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

Kazuro Furukawa
for Injector Linac, KEK

Overview

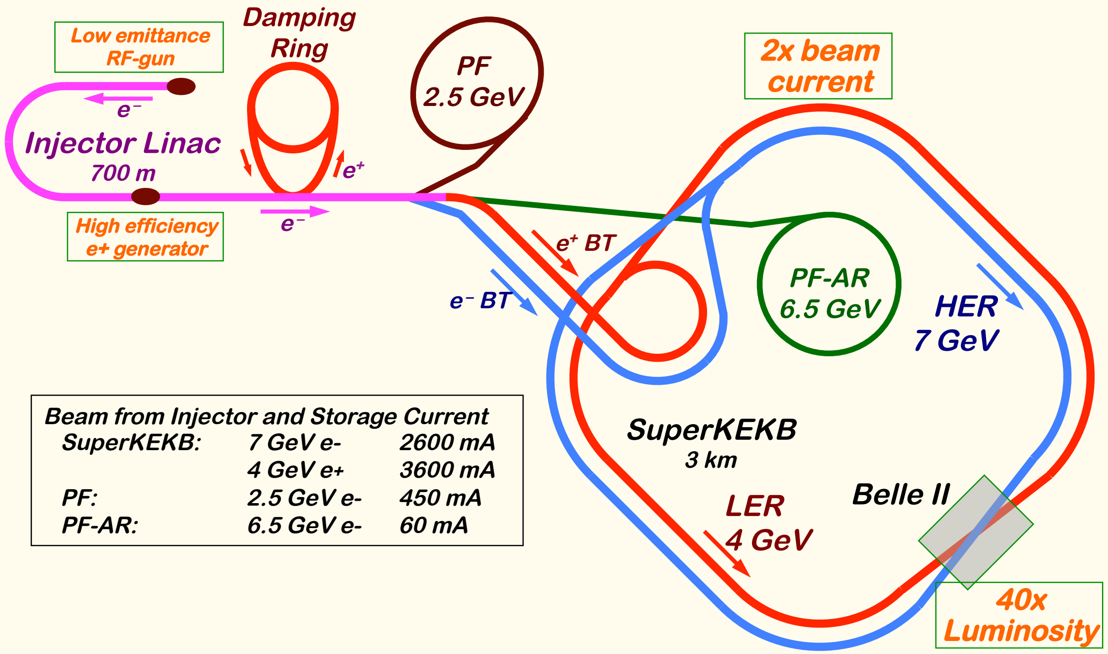
Beam Quality Management

Accelerating Structure

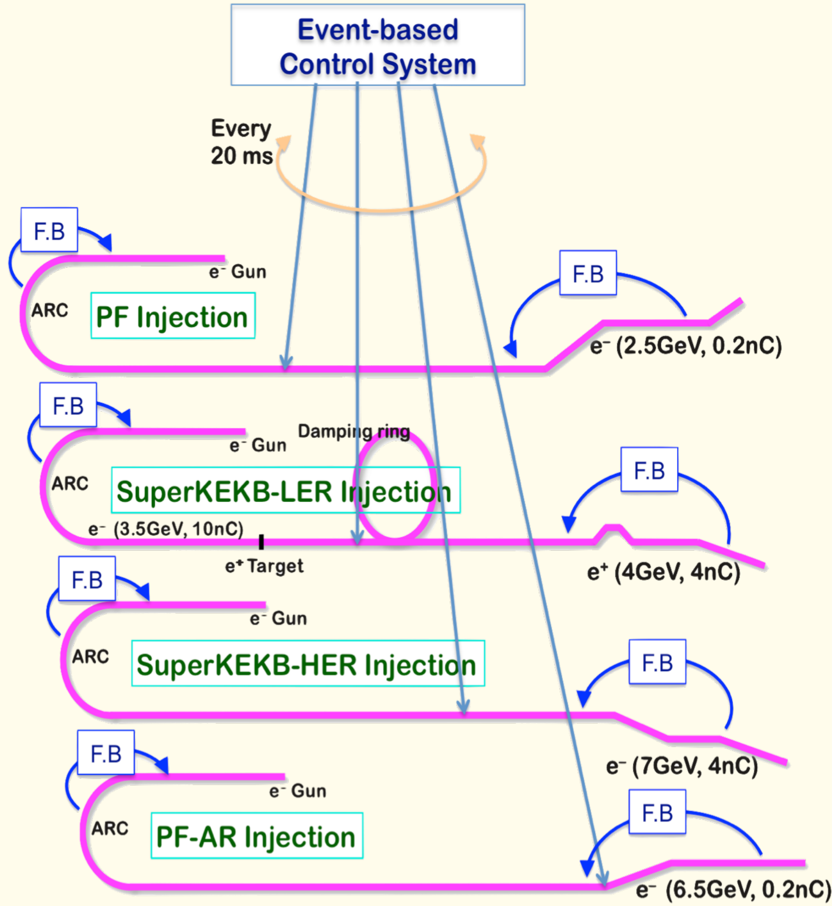
Summary

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

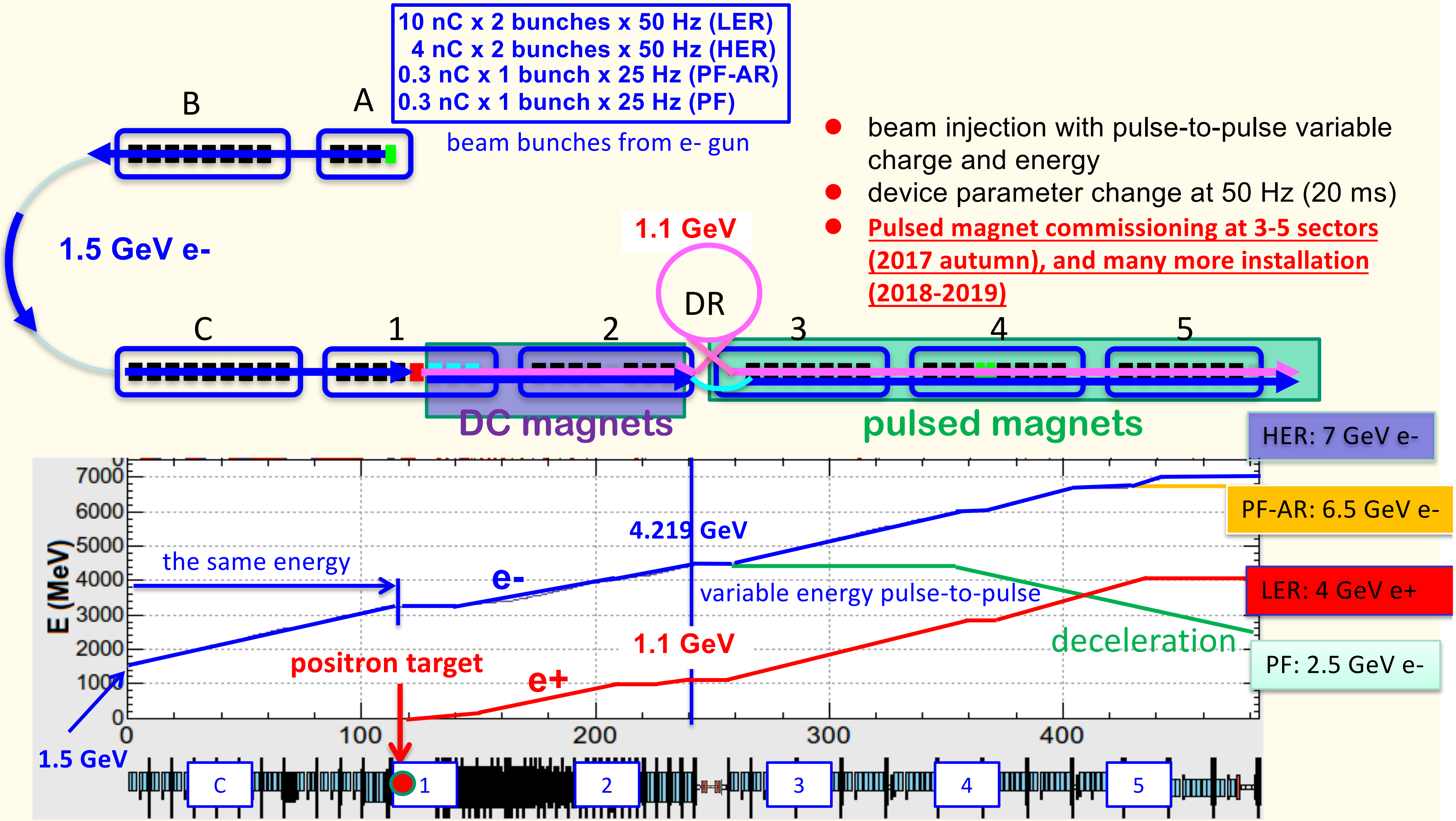


Beam from Injector and Storage Current		
SuperKEKB:	7 GeV e-	2600 mA
	4 GeV e+	3600 mA
PF:	2.5 GeV e-	450 mA
PF-AR:	6.5 GeV e-	60 mA



