SuperKEKB Status

BPAC

Kyo Shibata (KEK Accelerator Laboratory)

2024.09.24

Contents

- Highlight from 2024ab run
- Major works during summer shutdown
- 2024c run schedule and plan
- Summary

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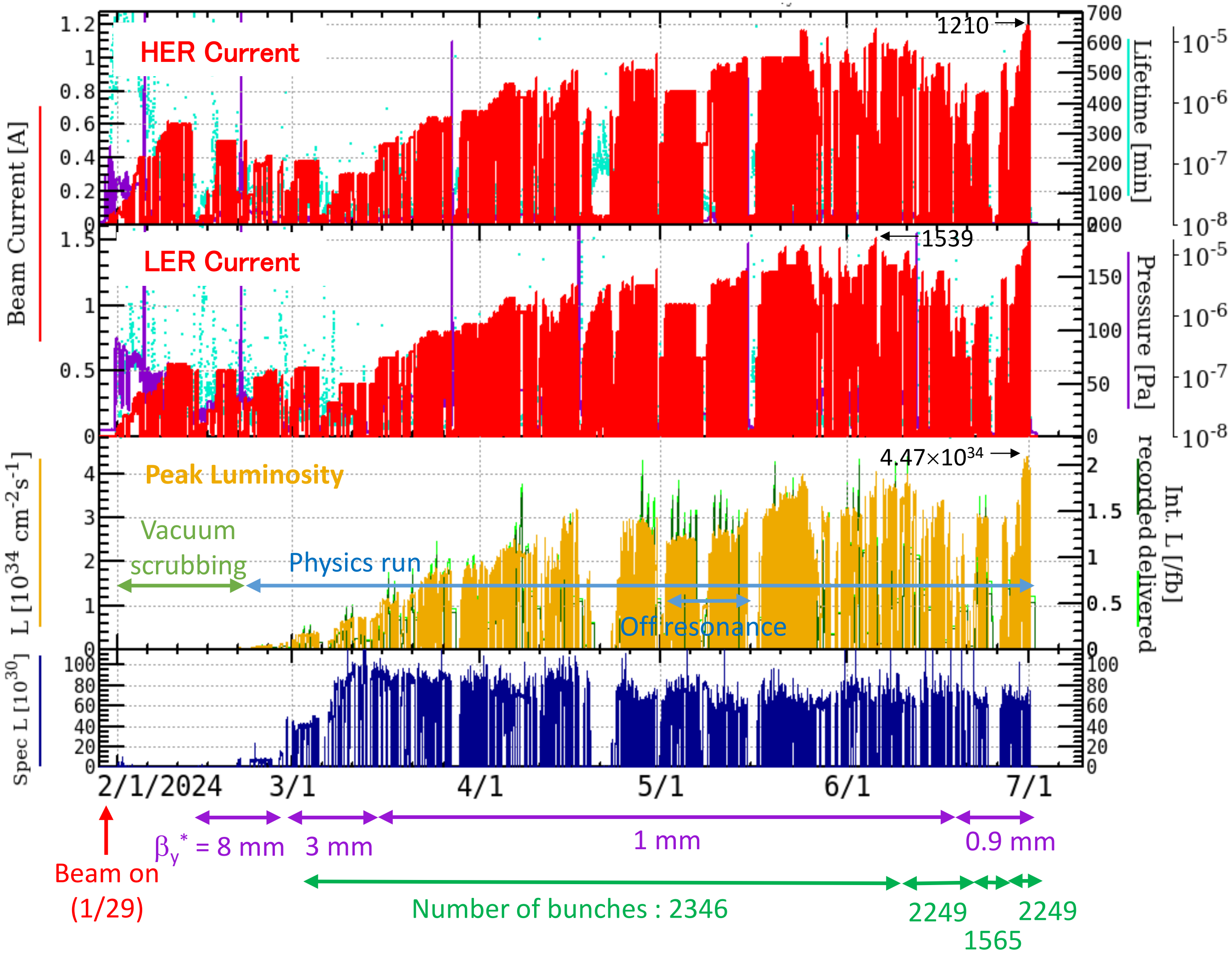
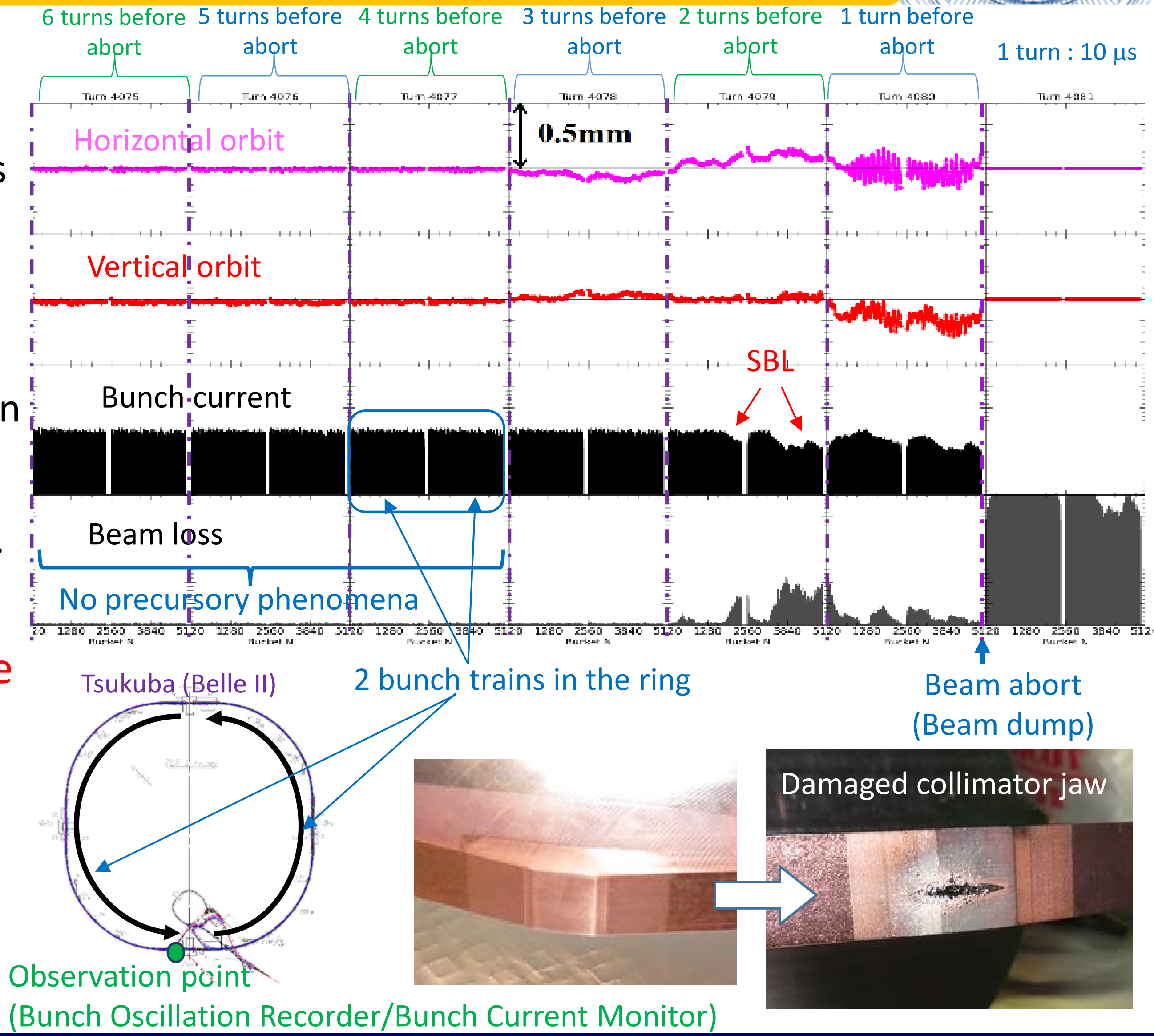
2024ab Run Overview

- Jan./29 – Feb./20
  - Vacuum scrubbing, Machine tuning, Machine study
- Feb./20 – July/1
  - Physics run, Machine tuning, Machine study
    - Struggling with Sudden Beam Loss, poor injection efficiency, low machine stability.
    - Many beam aborts caused by SBL and injection beam
    - May/1-12 : Off resonance operation
  - Peak luminosity : 4.47×10^{34} cm^{-2}s^{-1}
  - Integrated luminosity (2024ab) : 103 fb^{-1}
    - Max. Int. lumi. per day : 2.0 fb^{-1}/day
    - Total integrated luminosity : 527 fb^{-1}
  - Maximum beam current : HER/LER = 1210/1539 mA
  - β_y^*-squeezing (Vertical β-function at IP) : ~0.9 mm
    - Mostly operated with β_y^* = 1.0 mm
  - Others :
    - Fixed number of bunches mostly at 2346, finally at 2249
    - Crab waist ratio : HER/LER = 40/80 -> 60/80 %
    - Chromatic X-Y coupling correction by rotatable sextupole magnets.



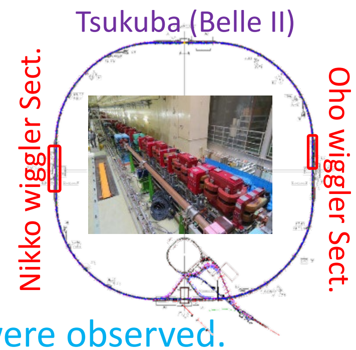
Sudden Beam Loss (SBL) #1

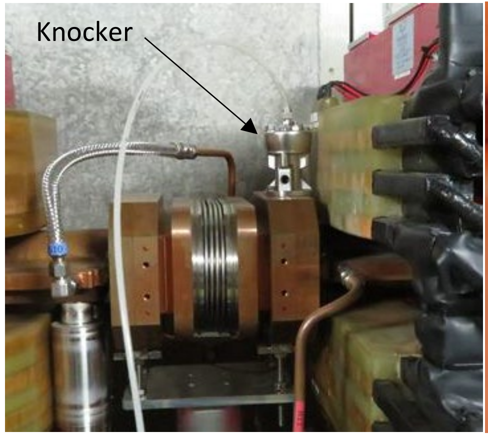
- Still struggling with SBL after LS1
  - Part of the beam is suddenly lost within a few turns.
  - Uncontrollable crazy beam can damage the collimators and Belle II detector.
    - It is difficult to maintain the MR in good working condition with damaged collimators.
    - SBL also can result in QCS quench.
    - Beam abort request is issued by beam loss monitors.
  - SBL is an obstacle to maintain stable machine operation and increase beam current.
  - SBL occurs more frequently in LER than in HER.
  - The cause of SBL has been unknow before 2024ab run.
    - New diagnostics tools (beam loss monitors, acoustic sensors, bunch oscillation recorders) were installed during LS1.
- Beam aborts with SBL and QCS quench damaged Belle II detector (PXD).
  - On 22nd/April and 6th/May
  - 10 % of PXD became unusable by these issues.
    - PXD HV was turned off to prevent further damage.
  - LER collimator D02V1 jaws were also damaged.
    - However, not large impact on beam operation fortunately.

