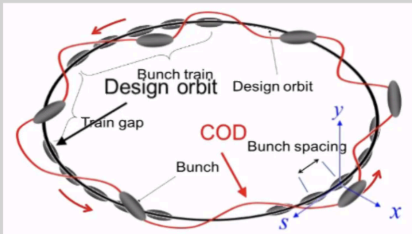
Components (7)

- **Key parameters (terms) in beam optics**
- Closed Orbit Distortion (COD)
  - The actual beam orbit shifts from the ideal (design) one because of errors of the magnets and so on.
  - When it's too large, the beam cannot circulate in the ring. The COD is corrected using the steering magnets.
- Actual orbit (shift from the ideal orbit):
  - Particle's orbit in horizontal direction: $x = x_{COD} + x_\beta + x_\eta$
  - Center of bunch in horizontal direction: $x = x_{COD}$
  - x_{COD}, y_{COD} are typically smaller than 1 mm.



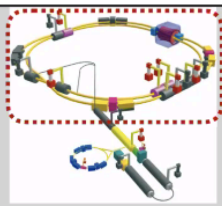
- Bunch size (beam size)
  - horizontal beam size: $\sigma_x = \sqrt{\left(\eta \frac{\Delta p_x}{p}\right)^2 + \epsilon_x \beta_x}$, vertical direction (in case of no-dispersion): $\sigma_y = \sqrt{\epsilon_y \beta_y}$

In the LER arc section: $\sigma_x \approx 440\,\mu\mathrm{m}, \sigma_y \approx 9\,\mu\mathrm{m}$

  - bunch length (longitudinal beam size) depends on the RF voltage in the cavities and so on.

$\sigma_z \approx 6\,\mathrm{mm}$

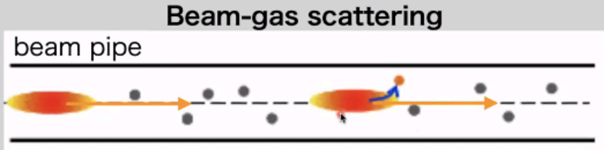
Components (8)



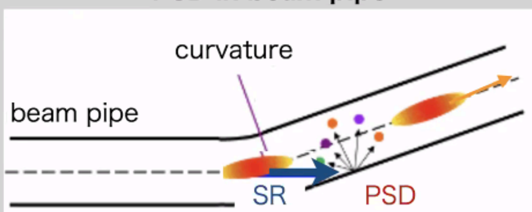
- **Vacuum system**
- used to secure enough beam life, which is determined by the beam-gas scattering, with pumping the inside of the pipes.
- The beam-gas scattering can be a source of backgrounds in Belle II, thus this is very important to reduce it.
  - The design pressure in the beam pipes is $\sim 10^{-7}\,\mathrm{Pa}$, and this corresponds to 10 hours or more in the beam life time determined by the beam-gas scattering.
  - The dominant gas load in SuperKEKB is desorptions from the chamber-wall by the photon stimulation (Photons in the SR strikes the residual gas on the wall). This is called photon stimulated desorption (PSD).

    → Thus, the source of the gas is widely distributed in the ring, and the distributed pumping system is efficient to reduce the residual gas.

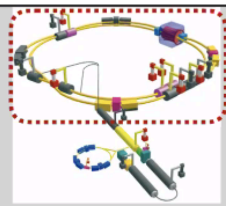
Beam-gas scattering



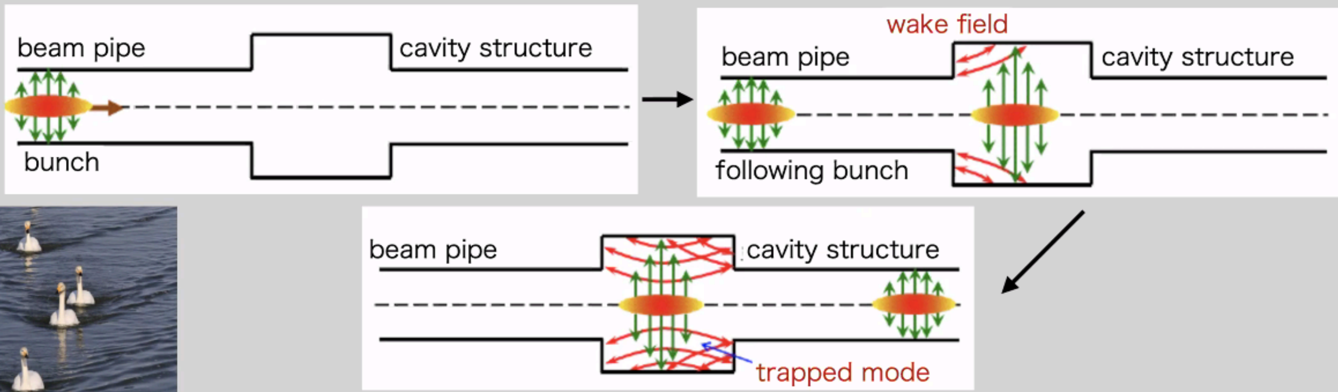
PSD in beam pipe



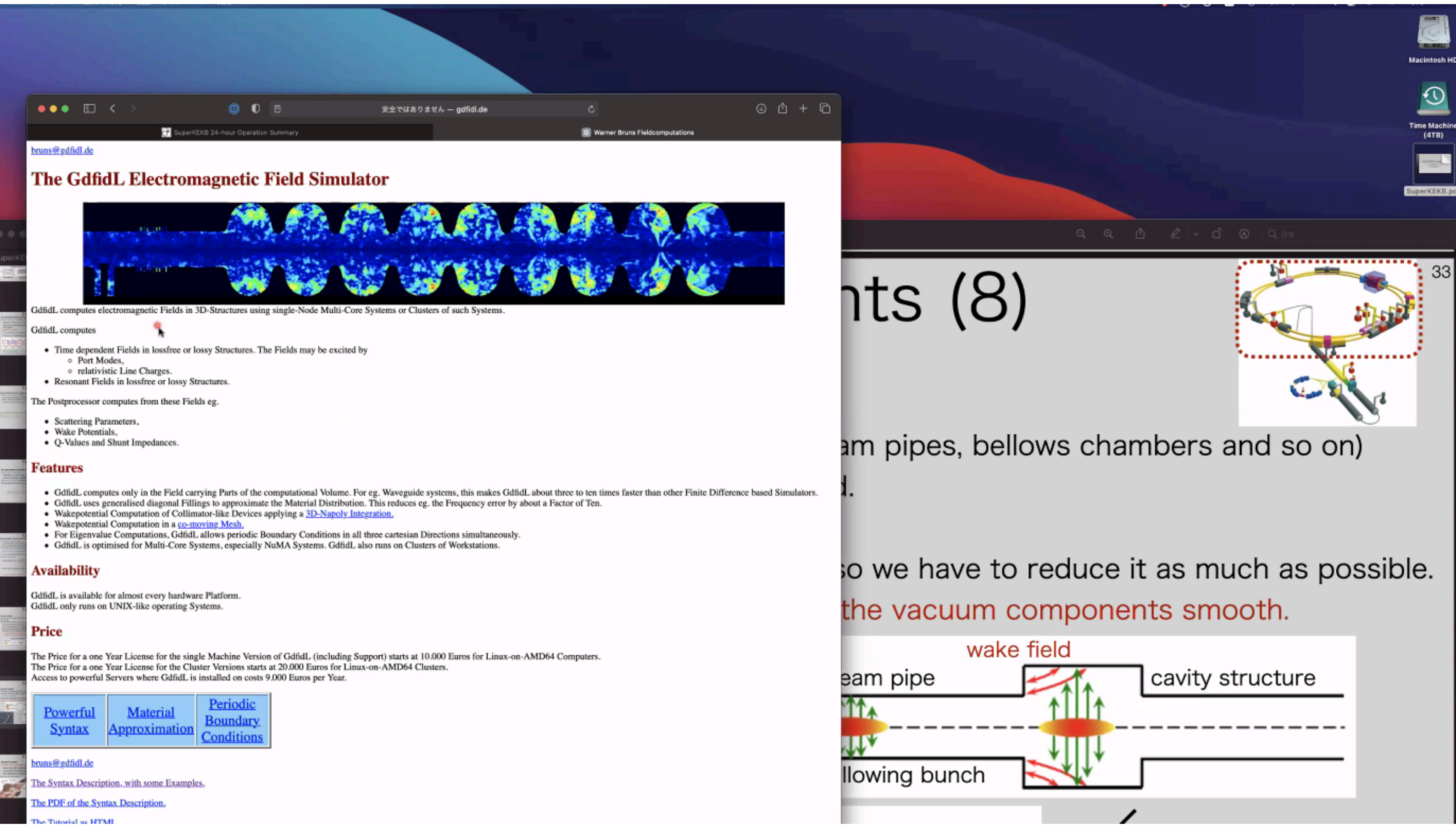
Components (8)



