Electron/Positron Injector Phase-2 Status and Phase-3 Plan

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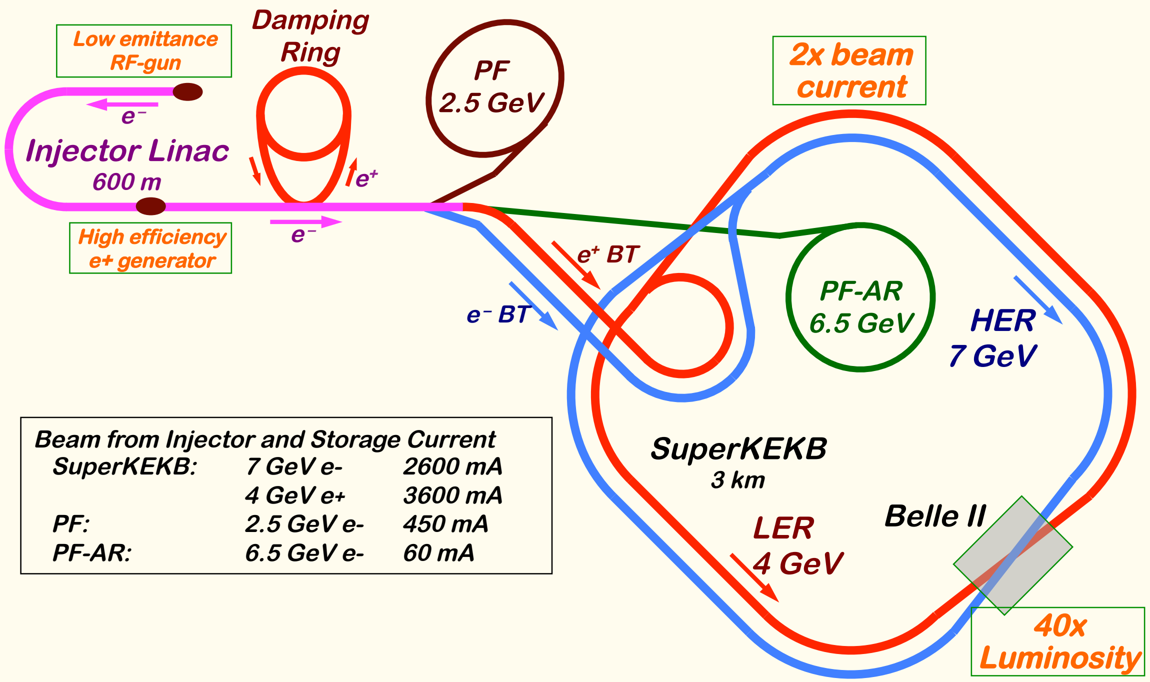
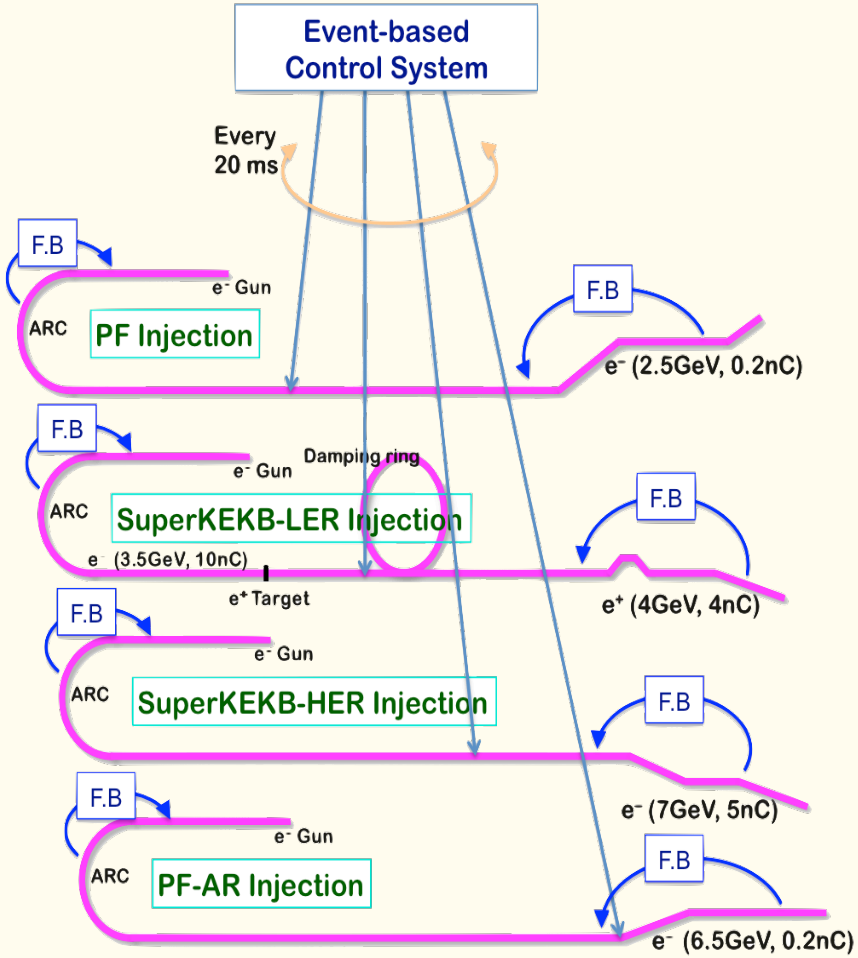
for Injector Linac, KEK

Mission of Electron/positron Injector in SuperKEKB

- **For 40-times higher luminosity in SuperKEKB collider**
- **Low emittance & low energy spread injection beams with 4 times higher beam current**
  - **New high-current photo-cathode RF gun**
  - **New positron capture section**
  - **Positron damping ring injection/extraction**
  - **Optimized beam optics and correction**
  - **Precise beam orbit control with long-baseline alignment**
  - **Simultaneous top-up injection to DR/HER/LER/PF/PFAR**
- **Balanced injection for the both photon science and elementary particle physics experiments**



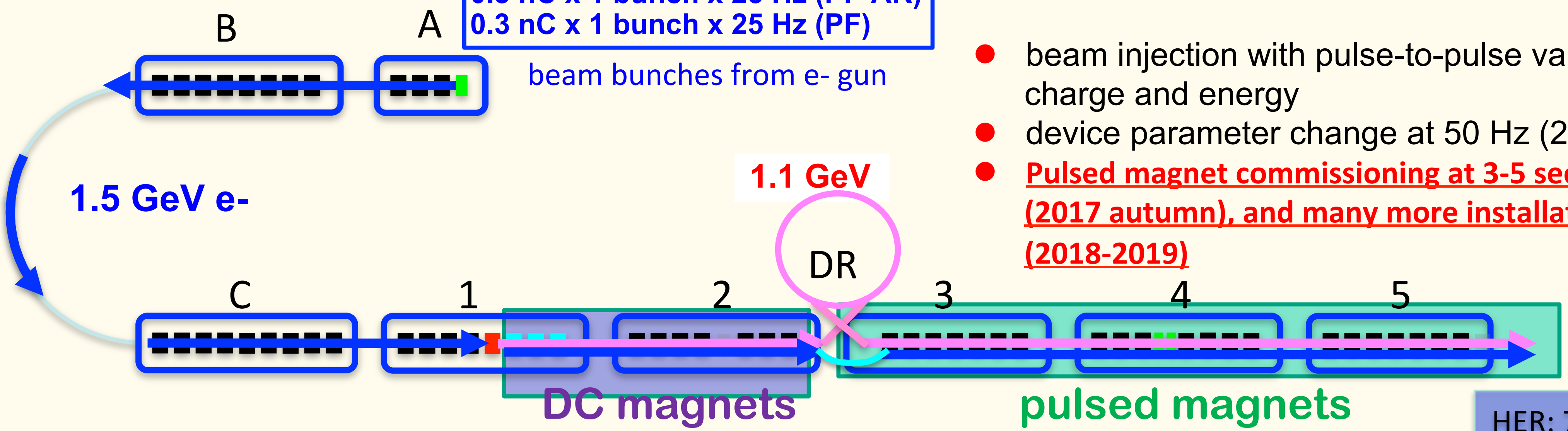
Beam from Injector and Storage Current		
SuperKEKB:	7 GeV e-	2600 mA
	4 GeV e+	3600 mA
PF:	2.5 GeV e-	450 mA
PF-AR:	6.5 GeV e-	60 mA



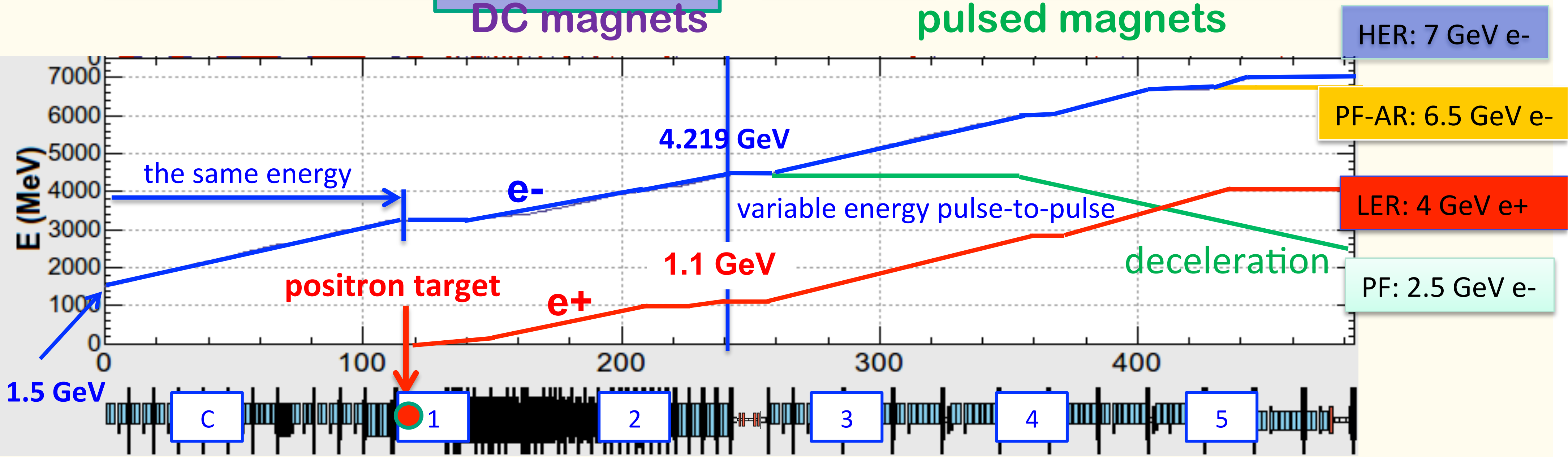
The single injector would behave as multiple injectors to multiple storage rings by the concept of virtual accelerator

Injector Linac Operation in Phase II - III

10 nC x 2 bunches x 50 Hz (LER)
4 nC x 2 bunches x 50 Hz (HER)
0.3 nC x 1 bunch x 25 Hz (PF-AR)
0.3 nC x 1 bunch x 25 Hz (PF)



