Injector Linac Status

Fusashi Miyahara (KEK, Acc. Lab.)
for Injector Linac Group

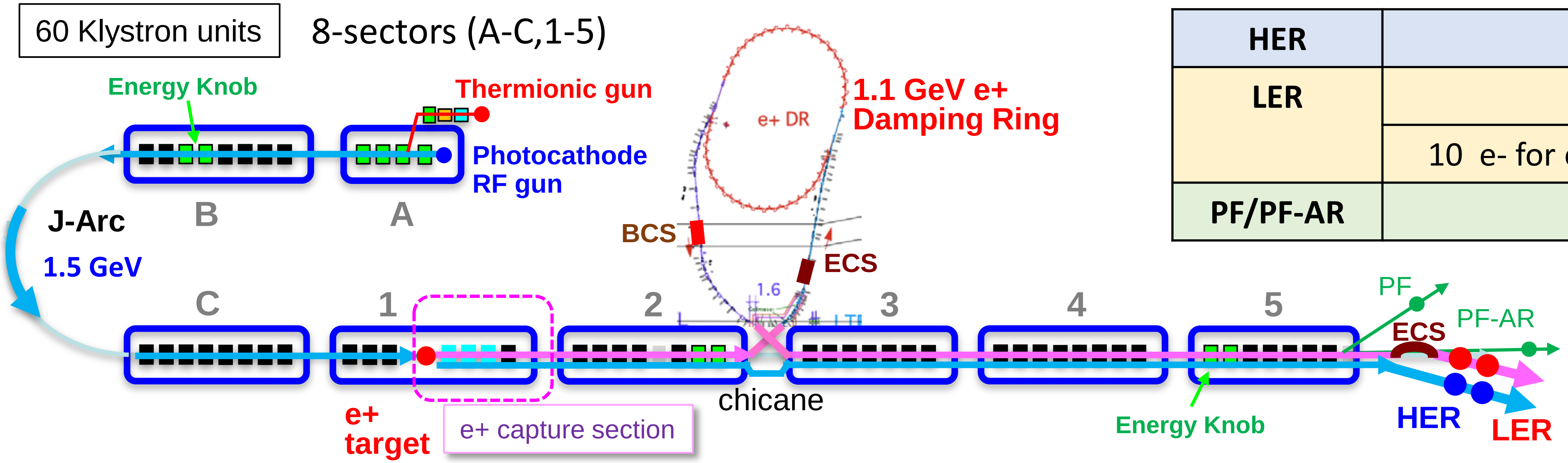
B2GM, Oct. 18, 2021

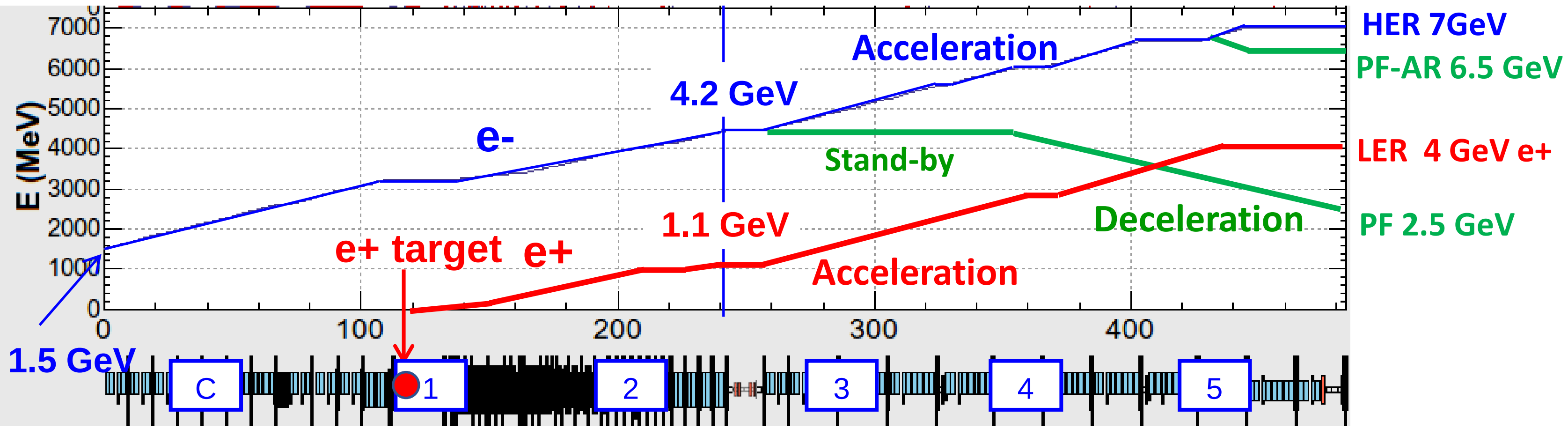
4+1 ring simultaneous injection

Beam injection to each accelerator has been stable.

Bunch charge [nC/bunch]

HER	2
LER	2
	10 e- for e+ production
PF/PF-AR	0.3





Beam energies for each beam modes after the J-Arc.

Linac Beam Parameters for SuperKEKB

Stage	KEKB (final)		Phase-I		Phase-II		Phase-III (interim)		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	**2.5**	**2**	primary e- 10 → **4**	**4**
Norm. Emittance (γβε) (mmrad)	1400	310	1000	130	200/40 (Hor./Ver.)	150	**100/60** (Hor./Ver.)	**100/80** (Hor./Ver.)	**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 (LER, HER, DR, PF, PF-AR)		4+1 rings (LER, HER, DR, PF, PF-AR)	

Electron Beam Status

Photocathode RF gun

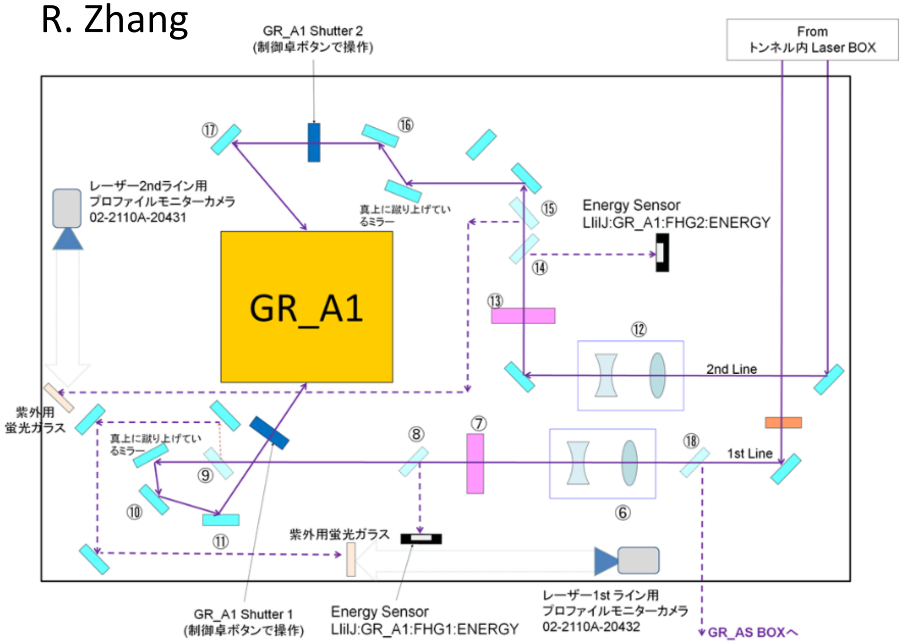
Diffractive optical element (DOE) was installed in 1st laser line from 2020c.

・Elliptical flat-top (uniform) spatial distribution on the surface of photocathode

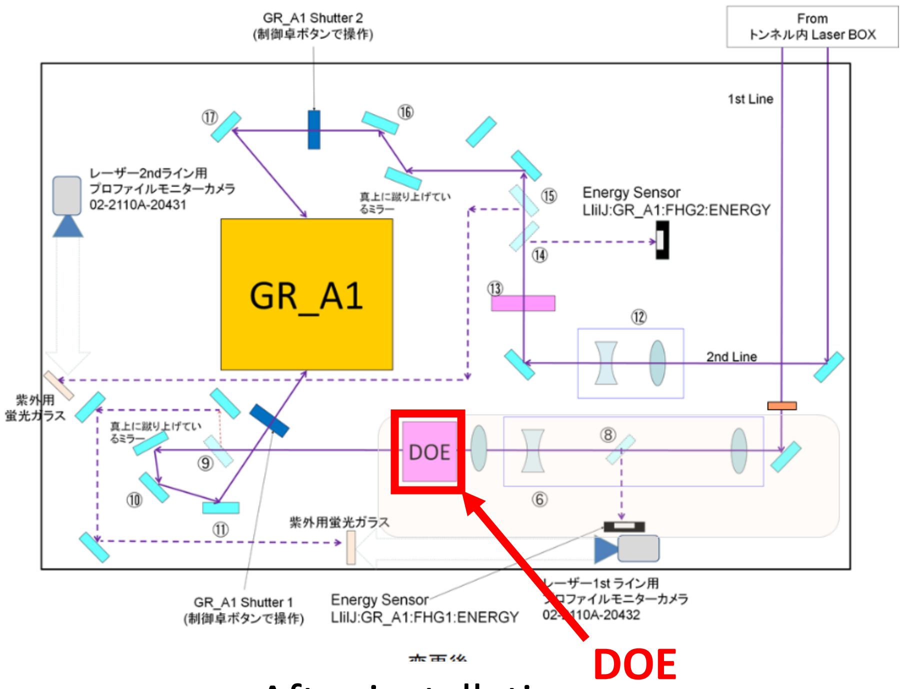
→

・**Low emittance e- beam generation**
・**High stability** (Shot-by-shot variation ↓, Discharge ↓)
・**No discharges due to strong convergence of laser**

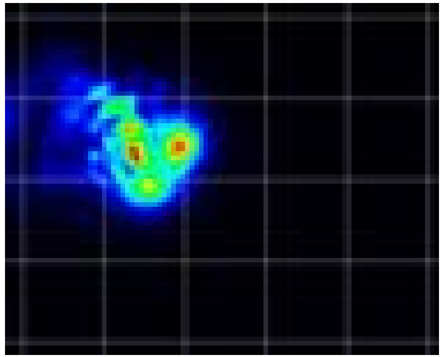
R. Zhang



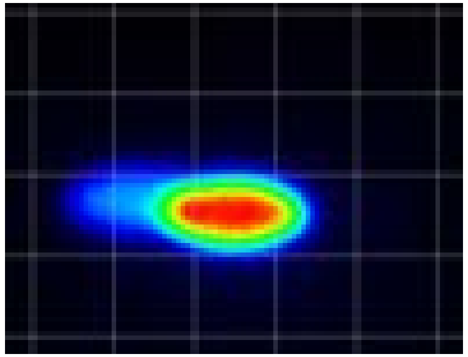
Before installation



After installation



without DOE



with DOE

Laser profiles on the cathode.

