Injector challenges

2020.2.10

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for Injector Linac Group

14th annual Belle PAC Review meeting, Feb. 10-12, 2020

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- Injector operation status
- e- and e+ beam sources
- Accelerating structures
- Beam controls
  - Energy and orbit feedback loops
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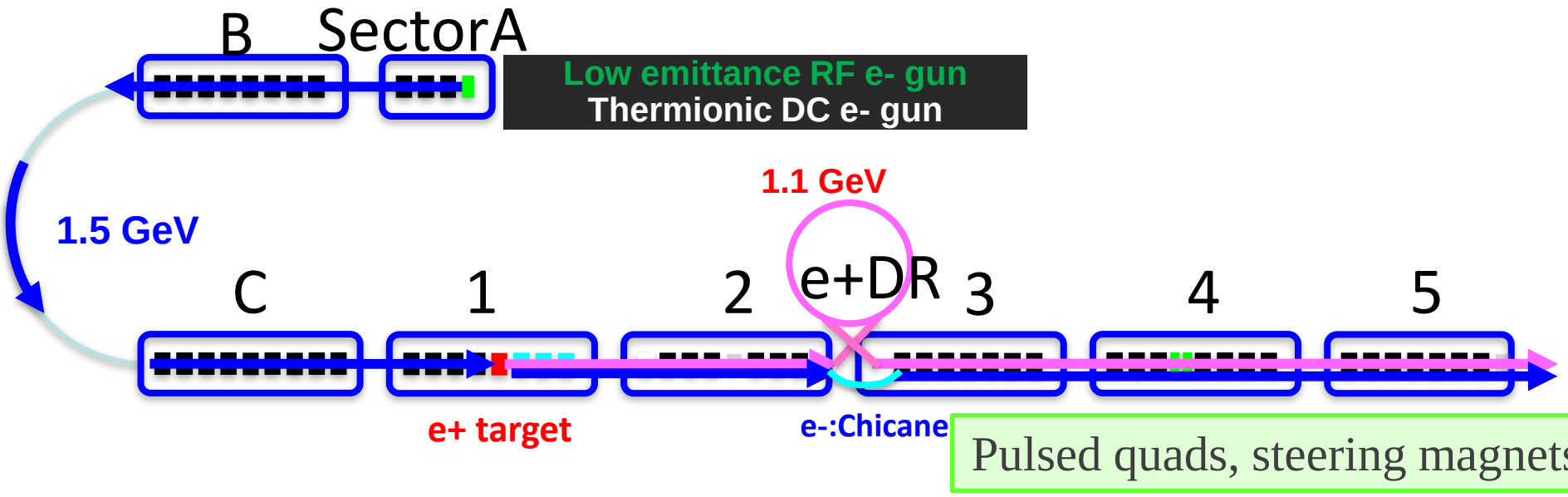
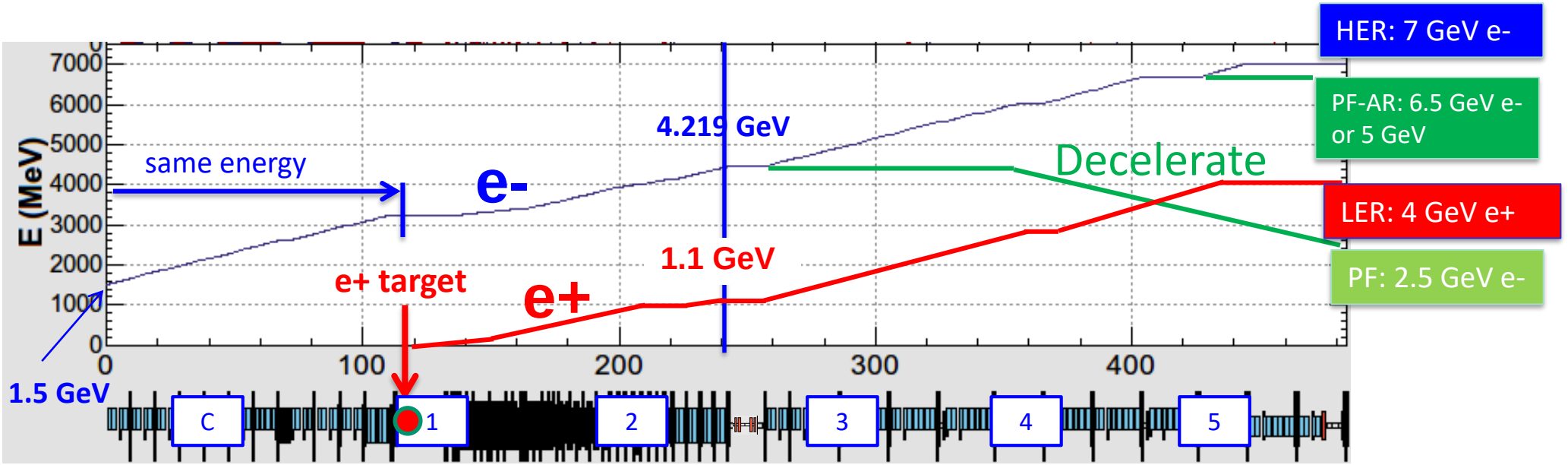
Linac Beam Parameters for KEKB/SuperKEKB

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	2	primary e- 10 → **4**	**4**
Norm. Emittance (γβε) (μmrad)	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)	

Injector overview

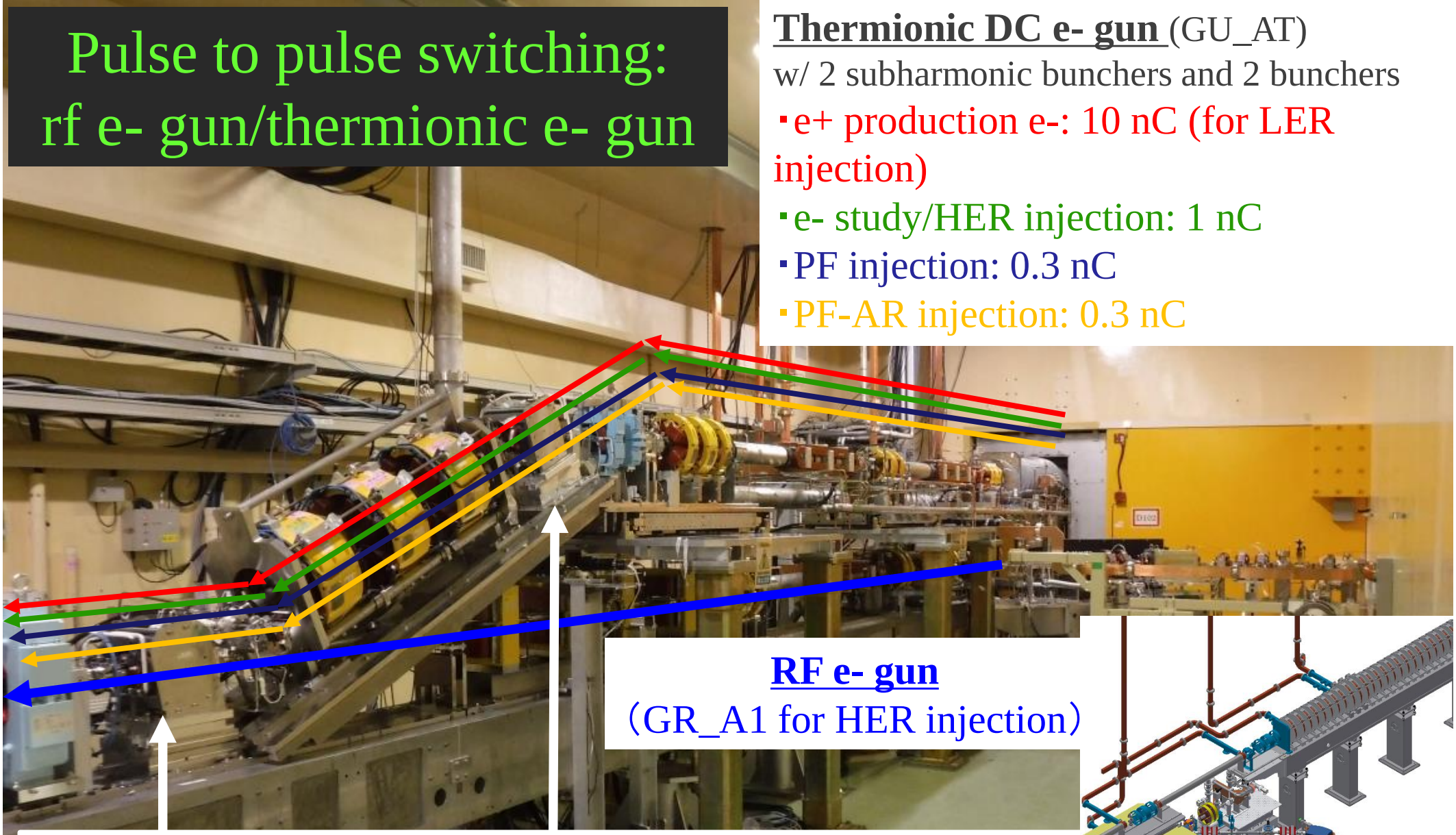
- Photocathode RF gun for HER injection
- Thermionic gun for LER, PF, PF-AR





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: 1 nC
- PF injection: 0.3 nC
- PF-AR injection: 0.3 nC

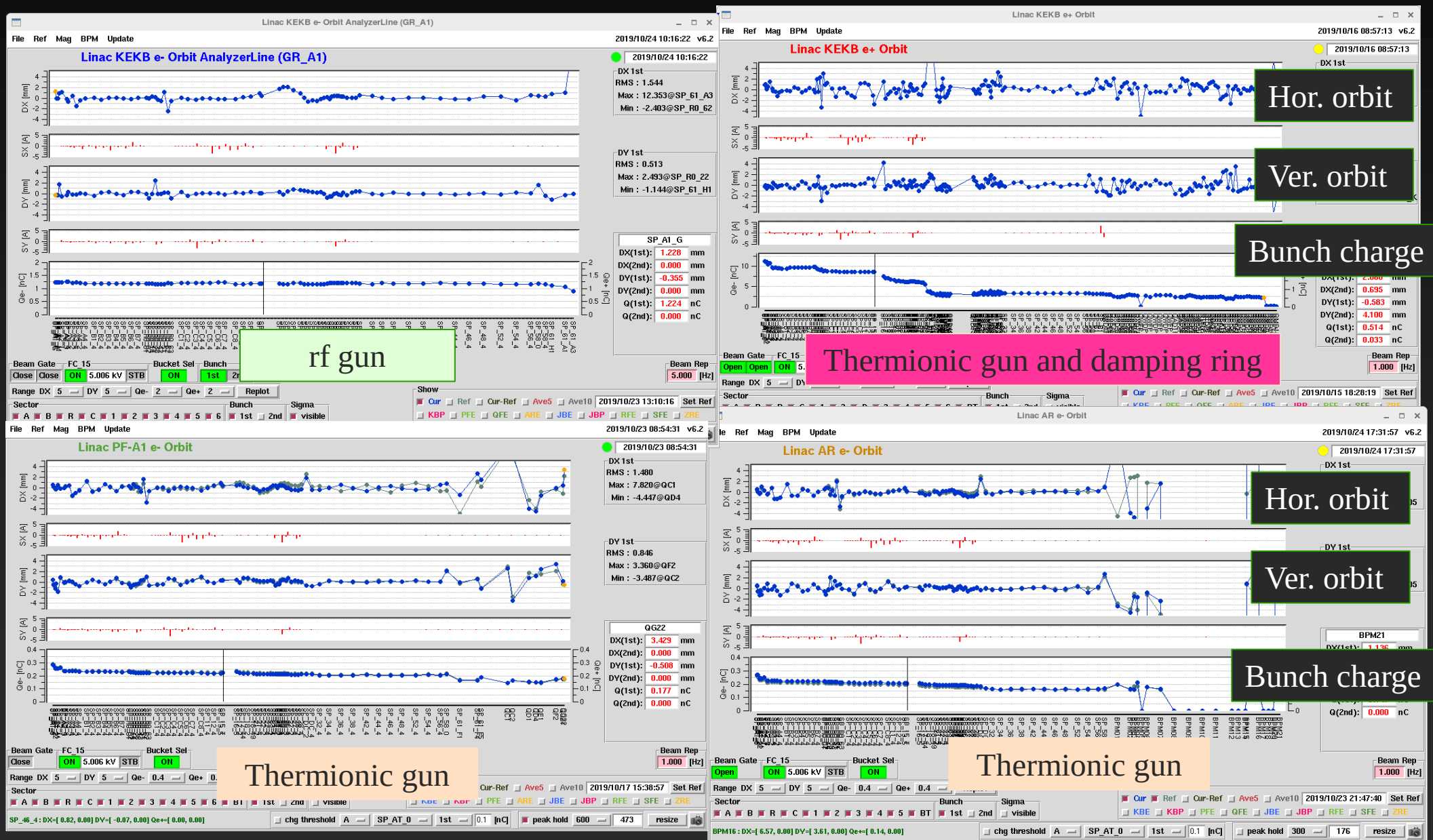


RF e- gun
（GR_A1 for HER injection）

Pulsed bend rep. up to 25 Hz (LER + PF + PF-AR)
(magnet coil and chamber heating issue)
It will be replaced by new one in summer shutdown 2020.

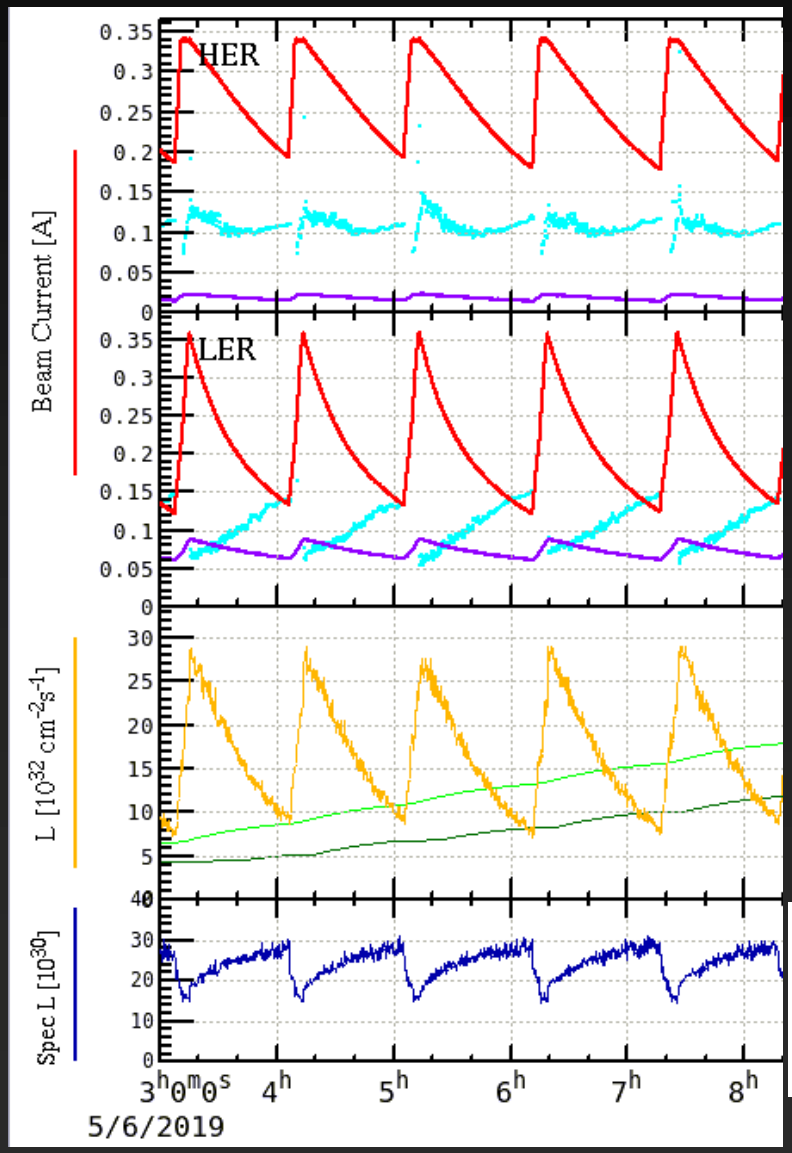
Simultaneous beam operation (w/ thermionic and rf e- gun)

- Stable simultaneous top up injection to 4 storage rings (HER, LER, PF, and PF-AR) w/ thermionic gun, rf gun, pulsed magnets.



