Operation, Challenges and Future Prospects of SuperKEKB

Tetsuo ABE

(KEK/ACCL)

on behalf of SuperKEKB commissioning group

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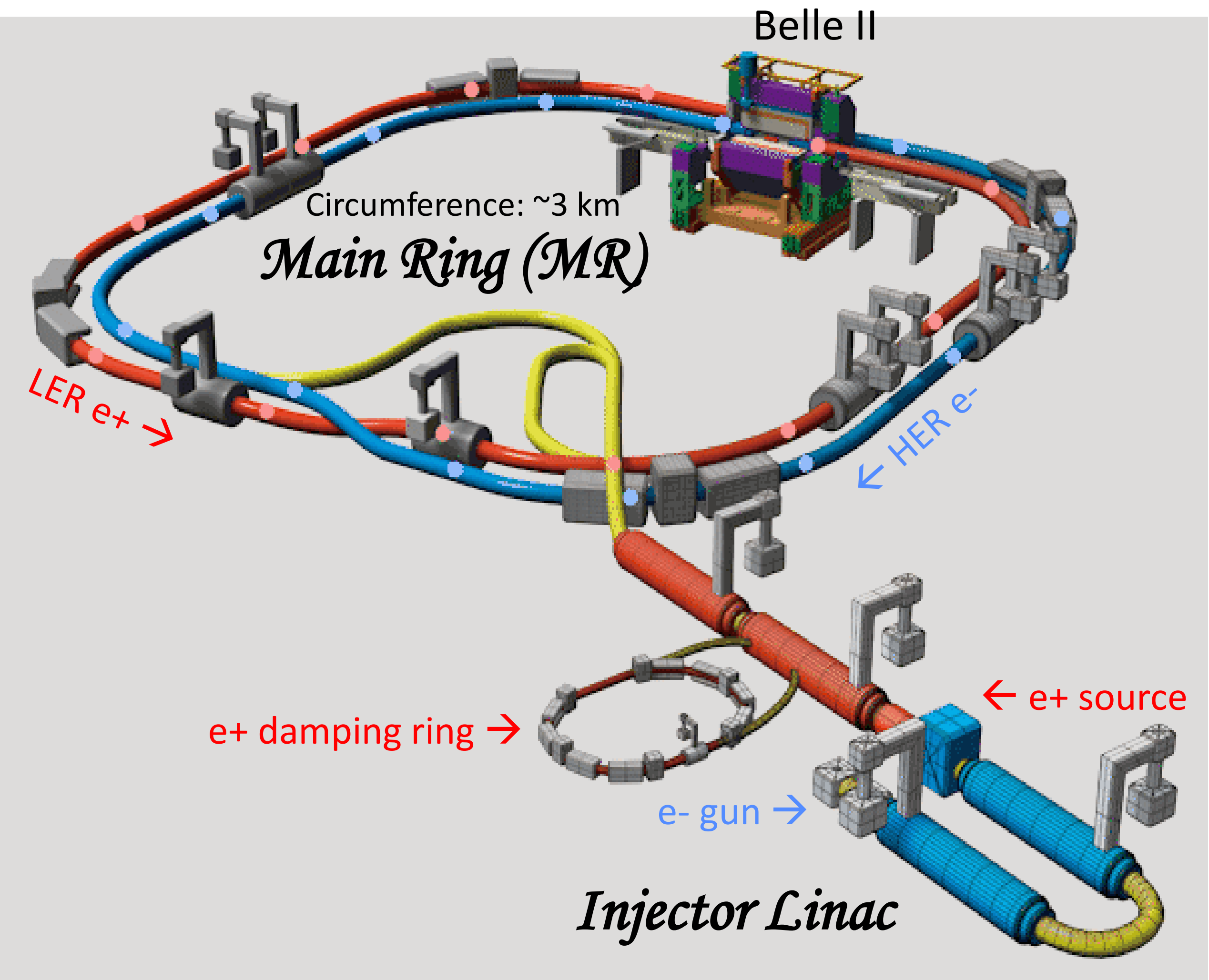
2023-07-20

SuperKEKB Accelerator

~ *Asymmetric-energy e+e- collider* ~

- Upgraded from KEKB B-factory (KEKB)
- Stored-beam energies
  - High Energy Ring (HER) : 7.0 GeV (e-)
  - Low Energy Ring (LER) : 4.0 GeV (e+)
- $E_{\text{cms}} \approx M_{\Upsilon(4S)}$
- Stored-beam currents (design)
  - HER : 2.6 A
  - LER : 3.6 A
- Positron damping ring newly constructed
- Final target luminosity: 6.0×10^{35} cm$^{-2}\cdot$s^{-1}
  - Higher beam currents than those at KEKB
  - Squeezing β_y^* with the nano-beam collision scheme
- Goal: 50-fold more integrated luminosity than recorded in KEKB



History of the SuperKEKB Project

The 1st Long Shutdown (LS1) (Jun., 2022 – Dec., 2023)

- Belle II: additional installation and replacement of sub-components, etc.
- SuperKEKB: many various modifications and improvements

Phase 3 (Since Mar., 2019)

- Physics run with the fully-installed Belle II and IR.

Phase 2 (Mar. to Jul., 2018)

- Belle II w/o the beam-sensitive vertex detectors (PXD nor SVD)
- Super-conducting final focus magnets installed in the IR
- Demonstration of the nano-beam collision scheme at SuperKEKB
- Beam background study for the nano-beam collision scheme

(PXD: Pixel vertex detector)
(SVD: Silicon vertex detector)

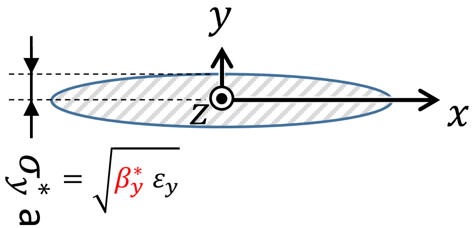
Phase 1 (Feb. to Jun., 2016)

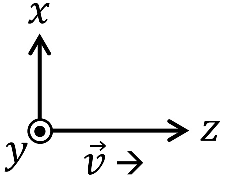
- W/o the Belle II detector nor final focus magnets in the IR (no collision)
- Vacuum scrubbing
- Low emittance beam tuning
- Beam background study for the Belle II detector installation

(IR: Interaction Region)

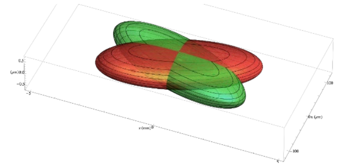
Hourglass Effect and Nano-Beam Collision Scheme

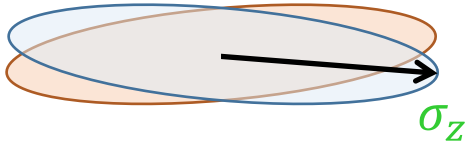
Flat beam bunch





KEKB IP

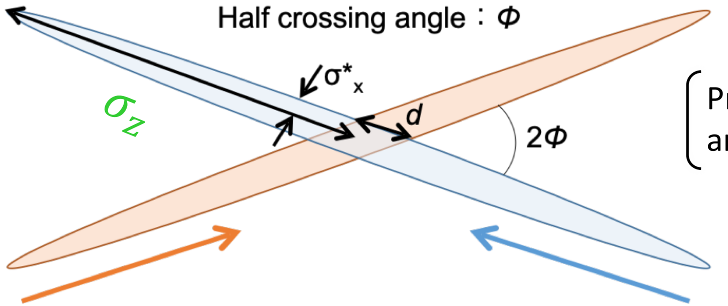




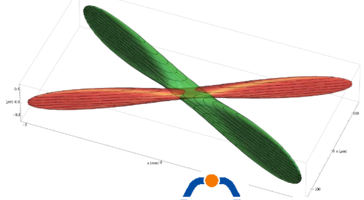
$$\mathcal{L} \propto \frac{1}{\beta_y^*}$$ (roughly)

↑ Vertical beta function at the IP

SuperKEKB IP with the nano-beam scheme



Proposed by P. Raimondi, and adopted by SuperKEKB



Too small β_y^* (too strong final focus) makes colliding bunches hourglass-shaped in the crossing region.

➔ Luminosity ($\mathcal{L}$) decreased by the geometrical loss

To avoid the hourglass effect

Operational $\beta_y^* > \sigma_z \approx \mathbf{6\ mm}$

- ✓ Long, slender, and flat bunches
  - Longitudinal: ~6 mm
  - Horizontal: ~10 μm
  - Vertical: ~50 nm
- ✓ Large crossing angle: ~5 deg
- ✓ Small crossing region
- ✓ The Hourglass effect is small.

Operational $\beta_y^* > \frac{\sigma_x^*}{\phi} \approx \mathbf{0.3\ mm}$

(IP: Interaction Point)

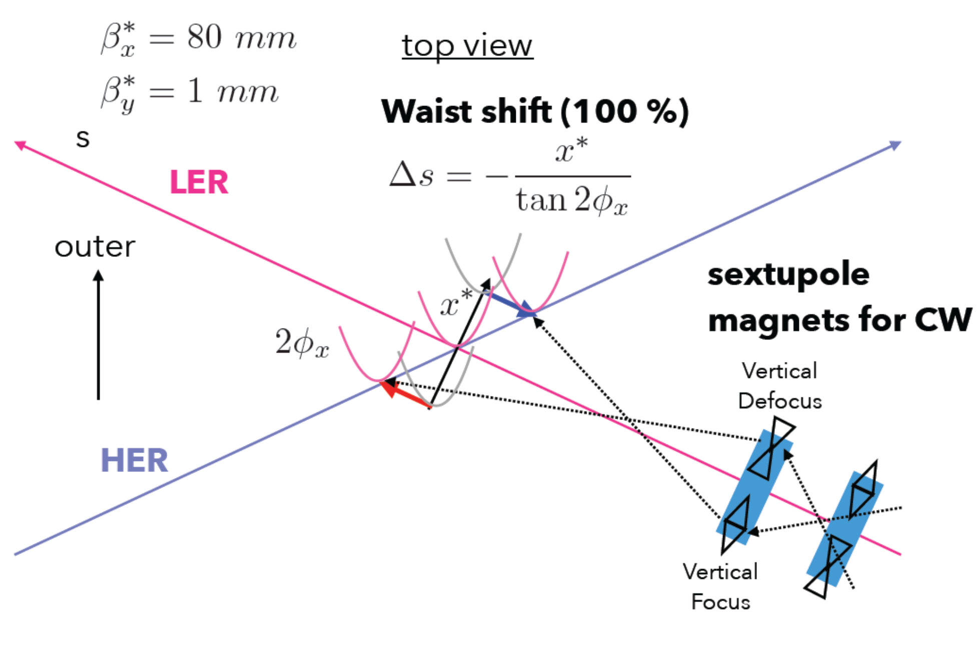
Crab waist scheme successfully applied

Not only the geometric luminosity loss but also the beam-beam resonances can be suppressed.

$$\mathcal{L}_{sp} = \frac{\mathcal{L}}{n_b I_{b+} I_{b-}} \propto \frac{1}{\sqrt{\sigma_{z+}^2 + \sigma_{z-}^2}\sqrt{\sigma_{y+}^{*2} + \sigma_{y-}^{*2}}}$$

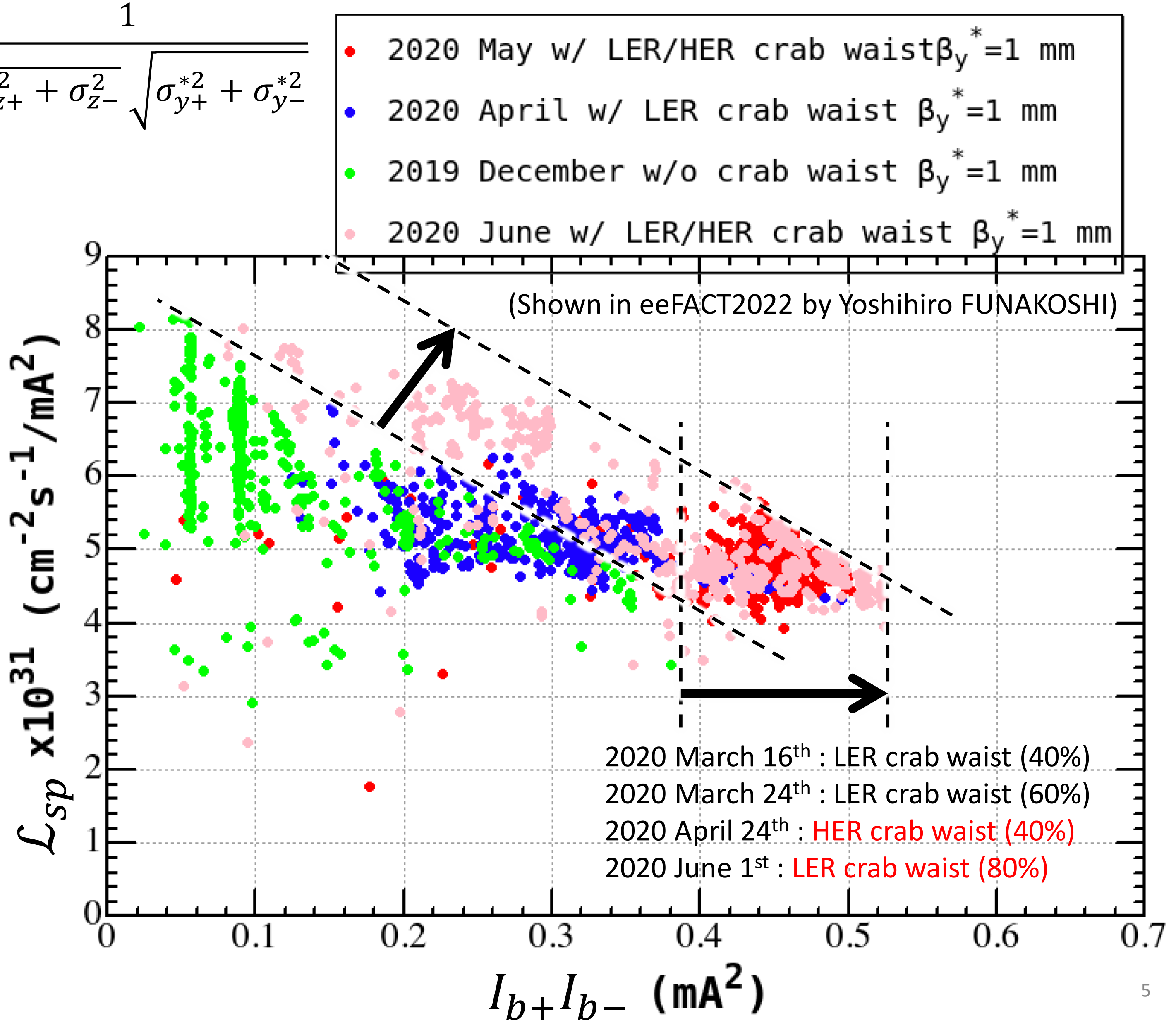
(Proposed by P. Raimondi)

Crab Waist Scheme (CW)



The LER waist (the minimum beam size) can be shifted proportional to the horizontal orbit offset at the IP and aligned on the HER beam line.