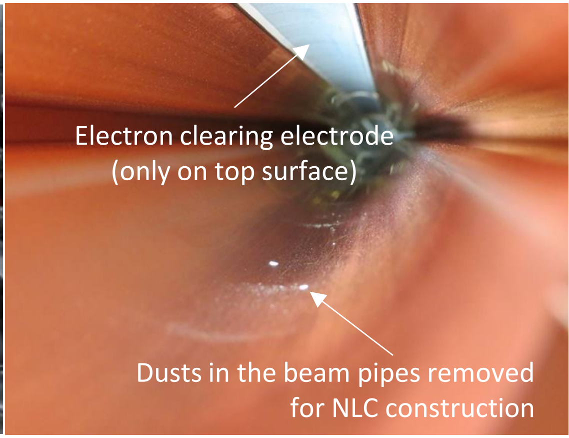


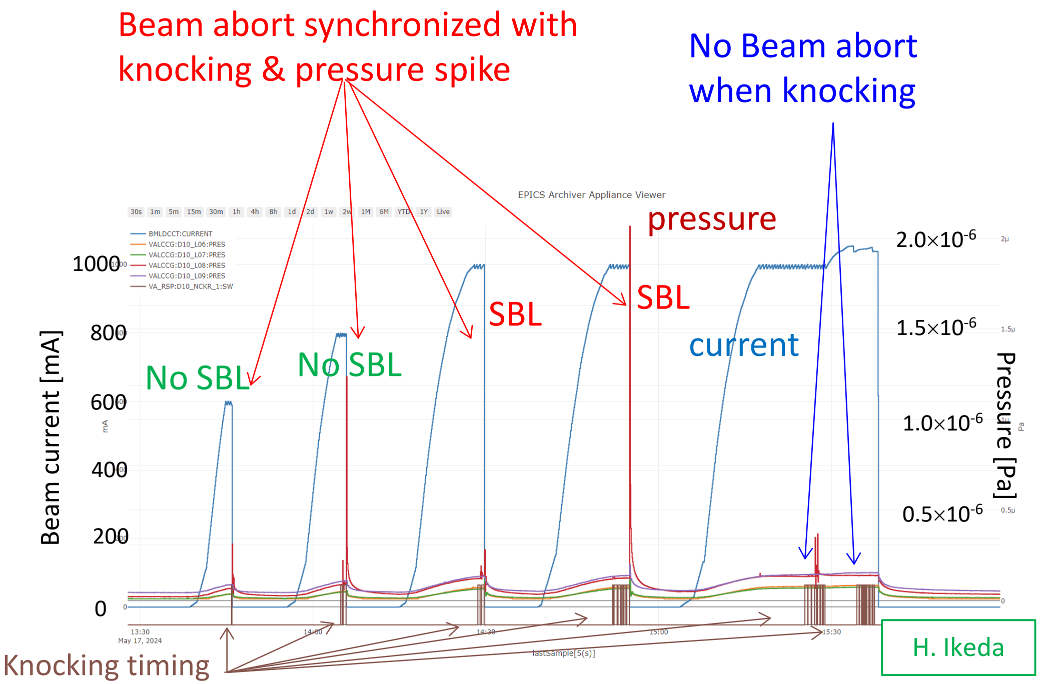
Sudden Beam Loss (SBL) #2

- Identifying the cause of SBL was the most important and urgent task in 2024ab run.
  - Belle II and SuperKEKB had formed a strong collaborative team to address the SBL.
  - A great deal of time has been spent on the machine study on the SBL.
- Many findings were made during 2024ab run
  - SBL happens
    - with a single beam as well as in collision.
    - even at lower bunch currents.
    - at $\beta_y^* = 3$mm, as well (not only at $\beta_y^* = 1$mm).
  - Vertical beam size increases when SBL occurs.
  - In most cases, the pressure spikes in the wiggler sections were observed.
    - Downstream of Oho Wiggler Section (D04 straight section)
    - Downstream of Nikko Wiggler Section (D10 straight section)
    - Beam pips with electron clearing electrodes for countermeasure against the electron cloud effects in LER
  - Knocking the beam pipes at wiggler sections with a “knocker” can cause SBL.
    - Thin electrode (0.1 mm tungsten on 0.2 mm Al_2O_3 ceramic) only on top surface
    - Dusts in the beam pipes removed for NLC construction
  - Knocking beam pipes can reduce SBL.
  - Higher total currents result in more frequent SBL.
- No data to suggest that anything other than dust is the cause of SBL.
  - No data showing discharge at LER collimators.
  - Most likely cause of SBL at LER is dust at wiggler sections.



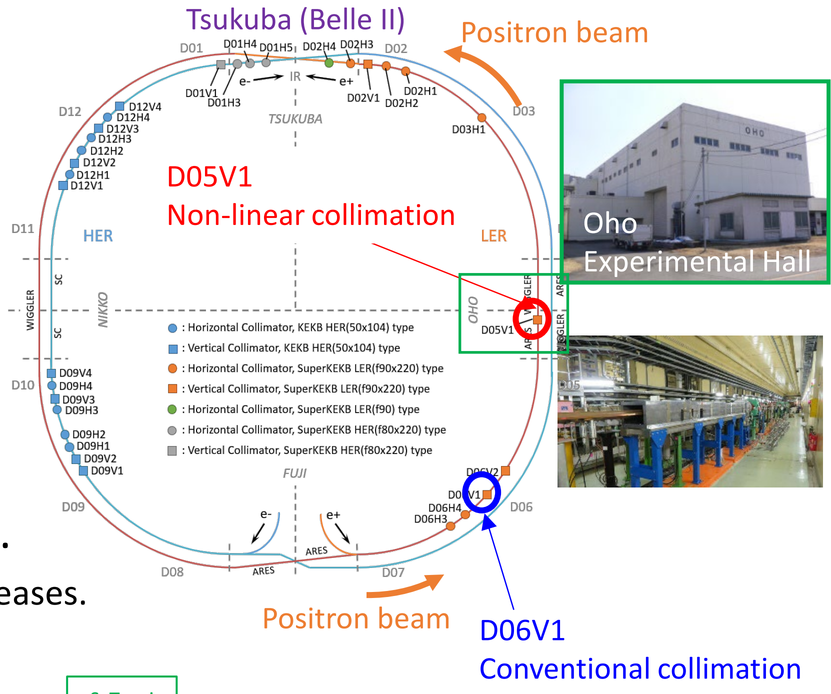




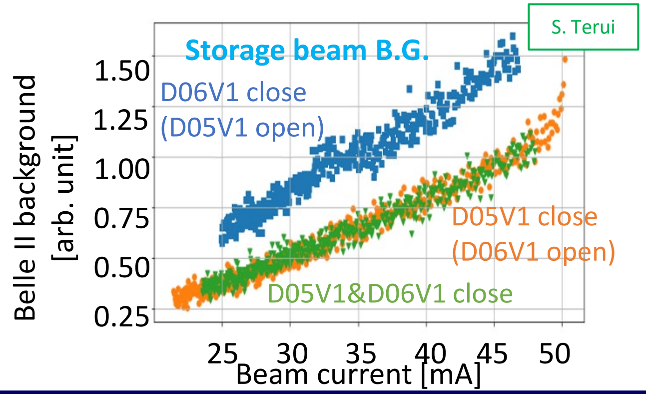


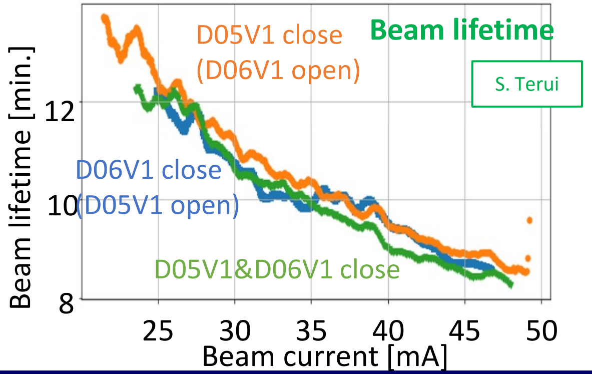
First Trial of Non-Linear Collimator

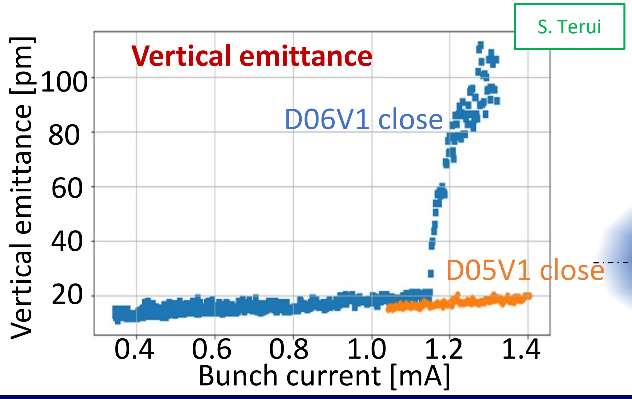
- Comparison between D05V1(NLC) and D06V1(Conventional type) with the same effective collimation gap
  - Storage beam B.G. : D05V1 suppressed more beam B.G. than D06V1
  - Beam lifetime : Very similar between D05V1 and D06V1
  - Beam blowup : No vertical blowup was observed with D05V1 (Suppression of beam instability (TMCI))

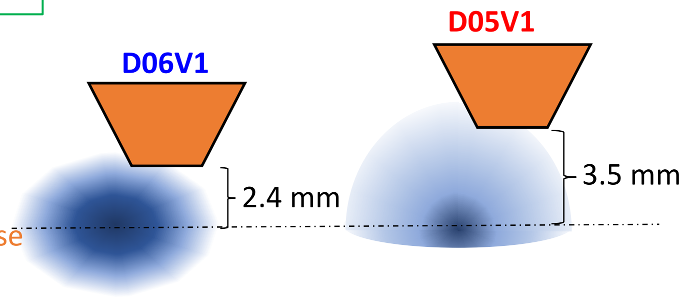


- Other findings :
  - Injection beam B.G. may also be reduced by NLC with tuning of β_x at the skew sextupole magnets.
    - It will be tested during 2024c run.
  - Radiation level in the Oho Experimental Hall increases as closing the D05V1 gap.
    - Though it was still lower than the regulatory limit, measures are required for future current increases.
    - During the summer shutdown, additional radiation shielding will be installed.