Simultaneous Top-up Injections

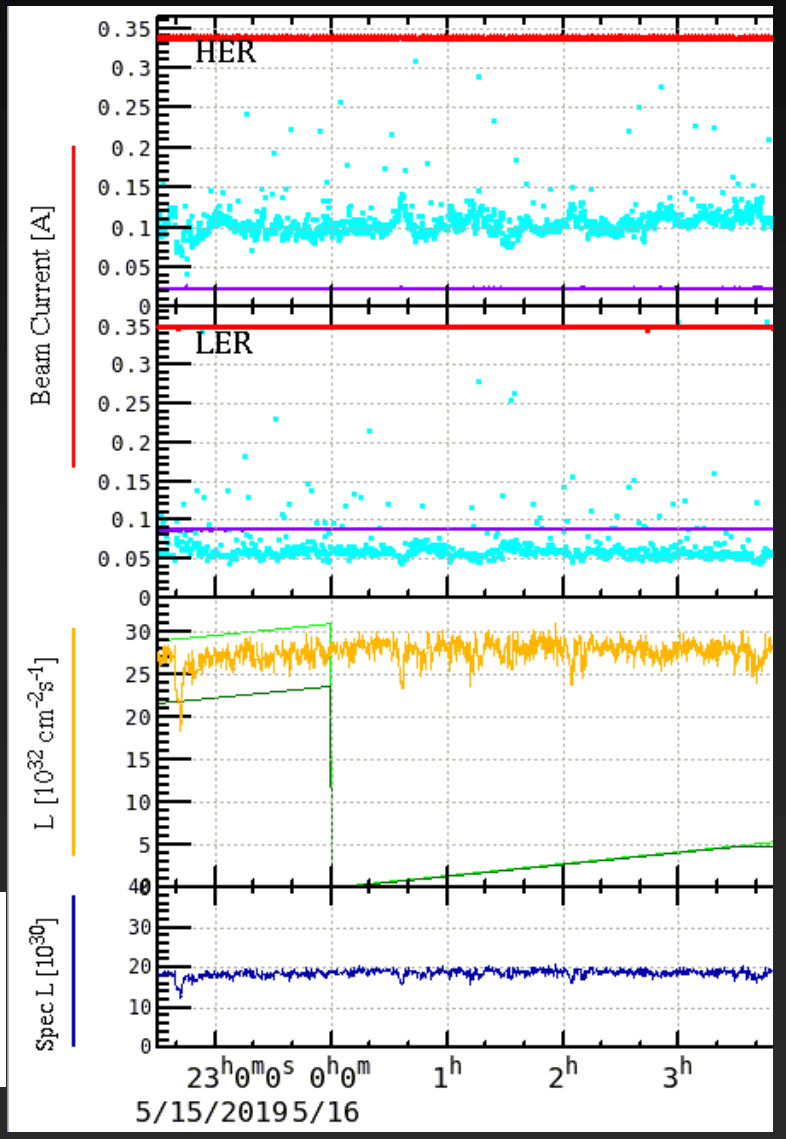
- SuperKEKB integrated luminosity improvement



17.5 /pb in 5.15 hr
(5 fills)
on May. 6

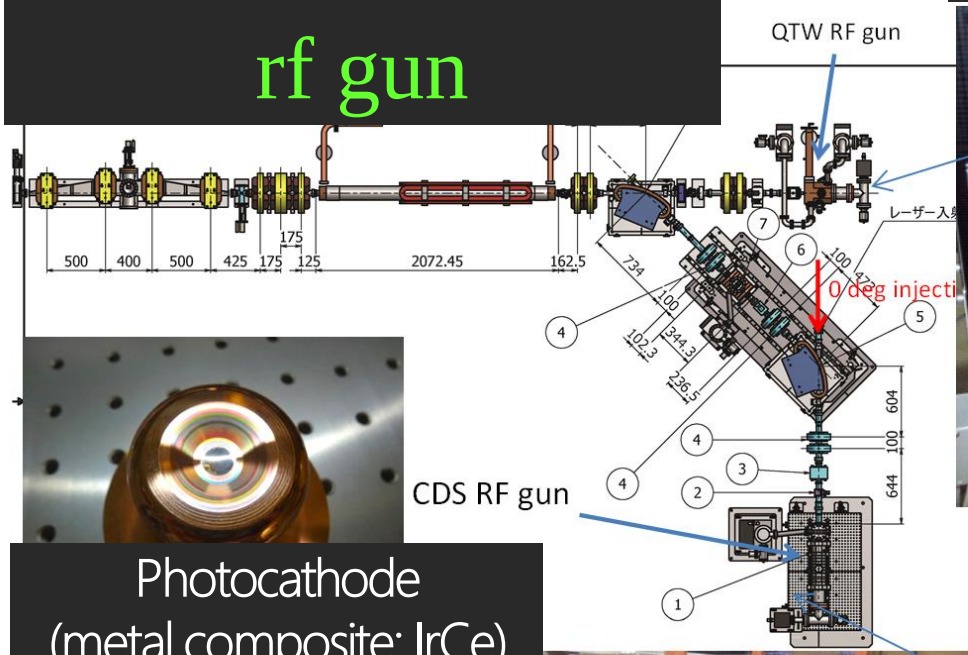
41.6 /pb in 5.15 hr
(top-up)
on May. 16

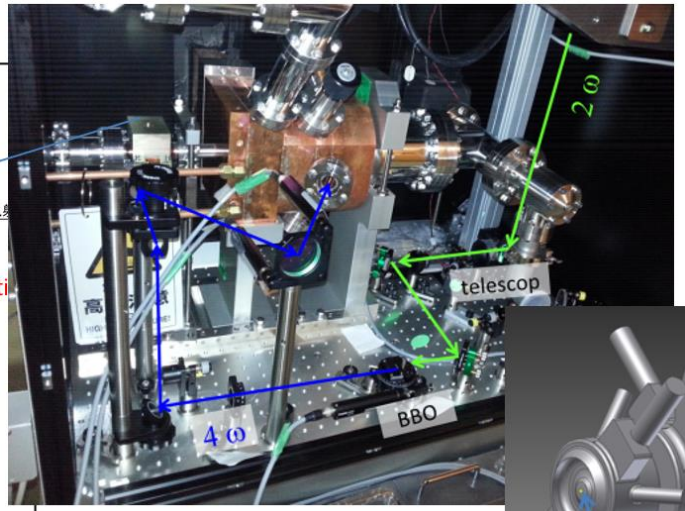
237%
improvement

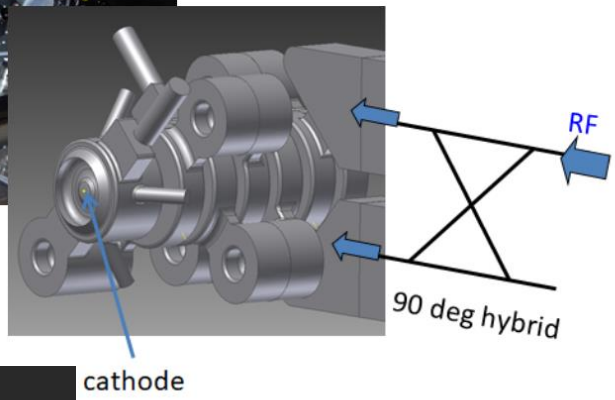


Low emittance rf gun

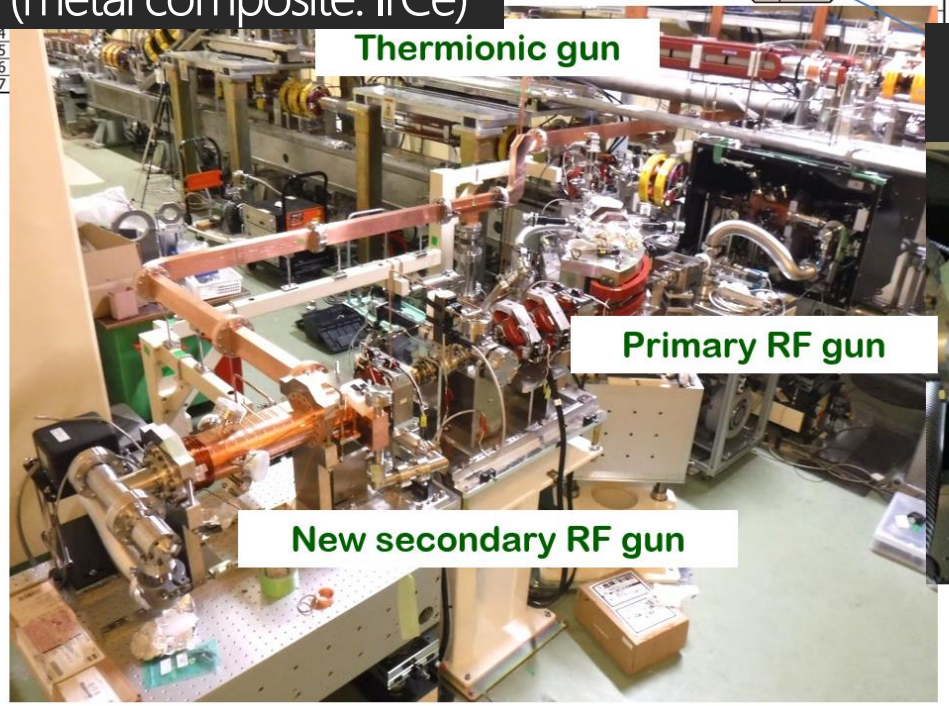
QTW RF gun or operation (0 deg. Line)







Photocathode
(metal composite: IrCe)

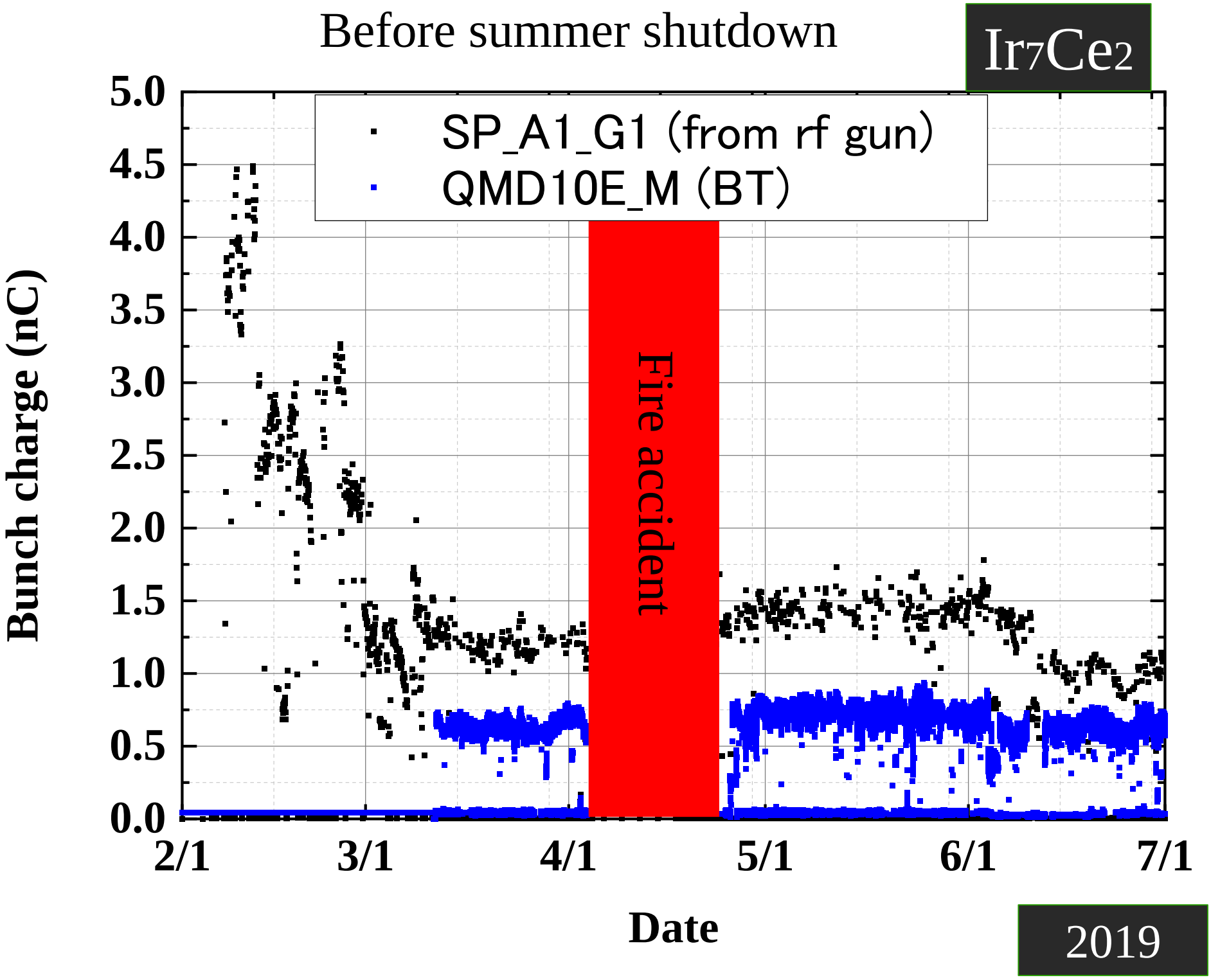


CDS RF gun
for backup (90 deg. Line)

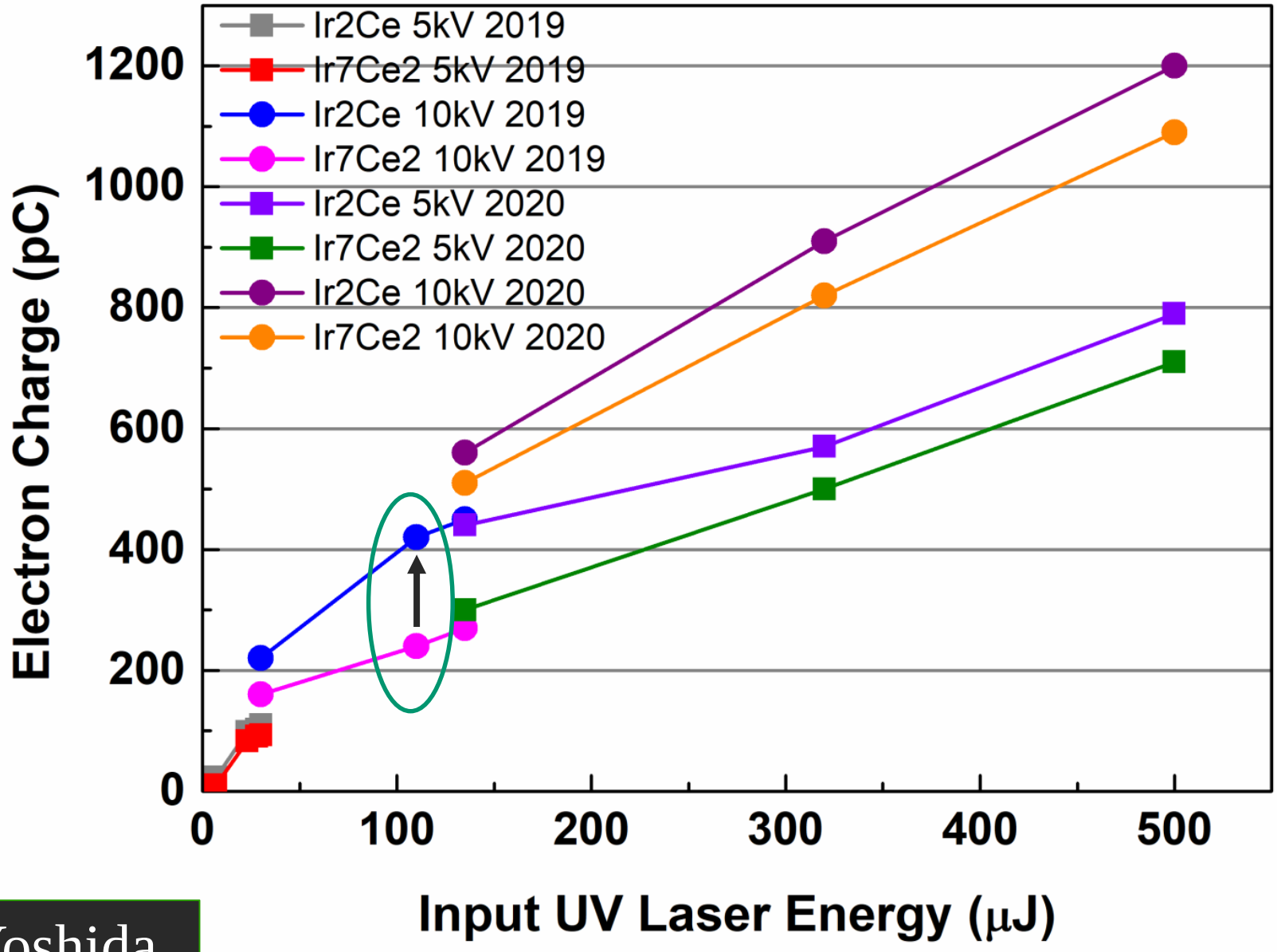
- Yb-doped-fiber and Nd/Yb:YAG laser
- IrCe cathode
- QTWSC or cut disk cavities

HER injection beam (rf e- gun) status

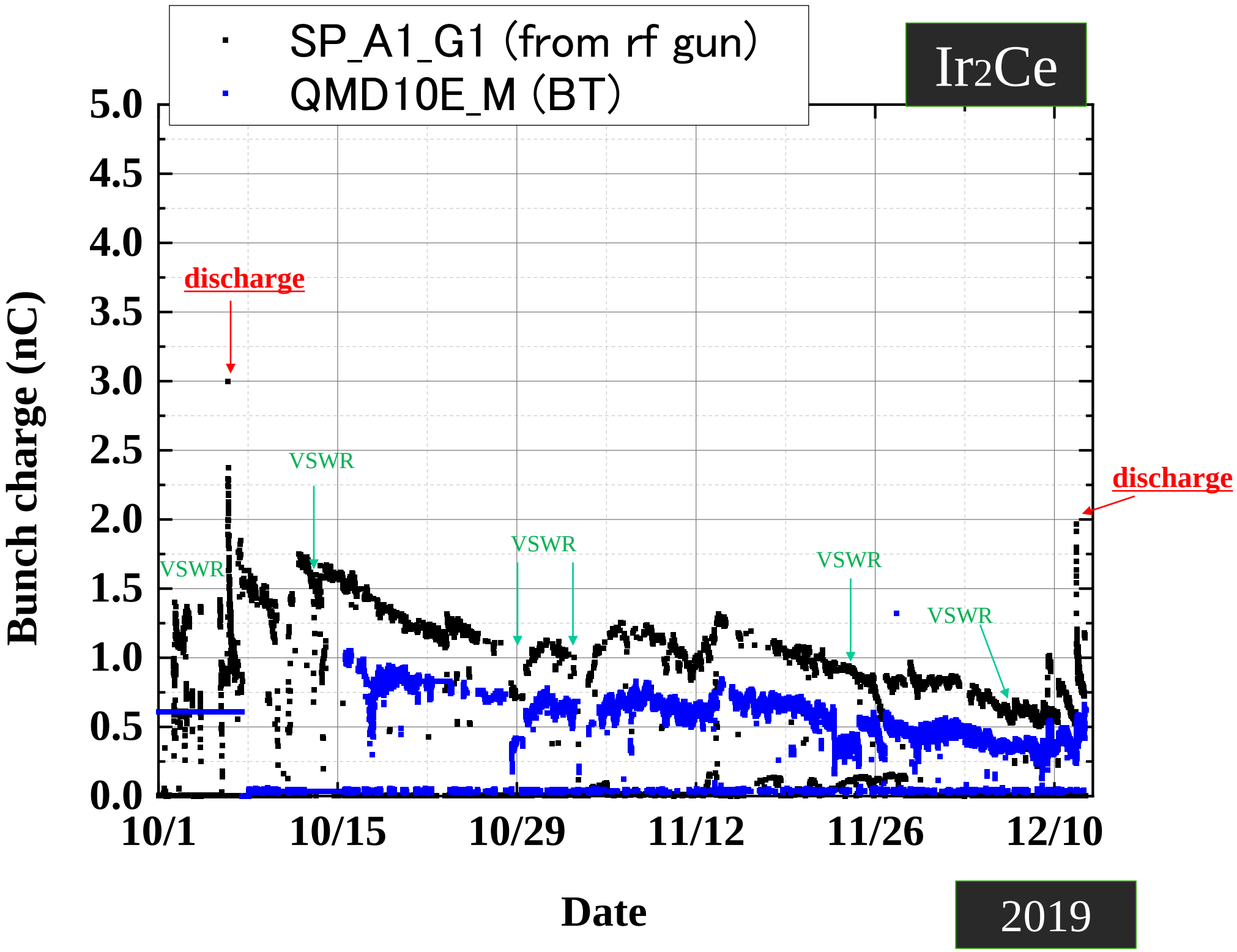
- HER injection has been done w/ only rf gun from PhaseIII day 1. (Mar. 11^{th} , 2019)
- Laser system has no significant fault.
- In summer shutdown of 2019, photocathode (Ir_7Ce_2) was replaced by new one (Ir_2Ce) for aiming at better quantum efficiency (Qe).
  - Discharge, frequent VSWR, gradual decrease of bunch charge
- In this winter shutdown,
  - Even after applying thermal cleaning of cathode, bunch charge is not stable.
  - Finally, photocathode was replaced by previous one (Ir_7Ce_2) toward next run. Now, under rf conditioning.


