Linac status

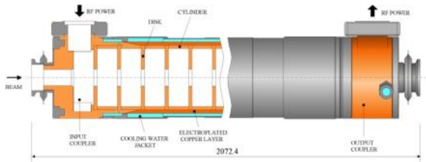
Masanori Satoh (Acc. Lab. Div. V, KEK)
on behalf of Injector Linac Group and Linac Commissioning Group

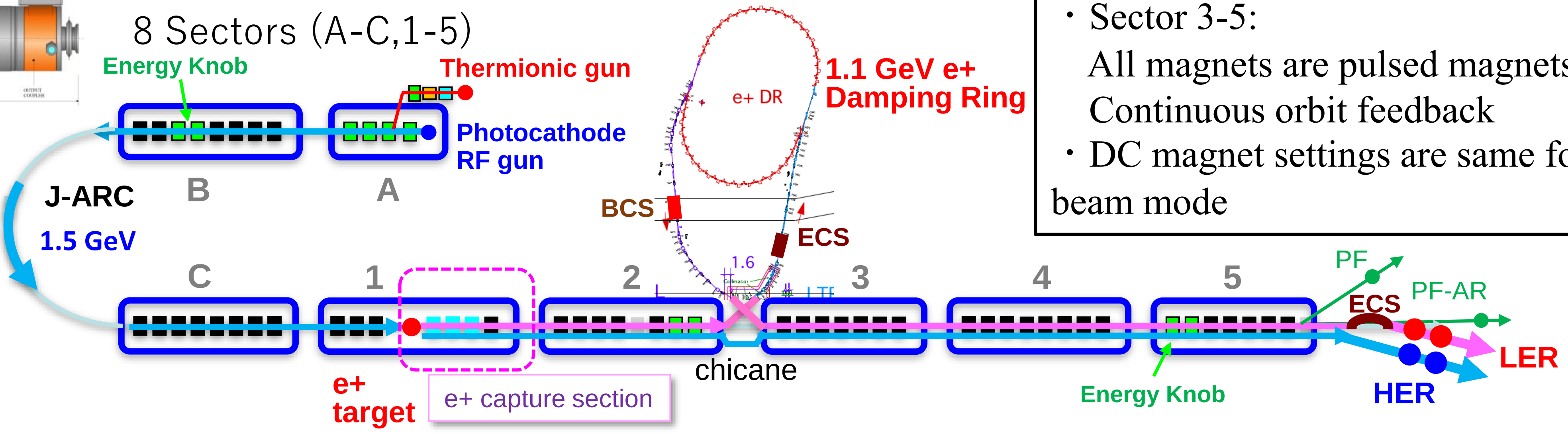
Contents

- Injector outline, e-/e+ status and issue
- Upgrade work during LS1
- ARC recommendations
- Summary

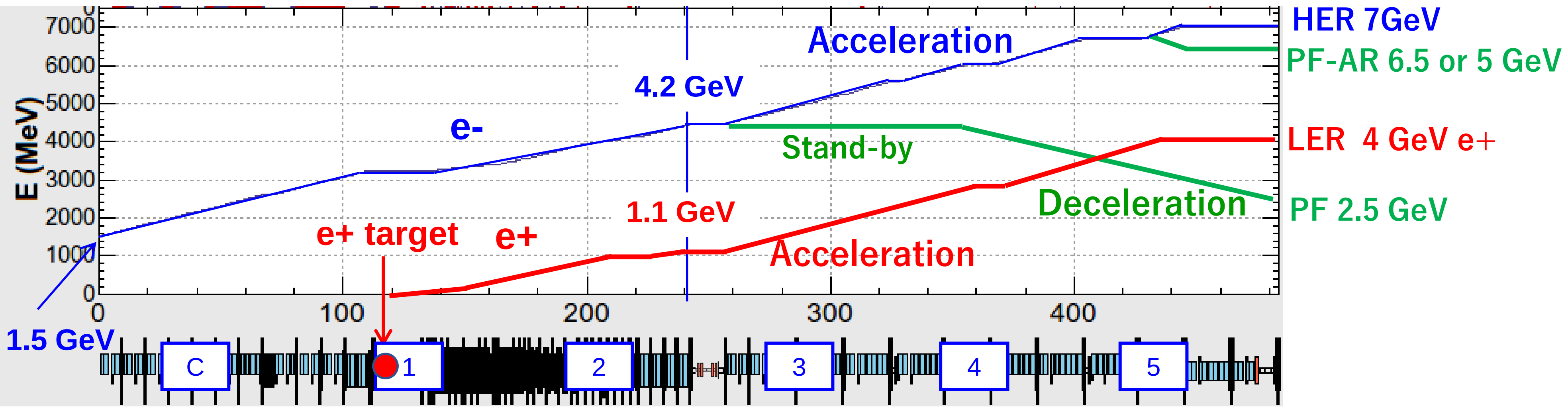
Injector Linac Layout

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



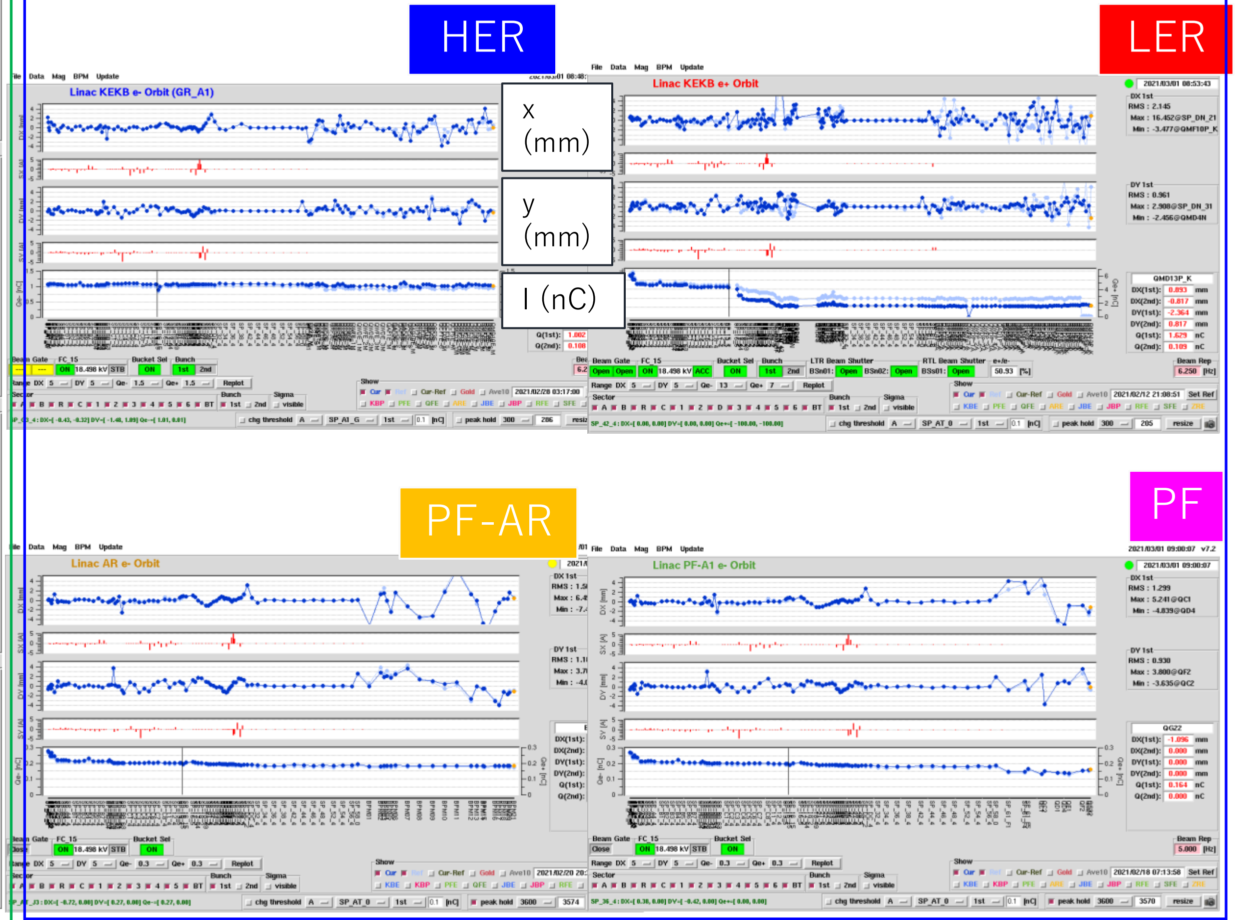
Beam energy variation for each beam mode along the beam line after J-ARC

Simultaneous top up injection to 4 rings + DR (May 2018-)
- stored current and linac beam orbit -

Outline

Stored current (1 day)

Linac/BT beam orbit

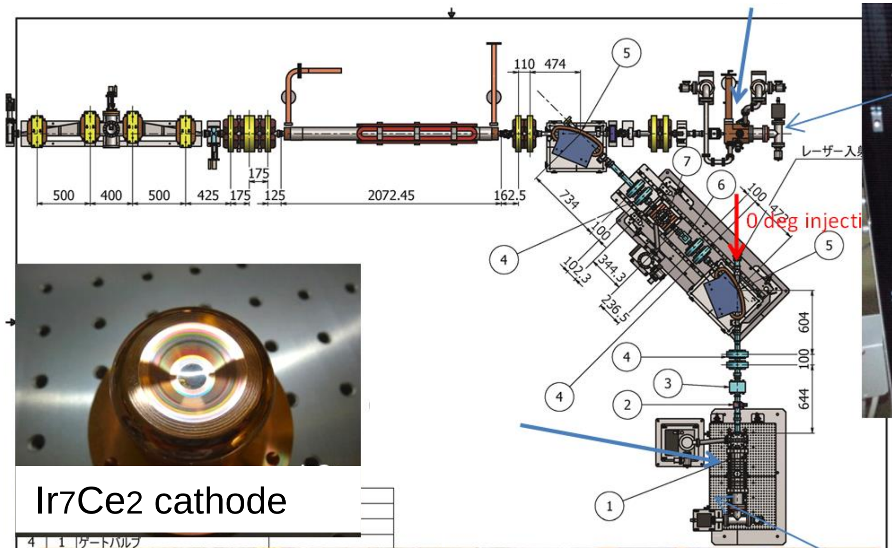


since May 2018

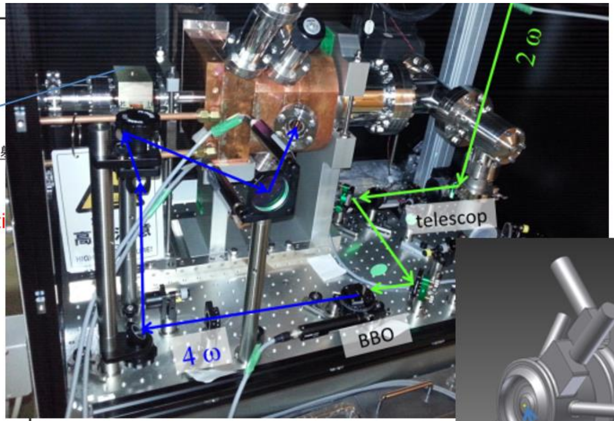
e- beam status and issue

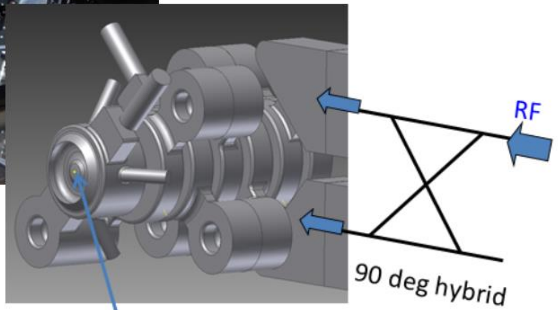
Low emittance photocathode rf e- gun

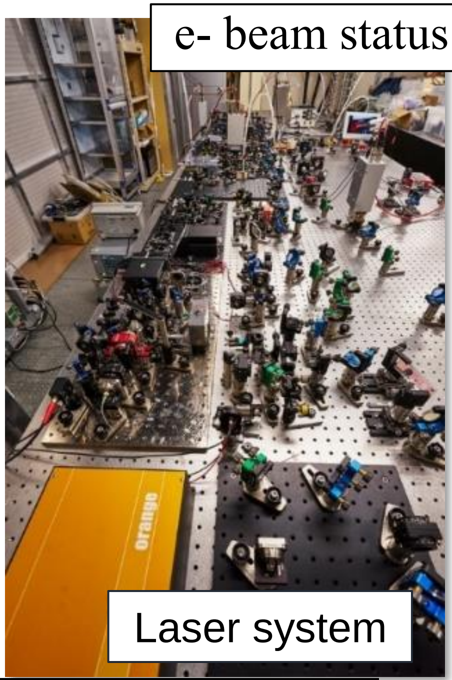
e- beam status



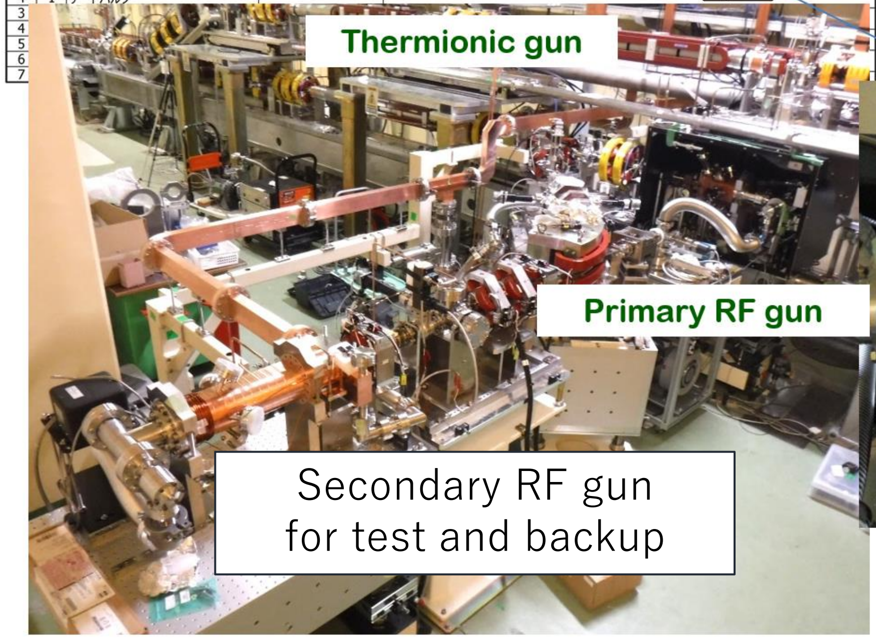
Ir_7Ce_2 cathode





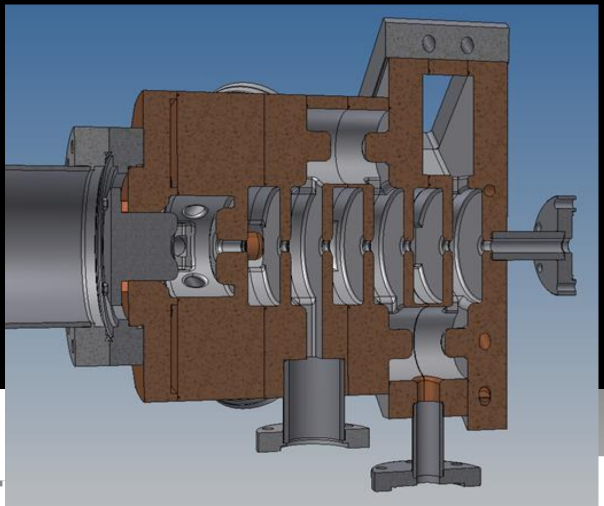


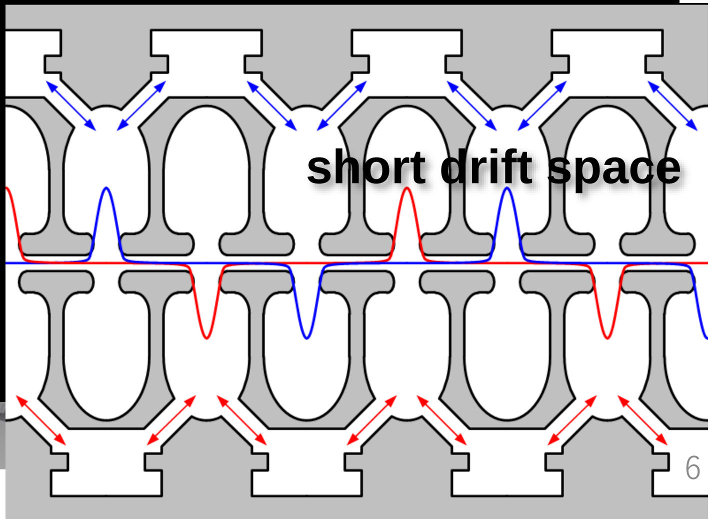
Laser system



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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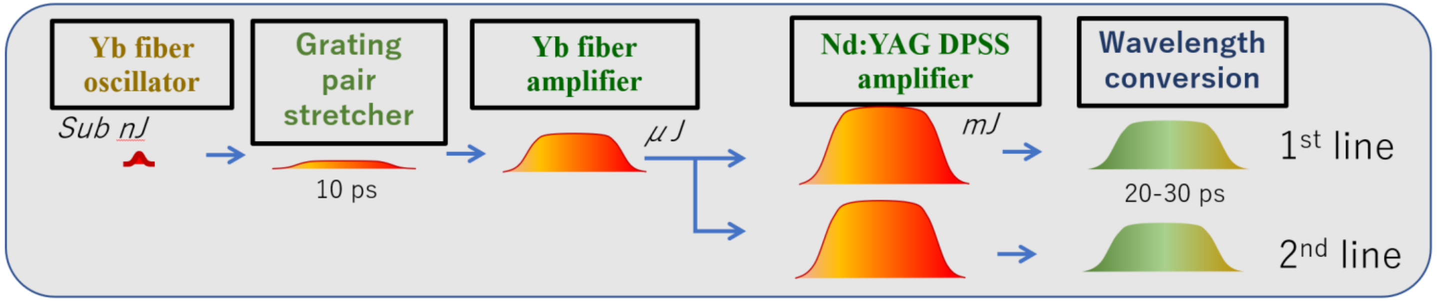
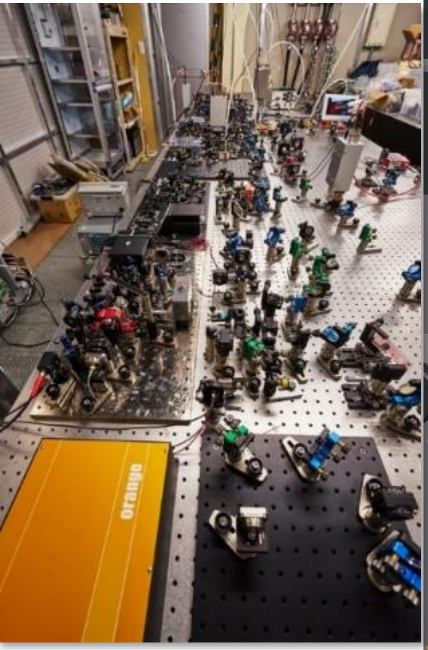
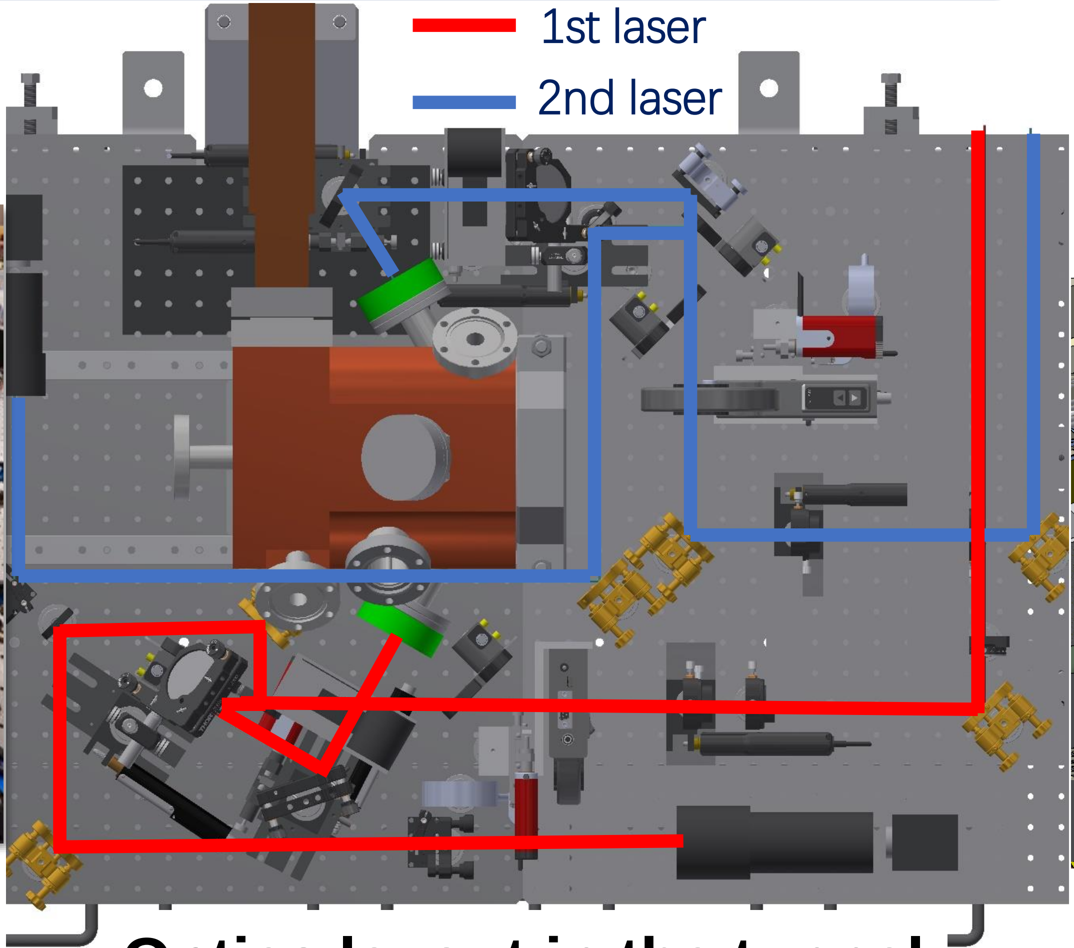
Hybrid laser system for rf e- gun

