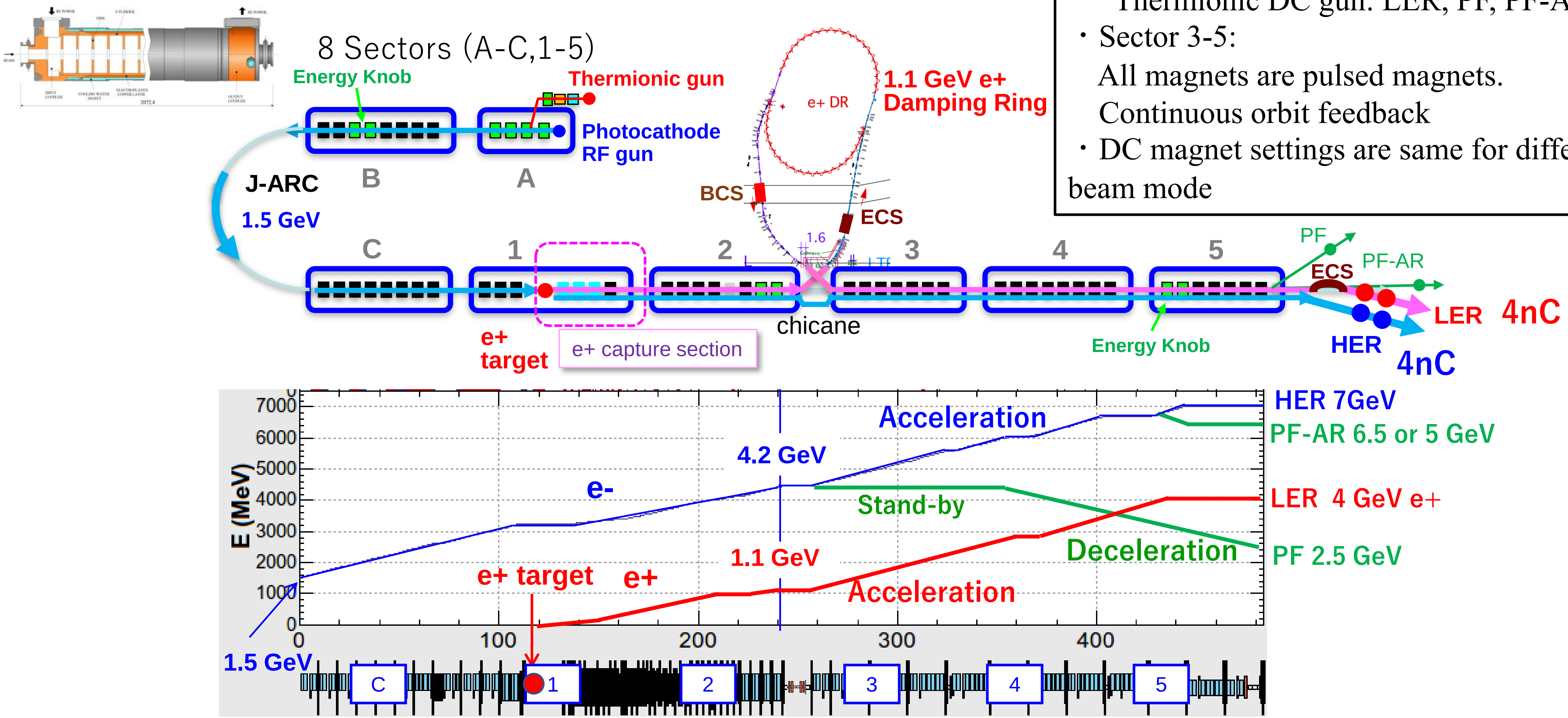
Linac status

Mitsuhiro Yoshida (Acc. Lab. Div. V, KEK)
on behalf of Injector Linac Group and Linac Commissioning Group

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

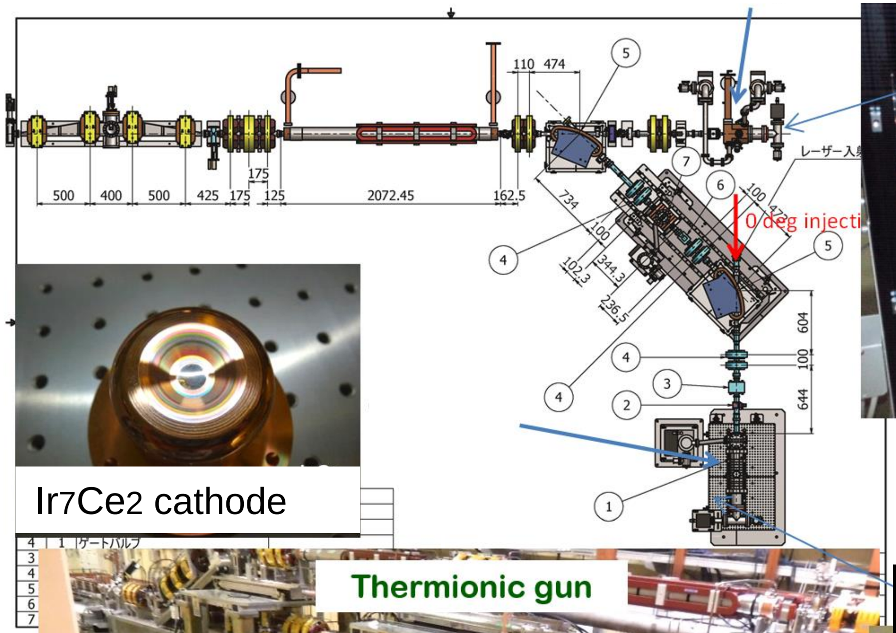


Beam energy variation for each beam mode along the beam line after J-ARC

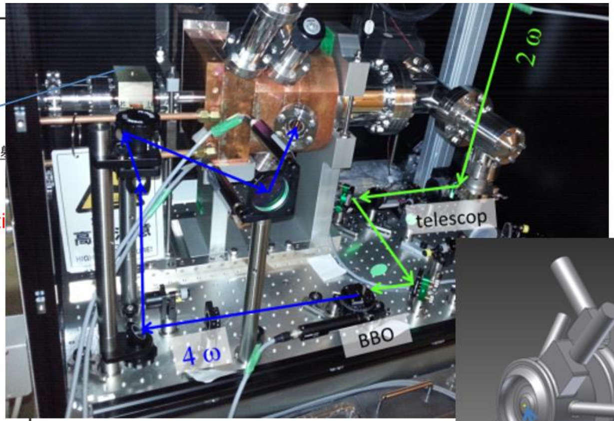
e- beam status and issue

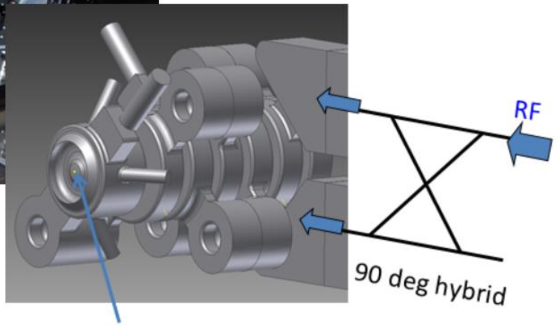
e- beam status

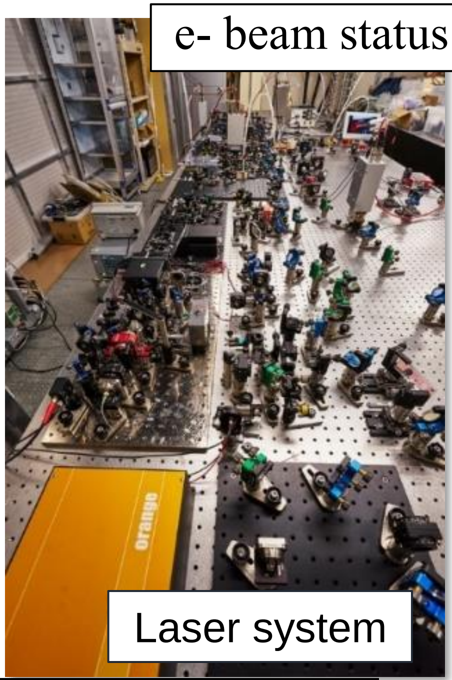
Low emittance photocathode rf e- gun



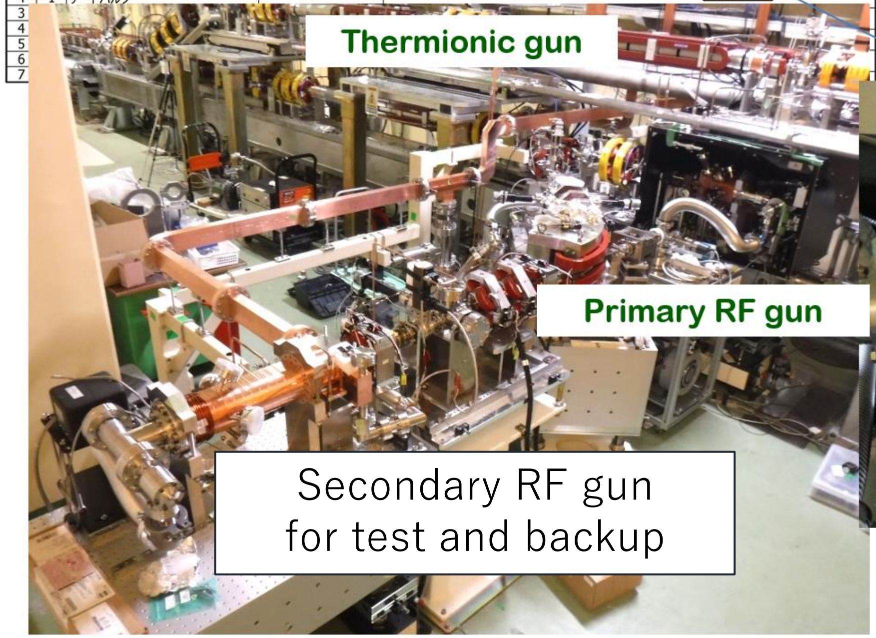
Ir7Ce2 cathode





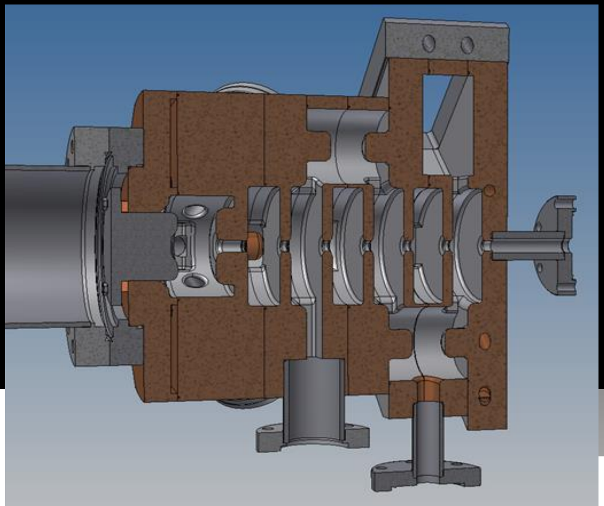


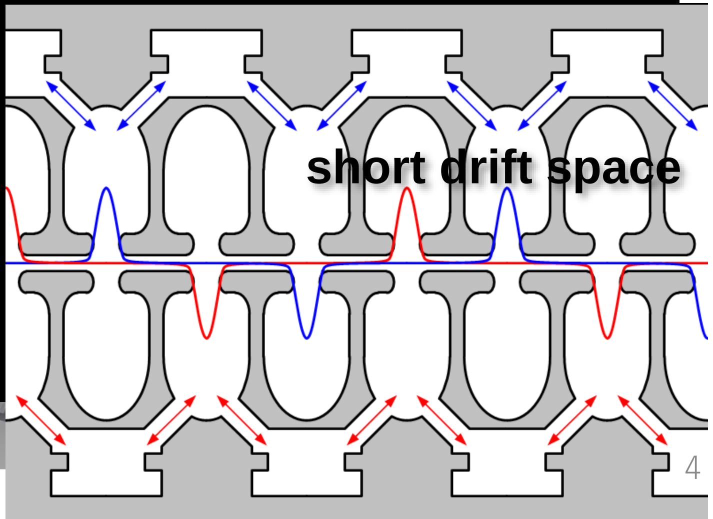
Laser system



Secondary RF gun
for test and backup

- Photocathode: Ir7Ce2
- Cavity: QTWSC (Quasi Travelling Wave Side Couple)
  - Strong focusing electric field

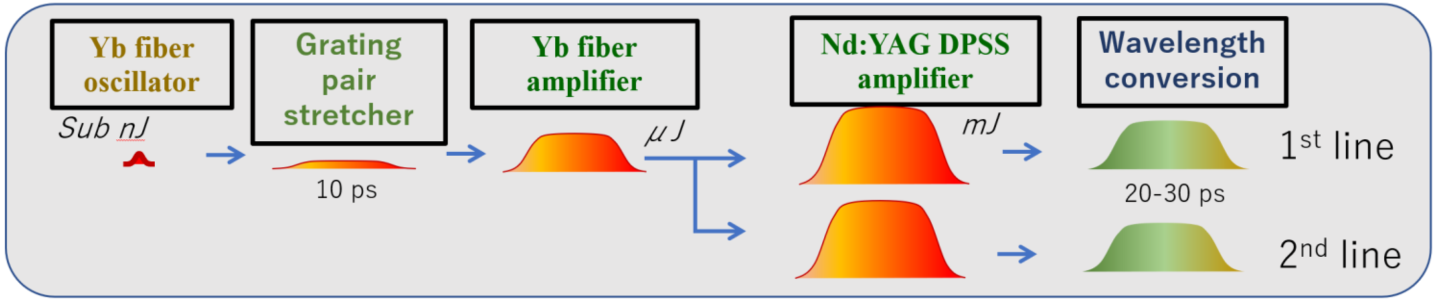




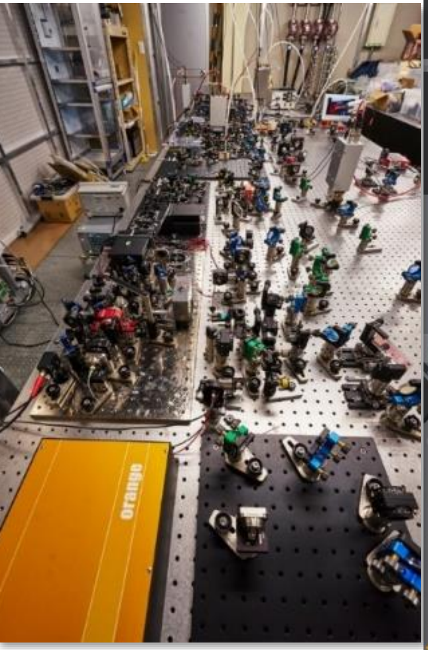
M. Yoshida et al.