- **Vacuum system**
- The beam couples with the vacuum components (beam pipes, bellows chambers and so on) through the intermediary of the electromagnetic field.
  → beam impedance
- High beam impedance can cause beam instabilities, so we have to reduce it as much as possible.
- In order to reduce the impedance, it's need to make the vacuum components smooth.



ref: http://www.gdfidl.de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SuperKEKB 24-hour Operation Summary
Werner Bruns Fieldcomputations
bruns@gdfidl.de
The GdfidL Electromagnetic Field Simulator
GdfidL computes electromagnetic Fields in 3D-Structures using single-Node Multi-Core Systems or Clusters of such Systems.
GdfidL computes
Time dependent Fields in lossfree or lossy Structures. The Fields may be excited by
Port Modes,
relativistic Line Charges.
Resonant Fields in lossfree or lossy Structures.
The Postprocessor computes from these Fields eg.
Scattering Parameters,
Wake Potentials,
Q-Values and Shunt Impedances.
Features
GdfidL computes only in the Field carrying Parts of the computational Volume. For eg. Waveguide systems, this makes GdfidL about three to ten times faster than other Finite Difference based Simulators.
GdfidL uses generalised diagonal Fillings to approximate the Material Distribution. This reduces eg. the Frequency error by about a Factor of Ten.
Wakepotential Computation of Collimator-like Devices applying a 3D-Napoly Integration.
Wakepotential Computation in a co-moving Mesh.
For Eigenvalue Computations, GdfidL allows periodic Boundary Conditions in all three cartesian Directions simultaneously.
GdfidL is optimised for Multi-Core Systems, especially NuMA Systems. GdfidL also runs on Clusters of Workstations.
Availability
GdfidL is available for almost every hardware Platform.
GdfidL only runs on UNIX-like operating Systems.
Price
The Price for a one Year License for the single Machine Version of GdfidL (including Support) starts at 10.000 Euros for Linux-on-AMD64 Computers.
The Price for a one Year License for the Cluster Versions starts at 20.000 Euros for Linux-on-AMD64 Clusters.
Access to powerful Servers where GdfidL is installed on costs 9.000 Euros per Year.
Powerful Syntax
Material Approximation
Periodic Boundary Conditions
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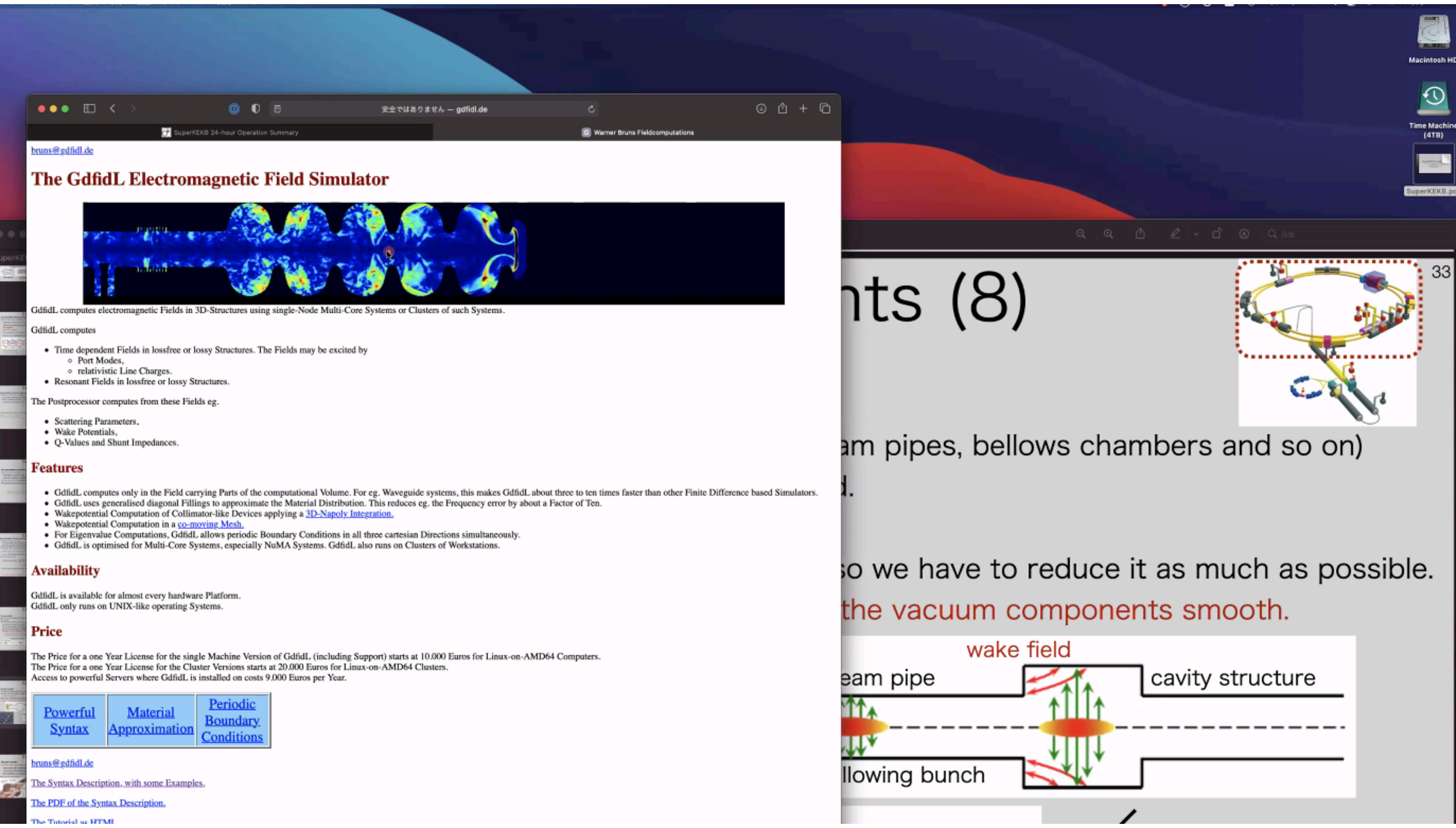

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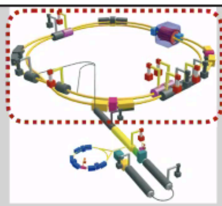

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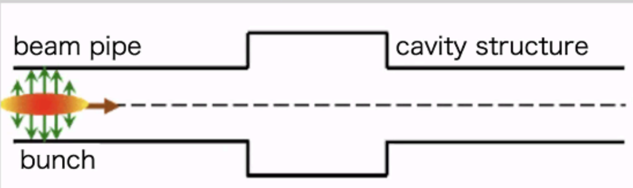

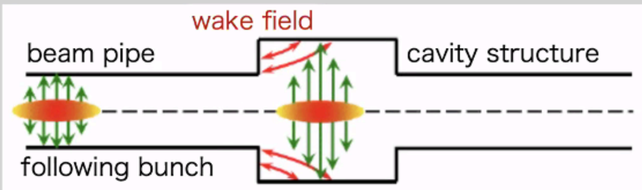

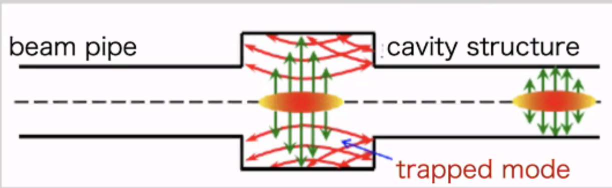

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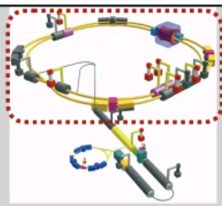
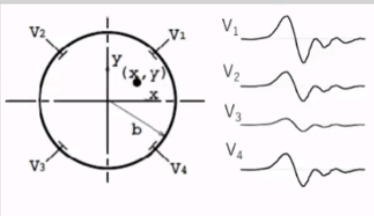
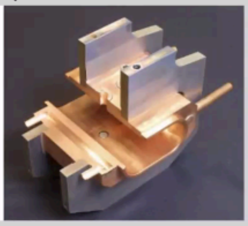
Components (9)



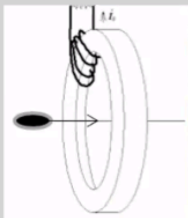
- **Beam monitor system**
- In order to store the beam stably, it's need to monitor the beam current, position, size and so on and feed it back using the information if necessary.