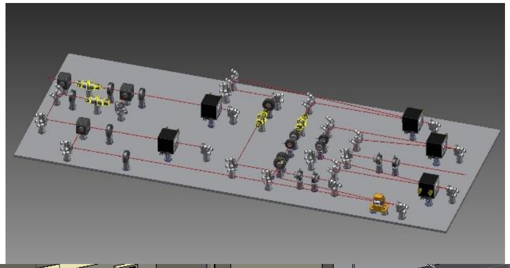
- Yb doped fiber and Nd:YAG DPSS module Amplifier

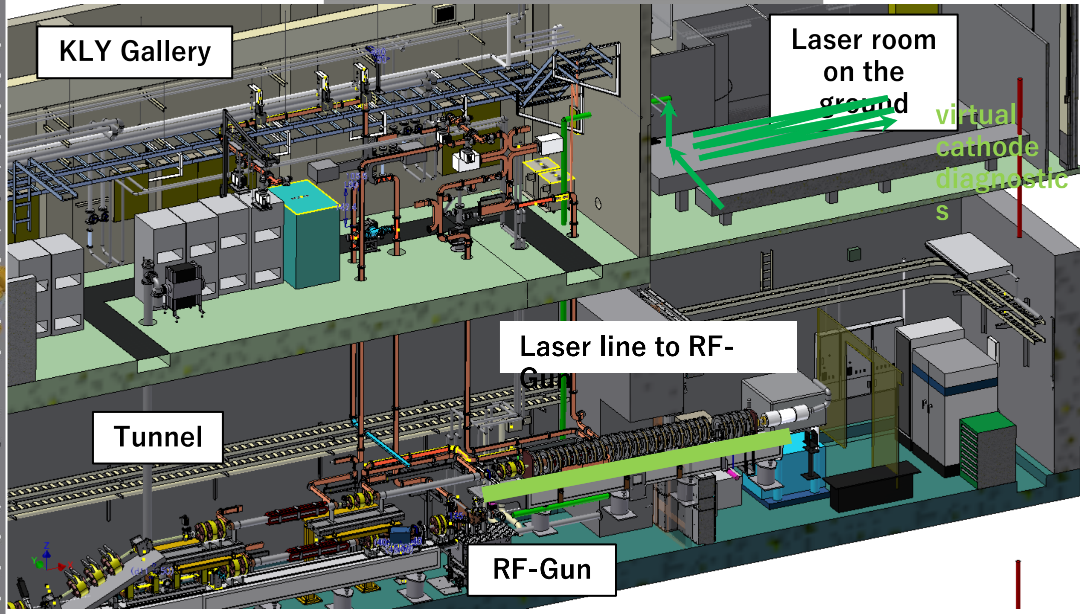


- **Output Power in 1st line:**
- *ω (1064 nm): 32 mJ*
- *2ω (532 nm): 12 mJ*
- *4ω (266 nm): 1.3 mJ*









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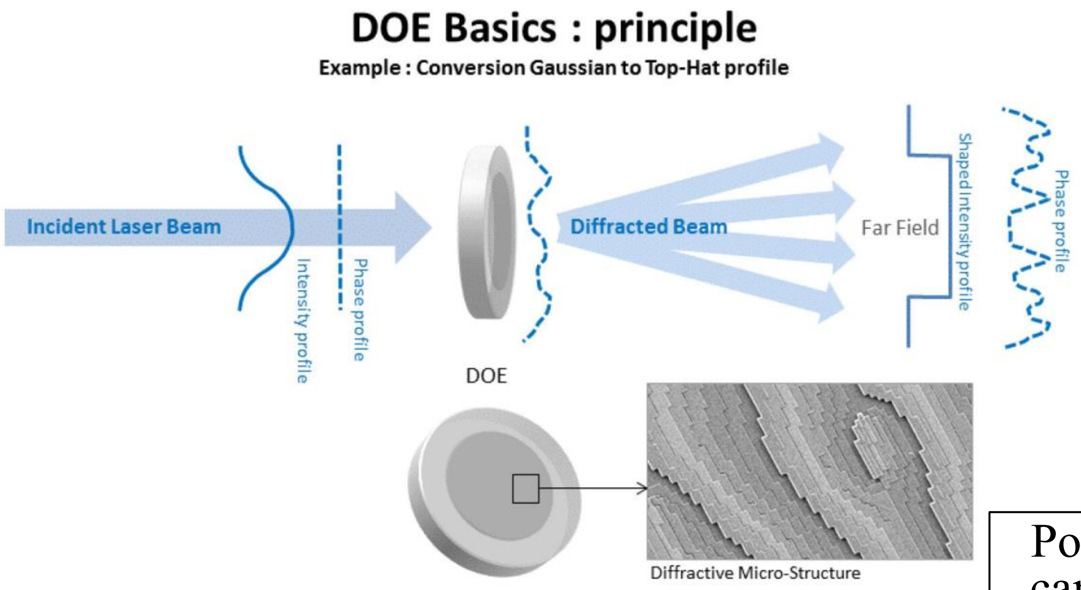
Optics layout in the tunnel

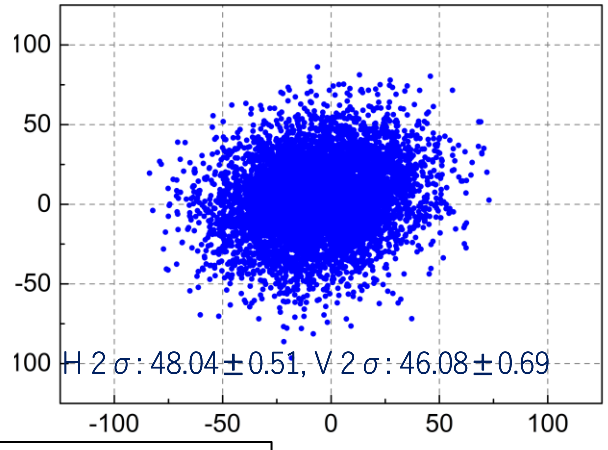
Laser transport line

DOE for reshaping of laser spatial distribution

e- beam status

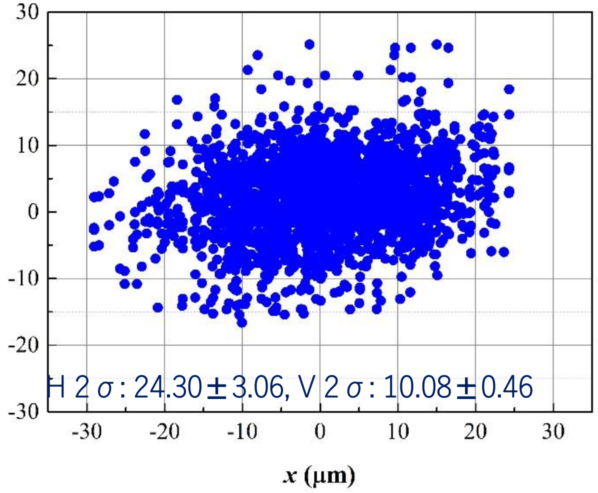


2019.06 without DOE & beam position sensor

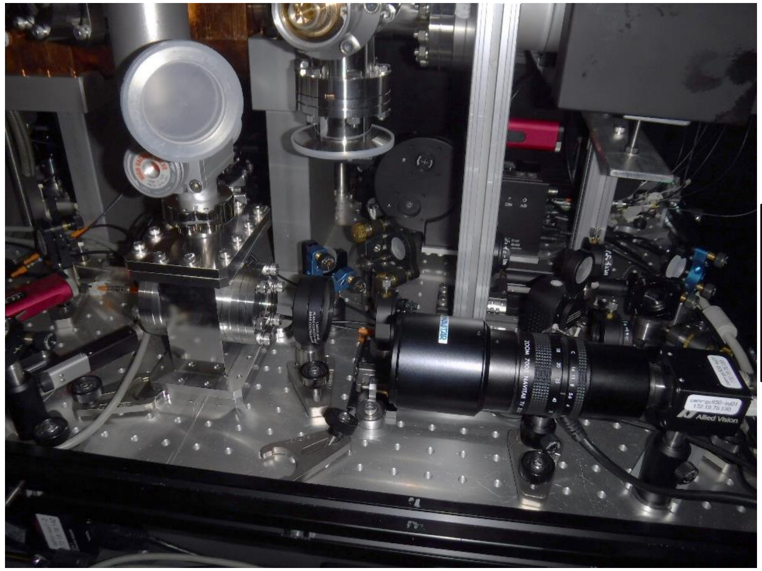


x (μm)

2021.06 with DOE & beam position sensor

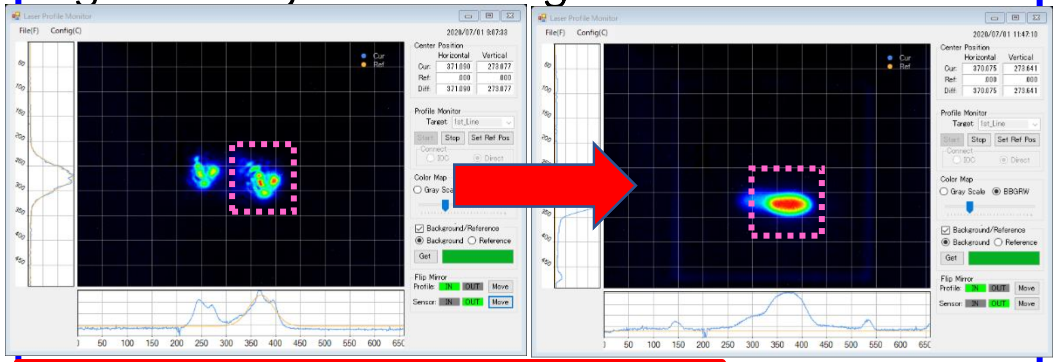


Pointing stability can be improved.



DOE is installed in vacuum chamber filled with Argon gas.

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.

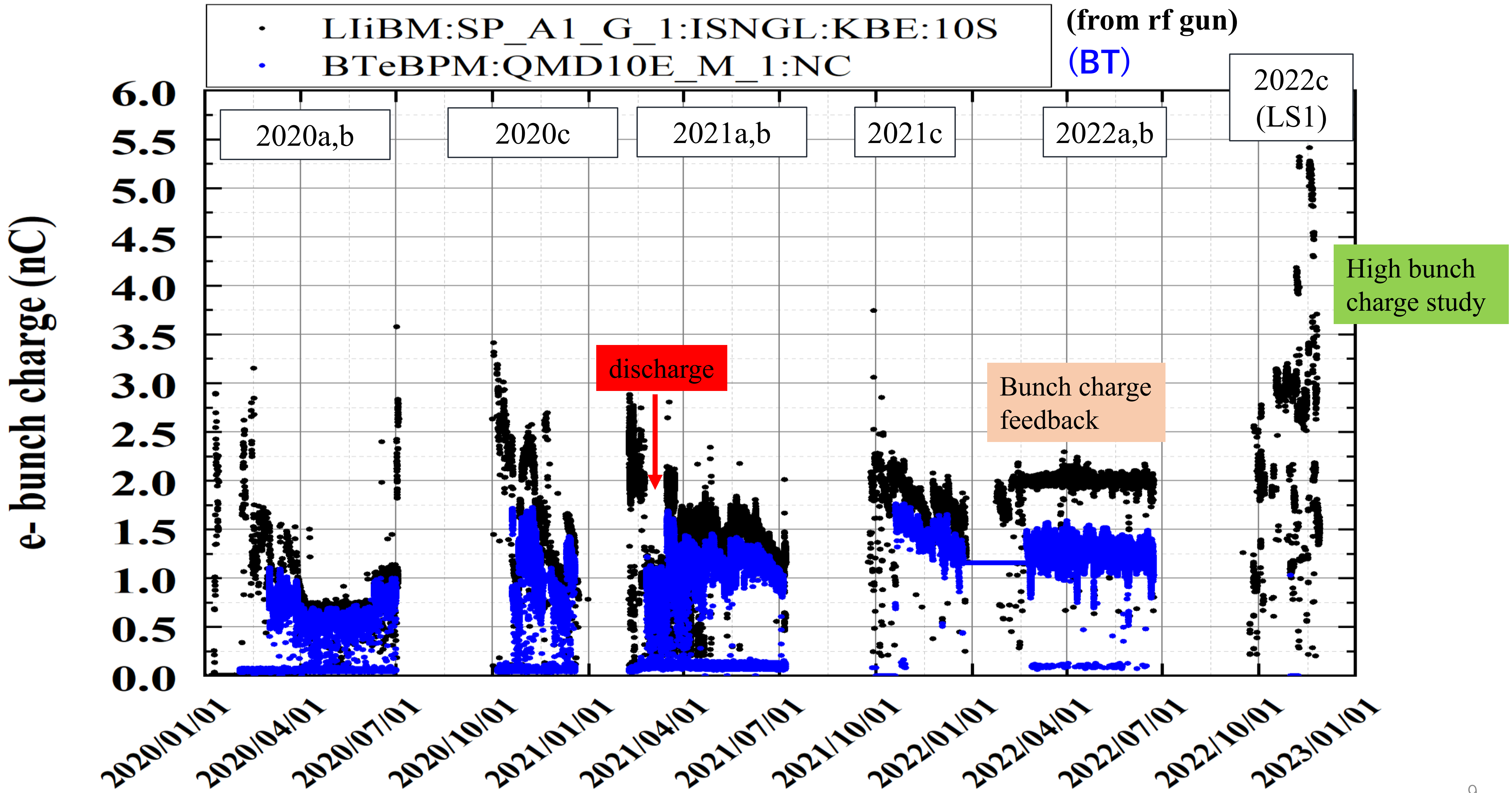


world first DOE application in UV laser

R. Zhang

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

e- beam status

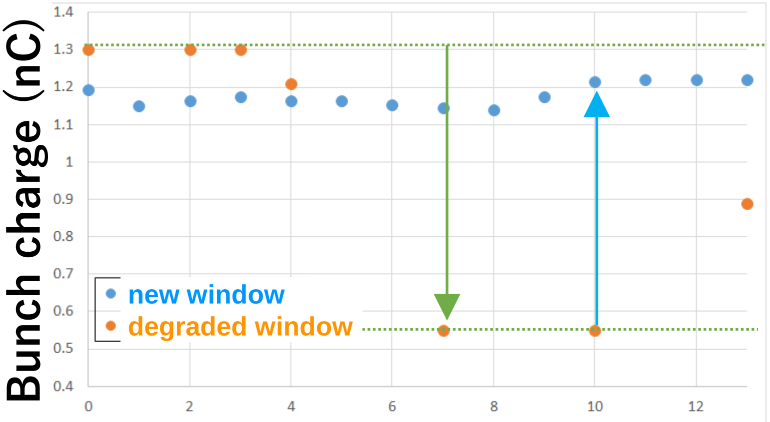


Issue of rf gun laser window degradation

e- beam issue

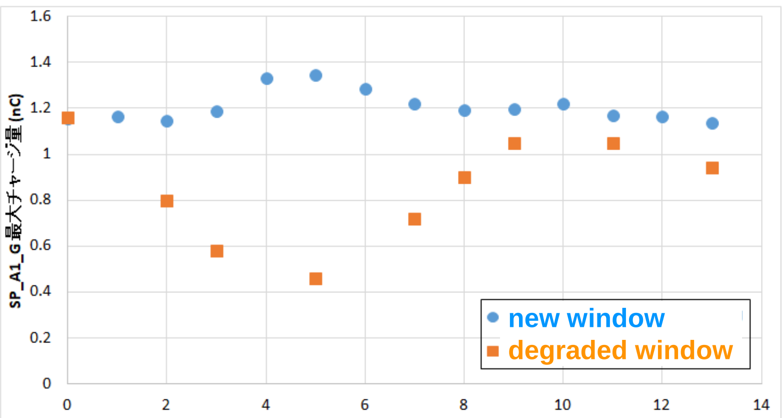
- Long term operation makes rf gun laser windows dirty for both of 1st and 2nd line.
- It decrease the transmittance of laser power through window and bunch charge intensity.
- After replacement of the laser window, the bunch charge intensity is recovered.
- Vacuum ion pump was installed between the 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

