Beam Background and Machine-Detector Interface at SuperKEKB/Belle II

LAU Tak Shun (KEK)
on behalf of SuperKEKB / Belle II collaboration

Outline

- Introduction to Belle II and SuperKEKB :
  The Belle II Detector
  SuperKEKB Accelerator

- Before beam operation :
  Beam background at SuperKEKB
  More about beam background
  Beam Background Countermeasures
  Beam background Simulation

- After beam operation :
  Sudden Beam Loss
  Beam injection performance

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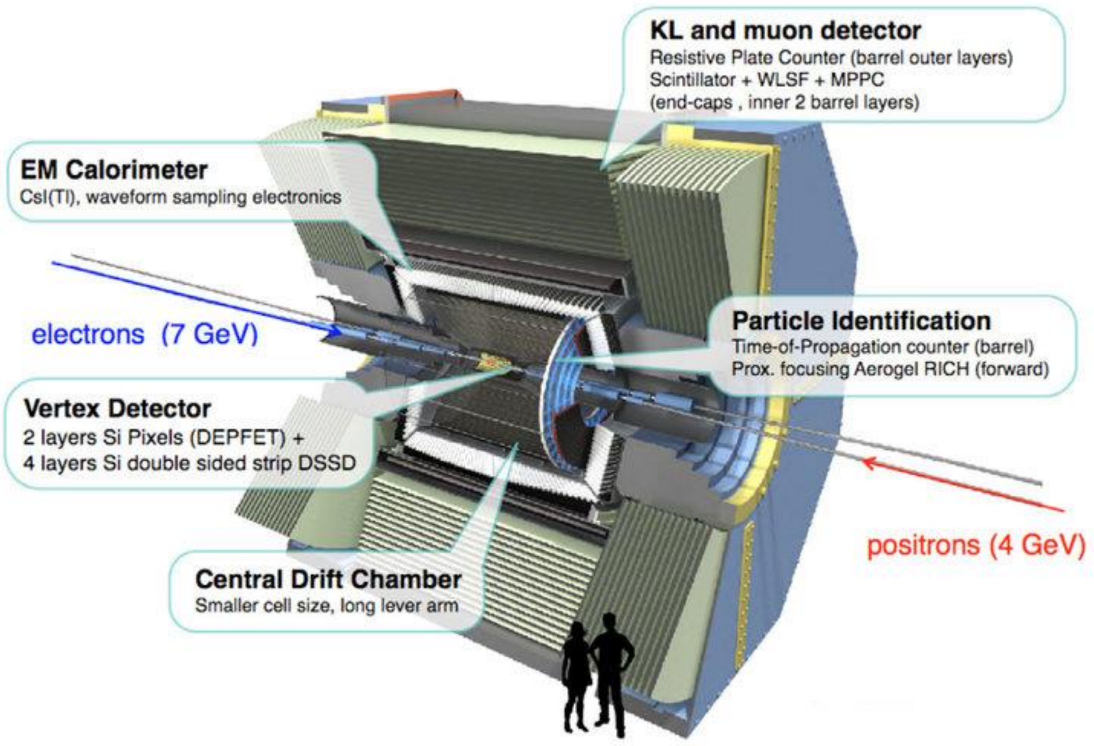
The Belle II detector

- Belle II is a detector complex to observe decay products of electron-positron collisions at higher rate , with improved vertex resolution, a novel particle identification system, and enhanced precision.

- Goals :
  Study the CP-symmetry violation in the B-meson system.
  Searching for New Physics beyond the Standard Model.

- The Belle II detector is asymmetric to match the boosted B-meson produced by SuperKEKB's asymmetric beam energies, enabling precision tracking of their decays.

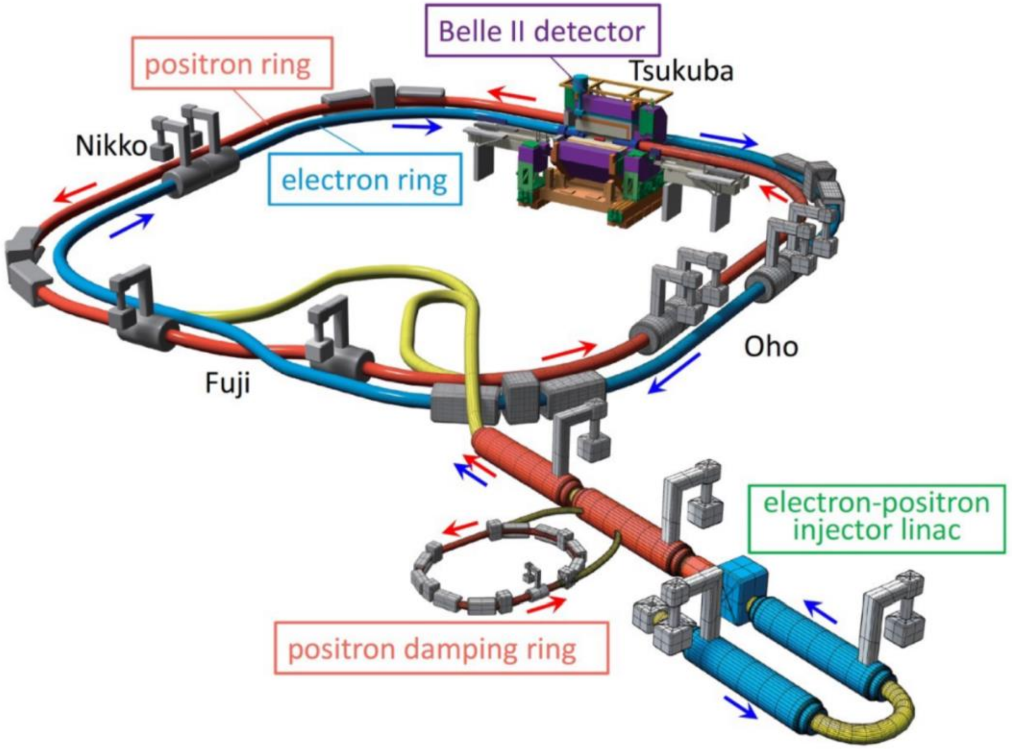


SuperKEKB accelerator

- The SuperKEKB consists of two rings: a low-energy ring (LER) for 4 GeV positrons, and a high-energy ring (HER) for 7 GeV electrons.

- The center-of-mass energy of SuperKEKB is set at **10.58 GeV**
  => $\Upsilon(4S)$ resonance
  => optimal production of B meson pairs.

- The asymmetric energy is used to boost B-mesons, enable precise measurements of their decays via time dilation.



- World record breaking luminosity $4.7 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (22nd June, 2022)

- Still a long way to reach the target luminosity, i.e. $6 \times 10^{35} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  There are 2 main difficulties : **Beam background** and **beam injection performance** (we will explain soon).

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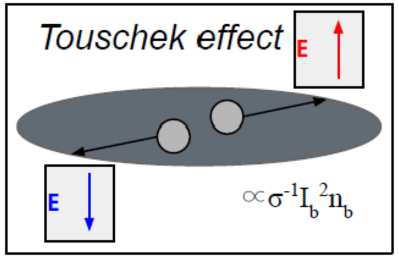
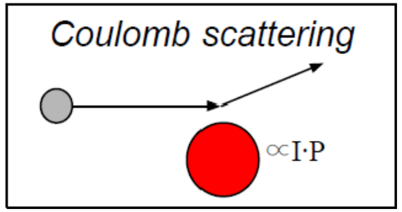
Beam background at SuperKEKB

- Achieving high luminosity is the highest priority target of SuperKEKB.
- But…higher luminosity
  -> higher beam current, smaller vertical beta function
  -> requires a more frequent top-up beam injection
  -> higher beam induced background (Beam BG)
- Beam BG is dangerous for SuperKEKB/Belle II :
  1. Increased Belle II hit occupancy and physics analysis background
  2. Determines the survival time of Belle II sensor components
  3. Seriously damage may occur

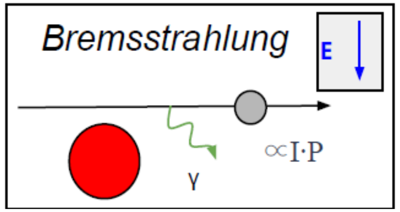
- Touschek Effect:
  Coulomb Scattering between particles in the same beam bunch.



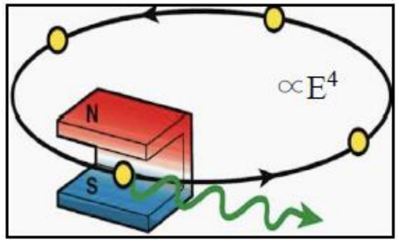
- Beam-gas Coulomb BG:
  Coulomb interaction with residual gas.



- Beam-gas Bremsstrahlung:
  Scattering with residual gas molecules via Bremsstrahlung.



- Synchrotron Radiation:
  X-rays emitted when electrons or positrons pass through the strong magnetic field.

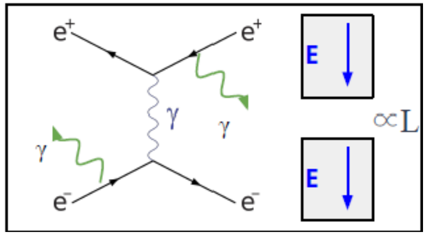


Graphics by Andrii Natochii

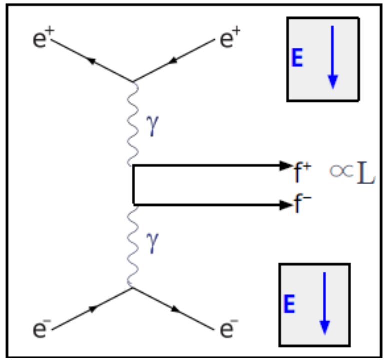
More about beam background

- Luminosity Background:
  Physics process with high cross-section. The rate is directly proportional to the luminosity. Since we are aiming to increase the luminosity, this kind of background would be larger in the future.