Beam Position Monitor (BPM)

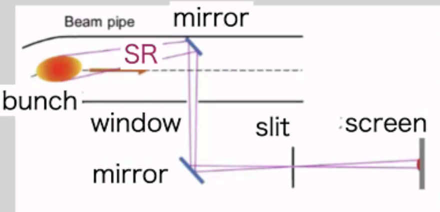




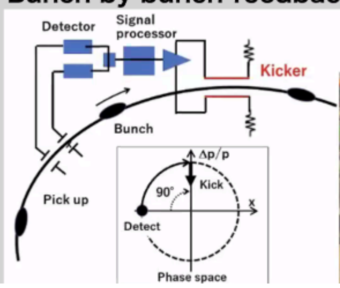
Beam current monitor

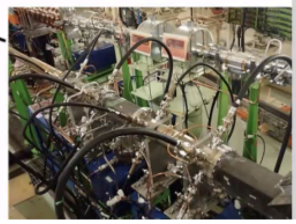


Beam size monitor

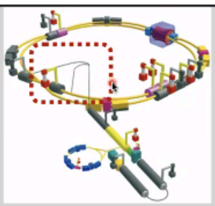


Bunch by bunch feedback (transverse kicker)



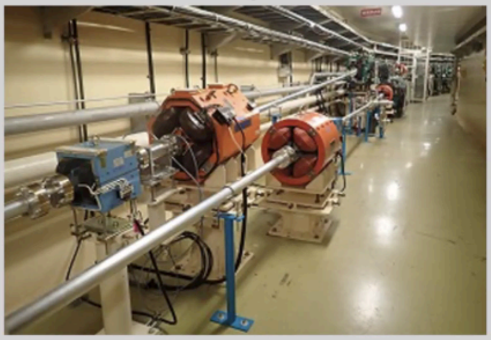


Components (10)

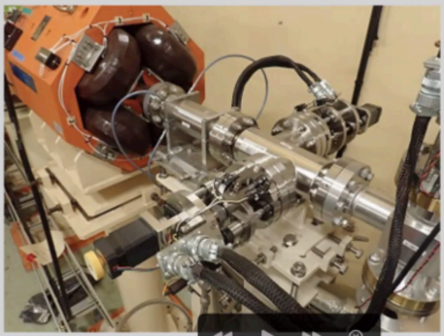


- **Beam Transport (BT) line**
- transport the beam from the linac to the ring with keeping the beam quality.
- The BT line measures features of the beam, which are the emittance, energy spread and so on, and feed them back to the linac operation.

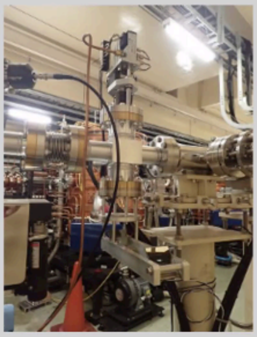
BT line for SuperKEKB MR



Beam collimator

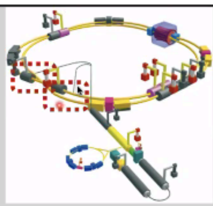


Screen monitor



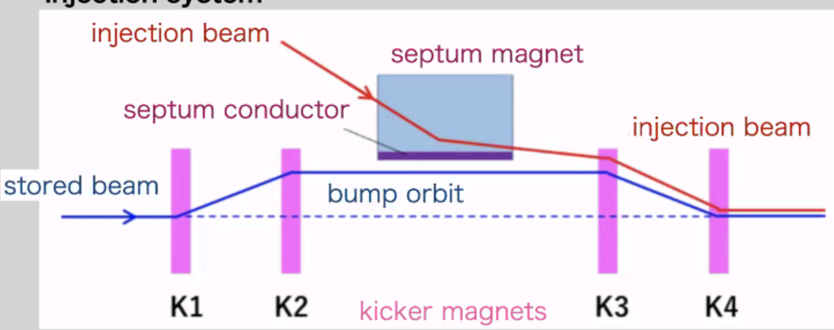
Wire scanner

Components (11)

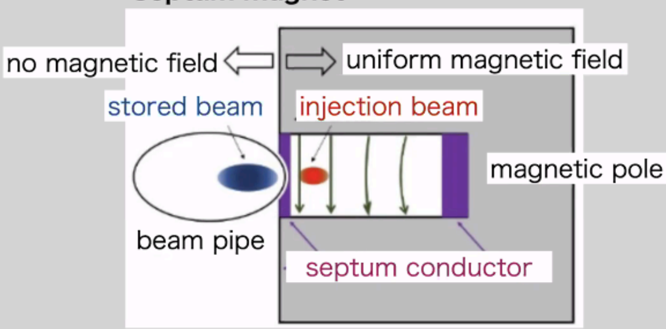


- **Beam injection system**
- inject the beam to the ring.
- This system consists of special components such as pulse magnets, septum magnets, ceramic chamber and so on.

Injection system



Septum magnet



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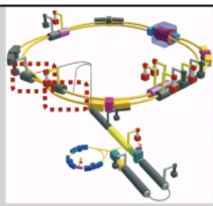

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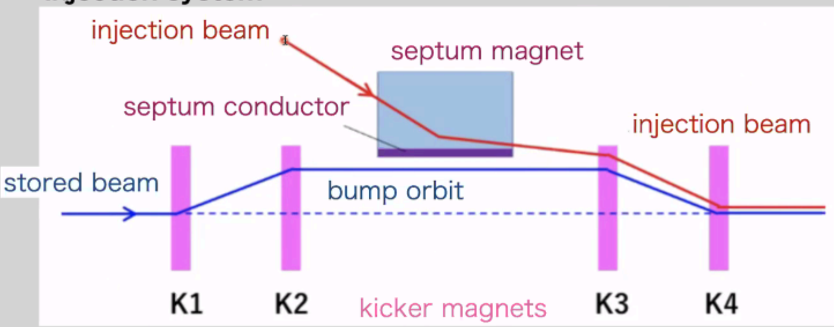
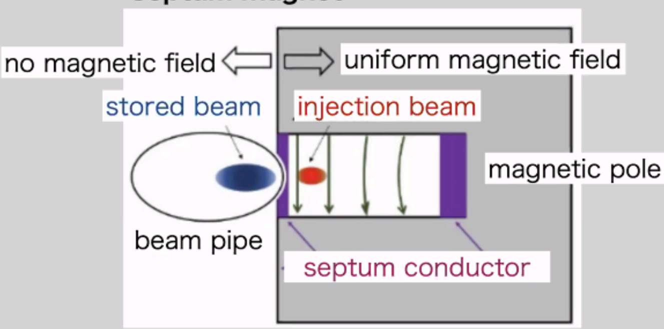


Septum magnet



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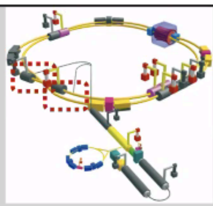

- **Beam injection system**
- inject the beam to the ring.
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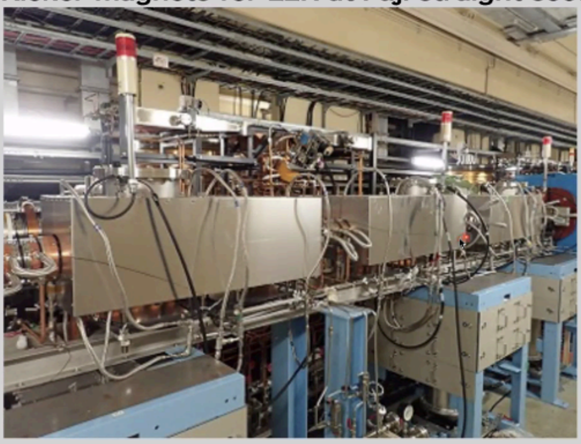
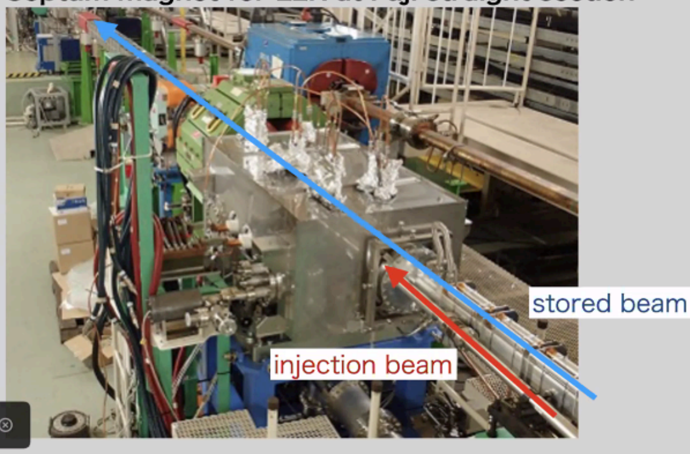
Kicker magnets for LER at Fuji straight section