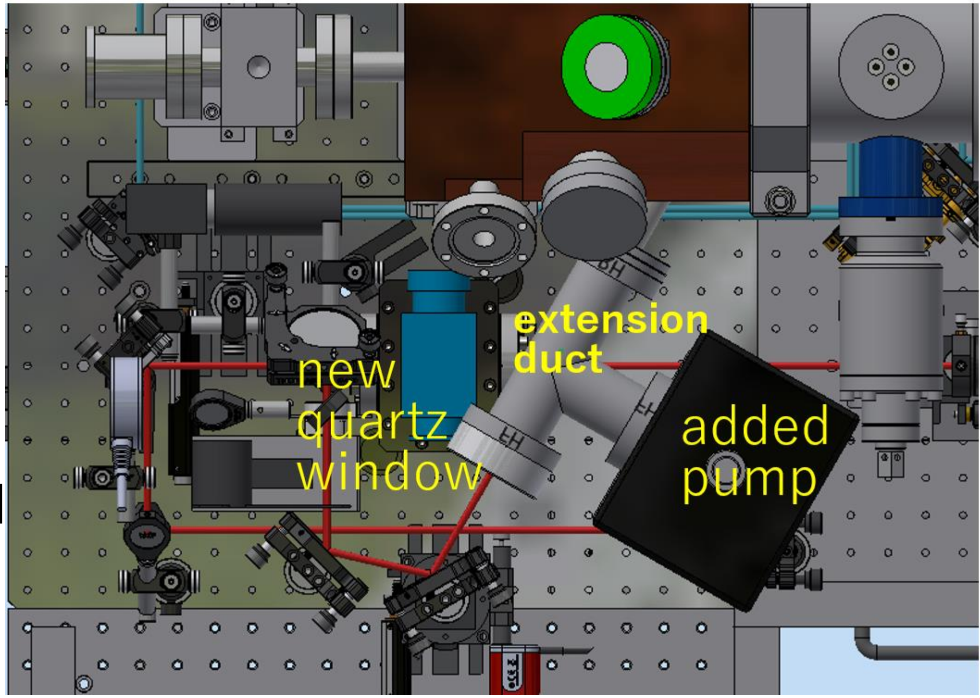


1st-line laser incident position [mm]

e- intensity by 2nd-line laser



2nd-line laser incident position [mm]

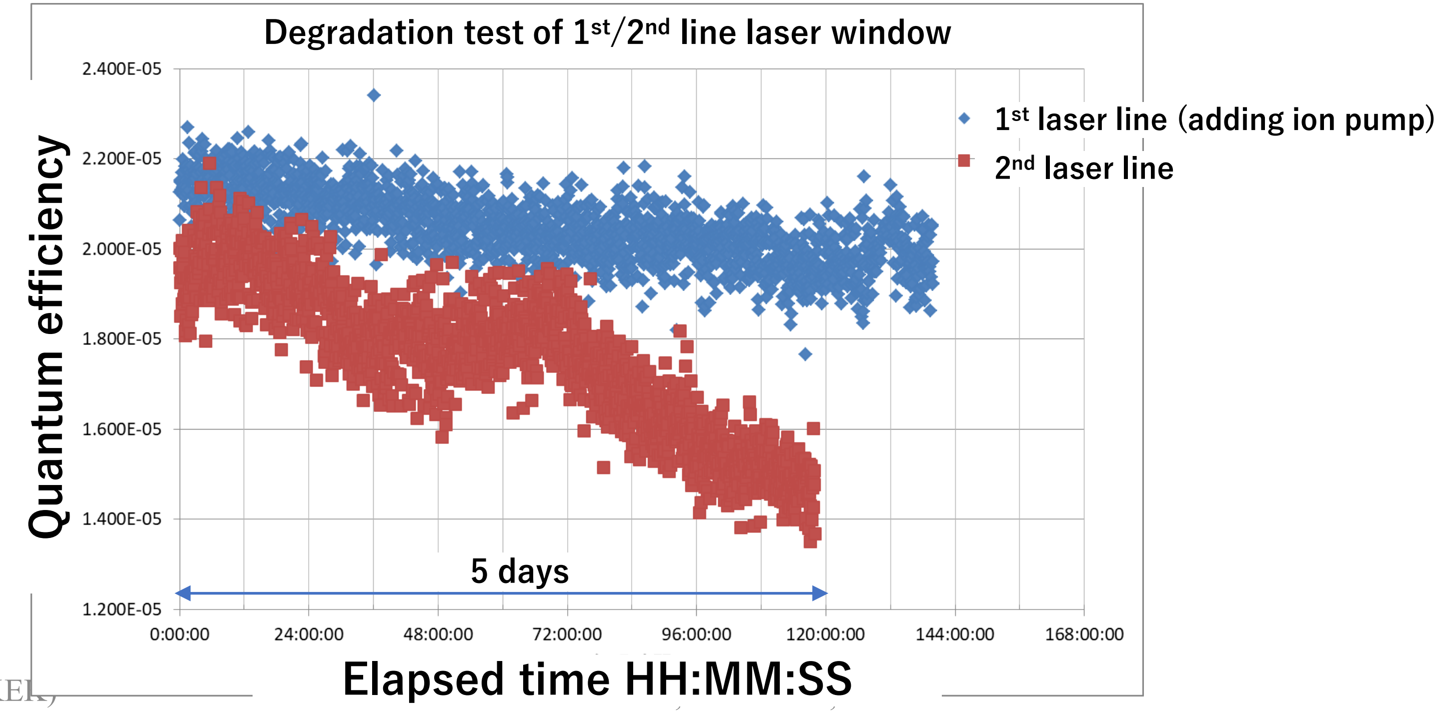


M. Yoshida

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

e- beam summary and issue

- Thermionic DC e- gun has worked fine.
- Photocathode rf e- gun
  - Laser system and DOE element has worked fine without any significant trouble.
- Increase of bunch charge
  - High bunch charge e- was demonstrated. Achieved 5 nC from e- gun and 4 nC at the linac end.
  - However, the beam loss at J-ARC and e+ target location should be minimized. Beam orbit stability should be also improved.
  - Further beam study will be continued during LS1.
- Issue
  - Gradual decrease of bunch charge due to laser window deterioration. It could be solved by adding the extension vacuum chamber and ion pump.
  - 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.

<u>e- emittance</u>

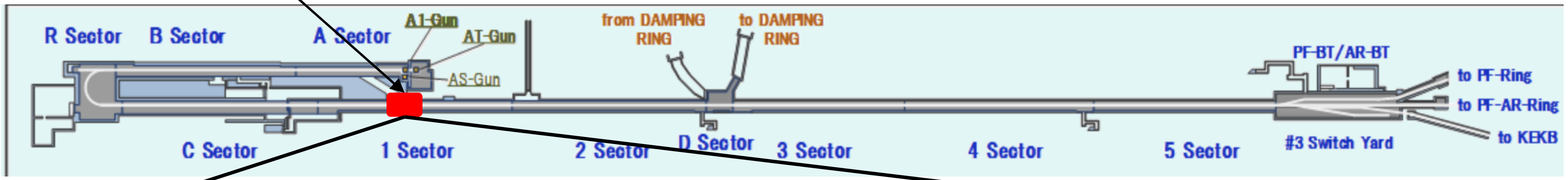
Measured $\varepsilon_{nx,nxy}$ (2 nC) : 20/20 μm (at BT1)

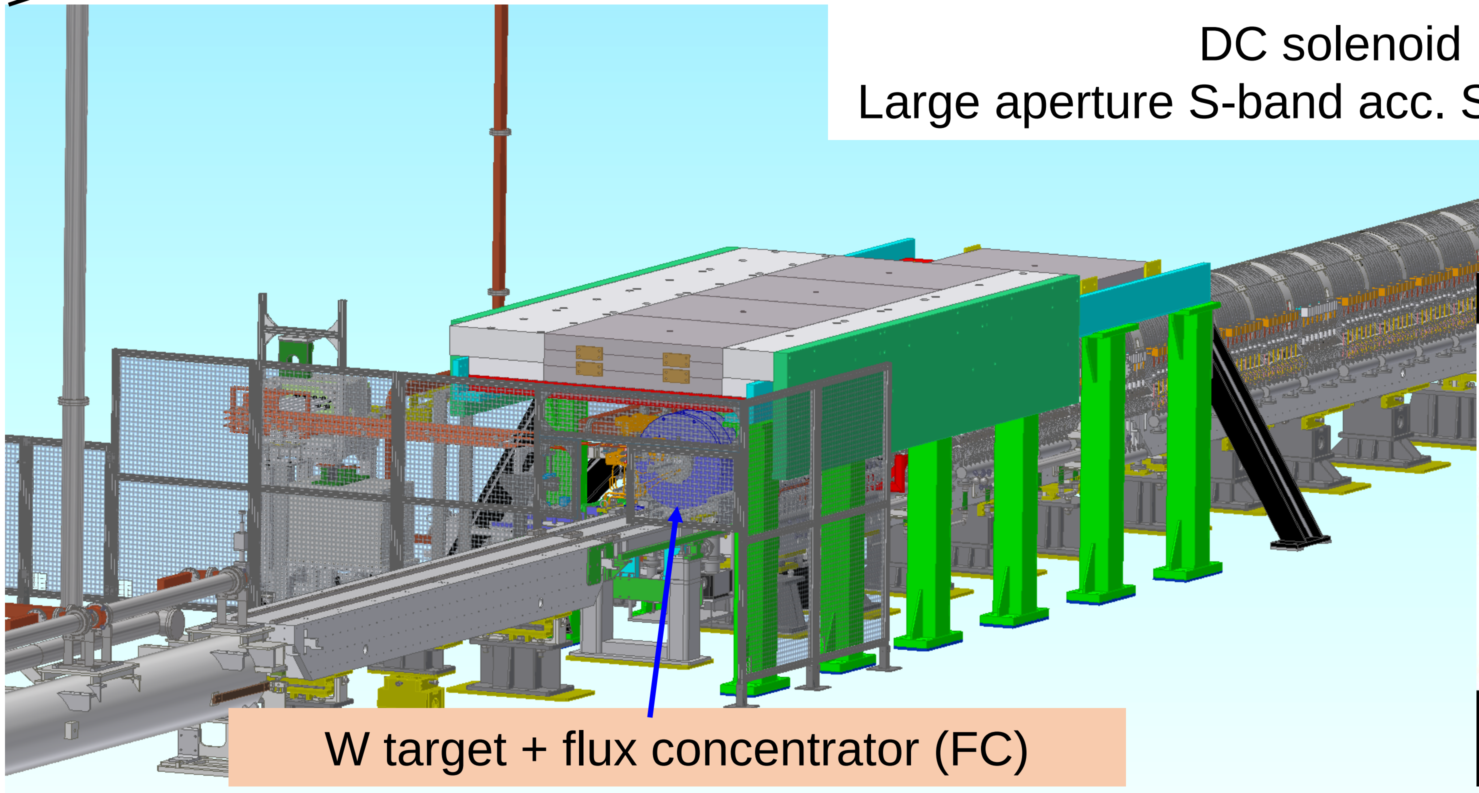
Goal: $\varepsilon_{nx,nxy}$ (4 nC) : 40/20 (H/V) μm

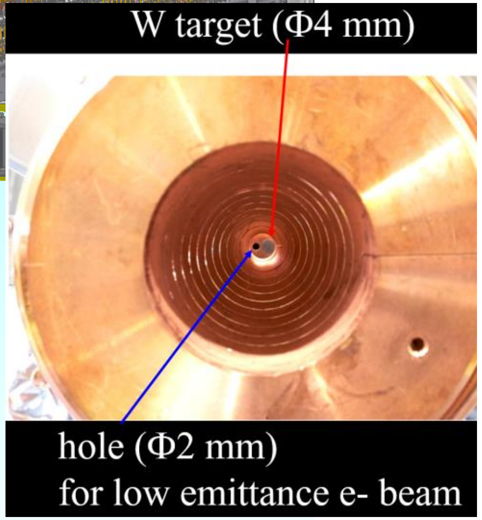
e+ beam status and issue

Positron source setup at Sector1

Positron target and capture section







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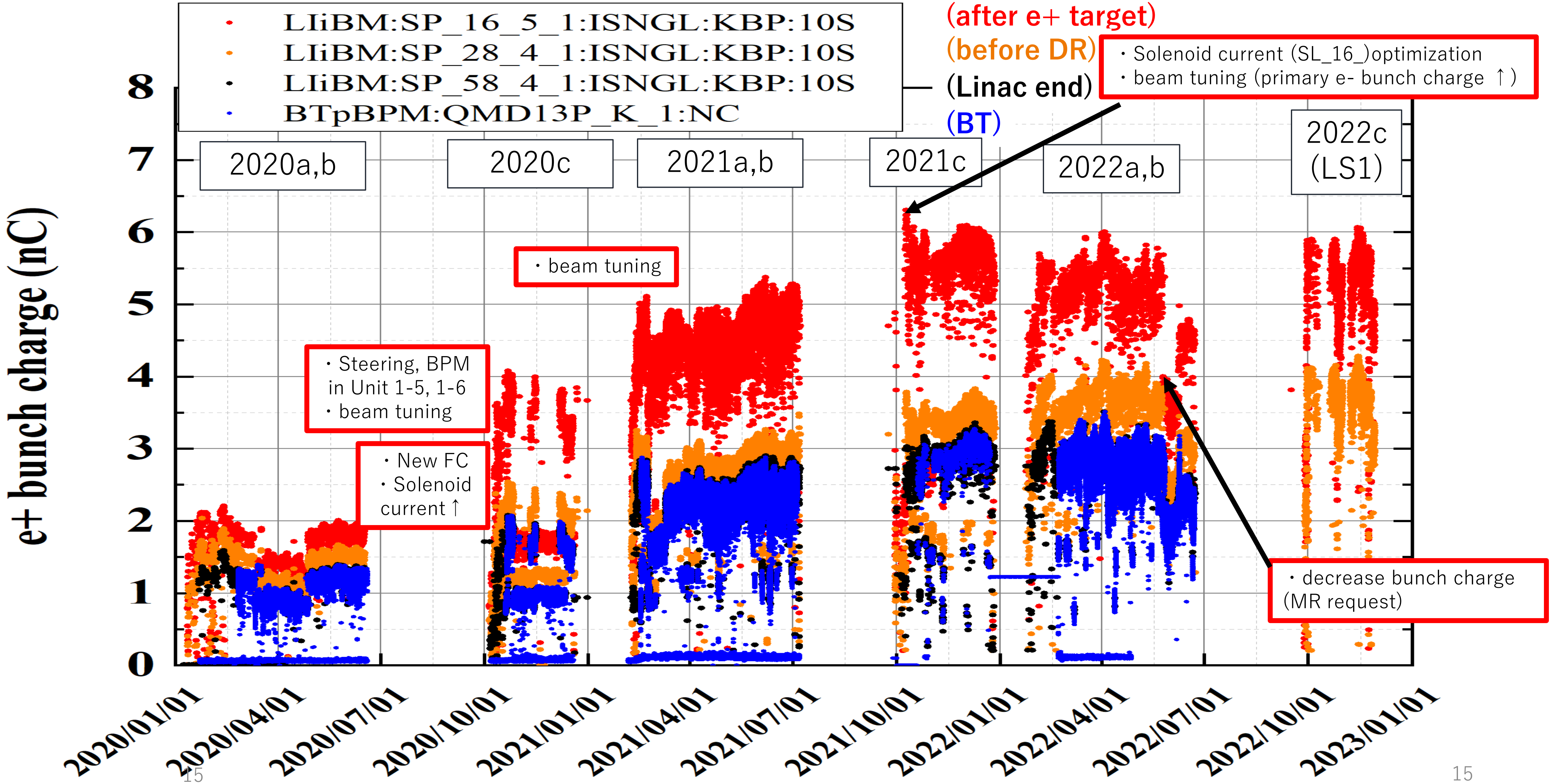
e+ bunch charge history (2020a to 2022c)

e+ beam status



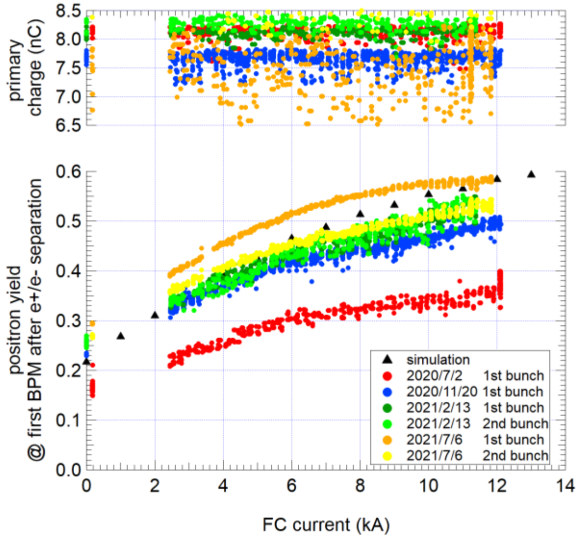
e+ beam summary and issue

- 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
- 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.
  - Horizontal emittance after DR is larger than design value. Low emittance DR optics will be tested after LS1.

<u>e+ emittance</u>

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

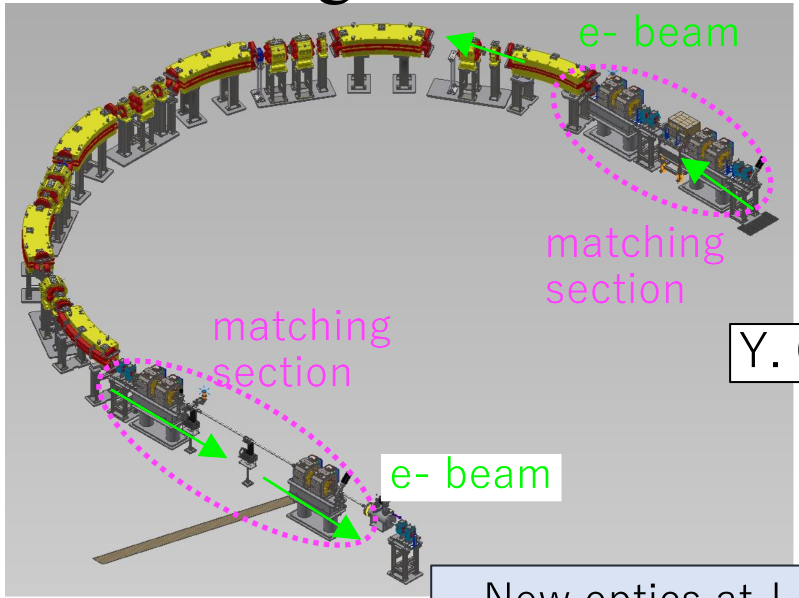
Upgrade work during LS1

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

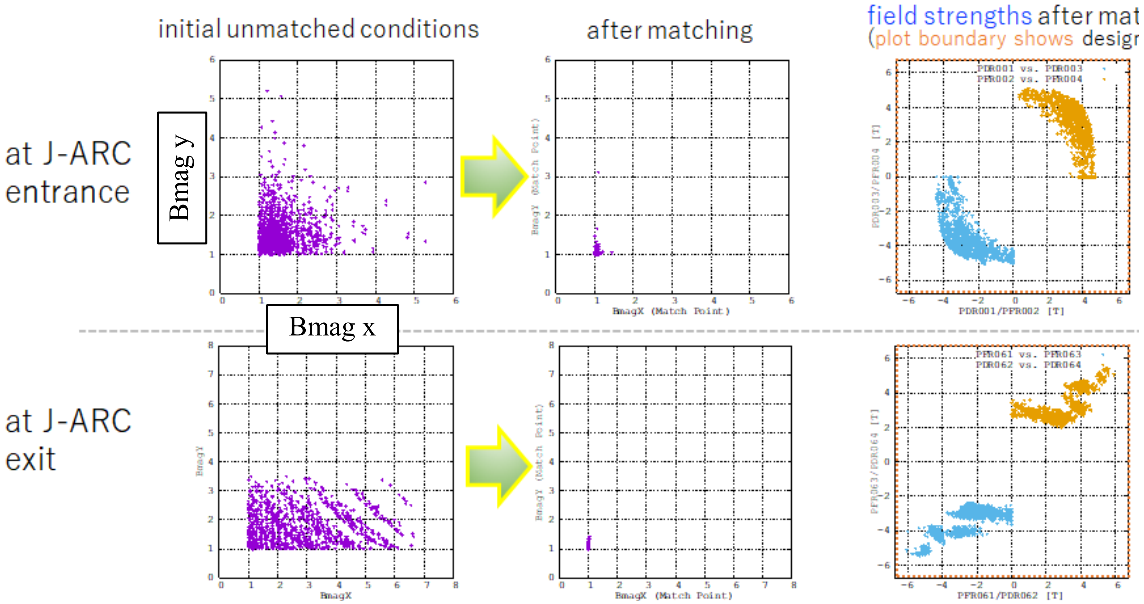
Upgrade during LS1

Pulsed Quads at J-ARC for optics matching

- 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.