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



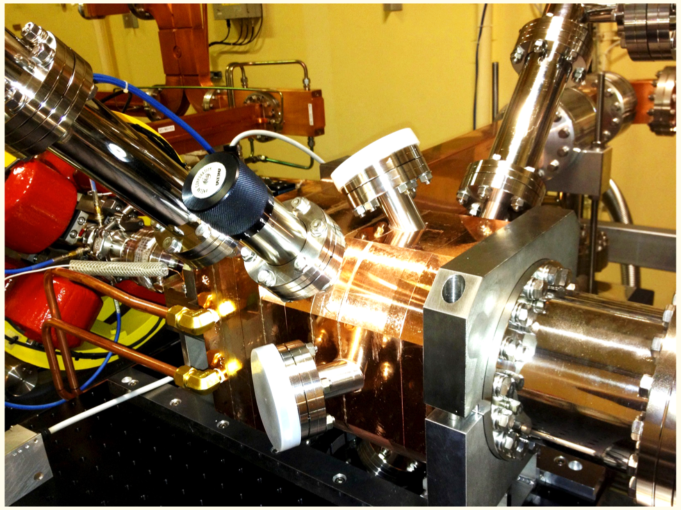
- beam injection with pulse-to-pulse variable charge and energy
- device parameter change at 50 Hz (20 ms)
- **Pulsed magnet commissioning at 3-5 sectors (2017 autumn), and many more installation (2018-2019)**

Required injector beam parameters

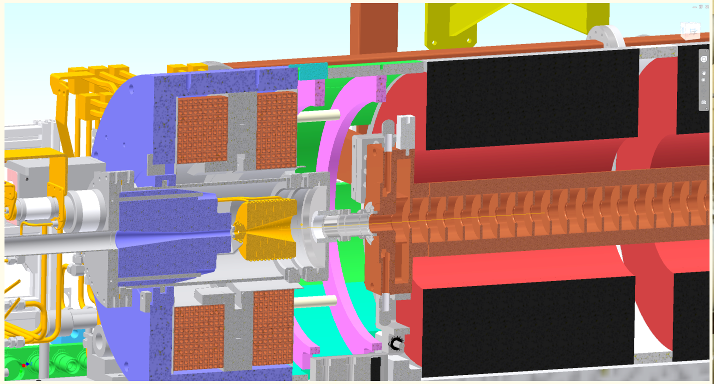
Stage	KEKB (final)		Phase-I		Phase-II		Phase-III (2019)		Phase-III (final)	
Beam	e+	e–	e+	e–	e+	e–	e+	e–	e+	e–
Energy	3.5 GeV	8.0 GeV	4.0 GeV	7.0 GeV	4.0 GeV	7.0 GeV	4.0 GeV	7.0 GeV	4.0 GeV	7.0 GeV
Stored current	1.6 A	1.1 A	1.0 A	1.0 A	–	–	1.8 A	1.3 A	3.6 A	2.6 A
Life time (min.)	150	200	100	100	–	–	–	–	6	6
Bunch charge (nC)	primary e- 10 → 1	1	primary e- 8 → 0.4	1	0.5	1	→ 2	→ 2	primary e- 10 → 4	4
Norm. Emittance (γβε) (mrad)	1400	310	1000	130	200/40 (Hor./Ver.)	150	100	40	100 / 15 (Hor./Ver.)	40 / 20 (Hor./Ver.)
Energy spread	0.13%	0.13%	0.50%	0.50%	0.16%	0.10%	0.16%	0.10%	0.16%	0.07%
Bunch / Pulse	2	2	2	2	2	2	2	2	2	2
Repetition rate	50 Hz		25 Hz		25 Hz		50 Hz		50 Hz	
Simultaneous top-up injection (PPM)	3 rings (LER, HER, PF)		No top-up		Partially		4+1 rings		4+1 rings (LER, HER, DR, PF, PF-AR)	

Beam Commissioning Activities

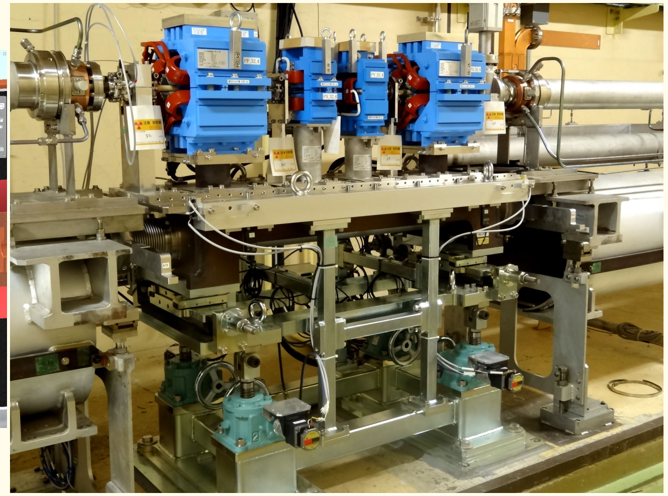
Low emittance electron from RF gun



High efficiency positron capture



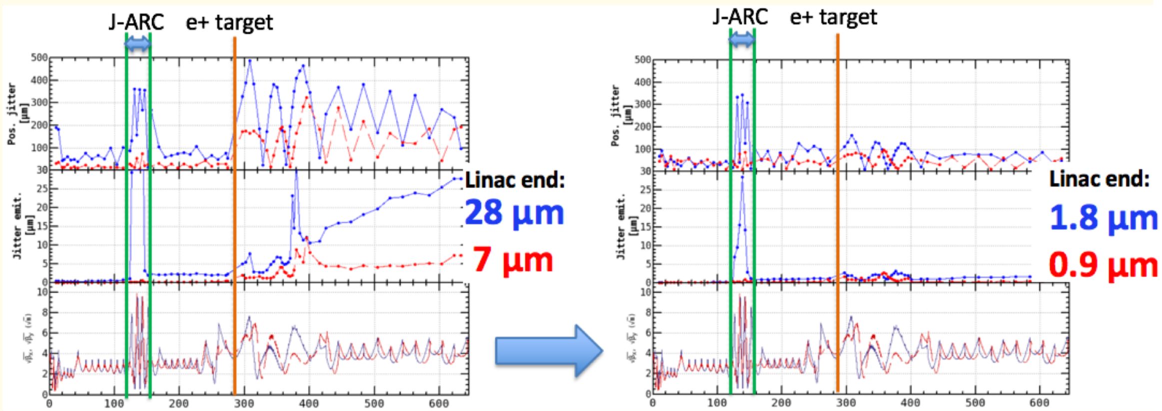
Beam control with ~70 pulsed magnets



Injection beam for SuperKEKB

	KEKB (– 2010)		SuperKEKB Phase III	
Beam	e+	e–	e+	e–
Bunch charge (nC)	1.0	1.0	4.0	4.0
Normalized Emittance (μm)	1400	310	100/15 (Hor./Ver.)	40/20 (Hor./Ver.)
Energy spread	0.125%	0.125%	0.16%	0.07%

Emittance optimization



Injector FY2019 Plan

- Realize stable and sufficient beams for the first year of Phase 3 commissioning
- Perform 3-year program to recover degradation of accelerating structures
- Postpone remaining upgrades until later years, limit backup devices, in order to support longer operation hours even under limited resources in FY2019

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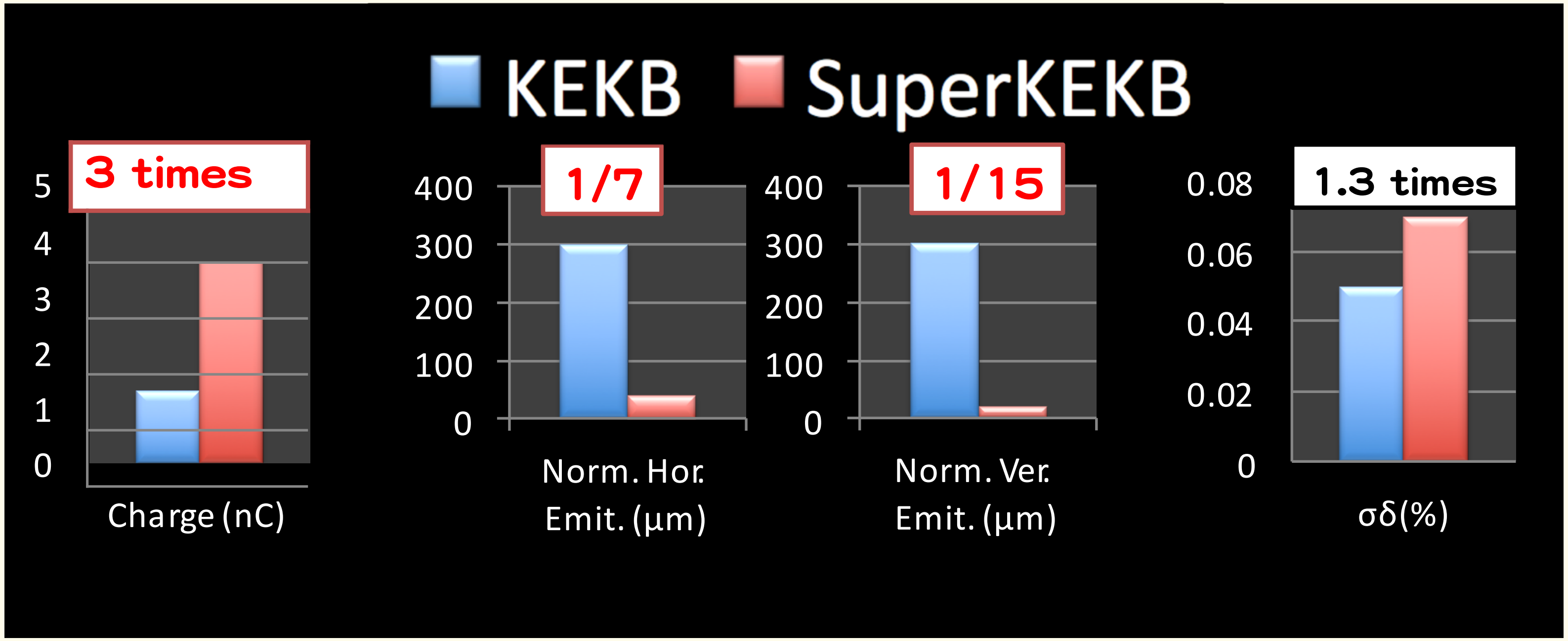
Injector Operation in Autumn 2018