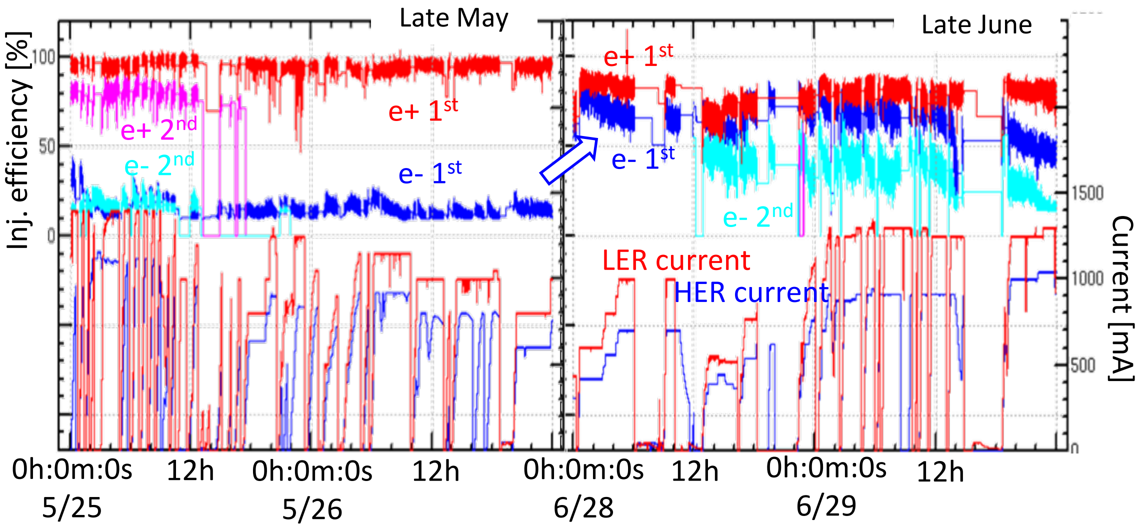


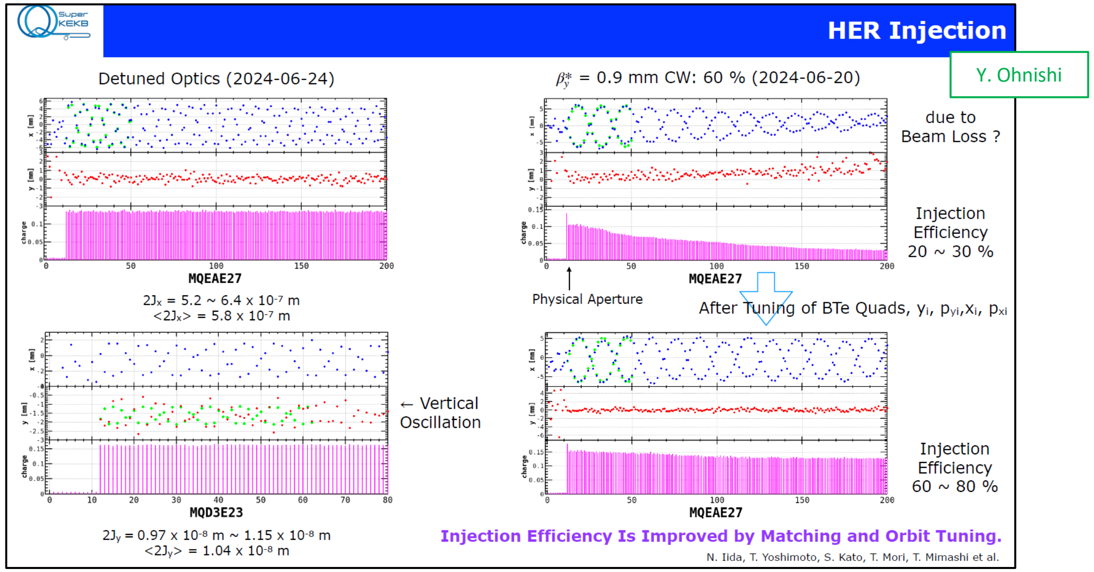


Same effective collimation gap : $64\sigma_y$

Injection & Maximum Beam Currents

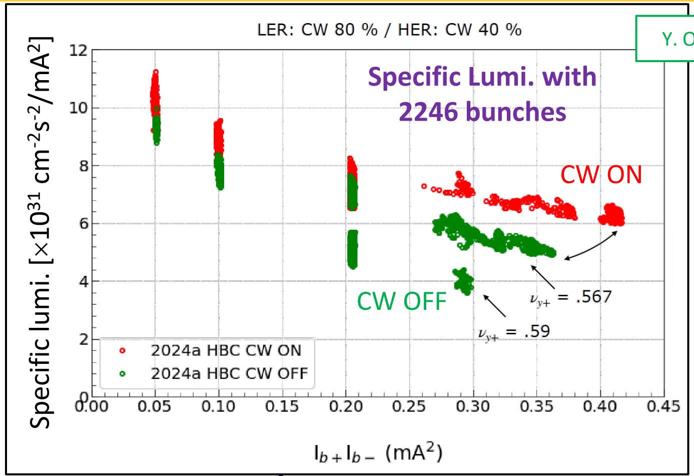
- HER: maximum beam current 1.2 A (Target : 1.4 A)
  - Had straggled with poor injection efficiency and stability despite upgrade to HER injection point during LS1 (aperture enlargement, new septum magnet).
    - Frequent beam aborts caused by injection beam (especially 2nd bunch)
    - Long-term dedicated beam studies and injection tuning
  - Finally, injection efficiency improved significantly during last 2 weeks of 2024ab run.
    - Precise measurement of injection beam orbit and its correction
    - Fine optics matching between MR and BT
    - Benefit of the LS1 upgrade
  - It seems possible to further increase the beam current.
- LER: maximum beam current 1.5A (Target : 1.8 A)
  - It was found that injection degradation occurs due to Beam-Beam Interaction effect at high bunch current.
    - Lower betatron tune can improve injection efficiency.
  - For further beam current increase, it is necessary to maintain stable 2-bunch injection, which could not be maintained for a long period during this run.
- Plan for 2024c run
  - Further beam current increase (> 2 A) to make new luminosity record
    - Deeper understanding of Beam-Beam interaction effect
    - Finding a good operation point (good betatron tunes for both Injection and luminosity)
    - Establishment of stable 2-bunch injection in advance

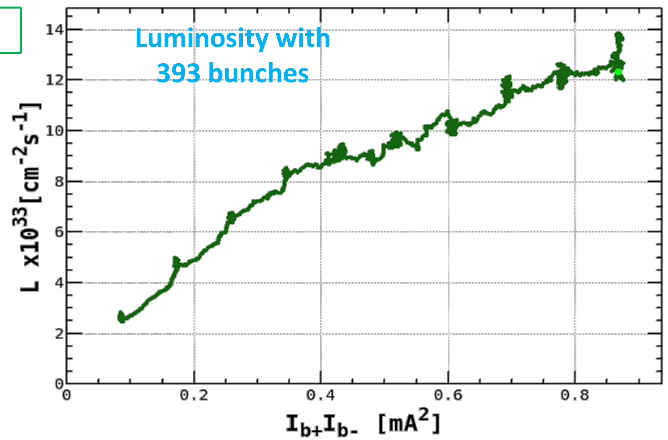




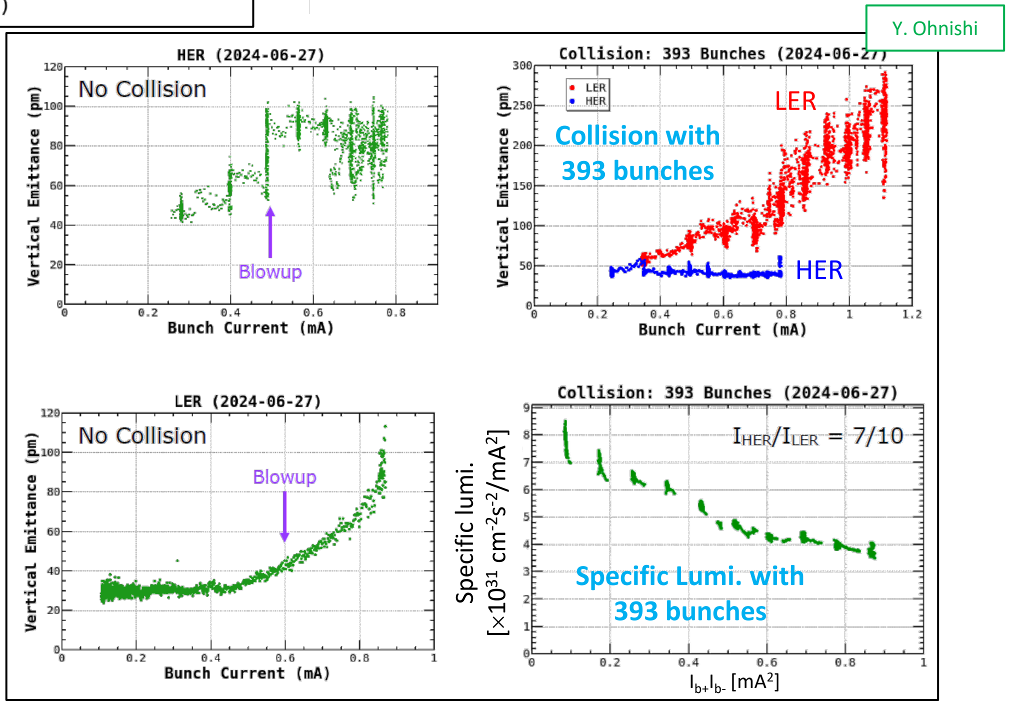
Luminosity

- Peak luminosity L_p = 4.47×10^{34} cm^{-2}s^{-1}
  - Specific luminosity L_{sp} = 5.9×10^{31} cm^{-2}s^{-1}/mA^2
  - β_y^* = 0.9 mm
  - Beam current : HER/LER = 1180/1450
  - Number of bunches : 2249
  - Bunch current product ($I_{b+}I_{b-}$) : 0.338 mA^2
  - Crab waist ratio : HER/LER = 60/80 %





- Findings from Beam-Beam Study & High Bunch Current Study
  - Crab waist is effective to increase luminosity and $I_{b+}I_{b-}$
  - Single beam vertical blowup was observed over 0.5 mA/bunch in both rings.
  - LER vertical blowup due to Beam-Beam effect was observed
  - Lowering horizontal tune improves LER injection efficiency and helps to increase beam current.
  - L_p reached 1.38×10^{34} cm^{-2}s^{-1} with 393 bunches



- Outlook for 2024c run
  - Increase total current (number of bunches) :

    L_p = 1.38×10^{34} cm^{-2}s^{-1} × 2346/393 = 8.27×10^{34} cm^{-2}s^{-1}
  - Further β_y^* squeezing (0.8 mm) and increasing total beam current

    Target : L_p = 1×10^{35} cm^{-2}s^{-1}

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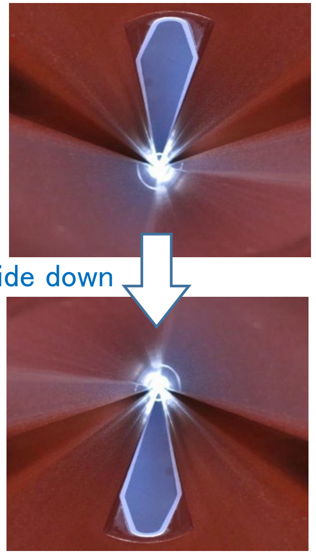
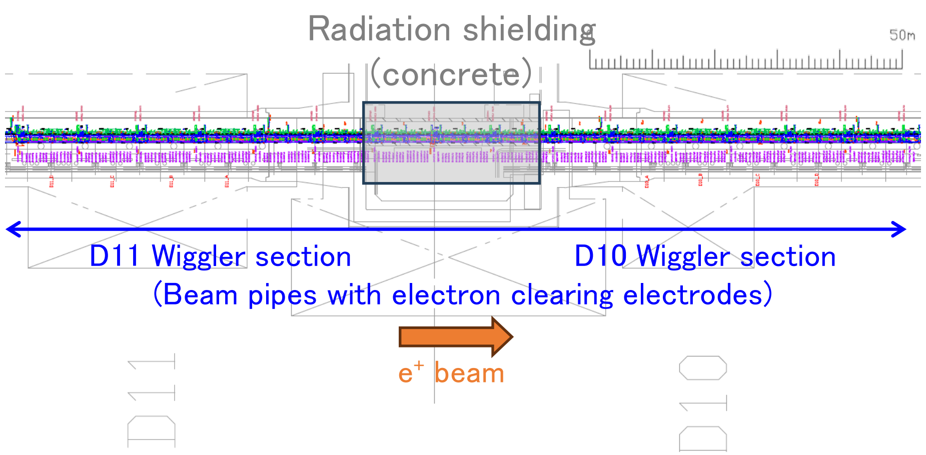
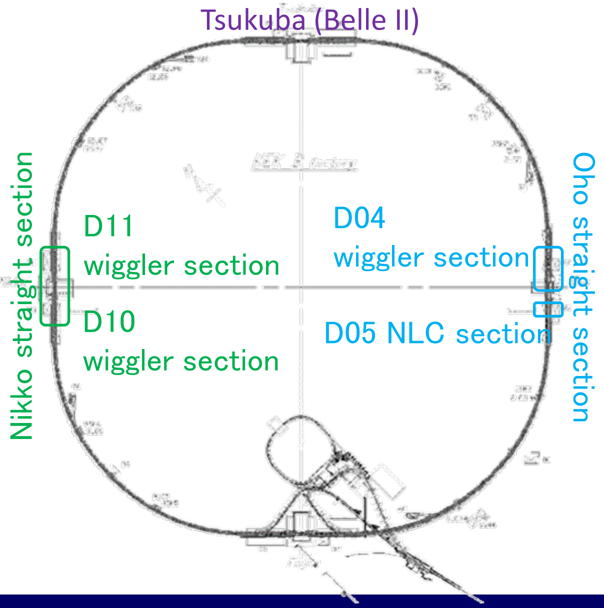
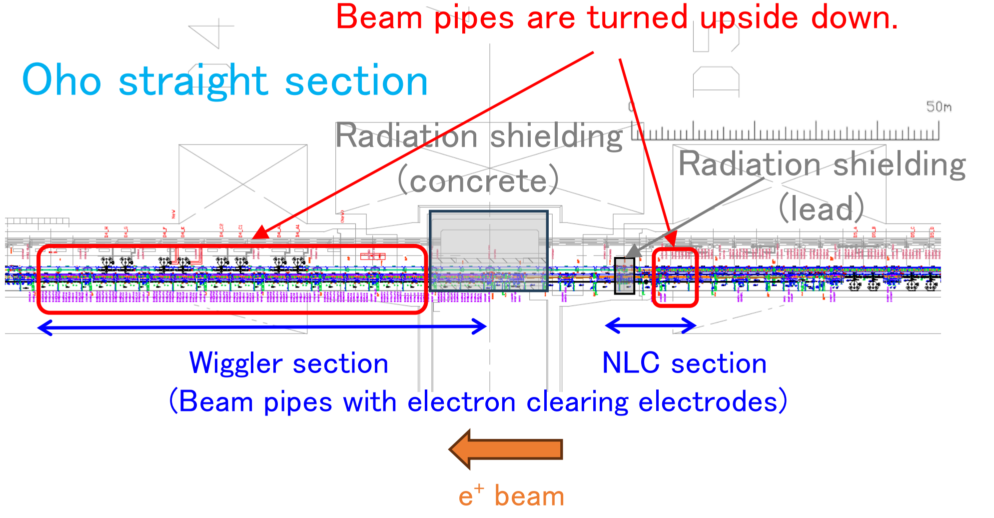
Countermeasure against SBL

- Turning beam pipes with electron clearing electrode upside down
  - 15/50 beam pipes are turned upside down. (56 m/185 m = 30 %)
  - Oho straight section : 13/16 beam pipes (D04 wiggler section) and 2/4 beam pipes (D05 NLC section) were turned upside down.
    - D05 NLC section (2/4) : Done
    - D04 wiggler section (13/16) : In progress now (until the end of September)
  - Nikko straight section : 30 beam pipes at Nikko wiggler section will not be turned upside down.
- Visual check and dust cleaning of beam pipes which are turned upside down.
- Knocking as many beam pipes (with electron clearing electron or groove structure) as possible.