- beam injection with pulse-to-pulse variable charge and energy
- device parameter change at 50 Hz (20 ms)
- <u>**Pulsed magnet commissioning at 3-5 sectors (2017 autumn), and many more installation (2018-2019)**</u>



Required injector beam parameters

Stage	KEKB (final)		Phase-I		Phase-II		SuperKEKB (final)	
Beam	e+	e–	e+	e–	e+	e–	e+	e–
Energy	3.5 GeV	8.0 GeV	4.0 GeV	7.0 GeV	4.0 GeV	7.0 GeV	4.0 GeV	7.0 GeV
Stored current	1.6 A	1.1 A	1 A	1 A	–	–	3.6 A	2.6 A
Life time (min.)	150	200	100	100	–	–	6	6
Bunch charge (nC)	primary e- 10 → 1	1	primary e- 8 → 0.4	1	0.5	1	primary e- 10 → 4	4
Norm. Emittance (γβε) (μrad)	1400	310	1000	130	200/40 (Hor./Ver.)	150	100/15 (Hor./Ver.)	40/20 (Hor./Ver.)
Energy spread	0.125%	0.125%	0.5%	0.5%	0.16%	0.1%	0.16%	0.07%
Bunch / Pulse	2	2	2	2	2	2	2	2
Repetition rate	50 Hz		25 Hz		25 Hz		50 Hz	
Simultaneous top-up injection (PPM)	3 rings (LER, HER, PF)		No top-up		Eventually		4+1 rings (LER, HER, DR, PF, PF-AR)	

Phase II Operation

Summer Shutdown

Autumn Operation

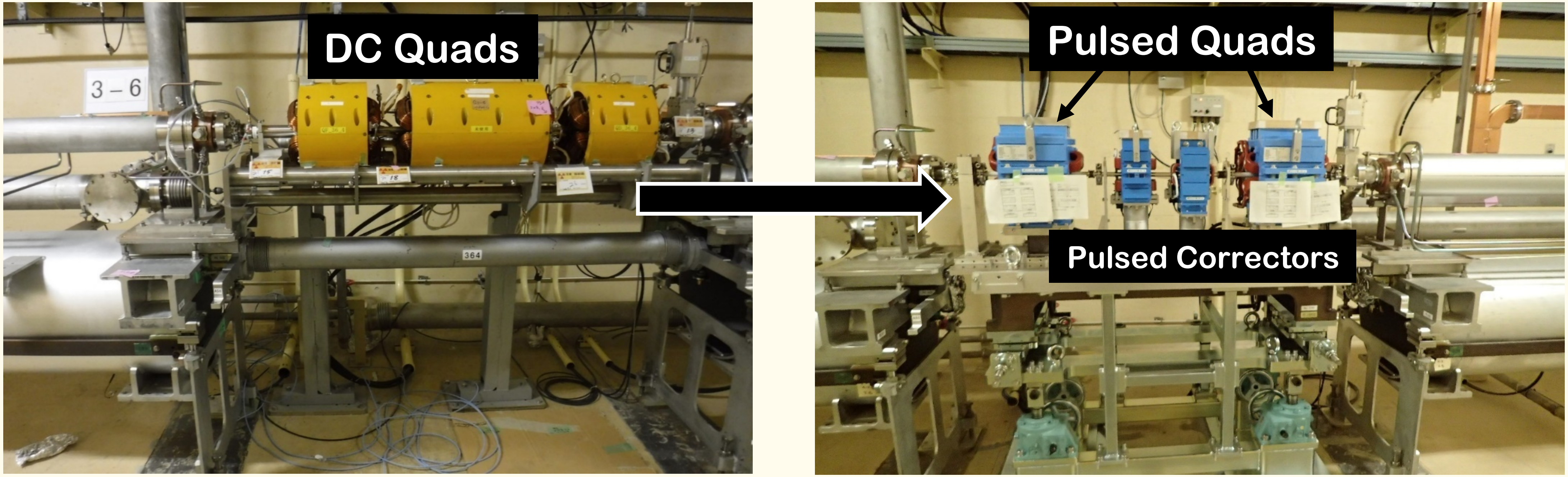
Phase III

Summary

Phase II Operation

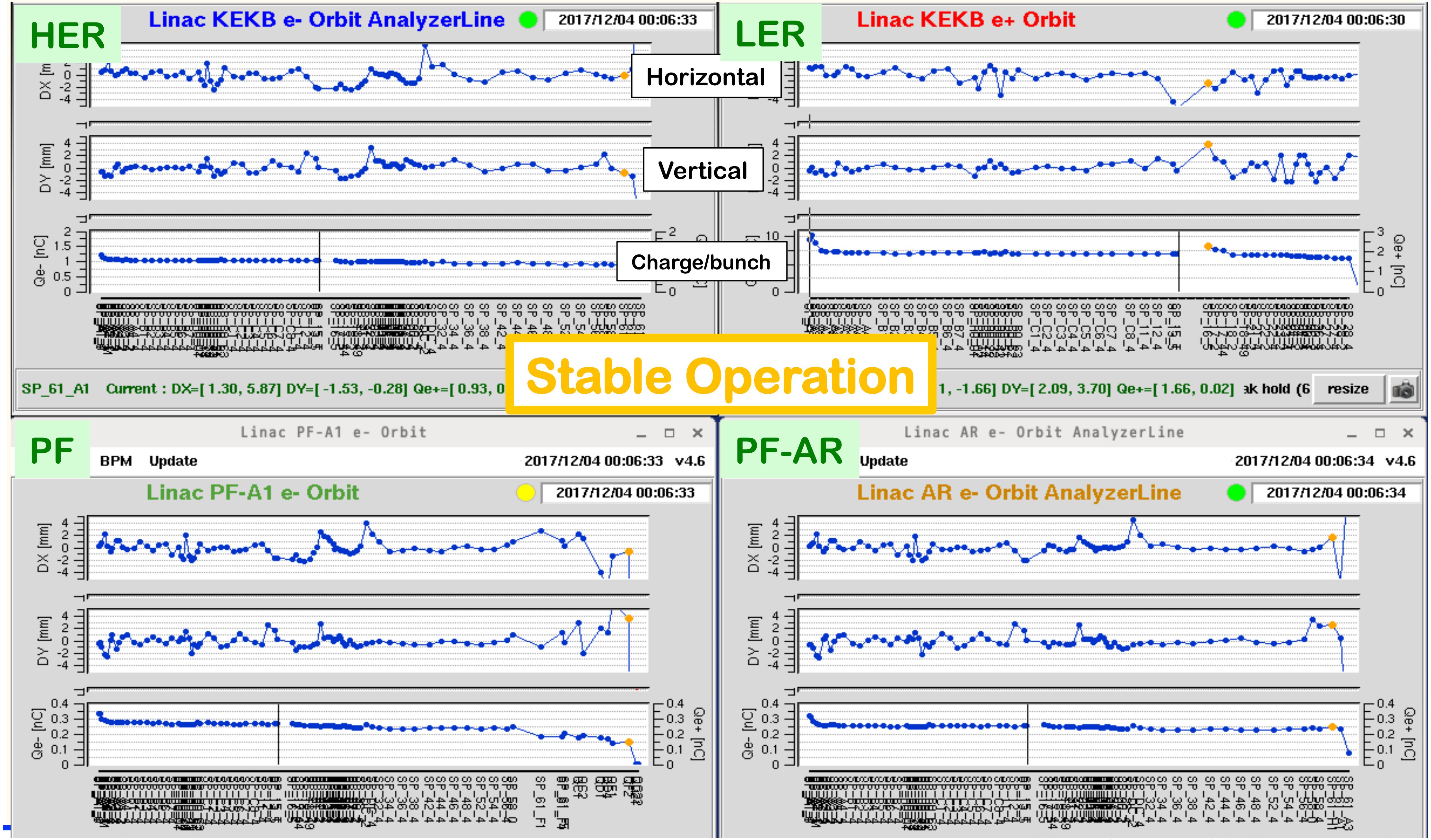
- Injector operation: Jan.12 – Jul.17
- Proper SuperKEKB injection
- Light source injection
  - 3 injections a day, top-up injection for hybrid mode PF experiments
  - 5-GeV PF-AR injection test
- Stable operation of 64 new pulsed magnets at 50 Hz
- 4-beam simultaneous operation with thermionic gun
- HER injection from RF-gun with slower beam switching
- LER positron injection via damping ring
  - with adequate timing and bucket selection
- Instrumentation improvements
  - Beam position monitors, profile monitors, bunch monitors
  - Microwave monitors