Septum magnet for LER at Fuji straight section



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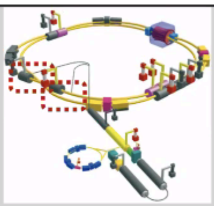

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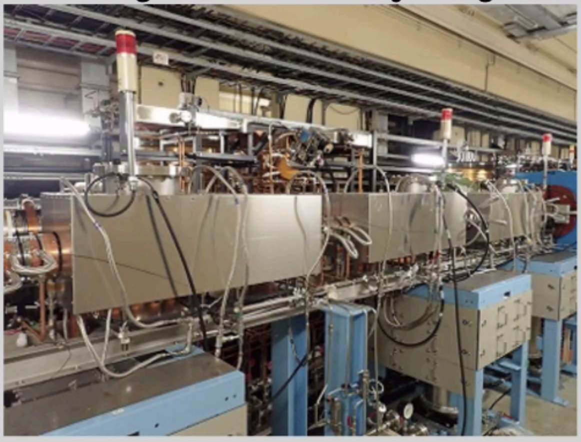
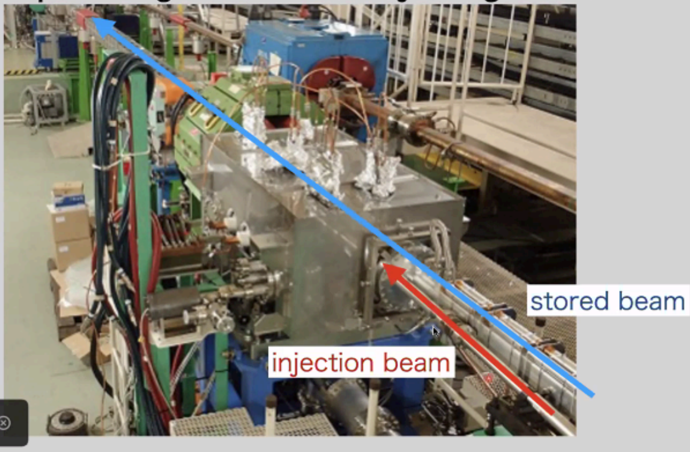


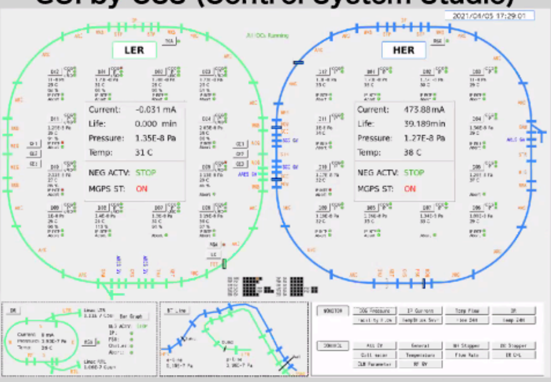
Septum magnet for LER at Fuji straight section



Components (12)

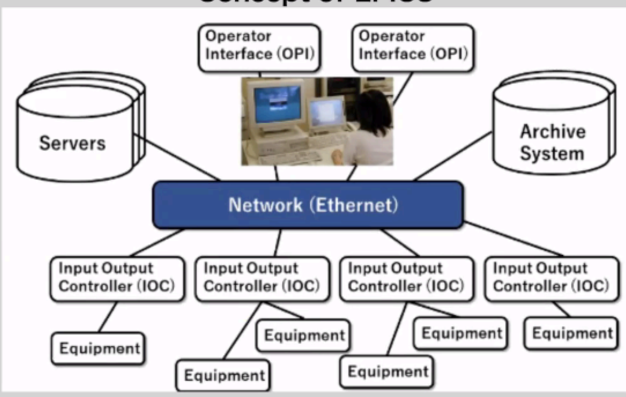
- **Control system**
- monitor, record and control huge amount of signals from various components.
- EPICS (Experimental Physics and Industrial Control System) has been adopted for the base control system.

GUI by CSS (Control System Studio)

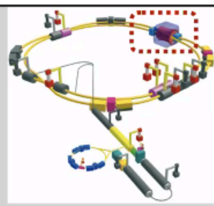


SuperKEKB control room

Concept of EPICS

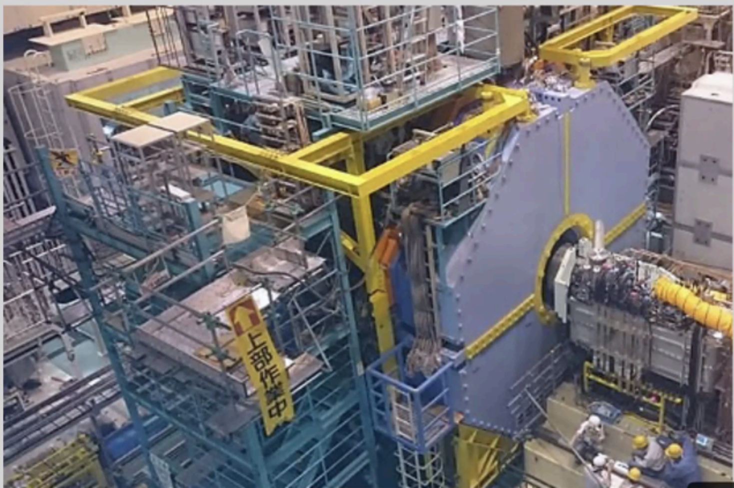


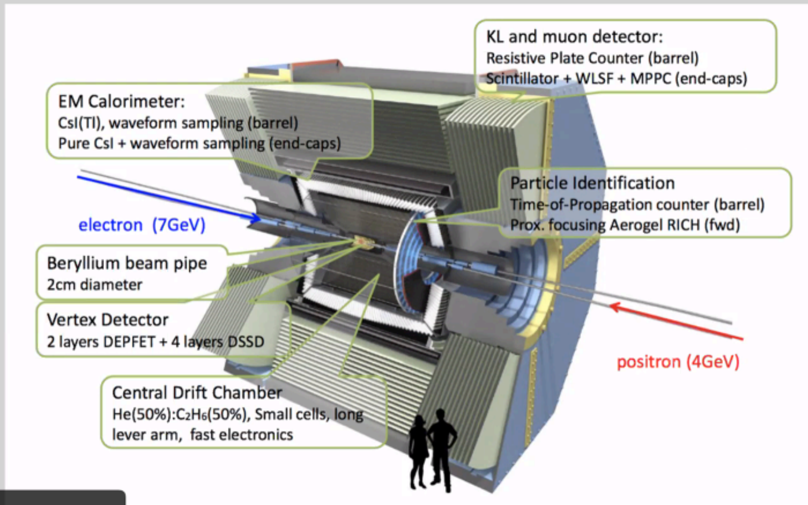
Components (13)



- **Particle detectors (Belle II)**
- The detail will be presented on “Belle II 実験” by I. Nakamura on July 14th in 2021 High Energy Accelerator Science Seminar.

Photo of Belle II



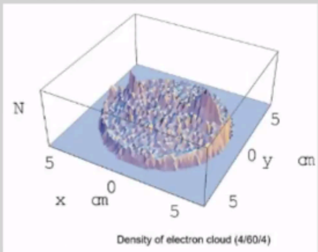


Components (14)

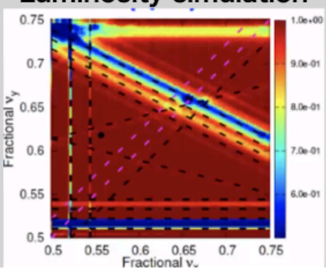
- **The other important components.**
- Beam simulation (beam dynamics, accelerator physics)
  - calculate interactions between the colliding beams and so on.
  - It's also important to estimate the performance of the actual machine compared with the model.
- Safety system
  - radiation monitor and management
  - human security
  - beam abort (system for beam dump)
- Loss monitor system
  - monitor locations at where the beam is lost.