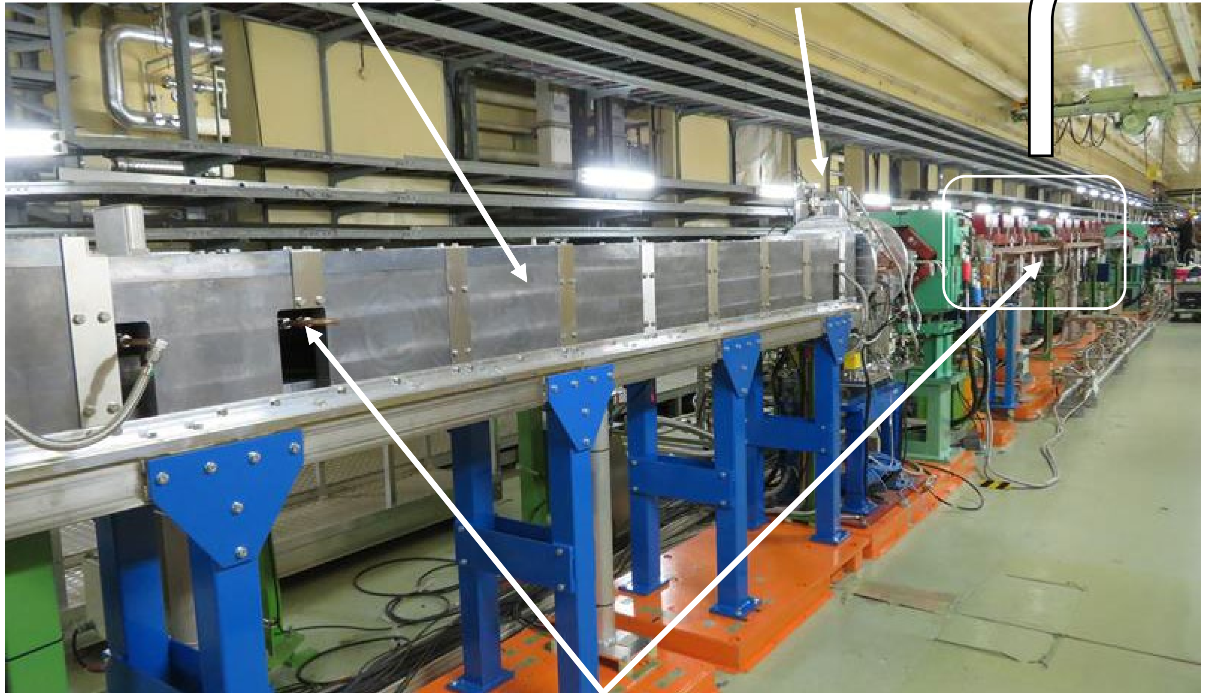




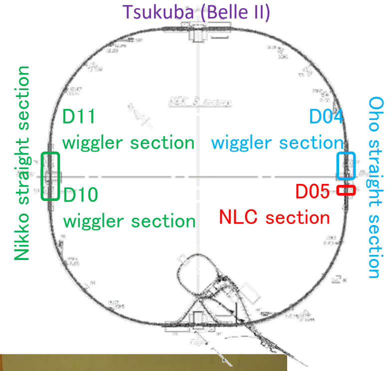


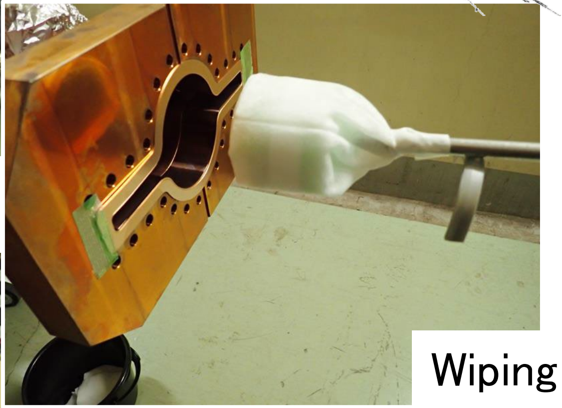


OHO D05 NLC Section



Removal



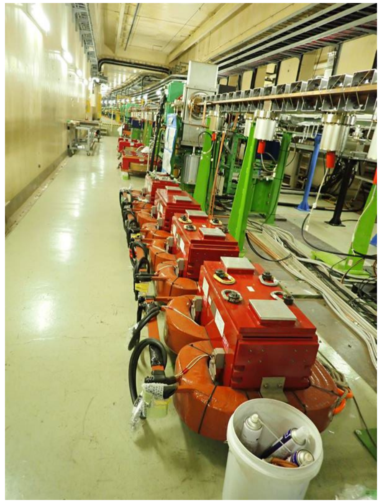


Wiping

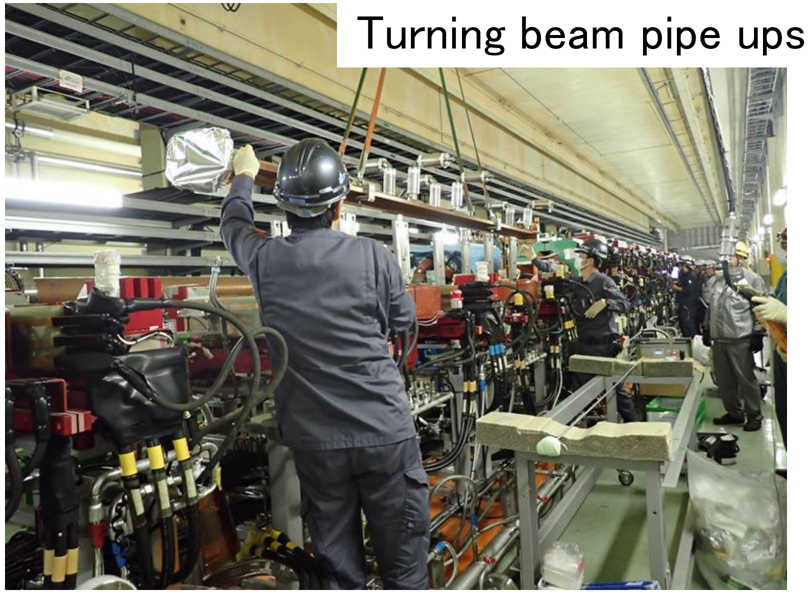
Reinstallation
(upside down)

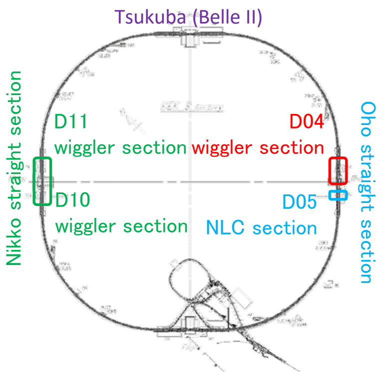
OHO D04 Wiggler Section (in progress)

Wiggler magnet disassembly

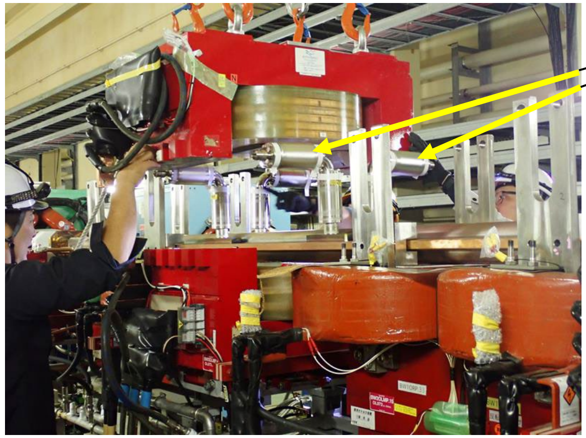


Turning beam pipe upside down



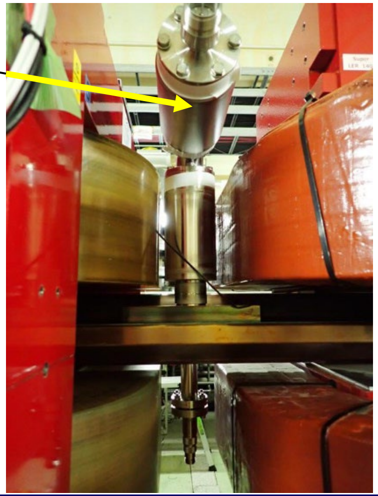


Wiggler magnet reassembly



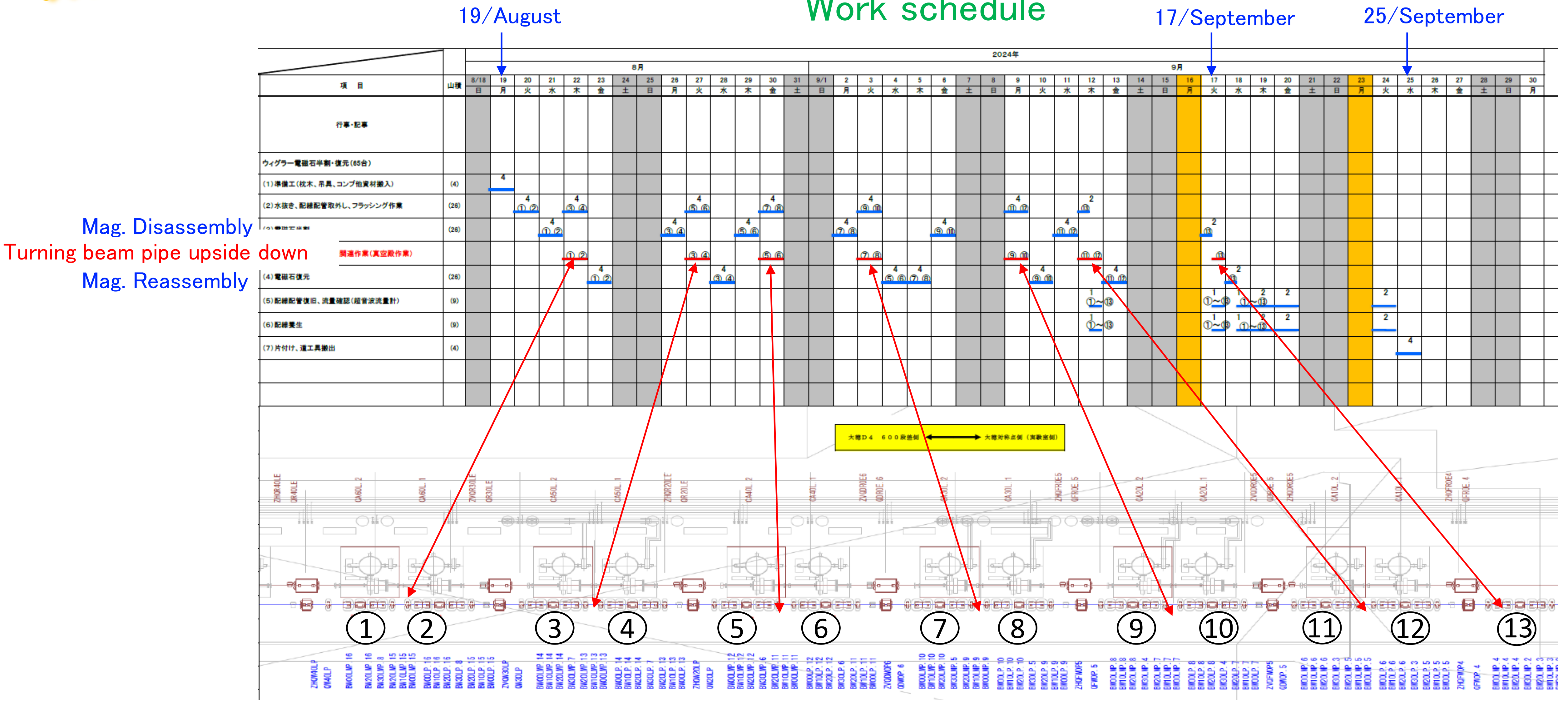
NEG pump

NEG pump position changes from the bottom side to the top side. NEG pumps are installed horizontally to prevent dusts from falling from NEG.

