Injector status

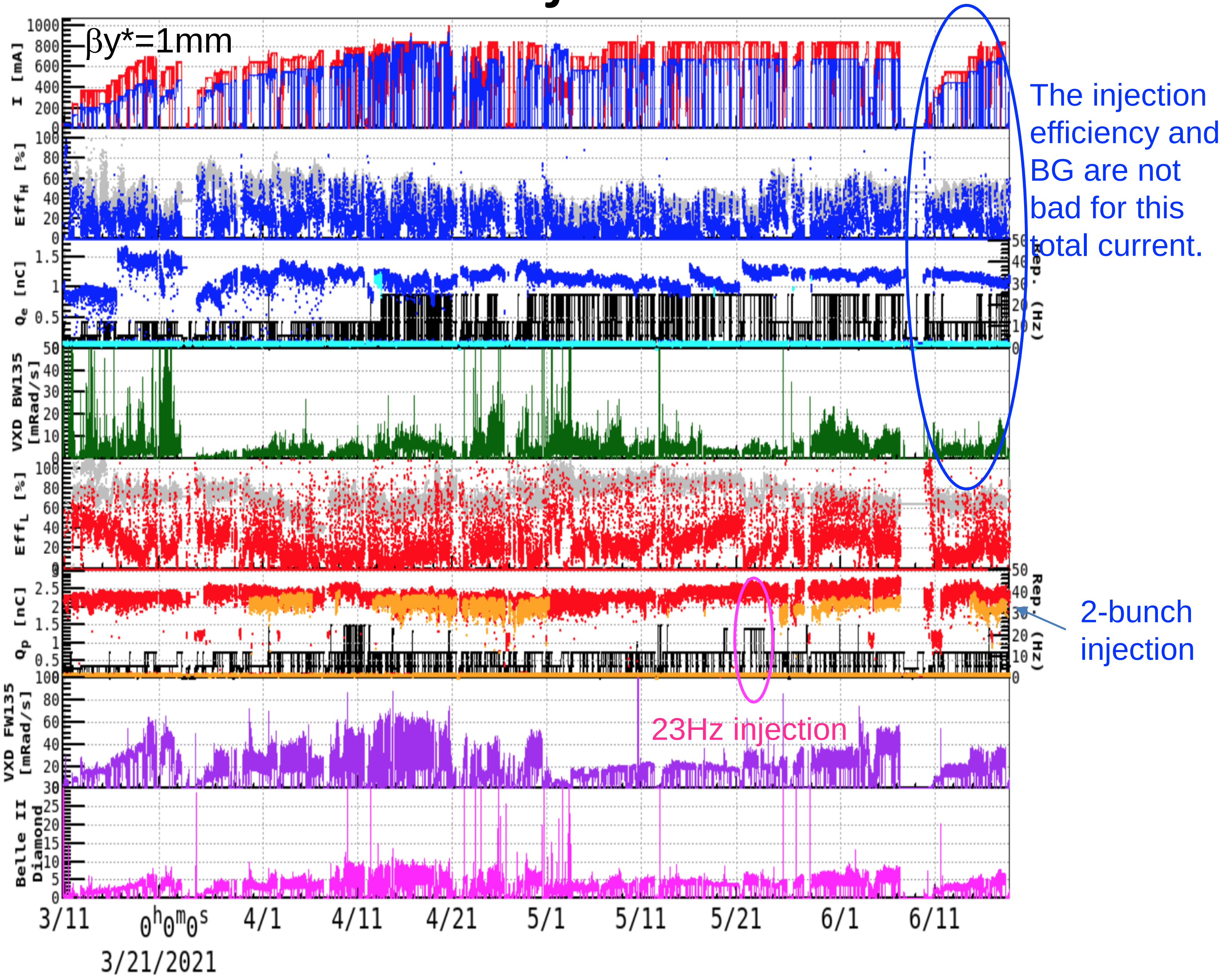
2021.06.21

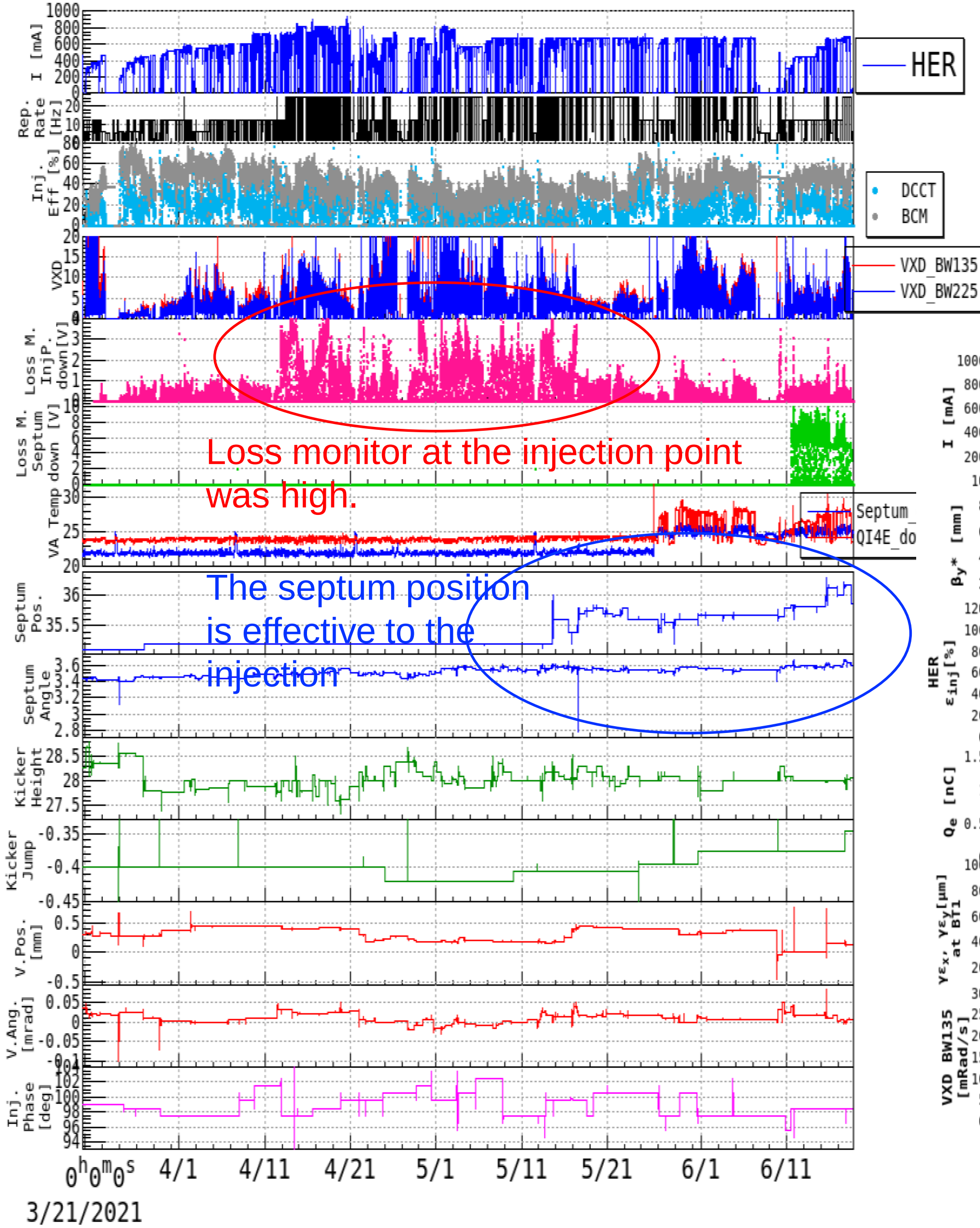
Mitsuhiro Yoshdia

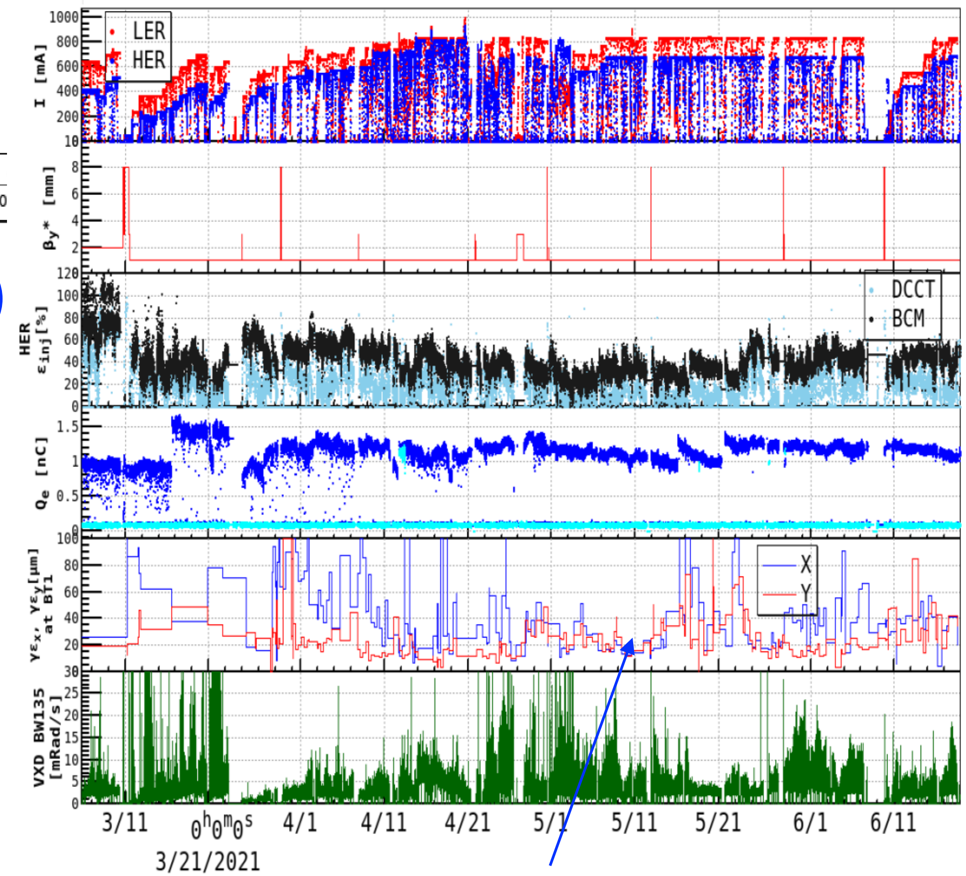
Linac Beam Parameters for KEKB/SuperKEKB

Stage	KEKB (final)		Phase-I (achieved)		Phase-II (achieved)		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	2	primary e- 10 → 4	4
Norm. Emittance (γβε) (mrad)	1400	310	1000	130	200/40 (Hor./Ver.)	150	150/30 (Hor./Ver.)	100/40 (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)	