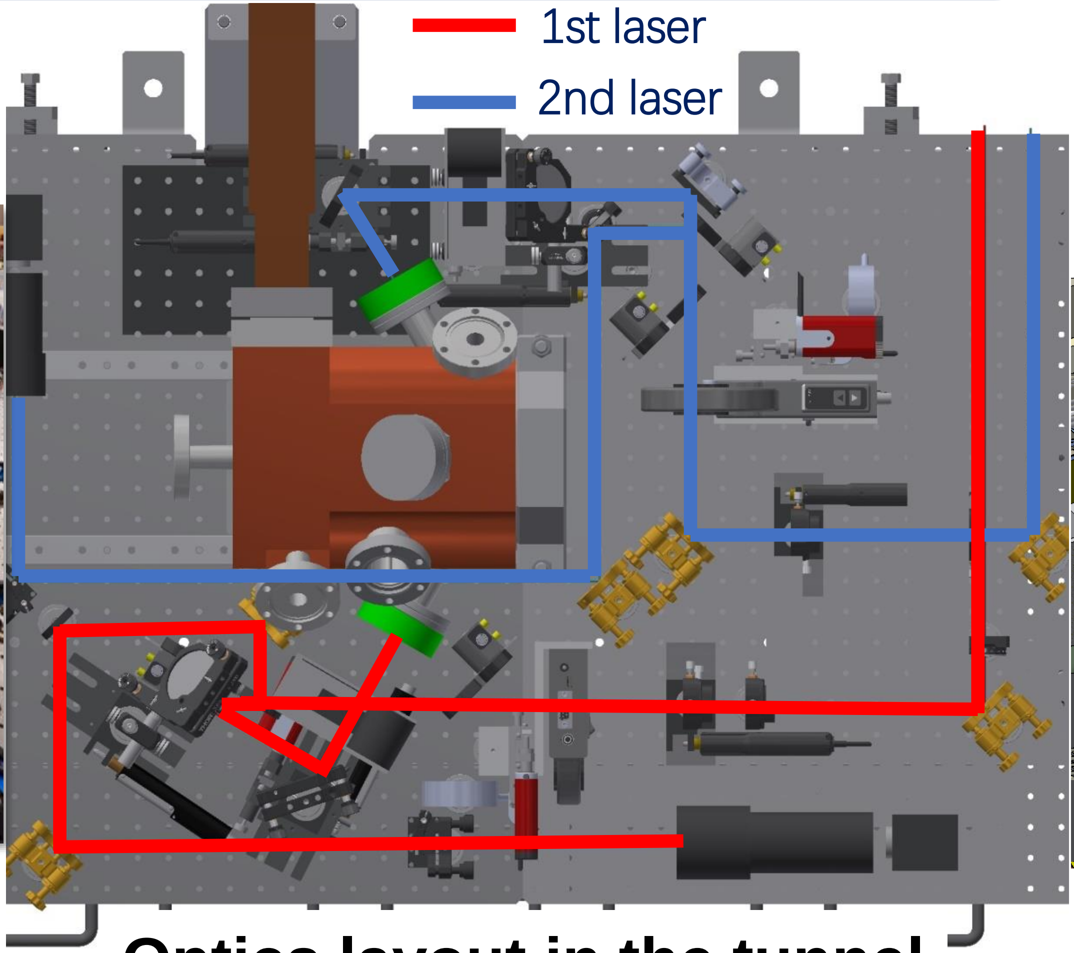
Hybrid laser system for rf e- gun

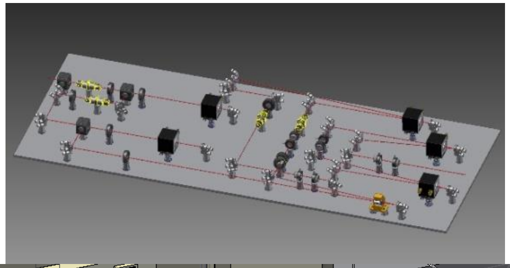
- Yb doped fiber and Nd:YAG DPSS module Amplifier

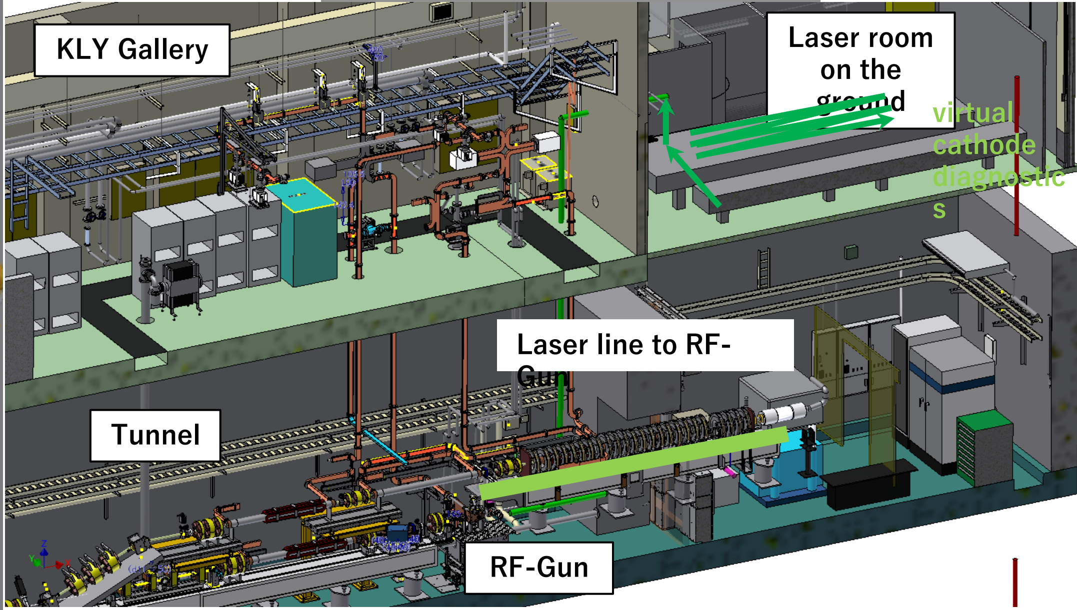


- **Output Power in 1st line:**
- ω (1064 nm): 32 mJ
- 2ω (532 nm): 12 mJ
- 4ω (266 nm): 1.3 mJ







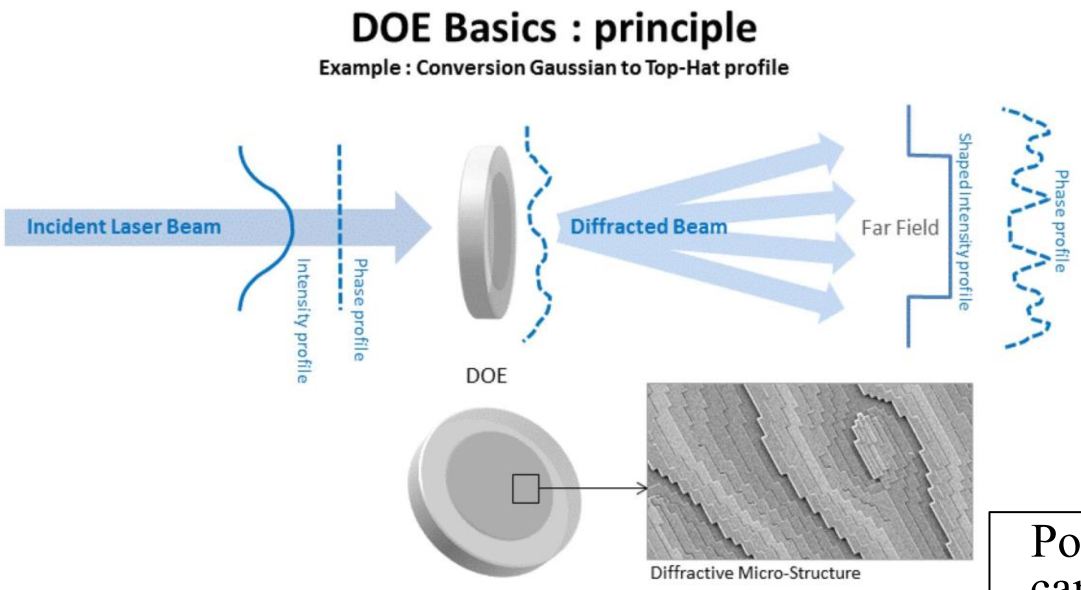


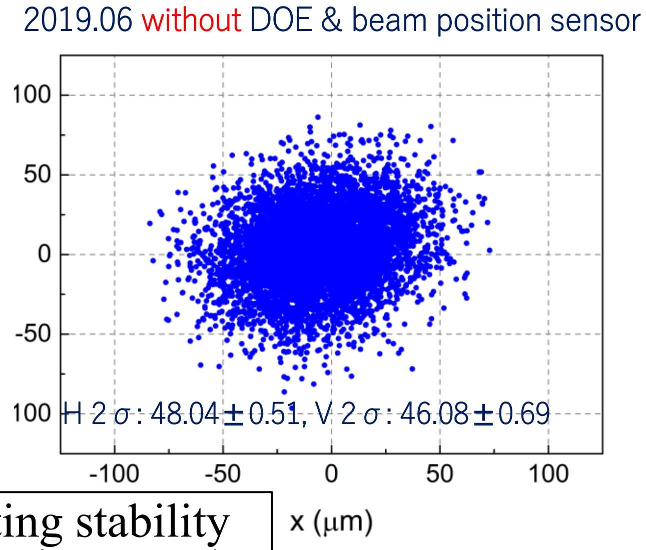
R. Zhang, X. Zhou et al.

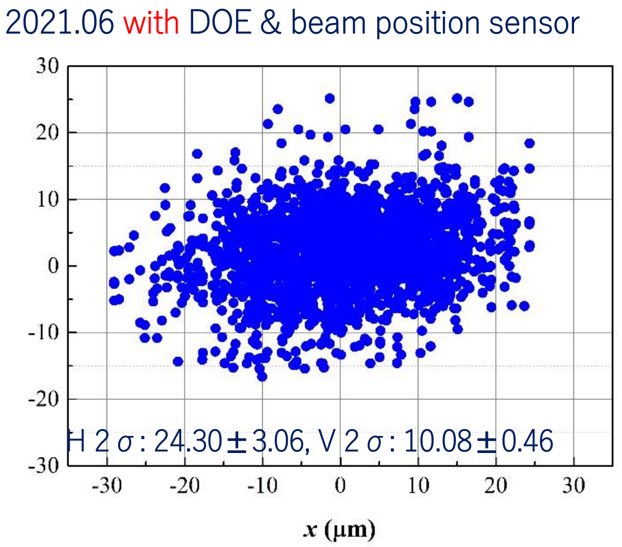
Optics layout in the tunnel

Laser transport line

DOE for reshaping of laser spatial distribution

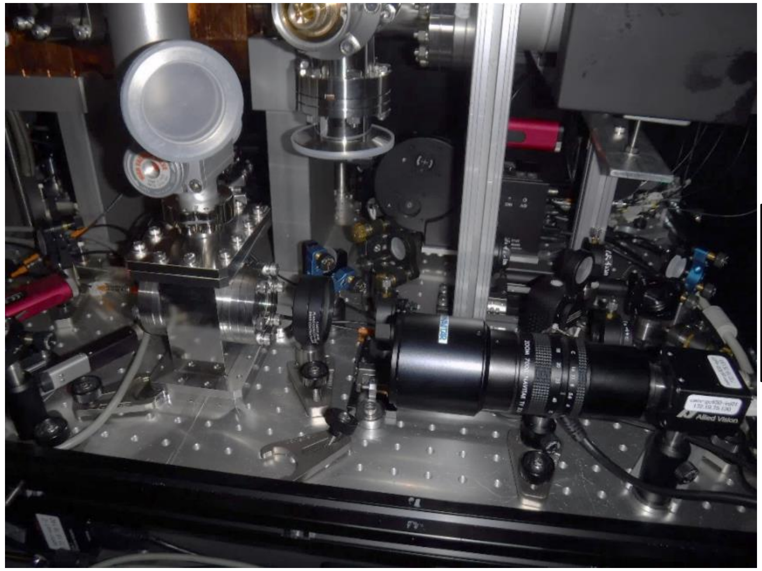




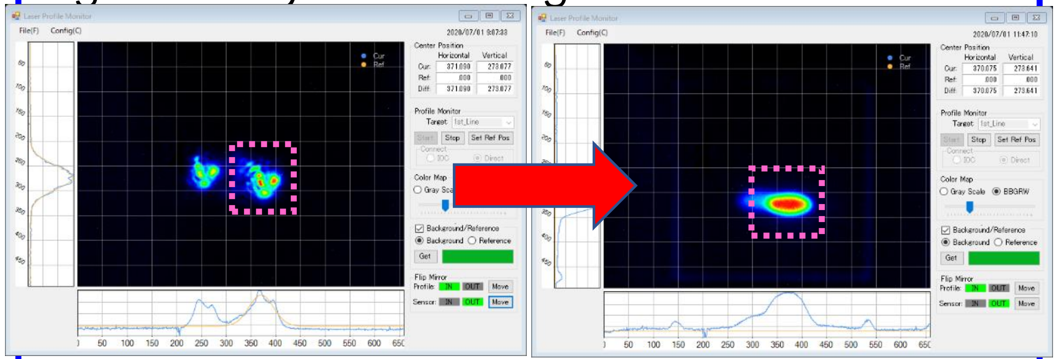


Pointing stability can be improved.

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.



DOE is installed in vacuum chamber filled with Argon gas.