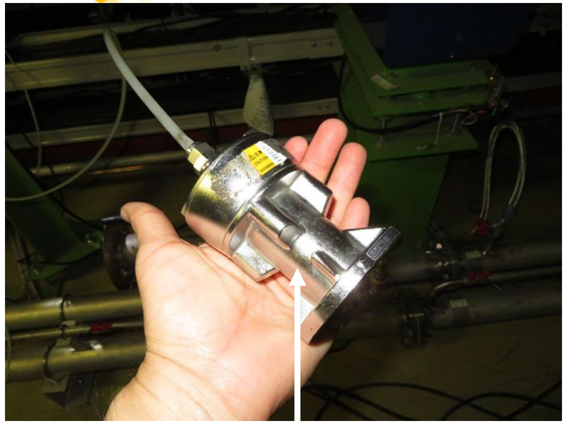


OHO D04 Wiggler Section (in progress)

Work schedule

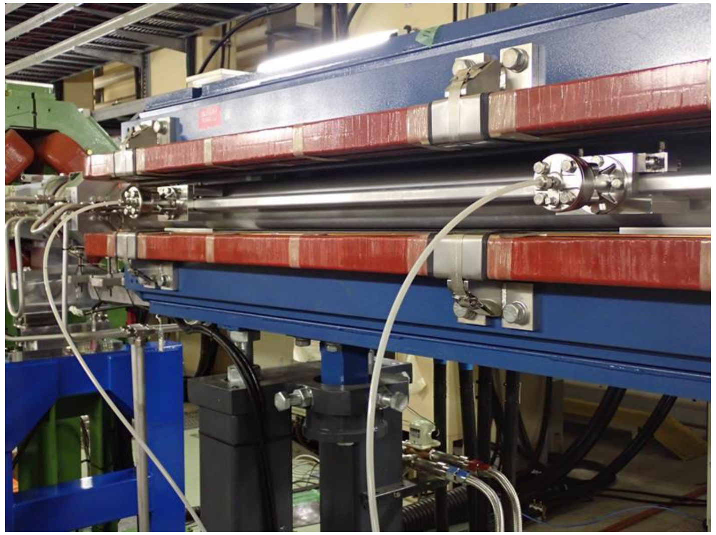
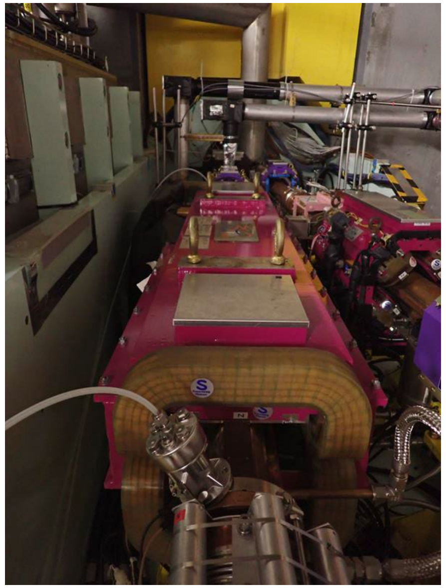


Beam Pipe Knocking to Remove Dust



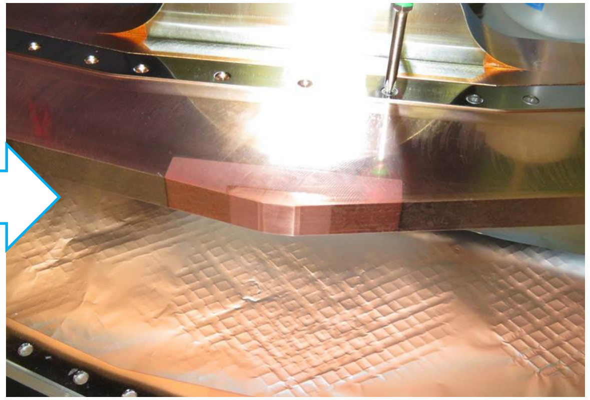
Knocker
(driven by compressed air)



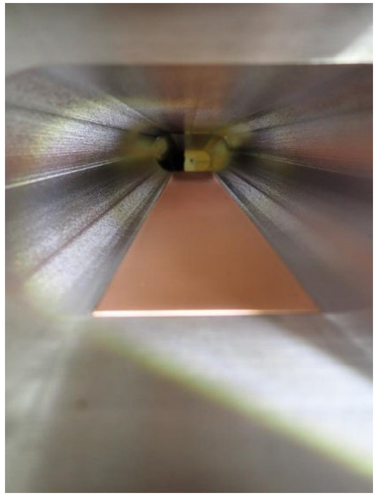



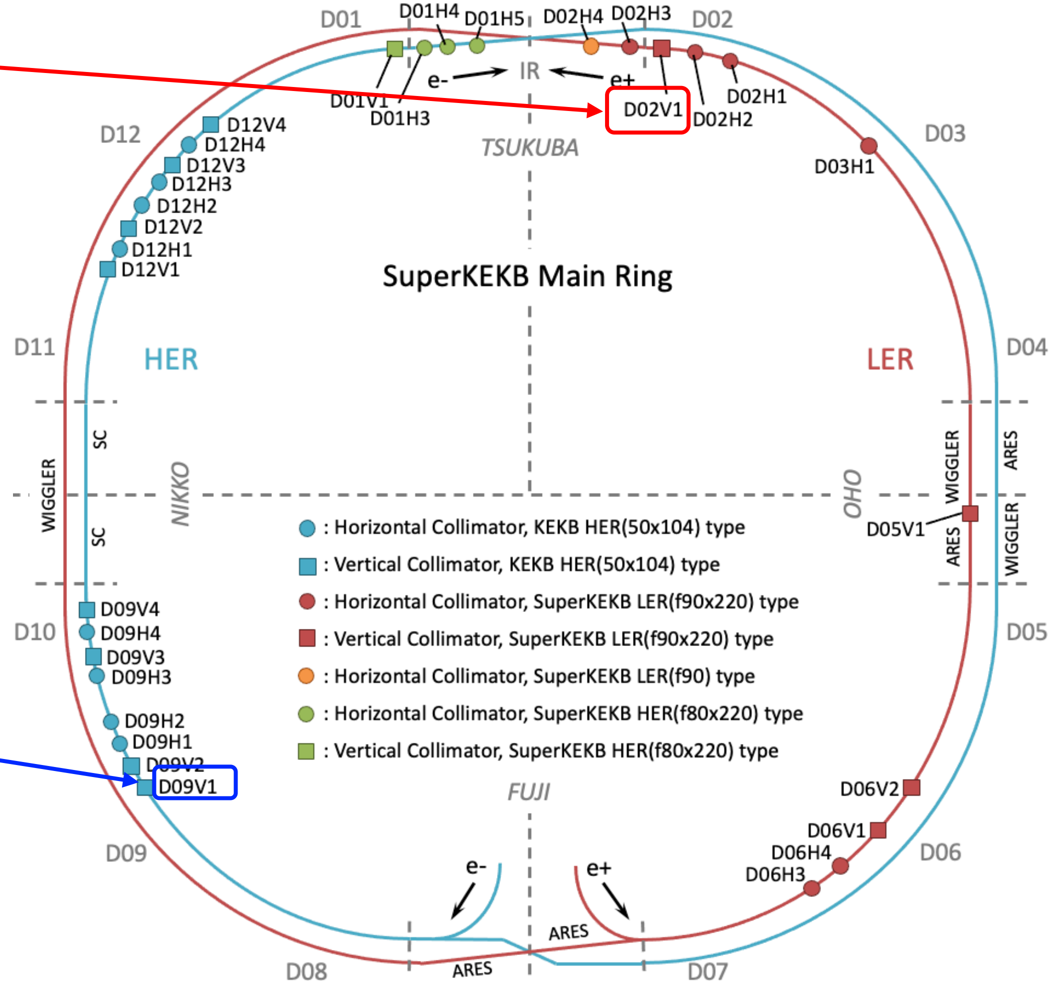
Collimator Works

- Replacement of damaged jaws
  - LER D02V1 (Done)



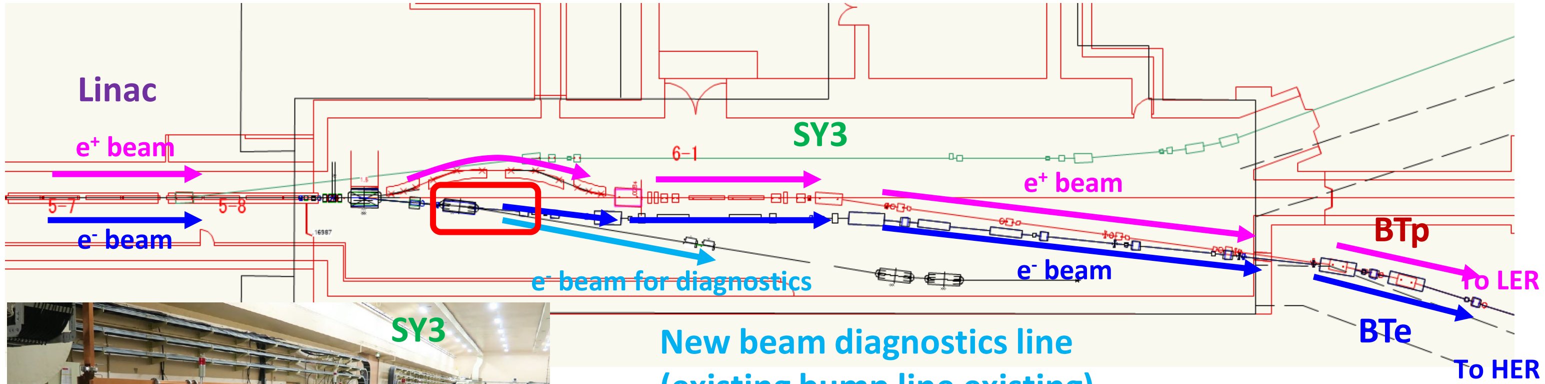
  - HER D09V1 (Done)





HER Inj. Efficiency Improvement Measures #1

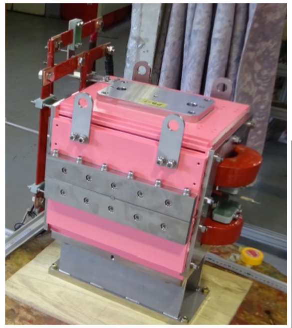
- New beam diagnostics line for e^- beam at Linac end (SY3)
  - Bunches are extracted to the existing dump line for beam diagnostics while keeping HER injection.
  - New DC & pulsed magnets, collimator, etc. were installed to extract e- bunches for beam diagnostics.
    - Maximum repetition rate for diagnostics : 5 Hz
    - Maximum repetition for HER injection : 25 Hz
    - A temporary SUS chamber was installed instead of the new collimator suffering from production problems.
    - Nonetheless, the new diagnostics line can be available although with restrictions in repetition rate and beam current to the line.



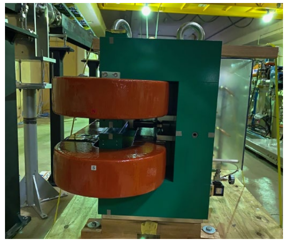
New beam diagnostics line
(existing bump line existing)

