Highlight from SuperKEKB Beam Commissioning after Upgrading during Long Shutdown 1 (LS1)

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On behalf of the SuperKEKB and Belle II Commissioning Group

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SuperKEKB

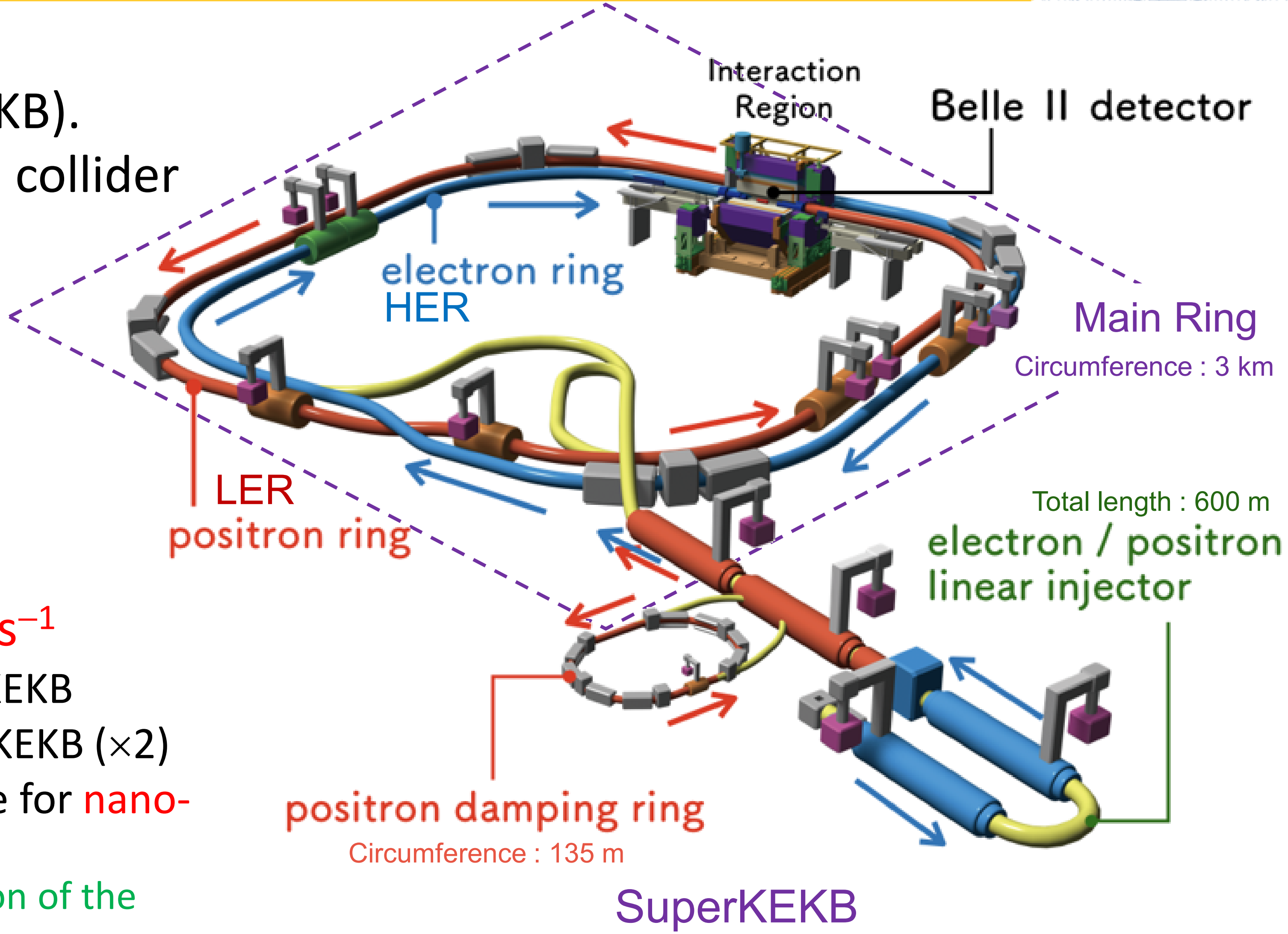
- SuperKEKB;
  - An upgrade of KEKB B-factory (KEKB).
  - High-luminosity electron-positron collider to seek out new physics hidden in subatomic particles.
  - Main ring (MR) is composed of

    Low Energy Ring (LER);

    4.0 GeV Positron, 3.6 A

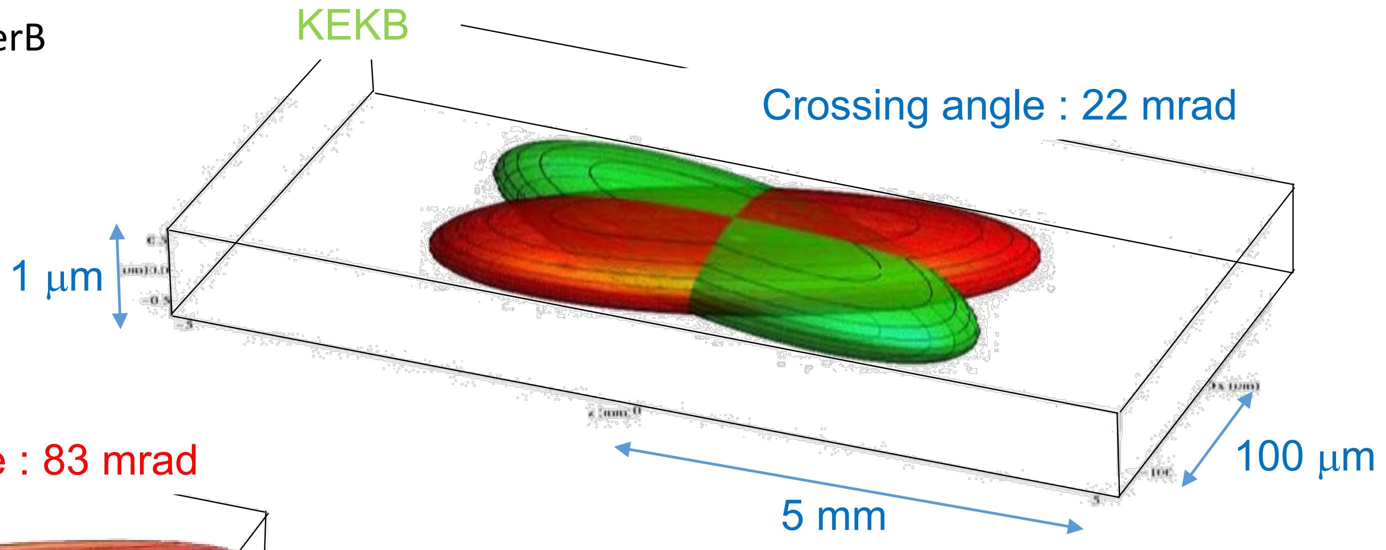
    High Energy Ring (HER);

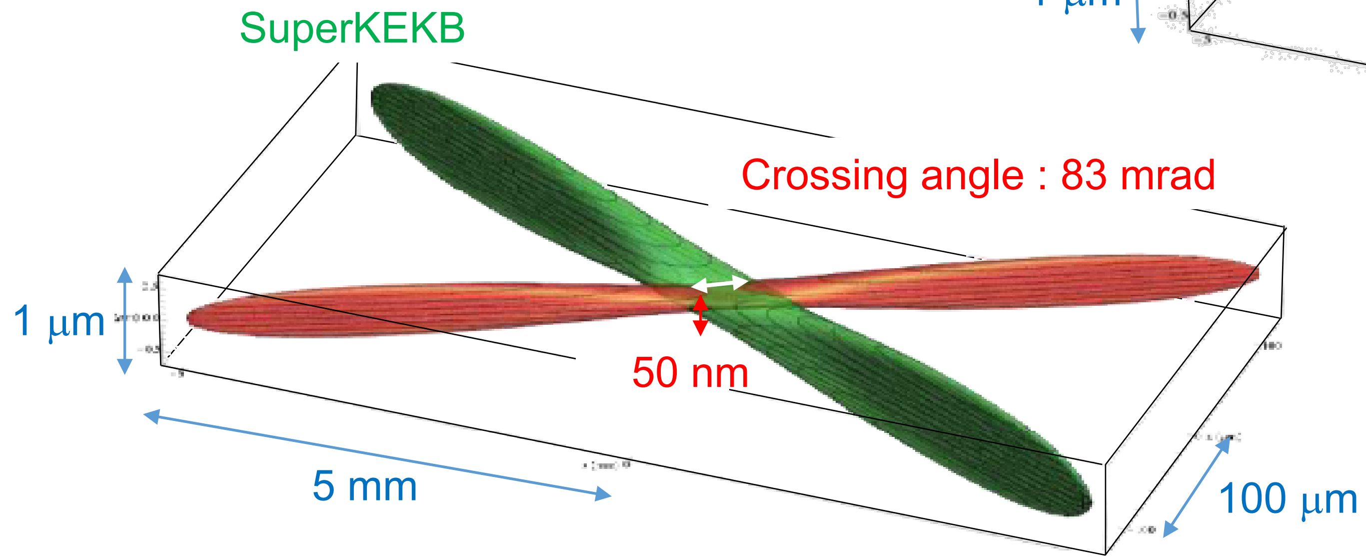
    7.0 GeV electron, 2.6 A
  - Target Luminosity : $\sim 6\times 10^{35}\ \mathrm{cm^{-2}\cdot s^{-1}}$
    - ✓ ~30 times maximum luminosity of KEKB
    - ✓ Higher beam current than those of KEKB (×2)
    - ✓ β_y^* squeezing and smaller emittance for nano-beam collision scheme
      - ✓ The world's first practical application of the nano-beam scheme



Nano-beam collision scheme

- Proposed by P. Raimondi at INFN-LNF for the Italian SuperB project around 2006 and tested successfully at DAΦNE.
- Implemented at SuperKEKB, for the first time, with low-emittance beams on a high-energy collider.





$$\begin{cases} L \approx \dfrac{\gamma_\pm}{2er_e}\left(\dfrac{I_\pm \xi_{y\pm}}{\beta^*_{y\pm}}\right) \\ \xi_{y\pm} \approx \left(r_e N_\mp / 2\pi\gamma_\pm \sigma^*_{x,\mathrm{eff}}\right)\sqrt{\beta^*_y/\varepsilon_y} \end{cases} \Rightarrow \begin{cases} L \propto \dfrac{I_\pm}{\beta^*_{y\pm}} \\ L_{sp} \equiv \dfrac{L}{n_b I_{b-} I_{b+}} \propto \dfrac{1}{\beta^*_{y\pm}} \end{cases}$$