Pulsed Magnets

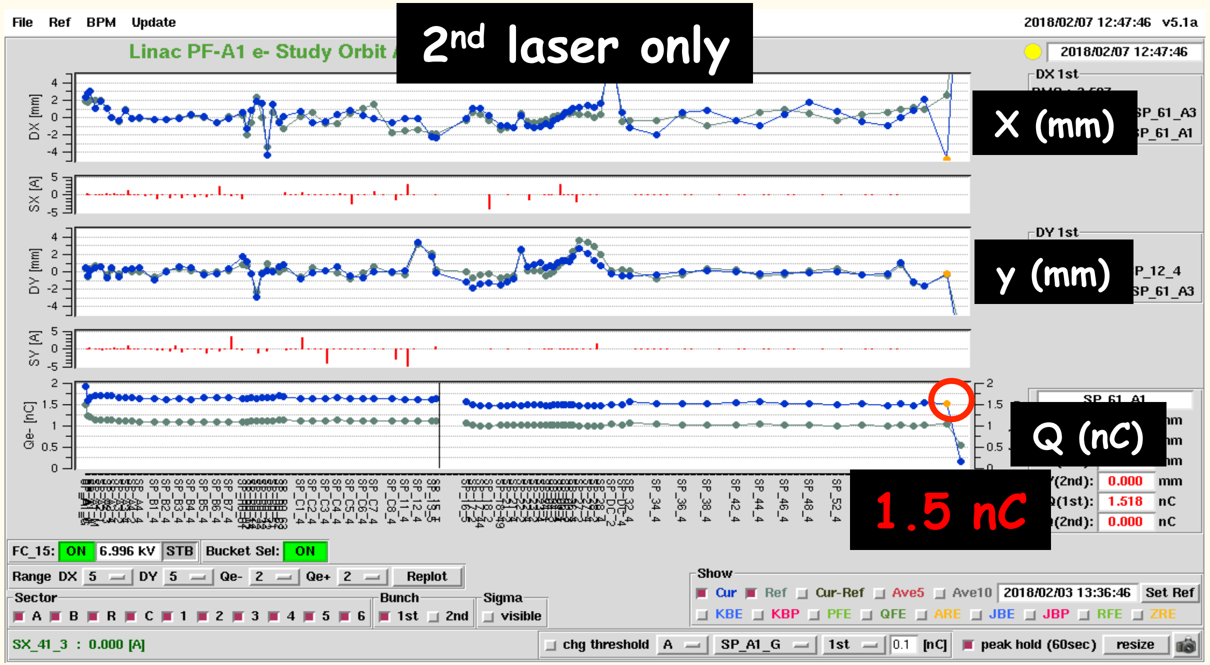


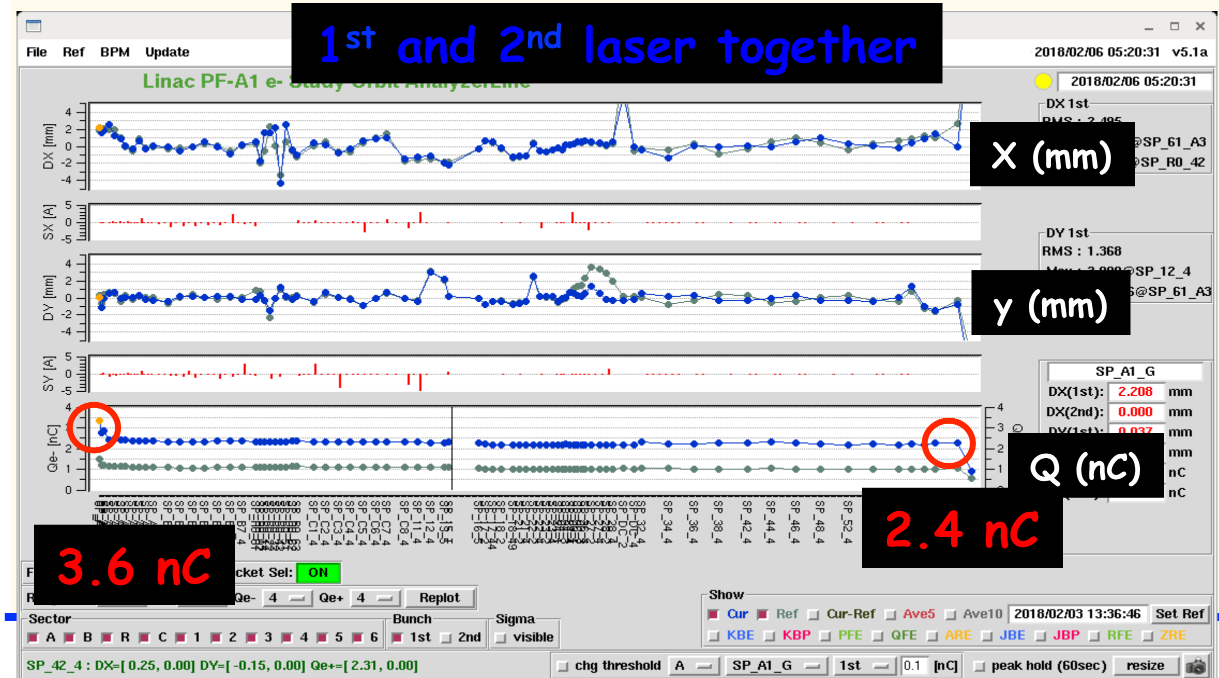
- **Pulsed quad x28 and pulsed corrector x 36 were newly commissioned on new girders** (2017 autumn)
- **Good power supply stability of 0.01% (24 hours)**
- **PXI bus, PXI-EVR, cRIO, 50 Hz controls with Windows and LabVIEW**
- **More pulsed magnet commissioning expected** (2018-2019)
- **Girder mover commissioning** (1 micron alignment enabled, 2018-)
  - **Emittance brow-up investigations and mitigations**

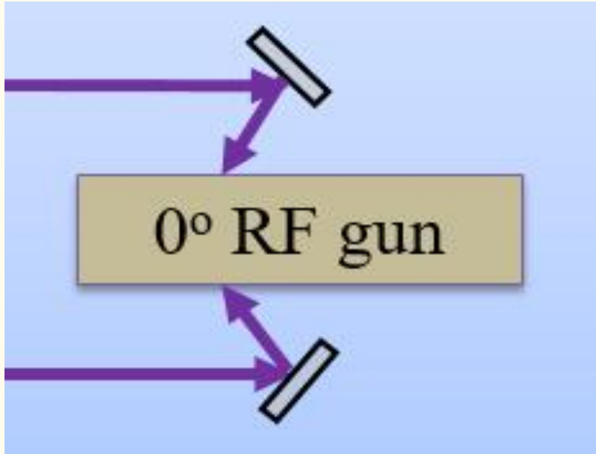
New Pulsed Magnets Enabled Simultaneous Injections



RF gun

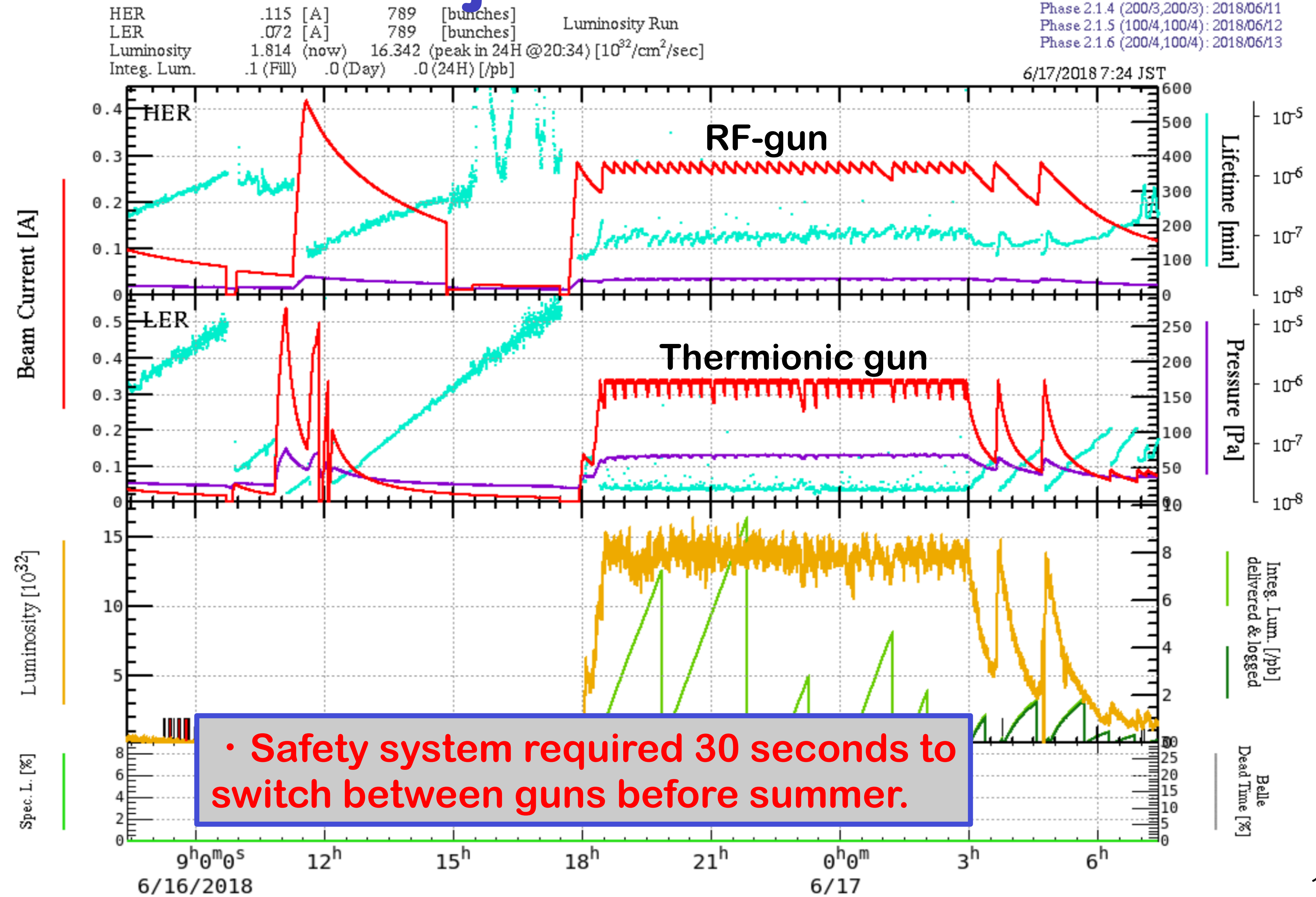






- Three Yb:YAG fiber oscillators
- Redundant Yb:YAG fiber and Nd:YAG disk hybrid laser amplifiers
- Dual laser injection on to IrCe cathode
- Bunch current up to 3.6 nC
  - 2.4 nC at the end of linac (Phase II requirement: 1 nC)

HER Injection with RF Gun

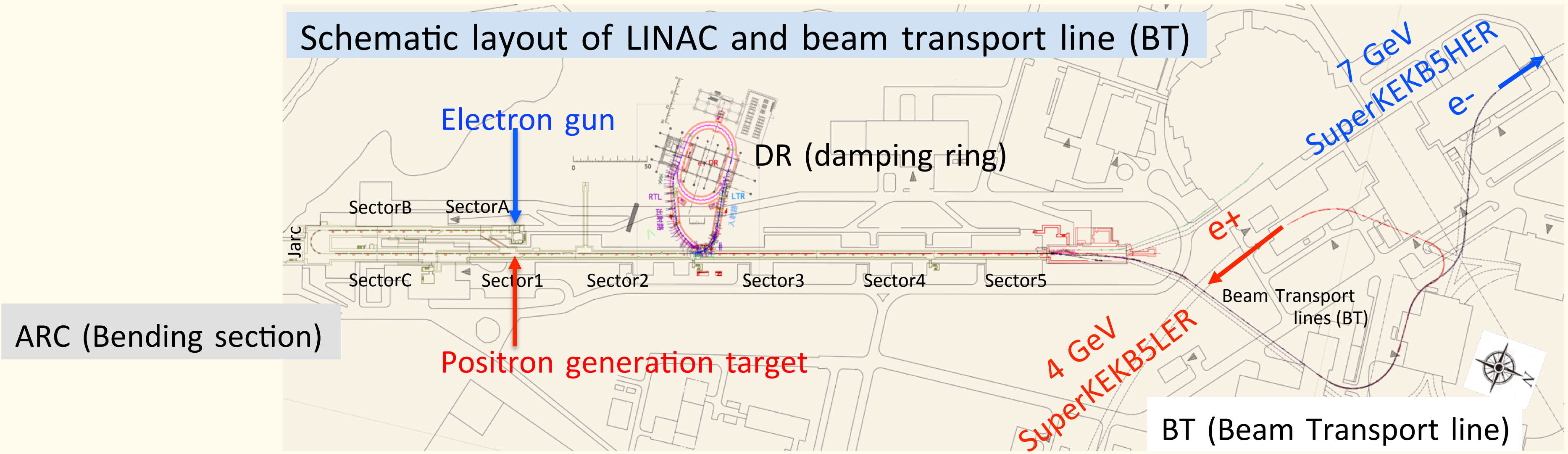


・Safety system required 30 seconds to switch between guns before summer.

