Introduction to SuperKEKB

v6

Tom Browder, University of Hawaii at Manoa

Introduction to the basics of accelerator physics for electron/positron storage rings

Luminosity Master Equation(s) (large crossing angle, nanobeam case)

B factory review (KEKB and PEP-II)

SuperKEKB overview (how is it similar to and different from the past generation of machines)

Mysteries + Near Future Plans

Feel free to interrupt with questions and comments.

One useful resource: The 1969 typewritten notes of Matt Sands.

SLAC-121
UC-28
(ACC)

THE PHYSICS OF ELECTRON STORAGE RINGS
AN INTRODUCTION

MATTHEW SANDS*
UNIVERSITY OF CALIFORNIA, SANTA CRUZ
SANTA CRUZ, CALIFORNIA 95060

PREPARED FOR THE U. S. ATOMIC ENERGY
COMMISSION UNDER CONTRACT NO. AT(04-3)-515

November 1970

Reproduced in the USA. Available from the National Technical Information Service, Springfield, Virginia 22151.
Price: Full size copy $3.00; microfiche copy $.65.

$26.30 in 2025 dollars

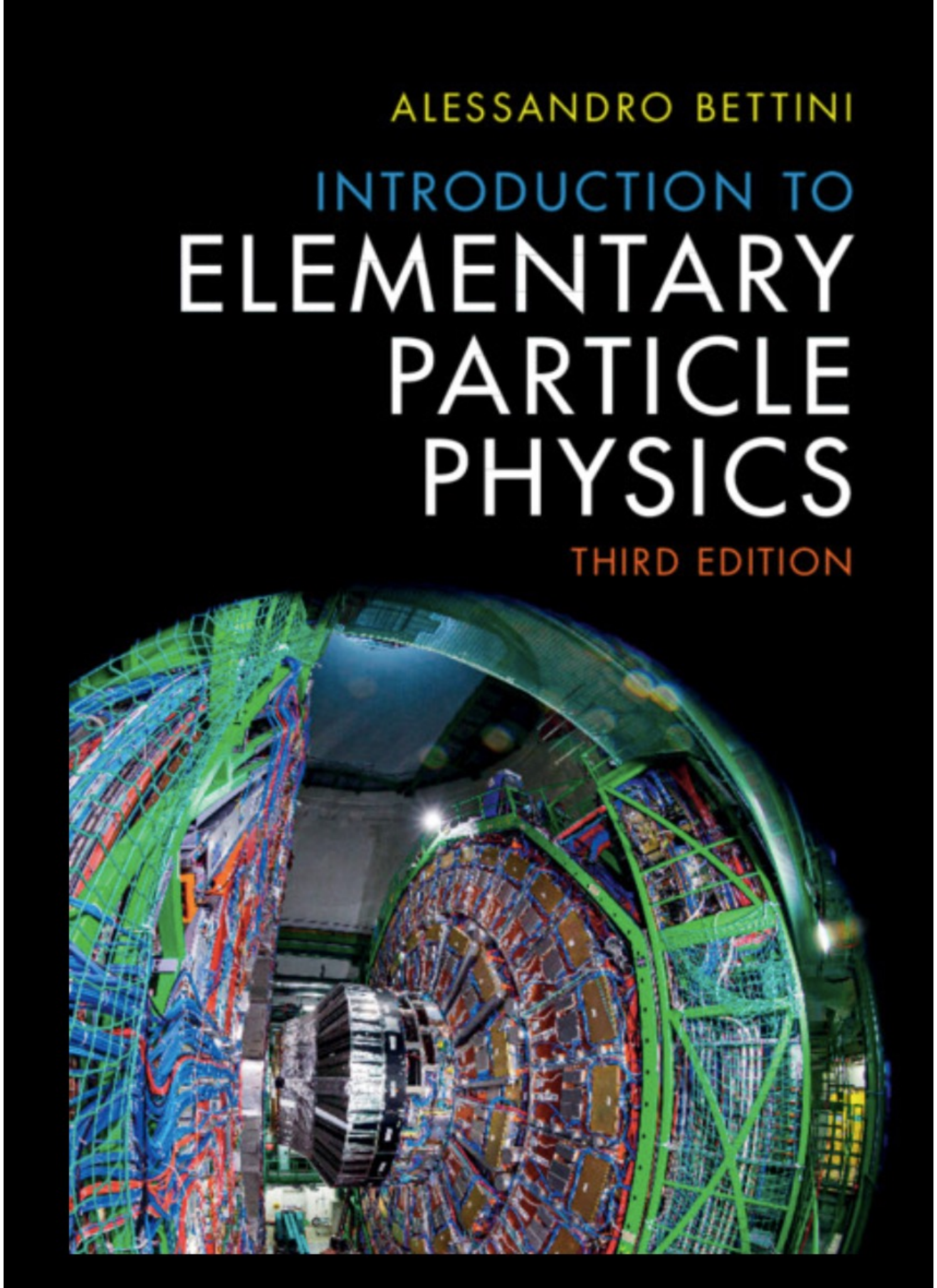
Dog-eared Xerox copies used to be common. Now available as a pdf.

*Consultant to the Stanford Linear Accelerator Center.

A more advanced textbook, Accelerator Physics, S.Y. Lee, 4th edition is now Open-Access

Another more conventional resource: Particle Physics Textbooks.

The 3rd edition of Bettini (2024) is "Open-Access".



Learning goals at the Belle II Summer Workshop

1. Understand enough of the basics of SuperKEKB to do BCG (Belle II Commissioning Group) and experimental control room shifts.

2. Understand how the accelerator and luminosity are related. Learn how SuperKEKB and the previous accelerators are different.

3. Understand enough of the accelerator to study and mitigate beam backgrounds (See talks at the B2SW by Dr. Qingyuan Liu and Prof. Keisuke Yoshihara).

Stretch goals for those who are interested:

4. Become an MDI (Machine Detector Interface) expert

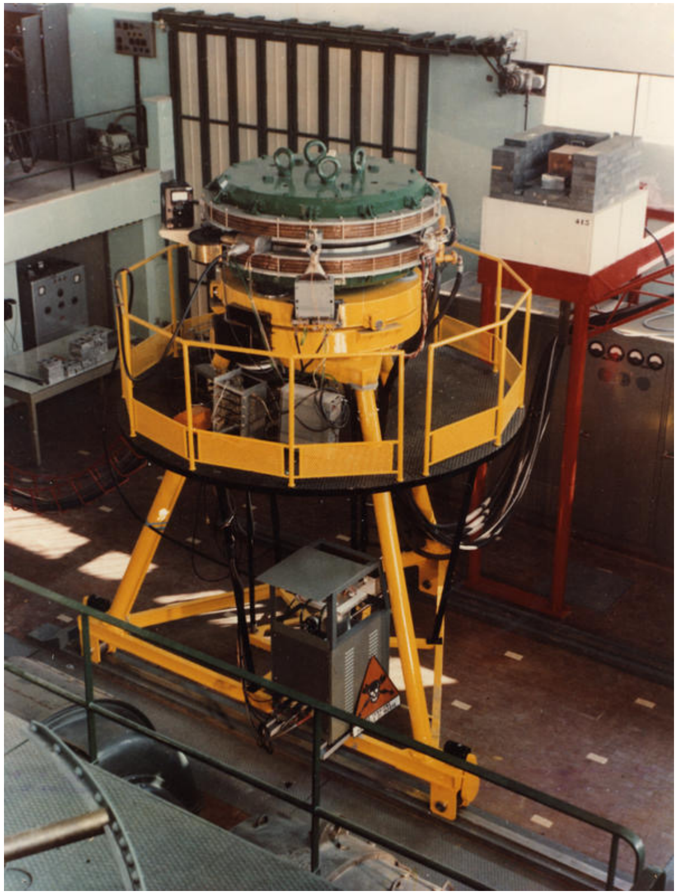
5. Become an accelerator physicist. According to the US National Academy of Sciences 2025, we need a factor of 3-4 x more accelerator physicists to realize current and future colliders (e.g. FCCee, EIC, muon collider), light sources, and industrial applications.

From the first electron-positron (e^+e^-) collider to SuperKEKB

G. K. O'Neill had conceived and built the first e- e- "storage ring" at Stanford in the late 1950's.

Bruno Touschek built the first (250 MeV) e^+e^- storage ring and collider at Frascati, Italy.

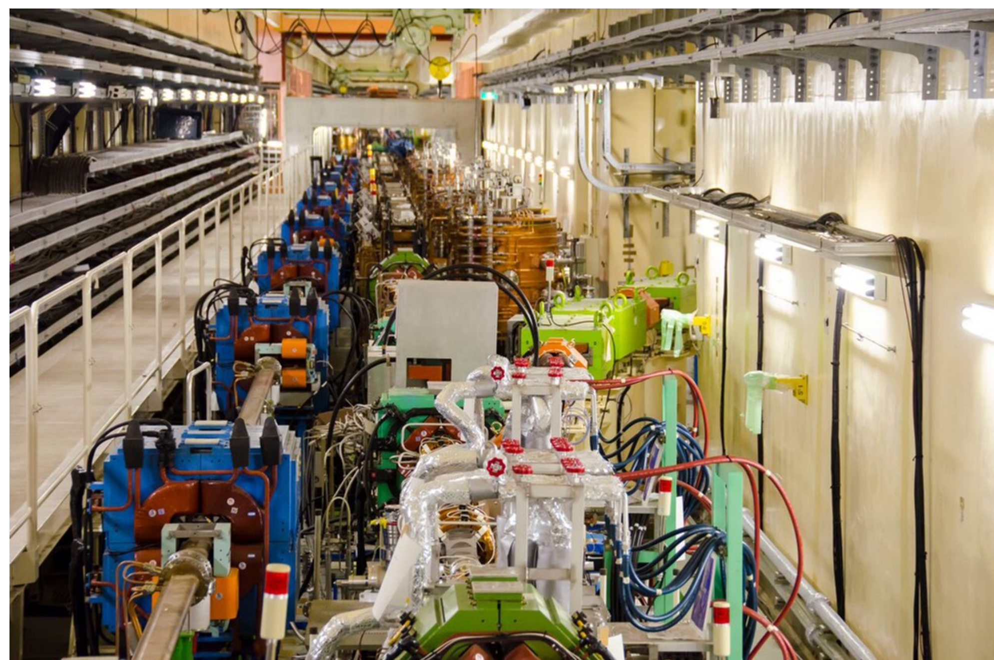
This was followed by improved machines at BINP in Novosibirsk, Russia [Siberia], at SLAC in Stanford, CA, USA (incl. SPEAR, PEP, DESY, CESR, LEP@CERN, , PEP-II, KEKB)



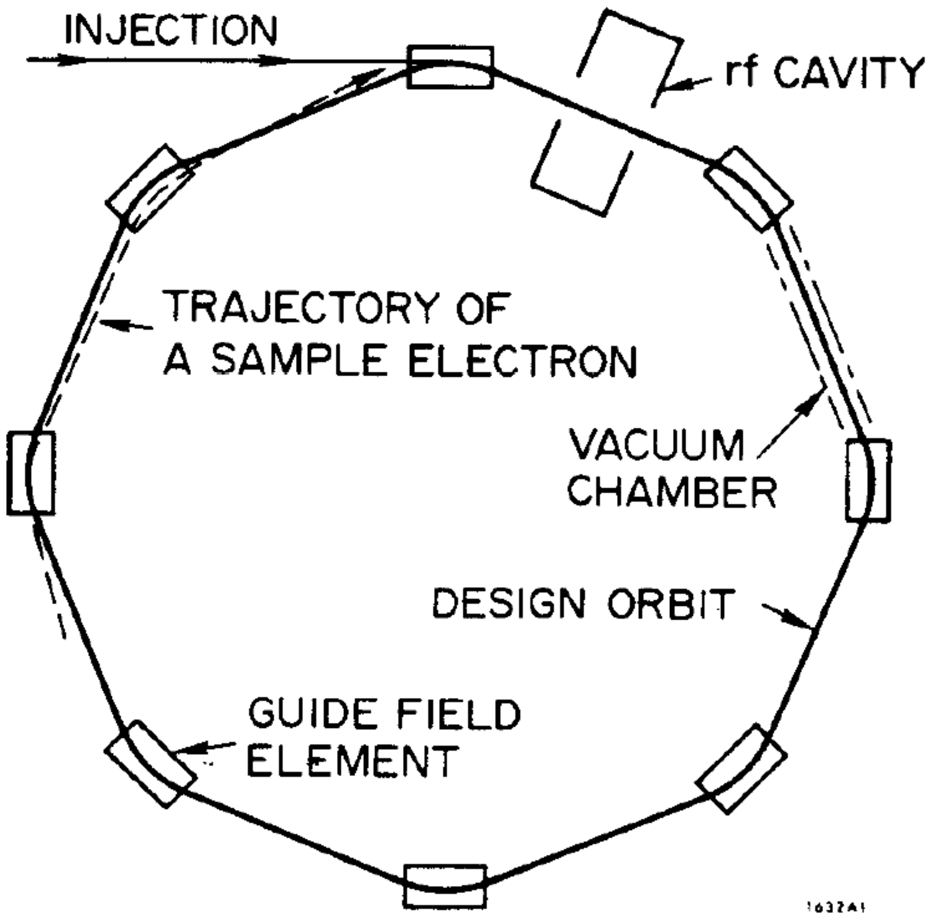
Annello Di Accumulazione (1960)

Courtesy of INFN

2016: Circumference 3km, 4 (e+) GeV on 7 GeV (e-)



Back to basics

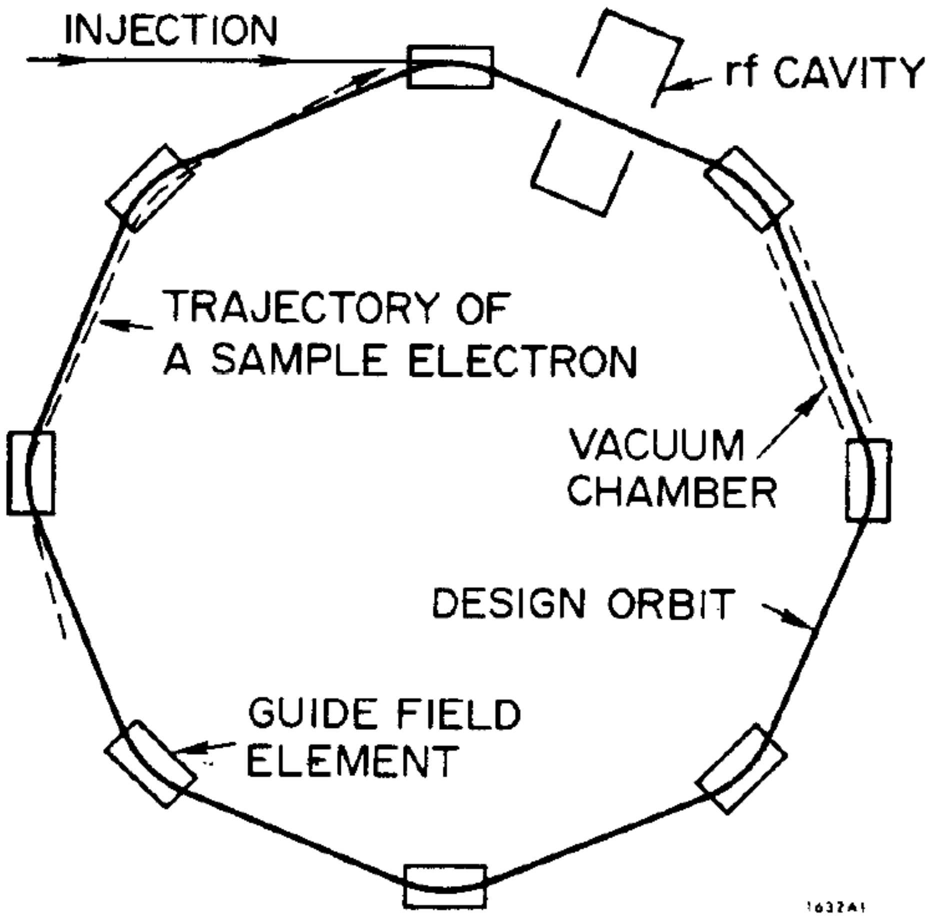


A short pulse of a beam of electrons ("a bunch") is injected into a vacuum chamber in a more-or-less circular magnetic guide field. The guide field leads the electrons around the ring to make a stored beam.

Schematic diagram of an electron storage ring.

M. Sands and the SLAC drafting room

Back to basics



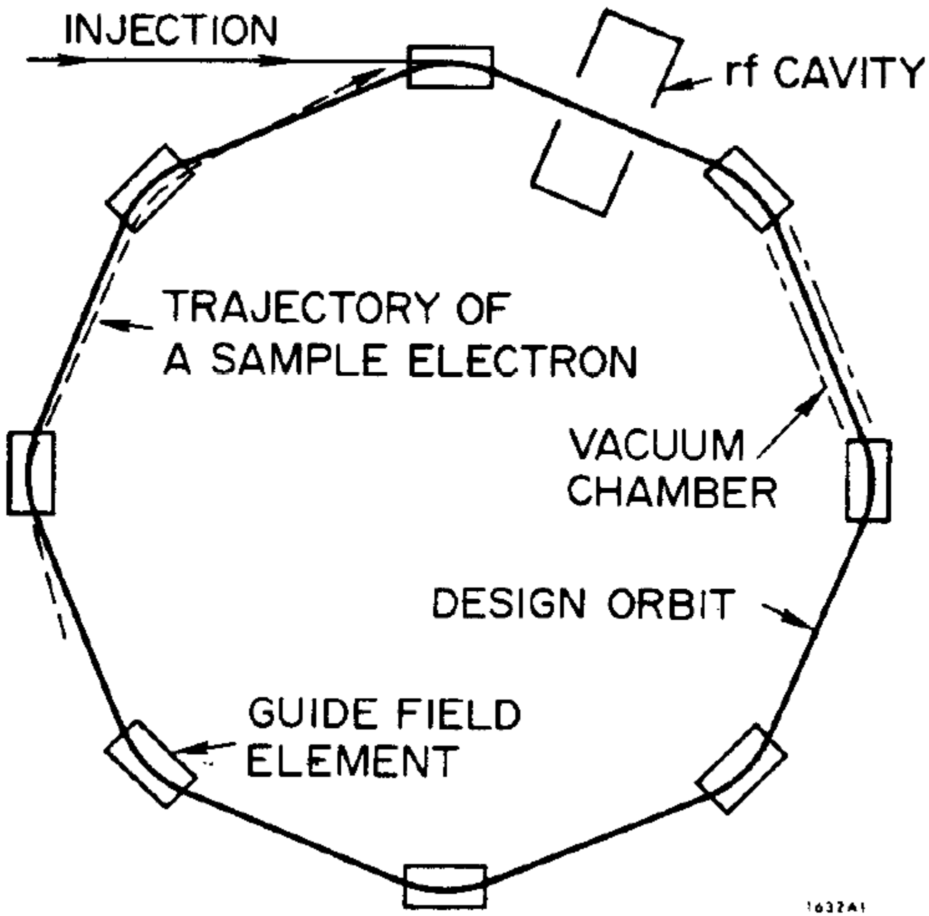
A short pulse of a beam of electrons ("a bunch") is injected into a vacuum chamber in a more-or-less circular magnetic guide field. The guide field leads the electrons around the ring to make a stored beam.