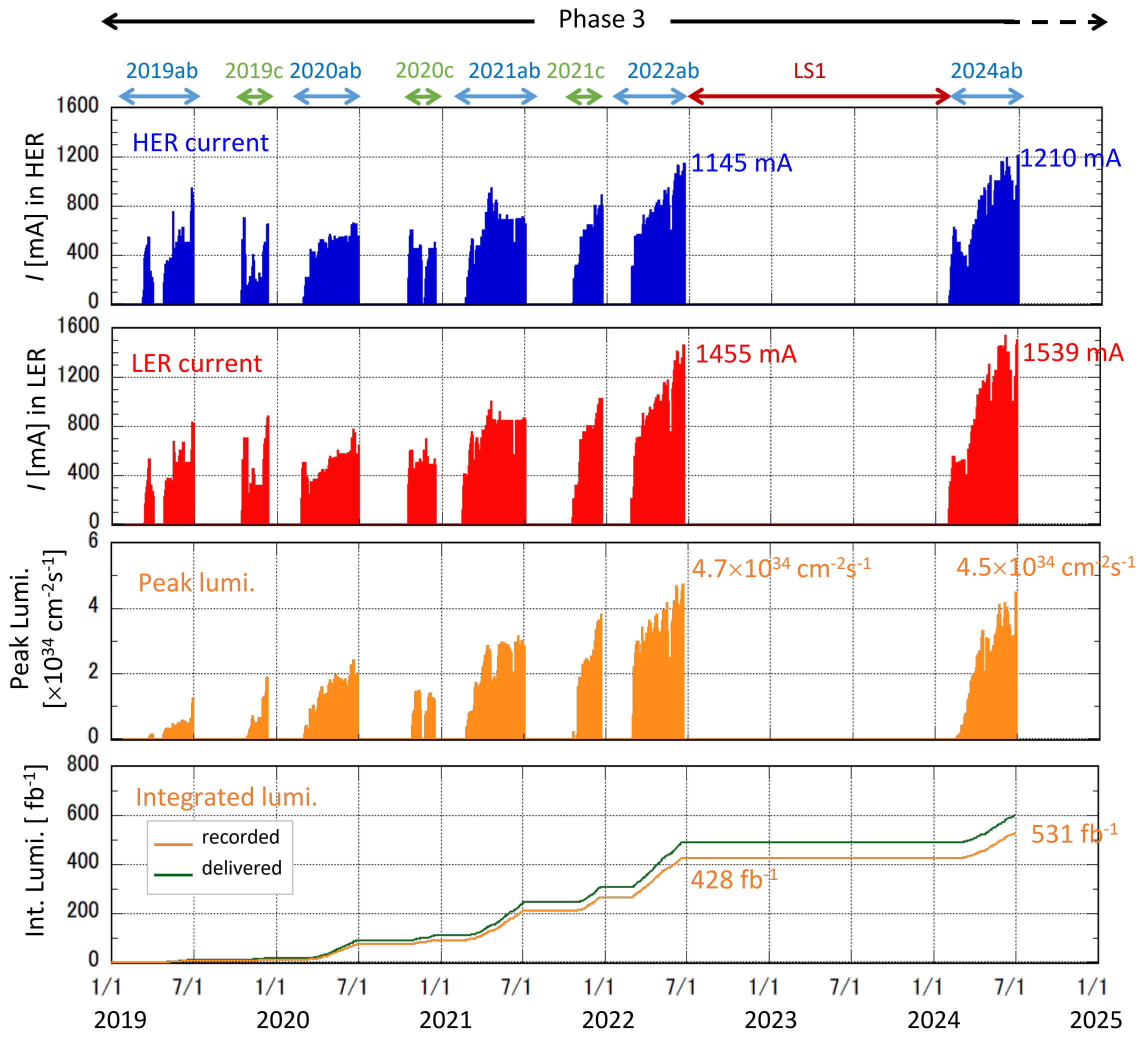
(β^*_y/ε_y: Keep constant)

- To avoid Hourglass effect:
  - Beam bunces collide
    - ✓ With sufficiently small σ_x*.
    - ✓ At a large horizontal crossing angle.
  - The longitudinal size of the overlap between colliding bunches is much shorter than bunch length.
- It is possible to squeeze β_y* much smaller than bunch length.
  - Luminosity increases in proportion to $1/\beta_y^*$.

Phase 3 commissioning history

- Phase3 operation (2019.March~);
  - Physics run with fully instrumented detector
  - Naming rule of Phase3 operation
    - "YYYYxx run"
      - YYYY: Calendar year
      - xx:
        - a : End of winter shutdown - March
        - b : April – Start of summer shutdown
        - ab : End of winter shutdown – Start of summer shutdown
        - c : End of Summer shutdown – Start of winter shutdown

      March is end of Japanese fiscal year.
  - 2019/March-2022/Jun : Run1
    - 2019c, 2020ab, 2020c, 2021ab, 2021c, 2022ab
    - Luminosity (peak/integrated) : 4.7×10^{34} $cm^{-2}s^{-1}$/428 fb^{-1}
    - β_y^* squeezing : ~0.8 mm (1 mm for most of the time)
    - Maximum beam current : HER/LER = 1145/1455
    - Facing various challenges for luminosity improvement
      - Severe beam-beam effect, Shorter beam lifetime, Lower bunch current limit, Low machine stability, Low injection efficiency, Sudden beam loss, Aging of hardware and facilities.
  - 2022-2024 : Long shutdown 1 (LS1)
    - Accelerator upgrades
    - Belle II reinforcement and maintenance
  - 2024/Jan.- : Run2
    - 2024ab (2024/Jan.-July)
      - 155 days (3696 hours)
    - Start-up after a long shutdown
    - Aiming to make new world luminosity record
    - 2024c will start on Oct./9th. (~2 months)



Major upgrades during LS1

- All planed upgrades during LS1 to overcome accelerator challenges were completed almost on schedule.

Challenges as Lumi. Frontier machine

1. Short beam lifetime
2. Beam instabilities
3. Low machine stability
4. Low injection efficiency

Luminosity after LS1 : $\sim 2.4\times10^{35}$ $cm^{-2}s^{-1}$

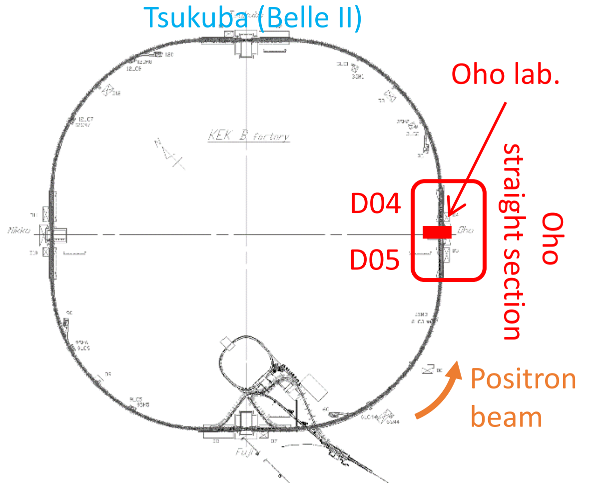
- ✓ Increasing total beam currents
- ✓ Increasing bunch current (beam current)
- ✓ Squeezing β_y^*

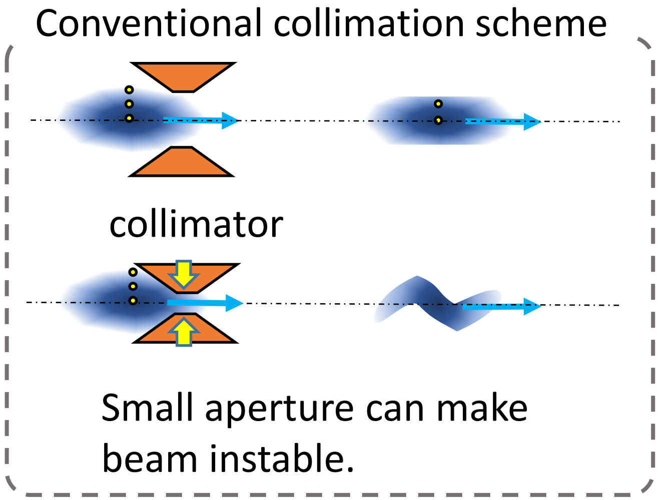
Major upgrades

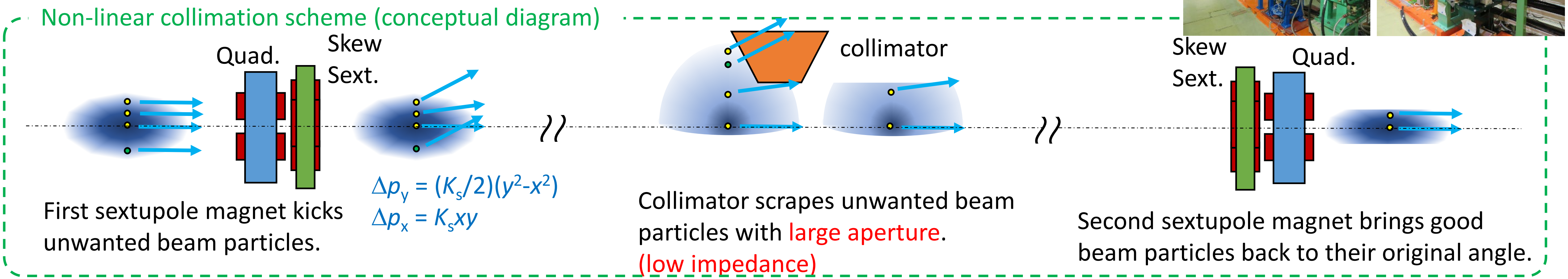
- Radiation shield enhancement at IR
- Non-linear collimator with low impedance in LER
- Robust collimator head in LER
- Modification of HER injection point
- New equipment to investigate Sudden Beam Loss
- Pulsed quad. magnet at Linac
- New accelerating structure at Linac
- Fast kicker for 2^{nd} bunch orbit correction at Linac
- Magnet alignment at BT
- Etc.

Non-Linear Collimation (NLC) system

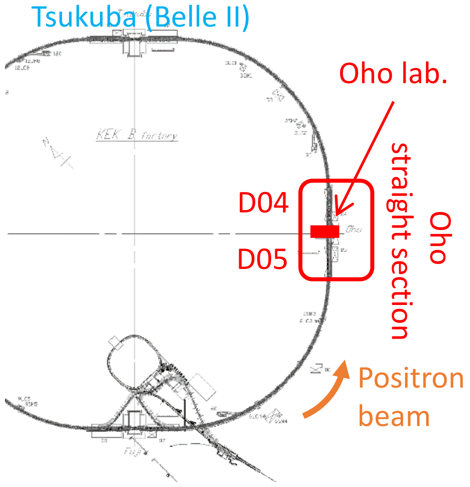
- Non-linear collimation (NLC) system was installed in LER Oho straight section.
  - Impedance of NLC is much lower than that of conventional collimator due to its large aperture.
  - NLC can relax TMCI bunch current limit.
  - Oho straight section is the location where the optics satisfies the requirements 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.