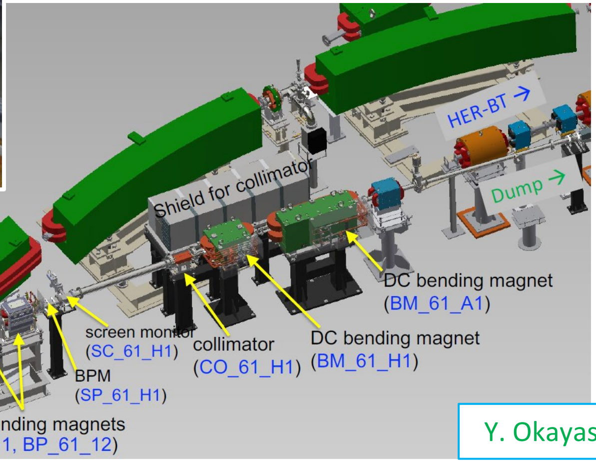
T. Kamitani

K. Yokoyama



T. Kamitani

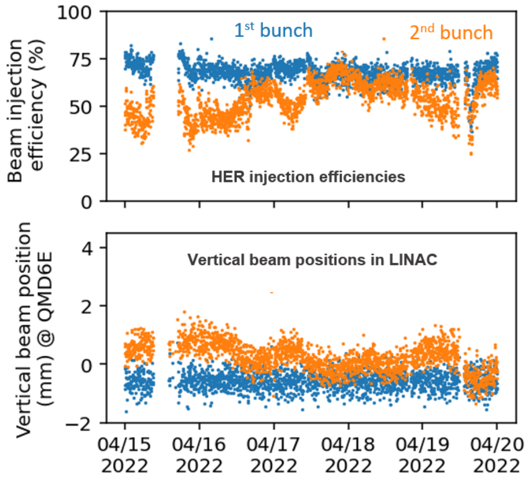


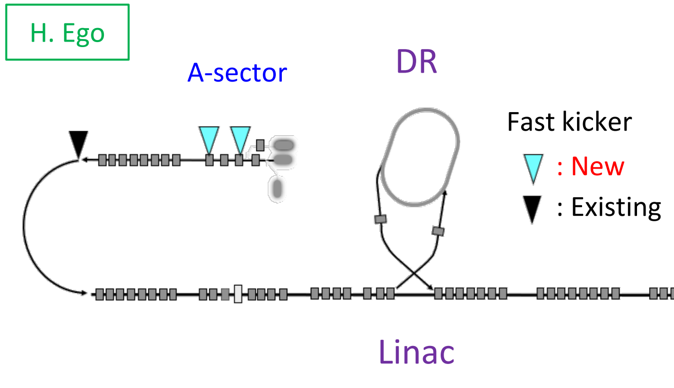


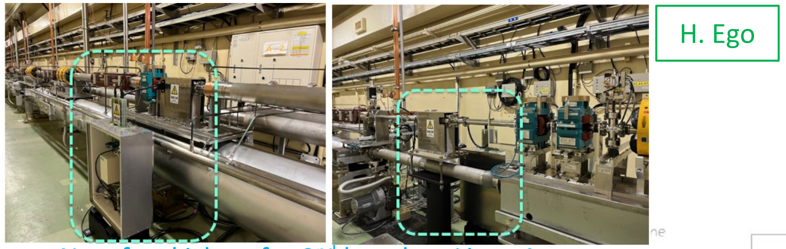
Y. Okayasu

HER Inj. Efficiency Improvement Measures #2

- Two more fast-kickers for orbit collection of electron 2nd bunch at Linac
  - Vertical orbit change at Linac causes HER injection efficiency reduction.
    - Vertical orbit correction at A-sector can improve injection efficiency.
  - Two more fast-kickers were installed for 2nd bunch orbit correction at Linac A-sector (most upstream of Linac).
    - It has been demonstrated that the fast-kickers correct the vertical orbit of only the 2nd bunch.

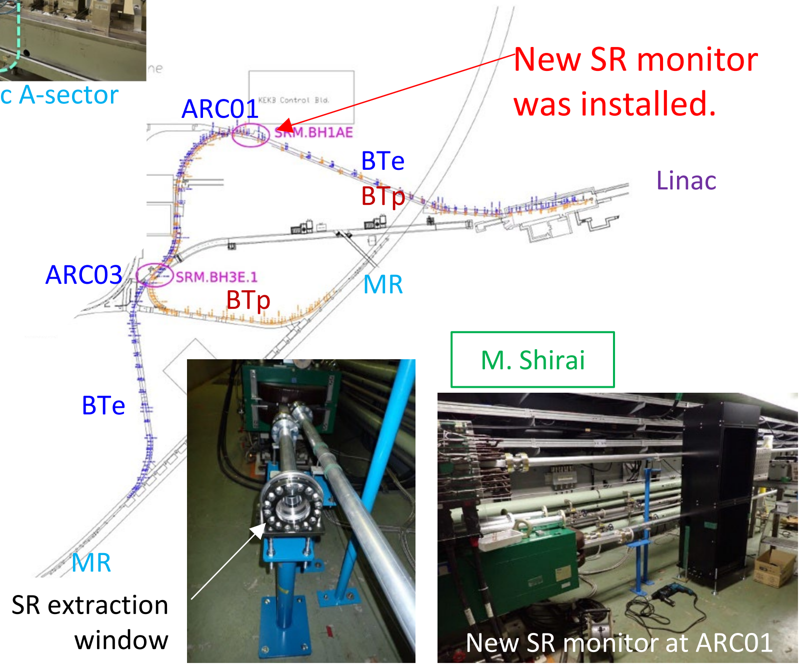






New fast kickers for 2nd bunch at Linac A-sector

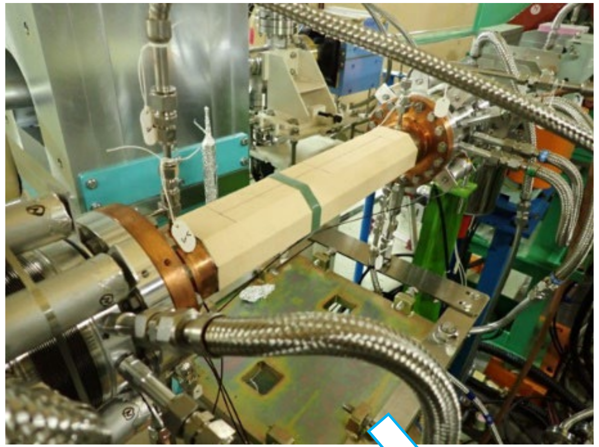
- New SR monitor for beam diagnostics at ARC01 of BTe
  - New SR monitor was installed at ARC01 of BTe.
  - There is an existing SR monitor at ARC03.
  - Two SR monitors make it possible to diagnostic electron beam at BT more precisely while keeping beam injection.



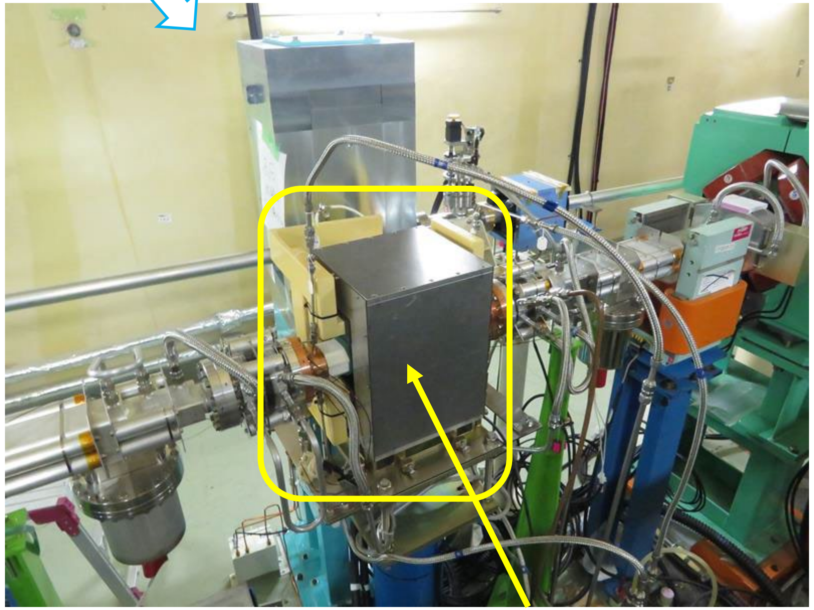
LER Injection and Kicker Related Works

- Installation of new vertical kicker magnet and its power supply in LER
  - It will be very useful for studies on vertical aperture, beam lifetime, and injection.
  - In HER, vertical kicker has been available since 2024ab run.
- Improvement of LER injection kicker trigger system
  - To prevent Inj. Kicker accidental firing, thyratron trigger system was improved from single trigger to double trigger.
  - All LER Inj. Kicker thyratrons have double trigger system.
  - In HER, Inj. Kicker accidental firing seldom occurs so far.
- Relocation of OTR screen monitor at BTp
  - To more precise monitoring of beam quality at BTp, OTR #15 at ARC04 was moved to a more appropriate location.

M. Shirai



Ceramics beam pipe for vertical kicker magnet

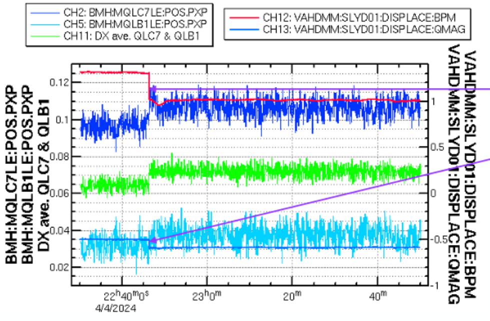


New vertical kicker magnet in LER

Isolation of Q-magnet from Beam Pipe

- Orbit change at strong sextupole magnet causes degradation of machine performance and stability.
  - Displacement of quadrupole magnet (Quad.) makes orbit change at nearby sextupole magnet.
  - BPM block is fixed to Quad. via conventional BPM support.
  - Deformation of beam pipe due to SR heating can move Quad. and result in machine performance degradation.
  - It is required that the orbit change (Quad. displacement) should be less than a few μm.
- New BPM support separating beam pipes and Q-magnet was installed in LER.
  - If its effectiveness is confirmed during 2024c run, a few more supports will be installed in LER this winter.
  - In HER, three supports have already been installed during 2024ab run.
    - It was confirmed that the isolation works very well in HER.

Y. Onishi



Gap Sensor and Beam Position Measured by BPMs

Displacement of BPM Block ~ 30 μm

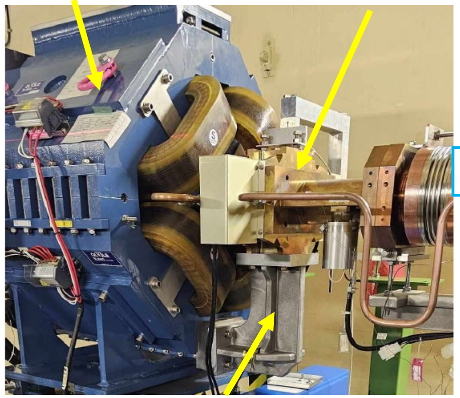
Displacement of Quadrupole Magnet ~ 5 μm

We Observed Quadrupole Magnet Moved Suddenly.
Beam Abort might be cased by the Displacement.

M-L. Yao

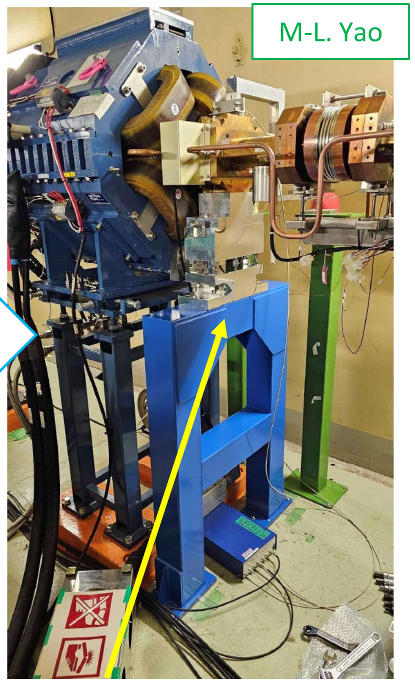
Quadrupole magnet

BPM block



BPM block was fixed to the Q-magnet via conventional BPM support.

M-L. Yao



NEW BPM support can separate BPM and Q-magnet.

Contents

- Highlight from 2024ab run
- Major works during summer shutdown
- 2024c run schedule and plan
- Summary

2024c Operation Schedule

	Early Sep.	Mid. Sep.	Late Sep.	Early Oct.	Mid. Oct.	Late Oct.	Early Nov.	Mid. Nov.	Late Nov.	Early Dec.	Mid. Dec.	Late Dec.
Linac		17/Sep.										27/Dec.
DR		19/Sep.										27/Dec.
BT			27/Sep.									27/Dec.
MR				9/Oct.						Electricity budget may run out.		27/Dec.

- Necessary budget for MR operation until the end of Nov. has been secured.
- We are making effort to get the budget for MR operation until the end of Dec.

	Early Sep.	Mid. Sep.	Late Sep.	Early Oct.	Mid. Oct.	Late Oct.	Early Nov.	Mid. Nov.	Late Nov.	Early Dec.	Mid. Dec.	Late Dec.
PF				7/Oct.								27/Dec.
PF-AR					17/Oct.						16/Dec.	

2024c Operation Plan

- Target luminosity of 2024c run is 1×10^{35} cm^{-2}s^{-1}.
  - General plan is increasing the beam currents keeping β_y^* at 0.9 mm.
    - L_{sp} = 5 x 10^{31} cm^{-2}s^{-1} was achieved already with smaller number of bunches (393).
    - By increasing the beam current to 2.58A/1.83A (2346 bunches), the luminosity is aimed at 1×10^{35} cm^{-2}s^{-1} (B).
  - Detailed operation planning is underway.