The guide field has focusing properties, which drives all electrons an ideal design orbit and causes them to execute lateral (radial and vertical) betatron oscillations about the ideal closed path.

Schematic diagram of an electron storage ring.

M. Sands and the SLAC
drafting room

Back to basics



A short pulse of a beam of electrons ("a bunch") is injected into a vacuum chamber in a more-or-less circular magnetic guide field. The guide field leads the electrons around the ring to make a stored beam.

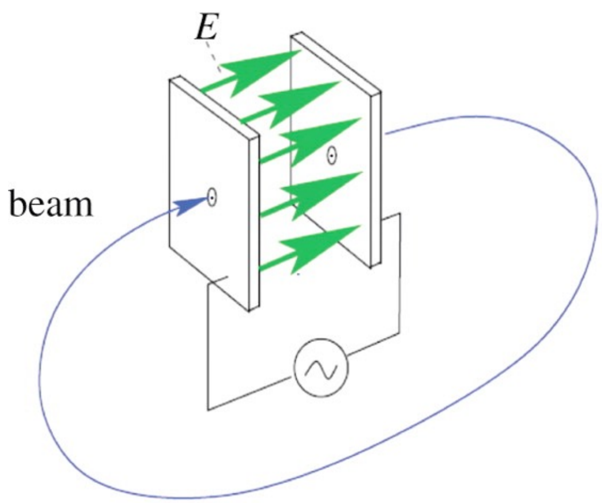
The guide field has focusing properties, which drives all electrons an ideal design orbit and causes them to execute lateral (radial and vertical) betatron oscillations about the ideal closed path.

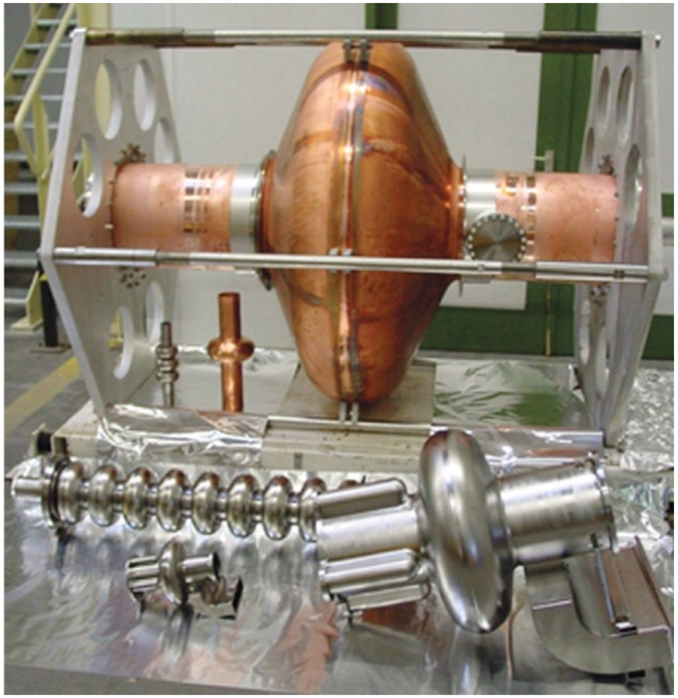
During each revolution, an electron loses a fraction of its energy by synchrotron radiation. For stored electrons this energy loss is compensated by RF cavities.

Schematic diagram of an electron storage ring.

M. Sands and the SLAC drafting room

The first stage of accelerators uses electric fields to accelerate charged particles (electron, protons, heavy ions) to high energies.





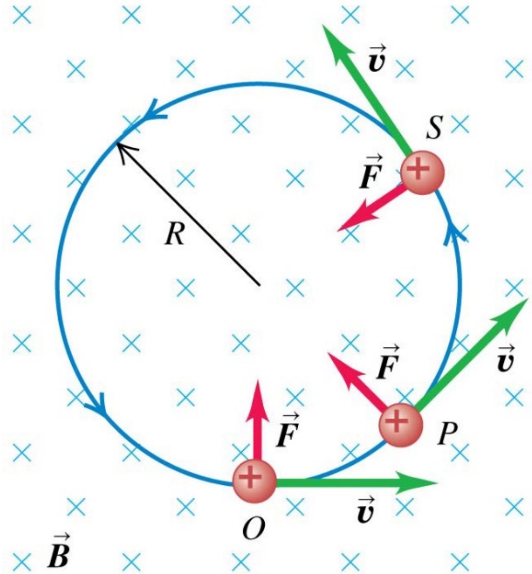
First electron linacs in the 1940's at SLAC.

$$F = qE \Rightarrow Ed = qV = U$$

Use DC High Voltage up to about 20 MeV. For higher energies, use high frequency AC voltage and carefully time each bunch of particles to obtain a series of accelerating kicks.

In a circular accelerator, use a radio-frequency (RF) voltage source.

A charge moving at right angles to a uniform $\vec{B}$ field moves in a circle at constant speed because $\vec{F}$ and $\vec{v}$ are always perpendicular to each other.



Suppose a particle is moving in a circle with velocity v in a B field (perp to the paper)

$$F = |q|vB = \frac{mv^2}{R}$$

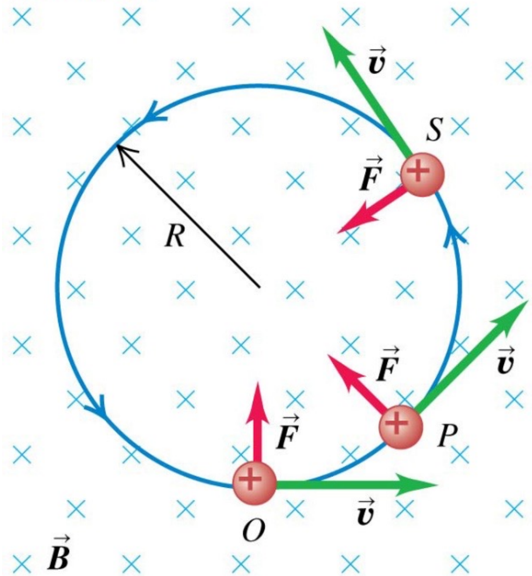
"Cyclotron Radius"

$$R = \frac{mv}{qB} \quad \Rightarrow \quad R = \frac{p}{qB}$$

"Cyclotron frequency"

$$\omega = \frac{v}{R} = v\frac{|q|B}{mv} = \frac{|q|B}{m}$$

A charge moving at right angles to a uniform $\vec{B}$ field moves in a circle at constant speed because $\vec{F}$ and $\vec{v}$ are always perpendicular to each other.



Suppose a particle is moving in a circle with velocity v in a B field (perp to the paper)

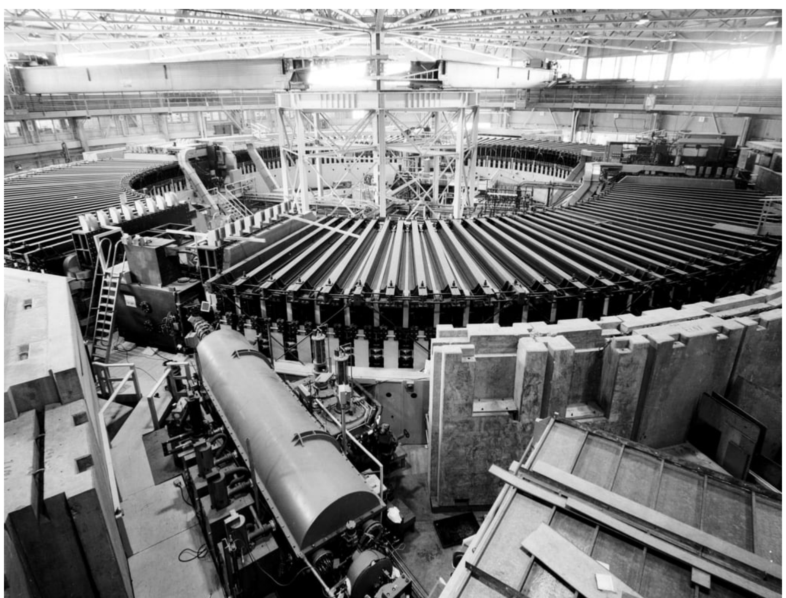
$$F = |q| vB = \frac{mv^2}{R}$$

"Cyclotron Radius"

$$R = \frac{mv}{qB} \rightarrow R = \frac{p}{qB}$$

"Cyclotron frequency"

$$\omega = \frac{v}{R} = v\frac{|q|B}{mv} = \frac{|q|B}{m}$$



The Bevatron, a fixed target proton cyclotron in the hills of Berkeley, CA. Used to discover the anti-proton. (*Requires* a very large aperture magnet).

Let's move on to the synchrotron, following Bettini's textbook.

A synchrotron contains a large number of dipole magnets to confine the beam *AND* quadrupole magnets to keep the beam stable. A synchrotron has practical small aperture magnets. With mixed units,

$$p(GeV) = 0.3B(T)R(m)$$

Example: If the radius of curvature of a synchrotron ring is 1 km and there is a constant B field of 3.3 T supplied by dipoles, what is the maximum energy that can be stored ?

$$p_{\max} = (0.3)(3.3T)10^3 m = 10^3 GeV = 1TeV$$

For conventional electromagnets, B_{max}~1.4 T; For superconducting magnets B_{max}~ 9.0 T ➔ LHC, FNAL and the HERA proton ring used superconducting magnets

There are RF (radio frequency) cavities to maintain the energy.

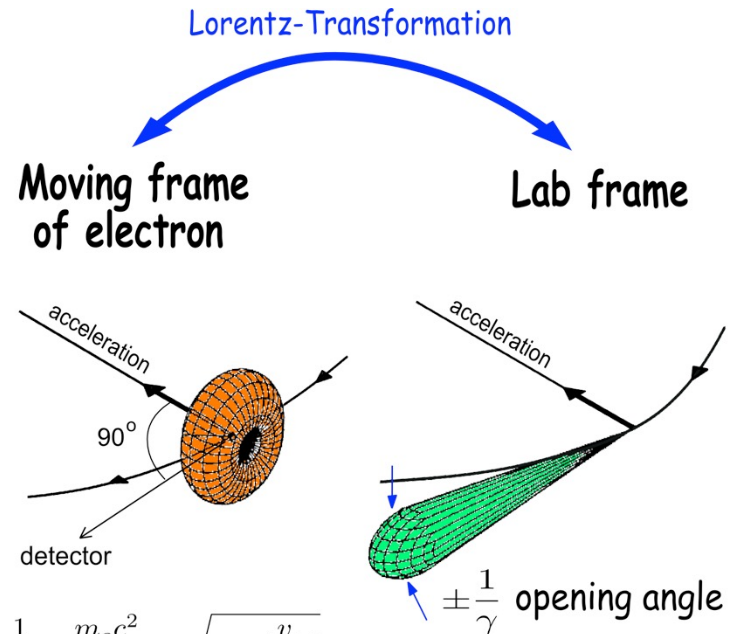
The beam circulates in a vacuum tube (why?) and is grouped into "bunches". B2SW Q: Why not continuous beams?

There is a large difference between an electron and a proton accelerator: *electrons emit synchrotron radiation (SR) when they bend.*

Remember, accelerated charges radiate.

For a 10 GeV/c electron in a 1 km radius ring, the SR loss is about 1 MeV/turn.

$$\Delta E_{SR} = \frac{4\pi}{3}\left(\frac{e^2\beta^3\gamma^4}{\rho}\right)$$



$$\frac{1}{\gamma} = \frac{m_o c^2}{E} = \sqrt{1-(\frac{v}{c})^2}$$

Question: Can one build a 1 TeV e+e- collider in a km or few km radius ring ?

Ans: No, in a 1 km ring, since the SR losses go like E^4 ; the SR loss would be 10^{12} x 1 MeV= 10^6 TeV/turn.

Question: How can you make a 1 TeV e+e- machine ? (Why is this harder than a 14 TeV p p machine ?)

Ans: e.g. ILC (a linear collider, 30 km long in Japan) or CLIC at CERN

Question: Is the SR *background* useful for anything ?

M. Sands

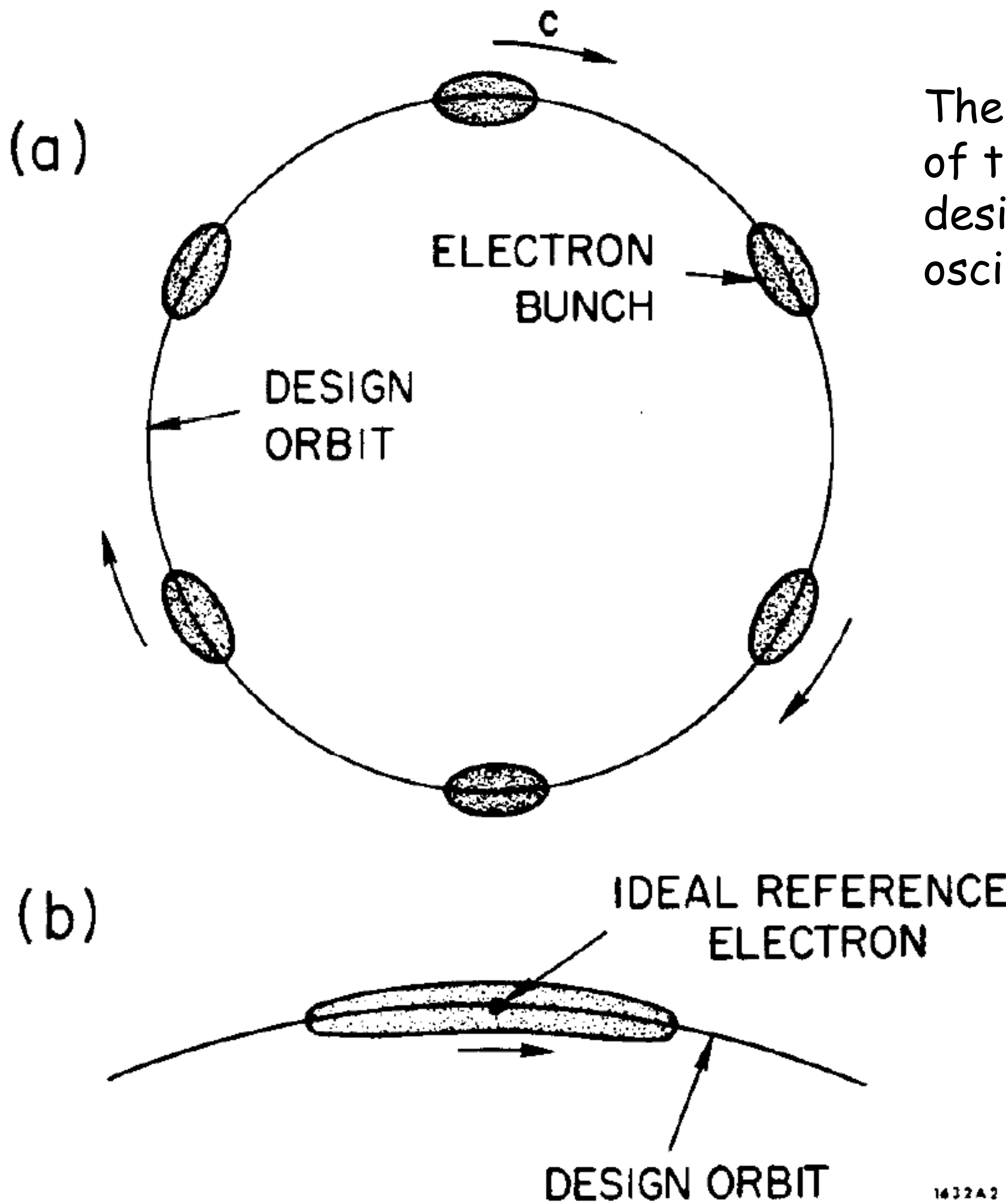


FIG. 2--Circulating bunches in a stored beam.

There are longitudinal oscillations of the beam relative to the design orbit called "synchrotron oscillations".

There are two competing effects: slow radiation damping and quantum fluctuations in SR.

In stationary conditions, an equilibrium is reached between quantum excitation and radiation damping. The bunch then is a stationary size and shape with a Gaussian distribution in s (or z). However, the shape of the bunch will depend on the local B guide field.

M. Sands

Aperture and lost electrons

-- For each coordinate of an electron there is some maximum oscillation amplitude above which the electron no longer remains captured in the bunch. We may refer to the range of stable amplitude in each coordinate at its aperture. An electron is lost from a bunch when some disturbance increases the amplitude in any coordinate beyond the corresponding aperture limit. The aperture limit for each coordinate may be set by a physical obstacle which intercepts the electrons, or by nonlinear effects in the focussing forces which lead to unbounded trajectories for large displacements from the ideal reference electron. Inj. bkgs

-- Electrons may be lost by scattering or energy loss in collisions with molecules of the residual gas in the vacuum chamber,[†] or by a large statistical fluctuation in the quantum excitation of an oscillation amplitude.