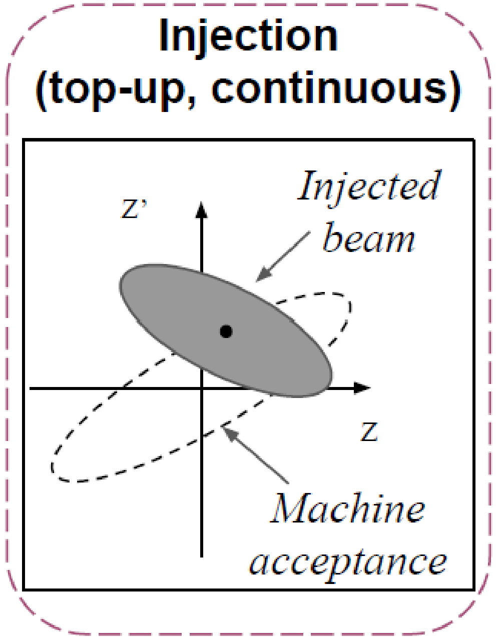
  1. Radiative Bhabha scattering $(e^+e^- \to e^+e^-\gamma)$
  => The spent electron/positron may be strongly kicked by the solenoid field, leading to potential damage.
  => The photon may produce secondary particles such as neutron via giant dipole resonance when it interacts with the down-stream magnet, causing radiation damage to the sensitive components.



  2. Two-photon process $(e^+e^- \to e^+e^-e^+e^-)$
  => The emitted pair electrons (usually low energies) may keep curling in the beam pipe and keep hitting the pipe or the inner detector under the magnetic field.
  => Causing the trigger and data acquisition systems overloaded



- Beam Injection Background:
  Bunches are continuously refilled to keep the current stable. The optics mismatches between the injection chain and the main ring, resulting in higher particles losses.



Graphics by Andrii Natochii

Beam Background Countermeasures

- To mitigate the beam background, there are different method for different kinds of backgrounds.

- For particle scattering type beam BG, collimators (in next page) are used to cut away the beam halos. Vacuum scrubbing is also used to reduce beam-gas beam BG. Heavy metal shielding is also used to protect the detector.

- For luminosity background, there is no way to mitigate it directly. Again, shielding is a way to protect the detector.

- For synchrotron radiation around the interaction region, beam pipe design is helpful.

- And for injection BG, we may need to find a way for better injection performance.

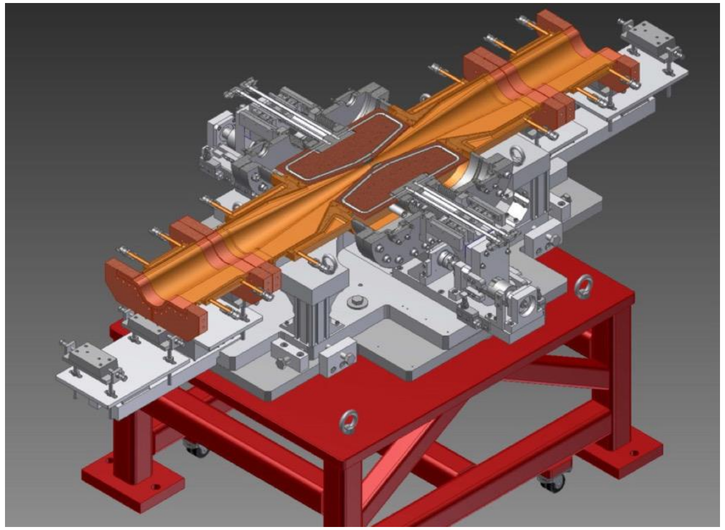
Beam Background Countermeasures
Collimators at SuperKEKB

- Collimators in the main ring can help cutting the beam tails/halos, to stop the stray particles before they reach the Belle II detector region. There are 2 types, KEKB type and the SuperKEKB type. The latter one has 2 moveable jaws.

KEKB type

- The Horizontal Collimators can help reducing the Touschek BG. They are Installed where β_x is large.

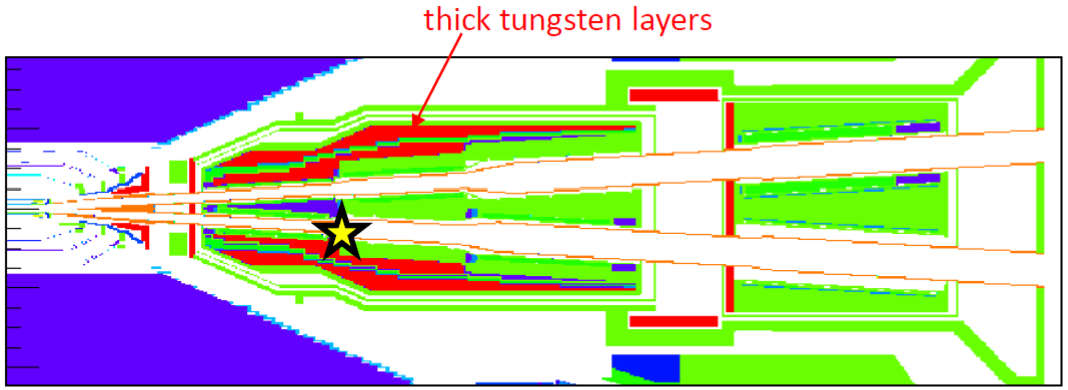
- The Vertical Collimators can help reducing the Beam-gas Coulomb BG.
  We may want to install the collimators where β_y is large, but due to the Transverse Mode Coupling Instability (TMCI), they were installed at smaller β_y to avoid the problem.

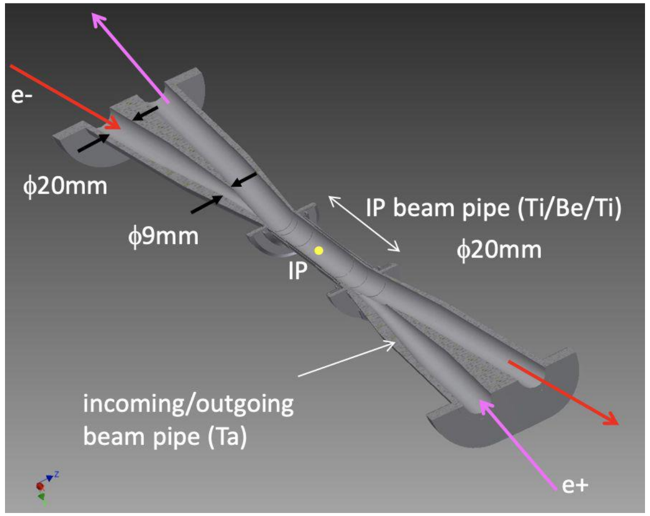


SuperKEKB type

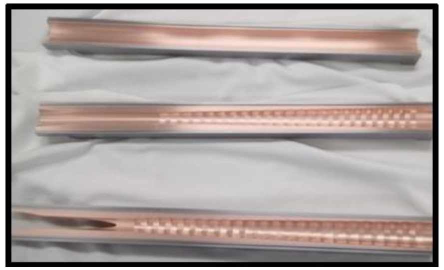
Other Beam Background Countermeasures

- Vacuum Scrubbing :
  Residual gas pressure reduction
- Thick Tungsten shield inside final quad cryostat :
  Since beam loss "hot spot" were found inside the final quad magnets, heavy-metal shield were requested to put inside the cryostat.
  (Major modification was done after the already-started cryostat fabrication process. RESERVING enough space in early stage is highly recommended!)
- Interaction Region (IR) Beam pipe design :
  1. Geometry, (ingoing) pipe diameter decrease from 20mm to 9mm can block most of the SR photon.
  2. Ridge structure to avoid the SR (if not blocked) reflecting to the detector.
  3. A thin gold layer was coated on the Beryllium beam pipe to protect the VXD from X-ray.





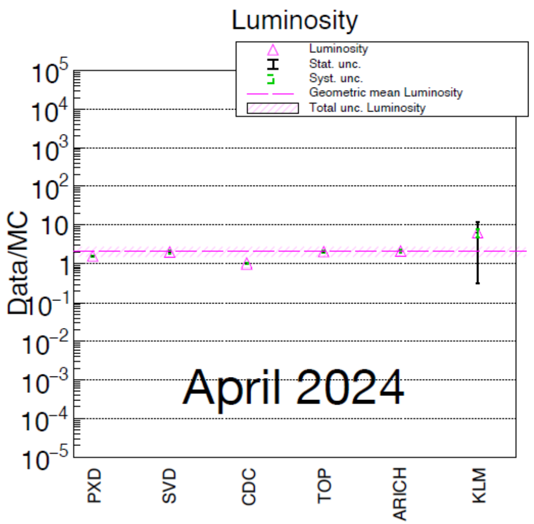
Beam pipe geometry



Ridge structure of beam pipe

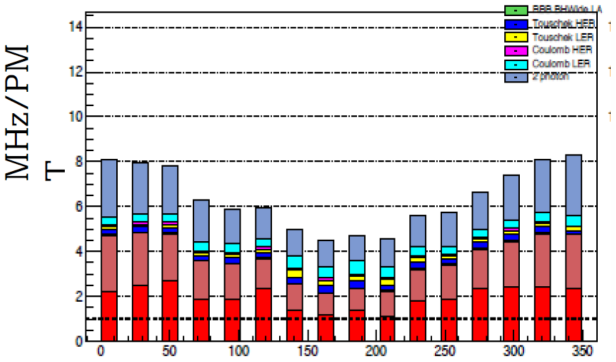
Beam Background Simulation

- Before starting the beam operation, simulation is needed to predict the beam background. And to make sure the operation is safe.
- To have a realistic simulation, the simulation includes collimator description, detector modelling, and magnetic field. (Details in Appendix)
- The simulation result has also been verified after the beam operation.