Requirement for SuperKEKB

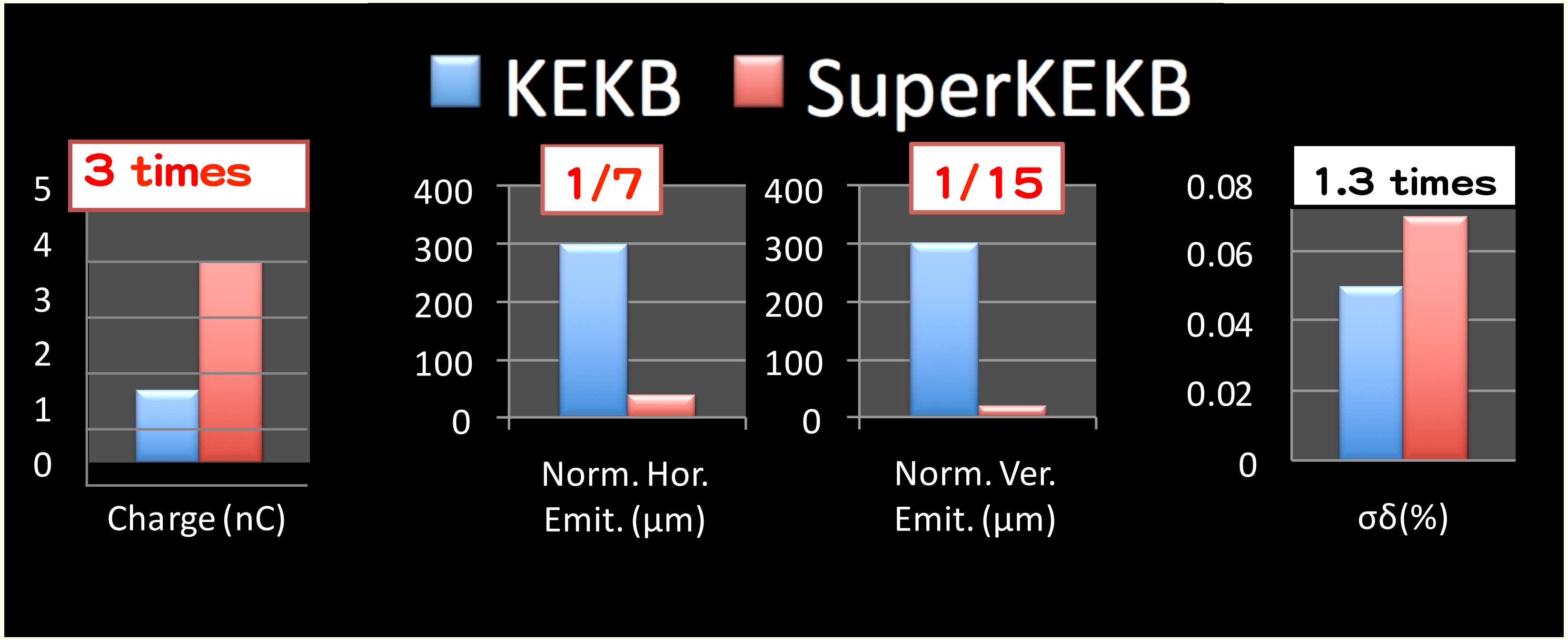
- After the LINAC, beam go through BT.
- In Phase5III final, requirement of beam charge is 4 nC for both beam.
- Requirement for H/V emittance of e+ beam is 100/15 μm.
- Requirement for H/V emittance of e- beam is 40/20 μm.
- We have to realize the high quality beam transportation to main ring without emittance growth as far as possible.
- Otherwise, injection rate is worse and luminosity can not reach the target value.

Stage	Phase II (Mar. – Jul. 2018)		Phase III (Mar. 2019 –)	
Beam	e+	e–	e+	e–
Bunch charge (nC)	1.5	1	4	4
Norm. Emit. μm	200/40 (Hor./Ver.)	150	100/15 (Hor./Ver.)	40/20 (Hor./Ver.)
Energy spread	0.16%	0.1%	0.16%	0.07%



Injection Beam at KEKB and SuperKEKB

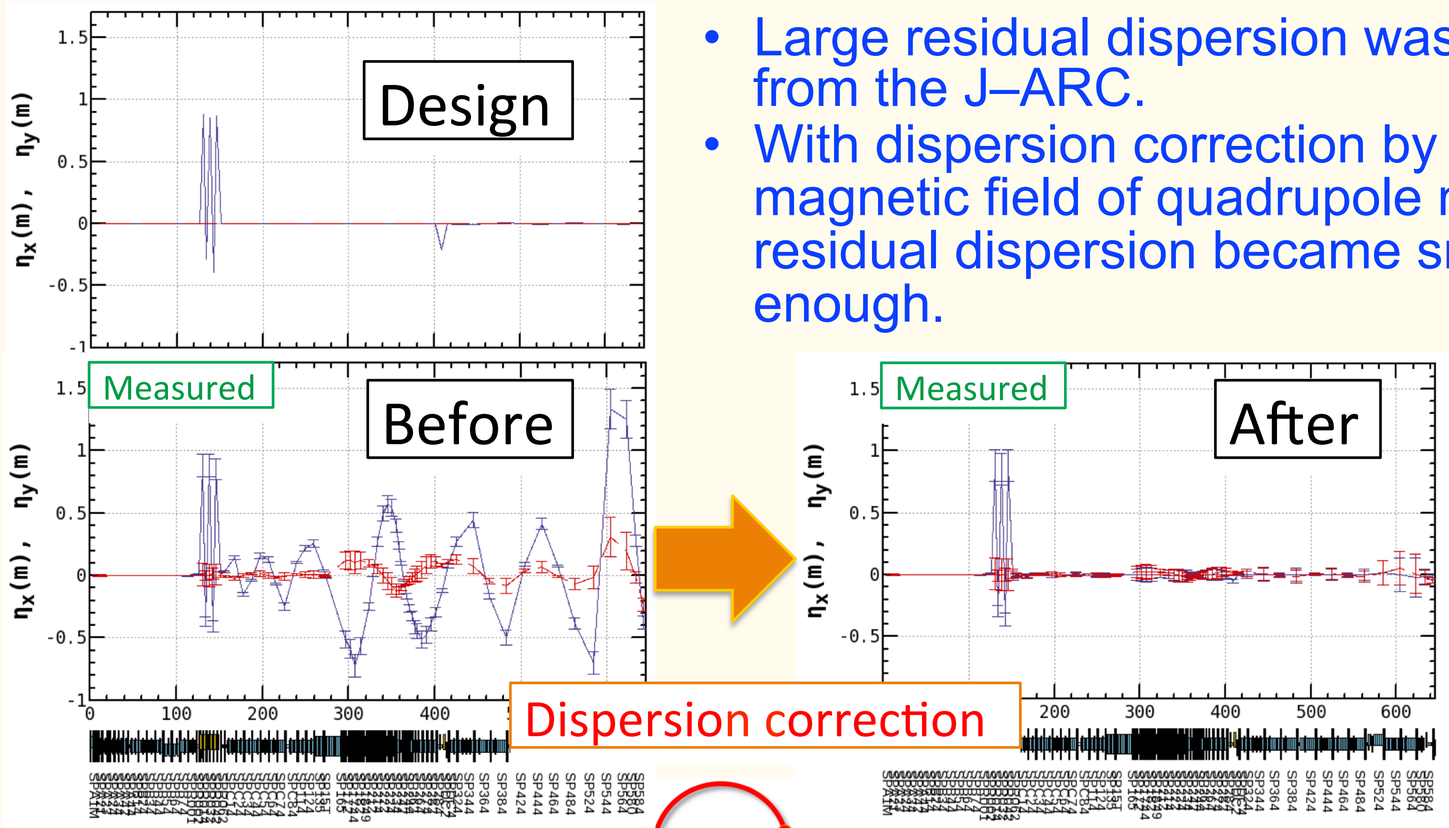
- **Comparison between achievement at KEKB and requirement at SuperKEKB Phase III**
  - **Much smaller emittance even with 3-fold higher beam charge**
  - **Still a big challenge that is being resolved**

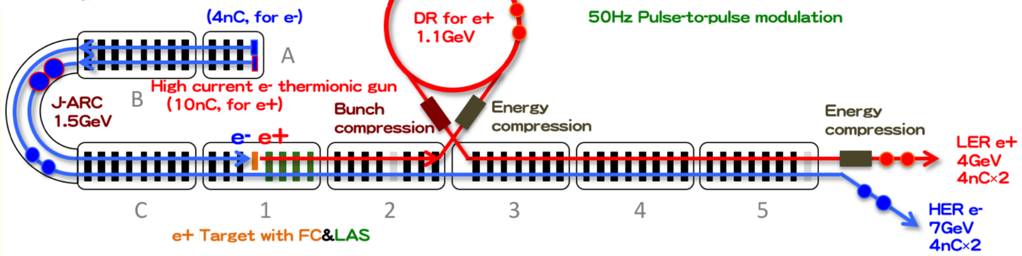


Residual Dispersion Function in Linac

Y. Seimiya et al.

- Large residual dispersion was generated from the J–ARC.
- With dispersion correction by tuning the magnetic field of quadrupole magnets, residual dispersion became small enough.





Residual Dispersion Function in DR RTL

- This table shows values of residual dispersion before and after correction.
- Residual dispersion became smaller in both ARCs.

Y. Seimiya et al.

There are two ARCs in the DR extraction line.

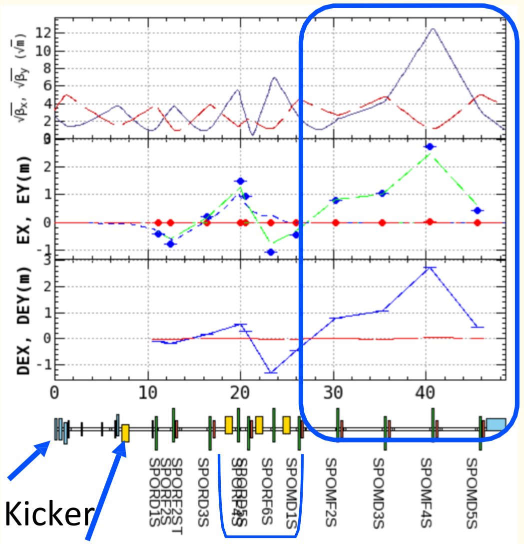
e+	$\langle\eta x^2\rangle^{1/2}$ [m]		$\langle\eta y^2\rangle^{1/2}$ [m]		Fudge Factor of Quad.
Correction	Before	After	Before	After	[%]
2nd ARC	0.079	0.019	0.0094	0.0077	C 4.5
1st ARC	1.05	0.09	0.02	0.01	C 8.2

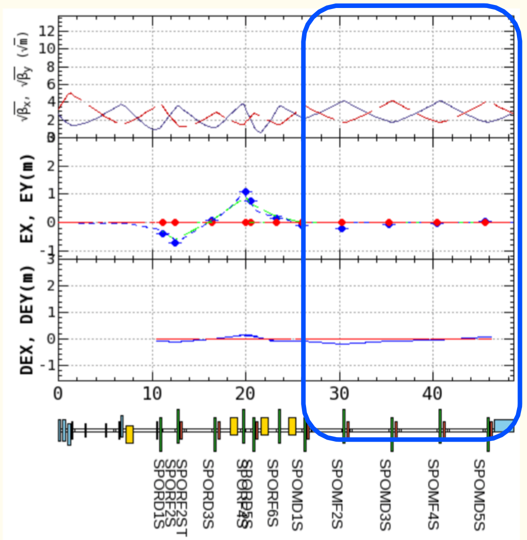
Need more study

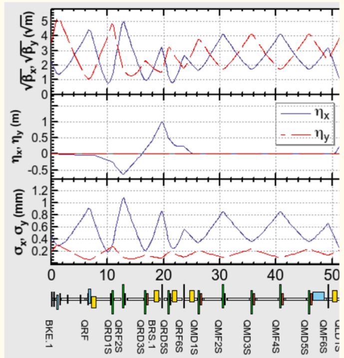
Example: 1st ARC

Before → After dispersion correction

Optics of the extraction line







The third graph shows residual dispersion. Blue is horizontal and red is vertical.