(see the B2SW talks on beam background (Qingyuan Liu) and MDI (Keisuke Yoshihara)

M. Sands

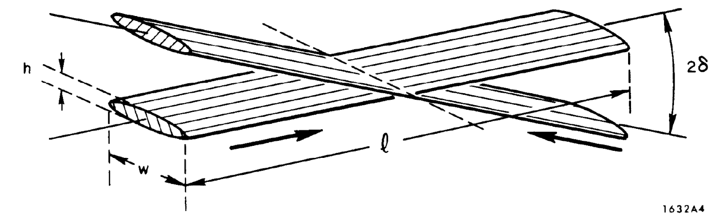
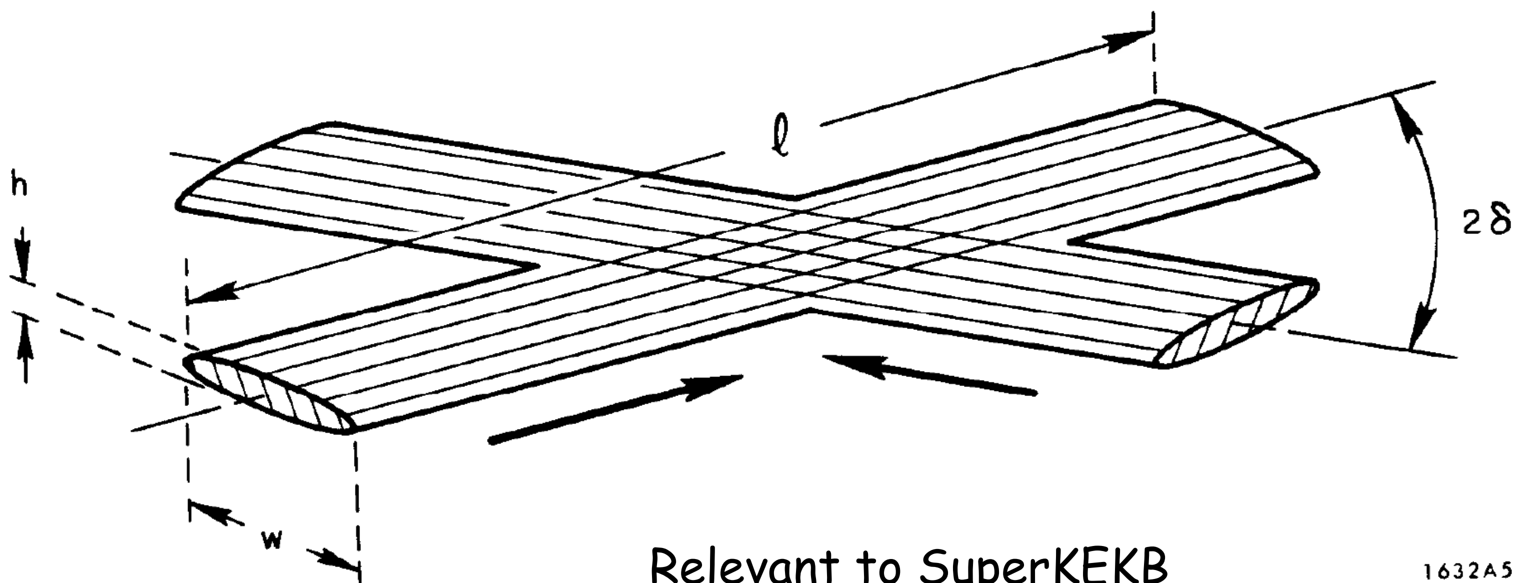


FIG. 4--Bunches colliding with a vertical crossing angle.



Relevant to SuperKEKB

FIG. 5--Bunches colliding with a horizontal crossing angle.

M. Sands

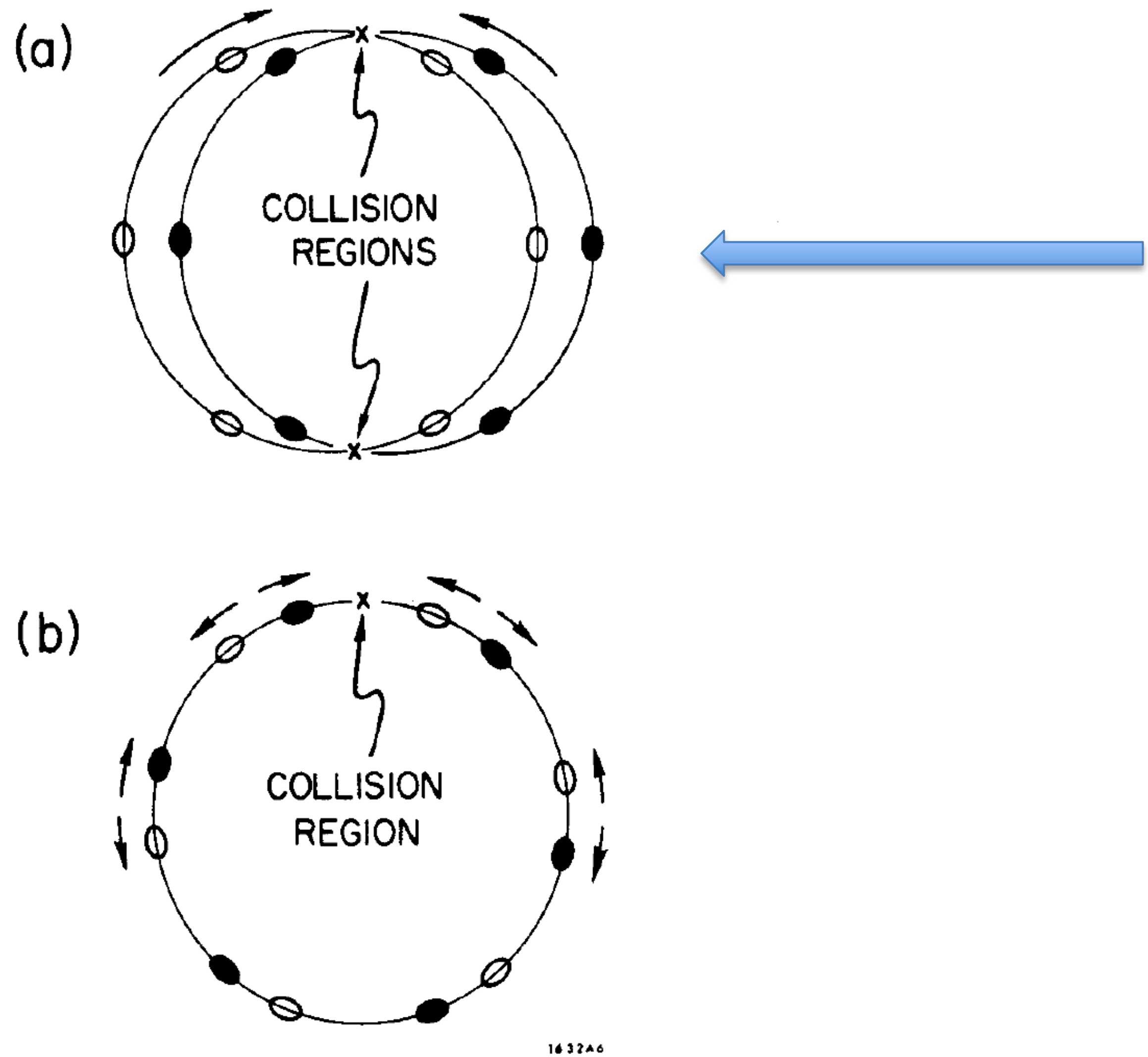


FIG. 6--Beam collision geometries with several circulating bunches.

M. Sands

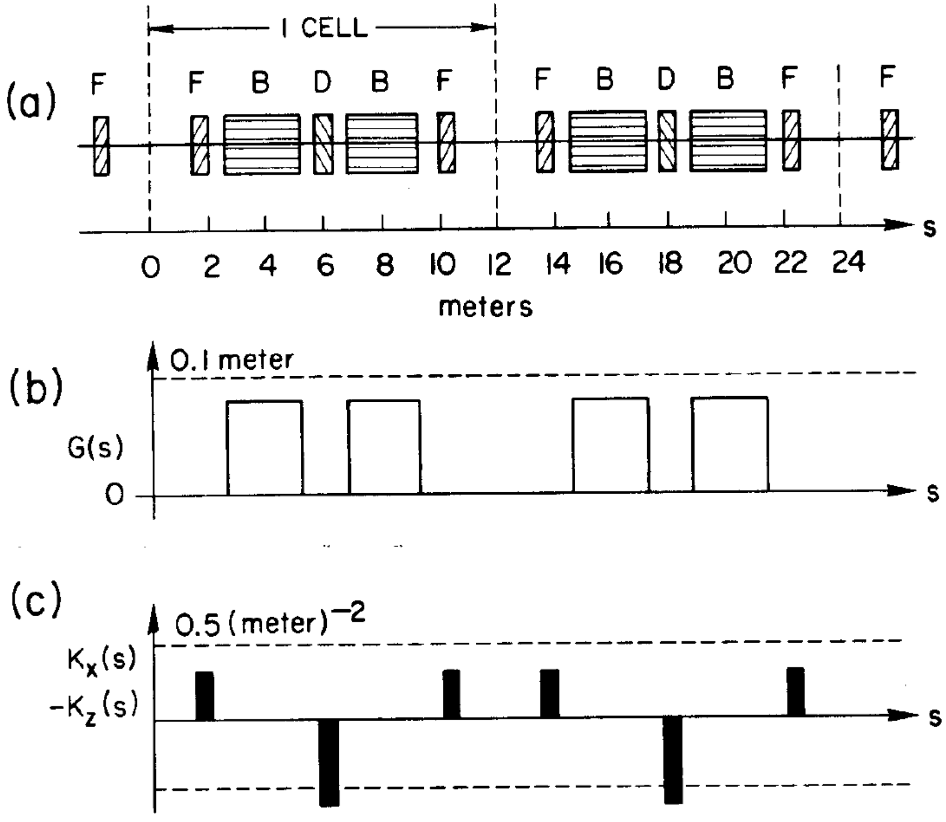


FIG. 10--Magnet lattice and focussing functions in the normal cells of a particular guide field.

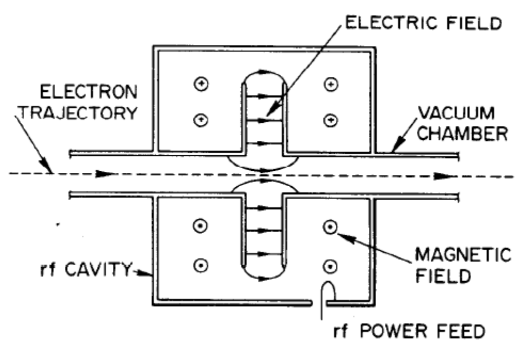


FIG. 30--Schematic diagram of an rf accelerating cavity.

RF Cavity

B is a dipole or "bend" magnet.

F and D refer to focusing or defocusing quadrupoles.

Alternate gradient focusing is used in most storage rings.

N.B. If we focus in one dimension, we defocus in the orthogonal dimension.

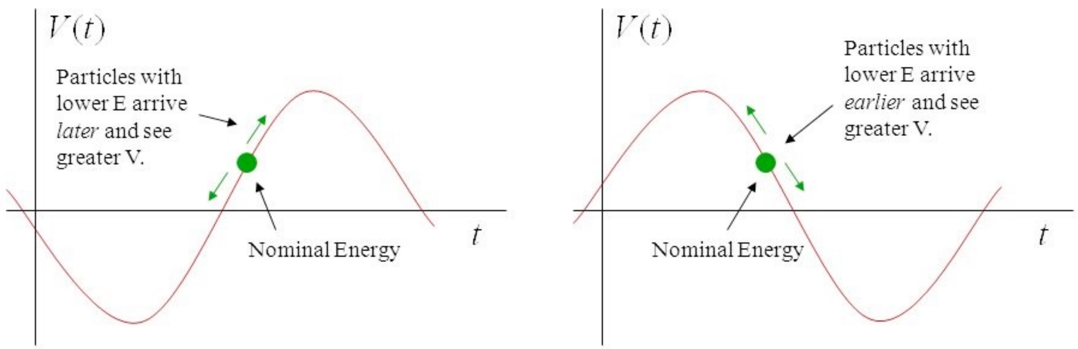
p.34 of Bettini

Longitudinal Motion: Phase Stability

Surfing analogy.

As particles circulate around a ring, they pass through standing RF waves in accelerating cavities. The stability depends on the relative energy received by off-energy particles

"The particle accelerator is unstable; such an accelerator cannot work"



Below Transition

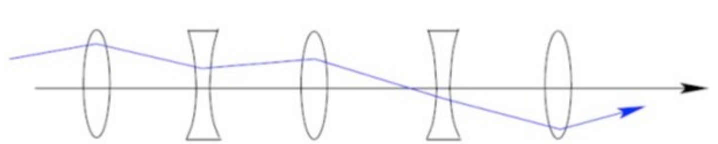
Above Transition

RF cavities

Veksler and McMillan

N.B. If we focus in one dimension, we defocus in the orthogonal dimension.

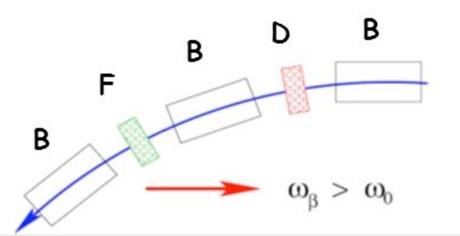
FOCUSSING



"Alternate gradient focusing" gives an overall fokussing effect (compare for example optical systems in cameras)

The beam takes up less space in the vacuum chamber, the amplitudes are smaller and for the same magnet aperture the field quality is better (cost optimization)

Synchrotron design: The magnets are of alternating field (focusing-defocusing)



Quadrupole magnets

Courant, Snyder and Livingston

Probably also invented by N. Christofilos

M.Sands

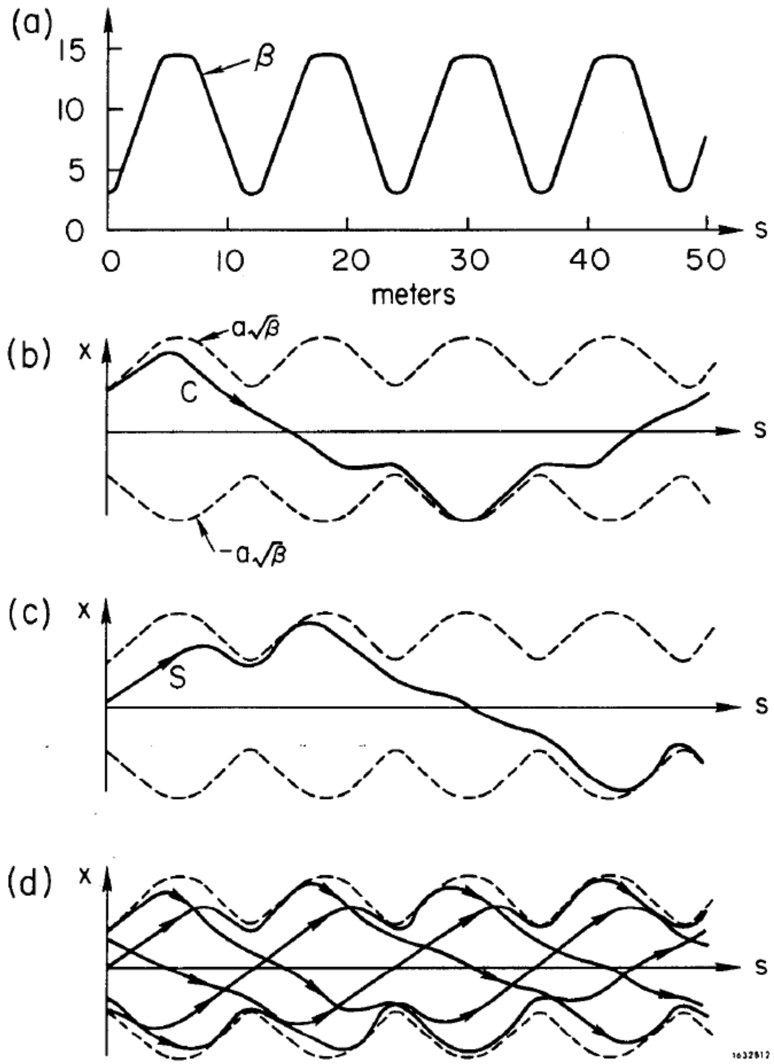


FIG. 12--(a) Betatron function. (b) Cosine-like trajectory for s=0. (c) Sine-like trajectory for s=0. (d) One trajectory on several successive revolutions.

The guide field has focusing properties, which drive all electrons on an ideal design orbit and cause them to execute lateral (radial and vertical) betatron oscillations about the ideal closed path.

$$\beta(s) = \beta(s+L),\ L = \text{circumference}$$

$$x_s(t_j) = a\sqrt{\beta(s)}\cos(\nu\omega_r t_j + \phi_{0s})$$

The value of the beta function at the IP is called "beta star".

$$\beta(s) = \beta^* + \frac{s^2}{\beta^*}$$

The smaller the beam size at the IP, the faster the rise of the beta function when going away from the IP. The aperture of beam line elements can limit how small β^*y can be made.