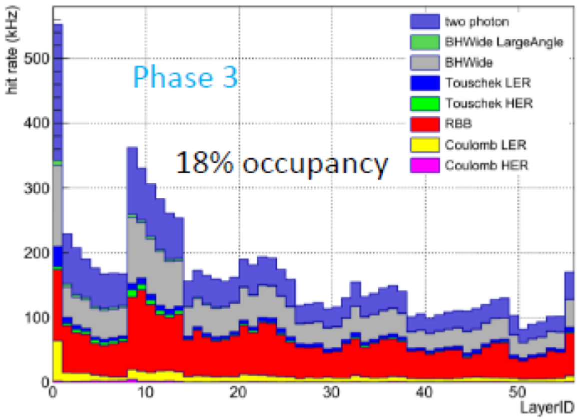


Plots by Qingyuan Liu

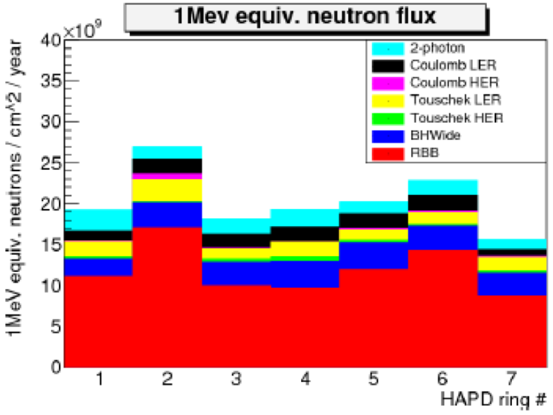
TOP PMT rate



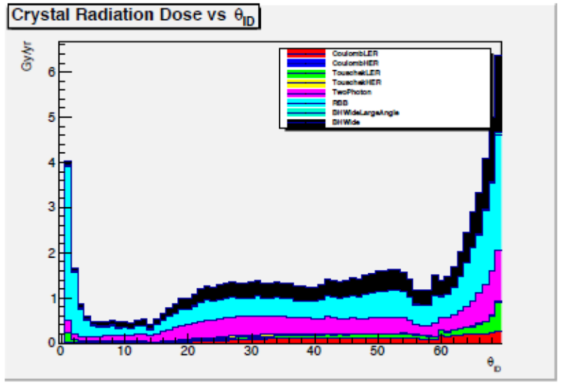
CDC wire rate



ARICH neutrons



ECL crystal



Plots by Hiroyuki Nakayama

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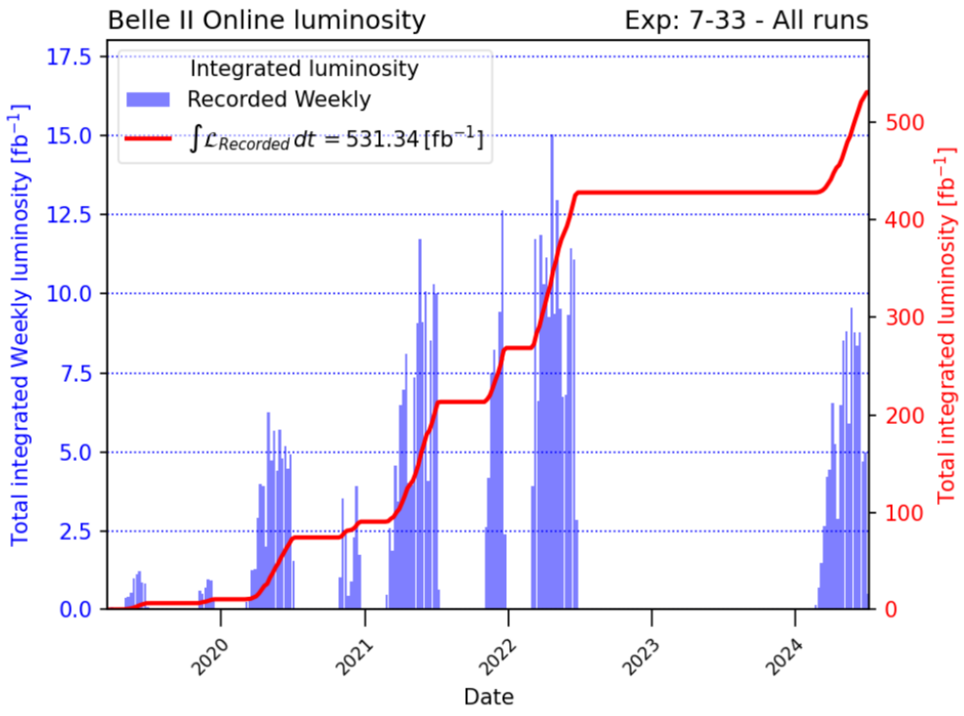
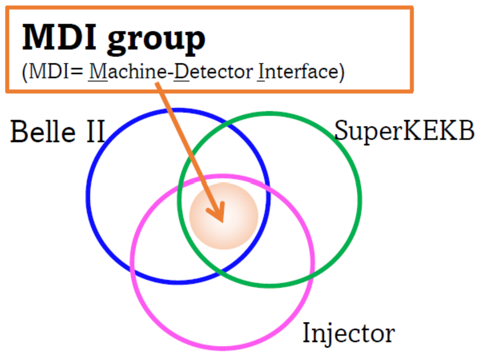
Current status of the beam operation

- After the beam operation had been started, besides the beam background, there are other issues that lead us difficult to achieve higher luminosity, such as :
  1. Sudden Beam Loss (SBL) (explain later)
  2. Poor injection efficiency
  3. Low machine stability

- The Machine-Detector Interface (MDI) group is comprised of members from Belle II, SuperKEKB, and injector.

- In Belle II, instead of the mechanical design of interaction region, MDI group is formed to tackle these common issue.



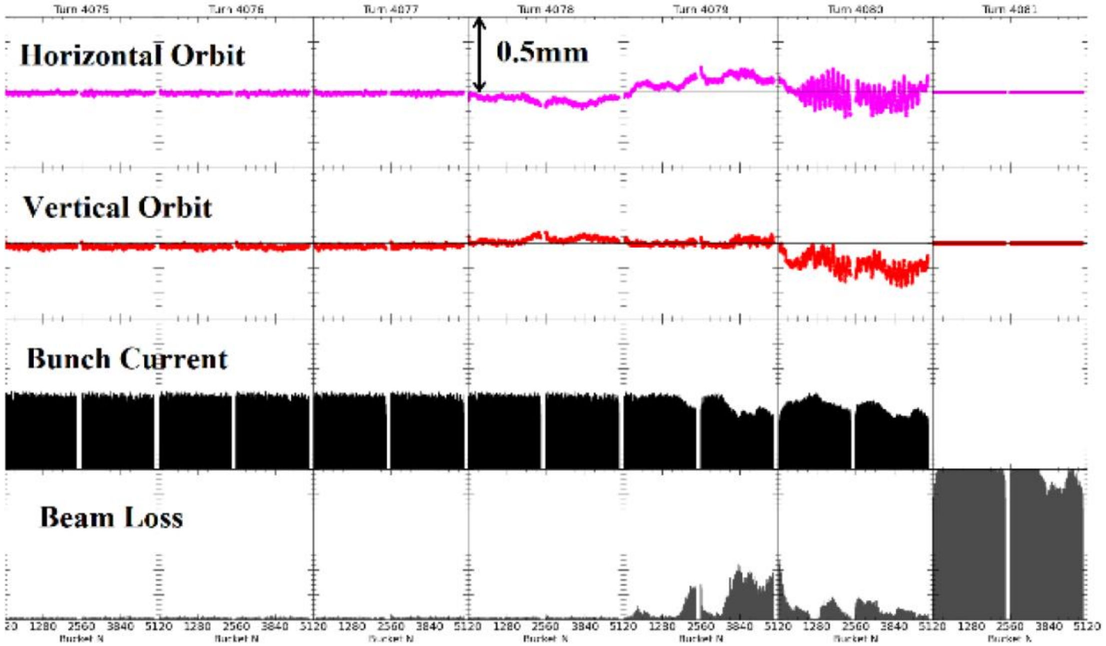


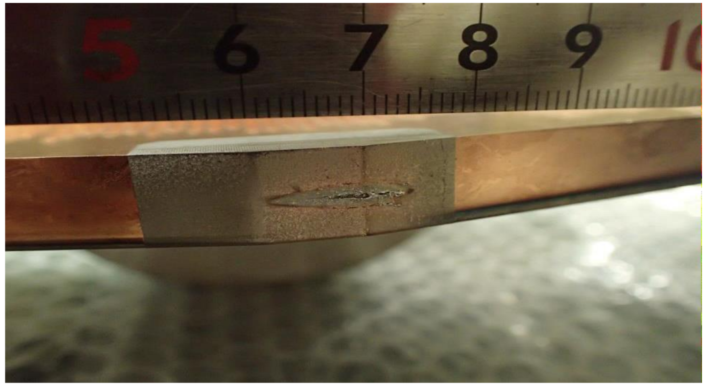
Sudden Beam Loss

- Beam loss that occurs suddenly within a few turns (1turn = 10μs) without precursory phenomena.
  = Sudden Beam Loss （SBL）

- Damaged Belle II detector and accelerator equipment, such as QCS quench or collimator damage.
  => Operation time loss by replacement work
  => Collimator had to be used wider than ideal
  => Difficult to control storage/injection BG.

