Commissioning of SuperKEKB
the world's highest luminosity collider

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AccelApp'24

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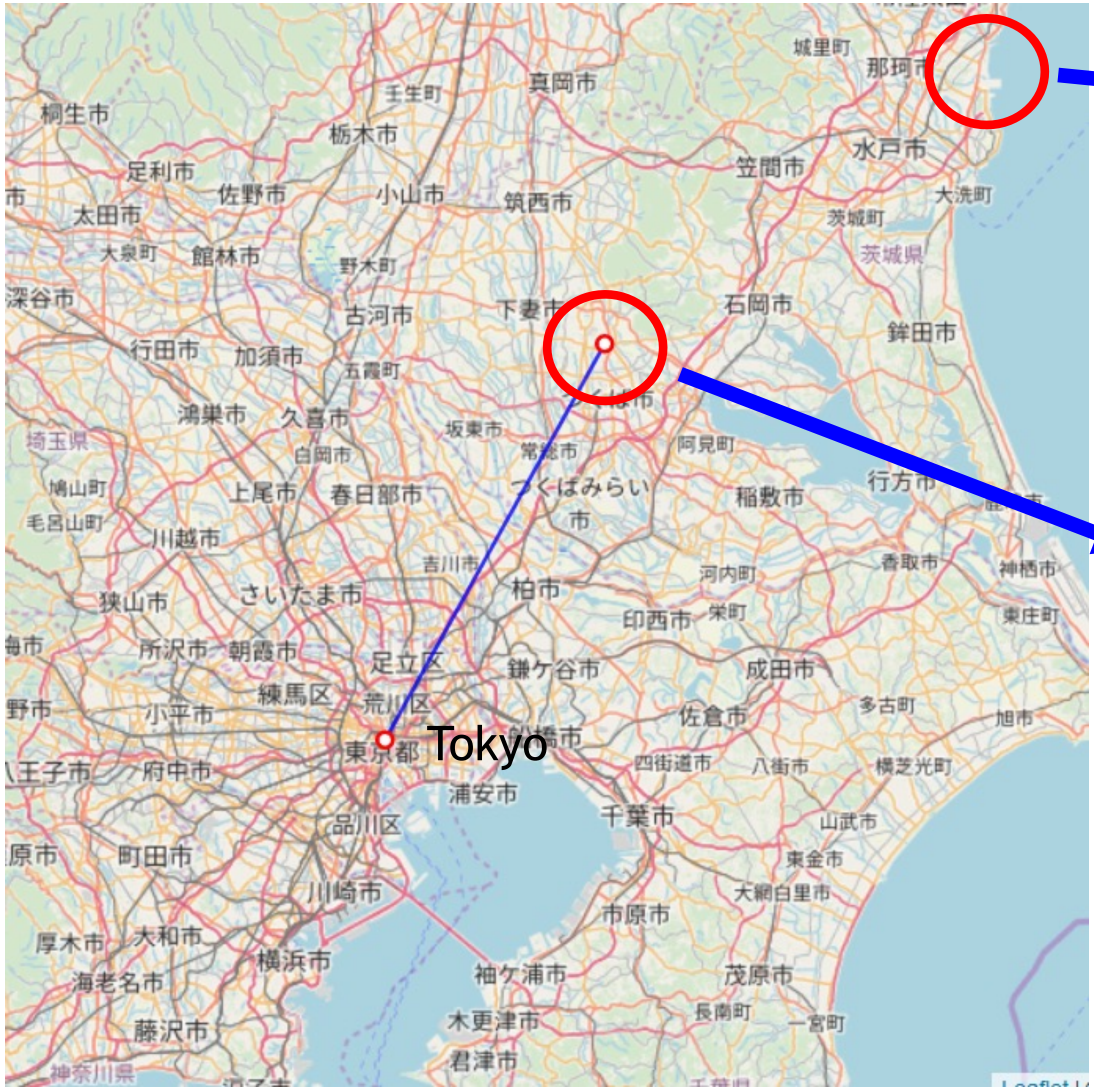
KEK
Tsukuba campus since 1971



Tokai campus

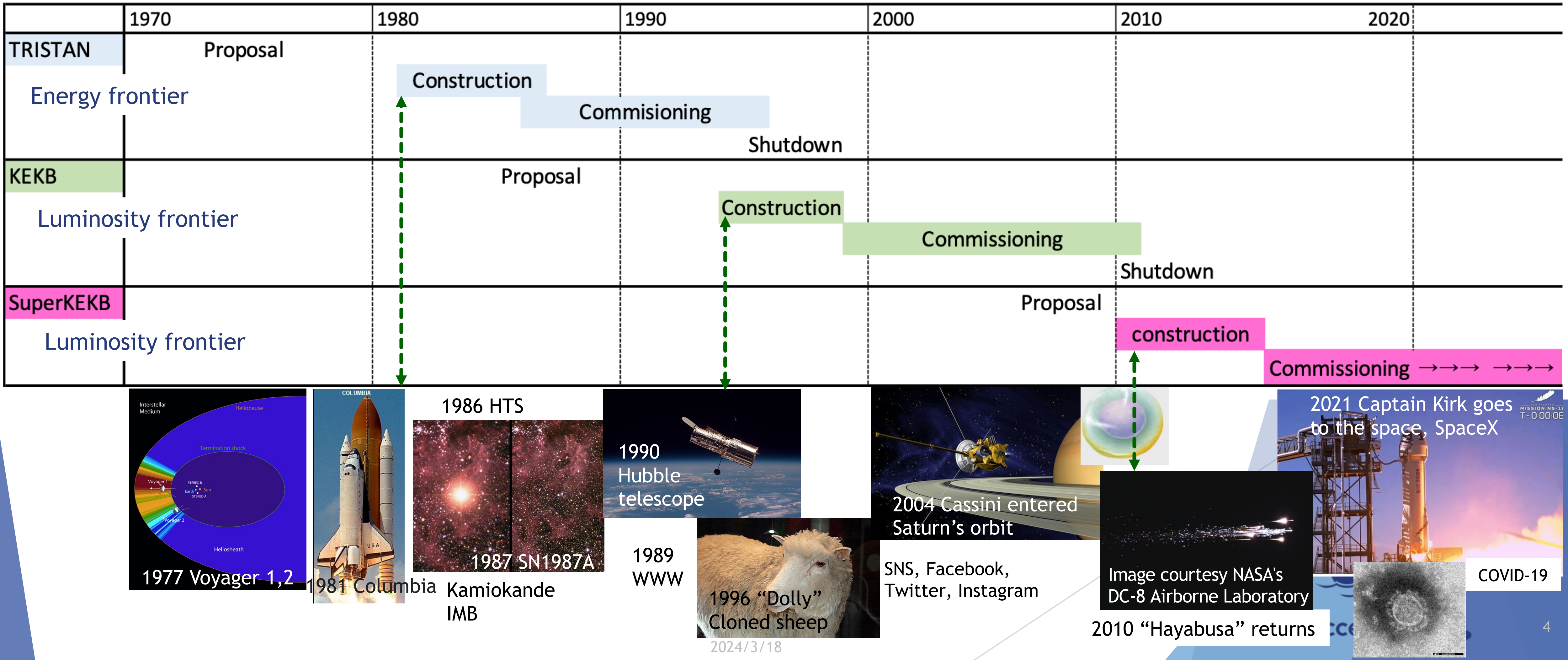
J-PARC
Proton synchrotron

Tsukuba campus

SuperKEKB, Light sources
Test faclities, cERL

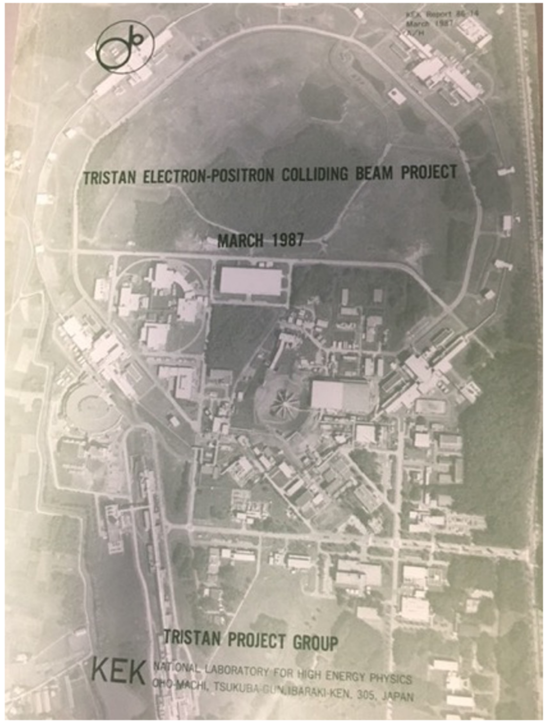
Three generations of e^+e^- colliders at KEK

KEK established in 1971

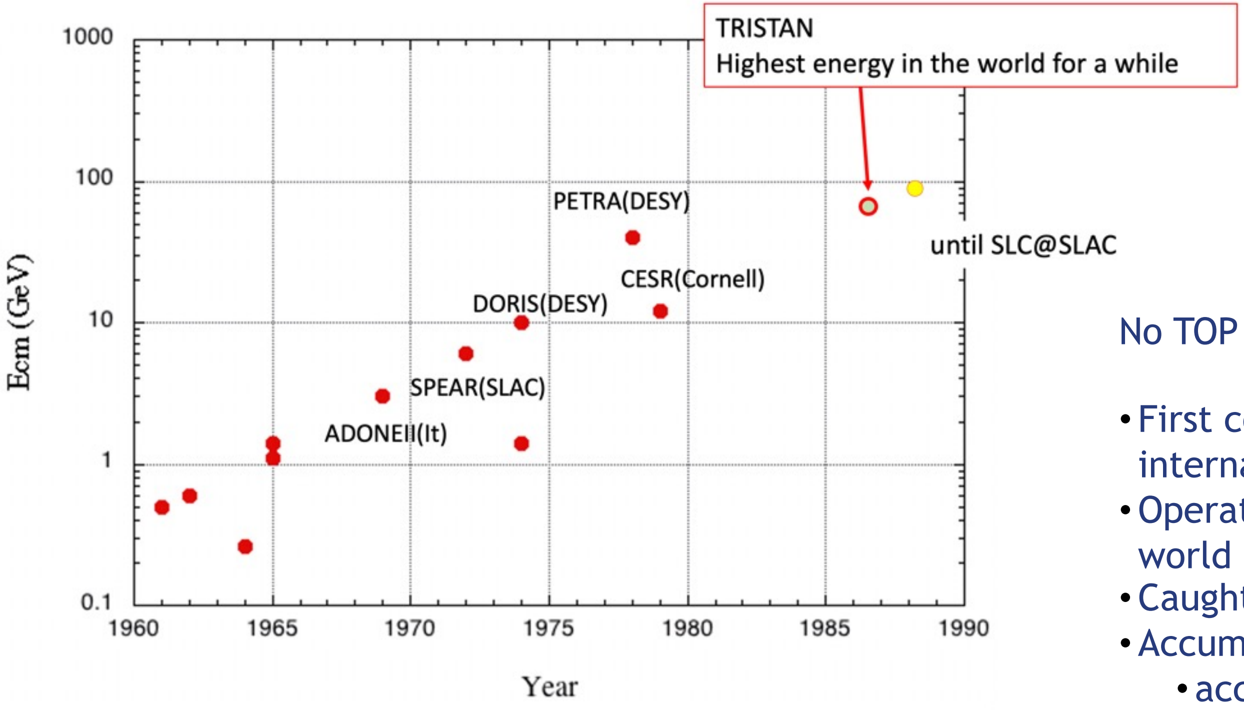


History of e^+e^-colliders
TRISTAN→KEKB B-factory→SuperKEKB

TRISTAN (1986-1995)
Transposable Ring Intersecting STorage Accelerators in Nippon
"There has been a longstanding desire in Japan to build a high energy accelerator so that Japan can join a forefront physics program at home. After thorough discussion it was decided that TRISTAN should be an e^+e^- collider, reaching 30 GeV × 30 GeV and aim at finding top quark. . ."



~3km tunnel, 11 m below G.L.
Still being used as SuperKEKB tunnel today.



No TOP quark found but

- First collider and large-scale international collaboration in Japan.
- Operated at the highest energy in the world for a few years.
- Caught up with the world.
- Accumulation of know-hows on
  - accelerator construction
  - technologies
    - superconducting rf
    - superconducting magnet
  - beam operation
  - physics detectors

History of e^+e^-colliders
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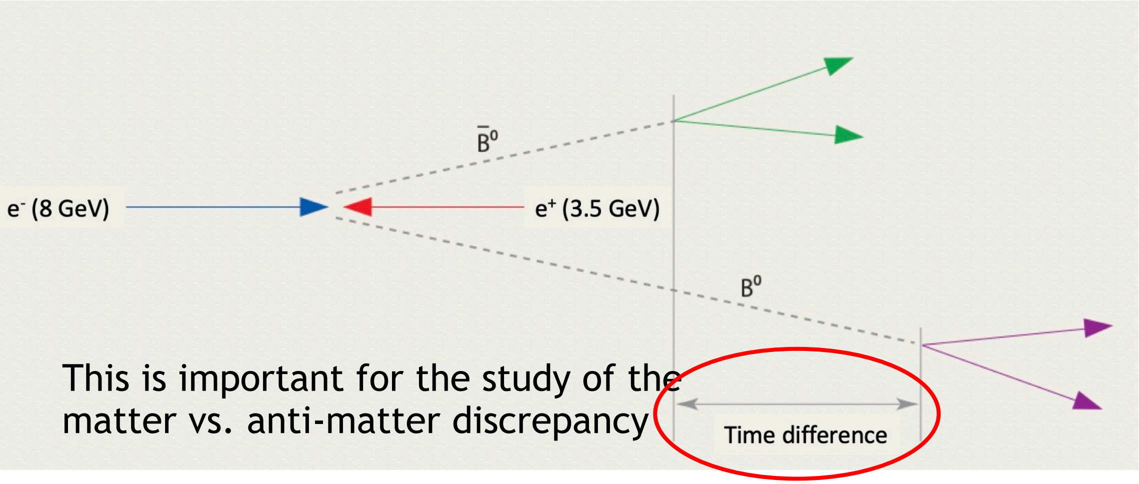
Motivation for B-factory

Development of the theory of CP violations in B meson decays gave a strong motivation for building a B-Factory machine.

- 8 GeV electron and 3.5 GeV positron beam, asymmetry in energy



- High yield

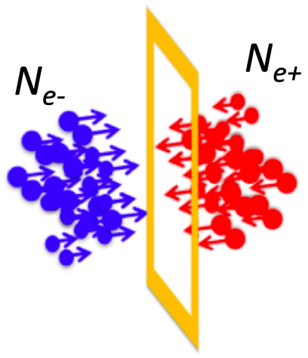
Founding Fathers of the B Factory Experiments (Drs. Fumihiko Takasaki, Stephen Olsen, Jonathan Dorfan and David Hitlin) Awarded Panofsky Prize, 2016

History of e^+e^-colliders
TRISTAN→KEKB B-factory→SuperKEKB

$$yield = L\sigma$$

We don't have any control over σ

High yield→ High luminosity (L) is required



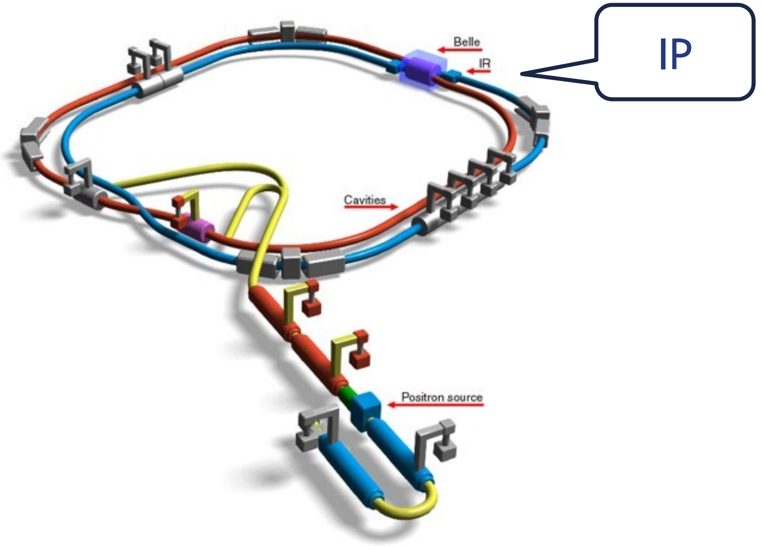
$$L = \frac{N_{e+}N_{e-}f}{A}$$

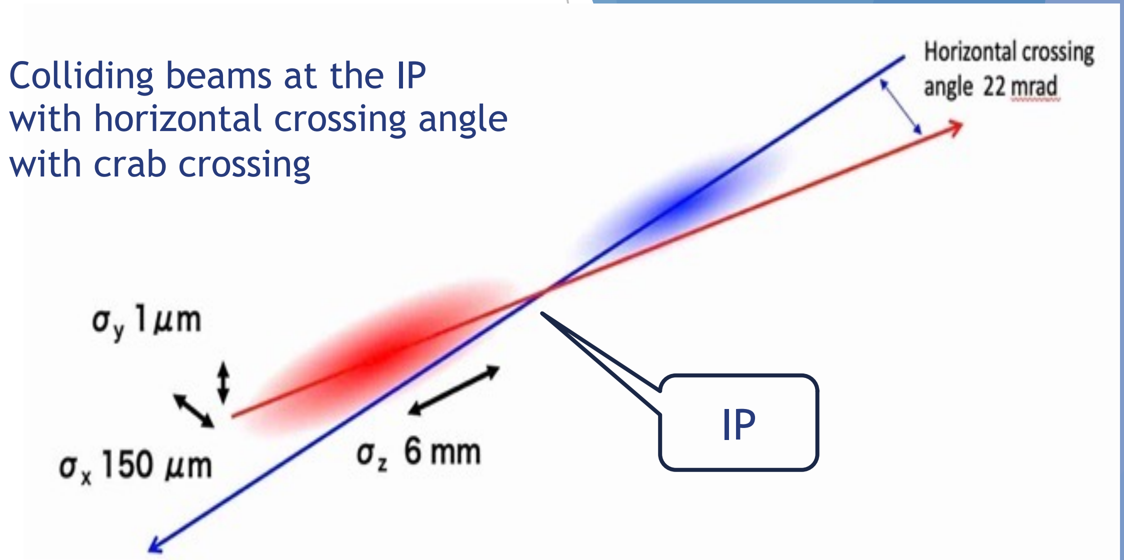
# of particles per unit area per unit time