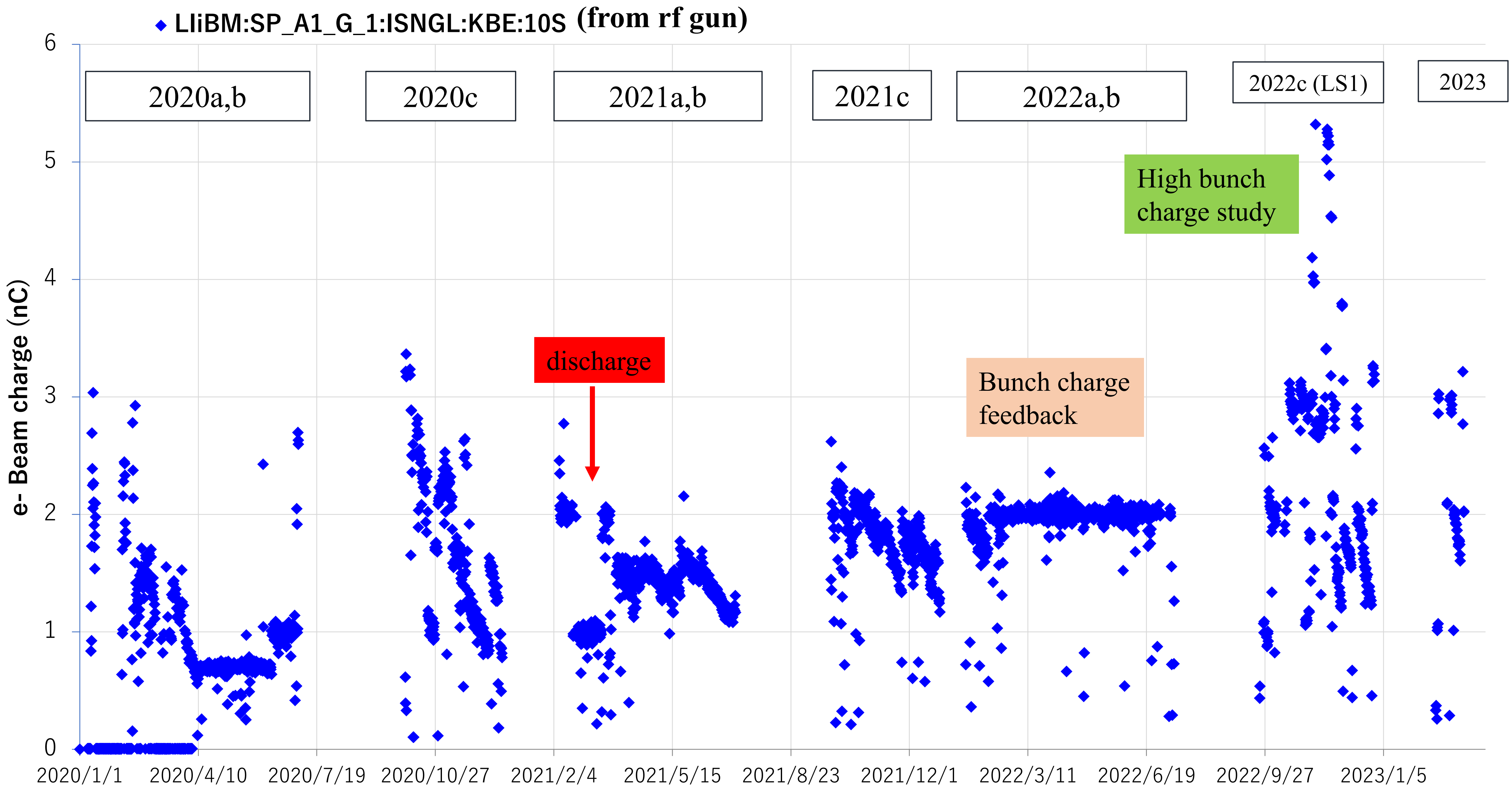
world first DOE application in UV laser

R. Zhang

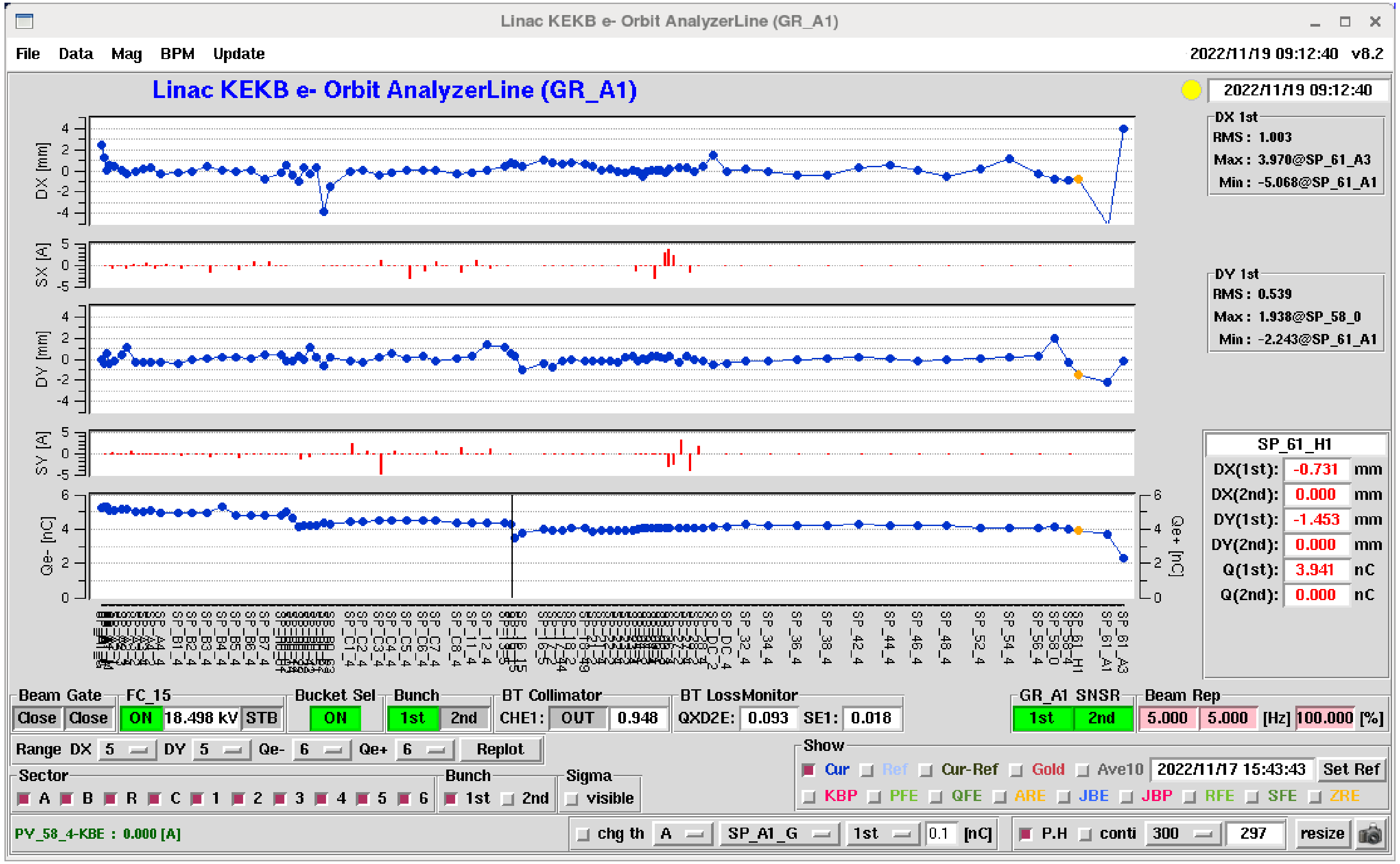
Masanori Satoh (KEK)

e- bunch charge history (2020a to 2023)

e- beam status



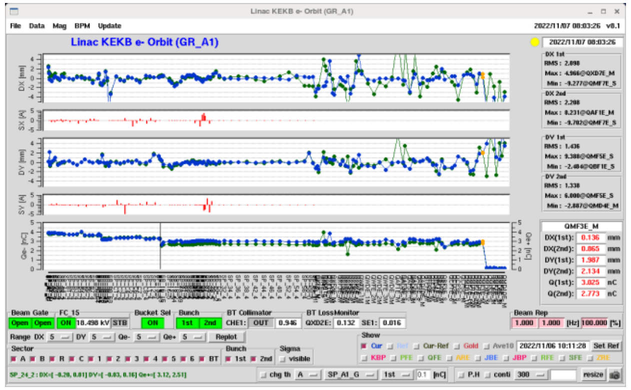
SP_61_H 4nC achievement



SP_A1_G 5.2nC, SP_61_H 4 nC reached.

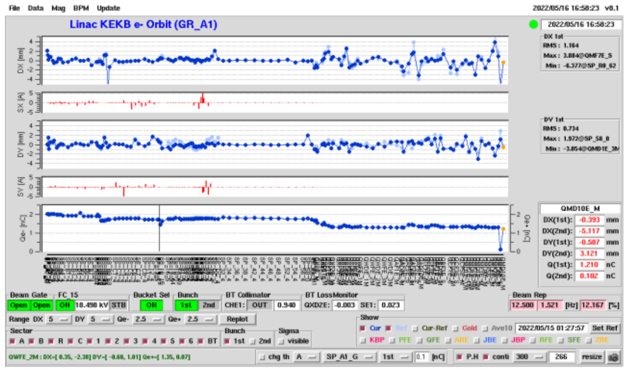
B sector emittance $\gamma\varepsilon x$=57.534±19.037), BmagX 2.090, $\gamma\varepsilon y$=85.974±20.111, BmagY 1.104

KBE Emittance at each charge condition



SP_A1_G 4.0nC、SP_61_H 3.0nC

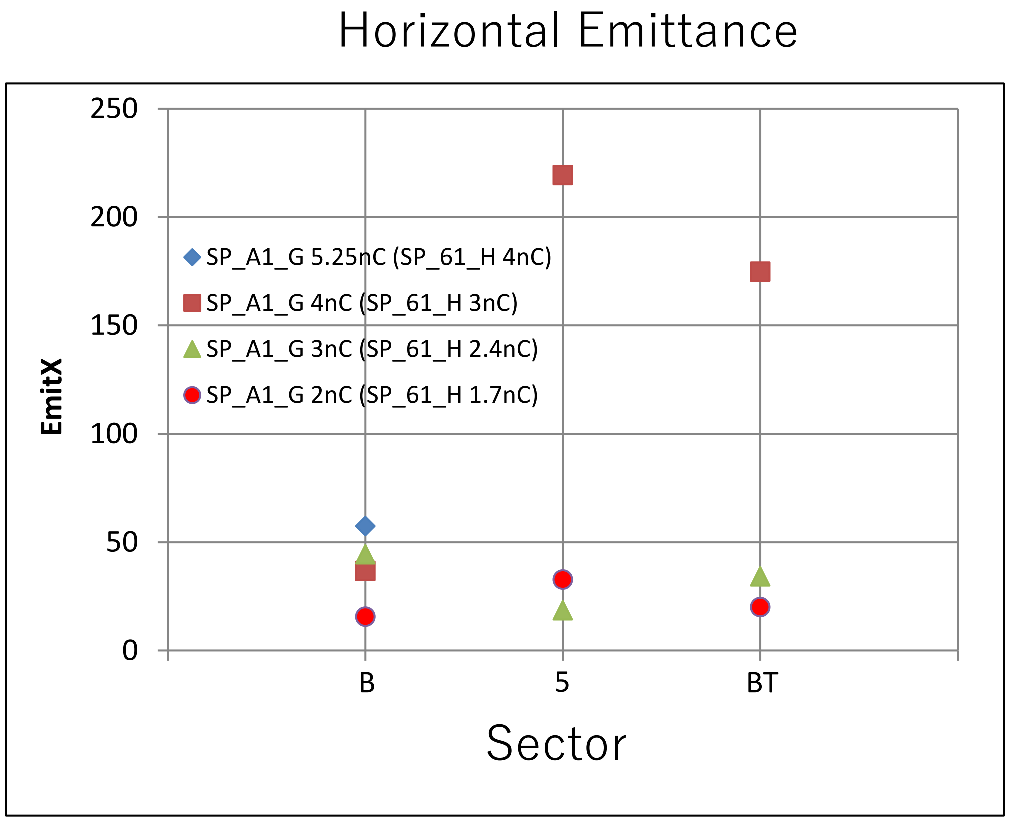
SP_A1_G 3.0nC、SP_61_H 2.4nC

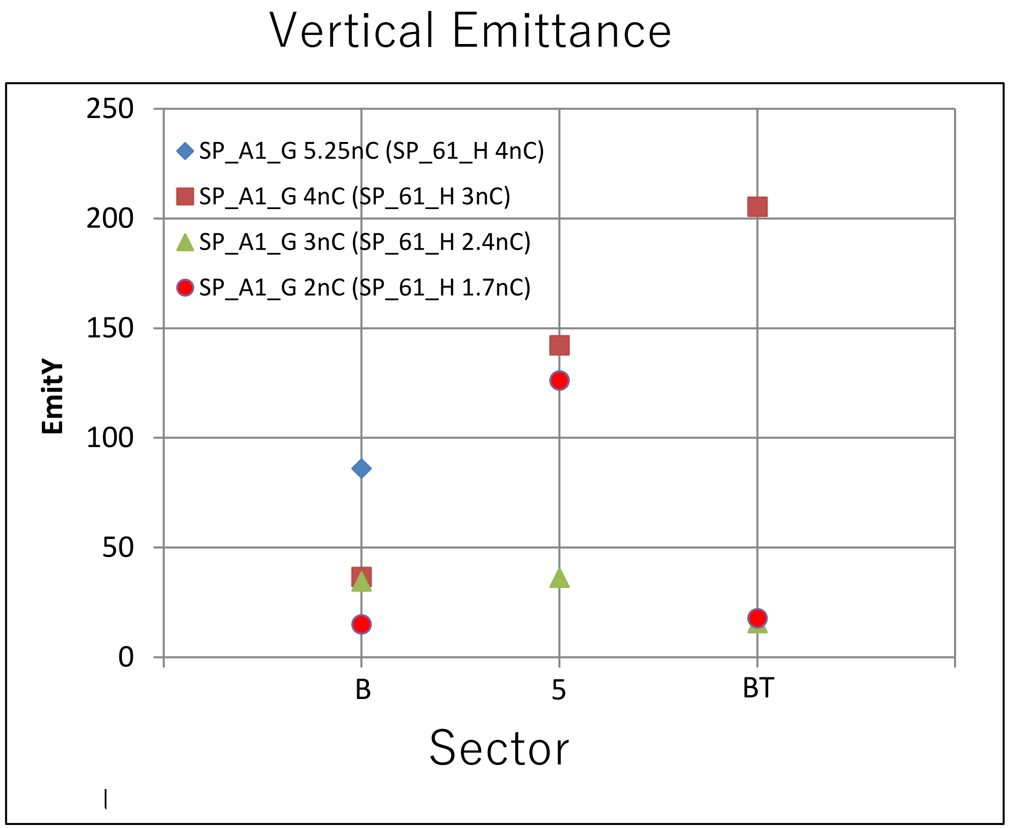


SP_A1_G 2.0nC、SP_61_H 1.7nC

SP_A1_G Charge (nC)	SP_61_H Charge (nC)	BT End Charge (nC)	B-sector				5-sector				BT			
			EmitX	BmagX	EmitY	BmagY	EmitX	BmagX	EmitY	BmagY	EmitX	BmagX	EmitY	BmagY
5.25	3.94	–	57.534 (Δ19.037)	2.09	85.974 (Δ20.111)	1.104	–	–	–	–	–	–	–	–
4.0	3.0	3.0	36.897 (Δ 7.623)	3.814	36.659 (Δ17.921)	1.138	219.399 (Δ265.59)	1.86	142.239 (Δ 46.19)	1.073	174.842 (Δ475.13)	5.214	205.440 (Δ56.42)	1.029
3.0	2.4	2.2	–	–	–	–	18.650 (Δ 32.39)	2.709	36.270 (Δ 6.078)	1.581	34.359 (Δ 6.223)	1.03	15.567 (Δ 7.388)	2.013
2.0	1.7	1.2	15.723 (Δ 4.571)	25.011	15.061 (Δ 4.469)	2.884	32.800 (Δ214.29)	5.05	126.186 (Δ 40.76)	1.061	20.144 (Δ 3.310)	1.046	17.826 (Δ 2.720)	1.054