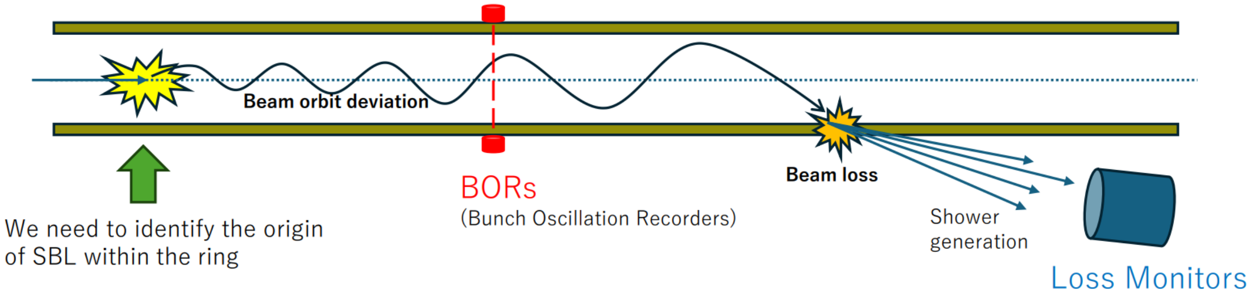
- Seems to occur more in higher beam current.
  => Limit maximum beam currents!



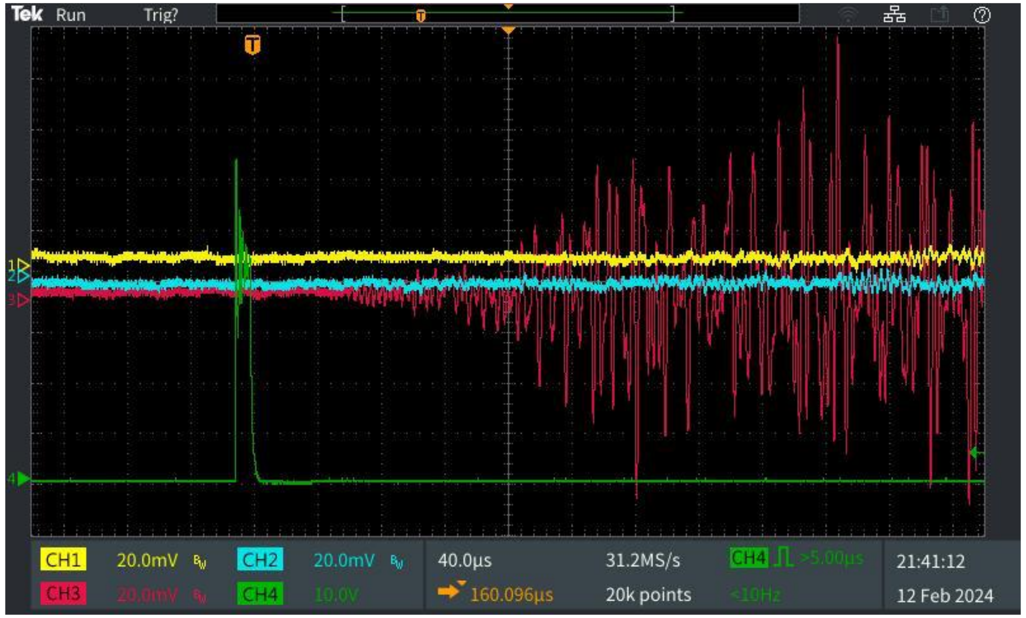


Understanding the Sudden Beam Loss

- Where beam loss starts?
  => The Loss Monitors were equipped with fast readout, also providing chronological order of beam loss along the ring
- Is there any abnormal behavior of beam orbit?
  => Beam Orbit Recorders (BORs) were installed to observe earlier stage of beam orbit deviation.
  => In most cases, beam orbit deviation were observed, but the source was not identified.



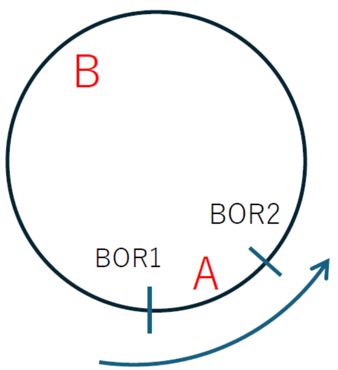
- Possible candidate of SBL : electric discharge
  => Electric discharge may happen on collimators
  => 34 Acoustic Emission Sensors were installed around collimators.
  => No discharge around happened around collimators.



Acoustic wave on 2024 Feb. 12th

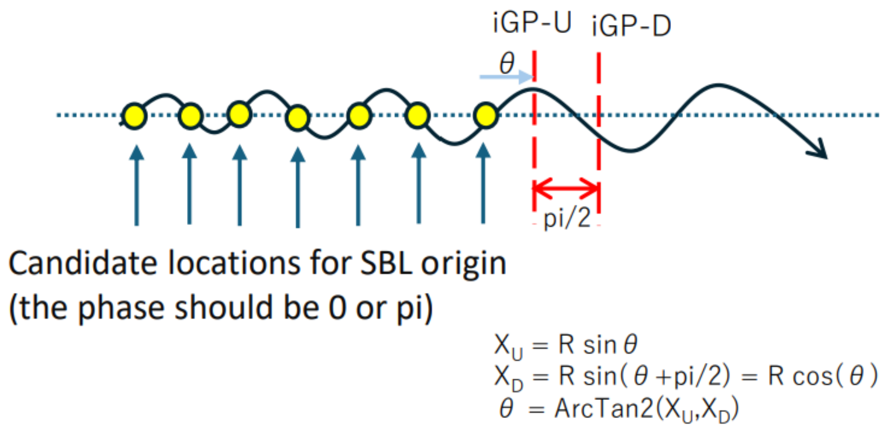
Tracing the starting point by BOR analysis

- BORs reveal the ring section which includes the location of SBL origin. With n BORs installed, we can divide the ring into n potential sections.



If BOR2 saw oscillation in the first turn but BOR1 didn't, the location of SBL origin should be included in the ring section A, not B.

- Betatron phase :
  By comparing the size of deviation of BORs at the locations with $\pi/2$ phase difference, the betatron phase of the location of SBL origin can be estimated.
  (1 revolution
  ≈ 45 rotations of phase
  ≈ 90 candidate locations)



Graphics by Hiroyuki Nakayama

Other issues during beam operation

- Other issues :
  Poor injection efficiency
  Low machine stability

- As our target is to have higher luminosity, higher beam current and longer beam lifetime plays an important role.

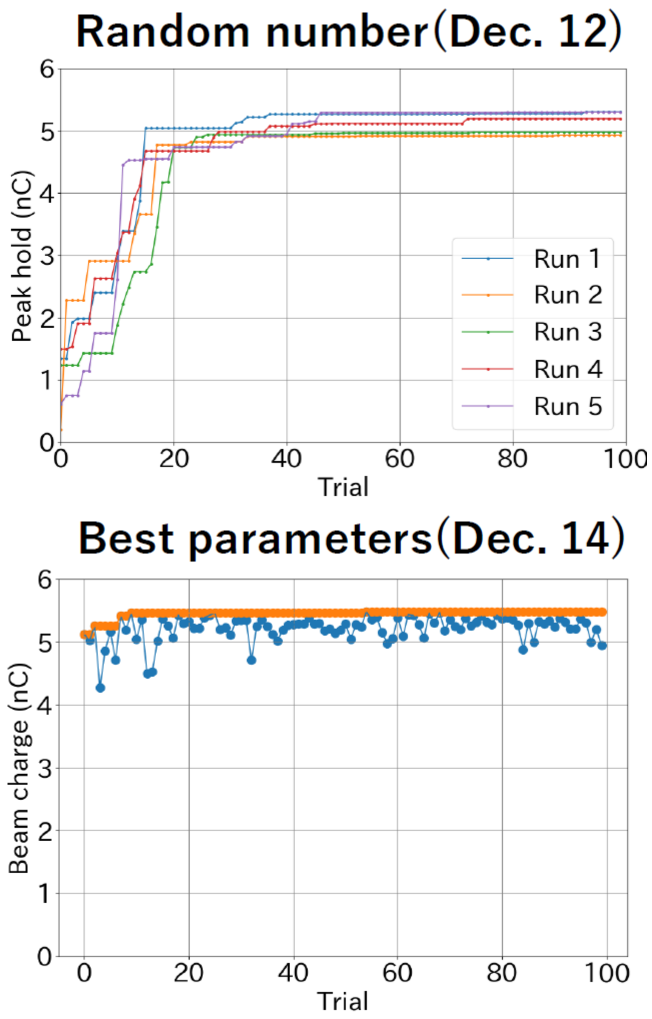
- To improve the beam injection performance, more experts are needed, but not realistic.

- Machine Learning (ML) is a way to deal with it.