Recent injection



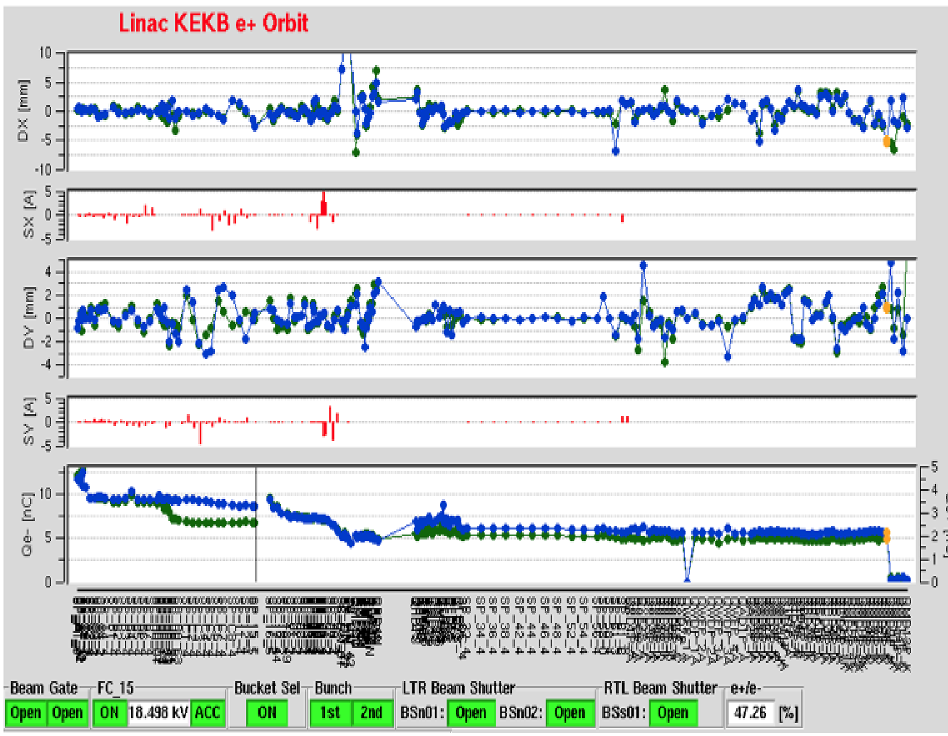




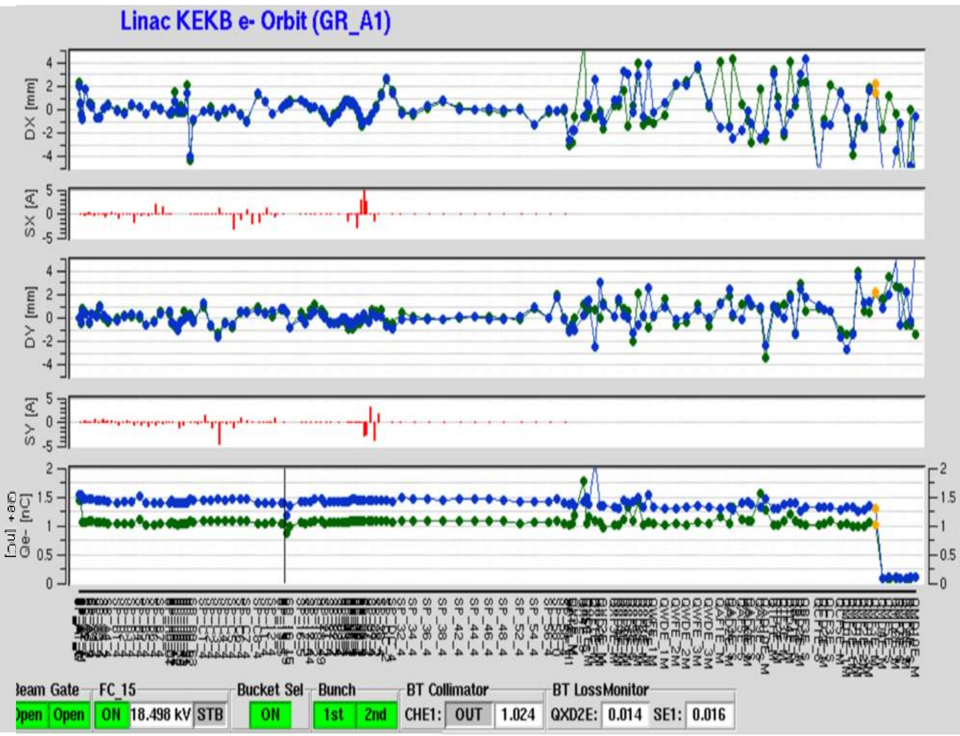
The measured emittances in the upper part of e-line have kept lower level.

2-bunch injection orbits

LER



HER

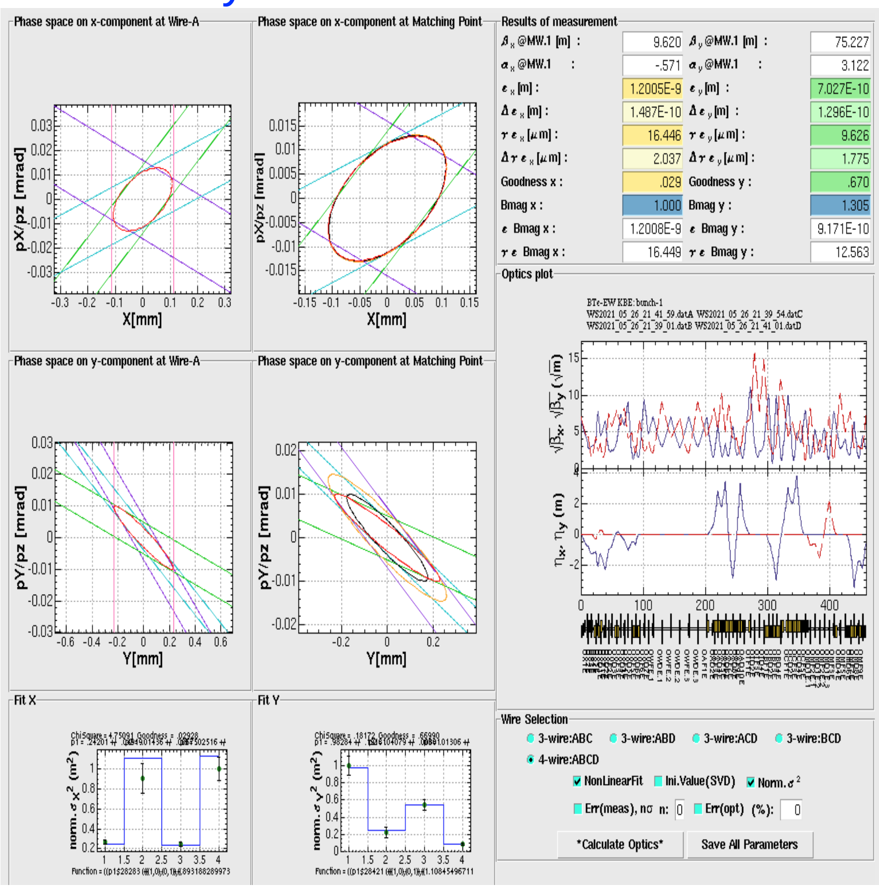


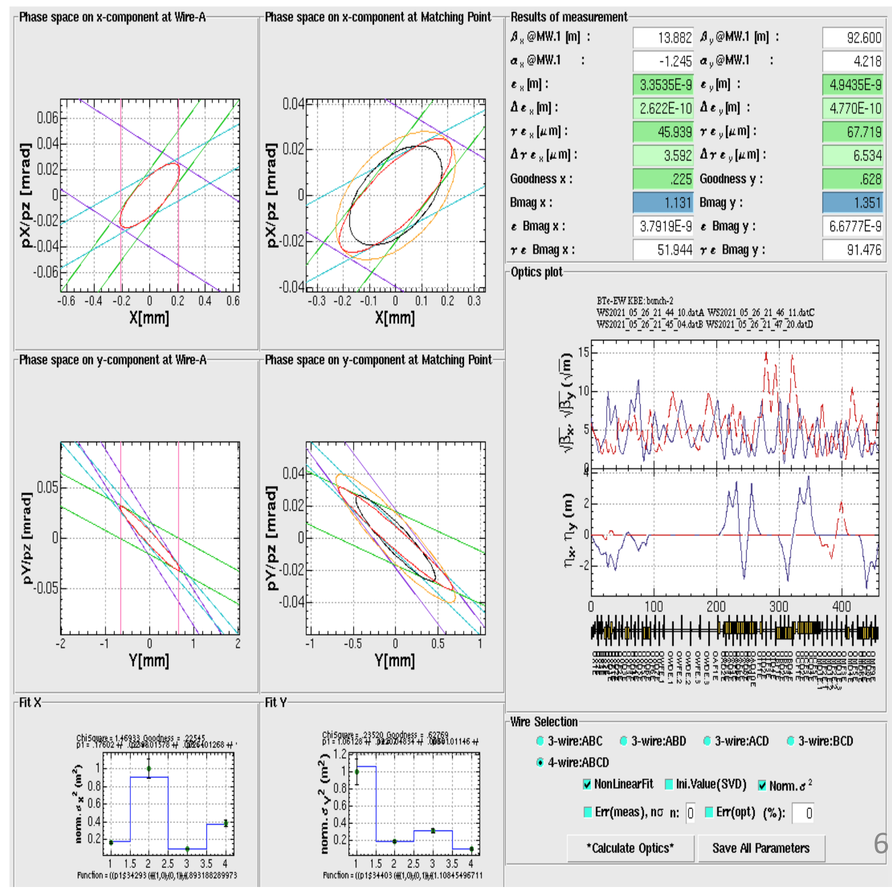
HER 2-bunch injection

	1st bunch	2nd bunch
γεx [μm]	16.4±2.0	45.9±3.6
BMAGx	1.00	1.13
γεy [μm]	9.63±1.78	67.7±6.5
BMAGy	1.31	1.35

The emittances of the 1st bunch are very small.

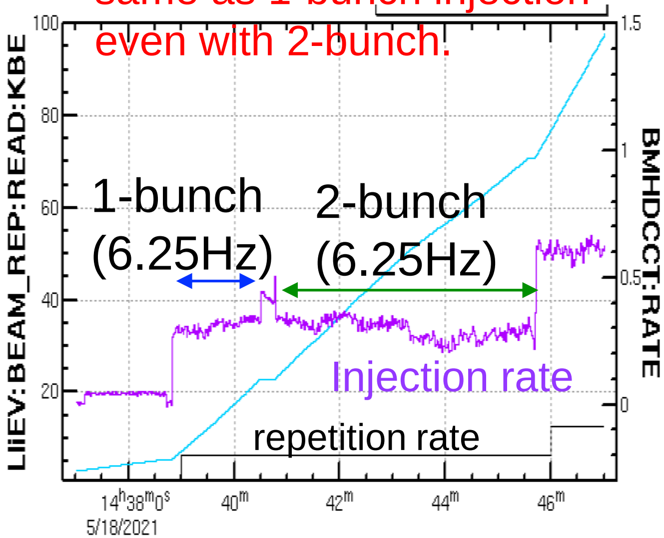
The emittances of the 2nd bunch are large.

