SuperKEKB Accelerator Review Committee
2024 March 25

Linac upgrade with Pulsed Magnets

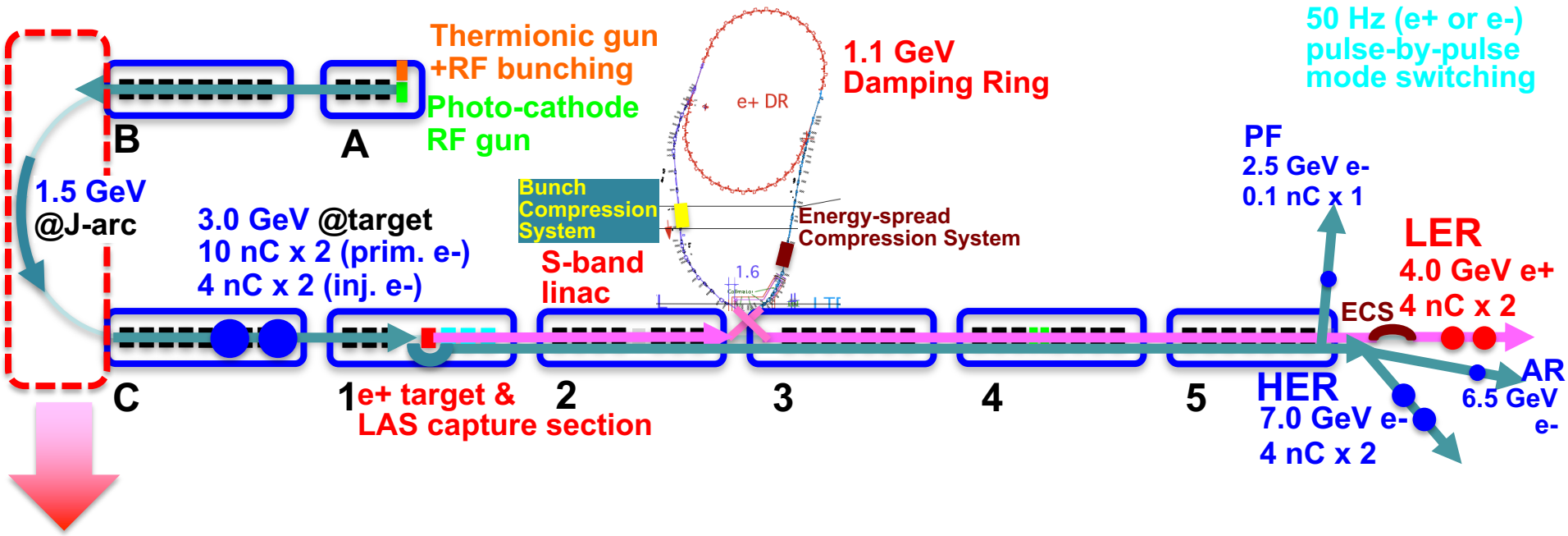
Takuya Kamitani
on behalf of
KEK e+/e- injector linac group

Pulse magnet related upgrade items

1. Pulsed quads at J-arc matching section
   - Installed in 2023 summer
2. Pulsed quads at e+/e- compatible optics region
   - Installed in 2023 summer
3. Linac fast kicker for bunch orbit difference tuning
   - Installed at J-arc, linac-end & HER-BT until 2024 January
   - To be installed at linac low energy region in 2024 summer
4. Pulsed beam switch-yard for beam diagnosis
   - To be installed in 2024 summer

Upgrade item [1]
Pulsed quads
at J-arc matching section

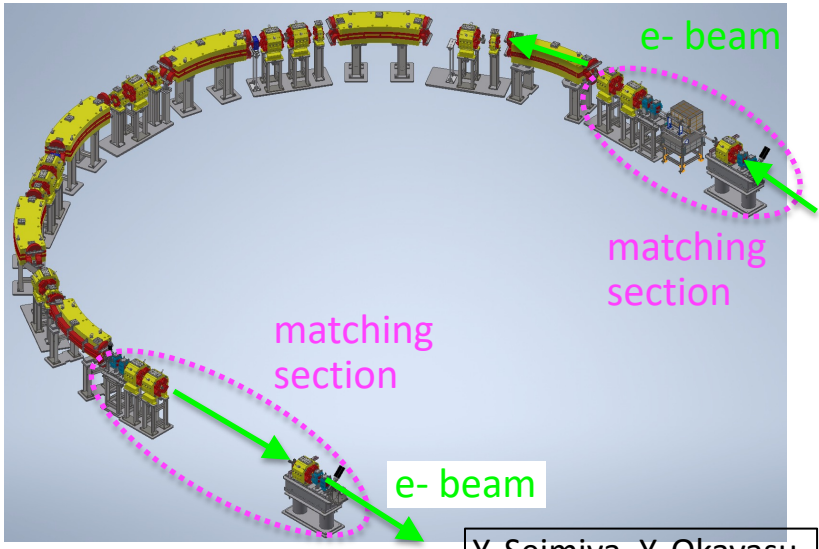
J-arc in injector linac



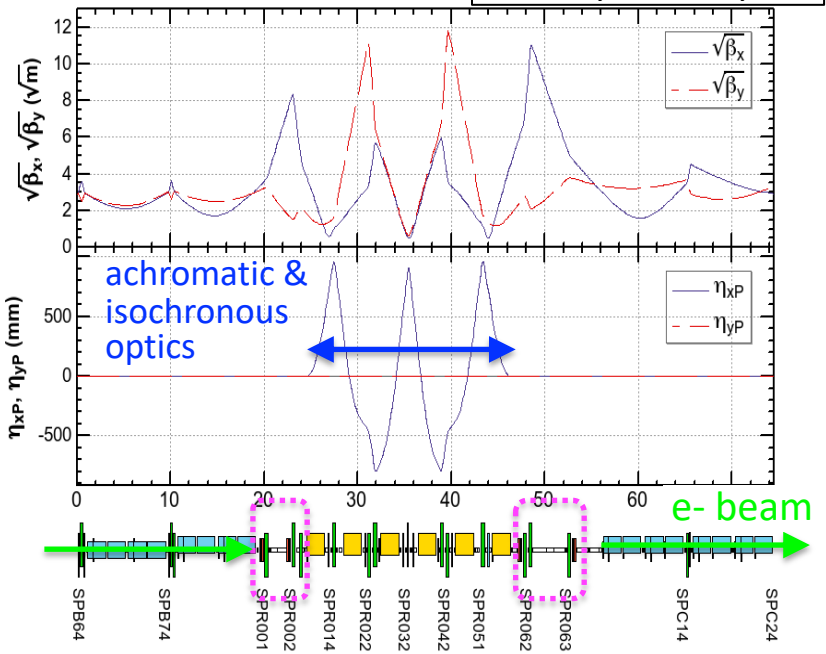
- Four different modes of beams pass through 180-degree beam turn (J-arc).
  KBE(injection e-), KBP(primary e- for e+ generation) and PF, AR
- J-arc was designed to be achromatic (for emittance(ε) preservation) and isochronous [$R_{56} = 0$] (for bunch-length preservation).
- Later, it was modified to be non-isochronous [$R_{56} \neq 0$] for bunch compression.

Motivation for pulsed quads in matching section

- beam optics situation @J-arc
  - since it has large beta-function and energy dispersion, beams have large beam size, so beam optical matching is essential to avoid beam loss and degradation.
  - optical mismatch tend to cause a particle loss in primary e- beam for large emittance (KBP).
  - tuning of quads for matching often makes emittance degradation in injection e- beam (KBE).
- motivation for pulsed quad
  - pulsed quads in matching section enables independent beam optics matching for each mode

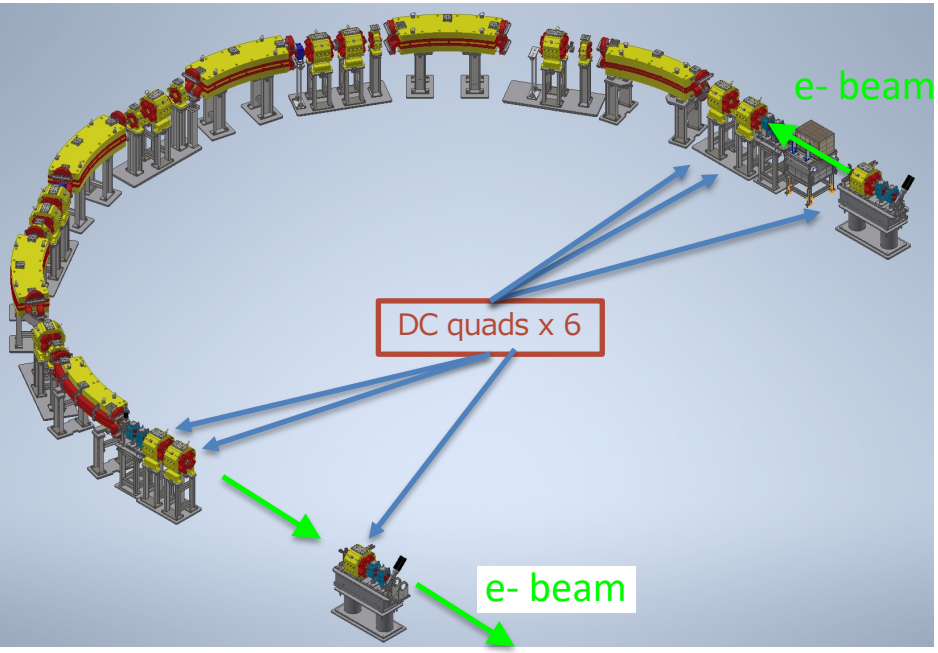


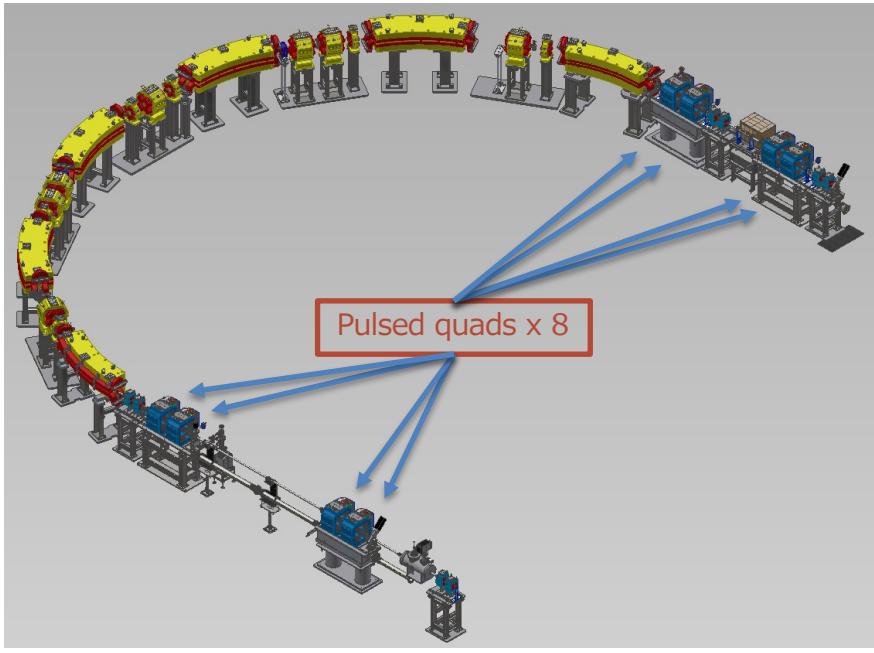
Y. Seimiya, Y. Okayasu



Pulsed quads layout at J-arc

- 6 DC quads at entrance and exit of J-arc → 8 pulsed quads
  - ensure sufficient free matching parameters (α_x, β_x, α_y, β_y) @ (entrance, exit) in J-arc region
- These quads required to have large apertures to accept large beta-function for matching
- quads layout slightly modified to lower the peak value of beta-function
- In 2023 summer, the layout renewed, 7 pulsed quads installed and 1 DC quad remained for investigation of coil heating issue

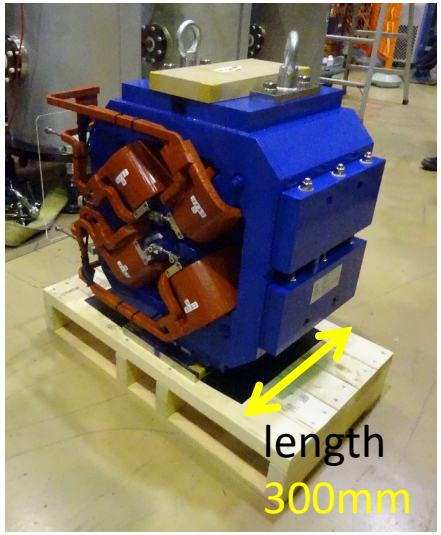


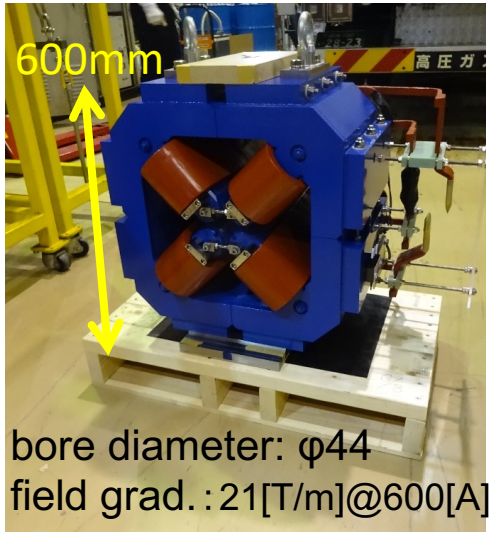


specification of pulse quad for J-arc

- requirement on field strength is minimized by simulation while keeping the beam matching performance and margin.
- bore size remains the same for sufficient aperture.
- current and turns/coil are optimized, however, requires larger capacity pulse driver.
- magnet (size) and ceramic duct are designed to be almost comparable to existing DC quad and duct.