M. Sands

Tunes and operating point of the accelerator

$$x_s(t_j) = a\sqrt{\beta(s)}\cos(\nu\omega_r t_j + \phi_{0s})$$

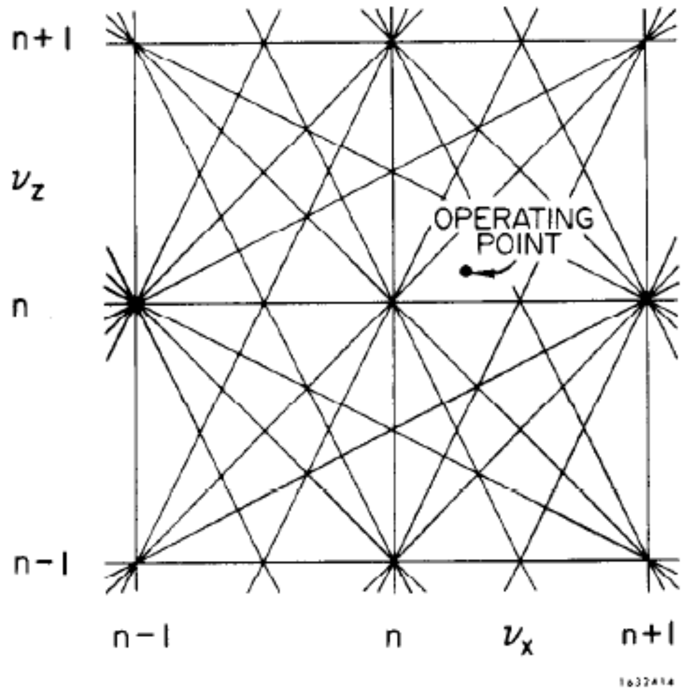


FIG. 14--Lower order resonance lives on a ν_x, ν_z diagram.

The operating point and resonance lines in the tune plane are shown. The beam is lost if the tune hits a resonance.

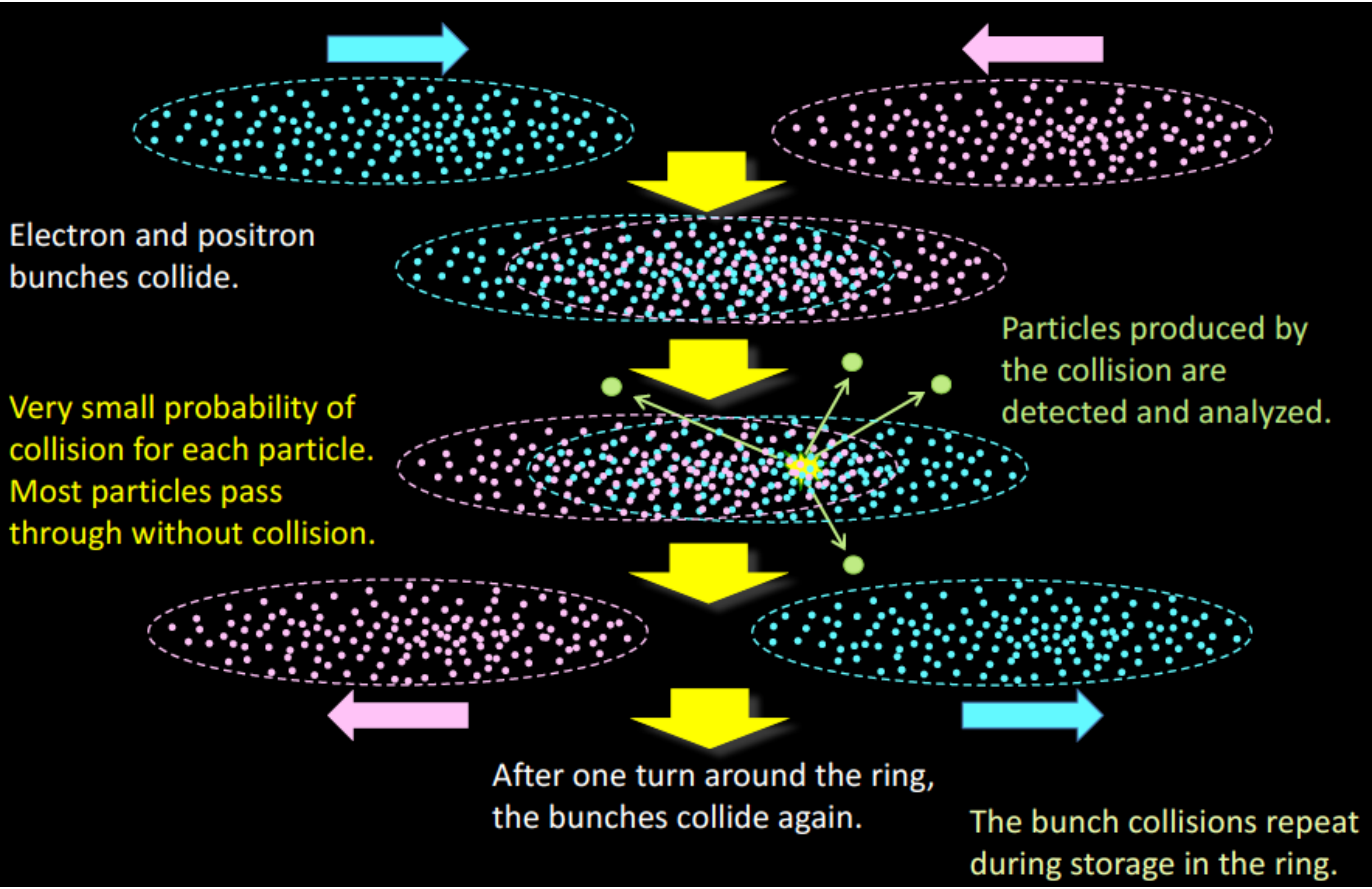
Review questions for part I

1. What limits does SR impose on e+e- colliders?
2. What is alternate gradient focusing?
3. What are betatron oscillations? What are tunes?
4. What is longitudinal phase stability?
5. What is the "aperture" of an e+e- accelerator?
6. Why are RF cavities needed?
7. Does SuperKEKB use a continuous beam or bunched beam? Why ?

8. Why does the vacuum chamber of SuperKEKB require a high vacuum of order (10^{-9} Torr) ?

9. Would a non-zero vertical crossing angle be useful for luminosity?

What happens in an electron-positron collider (N.B. pictures not to scale) ?



K. Akai

Recall the first and most basic "luminosity master equation"

$$N(\text{number of events produced per sec}) = \sigma \times \mathrm{L}$$

Here, σ is the cross-section of the process of interest (a constant of Nature), L is the luminosity, which is determined by accelerator performance.

Let's do a simple but instructive example:

$$\sigma(e^+e^- \to b\bar{b}) \sim 1nb$$

$$L = 1\times 10^{33} / cm^2 / \sec$$

$$\Rightarrow N = (1\times 10^{-9} \times 10^{-24} cm^2) \times 10^{33} / cm^2 / \sec$$

So we would produce one B Bbar pair per sec (1 Hz) at this luminosity.

A Snowmass year has 10^7 sec→So in one Snowmass year, we produce 10^7 b b pairs at this luminosity. *This is not enough and we are not satisfied.*

Comment on cross-sections.

No barns in Hawaii Or in Tsukuba ! But plenty in Blacksburg.

1 barn = 10^{-28} m^2 and is about the size of an A=100 nucleus (huge !!).

Unit invented by "Midwestern farm boy" nuclear physicists at Purdue University. Also trying to confuse the enemy during WWII. (source: FNAL symmetry magazine)

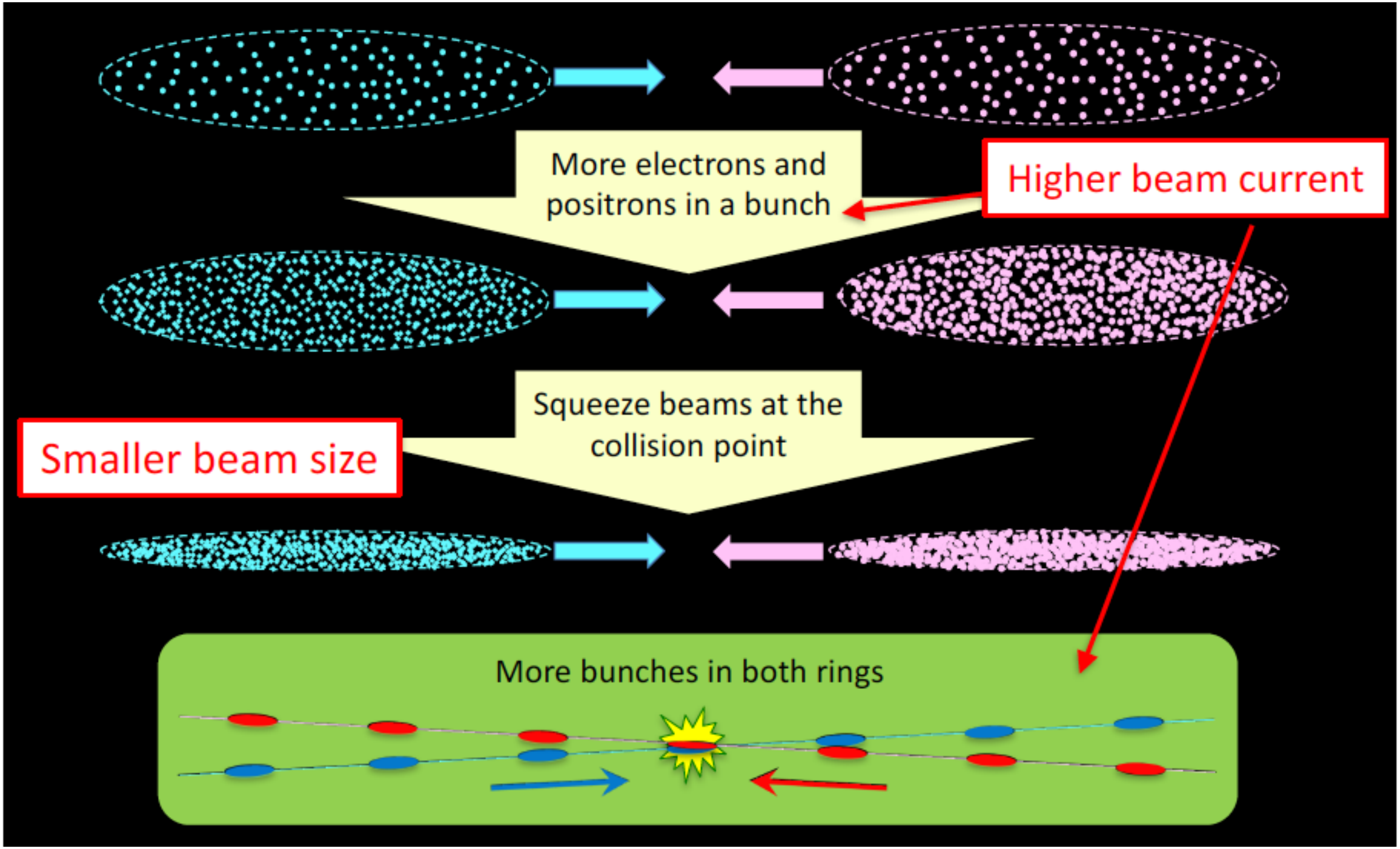
Most cross-sections in particle physics as opposed to nuclear physics are somewhat smaller than in a barn and are measured in mb ("millibarns"), μb ("microbarns"), nb ("nanobarns"), pb ("picobarns").

$$\sigma(e^+e^- \to \Upsilon(4S)) = 1nb = 10^{-9}\, barns;$$

$$\sigma(p\bar{p} \to b\bar{b}X) \sim O(10\mu b) = 10^{-6}\, barns \text{ at } \sqrt{s} = 2 \text{ TeV}$$

Note that hadronic cross-sections are much larger but the event environment is challenging i.e. point-like particles versus smashing "Swiss watches"

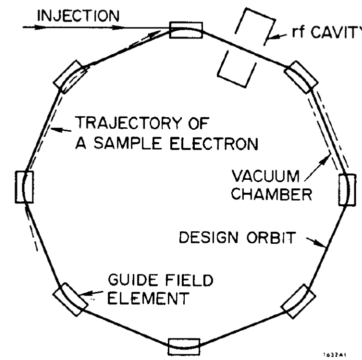
Possible Paths to Higher Luminosity (cont'd)



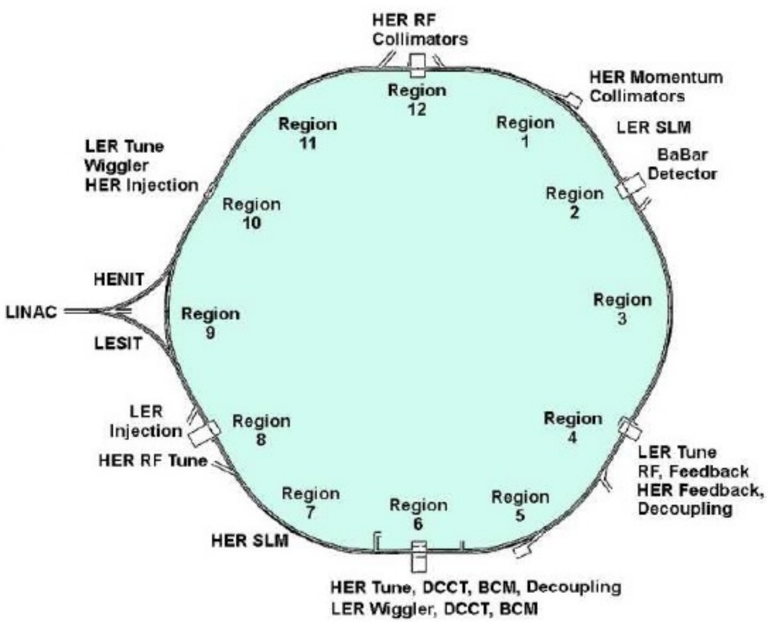
K. Akai

Below are the B factory accelerators (*the first generation*) used in the race to discover time-dependent CP violation).

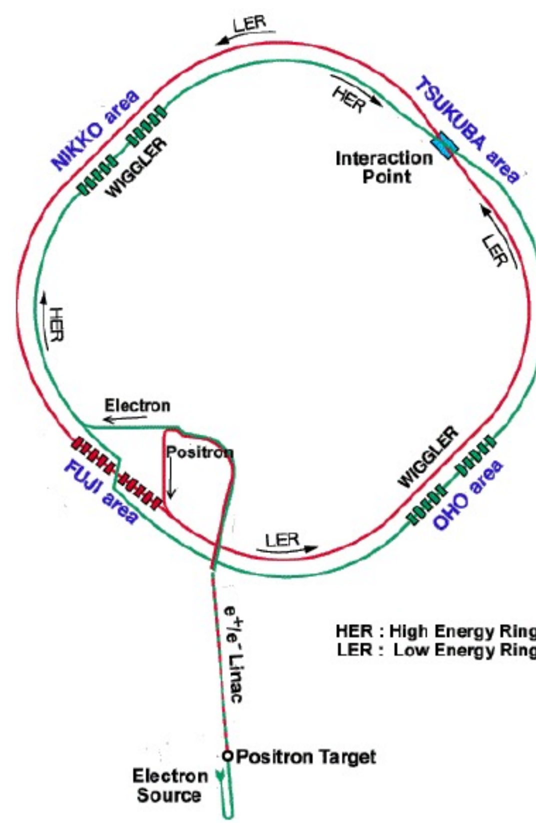
Note the features common to Sand's prototype accelerator. (Thousand of magnets are not shown)
B2SW Q: Where are the interaction points?



PEP-II



KEKB



1999

From the B Factory Physics Book, p.34, arXiv: 1406.6311

1.4.4.4 Early operation

Belle rolled into place on May 1, 1999 and saw first collisions (25 mA positron beam on a 9 mA electron beam) on June 1. Early running was plagued by high occupancy in the CDC caused by synchrotron radiation produced by the electron beam. The origin of this problem was traced to back-scattered X-rays from the aluminum section of the down-stream beam-pipe that was installed during the KEKB commissioning run. In addition, in July, there was an abrupt deterioration in the performance of the inner-most layer of SVD1.0. This was found to be due to low-energy synchrotron X-rays produced in one of the upstream correction magnets in the HER.

SVD 1.0 was replaced by the spare SVD1.1 during the two-month summer shutdown. Added gold shielding on the beampipe. Fixed CDC grounding, added masks.

History: Summer 2000, Osaka ICHEP Conference

CERN Courier Report

In a plenary session talk, Belle spokesperson Hiroaki Aihara of Tokyo reported Belle's first results on the relevant CP-violating parameter as 0.45 + 0.44 – 0.45. Although Belle's current data sample is only about half that of BaBar's at SLAC, Belle managed to get a competitive measurement by including many CP eigenstate decay channels, including the important but experimentally challenging J/psi and long-lived kaon B decay.

BaBar had integrated a substanstial sample: 9 fb^{-1} and reported

$$\sin(2\beta) = 0.12 \pm 0.37(stat) \pm 0.09(sys)$$

History:

July 23, 2001, Rome

The values of $\sin(2\beta)$ presented here by the two experimental groups[6,7] are:

$$\sin(2\beta) = 0.59 \pm 0.14_{\rm stat} \pm 0.05_{\rm syst} \text{ (Babar)}$$
$$\sin(2\beta) = 0.99 \pm 0.14_{\rm stat} \pm 0.06_{\rm syst} \text{ (Belle)} \quad (8)$$

J. Dorfan (SLAC)

S. Olsen (Hawaii)

These are impressive results: each of them by itself establishes the existence of CP violation in B^0 decays to many σ's. It is remarkable that two rather different experiments at different accelerators and in different Laboratories were able to obtain results of comparable accuracy within a few days of each other.