- ML technique has already been tested in SuperKEKB. (Next slides)

Improvement on Injection Efficiency

- Using Bayesian Optimization to Iterate. One iteration is one “trial”.
- For someone uses random number as initial machine setting, the beam charge was optimized at about 30 trials (5mins)
- But if using initialization with best parameters (refer to 2 days ago) optimize in less than a minute.



Plots by Shinnosuke Kato

Machine Learning for Machine Stability

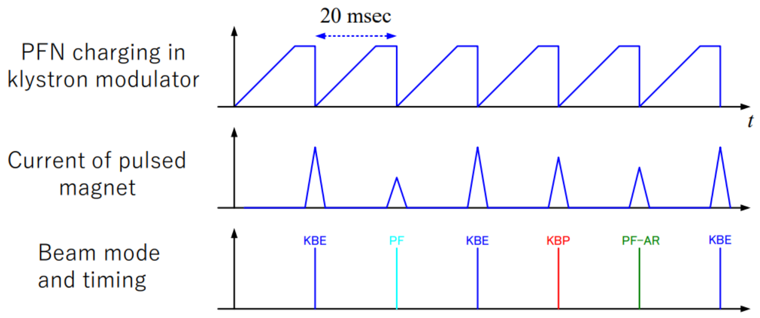
- Besides Belle II, there are other facilities also need beams for their experiments.

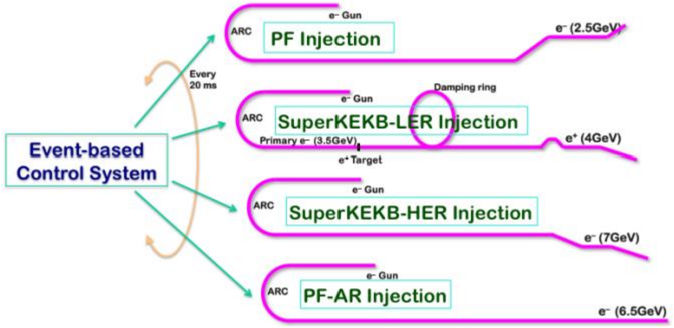
- The interval between beams is **20ms**. The time between beams is used for Pulse-Forming Network (PFN) charging.

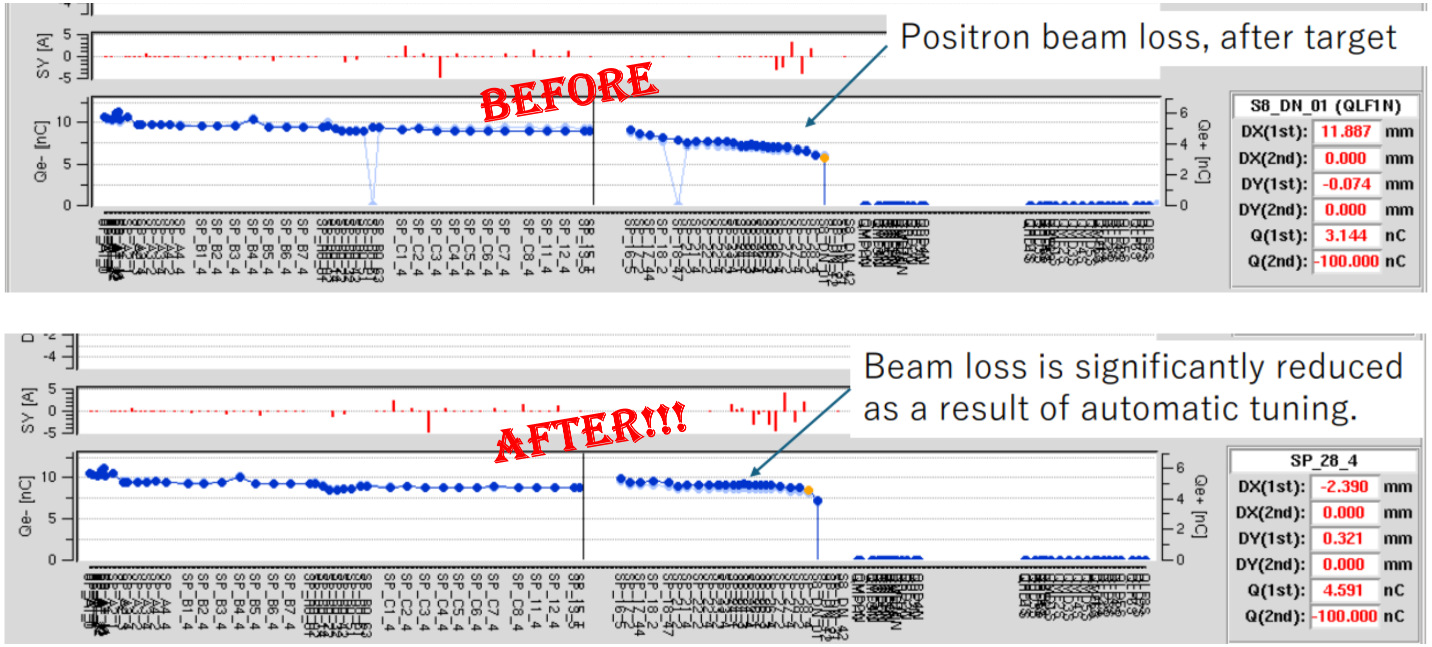
- Automatic tuning using machine learning!

- Both Bayesian optimization and the downhill simplex method are used.

- The automatic tuning significantly increase the position production.







Graphics by Takuya Natsui

Summary

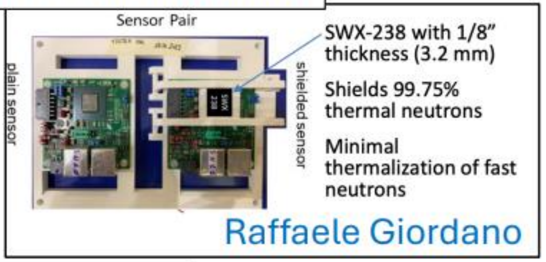
- Beam Background at SuperKEKB is dangerous and various countermeasures have been implemented.
- MDI framework successfully promotes collaboration between detector and machine groups, to overcome our shared challenges.
- SBL understanding with improved observations by more loss monitors and more BORs.
- To further expand ongoing MDI collaborations, Machine-Learning is a hot area. You are more than welcome to join us!

Appendix : Neutron Detector for BG

Neutron detectors

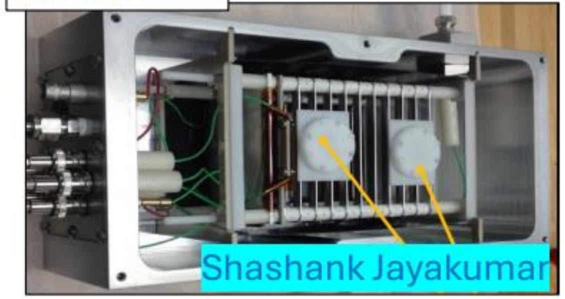
	FPGAs	He-3 tubes	BEAST TPCs
Setup	Three pairs of sensors are installed around Belle II - 1 on the FWD QCS "boat" - 1 on the BWD QCS "boat" - 1 atop Belle II near PXD racks	Four detectors are installed around Belle II - 1 in the FWD tunnel (~6 m from IP) - 1 in the BWD tunnel (~6 m from IP) - 2 atop Belle II near PXD racks	
Status	- Operated smoothly in 2024ab - Preliminary neutron flux estimates differ between FWD and BWD tunnels ← partially in agreement with Run-1 TPC/He-3 data - No events atop Belle II - Performed irradiation test at a nuclear reactor to study SWX- 238	- The DAQ system is turned On - Issues with transferring summary ROOT files to KEKCC - Voltage monitoring issue	- Online fast neutron displays are available for BCG shifters - One TPC in the FWD tunnel stopped collecting data early in Run 2
Plans	- Connect a new PSU during B2GM - Turn On the system after B2GM - Compare with He-3 and TPCs - Complete the data analysis for nuclear reactor measurements	- Address the listed issues above - Investigate the long-standing issue with the recorded raw data time shift	- A new postdoc from the Univ. of Hawaii, Shashank Jayakumar, joined our group - Currently learning about the TPC system, becoming a new expert in Belle II neutron BGs

FPGA SEU monitor



He-3 tube

BEAST TPC



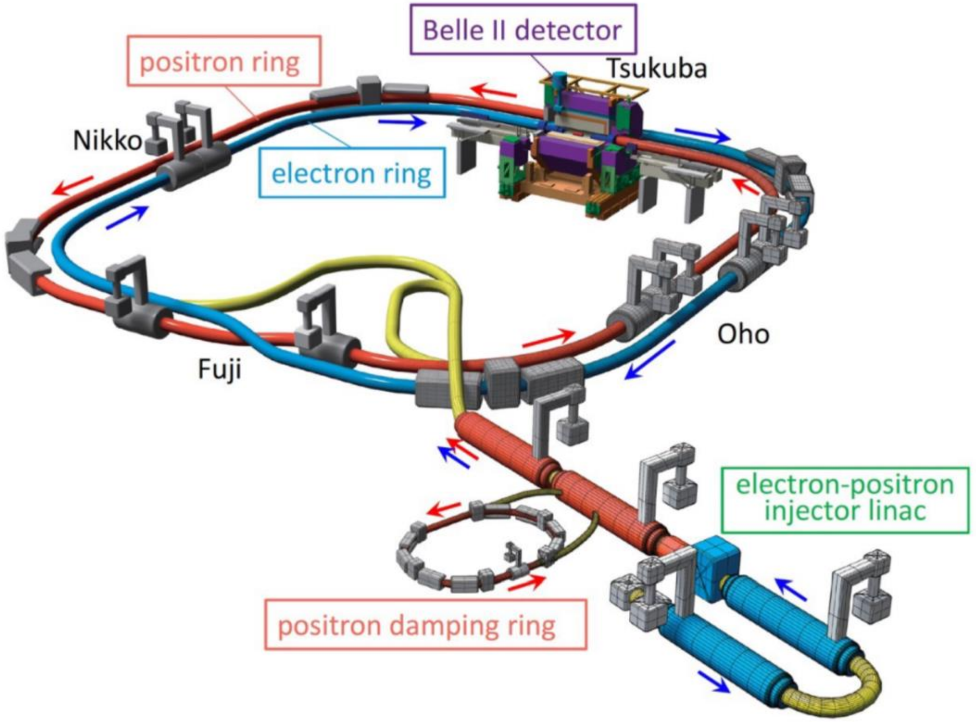
October 8, 2024 A. Natochii | BG Group Report 4