and so on…

Electron cloud simulation



Luminosity simulation

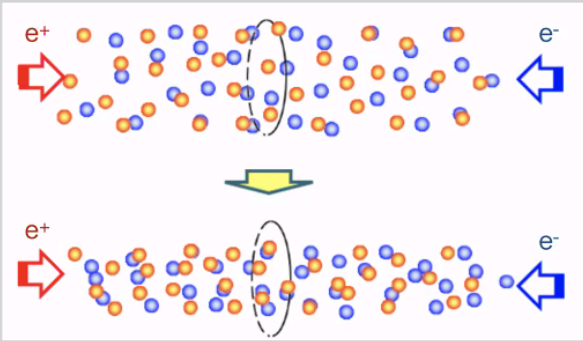


Features (1)

- **High luminosity**
- The luminosity is almost decided by the beam current and beam size at the interaction point (collision point).
- When the number of the particles is the same, the collision frequency is higher for the smaller beam-cross section at the interaction point.

$$L = \frac{N_{-}N_{+}n_b f_0}{4\pi\sigma_x^*\sigma_y^*}$$

N_{-}, N_{+} : number of e⁻/e⁺ in a bunch
n_b : number of bunch
f_0 : revolution frequency
σ_x^*, σ_y^* : beam size at interaction point



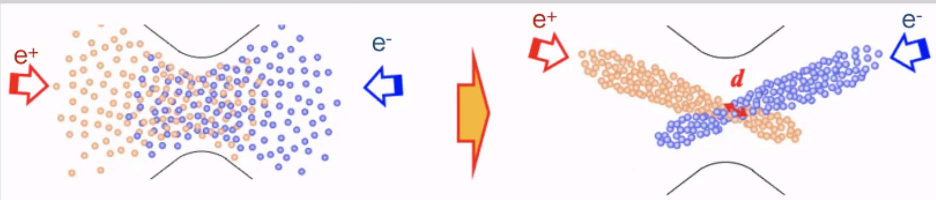
- $\sigma^* = \sqrt{\epsilon\beta^*}$ → need small ϵ and small β^* to increase the luminosity, basically.
- However, it doesn't mean that the smaller β^* can just achieve the high luminosity.

Features (1)

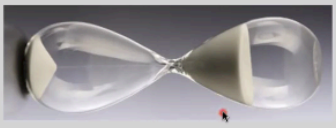
- **Nano-beam collision scheme**
- When we squeeze the β smaller than the bunch length, the beam size around the longitudinal end of the bunch becomes large. Then, the interaction between the collision bunches becomes stronger, and the luminosity degrades by this effect. → called hourglass effect
- As a countermeasure for this, we collide the beams with an extreme small beam size and large crossing-angle.
  → The overlapping part of the beams becomes smaller and the collision efficiency doesn't decrease.
  → called nano-beam collision scheme (proposed for SuperB in Italy [P. Raimondi, 2nd SuperB Workshop (2006)])

conventional collision scheme **nano-beam collision scheme**

$\beta_y^* \leqq \sigma_z$



$\beta_y^* \geqq d \ll \sigma_z$



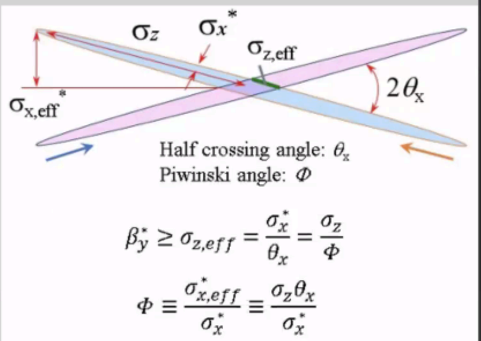
- SuperKEKB has adopted this scheme for the first time in the world as a practical machine.

Features (1)

- **Luminosity in nano-beam collision scheme**

$$L = \frac{N_- N_+ n_b f_0}{4\pi \sigma_x^* \sigma_y^*} = \frac{N_- N_+ n_b f_0}{4\pi \sigma_{x,eff}^* \sqrt{\epsilon_y \beta_y^*}} \approx \frac{\gamma_\pm}{2er_e}\left(\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}\right)$$

$$\xi_{y\pm} \approx \frac{r_e N_\mp}{2\pi \gamma_\pm \sigma_{x,eff}^*}\sqrt{\frac{\beta_y^*}{\epsilon_y}}$$: beam-beam parameter



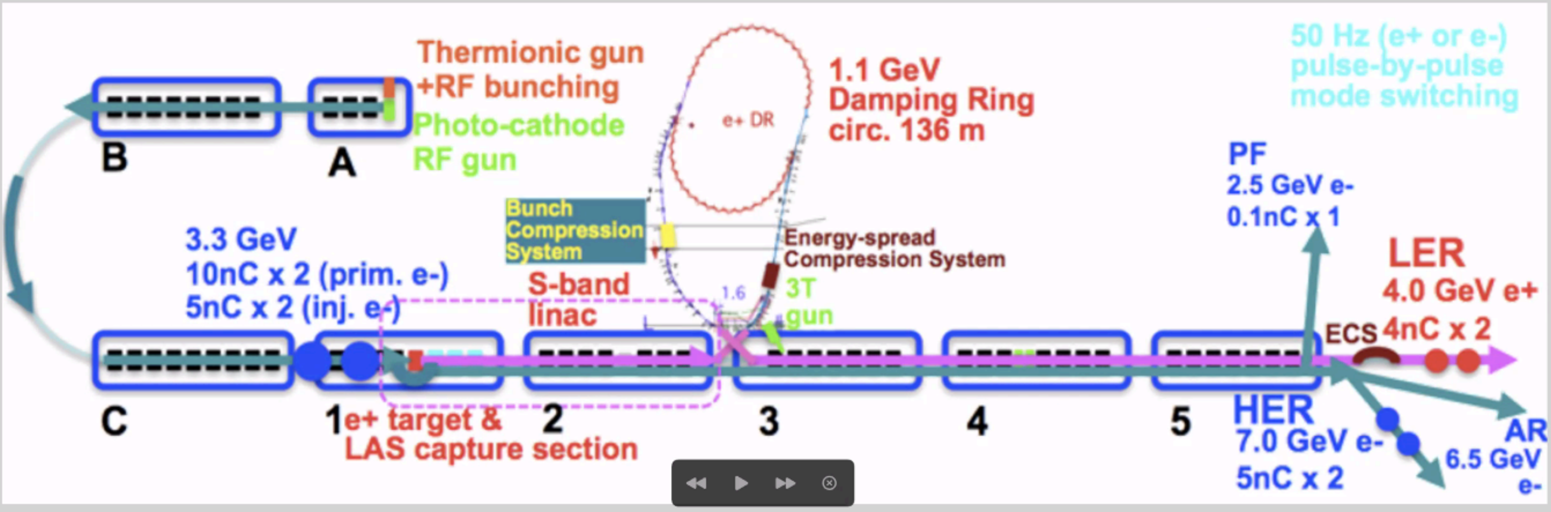
  - When the $\xi_{y\pm}$ is constant, L is proportional to I and $1/\beta_y^*$.
  - It's important to also make σ_x^* smaller for smaller β_y^*.

- **Specific luminosity** L_{sp} →luminosity per bunch current

$$L_{\mathrm{sp}} \equiv \frac{L}{n_b I_{b-} I_{b+}} \propto \frac{L}{N_- N_+ n_b f_0^2} \propto \frac{1}{\beta_{y\pm}^*} \qquad (\xi_{y\pm} = \mathrm{const.})$$

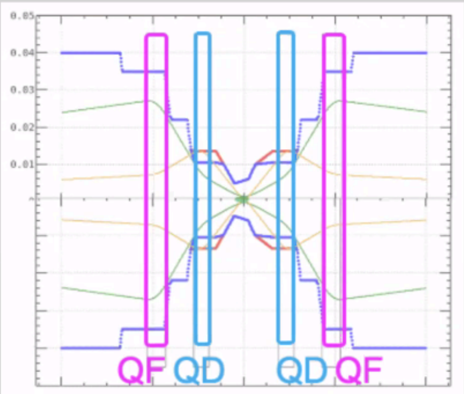
Features (2)

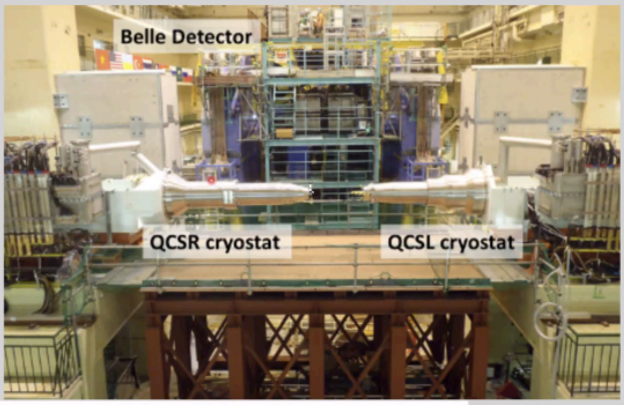
- **Linac provides beams with low emittance and high bunch charge.**
  - This is essential for the nano-beam collision scheme and short beam life time.
    - electron beam: photo cathode RF-gun
    - positron beam: high yield positron source, damping ring
  - then, need injections to the 5 rings simultaneously at Tsukuba campus.
    - separate the beam conditions using 50 Hz pulse magnets depending on the ring specifications