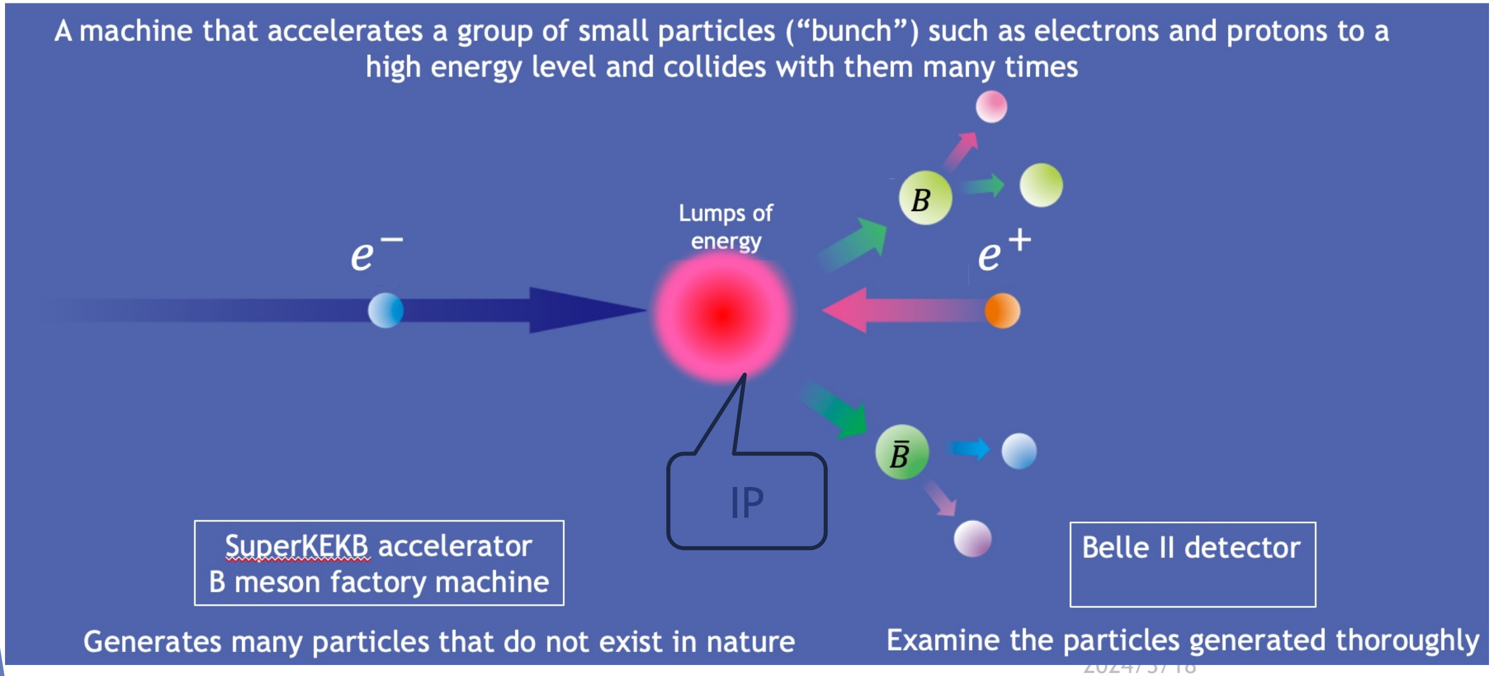
KEKB'S Target Peak luminosity $1\times10^{34}cm^{-2}s^{-1}$
an order of magnitude higher than the existing colliders

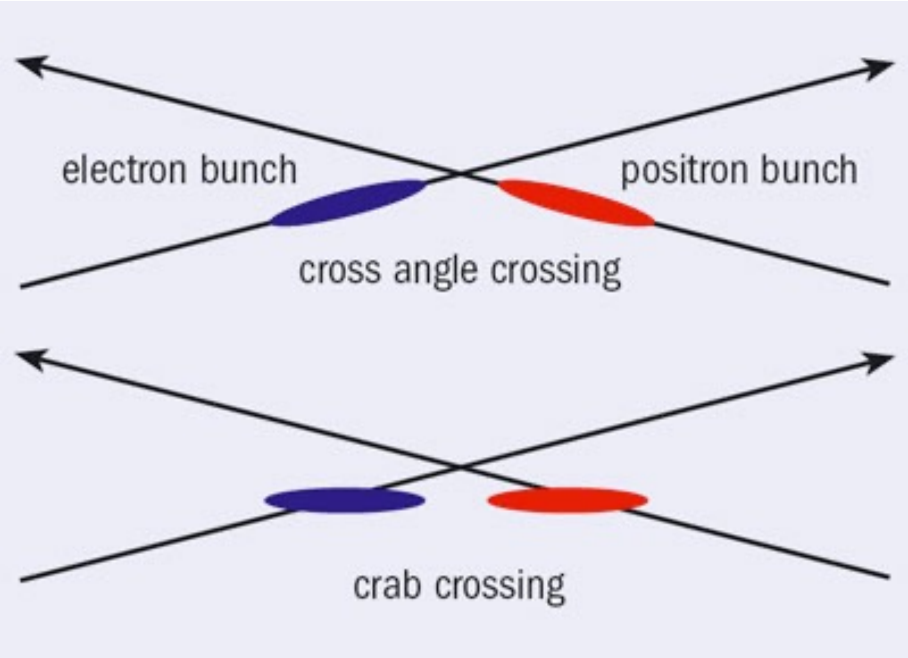
History of e^+e^-colliders
TRISTAN→KEKB B-factory→SuperKEKB

KEKB (1998-2010)
A double ring collider
$E_{c.m.} = 10.58\ (\Upsilon_{4s})$ GeV







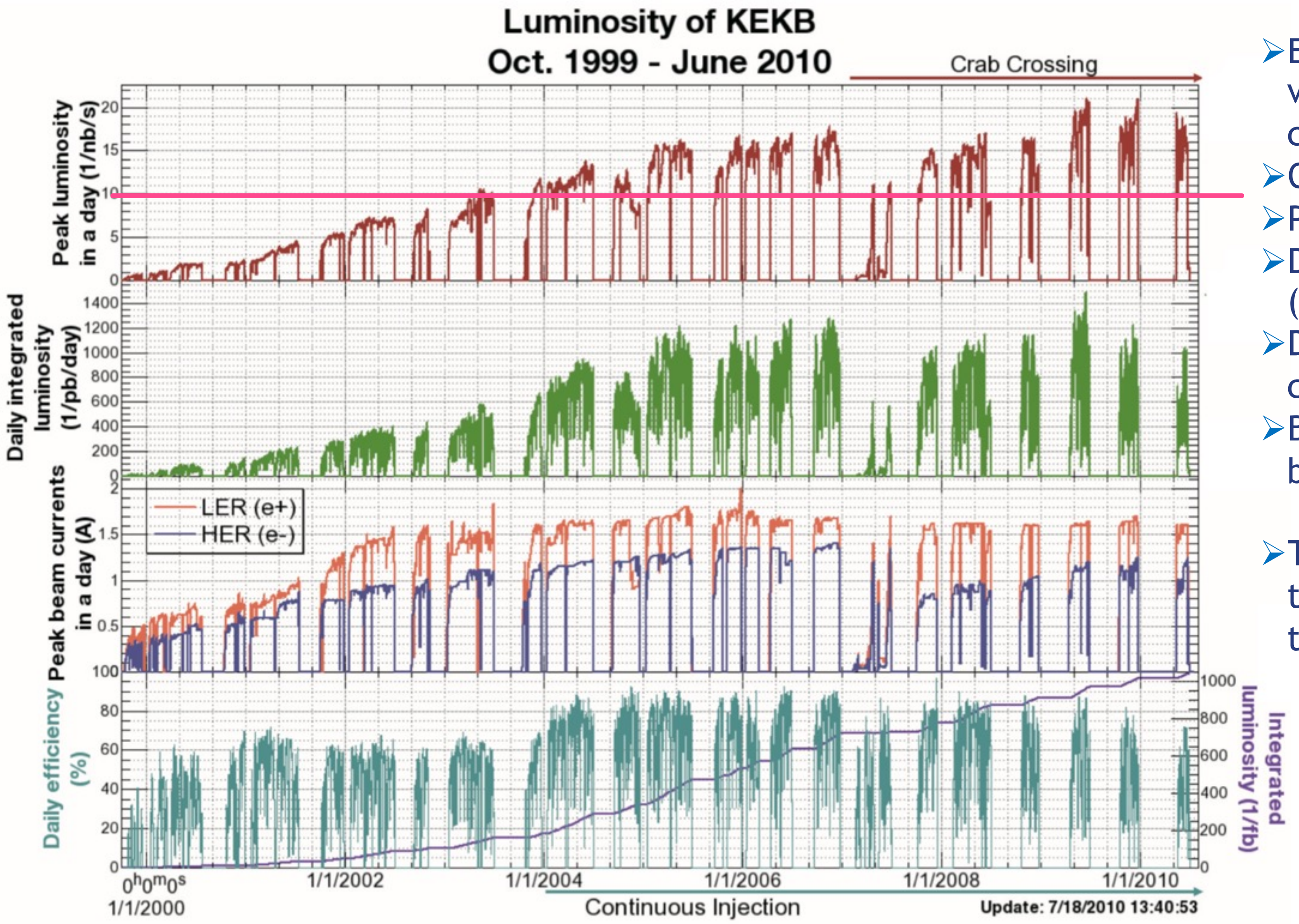


History of e^+e^-colliders
TRISTAN→KEKB B-factory→SuperKEKB

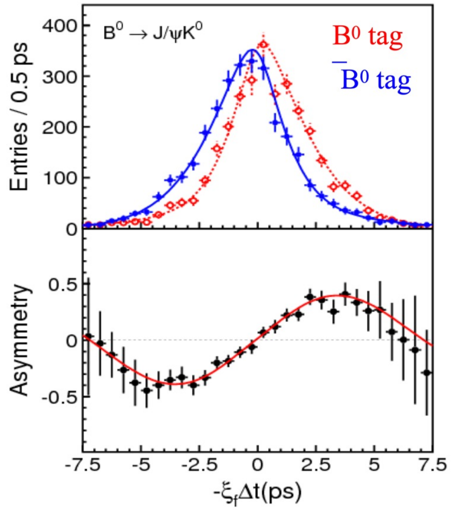
	TRISTAN	KEKB (LER/HER)
Beam Energy (GeV)	25-32	3.5/8.0
Beam Current (A)	0.014	1.64/1.19
# of bunches	2/2	1584/1584
β_x^* / β_y^* (mm)	1000/40	1200/5.9, 1200/5.9
σ_x^* / σ_y^* (μm)	250/8	147/0.94, 170/0.94
Luminosity ($\times 10^{34}$cm^{-2}s^{-1})	0.0045	2.1

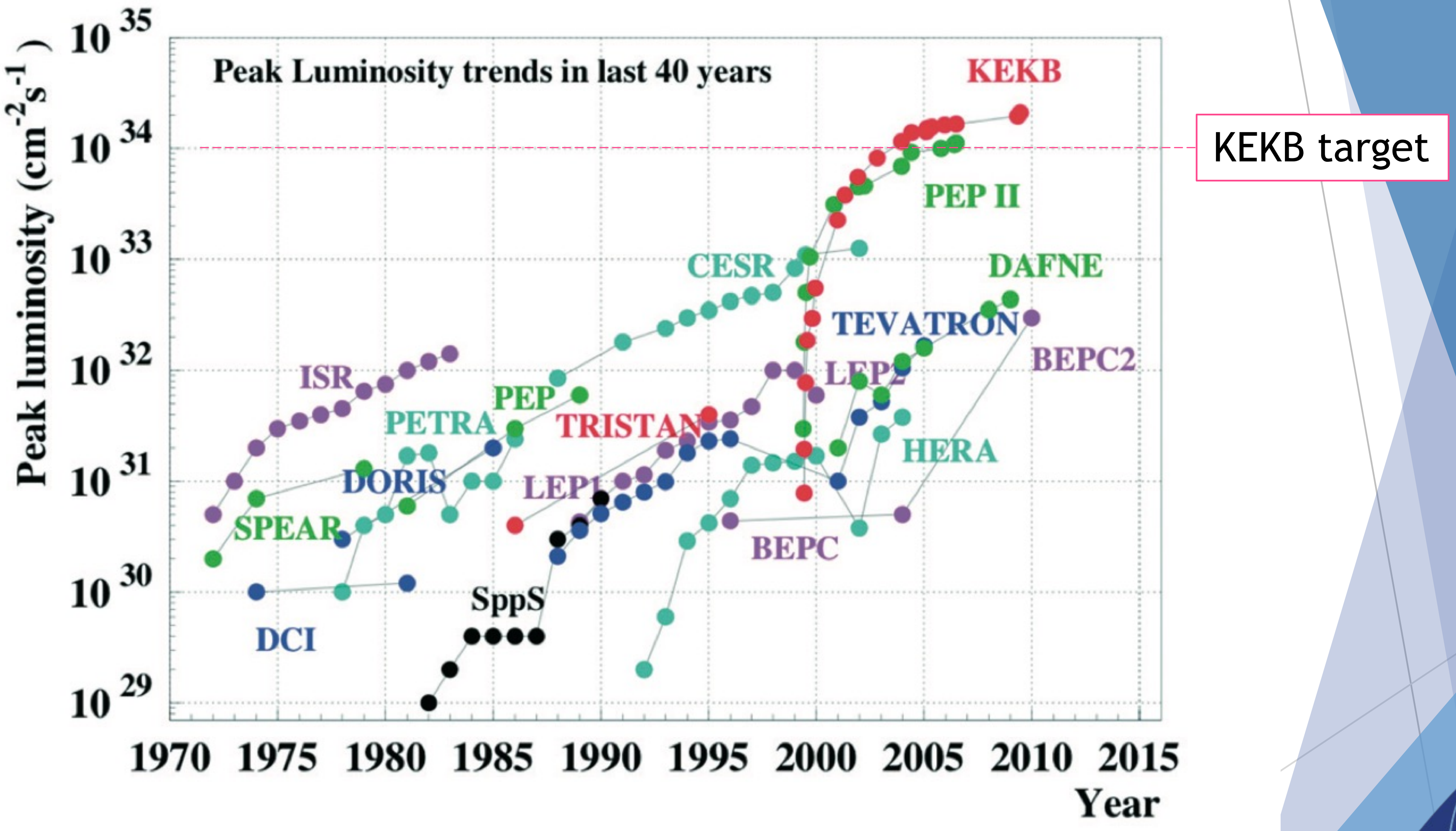
- Higher beam current
(from TRISTAN's mA to Amperes !)
- Smaller beam size
  - ~250 times higher peak luminosity than TRISTAN achieved!

History of e^+e^-colliders
TRISTAN→KEKB B-factory→SuperKEKB



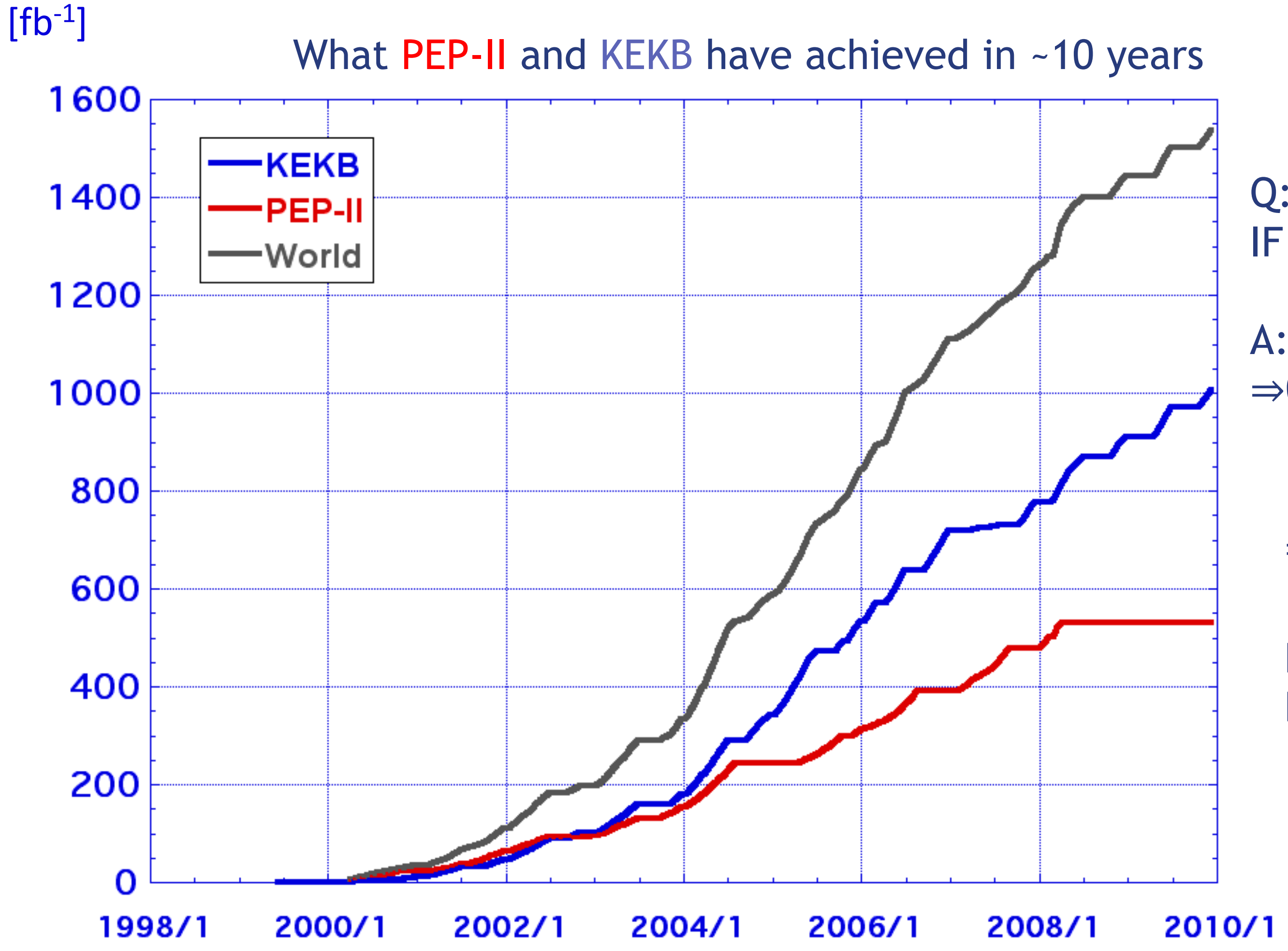
- Establishment of technology of key components, such as RF, vacuum and beam monitors, to handle multi-ampere beam currents and control system (EPICS).
- Operation with crossing angle, and crab cavities.
- Proof that IR configuration with superconducting magnets works.
- Detector backgrounds at manageable level with continuous (trickle-charge) injection scheme.
- Demonstration of effectiveness of solenoids against electron clouds.
- Benchmarks for simulations made and further understanding of beam dynamics obtained.
- The experiments at the KEKB B-Factory and PEP-II contributed to the 2008 Nobel Prize in Physics for the Kobayashi-Maskawa theory.