KBE Emittance at each charge condition



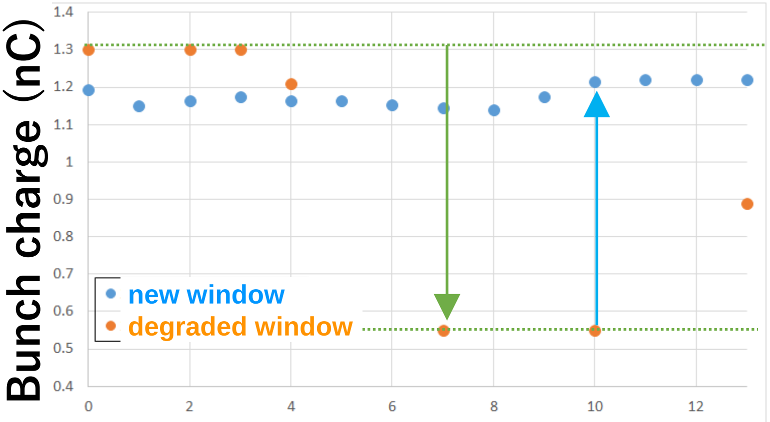


Issue of rf gun laser window degradation

e- beam issue

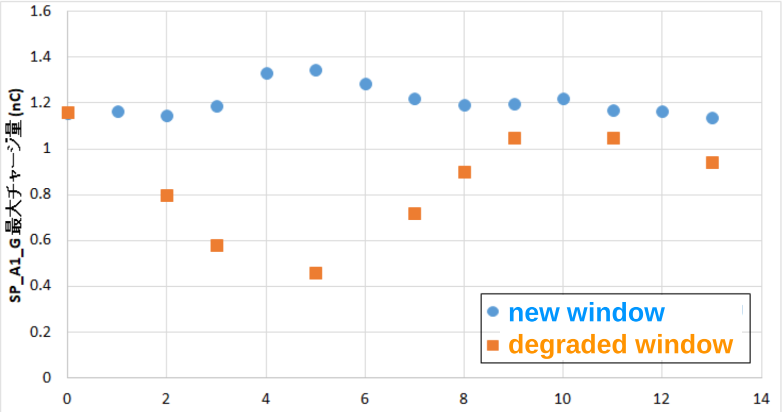
- Long term operation makes rf gun laser windows dirty for both of 1st and 2nd line.
- It decrease the transmittance of laser power through window and bunch charge intensity.
- After replacement of the laser window, the bunch charge intensity is recovered.
- Vacuum ion pump was installed between the laser window and rf gun cavity with the extension vacuum duct for the 1st line laser in this summer maintenance '22.

e- intensity by 1st-line laser

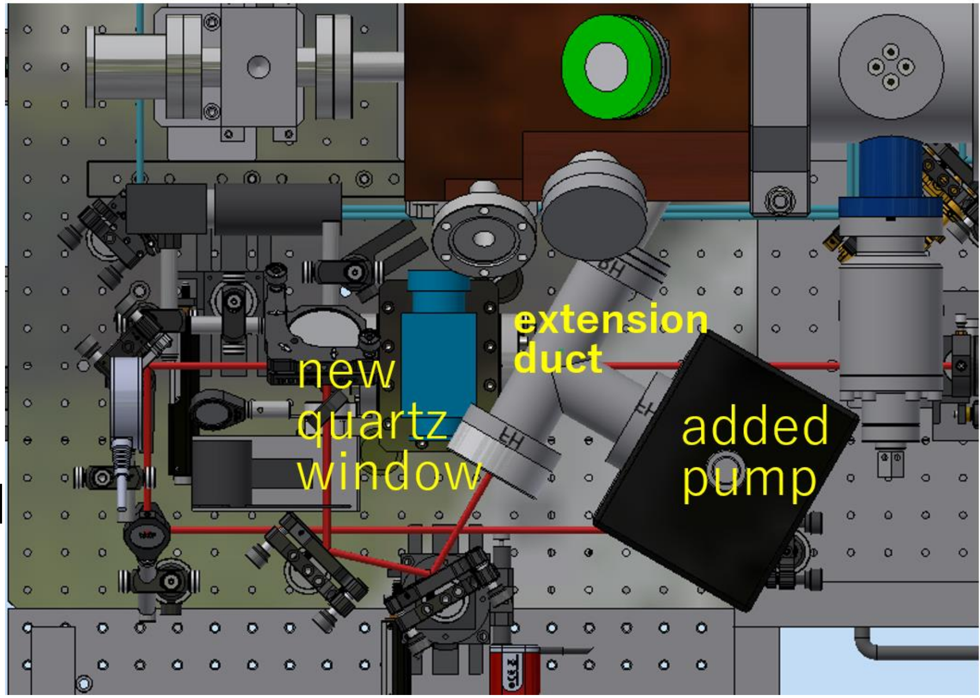


1st-line laser incident position [mm]

e- intensity by 2nd-line laser



2nd-line laser incident position [mm]

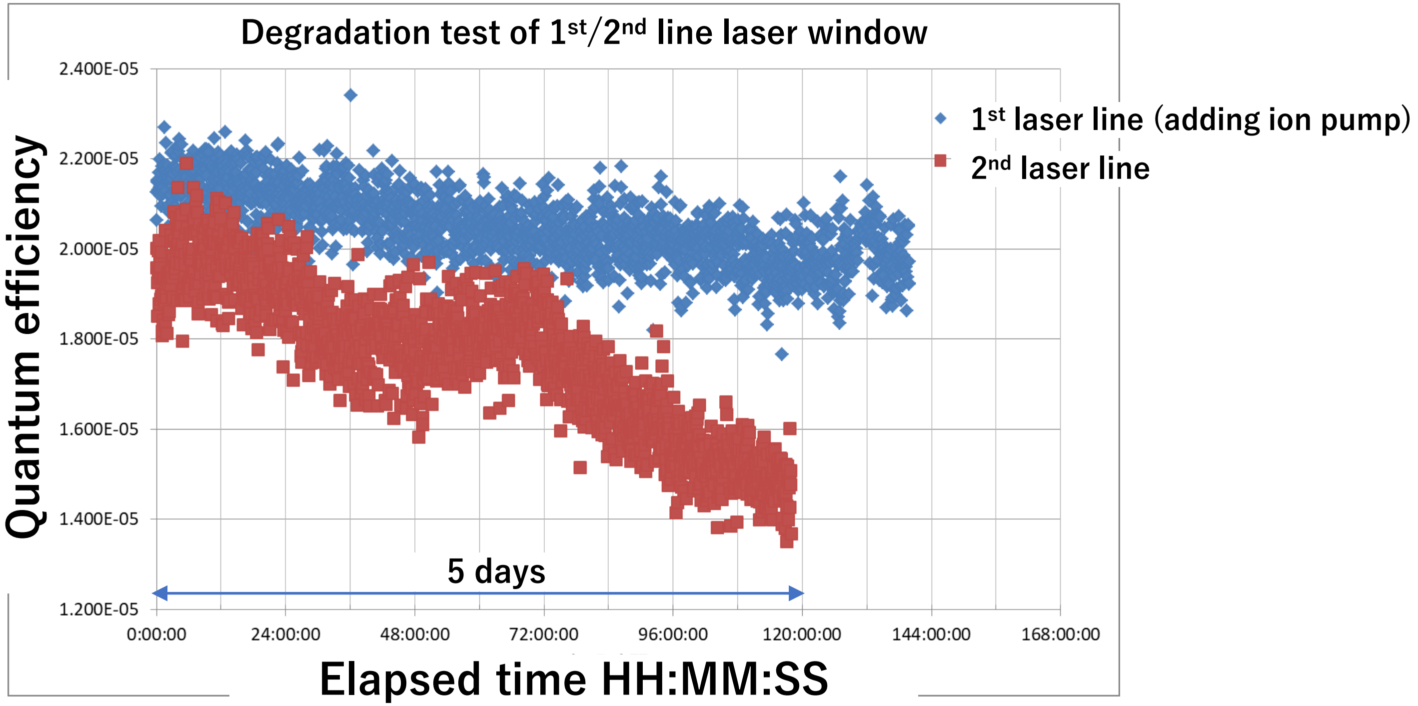


M. Yoshida

Improvement of laser window degradation with ion pump

e- beam issue

- Long term operation for keeping e- bunch charge is very important issue.
- Continuous beam test at e- beam repetition of 22 Hz has been conducted more than 5 days.
- Installed ion pump could help to mitigate the laser window degradation from the experimental results.
- This test will be continued until the end of this run. Further improvement is also being considered.

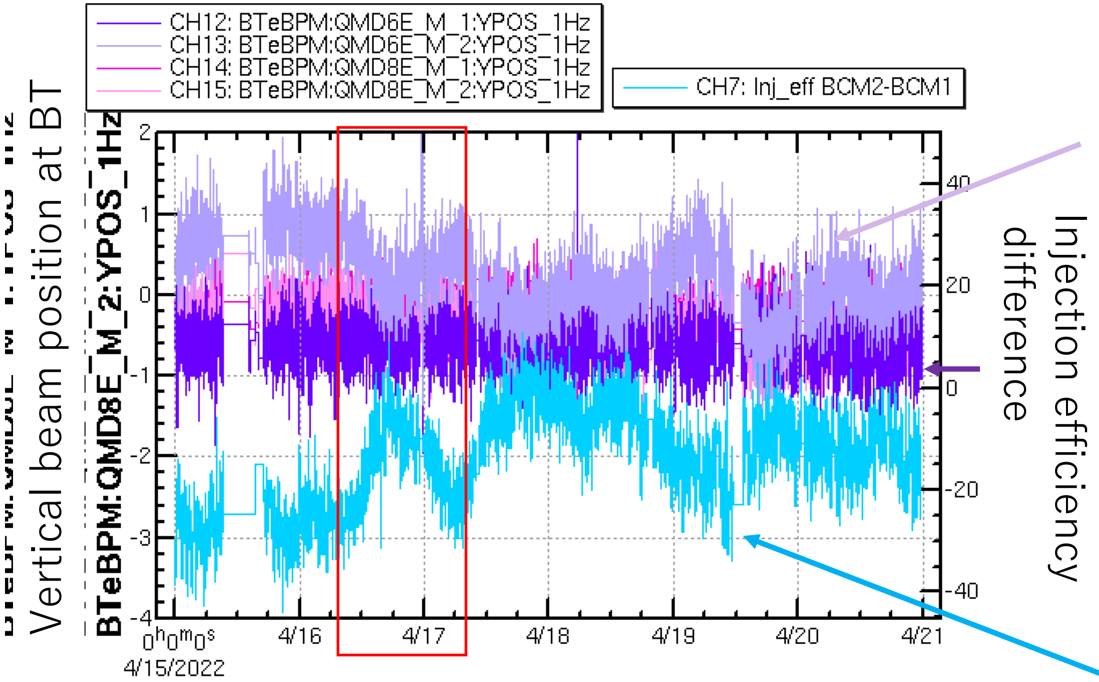


M. Yoshida

Injection efficiency of 2nd bunch

e- beam issue

- HER injection efficiency of e- 2nd bunch is lower than that of 1st bunch and varies gradually.
- In some cases, there is not clear correlation between injection efficiency and orbit of 2nd bunch.
- Low injection efficiency could be also caused by the emittance deterioration.
- Fast kicker for 2nd bunch orbit correction could be effective. Two fast kickers will be installed at the linac end and the beginning of BT in summer ’23.
- Prototype kicker was installed at the entrance of J-ARC in this summer ’22. Beam test will be conducted soon.



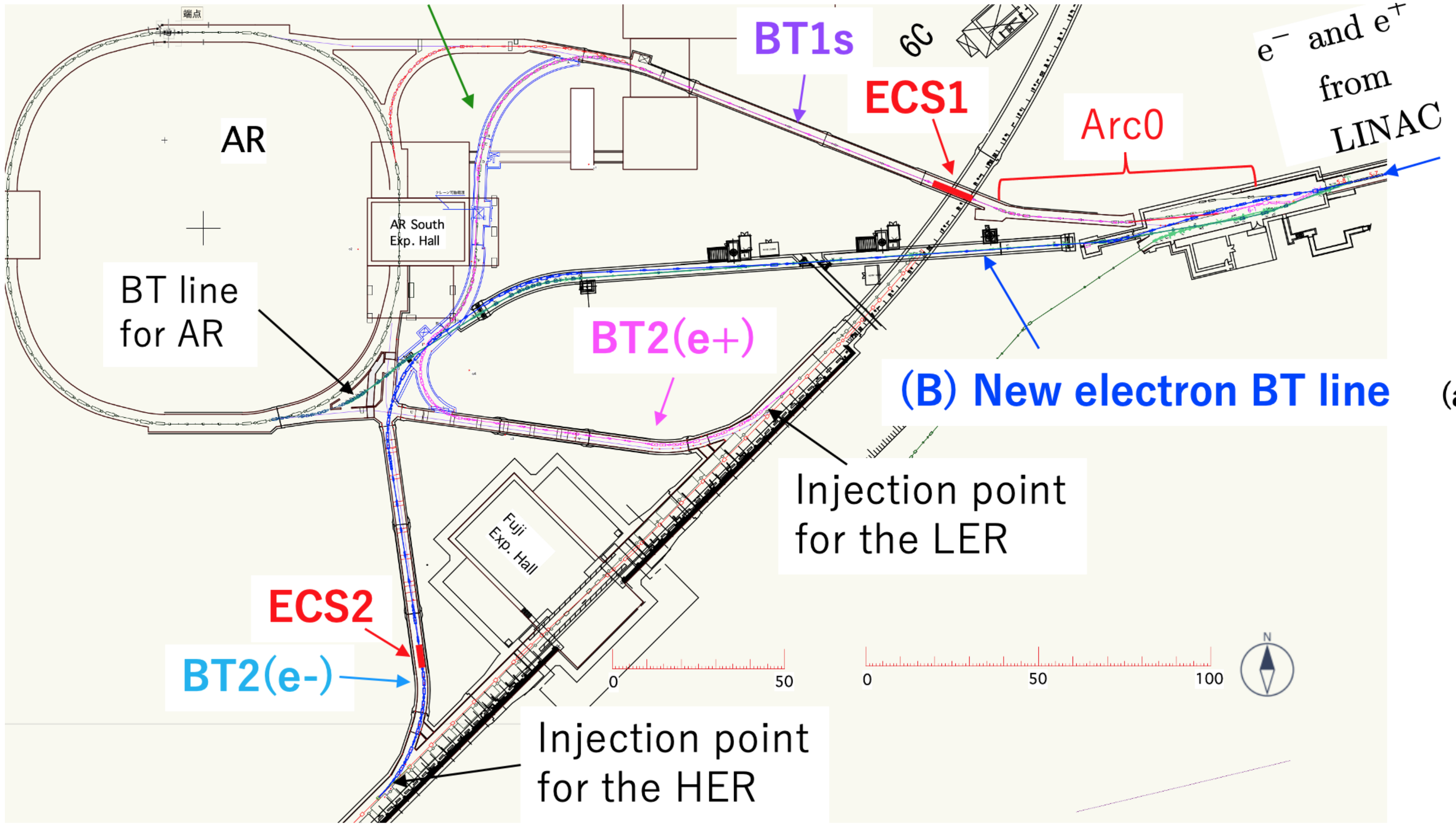
Ver. position of 2nd bunch at the BT end

Ver. position of 1st bunch at the BT end

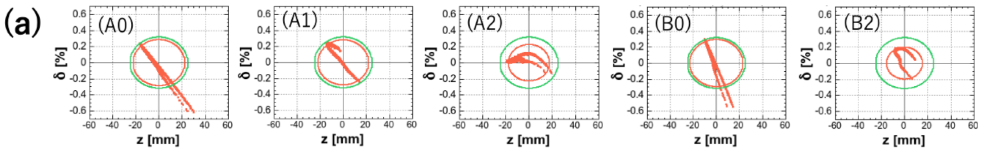
Difference between 2nd and 1st bunch Injection efficiency
(Lower 2nd bunch efficiency means negative value)