parameters	DC quad R0_01 type	new pulsed quad R0_01
bore diameter [mm]	44	44
field gradient [T/m]	26.1	21
max. current [A]	56	600
pole length [mm]	300	300
effective length [mm]	323	333
B'L [T]	8.43	7
nI [A.turn]	5040	4200
turn of coil /pole	90	7
inductance [mH]	200	1.5



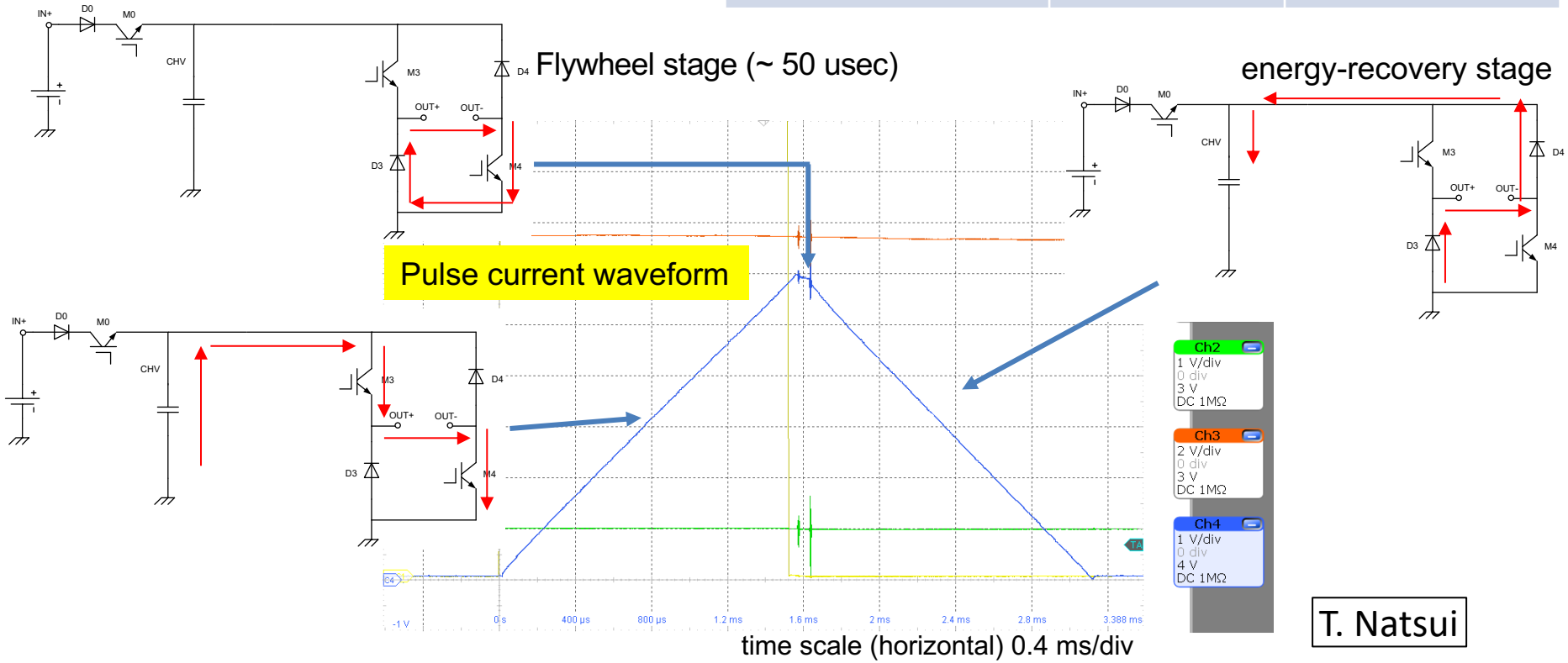


K. Yokoyama

new pulse driver for J-arc quads

- new pulse driver is developed for large-aperture J-arc pulsed quads.
- scheme was changed from current feedback to pulse width feed-forward control.

	3-5 sector type	New pulse driver
Max Voltage	230 V	400 V
Max Current	330 A	600 A
Magnet aperture	23 mm	44 mm
Magnet inductance	1 mH	1.5 mH
Control method	I_D-V_{GE} analog control	Pulse Width Feed-forward control



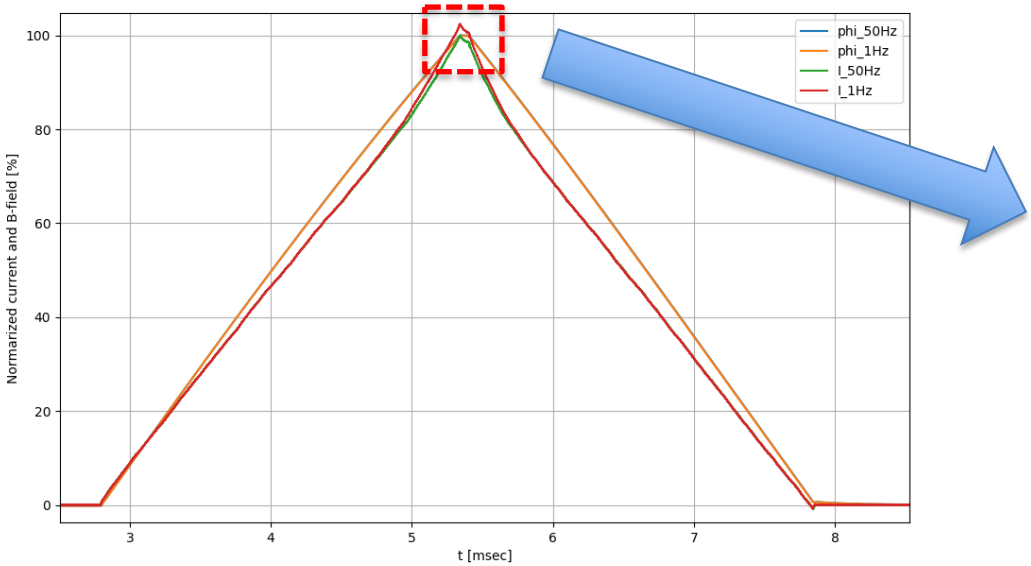
T. Natsui

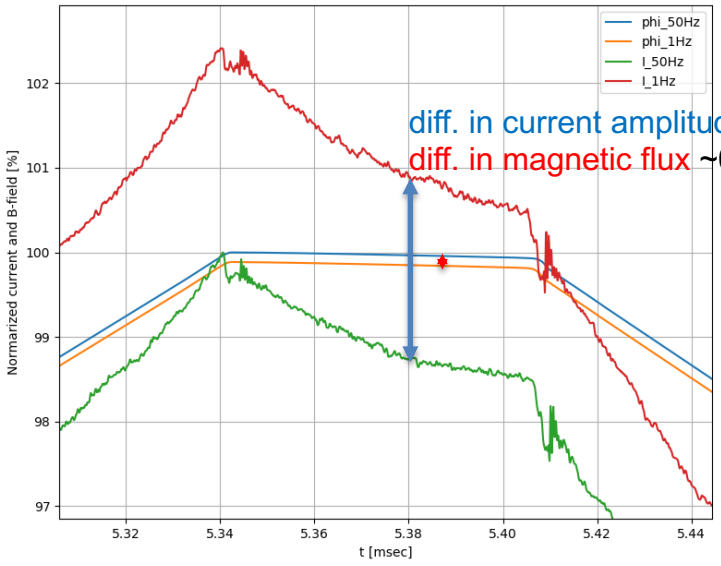
Current amplitude and Magnetic flux

- Pulse width control scheme in pulse driver make a difference in current amplitude for 1Hz and 50 Hz pulse repetitions. (due to change in effective inductance)
- However, change in magnetic flux (beam feels) is small. (1Hz, 50 Hz in figures)
- Pulse current variation upon coil-temperature should be monitored.


Magnetic flux is measured with one-turn pickup coil.

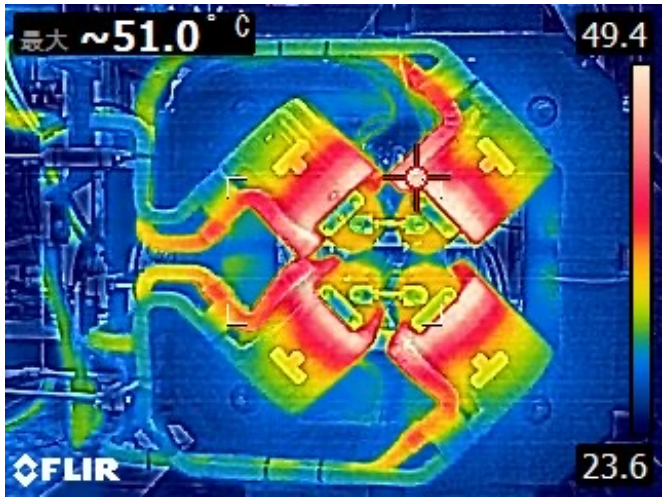
Pulse current & Magnetic flux waveforms

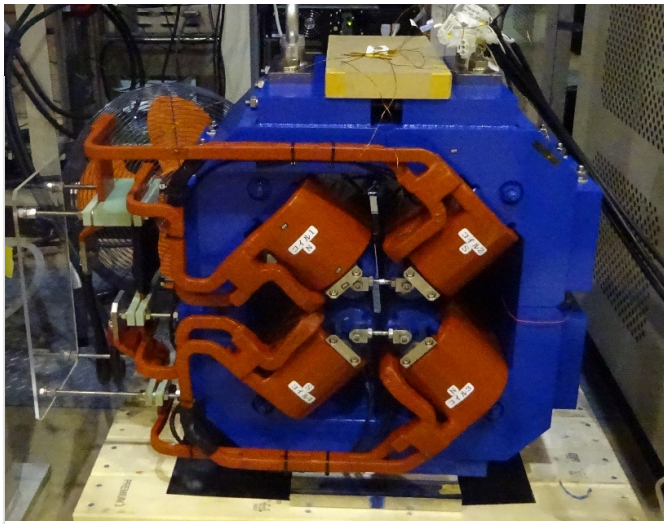


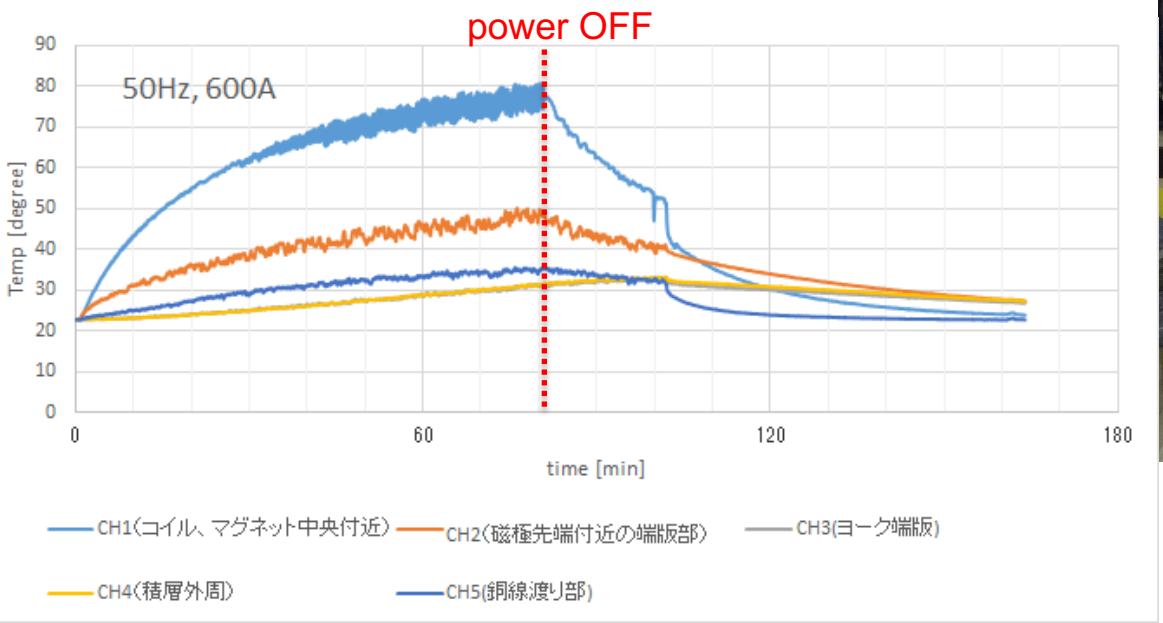


excessive heating in quad coils

- In the full-spec. (600A, 50 Hz) operation test before installation, excessive heating in inner most layers of quad coils was observed.
- It is due to eddy current in coil conductor by leakage field from the pole.
- The coils were designed to be air-cooled, the temperature rose up to 80 degree (~interlock limit) in 80 minutes at 600A, 50Hz.