Before summer shutdown
Ir7Ce2
SP_A1_G1 (from rf gun)
QMD10E_M (BT)
Fire accident
Bunch charge (nC)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
2/1
3/1
4/1
5/1
6/1
7/1
Date
2019

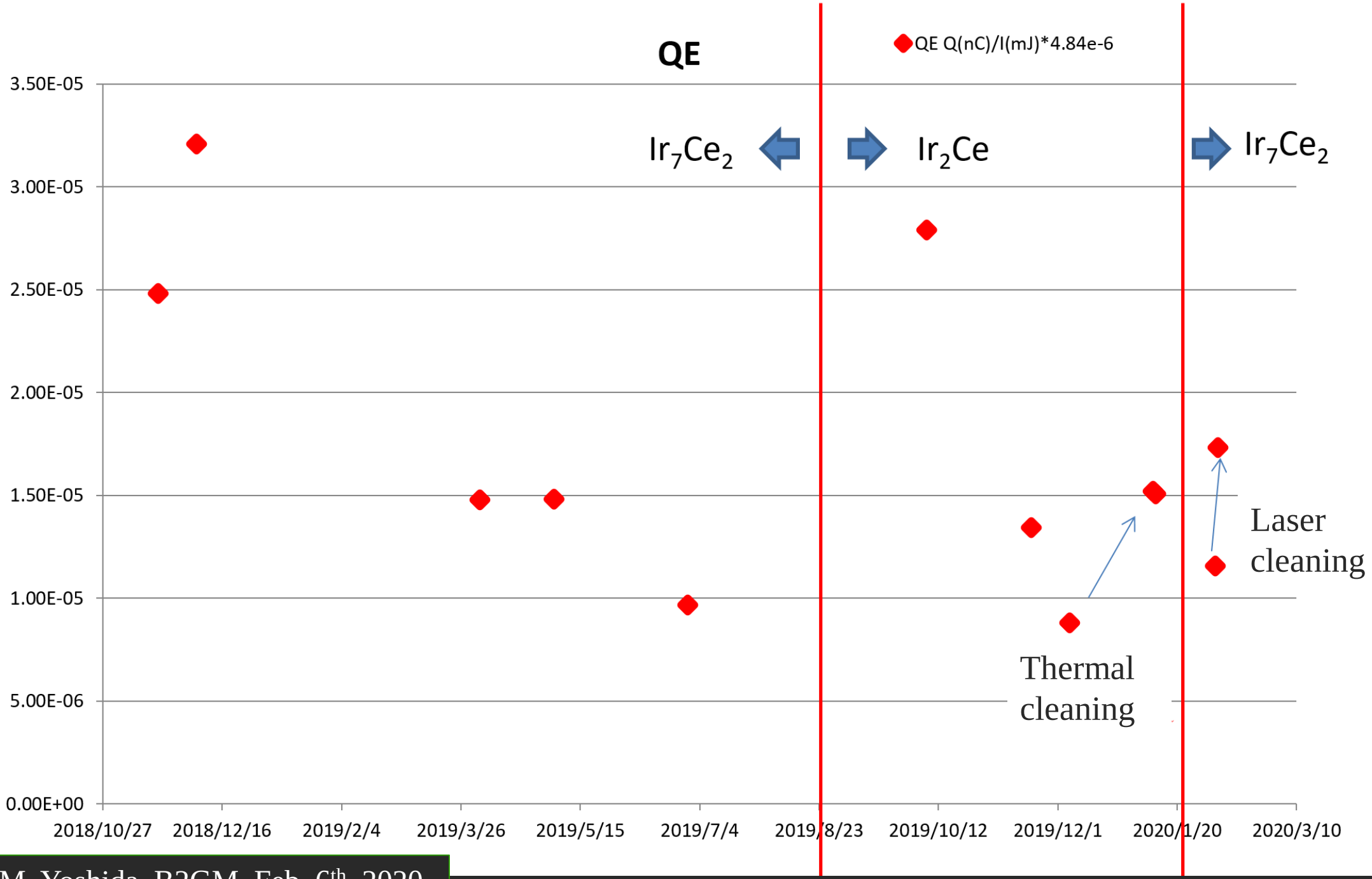
Qe of photocathode (Ir_7Ce_2, Ir_2Ce)



M. Yoshida

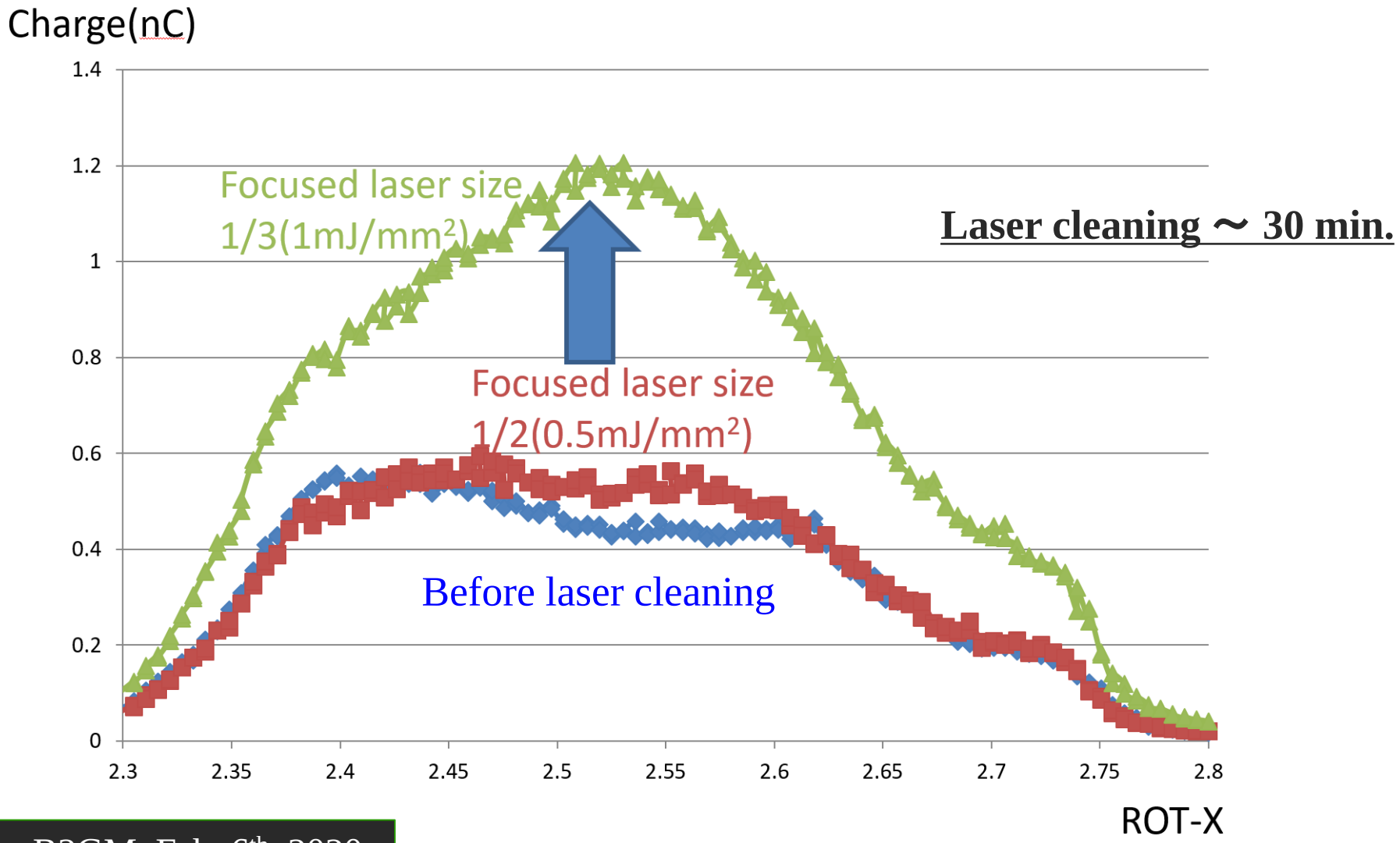

SP_A1_G1 (from rf gun)
QMD10E_M (BT)
Ir2Ce
Bunch charge (nC)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
discharge
VSWR
VSWR
VSWR
VSWR
VSWR
discharge
10/1
10/15
10/29
11/12
11/26
12/10
Date
2019

QE Comparison



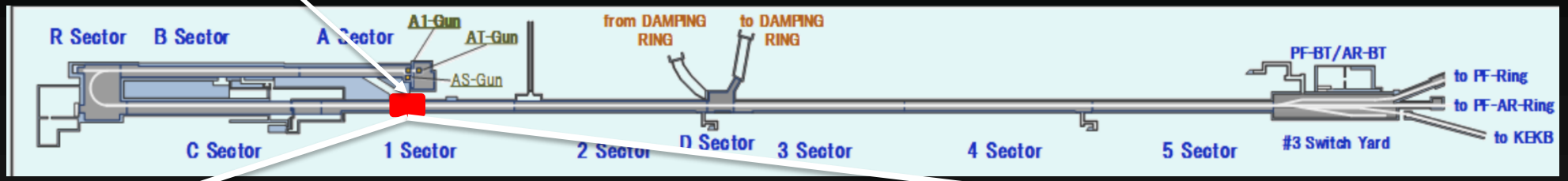
Laser cleaning / Focused laser size

- 2nd Laser only
- Scan using focused laser beam without RF



e+ source setup 1

Positron target and capture section



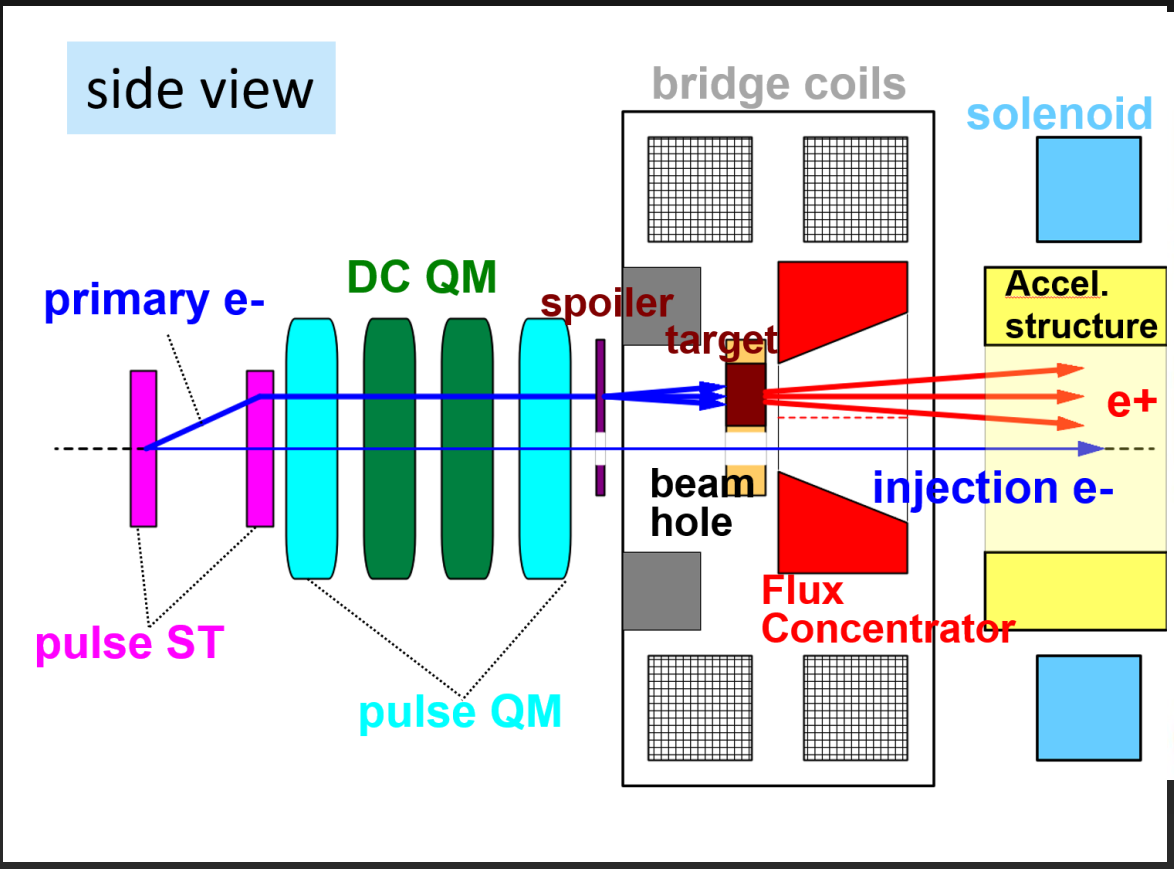
DC solenoid
Large aperture S-band acc. Structures (x10)

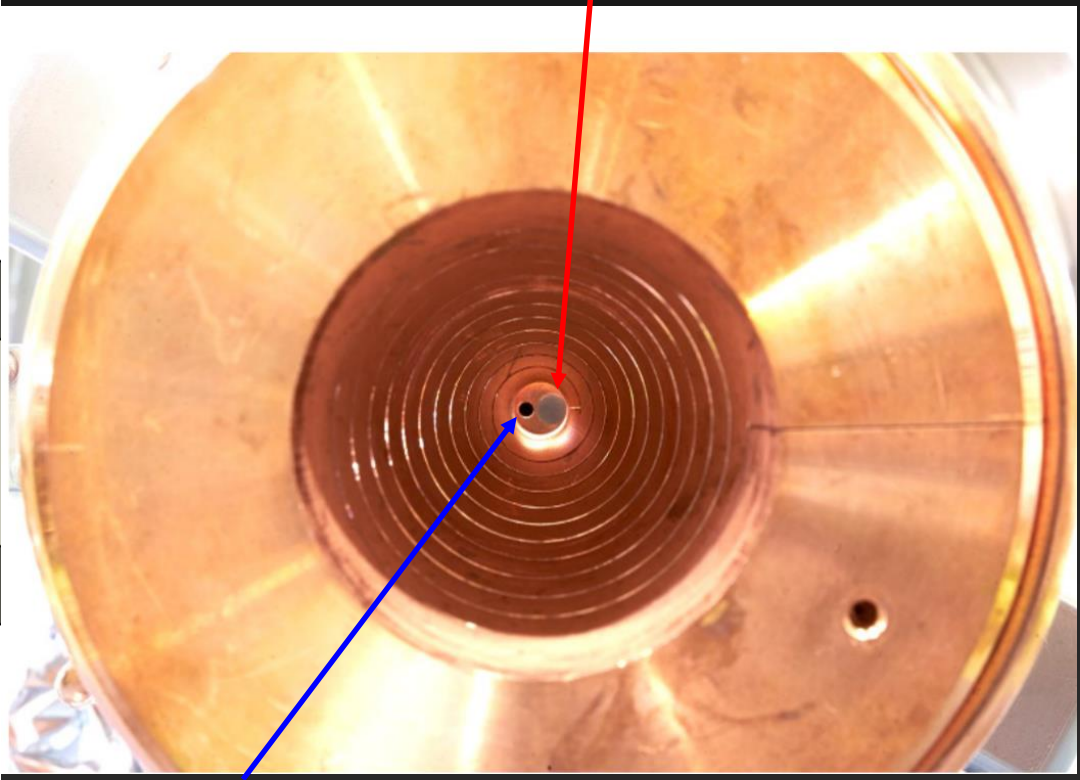
W target + flux concentrator (FC)