The 1st application to DAΦNE,
The 2nd application to SuperKEKB

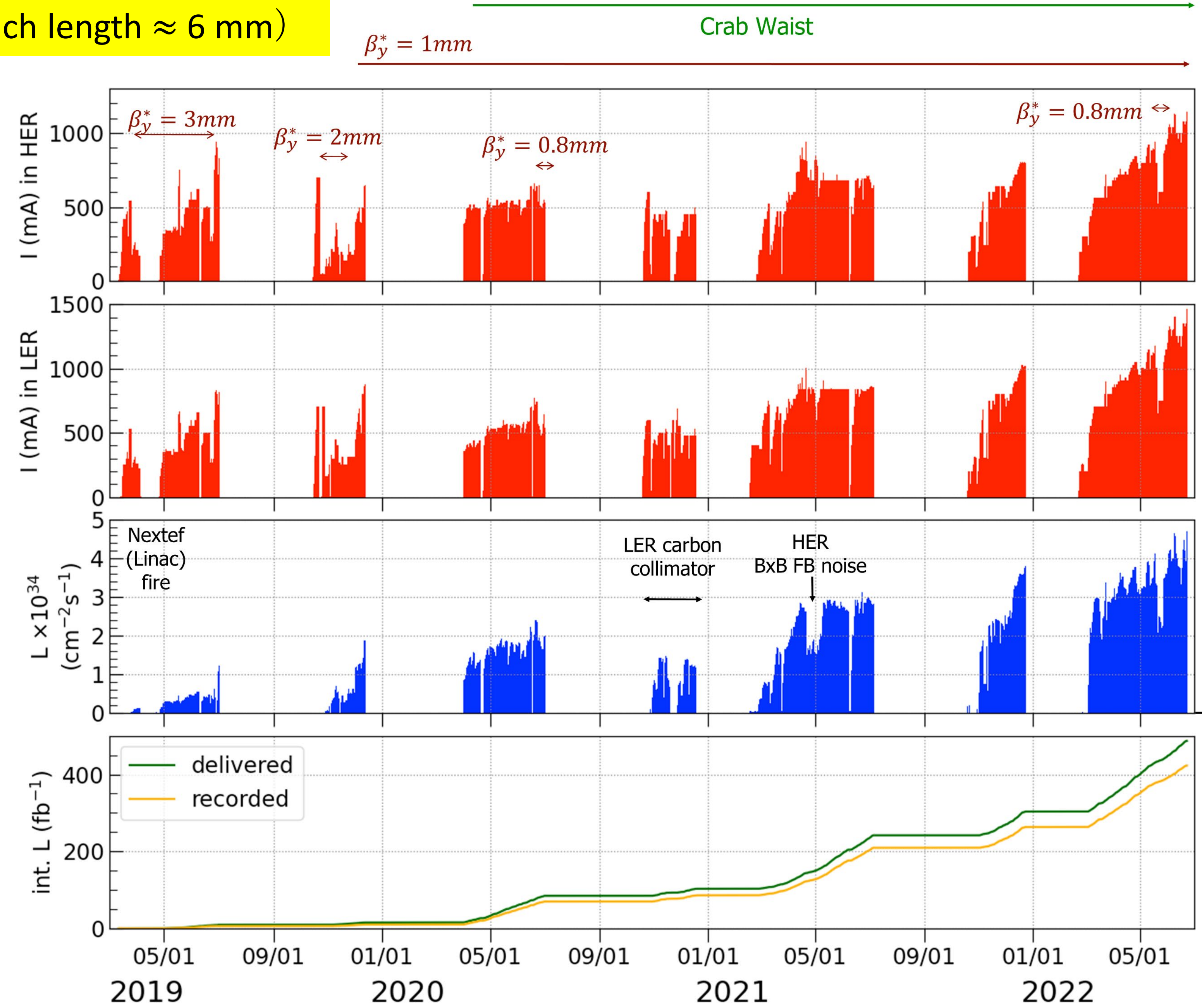


β_y^* **successfully squeezed**
< (Bunch length ≈ 6 mm)

Operation History in Phase 3

The smallest β_y^* and beam size in the world among the colliders

Difficult to enter $\beta_y^* < 1.0$ mm



1145 mA

Design of SuperKEKB: 2.6 A
Record in KEKB: 1.4 A

1460 mA

Design of SuperKEKB: 3.6 A
Record in KEKB: 2.0 A

4.65 x 10^{34} $cm^{-2}s^{-1}$
(4.71 x 10^{34} $cm^{-2}s^{-1}$)

Updating the world record!

1st Long shutdown (LS1)

424 fb^{-1} / 491 fb^{-1}

Machine Parameters at the Highest Luminosity Record

(...): final design parameter

	LER	HER	
Beam Energy	4.0 (4.0)	7.0 (7.0)	GeV
Circumference	3016 (3016)		m
Crossing angle	83 (83)		mrad
Crab waist ratio	80	40	%
Beam current @Maximum Luminosity	1.321 (3.6)	1.099 (2.6)	A
Number of bunches	2249 (2500 with one abort gap)		
Bunch current @Maximum Luminosity	0.5873 (1.44)	0.4887 (1.04)	mA
Total RF voltage V_c	9.12 (9.4)	14.2 (15.0)	MV
Synchrotron tune ν_s	-0.0233 (-0.0245)	-0.0258 (-0.0280)	
Bunch length σ_z	5.69 (6.0)	6.03 (5.0)	mm
Momentum compaction α_c	2.98E-4 (3.20E-4)	4.54E-4 (4.55E-4)	
Betatron tune ν_x / ν_y	44.524/46.592 (44.53/46.57)	45.532/43.575 (45.53/43.57)	
Beta function at IP β_x^* / β_y^*	80/1 (32/0.27)	60/1 (25/0.30)	mm
Measured vertical beam size (XRM) @IP σ_y^*	0.224 (0.048)	0.224 (0.062)	μm
Vertical beam-beam parameters ξ_y	0.0407 (0.0881)	0.0279 (0.0807)	
Beam lifetime	8	24	min.
Luminosity (Belle 2 CsI)	4.65 (60)		10^{34} cm^{-2} s^{-1}

← Touschek dominant

(Shown in eeFACT2022 by Yoshihiro FUNAKOSHI)

Overview for Luminosity Improvements

Powerful direction

Higher beam currents requires:

- Higher bunch currents (max. # of bunches, 2345, with two abort gaps already achieved)
- Suppressing the Transverse Mode Coupling Instability (TMCI)
  because of the narrow physical aperture of the vertical beam collimators
- Overcoming an obstacle of "Sudden Beam Losse"
- Better beam injection to compensate shorter stored-beam lifetimes
- etc.

Smart direction

Squeezing the beta function at the IP (β_y^*) requires:

- Better beam injection to compensate shorter stored-beam lifetimes
- More sophisticated tunings of collision, luminosity, collimators, etc.
- etc.

(IP: Interaction Point)

Basis

Better beam injection requires:

- Higher bunch charges and lower emittances in Linac
- Emittance preservation in $BT_{(Linac \rightarrow MR)}$
- More sophisticated beam-orbit and injection tunings
- Wider dynamic apertures in MR during collision
- etc.

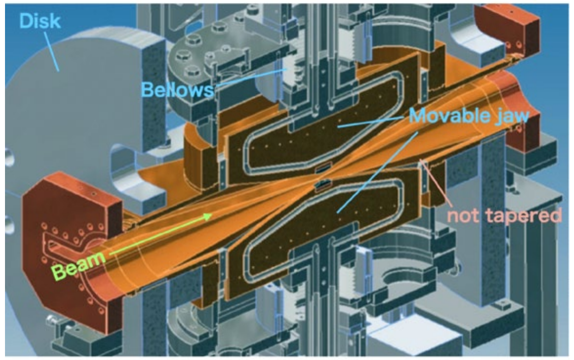
(BT: Beam Transport line)
(MR: Main Ring)

Transverse Mode Coupling Instability (TMCI)

= Strong head-tail instability

(first observed at DESY/PETRA, 1985)

Vertical movable collimator



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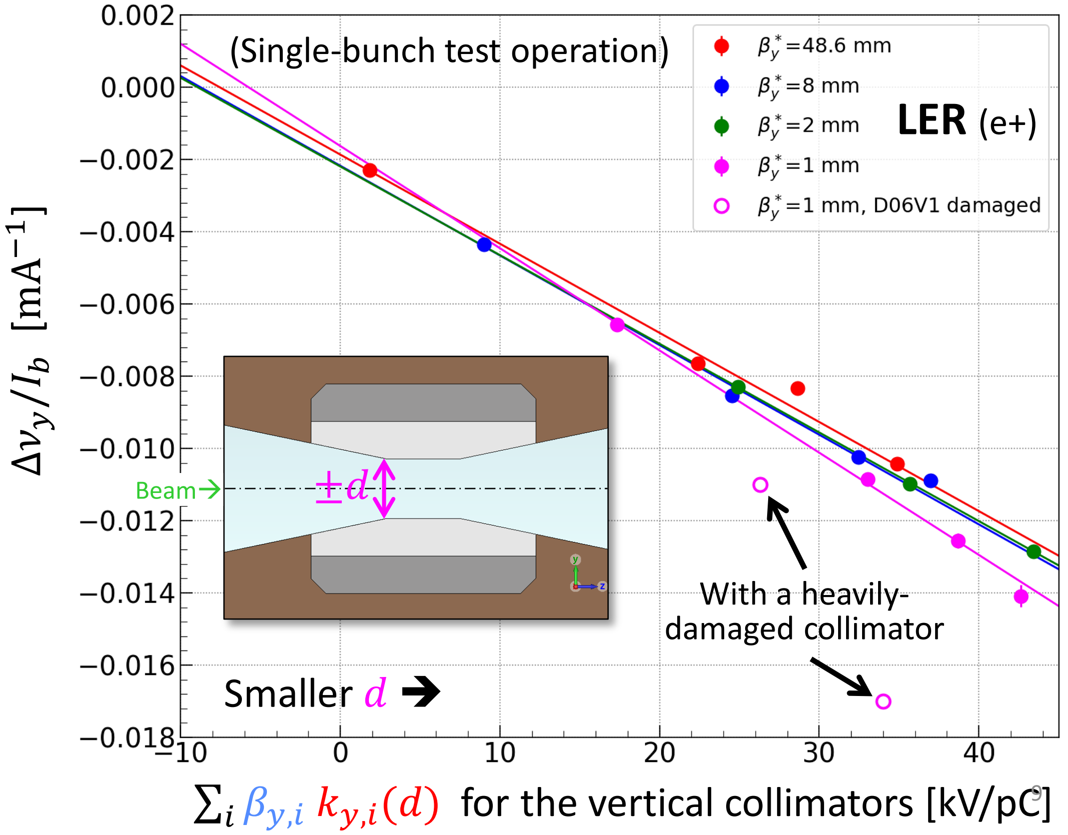
- **Sets a severe bunch current limit for the LER (e+) due to the narrow aperture (d ≈1 mm at min.) of the movable vertical beam collimators.**
  - (Bunch current threshold of TMCI) $= \dfrac{C_1\ f_s\ E/e}{\sum_i \beta_{y,i}\ k_{y,i}(\sigma_z, d)}$ $(C_1 \approx 8,\ f_s \approx 2\text{kHz},\ E/e = 4\ \text{GeV})$

    Vertical beta function↑ ↑Kick factor from the vertical impedance

- **Observation of the vertical impedance with a tune shift**
  - Vertical tune shift: $\dfrac{\Delta\nu_y}{I_b} = -\dfrac{T_0}{4\pi\ E/e}\sum_i \beta_{y,i}\ k_{y,i}(d)$
  - **The vertical collimators have ~70% of the total impedance.**
- Temporarily using carbon collimator heads with a high imp.,
  → TMCI was observed at SuperKEKB LER (e+).
- Roughly, $d \propto \beta_y^*$
- TMCI will limit the bunch currents in the near future.

(Shown in IPAC'23 by Yukiyoshi OHNISHI)



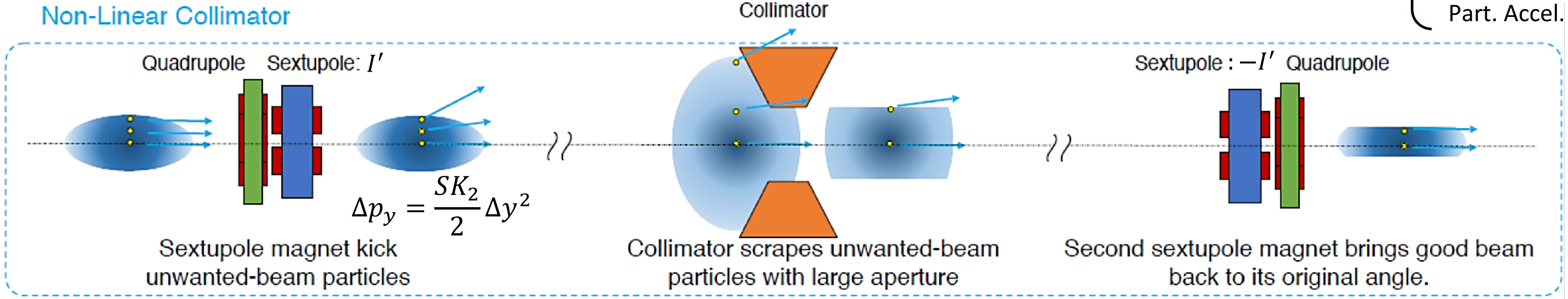
Introduction of a Non-Linear Collimator (NLC)

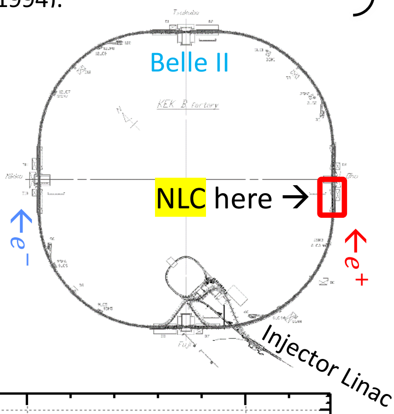
Installing a Non-Linear Collimator (NLC) during LS1

To make the collimator aperture wider, resulting in the lower transverse impedance

The first application to beam operation at SuperKEKB

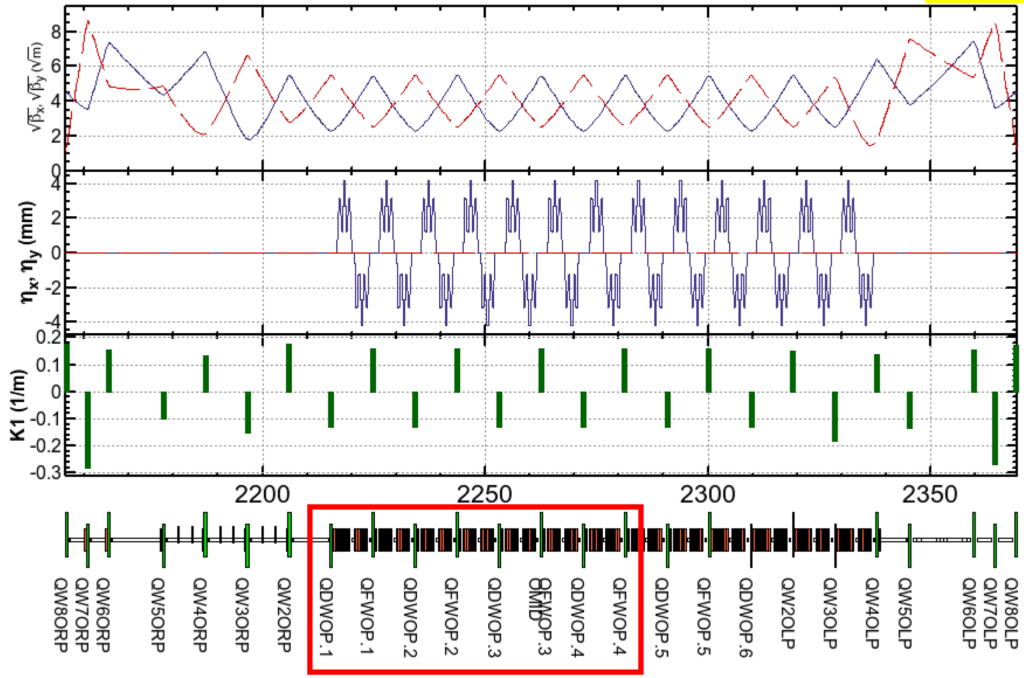
The first (?) proposal in
N. Merminga, J. Irwin, R. Helm, and R. Ruth, COLLIMATION SYSTEM FOR A TEV LINEAR COLLIDER, Part. Accel. 48, 85 (1994).