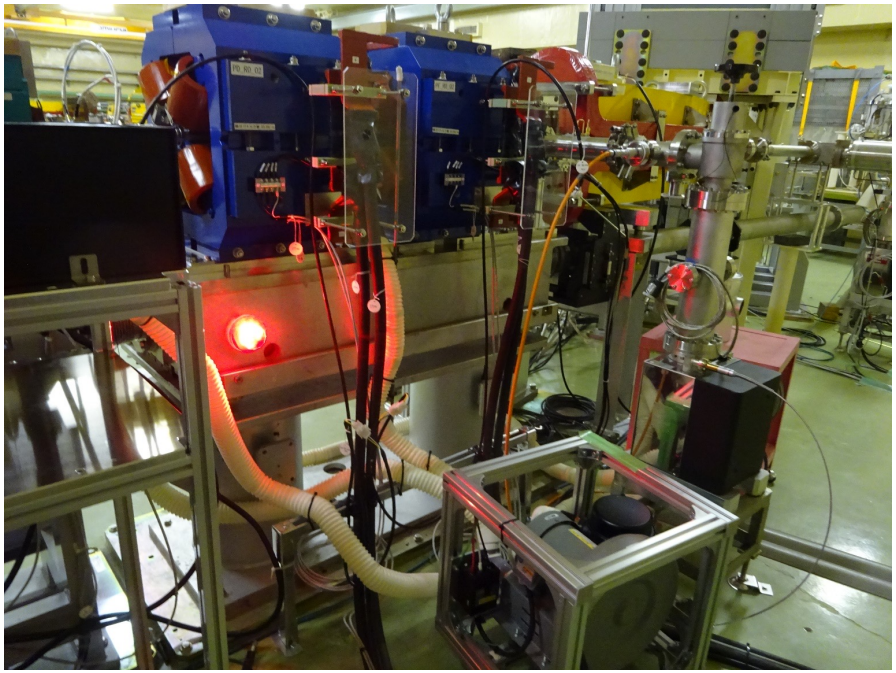






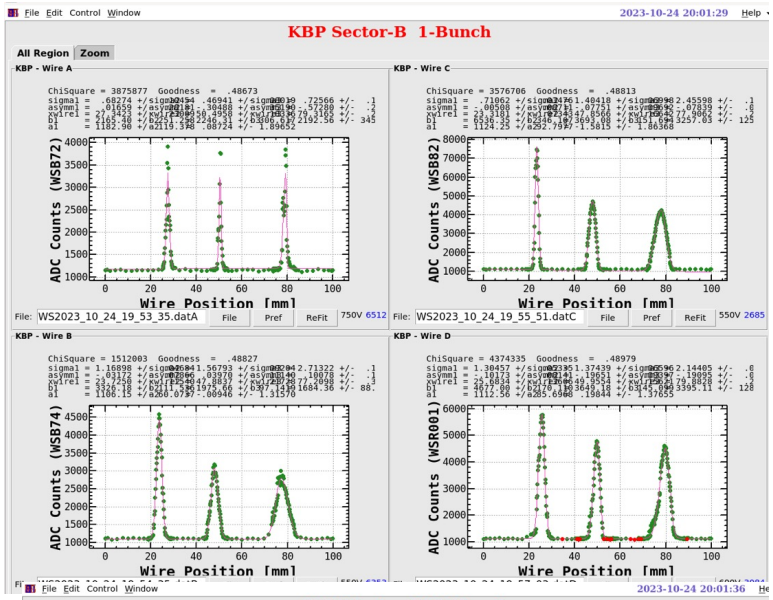
forced air cooling with blowers

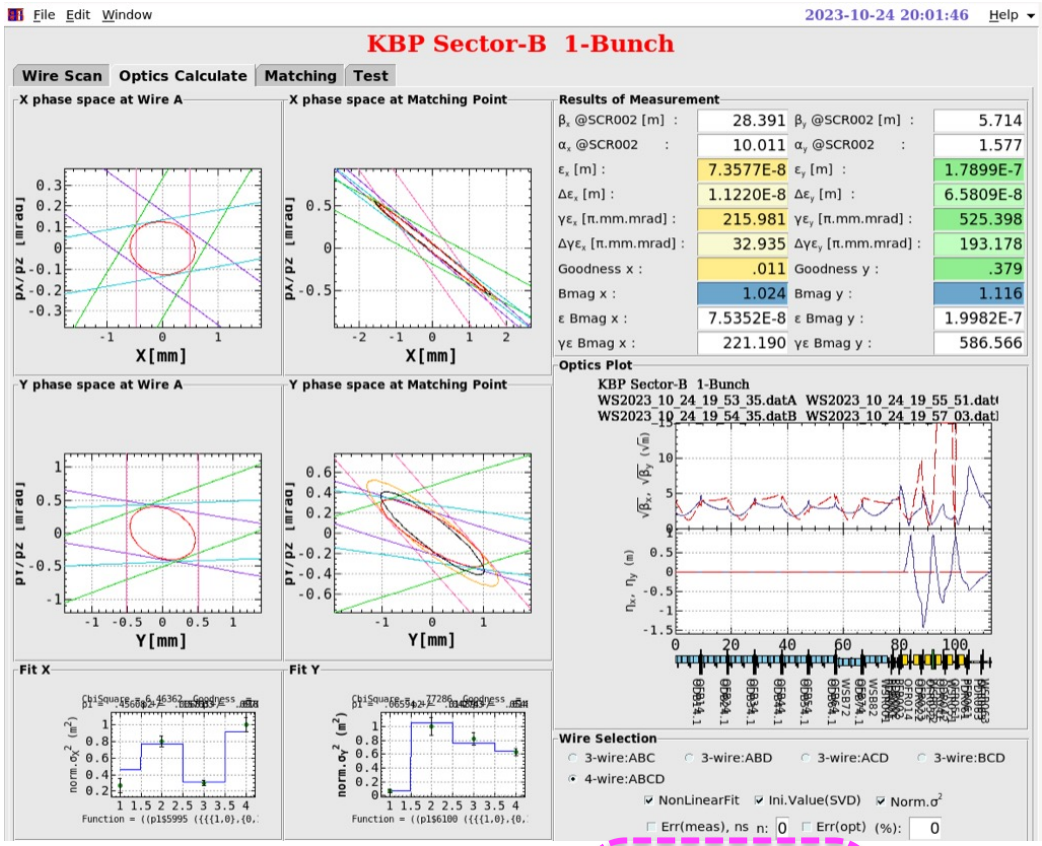
- temperature rise test operation showed
  - 600A, 50 Hz (full spec.) → NG
  - 600A, 25 Hz operation → OK
  - < 400A, 50 Hz operation → OK
- blowers for forced air cooling installed for 4 quads whose operation current higher than 400 A.
- with the blower, coil temperature was kept below 58 degree at full spec.
- new water-cooled coils are designed and to be tested soon for future replacement. An uninstalled pulse quad is used for this test.

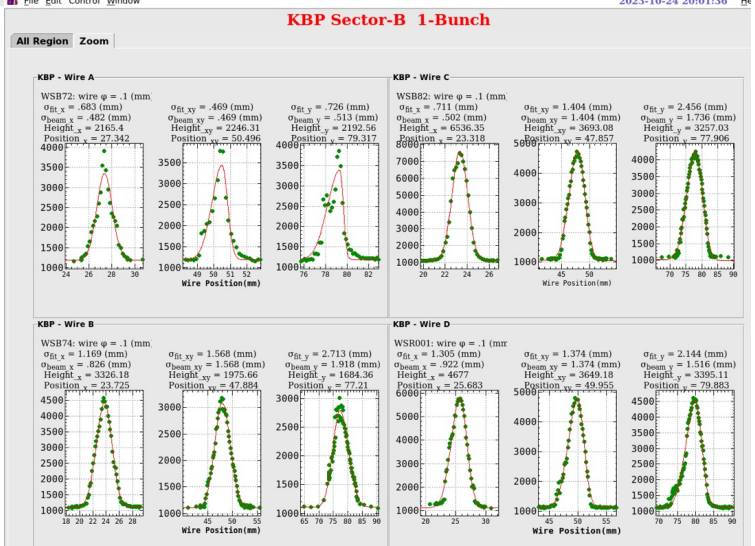


KBP 10nC e- beam matching with pulsed quads

- B_{MAG}~1 means good beam optical matching achieved for KBP e- beam





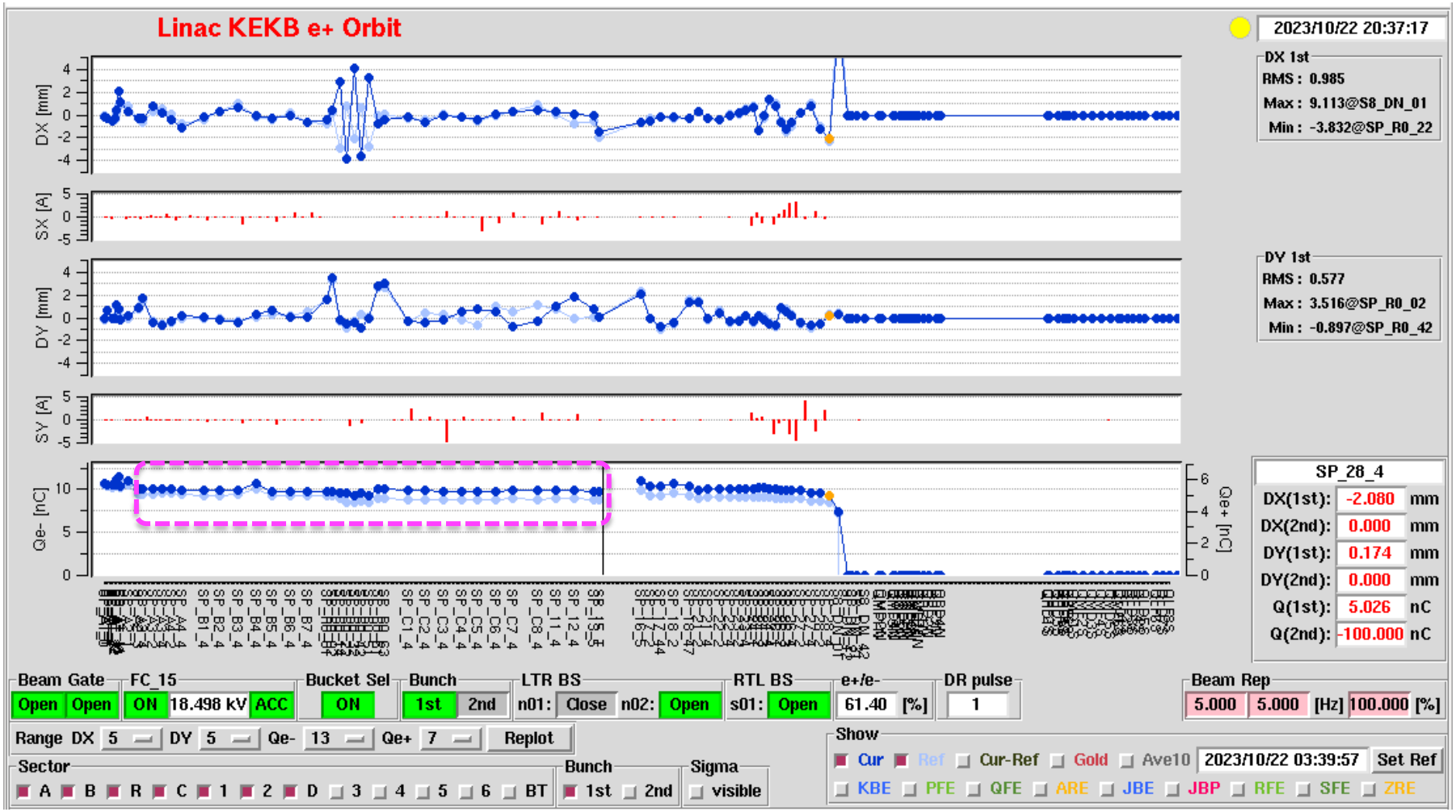


	γε [μm]	B_{MAG}
X	216.0±32.9	1.02
Y	525.4±193.2	1.12

(N. Iida 2023.10.25 LCG report)