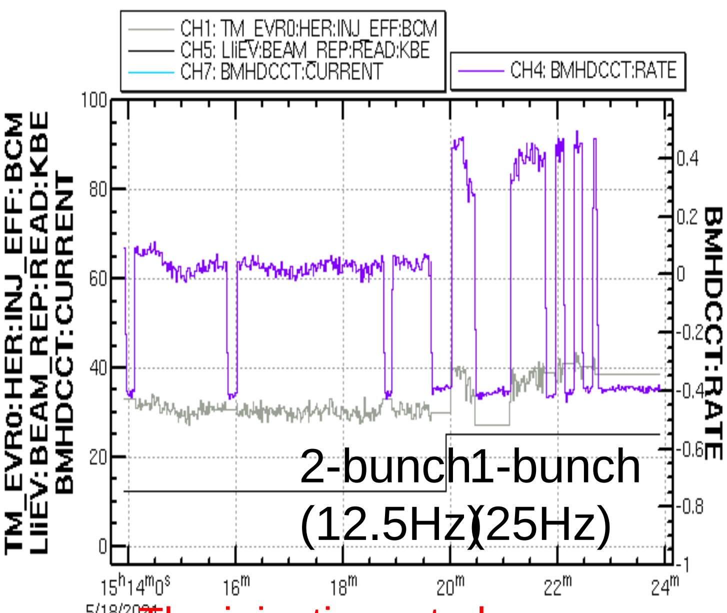




May/18

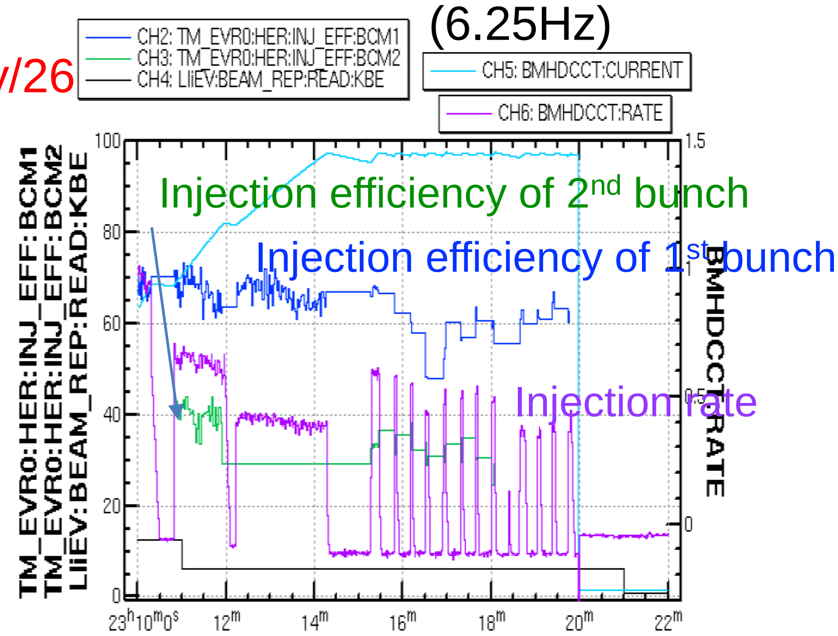
The injection rate was almost same as 1-bunch injection even with 2-bunch.

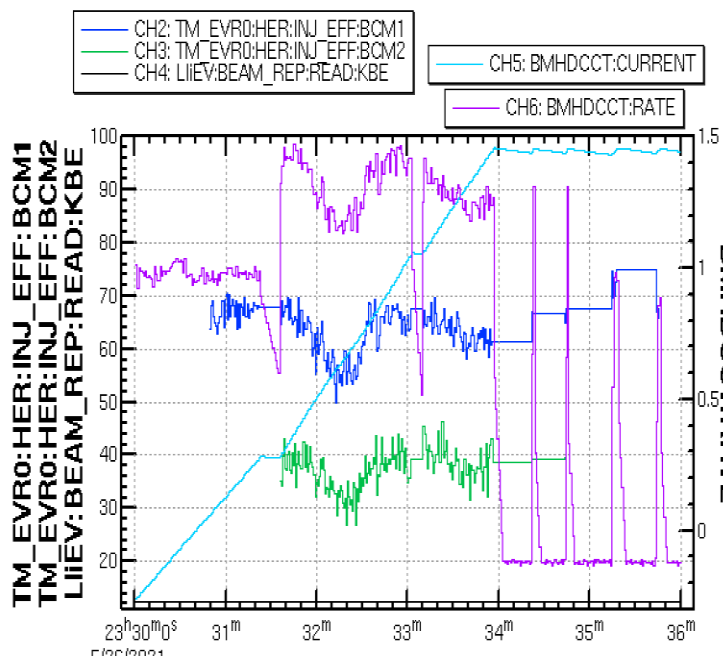




The injection rate became twice just due to the double repetition rate

May/26





The injection efficiencies of 1st and 2nd bunches were 70% and 40%

LER 2-bunch injection study

T. Mori

BT1

BT2
y only

Bunch-1

Results of measurement

β_x@MWP.1 [m] :	7.598	β_y@MWP.1 [m] :	28.975
α_x@MWP.1 :	-.371	α_y@MWP.1 :	3.125
ε_x [m] :	1.8862E-8	ε_y [m] :	2.940E-10
$\Delta\varepsilon_x$ [m] :	1.1485E-9	$\Delta\varepsilon_y$ [m] :	8.229E-11
$\gamma\varepsilon_x$ [μm] :	141.793	$\gamma\varepsilon_y$ [μm] :	2.210
$\Delta\gamma\varepsilon_x$ [μm] :	8.634	$\Delta\gamma\varepsilon_y$ [μm] :	.619
Goodness x :	.156	Goodness y :	.022
Bmag x :	1.018	Bmag y :	2.277
ε Bmag x :	1.9211E-8	ε Bmag y :	6.693E-10
$\gamma\varepsilon$ Bmag x :	144.415	$\gamma\varepsilon$ Bmag y :	5.031

Parameters at Scanned Q-magnet

β_y =	57.976	±	16.944	[m]
α_y =	-5.548	±	1.647	
ε_y =	7.701	±	1.657	[nm]
$\gamma\beta\varepsilon_y$	62.675	±	13.486	[μm]
$B_{m;y}$ =	5.295	±	8.943	

Bunch-2

Results of measurement

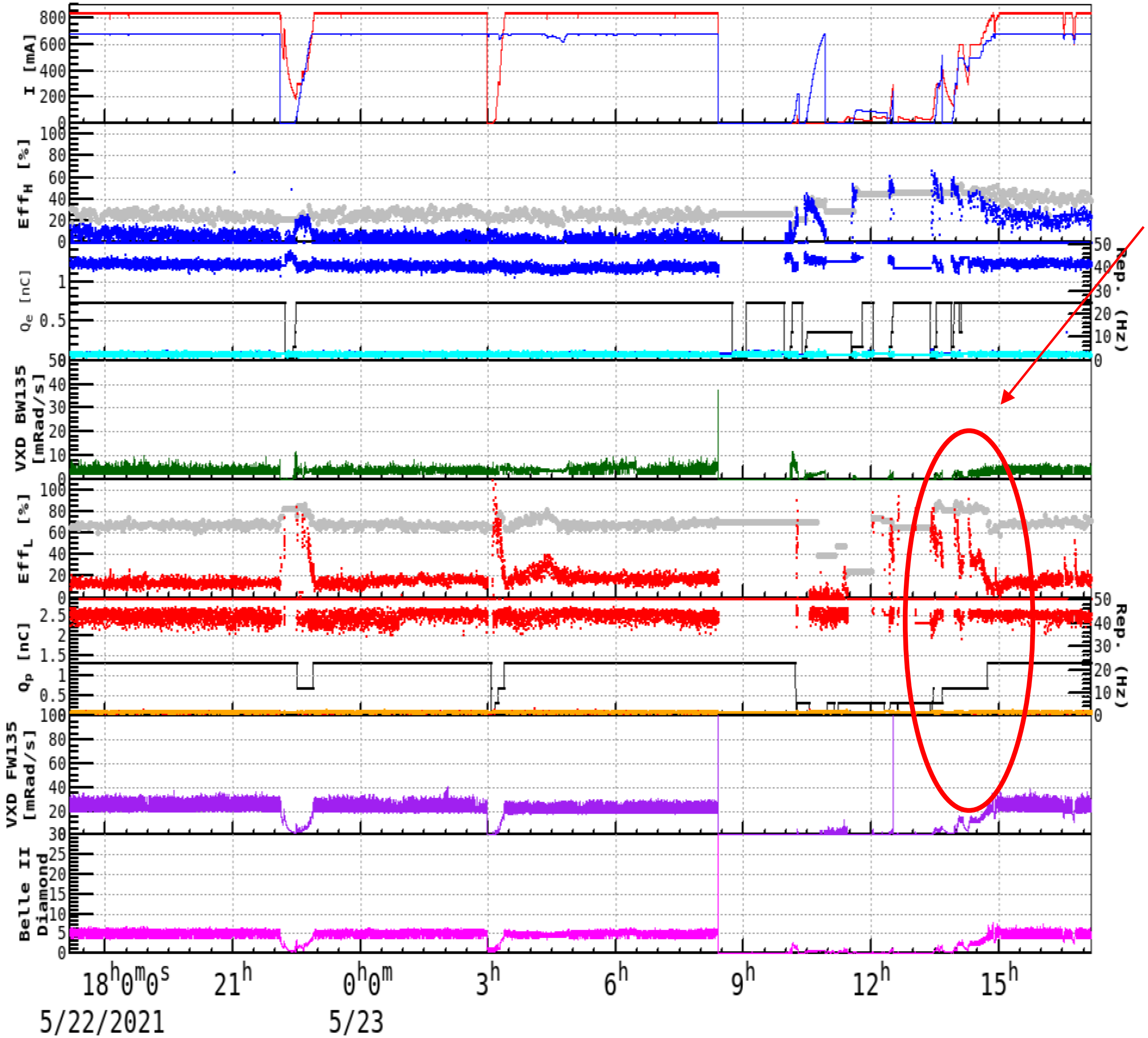
β_x@MWP.1 [m] :	8.365	β_y@MWP.1 [m] :	21.911
α_x@MWP.1 :	-.739	α_y@MWP.1 :	1.304
ε_x [m] :	2.1374E-8	ε_y [m] :	4.690E-10
$\Delta\varepsilon_x$ [m] :	1.2856E-9	$\Delta\varepsilon_y$ [m] :	3.480E-11
$\gamma\varepsilon_x$ [μm] :	160.670	$\gamma\varepsilon_y$ [μm] :	3.526
$\Delta\gamma\varepsilon_x$ [μm] :	9.664	$\Delta\gamma\varepsilon_y$ [μm] :	.262
Goodness x :	.192	Goodness y :	1.4702E-6
Bmag x :	1.010	Bmag y :	1.152
ε Bmag x :	2.1595E-8	ε Bmag y :	5.404E-10
$\gamma\varepsilon$ Bmag x :	162.336	$\gamma\varepsilon$ Bmag y :	4.062

Parameters at Scanned Q-magnet

β_y =	66.547	±	10.195	[m]
α_y =	-6.538	±	1.049	
ε_y =	7.364	±	.866	[nm]
$\gamma\beta\varepsilon_y$	59.93	±	7.051	[μm]
$B_{m;y}$ =	5.664	±	6.28	