Peak Luminosity trends in last 40 years
Peak luminosity ($cm^{-2}s^{-1}$)
10^{35}
10^{34}
10^{33}
10^{32}
10^{31}
10^{30}
10^{29}
1970 1975 1980 1985 1990 1995 2000 2005 2010 2015
Year
KEKB
PEP II
CESR
DAFNE
TEVATRON
BEPC2
LEP2
HERA
ISR
PETRA
PEP
TRISTAN
DORIS
LEP1
SPEAR
BEPC
SppS
DCI
KEKB target

History of e^+e^-colliders
TRISTAN→KEKB B-factory→SuperKEKB

What PEP-II and KEKB have achieved in ~10 years



Now physicists want 50 ab^{-1}

Q: How many years would we need to accumulate 50 ab^{-1} IF we kept running the present KEKB?

A: With the peak luminosity of $2x10^{34}$ $cm^{-2}s^{-1}$
⇒0.3 ab^{-1}/year (assuming 1.5×10^7 seconds/year running)

⇒167 years.

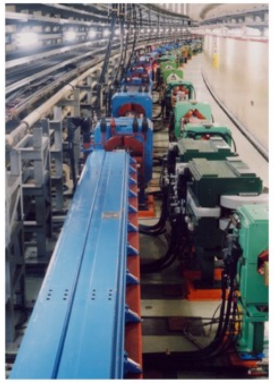
Need for <u>much higher</u> luminosity machines:
Next Generation B-factories

SuperKEKB

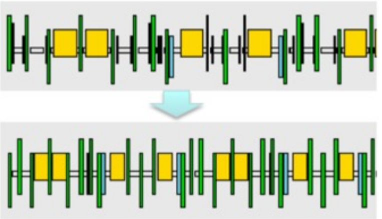
Norfolk, Virginia
AccelApp'24

History of e^+e^-colliders
TRISTAN→KEKB B-factory→SuperKEKB

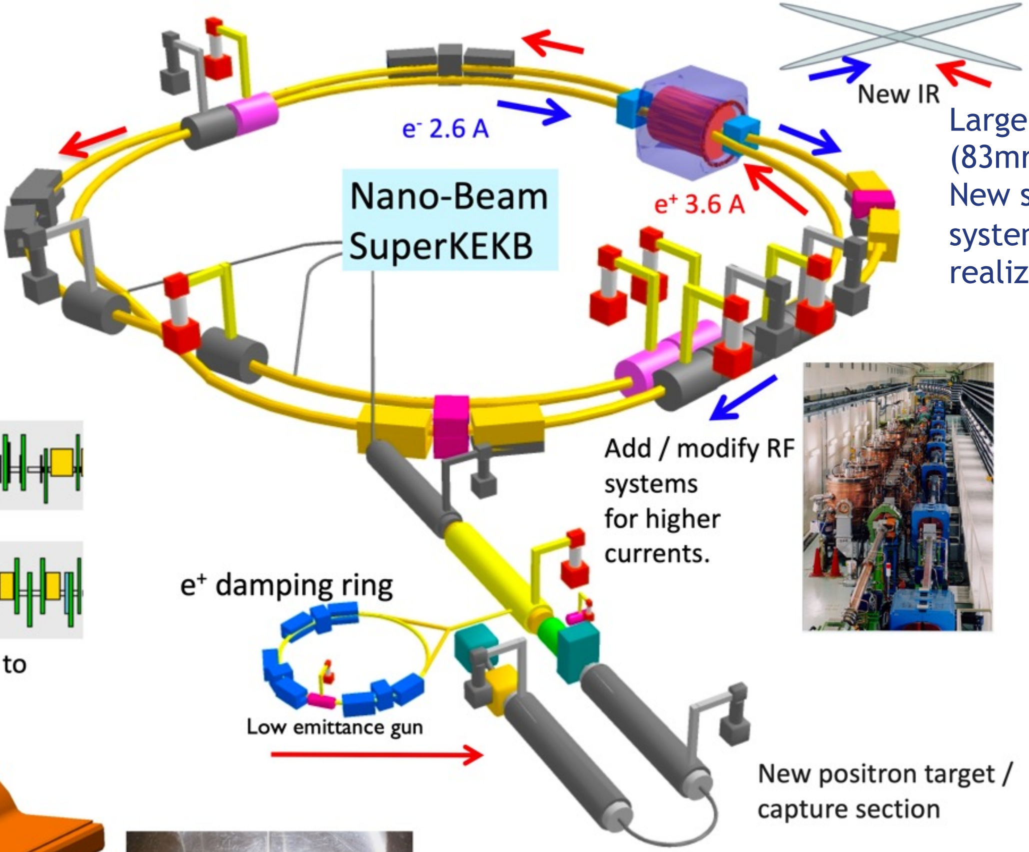
The world's first practical application of the nano-beam scheme



Replace long dipoles with shorter ones (HER).



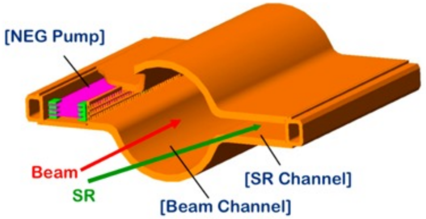
Redesign the HER arcs to reduce the emittance.



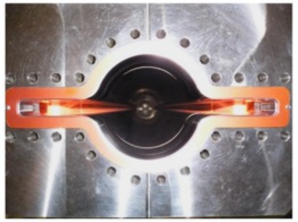
Larger horizontal crossing angle (83mrad) than KEKB.
New superconducting magnet system (QCS) around IP, for realizing nano-beam scheme.

Add / modify RF systems for higher currents.

New positron target / capture section



TiN coated beam pipe with antechambers

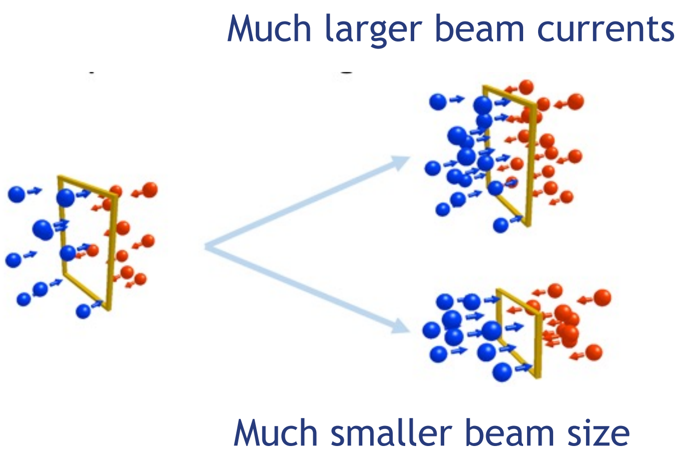


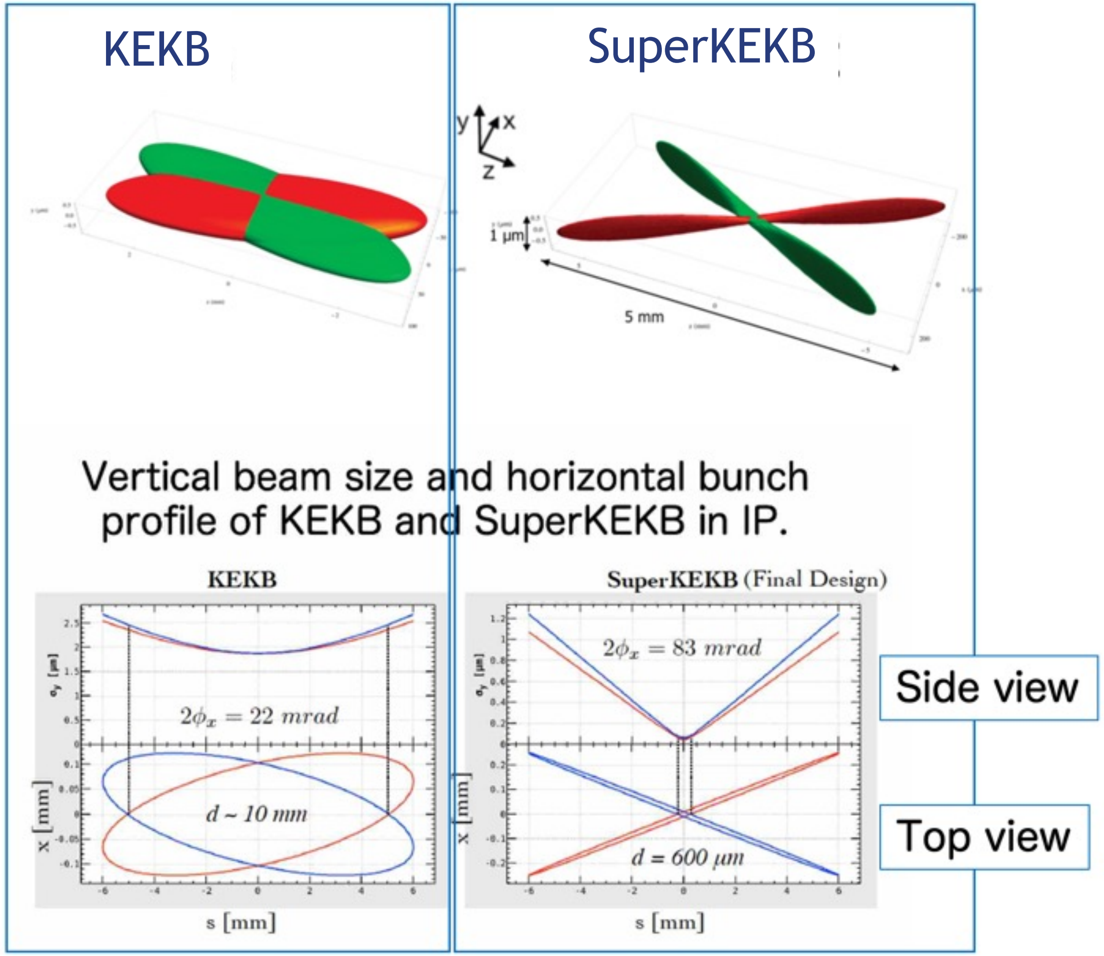
Change beam energies 3.5 / 8 (KEKB)⇒ 4 /7 GeV to achieve longer Touschek lifetime and mitigate the effect of intra-beam scattering in LER. It also helps lowering the emittance in the HER.

SuperKEKB Design concepts, strategy

Low emittance ("nano-beam") scheme
⇒ first proposed by P. Raimondi.
Collision with very small spot-size beam.

SuperKEKB is the first collider in the world to realize the nano-beam scheme

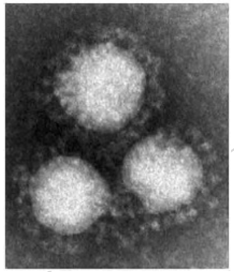


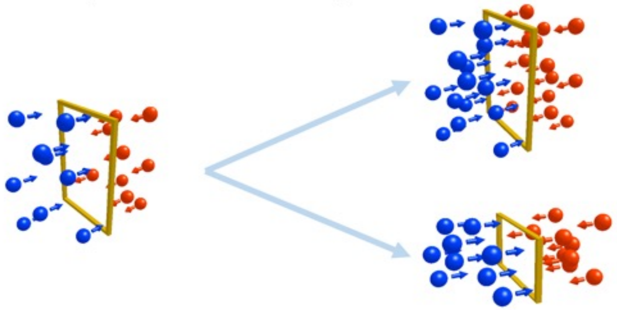


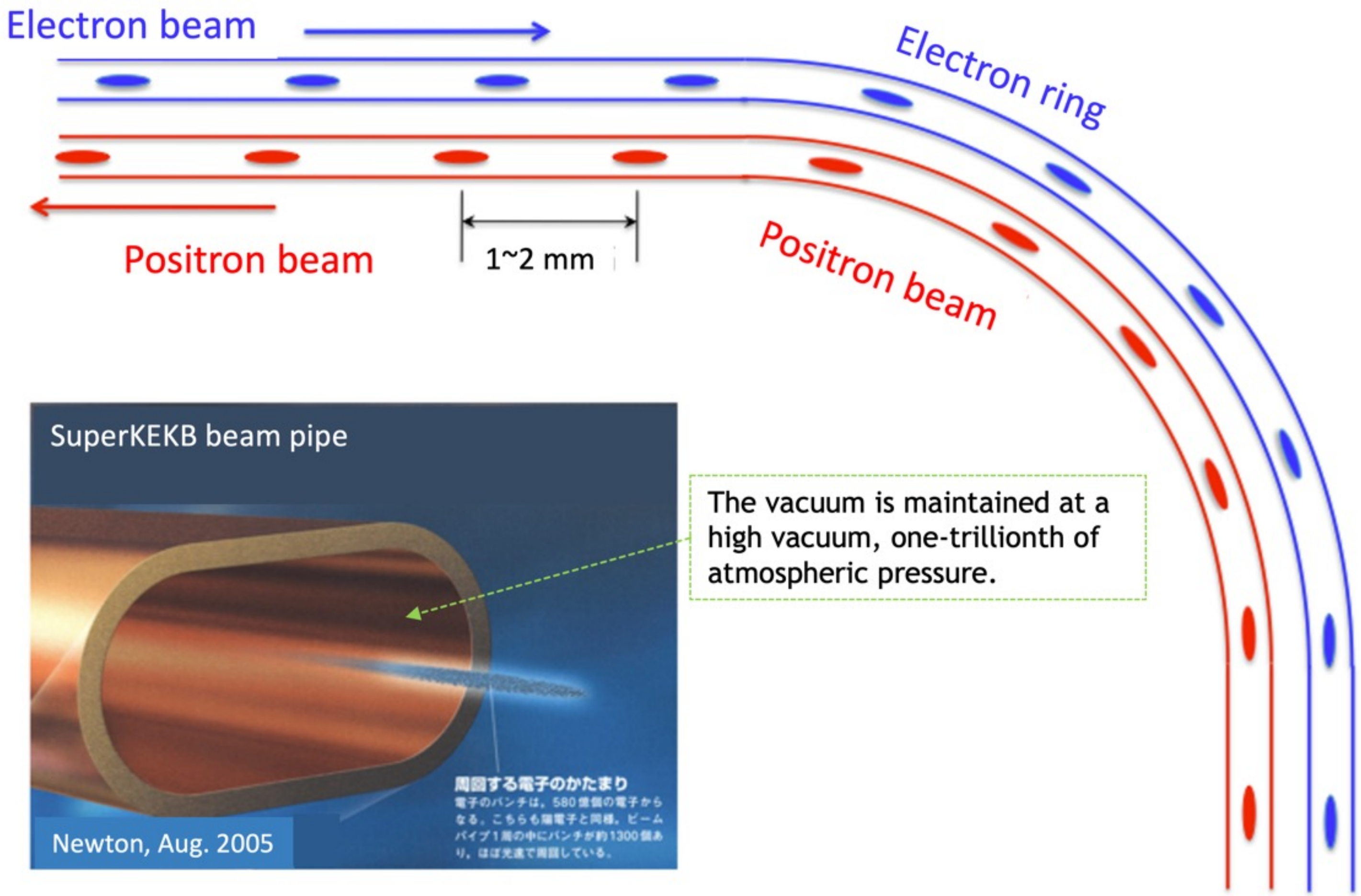
SuperKEKB Design concepts, strategy

	TRISTAN	KEKB (LER/HER)	SuperKEKB(LER/HER)
Beam Energy (GeV)	25-32	3.5/8.0	4.0/7.0
Beam Current (A)	0.014	1.64/1.19	3.6/2.6
# of bunches	2/2	1584/1584	2500/2500
β_x^* / β_y^* (mm)	1000/40	1200/5.9, 1200/5.9	32/027, 25/0.3
σ_x^* / σ_y^* (μm)	250/8	147/0.94, 170/0.94	10.1/0.048, 10.7/0.062
Luminosity $(\times 10^{34} cm^{-2} s^{-1})$	0.0045	2.1	60