Extraction Kicker

Extraction Septum

DC Bends

Instead of changing the energy of DR, I changed the strength of Bend, Quad all at once. For the kicker and septum, Response measurement was done.

Phase II Operation

Summer Shutdown

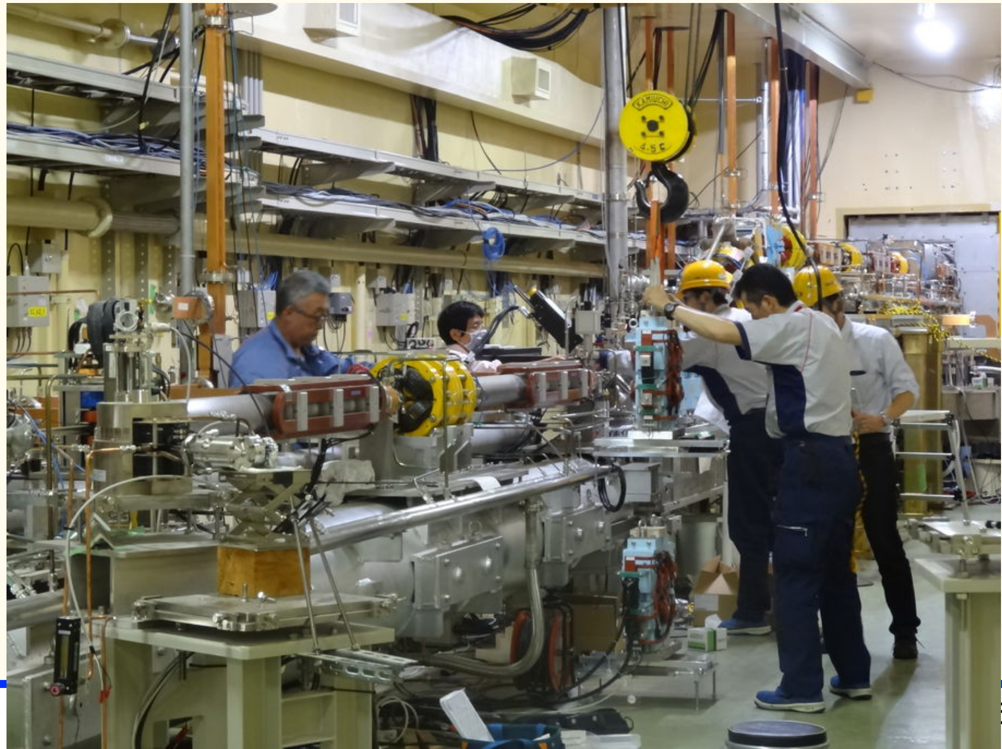
Autumn Operation

Phase III

Summary

Summer Maintenance and Improvements

- 105 items were performed
- From July 17th to October 22th
- There were several near misses (no injuries)
  - Taking measures against them
- Morning meetings every day

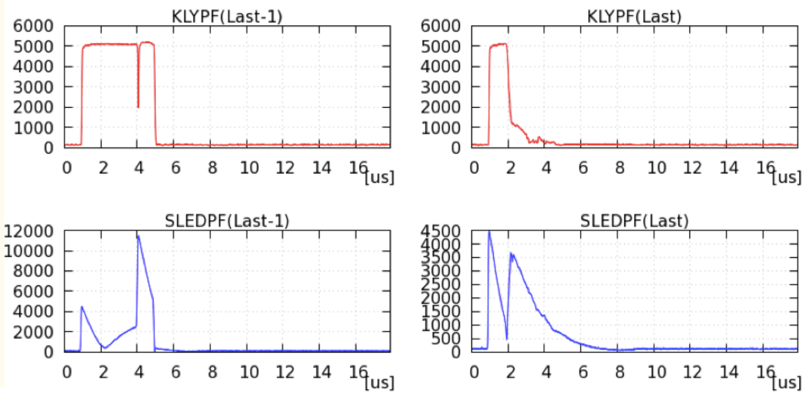


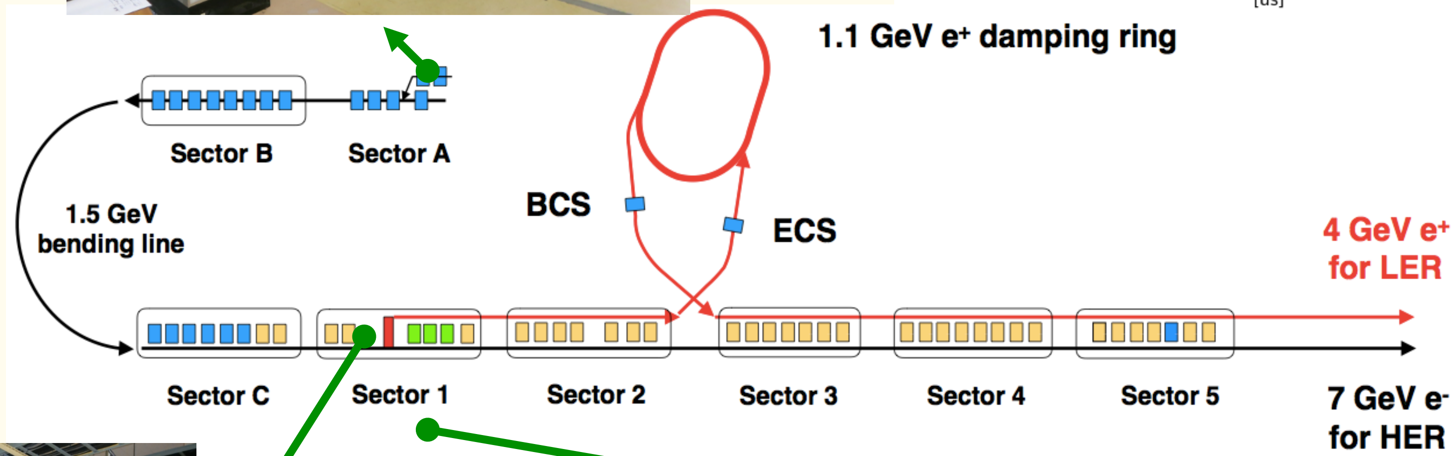
RF System Upgrade

Replacement of SHB1 Solid-State 10kW Amp.

20 years old, often unstable, degraded power

RF Monitor Upgrade (Pulse-Shortening Detector)

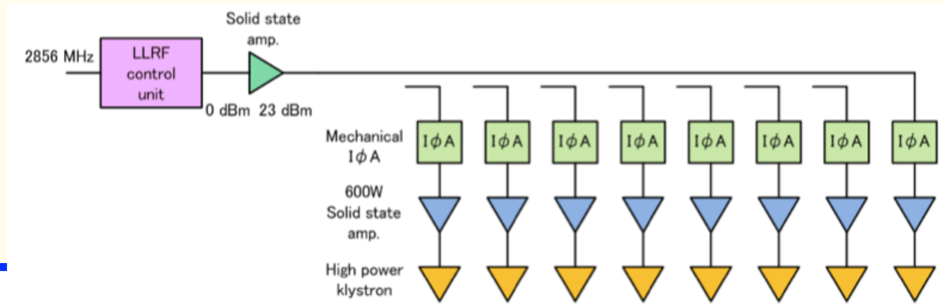




Solid-State Sub-Booster System

Replaced single 60-kW klystron with distributed 600W Solid-State Amplifiers

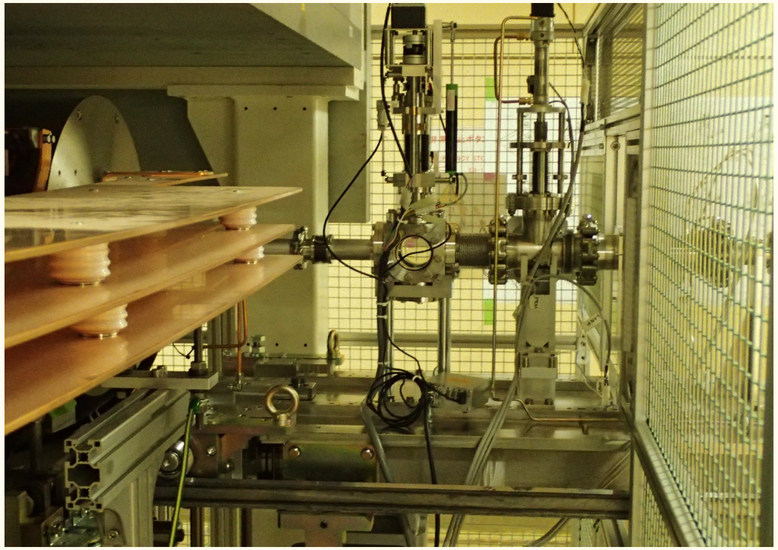
KL_13 Reinstallation

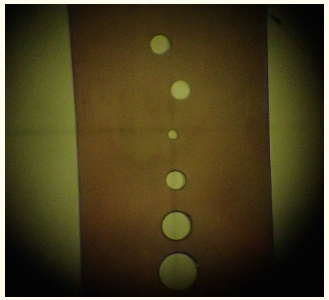


Accelerating Units and Target Hole

- Restoration of Unit 1-3
- Replacement of markedly deteriorate accelerating structures in Units 1-1 and 5-1 with spares capable of rated power operation
- Installation and adjustment of the power supplies for pulse magnets newly installed
- Removal of the used FC base-unit and installation of the dummy plunger with holes for beam jitter measurement
- Upgrade of control system for bending and solenoidal magnets

Restored Unit 1-3

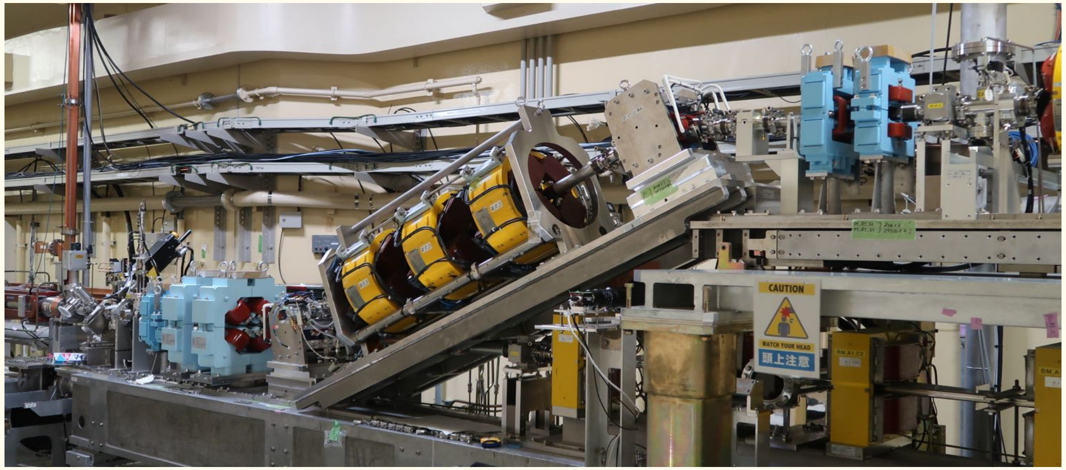




Dummy plunger with holes (replacing target)