Summary talk by Nicola Cabibbo at the 2001 Lepton Physics Symposium in Rome, Italy. (July 28, 2001)

Central Osaka

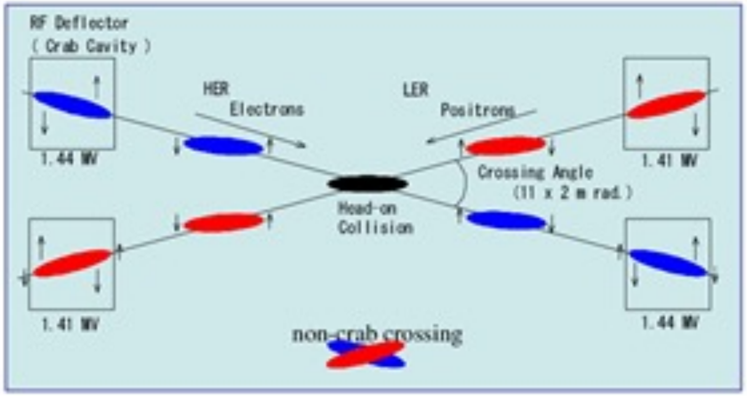
KEKB Crab Crossing

The crab crossing scheme allows a large crossing angle collision without introducing any synchrotron-betatron coupling resonances. [1, 2]

1) R.B.Palmer, SLAC-PUB-4707,1988
2) K.Oide and K.Yokoya, SLAC-PUB-4832,1989

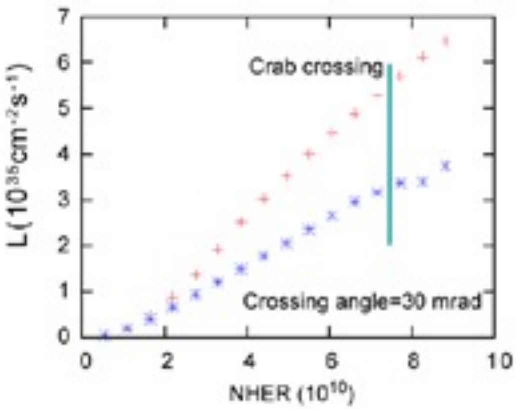
Original Crab Crossing Scheme

4 Crab Cavities at Colliding Section



Effect of Crab Crossing

(Simulation by Ohmi)

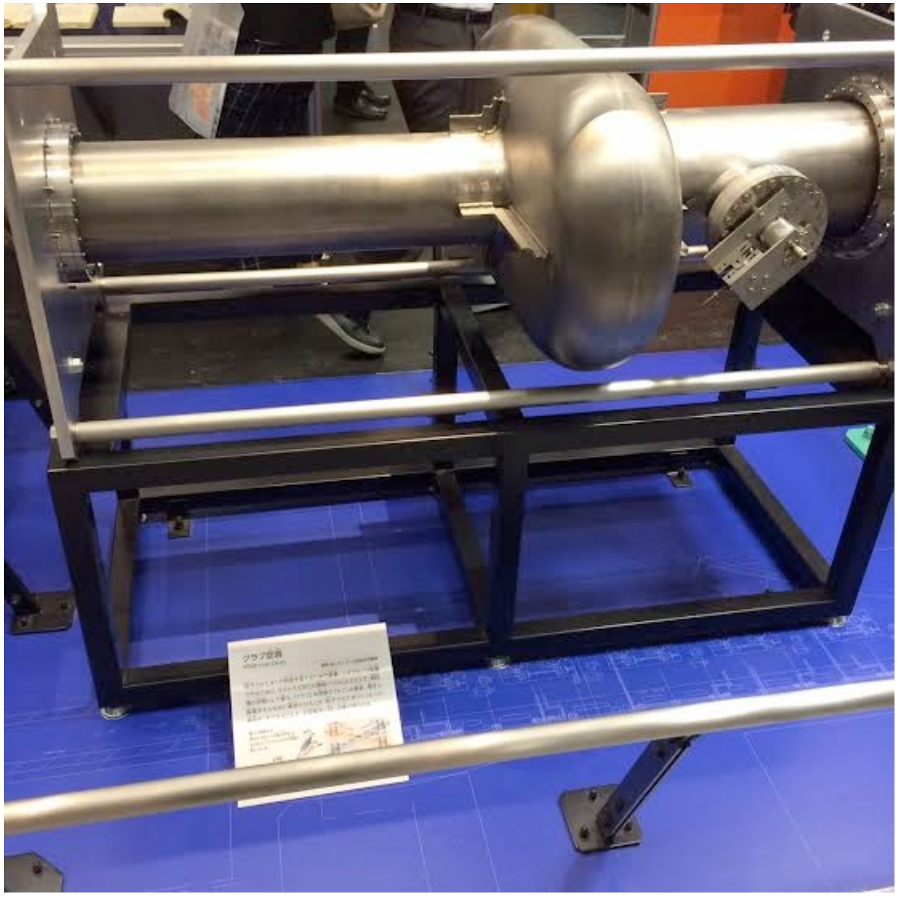


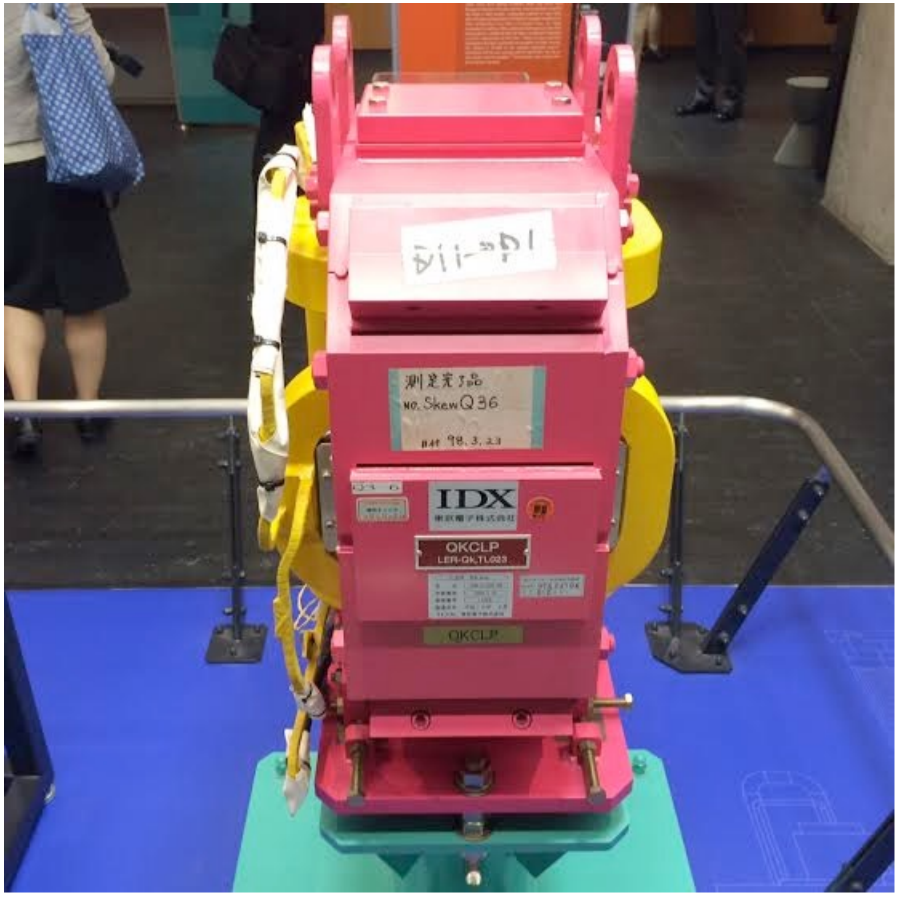
New Crab Crossing Scheme

2 Crab Cavities at "Nikko" → Beam-bunch wiggle around the whole ring!

Advantage: We can use existing cryogenic system for Acc. S.C. cavities

Crab cavity (superconducting) and a skew sextupole from KEKB in the Ueno Science Museum in Tokyo

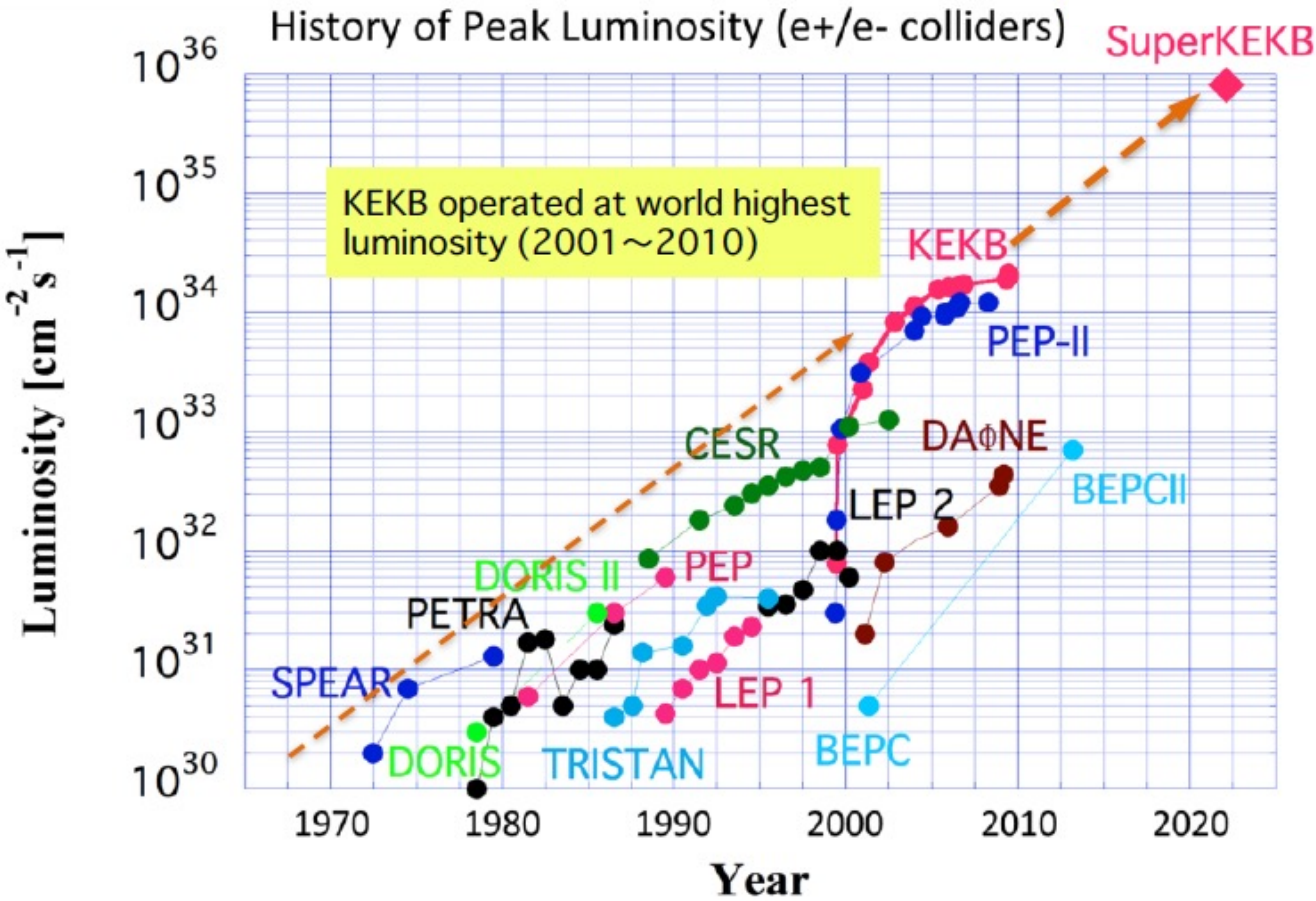




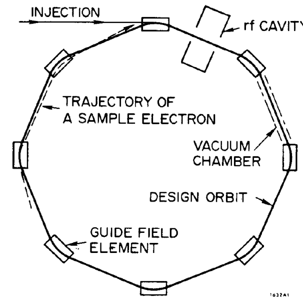
On the left is a superconducting crab cavity used to rotate the beams in the crossing-angle scheme so that they achieve <u>head-on collisions</u>. The crab cavities were not effective until skew sextupoles were added to correct optical defects. Combining these two elements, a peak luminosity of 2.1×10^{34} /cm^2/sec was achieved.

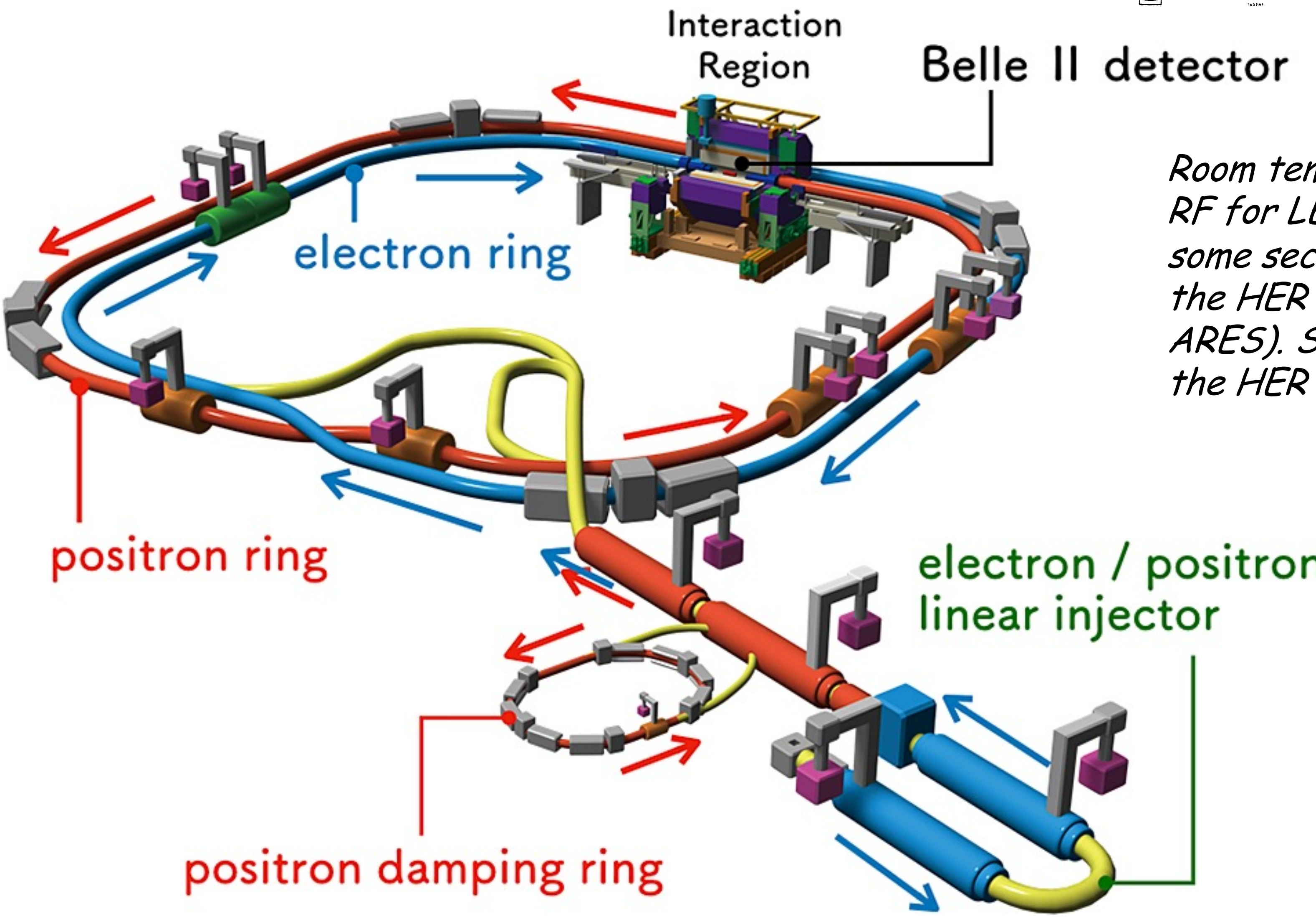
Warning and frequent point of confusion:
KEKB used special superconducting RF cavities to rotate the beams and improve peak luminosity. Crab cavities will also be used at the HL-LHC.

SuperKEKB uses the "crab waist" scheme of Raimondi et al to rotate the waists of the beams and stabilize the collisions. No crab cavities are used. (They don't work with nanobeams).


History of Peak Luminosity (e+/e- colliders)
SuperKEKB
KEKB operated at world highest luminosity (2001～2010)
KEKB
PEP-II
CESR
DAΦNE
BEPCII
LEP 2
PEP
DORIS II
PETRA
SPEAR
LEP 1
DORIS
TRISTAN
BEPC
Luminosity [cm-2s-1]
Year
10^36
10^35
10^34
10^33
10^32
10^31
10^30
1970
1980
1990
2000
2010
2020

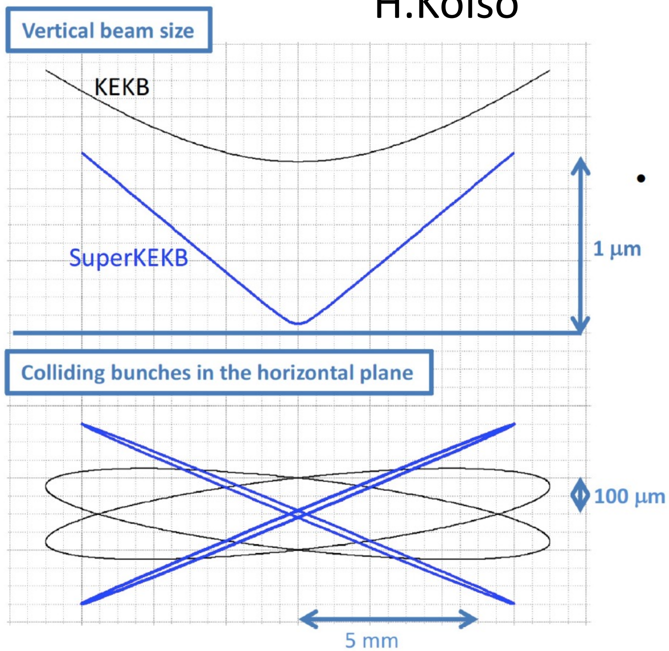
Note the features of SuperKEKB common to Sand's prototype accelerator. (Thousands of magnets are not shown)





Room temperature RF for LER and some sections of the HER (red ARES). SCC RF for the HER (blue)

H.Koiso



- The design strategy for SuperKEKB is based on the nanobeam scheme[1], in which bunches with small σ_x^* collide at a large crossing angle. The longitudinal size of overlap between colliding bunches decreases ~ 1/20 of the bunch length. To achieve this condition, σ_x^* should be sufficiently small, which means both small β_x^* and small horizontal emittance are required.