ε_x [m] :	1.4328E-9	ε_y [m] :	1.5402E-9
$\Delta\varepsilon_x$ [m] :	3.887E-10	$\Delta\varepsilon_y$ [m] :	5.398E-10
$\gamma\varepsilon_x$ [μm] :	19.628	$\gamma\varepsilon_y$ [μm] :	21.099
$\Delta\gamma\varepsilon_x$ [μm] :	5.324	$\Delta\gamma\varepsilon_y$ [μm] :	7.395

Electron beam emittance at BT1 (2nC, only 1st laser)

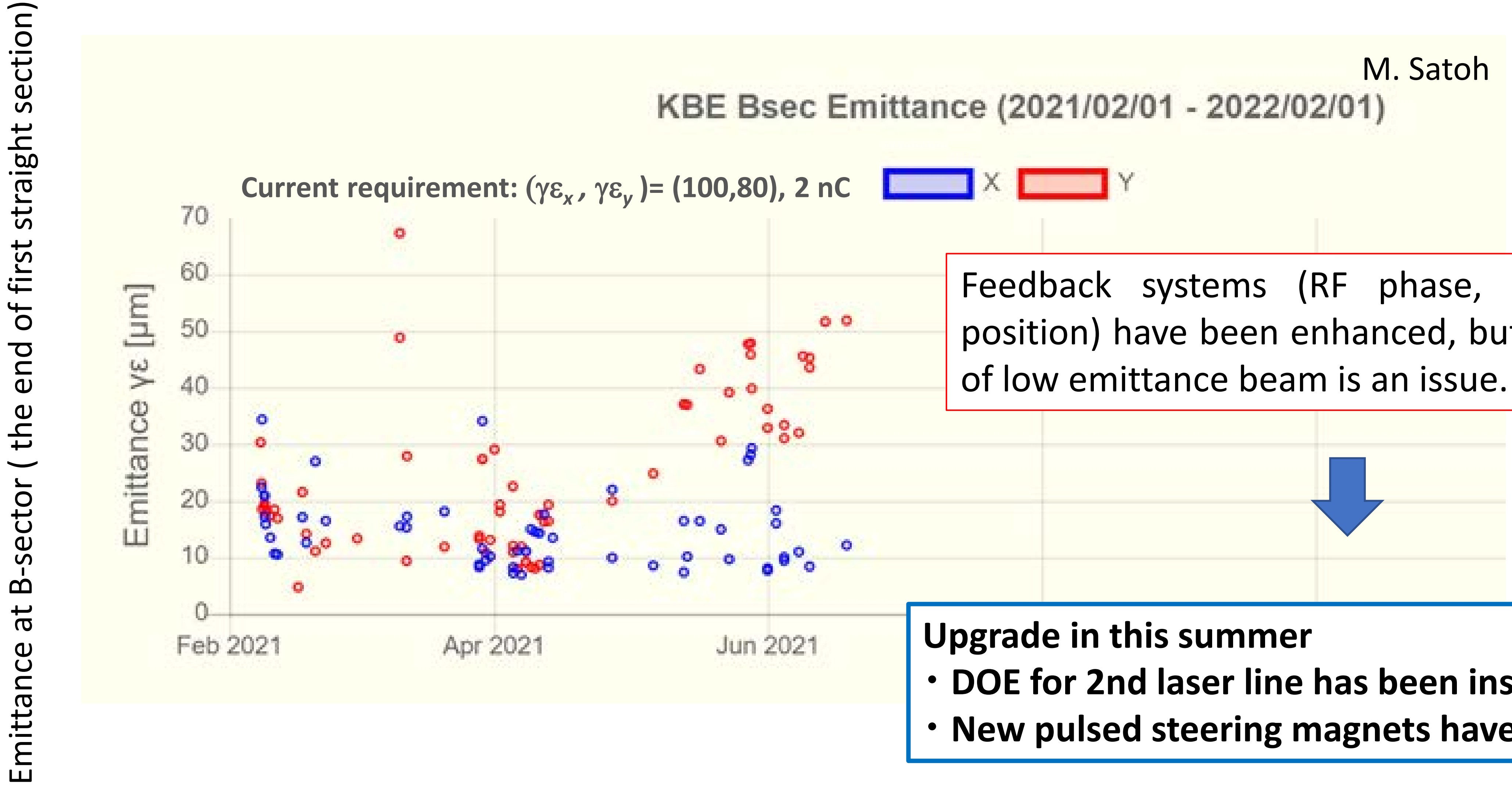
⇔

Goal

$(\gamma\varepsilon_x, \gamma\varepsilon_y) = (40,20)$
q= 4 nC

Very low emittance beam at BT1 was achieved.

e- emittance history



Feedback systems (RF phase, energy, laser position) have been enhanced, but preservation of low emittance beam is an issue.

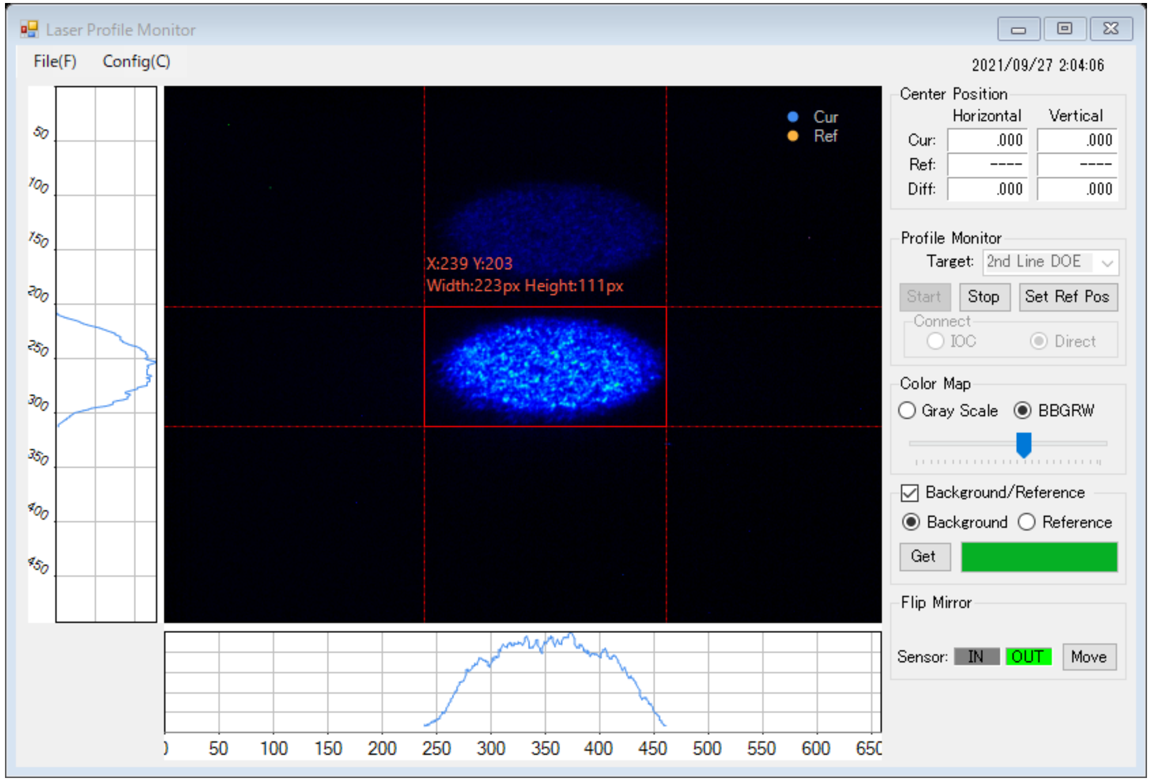
Upgrade in this summer

- **DOE for 2nd laser line has been installed**
- **New pulsed steering magnets have been installed**

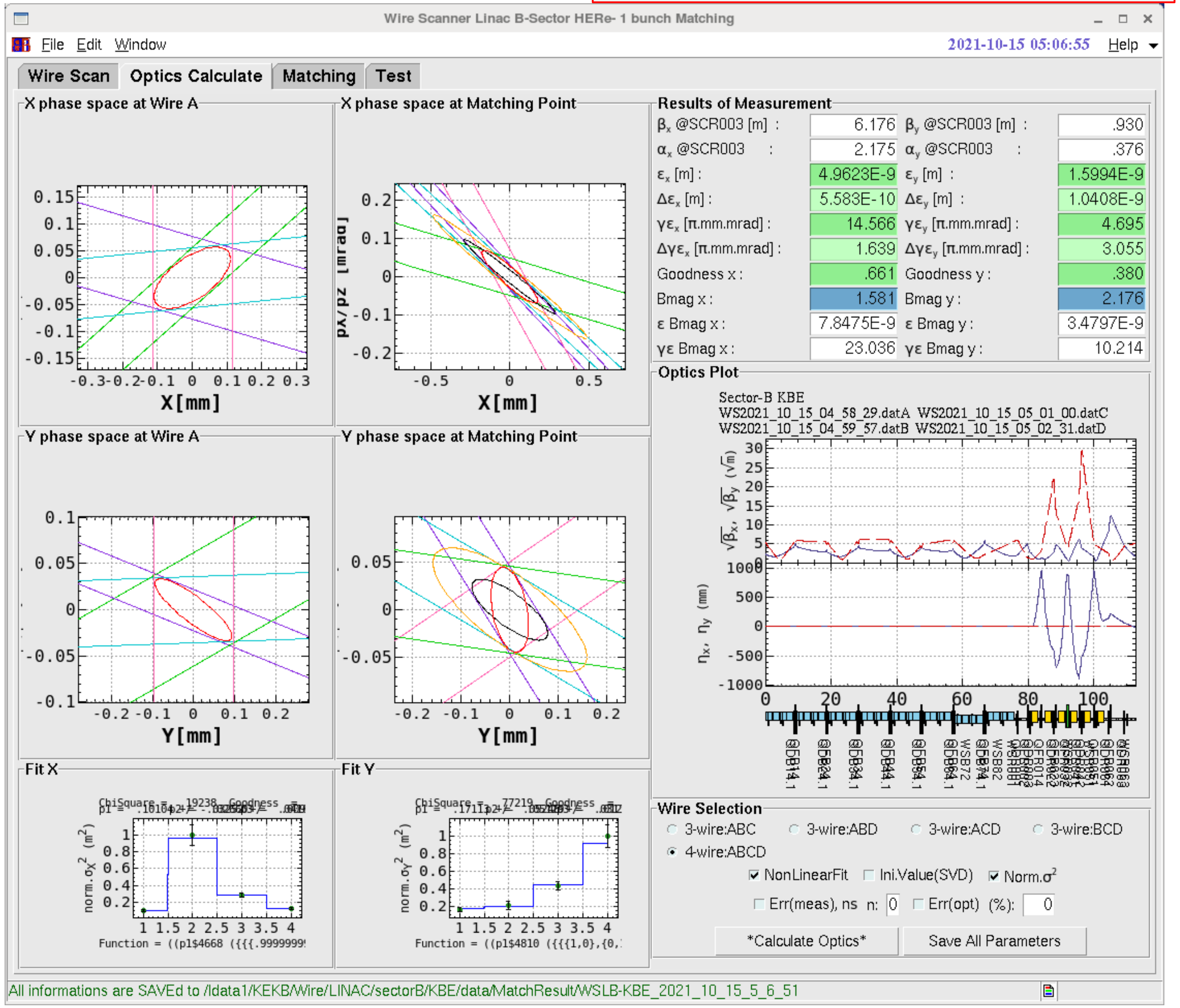
DOE for 2nd laser line

Beam tuning is still in the process

A new DOE for 2nd laser line has been installed this summer.