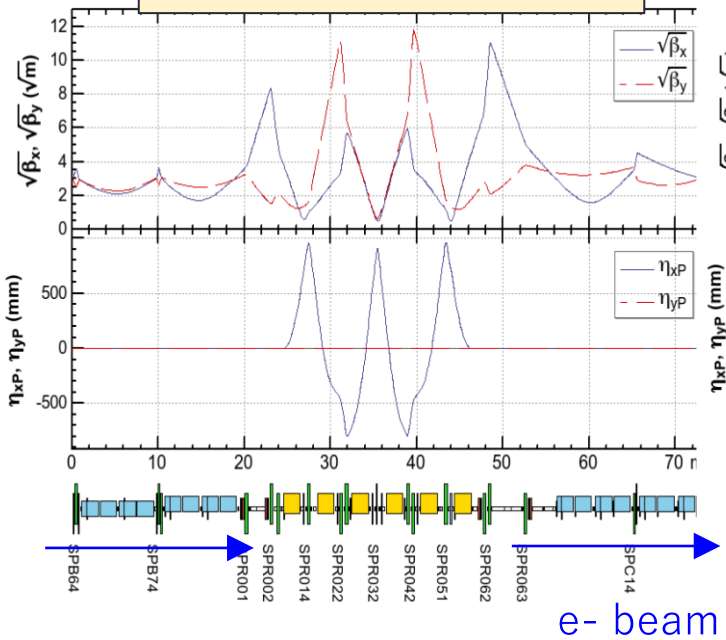


Y. Okayasu

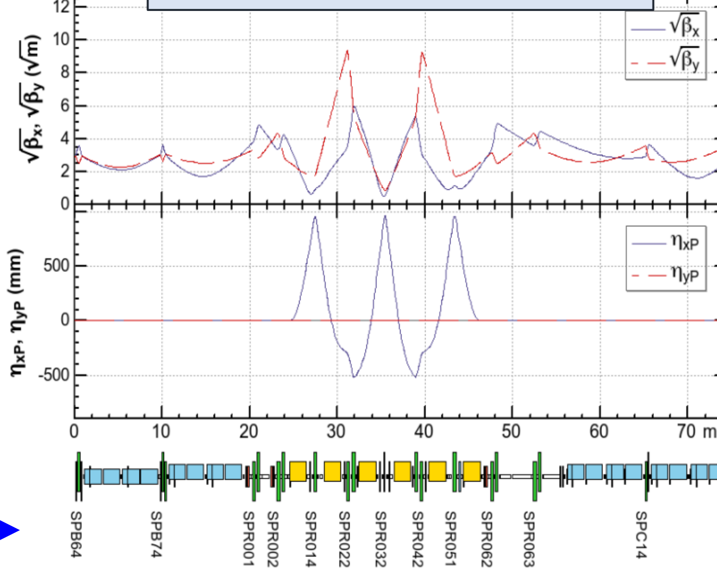


Matching simulation

Current optics at J-ARC



New optics at J-ARC with pulsed quads

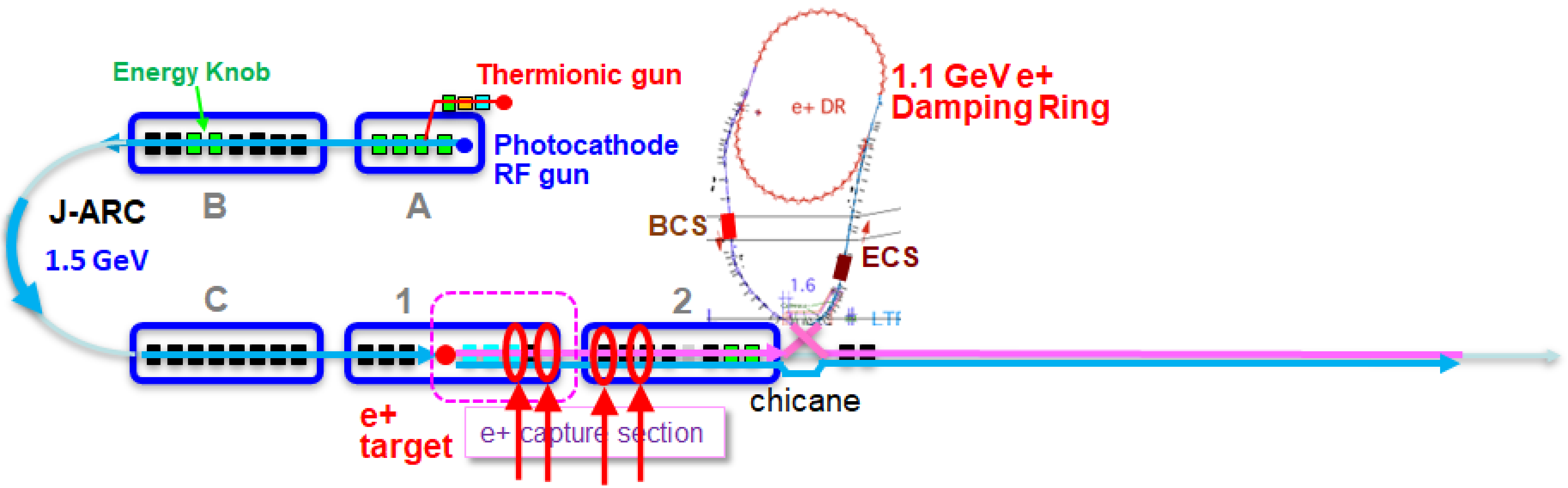


Y. Seimiya

Upgrade during LS1

Pulsed Quads at Sector1, 2 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.

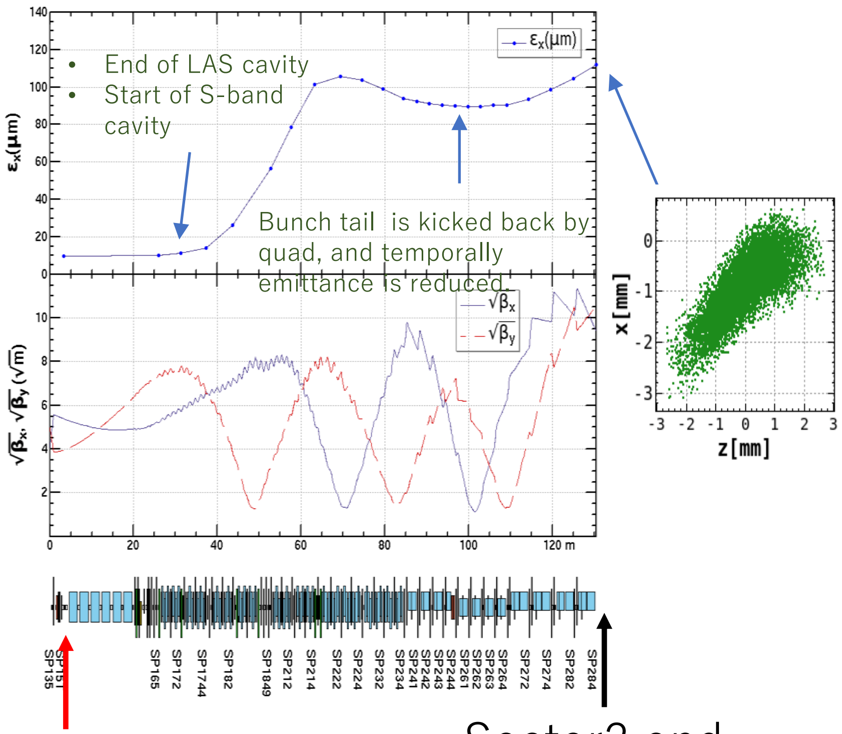


Four DC quads will be replaced by pulsed one.

Pulsed Quads at Sector1, 2 for e- low beta optics (cont'd)

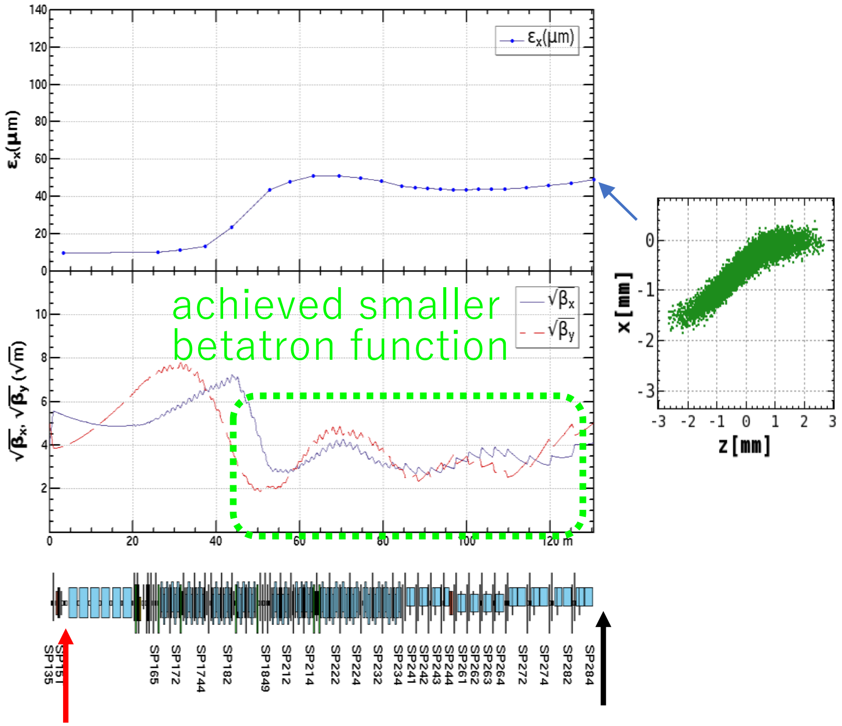
- After only these four pulsed quads are optimized for the e- beam, the betatron function can be decreased.
- Simulation result shows that it can help to decrease the emittance less than half.

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



Before optimization

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

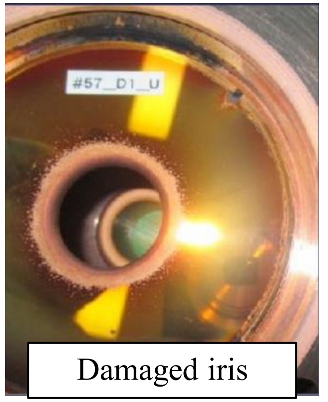


After optimization

Y. Seimiya

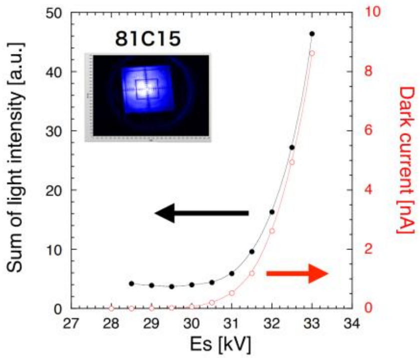
New accelerating structure

Upgrade during LS1

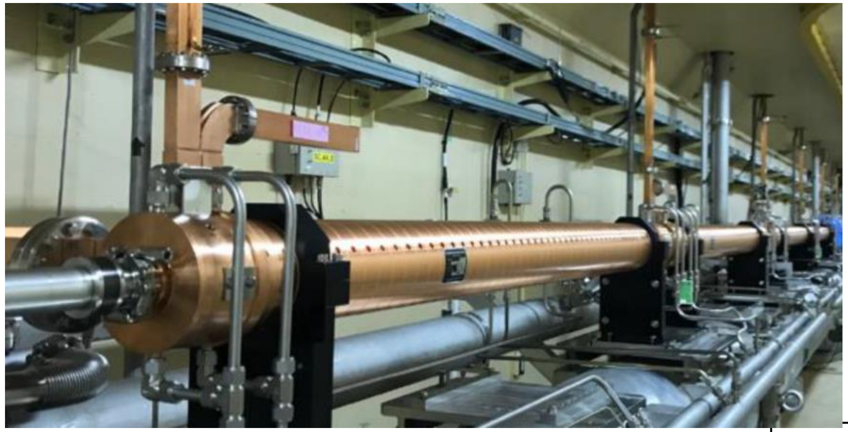


Damaged iris

- Mitigation of accelerating structure failures
  - Originally designed for 8 MeV/m (PF injector), but used at 20 MeV/m (KEKB upgrade)
  - Degradation 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 Υ(6S) but even Υ(4S) could be suffered

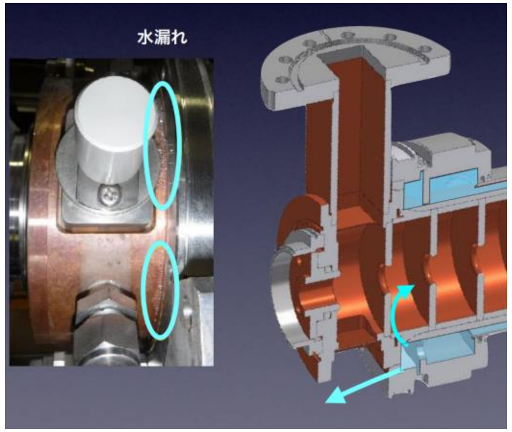


- 5-year upgrade plan to fabricate and install new accelerator structures (FY2018 – FY2022)
  - 4 units (16 acc. structures) will be replaced by new one. (Unit44 was replaced in this summer)
  - New acc. structure: acc. gain ↑7%, surface field ↓20% (reduce breakdown)
  - New pulse compressor (SCPC) was also developed and installed in Unit44.



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

New pulse compressor
Spherical-Cavity Pulse Compressor (SCPC)



Colling water leakage

H. Ego

ARC Recommendations:

- **R7.1: Perform systematic measurements of the orbit jitter of the two electron bunches and correlations with possible sources. Advance the synchronous data acquisition between Linac and BT.**
- **R7.2: More generally, perform a feasibility study for the implementation of synchronous beam data acquisition, which will be extremely useful for studying drift and instability.**

Improve the postmortem analysis tools using the synchronous beam, rf monitor, pulsed magnet data

- **R7.3: Implementation of an orbit feedback if the use of pulsed magnets allows for this.**

Orbit FB with pulsed magnet is already in operation (Sector3-Sector5).

- **R7.4: Continue with the upgrade plan as presented in the summary slide.**

- **R7.5: Concerning the emittance growth of the second electron bunch, study the effect of long range-wakes in the linac.**

Fast kicker for 2nd bunch orbit correction could mitigate the 2nd bunch emittance growth.

- **R7.6: Identify the causes limiting the charge of the electron bunch along the injector.**

Simulation work and beam study will be conducted during LS1.

- **R7.7: Discover the loss locations and causes for the positron transport in the linac.**

Simulation work is now in progress. Beam matching after e+ target will be tested soon to reduce the beam loss.

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 will be continued during LS1.

- 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

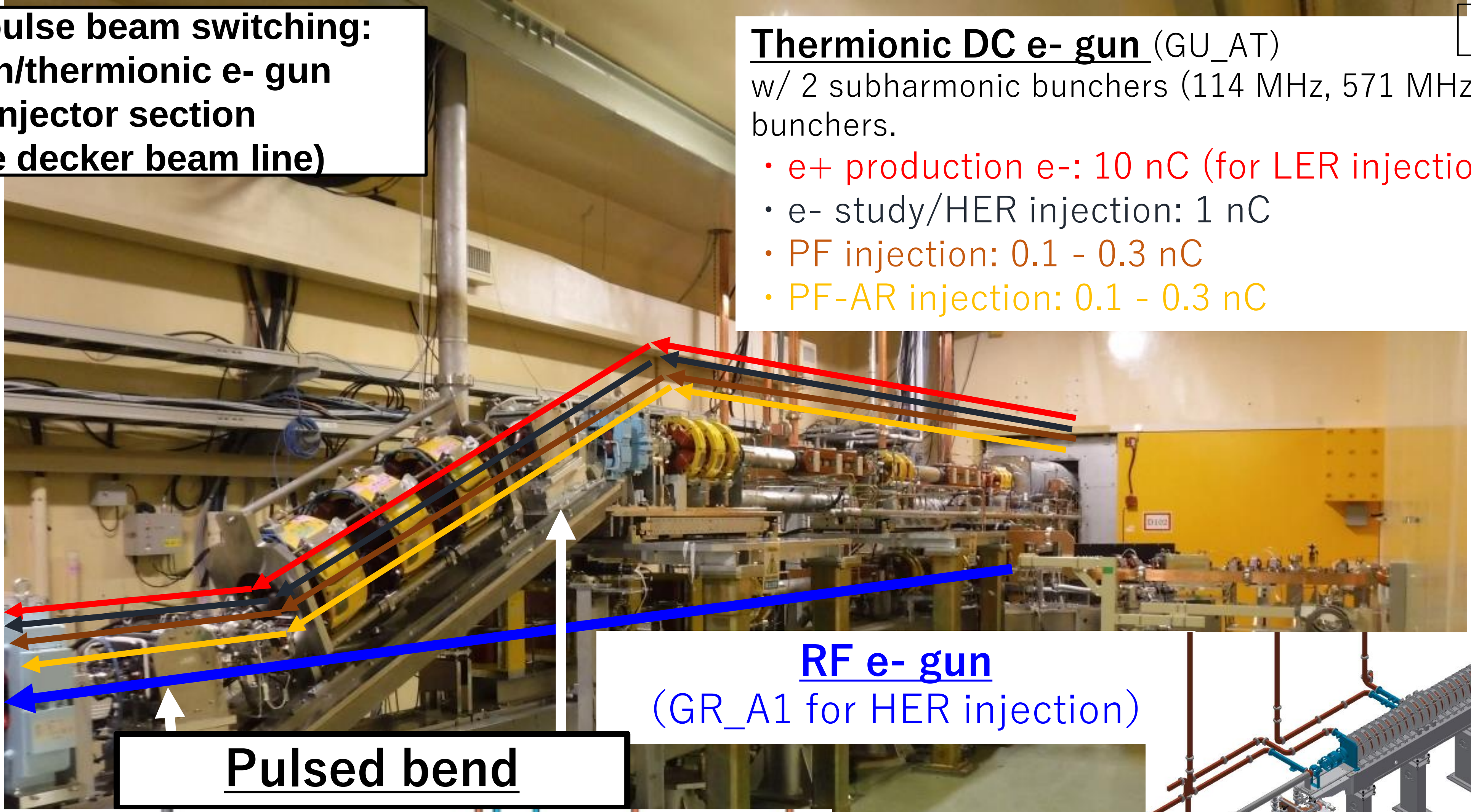
- Issues
  - Emittance growth at end of BT for both of e- and e+ beam
  - Low e- injection efficiency of 2nd bunch (fast kicker could help)
  - Increase the e- bunch charge while keeping small emittance

Backup

Parameters

Stage	KEKB (achievement)		SuperKEKB Phase-I (achievement)		Phase-II (achievement)		Phase-III Summer'19 (achievement)		Phase-III Summer'20 (achievement)		Phase-III Summer'21 (achievement)		Phase-III Summer'22 (achievement)		Phase-III (final)	
Beam	e+	e–	e+	e–	e+	e–	e+	e–	e+	e–	e+	e–	e+	e-	e+	e–
Energy (GeV)	3.5	8.0	4.0	7.0	4.0	7.0	4.0	7.0	4.0	7.0	4.0	7.0	4.0	7.0	4.0	7.0
Stored current (A)	1.6	1.1	1.0	1.0	1.0	1.0	0.83	0.94	0.712	0.607	0.790	0.687	1.460	1.145	3.6	2.6
Life time (min.)	150	200	100	100	50	100	20 (typ.)	70 (typ.)	12	21	9	22	6.7	26	6	6
Bunch charge (nC)	primary e- 10 1	1	primary e- 8 → 0.4	1	1.6	3.6	1.35	3.5	1.6	3	2.5	2	primary e- 10 → 3.5	2.1	primary e- 10 → **4**	**4**
Norm. Emittance (γβε) (mmrad)	1400	310	1000	130	200/5 (Hor./Ver.)	200/40	120/6	54/67	100/2	41/45	100/6	100/80	120/5 (BT1)	20/20 (BT1)	**100/15**	**40/20**
Energy spread	0.13%	0.13%	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	-	-	0.16%	0.07%
Bunch/Pulse	2	2	2	2	2	2	1	1	1	1	2	1	2	1	2	2
Repetition rate (Hz)	50		25		25		50 (LER+PF+PF-AR < 25 Hz)		50 (LER+PF+PF-AR < 25 Hz)		50 Hz		50 Hz		50 Hz	
Simultaneous top-up injection	3 rings (LER, HER, PF)		No top-up		Partially		4+1 rings (LER, HER, DR, PF, PF-AR)									

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



Thermionic DC e- gun (GU_AT)

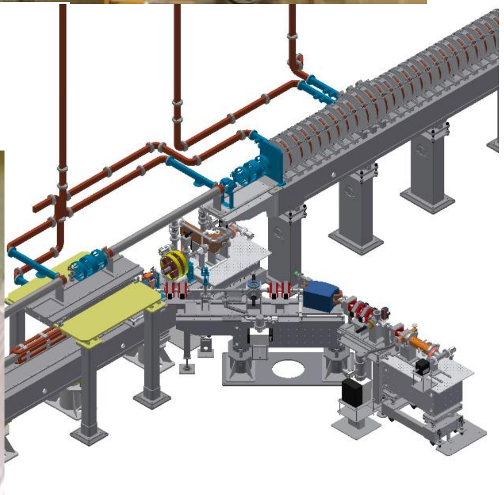
w/ 2 subharmonic bunchers (114 MHz, 571 MHz) and 2 bunchers.