[1] "SuperB Conceptual Design Report", INFN/AE-07/2, SLAC-R-856, LAL 07-15, March 2007

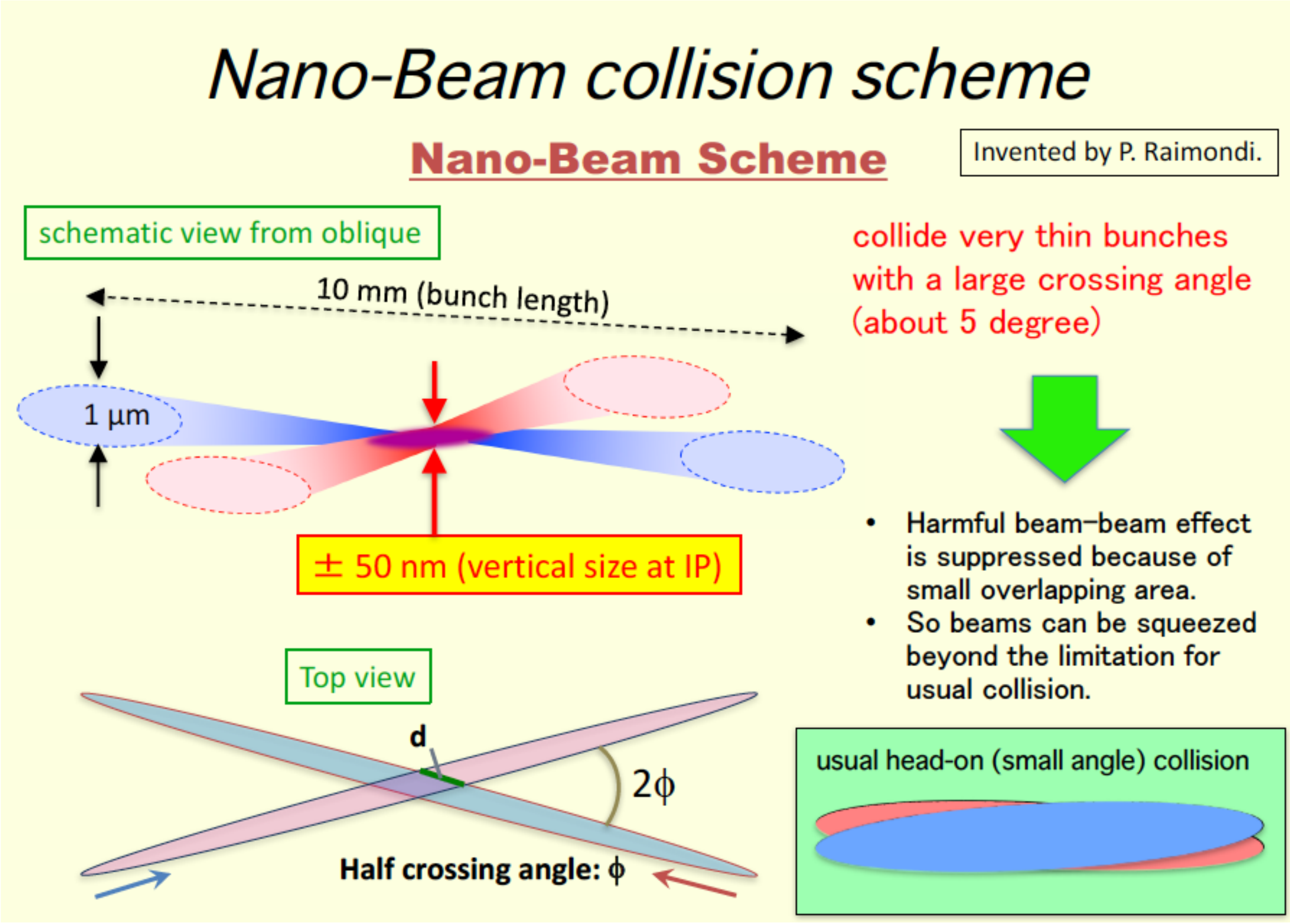
First proposed by P. Raimondi for the SuperB project in Italy

Frequent point of confusion:

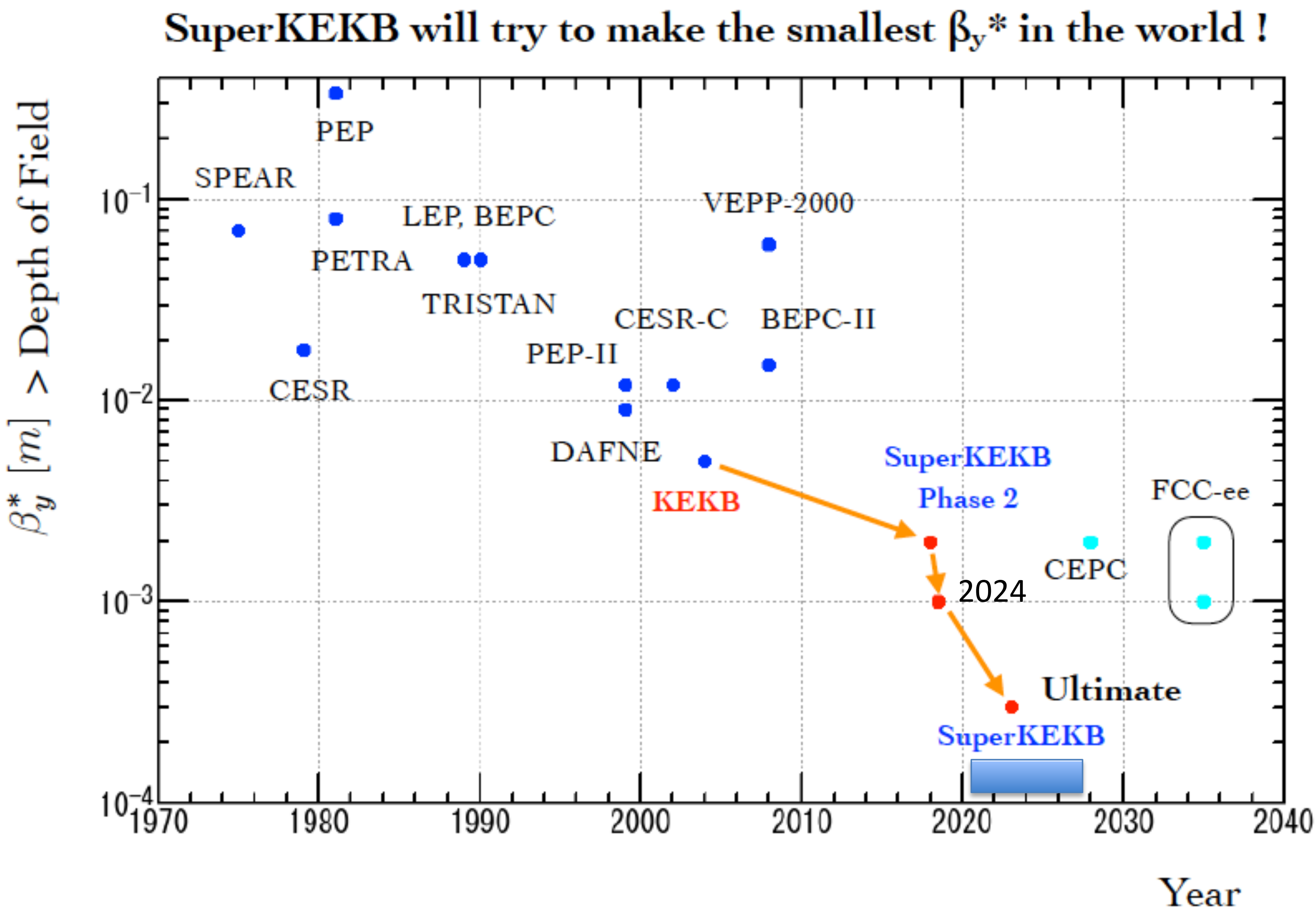
SuperKEKB is not a conventional accelerator. It uses nanobeams, a complex superconducting final focus and a large crossing angle to achieve very high luminosity. PEP-II (magnetic separation) and KEKB (crossing angle) were more or less conventional accelerators with double storage rings. CESR (Cornell Electron Storage Ring) was an important precursor to the B Factories.

SuperKEKB is the world's highest luminosity particle collider: $L \sim 5.1 \times 10^{34}$ /cm^2/sec. So far, it has not run for a long period with high efficiency (only ~0.6 ab^{-1} integrated so far).

Add a factor of two more current to each beam. However, the largest improvement is from "nano-beams".



Ohnishi-san's view: It's all about how much we can squeeze the beam with the superconducting final focus. (N.B. the vertical scale is logarithmic.)



More Luminosity Master Equations

$$L = \frac{N_- N_+ n_b f_0}{2\pi\sqrt{(\sigma^{*2}_{x-} + \sigma^{*2}_{x+})(\sigma^{*2}_{y-} + \sigma^{*2}_{y+})}}$$

Here f_0=99.4 kHz

$$\sigma_{x-} = \sigma_{x+} = \sigma_z \phi_x \qquad \sigma_{y-} = \sqrt{\varepsilon_{y-}\beta^*_{y-}} \quad \sigma_{y+} = \sqrt{\varepsilon_{y+}\beta^*_{y+}}$$

σ_z is the bunch length, ϕ_x is the horizontal crossing angle

ε_y is the vertical emittance, β^*_y is the vertical β function at the IP

Example: the TDR vertical emittance of the LER is 8.64 picometers with β_y^*=0.27mm

$$\sigma_{y-} = \sqrt{\varepsilon_{y-}\beta^*_{y-} = (8.64\times 10^{-12} m)(0.27mm)} = 48\text{nm}$$

B2SW exercise: Calculate the vertical and horizontal beam size(s) for KEKB and the design.

Compare the Parameters for KEKB and SuperKEKB

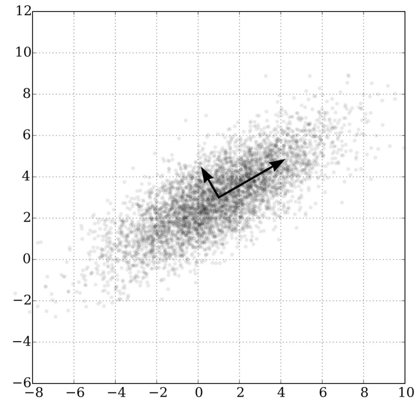
	KEKB Design	KEKB Achieved : with crab	SuperKEKB Nano-Beam
Energy (GeV) (LER/HER)	3.5/8.0	3.5/8.0	4.0/7.0
$\beta_y{}^*$ (mm)	10/10	5.9/5.9	0.27/0.30
$\beta_x{}^*$ (mm)	330/330	1200/1200	32/25
ε_x (nm)	18/18	18/24	3.2/5.3
$\varepsilon_y / \varepsilon_x$ (%)	1	0.85/0.64	0.27/0.24
σ_y(mm)	1.9	0.94	
σ_x(cm)	0.052	0.129/0.090	
σ_z (mm)	4	6 - 7	6/5
I_{beam} (A)	2.6/1.1	1.64/1.19	3.6/2.6
$N_{bunches}$	5000	1584	2500
Luminosity (10^{34} cm^{-2} s^{-1})	1	2.11	80

Nano-beams are the key (vertical spot size is ~50nm !!)

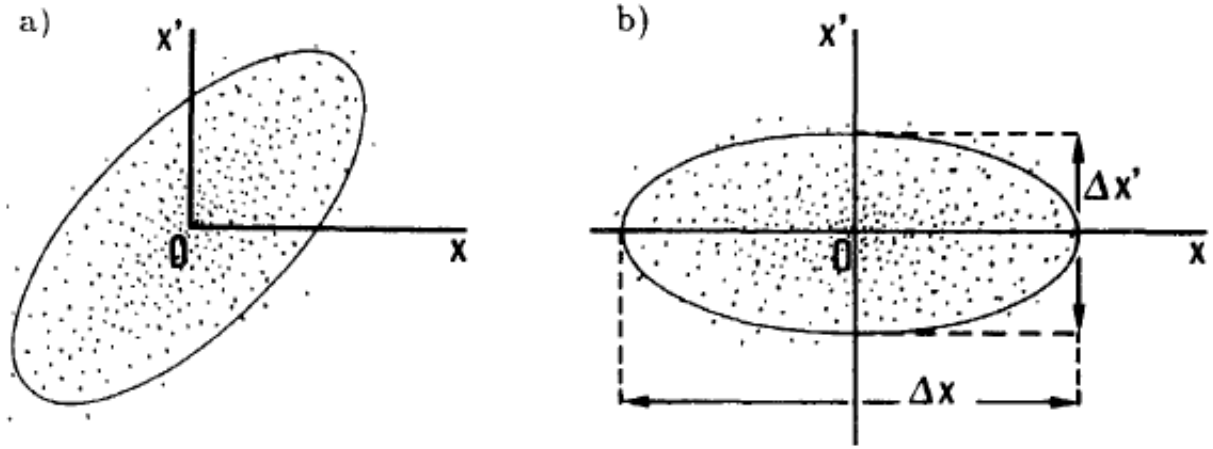
This is not a typo

Emittance, an invariant in charged particle rings.

Slope p_y



Position y



$$z_i(s) = \sqrt{\varepsilon\beta(s)}\cos(\Phi(s) + \delta_i)$$

Fig. 1 : A set of points representative of a beam in the 2-dimensional (x, x') phase space
a) Tilted emittance ellipse.
b) Upright emittance ellipse.

Buon, 1990

Liouville's Theorem states that the area of the phase space ellipse is invariant as the beam propagates around the storage ring.

Scaling laws from the Luminosity Master Equations

$$L = \frac{f_{rev} N_+ N_- n_b}{2\pi\sqrt{2}\sigma_z \phi_x \sqrt{(\varepsilon_y^- + \varepsilon_y^+)\beta_y^*}}$$

B2SW exercise: Verify this result. (Even I could do it !)

$$\xi_\pm \simeq \frac{r_e}{2\pi\gamma_\pm} \frac{N_\mp \beta^*_{y\pm}}{\sigma_z \phi_x \sqrt{\epsilon_{y\mp} \beta^*_{y\mp}}} = \frac{r_e}{2\pi\gamma_\pm} \frac{N_\mp}{\sigma_z \phi_x} \sqrt{\frac{\beta_y^*}{\epsilon_y \mp}}$$

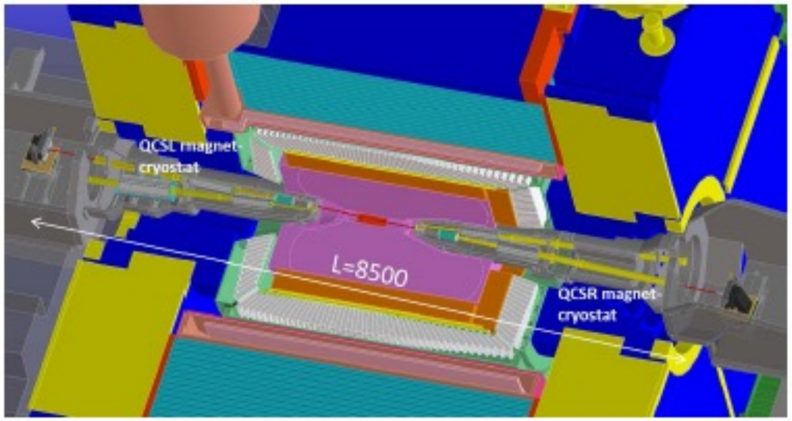
This is the beam-beam interaction parameter. (the derivation assumes flat beams and a large crossing angle).

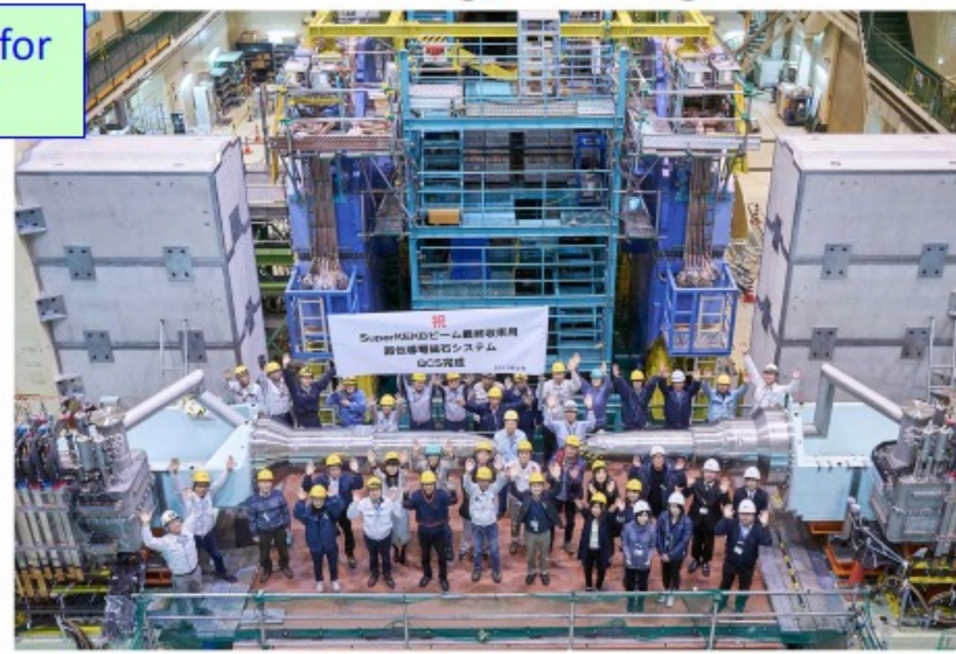
$$L \propto \frac{1}{\sqrt{\beta_y^*}} \qquad \xi_{y\pm} \propto \sqrt{\beta_y^*}$$

Scaling laws: luminosity goes up as beta*y is squeezed, as the beam-beam interaction becomes weaker