SuperKEKB Design vertical beam size ~ COVID19 virus







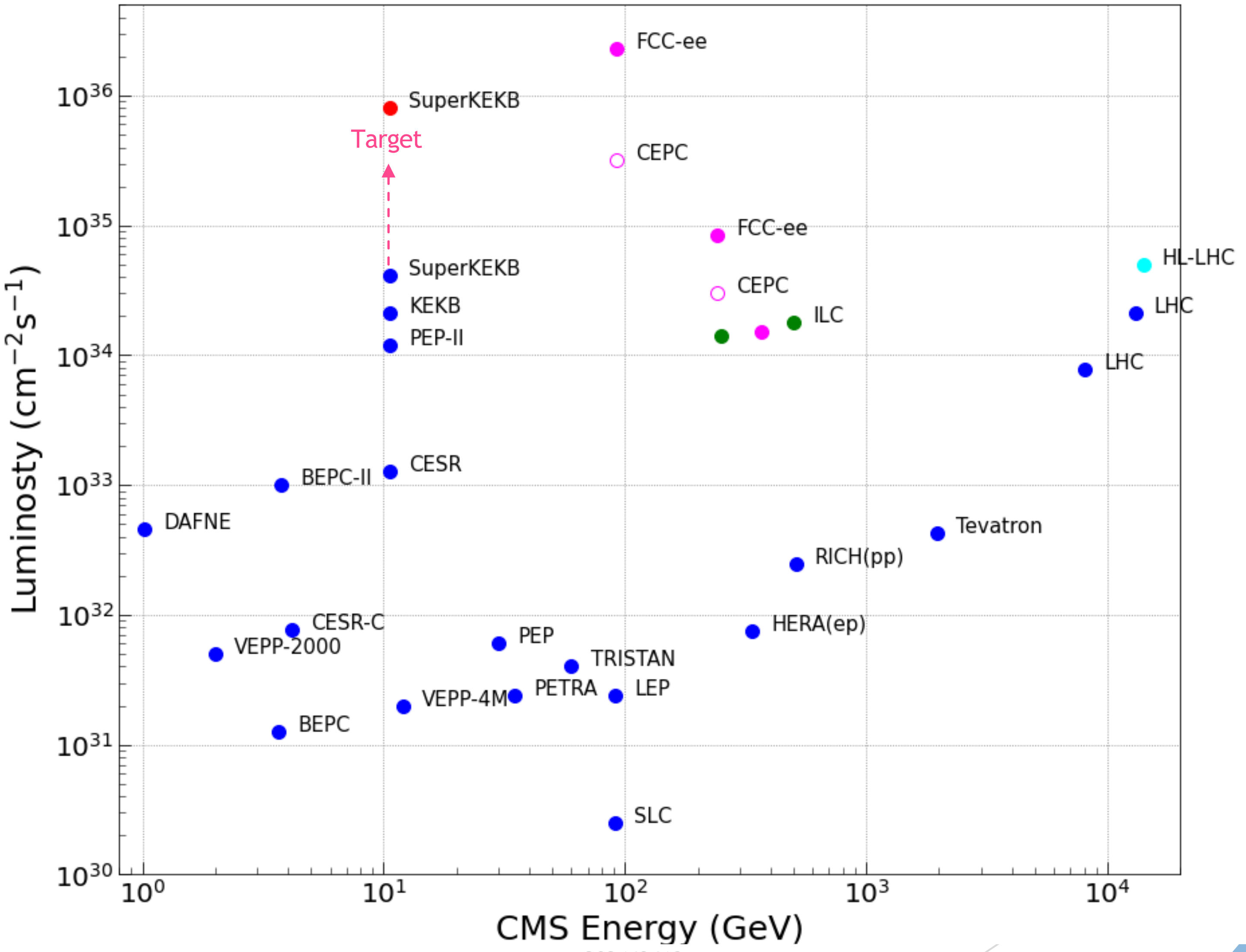
"bunch"
the particles get "clumped" around the synchronous particle in a BUNCH.

SuperKEKB

- Bunch size
  - ~ 12 mm in length
  - ~ several 100 μm in width
- There are 60~900 billion electrons/positrons in a bunch
- There are 1500~2500 such bunches in a ring
- And they collide at the IP (Interaction Point)

History of e^+e^-colliders
TRISTAN→KEKB B-factory→SuperKEKB

SuperKEKB : Luminosity frontier e^+e^- collider with innovative “nano-beam” scheme



History of e^+e^-colliders
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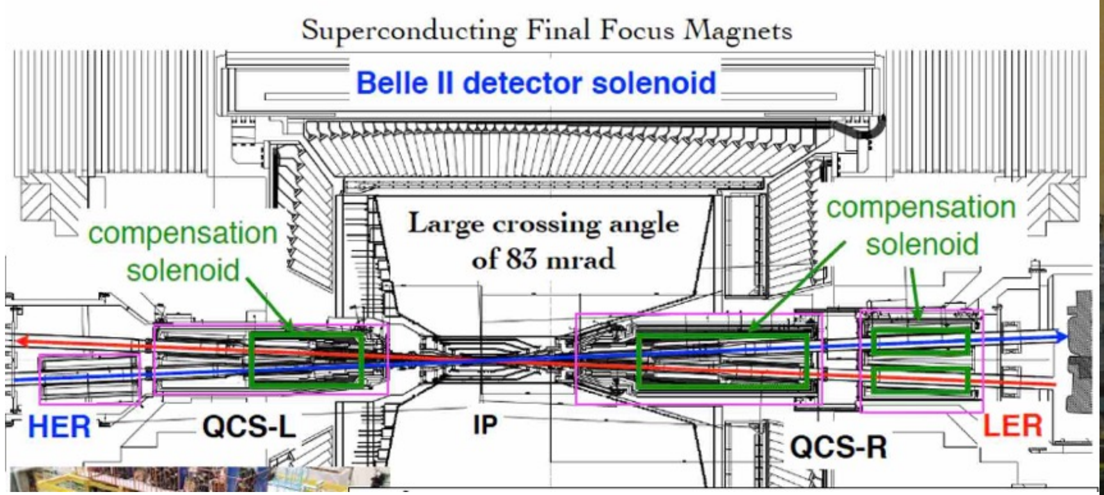
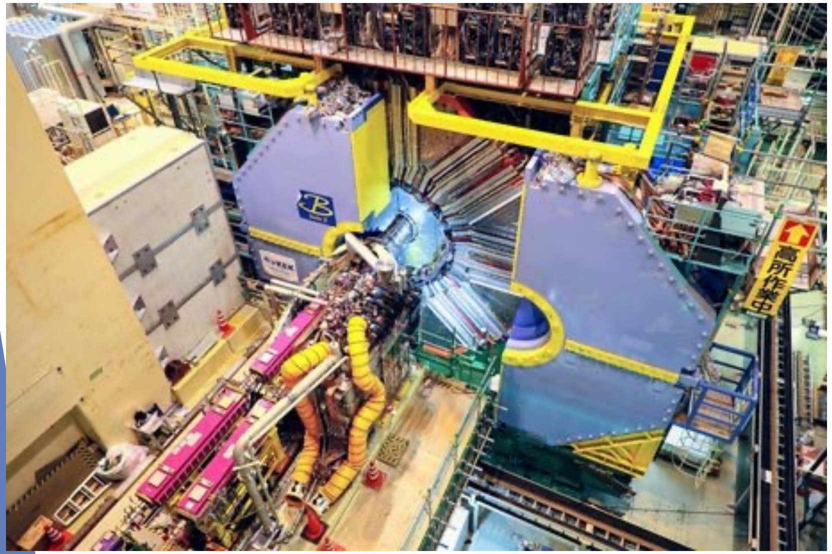
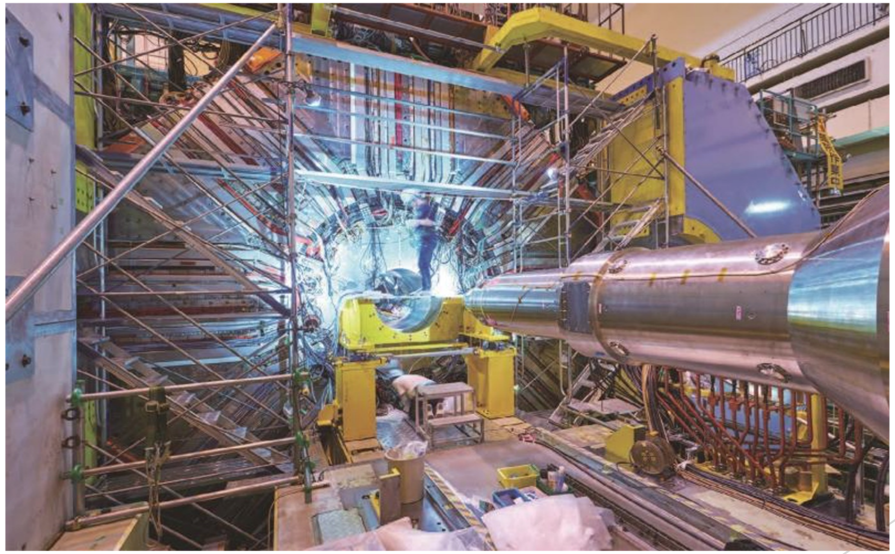
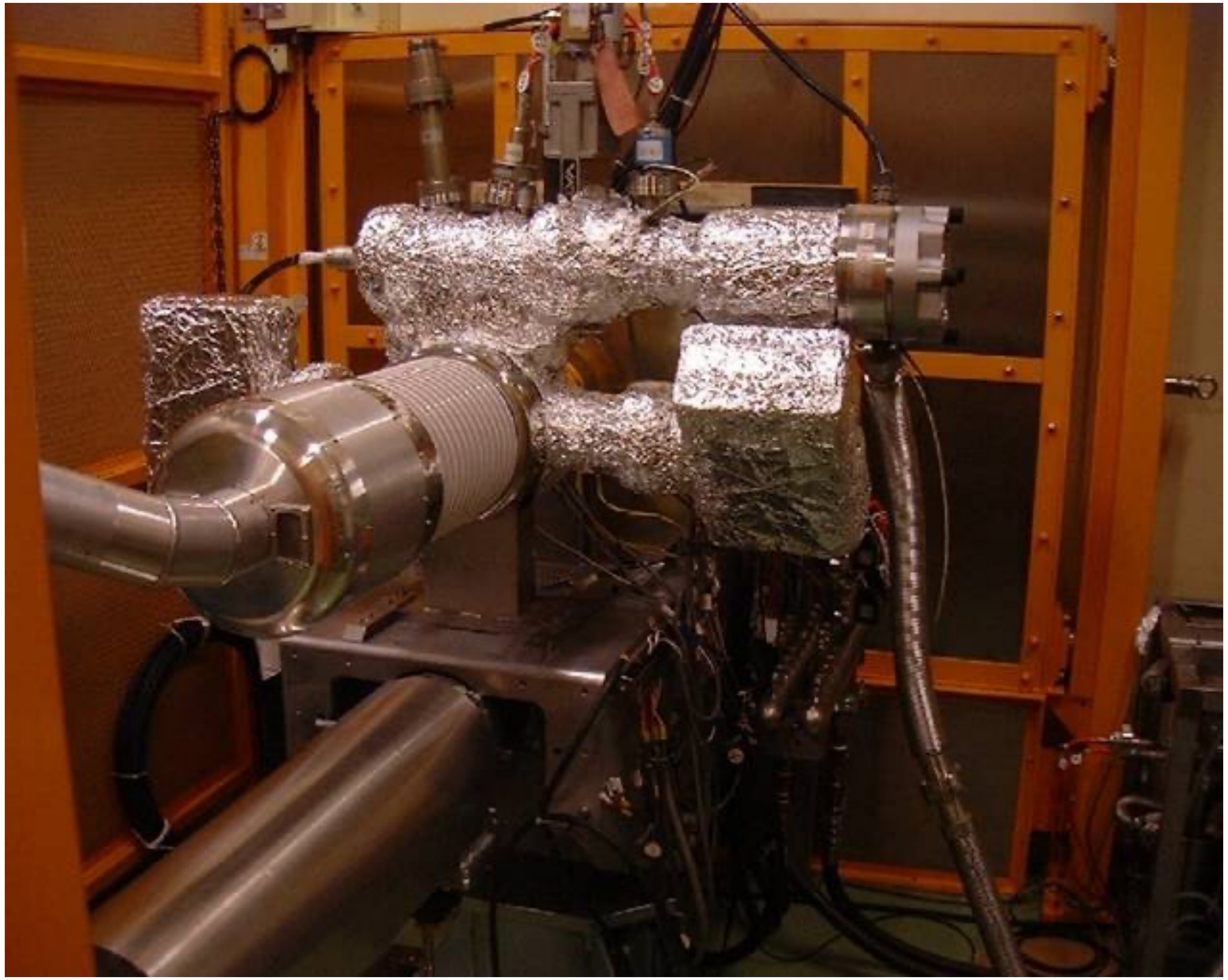


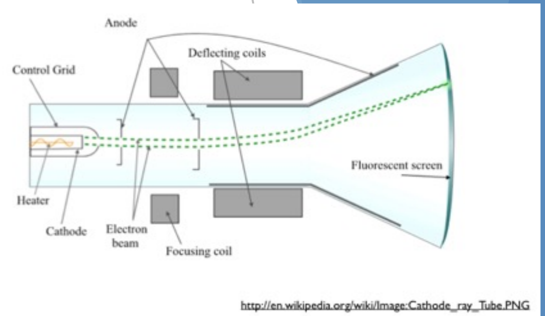


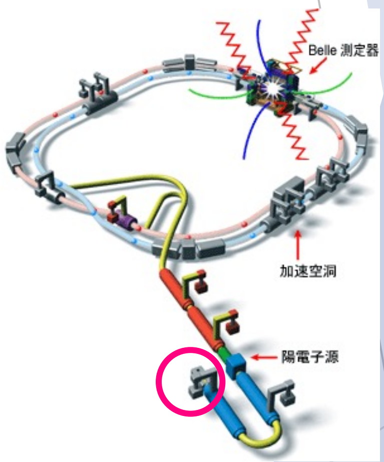


Superconducting final focusing magnet system (QCS)
provides strong focusing to the HER/LER beams.