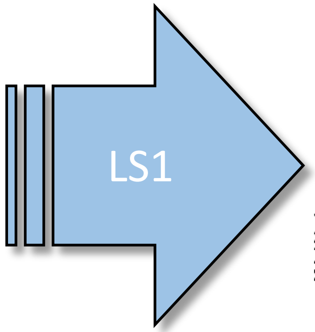




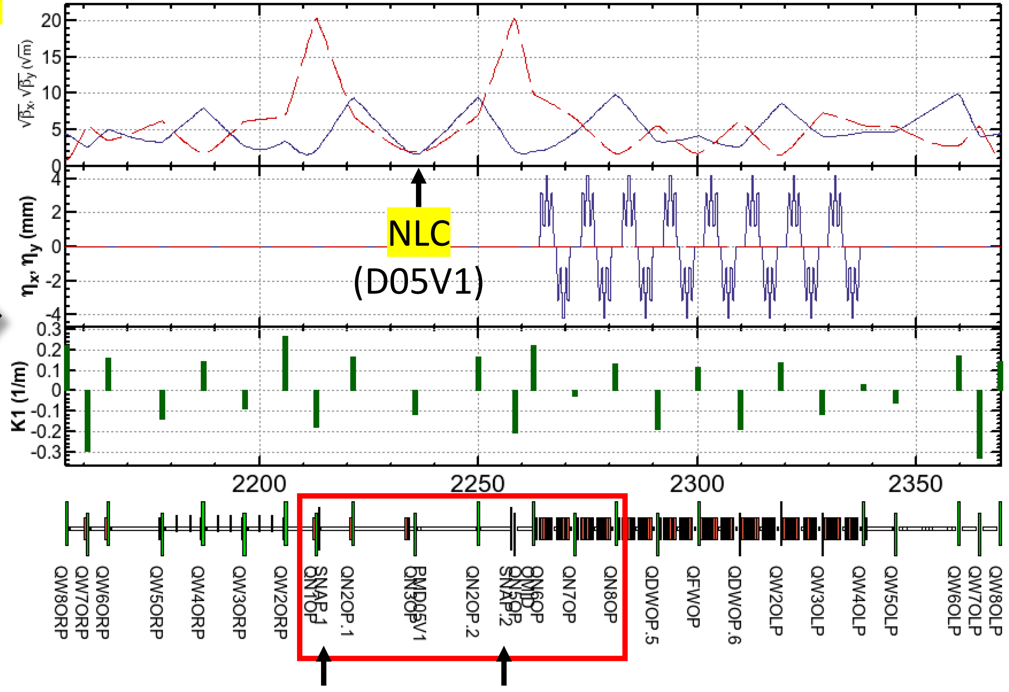
Wider aperture (➔Lower impedance)

Before LS1





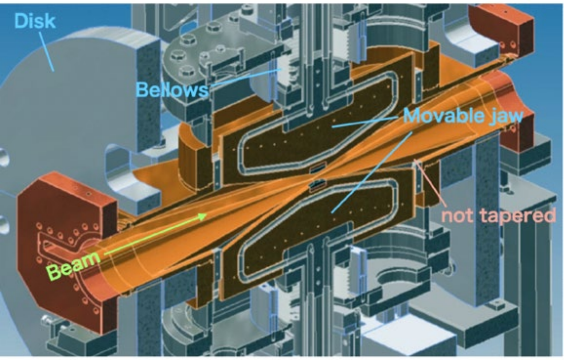
After LS1



Skew sextupole pair

The installation of the collimator for the NLC system almost completed

As of 2023-07-13 at SuperKEKB / OHO straight section



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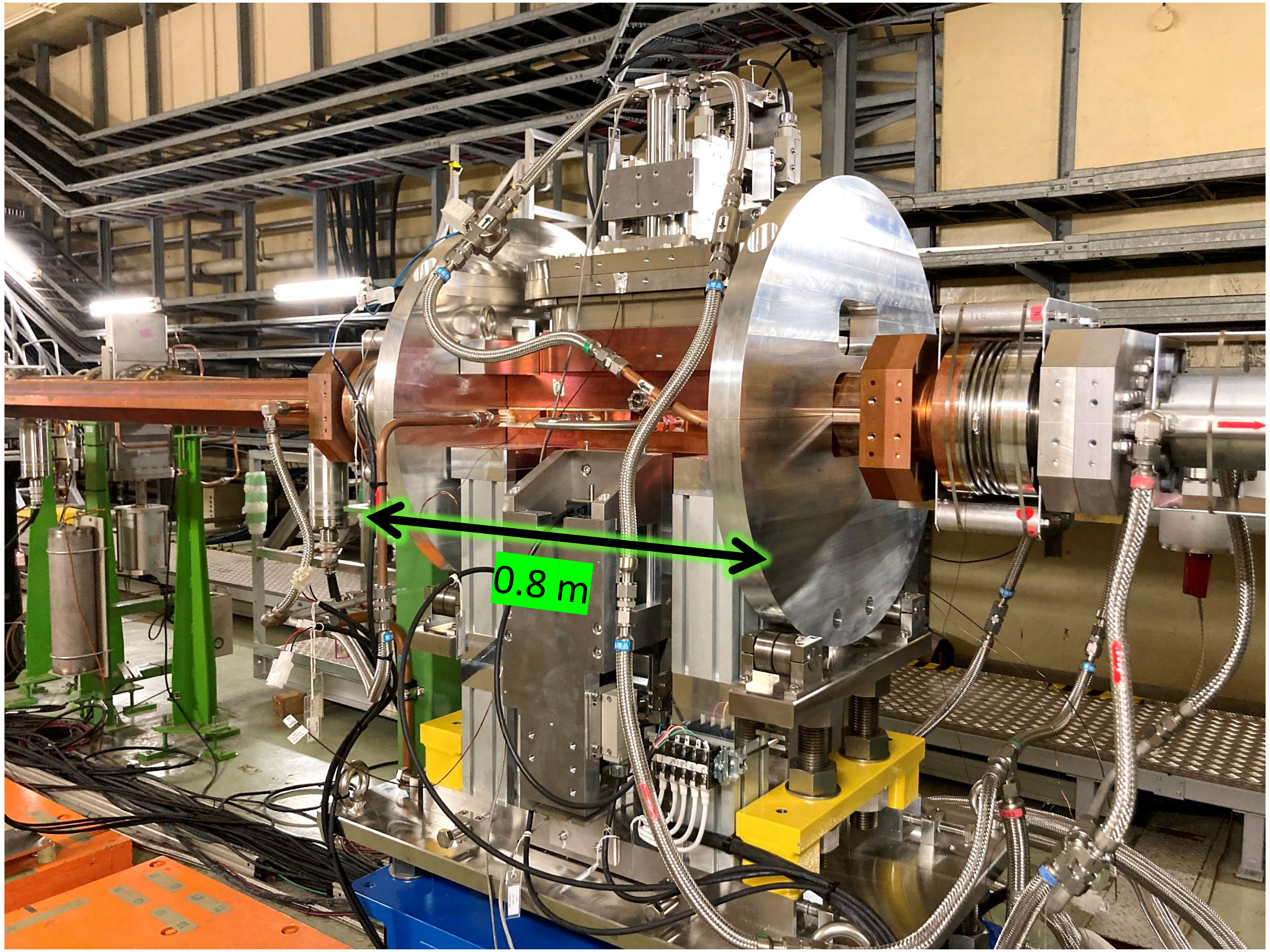
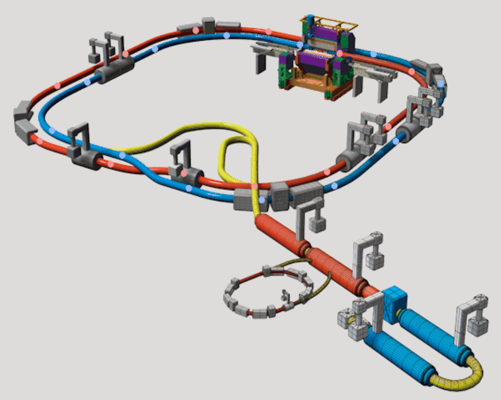
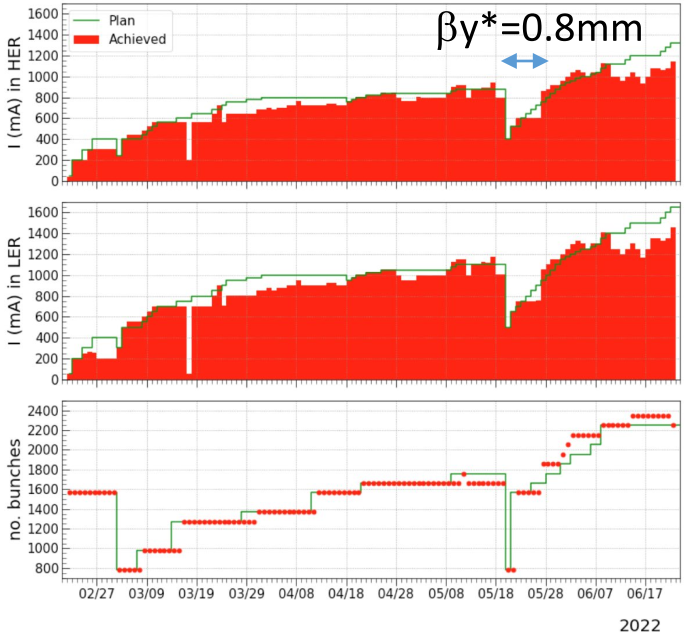


A pair of skew sextupole magnets and additional radiation shields will be installed after this summer.

Better beam injection



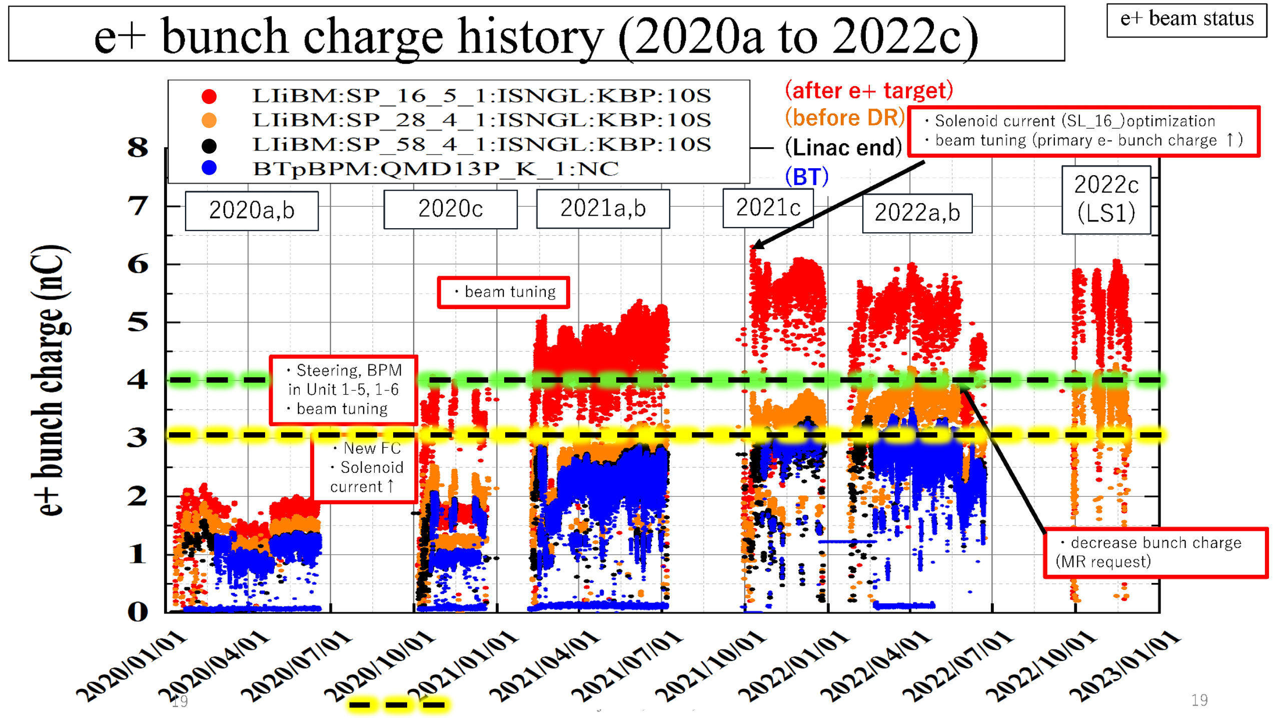
- SuperKEKB injection scheme
  - Injector Linac provides e- and e+ beams to MR.
  - Synchronization between Linac and MR ➔ 1-bunch or 2-bunch (per RF pulse) injection
  - Top-up injection achieved for e- and e+ beams at 50 Hz max.
- Particularly for $\beta_y^* < 1\ \mathrm{mm}$, the lifetime of the stored beams becomes too short, so that the beam injection rate (ΔI_{inj}) can not be made higher than the beam loss rate (ΔI_{loss}), $i.e.\ \Delta I_{inj} < \Delta I_{loss}$.
  - Depending on not only β_y^*, but also bunch currents, machine tuning, collimator setting, etc.
  - Typical values of the injection efficiencies with $\beta_y^* = 1\ \mathrm{mm}$: ~50% (LER), ~40% (HER)
- We tried squeezing β_y^* down to 0.8 mm twice, and in both cases, the injection limited the luminosity.