Final-focus superconducting magnets

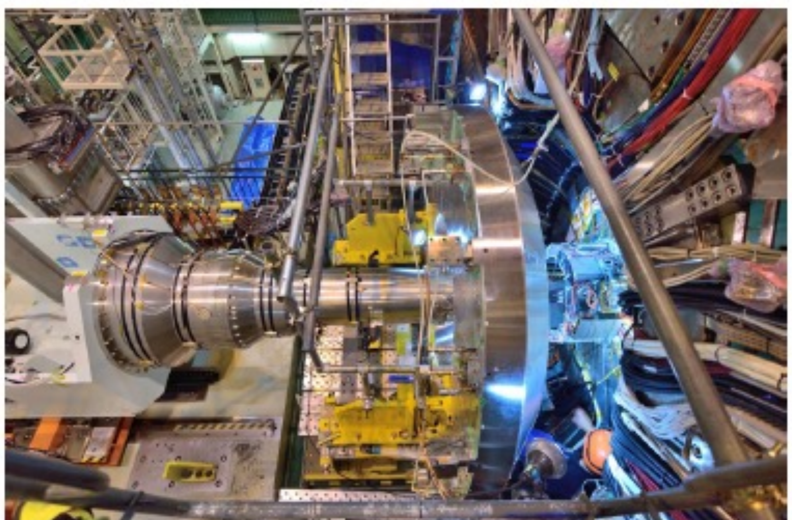
State-of-the-art superconducting magnets for squeezing beams at the interaction point





QCS(L) and QCS(R) installation completed (Feb. 2017)

QCS(R) before connecting to Belle II



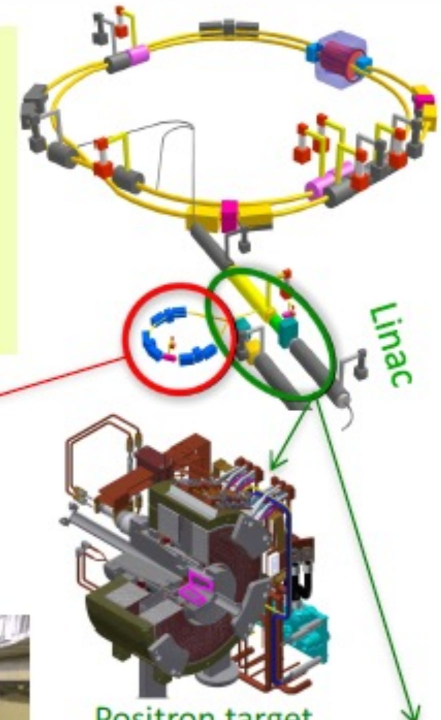
QCS(L) successfully connected to Belle II (Jan. 2018)

Upgraded linac and positron damping ring

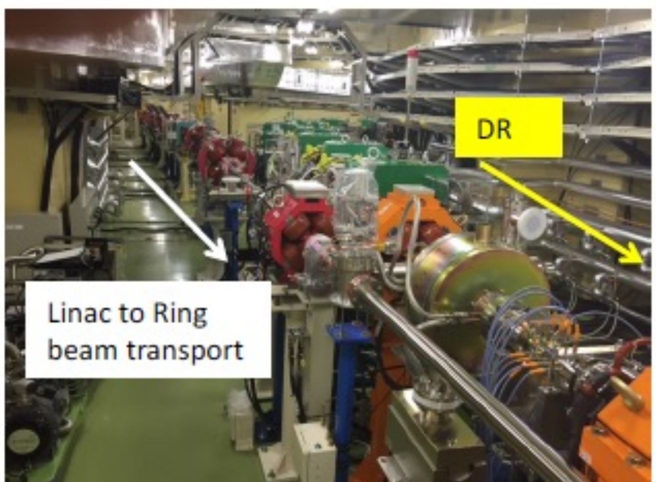
B2SW Q: Why is a positron (e^+) damping ring needed?

DR tunnel construction (2012-13)

- High charge, low-emittance beams are required for injection into LER and HER.
- Injector Linac upgrade and new DR construction.



Damping Ring (DR)



DR injection part

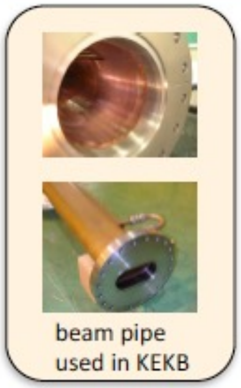
DR arc section

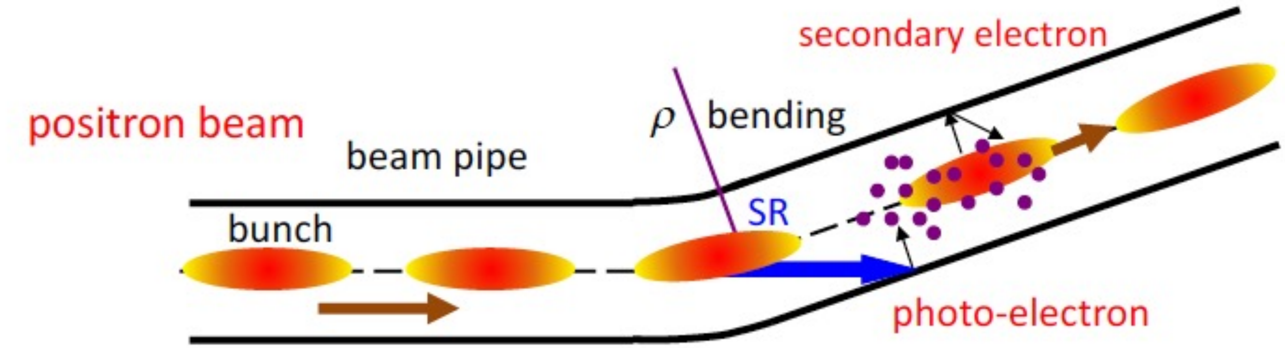
RF electron gun

"A whole new 3 km LER ring" (upgrade after KEKB)

B2SW Q: What is the electron cloud effect?

Mitigation of the electron cloud effect or photo-electron instability.

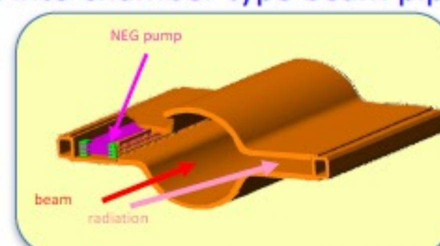


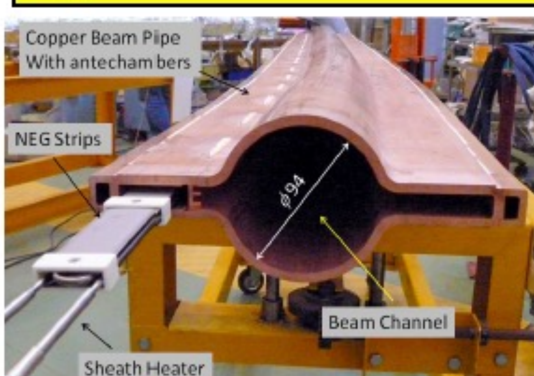


Replace beam pipes with ante-chamber type ones for almost all part of the LER. In addition, various measures are taken to suppress the electron cloud issue.

① TiN conting inside
② groove in bending section
③ clearing electrode
④ solenoid field

Ante-chamber type beam pipe





groove
(bending section)

clearing electrode
(wiggler section)

Increase beam currents: but try to “keep it cool” - don’t want to melt vacuum chamber components !

Need RF cavities to replace energy lost to SR

Energy lost per turn is 1.86 MeV in the LER and 2.43 MeV in the HER

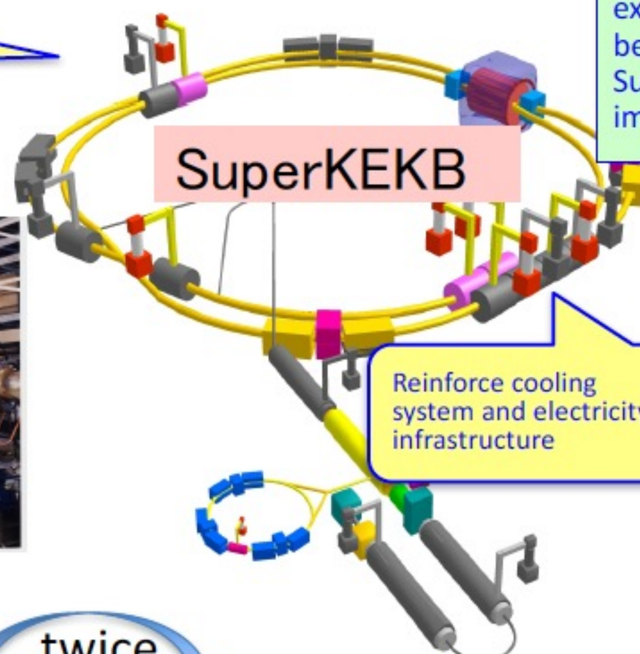
Vacuum system upgrade

- Higher HOM power and SR power
- Countermeasure for electron cloud

Superconducting cavities
- World-highest beam current and power for superconducting cavities

twice

	KEKB	SuperKEKB
Positron beam	1.8 A	3.6 A
Elecron beam	1.4 A	2.6 A



Reinforce cooling system and electricity infrastructure

Linac upgrade for increasing charge

The RF system, which proved excellent performance with high beam currents in KEKB, is reused in SuperKEKB with necessary improvements and reinforcements.

ARES cavities
- Stable with high beam current
- Unique structure developed at KEK

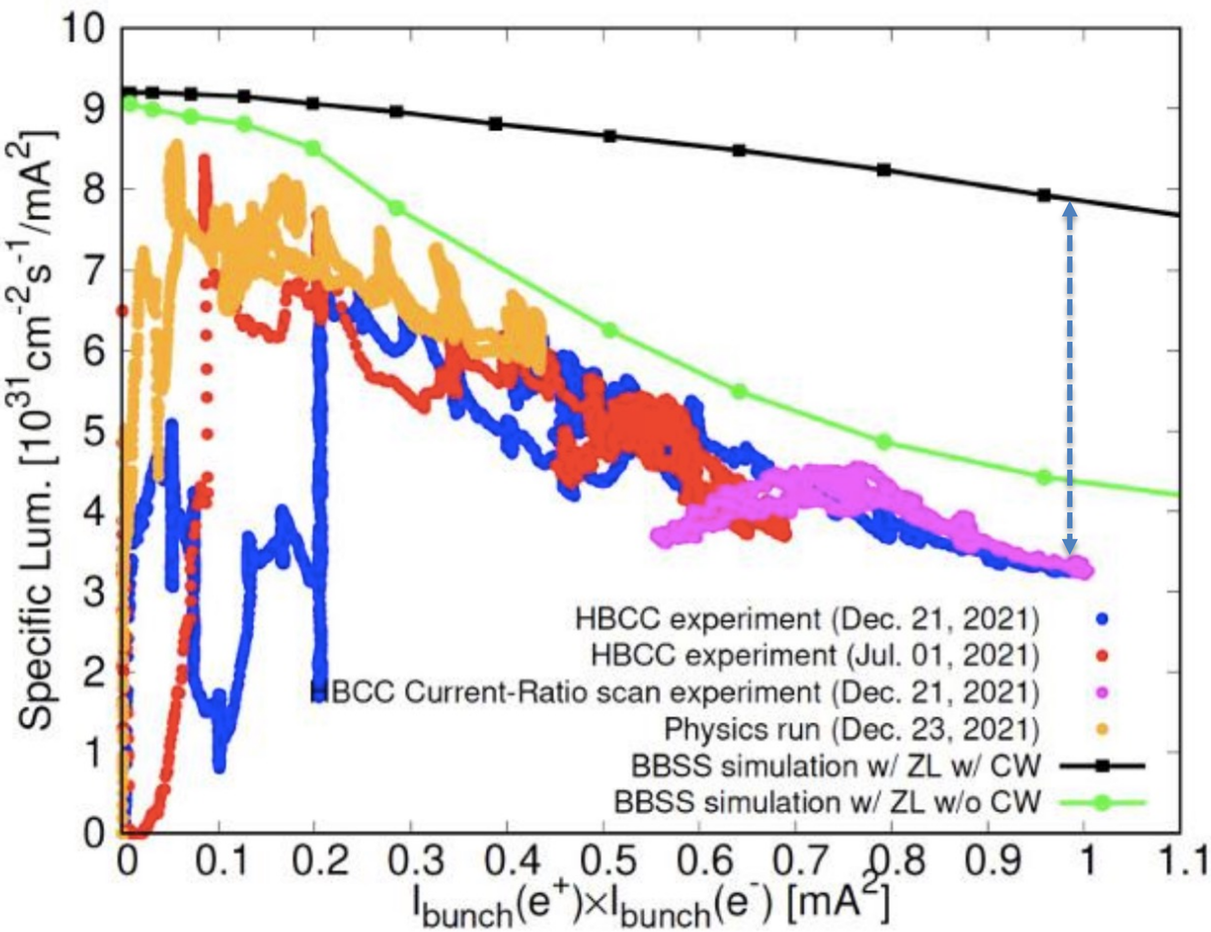
Compare the Parameters for KEKB and SuperKEKB

	KEKB Design	KEKB Achieved : with crab	SuperKEKB Nano-Beam
Energy (GeV) (LER/HER)	3.5/8.0	3.5/8.0	4.0/7.0
β_y * (mm)	10/10	5.9/5.9	0.27/0.30
β_x * (mm)	330/330	1200/1200	32/25
ε_x (nm)	18/18	18/24	3.2/5.3
ε_y /ε_x (%)	1	0.85/0.64	0.27/0.24
σ_y(μ m)	1.9	0.94	0.048/0.062
σ_x(cm)	0.052	0.129/0.090	0.09/0.081
σ_z (mm)	4	6 - 7	6/5
I_{beam} (A)	2.6/1.1	1.64/1.19	3.6/2.6
$N_{bunches}$	5000	1584	2500
Luminosity (10^{34} cm^{-2} s^{-1})	1	2.11	80

Nano-beams are the key (vertical spot size is ~50nm !!)

This is not a typo

Current Key Unsolved Mystery:
Why is the specific luminosity a factor of 2.-2.5 below beam-beam simulations?



Possible answers: imperfections in the machine e.g. misalignments at the IP or errors in the QCS corrector coils, feedback noise.

Conclusions and Future Plans

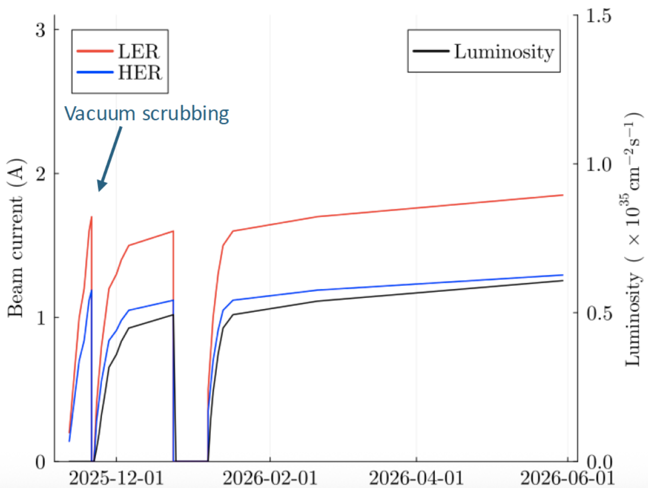
Operational Plan for 2025c-2026b

Accelerator efficiency
= (Actual daily ∫Ldt) / (Ideal ∫Ldt at peak L for 24 hours)

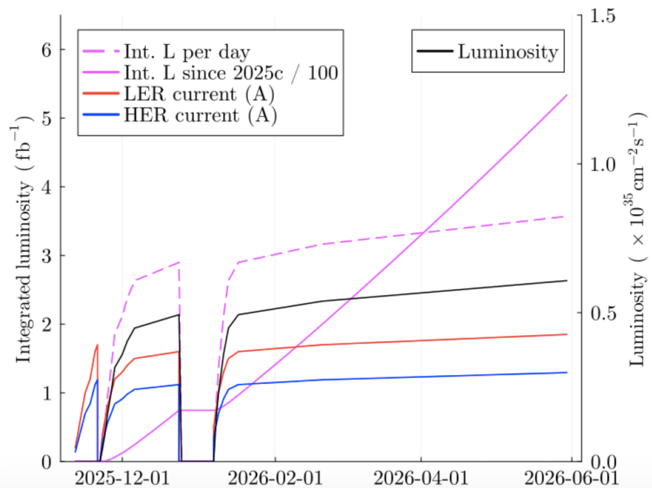
- Plan B (Optional Plan): Target peak luminosity: 6×10^{34} $cm^{-2}s^{-1}$, Target integrated luminosity: ≥ 425 fb^{-1}
  - If we cannot increase the beam current much, 6×10^{34} $cm^{-2}s^{-1}$ and 0.85 efficiency are required to achieve 534 fb^{-1}
- For the integrated luminosity estimation:
  - Physics runs account for 80% of the full collision operation period (with 4 days per 3-week cycle allocated to studies).
  - The accelerator efficiency is assumed to be 0.85 (highest efficiency level achieved during 2022b)
  - The estimated integrated luminosity (delivered) is 534 fb^{-1}.

[G. Mitsuka *et al.*]

Beam current and peak luminosity



Luminosity and integrated luminosity



24

Integrate and pass the 1 ab^{-1} milestone.