SuperKEKB: tour

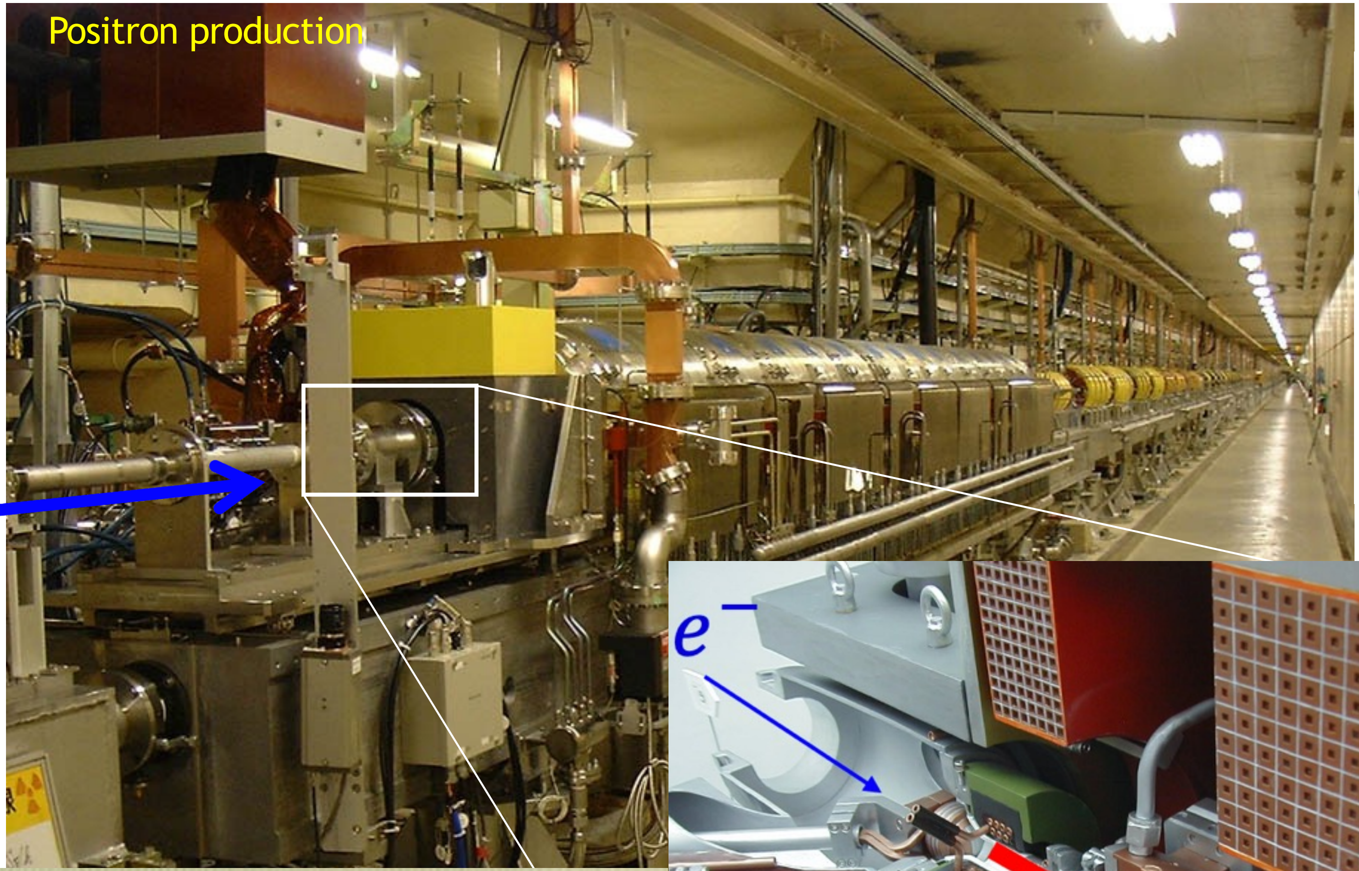


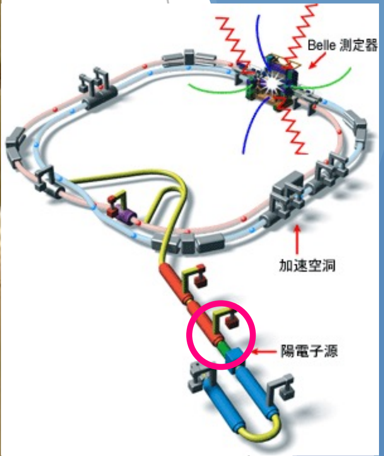


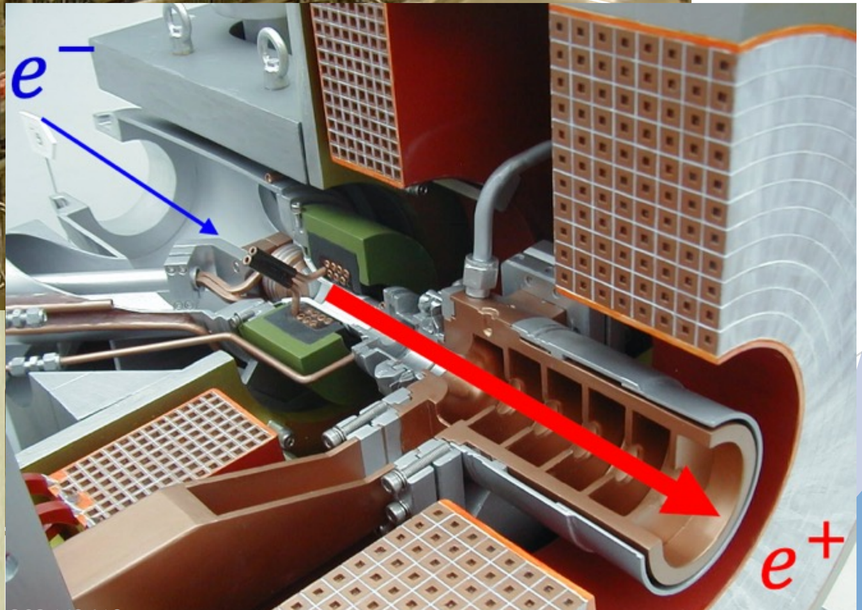


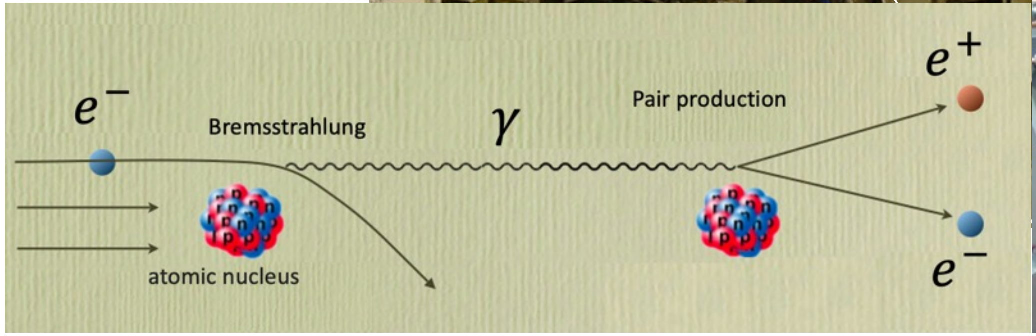
SuperKEKB: tour

e^-

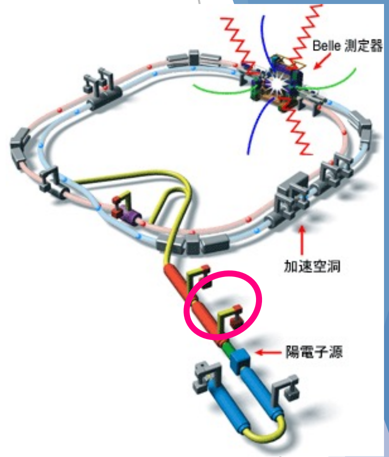


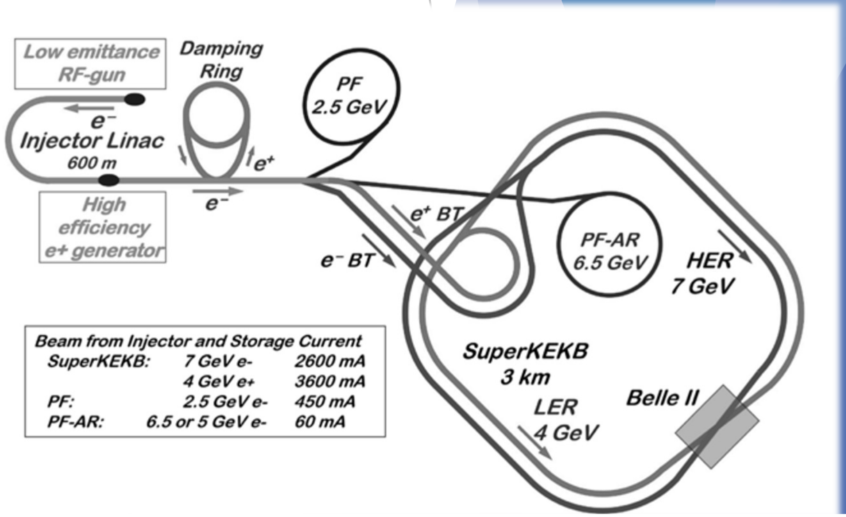






SuperKEKB: tour

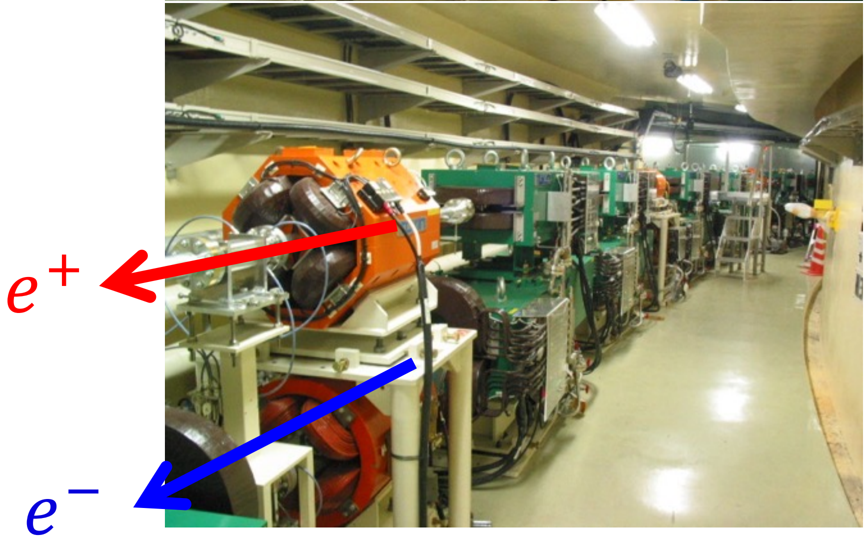




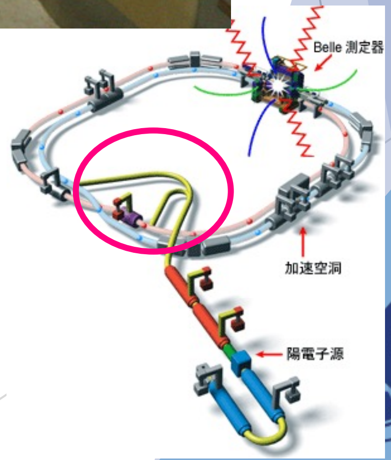
Simultaneous Top-Up Injection into four Rings+ Damping Ring

SuperKEKB: tour

Beam transport

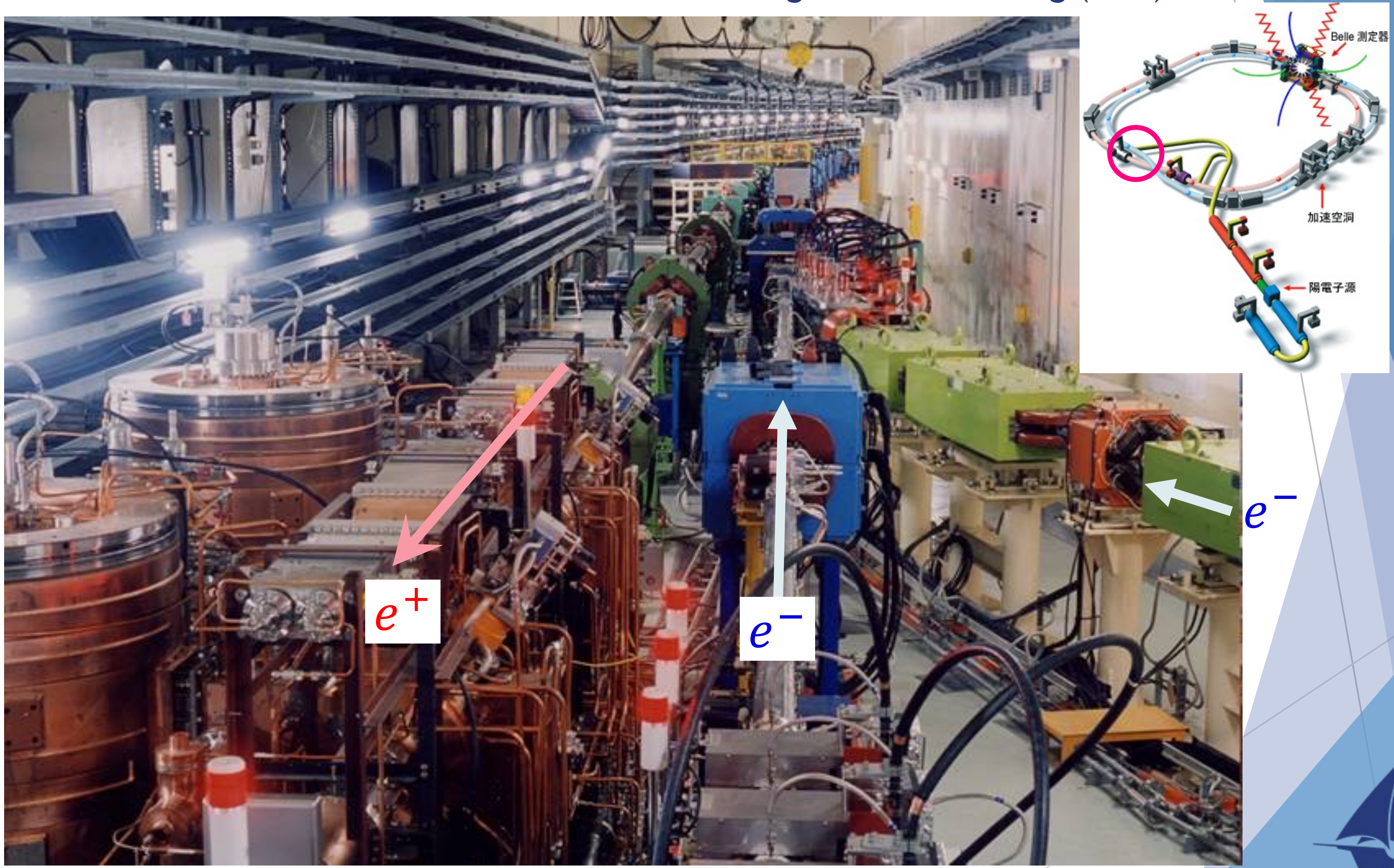


Slope section
From 5m below GL to 11m below GL (MR)



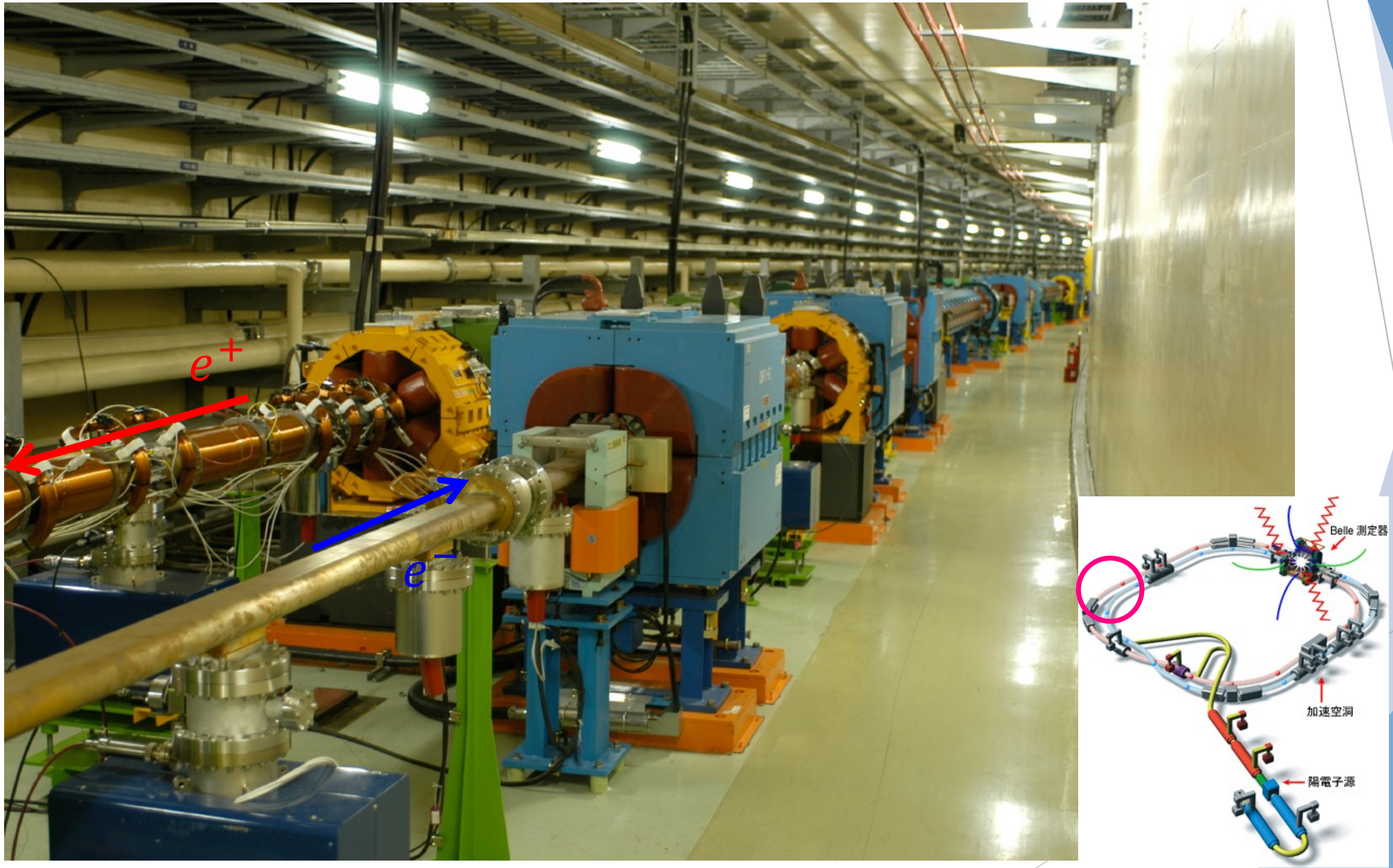
SuperKEKB: tour

Where the electron beam meets the electron ring of the main ring (HER)



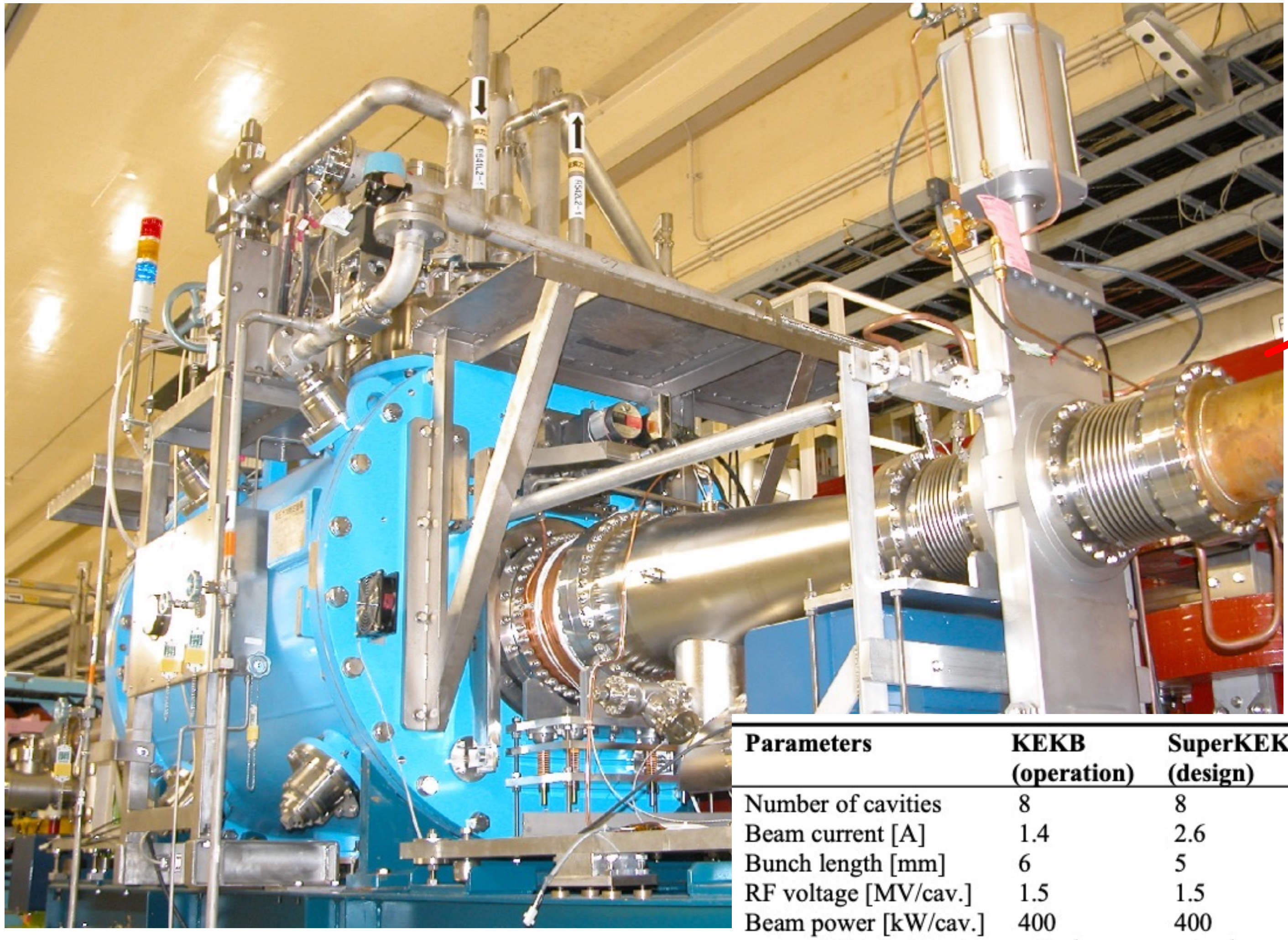
SuperKEKB: tour

Main Ring arc section
LER and HER are side by side. Distance between both rings averages roughly 1.1 m