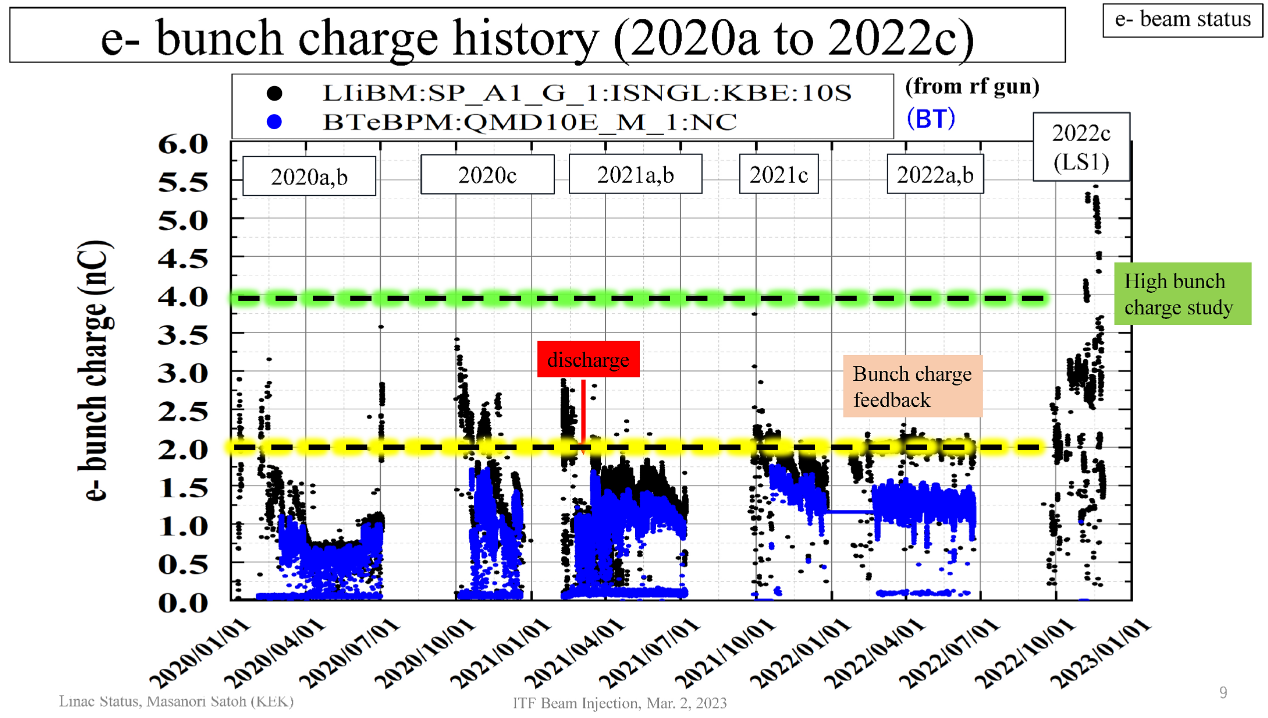


Better beam injection is needed to further squeeze β_y^* for higher luminosities

Bunch Charge Histories in Linac and Beam Transport line

(Plots made by Masanori SATOH)





(BT: Beam Transport line)

	e+	e-
Bunch charge for $1 \times 10^{35} \mathrm{cm}^{-2} \mathrm{s}^{-1}$	3	2
Design bunch charge	4	4

[nC/bunch]

✓ **We have achieved the bunch charges for the next luminosity milestone.**

✓ **We are approaching the design bunch charge.**

Measured Normalized Emittances in Linac and Beam Transport Line

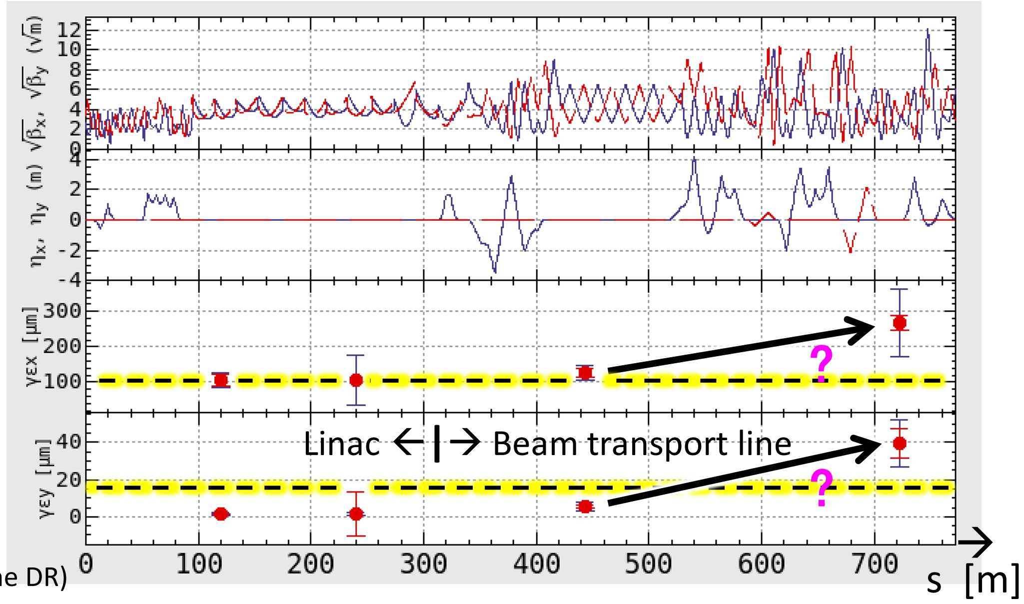
Error bars:
- Blue: RMS of multiple measurements
- Red: average of error of individual measurement

e^+

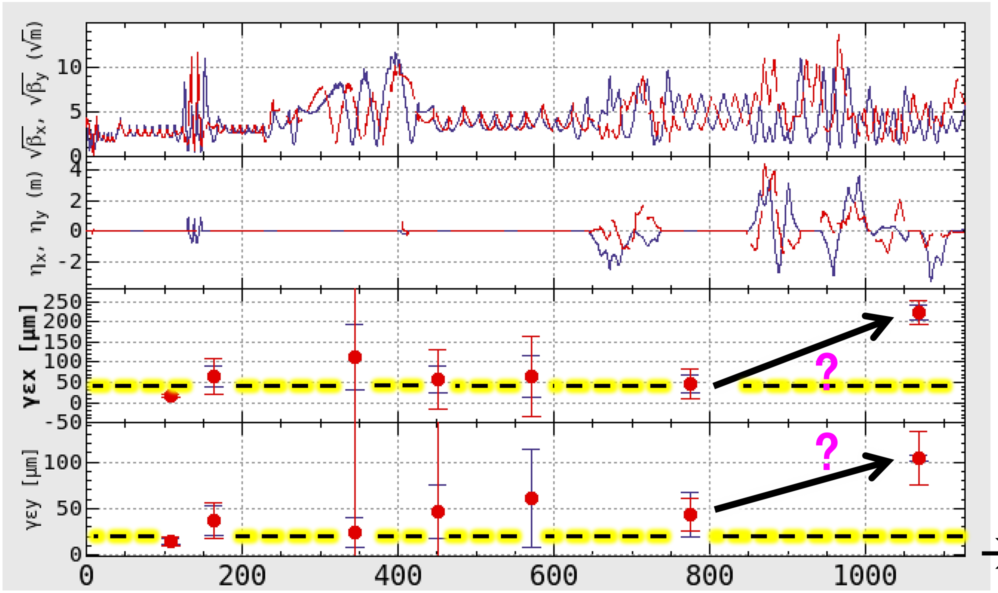
Horizontal →

Vertical →

(downstream the DR)



e^-



Linac ← | → Beam transport line

Target (design) values	e+	e-
Normalized emittance [μm] (Horizontal / Vertical)	100/15	40/20

(Plots made by Yoshihiro FUNAKOSHI)

- ✓ The design emittances of e+ and e- are mostly achieved in the Linac.
- ✓ **The emittances significantly grow at the end of the beam transport line.**
  - Beyond the acceptance of MR
  - Partially reproduced by the simulation of the Coherent/Incoherent Synchrotron Radiation (CSR/ISR)
  - Full understanding needed

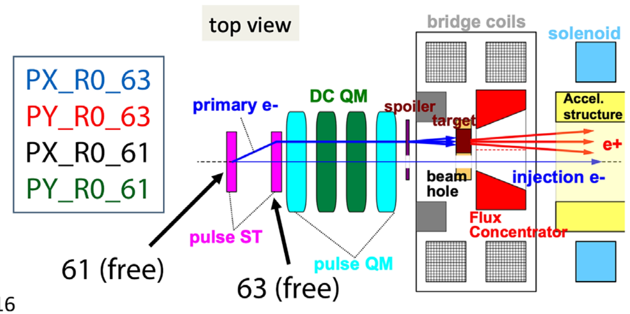
More sophisticated beam tuning

Example: Maximization of the e+ generation using a machine-learning technology based on Bayesian optimization for SuperKEKB

(Gaku MITSUKA)

Study II: 4 free parameters

- First, intendedly reduce the current of **PX/Y_R0_61** and **PX/Y_R0_63** by -1 A from the preset optimal values and accordingly reduce the e+ yields (4.8 nC → 0 nC)
  Then, try to recover the e+ yields by four parameters simultaneously tuning the current of **PX/Y_R0_61** and **PX/Y_R0_63**
- The charge of the BPM **SP_16_5_1** downstream of the e+ conversion obtains e+ yield.
- Search the optimal pulse steering currents at a relatively tiny range [-3 A, 1 A], although the soft limit is wider [-20 A, 20 A]
- We did the machine study on 20 Dec. 2022, 15:30-.



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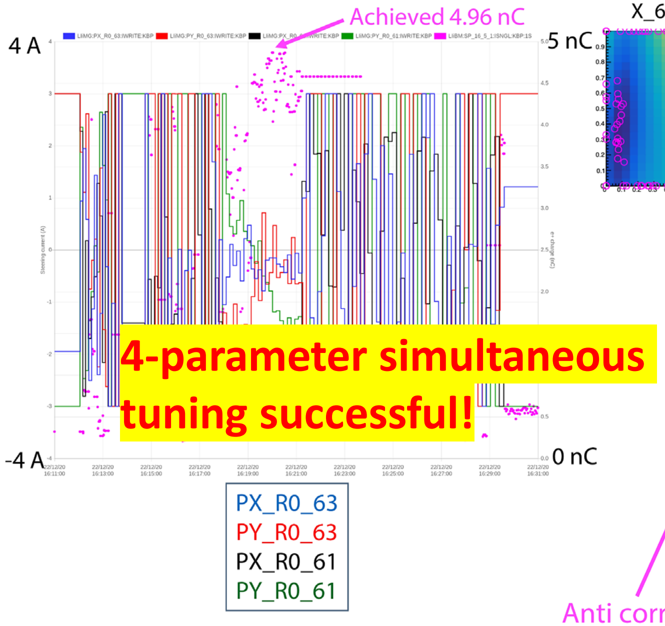
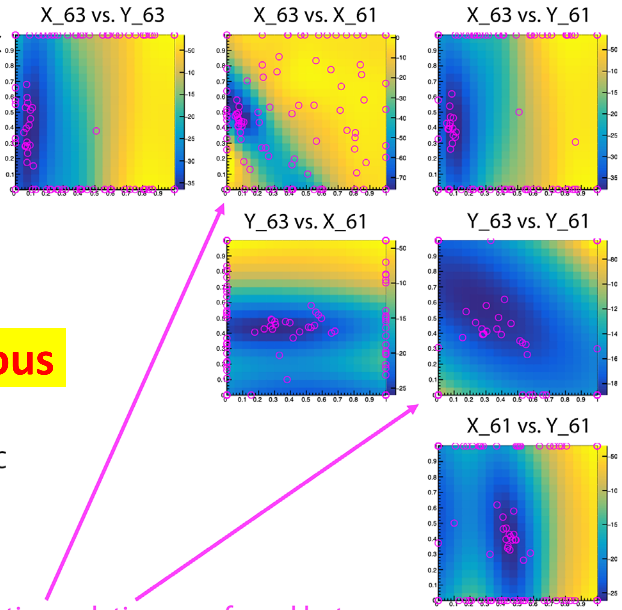
~10 mins to reach the max.
(~30—60 mins by human experts)

Annealed lower confidence bound





("A statistical method for global optimization", Cox and John, 1992)

Anti correlations are found between X and Y of two steering magnets.

- "cLCBa" represents an annealed version of the exploration/exploitation trade off.
- Data points spread across the bound area compared with LCB.

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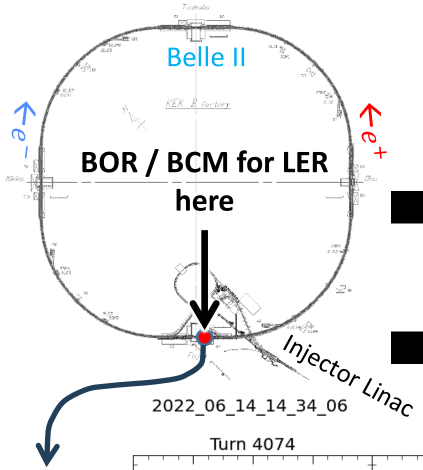
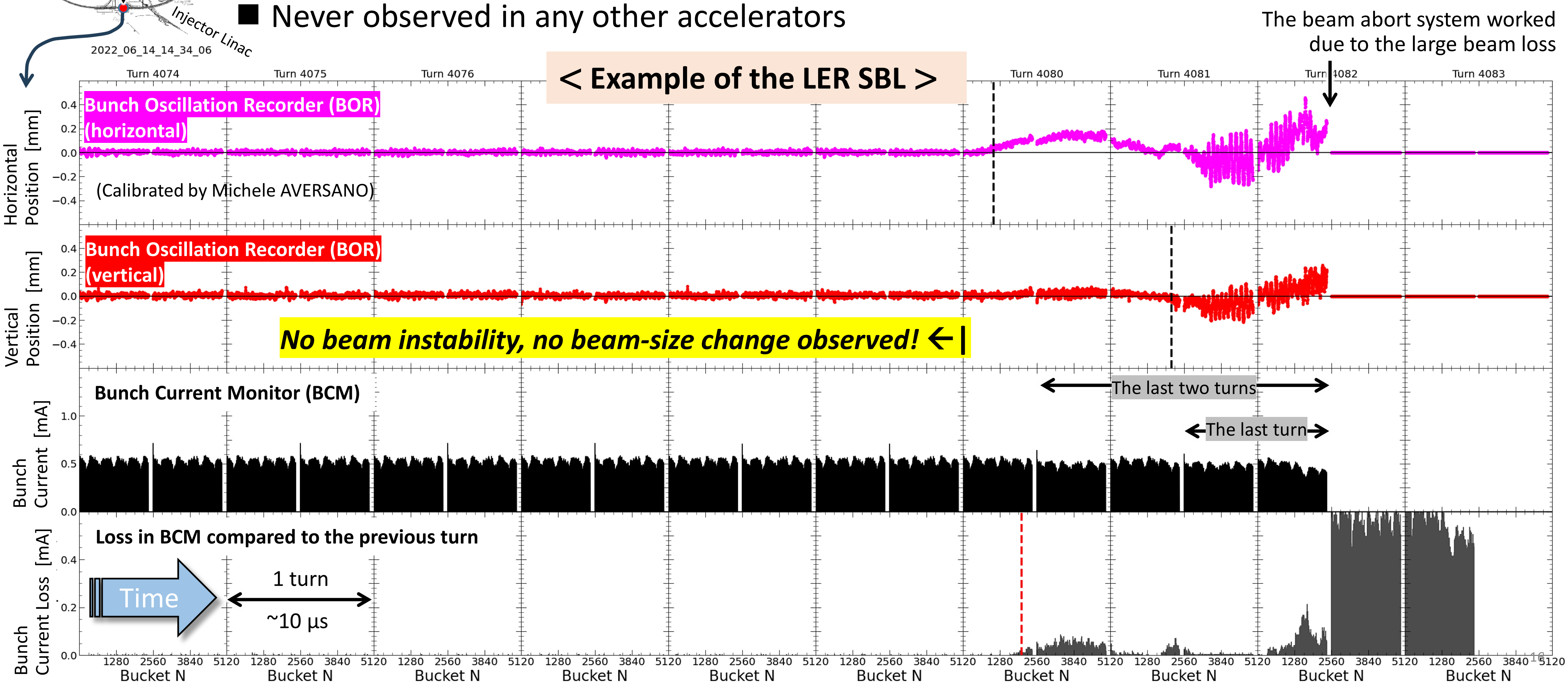
To be applied to tunings of
- Beam injection (~6 parameters)
- Collision and luminosity (~10 parameters)

What’s Sudden Beam Loss (SBL)?