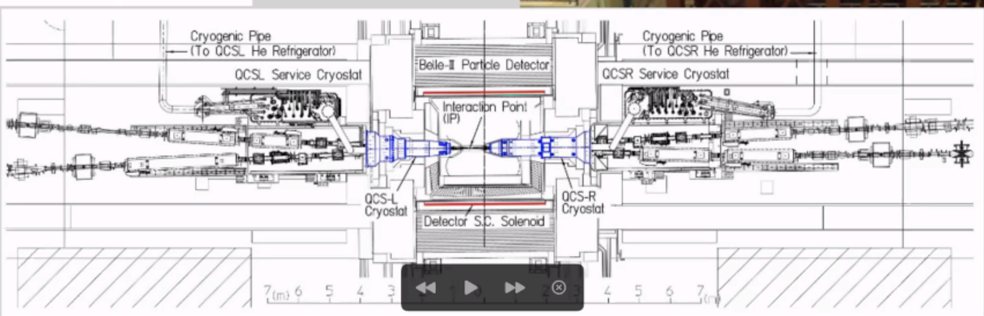


Features (3)

- **Final focusing superconducting magnets (QCS)**
- focus the beam at the interaction point to achieve the nano-beam collision.







Features (4)

- **Countermeasures for electron cloud effect (ECE) in LER.**
- interaction between the positron beam and electrons (positron, proton ring)
  - SR hit the wall of the beam pipes, and it emits photo-electrons.
  - The electric filed of the bunches accelerate the photo-electrons, and they h
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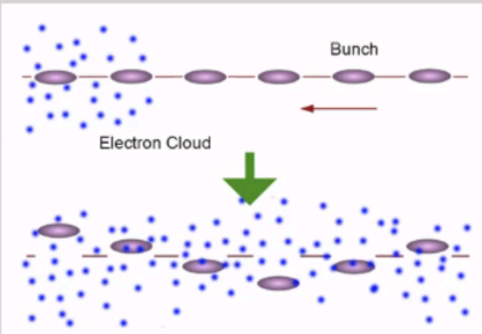
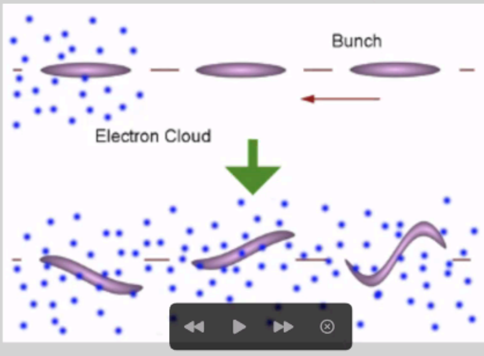
  - The positron beam attracts these electrons and electron cloud is formed ar
- The electron cloud can induce instabilities when the density in the ring becom

Multi-bunch instability



Single-bunch instability
(head-tail instability)



electron cloud instabilit
→ beam size blowup by
bunch instability
→ degrades the lumino

Features (4)

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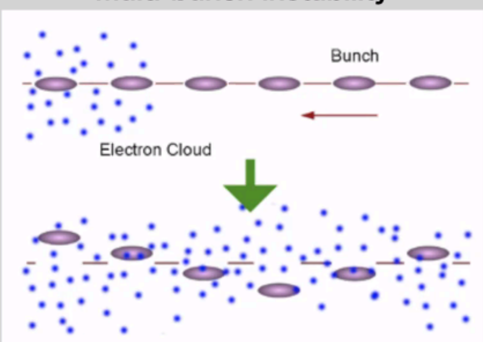
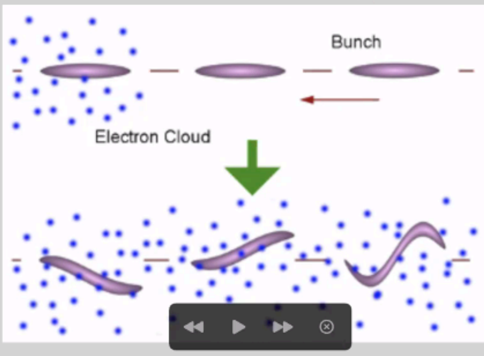
- interaction between the positron beam and electrons (positron, proton ring)
  - SR hit the wall of the beam pipes, and it emits photo-electrons.
  - The electric filed of the bunches accelerate the photo-electrons, and they hit the beam pipes and emits secondary electrons.
  - The positron beam attracts these electrons and electron cloud is formed around it.
- The electron cloud can induce instabilities when the density in the ring becomes high.

Multi-bunch instability



Single-bunch instability (head-tail instability)



electron cloud instability
→ beam size blowup by single-bunch instability
→ degrades the luminosity

Features (4)

- **Countermeasures for ECE in LER.**
  - (a) antechamber
  - (b) TiN coating for low secondary electron yield (SEY)
  - (c) clearing electrode
  - (d) groove structure
  - (e) permanent mangnet
  - (f) solenoid coil

Counter-measures	Applied regions
Solenoid	Drift region, in steering magnets, bellows chambers
TiN coating	Most of new beam pipes (all of aluminum alloy beam pipe)
Antechamber structure	Most of new beam pipes
Groove structure	In dipole-type magnets
Clearing electrode	Wiggler magnets

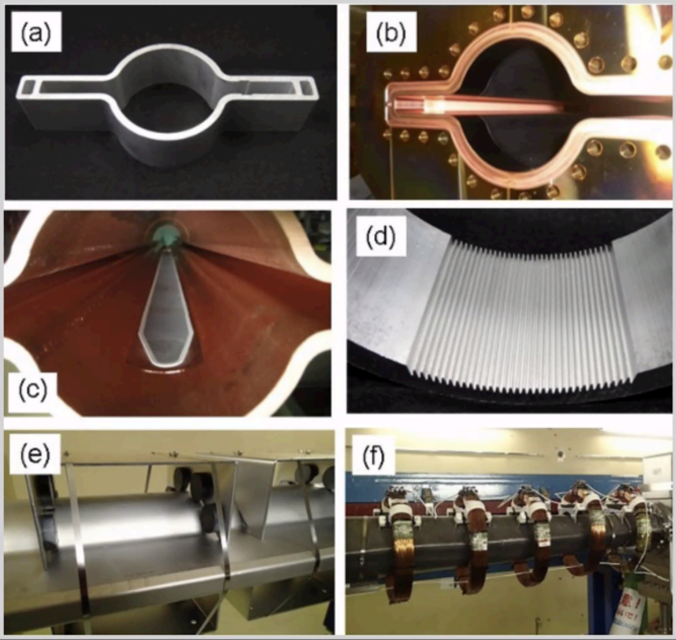
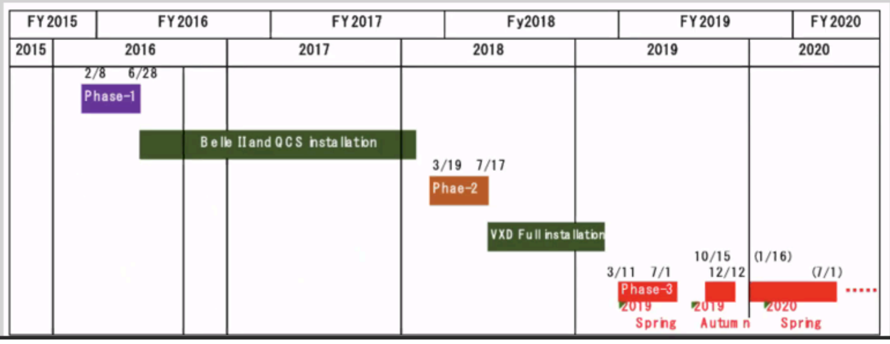