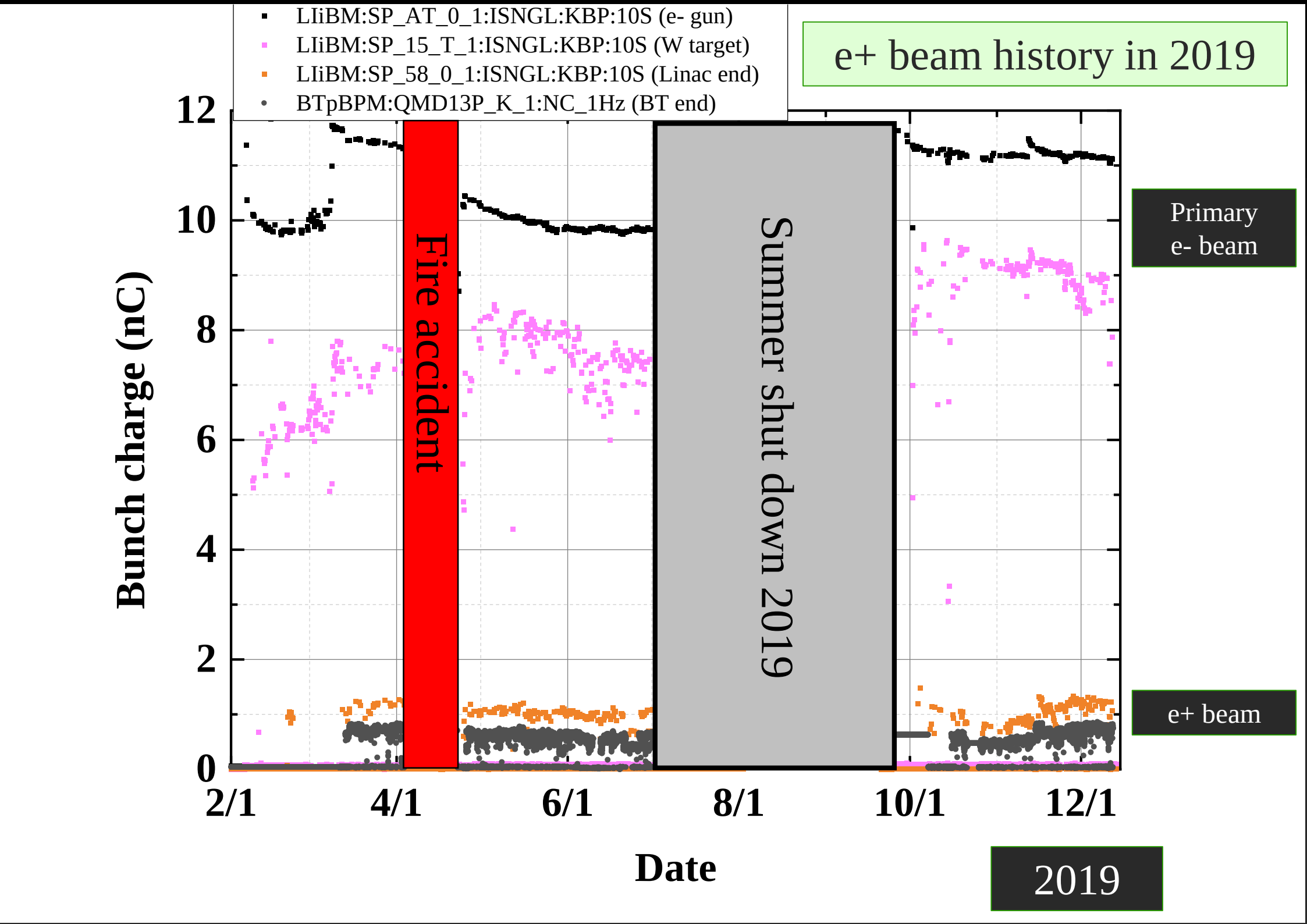
Y. Enomoto, SuperKEKB review, 2019

Pulse to pulse e-/e+ beam switching

- Pulsed steering magnet control e- beam orbit.
- Low emittance e- beam goes through a hole at center of beam line.






LIiBM:SP_AT_0_1:ISNGL:KBP:10S (e- gun)
LIiBM:SP_15_T_1:ISNGL:KBP:10S (W target)
LIiBM:SP_58_0_1:ISNGL:KBP:10S (Linac end)
BTpBPM:QMD13P_K_1:NC_1Hz (BT end)
e+ beam history in 2019
Bunch charge (nC)
12
10
8
6
4
2
0
Fire accident
Summer shut down 2019
Primary e- beam
e+ beam
2/1
4/1
6/1
8/1
10/1
12/1
Date
2019

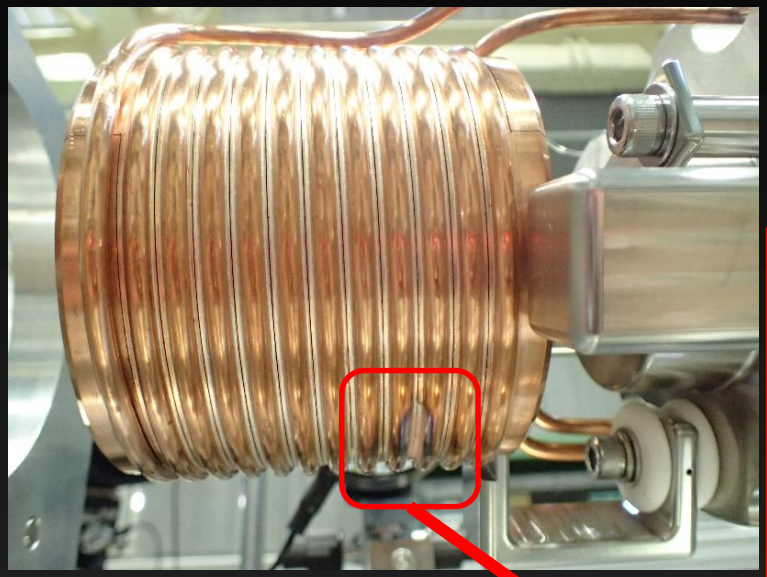
LER injection beam status

- Bunch charge
  - Stable and enough bunch charge in this stage
  - Primary e-: 11 nC (from gun), 9 nC (on W target), e+ : 1.2 nC (linac end), 0.8 nC (BT)
- Flux concentrator (FC)
  - Previous FC was damaged by large discharge during PhaseII. It was removed in Sept. 2018.
  - Current FC was installed in Jan. 2019.
  - 2 ～ 3 kA operation current (design 12 kA) for stable operation. no significant fault.

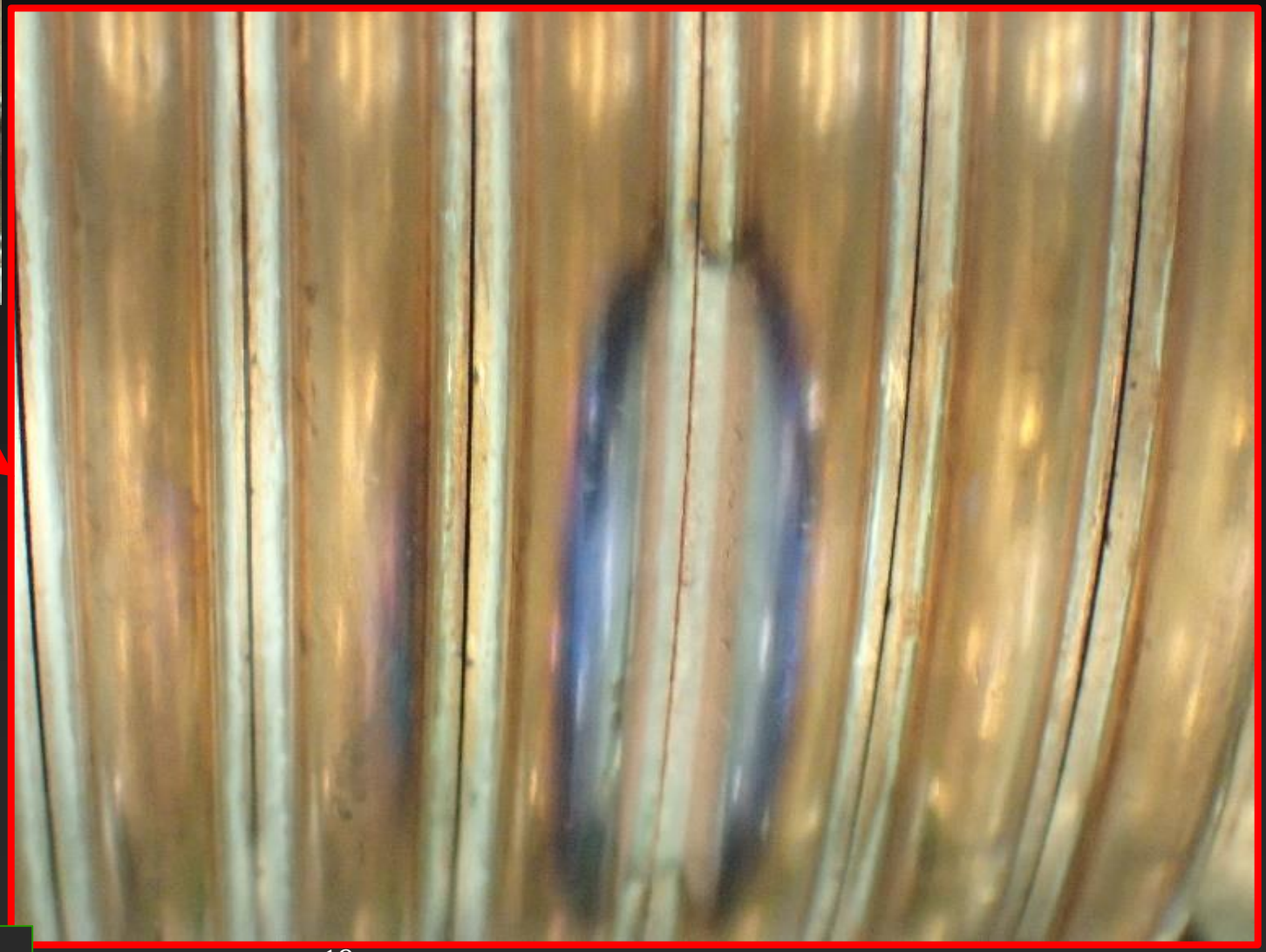
Requirements for material of the FC head are
- Good brazing characteristic
- High yield strength even after brazing
- High electric and thermal conductivity

  - New FC made of Cu-alloy (NC50: Cu-Si-Ni) has been tested w/o fault (～ 12 kA).
  - New FC will be installed in summer shutdown of 2020 for aiming at design operation current.

After large discharge…



After large discharge



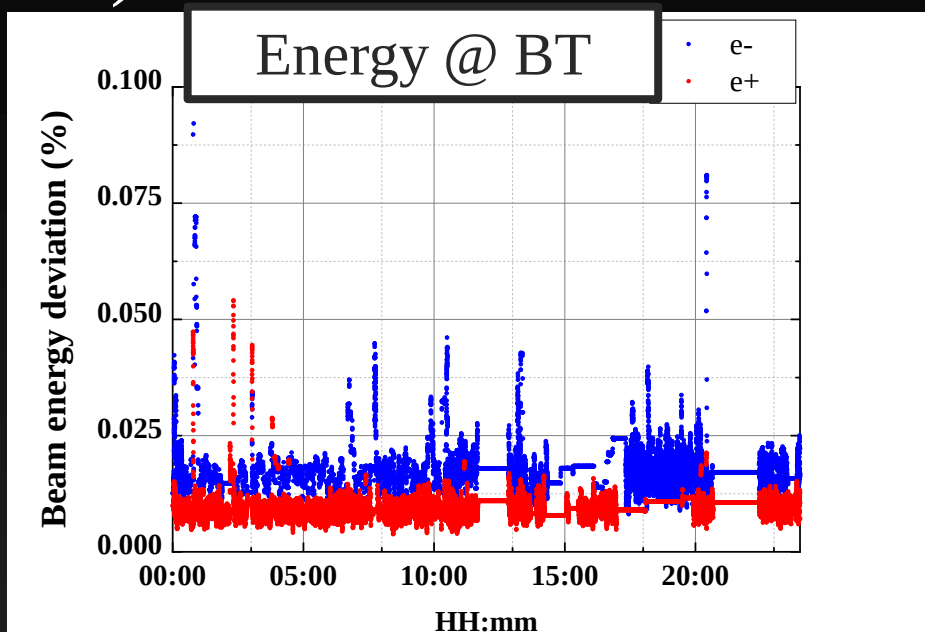
Slit gap got narrow.
Not possible to apply high voltage unless the gap will be expanded.

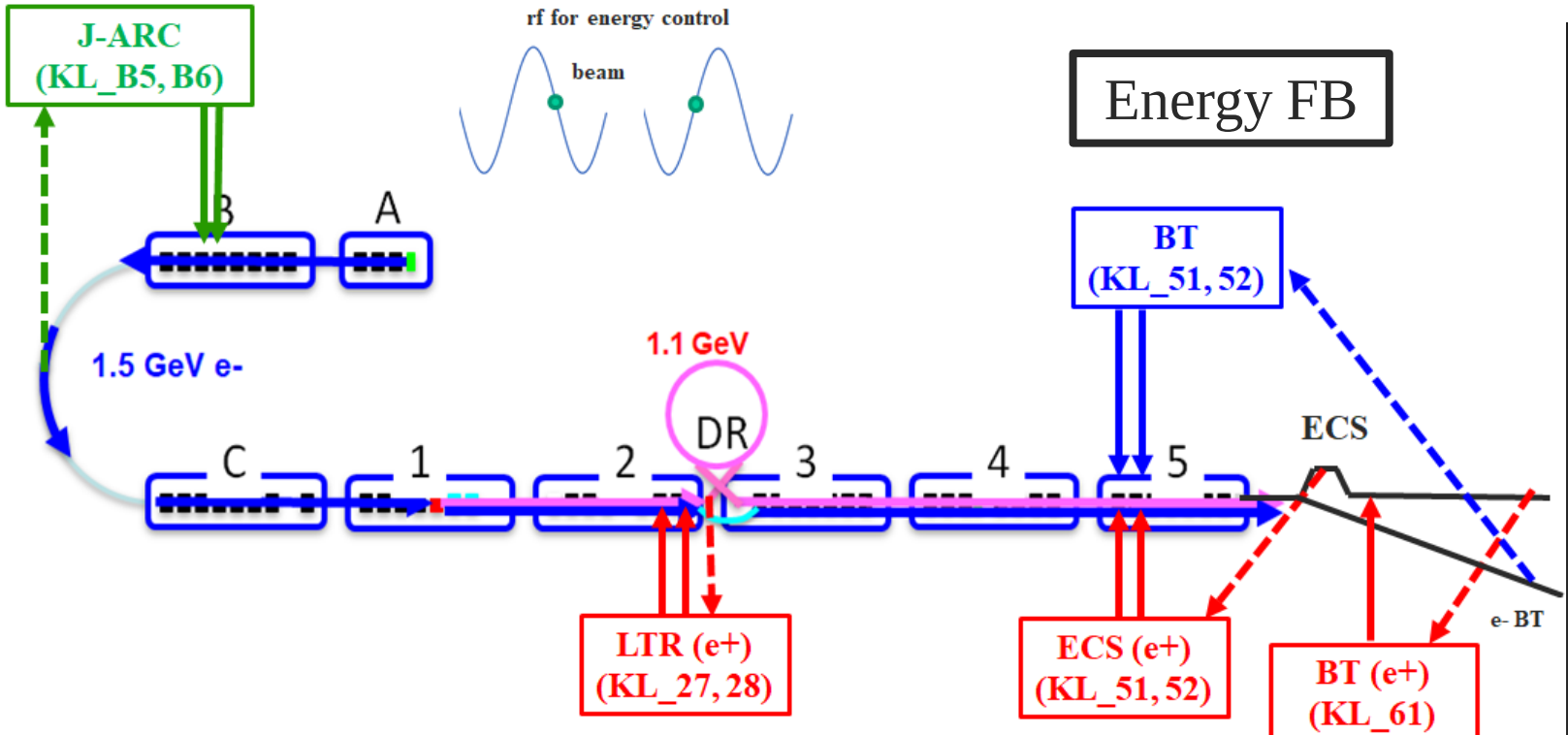
Accelerating structures

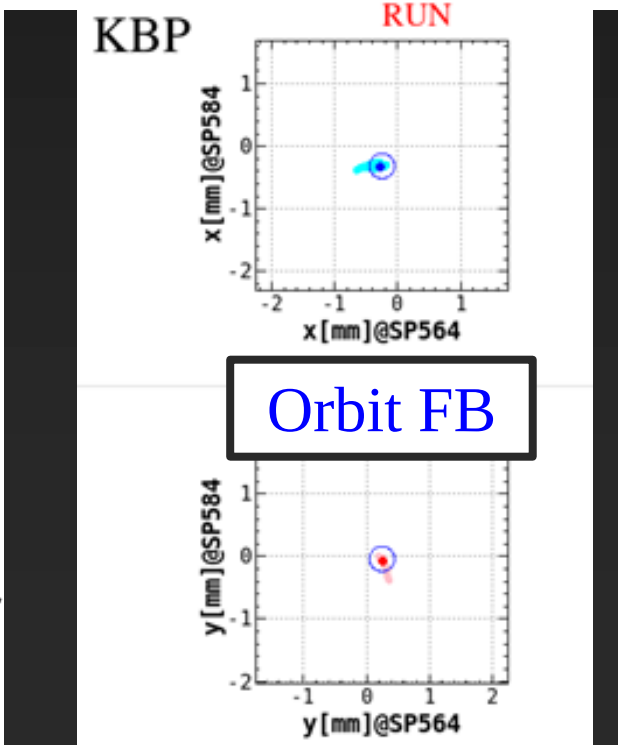
- Approx. 230 accelerating structures employed
- Many aged (40 years-old) structures are degraded
  - Risk of 7 GeV / 4 GeV acceleration for Y(4S)
  - Cannot reach Y(6S)
- As a 4-5 year plan, structures are being fabricated since the last year
- First tests will be performed at the assembly room
- Possibly, a couple of structures would be installed during summer

Feedback loops

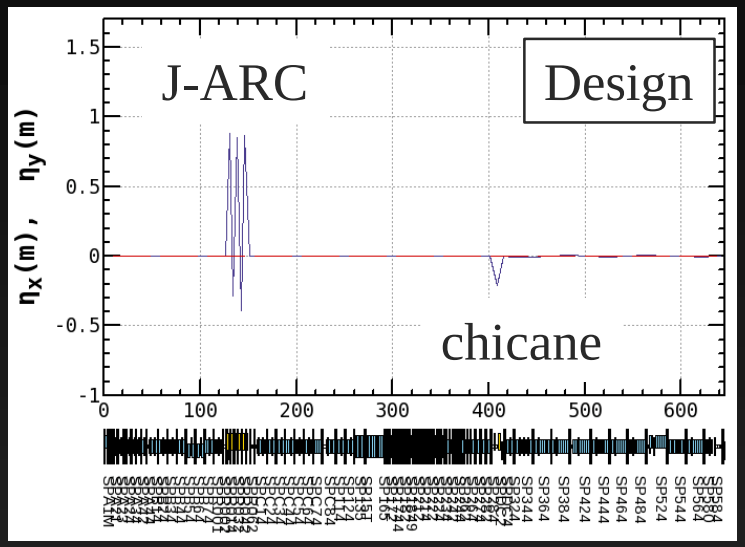
- Energy feedback (J-ARC, LTR, ECS, BT) work fine.
  - Energy stability at BT line < 0.025%
- Orbit feedback at some locations.
  - Large drift (～ 1 mm) can be corrected within ~ 0.1 mm w/ feedback.