NLC system construction

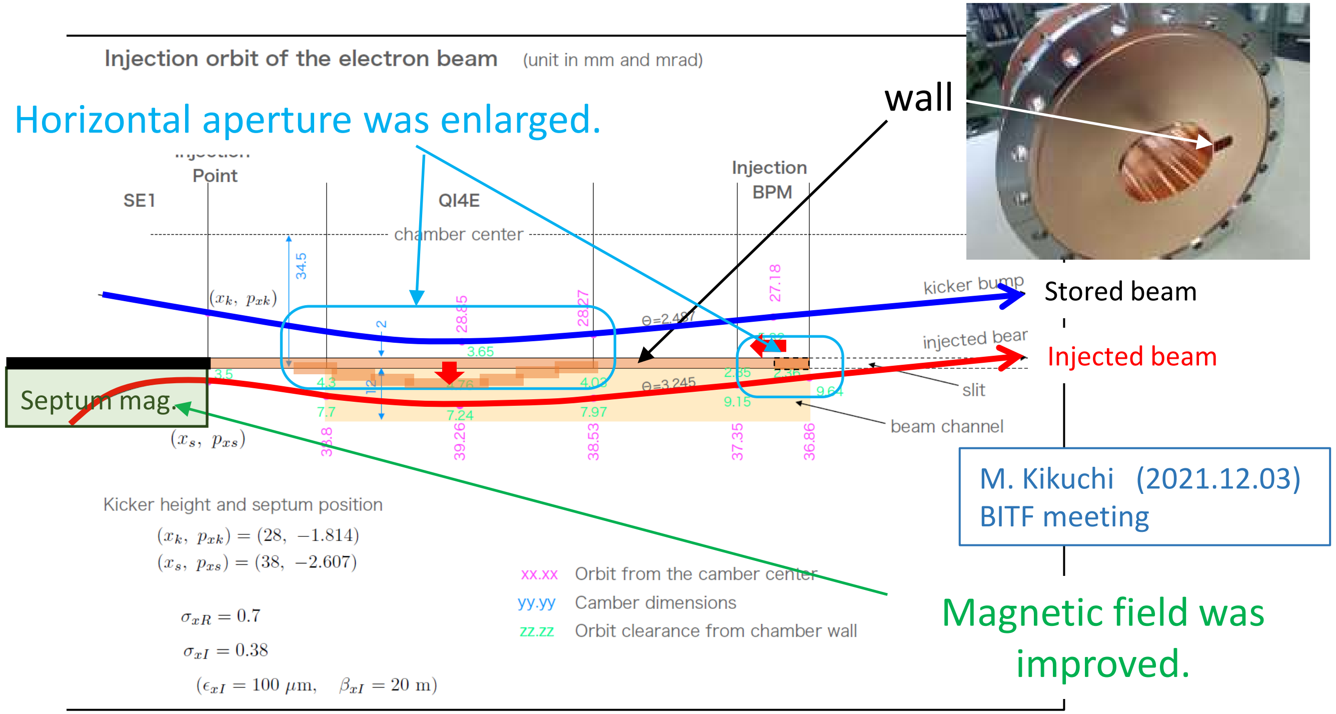


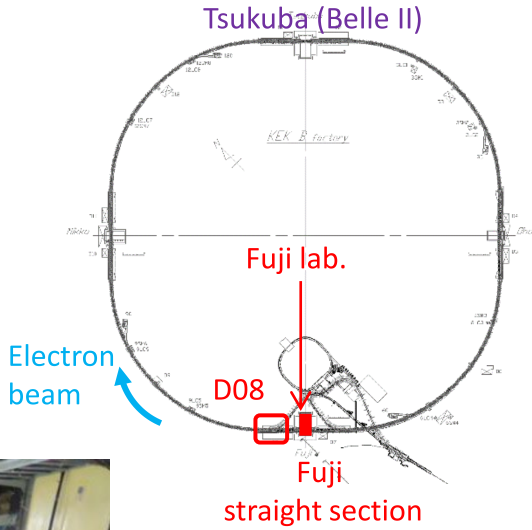
HER injection point upgrade

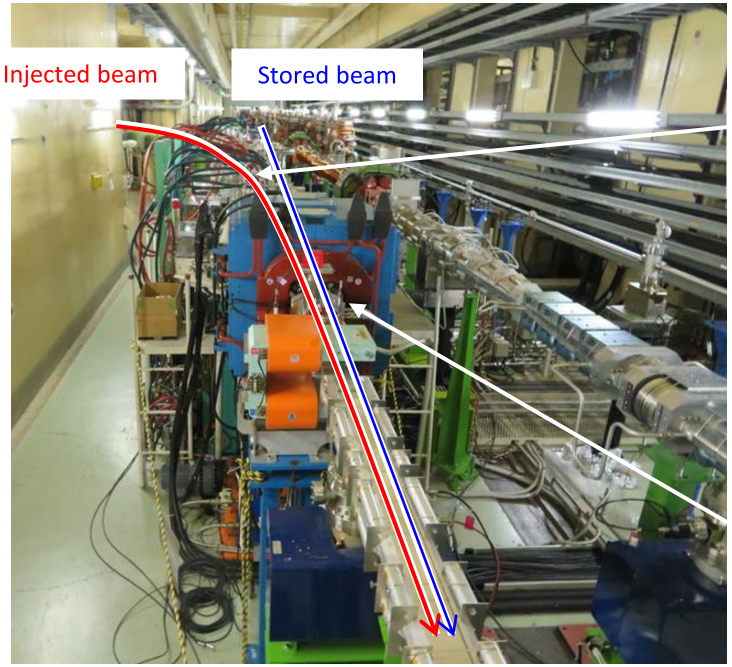
- Required upgrade to improve HER injection efficiency (what we have learned from beam operation until 2022b);
  - Enlargement of the horizontal aperture of beam pipe

  ➡ Replacement of beam pipes at injection point with new one with larger aperture
  - Reduction of amplitude of horizontal oscillation of injected beam

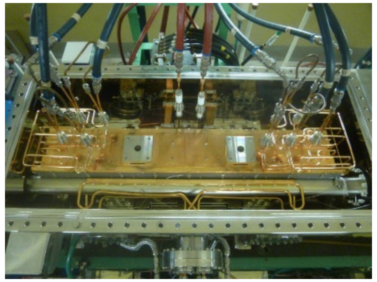
  ➡ Replacement of injection septum magnet with new one with improved magnetic field







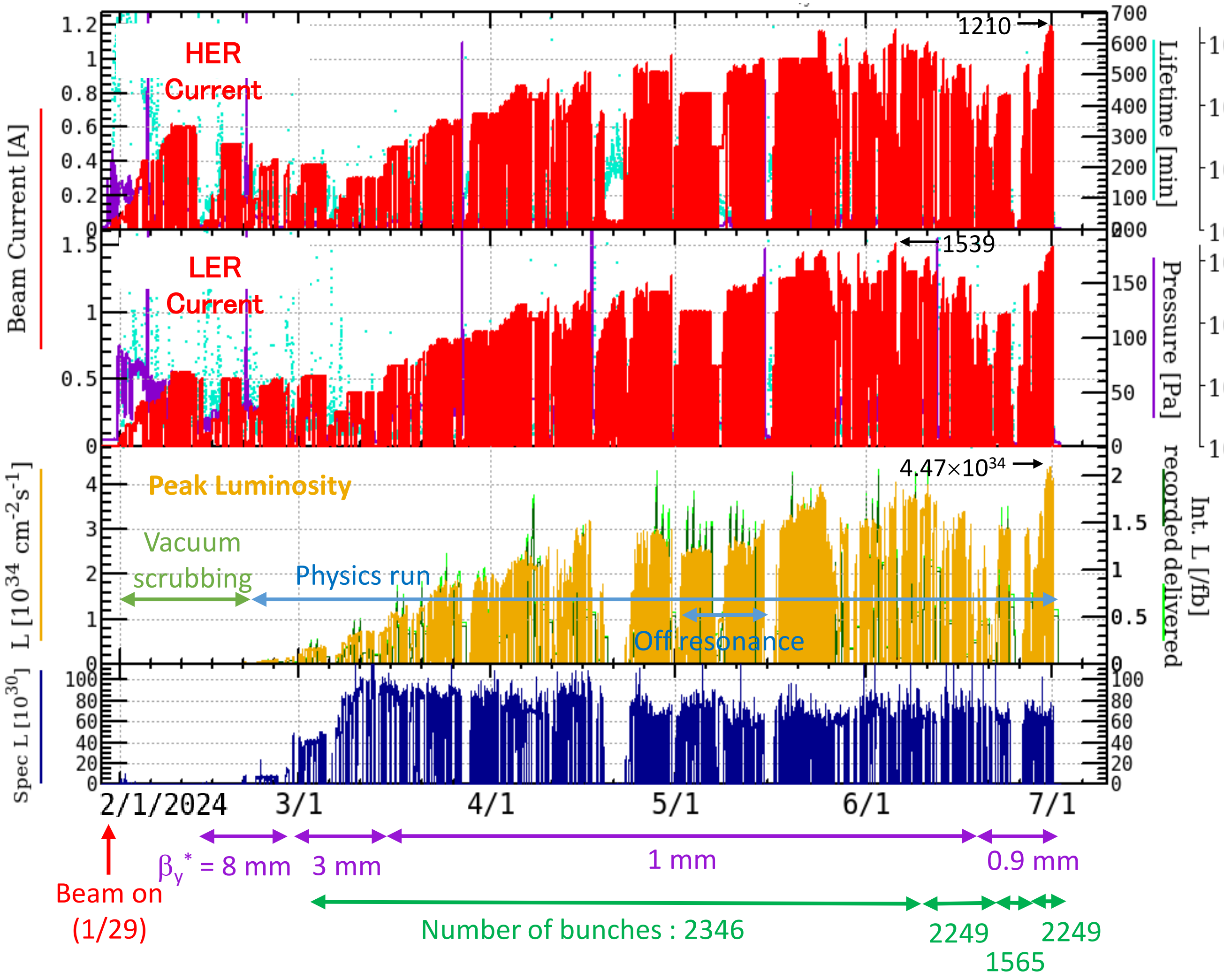
Septum magnet was replaced with new one.



New beam pipes with larger aperture

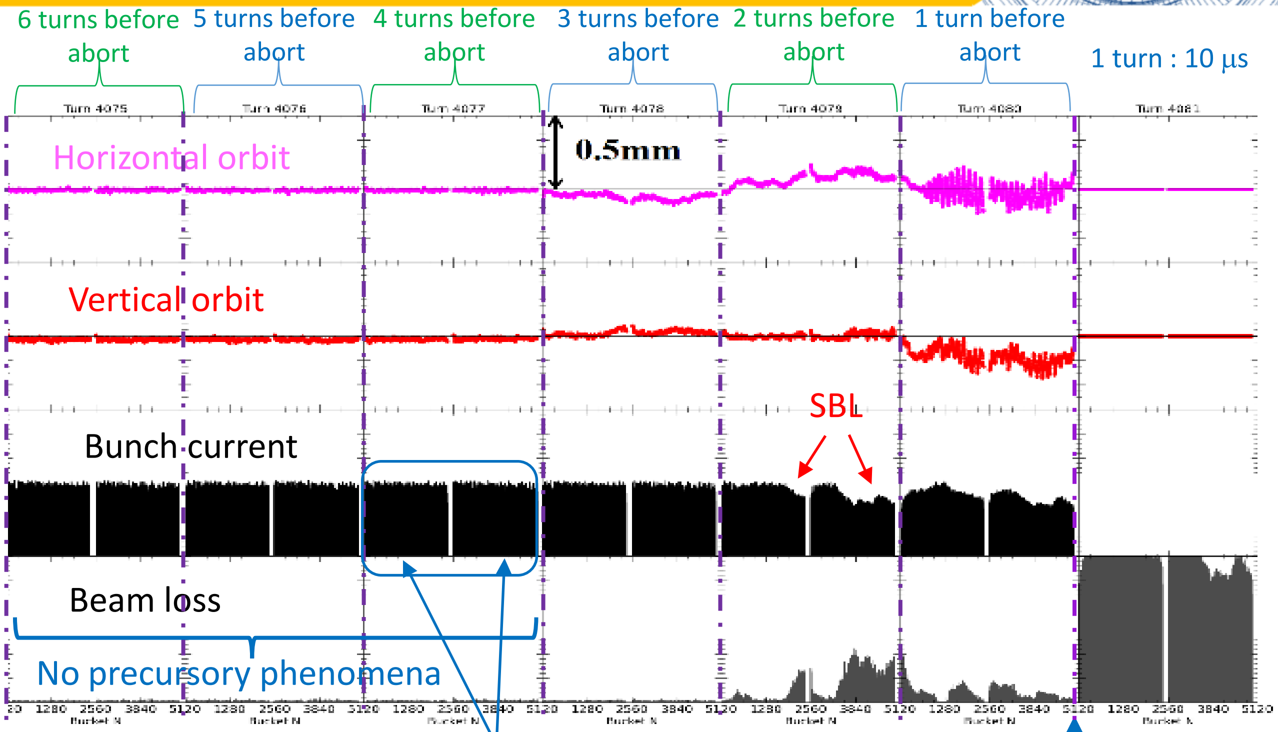
2024ab run overview

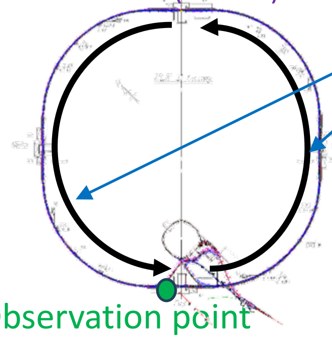
- Jan./29 – Feb./20
  - Vacuum scrubbing, Machine tuning, Machine study
- Feb./20 – July/1
  - Physics run, Machine tuning, Machine study
    - Struggling with Sudden Beam Loss, poor injection efficiency, low machine stability.
    - Many beam abort caused by SBL and injection beam
    - May/1-12 : Off 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.