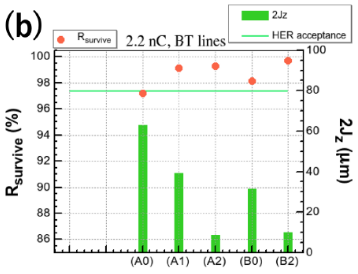
N. Iida

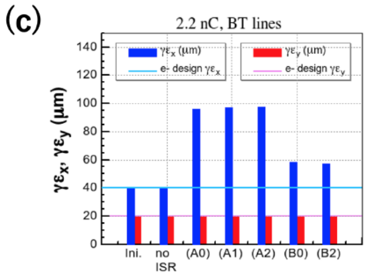
BTe-ECS (FY2024) to improve injection efficiency



	BT line	ECS	R_{56} [m]	V_c^{Total} [MV]
(A0)	Present	—	-0.11(Arc0)	—
(A1)	Present	"ECS1"	-1.0(Arc0)	72
(A2)	Present	"ECS2"	-4.3	34
(B0)	New	—	—	—
(B2)	New	"ECS2"	-1.6	70







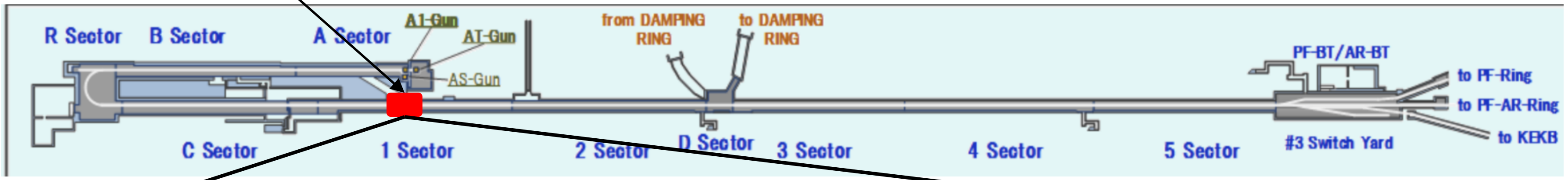
e- beam summary and issue

- Thermionic DC electron gun has worked fine to generate primary electron beam for positron production.
- Photocathode RF-Gun
  - Laser system and DOE element (5mm beam diameter) has worked fine without any significant trouble.
  - High bunch charge e- was demonstrated. Achieved 5 nC from e- gun and 4 nC at the linac end.
    ==== To Do ====
  - **DOE with large laser area** (fully covered 8 mm cathode area) will be installed until HER injection
    => Lower energy spared according to space charge suppression / Stability improvement
  - New piezo mirror feedforward system improve beam stability.
  - Better QE IrCe composite cathode is developed and under testing.
  - Gradual decrease of bunch charge due to laser window deterioration : extension vacuum chamber and pump.
  - New TW-Gun is under testing for better vacuum in cathode region and lower discharge.
  - Beam loss at J-ARC and e+ target location should be minimized : Pulsed magnet
  - Beam stability should be improved : Laser frequency comb in vacuum line(Zhou) / Pulsed modulator control.
- KBE Beam Issue and study in LS1 period.
  - Emittance at linac end and BT1 is almost satisfied 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
    BT ARC4 realignment / Vacuum chamber / Straight injection line
  - Increase of 2nd bunch injection efficiency and improvement of its stability are important issues.
    => Fast Kicker / Long range wakefield suppression
  - Auto tuning : Dispersion compensation / Fast emittance measurement are under test
  - BTe-ECS is planned to install at FY2024 in BT1 or BT2(Fuji-area).

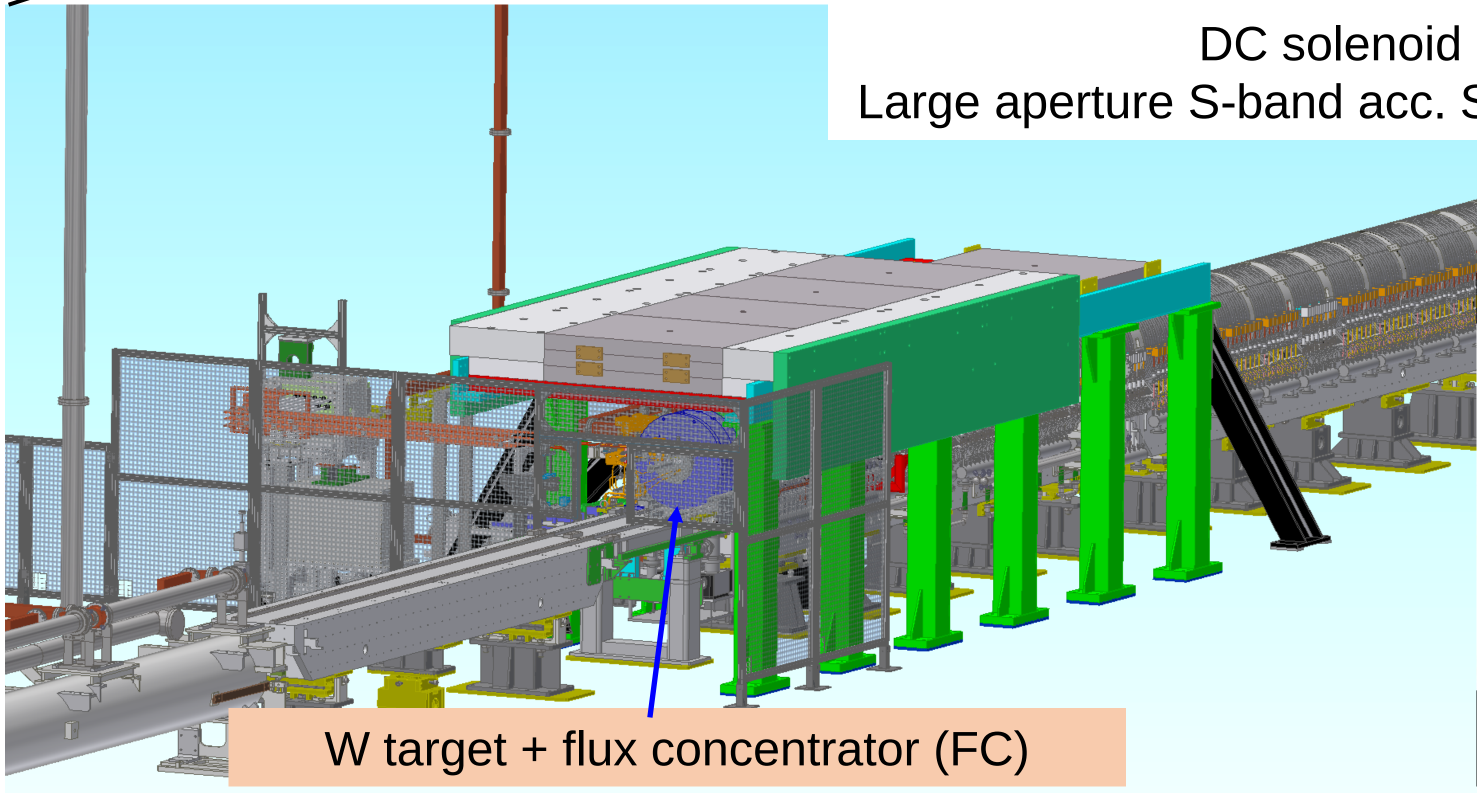
e+ beam status and issue

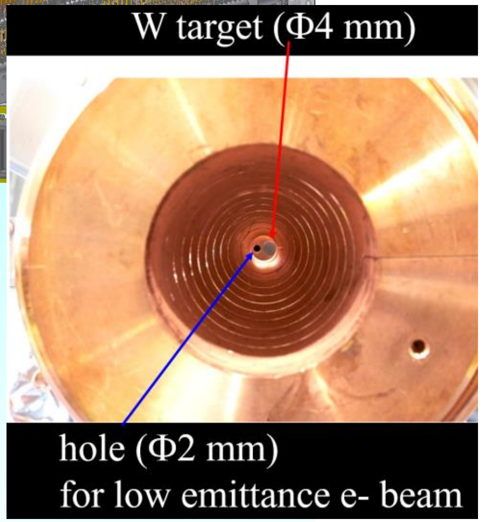
Positron source setup at Sector1

Positron target and capture section



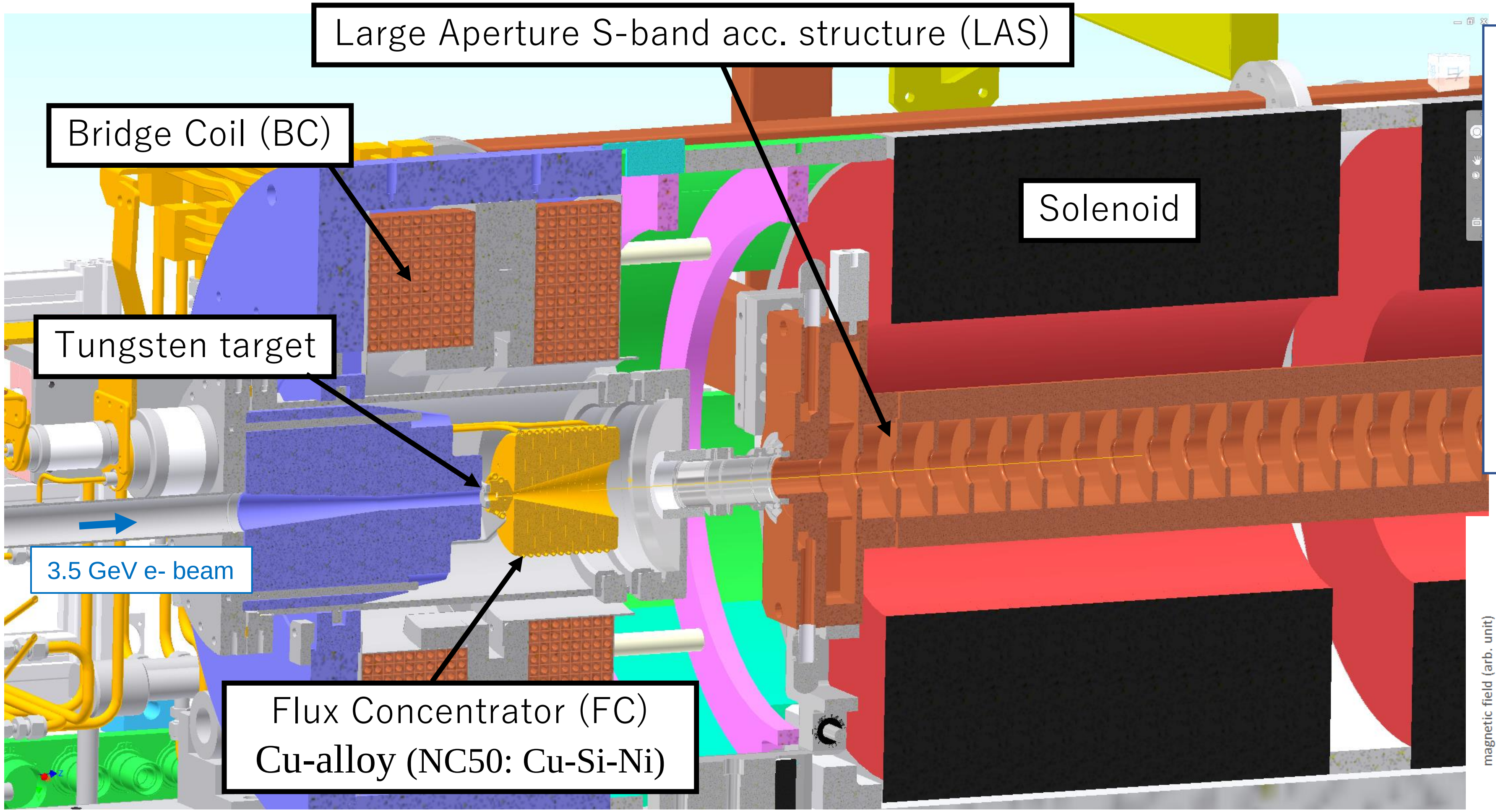
DC solenoid
Large aperture S-band acc. Structures (x10)



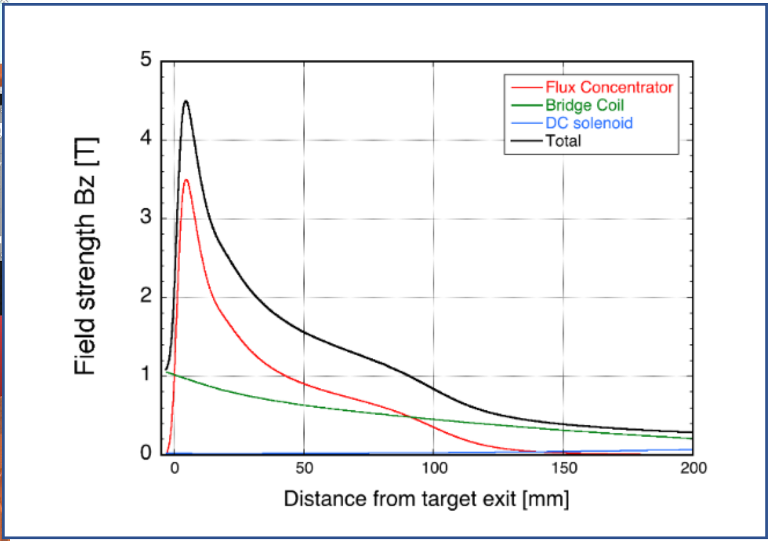


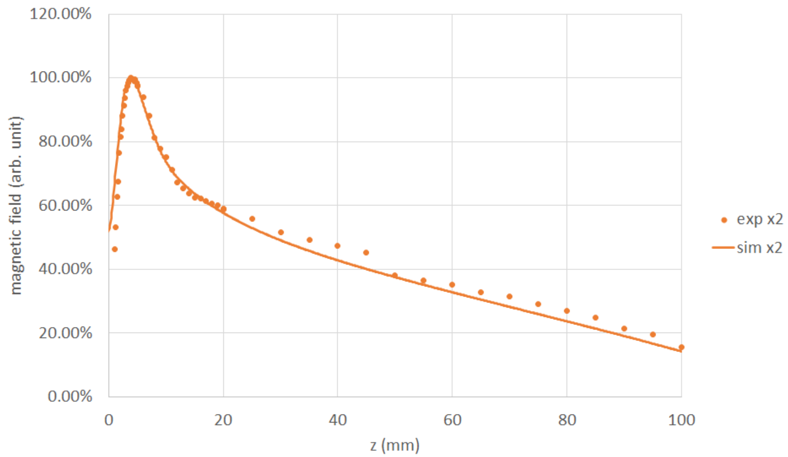
Y. Enomoto et al.