Improved beam transmission after J-arc upgrade

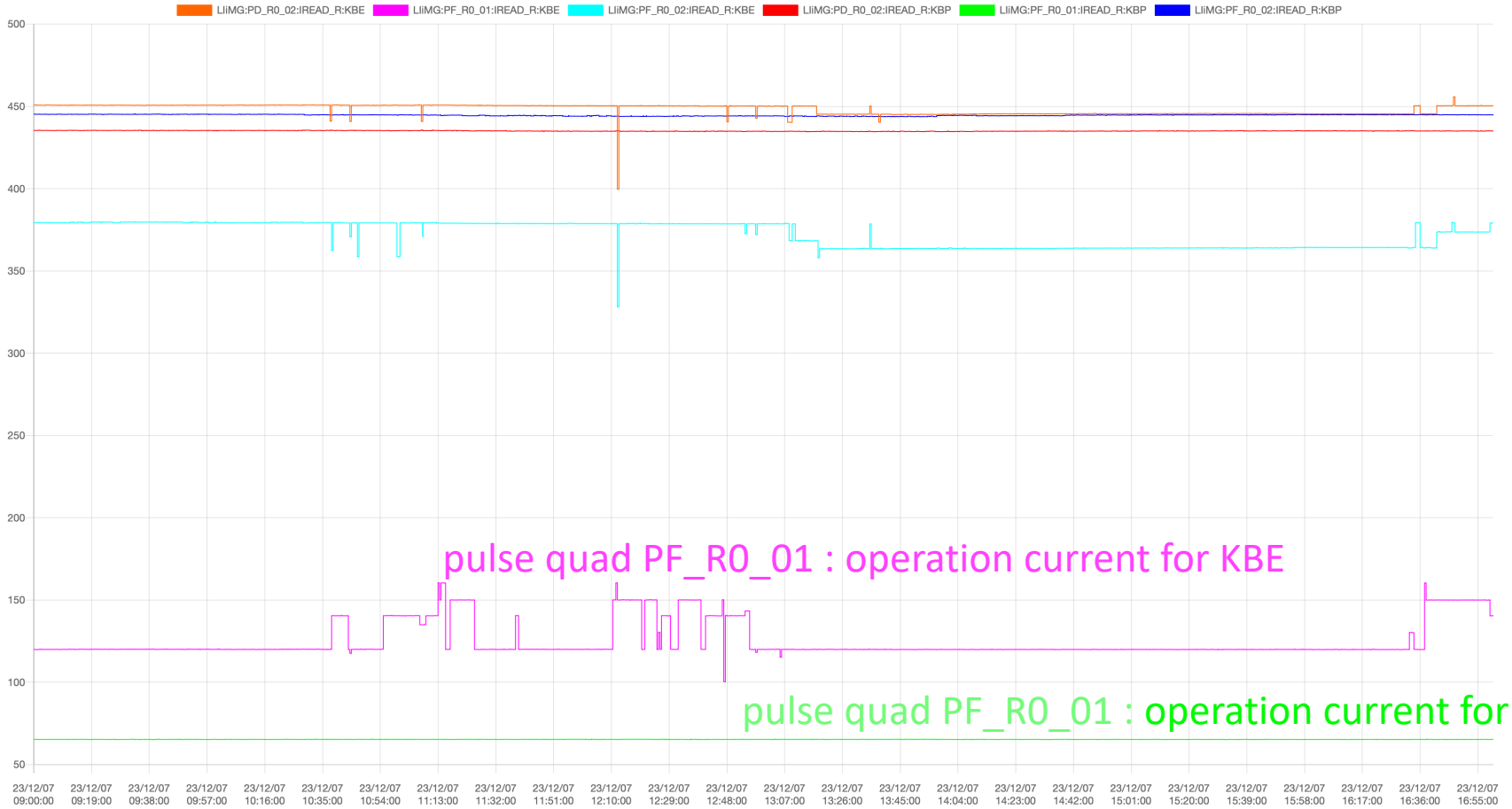
- Almost 100% transmission for KBP beam at J-arc after Natsui-san's automatic Bayesian parameter tuning of quad strength, orbit and RF phases.
- Improvement in optical matching contributes to the result.



(T. Natsui 2023.10.23 LCG report)

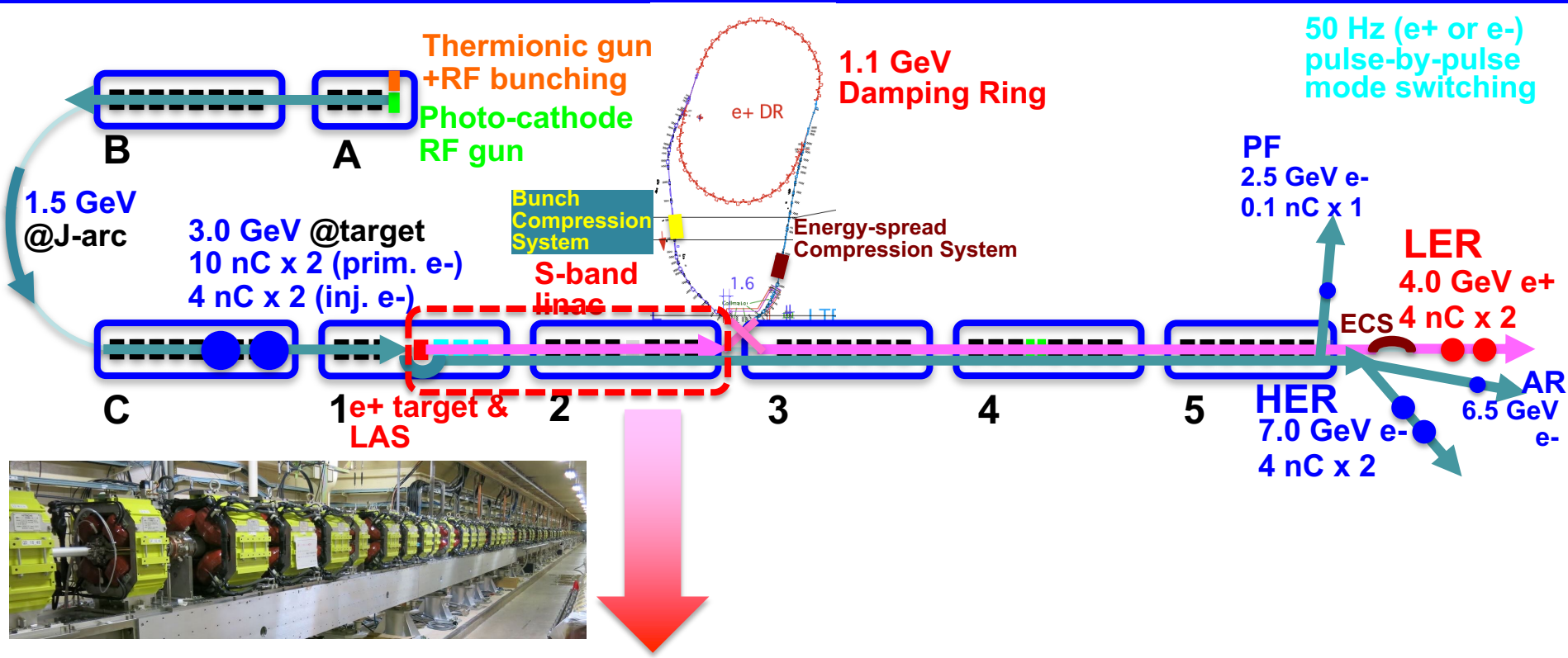
Independent KBE beam tuning at J-arc

- Under the situation with optimized matching for KBP beam, independent matching parameter tuning for KBE beam can be performed with the pulse quads.
- Variation in magnet current for KBE beam tuning is seen in the plot, while that for KBP is constant at the already optimized value.



Upgrade item [2]
Pulsed quads at e+/e- compatible optics region

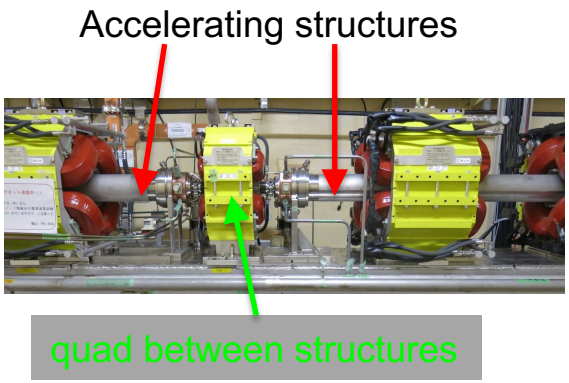
e+/e- compatible optics region in injector linac



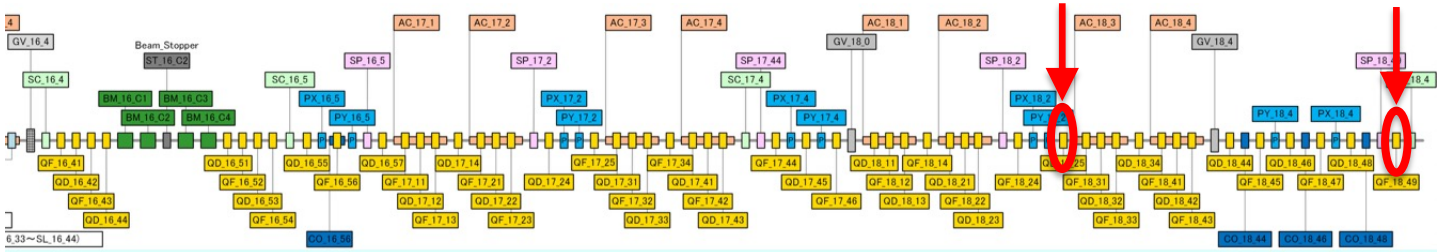
- beam optical design in the region (after e+ capture section to LTR entrance) is optimized for low-energy e+ beam transmission (E(e+) ~ 0.12 to 1.1 GeV)
- plenty of DC quads are used for this optics
- e- beam (with higher energy E(e-) ~ 2.9 to 4.2 GeV) experiences very weak focusing with large beta-function.
- slight change in orbit causes emittance growth of e- beam in this region

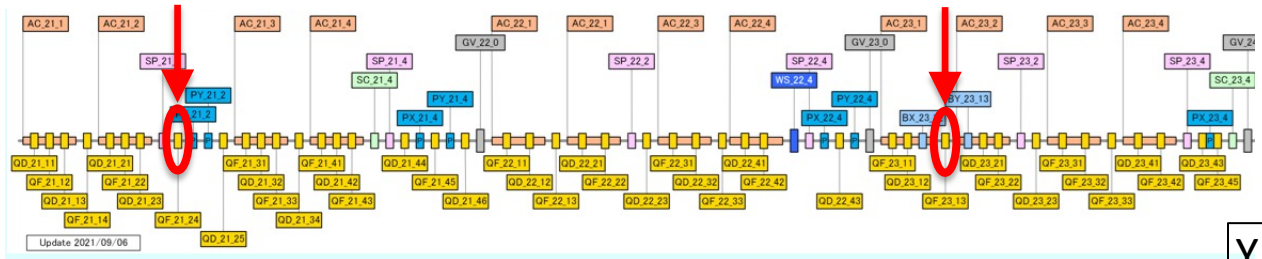
magnet layout in Sector-1, 2

- quads wrapping around the accelerating structure cannot be pulsed because of eddy current in copper
- only quads in between the structures can be pulsed
- only four DC quads shown below replaced with pulsed magnets