Some numbers of run 2024ab

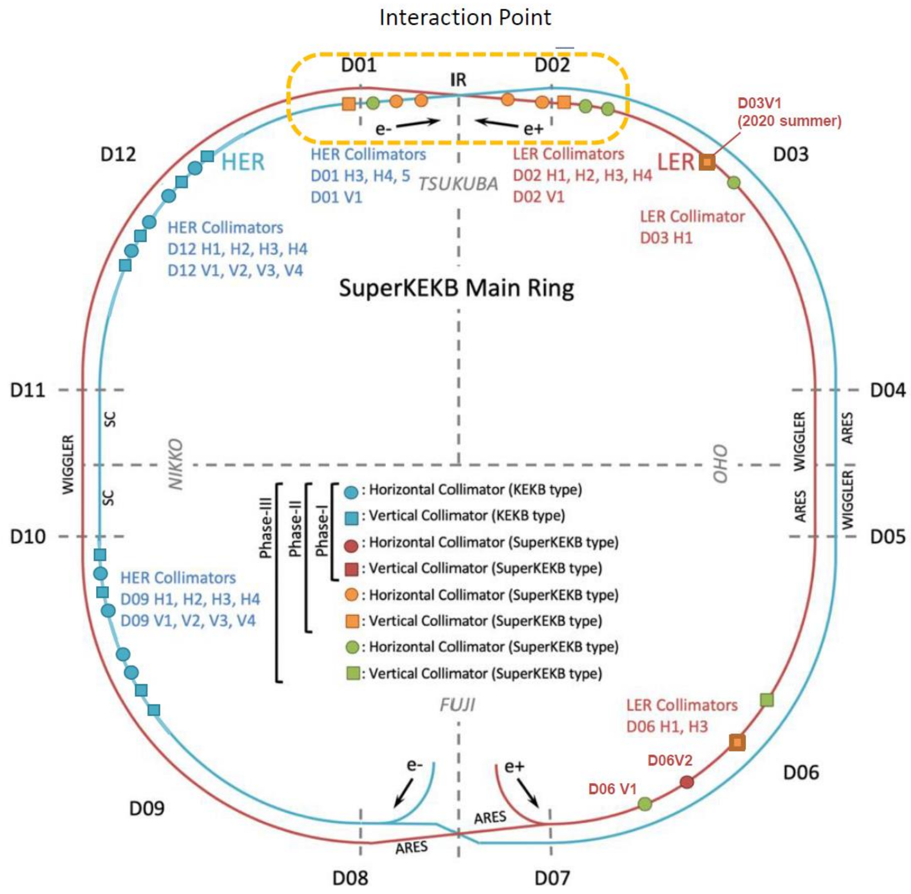
- Adopts "nano-beam" and "crab-waist" scheme, aiming for x40 times higher luminosity than the KEKB world record.

- Overview of 2024ab (29^{th} Jan – 1^{st} Jul) main ring operation :
  Peak Luminosity = $4.47 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$
  Specific Luminosity = $5.9 \times 10^{31}\ \mathrm{cm^{-2}s^{-1}mA^{-2}}$
  Beam Current of HER/LER = $1.18/1.45\ \mathrm{A}$
  Number of bunches = 2249
  Bunch Current product = $0.338\ \mathrm{mA^2}$
  Crab waist ratio of HER/LER = 60%/80%

- Integrated Luminosity (2024ab) = $103\ \mathrm{fb^{-1}}$
  Total Integrated Luminosity = $527\ \mathrm{fb^{-1}}$



Appendix : Position of Collimators

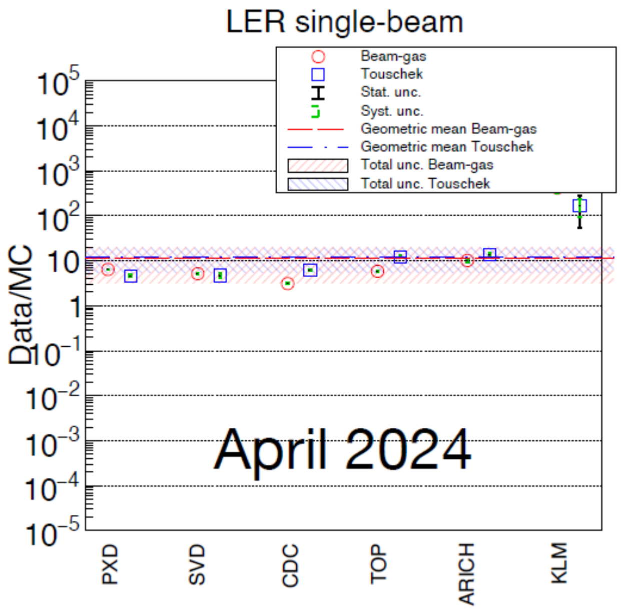


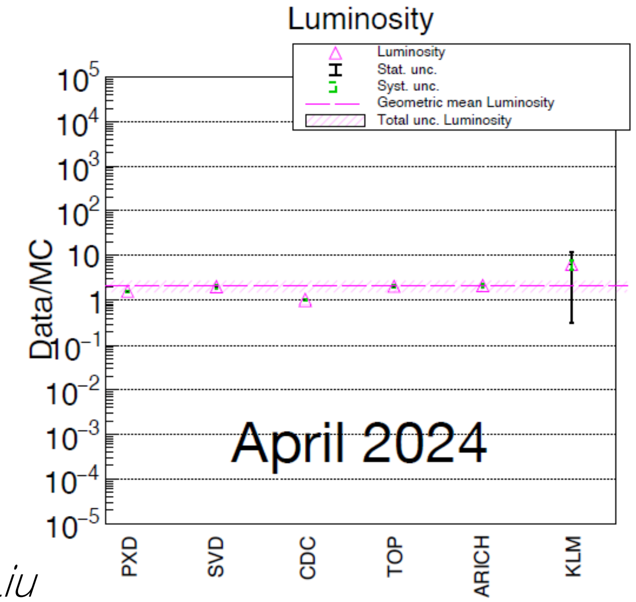
Appendix : Background Simulation Tools

- Strategic Accelerator Design (SAD@KEK) is used for single-beam background simulation, including the following features:
  1. Realistic Collimator Description (jaw profile, chamber)
  2. Particle Interaction with Collimators (tip-scattering)
  3. Vacuum Pressure Distribution
  4. Random Machine Errors (Sextuple Magnet Offset)

- Geant 4 :
  Detector modelling, Single-turn effect for luminosity background, Synchrotron Radiation modelling ($\pm 30\mathrm{m}$ from the IP)

- Basf2 :
  Magnetic field map for luminosity background simulation





Plots by Qingyuan Liu

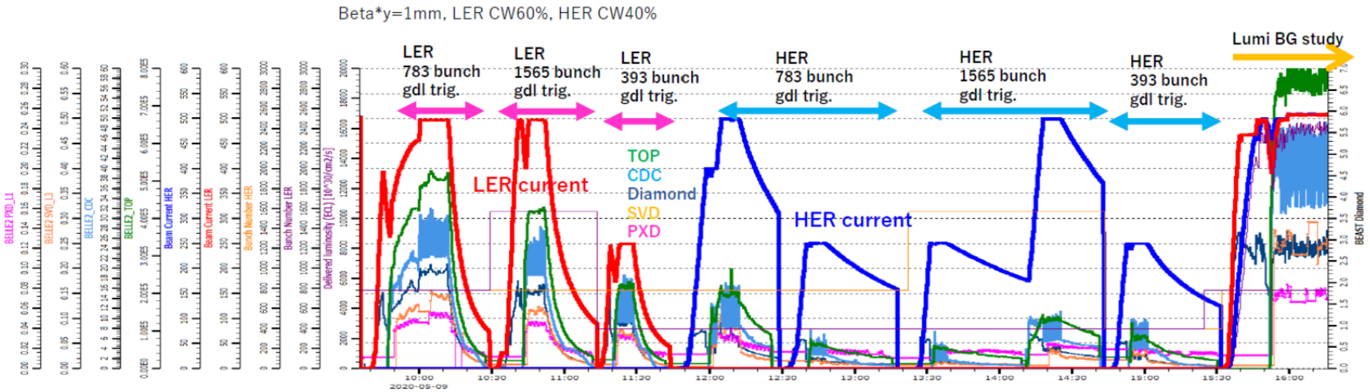
Appendix : Background Measurement

- Modelling :
  $O_{\mathrm{beam-gas}} = B \times IP_{\mathrm{eff}}$, $O_{\mathrm{touschek}} = T \times \frac{I^2}{n_{\mathrm{b}} \sigma_x \sigma_y \sigma_z}$
  $=> \frac{O_{single\ total}}{IP_{\mathrm{eff}}} = B + T \frac{I}{n_{\mathrm{b}} P_{\mathrm{eff}} \sigma_x \sigma_y \sigma_z}$

- By plotting $\frac{O_{single\ total}}{IP_{\mathrm{eff}}}$ versus $\frac{I}{n_{\mathrm{b}} P_{\mathrm{eff}} \sigma_x \sigma_y \sigma_z}$, we get B and T from the intercept and slope.