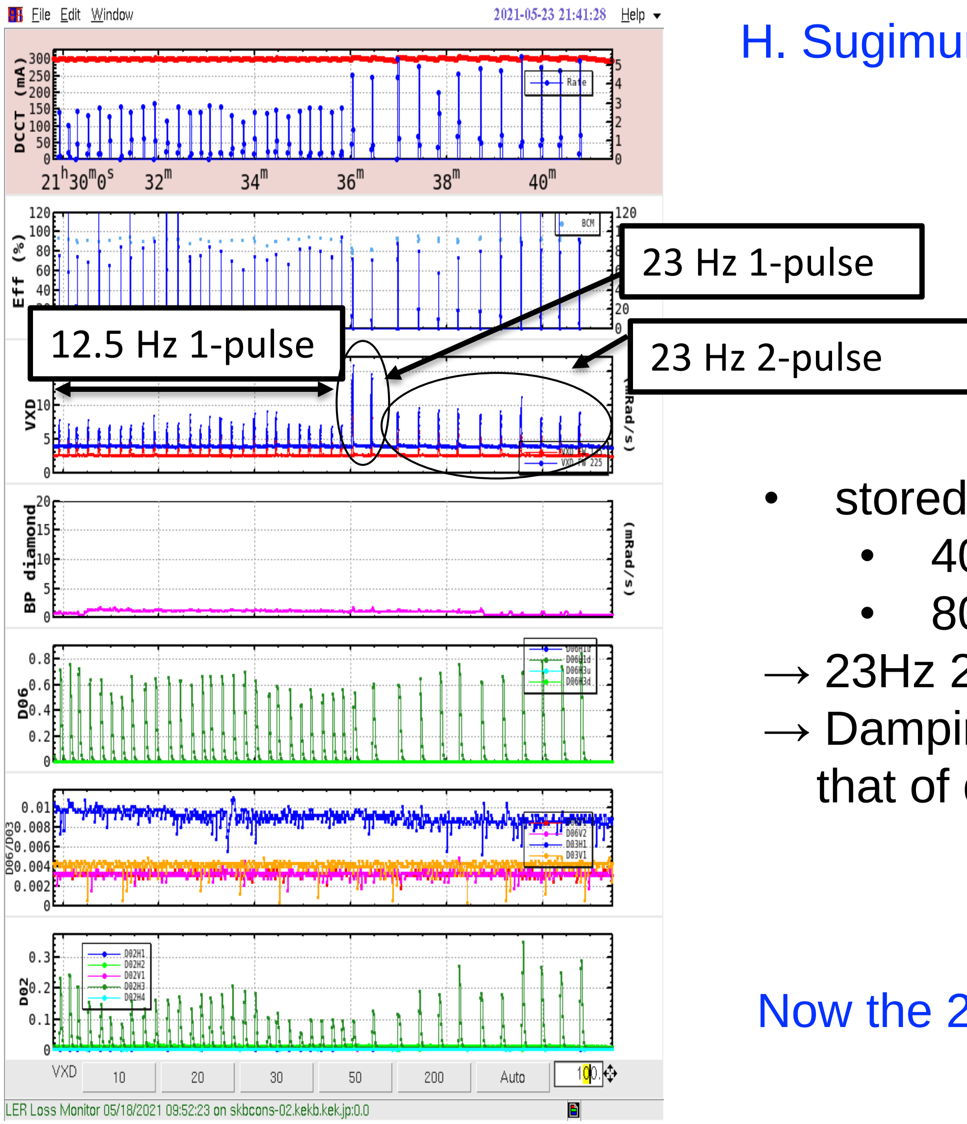
- Although there is still an enlargement of emittance from BT1 to BT2, Status of 2nd bunch is comparable to 1st bunch.

LER 23Hz injection



- The injection efficiency from BCM at 23Hz becomes lower than that at 12.5Hz.

Injection BG in LER 23 Hz w/ DR 2-pulse operation



H. Sugimura

- stored time in 23 Hz
  - 40 ms at 1-pulse
  - 80 ms at 2-pulse

→ 23Hz 2-pulse is lower BG than 1-pulse

→ Damping time is longer than that of design value

Now the 2-pulse operation in the DR is availa

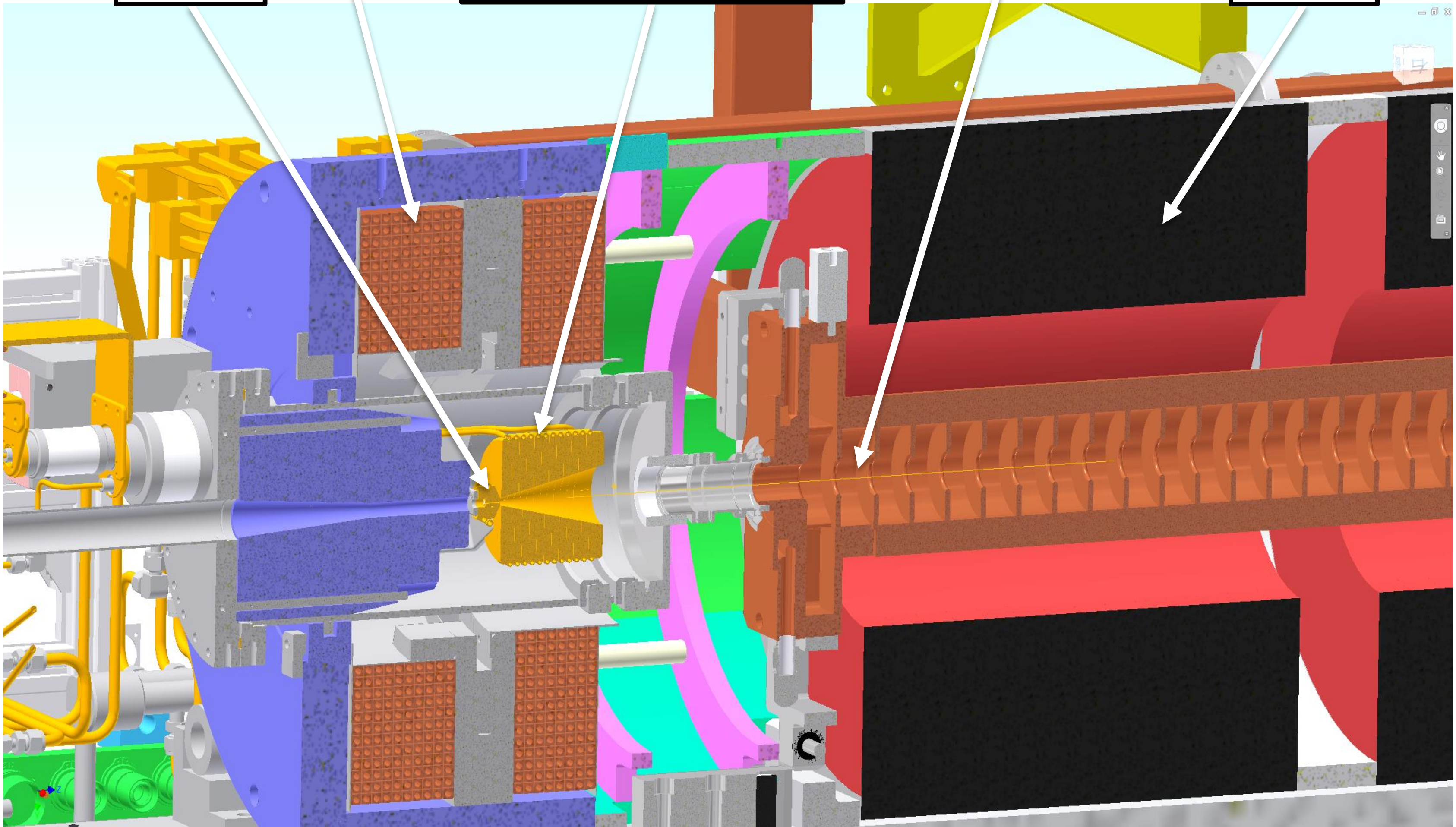
Positron generation

Positron generation

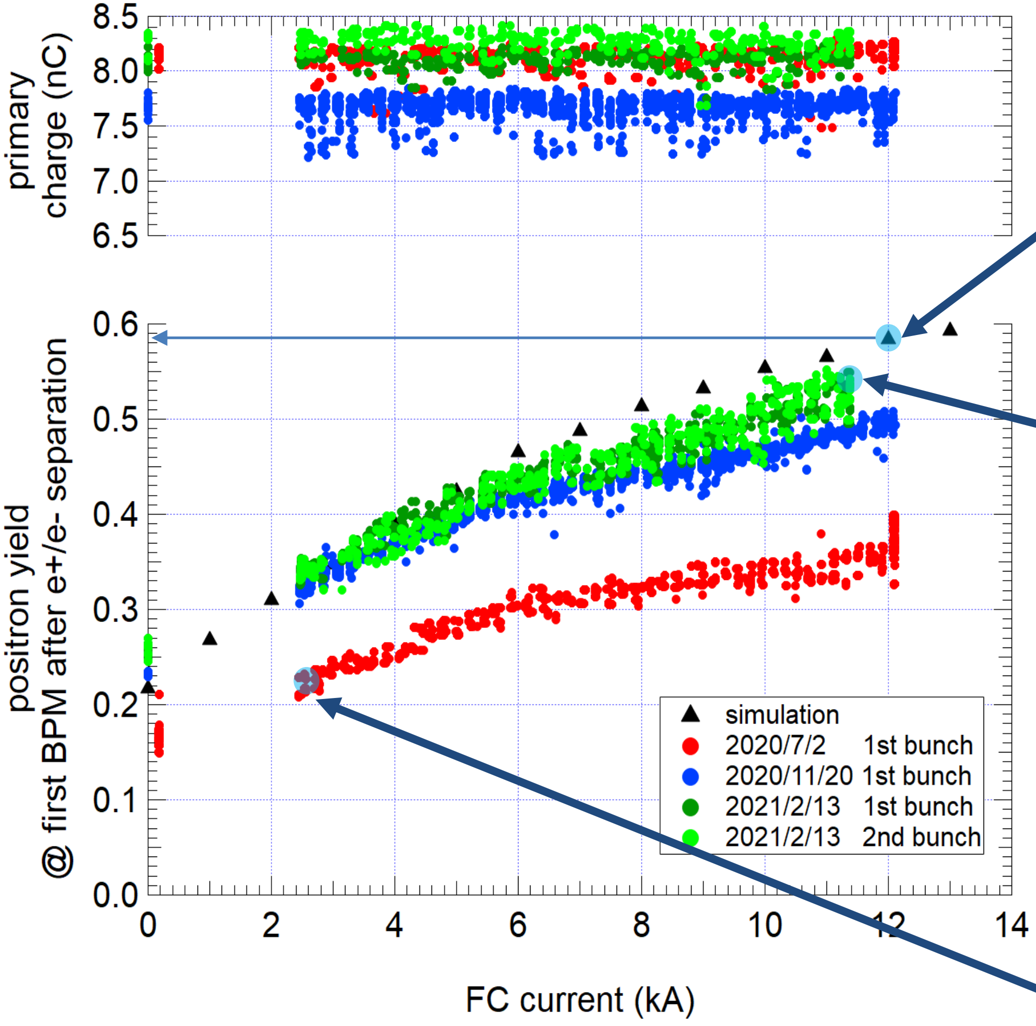
- Update from previous B2GM (2021/2 = before 2021a)
  - Charge is increased by beam adjustment
    - No hardware change
    - 5.4 nC after target, linac end 2.9 nC with primary electron charge of 9.6 nC
- Future upgrade for 4 nC
  - Improve target to DR transportation efficiency
    - 1-5 acceleration gradient is half than design.
      - Dummy load problem => Improved dummy load development is on going (Ego)
    - Pulse magnet installtion
      - Increase pulse steering (2021)
      - Replacement from DC Q to pulsed Q (2022)
  - Positron generation efficiency improvemnet
    - Increase the FC current (Upgrade the power supply by RF group at 2022)
  - Primary electron (Injector)
    - Limited by PF dark current
    - Test plan for the maximum charge of primary electron at 2021/7