- 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

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**



Beam Quality

- Beam emittance
- Beam energy spread
- Stabilities of beam position, energy, etc
- Beam position jitter (painted jitter emittance)
- Beam energy jitter (painted energy spread)
- Degradation of above beam qualities can be the source of injection background

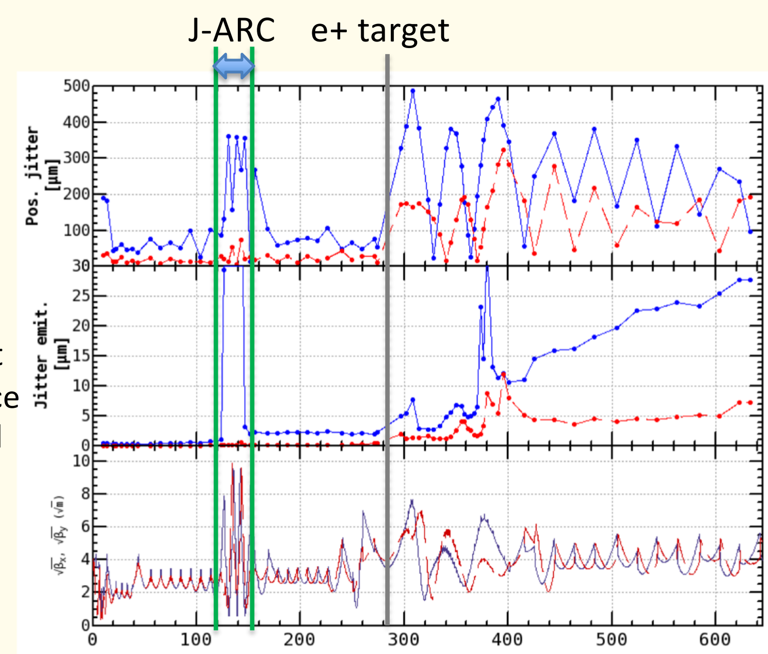
- Hardware components and their monitor systems were much improved

Beam Phase Space Jitter Reduction

Seimiya et al.

The top plot shows the standard deviation of beam position. The middle plot shows emittance growth induced by beam jitter.

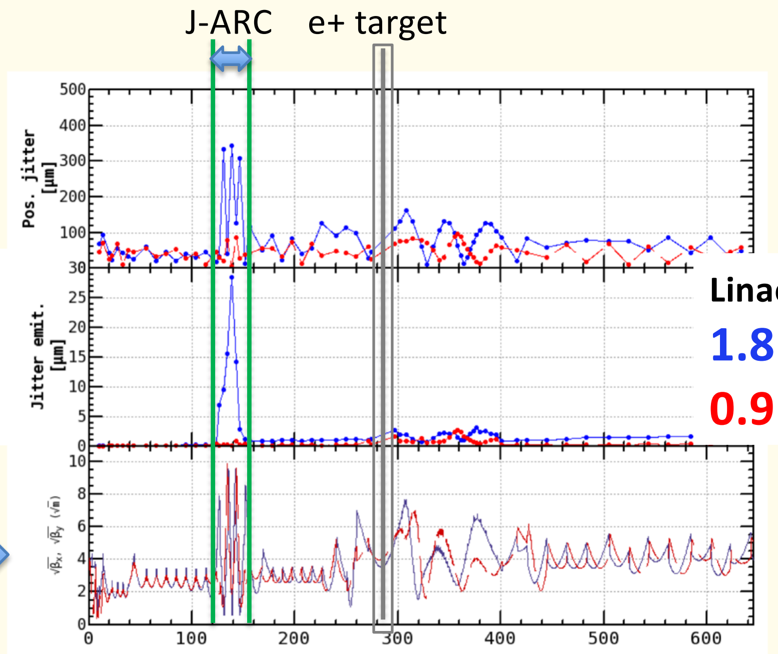
Before dispersion correction



1nC

Linac end:
28 µm
7 µm

After dispersion correction



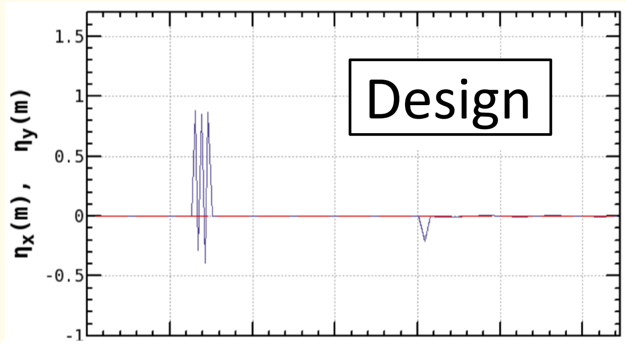
Linac end:
1.8 µm
0.9 µm

Beam phase space jitter is reduced by dispersion correction.

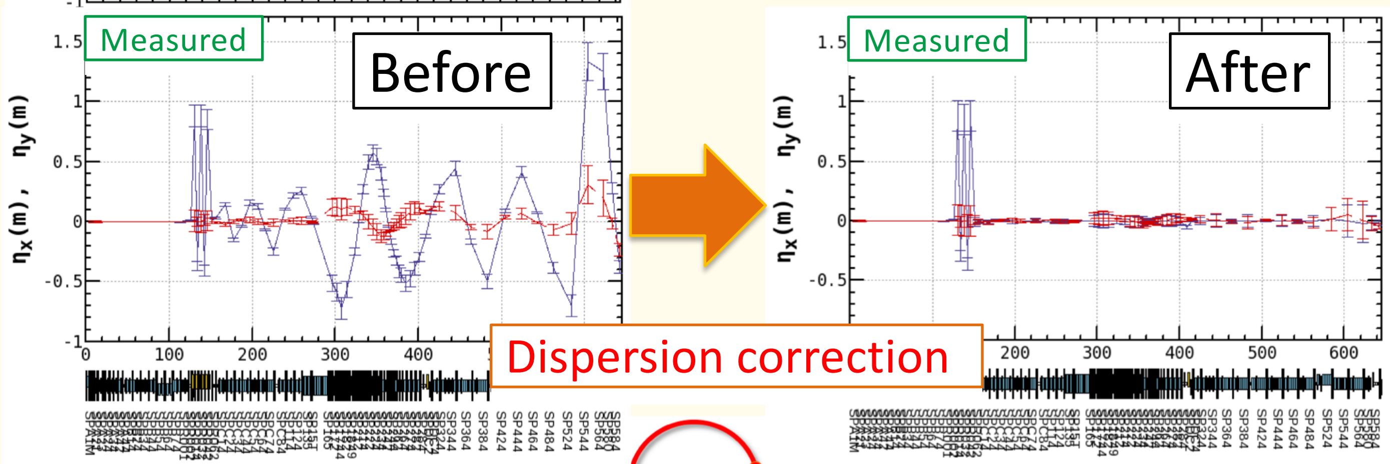
- Small emittance growth still occurred from after the target after the correction.
- We should understand the source of the beam jitter to prepare for the high charged beam (4 nC) and for accidental jitter source which occur at upstream the target.

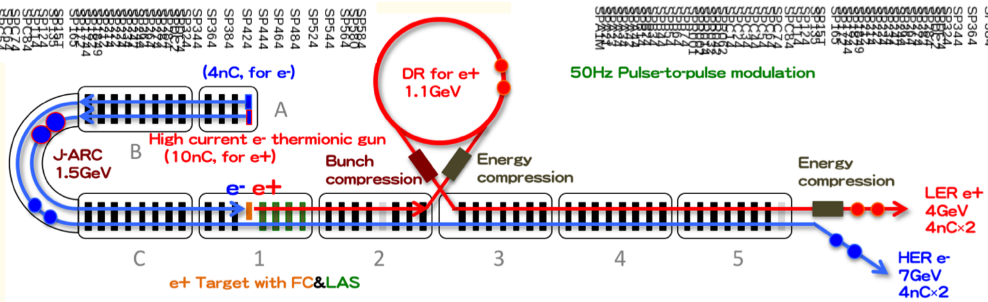
Residual Dispersion Function in Linac

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.