Table of Contents

Operation status

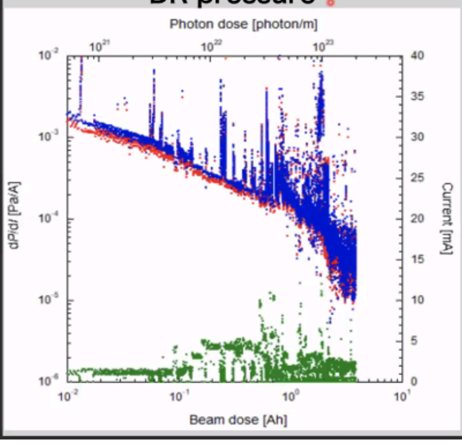
- The construction of SuperKEKB started since 2010.
- The operation has started since 2016.
- There are three commissioning phases.
  - Phase-1 (2016-02-08 to 2016-06-28): test run, machine tuning, vacuum scrubbing
    - no DR, no QCS, no Belle II (no collision)
  - Phase-2 (2018-03-19 to 2018-07-17): collision tuning
    - partial Belle II
  - Phase-3 (2019-03-11 ~): physics run
    - full Belle II



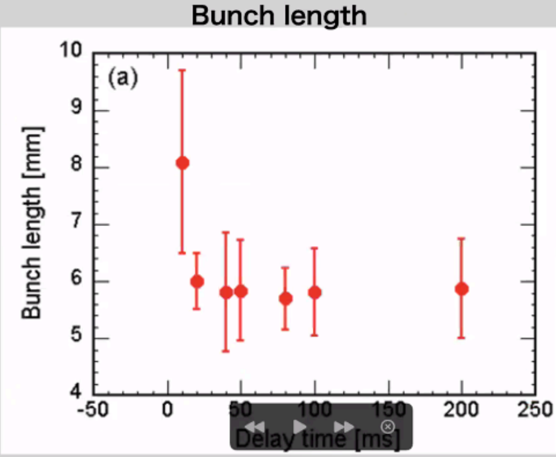
Operation status (1)

- **Achievement: DR, BT**
- Phase-2
  - The DR operation has started.
  - The beam size and bunch length decrease to the design values within 20 ms.
  - The pressure (dP/dI) in the arc section has steadily decreased.
  - also succeeded in the 2-pulse and 2-bunch operation.
  - The $\epsilon_{ny} \approx 5\,\mu\text{m}$ at just after the extraction from DR is almost the design value.

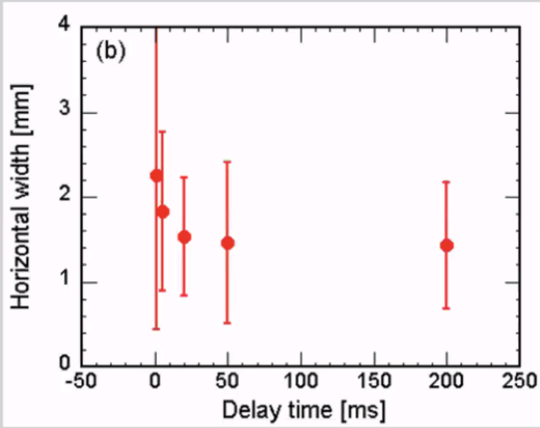
DR pressure



Bunch length



Bunch width

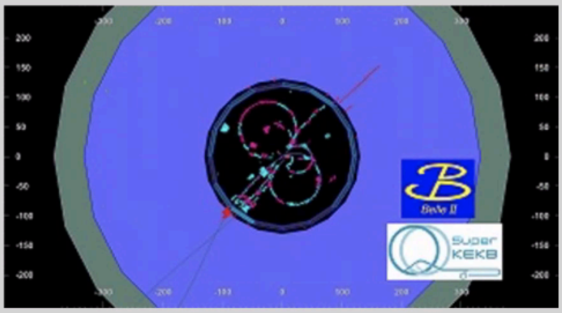


Operation status (1)

- **Achievement: MR**
- Phase-1 (no collision)
  - started to tune the injection since Feb. 8th, 2016.
  - confirmed the storage of the positron beam on Feb. 9th 17:09, 2016.
    - also checked that the magnets are located as designed with the blueprints, various components work normally.
    - There are no obstacles in the beam pipes.
  - After that, the beam current had gradually increased.
    - Max. current: LER 1010 mA, HER 870 mA (1576-bunch)
  - The background level in the interaction region was comparable with the expected.

Operation status (1)

- **Achievement: MR**
- Phase-2 (partial Belle II)
  - started to tune the collision with QCS and partial Belle II since Mar. 19th, 2018.
  - confirmed a hadron collision event for the first time on Apr. 26th 0:38, 2018.
  - Max. beam current: LER 860 mA, HER 800 mA (1576-bunch)
  - Max. luminosity: 5.5×10^{33} cm^{-2} s^{-1}
  - gradually squeeze β^* （β^* refers to β at the interaction point).
    - LER $\beta_x^* / \beta_y^* = 200 / 3\,\mathrm{mm}$
    - HER $\beta_x^* / \beta_y^* = 100 / 3\,\mathrm{mm}$
  - The β^* is a world's smallest value for the practical machine.

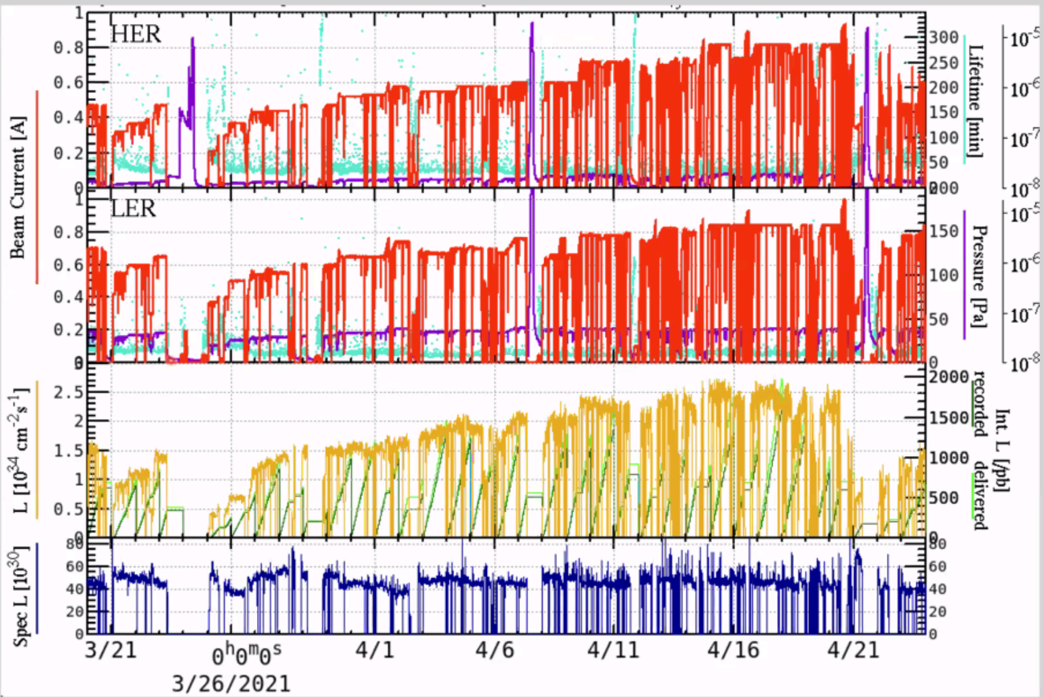


Operation status (1)

- **Achievement: MR**
- Phase-3 (full Belle II)
  - started the physics run with full Belle II since Mar. 11th, 2019.
  - Max. beam current: LER 1000 mA, HER 940 mA (1370-bunch)
  - Max. luminosity: 2.84×10^{34} cm^{-2} s^{-1} on 2021-04-14 16:08 (world record!)
    - * The previous world record was 2.14×10^{34} cm^{-2} s^{-1} with LHC in 2018.
  - Integrated luminosity (recorded in Belle II): ~129 fb^{-1} till 2021-04-27 05:24 [1 fb^{-1} = 1×10^{39} cm^{-2}]
  - β^*
    - LER $\beta_x^*/\beta_y^* = 80\,/\,1\,\mathrm{mm}$
    - HER $\beta_x^*/\beta_y^* = 60\,/\,1\,\mathrm{mm}$

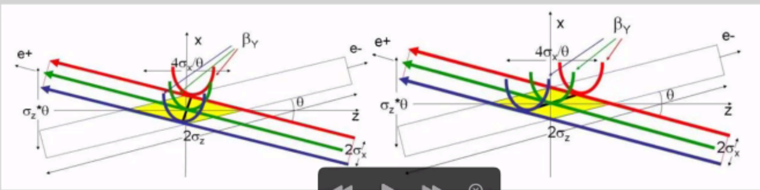
Operation status (1)

- **Achievement: MR**
- Phase-3 (full Belle II), Example (2021-03-20 to 2021-04-24)



Operation status (1)

- **Achievement: MR**
- Demonstration of the nano-beam collision scheme.
- Pressure (dP/dI) in the rings has decreased steadily.
  - The pressure in LER is higher compared with that in HER because most of the vacuum components are new ones.
  - This means that the contribution to the backgrounds derived from beam-gas scattering in LER is dominant.
- The optics is almost as designed.
  - establishment of the injection, correction and β squeezing scheme.
- The QCS has operated on track.
- A crab-waist scheme has been introduced [P. Raimondi, 2nd SuperB Workshop].