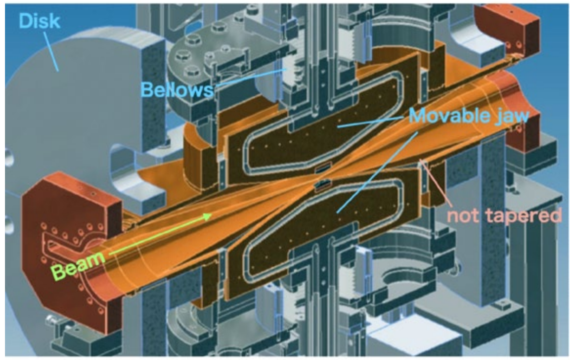
- Large beam losses suddenly occurred within a few turns (20—30 μs) without any precursor.
  - ➔ Serious damages on collimators, final focus superconducting magnets (→ quench), Belle II
- Never observed in any other accelerators

< Example of the LER SBL >



Example of serious damages due to SBL

Vertical collimator for LER just upstream the IP (D02V1)



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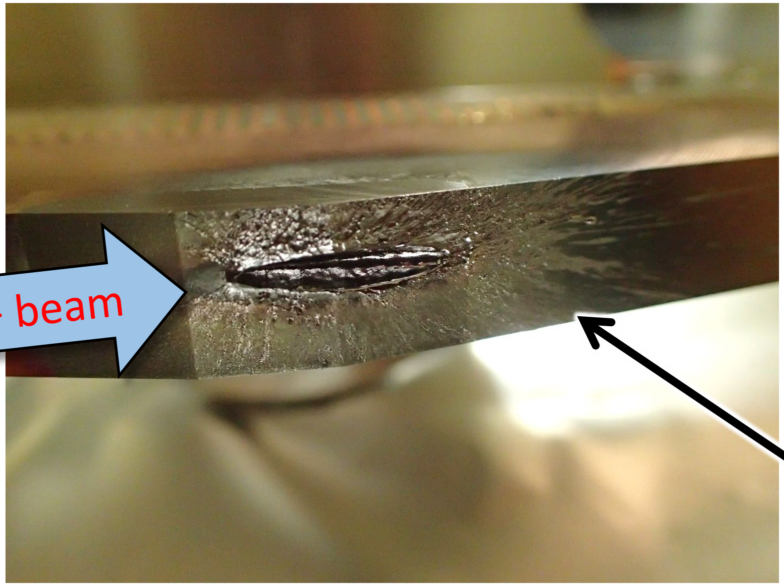
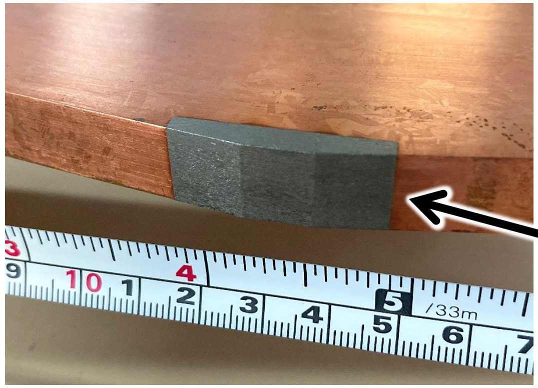
TOP side

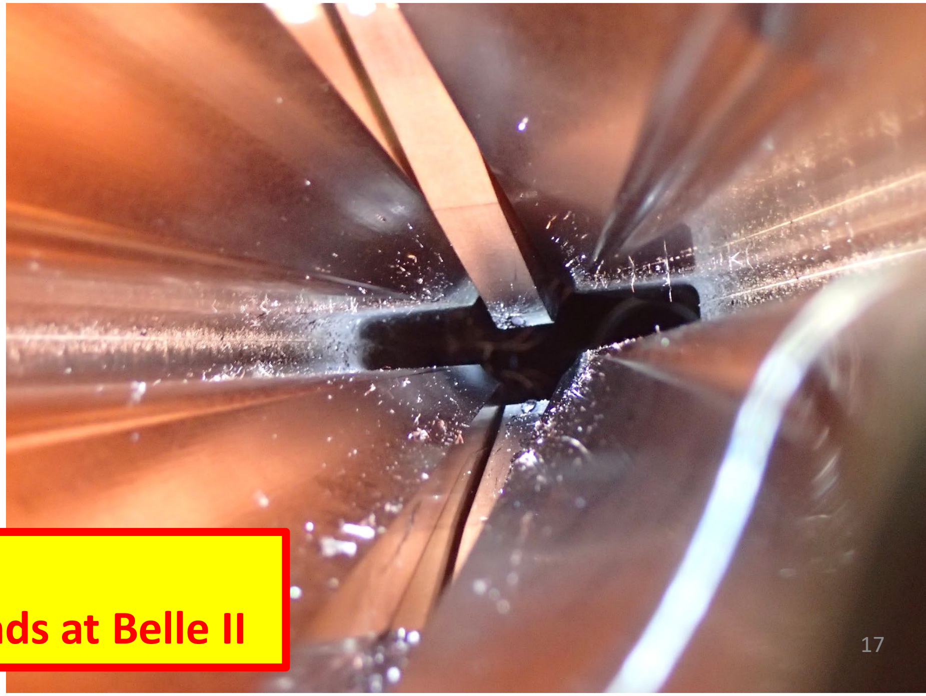




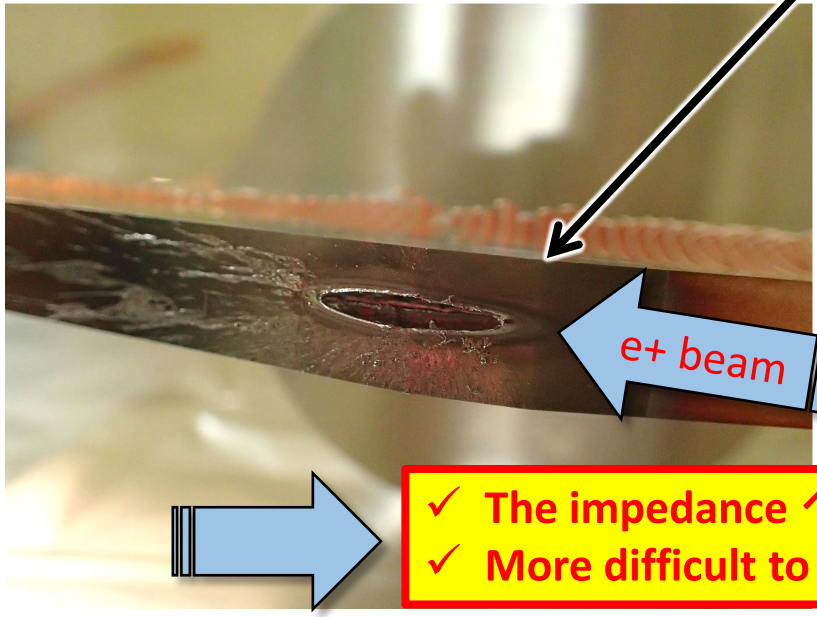
Cf. An undamaged head (W)

Damaged heads (Ta)

A lot of rubble of the Ta heads strewn



BOTTOM side



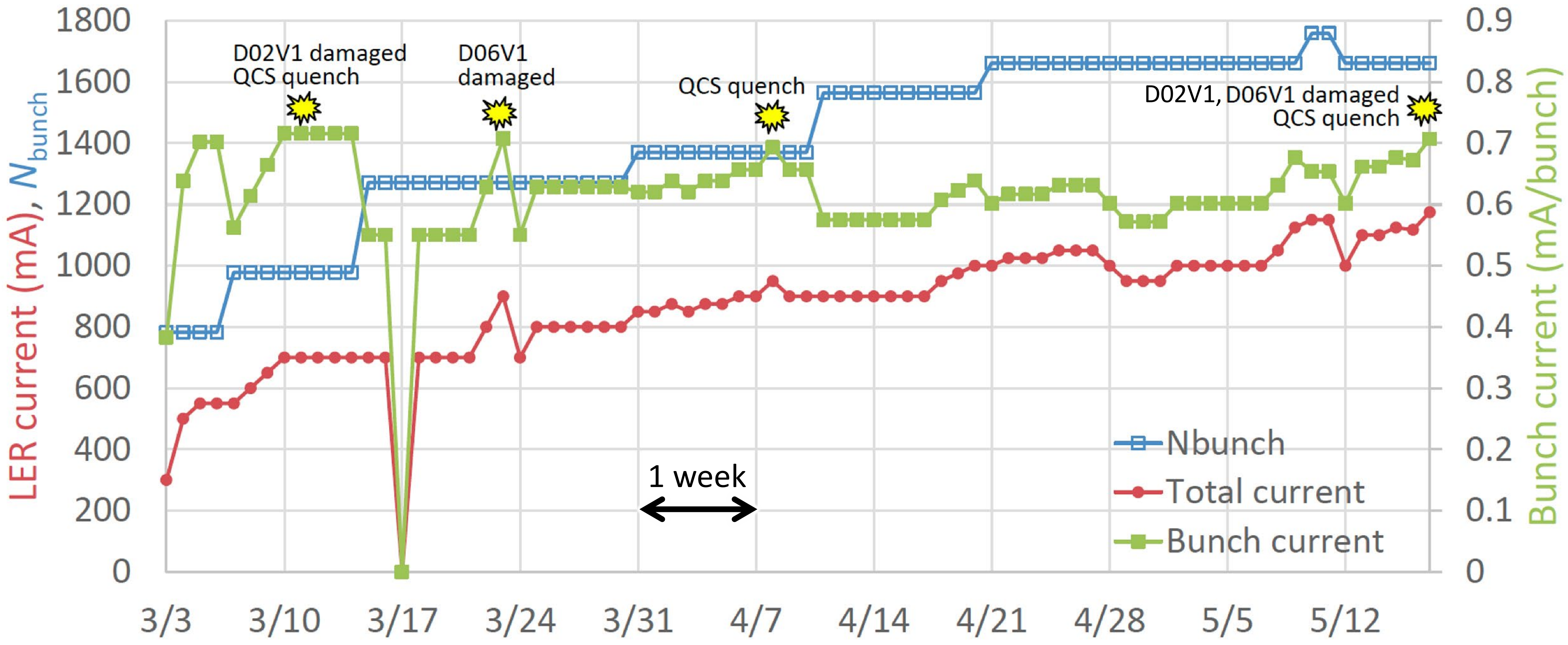
(Photos courtesy of Shinji TERUI)

- ✓ **The impedance ↑**
- ✓ **More difficult to suppress beam backgrounds at Belle II**

SBL occurrence seems to have a (quasi)-threshold in the bunch current: ~0.7 mA/bunch.

- D02V1, D06V1: vertical collimators for LER
- QCS: Super-conducting quadruple magnet system for the final focus at the IP

(Plots made by Kodai MATSUOKA)



It was difficult to increase the bunch current beyond ~0.7 mA/bunch.

Investigation of the cause of SBL

- **Machine performance failure?**
  - All of the relevant components are carefully monitored, and no suspicious one found

- **Vacuum arc at RF contacts in vacuum components?**
  - In this case
    - Any beam-phase change (= energy loss) should be observed in ~ms time scale.
  - SBL occurred in ~10μs time scale, and no beam-phase change observed

- **Dust-beam interaction?**
  - In this case,
    - Vacuum pressure bursts and ~ms-time-scale beam loss should be observed.
  - SBL occurred in ~10μs time scale mostly with no pressure burst

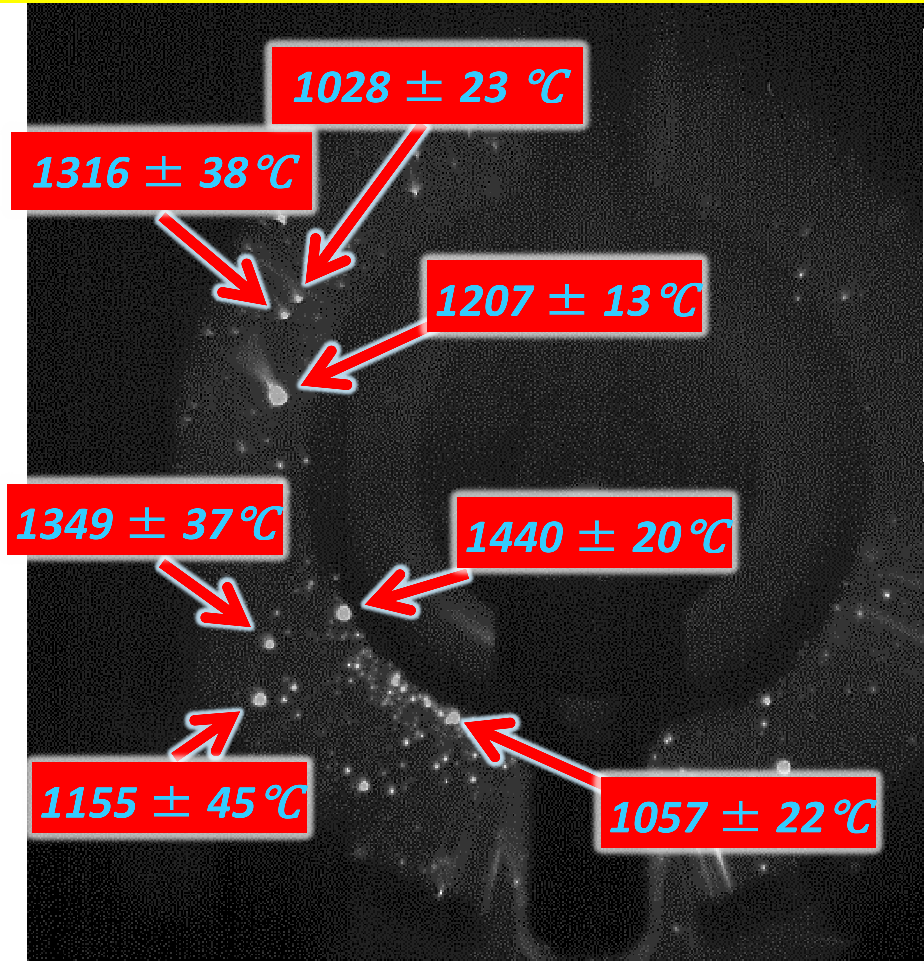
- **Electron cloud?**
  - In this case, SBL should occur only in LER (e+), but SBL also occurred in HER (e-).
  - Relevant simulation studies are on-going, and no clear relationship with SBL found so far