Magnets and Beamline

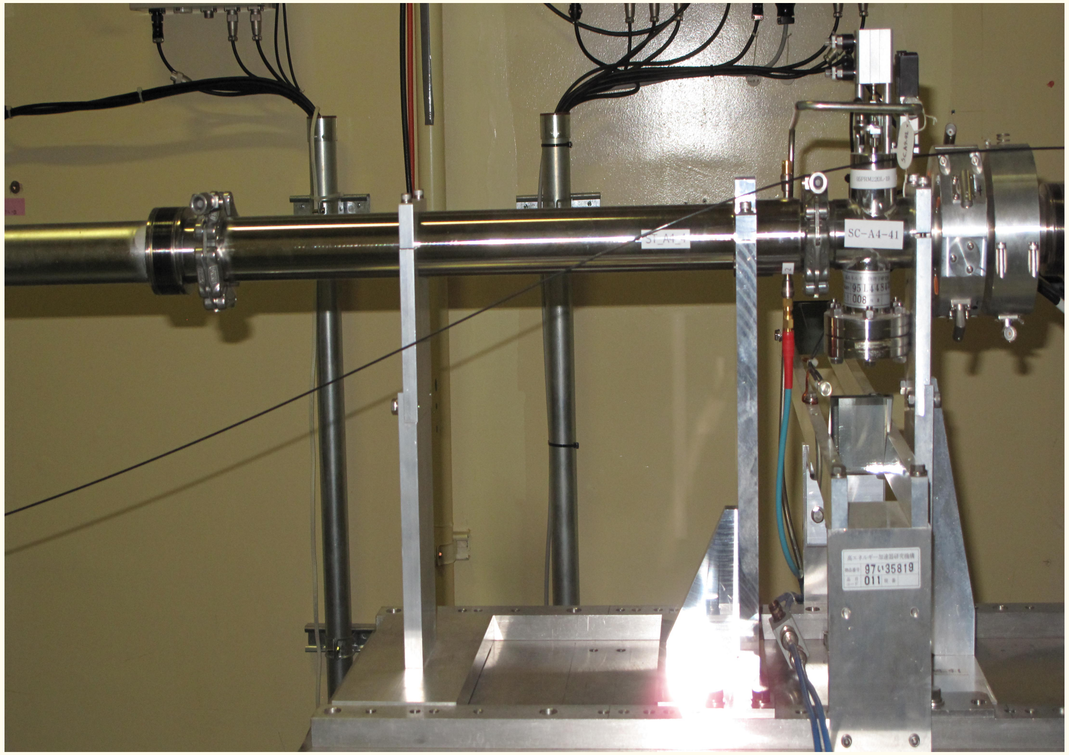
- **Pulse magnets installed in beam-merger line of two pre-injectors. (bends x2, quads x4, correctors x4)**



- **Corrector magnets added.** (PY_12_2 [pulsed], BX_DS_C2 [DC])
- **DC corrector magnets removed in Sector-3, 4, 5.**
  (pulsed correctors installed in summer 2017 summer)
- **Interlock system configuration improved.**
  (e+ focusing DC solenoids, beam dump line quads)
- **Alignment of all beam-line girders and quads measured. Those with large deviation adjusted.**
- **Remote control system installed in e+/e- beam separator.**

Development of New Beam Monitors

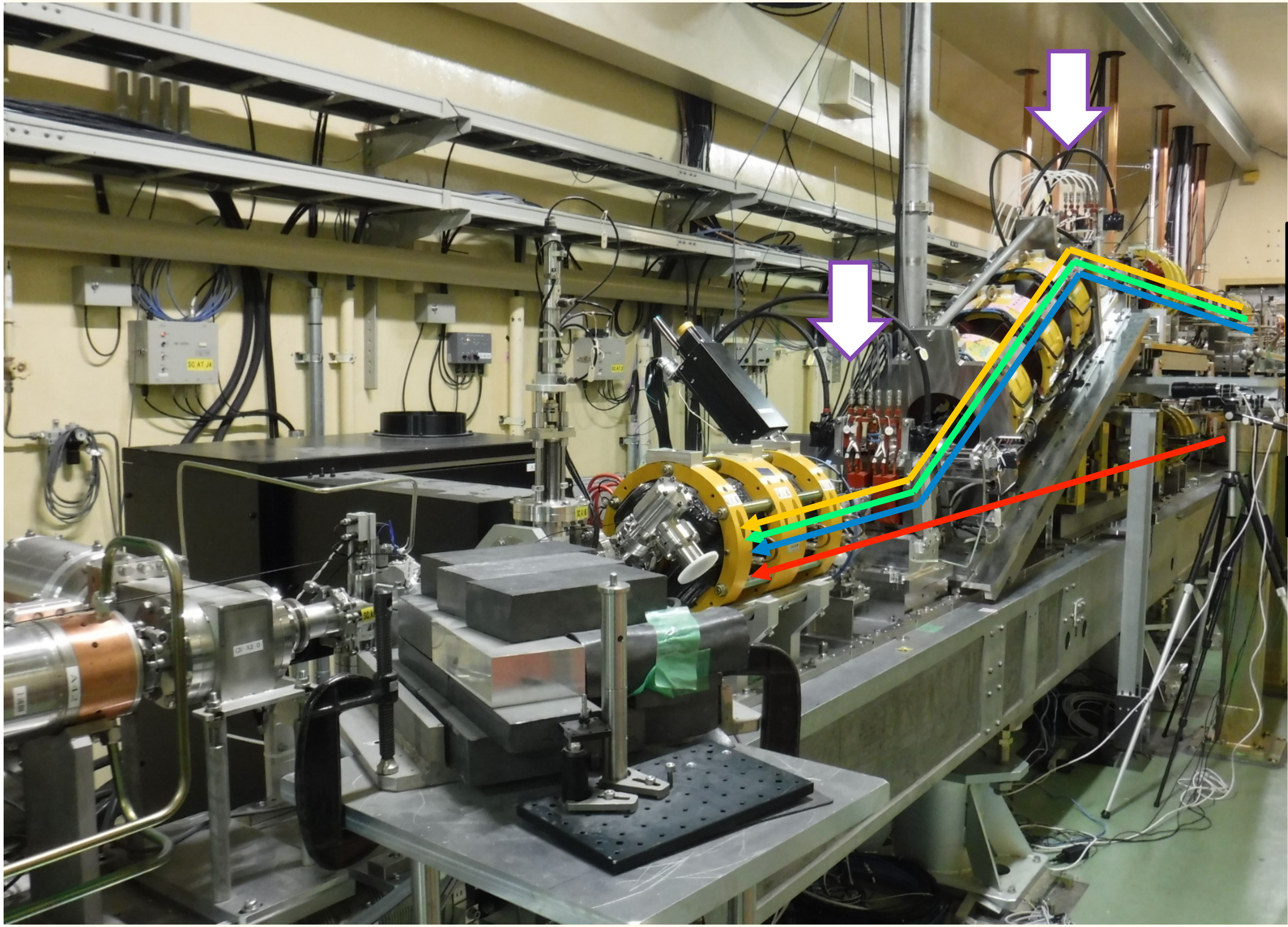
A new beam profile monitor with OTR target and high-precision optical focus system was installed at SY2 straight line. The resolution is expected to be 8 micron in FWHM.



A new beam timing monitor with stripline electrodes was installed at #A44. The resolution is expected to be 2 ps in RMS.

Beam induced RF monitors are improved to held each other.