Positron Capture Section: Flux concentrator, bridge coil, solenoid



I_{FC}= 12 kA

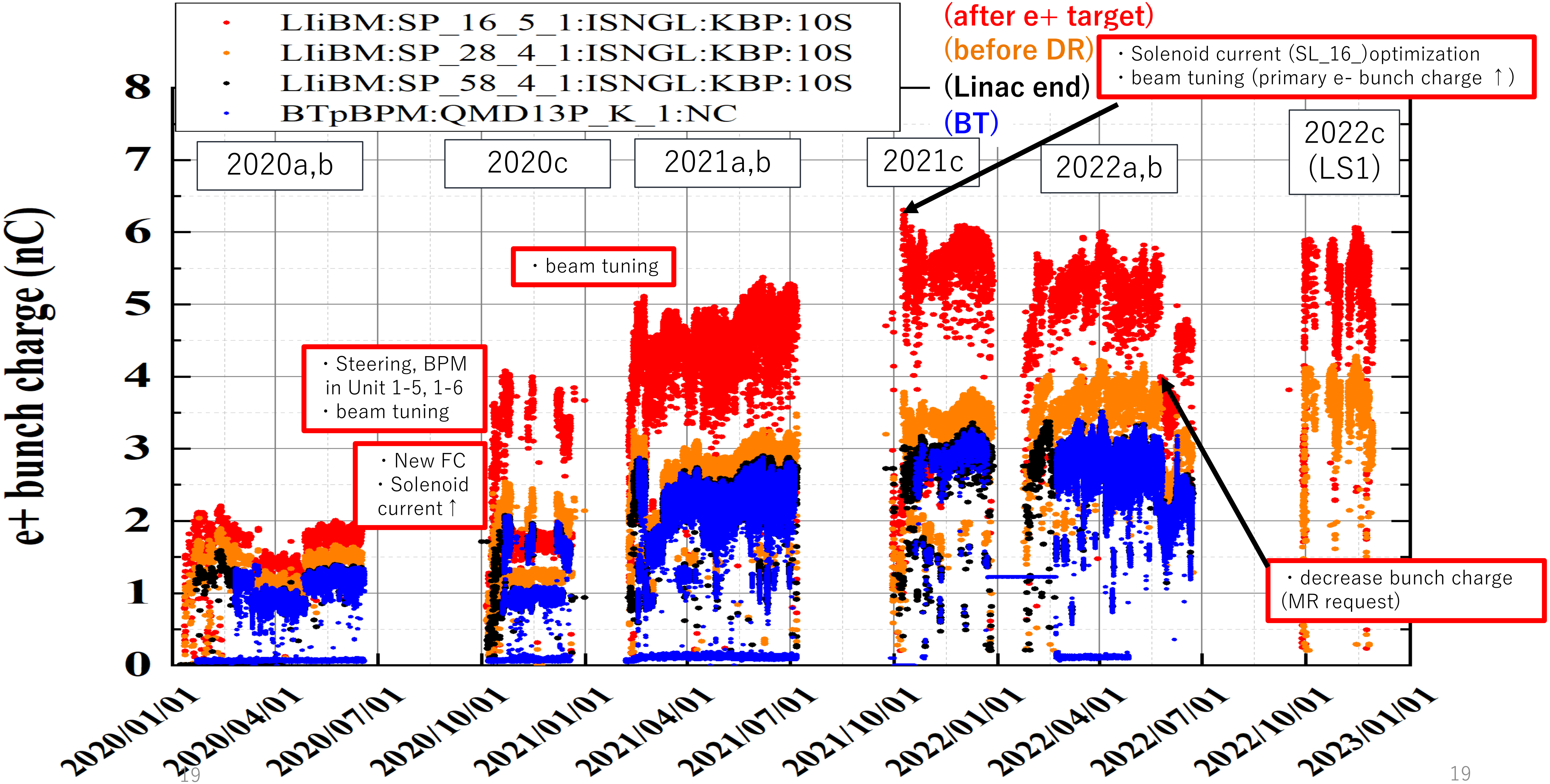




Y. Enomoto et al.

e+ bunch charge history (2020a to 2022c)

e+ beam status



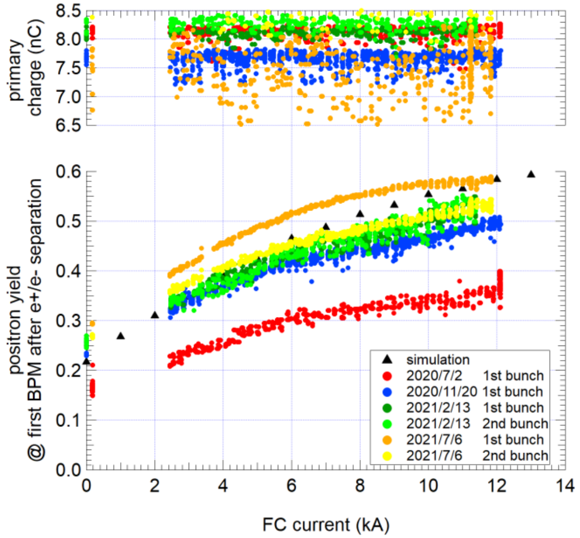
e+ beam summary and issue

- e+ bunch charge is almost achieved (final target: 4 nC)
  - 6 nC at BPM “SP_16_5” (1st BPM after e+ target) / 4 nC at LTR (Linac To damping Ring) / 3.5 nC at linac end and BT
  - e+ production efficiency with the current FC is reached the simulation result (60%).
- Further improvement of positron bunch charge
  - Increase acc. gradient of first two structures (AC_15_1[2]) at e+ capture section
  - Increase primary e- bunch charge, beam tuning, FC power supply upgrade, and so on
  - Auto tuning : 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)
- Issue
  - Emittance at linac end and BT1 (before Arc1) is almost satisfied the final goal.
  - However, emittance at BT2 is increased due to ISR, CSR, and some other reasons.
    BT ARC4 realignment / Vacuum chamber
  - 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



Y. Enomoto

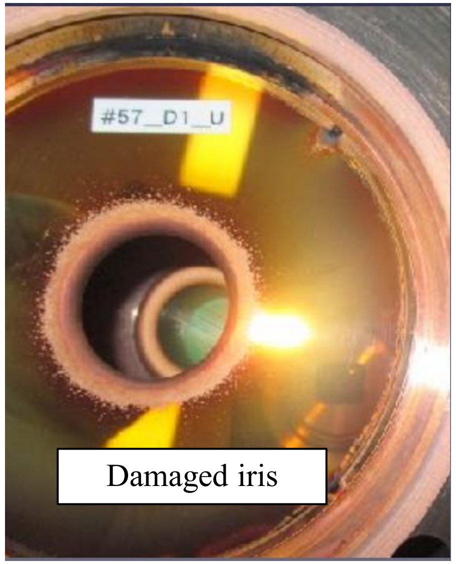
Upgrade work during LS1

- New accelerating structure
- Pulsed Quads
  - at J-ARC matching section
  - at Sector1, 2 (e-/e+ compatible optics region)

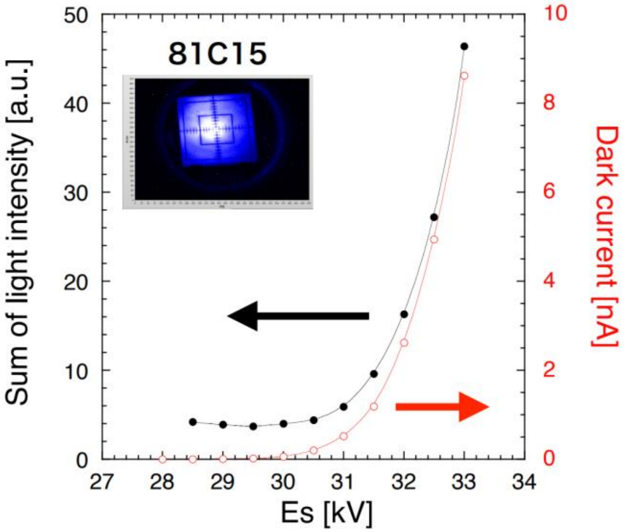
Accelerating structure

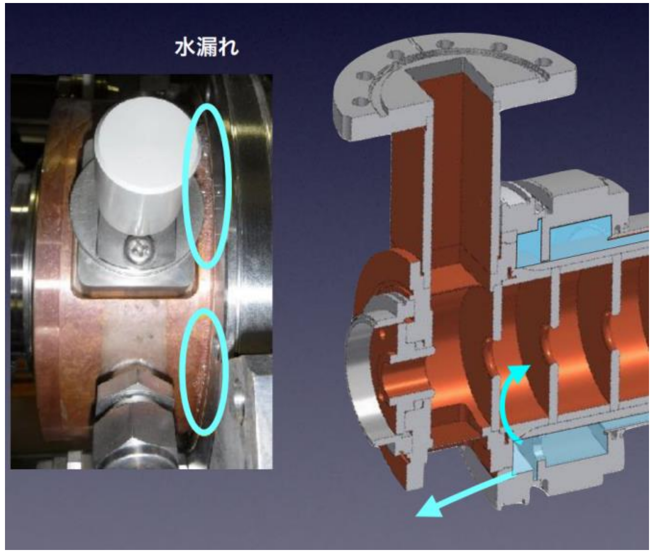
- Mitigation of accelerating structure failures
  - Originally designed for 8 MeV/m (PF injector), but used at 20 MeV/m (KEKB upgrade)
  - Degradation that lead to high field emission rate and discharges
  - Water leaks, field emission , discharge in waveguide, and so on (29 of 60 units have some problems)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

Upgrade during LS1



Damaged iris

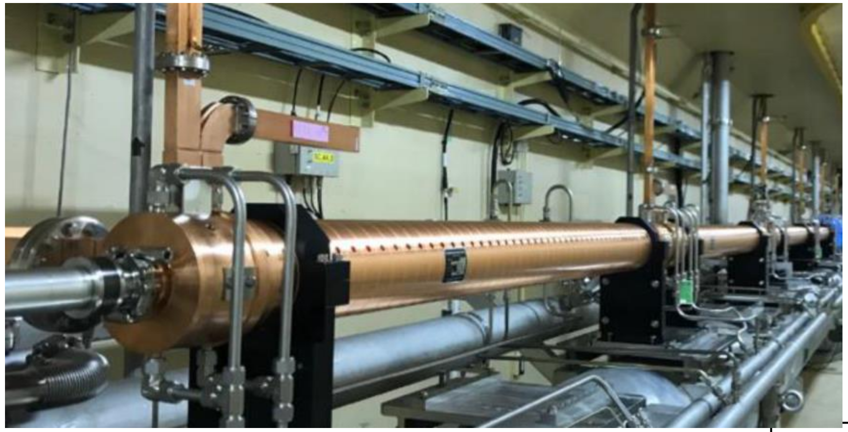




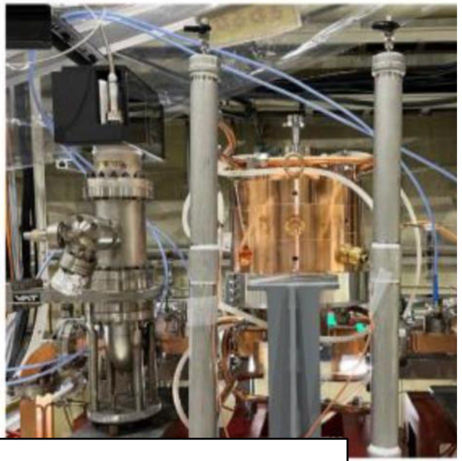
Colling water leakage

New accelerating structures and pulse compressor in beam-acceleration operation

- 5-year upgrade plan to fabricate and install new 16 structures (FY2018 – FY2022)
- Unit 44 already with four new structures and pulse compressor (SCPC) at the rated 20 MV/m
- Remodeled Unit 44 to be reinforced at an accelerating gradient of 30 MV/m in this summer
- New 12 structures completed for replacement of damaged old ones with water leaks or frequent power-reflections in this summer
- New structure: acc. gain ↑7%, surface field ↓20% (reduce breakdown) and 30 MV/m capable
- New pulse compressor (SCPC) : RF performance equivalent to the current KEK-SLED, super compact body, half fabrication-cost



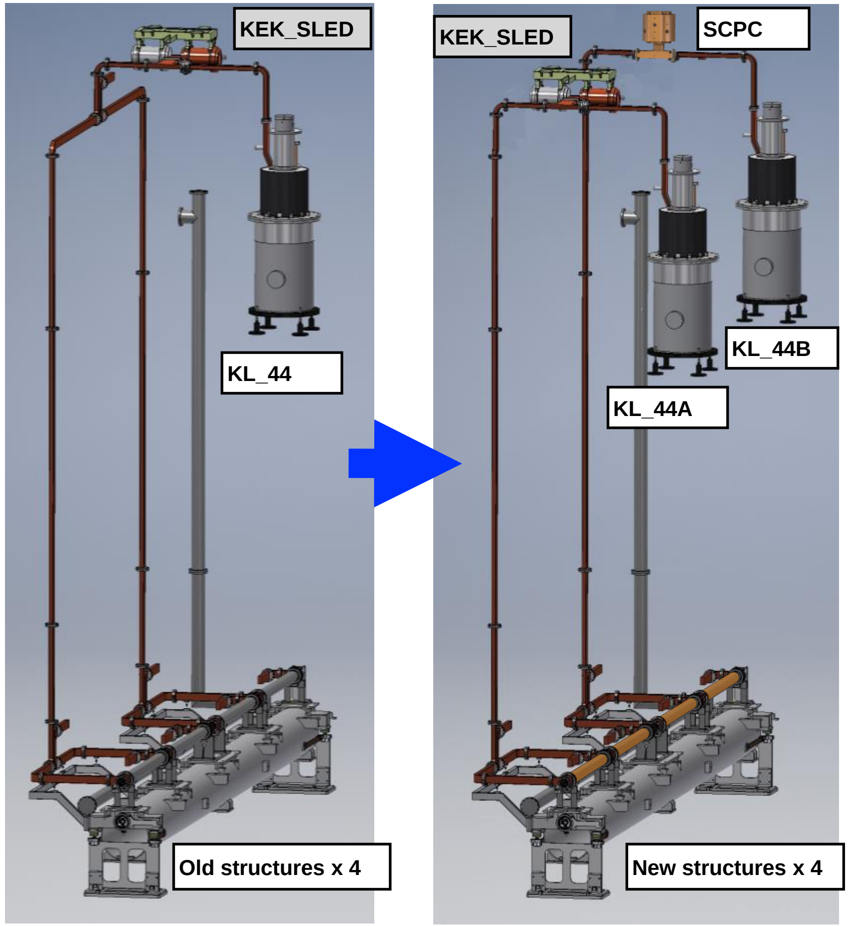
New S-band 2-m-long TW acc. structure



New pulse compressor
Spherical-Cavity Pulse Compressor (SCPC)