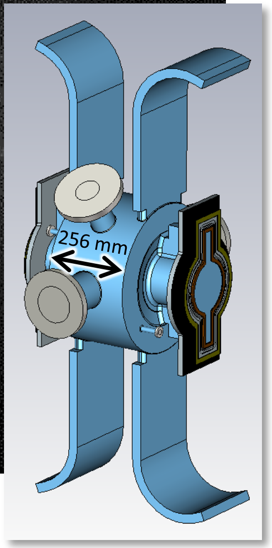
- **“Fireball”?**

“Fireball”-triggered vacuum breakdown observed in normal-conducting UHF RF cavities

End plate of the RF cavity during high-power operation

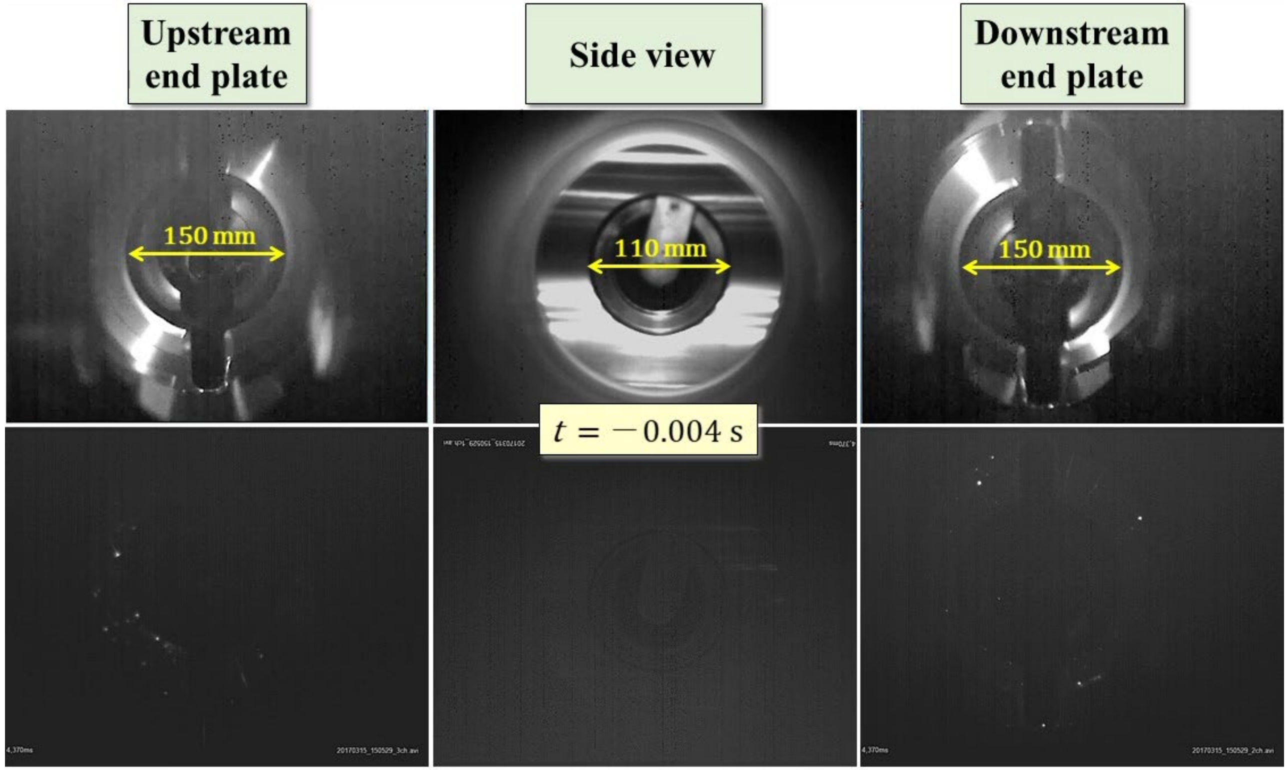
High-temperature (> 1,000℃) micro-particles (< 0.1 mm)





509 MHz RF cavity

A fireball caused cavity breakdown.

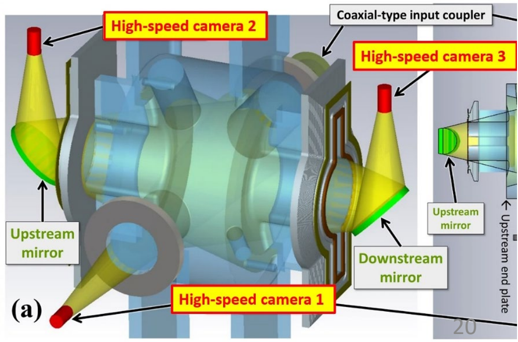


509 MHz cavity with a cavity gap voltage: 0.88 MV (= accelerating gradient: 3.4 MV/m)

Recorded by Tetsuo ABE (KEK)

For more details, please take a look at:

- **KEK Accl. Lab. Topics (Web article)**
  T. Abe, “*Minuscule Gremlins Cause Vacuum Breakdown in Radio-Frequency Accelerating Cavities*”
  https://www2.kek.jp/accl/eng/topics/topics190122.html
- **Original paper**
  T. Abe, *et al.*, "*Direct Observation of Breakdown Trigger Seeds in a Normal-Conducting RF Accelerating Cavity*", Physical Review Accelerators and Beams **21**, 122002, 2018.



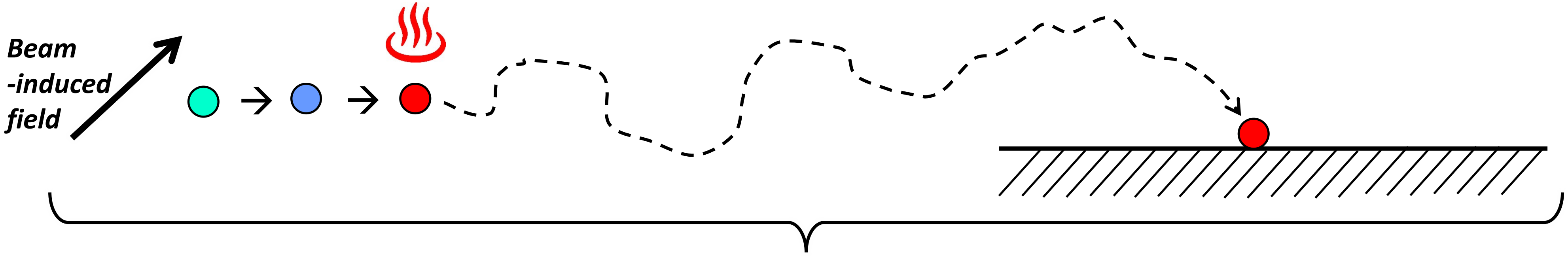
“Fireball” can be a cause of SBL?

“Fireball hypothesis”

① A micro-particle with a high sublimation point is heated by the beam-induced field.

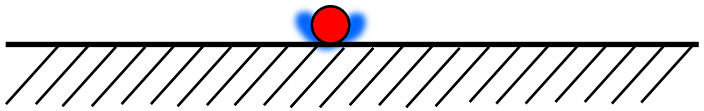
➔ **Fireball**

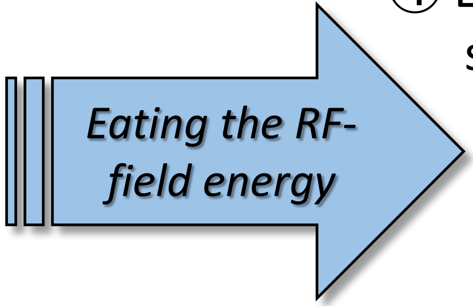
② The fireball touches some metal surface with a low sublimation point (e.g. copper).



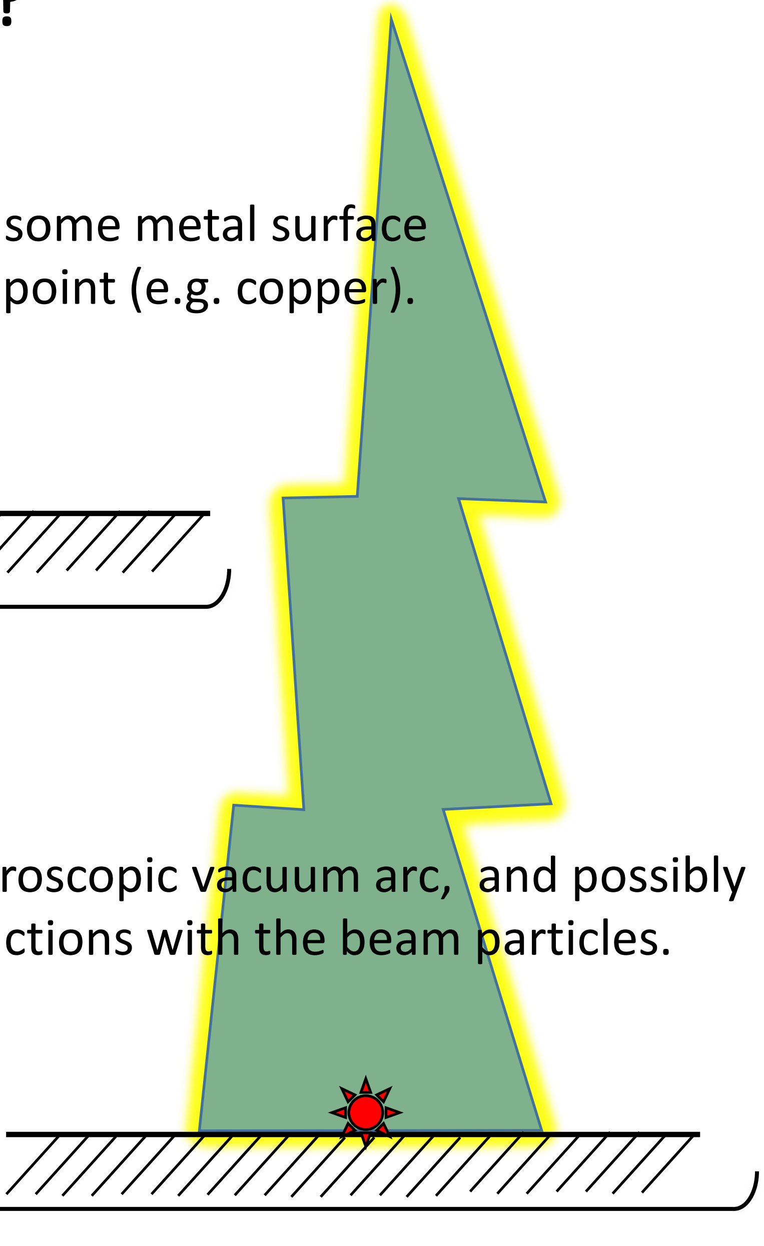
Order of ~ms or longer

③ Plasma is generated around the fireball with high RF fields applied.





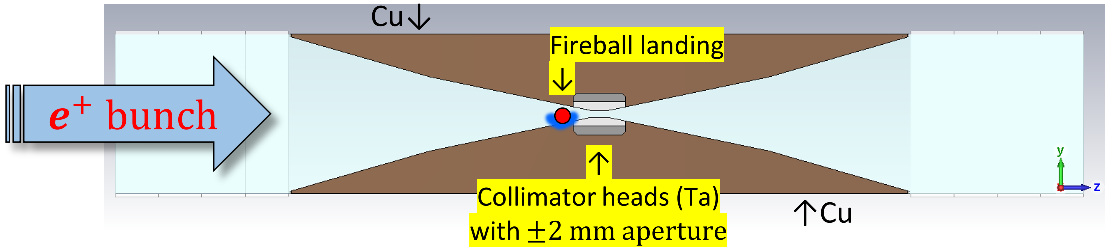
④ Leading to a macroscopic vacuum arc, and possibly significant interactions with the beam particles.



Order of ~µs or shorter

Relevant simulations and experiments on-going!

Using **CST PIC** solver



(Short range)

$t = 0 - 50$ ns

All particles displayed

Only Cu^+ displayed

Simulating how the beam particles are kicked

+ Positive charge

− Negative charge

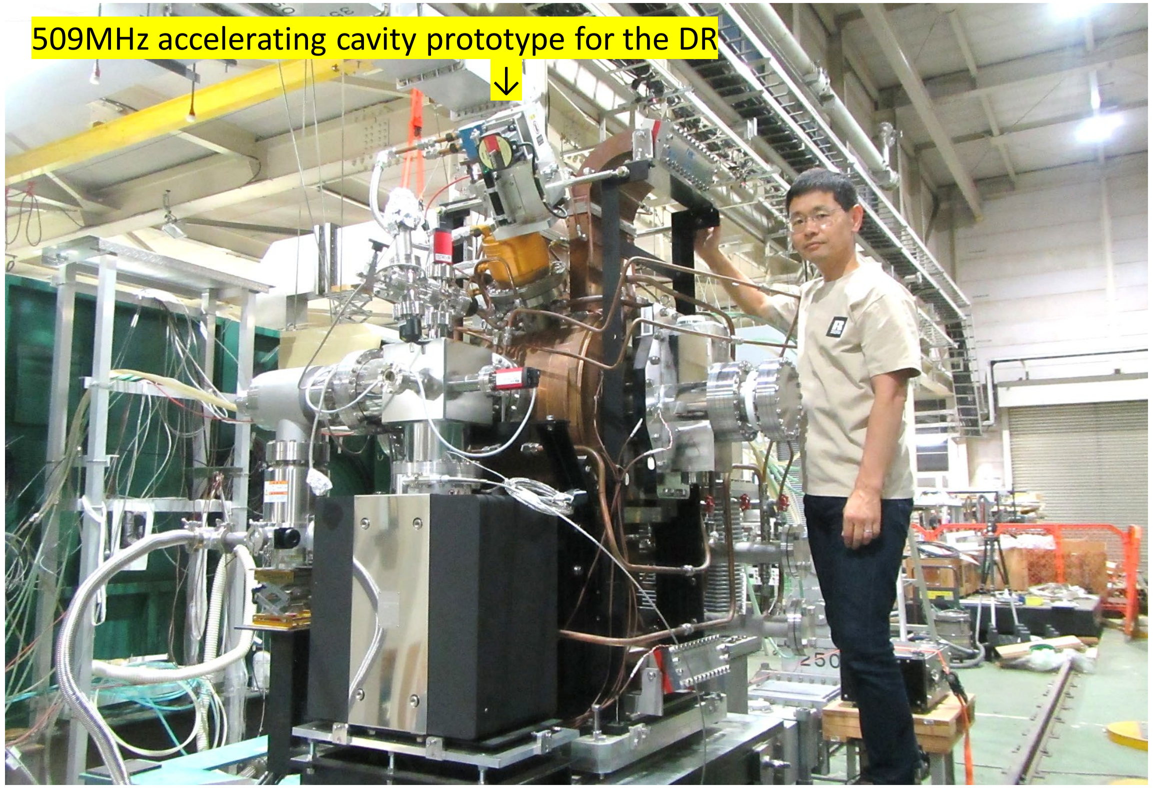
(Long range)