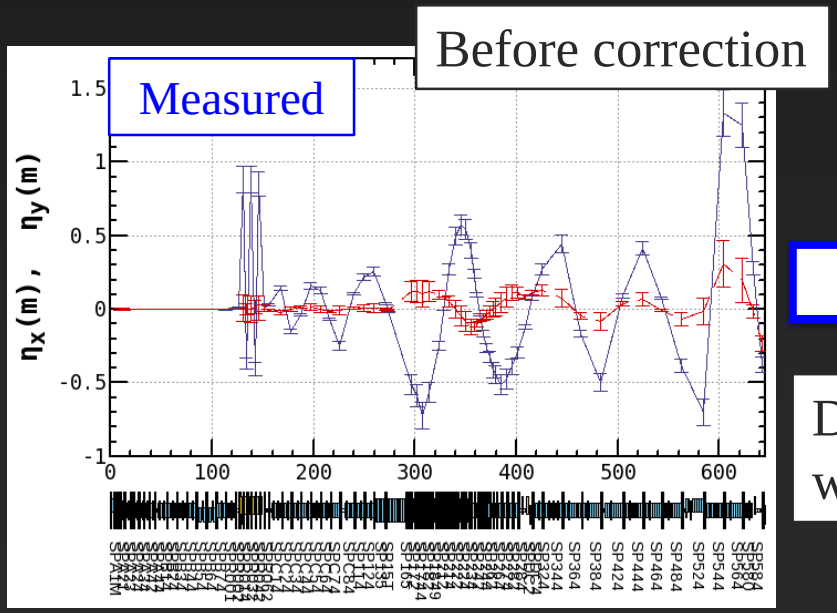




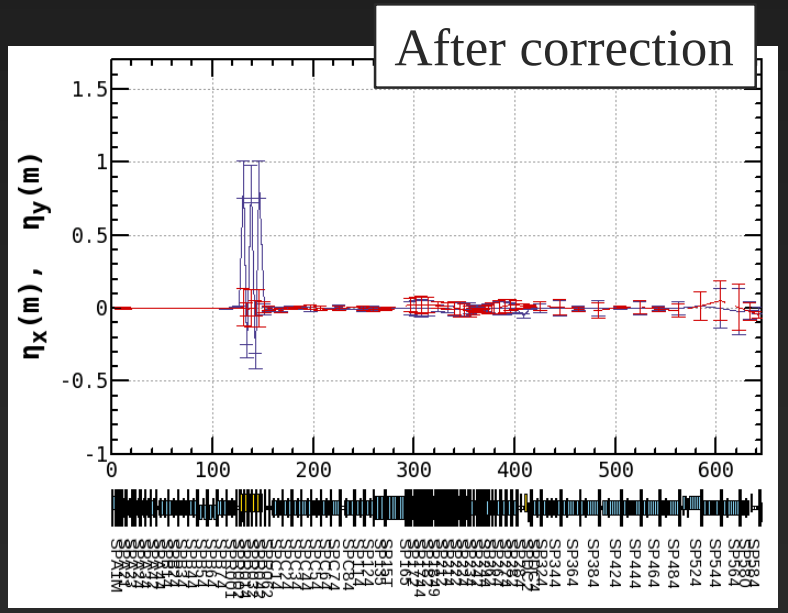
Dispersion measurement and correction



- Horizontal dispersion leakage from J-ARC causes the beam position jitter.
- Applying fudge factors to quads in J-ARC, dispersion is well corrected.

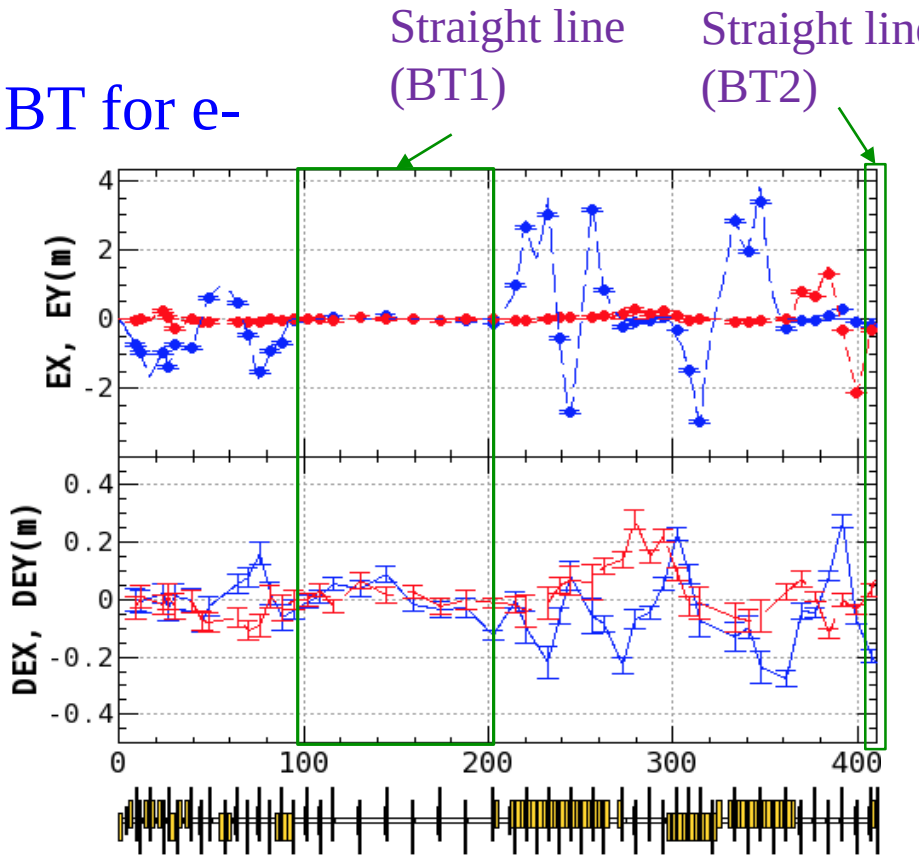


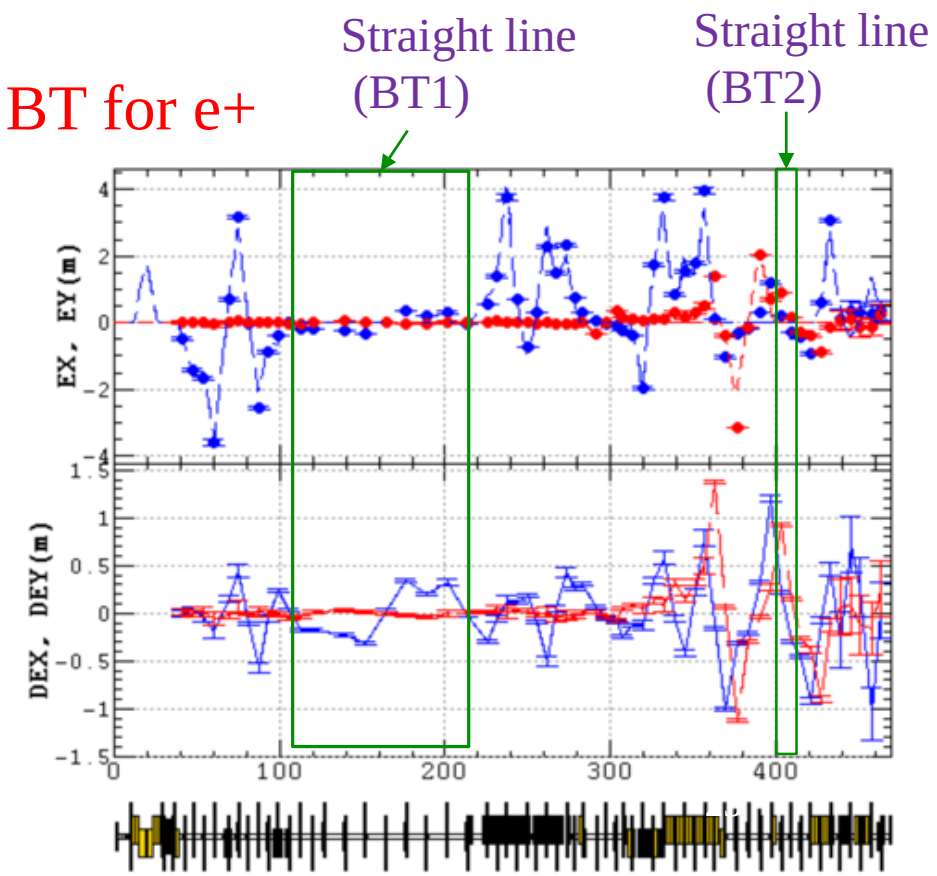
Disp. correction w/ quads



Residual Dispersion in the BT line

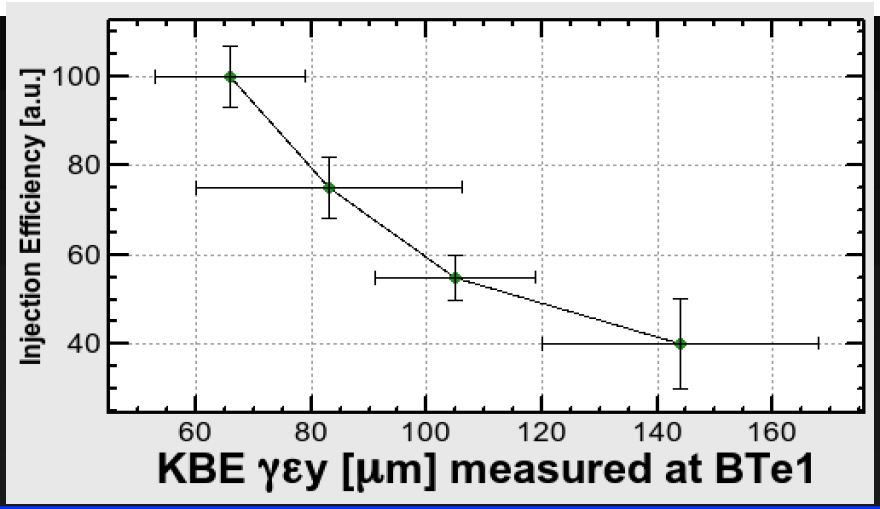
- The dispersion functions have been corrected for each BT ARC one by one.
- Non-negligible residual dispersion is still observed





Y. Seimiya

Vertical emittance vs. HER Injection efficiency



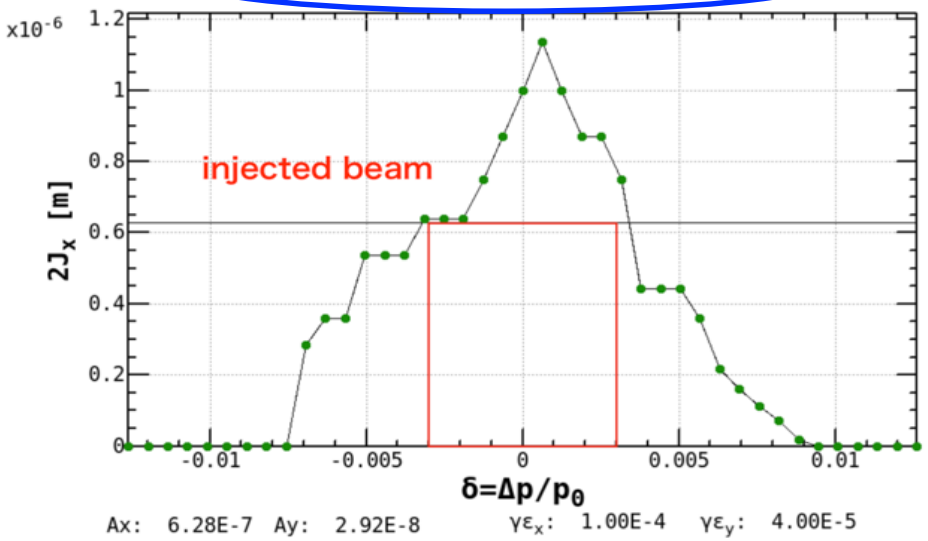
Y. Ohnishi

Dynamic Aperture for Injected Beam in HER

$\beta_x^* = 60$ mm / $\beta_y^* = 1$ mm

5780_60_1_A_YO3

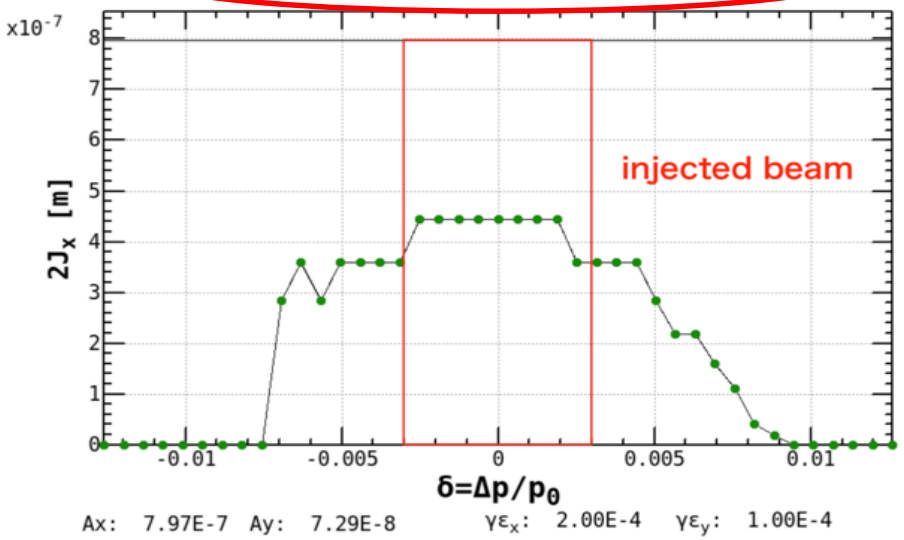
norm. emittance : 100 μm / 40 μm



QCS aperture only wit collimators

Injection efficiency = 100 % (no machine error)

norm. emittance : 200 μm / 100 μm

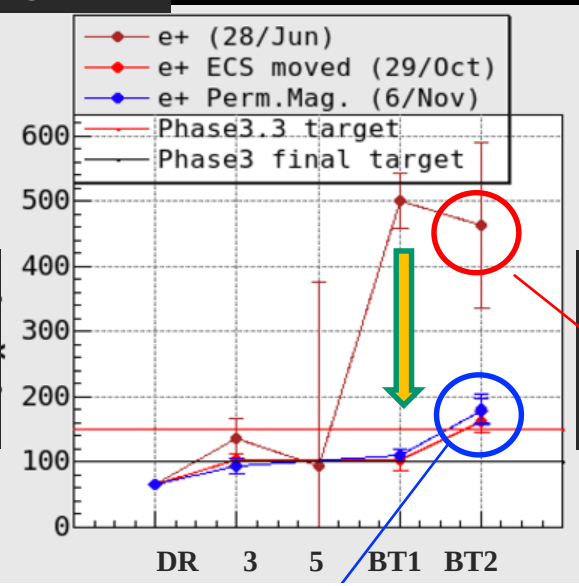


QCS aperture with collimators

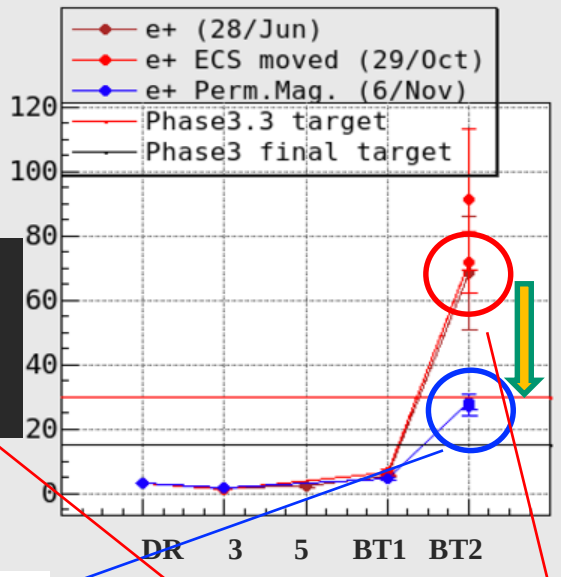
Injection efficiency = 53 %

LER

γεx [μm]



γεy [μm]



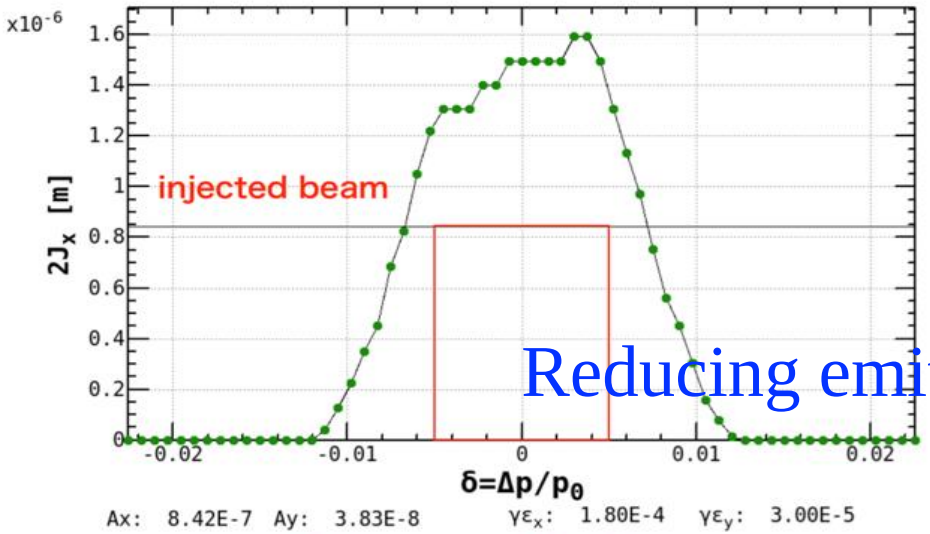
e+ horizontal emittance has been improved after ECS bend alignment.