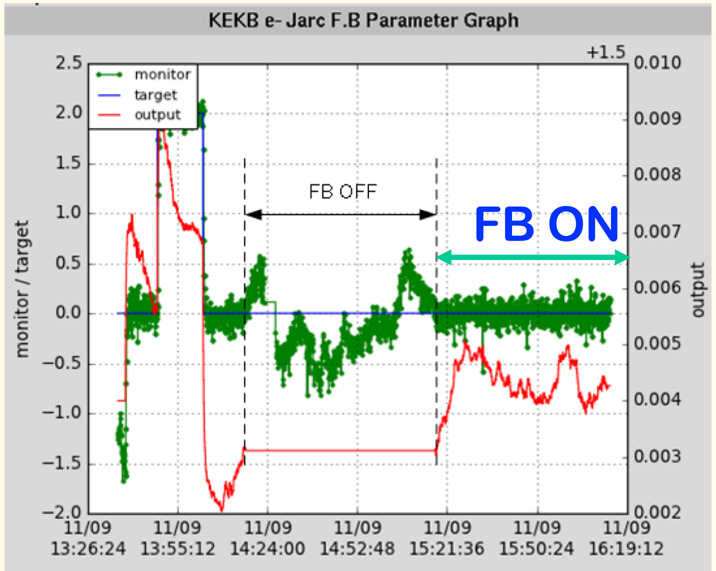




Energy Stabilizer (Energy FB)

Iida et al.

Jarc



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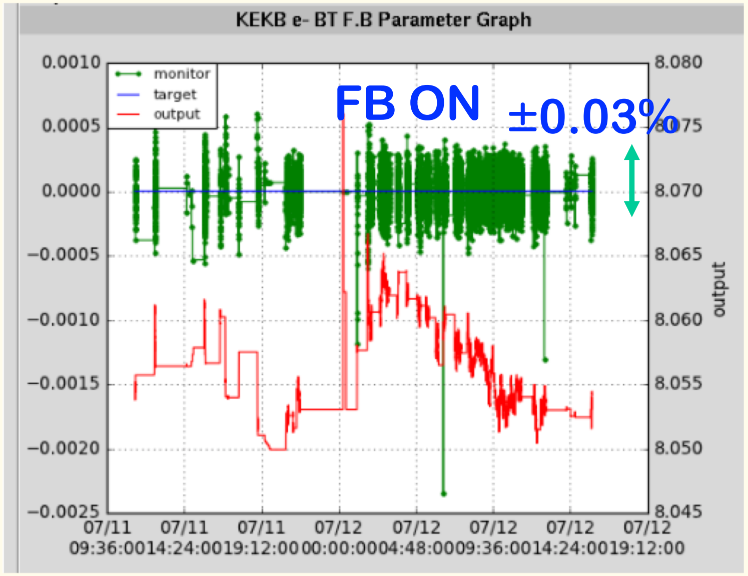


Target

Beam energy (monitored)

Energy knob

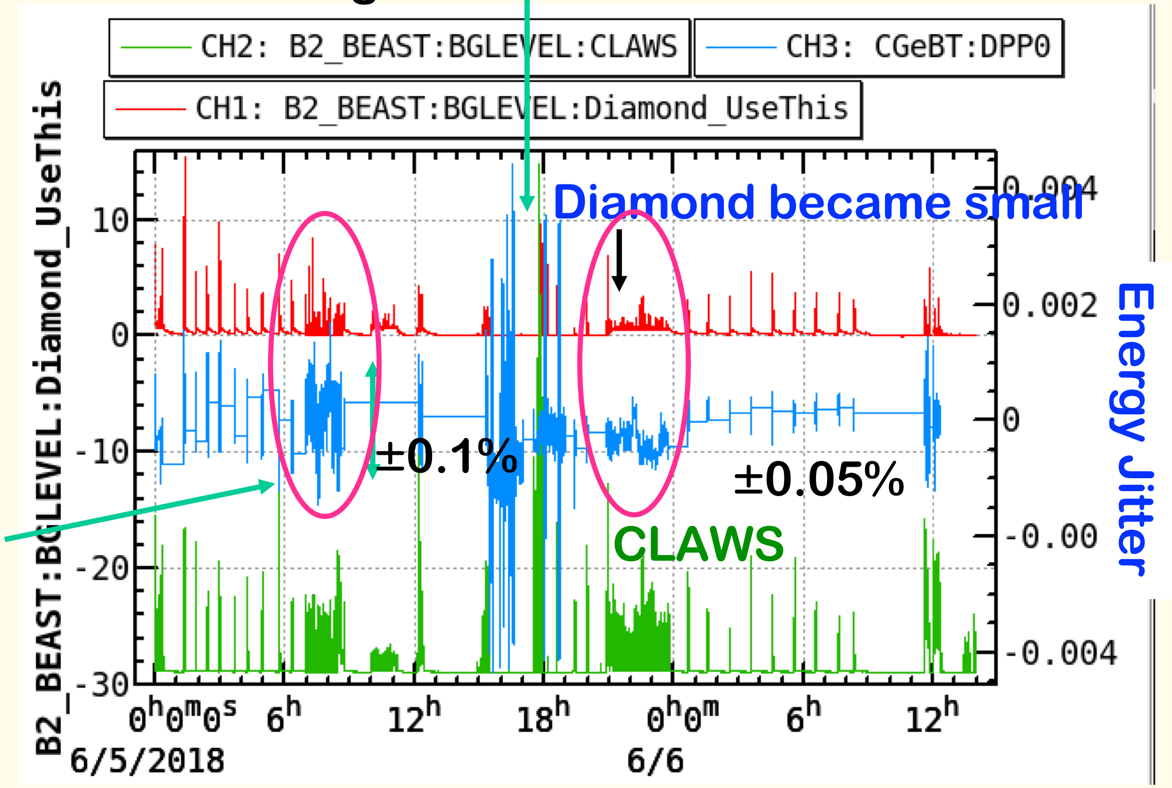
The injection energies have been stabilized within ±0.03% by the energy feedback.

Energy jitter

Iida et al.

After suppressing the energy jitter,
the signal from Diamond detector was reduced.

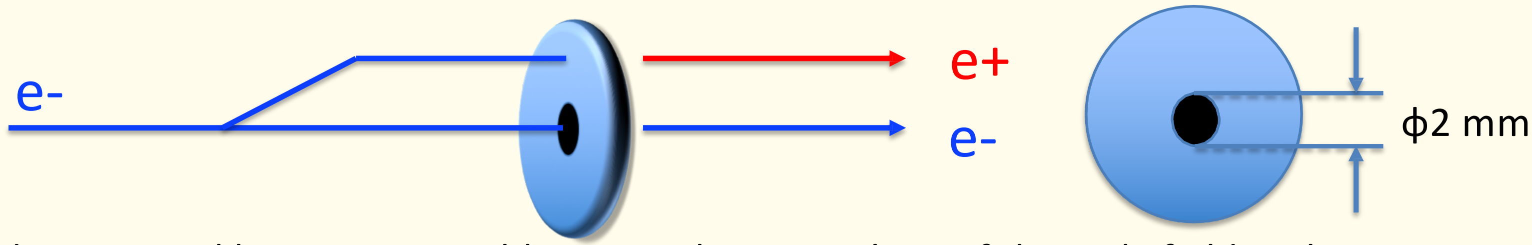
Energy FB did not work well.



Beam background is sensitive to the energy jitter.

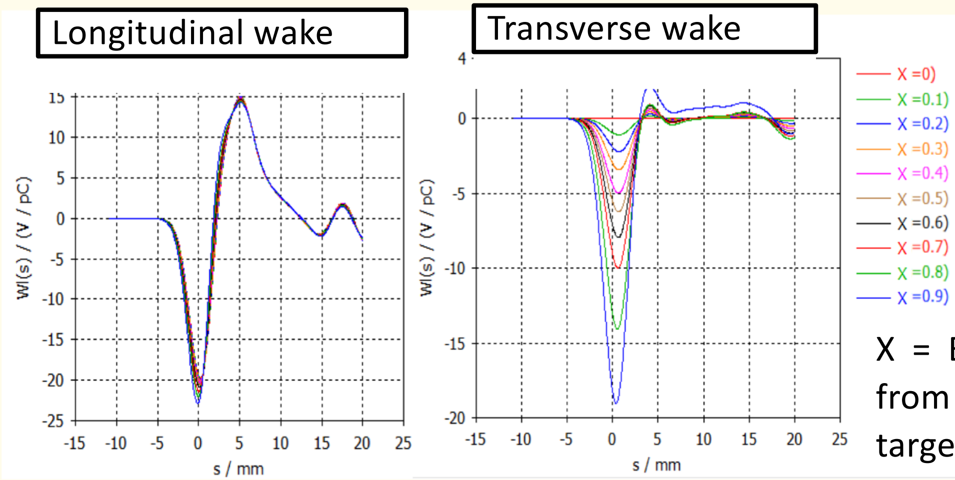
Emittance Growth at Target Hole (?)