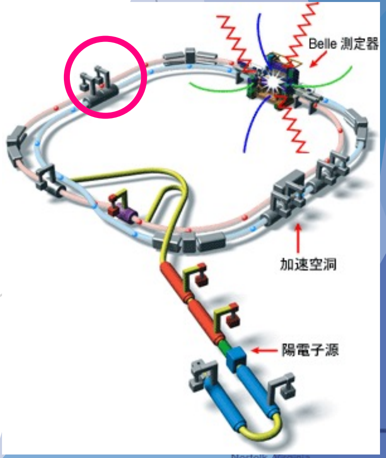
SuperKEKB: tour

Superconducting RF cavity (HER)



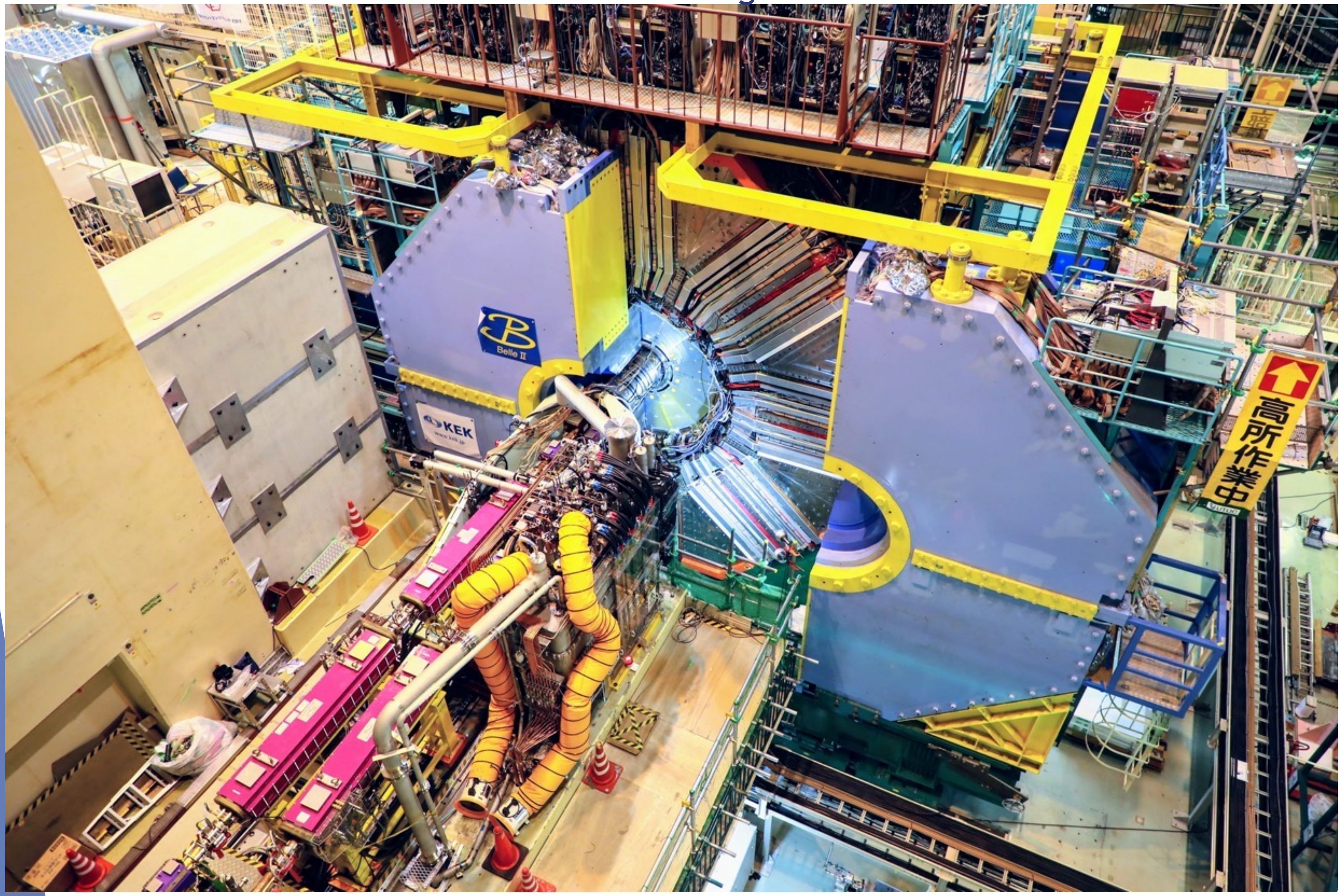
Parameters	KEKB (operation)	SuperKEKB (design)
Number of cavities	8	8
Beam current [A]	1.4	2.6
Bunch length [mm]	6	5
RF voltage [MV/cav.]	1.5	1.5
Beam power [kW/cav.]	400	400
External Q	5×10^4	5×10^4
Unloaded Q at 1.5 MV	1×10^9	1×10^9
HOM power [kW/cav.]	16	37

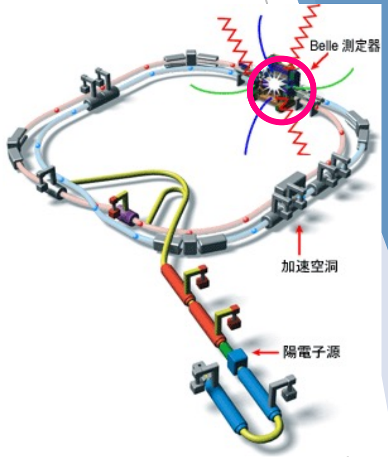
Wigglers (LER)

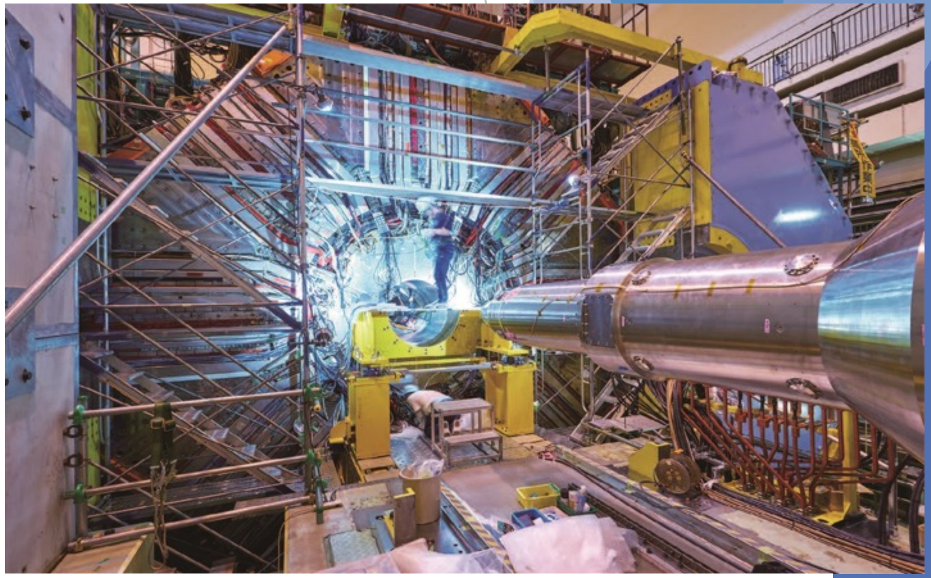


SuperKEKB: tour

Interaction Region

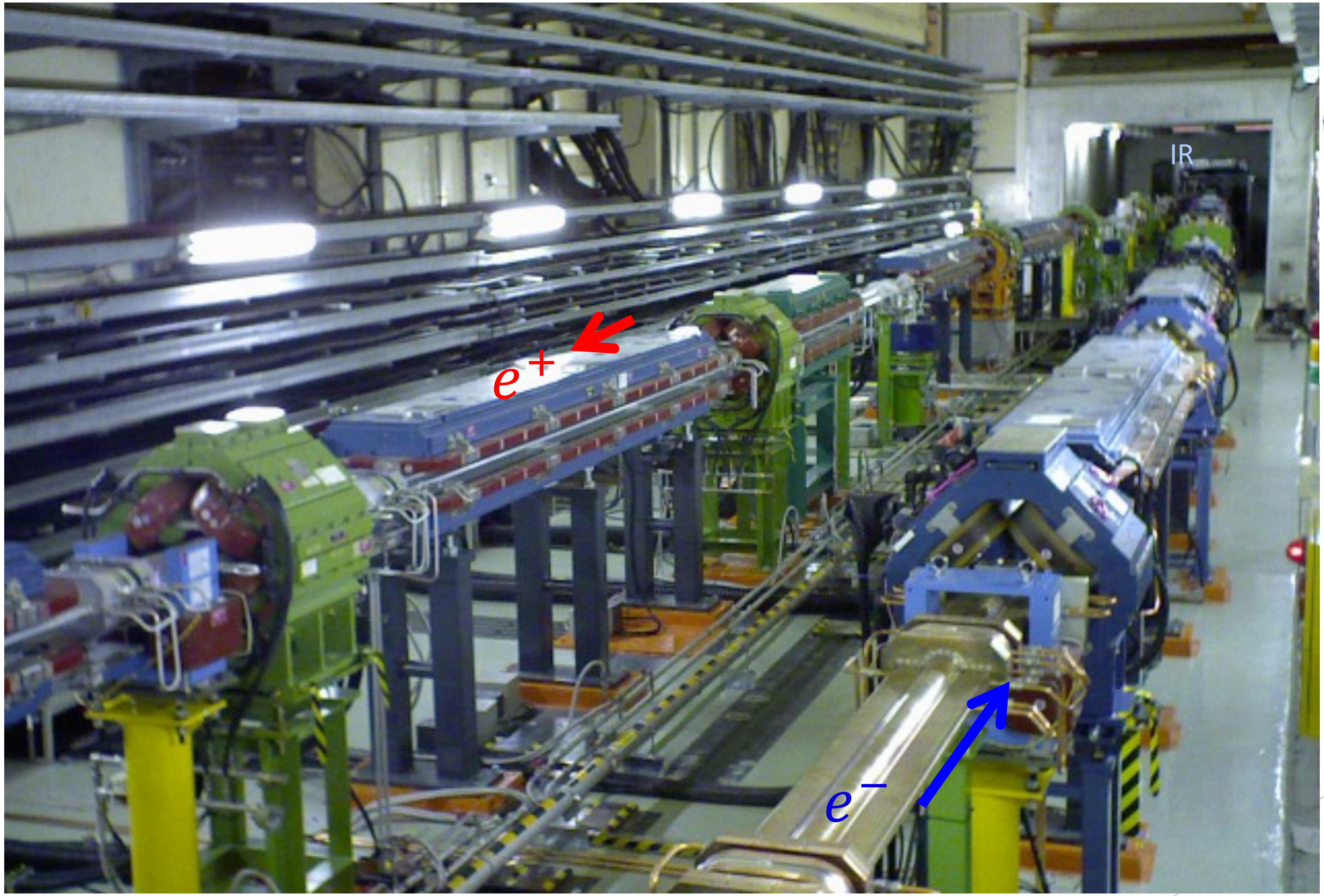


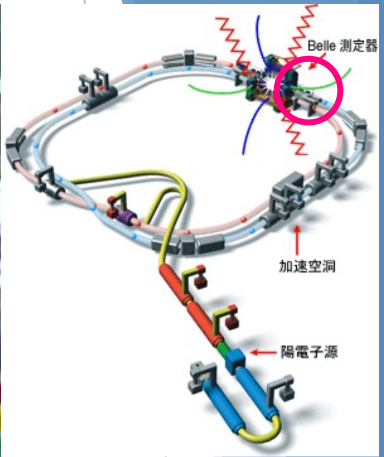




“QCS”
Final focusing superconducting magnets in the cryostat

SuperKEKB: tour

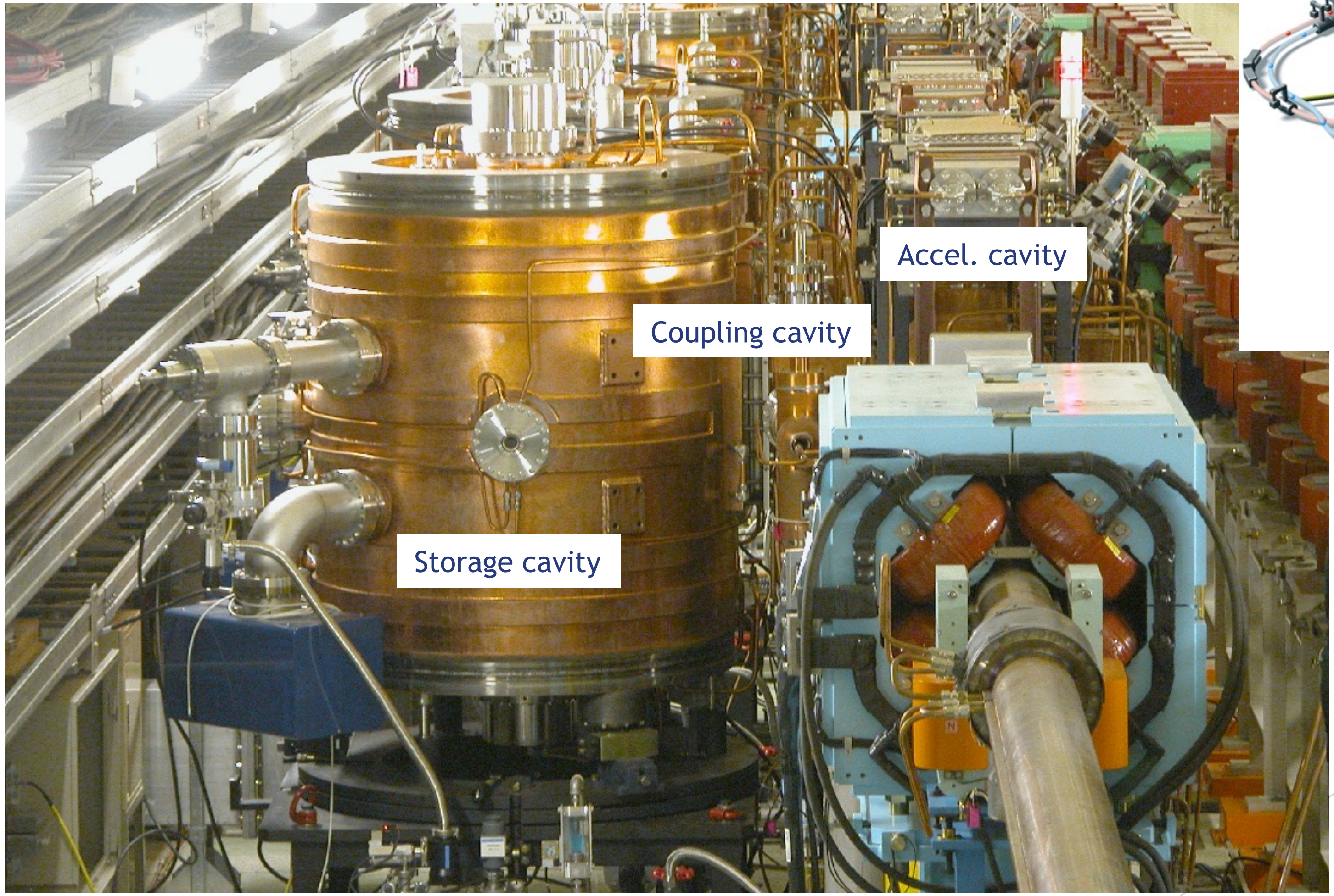




SuperKEKB: tour

SuperKEKB: tour

ARES (The Accelerator Resonantly coupled with an Energy Storage)