2nd line laser profile with DOE



Emittance measurement at B-sector for e- beam with DOSs (1st + 2nd)

$\gamma\varepsilon_x = 14.6 \pm 1.6$ [μm]

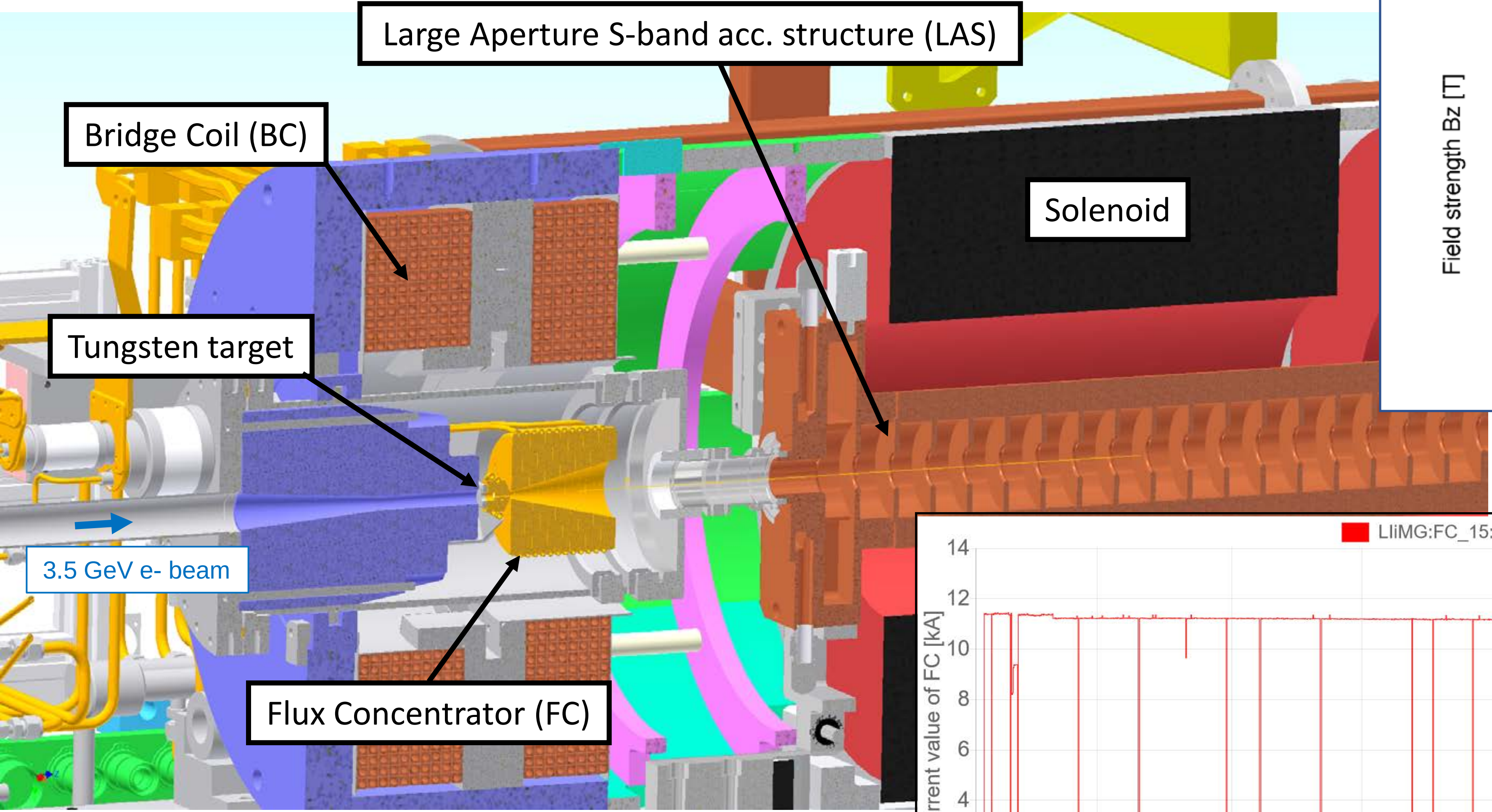
$\gamma\varepsilon_y = 4.7 \pm 3.1$ [μm]