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:

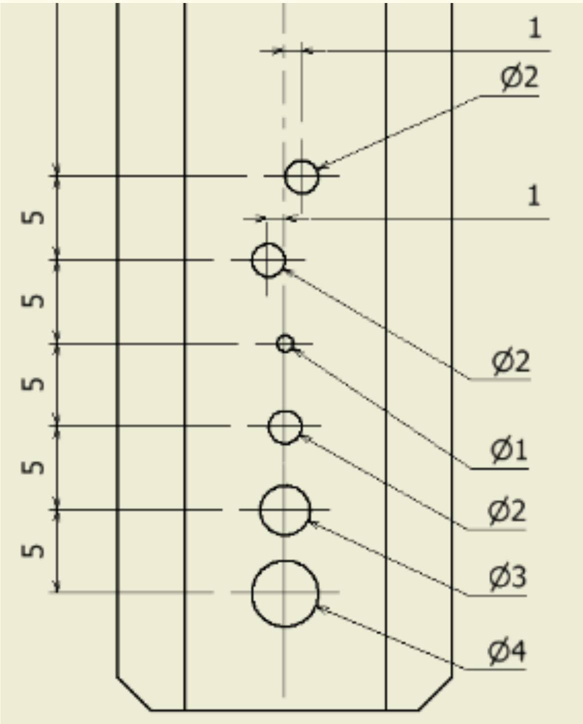
$$R_j = \frac{\beta \Delta y'}{\Delta y} = \frac{Q}{E_0} k_{\mathrm{T}} \beta_y$$

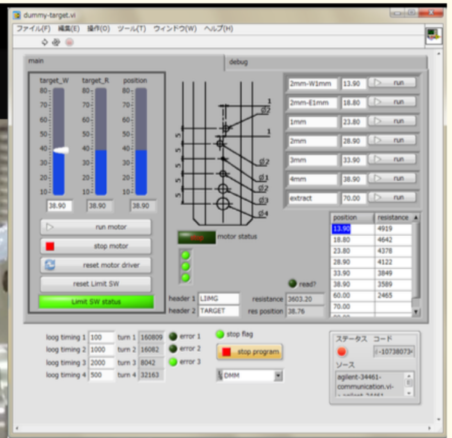
~ 0.1@1nC << Measured enlarged coefficient

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.

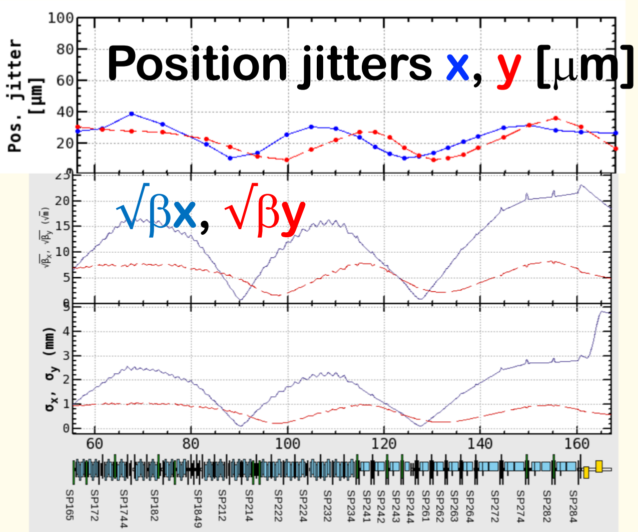




Jitter Emittance after Target

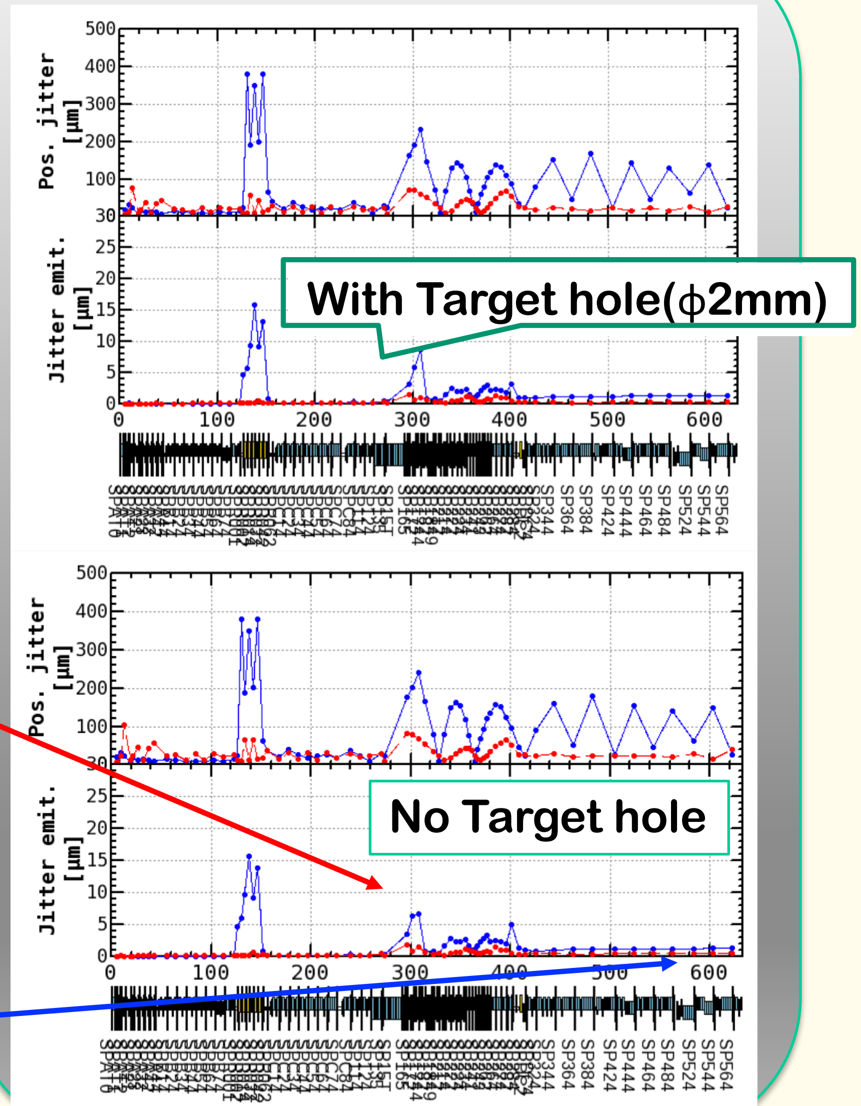
The result is;

- The growth of the jitter emittance has been nothing to do with the small hole.
- Strong correlation between orbit jitter and beta function.
- The beta function after the target is large to squeeze the beam sizes to pass through the hole, which causes the large orbit jitter.



Although the jitter emittances are still increased as shown in the jitter emittance plots, it is known that this jitter becomes smaller when Jarc's dispersion leakage is reduced.

They are small enough at the end of LINAC.



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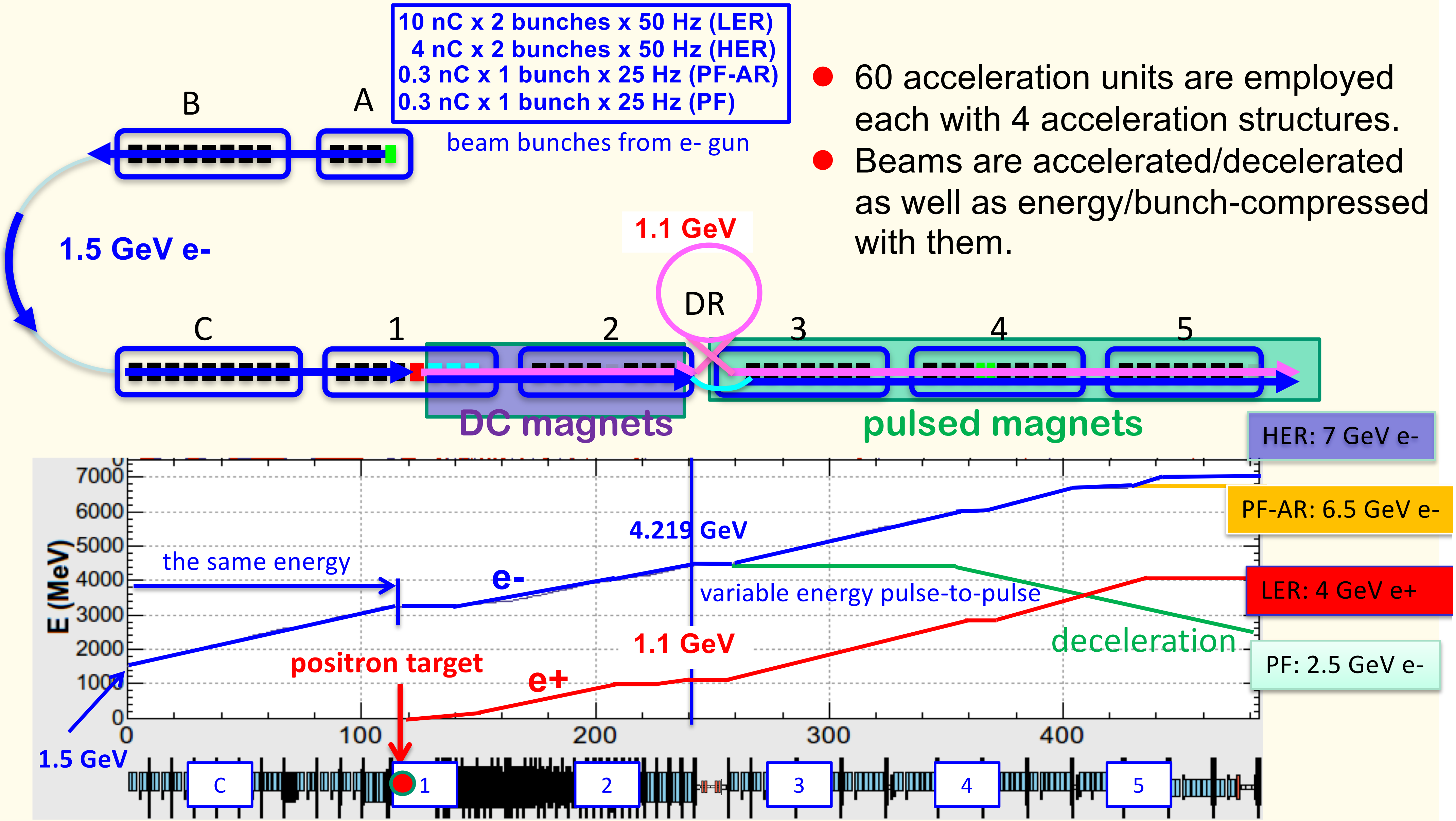
Accelerating Structure