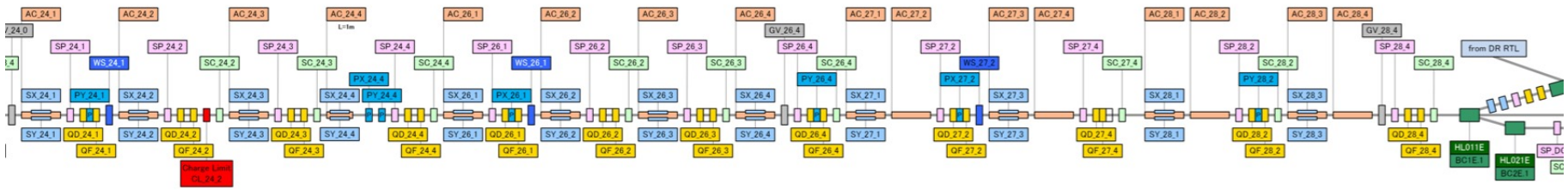


beam line layout in Sector-1, 2





Y. Seimiya

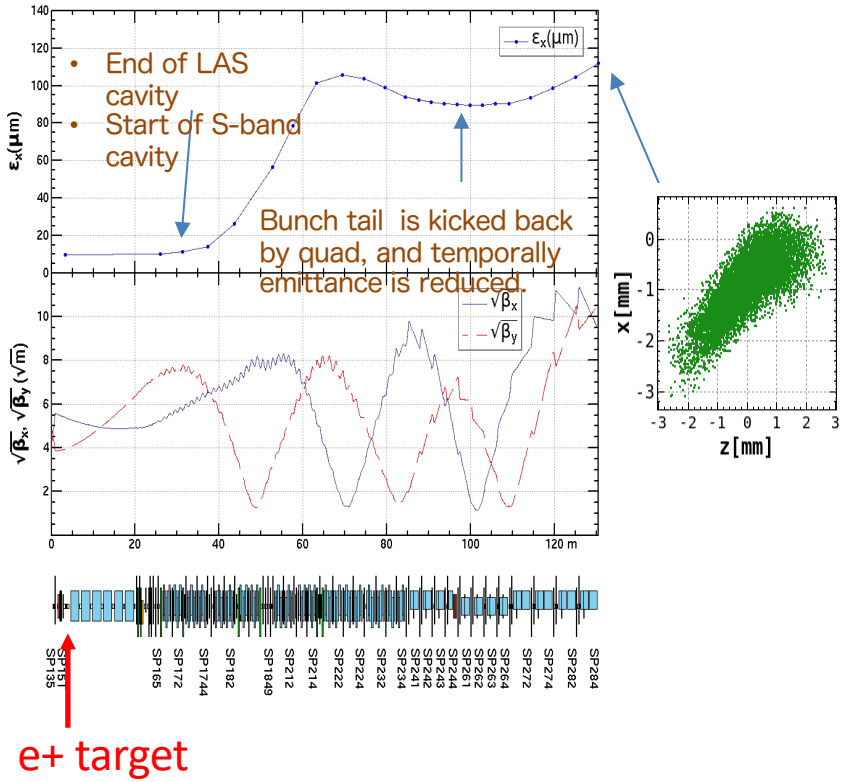


emittance growth reduction by low beta optics

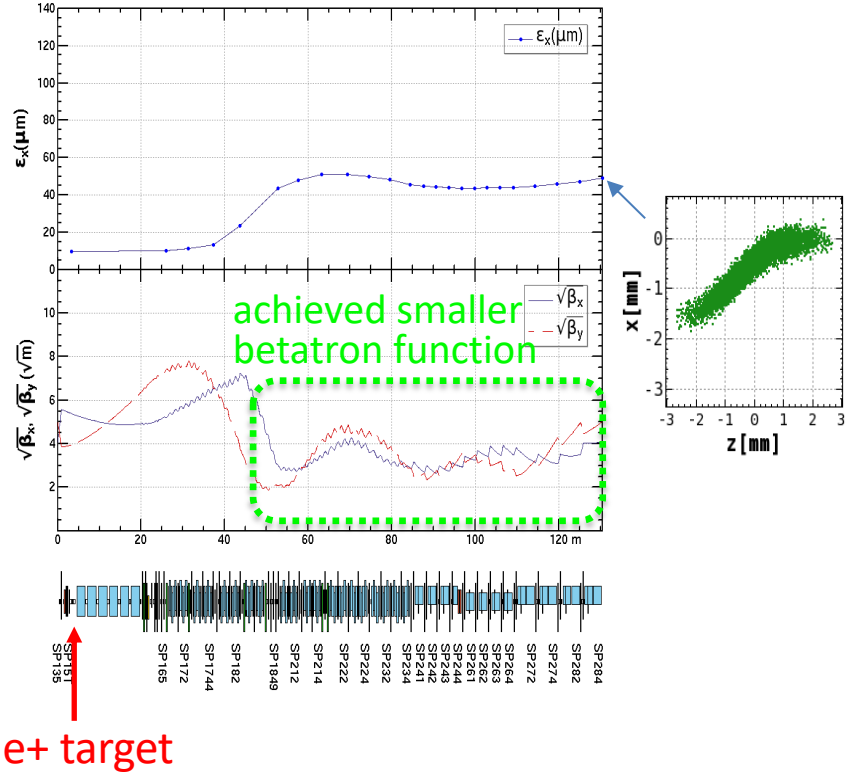
- lower beta-function can be achieved by setting four pulsed quads to e- oriented focusing strength
- it can reduce emittance growth rate less than half (simulation)

Y. Seimiya

$\Delta\gamma\varepsilon x$ ~ 100 um, $\overline{\beta x} = 45.2$ m



$\Delta\gamma\varepsilon x$ ~ 40 um, $\overline{\beta x} = 16.3$ m



specification of pulse quad for Sector-1, 2

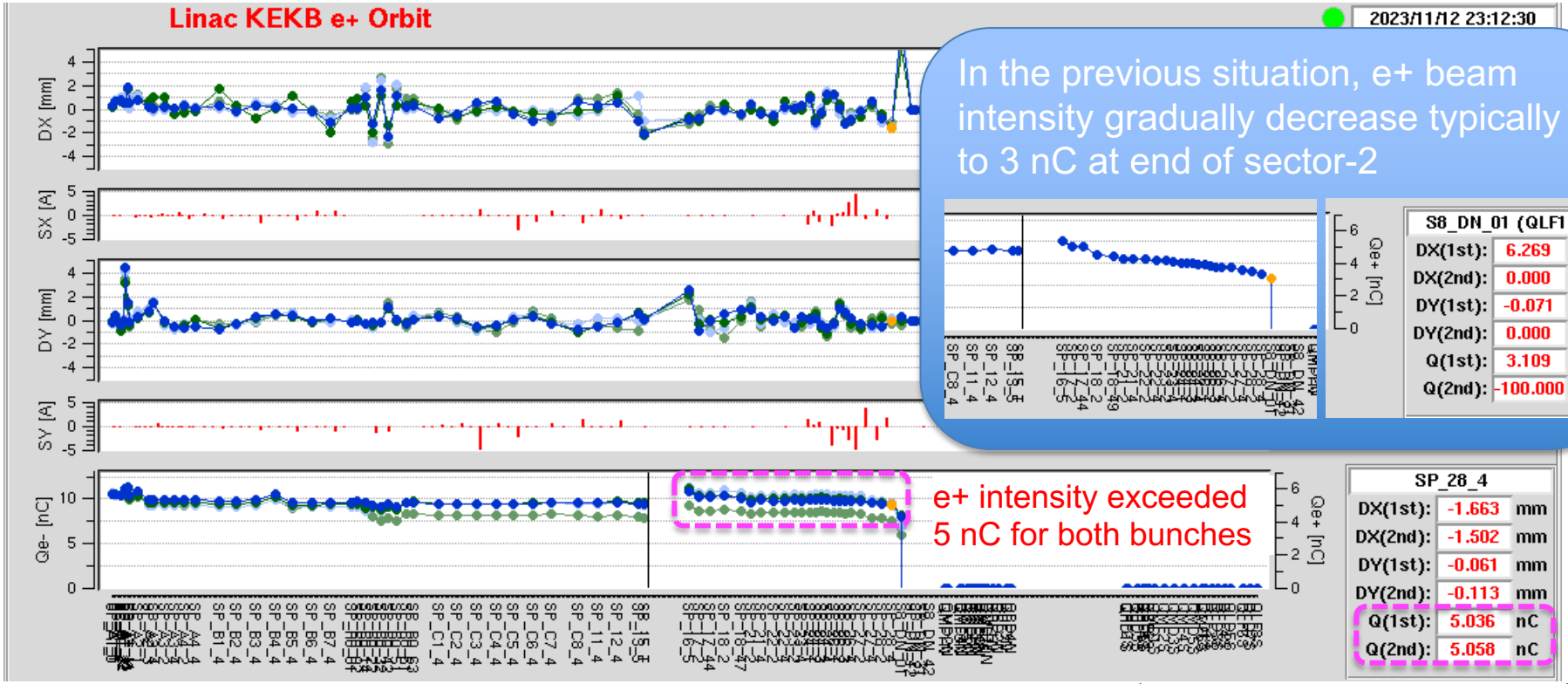
- requirements on bore size and field strength are minimized by simulation while keeping the performance.
- magnet (size) and ceramic duct are designed to be replaceable with existing DC quad and duct.
- current and turns/coil are optimized to be compatible with ordinary pulse driver.

parameters	DC quad 17_14 type	new pulsed quad 17_14
bore diameter [mm]	44	32
field gradient [T/m]	20.9	23.6
max. current [A]	80	300
pole length [mm]	160	160
effective length [mm]	173.8	168.0
B'L [T]	3.63	3.96
nI [A.turn]	3760	2400
turn of coil /pole	47	8
inductance [mH]	32.3	0.94

K. Yokoyama

e+ beam transmission improved

- e+ beam transmission greatly improved after Natsui-san's automatic Bayesian parameter tuning of quad strength, orbit and RF phases.

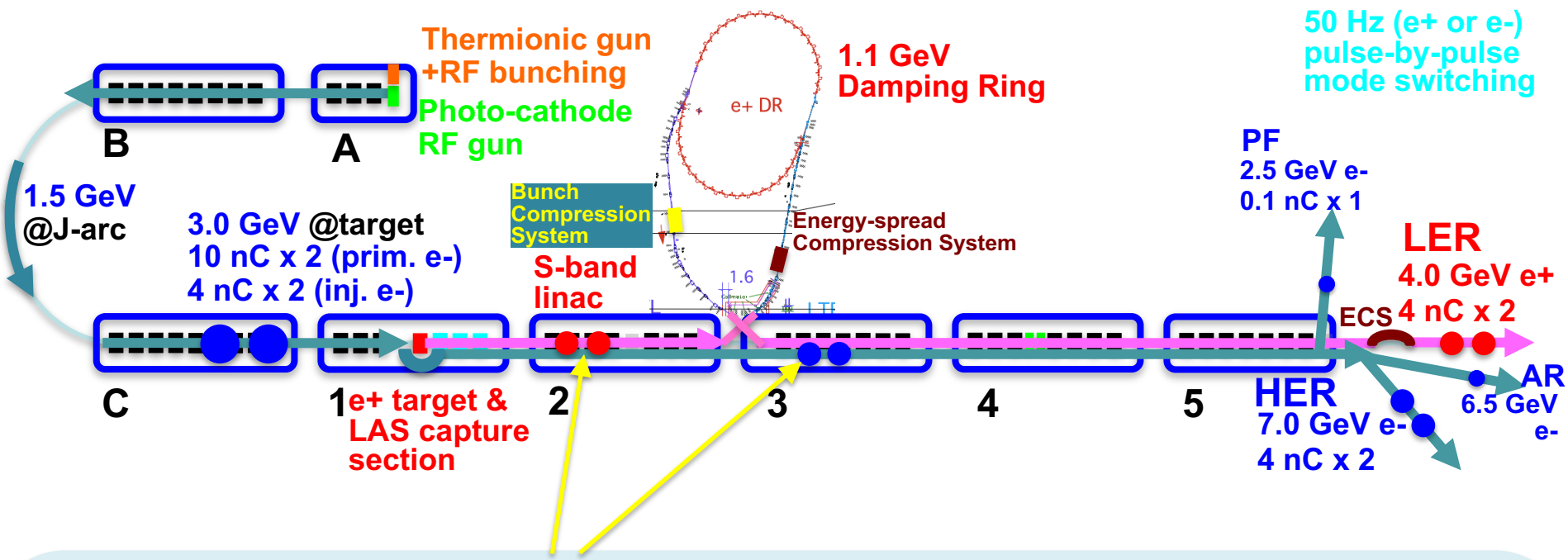


(T. Natsui 2023.11.13 LCG report)

- since thorough tuning of all the DC and pulsed quads resulted in this success, the contribution of pulsed quads are just a small part.
- However, we can proceed to low-beta optics tuning for e- beam with pulsed quads while keeping the good condition for e+ beam.

Upgrade item [3]
Linac fast kicker for bunch orbit difference tuning

2-bunch operation in injector linac



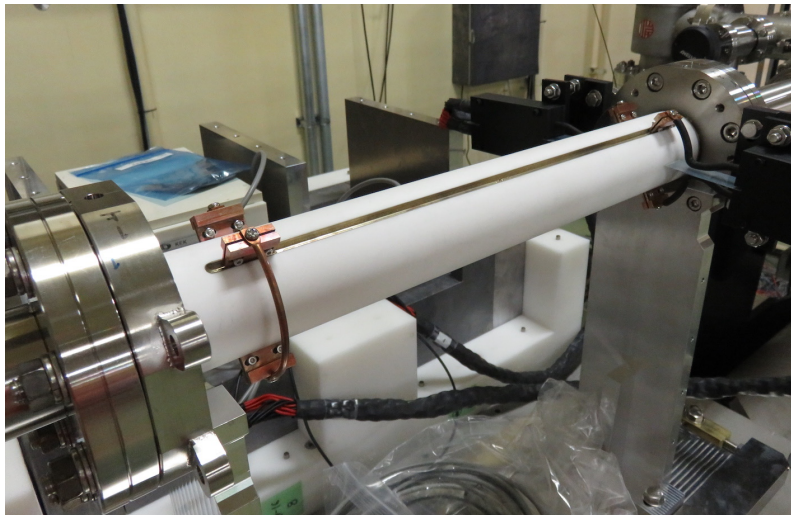
- Linac can inject two bunches per pulse to increase injection charge for SuperKEKB main rings (HER and LER).
- The 2nd bunch follows the 1st with 96 ns interval.
- The 2nd bunch can have slightly different beam orbit and Twiss parameters from the 1st, even their beam energies are equalized.
- The 2nd bunch tend to lose a fraction of charge at J-arc or at target-hole due to a deviation of the orbit.
- The 2nd bunch tend to have lower ring-injection efficiency as well.

