron. It is designed to use the same modulator.

gun parameter	
Voltage	250 kV
Total Current	440 A
# of beam	8
Current	55 A
uPy	0.44
Expected efficiency	71 %
Expected output power	80 MW

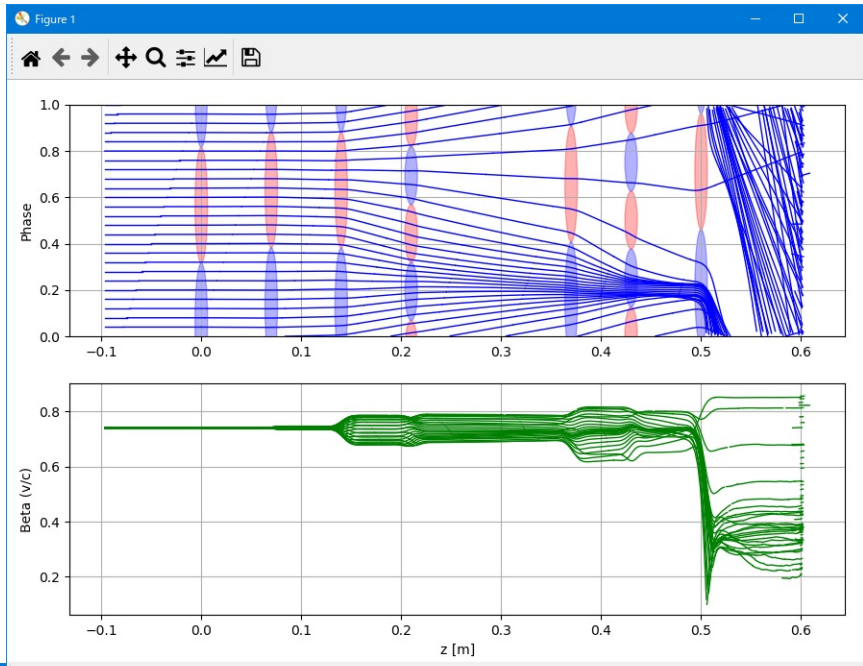
Preliminary

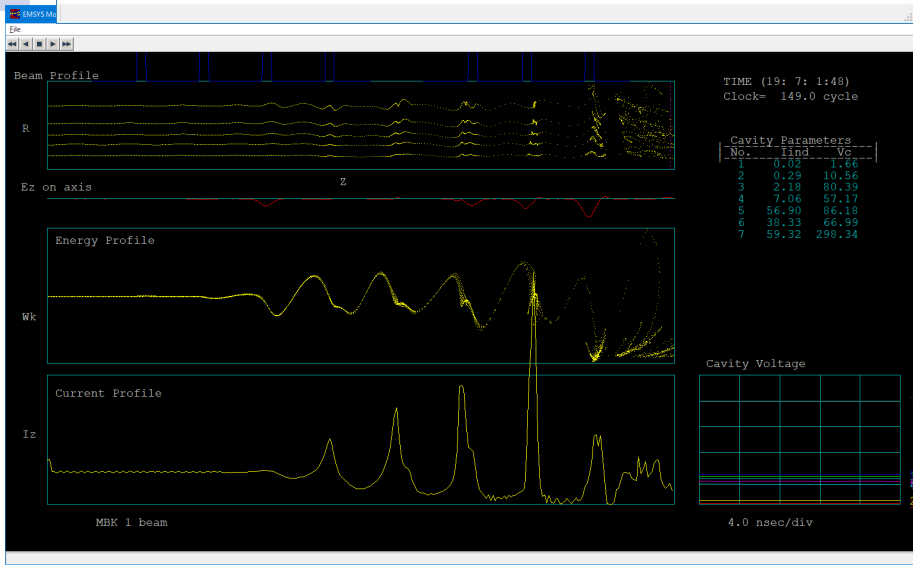


3D magnet design



2D,3D electron gun simulation





1D,2D klystron simulation

Summary

Electron beam

- Beam charge is stable at 2nC.
- Emittance is almost satisfied with a required value.

Next challenges

- 2 bunches operation.
- How to maintain good emittance.
- Increase beam charge, over 2.0 nC.
- Avoid emittance brow up at BT.

Positron beam

- Beam charge is almost reached the target value.
- 2 bunch operation is succeeded.
- Emittance is almost satisfied with a required value.

Next challenges

- Increase beam charge to 4.0 nC
- Stable operation.
- Avoid emittance brow up at BT.

Linac upgrade is ongoing.