$t = 0 - 10$ μs

All particles displayed

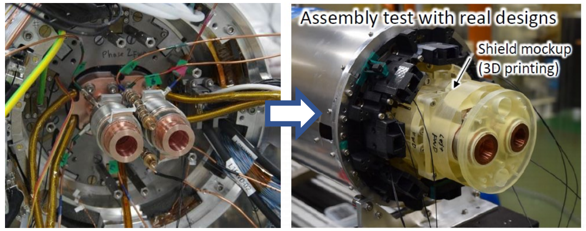
Only Cu^+ displayed

High-power RF-cavity test stand (MR-D1-AT)



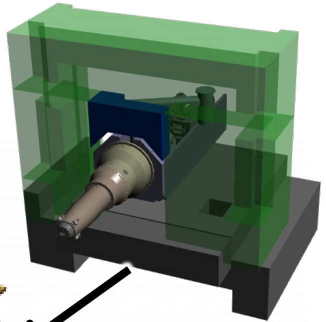
To measure fundamental parameters in the fireball hypothesis

Modifications and improvements during LS1

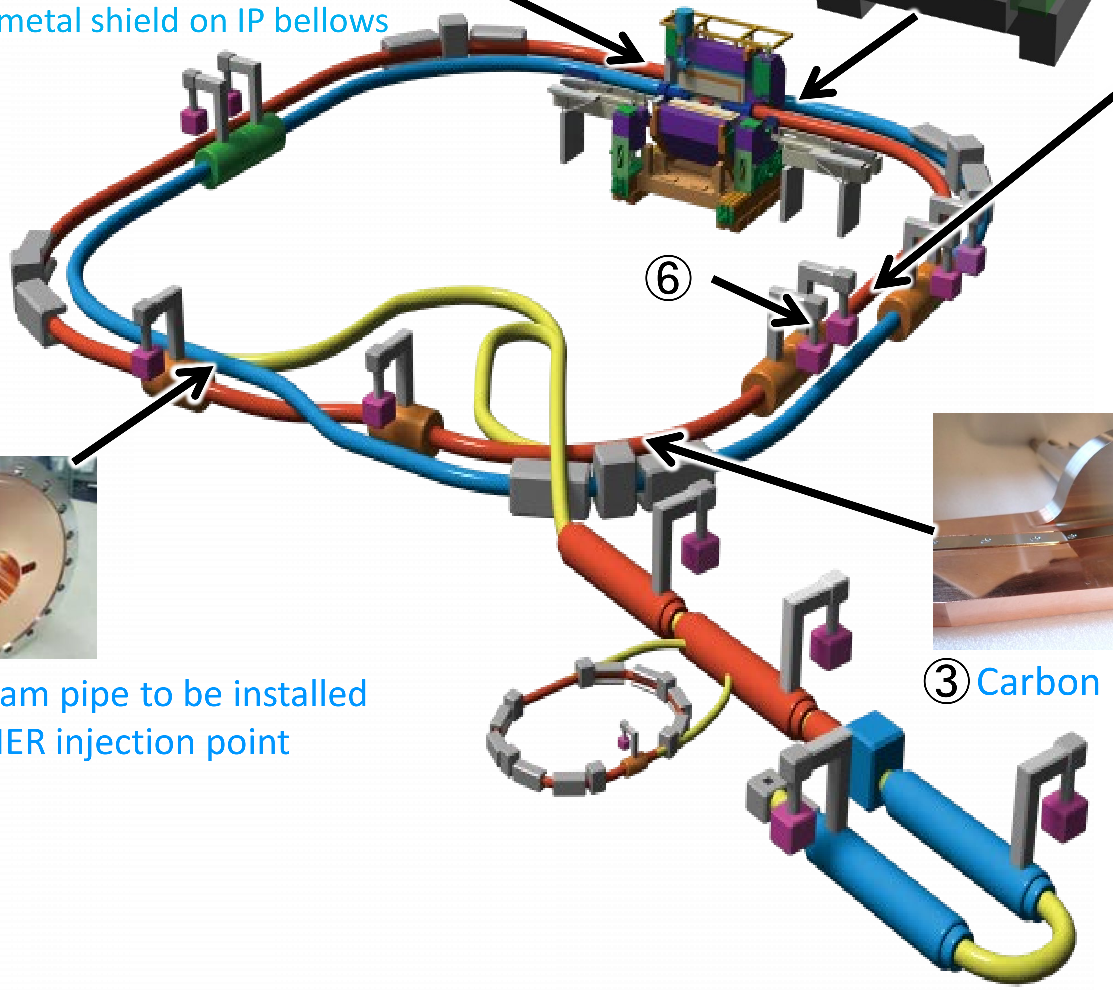


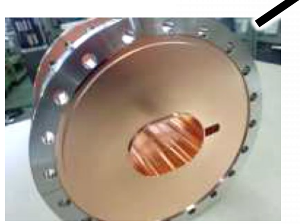
New heavy metal shield on IP bellows

← ② →

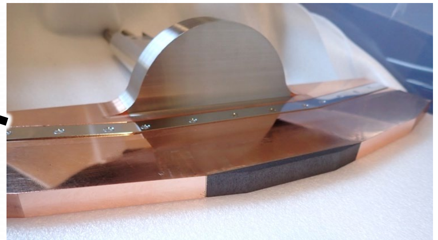


New Concrete Shields for IR





⑤ New beam pipe to be installed at the HER injection point



③ Carbon collimator head

① Nonlinear vertical collimator (LER)
- Reduction of impedance and backgrounds

② IR radiation shield improvements
- Reduction of backgrounds

③ Robust horizontal collimator head (LER)
- Replace by carbon heads for the horizontal collimator against mis firing of the injection kicker

④ Copper-coated vertical collimator head
- Reduction of impedance
- Possible countermeasure for "fireball"

⑤ New beam pipe at the HER injection point with a wider aperture and more precise BPMs

⑥ RF cavity replacement for LER
- Stable operation and larger beam current

⑦ etc.

⑥ RF cavity replacement

Summary

- **SuperKEKB has achieved and been updating world records in the luminosity and vertical emittance / beam size among the colliders.**
  - Luminosity record: $4.65 \times 10^{34} \mathrm{cm}^{-2} \mathrm{s}^{-1}$
  - Integrated so far: $424\ \mathrm{fb}^{-1}$ (at SuperKEKB)
- **The progress in the luminosity improvement is very slow, despite the expectations, due to the various obstacles; especially serious are:**
  - Sudden Beam Loss in MR
    - The biggest obstacle in increasing the beam (bunch) currents
    - The fireball hypothesis being studied theoretically and experimentally
  - Poor injection efficiency
    - Without solving this problem, difficult to squeeze β_y^* or increasing the beam (bunch) currents
    - Emittance blowup at the end of the beam transport line (BT) to be fully understood and suppressed
      - Most likely cause is CSR and ISR, but only partially reproduced by the current simulation
        - More advanced models to be implemented in the simulation.
      - Other possibilities being investigated
    - Wider MR dynamic apertures during collision needed
- **There are many other problems and challenges:**
  - **Linac**: 2nd bunch orbit stabilization, influence of the ambient temperature change on RF phase, etc.
  - **Injection**: auto tuning, better optics matching between BT and MR, new BT line, etc.
  - **MR**: auto luminosity / collimator tunings, tot. beam current dependent optics deformation, better beam-beam performance, etc.
- **During LS1, many modifications and improvements have been done.**

Future Prospects

■ The performance target after LS1

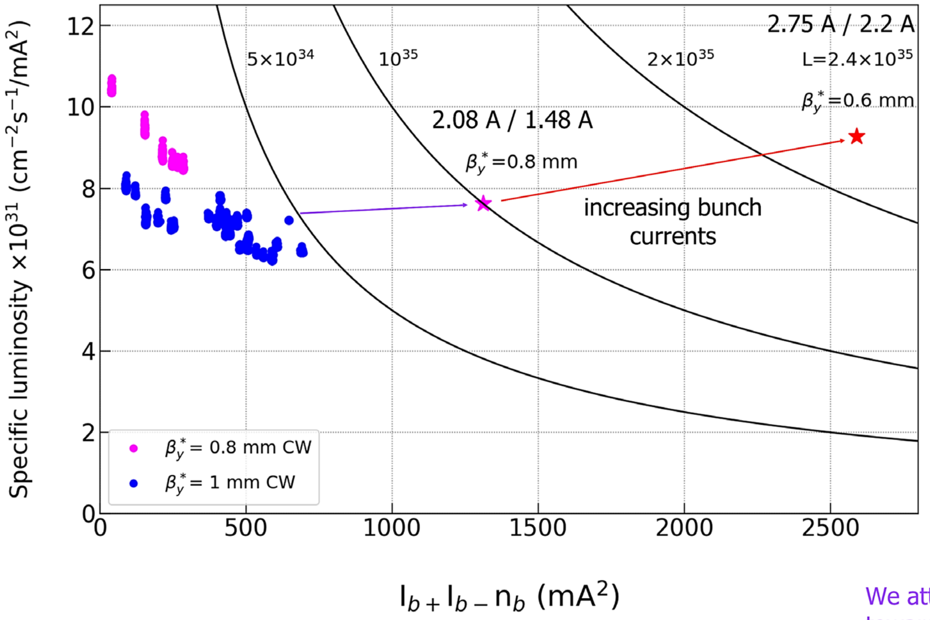
- Luminosity: $(1.0, 2.4) \times 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- To be integrated for 10 years: $15\ \mathrm{ab}^{-1}$
- Depending on how the obstacles will be overcome

Table 2: Machine Parameters in the Two-stage Improvement

Parameters	LER	HER	LER	HER
I (A)	2.08	1.48	2.75	2.20
n_b	2345		2345	
I_b (mA)	0.89	0.63	1.17	0.938
β_y^* (mm)	0.8		0.6	
ξ_y	0.0444	0.0356	0.0604	0.0431
ε_y (pm)	30		21	
Σ_y^* (μm)	0.218		0.160	
σ_z (mm)	6.49	6.35	7.23	7.05
L ($\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	10^{35}		2.4×10^{35}	

The first milestone after LS1 is $10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$.

(Shown in IPAC'23 by Yukiyoshi OHNISHI)



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

Unit of luminosity:

$10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ = 1 KEKB

$10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ = 1 SuperKEKB

We attempt to improve luminosity toward a new luminosity unit.

■ Discussion just started for further luminosity improvements beyond the above target

- LS2 needed with 3 possible scenarios:
  1. Moderate scale modification sometime after 2028 (> 1 year shutdown)
     - With the machine-detector interface (MDI) unchanged
  2. Larger scale modification, in addition to 1
     - With options of anti-solenoid re-configuration and MDI modification
  3. Much larger scale modification in 203X
- Final target luminosity : $6 \times 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- To be integrated by the final end : $50\ \mathrm{ab}^{-1}$
- Depending on results and achievements after LS1

Our efforts will continue!

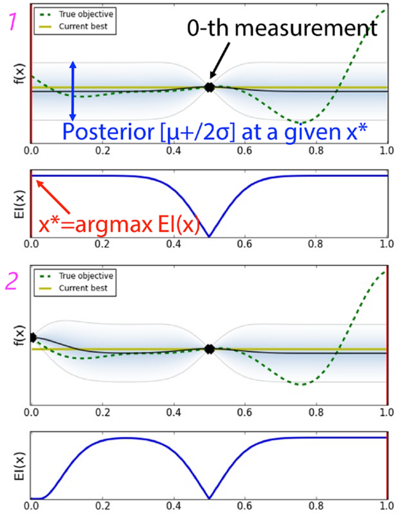
Backup Slides

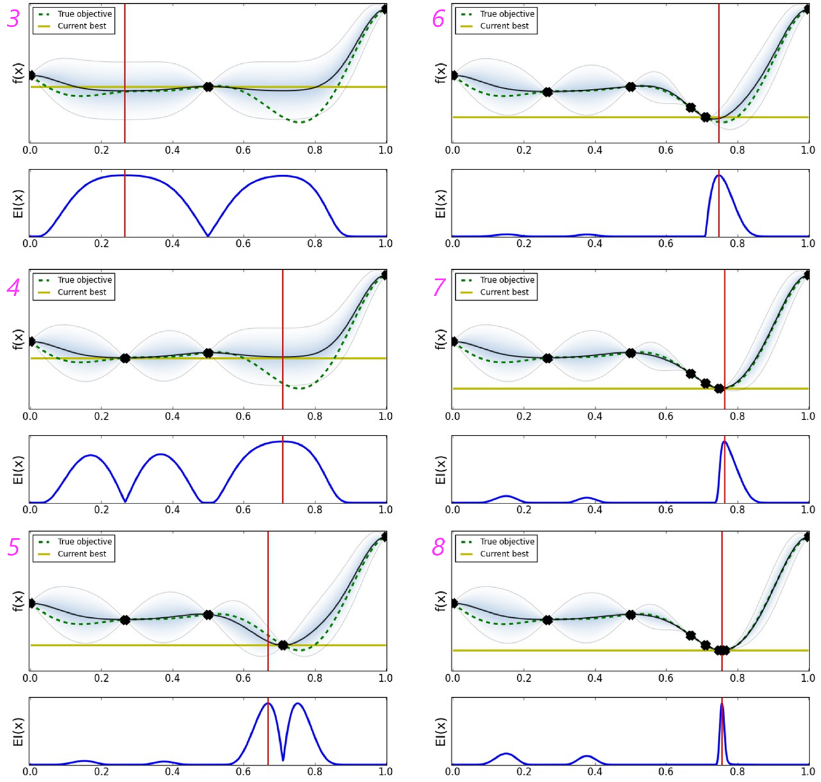
Auto tuning with Bayesian optimization

(Gaku MITSUKA)

Bayesian optimization

f(x): target function
looking for a minimum f(x)
EI(x): acquisition function
search for x where EI(x) is large





8

Posterior distribution of Gaussian process

$$p(y^*|\mathbf{x}^*, D) = \mathcal{N}(\mathbf{k}_*^T\mathbf{K}^{-1}\mathbf{y}, k_{**} - \mathbf{k}_*^T\mathbf{K}^{-1}\mathbf{k}_*)$$

$k(\mathbf{x}_n, \mathbf{x}_{n'})$: Kernel function

For example, for the Gaussian kernel function,

$$k(x_n, x_{n'}) = \theta_1 \exp\left(-\frac{(x_n - x_{n'})^2}{\theta_2}\right) + \theta_3\delta(x_n, x_{n'})$$

Hyper parameters Θ change a strength of the kernel function and auto correlation.