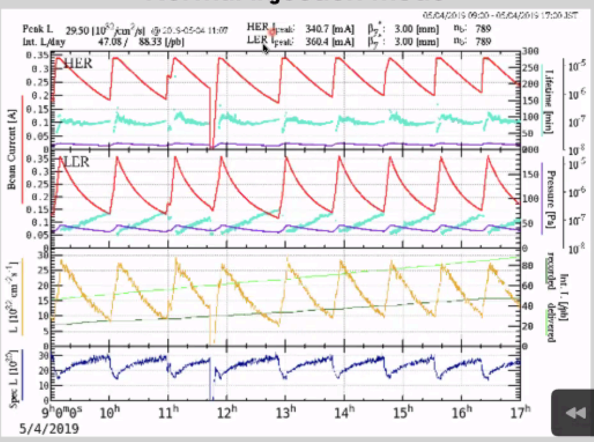
crab sext. off

crab sext. on

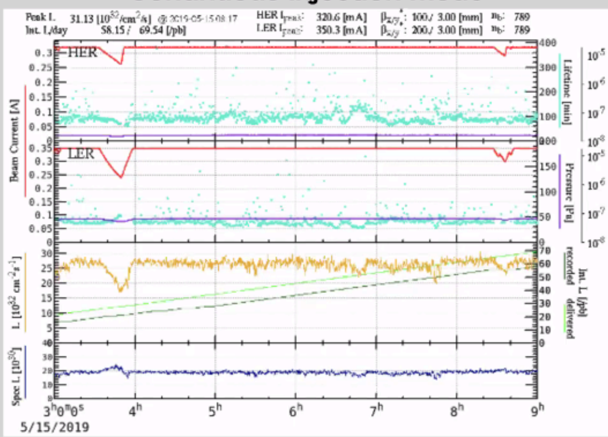
Operation status (1)

- **Achievement: MR**
- Physics run with the continuous injection.
  - Backgrounds level has been improved by the injection, collimator tuning and so on, thus we were able to introduce this.
- increase the integrated luminosity by a factor of ~3 compared with the normal injection mode.
  - In the normal injection, the data recording in Belle II had been stopped during the injection.

Normal injection mode



Continuous injection mode

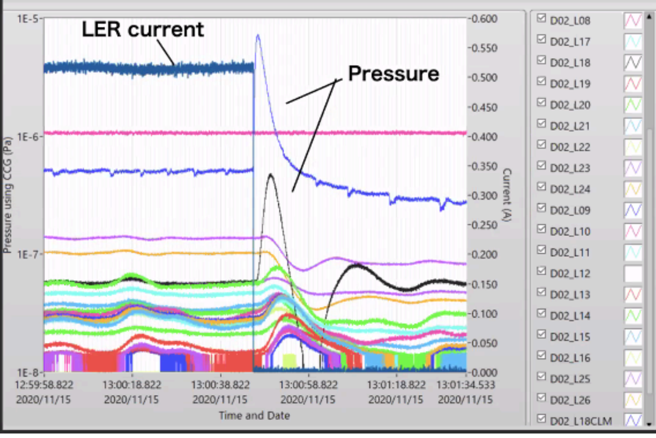


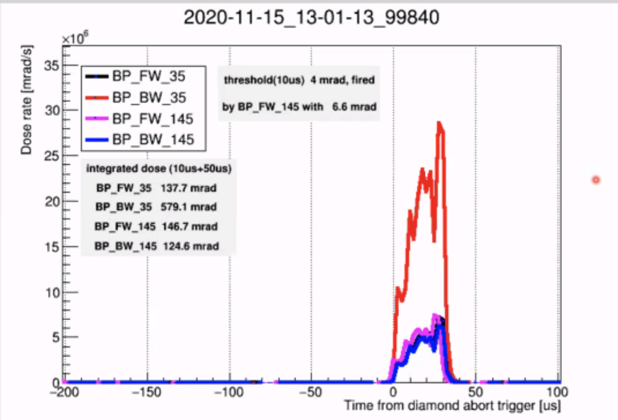
Operation status (2)

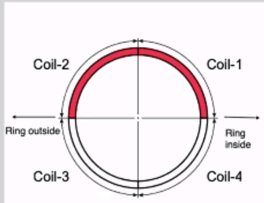
- **Problem: Damage of collimator**
- Collimators have been damaged by beam hit about every run period. The cause is known.

(example) 2020-11-15 13:01:13, beam abort with QCS quench

- LER: 509 mA, HER: 469.6 mA
- Pressure burst was observed in D02V1. The other pressure burst in D05 section was also observed (dust event?).
- After that, the BG levels were higher by a factor of 2 and limited the beam currents .
- The damaged jaws were replaced to spears from Nov. 18th to 21st.

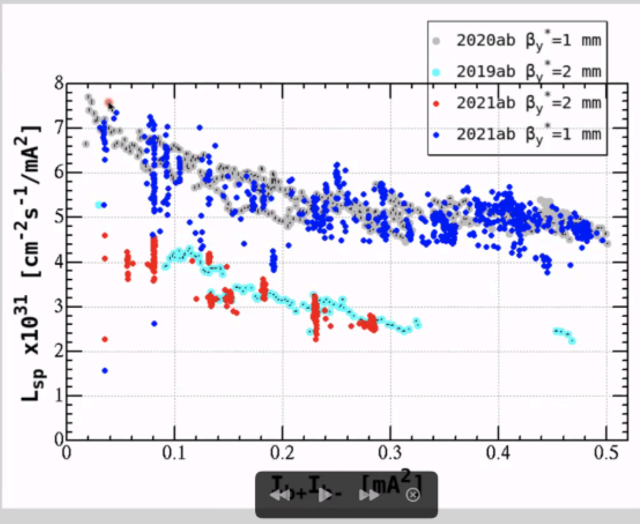






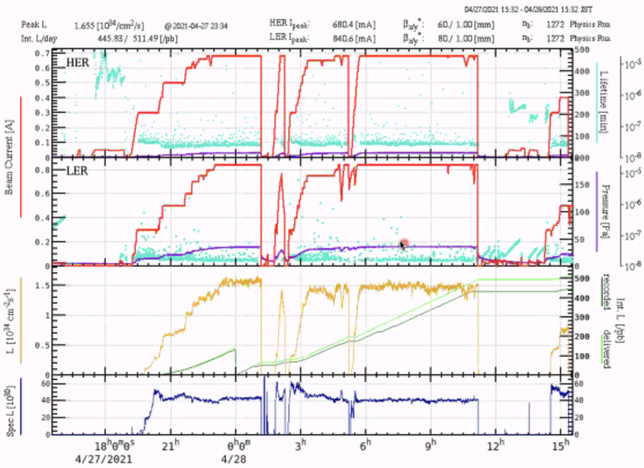
Operation status (2)

- **Problem:** **Specific luminosity in the higher bunch current region**
- The specific luminosity decreases in the higher bunch current.
  - This is caused by the beam size blowup due to the beam-beam effect.
  - We need to figure out the mechanism.



SuperKEKB 24-Hour Operation Summary

SuperKEKB 2021b operation.



Also available are [[Daily history]] [[Yesterday]] [2-hour operation] [Injection] [Damping ring] [Beam size] [1-day injector] [2-hour injector]

M. Satoh, Y. Ohnishi, K. Furukawa, SuperKEKB Commissioning Group, KEK
<webmaster@mail-linac.kek.jp> , Feb.9.2016 - Apr.17.2021.
[Linac Operation Log] [KEKB Operation Log] [Copy] [KCG Log] [Copy] [Linac] [SuperKEKB] [Accelerator] [Belle2] [KEK]

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Additional Info

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  - “Belle II 実験” by I. Nakamura on July 14th.
  - “電子陽電子入射器の概要” by Y. Seimiya on Jan. 26th.

- SuperKEKB 24-hour operation summary page:
  http://www-linac.kek.jp/skekb/snapshot/dailysnap.html

- OHO high energy accelerator seminar (Japanese)
  http://accwww2.kek.jp/oho/index.html
  related to SuperKEKB: 2019(SuperKEKB), 2004(KEKB), 1994(KEKB) and so on

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