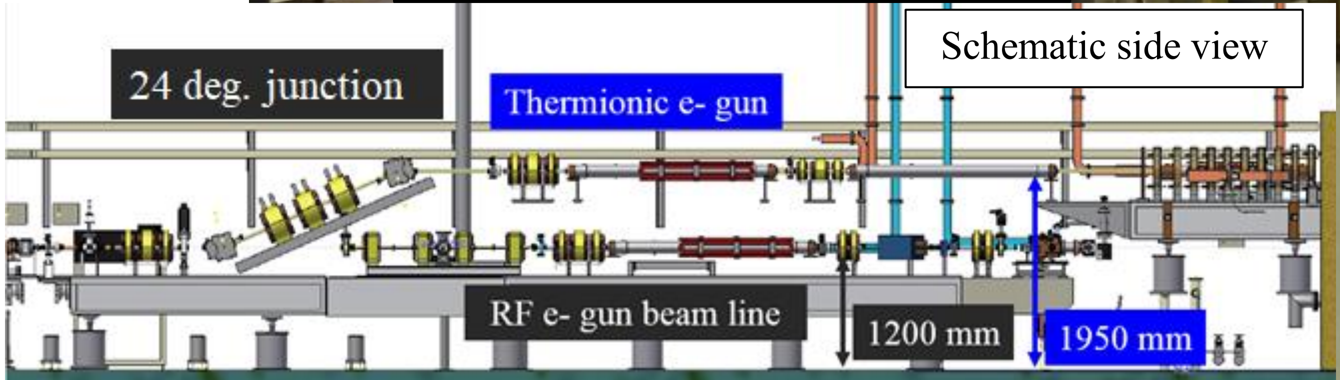
- e+ production e-: 10 nC (for LER injection)
- e- study/HER injection: 1 nC
- PF injection: 0.1 - 0.3 nC
- PF-AR injection: 0.1 - 0.3 nC

RF e- gun

(GR_A1 for HER injection)

Pulsed bend

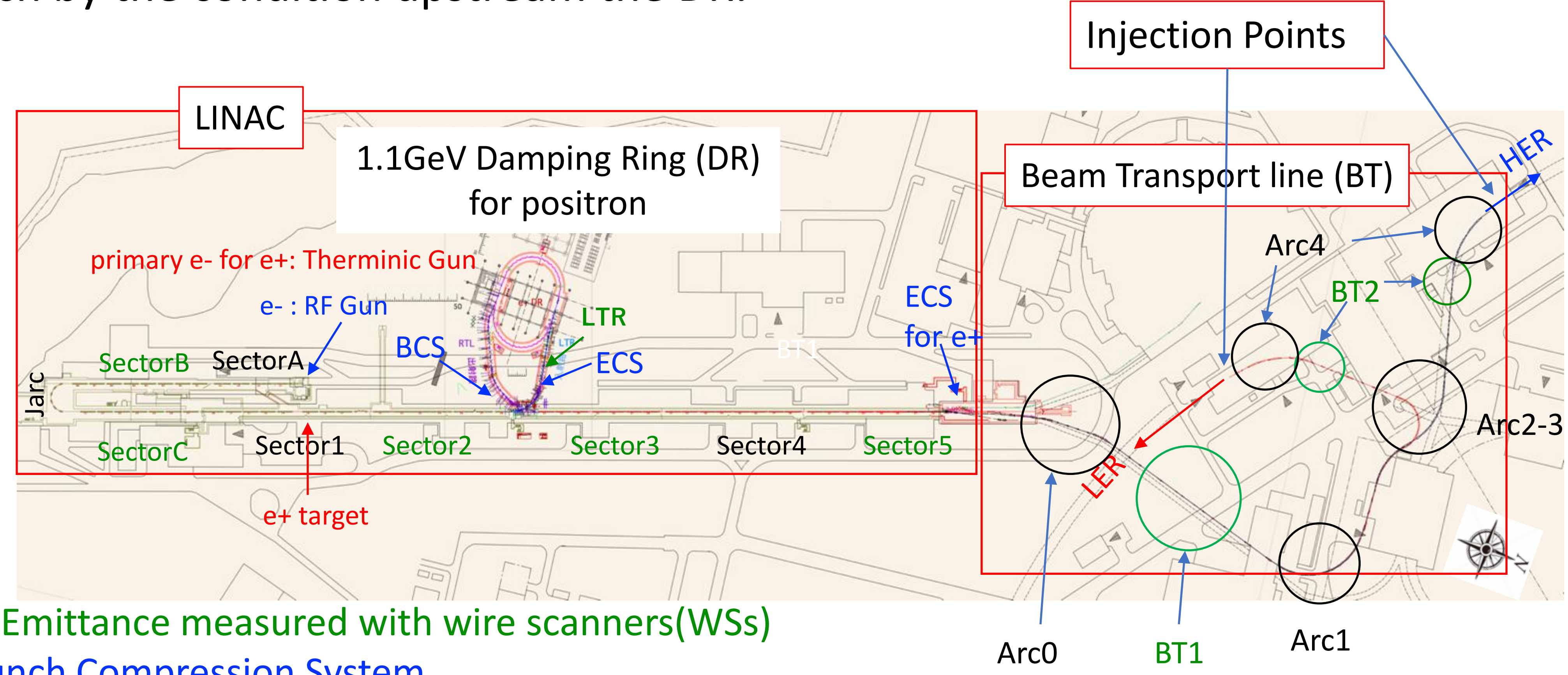




Layout of LINAC, BT to MR

e+ beam injects into LER via DR:
The injection BG is not affected very much by the condition upstream the DR.

e- beam directly injects into HER:
The injeciton BG is directly affected by the condition of RF-gun, LINAC, and BT.

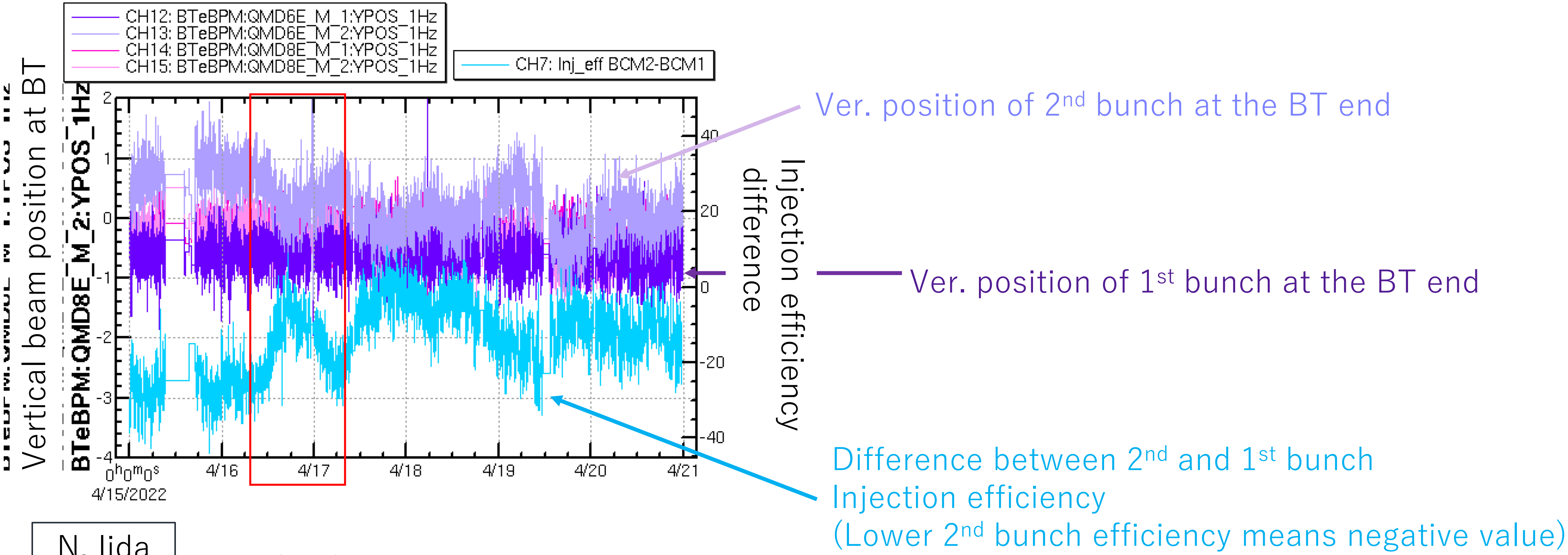


Green: Emittance measured with wire scanners(WSs)
BCS: Bunch Compression System
ECS: Energy Compression System

Injection efficiency of 2nd bunch

e- beam issue

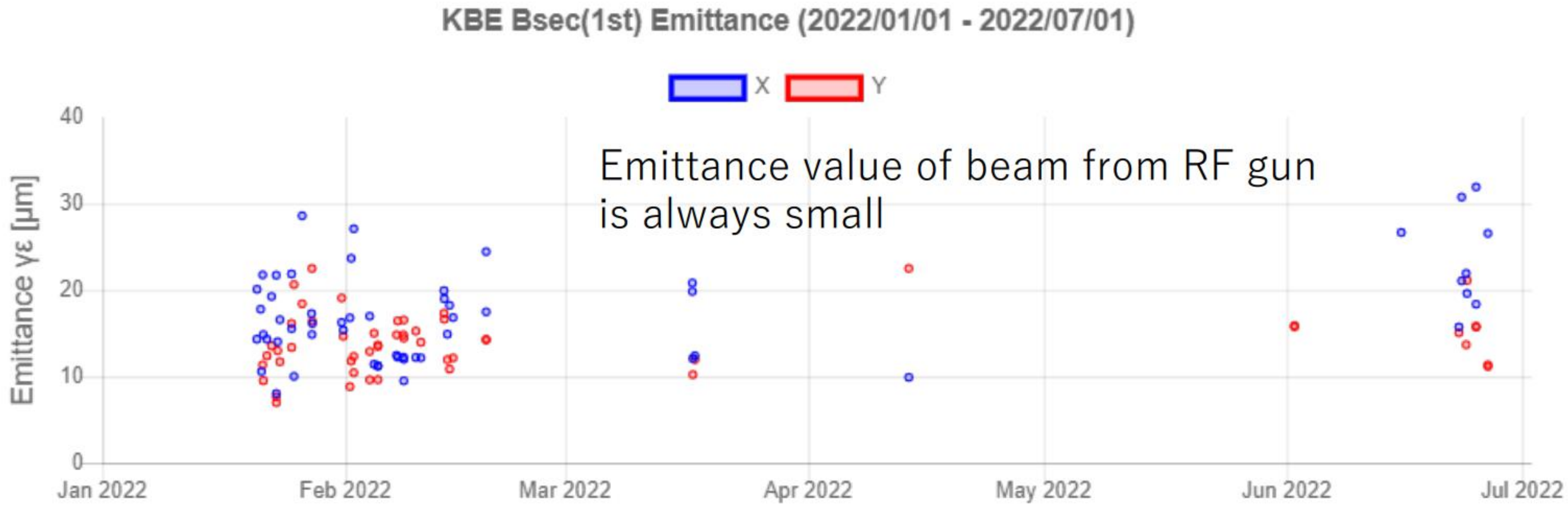
- HER injection efficiency of e- 2nd bunch is lower than that of 1st bunch and varies gradually.
- In some cases, there is not clear correlation between injection efficiency and orbit of 2nd bunch.
- Low injection efficiency could be also caused by the emittance deterioration.
- Fast kicker for 2nd bunch 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.



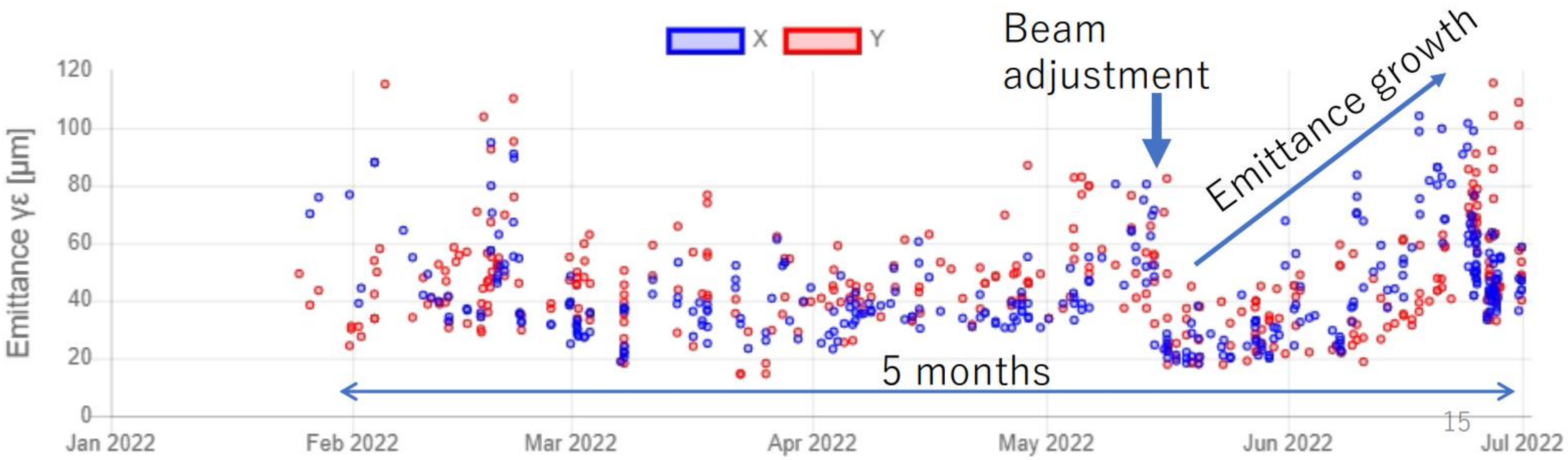
N. Iida

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

RF gun generation



End of Linac



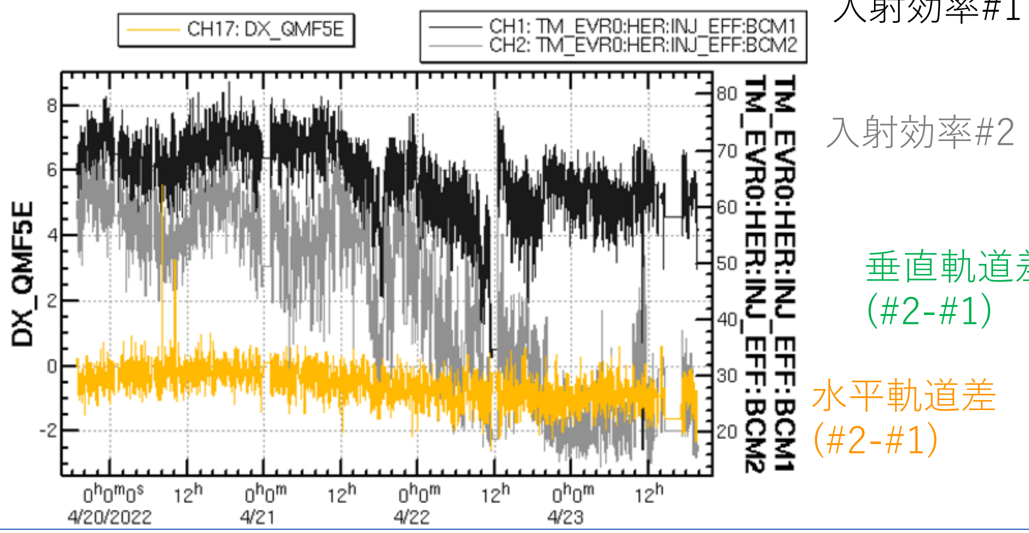
The measured emittance is meet the required value just after a beam adjustment. But the value increases gradually.