Summary

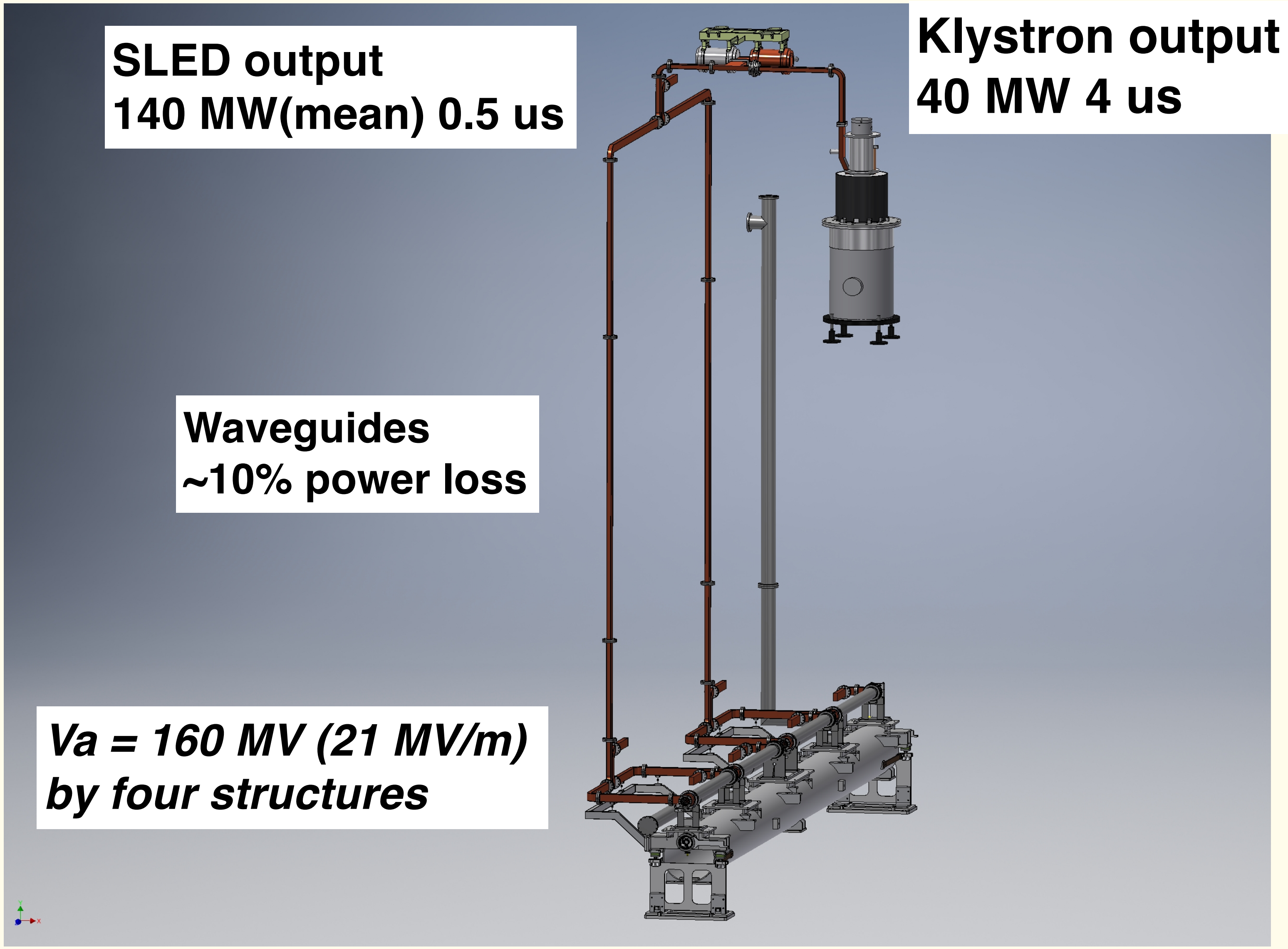
Injector Linac Beam Acceleration

- 60 acceleration units are employed each with 4 acceleration structures.
- Beams are accelerated/decelerated as well as energy/bunch-compressed with them.



Acceleration Unit Configuration

Designed performance of the accelerating unit



Accelerating Structures

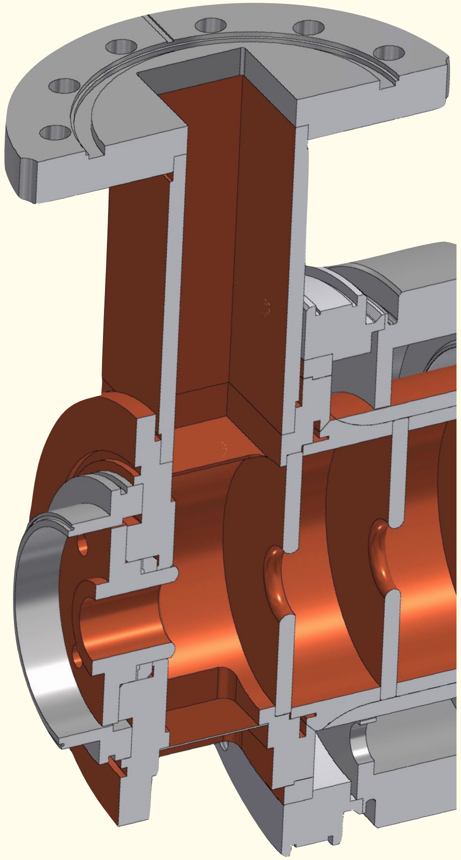
Three types of S-band quasi-constant-gradient accelerating structures of 2 m in length are employed as main accelerators

Type	Number in use
• **PF-type accelerating structures (19 + 6 units have issues)**	**142**
• **KEKB-type accelerating structures**	**74**
• **Large-aperture accelerating structures (LAS) ***	**10**

* special structure for the positron capture unit

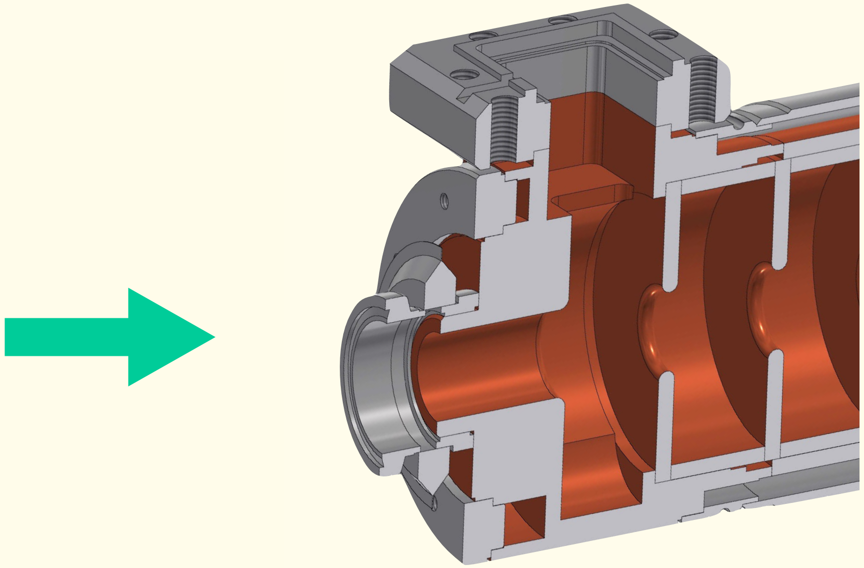
Accelerating Structures

PF-type structure



Not interchangeable

KEKB-type structure



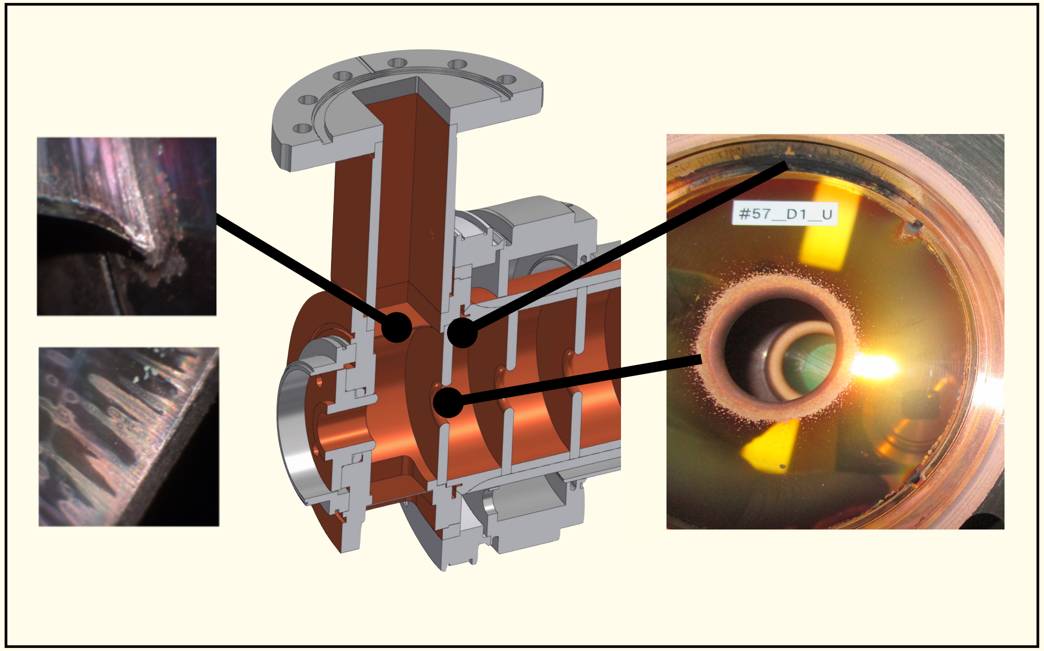
Complicated fabrication
Used at 8 MeV/m since 35 years ago
Later raised to 21 MeV/m