Planning Pulsed Magnets for Merger Line



24-degree Merger Bend x2

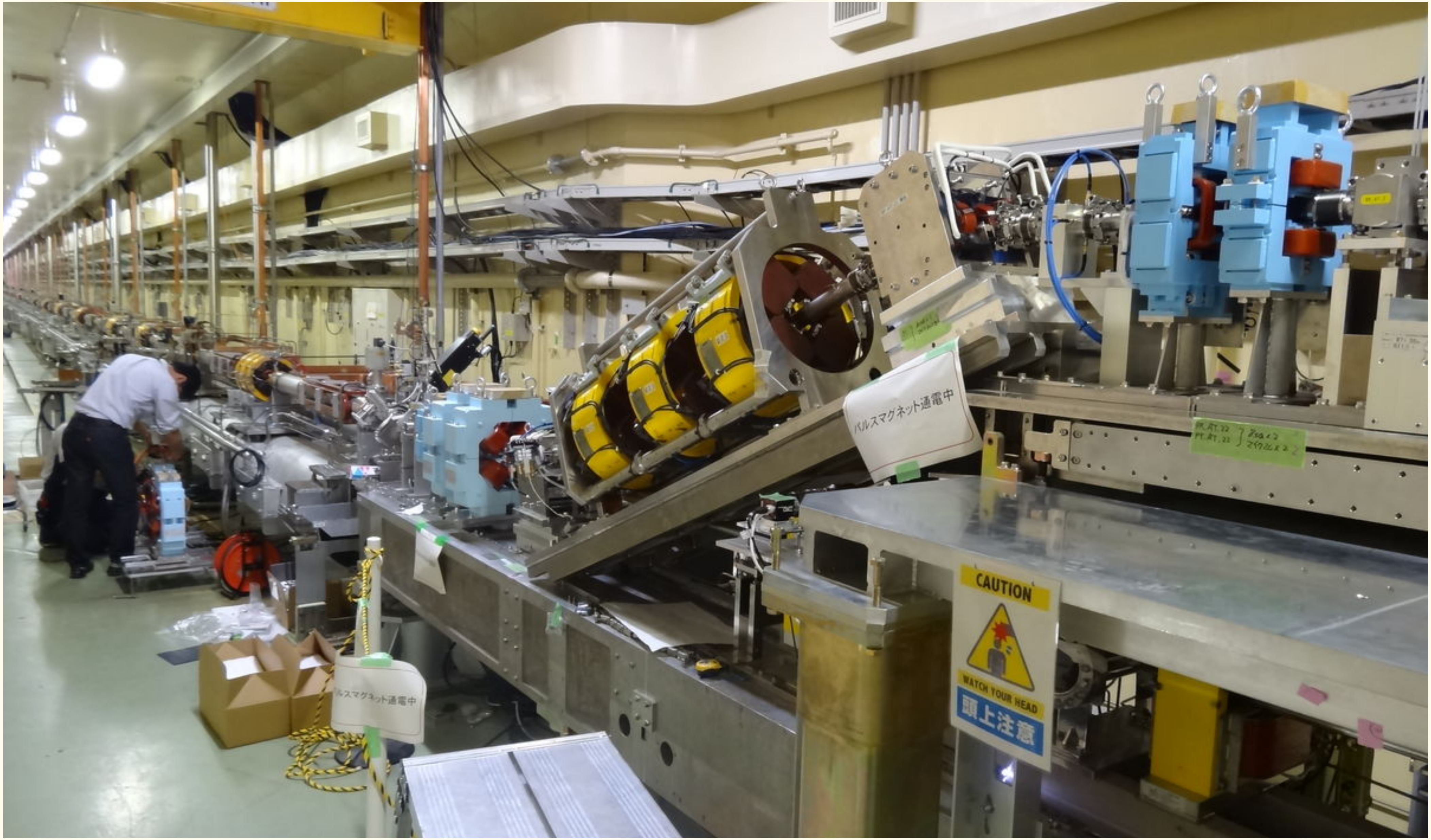
Thermionic Gun

PF-AR
LER (primary e– for e+)
PF

HER

Photo RF Gun

Pulsed Magnets for Merger Line



Phase II Operation

Summer Shutdown

Autumn Operation

Phase III

Summary

Injector Operation in Autumn 2018

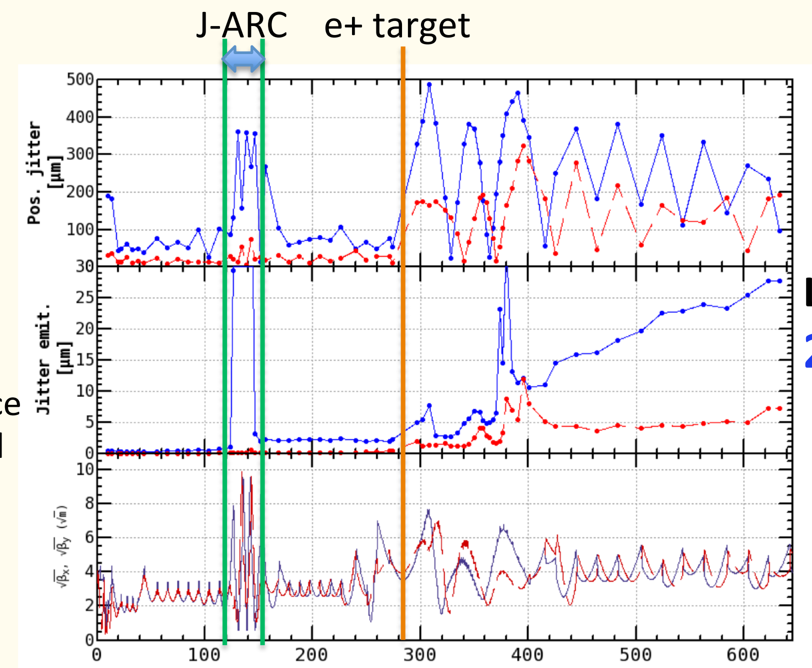
- Top-up injections to light sources, PF/PF-AR
  - With pulsed magnets at beamline merger of guns
- No positron damping ring operation
  - Opportunity to study beam behavior at target hole
- 25 Hz mostly, followed by 3-day 50-Hz hardware checks
  - First intense 50-Hz operation since 2011 earthquake in 2019
- Emittance brow-up studies and knowledge acquisition
  - Beam studies are planned, partially with simultaneous injection
- Emittance preservation
  - Beam orbit, optics controls and mover application
- Gradual beam current and gradient improvements
  - For later injection improvement

Beam Phase Space Jitter

First figure shows the standard deviation of beam position. Second figure shows emittance growth induced by beam jitter.

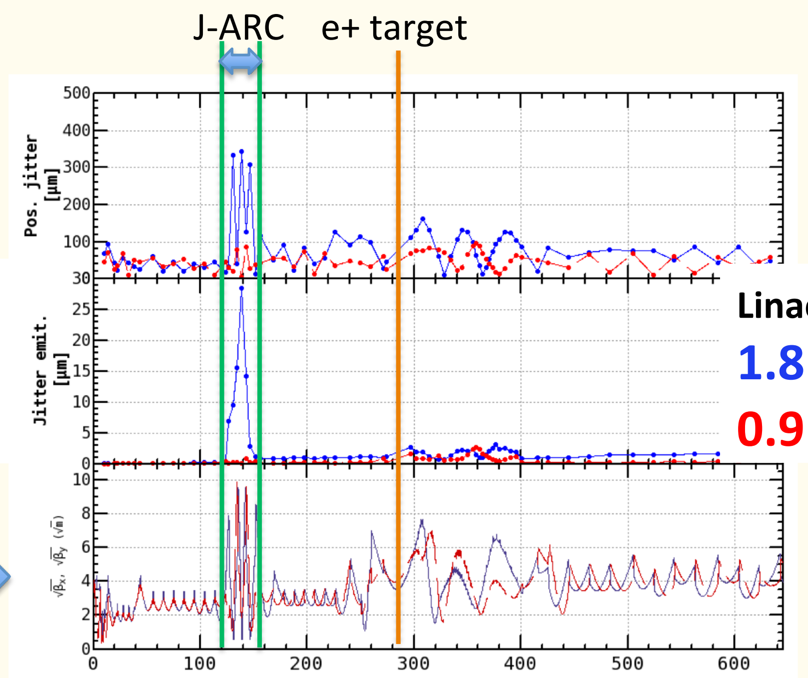
Before dispersion correction

1nC



Linac end:
28 µm
7 µm

After dispersion correction



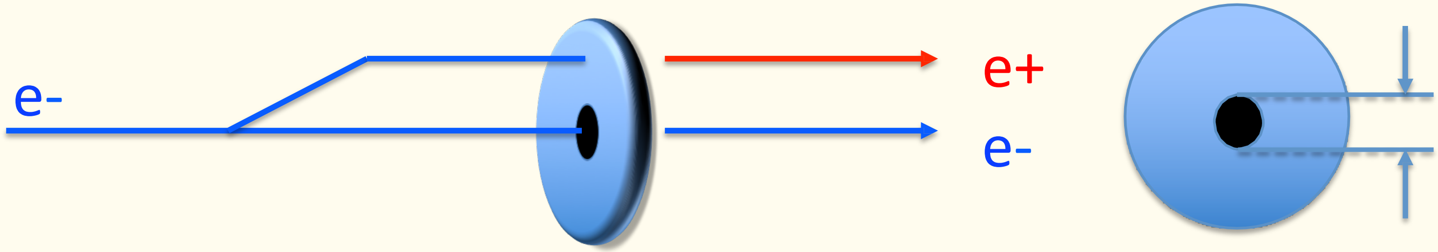
Linac end:
1.8 µm
0.9 µm

Beam phase space jitter is reduced by dispersion correction.

- Small emittance growth still occurred from after the target after the correction.
- We should understand the source of the beam jitter to prepare for the high charged beam (4 nC) and for accidental jitter source which occur at upstream the target.

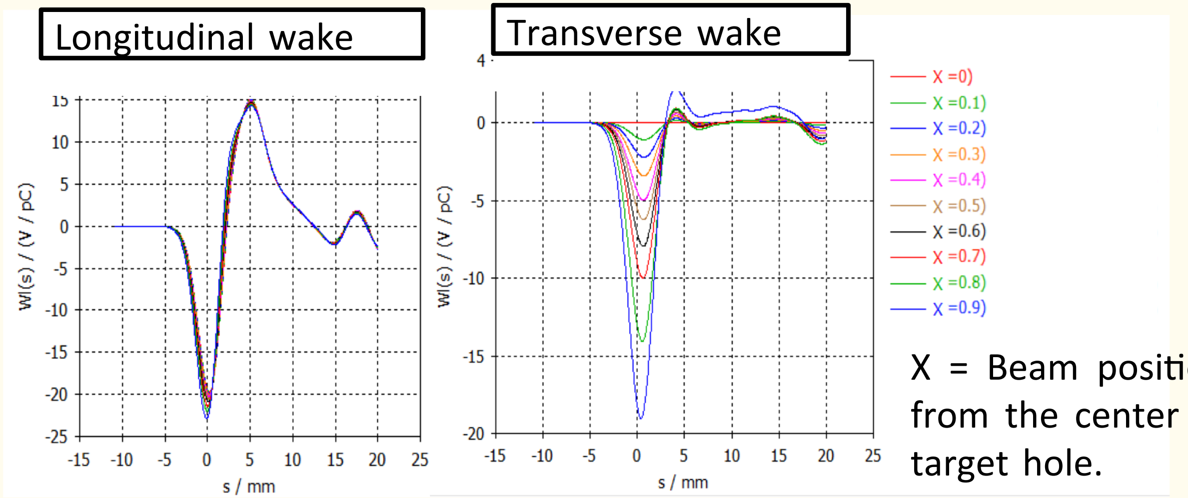
Emittance Growth at Target Hole (?)

Y. Seimiya et al.



- In order to reveal beam jitter problem, simulation analysis of the wakefield in the target hole was performed.
- Color variation shows difference of beam position from the center of target hole.

Wake potential in the target hole.



X = Beam position from the center of target hole.

Enlarged coefficient of beam position jitter:

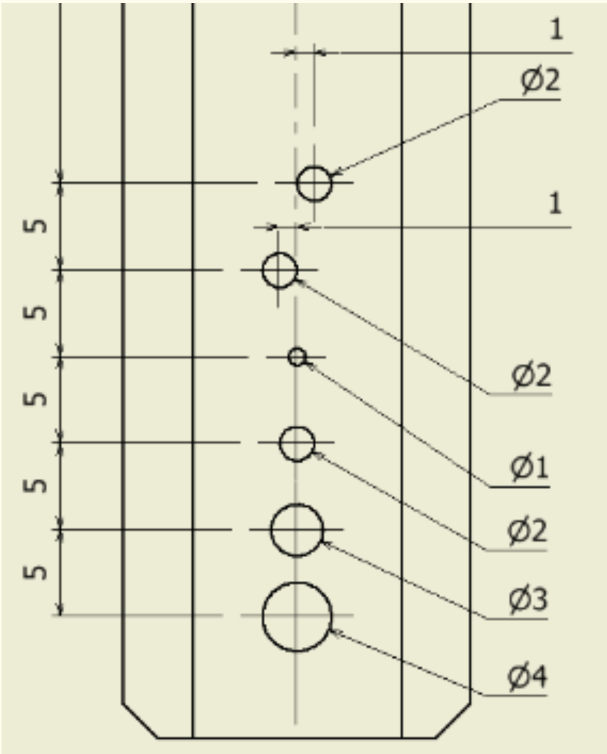
$$R_j = \frac{\beta \Delta y'}{\Delta y} = \frac{Q}{E_0} k_{\mathrm{T}} \beta_y$$