- For Luminosity, $O_{\mathrm{lumi}} = L \times Lumi = O_{\mathrm{measure}} - O_{single\ total,\,LER} - O_{single\ total,\,HER}$,

- Here $B, T, L, \sigma_i, n_{\mathrm{b}}, I$ are the Beam-gas, Touschek, Luminosity coefficient, i-th direction beam size, number of bunches, and beam current respectively,



- Number of bunches $n_{\mathrm{b}} = 783, 1565, 393$ stage by stage.

- As n_{b} was increased, O_{touschek} decreases, $O_{single\ total}$ then become smaller.

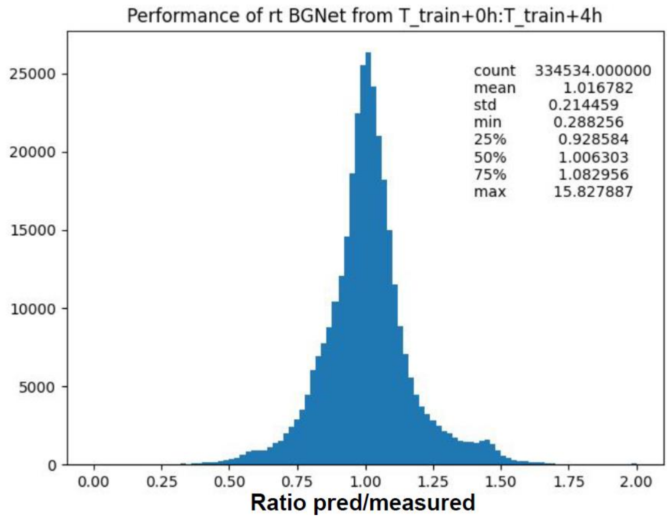
- Unexpected BG increase was observed at large beam size.

- Observed dependency are consistent with the $O_{single\ total}$. There is then no significant indication of other BG sources.

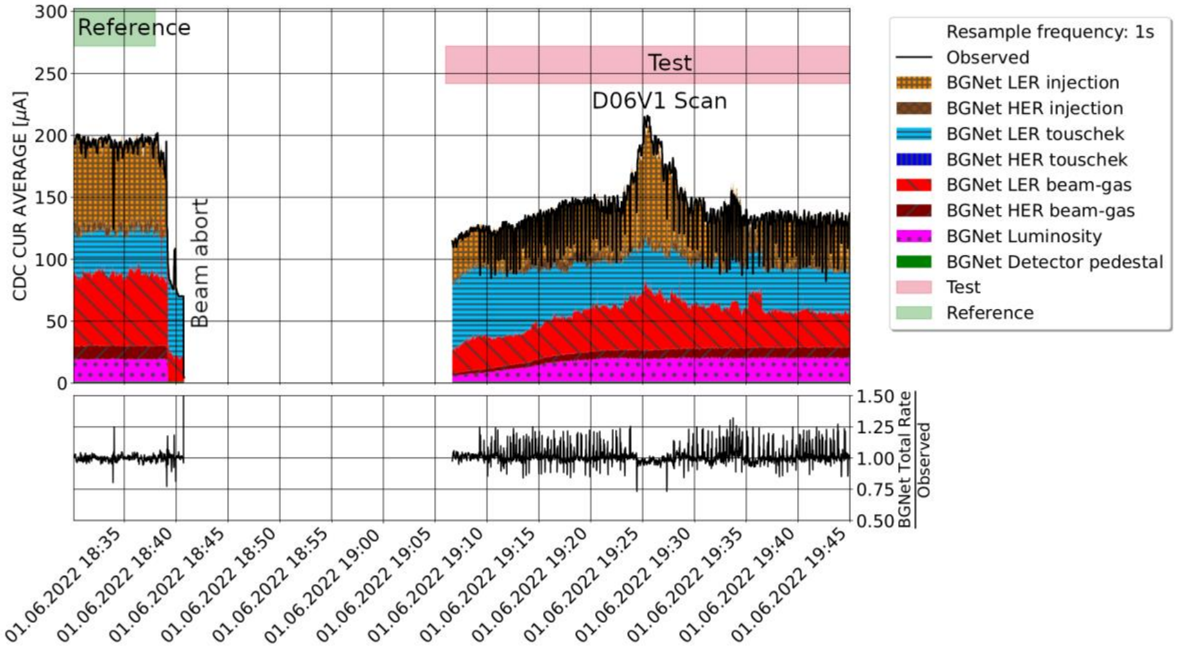
Appendix: Machine Learning - BGNet

- Background monitoring is important for both Belle II and SuperKEKB operation.
- We want real-time prediction of background components during operation.
- One of the most common method in 2020s is Machine Learning.
- The ML method is TensorFlow/Keras Neural Network. And the samples are the hit rate of the Belle II subsystems and the beam parameters such as beam current. pressure, and beam size.
- We are going to use BGNet before the end of the physics run 2024c.

B. Schwenker, L. Herzberg, Y. Buch, A. Frey, A. Natochii, S. Vahsen, H. Nakayama, "A neural network for beam background decomposition in Belle II at SuperKEKB", *Nucl. Instrum. Methods Phys. Res.*, 1049, 2023, 168112



Plots by Yannik Buch, Benjamin Schwenker



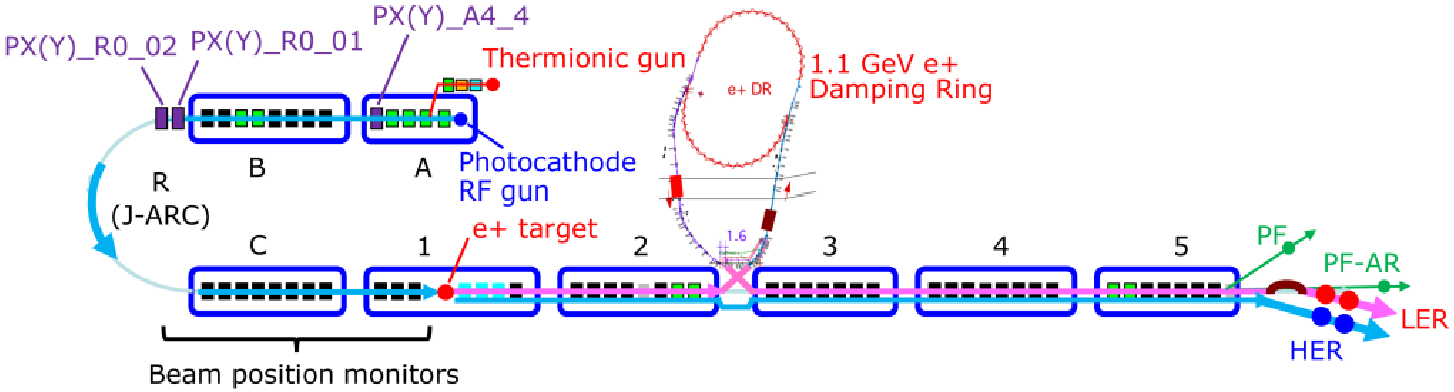
Appendix : Details of the ML on Beam Injection

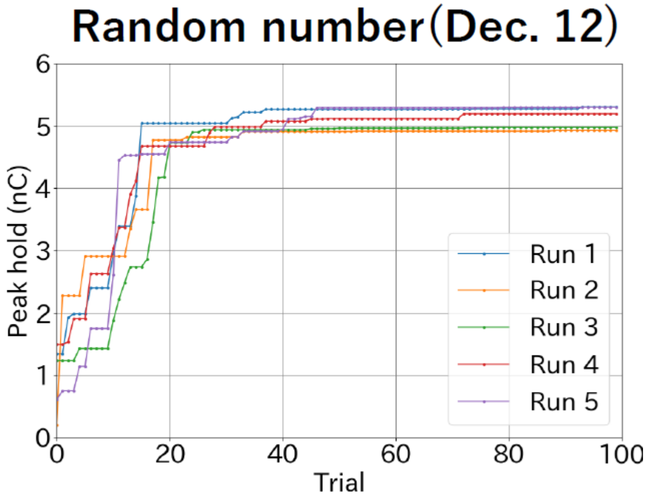
- Tuning Parameters :
  Applied Current of 6 steering magnets $(I_{x0}, I_{y0}, I_{x1}, I_{y1}, I_{x2}, I_{y2})$ (A)

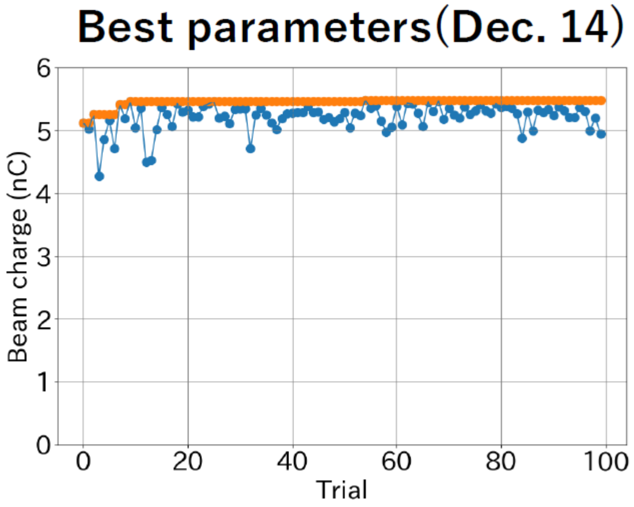
- Evaluation Parameter:
  Beam charge $Q(\mathrm{nC})$ measured by BPM.