Revised structure
Designed for 21 MeV/m

Degradation of Acceleration Units

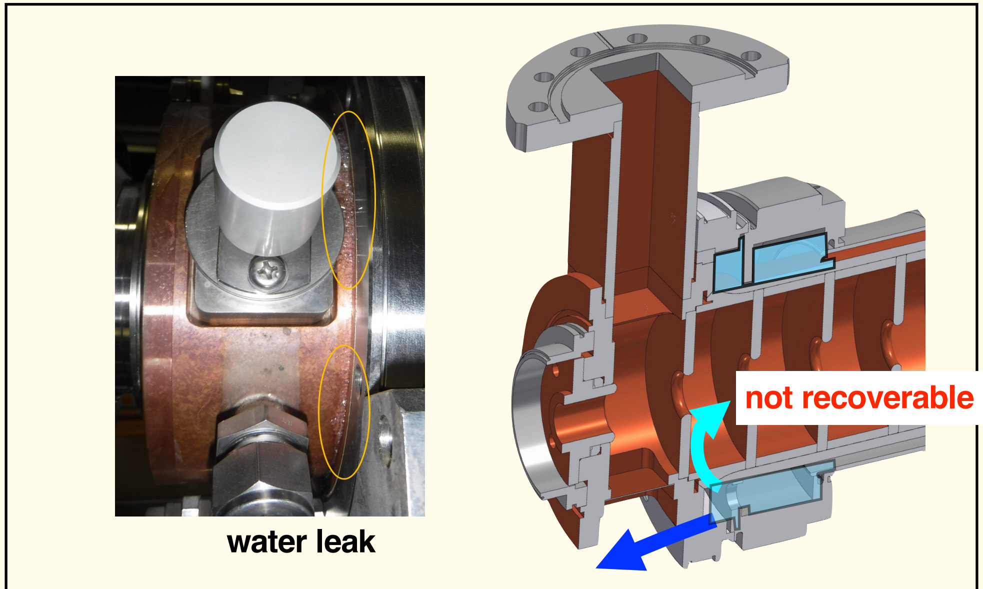
Field emission, reflection (19)

Lower acceleration



Cooling water leakage (6)

Has to fix

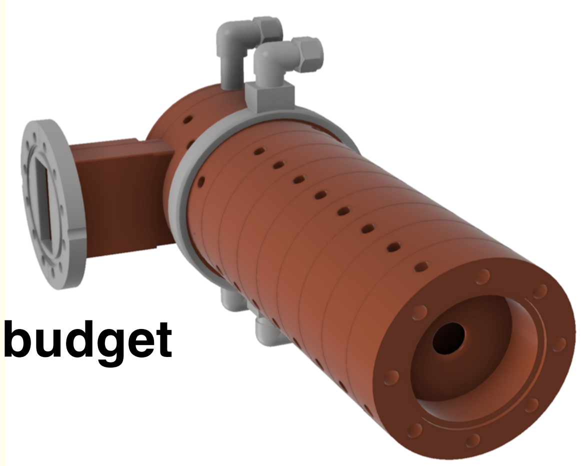


- Some of water leakage are fatal
- Approx. 3 leakages per year, in recent years
- May increase as they are built at a time
- Improving the identification of a damage in four structures
- No more healthy PF-type backup structures
- Have to utilize degraded structures in an emergency

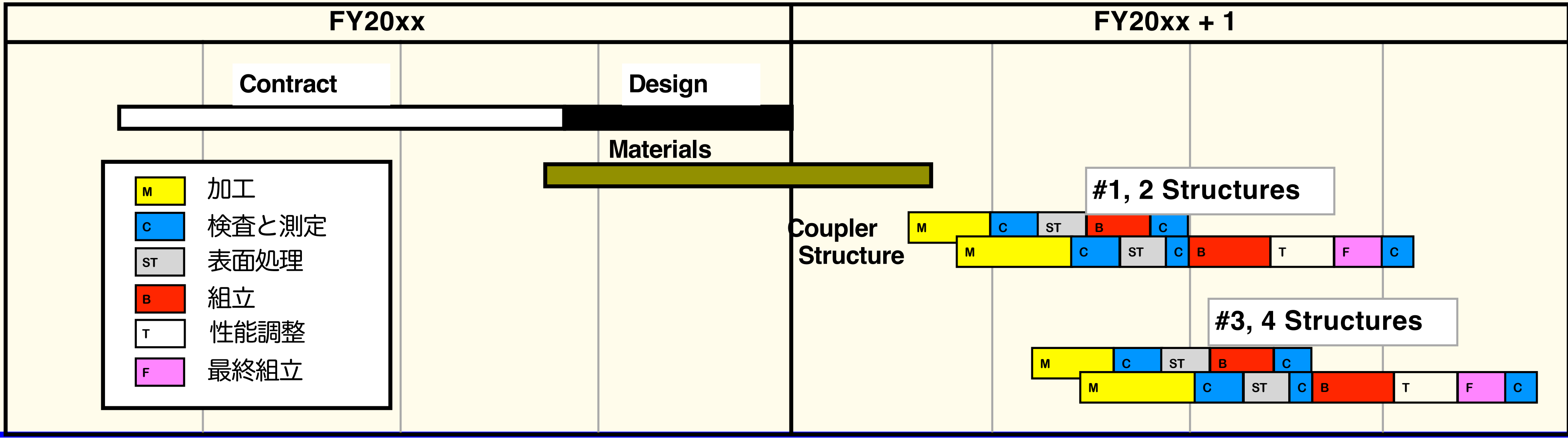
New Structure Production

As a solution, structures are newly designed with lower emission and higher gradient

- **4 structures per year**
- **12 structures for 3 years**
- **Scheduling from FY2018-9 even under limited budget stopping other improvements**



Fabrication schedule



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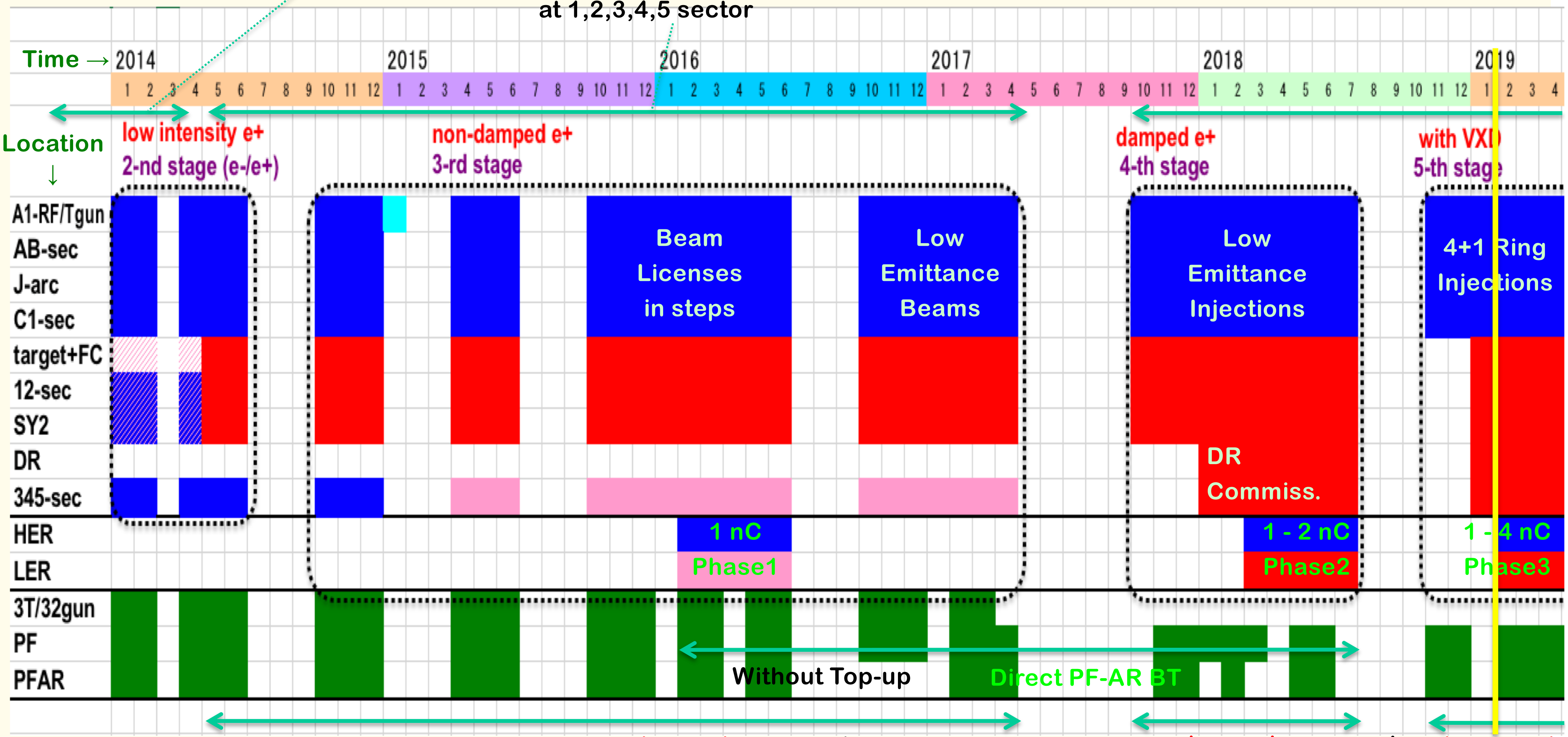
Linac Schedule Overview

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

- Positron target / flux concentrator restoration
- 50 Hz operation
- Simultaneous injections for 4 storage rings with beam stabilization feedback loops
- Further instability hunt
- Low emittance beam developments
- Reliability, reproducibility, automation, etc.