SuperKEKB positron source

FC head + BC + target = FC assembly



Positron yield vs FC current

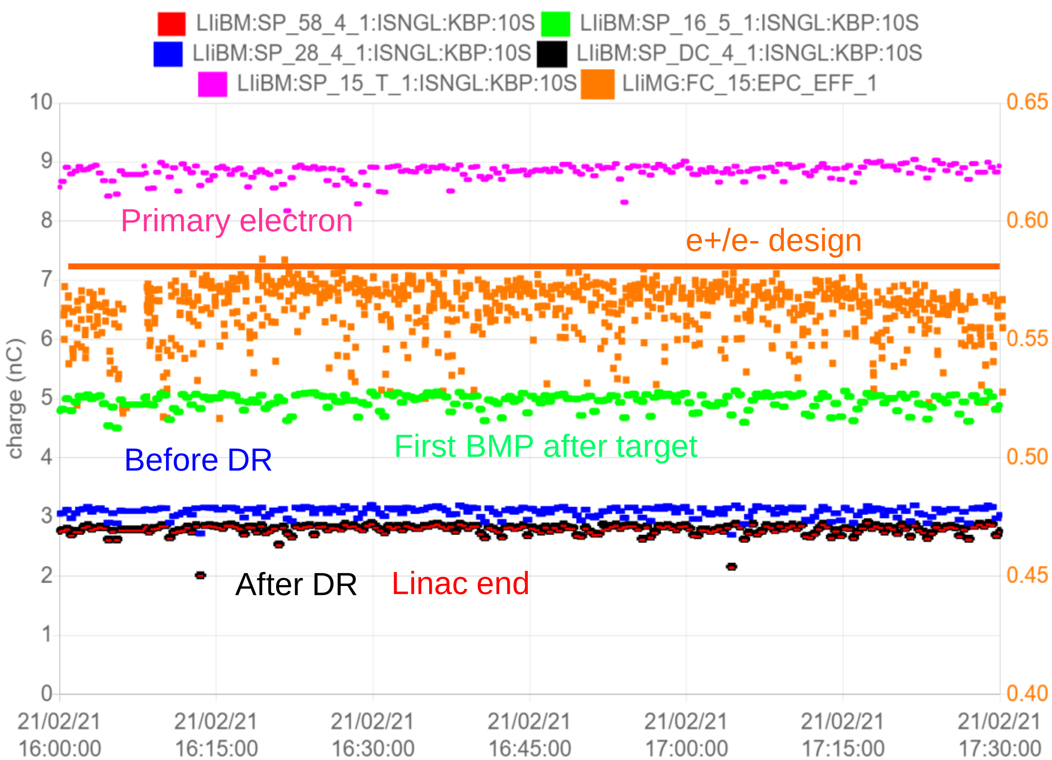


Design (0.58)

Present
(Further tuning was done after this measurement. Now the yield almost reached design value. See next page)

Before upgrade
(To avoid discharge,
FC current was limited very low)

Recent status (2021ab)



- Primary beam
  - 96% (9.6 nC / 10 nC)
- Positron yield（e+/e-）
  - 100% (0.58 / 0.58)
- transport
  - Target to DR
    - Should be improved
  - DR to Linac end
    - Little loss

Hardware upgrade (→ 2020c)

Further beam tuning (→ 2021a)

	design	2020ab	2020c	2021a	2021b
Energy (e-)	3.5 GeV	3.5 GeV	3.5 GeV	**3.5 GeV**	**3.5 GeV**
primary charge (e-)	10 nC	8.4 nC	8 nC	**9 nC**	**9.6 nC**
e+/e-	0.58	0.24	0.51	**0.58**	**0.58**
e+ @ first BPM after the target	5.8 nC	2.0 nC	4.1 nC	**5.1 nC**	**5.4 nC**
e+ @ before DR	-	1.6 nC	2.5 nC	**3.2 nC**	**3.3 nC**
e+ @ after DR	-	1.4 nC	2.1 nC	**2.9 nC**	**3.0 nC**
e+ @ Linac end	4 nC	1.4 nC	2.1 nC	**2.9 nC**	**2.9 nC**

Transport optimization is not sufficient

Gradient after the target

name	Design gradient (MV/m)	Operation gradient (MV/m) 2020/10/30	Max gradient @ KLY power = 40 MW
AC_15_1	14.0	7.3	17.0
AC_15_2	14.0	7.3	17.0
AC_16_1	10.0	**11.3**	12.2
AC_16_2	10.0	**11.3**	12.2
AC_16_3	10.0	**11.3**	12.2
AC_16_4	10.0	**11.3**	12.2

Data from H. Ego

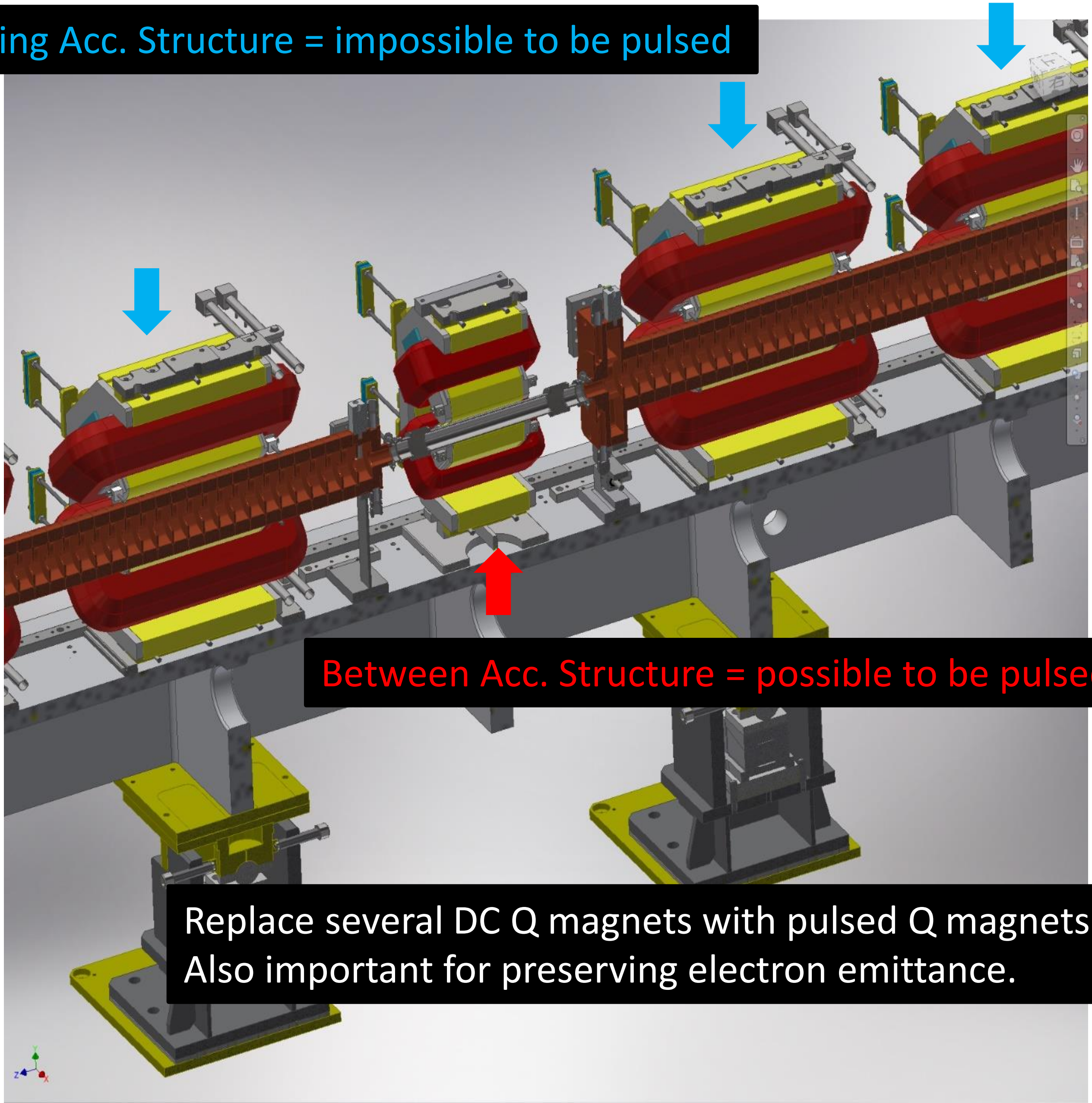
Table 3: Structure Parameters

Item	LAS
Frequency MHz	2856
# of regular cells	57
Active acc. Length [mm]	2064.40
Flange-flange length [mm]	2191.01
Beam hole dia. (2a) [mm]	31.9-30.0
Group velocity v_g/c [%]	4.2 – 3.5
Shunt impedance [MΩ/m]	46 – 48
Attenuation parameter τ	0.121
Filling time [ns]	185
Maximum E_p / E_{acc}	2.42
Input coupler iris	J-type Double
Output coupler iris	Double
Cell machining tool	Diamond
Coupler fabrication	Brazing
Assembly technology	Vacuum brazing
Cooling passage	Four channels

Due to the load problem, gradient of the first and second acc. structure after the target is low.
This may cause poor bunching which can be one of the reason for large beam loss during transportation to the DR.

https://www.pasj.jp/web_publish/pasj2014/proceedings/PDF/SAP0/SAP045.pdf
https://doi.org/10.18429/JACoW-IPAC2014-THPRI047

Transport between Target and DR – replace DC Q with pulsed Q



Surrounding Acc. Structure = impossible to be pulsed

Between Acc. Structure = possible to be pulsed

Replace several DC Q magnets with pulsed Q magnets (2022〜).
Also important for preserving electron emittance.

Short term plans（1～2 years）

Major upgrade was done in 2020 summer shutdown
Increase positrons up to 4 nC by several minor improvements.
Now, it’s time to consider new strategy for long term goal.