Need for Fast Kicker

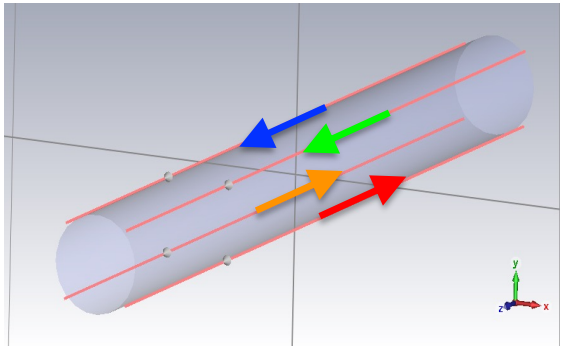
- The bunch interval 96 ns is too short for ordinary pulsed steering magnet (pulse rise time ~ several ms) to kick only either bunch.
- Fast kicker (< 96 ns) is necessary to control the bunch orbit independently.
- The kicker should have very low inductance.
- The pulse power supply should have pulse rise time < 96 ns.

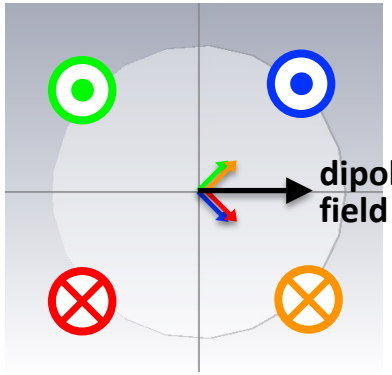
- Locations to install fast kicker
  - [1] entrance of J-arc
    for orbit tuning in J-arc, prototype test of kicker and power supply
  - [2] linac-end & BT-line
    for tuning of injection orbits for HER and LER
  - [3] low energy region of linac (sector-A)
    for orbit tuning at low energy

Ceramic chamber type Fast Kicker



C. Mitsuda

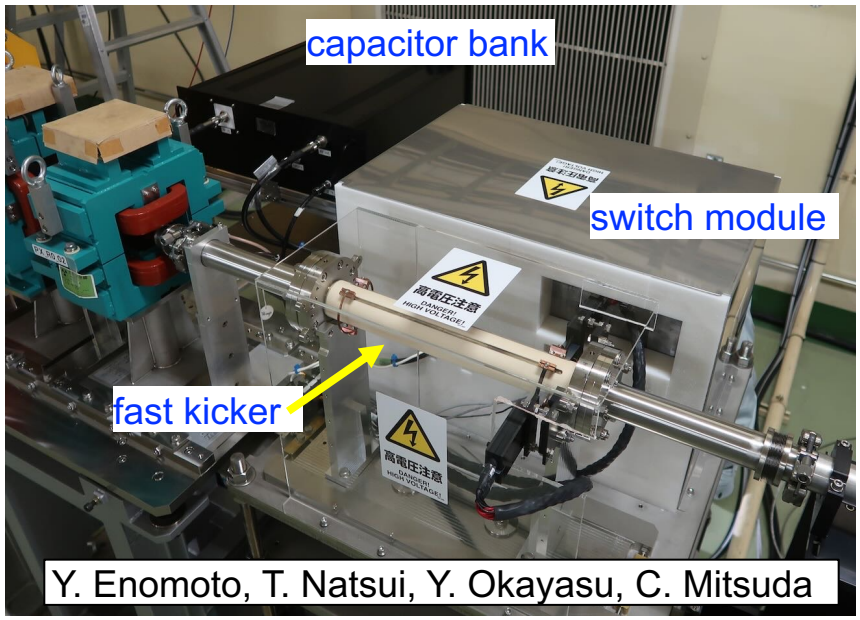


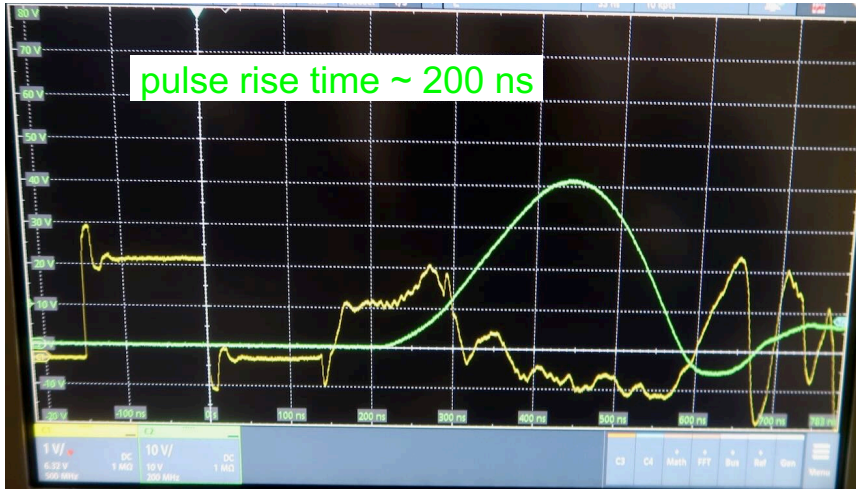


- CCiPM : Ceramics Chamber with integrated Pulsed Magnet developed by C. Mitsuda was introduced for linac bunch orbit kicker.
- Magnetic field type kicker
- This kicker has four parallel coil wires.
- The current configuration described above (parallel and anti-parallel currents) generates horizontal dipole magnetic field, (vertical beam kick).

Prototype fast kicker and power supply @J-arc

- fast kicker (installed in 2022 summer)
  - CCiPM D40 type
  - inner diameter 40 mm
  - coil length 300 mm
  - field strength 5.6 mT@200A
- pulse power supply
  - SiC FET high-voltage switch
    developed in collaboration of C. Mitsuda and Nexfi technology co.
  - pulse rise time < 96 ns (spec.)
    to kick only 2nd bunch
    achieved rise time ~ 200 ns
  - max current 400 A
  - mac voltage 10 kV
  - precise timing control
    for kick angle fine tuning
  - unipolar
  - switch module installed in the tunnel
    close to kicker magnet
    (needs thick radiation shield)
  - interference occurred in ordinary pulsed steering magnet power supply
    （kicker support exchanged with insulator）

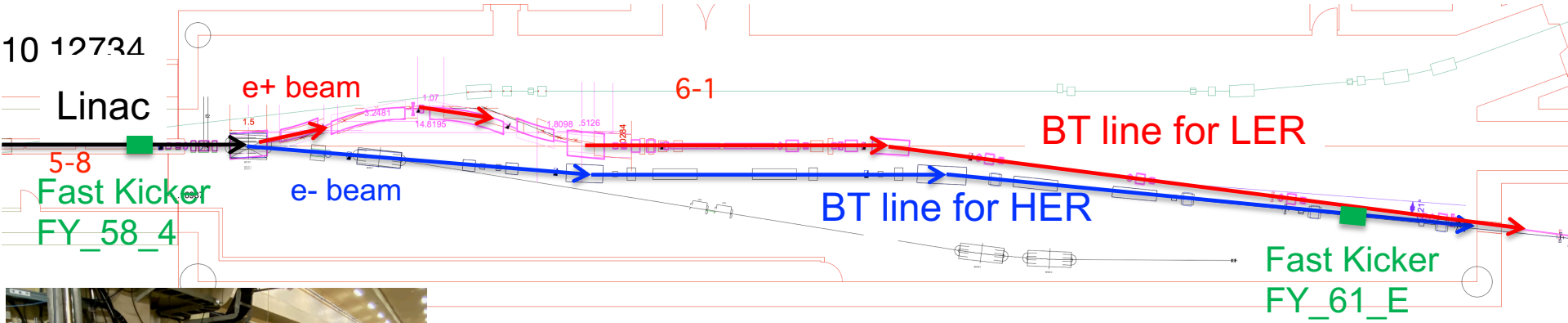


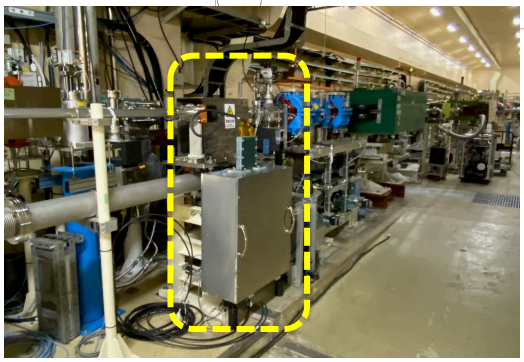


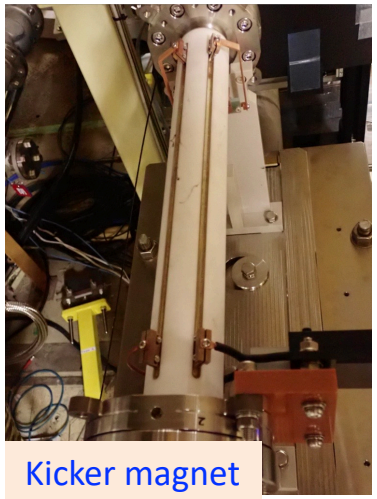
the slow rise time is expected to be due to additional inductance by connection cables.

Fast kicker at linac-end & HER BT line

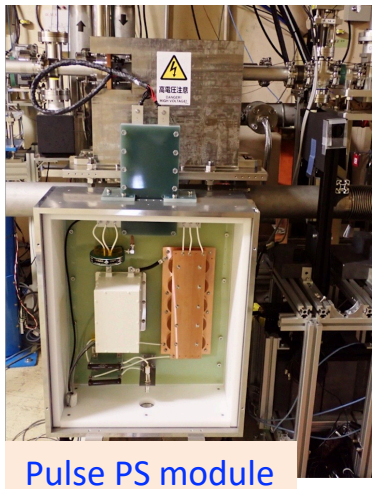
- Vertical fast kickers are installed in the linac end (58_4) and HER BT-line in 2023 summer.
- Kicker FY_58_4 started operation in 2023 autumn, FY_61_E in 2024 January.







Kicker magnet

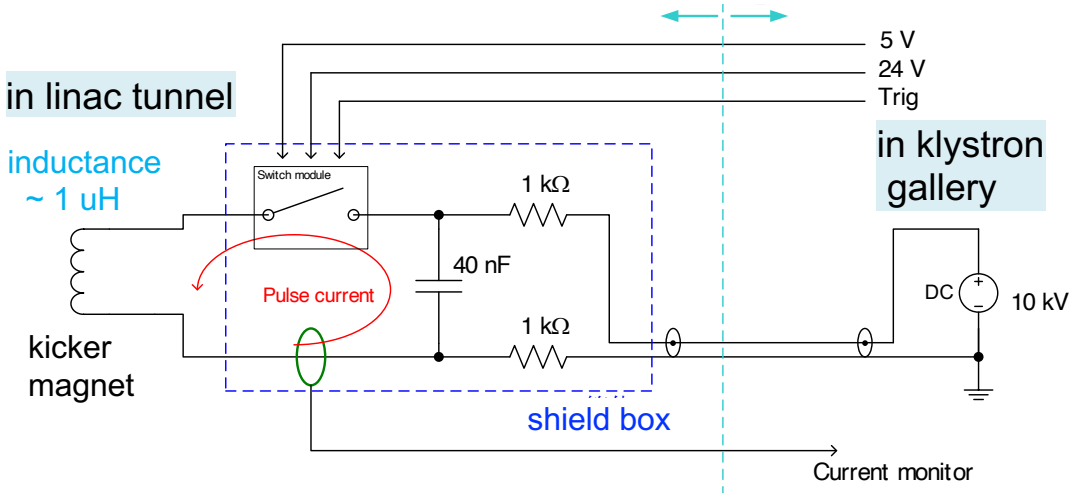


Pulse PS module

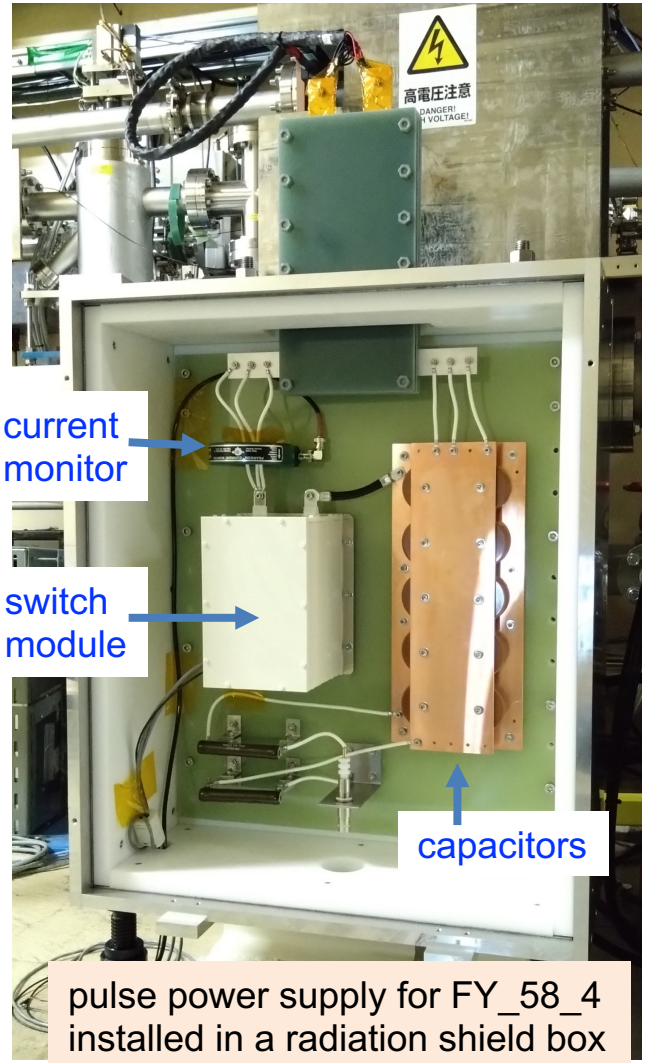
Y. Okayasu

Pulse power supply [ver-2 compactified]