…perture for Injected Beam in LER

1704_80_1_A_YO4

$\beta_x^* = 80$ mm / $\beta_y^* = 1$ mm

norm. emittance : 180 μm / 30 μm



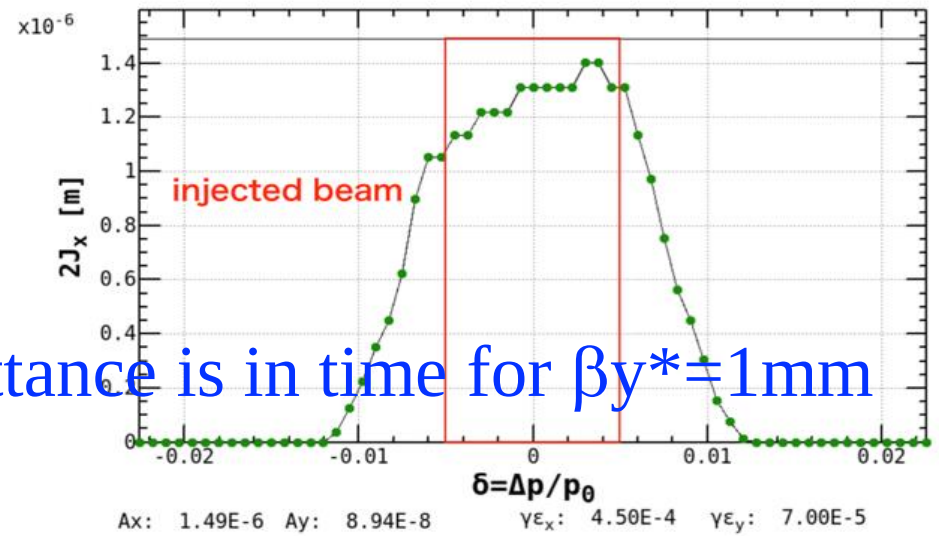
QCS aperture with collimators

Injection efficiency = 100 %

(no machine error)

(6/Nov/2019)

norm. emittance : 450 μm / 70 μm



QCS aperture with collimators

Injection efficiency = 86 %

(28/Jun/2019)

Before modification of ECS / BTp

Reducing emittance is in time for βy*=1mm

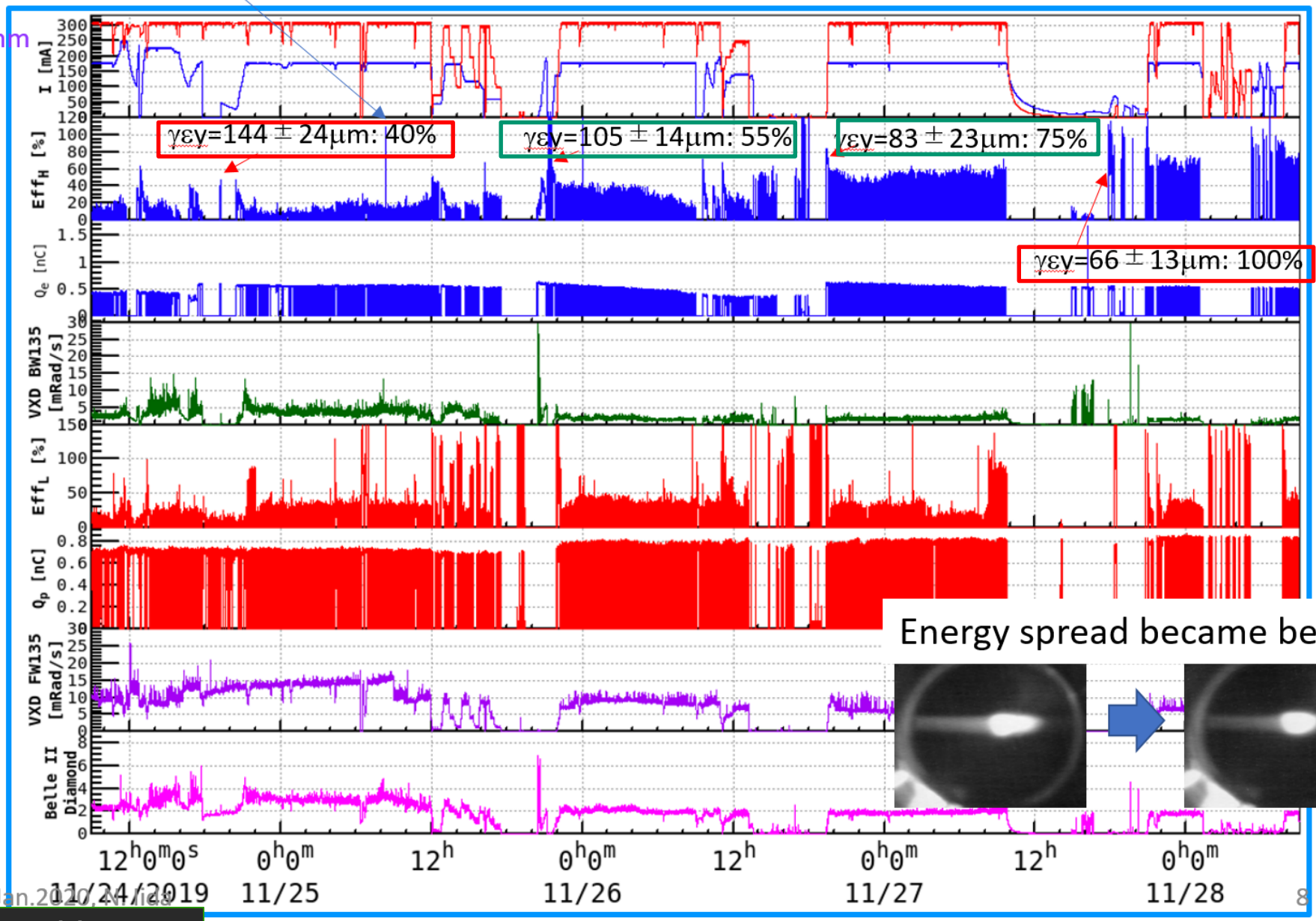
1. Injection efficiency and background

The injection efficiency increased as emittance decreased by tuning day by day.

Phase3.2
2019c(Autumn)

These efficiencies are calculated at the low current beam in the HER.
→ The effect of Touschek lifetime can be neglected.

βy*=1.0mm

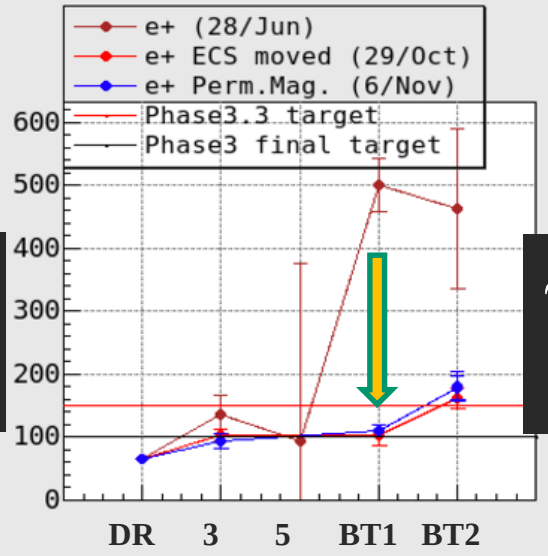


Energy spread became better

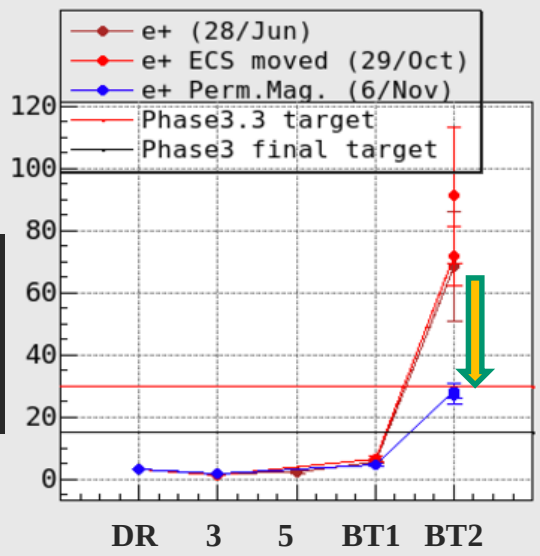
Measured emittance

e+ beam (Phase3.2(6.Nov.2019))

γεx [μm]



γεy [μm]



Phase3.3	e+	e-
γεx [μm]	150	100
γεy [μm]	30	40
σδ [%]	0.16(1σ)	0.1(1σ)

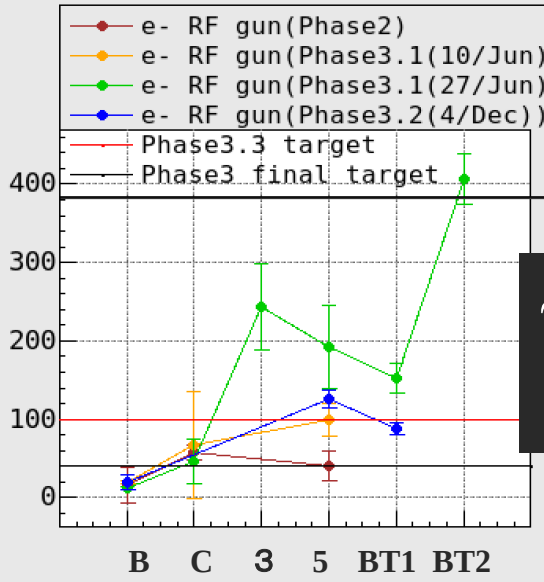
Emittances increase

- DR → Sector3
- BT1 → BT2

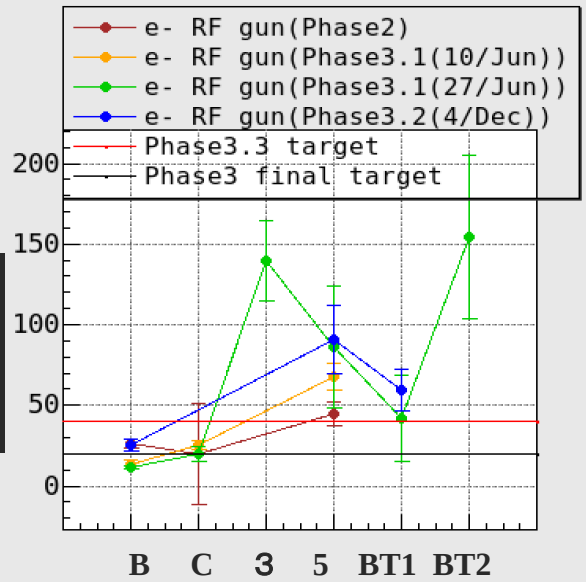
Beam study will be continued

e- beam (Phase3.2(4.Dec.2019))

γεx [μm]



γεy [μm]



Emittances increase

- C→Sector3
- BT1→BT2

Beam study will be continued

N. Iida, 31. Jan., 2020

Y. Seimiya, F. Miyahara, T. Miura, Y. Enomoto, H. Kaji et al.

Injection beam just before abort can be monitored by,

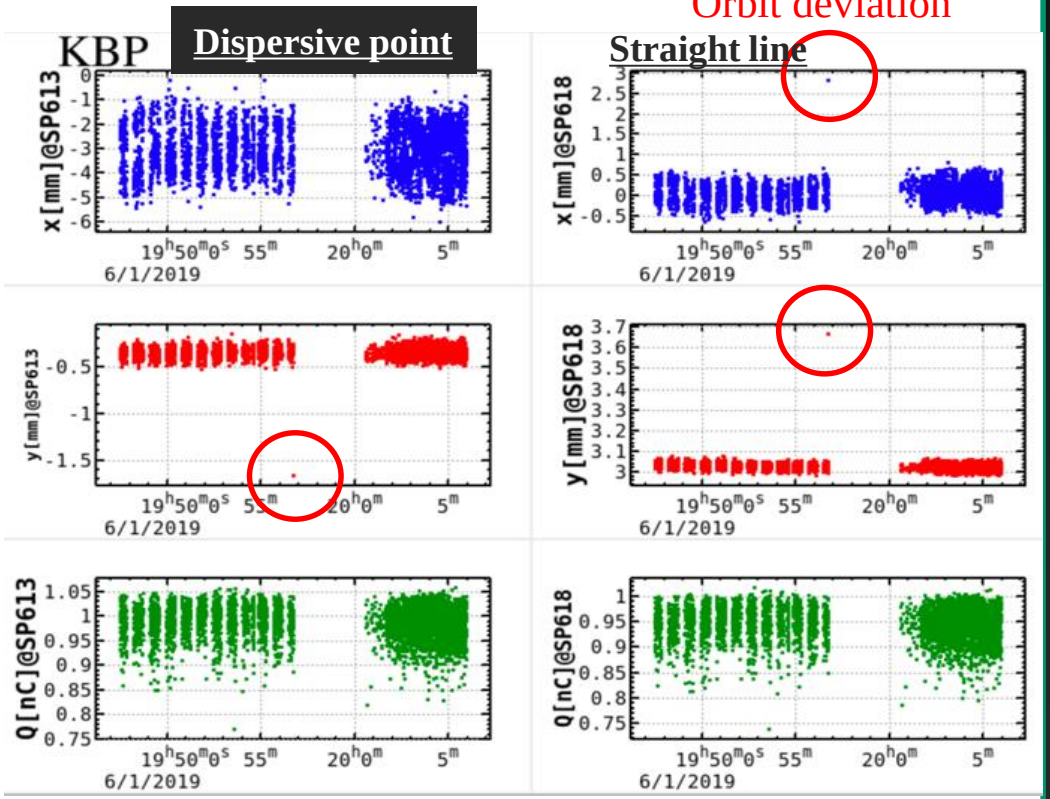
Fast beam position monitor(BPM) in LINAC

a. 1. Jun., 2019 19:56

LER D6V2 LM abort

No energy deviation

Orbit deviation

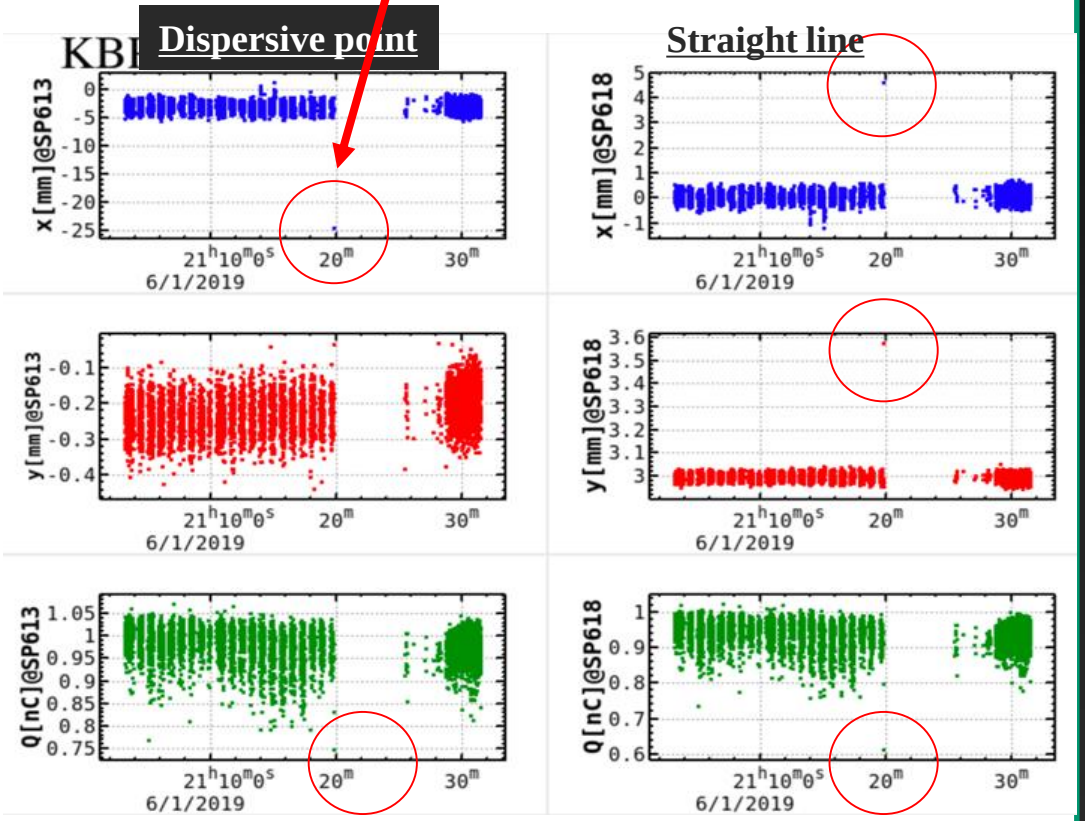


One station for the power supplies (PS) was set to 0 [A] due to a trigger missing of the PS.

b. 1. Jun., 2019 21:19

LER D6V2 LM abort

Beam energy was 50 MeV lower.