Conclusions and Future Plans

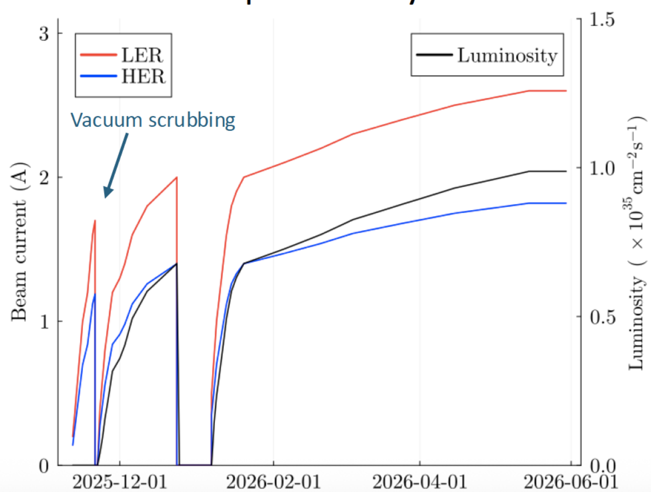
Operational Plan for 2025c-2026b

Accelerator efficiency
= (Actual daily ∫Ldt) / (Ideal ∫Ldt at peak L for 24 hours)

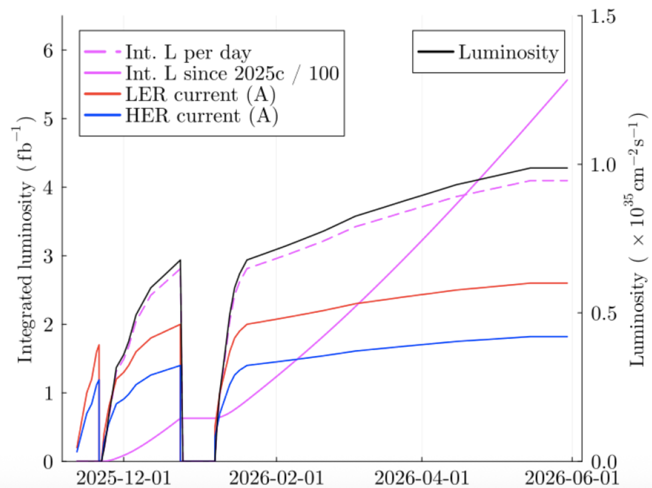
- 180 days of collision operation during the 2025c–2026b run
- Plan A (Base Plan): Target peak luminosity: 1×10^{35} cm^{-2}s^{-1}, Target integrated luminosity: ≥ 425 fb^{-1}
  - 1×10^{35} cm^{-2}s^{-1} can be achieved with β_y^*=1 mm if we can increase the beam current as shown in this plot.
  - 556 fb^{-1} (delivered) is estimated with 0.60 efficiency.
- For the integrated luminosity estimation:
  - Physics runs account for 80% of the full collision operation period (with 4 days per 3-week cycle allocated to studies).
  - The accelerator efficiency is assumed to be 0.60, lower than the ~67% achieved during the 2024c run due to high current conditions.
  - The estimated integrated luminosity (delivered) is 556 fb^{-1}.

[G. Mitsuka *et al.*]

Beam current and peak luminosity



Luminosity and integrated luminosity



23

Integrate and pass the 1 ab^{-1} milestone.

https://pubs.aip.org/physicstoday/article-abstract/78/3/20/3337084/Japan-accelerator-pursues-nanobeams-to-boost?redirectedFrom=fulltext

A non-technical short summary

Volume 78, Issue 3
1 March 2025

< Previous Article Next Article >

Japan accelerator pursues nanobeams to boost luminosity

Squeezing beams of electrons and positrons for the Belle II experiment at the SuperKEKB facility proceeds with halting progress.

Toni Feder

Check for updates

+ Author & Article Information
Physics Today **78** (3), 20–21 (2025);
https://doi.org/10.1063/pt.imsn.ildq

Share Rights and Permissions Cite

Accelerator physicists at the SuperKEKB electron–positron accelerator in Tsukuba, Japan, are celebrating their December 2024 world-record luminosity of 5.1×10^{34} cm^{-2} s^{-1}. At the same time, they are scratching their heads about how to reach their target luminosity, which is roughly an order of magnitude higher. Success has implications both for Belle II, the onsite experiment that studies B mesons and other particles, and for future electron–positron colliders.

Review questions for part II

1. What is emittance?

2. What is the electron cloud instability?

3. Why is a positron damping ring needed?

4. What are the mitigation measures for the electron cloud instability?

5. How does beam size depend on beta* and emittance?

6. Calculate the vertical and horizontal beam size(s) for KEKB and the SuperKEKB design.

7. Does SuperKEKB use crab cavities?

8. What are the advantages of a large crossing angle? What are the drawbacks?

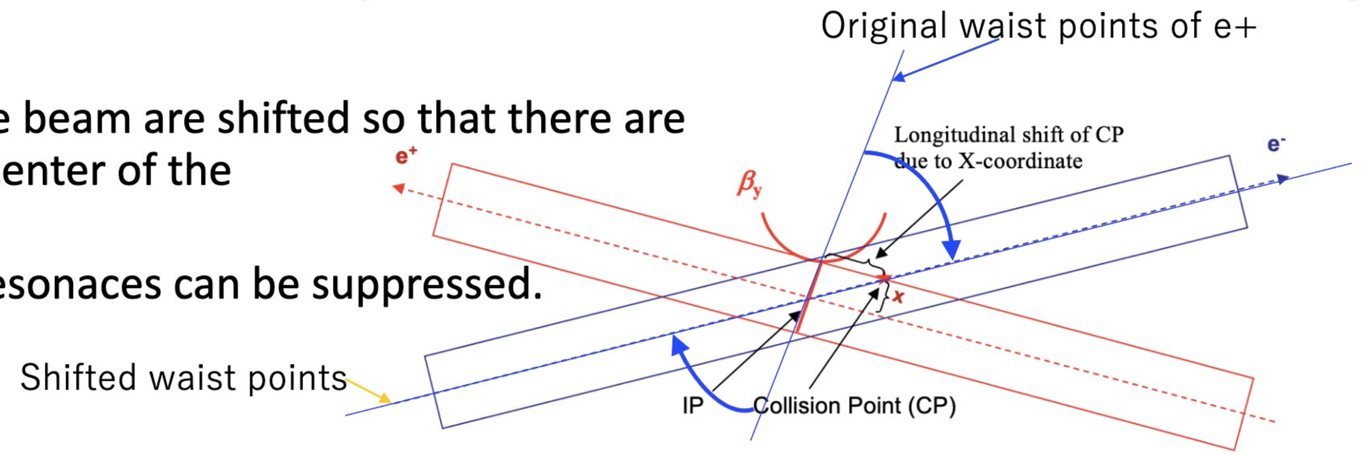
9. What is the current value of beta*y ? What is the design value ?

Backup material

Crab waist scheme

P. Raimondi

- Collision point with the center of the other beam for a partice with a horizontal offset
  - Due to large crossing angle, a parcle with horizontal offset collide with the center of the other beam at a location offset from the waist (minimum of β_y).
  - The vertical beam-beam kick depends on the horizontal offset.
    -> X-Y coupling resonances driven by the beam-beam interaction -> beam-beam blowup
- Crab waist scheme
  - Waist points of one beam are shifted so that there are aligned along the center of the other beam.
  - The X-Y coupling resonaces can be suppressed.

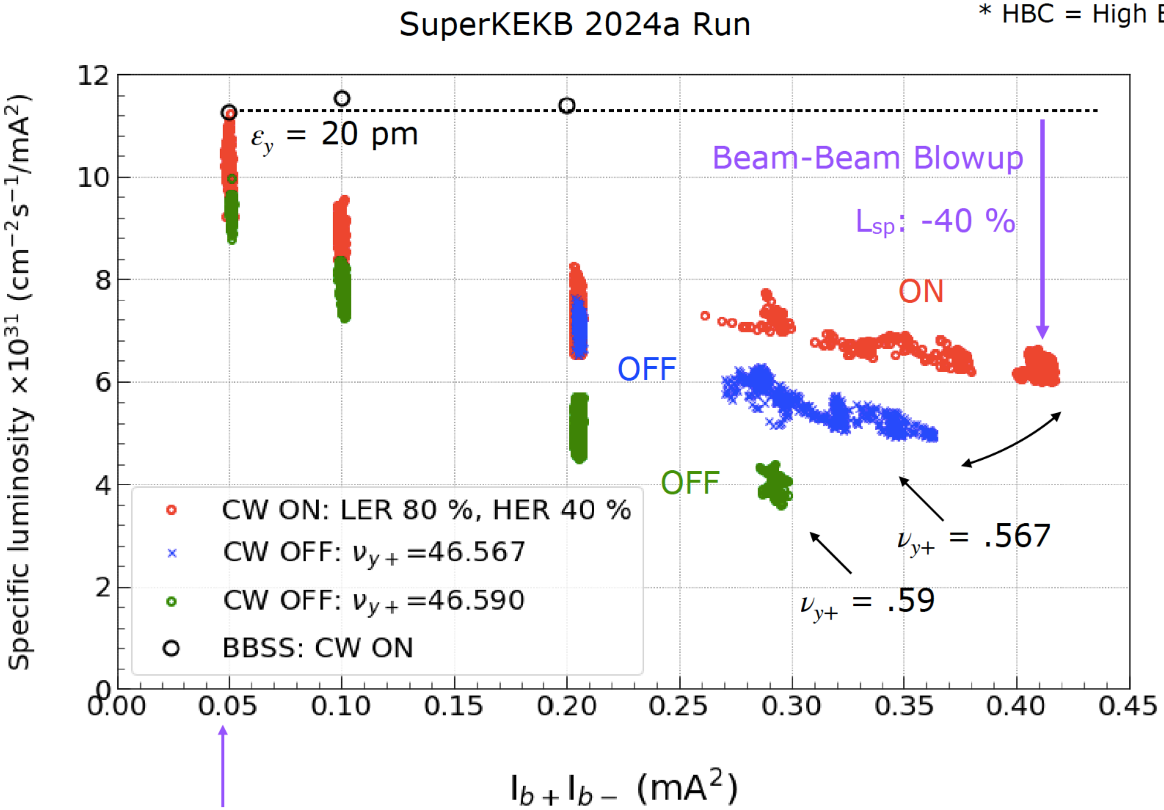


Y. Funakoshi

Observations of crab-waist in SuperKEKB

Crab Waist ON and OFF

Experiment on March 12 and March 21,-22 2024
* HBC = High Bunch Current (393 Bunches)



Luminosity is OK for small $I_{b+}I_{b-}$.

$$L_{sp} = \frac{L}{I_{b+}I_{b-}n_b} \propto \frac{1}{\sigma_y^*}$$

Crab waist is effective.

It makes strength of resonance lines weaker rather than geometrical gain.

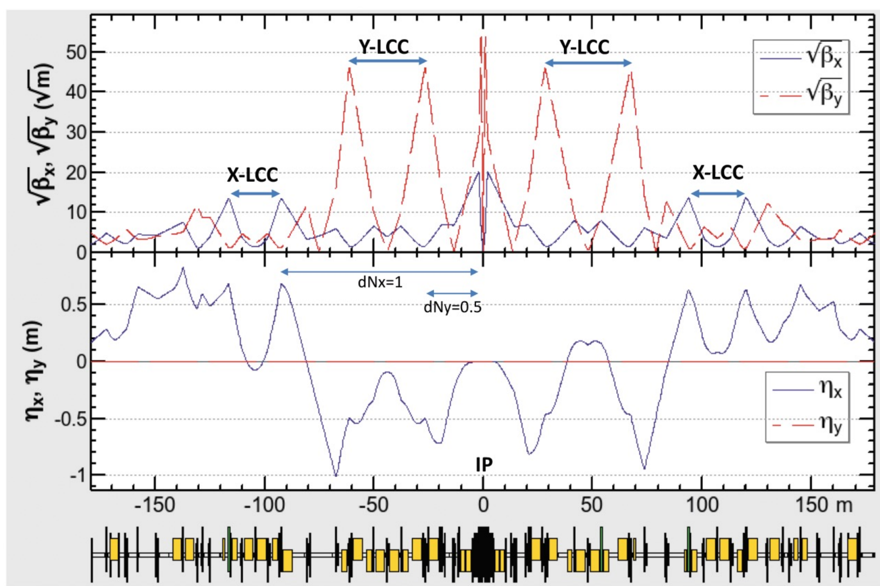
Y. Ohnishi

Chromaticity refers to the **variation of the betatron tune (or oscillation frequency) with respect to the energy change of the particles.**

This energy dependence of the focusing strength leads to a variation in the betatron tune for particles with different momenta. This tune spread, caused by chromaticity, is a significant problem.

Tune Spread and Resonances: The tune spread can push particles onto resonant tunes, leading to increased oscillation amplitudes and potential beam loss.
Head-Tail Instability: Chromaticity can also lead to the head-tail instability, a phenomenon where different parts of a particle bunch oscillate out of phase, potentially causing beam loss

Chromaticity can be corrected with sextupole magnets, following this scheme of Oide et al.



SuperKEKB has special rotatable sextupoles.

$$-I' = \begin{pmatrix} -1 & 0 & 0 & 0 \\ m_{12} & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & m_{34} & -1 \end{pmatrix}$$

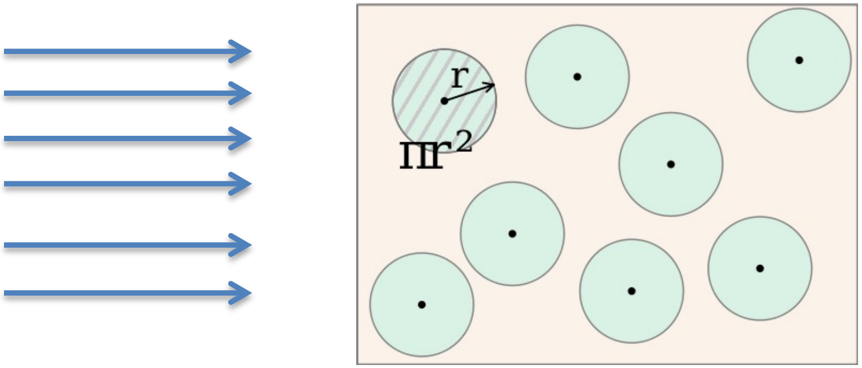
- To correct large chromaticity arising from small β^*, local chromaticity correction (LCC) sections for both the vertical and horizontal planes. A pair of identical sextupole magnets, connected by the pseudo $-I$ transformation, are placed in each LCC.

H. Koiso

Bettini, p.14

Cross-section is a measure of the strength of interaction between two-particles. It has dimensions of area (m^2) or barns (10^{-28} m^2)

Let's try to work out the cross-section for a fixed target reaction with a collimated incident beam.



Here n_t=number of scattering centers per unit volume; N_t is the total number of scattering centers.

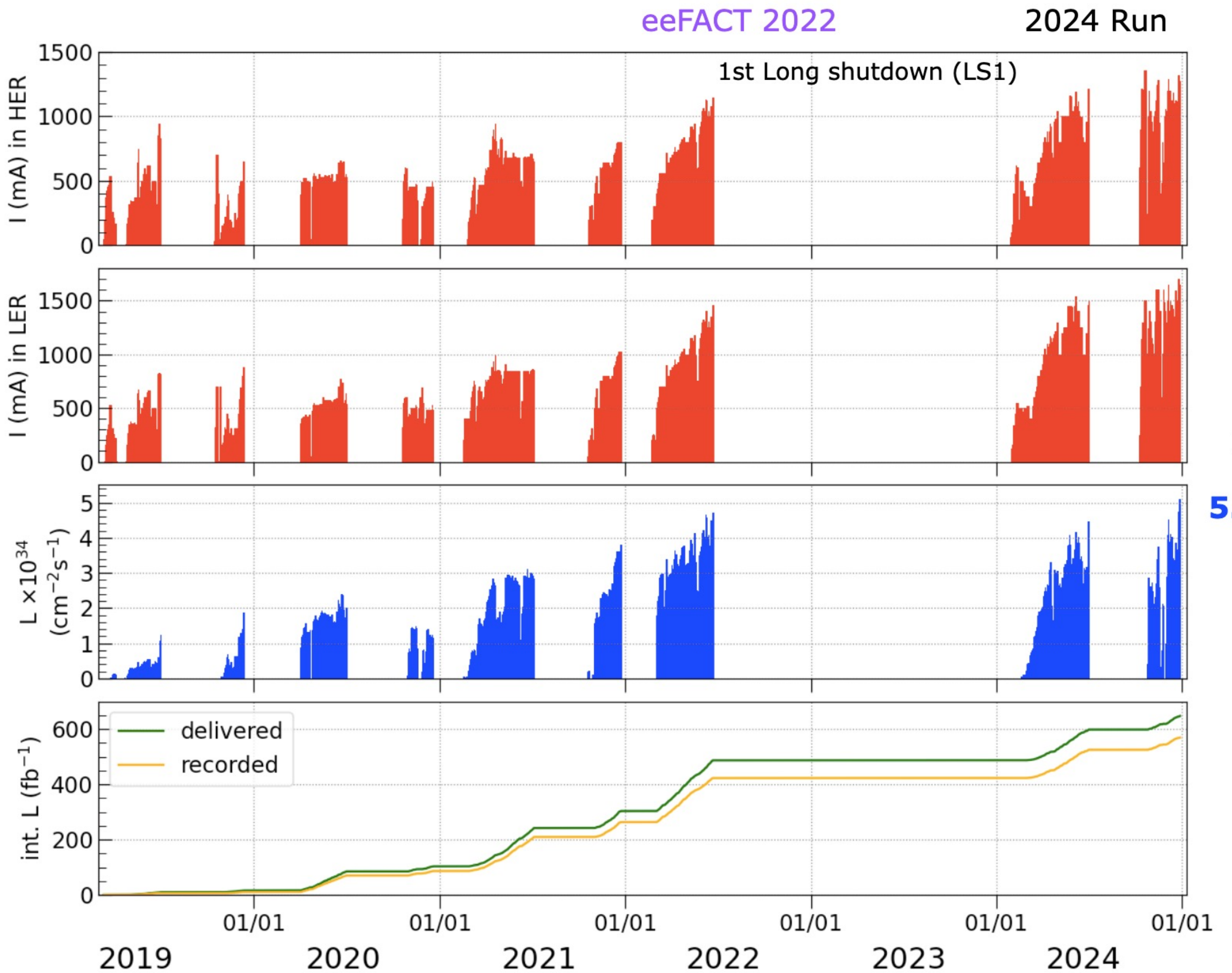
This is the rate of interactions.

$$R_i = \sigma N_t \Phi_b;$$

where Φ_b is the beam flux, σ is the interaction cross-section

Question:
What is the *flux* of the incident beam ?
(*or what are the dimensions of these quantities ? And how do they differ ?*)

$$\Phi_b = n_i v_i;\ (\#/m^3 \times m/s = \#/s/m^2)$$



New Record !

5.1 x 10^{34} cm^{-2}s^{-1}

Y. Ohnishi at eeFact2025