- pulse power supply for fast kicker
  - SiC FET high-voltage switch
  - pulse rise time < 96 ns
  - max current ~ 400 A
  - max voltage 10 kV



- pulse rise time ~ 100 ns achieved with
  - newer version SiC FET switch (Nexfi)
  - compact layout of circuit components in a box
  - parallel plate bus bar line
  - compact connection of transition wiring between the terminals

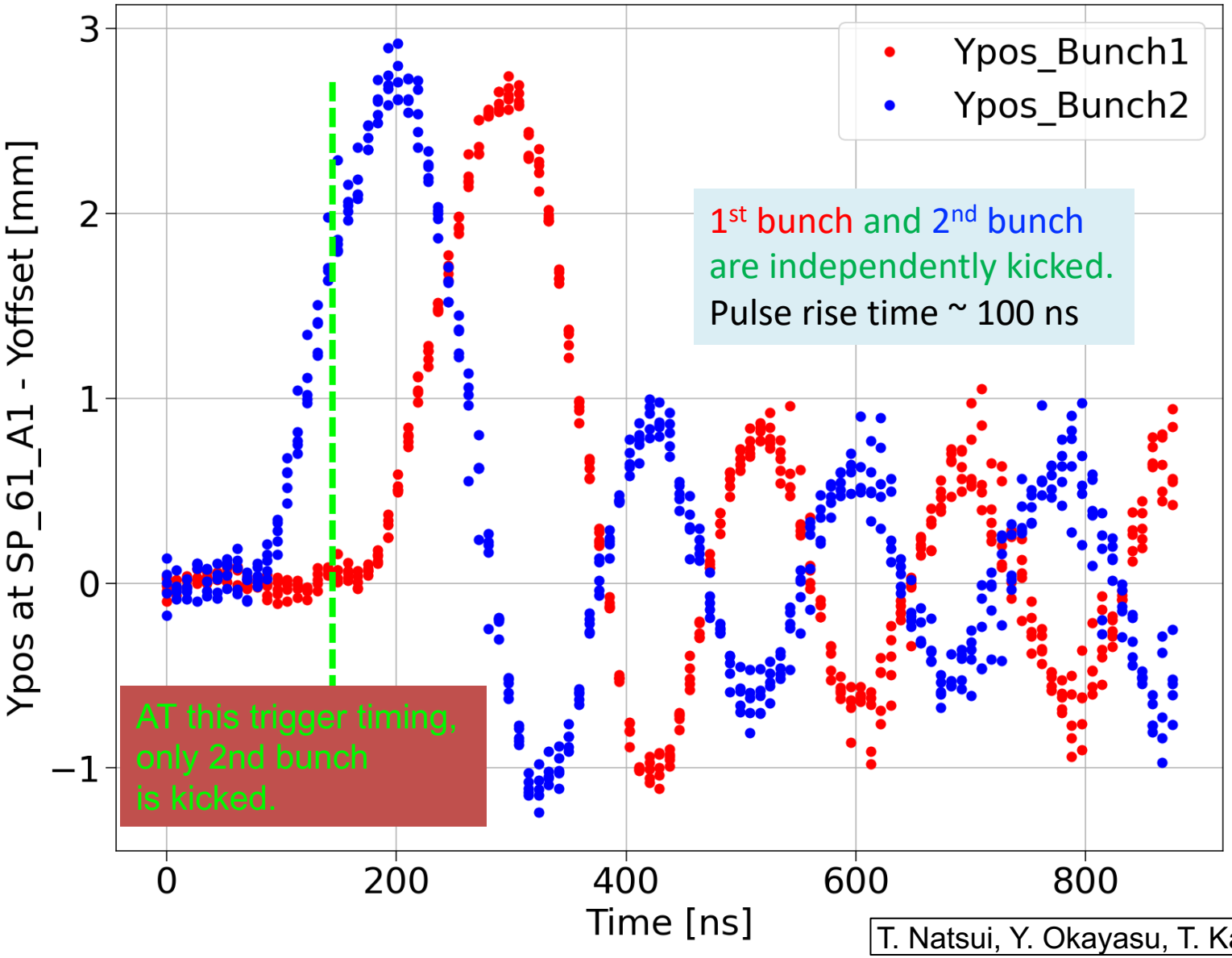


pulse power supply for FY_58_4 installed in a radiation shield box beside beam line at linac end

Y. Enomoto, T. Natsui,
S. Shinohara, Y. Okayasu

Beam kick test with kicker FY_58_4

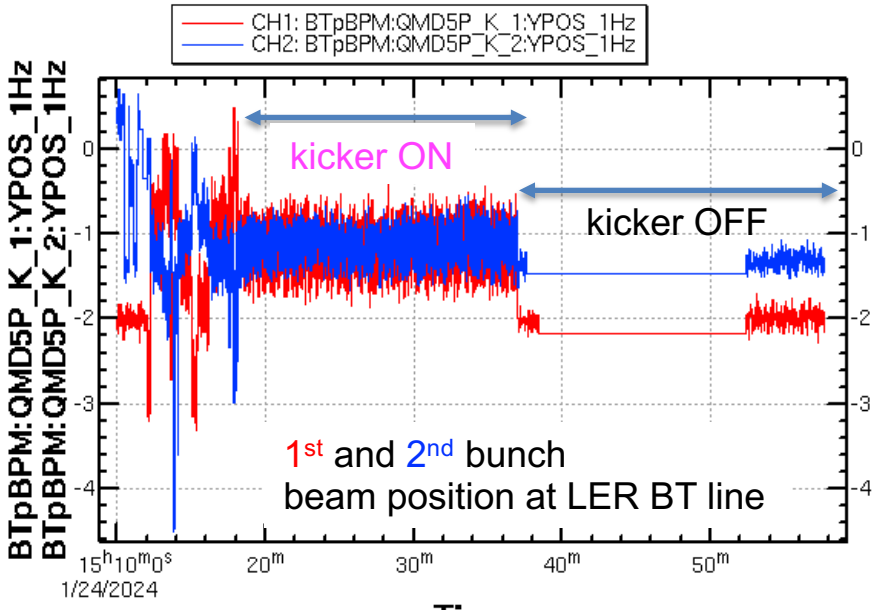
Observed vertical beam position at downstream of FY_58_4



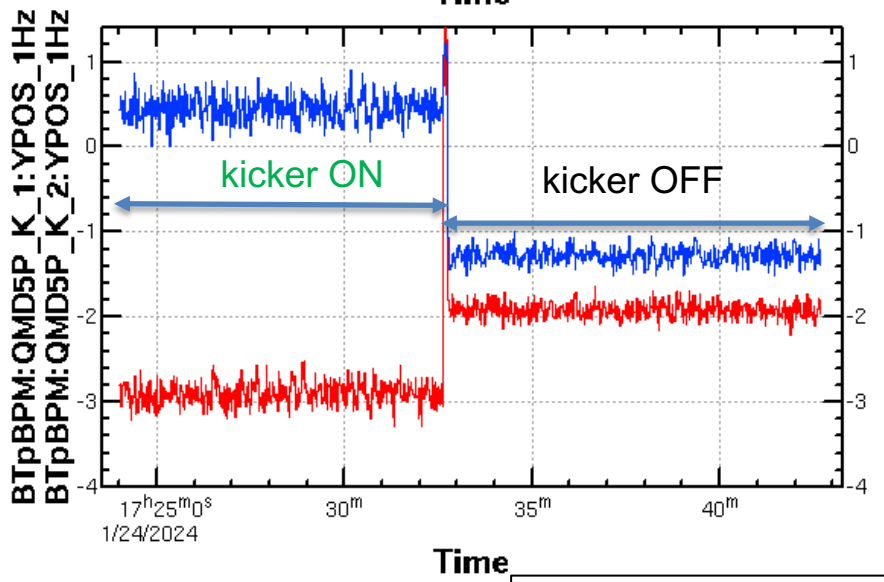
T. Natsui, Y. Okayasu, T. Kamitani

orbit jitter issue

- With fast kicker FY_58_4 ON, beam orbit of 1st and 2nd bunches at LER BT line was tuned to be at the same position by adjusting the trigger timing.
- However, the magnitude of position jitter increased with kicker.



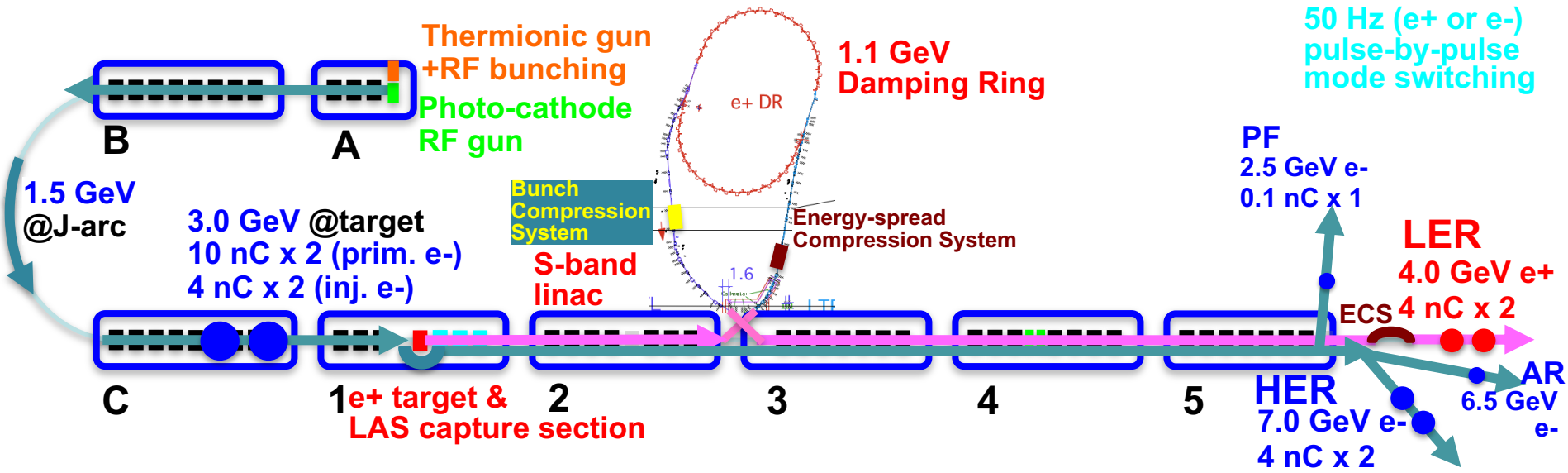
- By adjustment of pulse timing closer to the peak, the jitter magnitude can be smaller, but present.
- Timing jitter in switch module itself is < 0.1 ns.
- Investigation on the timing jitter of trigger signal after transmission is necessary.