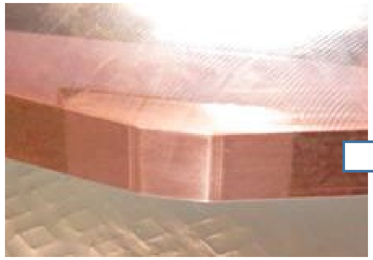


Sudden Beam Loss (SBL) #1

- 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.

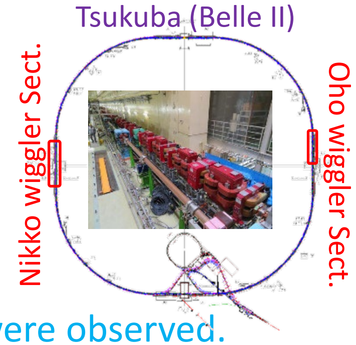


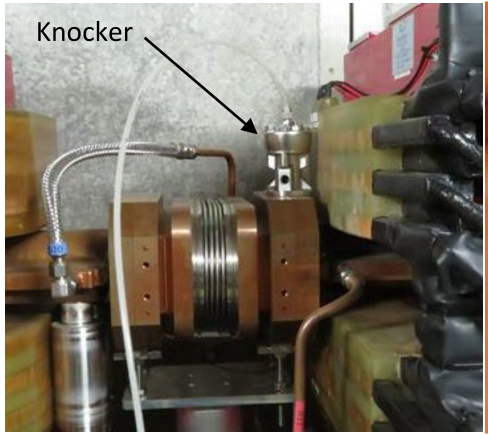


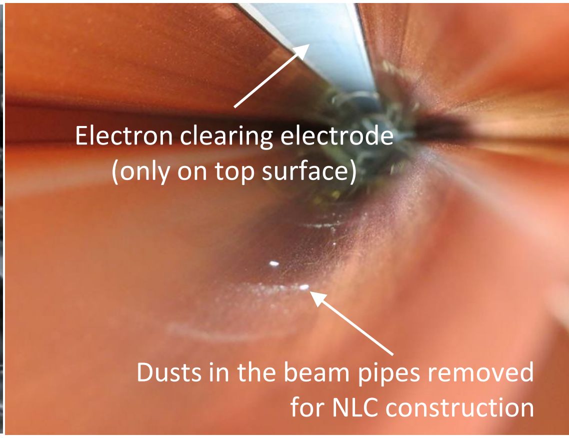


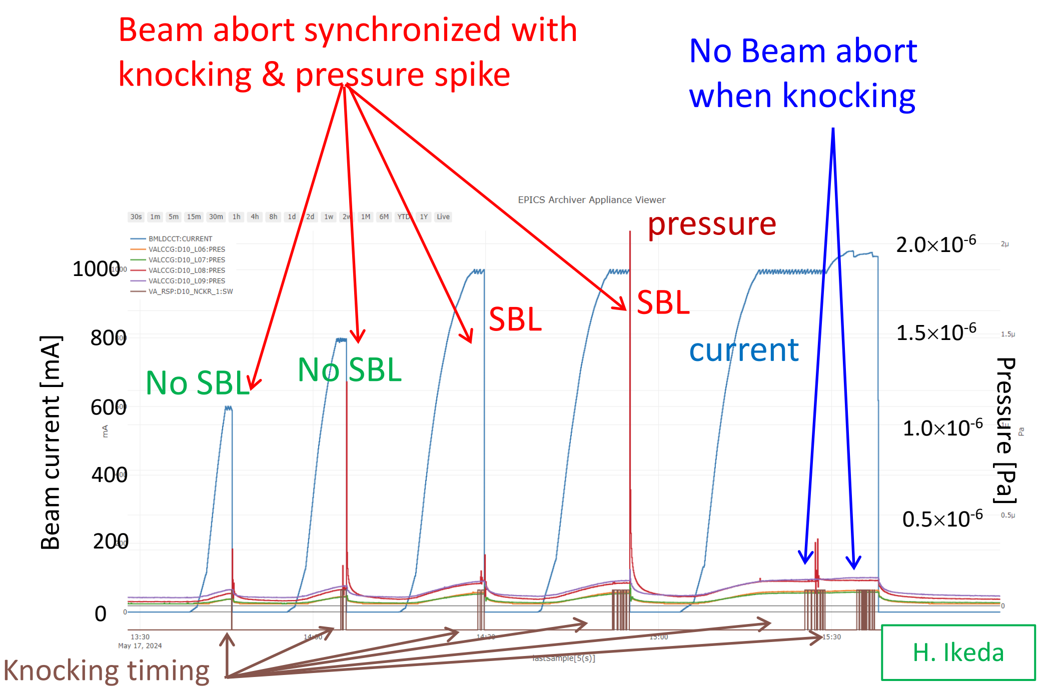
Sudden Beam Loss (SBL) #2

- 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.



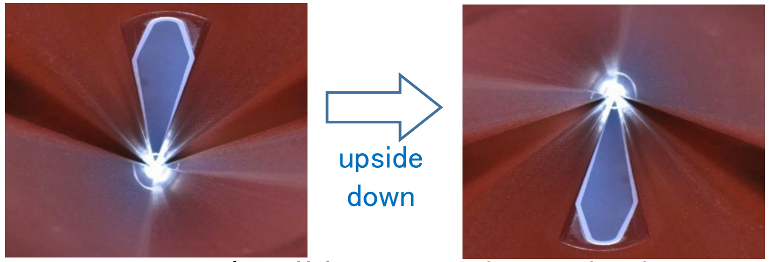


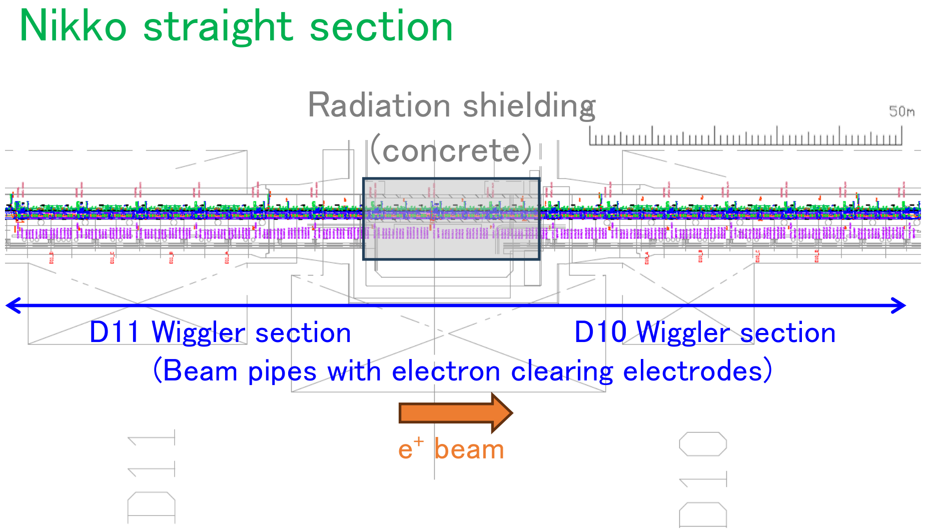


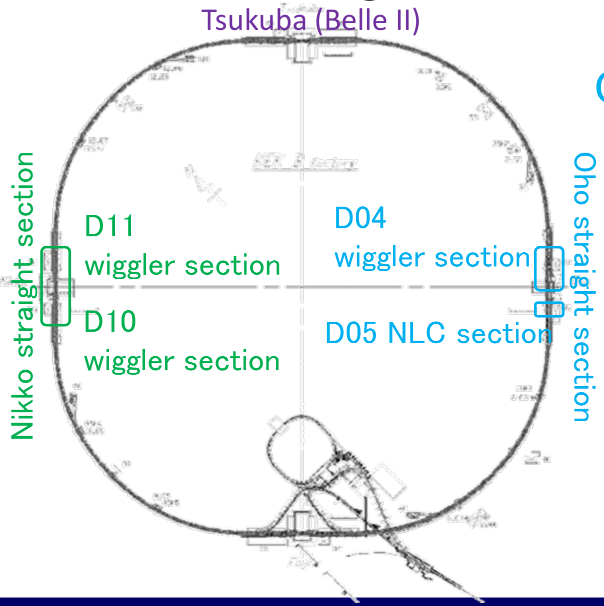


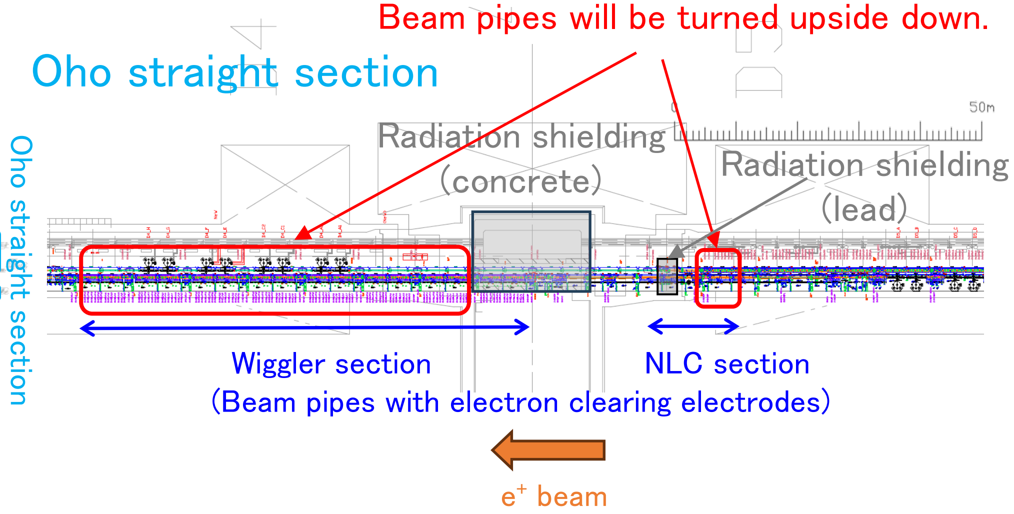
Sudden Beam Loss (SBL) #3

- Countermeasure against SBL during summer shutdown
  - Turning beam pipes with electron clearing electrode upside down
    - 15/50 beam pipes will be 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) will be turned upside down.
      - It takes over 1 month to turn 13 beam pipes upside down at D04 wiggler section.
    - 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 will not be turned upside down.
  - Knocking as many beam pipes (with electron clearing electron or groove structure) as possible.