Y. Onishi

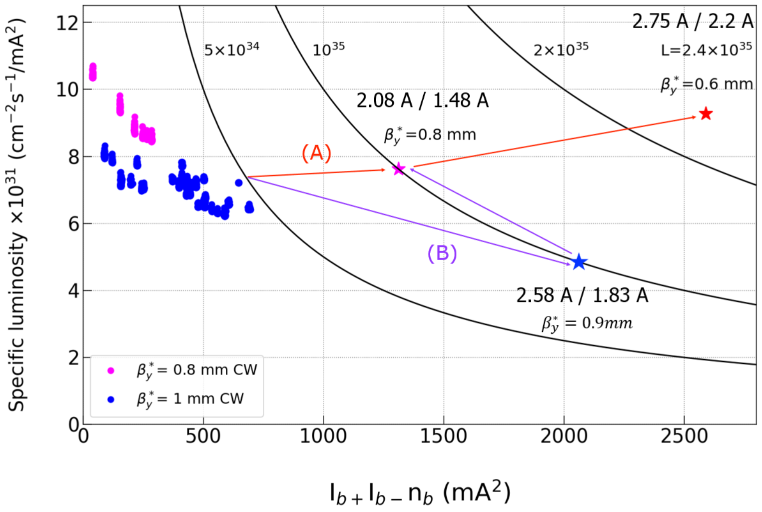
Strategy toward 2.4 x 10^{35} cm^{-2}s^{-1}

- Increase Beam Current
  - Up to 10^{35} cm^{-2}s^{-1}, Target: 2.58 A / 1.83 A with L_{sp} = 5 x 10^{31} cm^{-2}s^{-1}
  - Improve Injection Efficiency under influence of Beam-Beam Interactions
    - Reduce Injection Error with Modified Injection Scheme
- Squeeze Beta Function at IP
  - β_y^* Down to 0.6 mm for 2.4 x 10^{35} from 0.9 mm (3 Steps)
  - Dynamic Aperture (Touschek Lifetime): Sextupole Optimization, Off-Momentum Optics Tuning, Comparison between Simulations and Measurements of DA (x-y-z)
- Increase Beam-Beam Parameter
  - Improve Prediction Accuracy of Beam-Beam Simulation
  - Account for Lattice Nonlinearity and Impedance, and Their Interferences

Y. Onishi

Strategy toward 2.4 x 10^{35} cm^{-2}s^{-1}

$$L_{sp} = \frac{L}{I_{b+}I_{b-}n_b}$$



Machine Parameters

Machine Parameters

Y. Onishi

	June 8, 2022		Target at post-LS1 (1)		Target at post-LS1 (2)		Unit
Ring	LER	HER	LER	HER	LER	HER	
Emittance	4.0	4.6	4.0	4.6	4.0	4.6	nm
Beam Current	1321	1099	2080	1480	2750	2200	mA
Number of bunches	2249		2346		2346		
Bunch current	0.587	0.489	0.89	0.63	1.17	0.94	mA
Horizontal size σ_x*	17.9	16.6	17.9	16.6	17.9	16.6	μm
Vertical cap sigma Σ_y*	0.303		0.217		0.178		μm
Vertical size σ_y*	0.215		0.154		0.126		μm
Betatron tunes ν_x / ν_y	44.525 / 46.589	45.532 / 43.573	44.525 / 46.589	45.532 / 43.573	44.525 / 46.589	45.532 / 43.573	
β_x* / β_y*	80 / 1.0	60 / 1.0	80 / 0.8	60 / 0.8	80 / 0.6	60 / 0.6	mm
σ_z	4.6	5.1	6.5	6.4	6.5	6.4	mm
Piwinski angle	10.7	12.7	10.7	12.7	10.7	12.7	
Crab waist ratio	80	40	80	80	80	80	%
Beam-Beam ξ_y	0.0407	0.0279	0.0444	0.0356	0.0604	0.0431	
Specific luminosity	7.21×10^{31}		7.62×10^{31}		9.31×10^{31}		$cm^{-2}s^{-1}/mA^2$
Luminosity	4.65×10^{34}		1×10^{35}		2.4×10^{35}		$cm^{-2}s^{-1}$

10^{35} and 2.4×10^{35} are tentative and considered by Y. Funakoshi.

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Summary

- 2024ab run
  - Peak luminosity : $4.47\times1034\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
    - $L_{sp} = 5.9\times10^{31}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}/\mathrm{mA}^2$, $\beta_y^* = 0.9$ m, HER/LER = 1180mA/1450mA, 2249 bunches
  - Struggling with SBL and increasing beam current more than 1.5 A/1.2A (LER/HER)
    - New findings made during 2024ab run suggest that most likely cause of SBL at LER is dust at wiggler sections.
    - For HER, injection was improved from 30% to 80% at last.
    - For LER, it was found that injection degradation occurs due to Beam-Beam interaction effect at high bunch current.
  - Non-linear collimator
    - It was demonstrated that NLC can reduce B.G. with lower impedance.
- Summer works
  - Most of the planned works were carried out as scheduled.
    - SBL countermeasure : Turning beam pipes at OHO straight section, beam pipe knocking
    - Injection improvement : New beam diagnostics line at Linac (e-), New fast kickers at Linac(e-), New SR monitor at BT (e-), OTR monitor relocation at BT (e+), New vertical kicker in LER (e+),
    - Others : Damaged collimator replacement, LER Inj. Kicker trigger system improvement, New BPM support for isolating Q-mag and beam pipe, etc.
  - Some delayed works are postponed until the winter, but there will be no impact on 2024c run.
- 2024c run
  - MR beam operation : 10/9 – 12/27
    - Necessary budget for beam operation until the end of Nov. has been secured.
    - We are making effort to get the budget until the end of Dec.
  - Increasing the beam currents keeping at 0.9 mm-βy^* to aim at $1\times10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$.
    - Detailed operation planning is underway.

Fin.

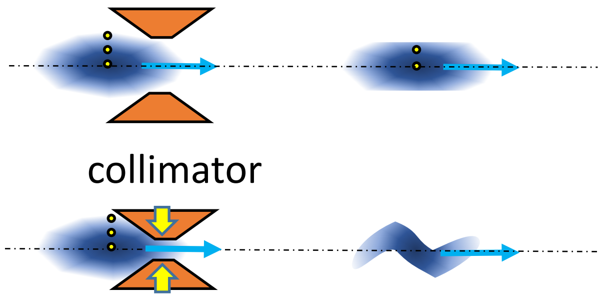
Thank you for your attention.

Backup

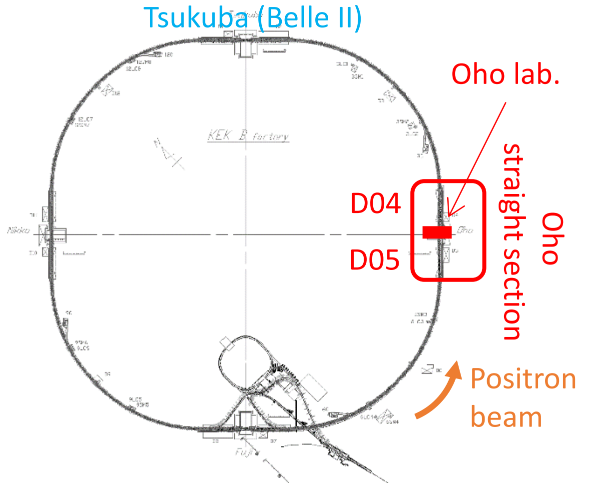
Non-Linear Collimation (NLC) System

- Non-linear collimation (NLC) system was installed in LER Oho straight section.
  - Impedance of NLC is much lower than that of conventional collimator due to its large aperture.
  - NLC can relax TMCI bunch current limit.
  - Oho straight section is the location where the optics satisfies the requirements for NLC.
  - A part of wiggler magnets was removed to make space for NLC.
  - New skew sextupole magnets and beam pipes in them were fabricated.
  - New power supplies, cabling works and new radiation shields were also required.

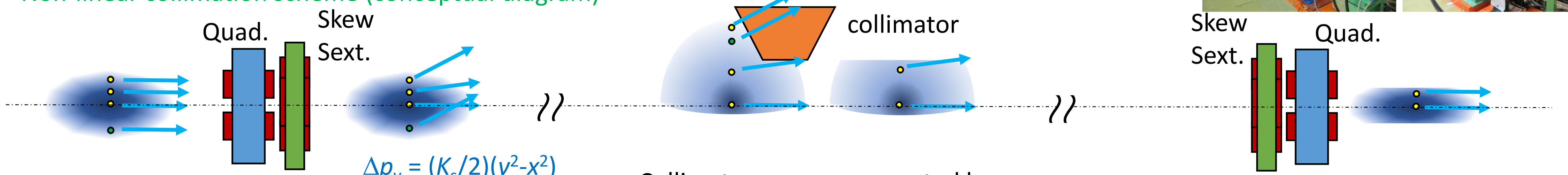
Conventional collimation scheme



Small aperture can make beam instable.



Non-linear collimation scheme (conceptual diagram)



$\Delta p_y = (K_s/2)(y^2 - x^2)$
$\Delta p_x = K_s xy$

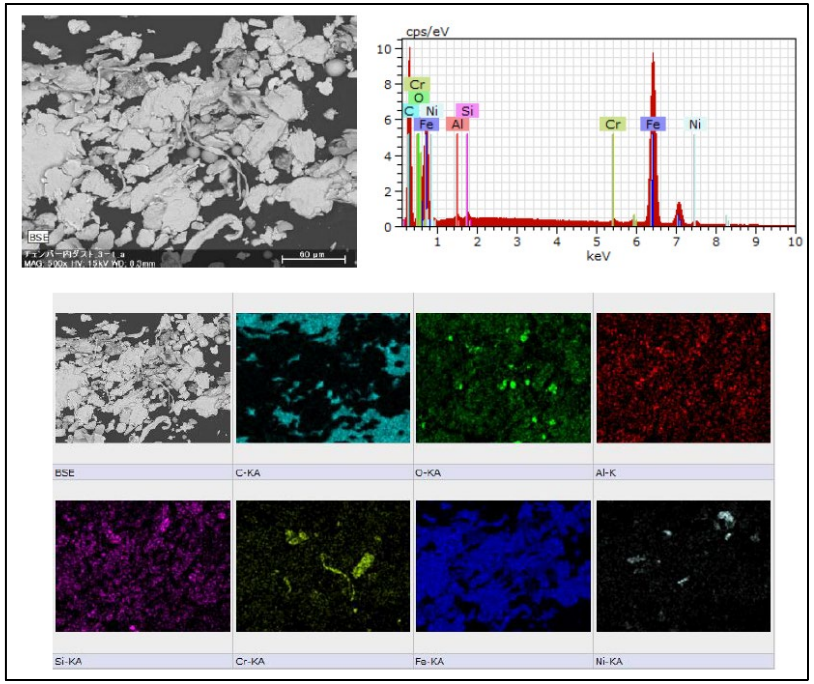
First sextupole magnet kicks unwanted beam particles.

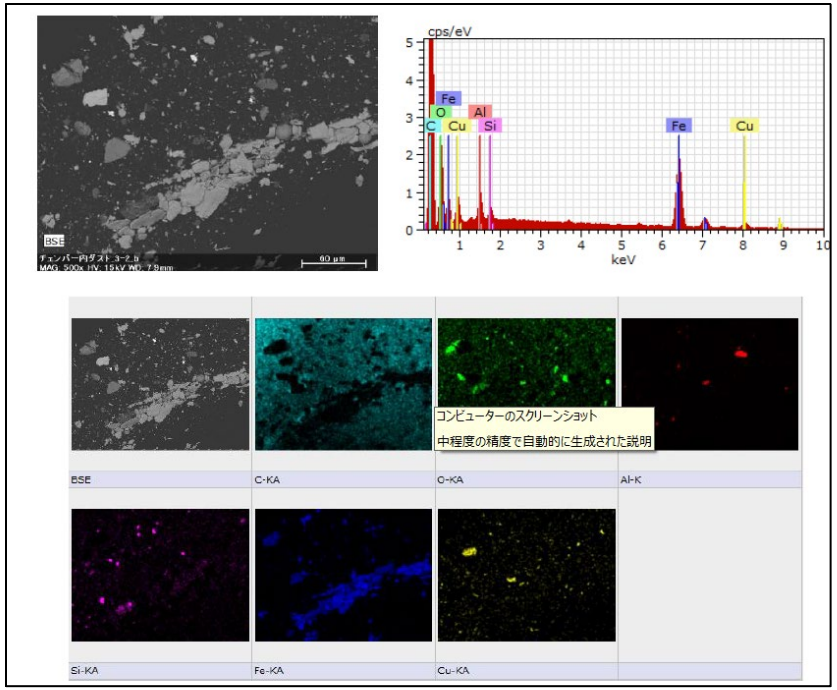
Collimator scrapes unwanted beam particles with large aperture. (low impedance)

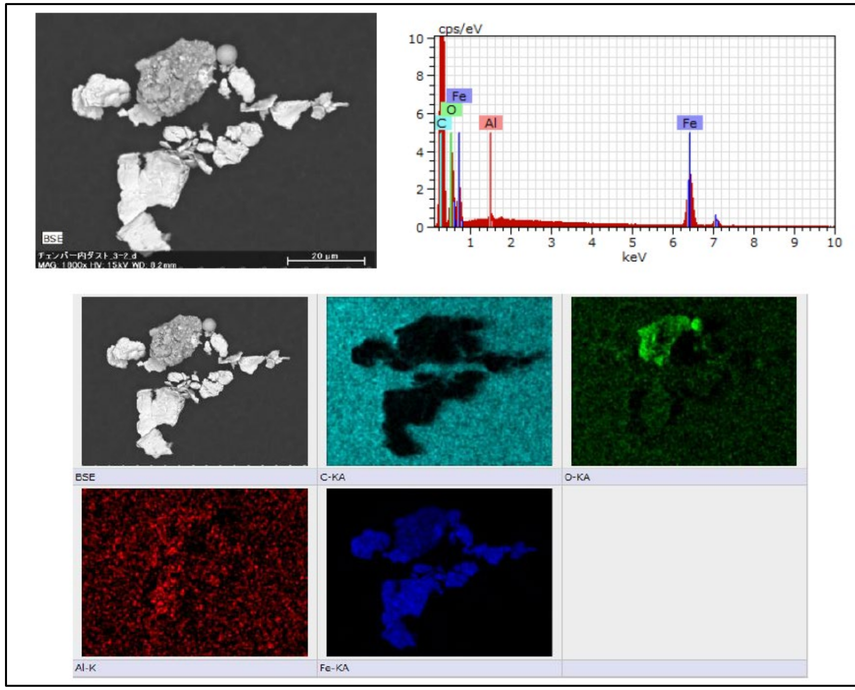
Second sextupole magnet brings good beam particles back to their original angle.