N. Iida, T. Natsui, H. Ito

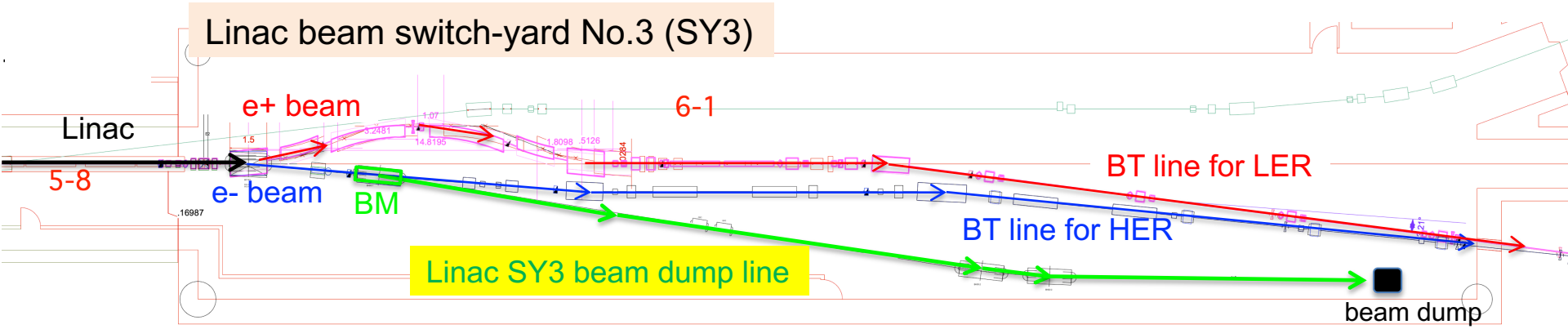
Upgrade item [4]
Pulsed beam switch-yard for beam diagnosis

Need for pulsed beam diagnostic branch line



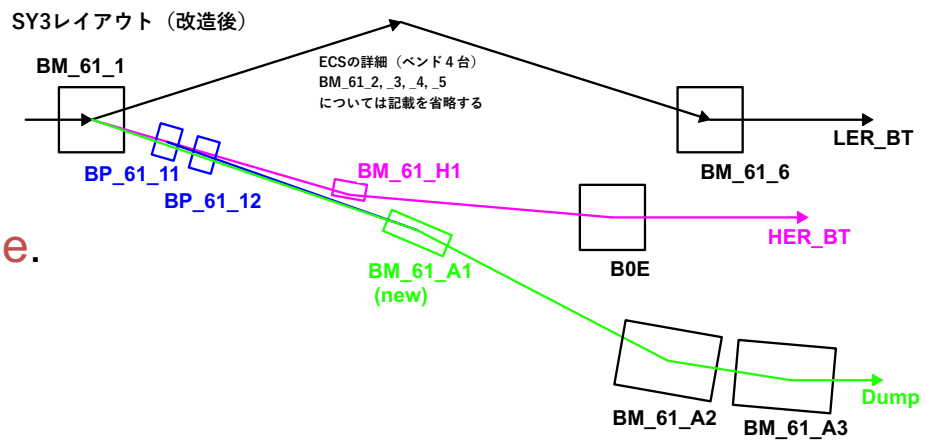
- Linac beam quality (energy-spread, emittance) is gradually degraded.
- e+ beam for LER is rather stable since e+ DR stabilize the beam condition.
- Degradation of e- beam quality directly lowers the injection efficiency to HER.
- e- emittance tuning needs a trial-and-error search for optimum orbit offset that takes at least several minutes or longer.
- the tuning is performed by extracting beams to linac switch-yard (SY3) or beam dump at the end of HER-BT line by interrupting the injection.
- it is to avoid storage beam abort initiated by a beam with large orbit deviation.
- pulsed diagnostic line enables emittance tuning in parallel with the injection.

Linac switch-yard No.3 (SY3) beam dump line



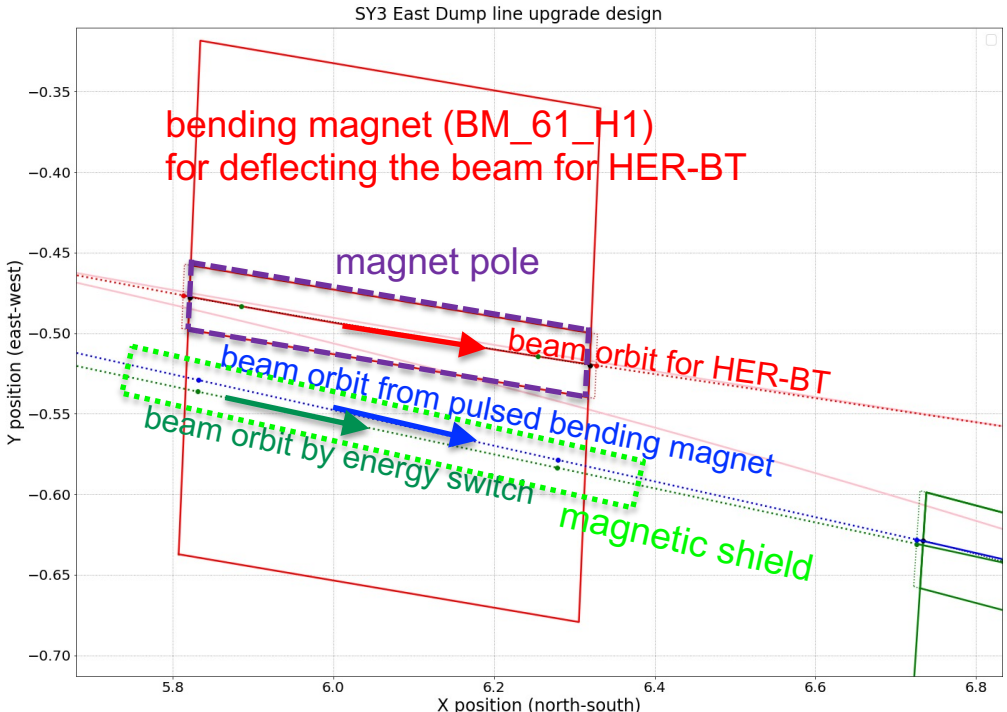
- For HER injection, the bending magnet (BM) deflect e- beam to HER BT line.
- For beam diagnosis, the BM deflect the beam to east beam dump line.
- This switching takes several minutes for changing polarity and current along hysteresis loop.

By replacing the existing large BM with two pulsed BMs,
a DC BM for HER-BT and
a DC BM for dump line,
pulse-by-pulse beam switching can be done.



beam lines proximity

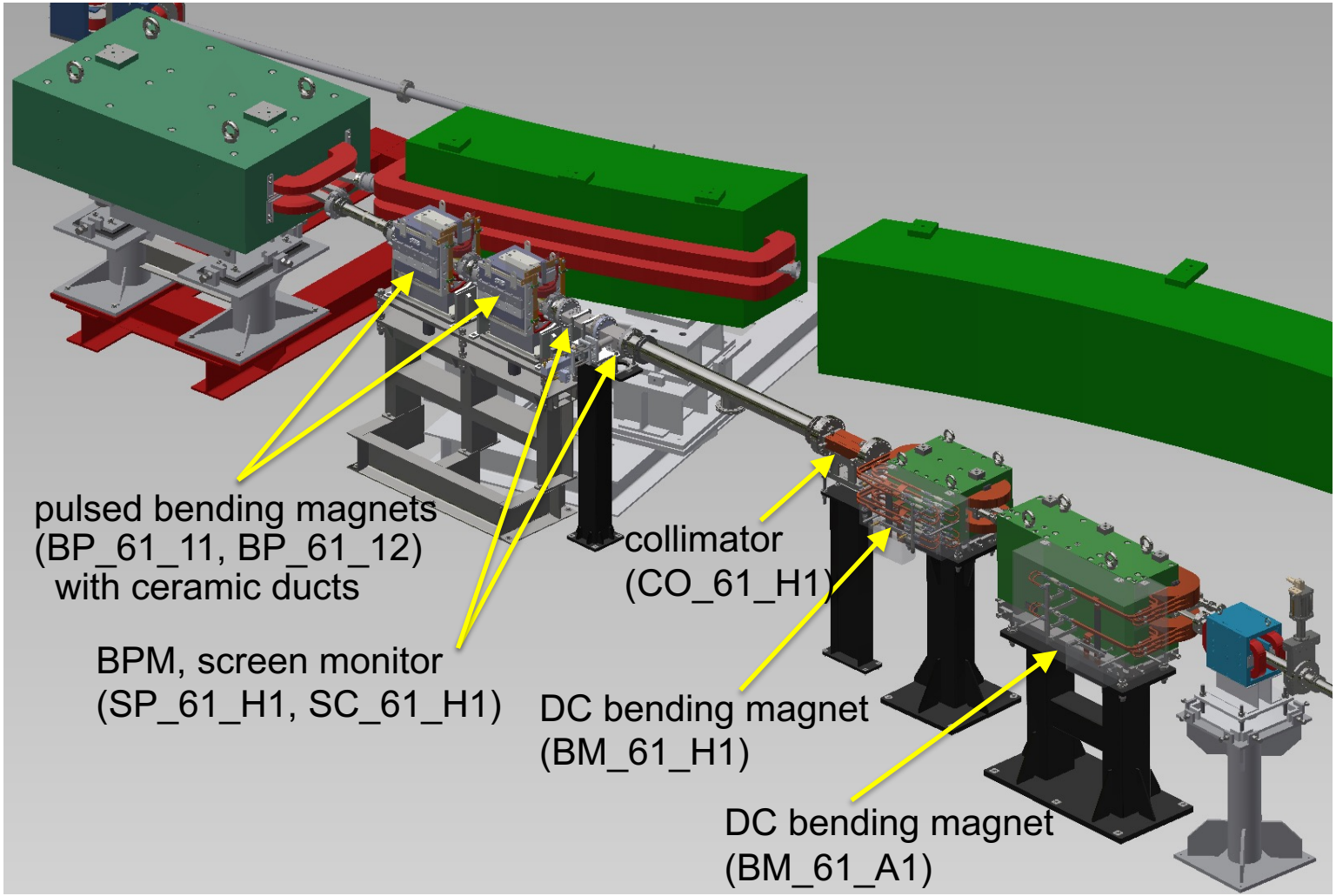
- New beam line for beam-dump runs in the vicinity of pole of the bending magnet for HER-BT line
- a magnetic shield is required to avoid the beam to be deflected by leakage field from the poles
- the magnetic shield can deform the field distribution in between the poles
- careful designing of the shield required to meet the both requirements



bending magnet (BM_61_A1)
for deflecting the beam
for the beam-dump

Pulsed beam switch-yard

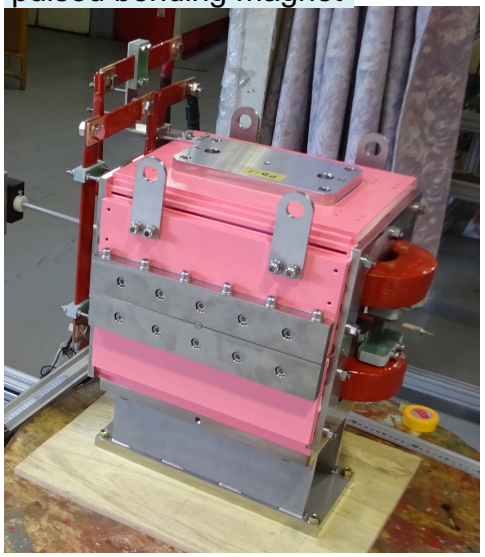
- Components to be installed in 2024 summer



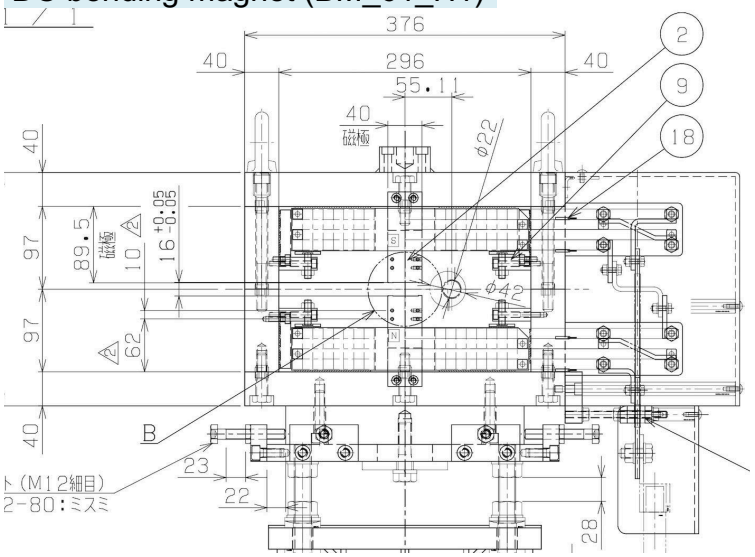
Component preparation status

- DC bend BM_61_H1 (completed)
- DC bend BM_61_A1 (completed)
- beam duct for DC BM and magnetic shield (to be manufactured)
- pulse bend BP_61_11, _12 (completed)
- ceramic duct for pulse bends (completed)
- beam collimator (to be manufactured)
- beam position monitor, screen monitor (completed)

pulsed bending magnet



DC bending magnet (BM_61_H1)



screen monitor

beam position monitor

Summary (Linac upgrade with Pulsed Magnets)

- Achieved items
  1. large aperture pulsed quads, ceramic ducts and new pulse drivers installed in J-arc matching section in 2023 summer
     → flexible matching tuning for each beam mode
  2. pulsed quads, ceramic ducts and ordinary pulse drivers installed in e+,e- compatible optics region in 2023 summer
     → flexible focusing tuning for each beam mode
  3. fast orbit kickers and pulse power supply installed in J-arc, linac-end, HER-BT until 2024 January
     → tuning of orbit difference between 1st and 2nd bunches
- remaining upgrade items and issues
  - Pulsed beam switch-yard for beam diagnosis (in 2024 summer)
  - J-arc last DC quad will be replaced with pulsed (in 2024 summer)
    and coil replacement in the future
  - fast orbit kickers in low energy region (sector-A) (in 2024 summer)
    and settling the jitter issue