$\mathbf{K}$: Kernel matrix $K_{nn'} = k(\mathbf{x}_n, \mathbf{x}_{n'})$

$\mathbf{y}$: Measured values

Kernel function k(.,.) : gives a correlation (weight) between given x_n and $x_{n'}$

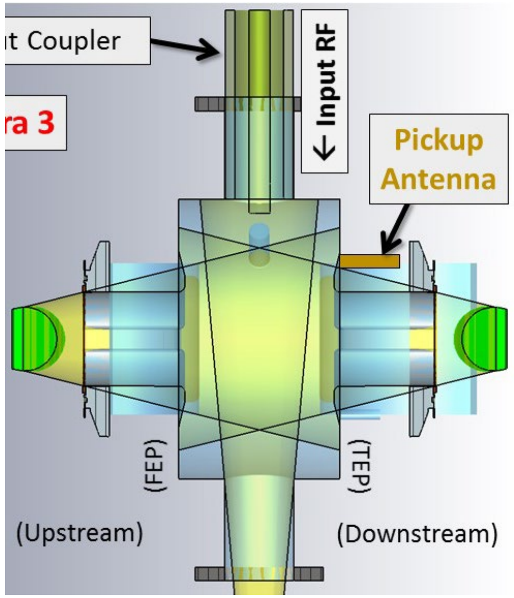
$\mathbf{k}_*^T\mathbf{K}^{-1}\mathbf{y}$: interpolate the measured *y* and expect *y** at *x** weighted by kernel functions

9

RF-Cavity Breakdown Signal A: Fast drop of the accelerating field

Decay time:

- ➢ Normal RF-switch OFF → Decay time: 8 μs
- ➢ Breakdown candidate → Decay time: ~500 ns



Pickup antenna

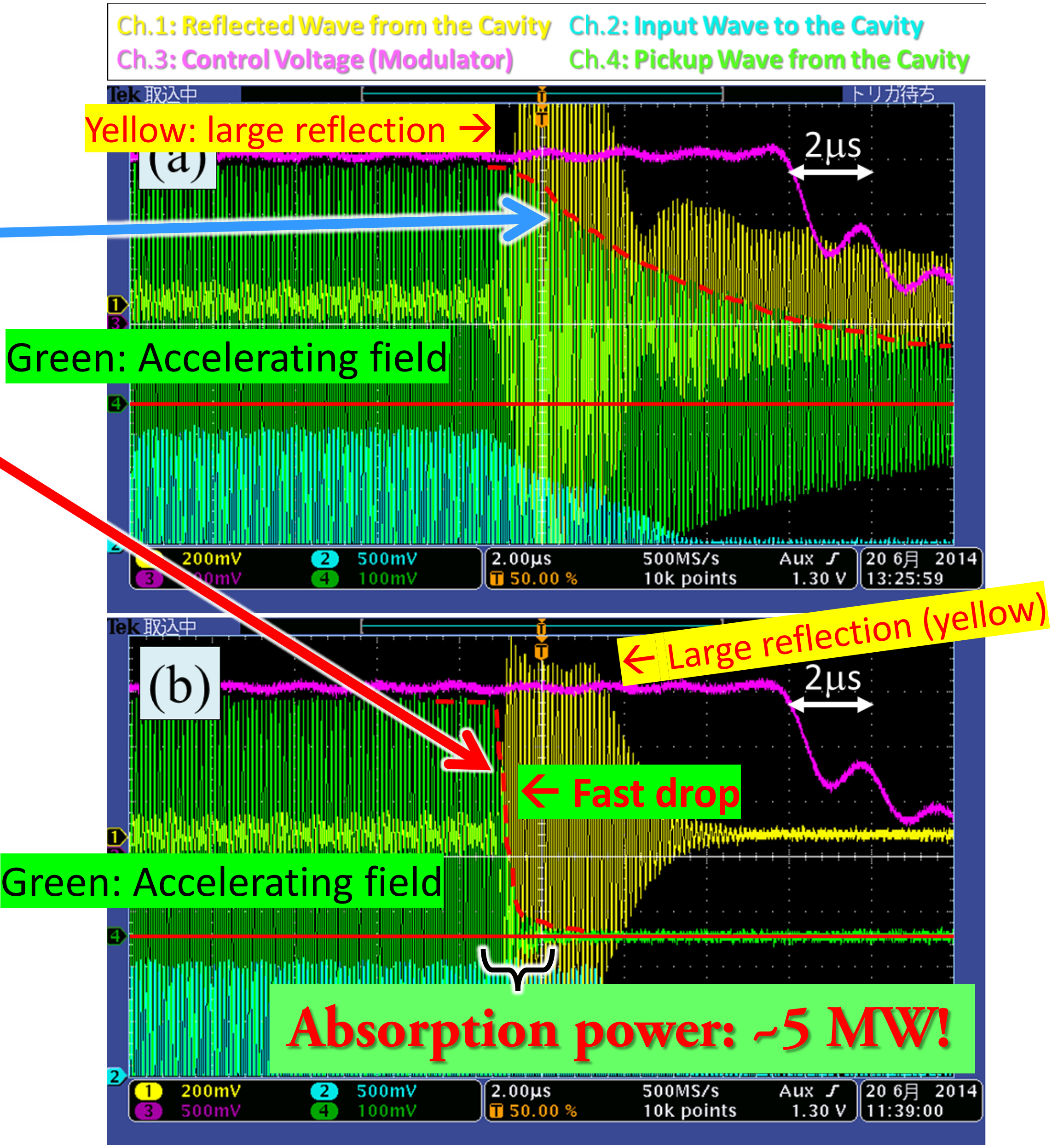


FIG. 6: Waveforms of the oscilloscope displayed for a time span of 20 μs (= 2 μs/div) when the interlock system was activated. The red dashed curves indicate the envelope of the 508.9-MHz pickup signal from DR Cavity No. 2, and the red solid lines indicate its zero level. (a) The RF switch was turned off for a reason related to the klystron. (b) Example of the cavity breakdown events.

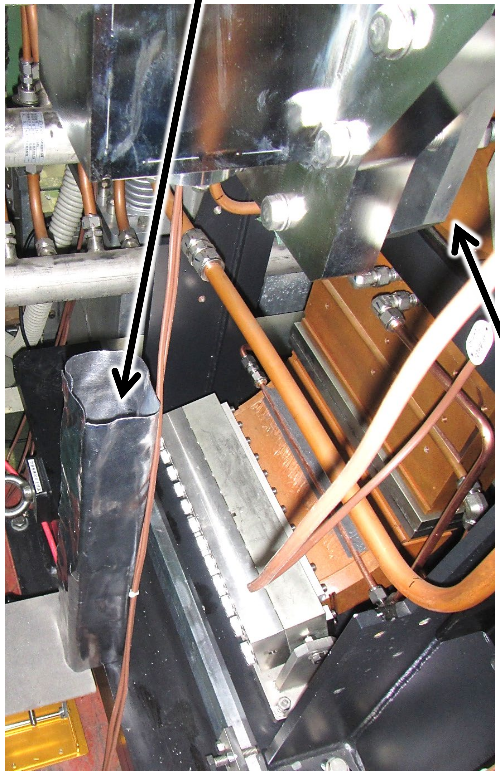
Q_L=13000@509MHz ⇒ Filling time: 8 μs

RF-Cavity Breakdown Signal B: Current flash

(During the high-power test of the RF cavity for the DR)

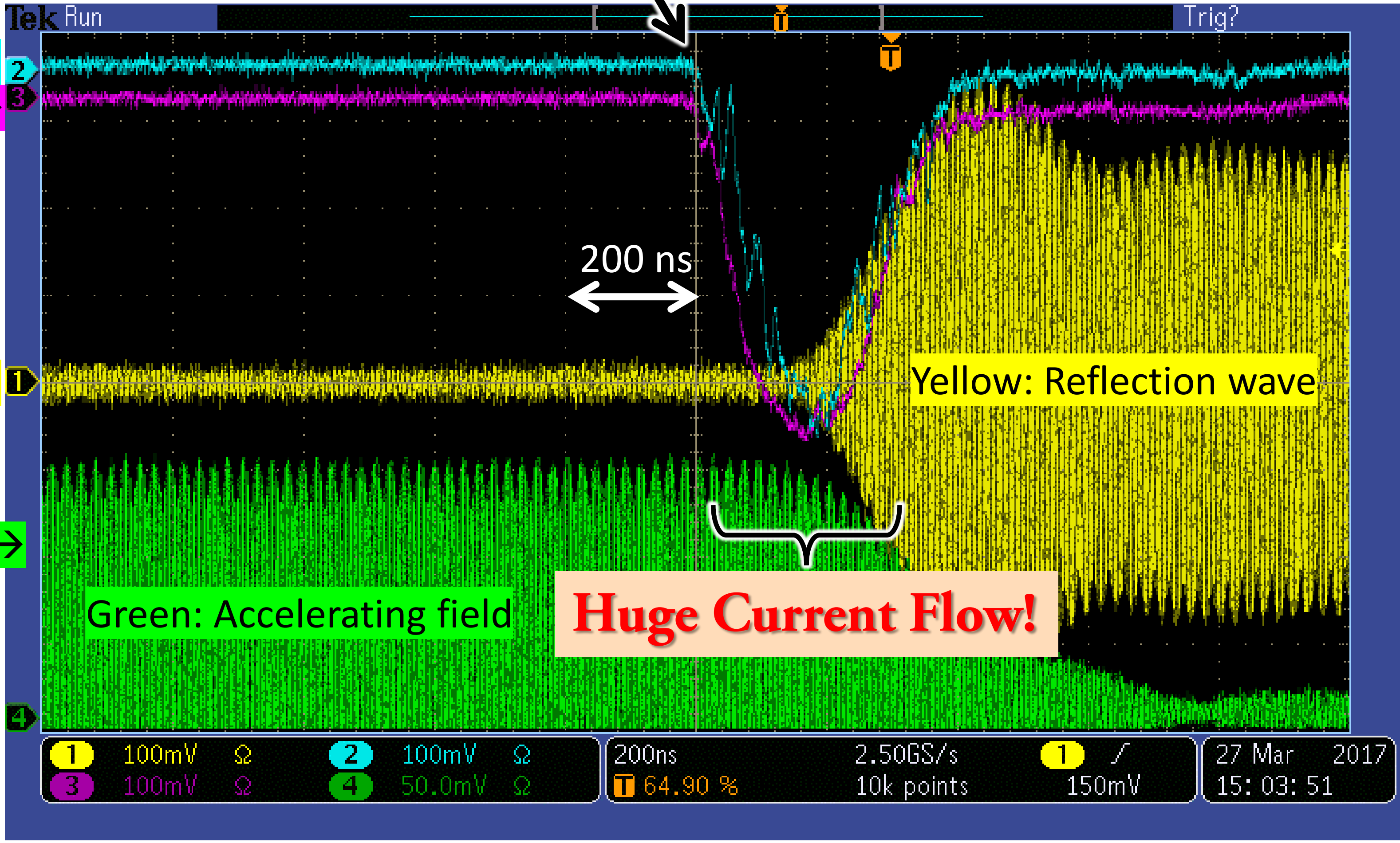
X-ray detector
(plastic scintillator + PMT)

Field emitted e^-
→ Impact on the metal surface
→ X-ray radiation



RF cavity
for the e+ DR

Ch.2 : X-ray (UP) →
Ch.3 : X-ray (DN) →
Ch.1 : Cav. Refl. →
Ch.4 : Cav. Pickup →

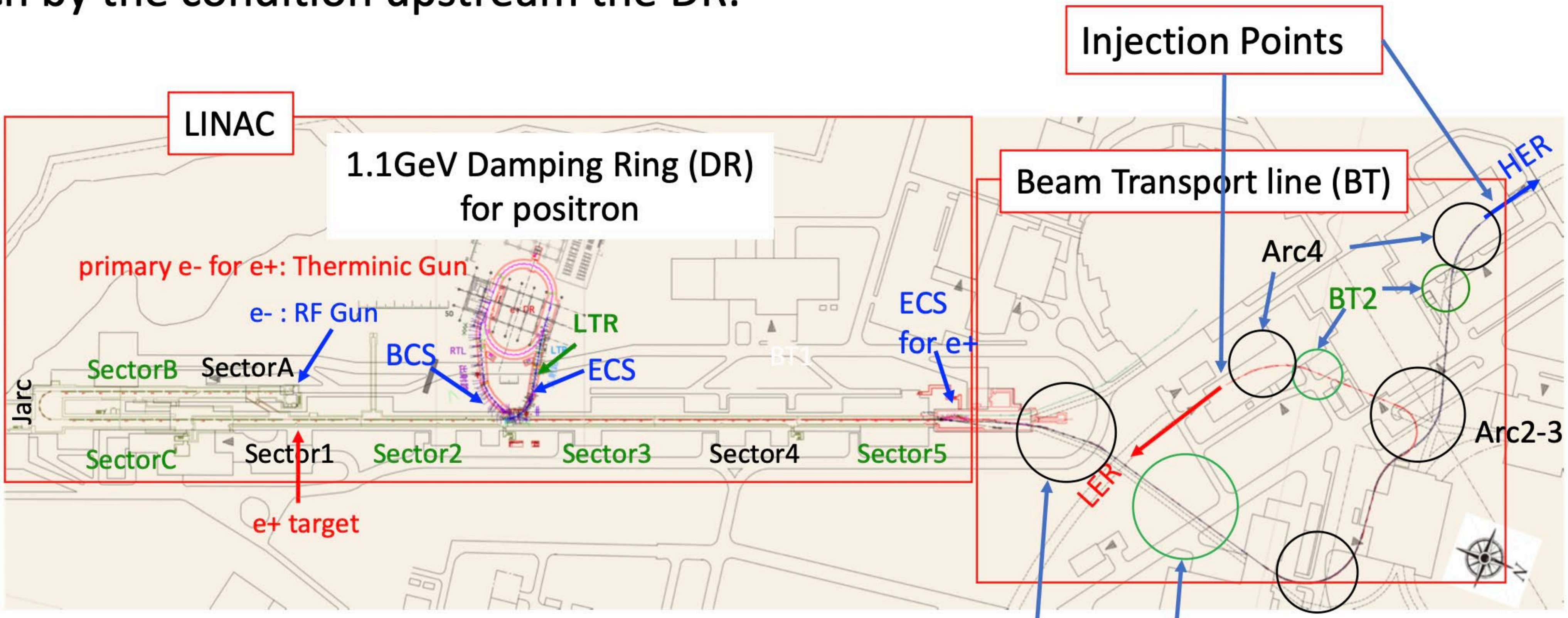


B) Layout of LINAC, BT, Injection to MR

(Naoko IIDA)

e+ beam injects into LER via DR:
The injection BG is not affected very much by the condition upstream the DR.

e- beam directly injects into HER:
The injeciton BG is directly affected by the condition of RF-gun, LINAC, and BT.



Green: Emittance measured with wire scanners(WS)

BCS: Bunch Compression System

ECS: Energy Compression System