- Using Bayesian Optimization to Iterate. One iteration is one "trial".

- In poor knowledge, the beam charge was optimized at about 30 trials (5mins), while initialization with best parameters (refer to 2 days ago) optimize in less than a minute.



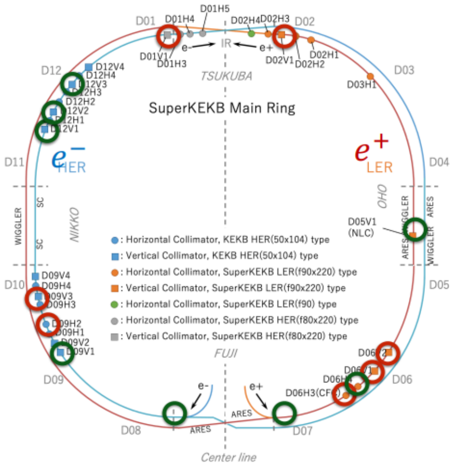




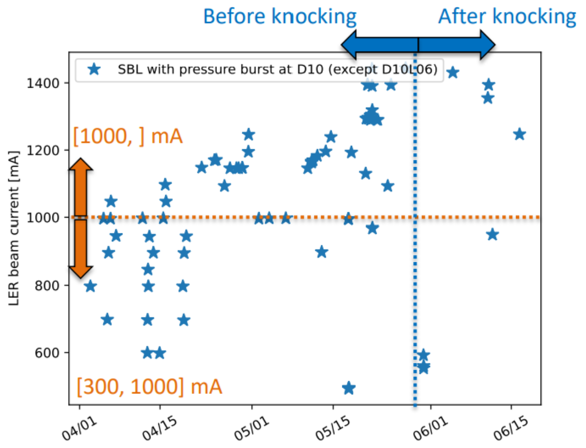
Plots by Shinnosuke Kato

Appendix : Sudden Beam Loss Countermeasure

- Works during LS1 :
  1. Replaced damaged collimator heads
  2. Copper coating of collimator head (Fireball hypothesis)
  3. Installed permanent magents in the SuperKEKB-type horizontal collimators (Electron Cloud effect)
  4. Installed more loss monitors and Bunch Oscillation Recorders to investigate the cause.

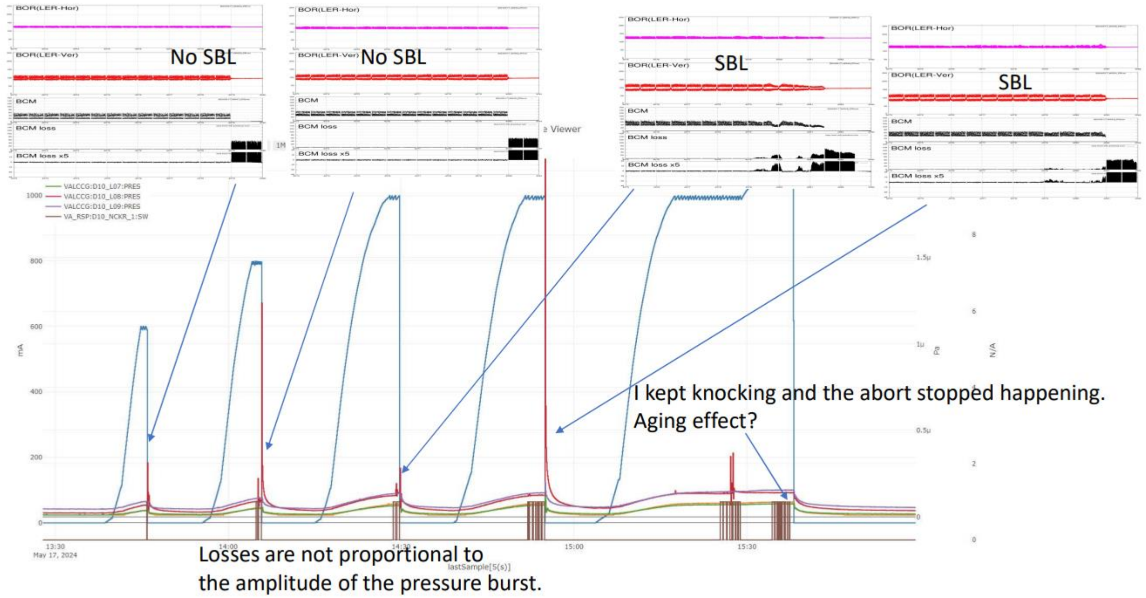


Installation in LS1
Installation before LS1



- Temporary PXD off since May 7 to avoid further damage

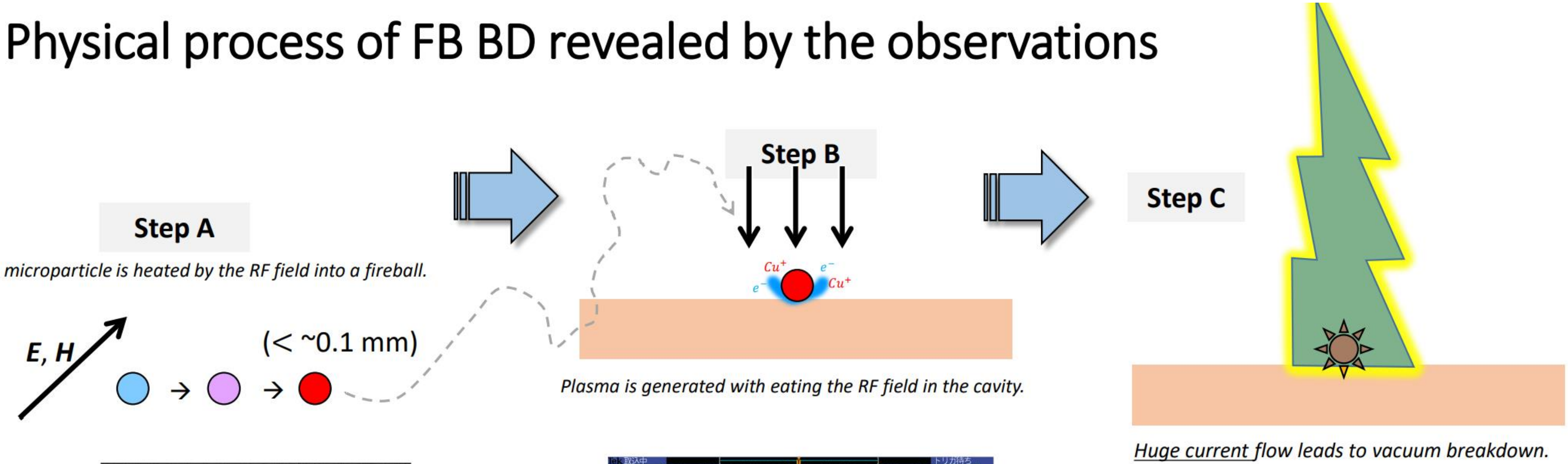
- Countermeasure against SBL after 2024ab :
  1. Turning (30%) beam pipes with electron clearing electrode upside down.
  2. Visual check and dust cleaning of beam pipes which will not be turned upside down.
  3. Knocking as many beam pipes as possible.
  4. Add Loss Monitors to understand HER SBLs

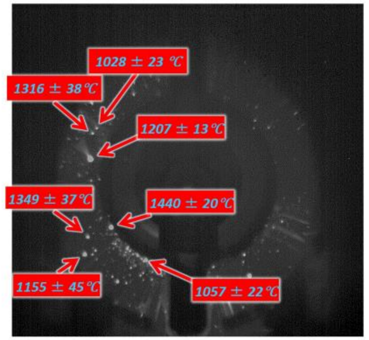


Plots by K. Uno and H. Ikeda

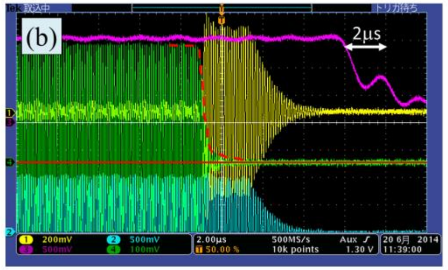
Appendix : Fireball hypothesis

Physical process of FB BD revealed by the observations

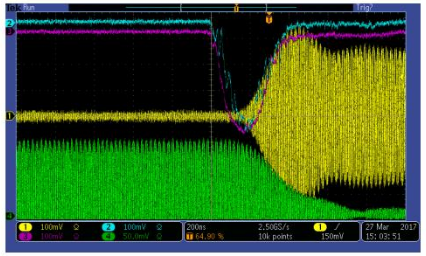




Temperature measurements



Very high power density of ~GW/cm²



Huge X-ray detected

(Plasma generation and its exponential growth are needed for vacuum breakdown.)