SEM/EDS analysis of dust particles 1

- Dust particles collected from beam pipes removed form D05 wiggler section for NLC construction
  - Small particles collected with tape
  - Main components : Fe, Al, O, C
  - Others : Si, Ni, Cu, Cr, etc.

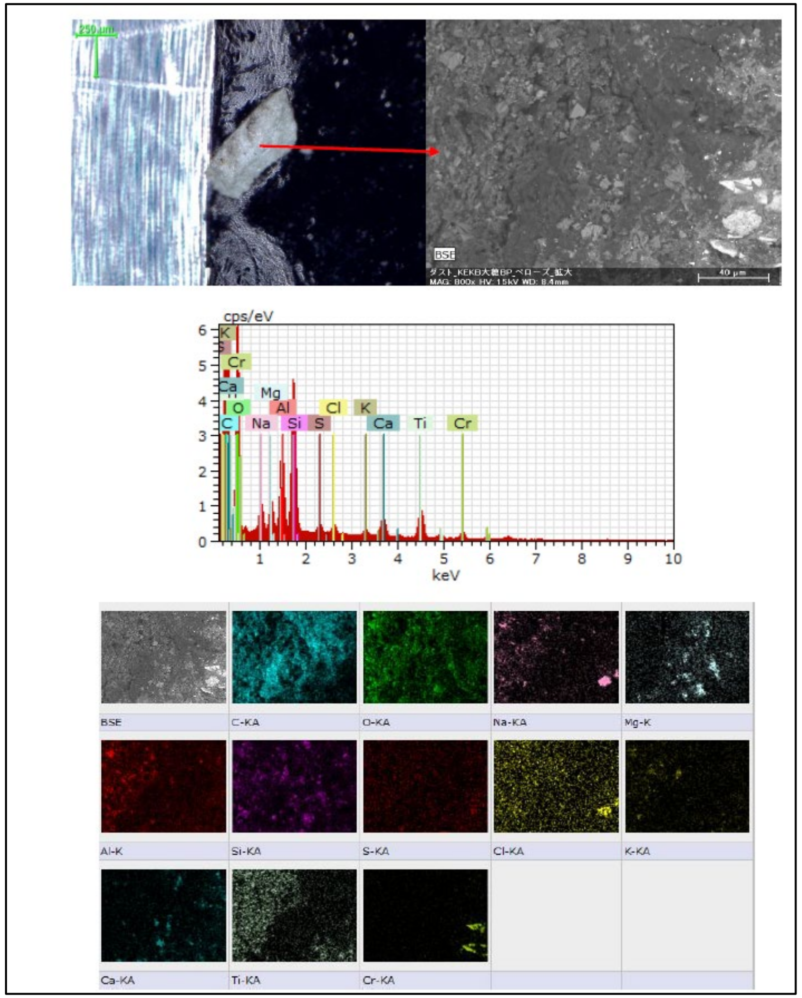


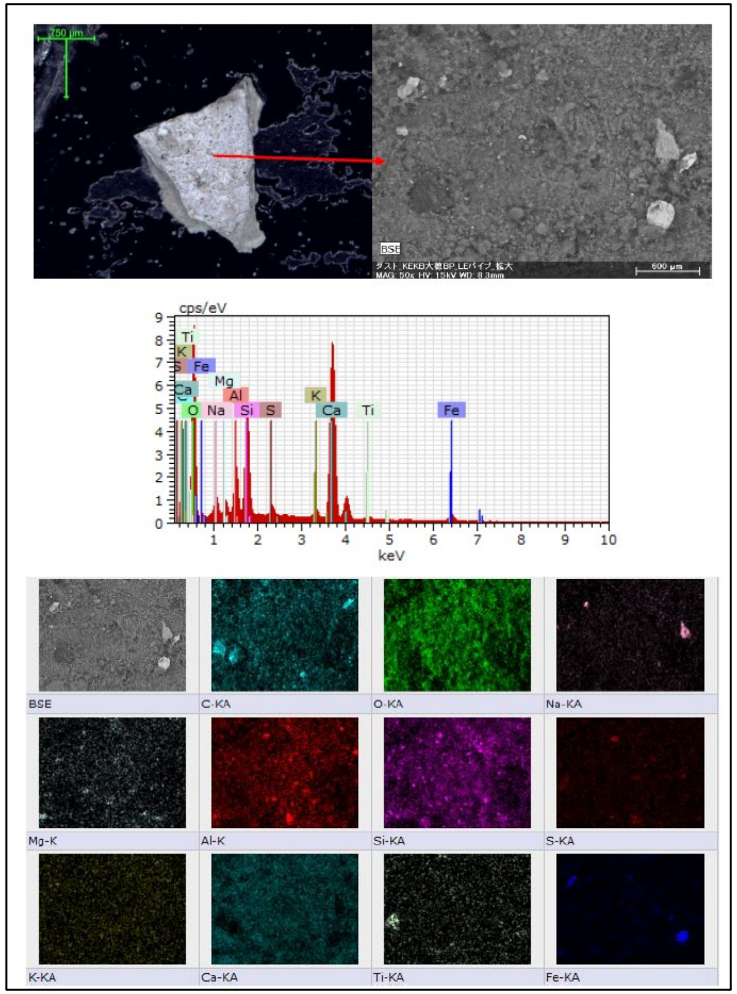




SEM/EDS analysis of dust particles 2

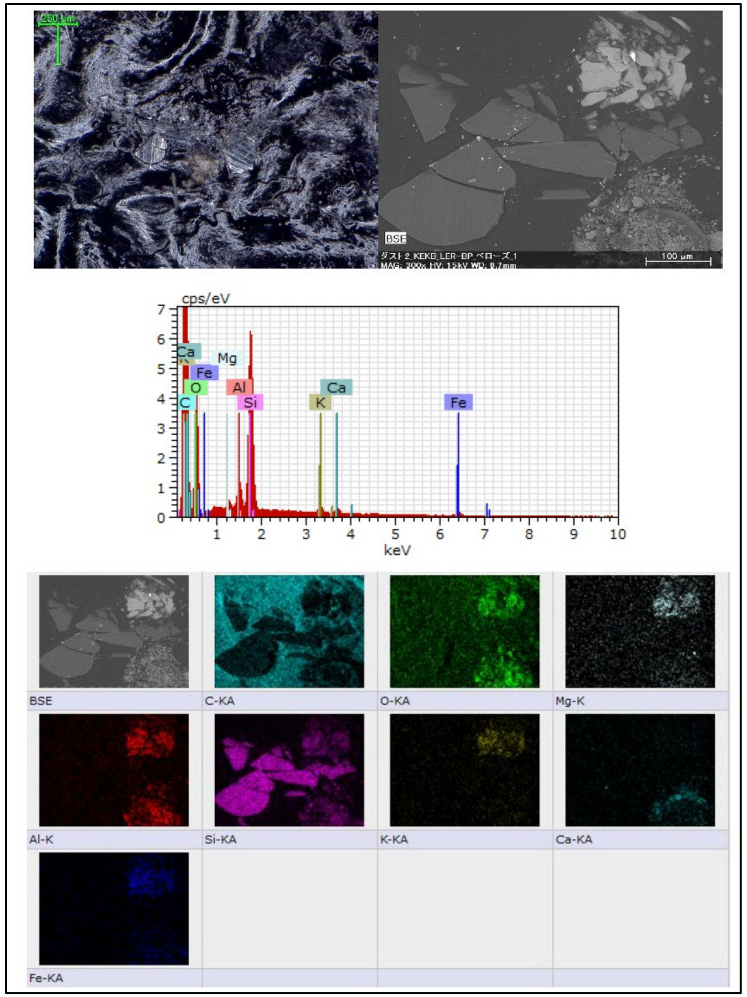
- Dust particles collected from beam pipes reinstalled in D05 NLC section
  - Large particles
  - Main components : O, Al, Si, Ca
  - Others : C, K, S, Mg, Ti, Cr, Fe, etc.

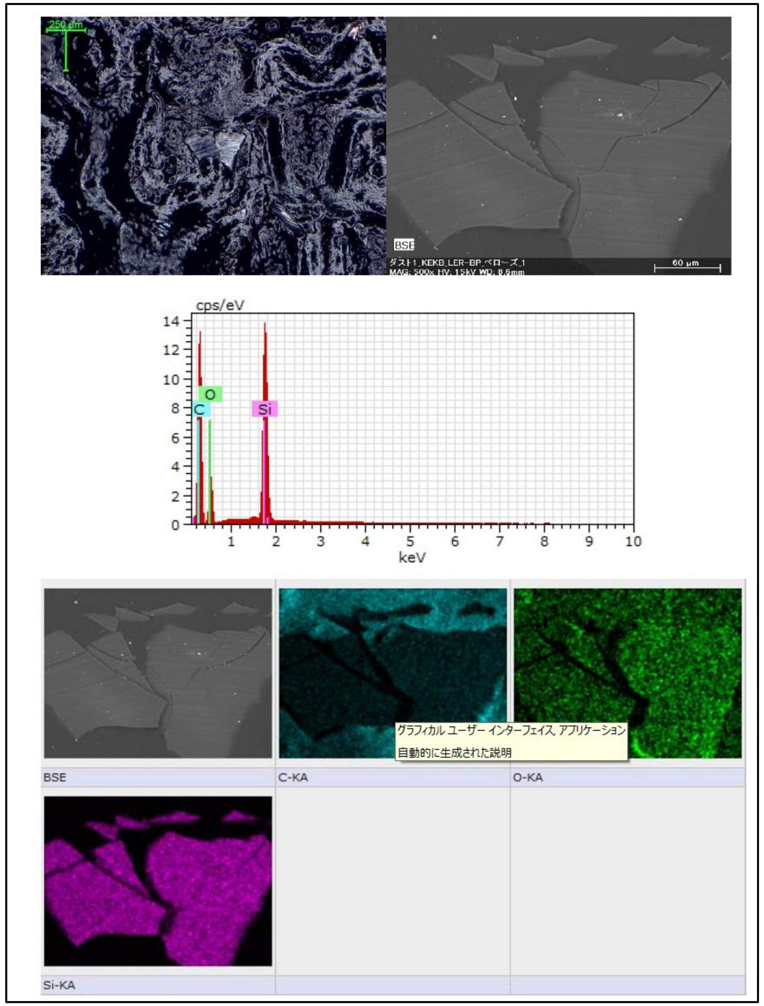




SEM/EDS analysis of dust particles 3

- Dust particles collected from beam pipes installed in D10 wiggler section
  - Middle size particles
  - Main components : O, Al, Si, Ca
  - Others : Mg, Ti, Fe, etc.





SEM/EDS analysis of dust particles 4

- Reference : Dust particles collected from electrode sample by ultrasonic cleaning
  - Main components : C, O, F, Al W, Cu