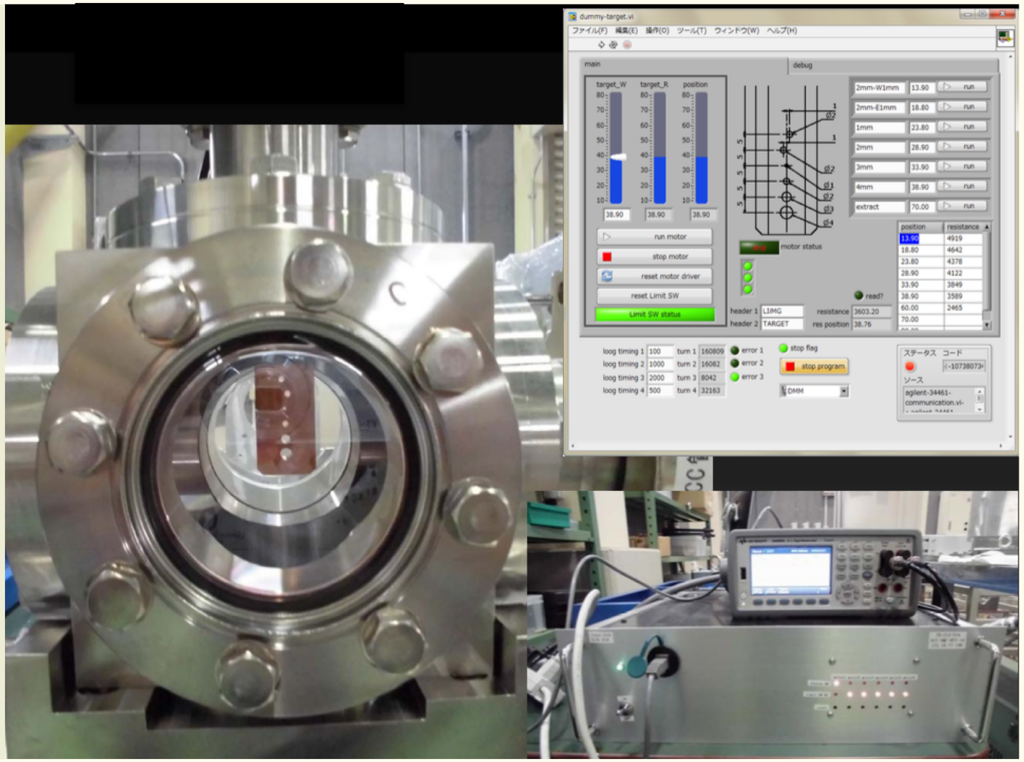
~ 0.1@1nC << Measured enlarged coefficient

Target Hole Study

Y. Enomoto et al.

- To reveal beam jitter source directly, we temporally replace the target to dummy target with several hole, which have different diameter.
- In this autumn, we will study the target hole effect on beam jitter.





Simulation for Minimizing Emittance Growth Induced by Wakefield in Acceleration Structure

Particle tracking simulation was performed to evaluate this emittance growth.

Simulation conditions:

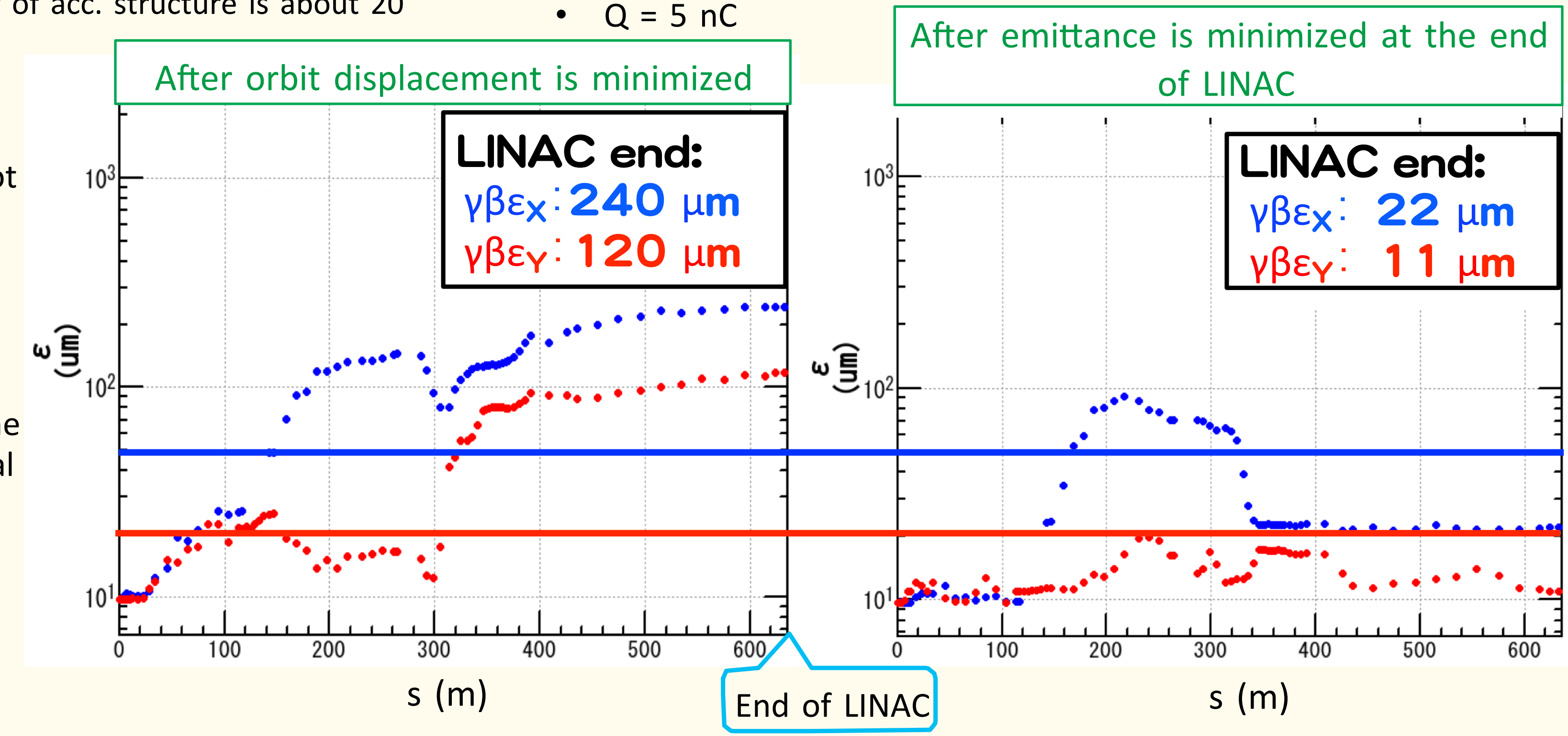
- Measured misalignments of acc. structure and quadrupole magnet were used.
- Iris diameter of acc. structure is about 20 mm.

- ε_{inj} = 10 μm
- σ_z = 1.3 mm
- σ_δ = 0.4%
- Q = 5 nC

Phase;III requirement:
Horizontal : − (<50 μm)
Vertical : − (<20 μm)

Blue and red dot show horizontal and vertical emittance, respectively.

Blue and red line shows horizontal and vertical requirement of Phase III.



By the orbit correction for minimizing emittance growth, requirement of Phase III can be satisfied.

Phase II Operation

Summer Shutdown

Autumn Operation

Phase III

Summary

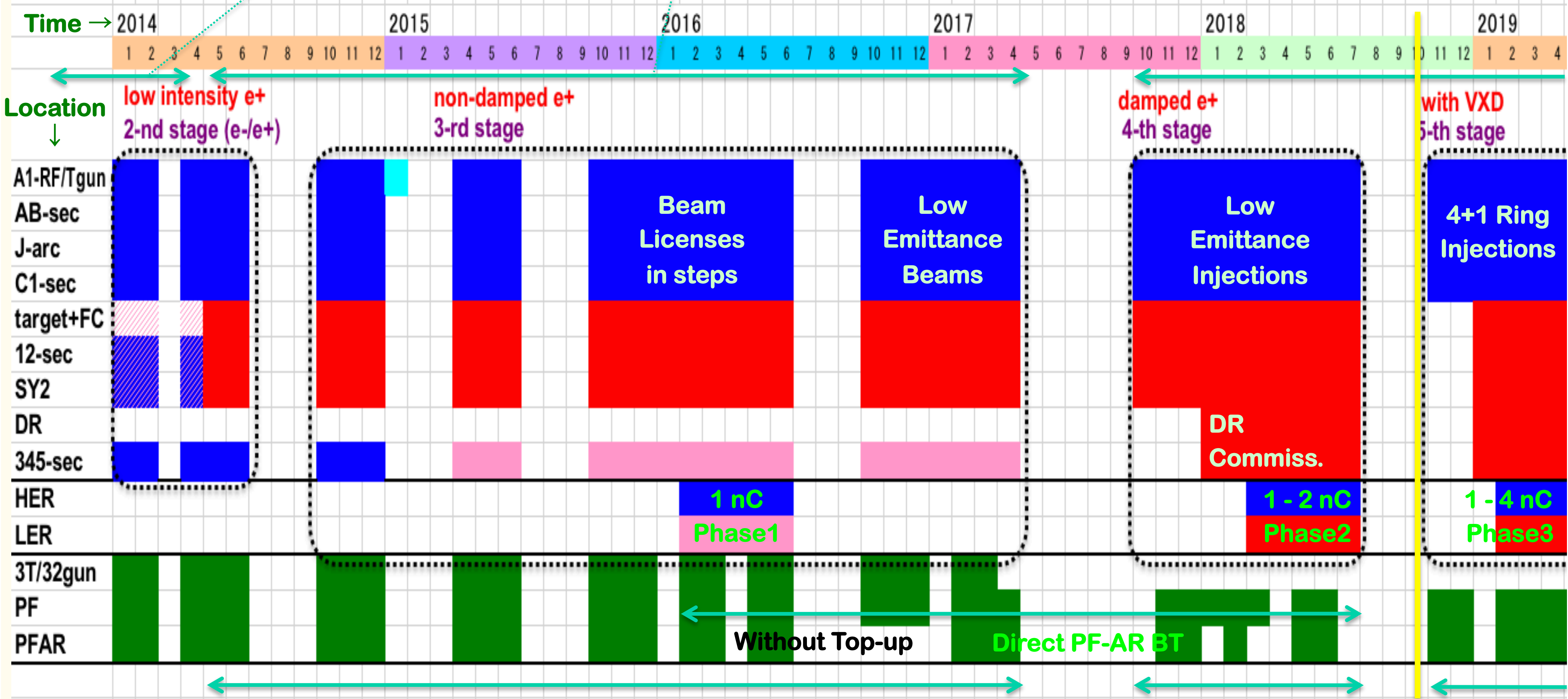
Linac Schedule Overview as of Jun.2018

RF-Gun e- beam commissioning at A,B-sector

e- commiss. at A,B,R,C,1

e+ commiss. at 1,2 sector (FC, DCS, Qe- 50%)
e- commiss. at 1,2,3,4,5 sector

Phase1: high emittance beam for vacuum scrub
Phase2,3: low emittance beam for collision



non damped e+ commiss. at 1,2, 3,4,5 sectors
e- commiss. at A→5 sectors

damped e+ commiss. at 1→5 Qe+ = 1~4nC
e- commiss. at A→5 Qe- = 1~4nC

Improved RF gun

■ : Electron
■ : Positron
■ : Low current electron

For Phase 3

- Simultaneous injections with some more pulsed magnets, in order to adjust beam optics and orbits
- Some more beam instrumentation improvements
- Positron target / flux concentrator restoration
- 50 Hz operation
- Further instability hunt
- Low emittance beam developments
- Reliability, reproducibility, automation, etc.

Summary

- The injector performed Phase-2 commissioning without much troubles

- The facility is believed to be ready for the first year in Phase-3, while it may face challenges to achieve the final beam qualities

Thank you