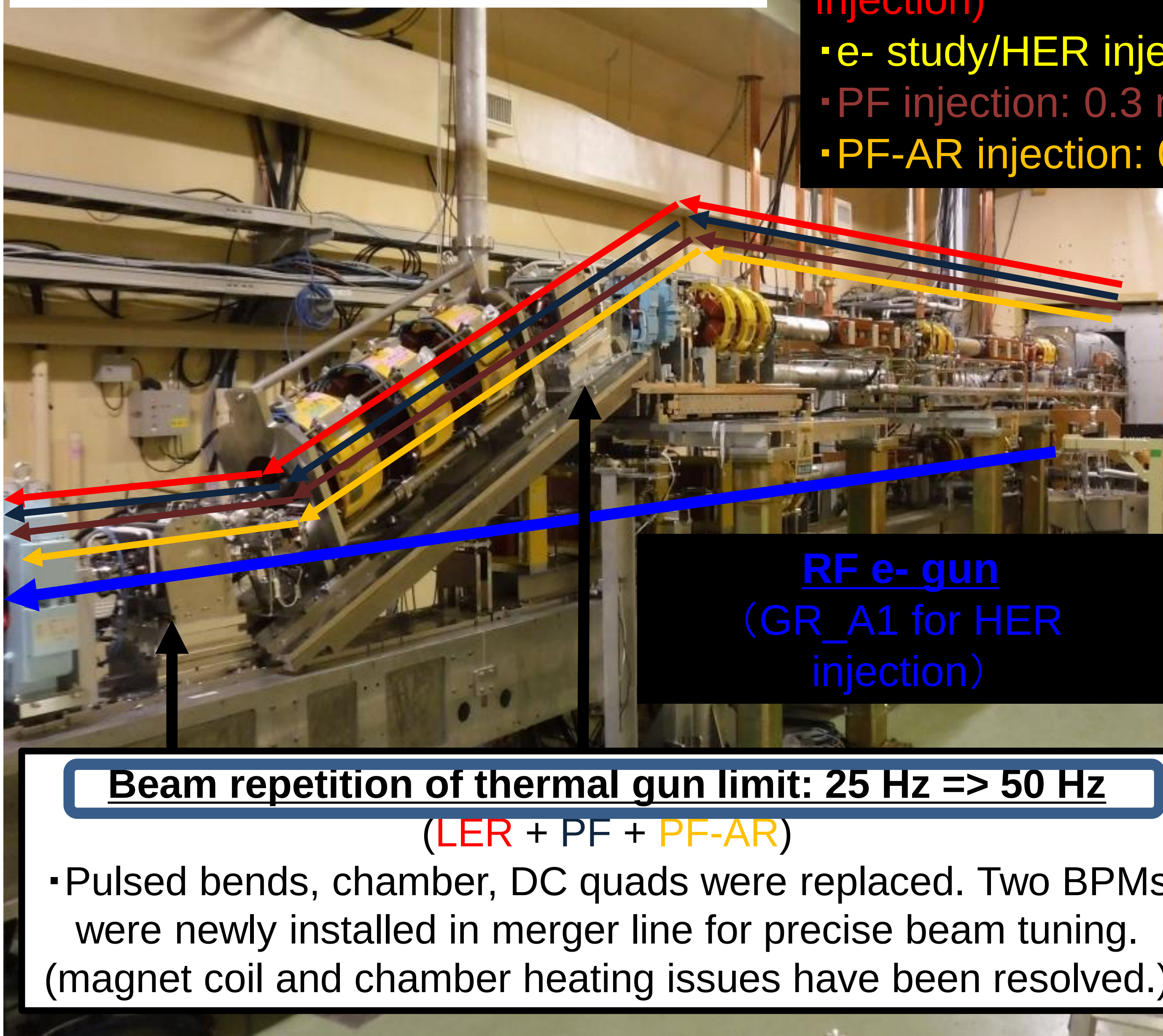
- Increase Acc. Gradient at 1-5 unit（H. Ego）
  - New load for the Acc. structure（under development）
- Install pulsed magnets between target and DR（T. Natsui、K. Yokoyama、Y. Okayasu、T. Kamitani、Y. Enomoto）
  - Increase steering magnets（2021）
  - Replace DC Q magnets with pulsed Q magnets（2022）
- Fast BPM （T. Suwada、F. Miyahara、A. Rehman）
  - Under test
- Increase FC current（RF group）
  - Thanks to new material, higher current operation may be possible.
    - Stable operation has been confirmed up to13 kA at test bench.
  - Upgrade of the power supply is necessary（2021～）
- Increase primary electron charge（Yoshida）
  - It’s not difficult to increase current by increasing heater current
  - Dark current to the PF ring issue have to be solved

Electron generation

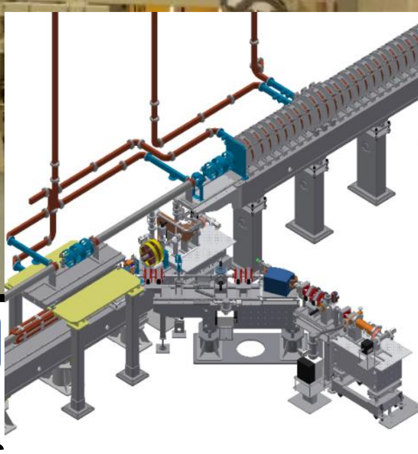
Pulse to pulse switching: rf e- gun/thermionic e- gun

Thermionic DC e- gun (GU_AT)
w/ 2 subharmonic bunchers and 2 bunchers

- e+ production e-: 10 nC (for LER injection)
- e- study/HER injection: 2 nC
- PF injection: 0.3 nC
- PF-AR injection: 0.3 nC



RF e- gun
(GR_A1 for HER injection)

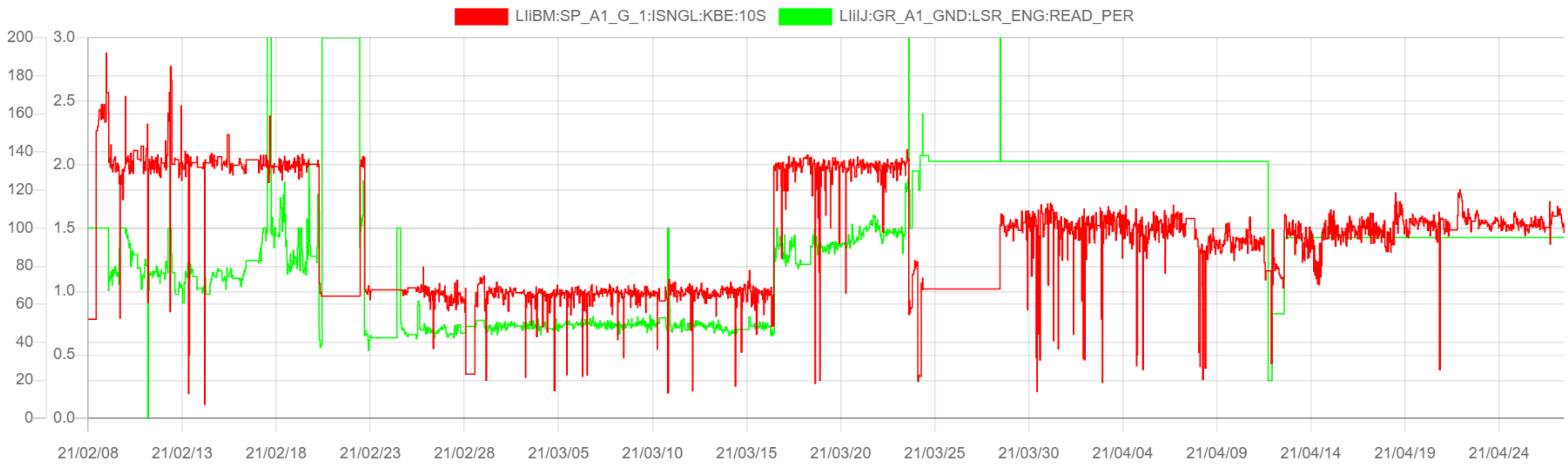


Beam repetition of thermal gun limit: 25 Hz => 50 Hz
(LER + PF + PF-AR)

- Pulsed bends, chamber, DC quads were replaced. Two BPMs were newly installed in merger line for precise beam tuning. (magnet coil and chamber heating issues have been resolved.)

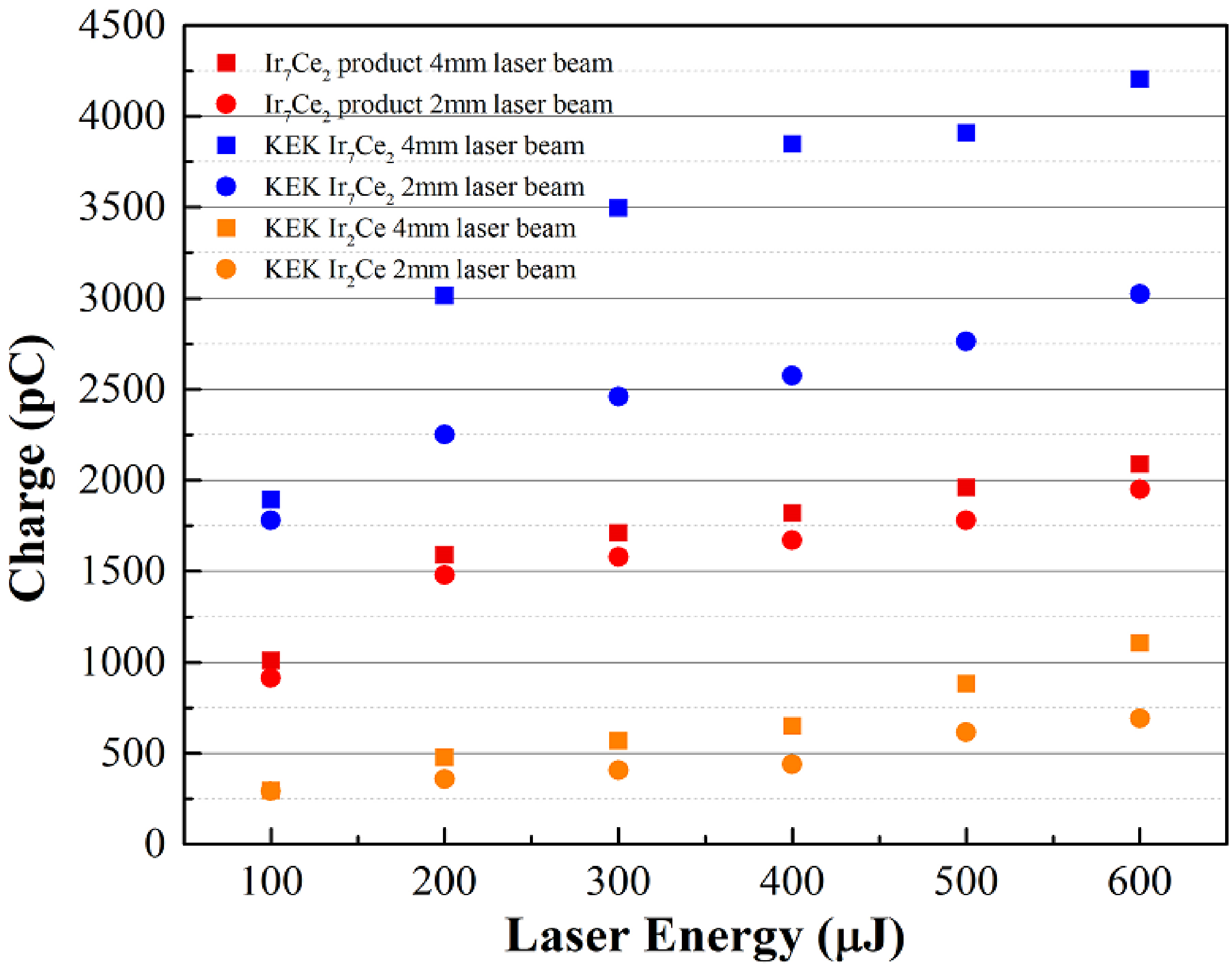
RF-Gun

- Newly improved Ir_7Ce_2 cathode keeps to generate 2 nC electron without cleaning.
  (QE was decreased by human error at the end of March, and currently 1.5nC by one side laser.)