T. Natsui, eeFACT2022

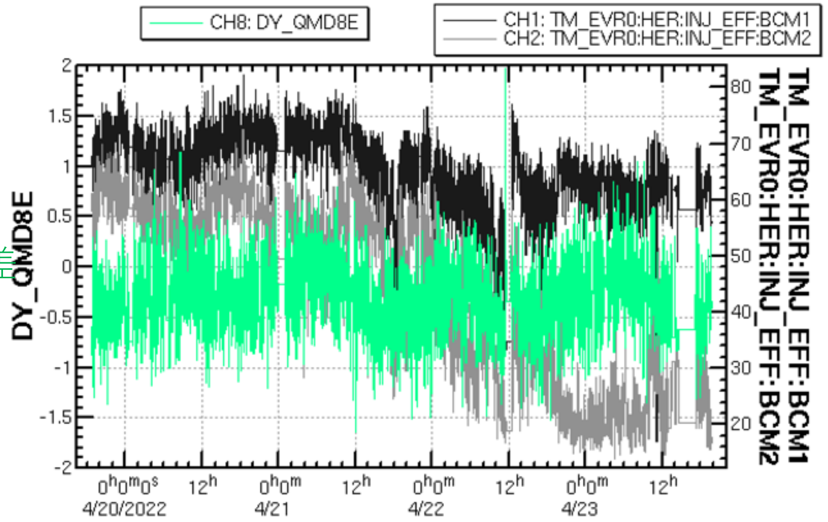
入射効率低下

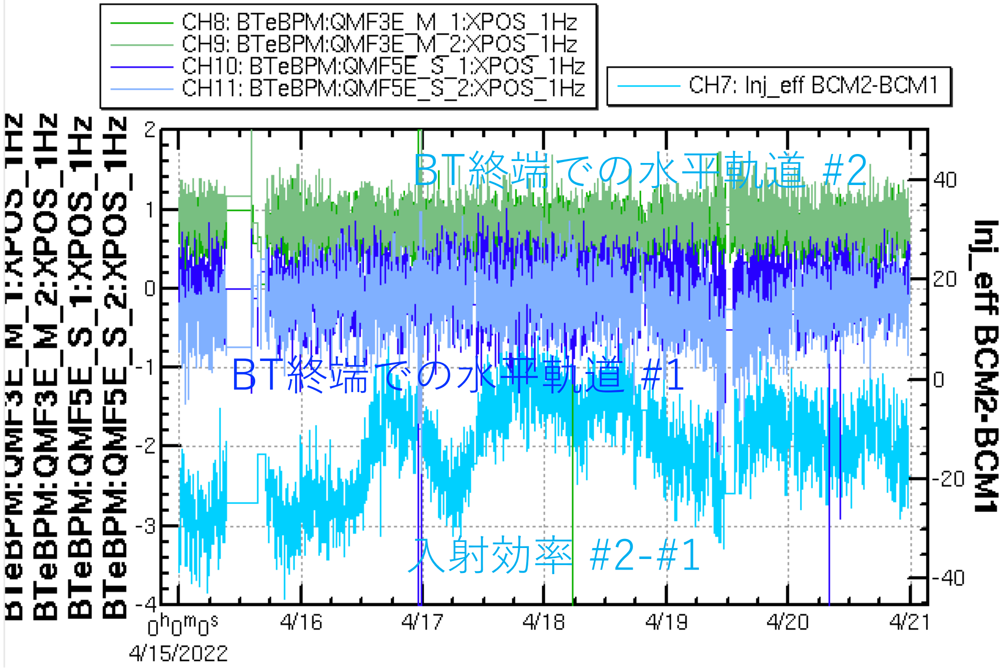
The different between 1st and #2 bunches have no dependent on the injection efficiencies.
It is considered that the emittance of 2nd bunch had been increased.

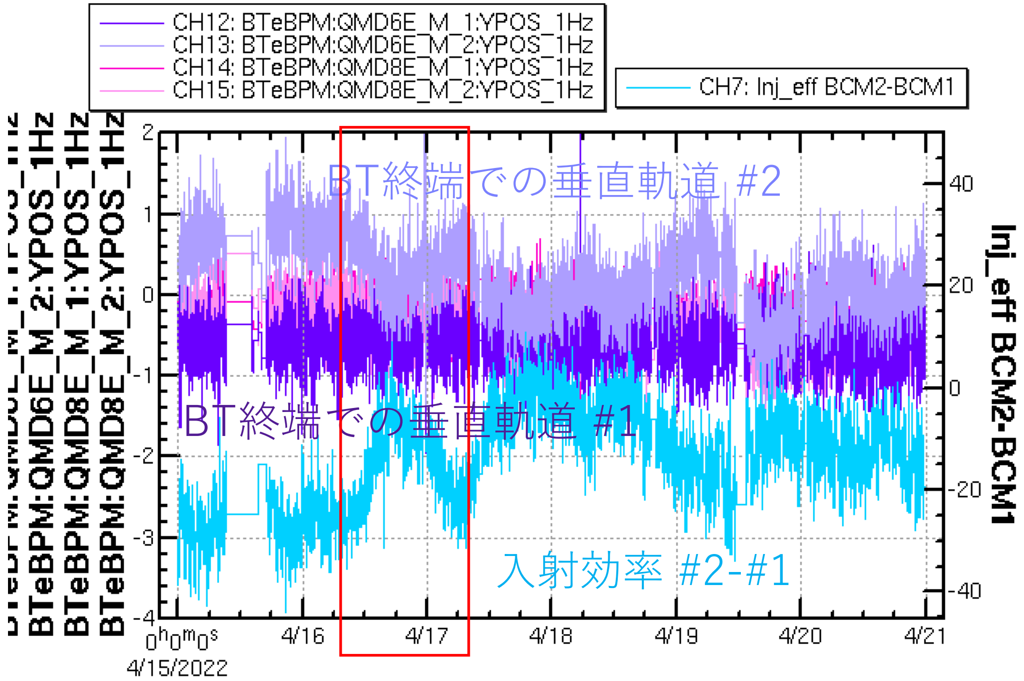
水平軌道差と入射効率



垂直軌道差と入射効率





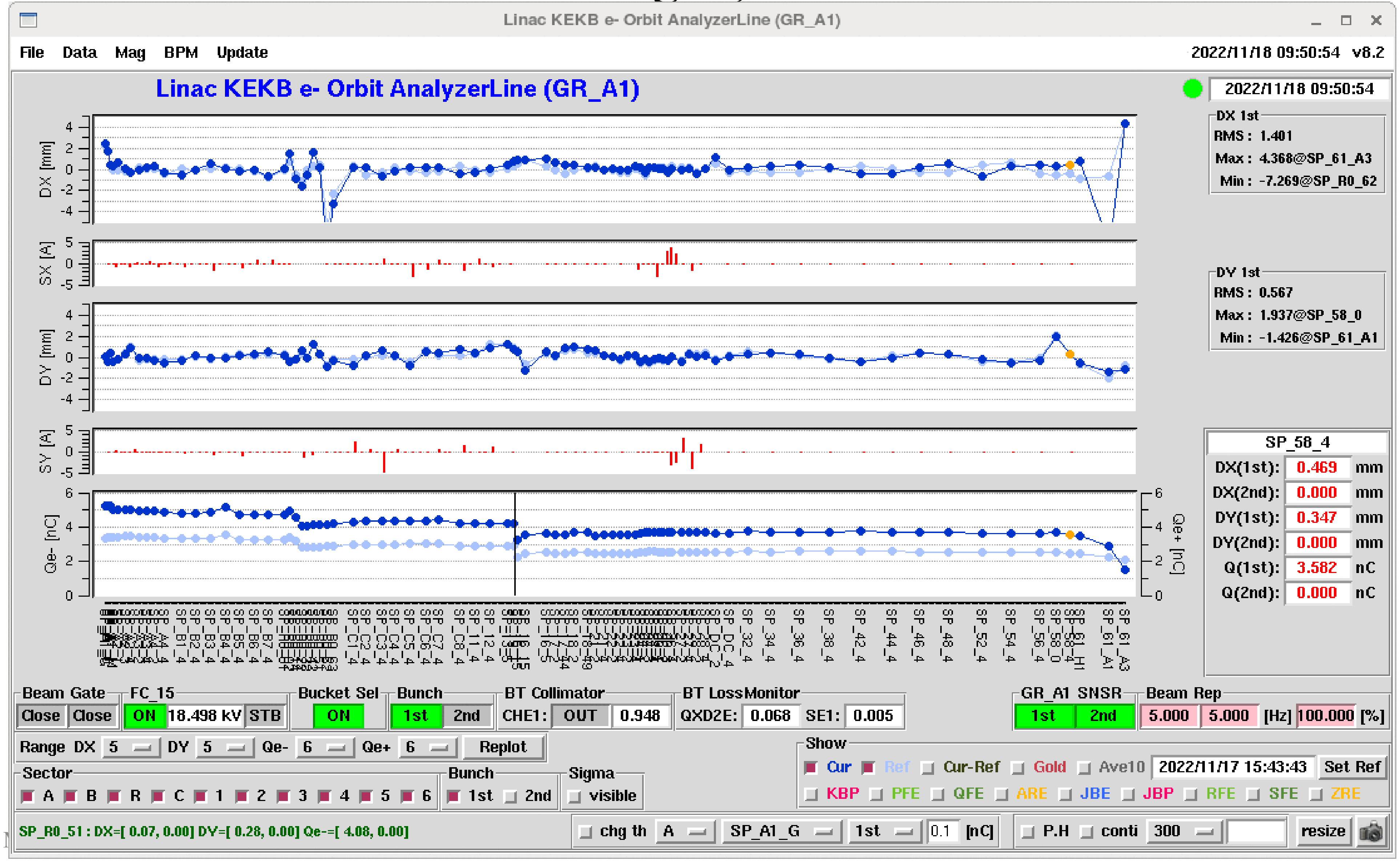


この時、水平軌道はほとんど変化がない。

特にHERでは、この期間は２バンチ目の入射効率は垂直軌道変化に依存している。
（１バンチ目のみ、軌道FBが働いているため、２バンチ目だけがDriftしている）
２バンチ目の垂直軌道補正のために、Fast kickerを設置する。

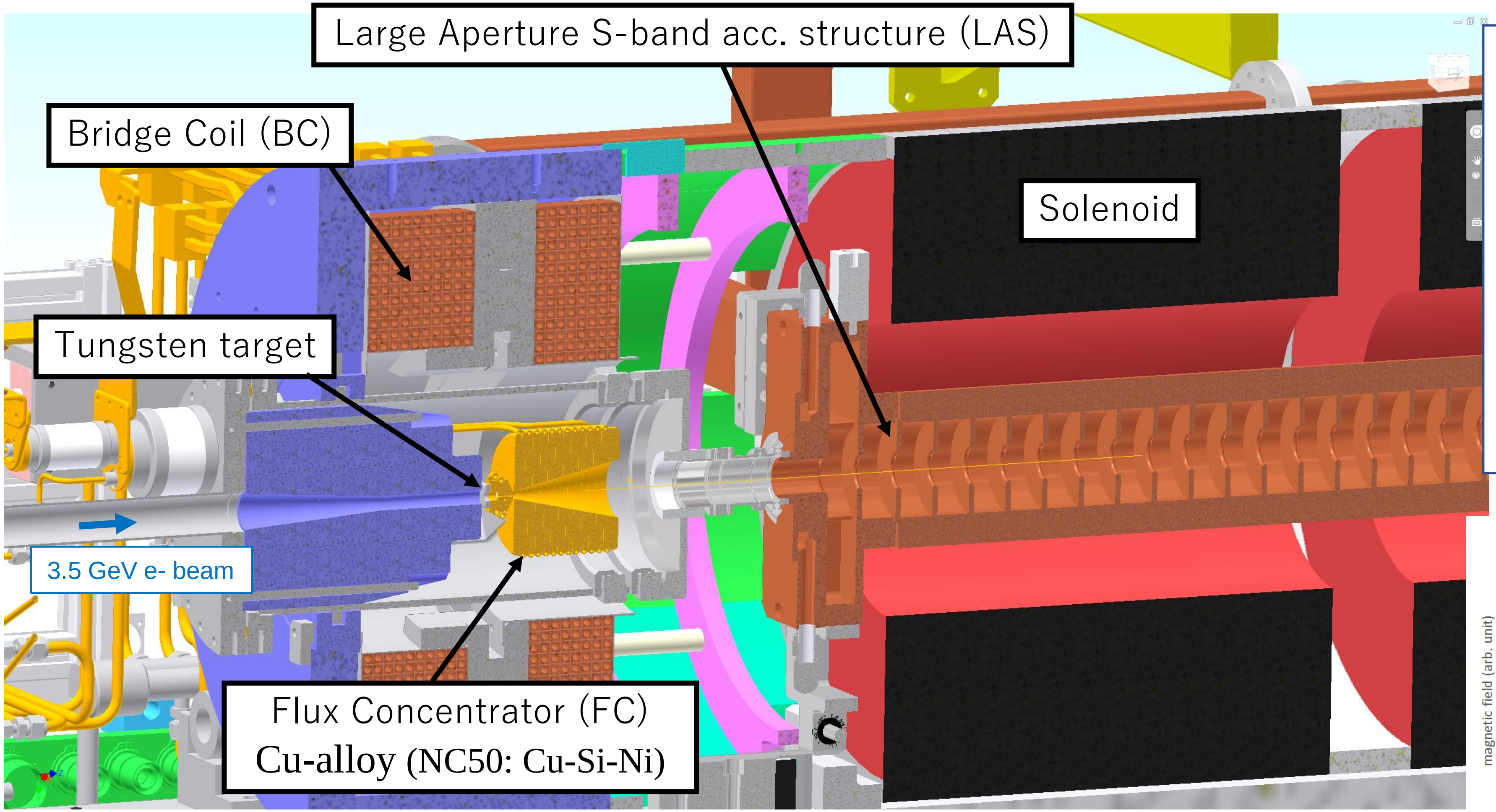
High bunch charge e- beam test

5 nC beam from rf e- gun, 4 nC at the linac end

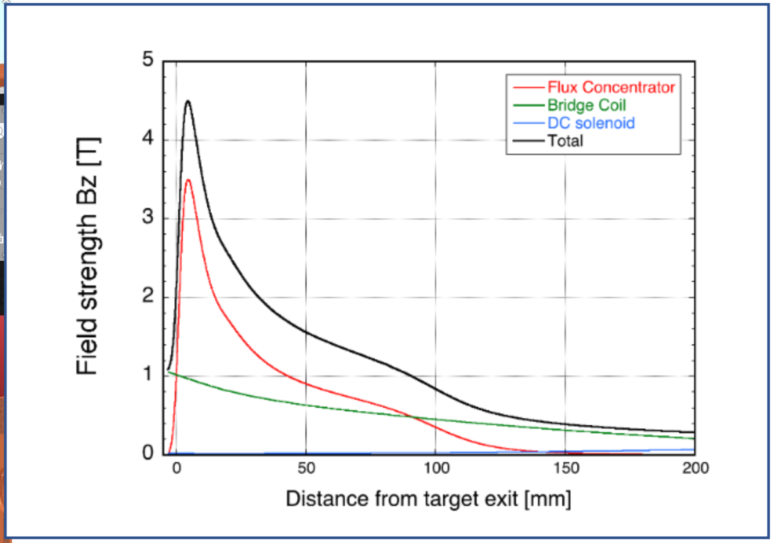


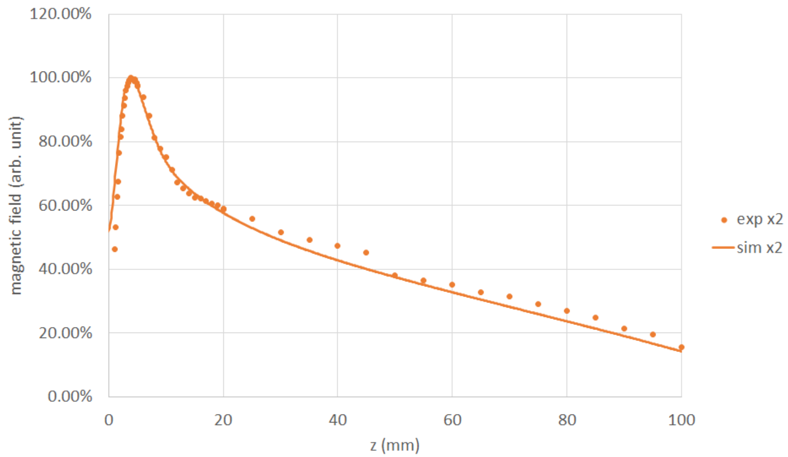
e+ beam

Positron Capture Section: Flux concentrator, bridge coil, solenoid



I_{FC}= 12 kA





Y. Enomoto et al.

FC assembly, base summary

	Phase 1	Phase 2	Phase 3	2019 autumn	2020 spring	2020 autumn	2021 winter～	delivery	removal	Present status (2020/6)	remark
Assembly 1								Before 2015	2017/3	Tunnel	
Assembly 2								2016/3		Beam line	
Assembly 3								2017/11		Test bench	
FC base 1								before 2015			Trial product
FC base 2								before 2015			Trial product
FC base 3								before 2015	2017/3	Assembly 1	
FC base 4									2018/9	Tunnel	
FC base 5								2016/7	2020/9	Beam line for operation	
FC base 6								2017/11		Reserved	Hardening (Toyama)
FC base 7*								2019/10		Finished long term test	
FC base 8**								2020/5		Under test	Final version modified
FC base 9**								2021/3		Under design	Final version spare

- *Base 7, 8, 9 (head : Cu → NC50, return yoke : SS400 → permendur)
- **Base 8, 9 Shape optimization (insulation, leakage magnetic field)

red： operation
blue： spare
black： test bench

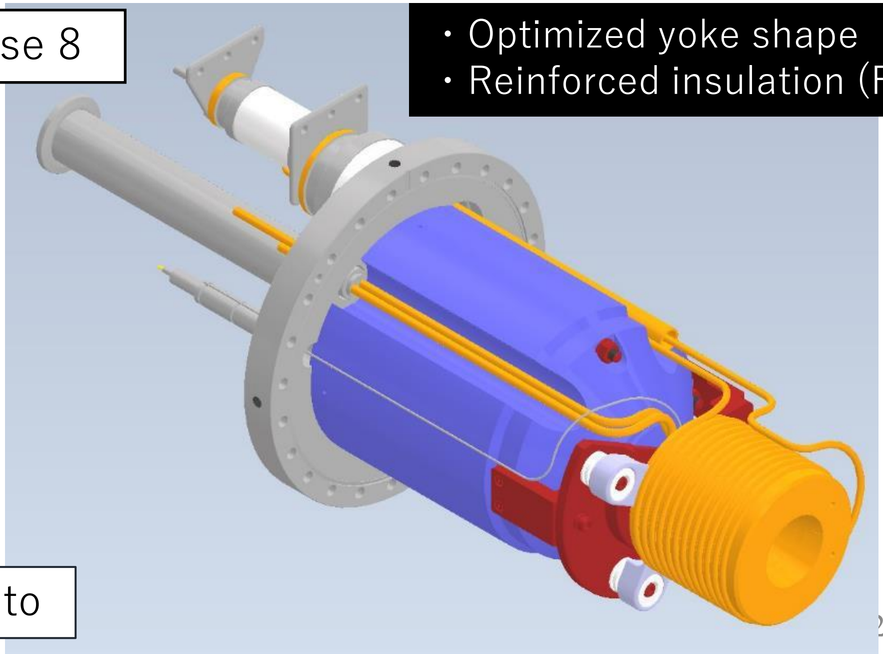
Y. Enomoto

Comparison FC base

	Material	Shape	Remark	For e-	For e+
Base 5	OFC + SS400	Old design	12 kA in beam line large slit gap	△	○
Base 7	NC50 + permendur	Old design	4.5 months test	○	○+ *
Base 8	NC50 + permendur	New design (optimized) in operation	Cooling water leakage was found. (already fixed and tested during 4 days)	◎	○+ *

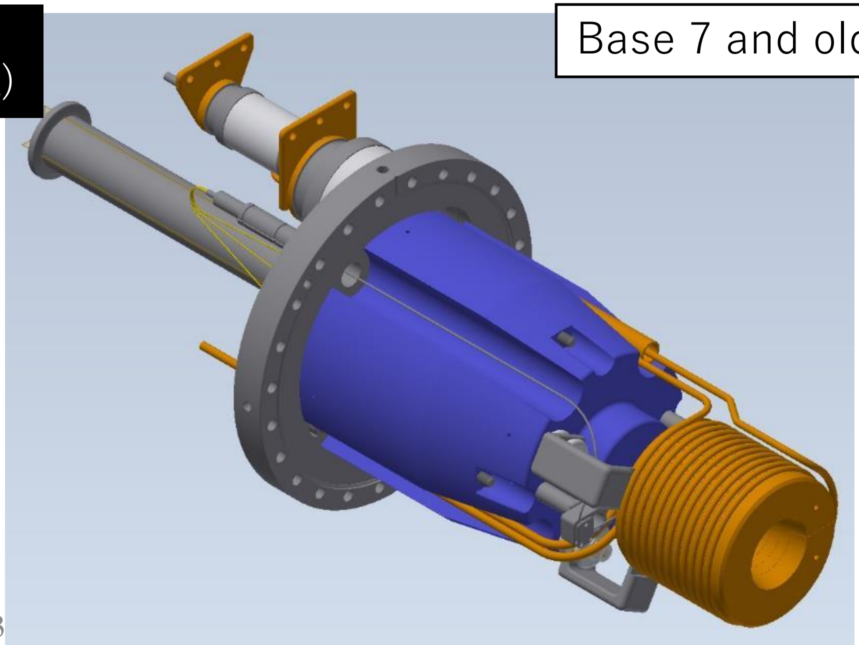
All FC bases achieve 12 kA in test stand. (*) return yoke (permendur) makes higher magnetic field.