The klystron 51 was down at the time.
The estimation was -46.5 MeV which is consistent with the beam position.

N. Iida, 31. Jan., 2020

Summary and plan

- Stable simultaneous top up injection to 4 storage rings (HER, LER, PF, and PF-AR) w/ thermionic gun, rf gun, pulsed magnets.
- HER injection has been done w/ only rf gun from PhaseIII day 1.
  - Laser system has no significant fault.
  - Photocathode: Ir_7Ce_2 => Ir_2Ce (summer of 2019) for higher Qe, however, bunch charge gradually decreased.

    In this winter shutdown: back to Ir_7Ce_2 photocathode
  - Laser cleaning can cure degradation of Qe
- Flux concentrator for e+ beam has no significant fault.
  - New flux concentrator will be installed for higher e+ bunch charge for higher e+ bunch charge.

Summary and plan (cont'd)

- **Smaller emittance, higher injection efficiency, smaller background.**

- Emittance growth (need more beam study)
  - btwn BT1 - BT2 (e-, e+)
  - DR – Sector3 (RTL) (e+), SectorC-Sector3 (e-)
  - Steering magnets and BPMs will be installed in e+ capture section (solenoid section) at Sector1.
  - Movable girder and precise orbit control will help for emittance preservation.

- Single shot beam w/ bad quality (energy, orbit) could cause abort.
  - Install collimator at ECS (end of linac) in this summer shutdown.
  - Reduce failure rate of PS control software

Backup

Fire recovery

- Fire at acc. structure assembly room on Apr. 3, 2019
  - Southern part of the injector was much damaged as well as the assembly room
- Interim injector recovery by Apr. 26, 2019
- Full injector recovery during summer shutdown
- The assembly room cleaned up
  - Restoration in April
  - S-band structure tests and RF conditioning soon

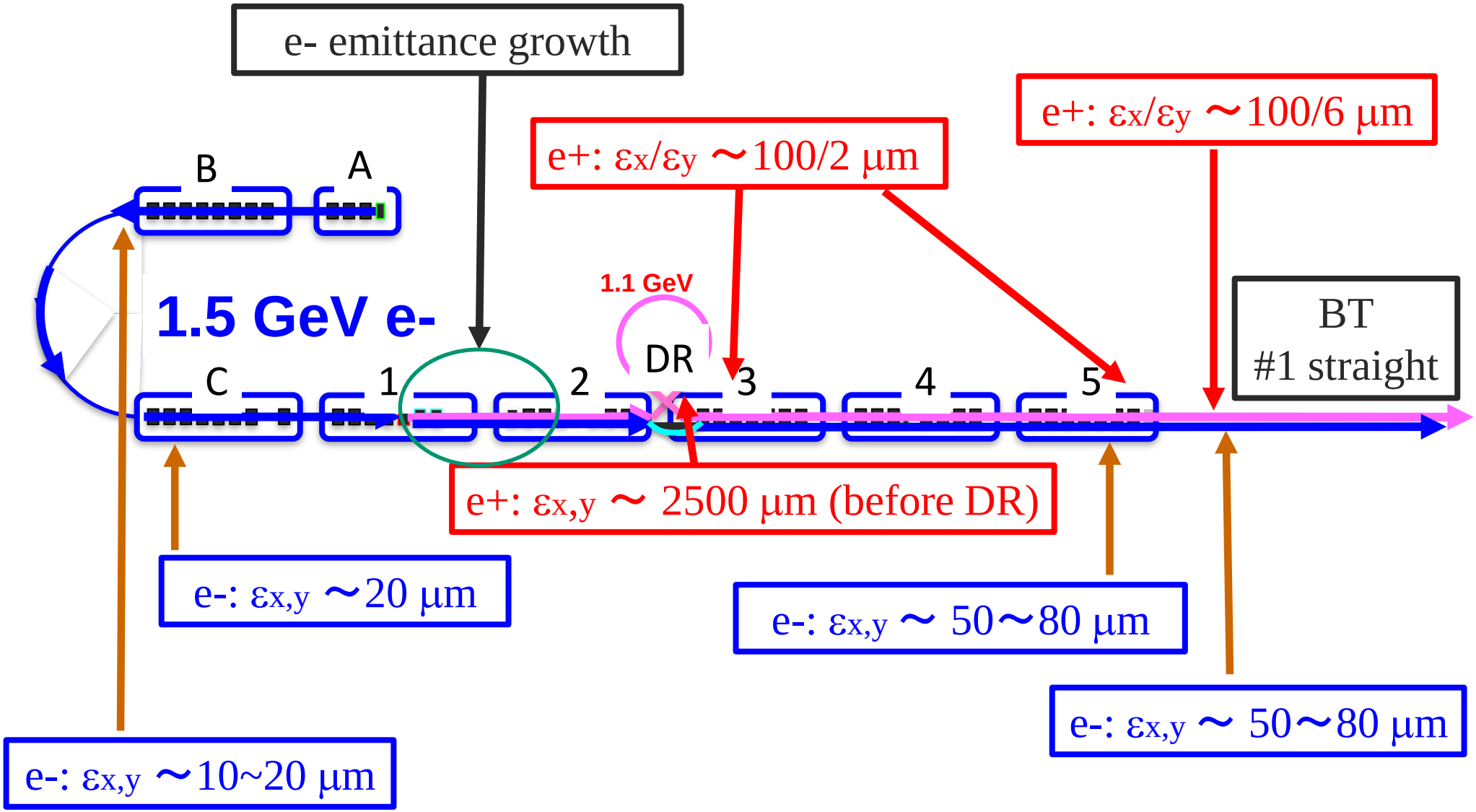
Scaffold to clean up walls and ceiling at acc. structure assembly room

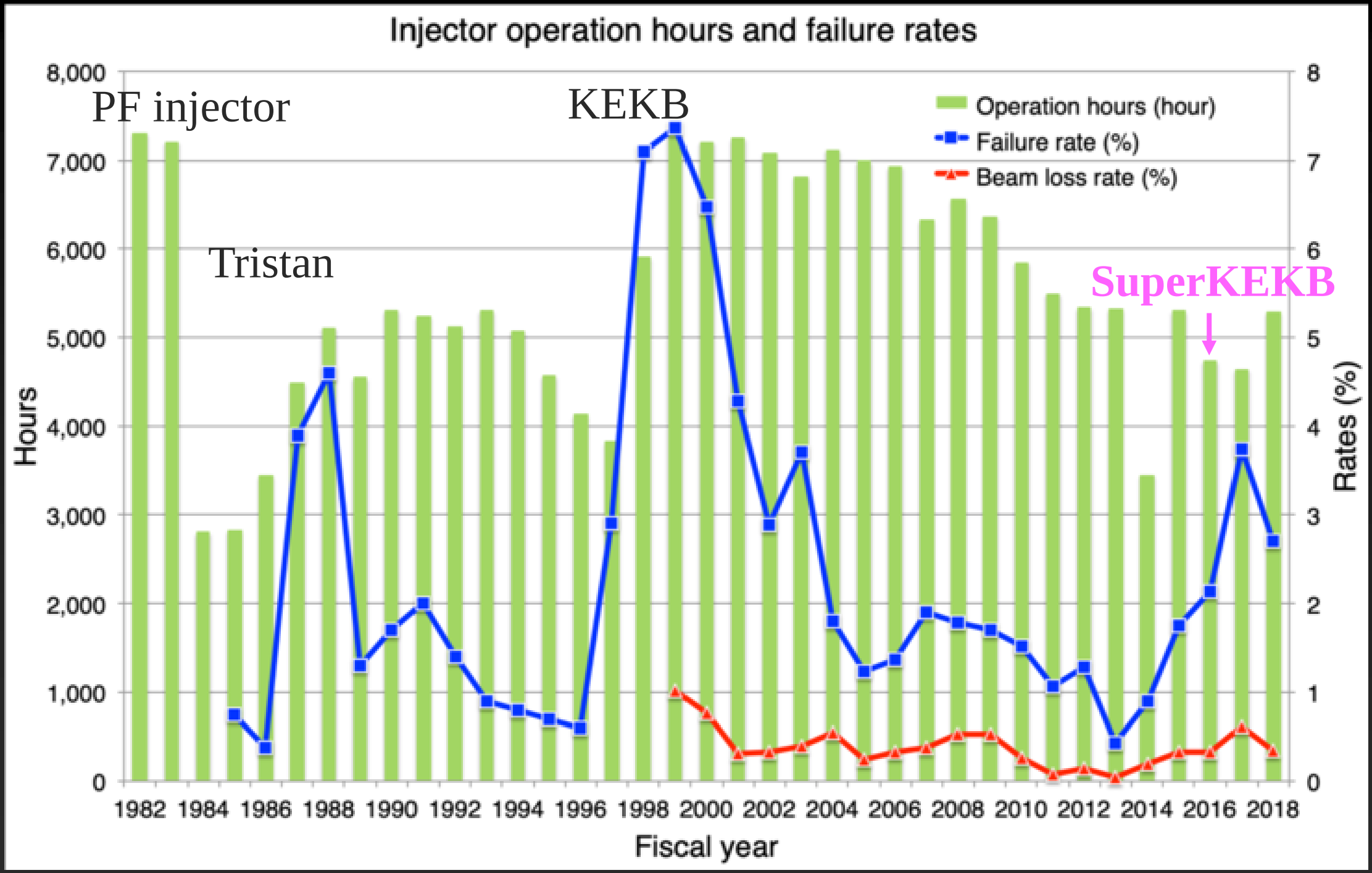
Beam emittance example (~1 nC) w/ multiple wire scanners

Final target (4 nC)

e-: $\varepsilon_x/\varepsilon_y$ 40/20 μm

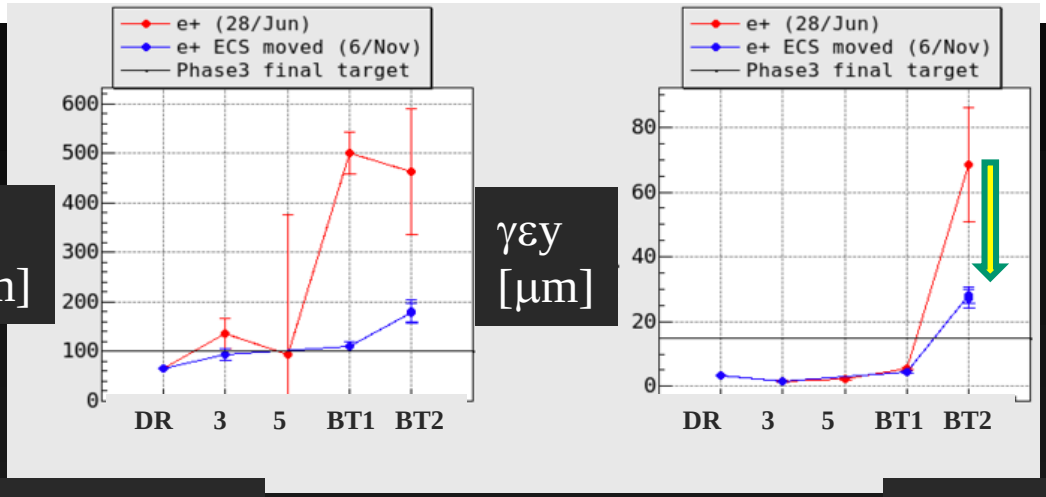
e+: $\varepsilon_x/\varepsilon_y$ 100/15 μm



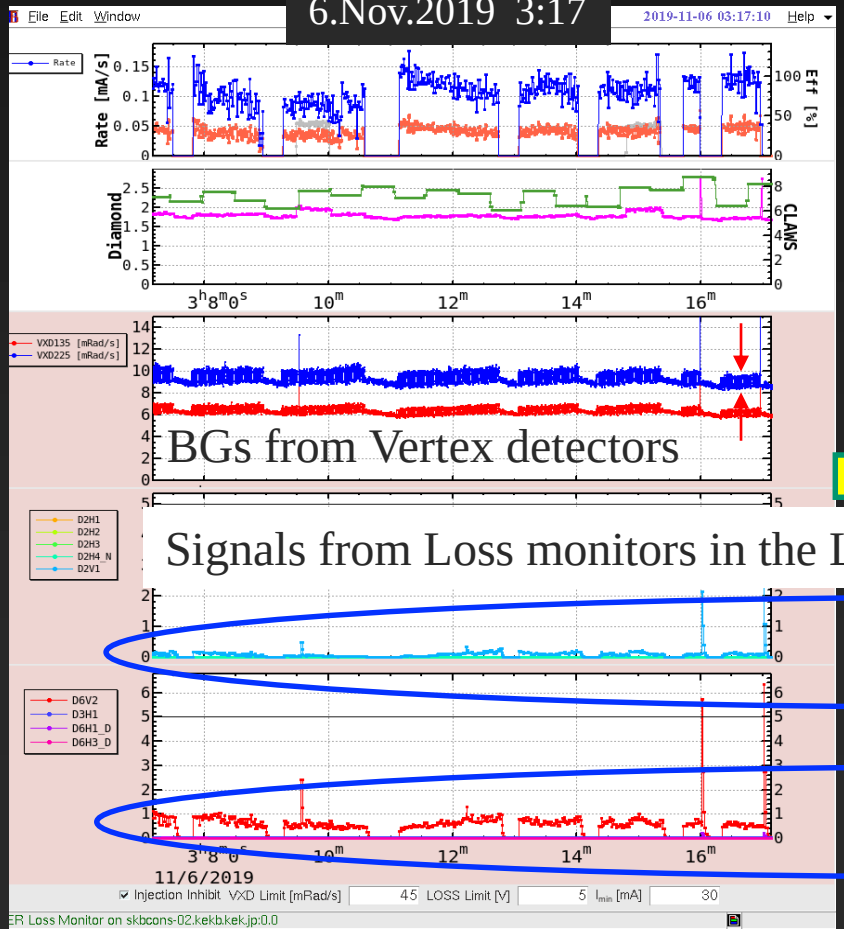

Injector operation hours and failure rates
PF injector
KEKB
Tristan
SuperKEKB
Operation hours (hour)
Failure rate (%)
Beam loss rate (%)
Hours
Rates (%)
Fiscal year
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
8
7
6
5
4
3
2
1
0
1982 1984 1986 1988 1990 1992 1994 1996 1998 2000 2002 2004 2006 2008 2010 2012 2014 2016 2018