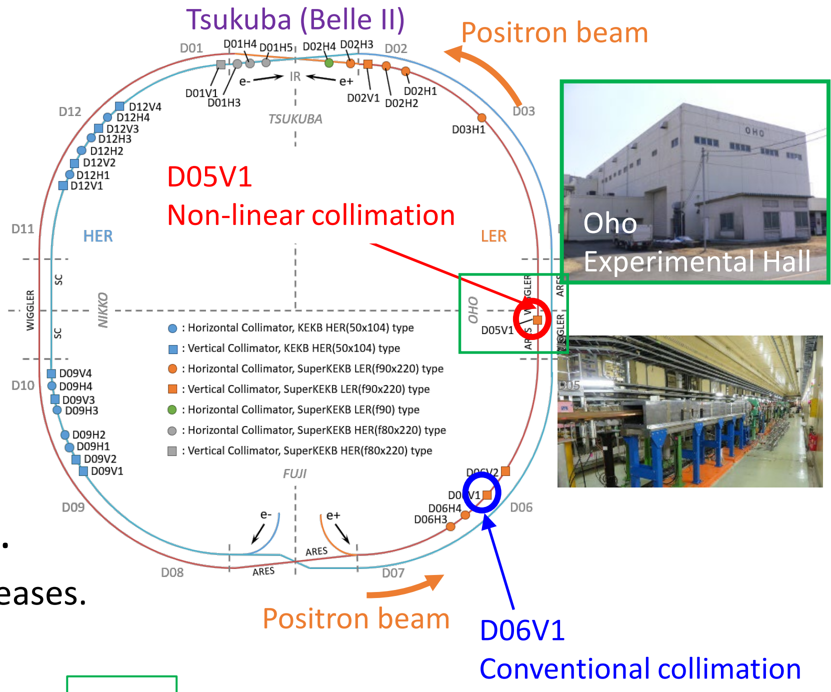




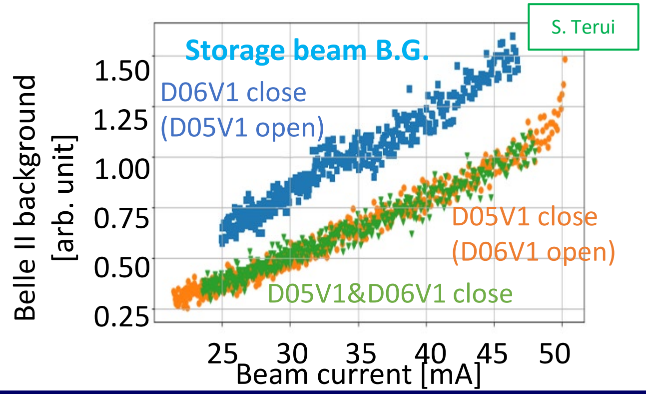


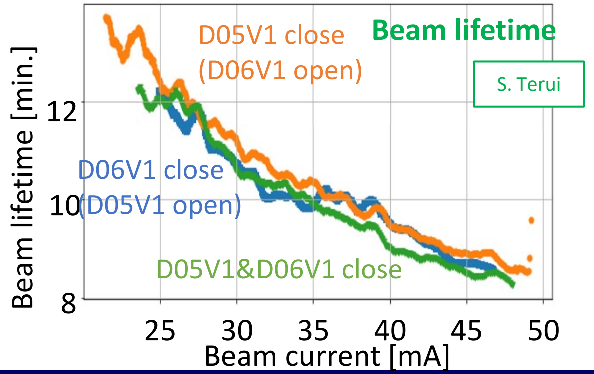
First trial of Non-linear collimation

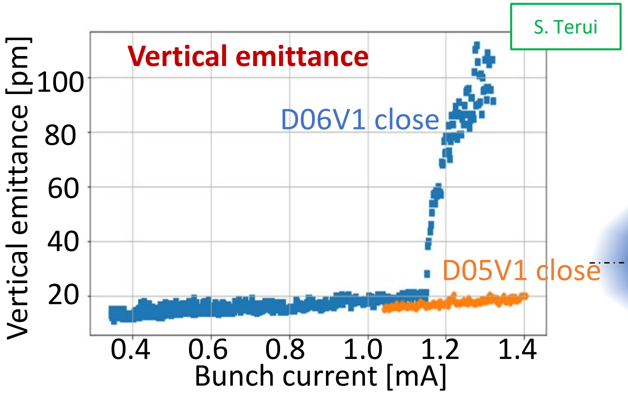
- Comparison between D05V1(NLC) and D06V1(Conventional type) with the same effective collimation gap
  - Storage beam B.G. : D05V1 suppressed more beam B.G. than D06V1
  - Beam lifetime : Very similar between D05V1 and D06V1
  - Beam blowup : No vertical blowup was observed with D05V1 (Suppression of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

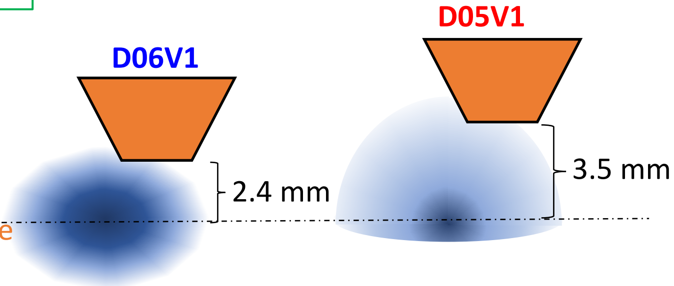


- Other findings :
  - Injection beam B.G. may also be reduced by NLC with tuning of β_x at the skew sextupole magnets.
    - It will be tested during 2024c run.
  - Radiation level in the Oho Experimental Hall increases as closing the D05V1 gap.
    - Though it was still lower than the regulatory limit,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





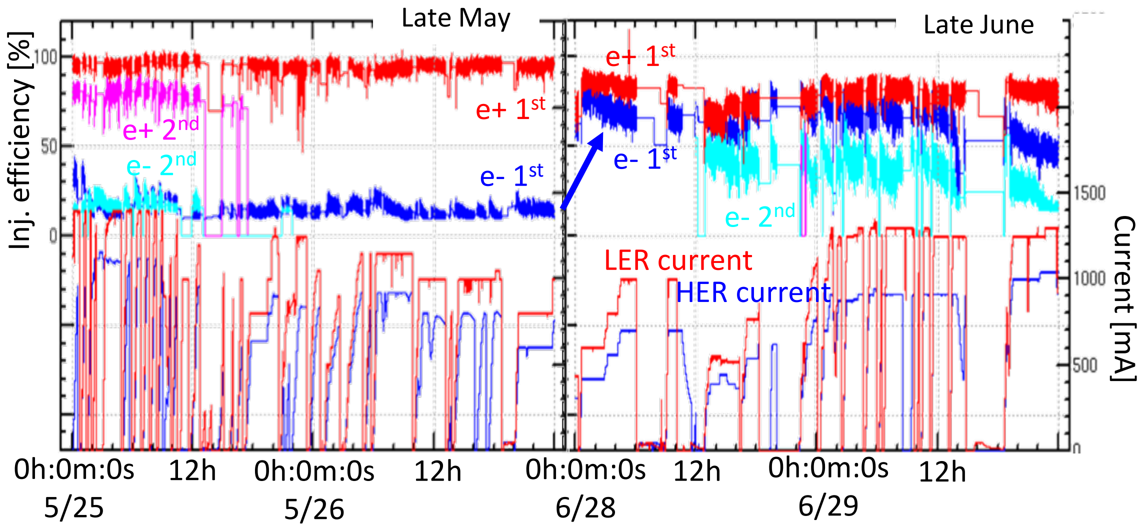


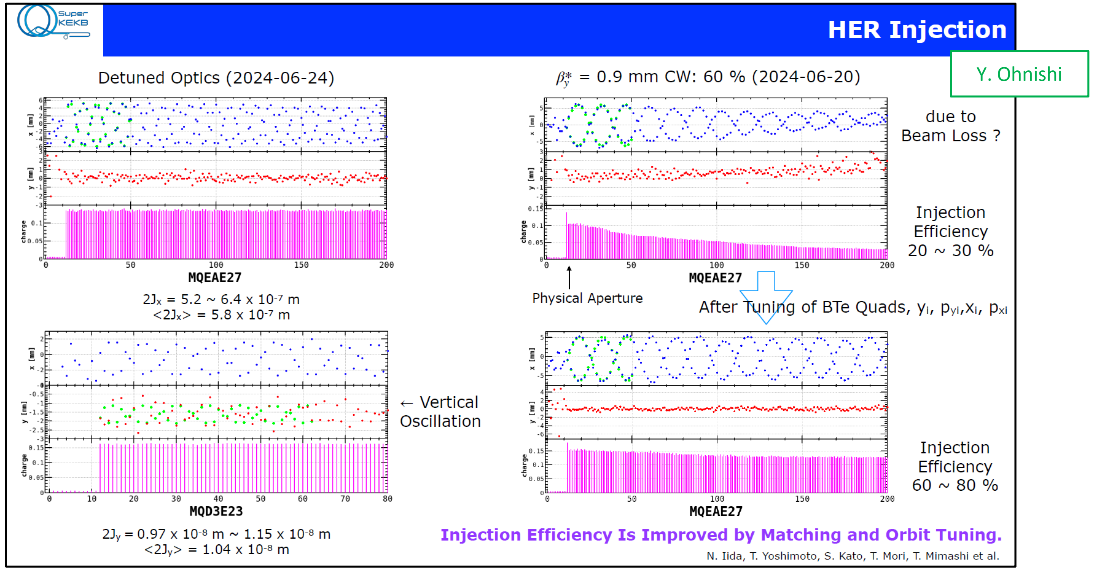


Same effective collimation gap : $64\sigma_y$

Injection & Maximum beam currents

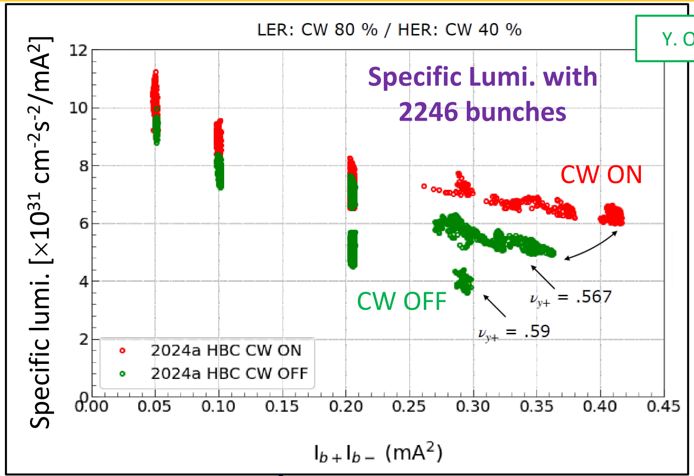
- HER: maximum beam current 1.2 A (Target : 1.4 A)
  - Had straggled with poor injection efficiency and stability despite upgrade to HER injection point during LS1 (aperture enlargement, new septum magnet).
    - Frequent beam aborts caused by injection beam (especially 2nd bunch)
    - Long-term dedicated 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