Base 8



・Optimized yoke shape
・Reinforced insulation (FC head support)

Base 7 and older

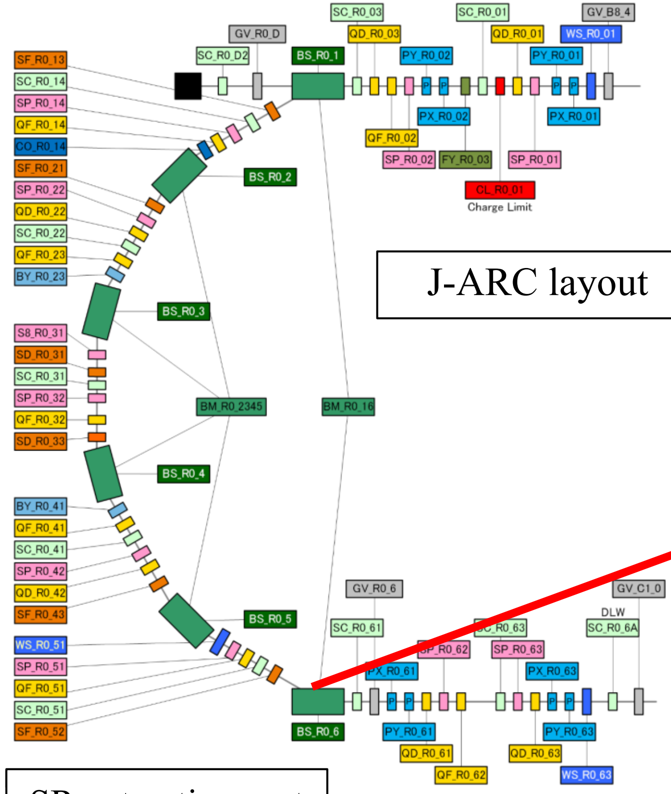


Y. Enomoto

Recent progress

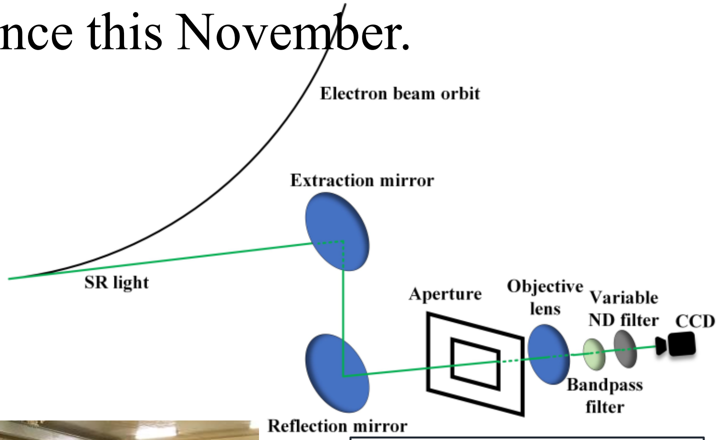
SR monitor at J-ARC

- SR monitors (SRM) were installed at J-ARC and ECS in the beginning stage of KEKB operation. After then, they became obsolete. SRM at ECS was removed after reconfiguration of ECS magnet.
- SRM at J-ARC is recently used as a non-destructive profile monitor with the reconstructed optical system.
- Similar system at BT has been also available since this November.

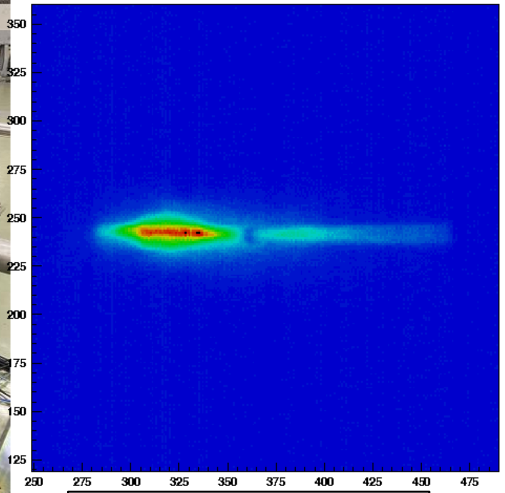


J-ARC layout

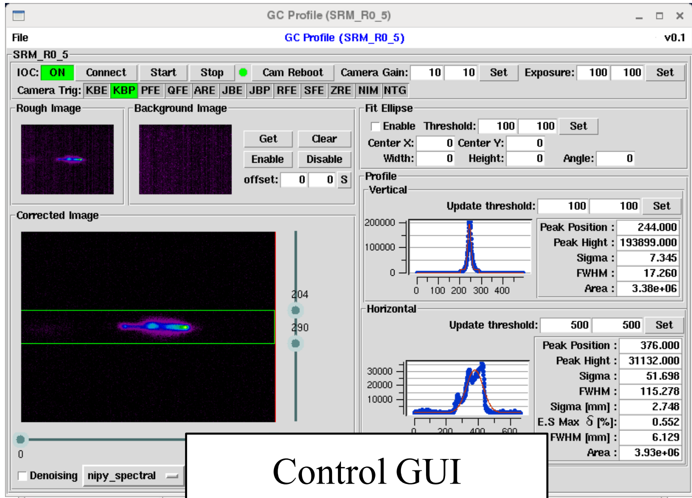
SR extraction port



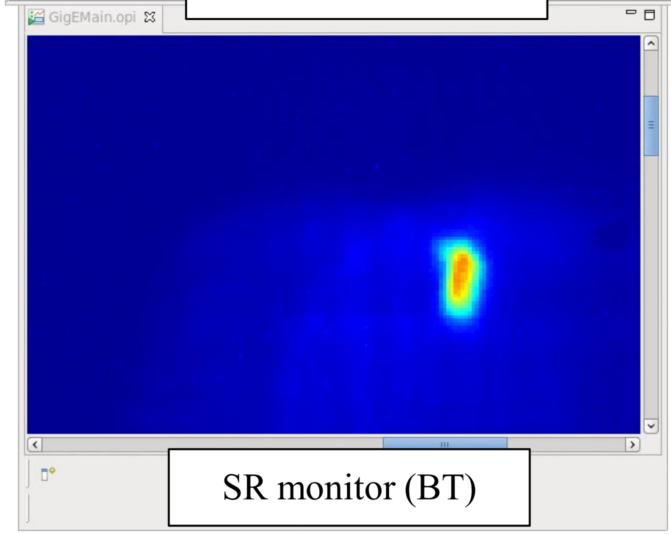
R. Zhang et al.



SR monitor (J-ARC)



Control GUI

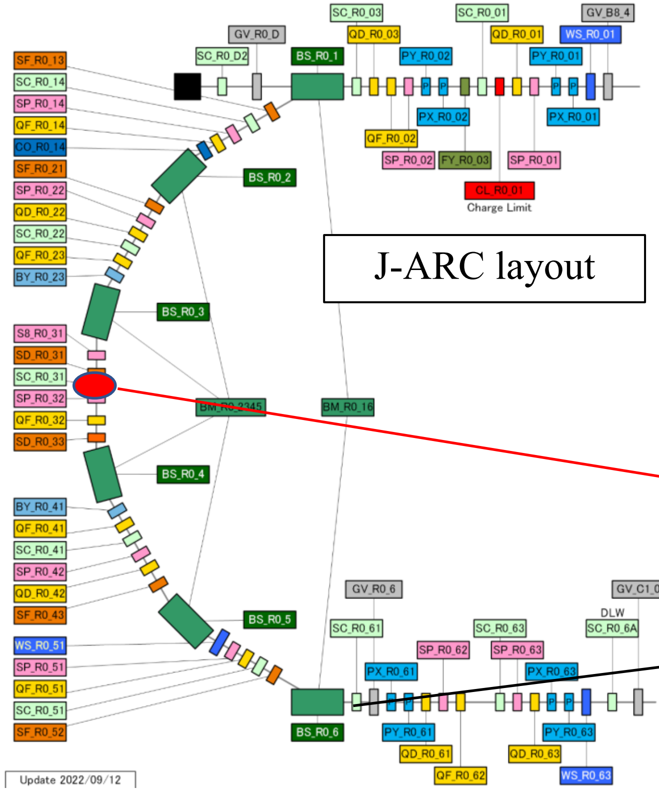


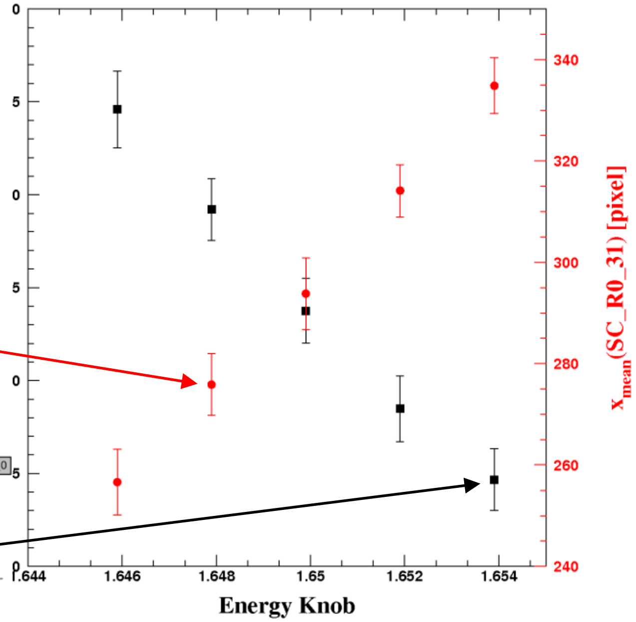
SR monitor (BT)

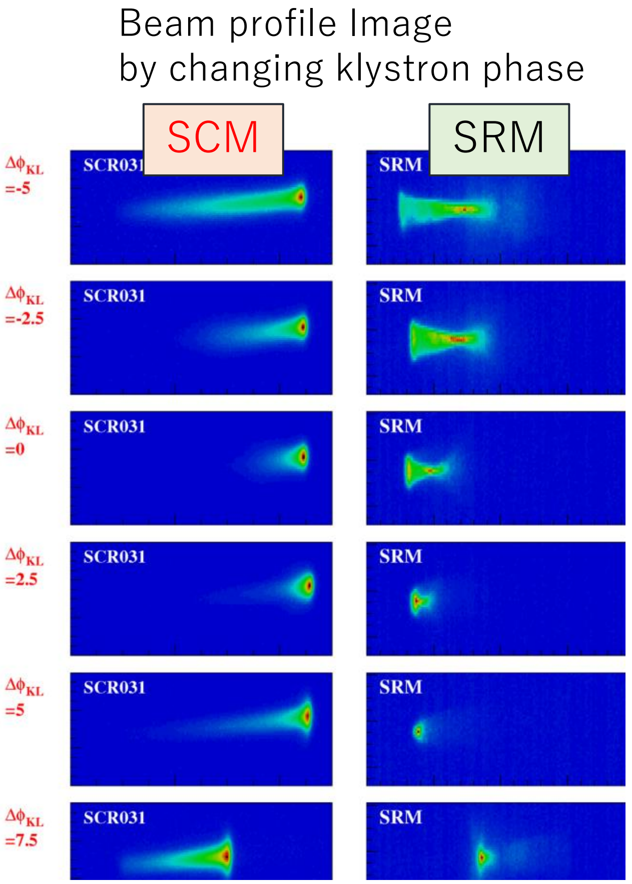
SR monitor at J-ARC (cont'd)

Recent progress

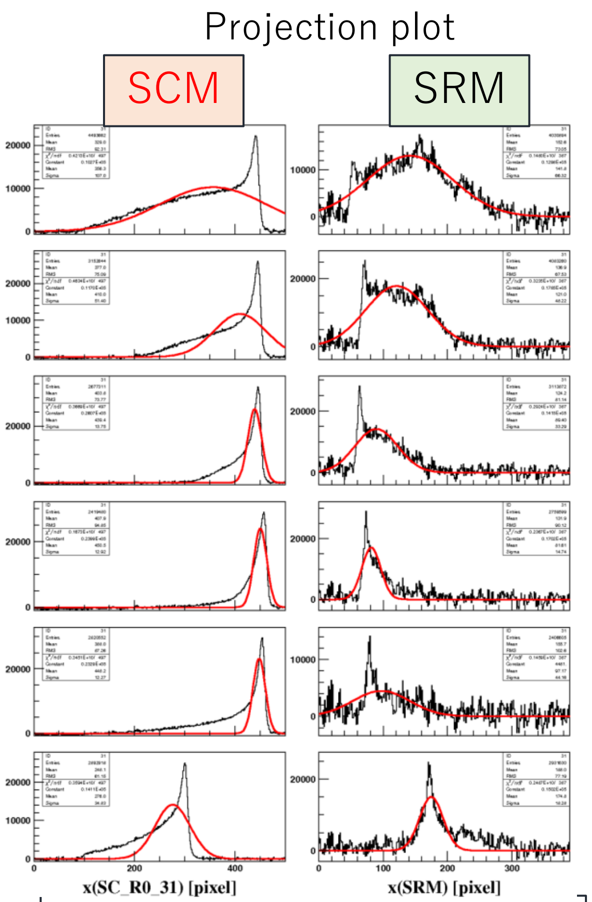
- Centroid position of the beam profile images are synchronously measured by SR monitor and screen monitor (SCM) with the different beam energy. Each of them and BPM show a good agreement.
- Measured profile images are slightly different between SCM and SRM.
- SRM could be a strong help for beam feedback as a nondestructive monitor.







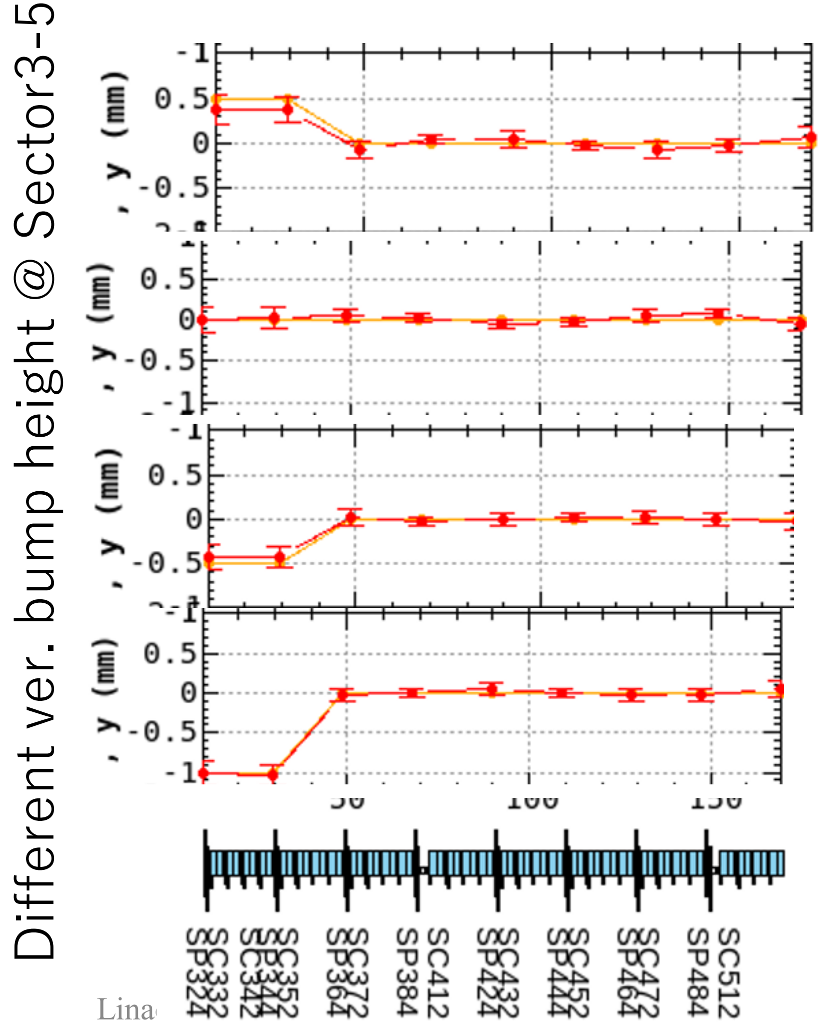
Right/Left definition is opposite btwn SCM and SRM

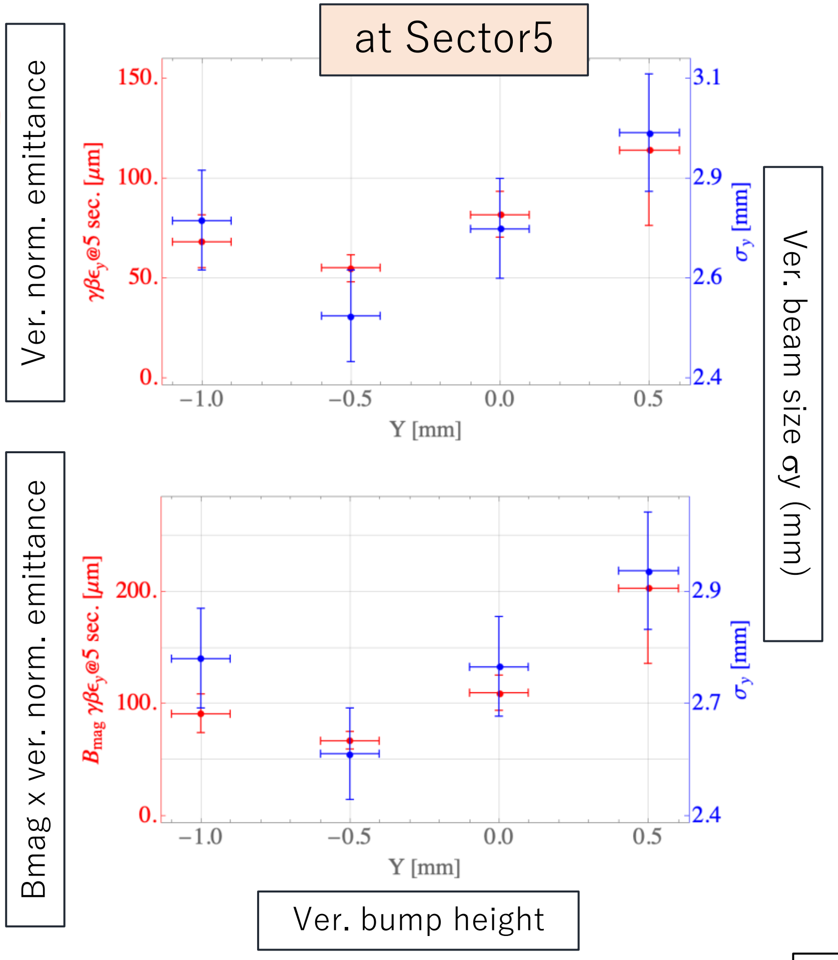


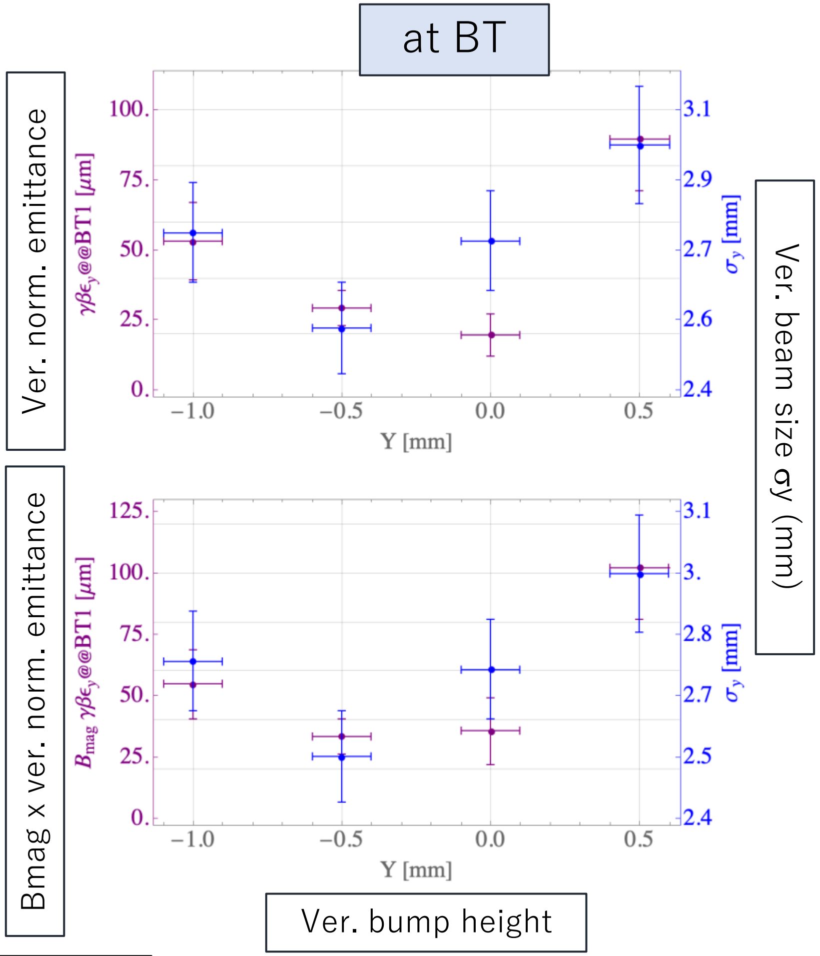
F. Miyahara, Y. Seimiya

Low emittance e- with bump orbit

- Measured emittance and beam size at Sector5 and BT by changing vertical orbit (Sector3-5)
- Finding the beam orbit minimizing emittance (mitigate emittance growth due to transverse wake field effect)
- Correlation btwn the emittance and beam size is confirmed with the measured data at Sector5 and BT.
- It could find and keep the orbit minimizing emittance with SRM at BT even during beam injection.