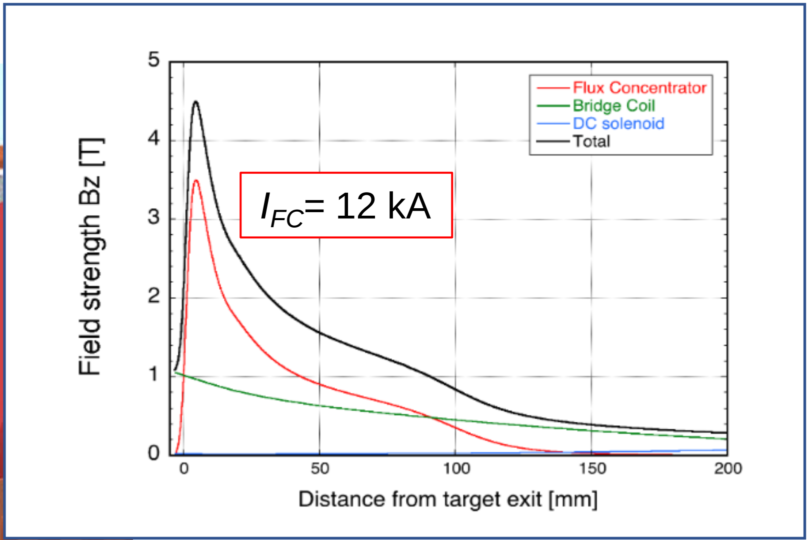
2 nC/bunch

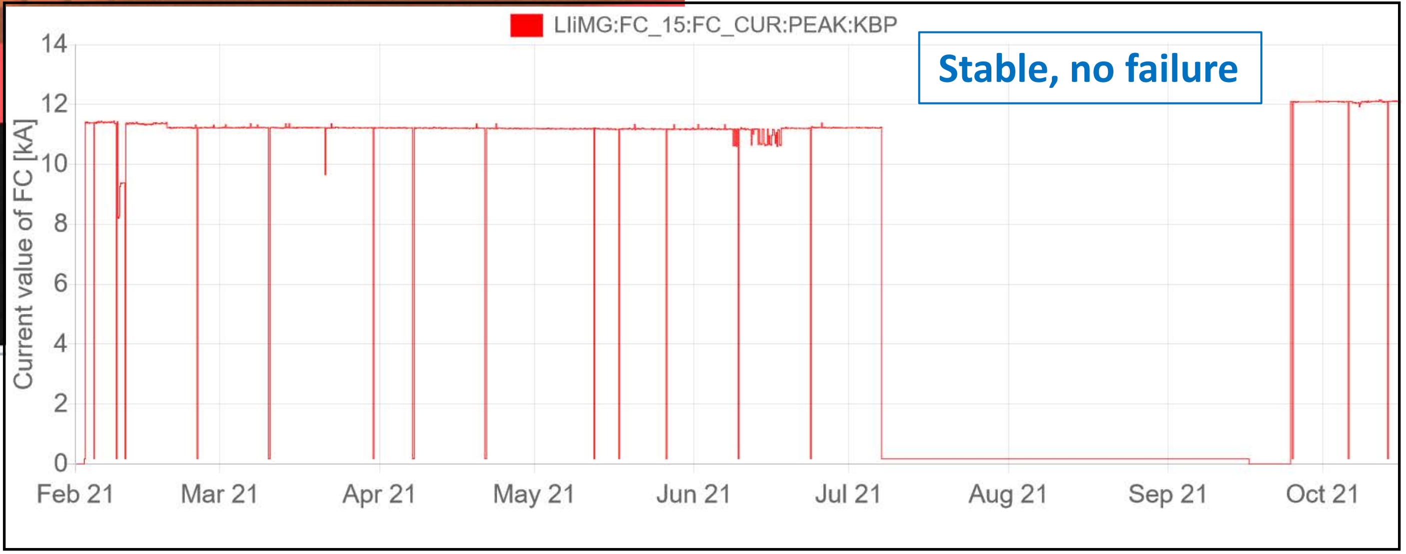
Positron Beam Status

Positron capture section

Y. Enomoto







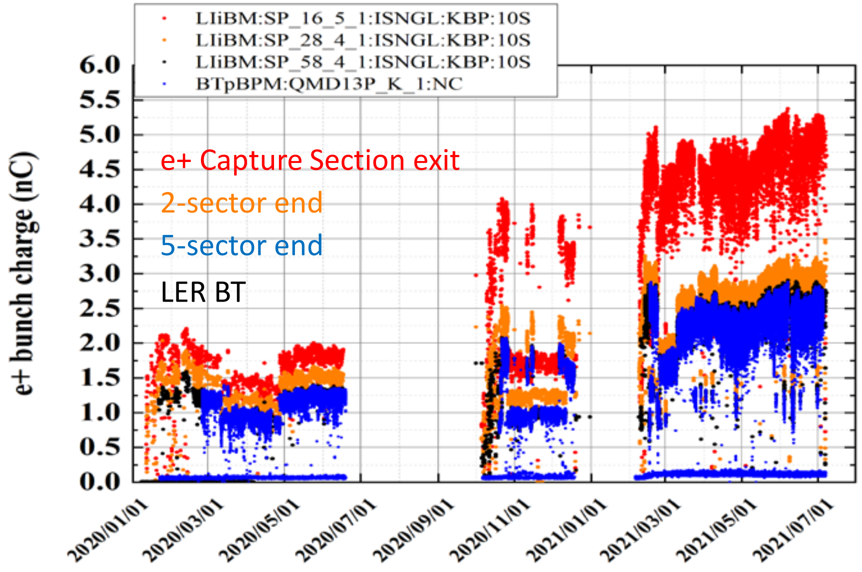
Current history of the FC

Positron yield

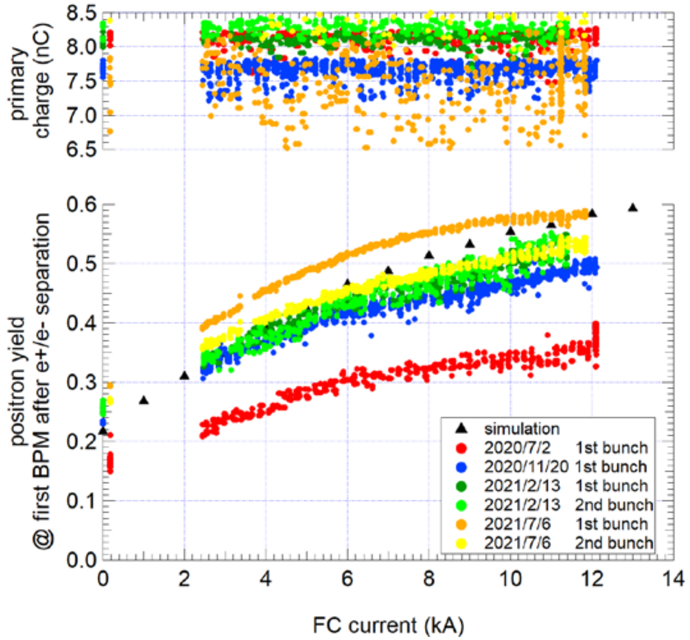
Y. Enomoto

		design	2020ab(運転)	2020ab(study)	2020c	2021a	2021b
			2020/7/1	2020/7/2	2020/10/12	2021/2/12	**2021/7/6**
	Energy (e-)*	3.46 GeV	3.01 GeV	3.01 GeV	2.87 GeV	2.89 GeV	**2.92 GeV**
Target	Bunch charge (e-)	10 nC	8.2 nC	8.3 nC	8.1 nC	8 nC	**9.0 nC**
Capture Sec. exit	e+/e- @ SP_16_5	0.58	0.23	0.38	0.51	0.55	**0.59**
	e+ @ SP_16_5	5.8 nC	1.9 nC	3.2 nC	4.1 nC	4.4 nC	**5.3 nC**
2-sec. end	e+ @ SP_28_4	-	1.6 nC	2.4 nC	2.5 nC	3.2 nC	**3.5 nC**
DR to linac	e+ @ SP_DC_4	-	1.3 nC	1.9 nC	2.1 nC	2.5 nC	**3.0 nC**
Linac end	e+ @ SP_58_4	4 nC	1.3 nC	1.9 nC	2.1 nC	2.5 nC	**3.0 nC**
LER BT	e+ @QMF8P_K**	4 nC				2.77 nC	**2.95 nC**

Yields at exit of the capture section almost reached the design value



Change in bunch charge at major point

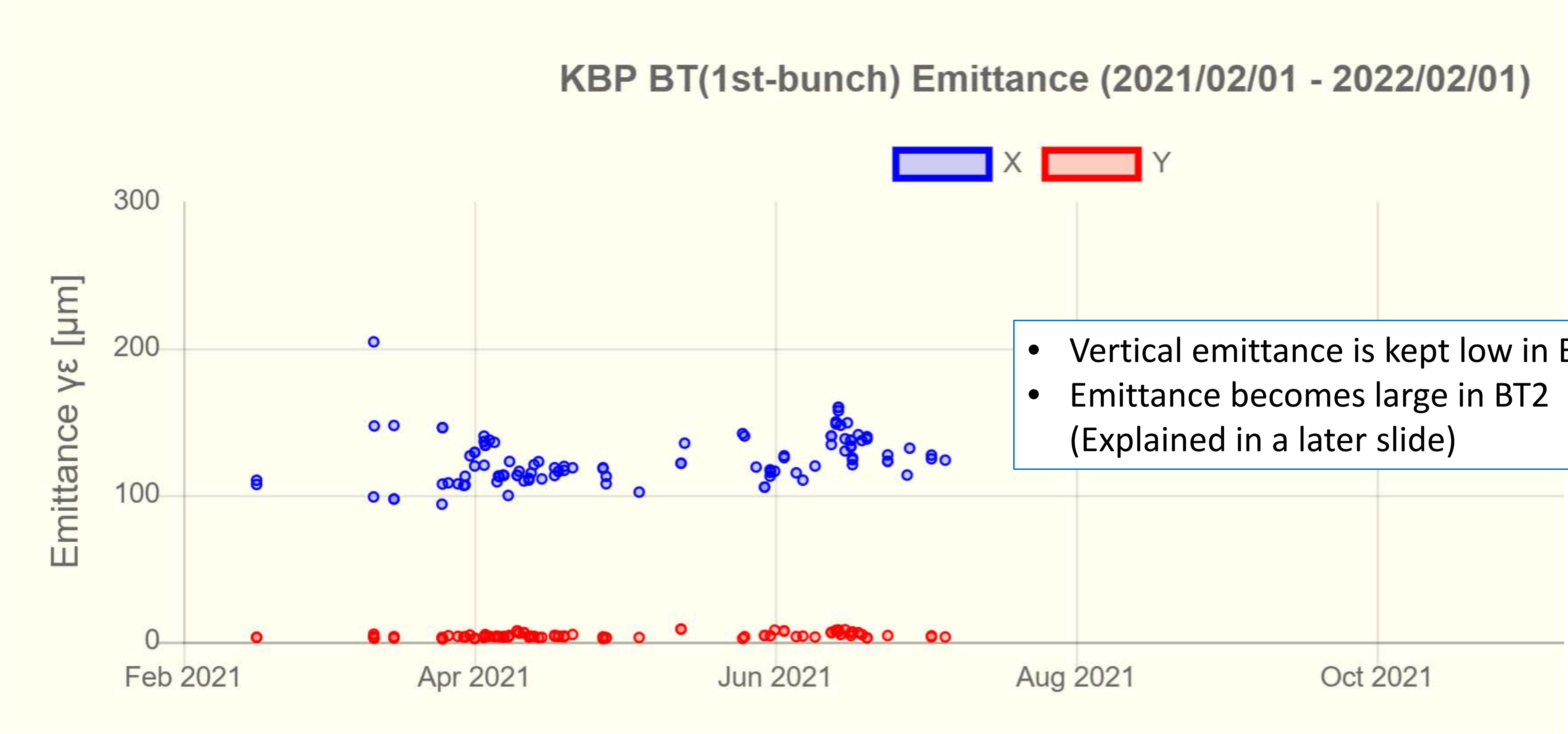


FC current and positron yield

Plan to increase yields

- Increase primary electron
- Decrease beam loss after the capture section
- Optimization of FC shape, etc.

e+ emittance history

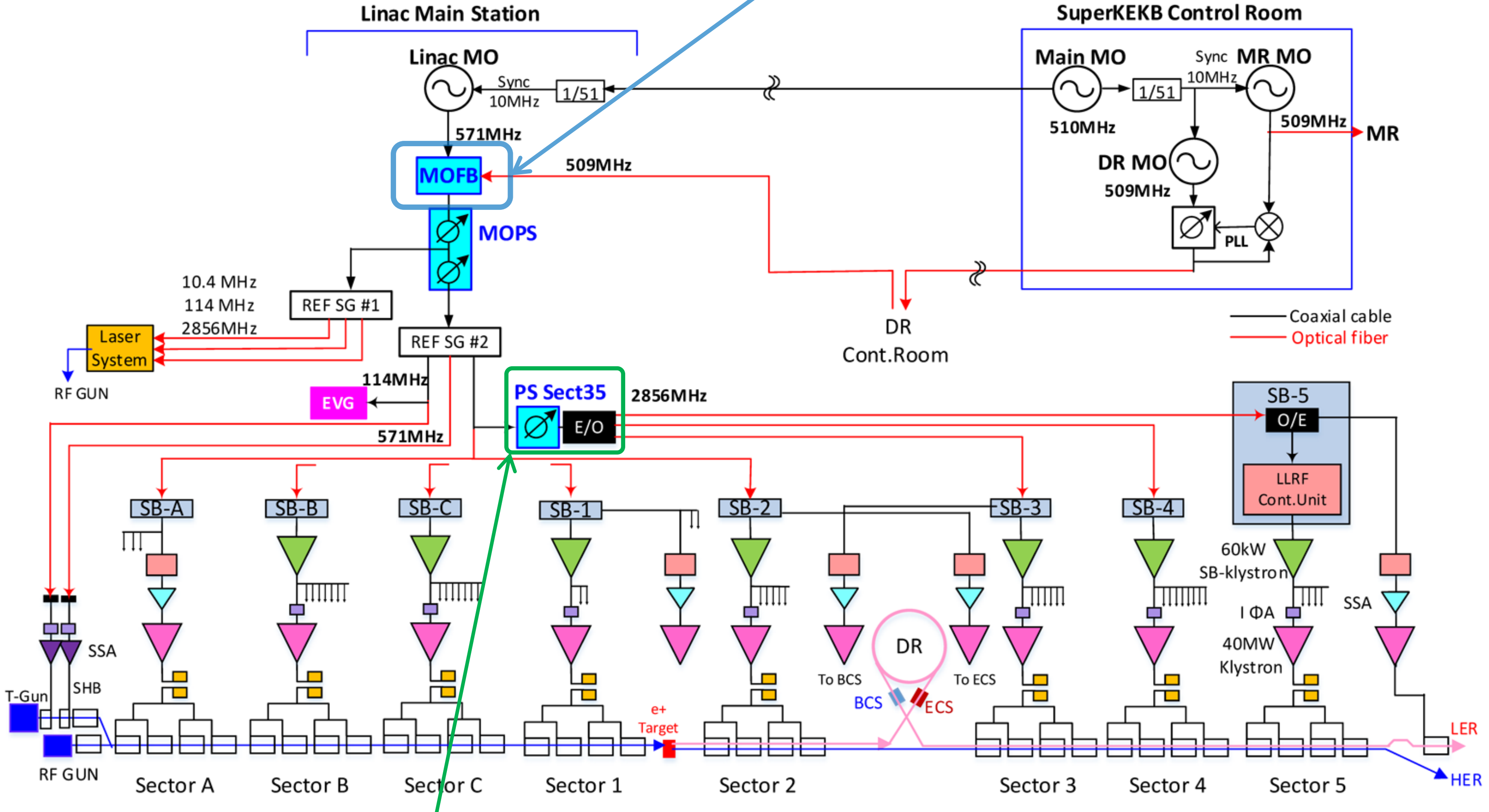


- Vertical emittance is kept low in BT1
- Emittance becomes large in BT2 (Explained in a later slide)

Stability, Upgrades

Upgrade of Low level RF

T. Miura

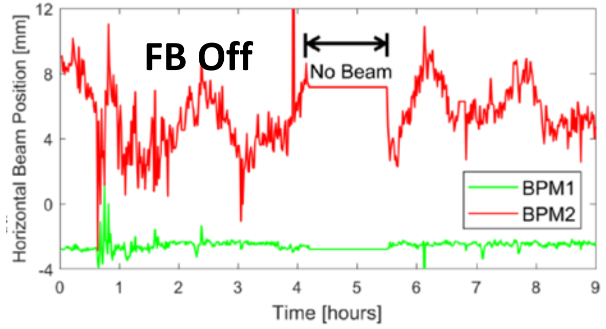


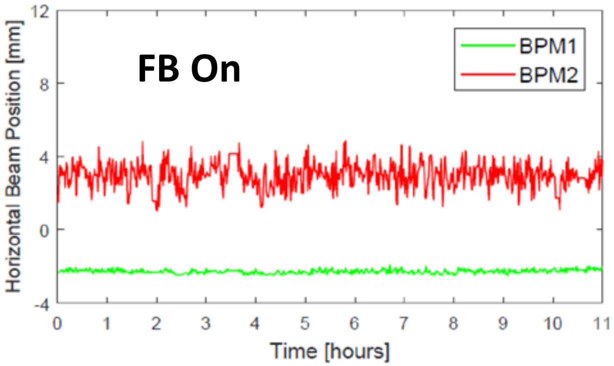
Phase shifter for linac downstream (3-5 sector)

→ Increase the number of rf bucket which synchronized with linac

MO feedback system

Linac master oscillator feedback system was introduced to make the Linac RF phase follow the Super KEKB ring rf phase.