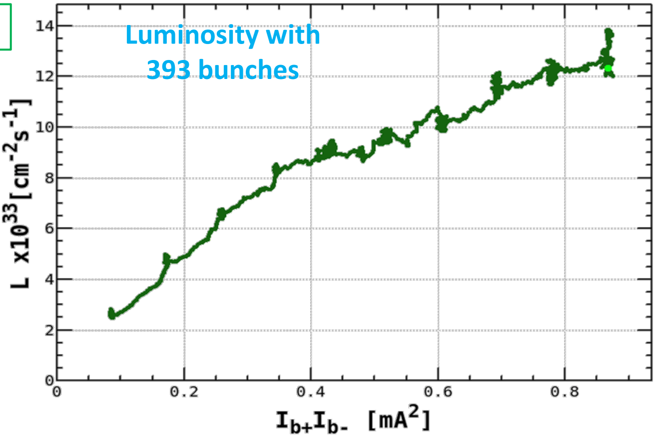




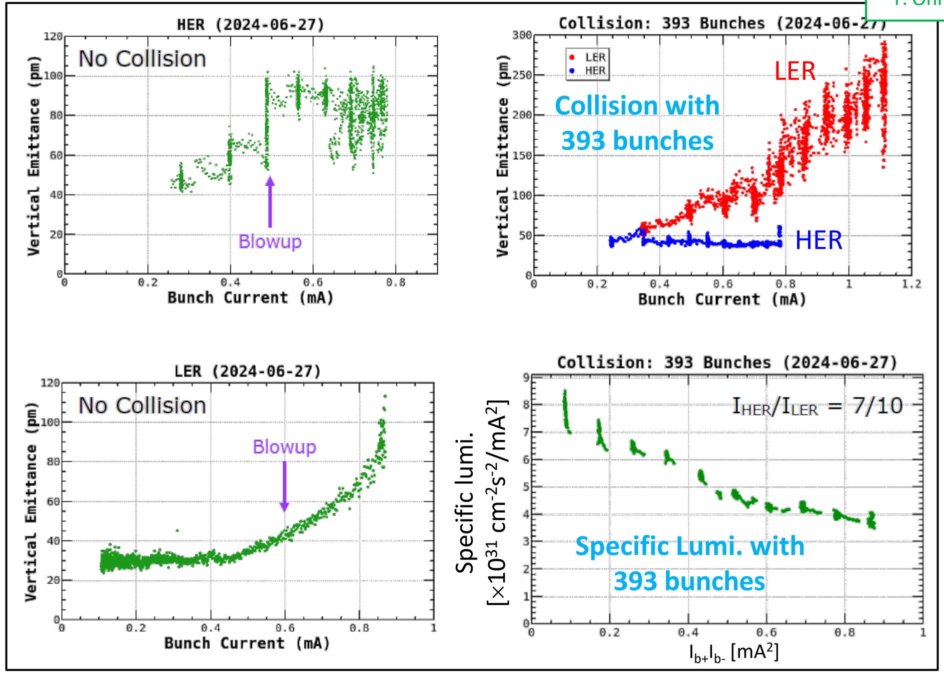
Luminosity

- 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}

Summary

- 2024ab run was conducted as scheduled from January 29th to July 1st.
  - First run after Long Shutdown 1
    - NLC system construction, upgrade of HER injection point, etc.
  - Peal luminosity : 4.47×10^{34} $cm^{-2}s^{-1}$
  - Integrated luminosity : 103 fb^{-1}
  - βy^* squeezing : mostly 1.0 mm, finally 0.9 mm
- There are many findings from 2024ab run
  - First demonstration of the effectiveness of the NLC system
  - Improvement of HER injection efficiency at last (30% -> 80%)
  - Still struggle with SBL, but on track to solve it for LER
    - Turning beam pipes with electron clearing electrodes upside down during summer shutdown
  - Also struggle with difficulty to increase beam currents and poor machine stability
- 2024c run will start on October 9th.
  - Operation period : 2 months
    - Extending operation time is difficult due to rising electricity prices.
  - Target luminosity : 1×10^{35} $cm^{-2}s^{-1}$
    - Need to overcome many challenges.

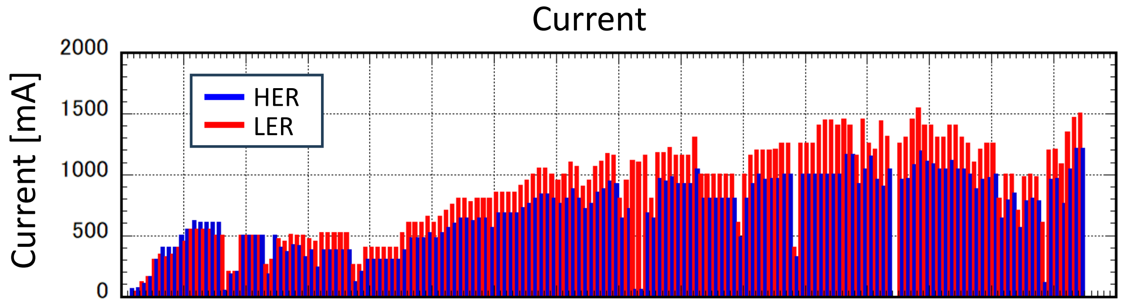
Fin.

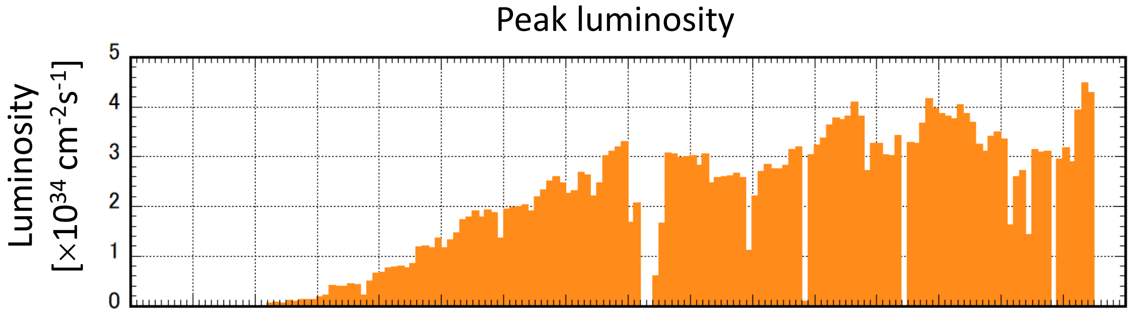
Thank you for your attention.

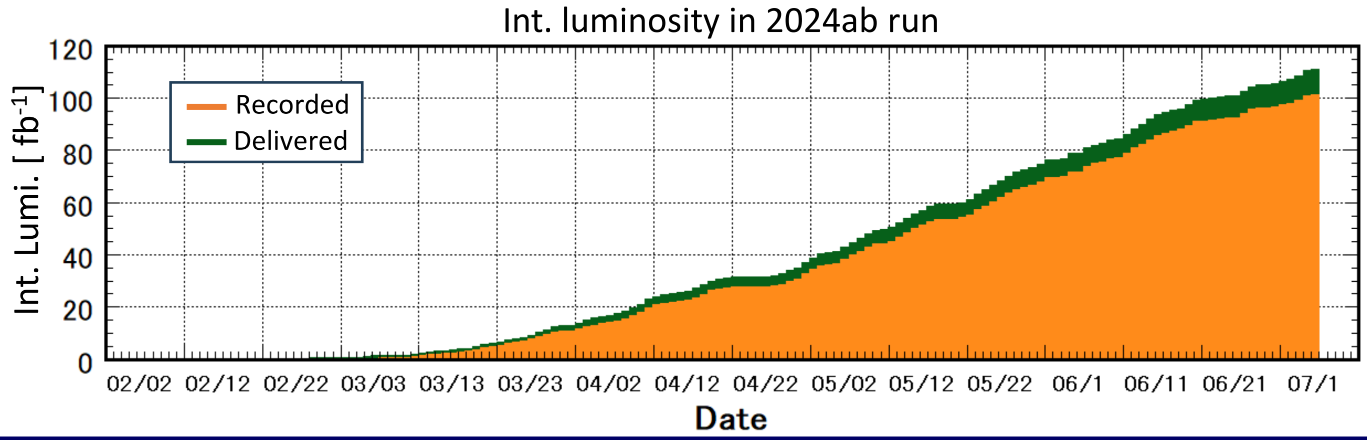
Back up

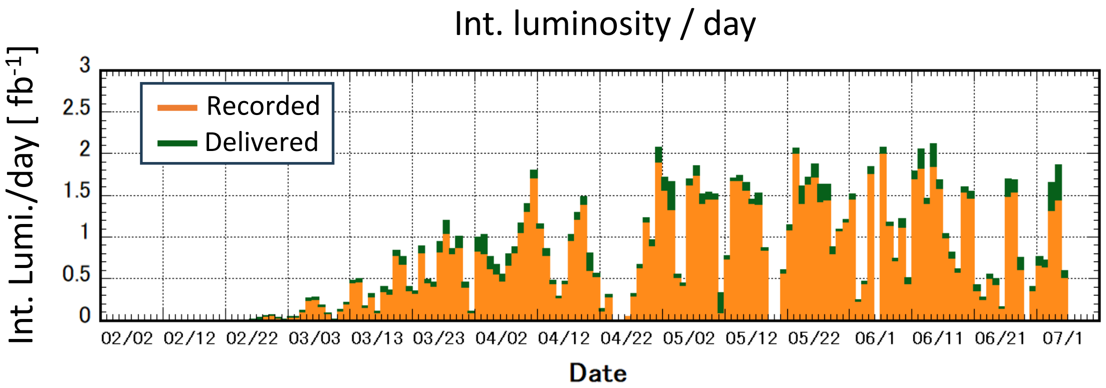
Beam currents & Luminosity (2024ab)

- Luminosity history
  - Peak Luminosity : 4.47×10^{24} cm^{-2}s^{-1}
    - 95 % of the world record achieved in 2022ab run
    - SuperKEKB world record : 4.7×10^{24} cm^{-2}s^{-1}
  - Maximum daily integrated luminosity :
    - Recorded : 2.01 fb^{-1}
    - Delivered : 2.11 fb^{-1}
  - Integrated luminosity in 2024ab run :
    - Recorded : ~103 fb^{-1}
    - Delivered : ~111 fb^{-1}