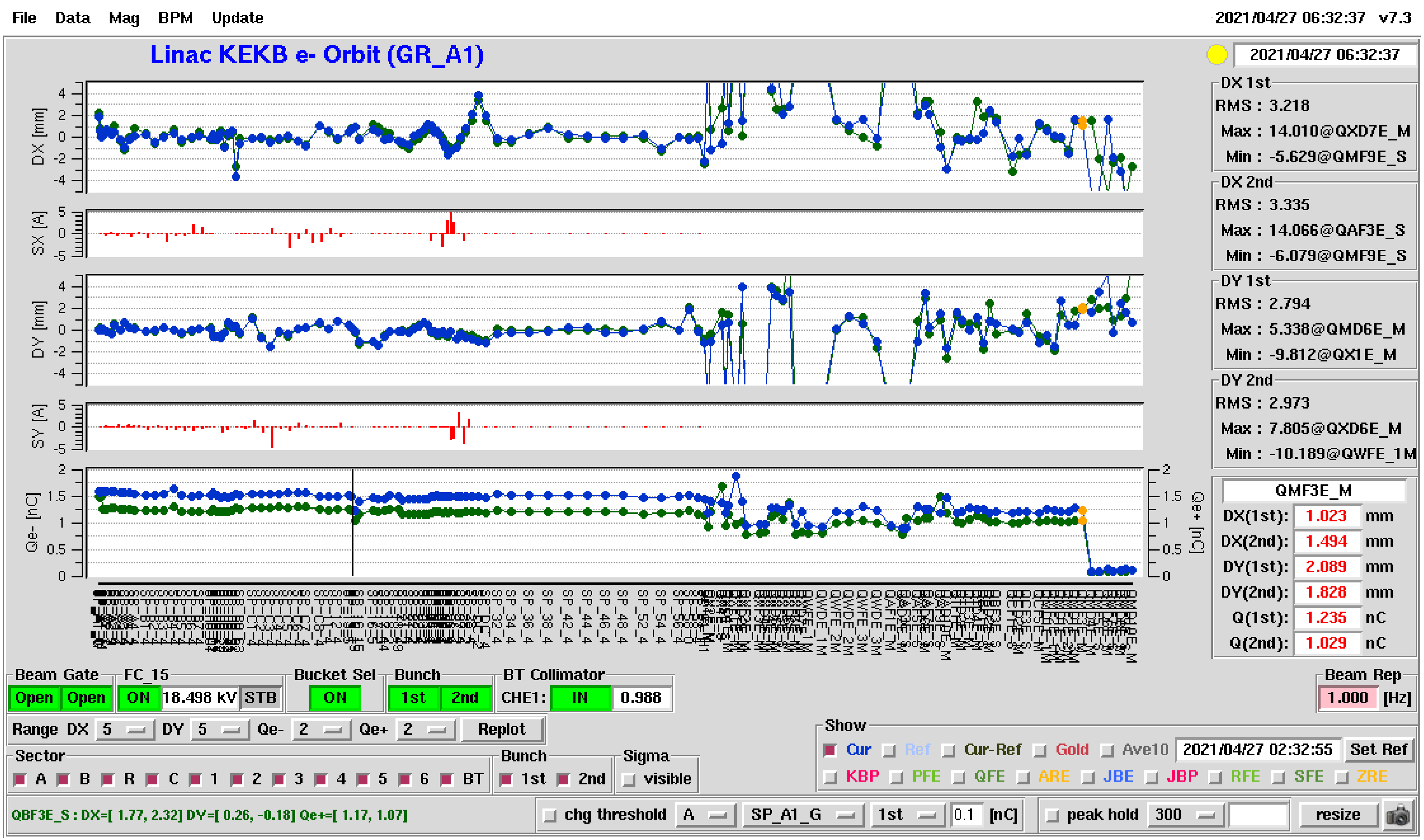


- Stable operation with low field operation
  (Es=35.5kV, 866ns)

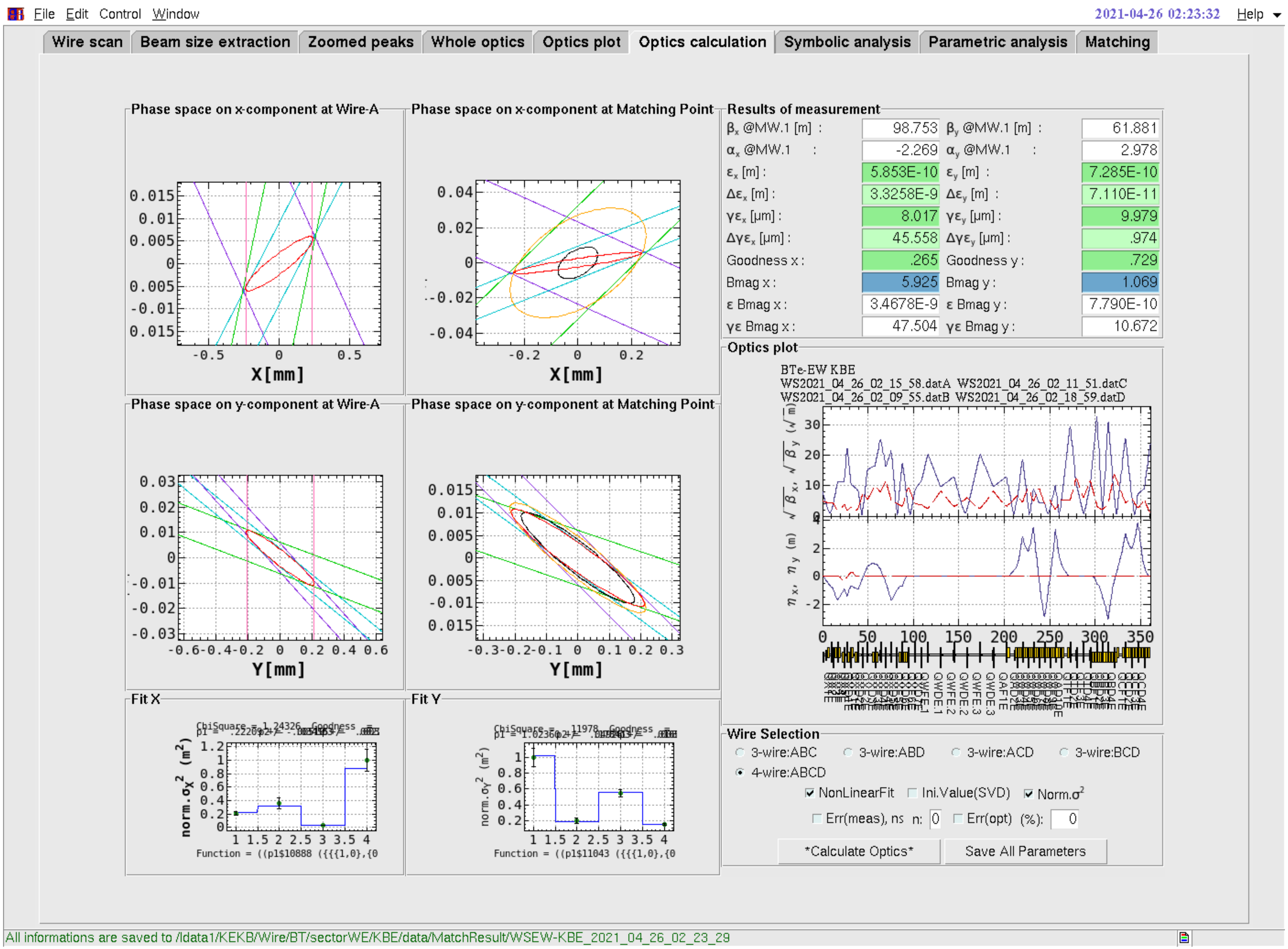
Quantum efficiency of IrCe



2-bunch (Es=35.5kV, 866ns)



Wire scanner (BT) 4/26 lowest emittance

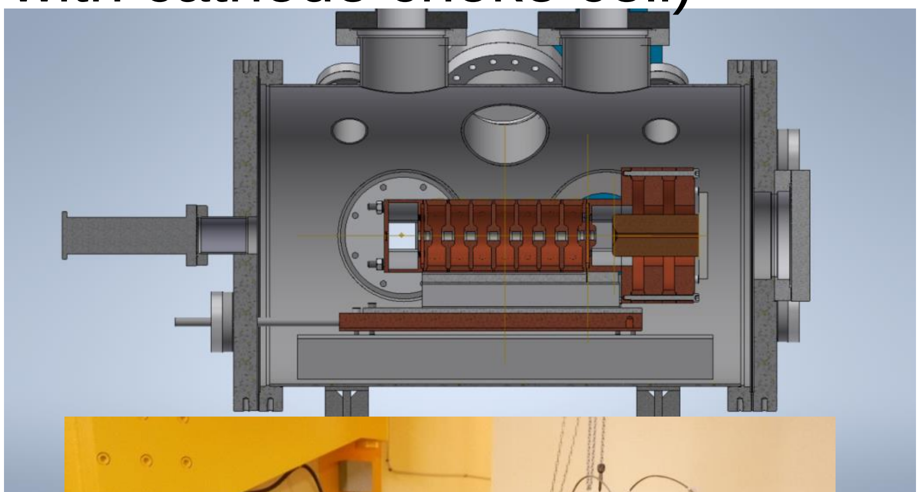


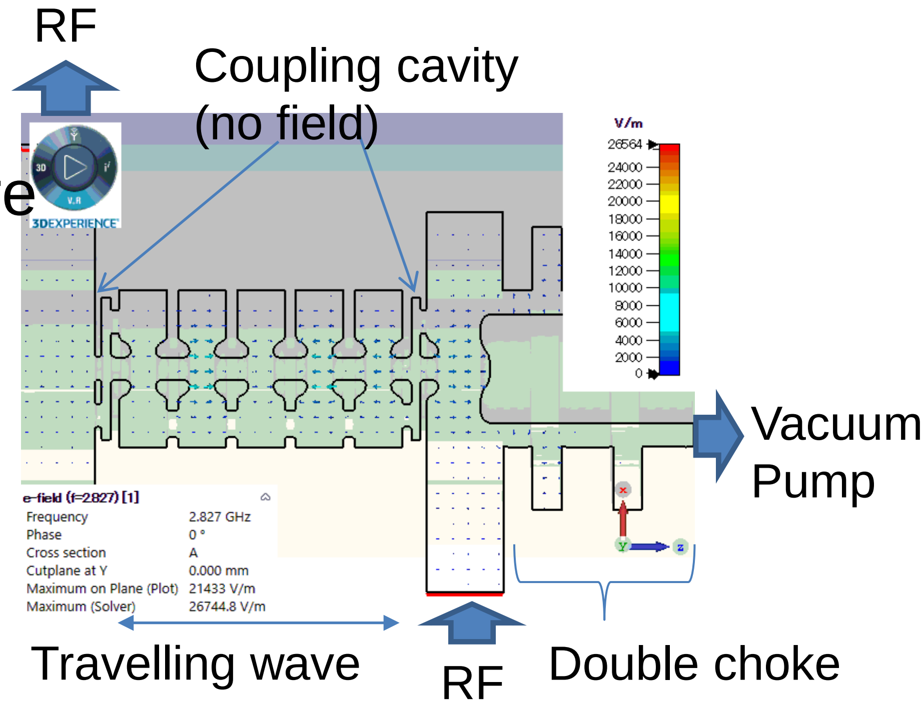
Future upgrade of RF-Gun for 4 nC

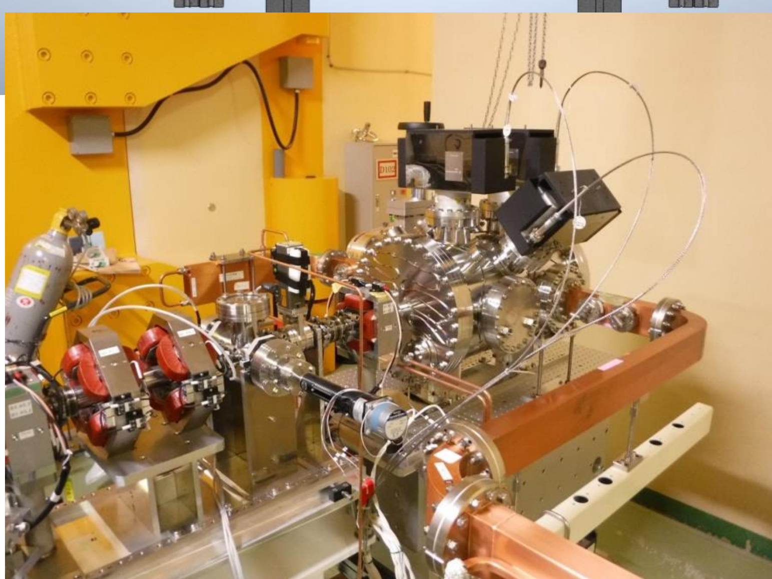
- New RF-Gun cavity
  - Vacuum improved and short pulse RF-Gun (Travelling wave cut disk structure with cathode choke cell)
- Improve IrCe cathode
  - KEK made Ir_7Ce_2 cathode
  - Development of the cleaning method
- Laser upgrade
  - Power up and DOE installation of 2^{nd} laser
  - Yb:YAG rod laser for lower energy spread
- Laser upgrade
  - Power up and DOE installation of 2^{nd} lase