H. Ego

Unit remodeled for acc.voltage reinforcement

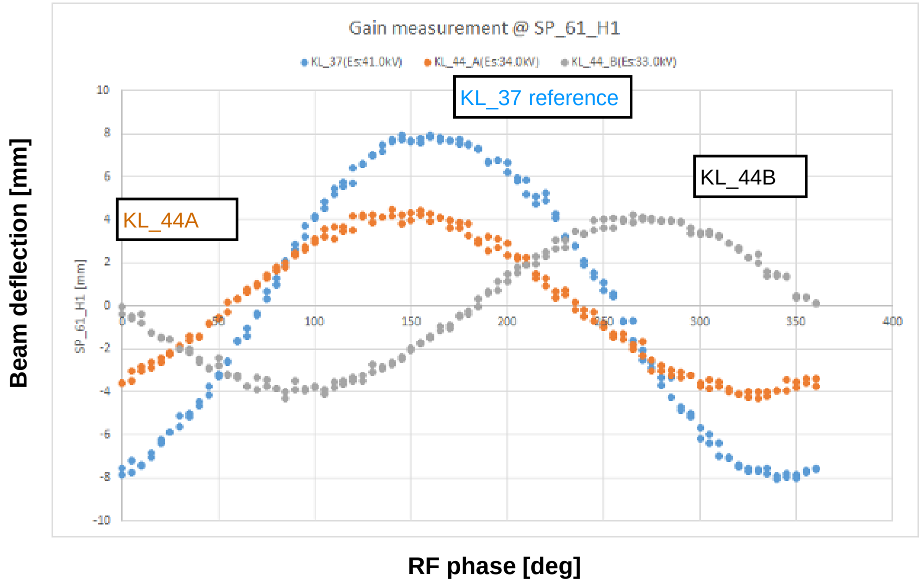


Before

After

SCPC installed in KL_44B

Structures in 44-unit

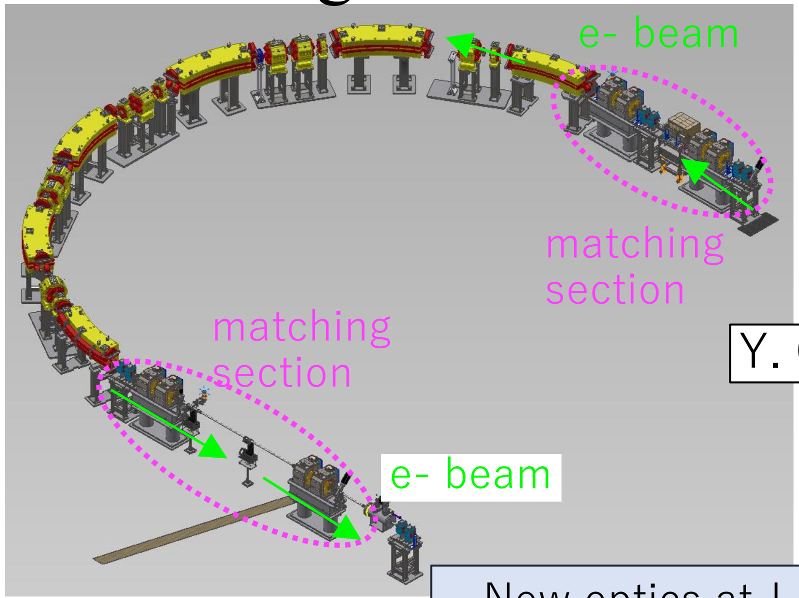


Demonstrated 20 MV/m beam-acceleration

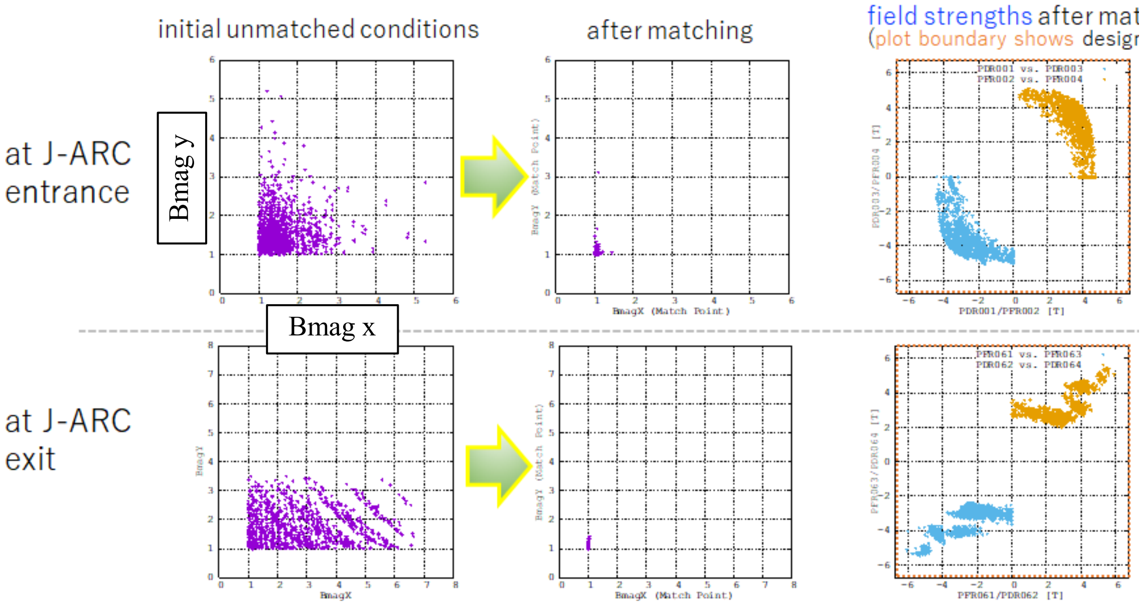
Pulsed Quads at J-ARC for optics matching

Upgrade during LS1

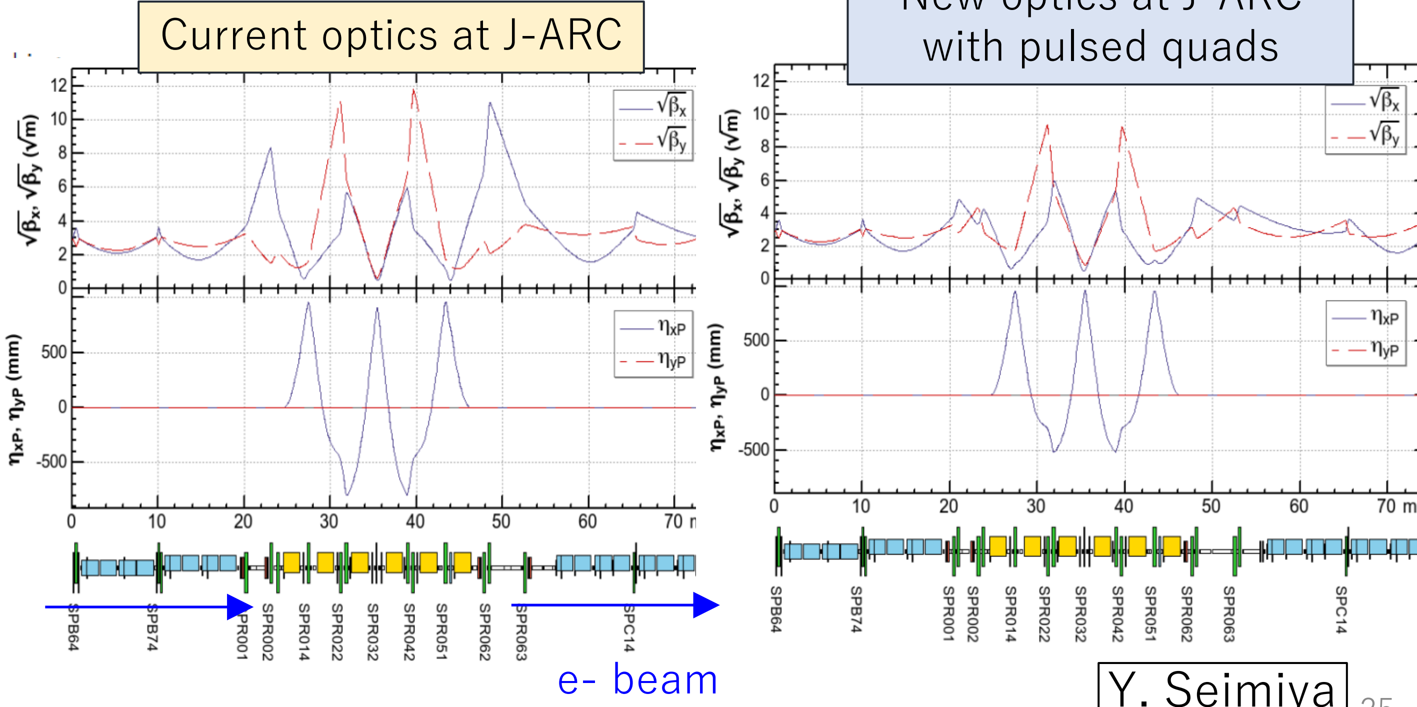
- At the entrance and exit of 180 deg. J-ARC region, a good optics matching is very important to mitigate beam loss and emittance growth.
- Simultaneous matching for both of HER/LER injection beam requires the pulsed quads.
- From the simulation result, 4 pulsed quads at both of entrance and exit of J-ARC are sufficient.



Y. Okayasu



Matching simulation

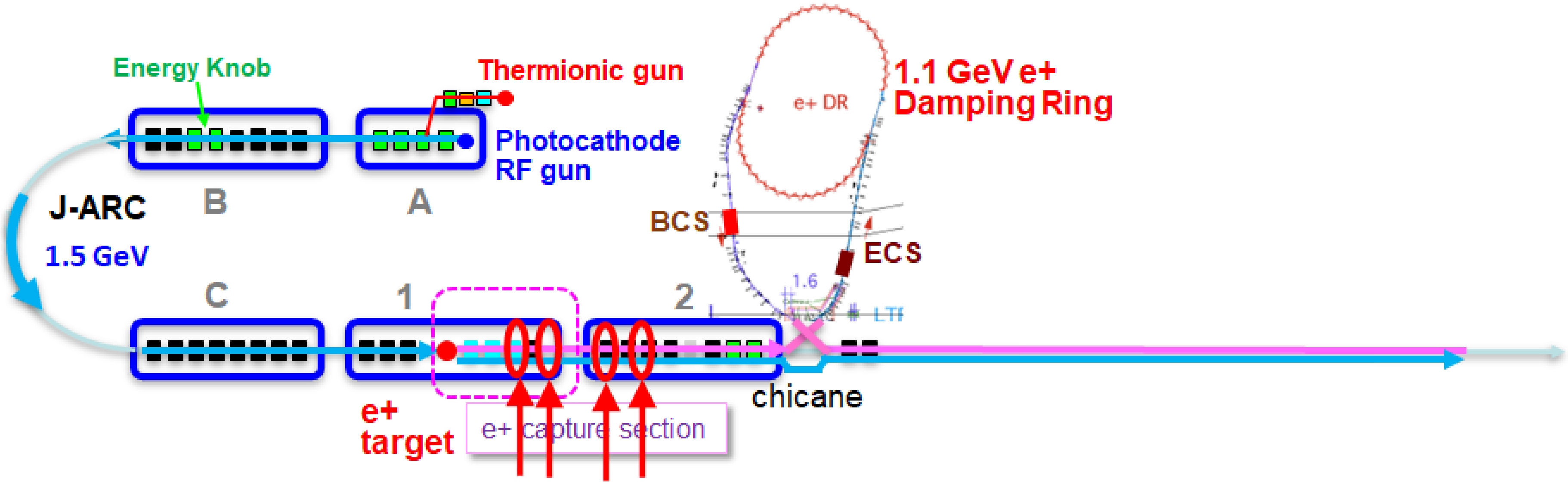


Y. Seimiya

Upgrade during LS1

Pulsed Quads at J-ARC for e- low beta optics

- Current optics at Sector1, 2
  - Large emittance e+ beam is accelerated from 0.1 GeV to 1.1 GeV for DR injection.
  - Quad settings is optimized for e+ beam.
  - For e- beam (3 ～ 4 GeV), focusing force is weak in comparison with optimum parameter. It could cause the emittance growth.

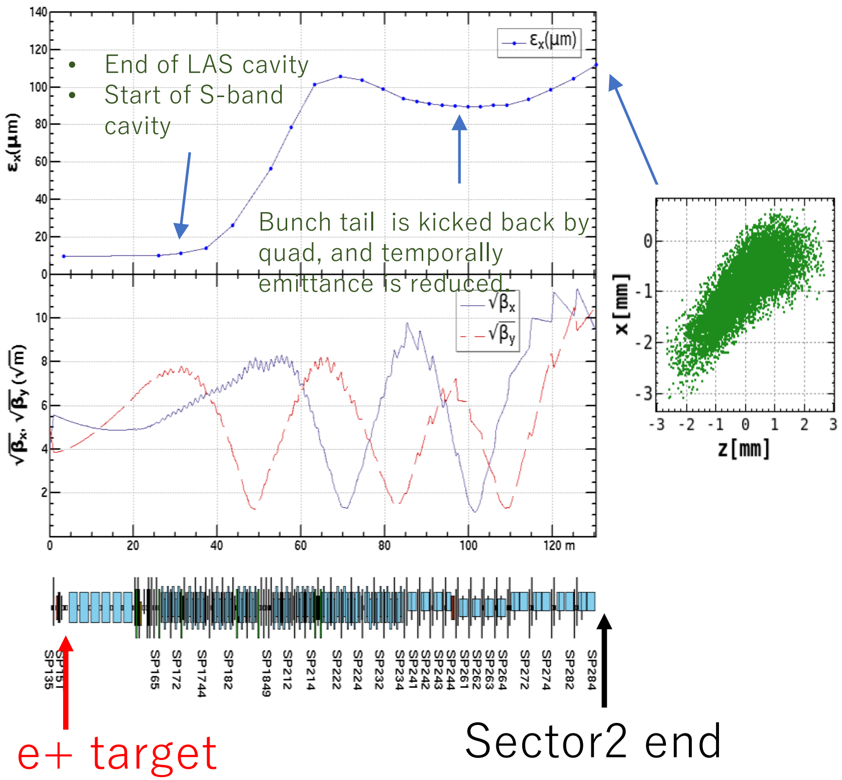


Four DC quads will be replaced by pulsed one.

Pulsed Quads at J-ARC for e- low beta optics (cont'd)

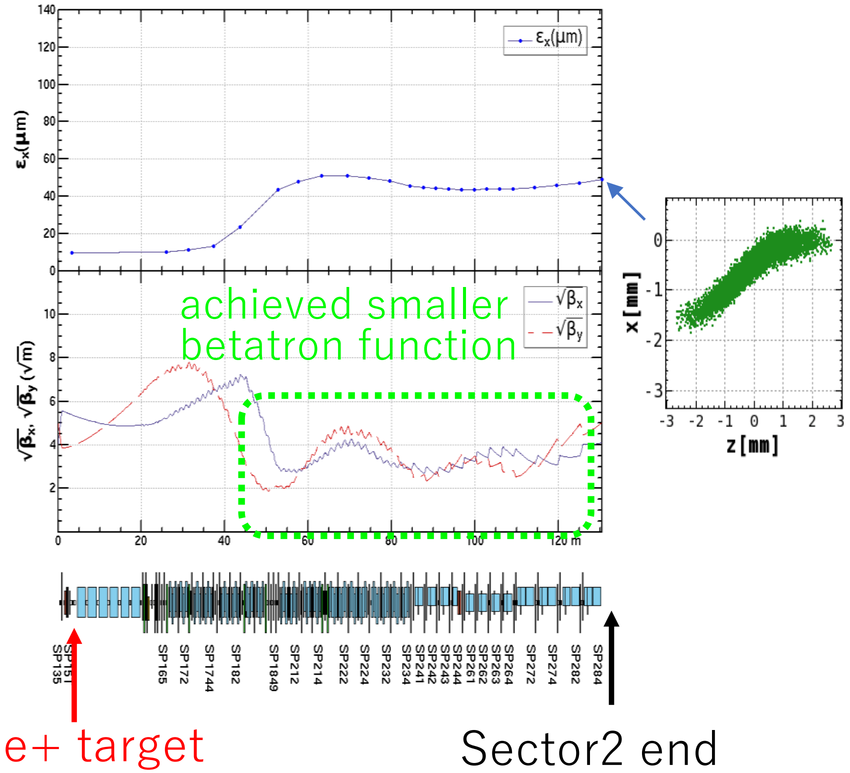
- After only these four pulsed quads are optimized for the e- beam, the betatron function can be decreased.
- Simulation result shows that it can help to decrease the emittance less than half.