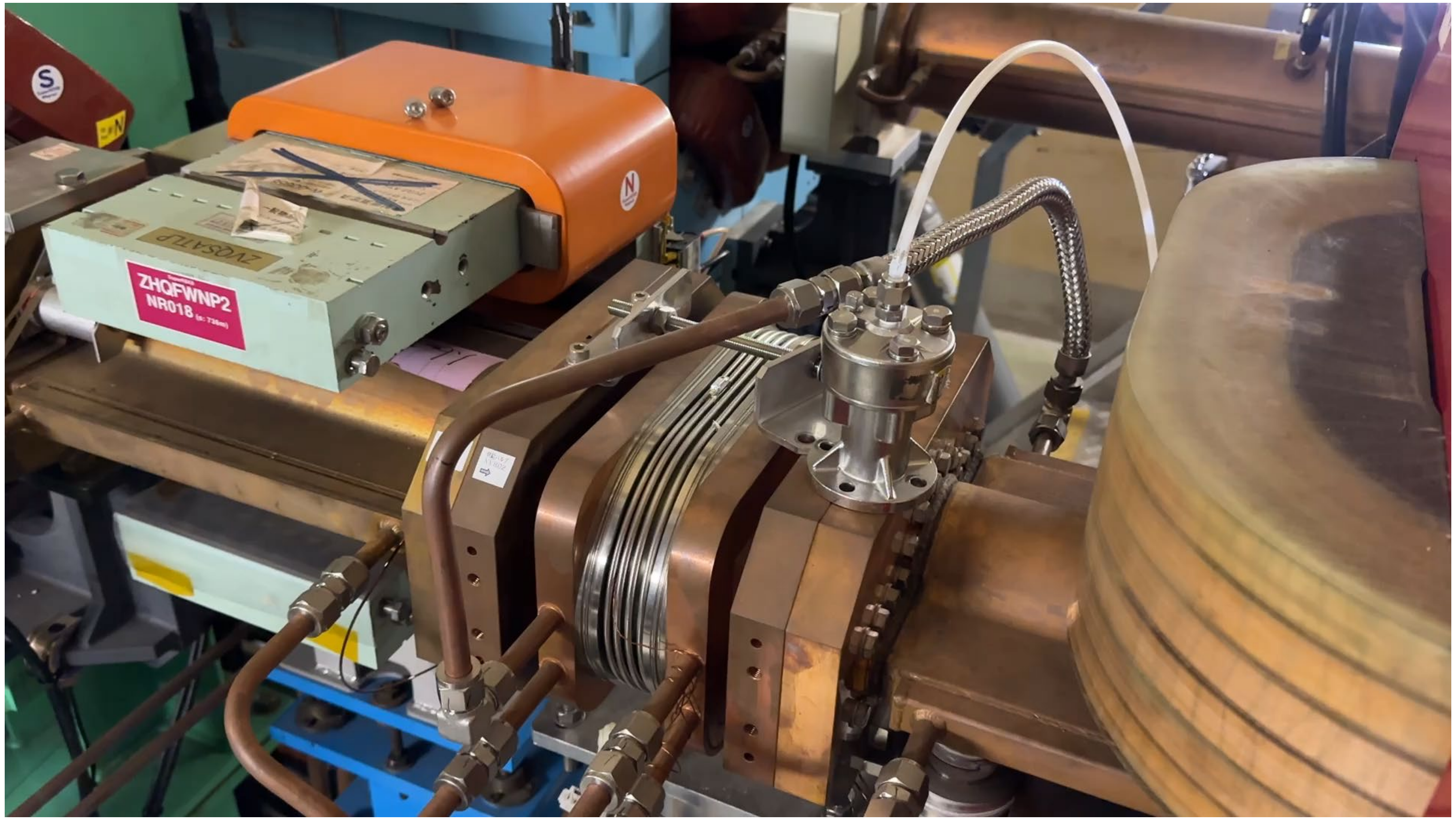


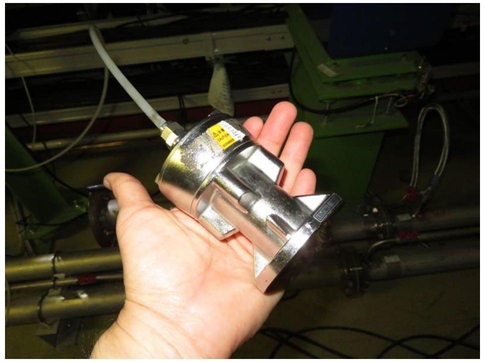




Beam pipe knocking

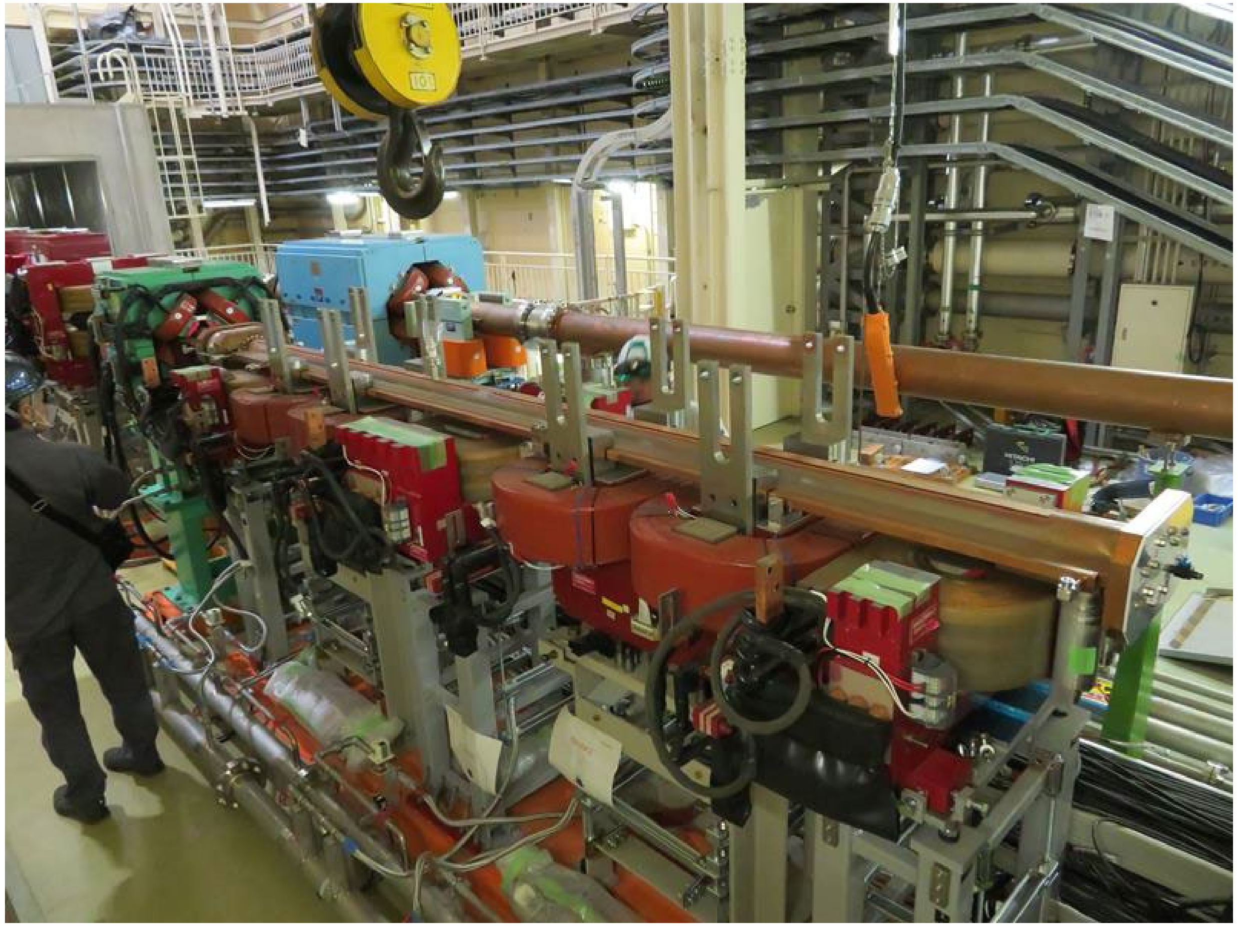
H. Ikeda





Oho straight section

- Beam pipe removal work for NLC construction



Oho straight section

- Beam pipe removal work for NLC construction

Nikko straight section

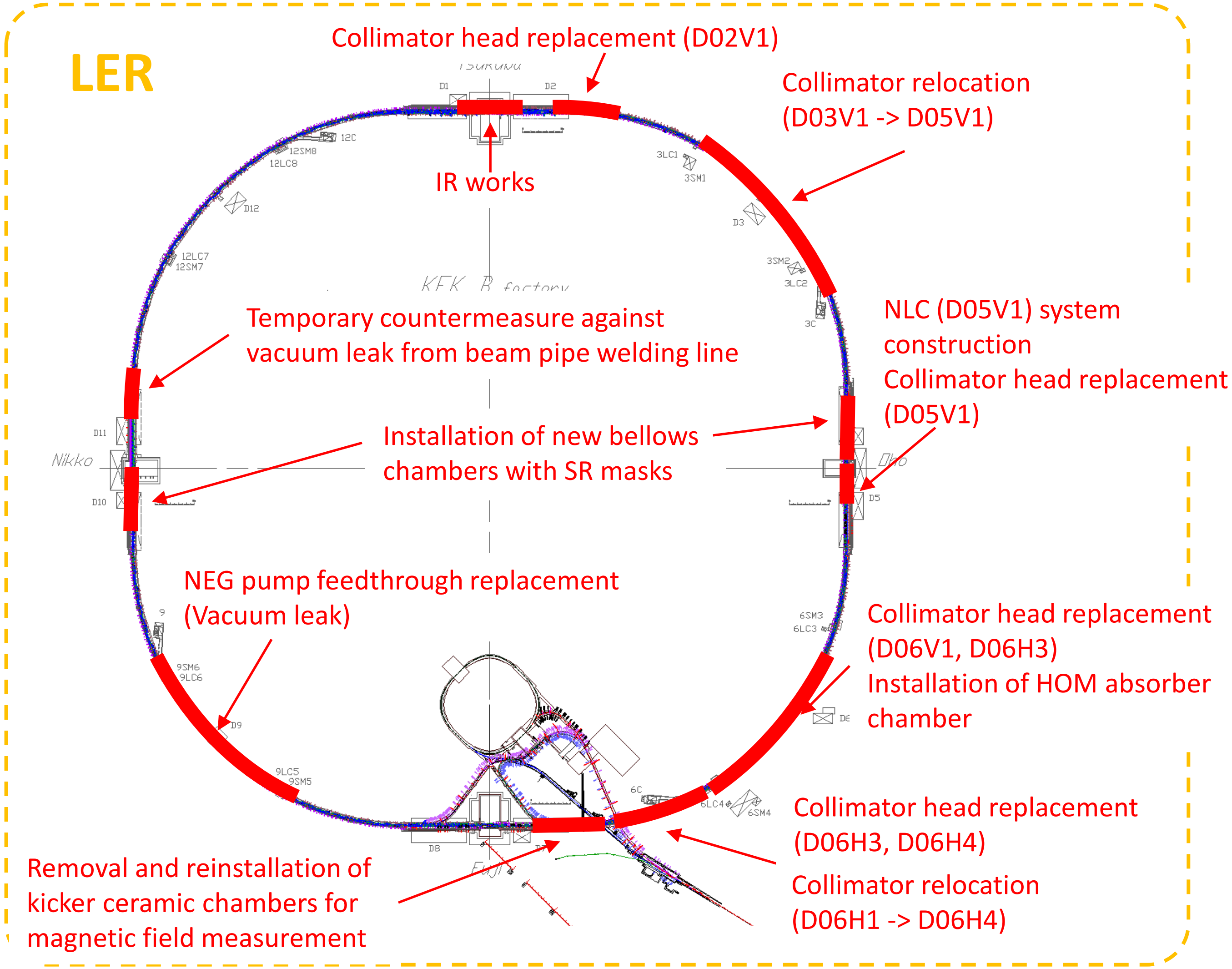
- There are also superconducting RF cavities at Nikko straight section.