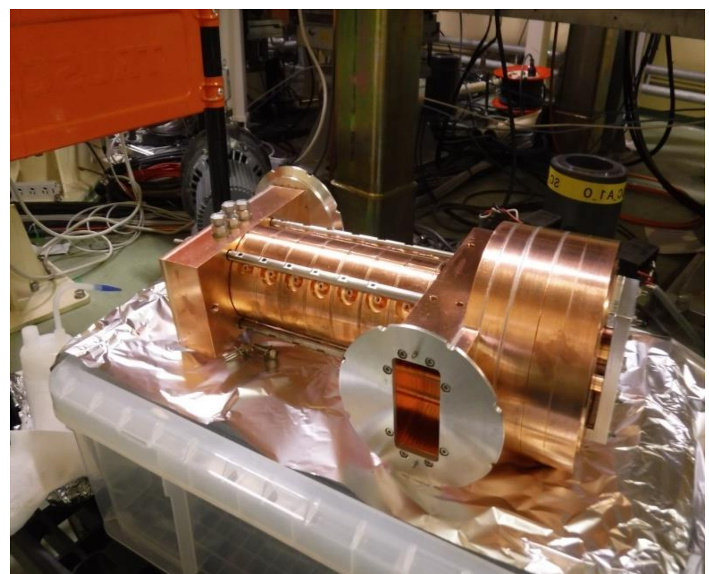
New RF-Gun cavity

Vacuum improved and
short pulse RF-Gun
(Travelling wave cut disk structure
 with cathode choke cell)



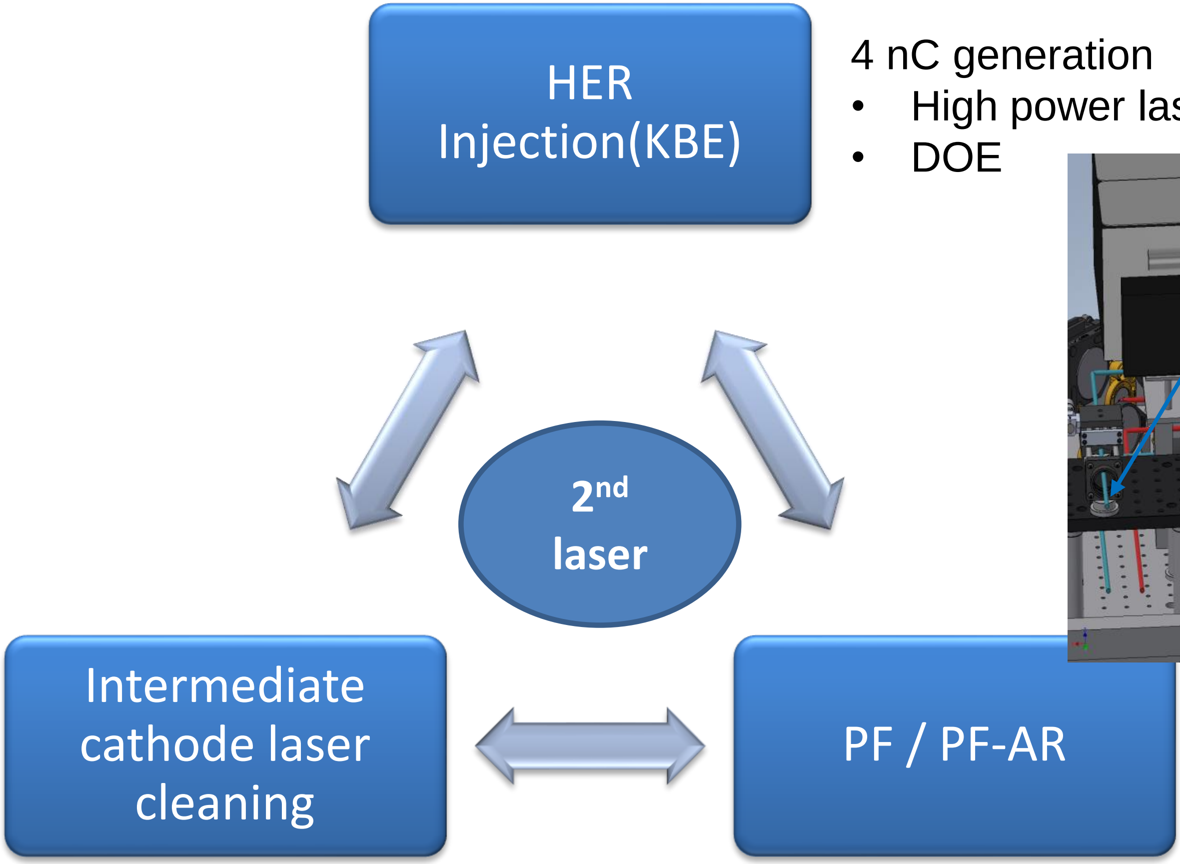






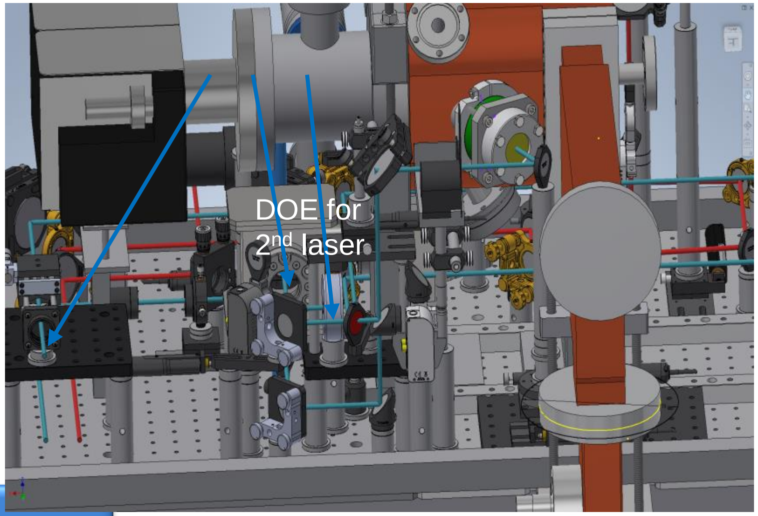
Laser upgrade of FY2021

- Higher power and multi-purpose usage of 2nd laser



4 nC generation

- High power laser module (15kW pump)
- DOE



Thermal electron gun can be optimized for positron generaion.

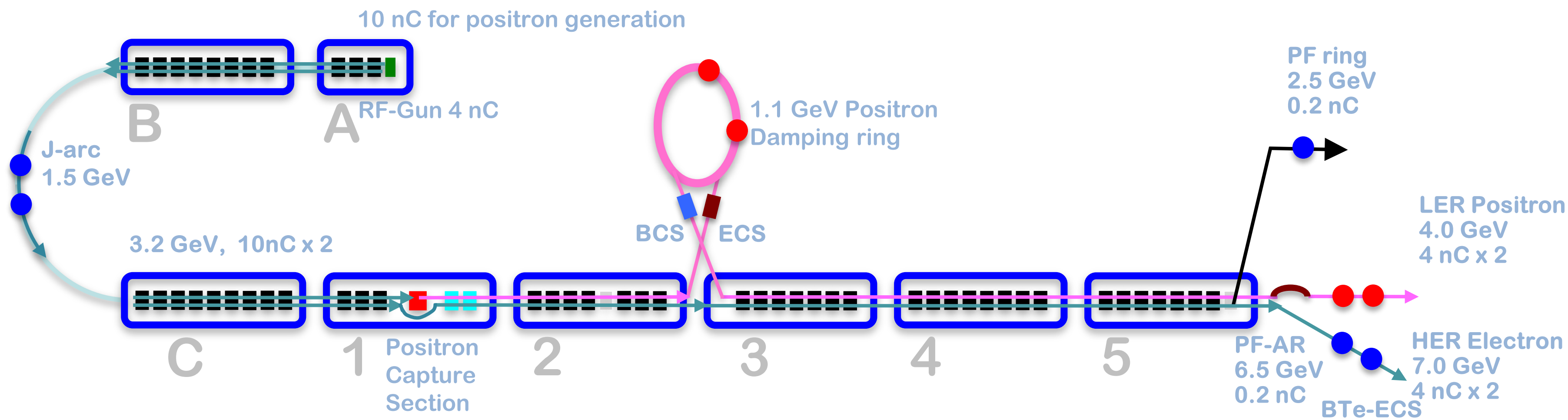
- Yb:YAG rod laser for lower energy spread
  => Lower emittance and energy spread

Future LINAC upgrade plan

Challenges in Linac upgrade

- Achieving the both of higher injection beam charge and lower transverse/longitudinal emittance
- Maintaining higher availability and stability
- Establishing injection energy for higher resonances
- Solutions with upgraded hardware
  - Precise pulsed magnets and kickers
  - Movable girders for quads and structures
  - Energy compression system (ECS)
  - Accelerating structures to replace aged ones
  - Low emittance and high charge RF gun
  - High efficiency positron capturing
  - Replacement of capacitors including PCB at power converters
- Polarized electron beam design for the future

Upgrade plan (2022 – 2026)



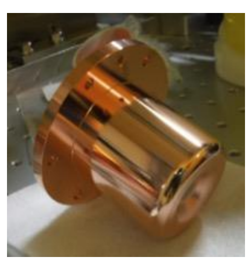
Injector **BT**

Fast pulsed kicker

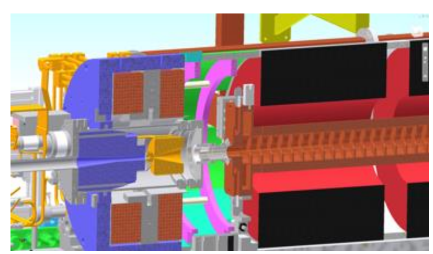
Mover

PCB capacitor replacement

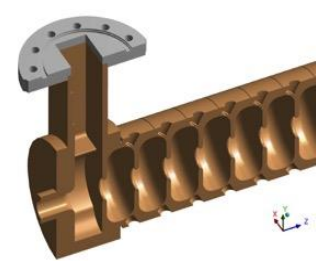
Electron-ECS



RF-Gun upgrade



Positron capture section



Accelerating structure replacement

Summary

- Recent injection
  - HER:
    - 1.5nC injection for lower emittance and higher injection efficiency
    - 2nd-bunch injection efficiency is low (Beam blow up at 1-sector)
  - LER:
    - 2nC injection and 2-bunch injection is stabele
    - 23Hz injection is ready to use
- Short term upgrade for 4nC generation
  - LER : New RF-Gun and laser upgrade
  - HER : High efficiency positron capturing
  - Transportation upgrade (pulse steering etc,.)
- LINAC upgrade 2022-2026
  - Precise pulsed magnets and kickers
  - Movable girders for quads and structures
  - Energy compression system (BTe-ECS)
  - Accelerating structures to replace aged ones
  - Replacement of capacitors including PCB at power converters