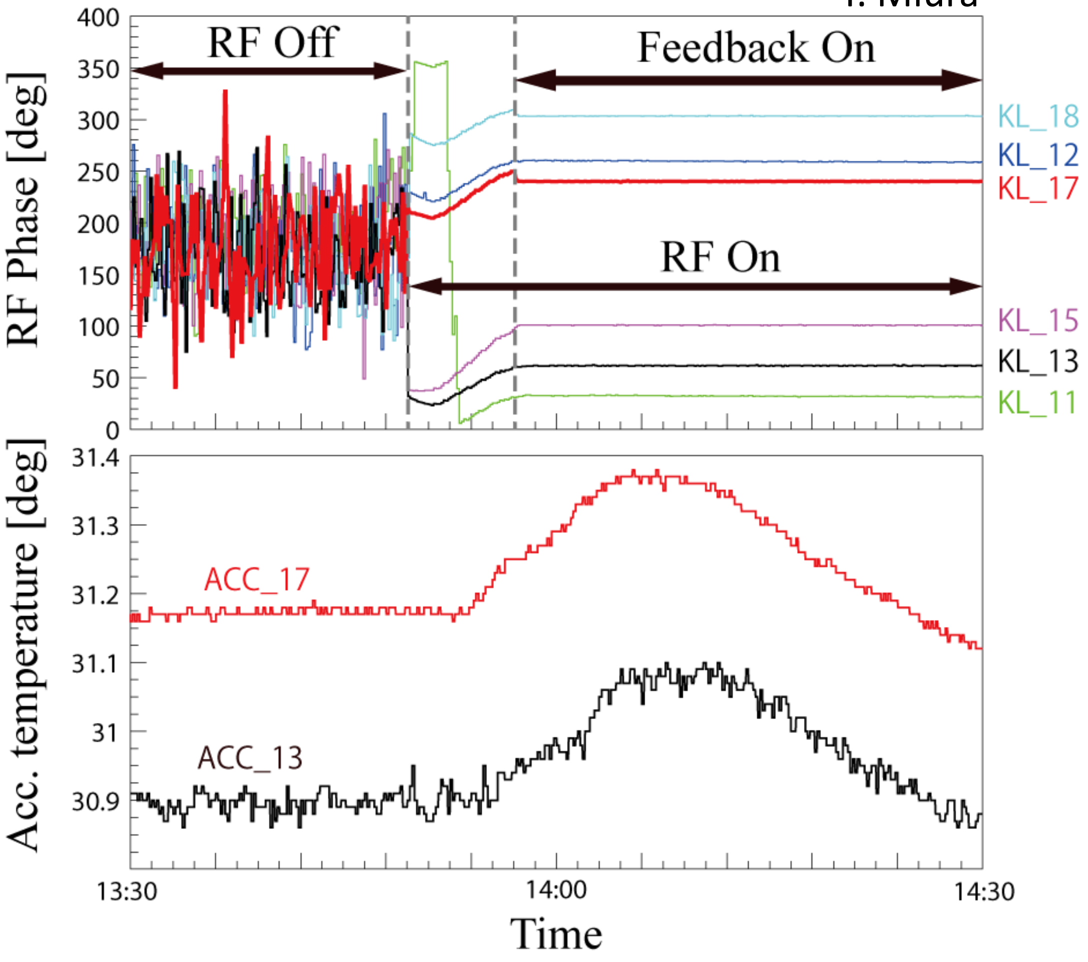


Beam position variation upstream (green) / downstream (red) of a cavity for bunch compression system (BCS) which located in the transport line between DR and linac.

RF phase feedback system

Phase feedback system stabilizes rf phases at exit of accelerating structures by monitoring rf of No Injection Mode (NIM).

T. Miura



Variation of rf phase and temperature of accelerating structure

Before

The beam cannot be emitted until the temperature of the acc. structures are stabilized if all klystrons are turned off.
= Waiting ~1 hour

After installation of the rf phase feedback

Beam operation is possible in ~**3 minutes from RF ON**.

In case of entering the linac tunnel, the operation can be started within 10 minutes of leaving the tunnel.

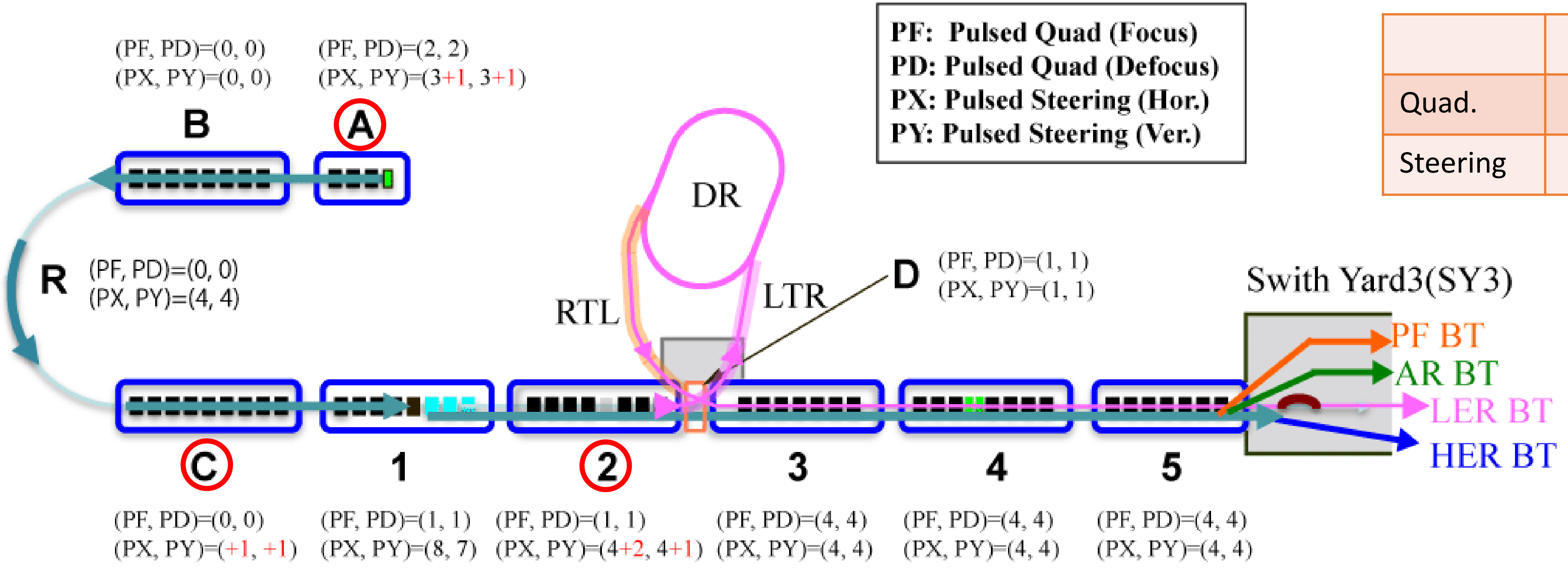
Until the temperature is stabilized, it is necessary to include NIM in the injection pattern.

T. Miura

Pulsed magnets

Y. Enomoto

1) New pulsed steering magnets have been installed in this summer.



Installed pulsed magnets at Jun. 2021: Qaudorupoles = 34, Steerings = 6

Newly installed pulsed magnets this summer: Steerings = 7

Current stability of pulsed magnet

	Required	Measured
Quad.	0.1%	< ~0.006%
Steering	0.01%	< ~0.003%

2) DCCT monitors for pulsed magnet power supply have been replaced to high resolution them.

Upgrade plan

・Adding more pulsed magnets → Increase the flexibility of beam tuning for each beam mode.
・Development of a quadrupole magnet with large bore radius and its power supply.
・Development of a fast pulsed steering magnet which acts only on the 1st or 2nd bunch.

Feedback Systems in Linac

Major feedback systems that contribute to bam stabilization

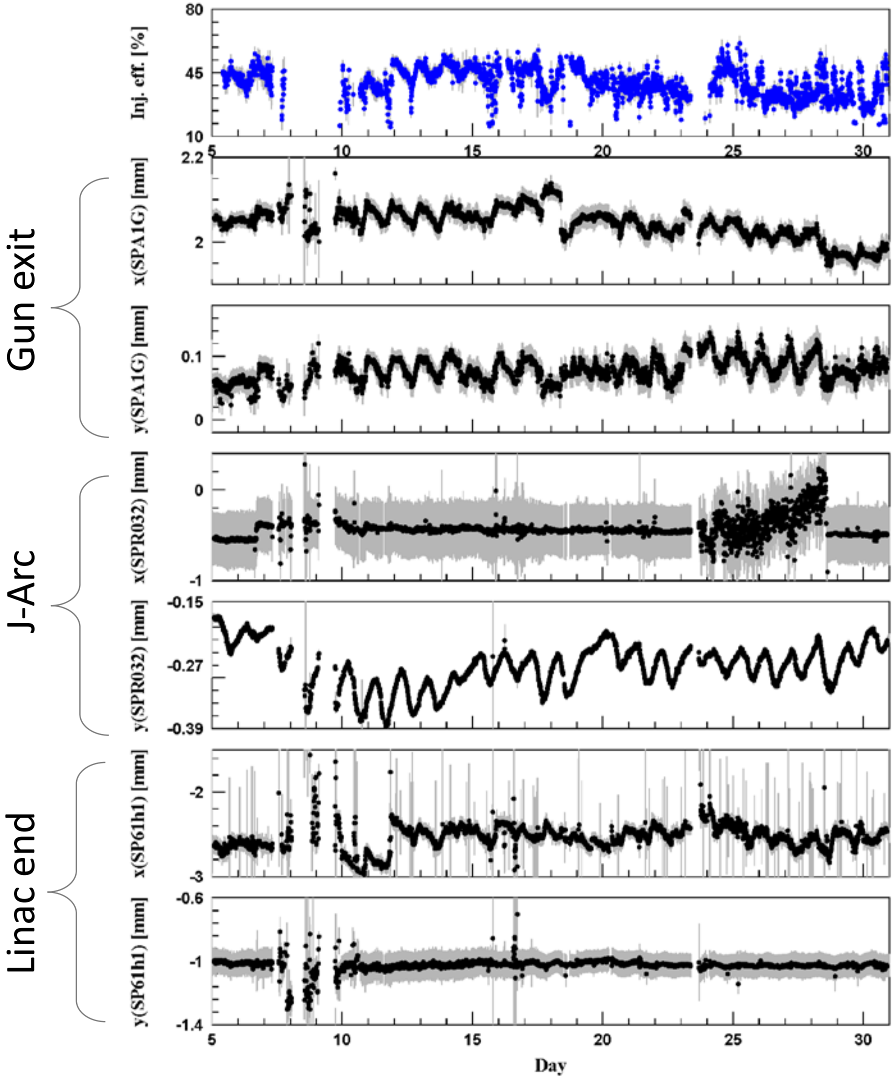
Laser	Laser line	Status
Position feedback	1st	OK