Summary

- The injector performed beam improvements after Phase-2 towards Phase-3 commissioning
- 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

Lifetime and injection rate

Example : Phase 3-3ex Parameter

Assumed from the lifetime of Phase 2

	LER	
Life time [sec.]	600	N_b=1578, I_{tot}=2.0A
Loss Rate [mA/sec]	3.0	

$$-\left.\frac{dI}{dt}\right|_{Loss} = 3.0\mathrm{mA/s} \qquad \text{for } \mathrm{I} = 2000\mathrm{mA}, \quad \tau = 600\mathrm{sec}$$

$$\left.\frac{dI}{dt}\right|_{Inj} = \mathrm{N_e\ f_{rev}} \qquad \mathrm{N_e = Q_{BTend} \cdot f_{rep} \cdot n_{bunch} \cdot eff_{inj}}$$

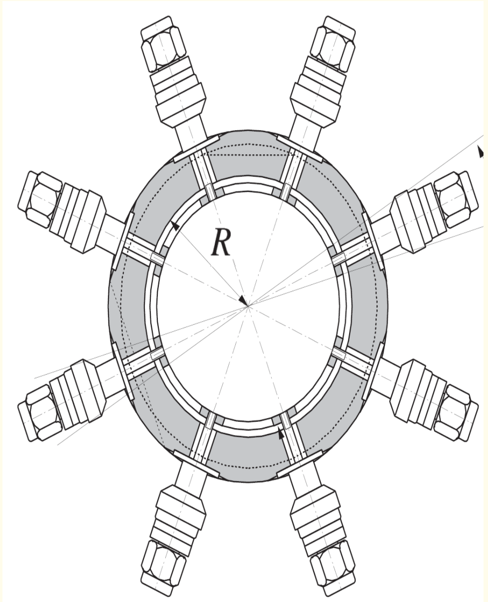
$$= 3.5\mathrm{mA/s}$$

frev=100kHz
Q_{BTend}=1.0nC
f_{rep}=25Hz
n_{bunch}=2
eff_{inj}=70%

Even if such a low charge injection, the total beam current can be kept with 25Hz injection.

Nondestructive Energy Spread Monitor：eight electrode BPM in Jarc

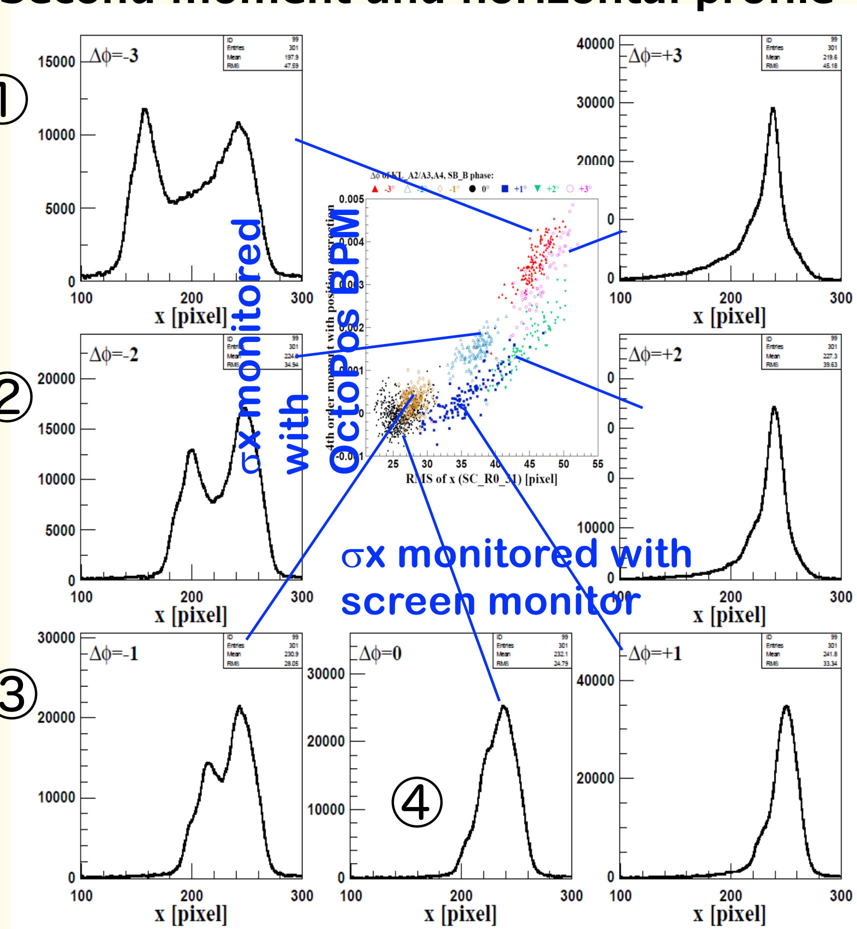
F. Miyahara



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

$$J_q = \frac{\sum_{i=1}^{N} V_i \cos 2\theta}{\sum_{i=1}^{N} V_i}.$$

Second moment and horizontal profile

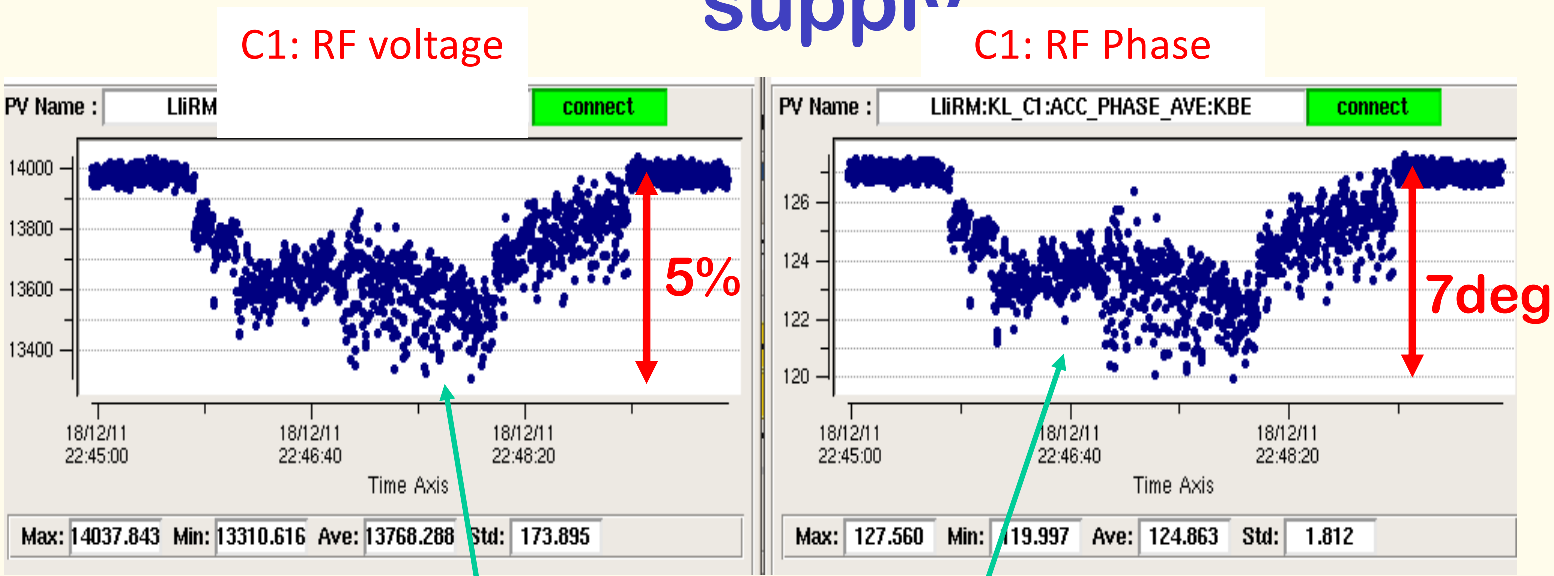


The beam spread can be measured from the second moment.

Although the profile with two peaks ② can not be recognized from ⑥ only with the second moment, it is important to keep the energy spread to ③ or ④.

Beam energy stabilization

Other voltage fluctuation of klystron power supply



RF voltage / phase variation

Sometimes the AC line voltage for klystron power supply drops.

Klystron output power is stabilized by
Induced Voltage Regulator (IVR) at the sudden change of AC line voltag
In Phase 2, IVR stabilization had been done once an hour.

It is planed to establish the IVR feedback in Phase 3.