$\Delta\gamma\varepsilon x$ ~ 100 um, $\overline{\beta x} = 45.2$ m



Before optimization

$\Delta\gamma\varepsilon x$ ~ 40 um, $\overline{\beta x} = 16.3$ m



After optimization

specification of pulse quad for Sector-1, 2

- requirements on bore size and field strength are minimized by simulation while keeping the performance.
- magnet (size) and ceramic duct are designed to be replaceable with existing DC quad and duct.
- current and turns/coil are optimized to be compatible with the existing pulse power supply.

parameters	DC quad 17_14 type	new pulsed quad 17_14
bore diameter [mm]	44	32
field gradient [T/m]	20.9	23.6
max. current [A]	80	300
pole length [mm]	160	160
effective length [mm]	173.8	168.0
B'L [T]	3.63	3.96
nI [A.turn]	3760	2400
turn of coil /pole	47	8
inductance [mH]	32.3	0.94

K. Yokoyama

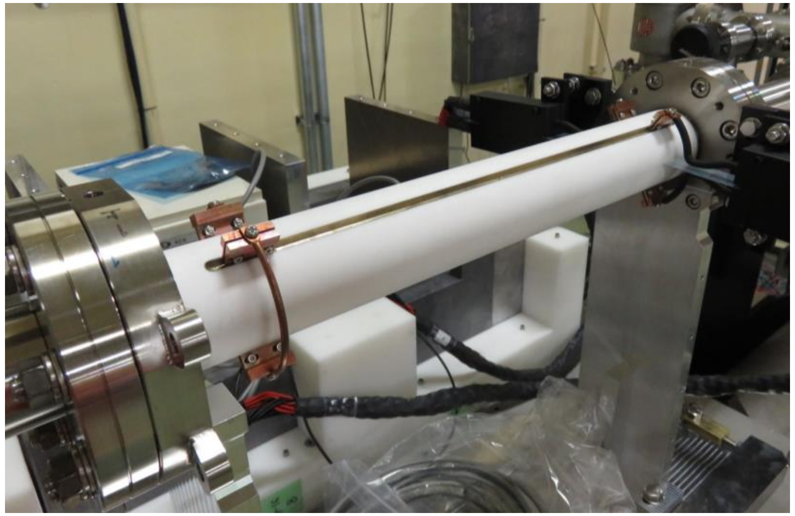
Linac Fast Kicker

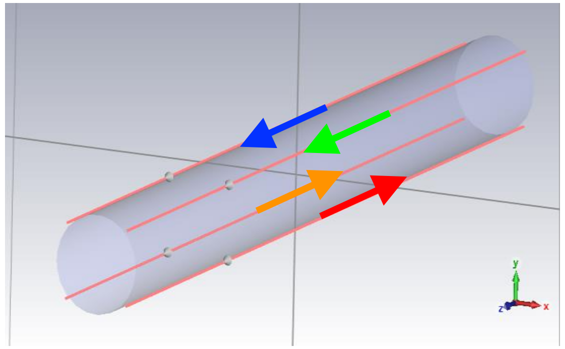
- $1^{st}/2^{nd}$ bunch orbit difference tuning is important because of
  - Injection efficiency improvement for both of bunches
  - Suppression of emittance growth with orbit offset in linac
  - Reduction of beam loss due to orbit difference

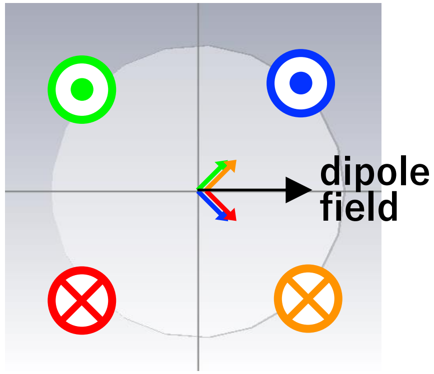
- Requirements for the linac fast kicker
  - pulse rise time < bunch interval (96 ns)
  - sufficient kick angle ~ 0.4 mrad @1.5 GeV
    BL = 2.0×10^{-3} T.m

Ceramic chamber type Fast Kicker

C. Mitsuda



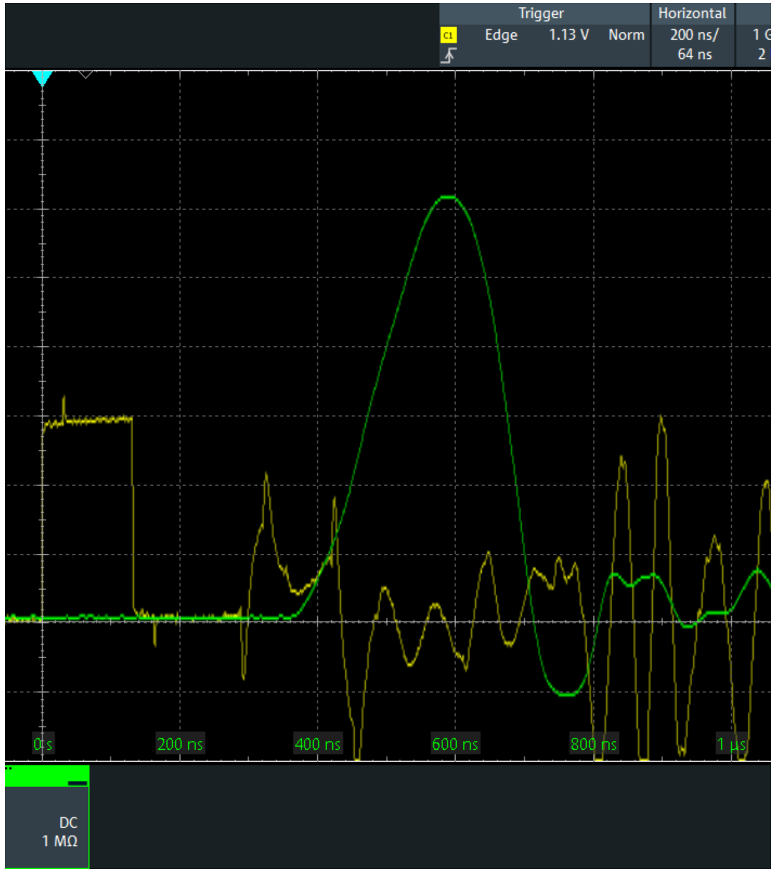




- CCiPM : Ceramics Chamber with integrated Pulsed Magnet
- Magnetic field type kicker
- This kicker has four parallel coil wires.
- The current configuration described above
  (parallel and anti-parallel currents) generates
  horizontal dipole magnetic field, (vertical beam kick).

Pulse power supply for fast kicker

- Characteristics of pulse power supply
  - SiC FET high-voltage switch (supplied by Nexfi company)
  - pulse rise time < 96 ns (target value) to kick only 2nd bunch
  - peak current 500 A
  - max voltage 10 kV
  - precise timing control for kick angle fine tuning
  - switch module installed in the tunnel close to kicker magnet (needs thick radiation shield)

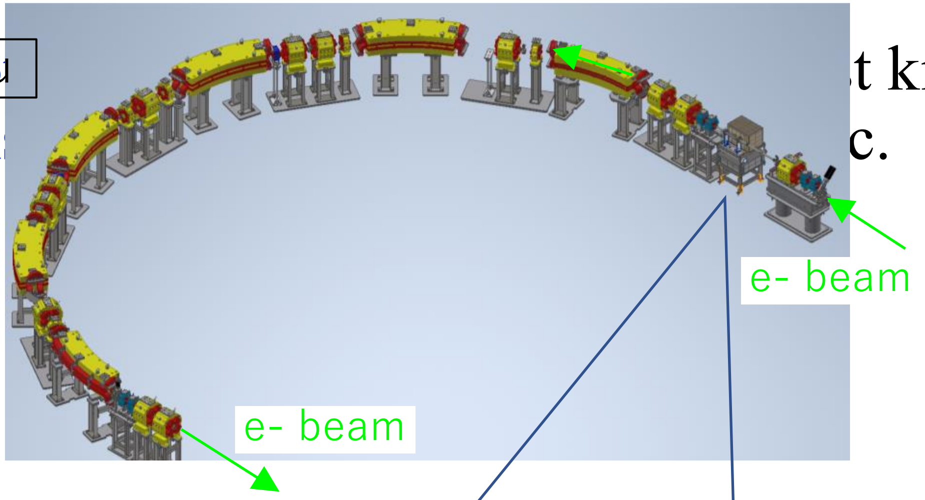


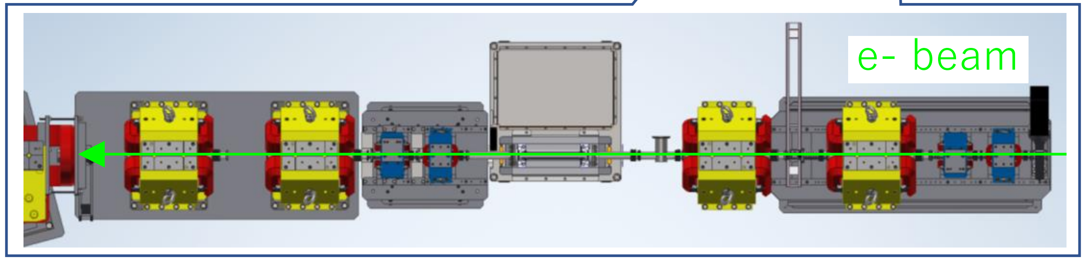
Achieved pulse waveform:
rise time ~ 200 ns
fall time ~ 100 ns

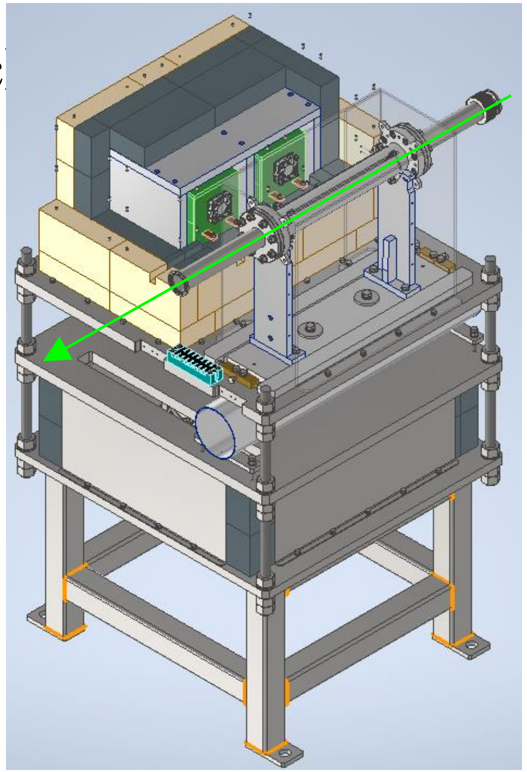
Y. Enomoto, T. Natsui, Y. Okayasu

Fast Kicker Installation

- The first proto Y. Okayasu t kic
  has been in c.

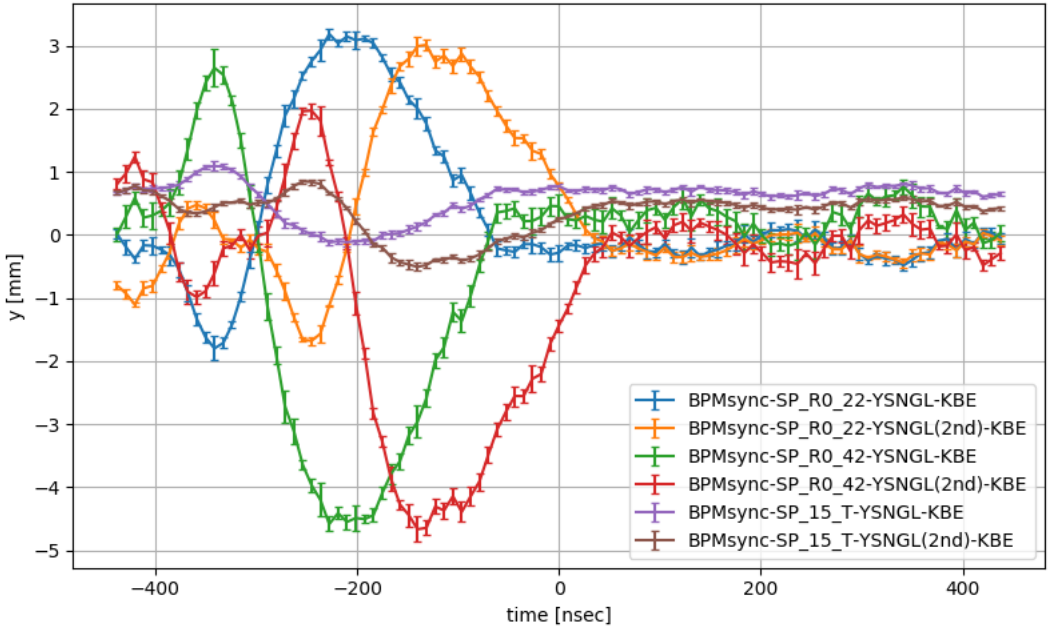






Bunch dependent kick test

- Bunch dependent beam kick test was performed with the prototype fast kicker in J-arc (2022.12.26).
- The blue and orange lines show the orbit deviations of the first and the second bunch of the electron beam as a function of fast kicker pulse timing.



- Next two kickers will be installed at linac Sector-5 and HER-BT in summer of 2023 for the operation after LS1

Summary

- Simultaneous top up injection operation of 4 storage rings (SuperKEKB HER/LER, PF, PF-AR) + DR has been successfully conducted.

- e- beam
    - Laser system has worked fine without any significant trouble.
    - DOE was installed also at 2nd laser line in the last summer maintenance, and it has worked fine.
    - In the run 2022a/b, bunch charge of 2 nC can be kept with bunch charge feedback.
    - 5 nC from gun was demonstrated. Further beam study is on-going during LS1.
    - New DOE with large area improve energy spread and emittance until HER injection.
    - BTe-ECS is planned to install at FY2024
- e+ beam
    - The new FC is working fine.
    - Reached bunch charge of 3.5 nC at BT end (final design 4 nC).
- Upgrade work during LS1
    - Pulsed Quads (x8) at J-ARC for the simultaneous dedicated matching of HER/LER injection beam
    - Pulsed Quads (x4) at Sector1, 2 for low beta optics of HER injection beam
    - New accelerating structure
    - Replacement of air conditioners at SectorA, B (in the accelerator tunnel)
    - Fast kicker for 2nd bunch orbit correction
- Issues
    - Emittance growth at end of BT2 for both of e- and e+ beam (BT report, Injection report)
    - Low e- injection efficiency of 2nd bunch
    - Increase the e- bunch charge while keeping small emittance