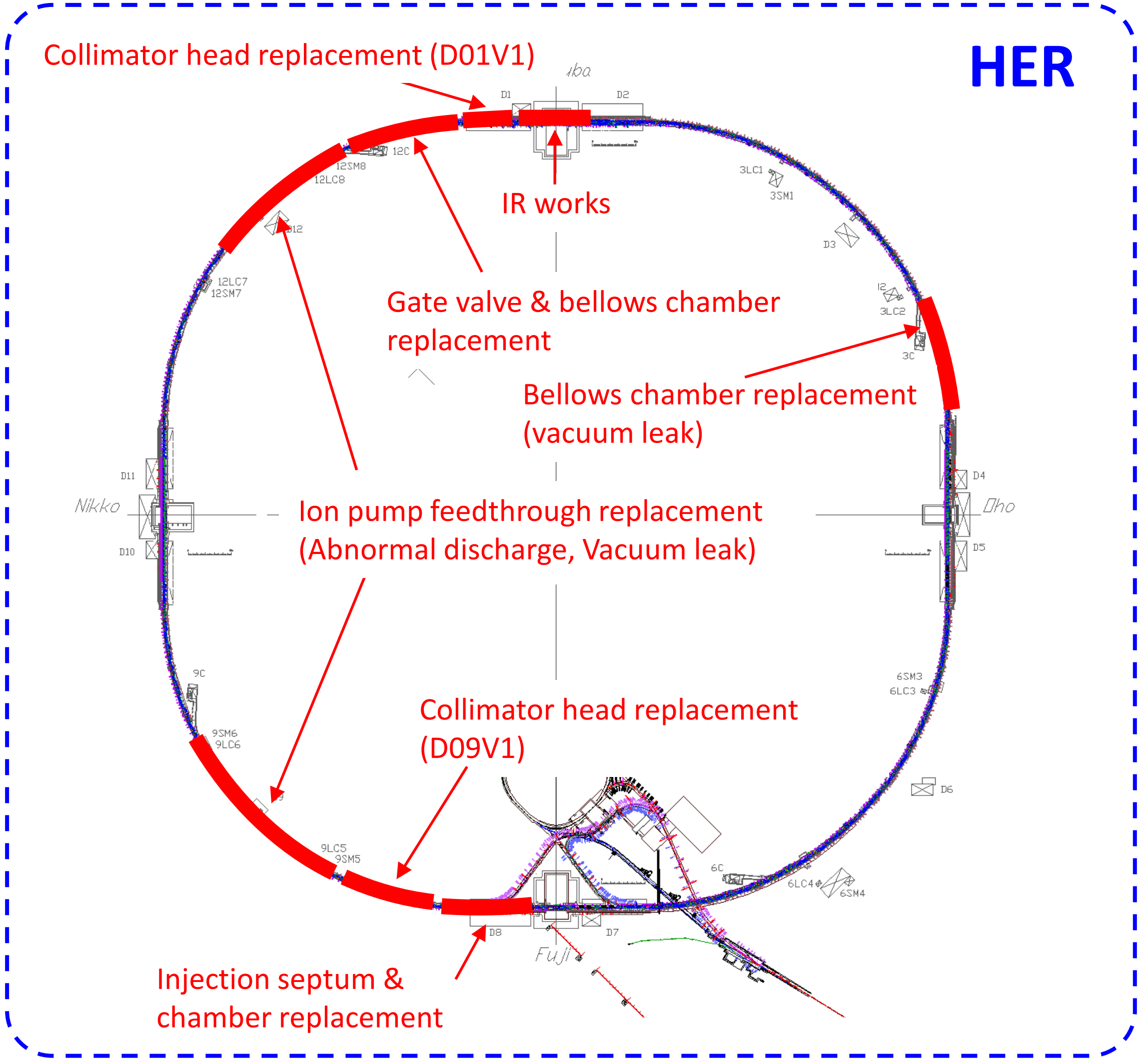
Nikko straight section

- There are also superconducting RF cavities at Nikko straight section.

Vacuum works during LS1 at a glance (MR)

: Area open to dry nitrogen or atmosphere





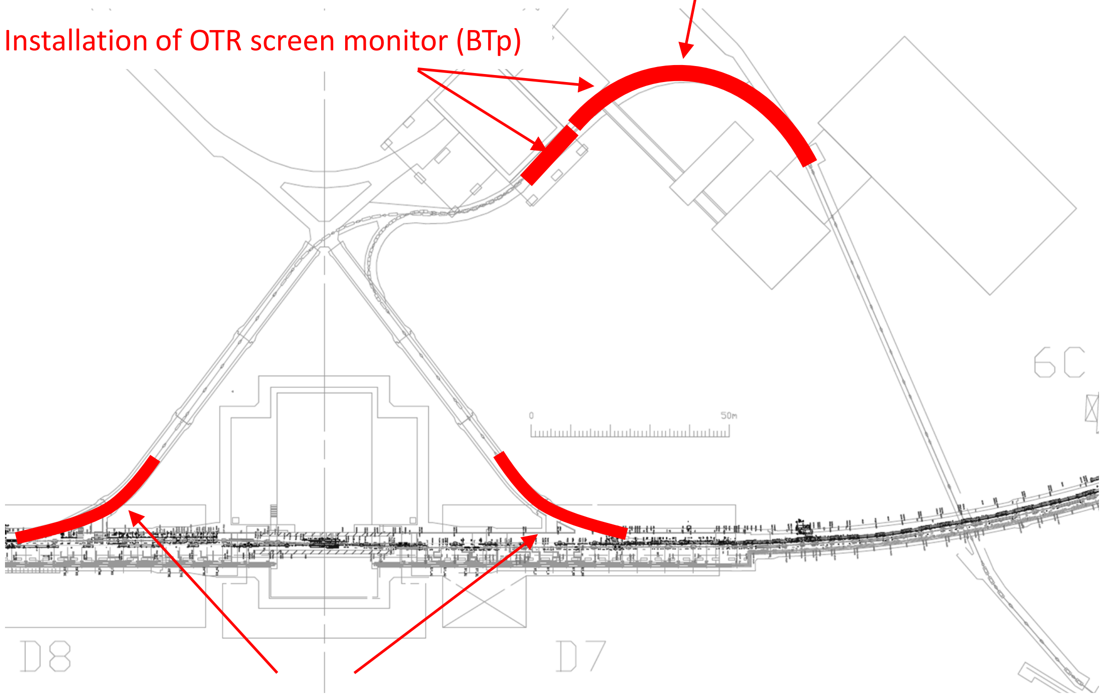
Vacuum works during LS1 at a glance (BT&DR)

: Area released with dry nitrogen or atmosphere

BT

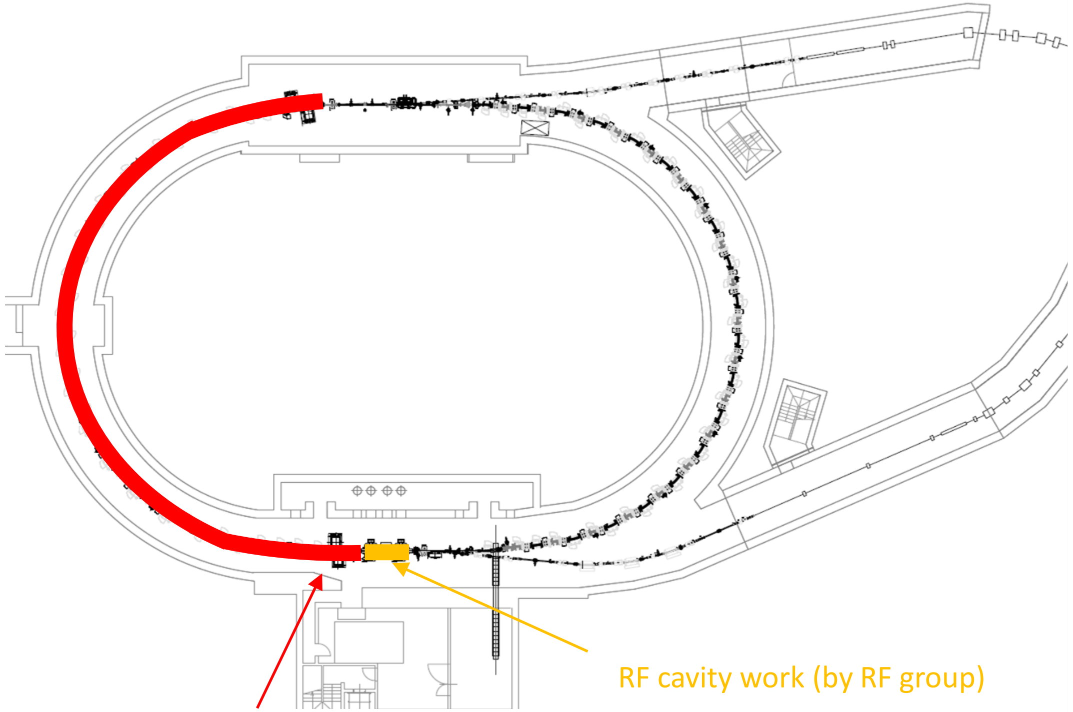
Installation of V-offset bellows chambers (BTp)
Installation of CSR monitor chamber (BTp)

Installation of OTR screen monitor (BTp)



Removal and reinstallation of bellows chambers for magnet alignment (BTe & BTp)

DR



RF cavity work (by RF group)

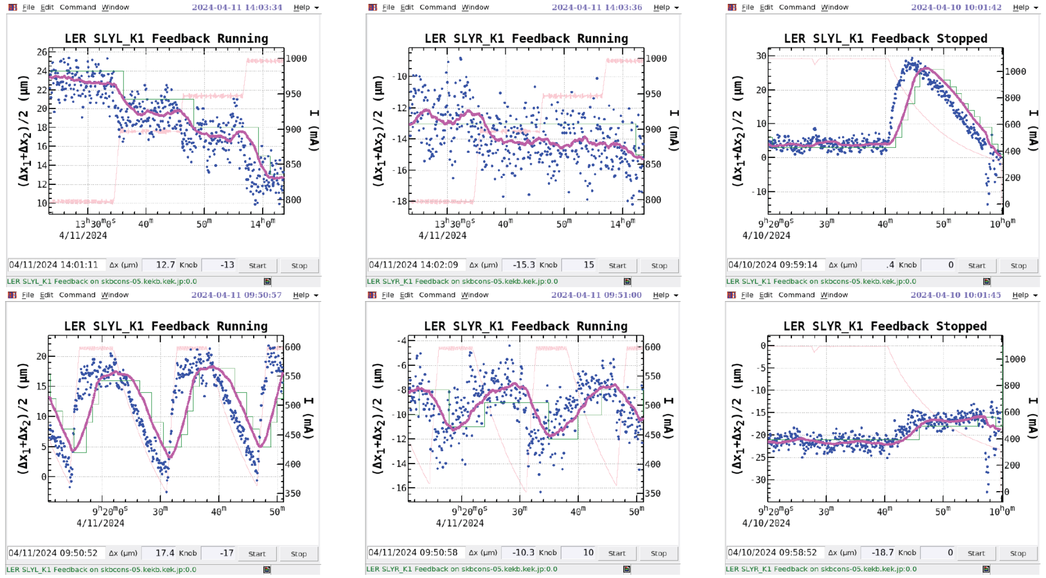
Removal and reinstallation of Ext. kicker chambers for Kicker PS work

Thermal deformation of beam pipes

- Efforts are underway to suppress the effects of thermal deformation of beam pipes due to SR irradiation for stable beam operation.
  - New BPM support to isolate the beam pipe and quadrupole magnet (Installed on April 17th)
    - Thermal deformation causes the quadrupole magnet to move, resulting in beam optics distortion.
  - New feedback system to suppress the effects of optics change due to thermal deformation at strong sextupole magnets. (From early April)

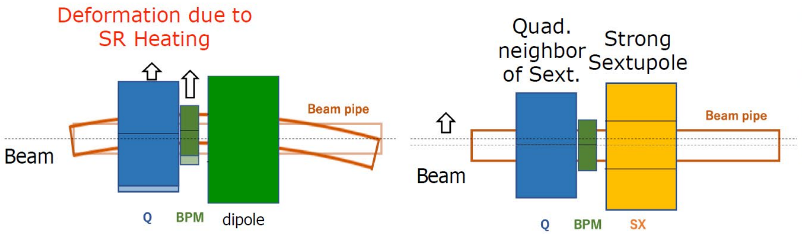
Orbit Change at Strong Sextupoles in LER

補償用Feedbackを最近かけ始めた。1 - 5 μmの戦い。BPMの精度は2 - 3 μm。

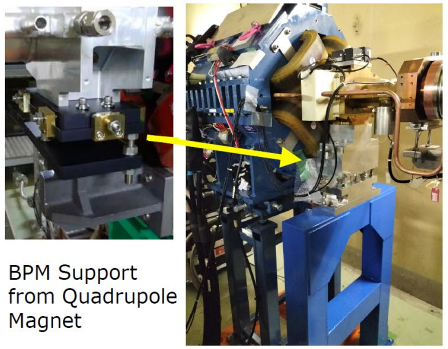


Beam Current Dependence for Beam Optics

- Try to Isolate BPM from Quadrupole Magnet
- Install Gap Sensor between Quadrupole Magnet and BPM



Investigate the Mechanism
Simple Case is Preferable.



BPM Support from Quadrupole Magnet

Install New BPM Support from Floor instead of Quadrupole Support
Not Yet.
Plan on the Next Maintenance.

Y. Ohnishi

Beyond 10^{35} strategy

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

Y. Ohnishi