Beam	Beam	Status
J-Arc energy feedback	e-: 1st, e+: 1st	OK
3-5 sector orbit feedback	e-: 1st + 2nd, e+: 1st + 2nd	OK
Linac end orbit feedback	e-: 1st + 2nd, e+: 1st + 2nd	OK
SY3 energy feedback	e+: 1st + 2nd	OK
BT energy feedback	e-: 1st, e+: 1st	OK
A-sector orbit feedback (new)	e-: 1st + 2nd, e+: 1st + 2nd	**Installed in 2021c**
C-sector orbit feedback (new)	e-: 1st + 2nd, e+: 1st + 2nd	**Installed in 2021c**

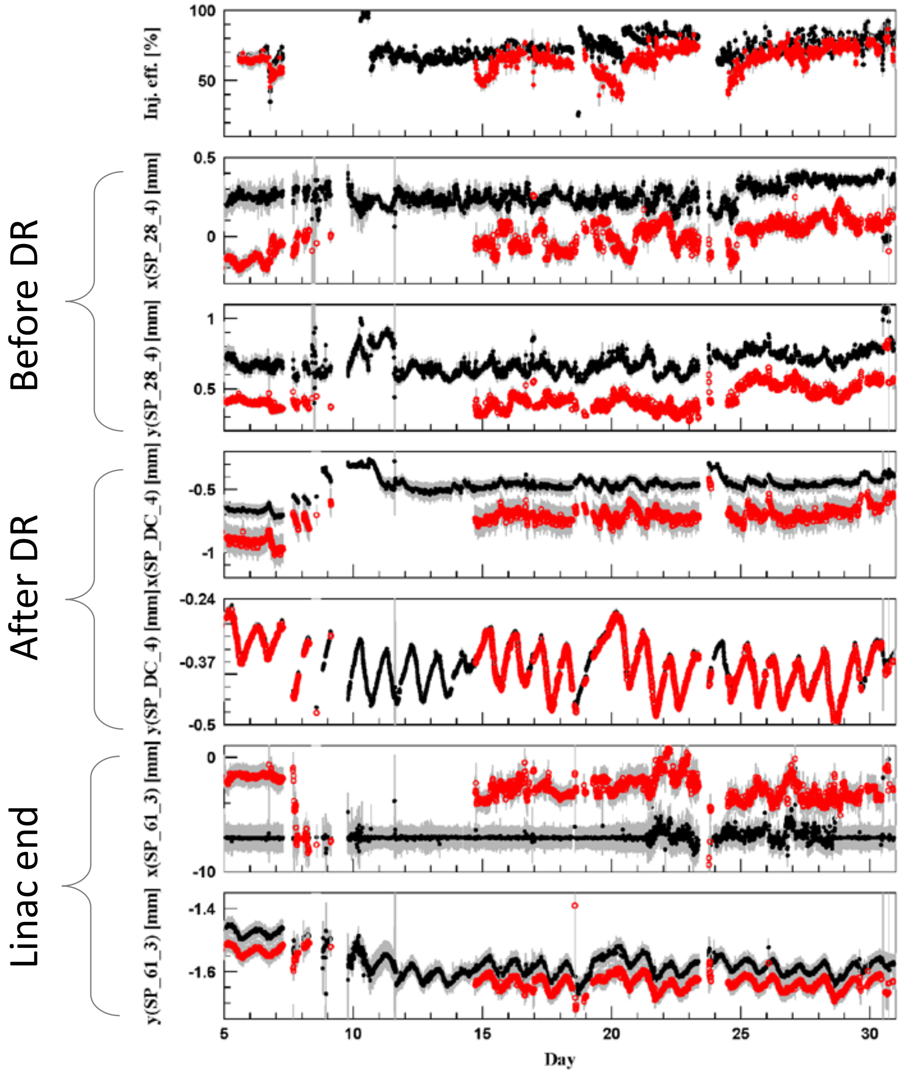
RF	Object	Status
Master Oscillator (MO) feedback	RF phase between LER/HER and Linac	OK
RF phase	RF phase of acc. structure, rf-gun	OK

Beam orbit stability

electron (only 1st bunch)



positron (•1st bunch, ◦ 2nd bunch)



Injection efficiency and beam orbit variation (10 minutes average) in 25 days (June 2021) at major point.
The RMS of beam position is shown in gray line.

Beam position at a particular bpm shows correlation with the injection efficiency

Room for improvement

- **Suppressing Daily variation**
- **Match the orbits of the 1st and 2nd bunch**

The causes are under investigation

- The 2nd line DOE may reduce the variation at gun exit
- Orbit feedback using new pulsed steering magnets

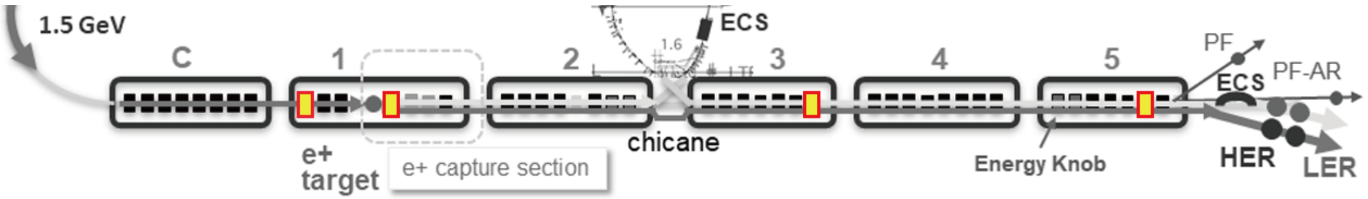
Energy Margin

Beam mode and Energy

Measured maximum beam energy at Linac end [GeV].

H. Ego

	Normal Operation	Additional Unit (Normally in standby mode)			
		KL38	KL38, KL57	KL38, KL57, KL11	KL38, KL57, KL11, KL15
KBE (e-) (1.9 nC)	6.943	7.130	7.311	7.438	7.458
KBP(e+) (1.2 nC)	4.000	4.160	4.320	-	-



Standby units

- RF unit (KL*) provides rf to 4 accelerating structures.
- Energy gain in a unit is ~160 MeV.
- The actual beam energy is slightly lower than the maximum value in order to align energy of bunch head and tail.

Beam test of higher energy operation

$\sqrt{s}$ [GeV] #	LER	HER	Linac status
10.579(Normal)	4.000	7.007	OK
10.657	4.029	7.059	OK
10.706	4.048	7.091	OK
10.751	4.065	7.121	OK
10.810	4.087	7.160	OK

#: Crossing angle: 83 mrad

Energy knob : KL51, KL52
Standby → Acc. : KL57
Standby: KL38

Higher energy operations keep one standby unit (KL38).