Y. Seimiya

Automatic beam tuning

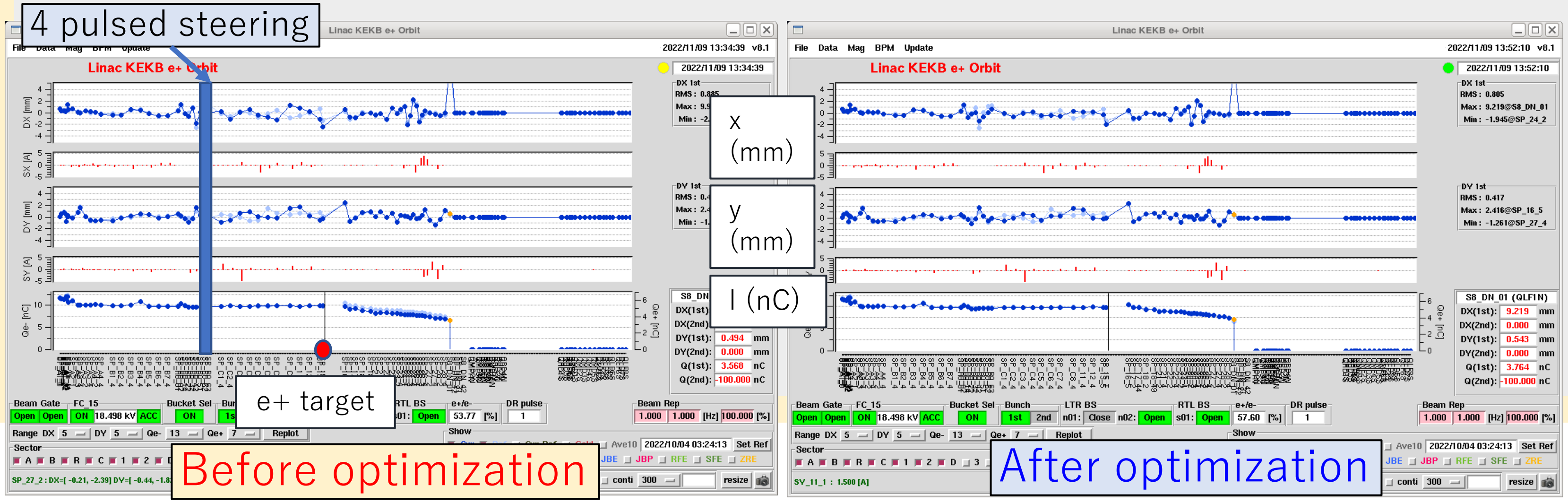
Recent progress

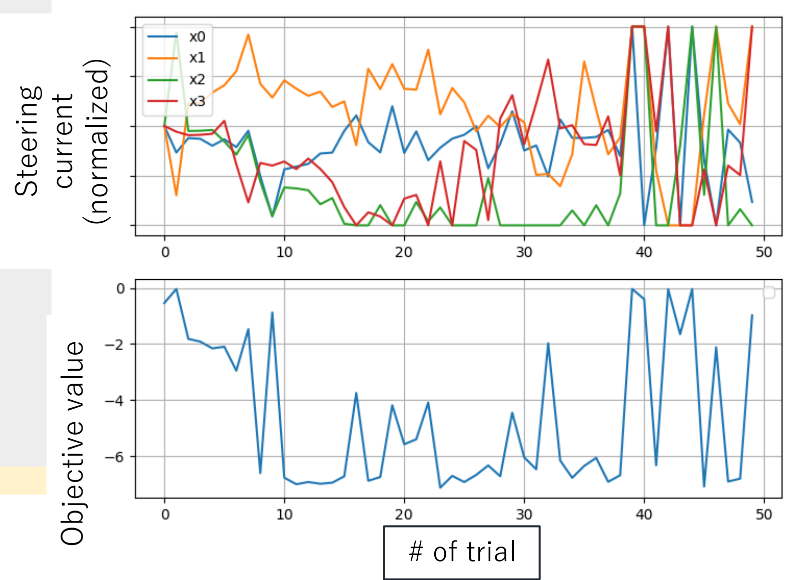
- Automatic beam tuning approach with machine learning is recent trend in accelerator operation.
- Bayesian Optimization approach is now under test by using the beam of injector Linac.
  - Implementation using GPyOpt Python library (T. Natsui) / In-house developed implementation (G. Mitsuka)

Preliminary test result with GPyOpt

T. Natsui

- Setup:
  - Explanatory variable: excitation current of 4 pulsed steering magnets at J-ARC exit
  - Objective function: bunch charge calculated from 4 BPMs at around the e+ target
- Bunch charge before LTR was increased from 3.5 nC to 3.7 nC after optimization.
  - Best parameter was found within ～ 5 min. (depending on beam rep. , # of number of averaging points, and so on)
  - Optimization result seems to be same level by the operator.
- In the future, try to apply it to more complicated tuning like 2nd bunch beam tuning, dispersion correction, injection tuning (after LS1).

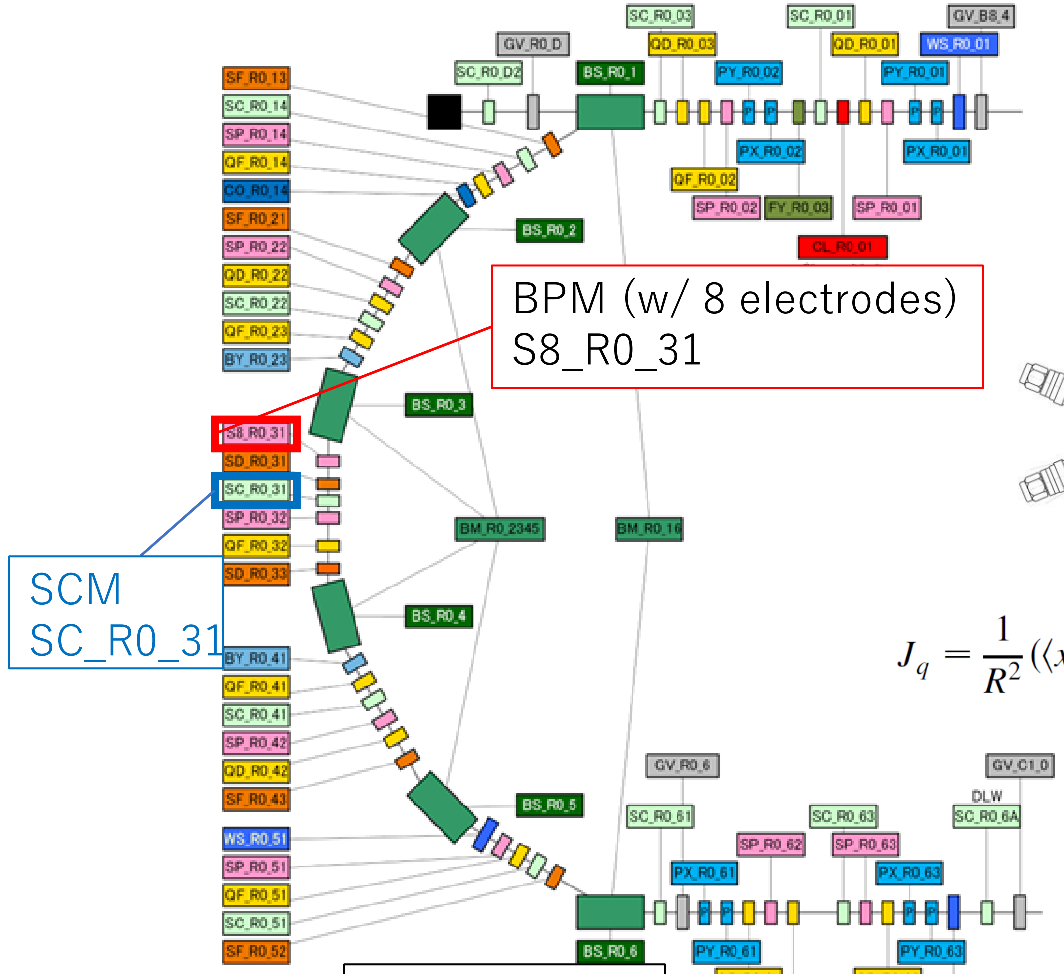




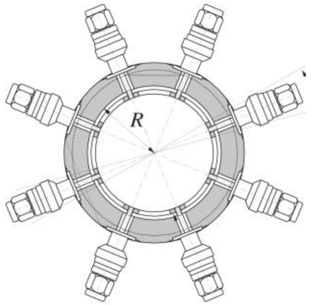
BPM (with 8 stripline electrodes) at J-ARC

Recent progress

- Special BPM (S8) at J-ARC can obtain the quadrupole moment (Jq) of beam. It help to measure the energy spread.
- Results measured with S8 (nondestructive) and SCM (destructive) are comparable.
- Both of S8 and SRM can work complementary as nondestructive monitor for beam tuning and feedback.

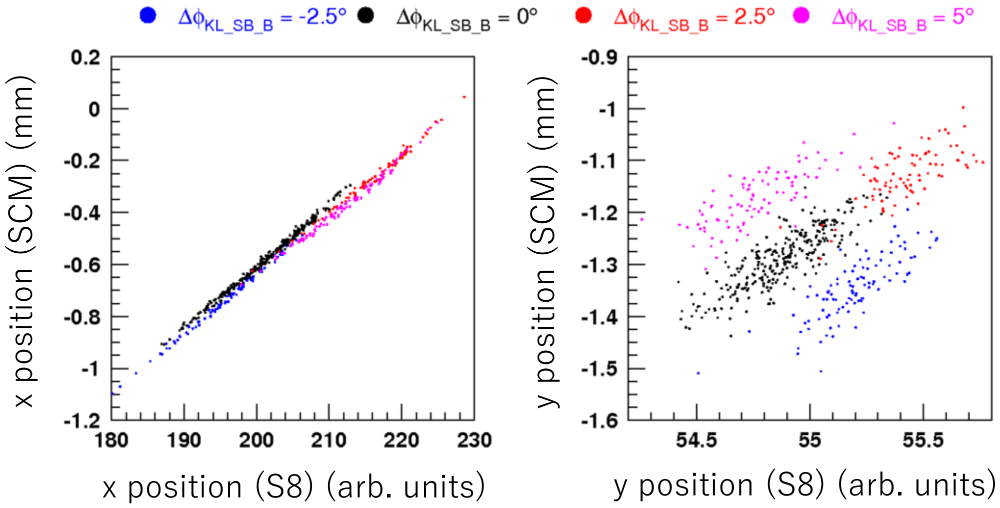


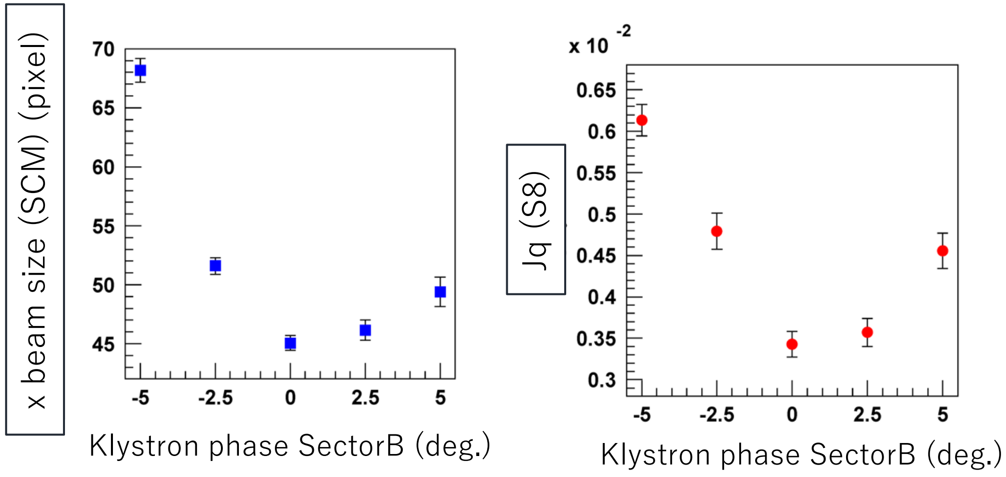
J-ARC layout



$$J_q = \frac{1}{R^2}(\langle x^2\rangle - \langle y^2\rangle + \langle x\rangle^2 - \langle y\rangle^2)$$

Changing klystron phase





F. Miyahara

Postmortem analysis of beam abort event

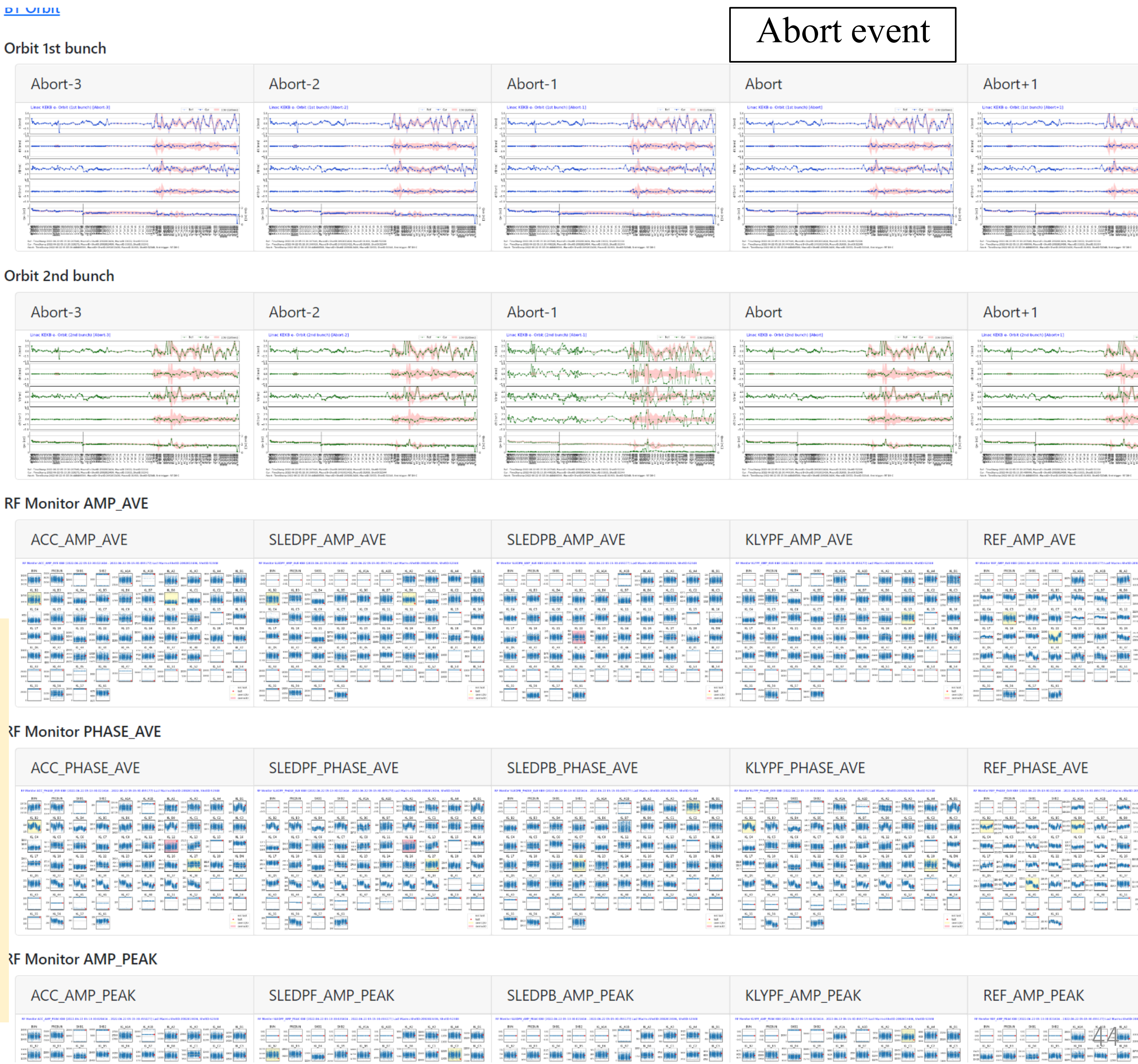
Recent progress

Postmortem analysis of beam abort event

Beam Abort Orbit [Search]

2022-06

Time Stamp	Beam Mode	Macro+ShotID
2022-06-22 05:15:30.448400500	KBE	2092813436
2022-06-17 22:52:49.830439000	KBE	2074385192
2022-06-17 19:53:16.155099200	KBE	2073846524
2022-06-17 19:17:39.271628900	KBE	2073739664
2022-06-17 18:44:31.273602400	KBP	2073640315
2022-06-17 02:48:08.786511500	KBE	2070771320
2022-06-16 12:39:51.985525300	KBE	2068226490
2022-06-14 03:09:56.111522400	KBP	2057876677
2022-06-08 06:55:02.225331500	KBP	2032631916



Beam abort coincidence w/ injection:

Linac/BT orbit, RF monitor, pulsed magnet PS are abnormal or normal?

It can be easily checked via web page automatically created.