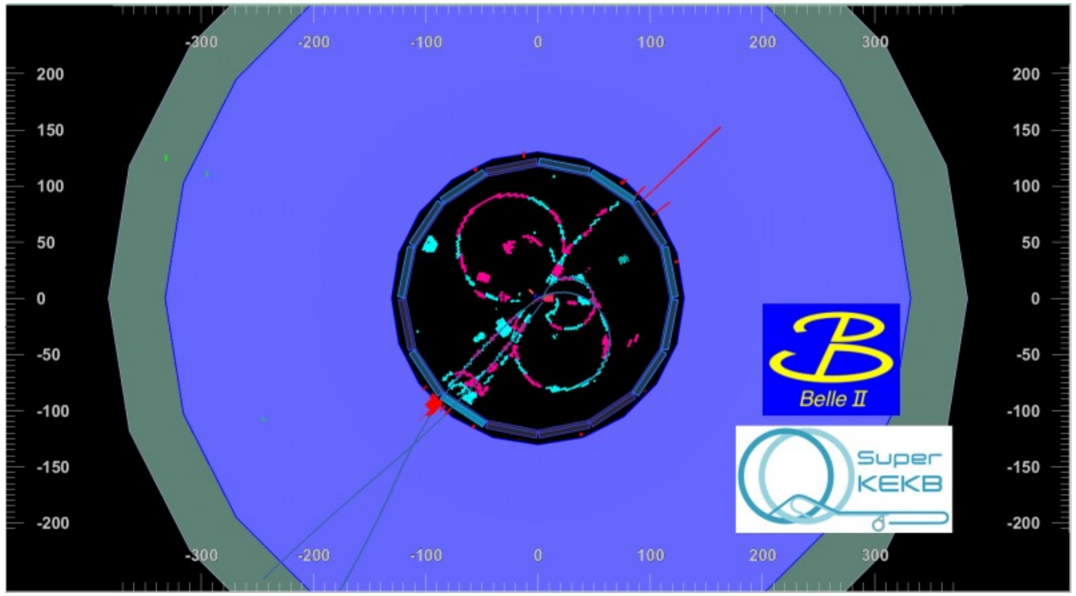


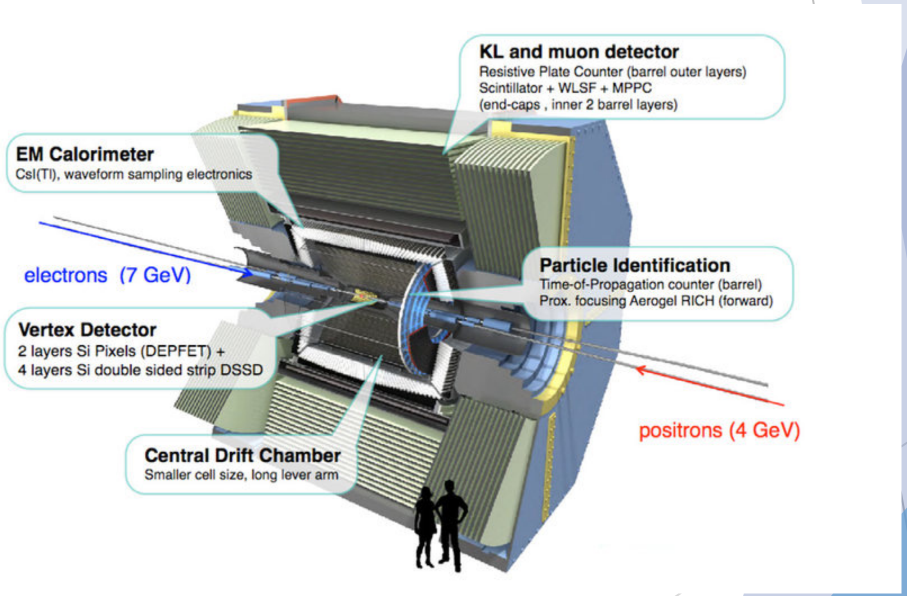
SuperKEKB: tour

Control room

History of e^+e^-colliders
TRISTAN→KEKB B-factory→SuperKEKB

SuperKEKB construction started in 2010
Great East Japan earthquake in 2011
First beam circulation in 2016 without final focusing superconducting magnets (QCS)
Commissioning with QCS/Belle II detector started in March, 2018 and
1st hadron event on April 26, 2018



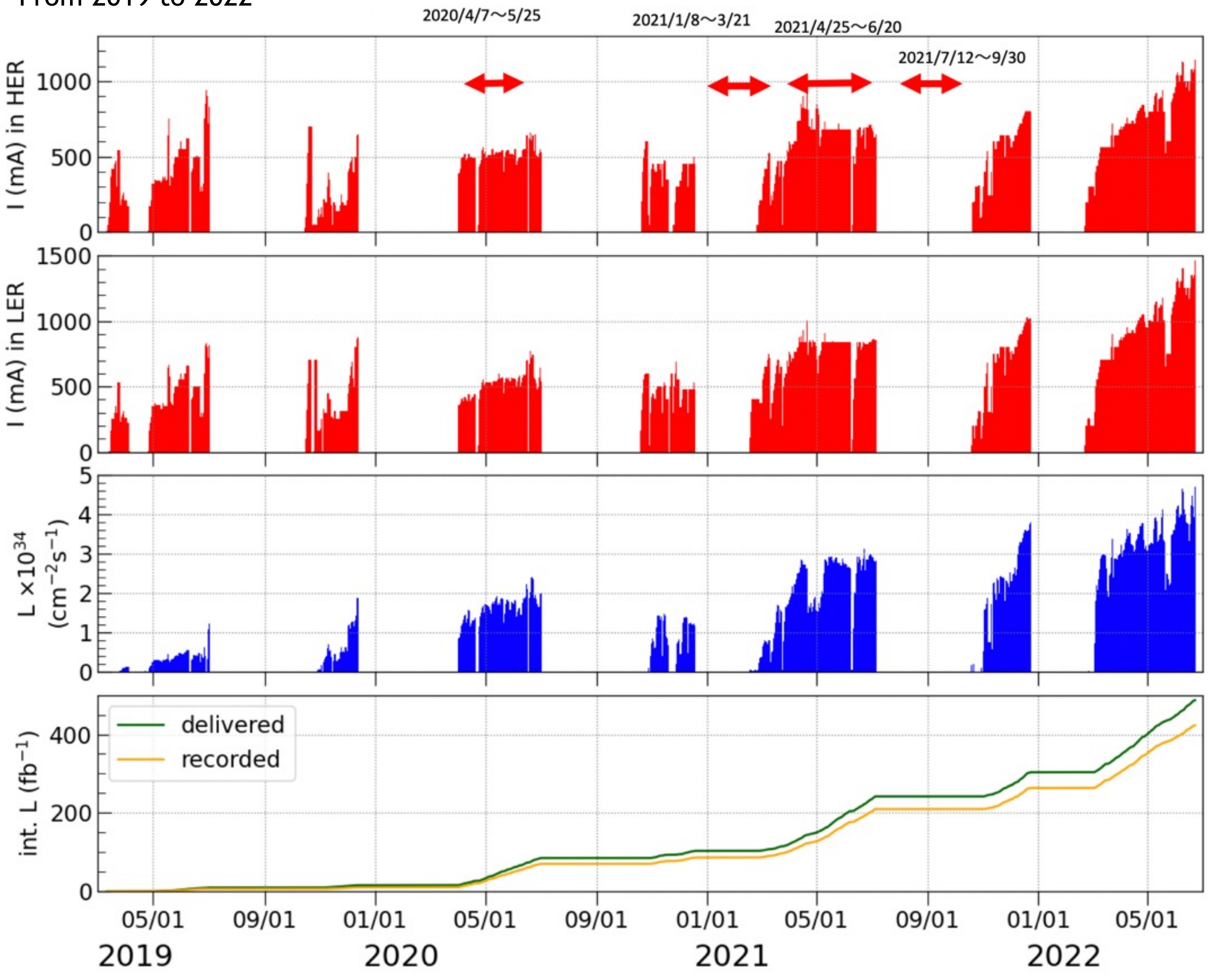


Visit
YouTube channel “A search for new Physics – The Belle II Experiment”

History of e^+e^-colliders
TRISTAN→KEKB B-factory→SuperKEKB

↔COVID-19 State emergency (Tokyo)

From 2019 to 2022



HER beam current reached 1145 mA

LER beam current reached 1460 mA

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

Integrated luminosity
424 fb^{-1} (recorded) Corresponds to ~ 40% of BELLE data)
491 fb^{-1}(delivered)

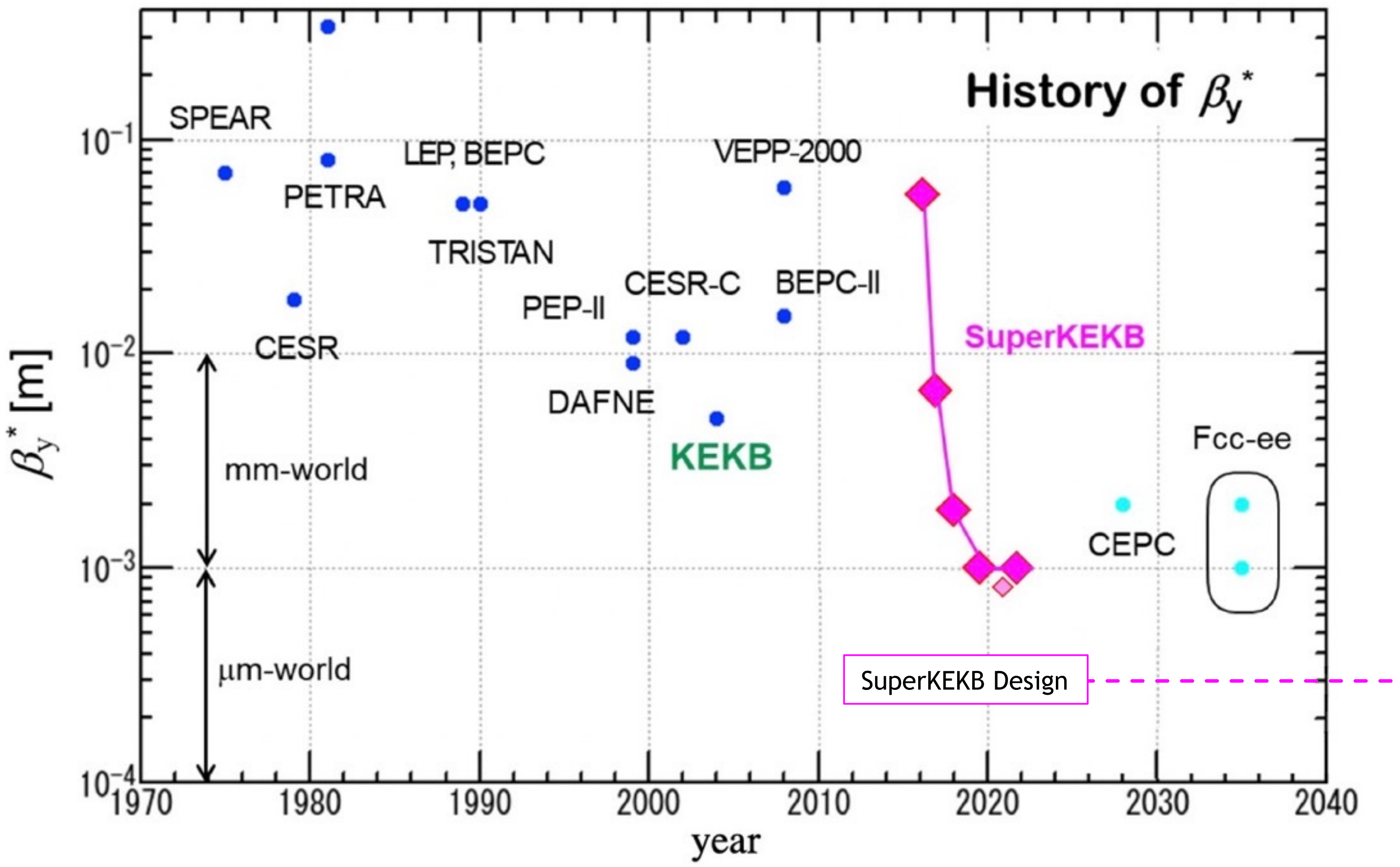
SuperKEKB luminosity already recorded more than twice the luminosity of KEKB in ~4 years.

Long shutdown1 (LS1) started in June of 2022 for improvements on the accelerators and Belle II detectors.

History of e^+e^-colliders
TRISTAN→KEKB B-factory→SuperKEKB

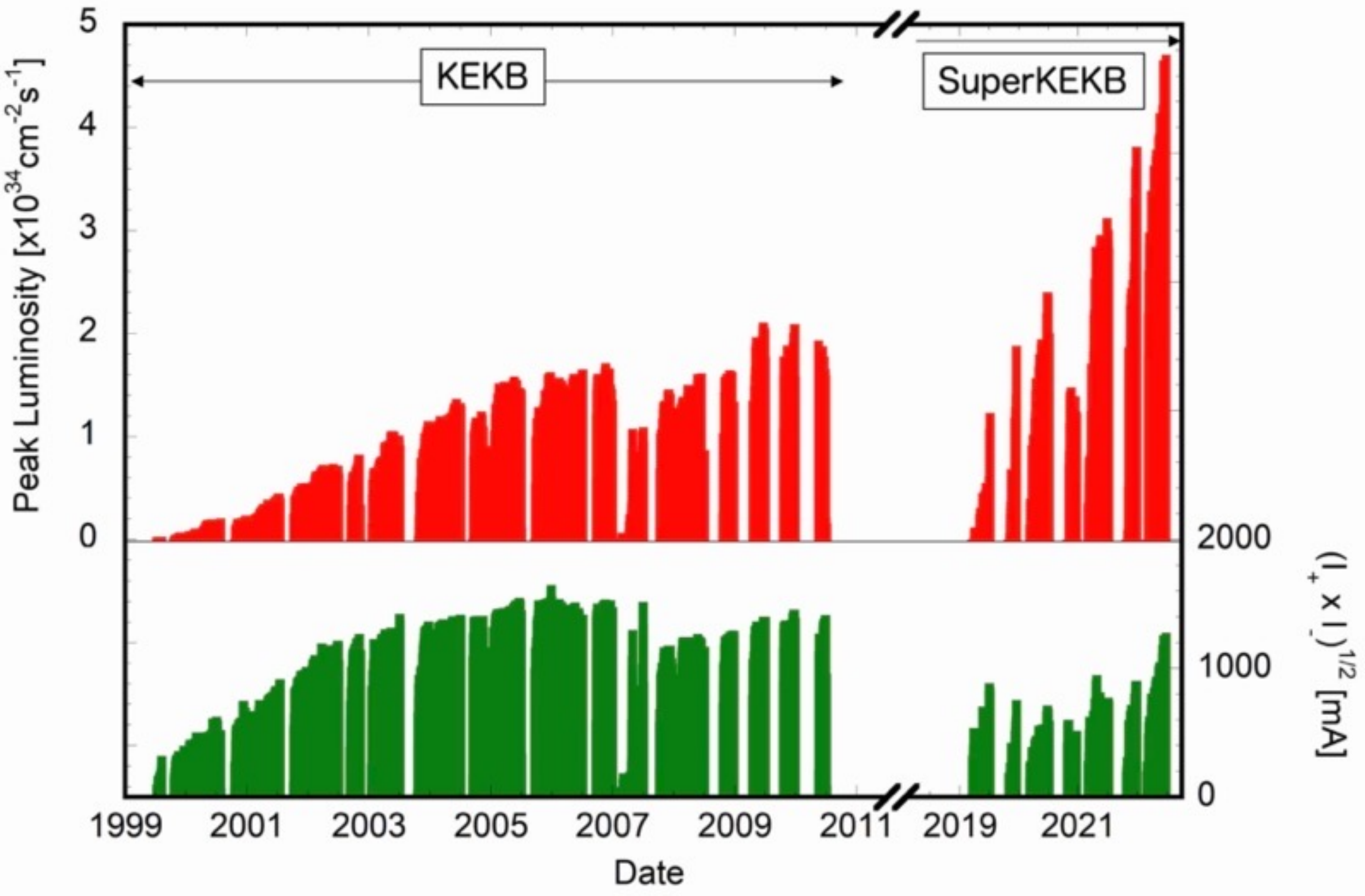
$$\sigma = \sqrt{\epsilon\beta}$$

The smaller β_y^* , the smaller σ_y^*



History of e^+e^-colliders
TRISTAN→KEKB B-factory→SuperKEKB

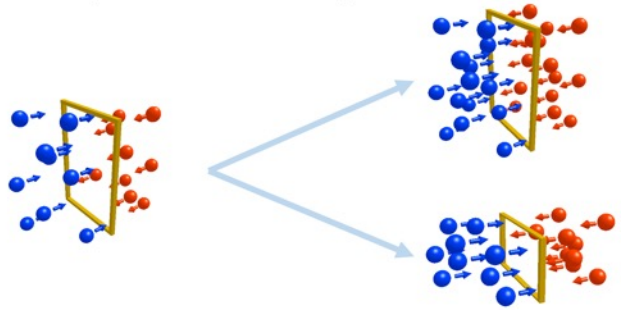
SuperKEKB can provide
higher luminosity with lower beam current than KEKB→ "eco" machine



History of e^+e^-colliders
TRISTAN→KEKB B-factory→SuperKEKB

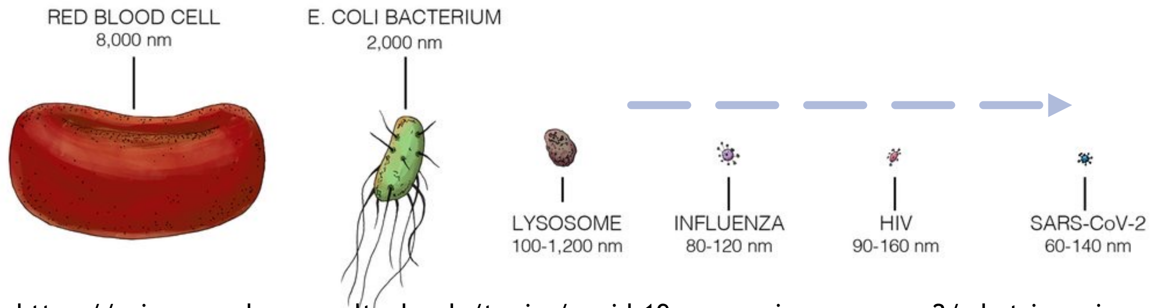
Machine parameters as of June 8th 2022, with the design values in ( )

Papameter	LER	HER	unit
Beam current	1321 (3600)	1099 (2600)	mA
# of bunches	2249 (2500)		
Bunch current	0.587	0.489	mA
β_x^*/β_y^*	80/1.0 (32/0.27)	60/1.0 (25/0.30)	mm
Beam-Beam Parameter ξ_y	0.0407 (0.088)	0.0279 (0.081)	
σ_y^*	0.215 (0.048)	0.215 (0.062)	µm
tunes (x/y)	44.525/46.589	45.532/43.573	
Specific luminosity($\times 10^{31}$)	7.21		$cm^{-2}s^{-1}/mA^2$
Luminosity($\times 10^{34}$)	4.65 (60)		