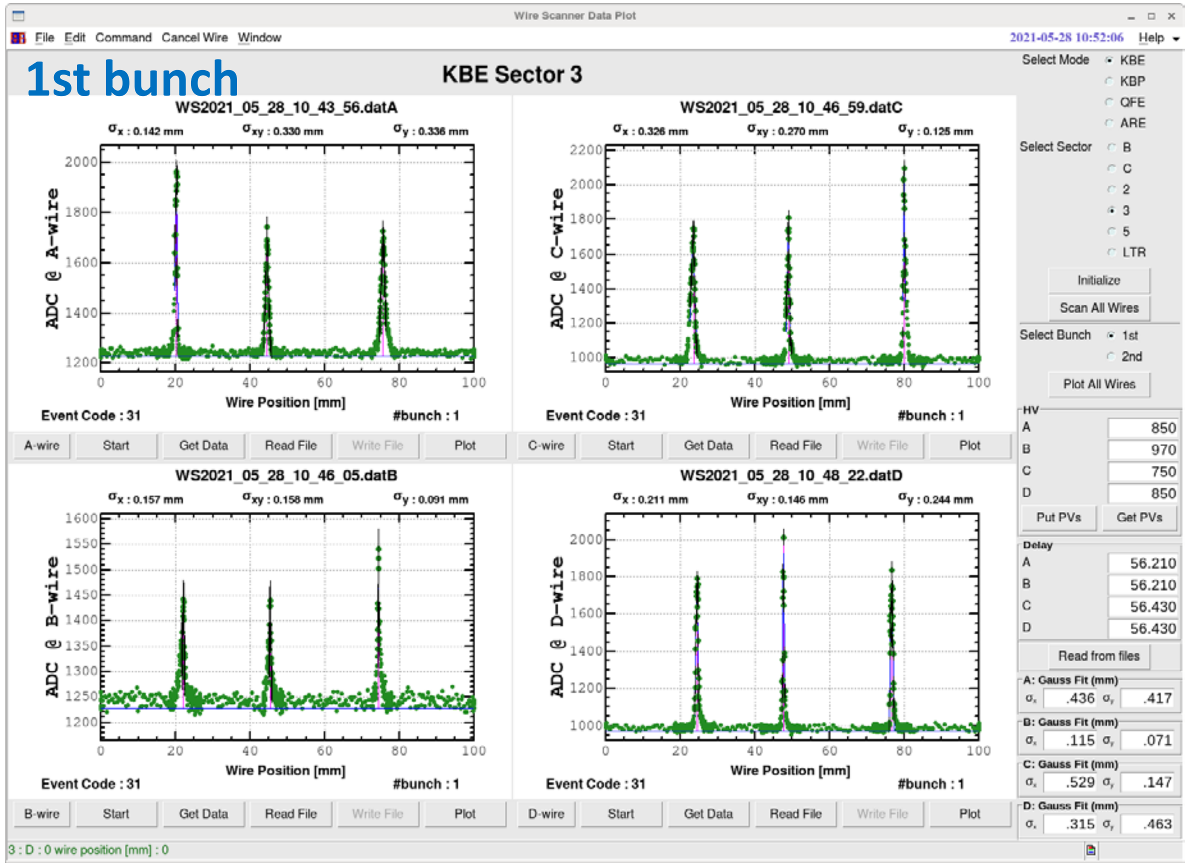
Current issue

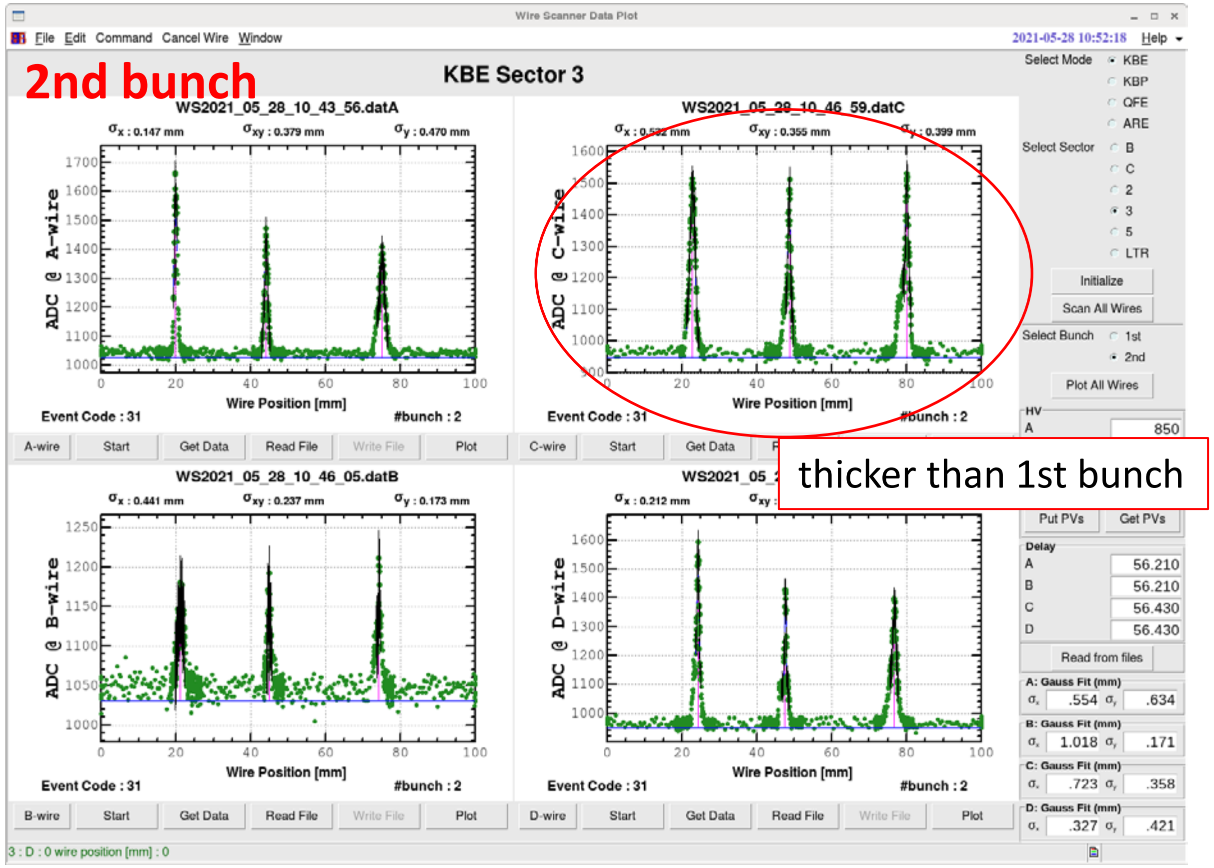
Emittance growth of electron 2nd bunch

Bean injection of electron 2nd bunch is difficult due to the large emittance

Emittances measured in HER BT

	1st bunch	2nd bunch
Horizontal: $\gamma\varepsilon_x$ [μm]	16.4 ± 2.0	45.9 ± 3.6
Vertical: $\gamma\varepsilon_y$ [μm]	9.6 ± 1.8	67.7 ± 6.5



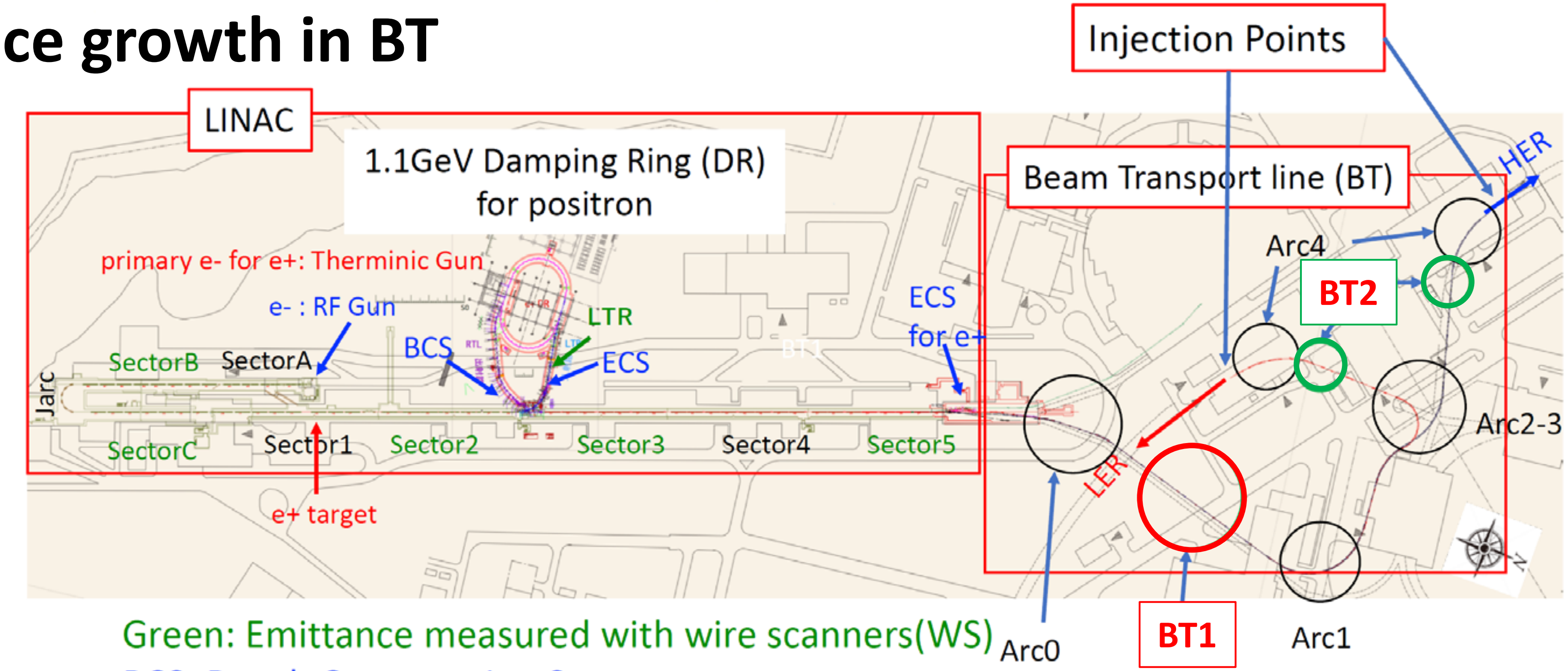


Beam profiles at 3-sector measured by wire scanner

M. Yoshida

The degradation of emittance may be occurring downstream from positron capture section.
The cause is still under investigation.

Large emittance growth in BT



Green: Emittance measured with wire scanners(WS)

BCS: Bunch Compression System

ECS: Energy Compression System

HER BT (e-)

Emittances of 1st bunch measured in BT1(wire), BT2(OTR) (Example)

2021.6.10	WS at BT1	OTR at BT2	BT2/BT1
$\gamma\varepsilon_x$ [μm]	29.8 ± 6.4		
$\gamma\varepsilon_y$ [μm]	48.6 ± 8.6 ⇒	82.8 ± 3.3	x 1.7

LER BT (e+)

Emittances measured in BT1(wire), BT2(OTR) (Example)

N. Iida, T. Mori

BTp1	1st bunch	2nd bunch
$\gamma\varepsilon_y$ [μm]	2.21 ± 0.62	3.53 ± 0.26

⇓

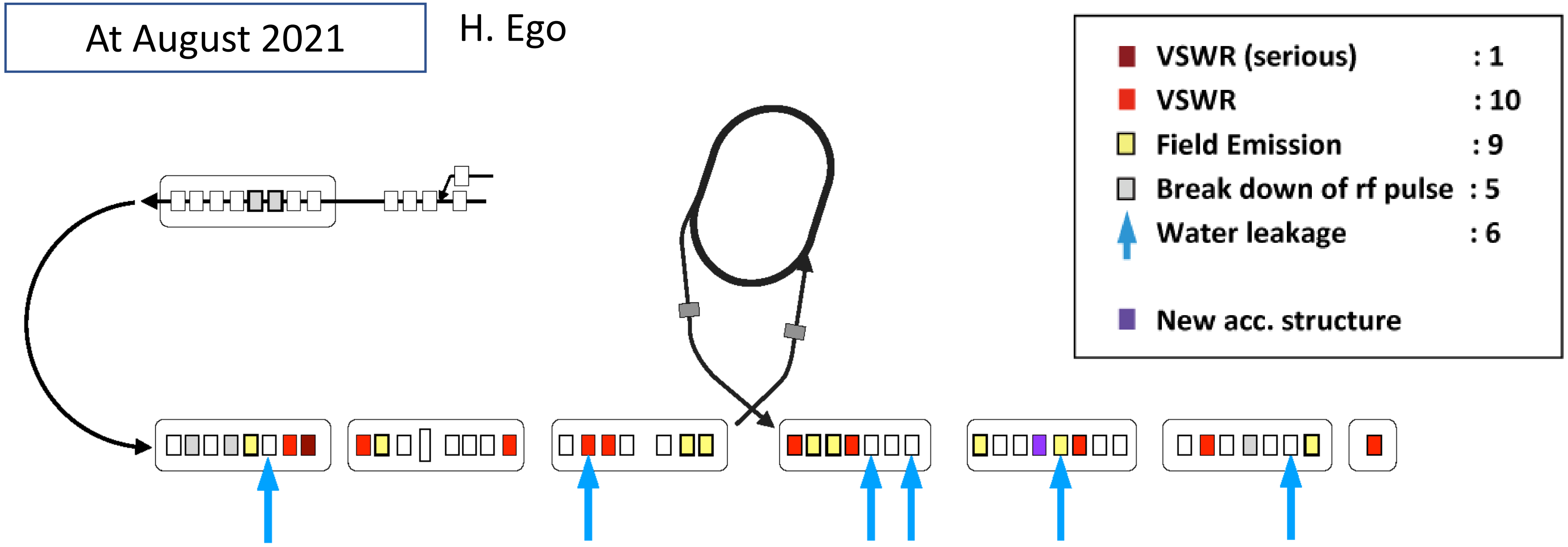
BTp2	1st bunch	BT2 /BT1	2nd bunch	BT2 /BT1
$\gamma\varepsilon_y$ [μm]	62.7 ± 13.5	x29	59.9 ± 7.1	x17

Degradation of accelerating structures

Electrical discharge and leakage of cooling water have been occurred due to degradation over time.

At August 2021

H. Ego



One accelerating structure failure leads to stop of 1 unit = 4 acc. structure = ~160 MeV.

・12 new accelerating structures are in production.
・Degraded acc. structures are scheduled to be replaced starting in the summer of 2022.
(Replacement will be done on a unit-by-unit basis)
・More new acc. structures will be manufactured, but the quantity will depend on the budget.