LER

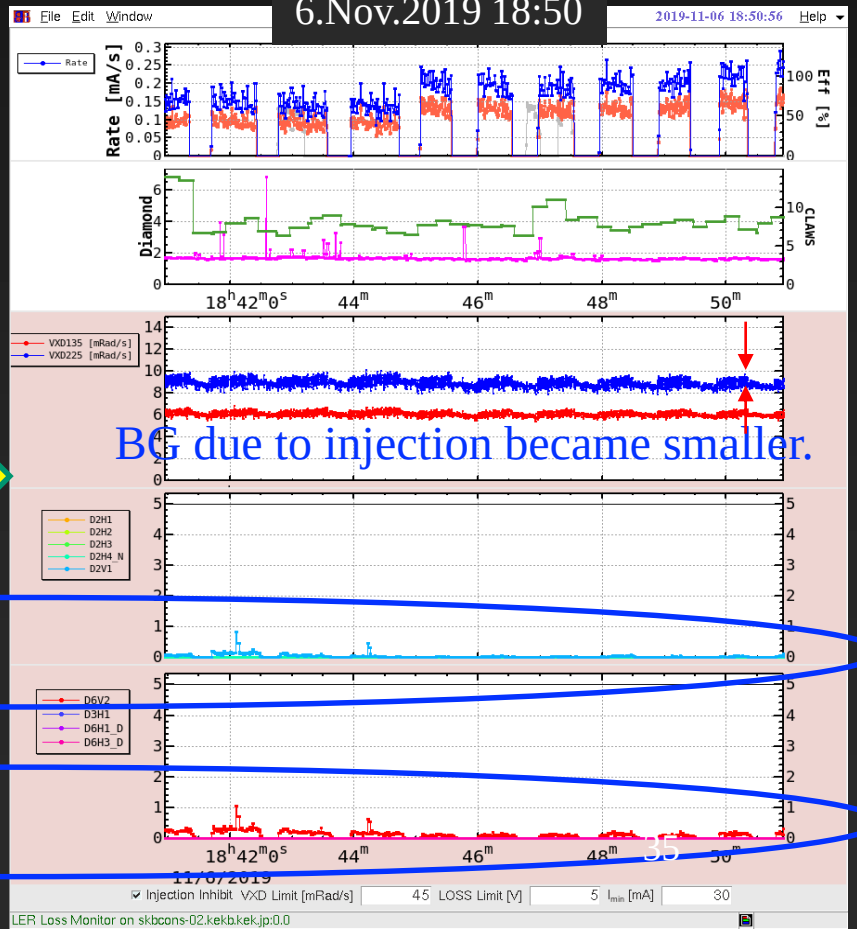
e+ vertical emittance was improved



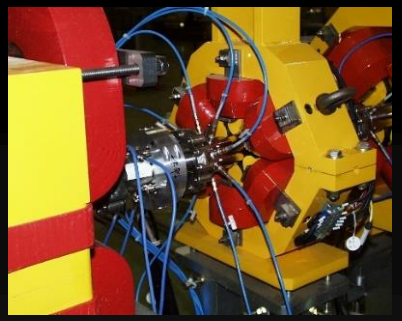
6.Nov.2019 3:17



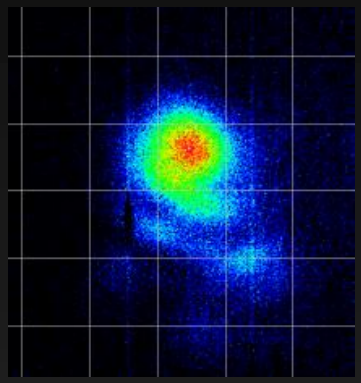
6.Nov.2019 18:50



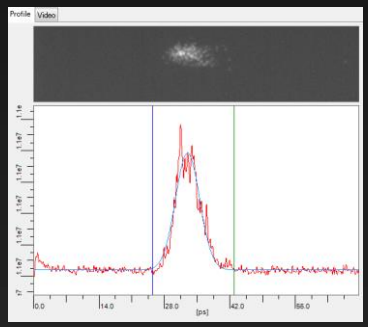
Monitors

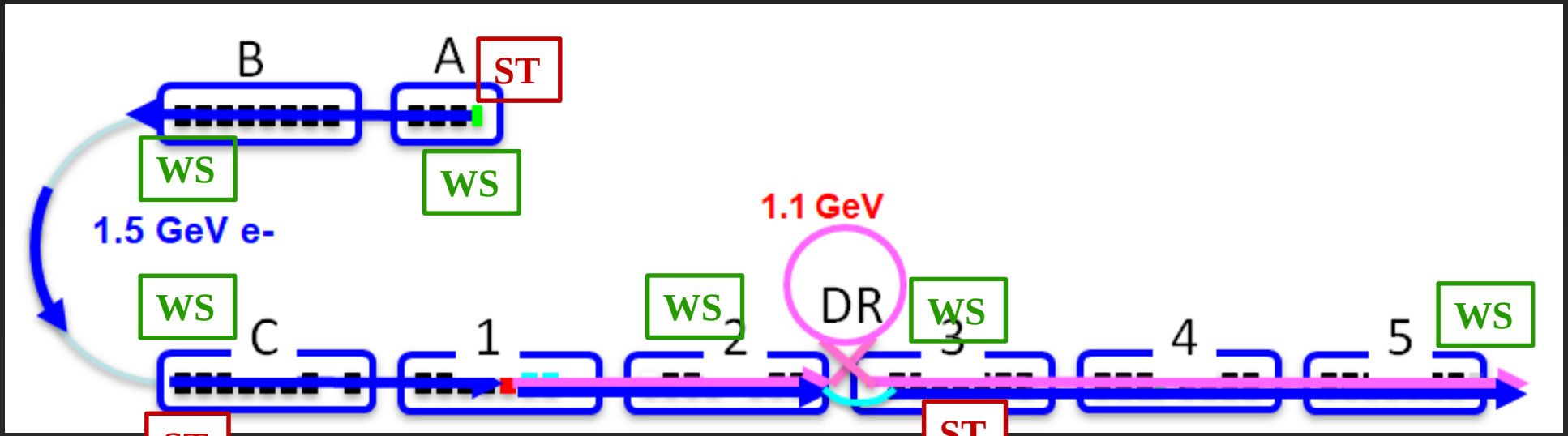


- Beam position monitor (x 103)
  - Four strip line electrodes (x 97)
    - **Measurement precision ~ 10 μm**
  - Eight strip line electrodes (x 6) (J-ARC, LTR x2, PF BT, HER BT, LER BT)
- Profile monitor (x 104)
  - Al_2O_3/CrO_3 (AF995R, Demarquest Co.). (t: 1 mm, 0.1 mm), YAG:Ce (t: 0.1 mm)



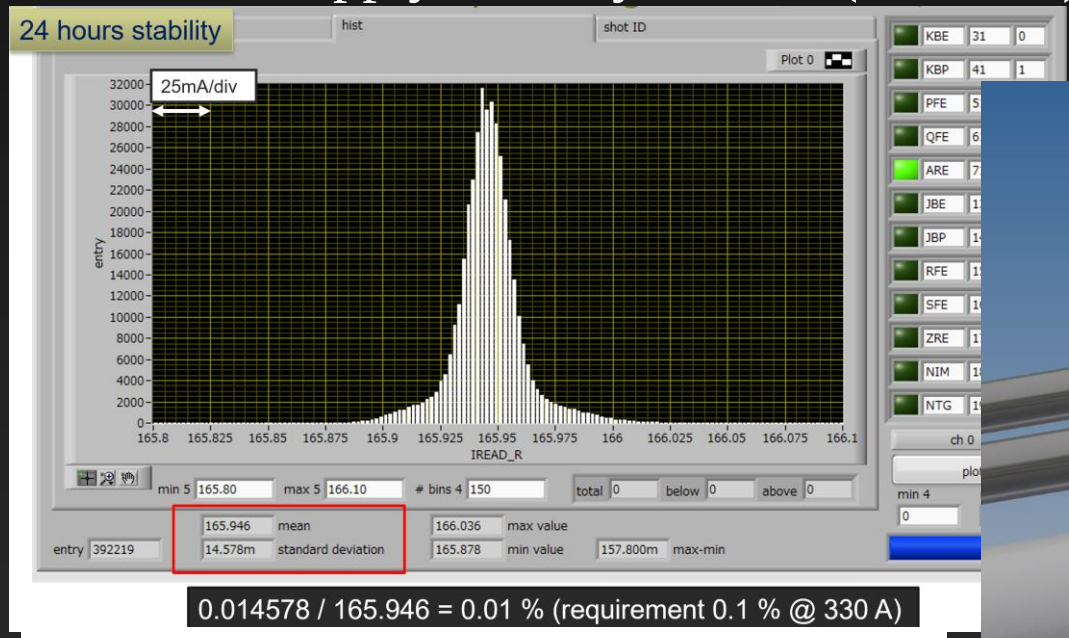
- Wire scanner (WS) (x 6)
  - SectorA, B, C, 2, 3, 5
- Streak camera (ST) (x 2)
  - SectorA, ~~C~~, 3
- RF monitors for klystron, SLED, acc. structure

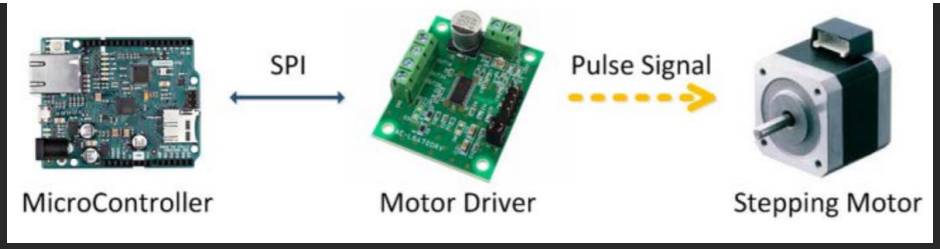


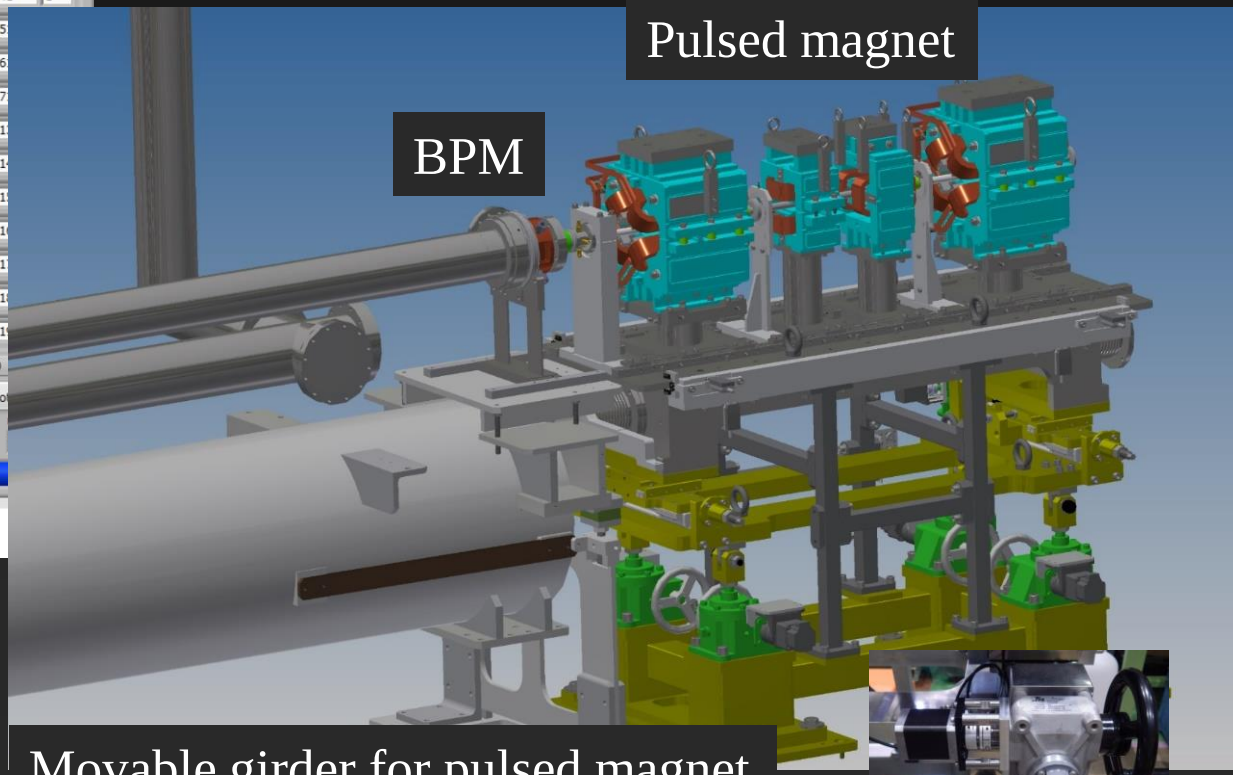


Pulsed magnet system

- Pulsed quads (x 28) (w/ ceramic duct) and steering (x 36) were installed at Sector3 to Sector5 in 2017 (on movable girder).
- Pulsed bend, additional quad and steering were installed in 2018 summer and winter shutdown.
- PXIe based control system (Windows 8.1, LabVIEW, EPICS) have worked fine w/o any serious trouble.
- Power supply stability: 0.01% (24 hours)



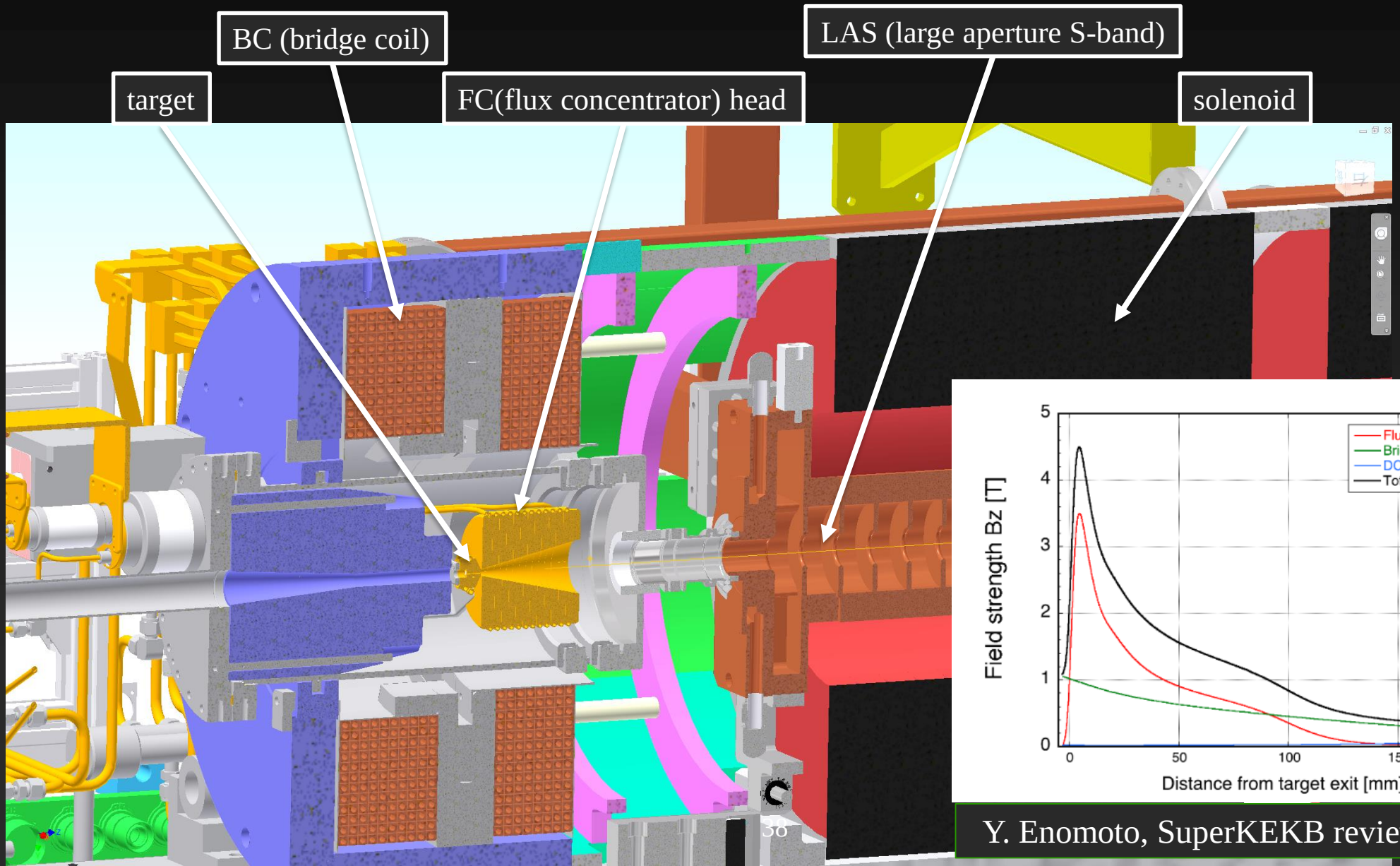




Movable girder for pulsed magnet
(remote controllable, 10 μm step)

e+ source setup 2

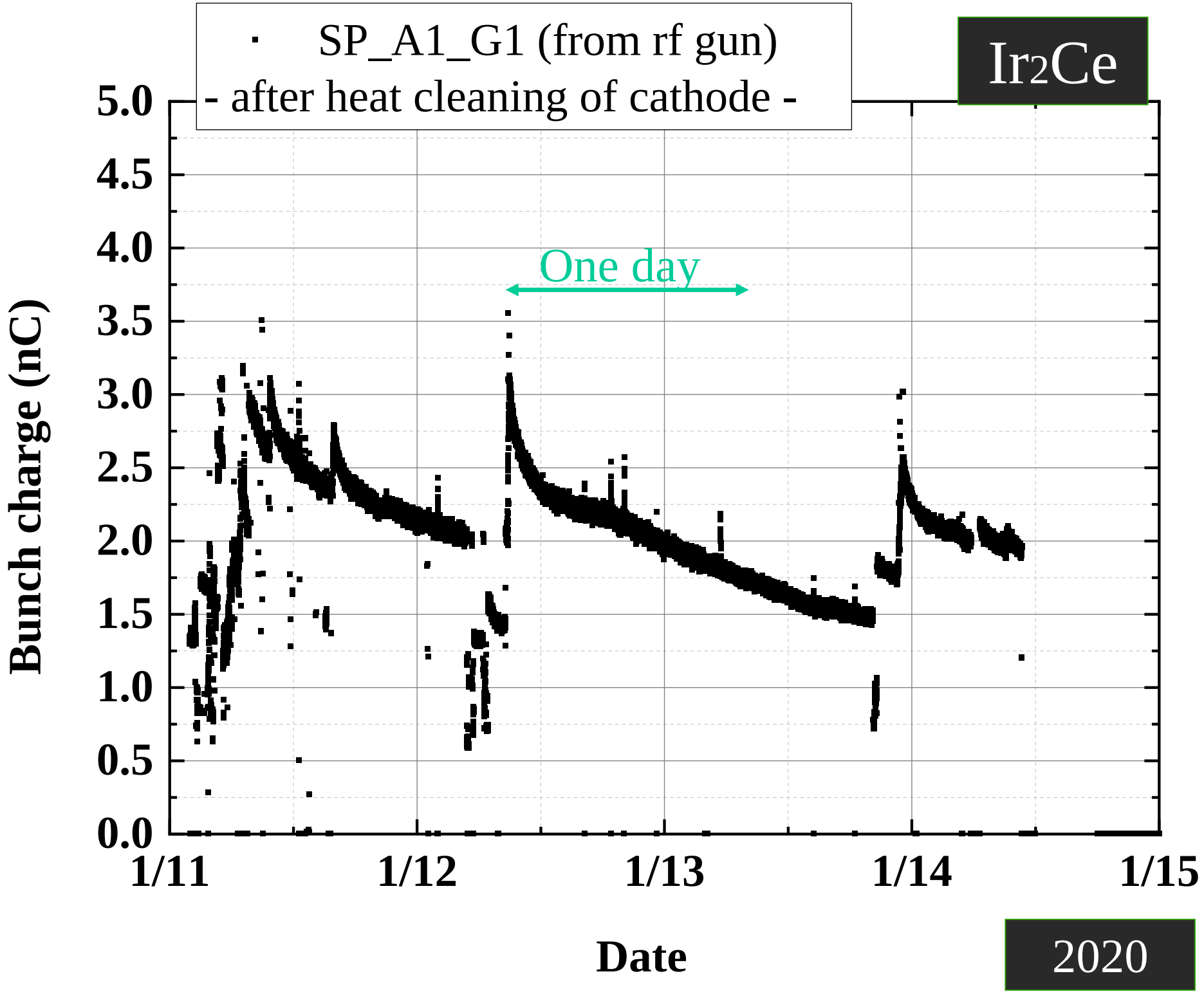
FC head + BC + target = FC assembly



Y. Enomoto, SuperKEKB review, 2019

Movable girder for accelerating structure

- Six movable girders have been installed in Sector3 (in summer shutdown of 2019).
  - Four 2-m-long accelerating structures are mounted on one girder.
- It could help to suppress emittance growth due to misalignment.


SP_A1_G1 (from rf gun)
- after heat cleaning of cathode -
Ir2Ce
One day
Bunch charge (nC)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1/11
1/12
1/13
1/14
1/15
Date
2020