Challenges
We need to double (or more) bunch currents

We need to shrink the beam size by about 3 times
- instability
- injector
- beam lifetime
- detector background
- collimator control

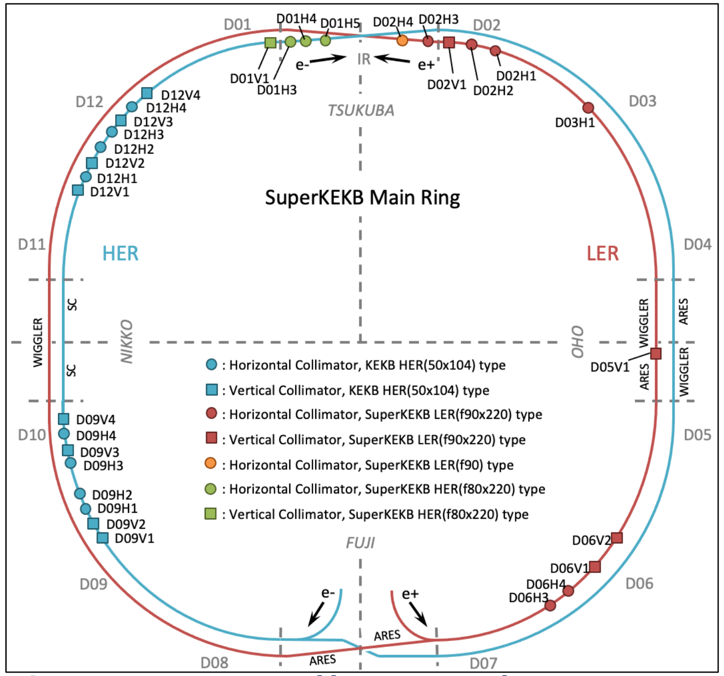


https://scienceexchange.caltech.edu/topics/covid-19-coronavirus-sars-cov-2/what-is-a-virus

History of e^+e^-colliders TRISTAN→KEKB B-factory→SuperKEKB

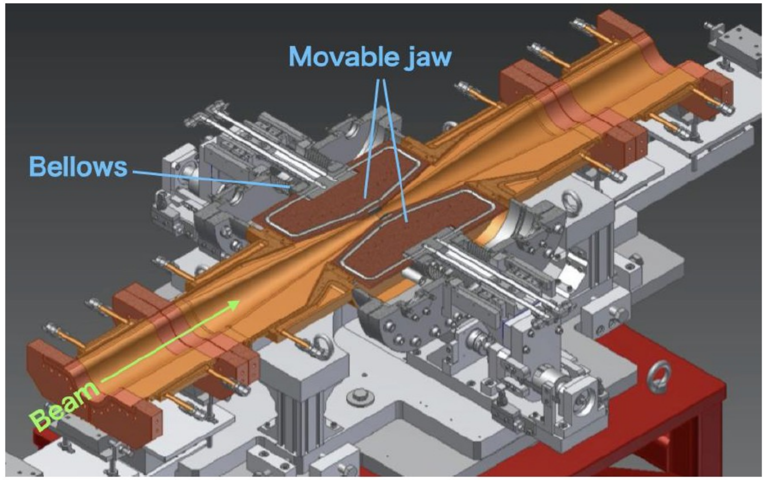
Collimators must efficiently remove stray particles and provide protection against uncontrolled losses.

- protection against detector and machine components
- detector background reduction

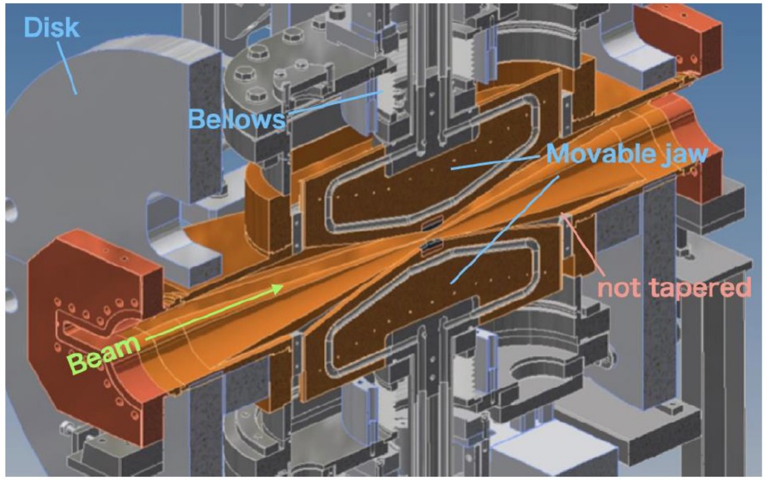


SuperKEKB collimator locations

SuperKEKB collimators



Horizontal direction

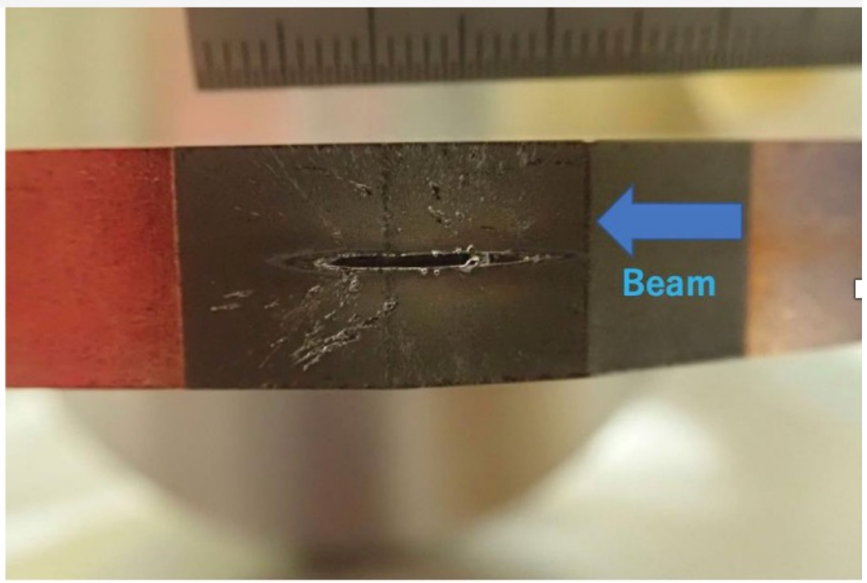


Vertical direction

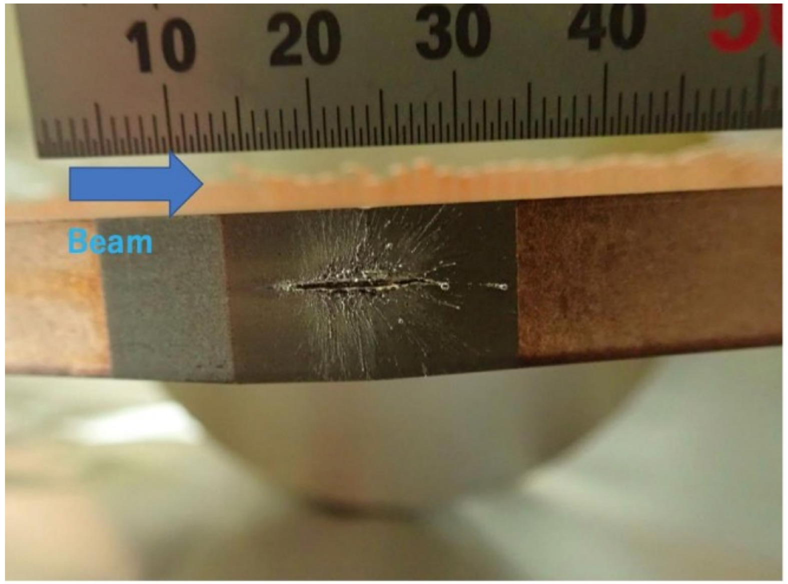
History of e^+e^-colliders
TRISTAN→KEKB B-factory→SuperKEKB

Difficulties of increasing beam currents

Damaged collimators



D02V1 top side (95 μSv/h)



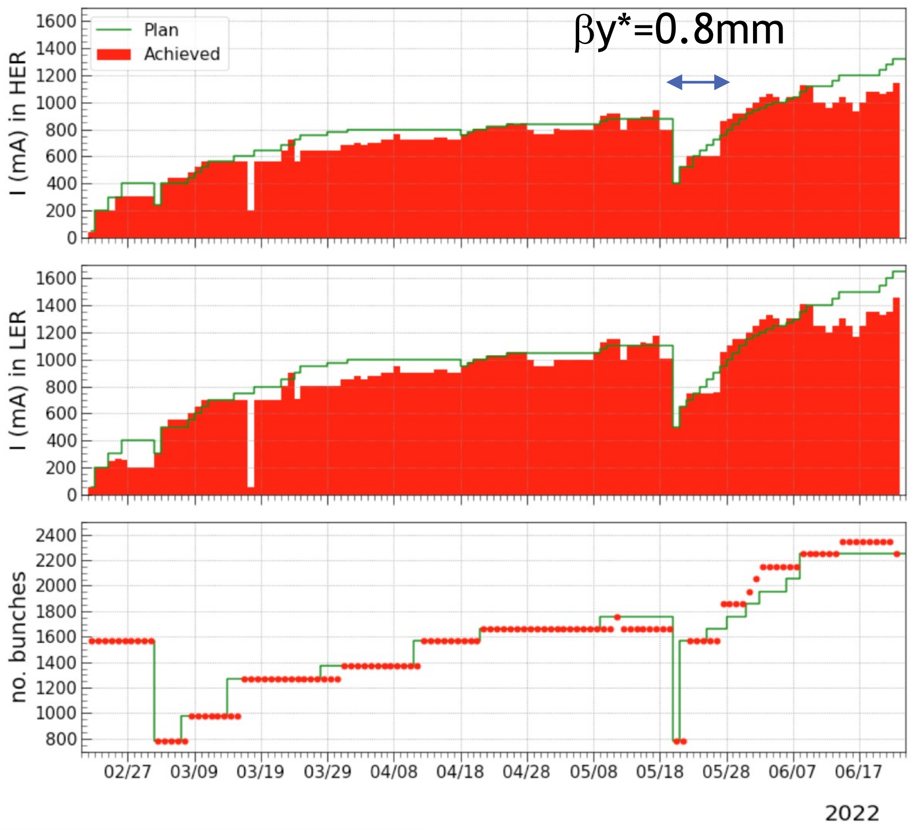
D02V1 bottom side (38 μSv/h)

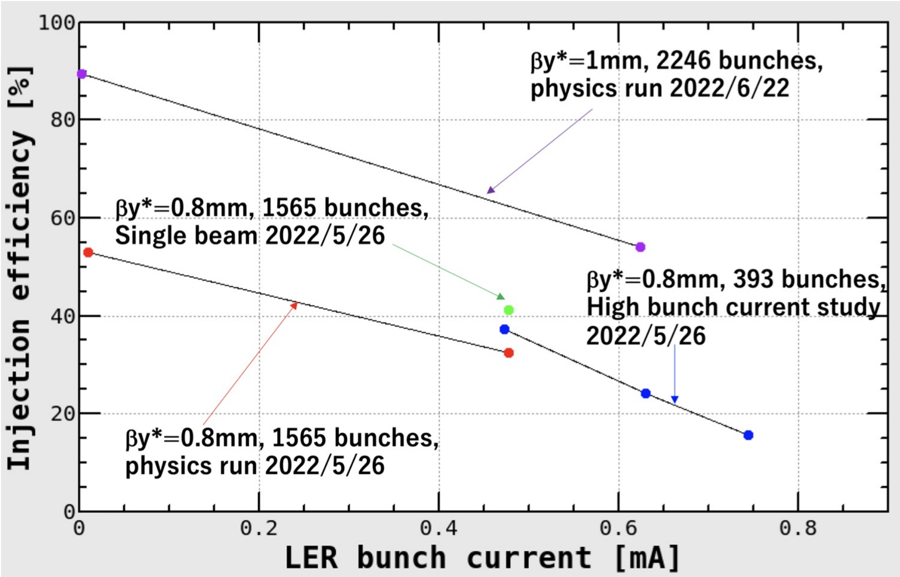

Replacing the damaged and radiated collimator

Due to "sudden beam loss (SBL)"
SBL issue is still a mystery.
A major obstacle for increasing beam currents, i.e., luminosity increase.

History of e^+e^-colliders
TRISTAN→KEKB B-factory→SuperKEKB

Injection efficiency becomes lower at higher bunch current and lower β_y^*





We tried squeezing β_y^* down to 0.8 mm for a short while.
Beam lifetime reduction > injection at 0.8 mm

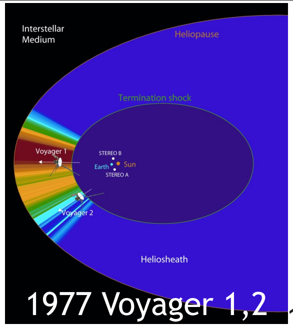
Better beam injection is needed to lowering β_y^* further.

- Technologies and expertise have been handed down from TRISTAN to KEKB B-Factory and SuperKEKB.
- SuperKEKB has achieved and been updating world records in the peak luminosity.
- We face challenges as a luminosity frontier machine
  - Difficulty in increasing bunch current
    - Sudden Beam Loss
    - Detector background, collimator damage
  - Squeezing the beam size down
    - Balance among injection charge, injection efficiency, beam quality (emittance) of the injected beam, MR beam lifetime and detector background.
- Solving the problems and aim at the peak luminosity of $1 \times 10^{35} cm^{-2} s^{-1}$ and higher.
- Our passion and dedication continue, from TRISTAN to SuperKEKB and to the future accelerator.

Three generations of e^+e^- colliders at KEK

KEK established in 1971

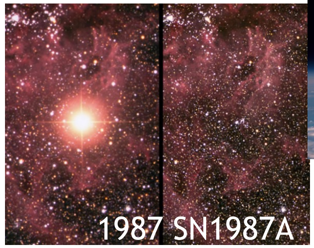
	1970	1980	1990	2000	2010	2020
TRISTAN	Proposal	Construction, Commisioning	Commisioning, Shutdown			
KEKB		Proposal	Construction	Commissioning	Shutdown	
SuperKEKB				Proposal	construction	Commissioning →→→ →→→



1977 Voyager 1,2

1981 Columbia

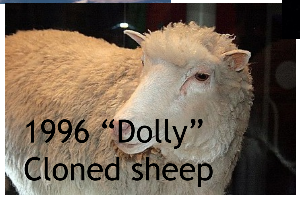
1986 HTS

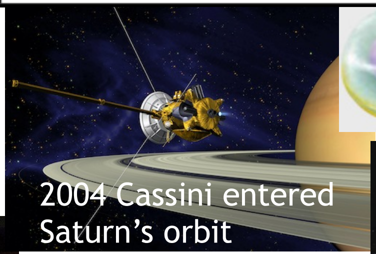

1987 SN1987A

Kamiokande
IMB


1990 Hubble telescope

1989 WWW


1996 "Dolly" Cloned sheep


2004 Cassini entered Saturn's orbit

SNS, Facebook, Twitter, Instagram

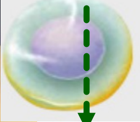
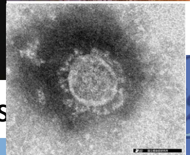



Image courtesy NASA's DC-8 Airborne Laboratory

2010 "Hayabusa" returns


2021 Captain Kirk goes to the space, SpaceX


COVID-19

Parameters	Unit	KEKB (achieved) LER	KEKB (achieved) HER			SuperKEKB (design) LER		SuperKEKB (design) HER	
Beam energy	GeV	3.5	8.0			4.0		7.0	
Beam current	A	2.0	1.4			3.6		2.6	
Bunch length	mm	6–7	6–7			6		5	
Number of bunch		1585	1585			2500		2500	
Total RF voltage	MV	8	13–15			10–11		15	
Energy loss/turn	MV	1.6	3.5			1.76		2.43	
Total beam power	MW	3.3	5.0			~8		~8	
RF frequency	MHz	508.9				508.9			
Revolution frequency	kHz	99.4				99.4			
Cavity type		ARES	ARES		SCC	ARES		ARES	SCC
No. of cavities		20	10	2	8	8	14	8	8
Klystron : cavities		1:2	1:2	1:1	1:1	1:2	1:1	1:1	1:1
No. of klystron stations		10	5	2	8	4	14	8	8
RF voltage/cavity	MV	0.4	0.31	0.31	1.24	~0.5	~0.5	~0.5	1.3–1.5
Beam poser/cavity	kW	200	200	550	400	200	600	600	400
R/Q of cavity	Ω	15	15	15	93	15	15	15	93
Loaded Q (Q_L)	$\times 10^4$	3	3	1.7	~5	3	1.7	1.7	~5

Machine parameters (June, 2022)

	LER	HER	
Beam Energy	4.0	7.0	GeV
Circumference	3016		m
Crossing angle	83		mrad
Crab waist ratio	80	40	%
Beam current @Maximum Luminosity	1.321	1.099	A
Number of bunches	2249		
Bunch current @Maximum Luminosity	0.5873	0.4887	mA
Total RF voltage V_c	9.12	14.2	MV
Synchrotron tune ν_s	-0.0233	-0.0258	
Bunch length σ_z	5.69	6.03	mm
Momentum compaction α_c	2.98E-4	4.54E-4	
Betatron tune ν_x / ν_y	44.524/46.592	45.532/43.575	
Beta function at IP β_x^* / β_y^*	80/1	60/1	mm
Measured vertical beam size (XRM) @IP σ_y^*	0.224	0.224	μm
Vertical beam-beam parameters ξ_y	0.0407	0.0279	
Beam lifetime	8	24	min.
Luminosity (Belle 2 CsI)	4.65		10^{34} cm^{-2} s^{-1}