Appendix

Assembly, base management (2021/1 ver.)

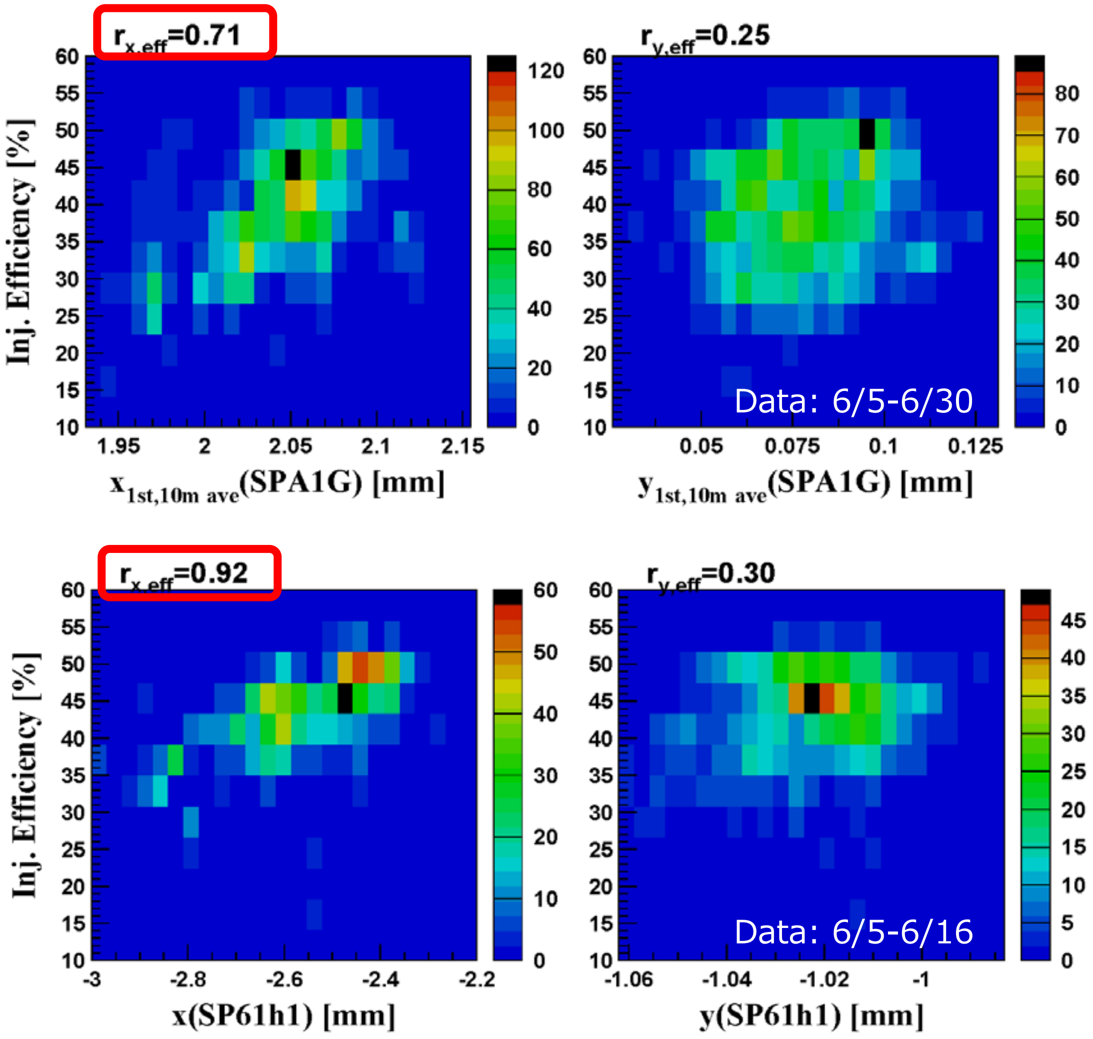
Y. Enomoto

	Phase 1	Phase 2	Phase 3	2019 Q4	2020 ab	2020c	delivered	removed	present	Note
Assembly 1							<2015	2017/3	In tunnel	
Assembly 2							2016/3		In operation	
Assembly 3							2017/11		Test bench	
FC base 1							<2015			Test
FC base 2							<2015			Test
FC base 3							<2015	2017/3	In tunnel	
FC base 4								2018/9	In tunnel	
FC base 5							2016/7	2020/9	In tunnel	
FC base 6							2017/11		Test bench	bad quality
FC base 7	Material test started in 2018/10						**2019/10**		**Test bench (back up)**	**New material**
FC base 8							**2020/6**		**In operation**	**Final version**
FC base 9							**2021/3**		**Test bench**	**Saper for Final version**

9号機以降は当面製作予定なし

in operation
spare
test bench

Correlation between position and injection efficiency (KBE)



Correlation between SP_A1_G / SP_61_H1 and injection efficiency. The correlation coefficient are shown at the top of the figure.

There is a correlation between beam position at the gun exit and injection efficiency.

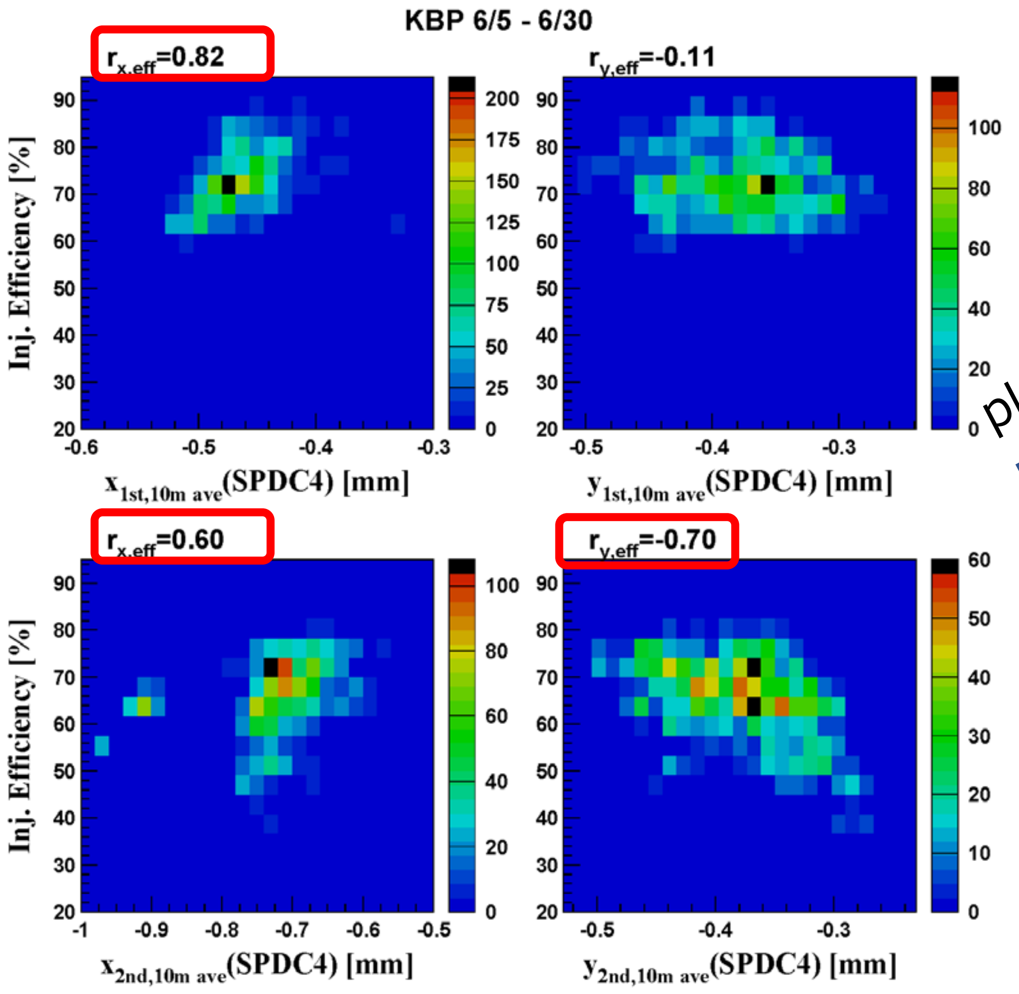
Variation of bunch profile (transverse/longitudinal)?

Correlation at SP_61_H1 with large dispersion function.

Correlations with other BPMs are given in the appendix.

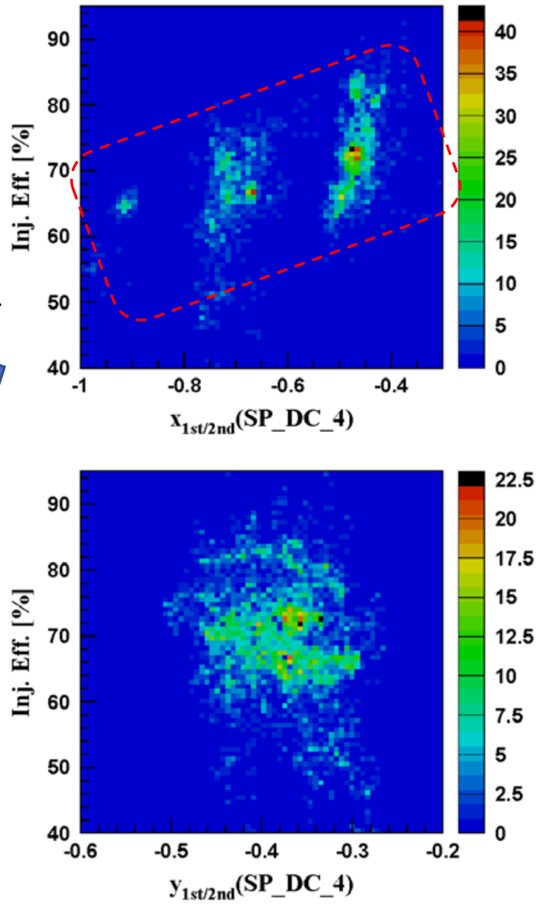
There is no clear correlation in other BPM. (Not all BPMs have been checked.)

Correlation between position and injection efficiency (KBP)

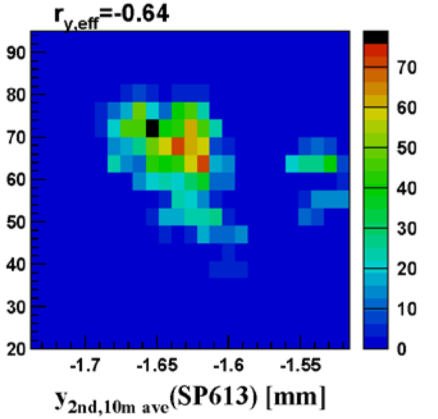


Correlation between SP_DC_4 (1st BPM in Linac after DR) and injection efficiency.

plot on same fig.



The cause of the difference in the orbit after the DR needs to be investigated carefully.



Correlation between y position of 2nd bunch at SP_61_3 and injection efficiency.