Brief History of e+e- Circular Colliders Emphasizing Future Applications

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U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

List of e+e- Colliders

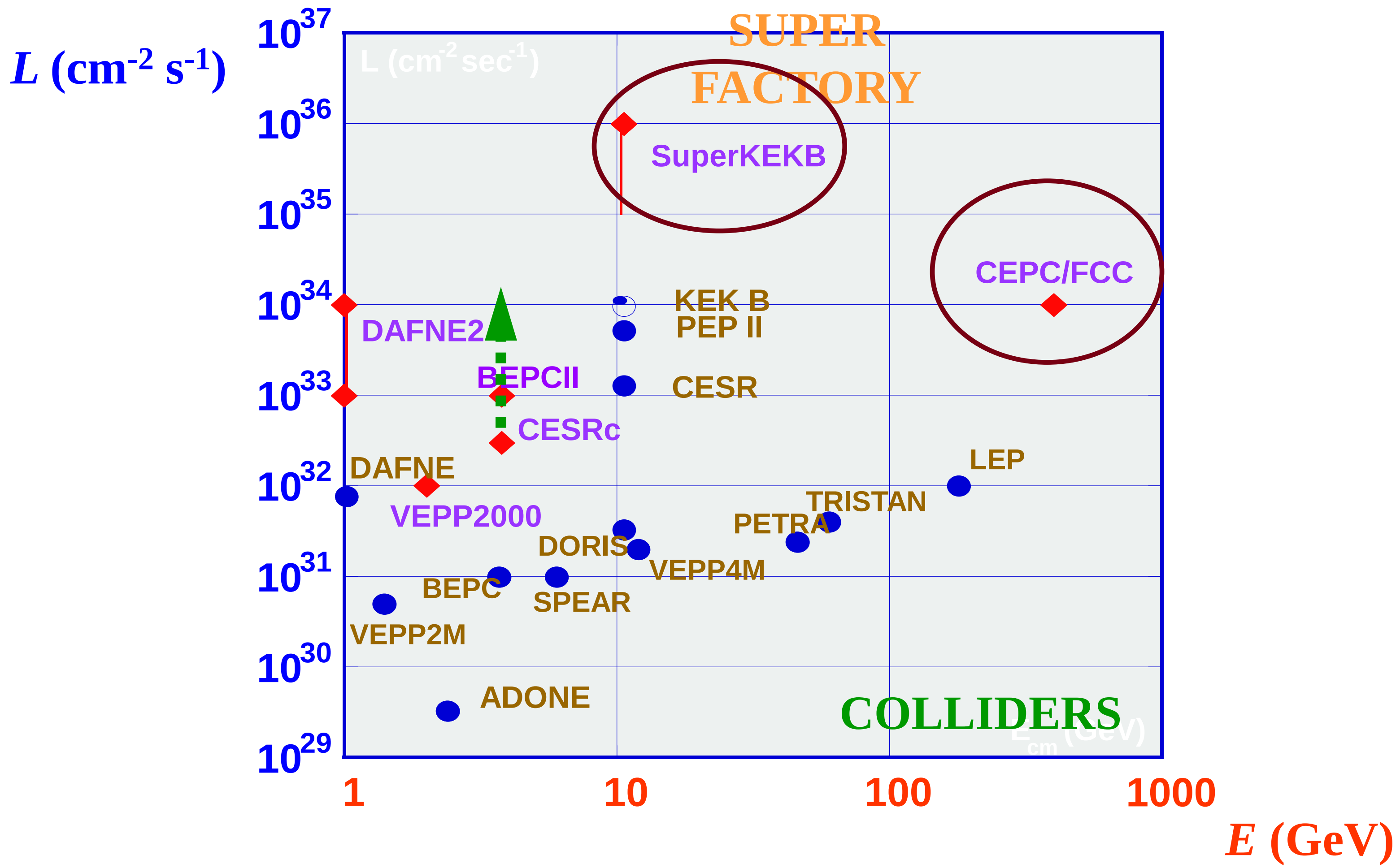
Collider	Laboratory	Date start-end	Circumf. (type) [m]	Beams	E [GeV]	Luminosity [10^{30} cm^{-2}s^{-1}]
ADA	Frascati, Italy	1961-1964	3 (SR)	e^-/e^+	0.25	Measured
VEP-1	BINP, Russia	1962-1967	2.7 (DR)	e^-/e^-	0.13	0.003
CBX	Stanford, USA	1963-1967	12 (DR)	e^-/e^-	0.5	0.0017
VEPP-2	BINP, Russia	1967-1970	11.5 (SR)	e^-/e^-	0.13	0.02
ACO	Orsay, France	1967-1972	22 (SR)	e^-/e^+	0.5	0.1
VEPP-2M	BINP, Russia	1974-2000	17.8 (SR)	e^-/e^+	0.7	100
ADONE	Frascati, Italy	1969-1993	105 (SR)	e^-/e^+	1.5	0.6
CEA Bypass	Cambridge, USA	1971-1974	225 (SR)	e^-/e^+	3.0	10
SPEAR	SLAC, USA	1972-1988	234 (SR)	e^-/e^+	2.5	12
DORIS	DESY, Germany	1973-1993	288 (DR,SR)	e^-/e^+	6.0	33
DCI	Orsay, France	1977-1984	95 (DR)	e^-/e^+	1.8	1.4
PETRA	DESY, Germany	1978-1986	2304 (SR)	e^-/e^+	19	23
CESR	Cornell, USA	1979-2008	768 (SR)	e^-/e^+	6.0	1100
VEPP-4	BINP, Russia	1979-present	366 (SR)	e^-/e^+	7.0	50
PEP	SLAC, USA	1980-1988	2200 (SR)	e^-/e^+	15	59

List of e+e- Colliders (cont)

Collider	Laboratory	Date start-end	Circumf. (type) [m]	Beams	E [GeV]	Luminosity [10^{30} cm^{-2}s^{-1}]
Tristan	KEK, Japan	1986-1995	3016 (SR)	e^-/e^+	32	140
SLC	SLAC, USA	1989-1998	4000 (linear)	e^-/e^+	49	2.8
BEPC	IHEP, China	1989-2004	240 (SR)	e^-/e^+	2.8	8
LEP	CERN, Switzerland	1989-2000	26659 (SR)	e^-/e^+	104	100
DAFNE	Frascati, Italy	1998-present	98 (DR)	e^-/e^+	0.7	453
PEP-II	SLAC, USA	1998-2008	2200 (DR)	e^-/e^+	3.1x9.0	12069
KEKB	KEK, Japan	1999-2009	3016 (DR)	e^-/e^+	3.5x8.0	21083
BEPC-II	IHEP, China	2008-present	240 (DR)	e^-/e^+	2.1	293
VEPP-2000	BINP, Russia	2006-present	24.4 (SR)	e^-/e^+	1.0	100

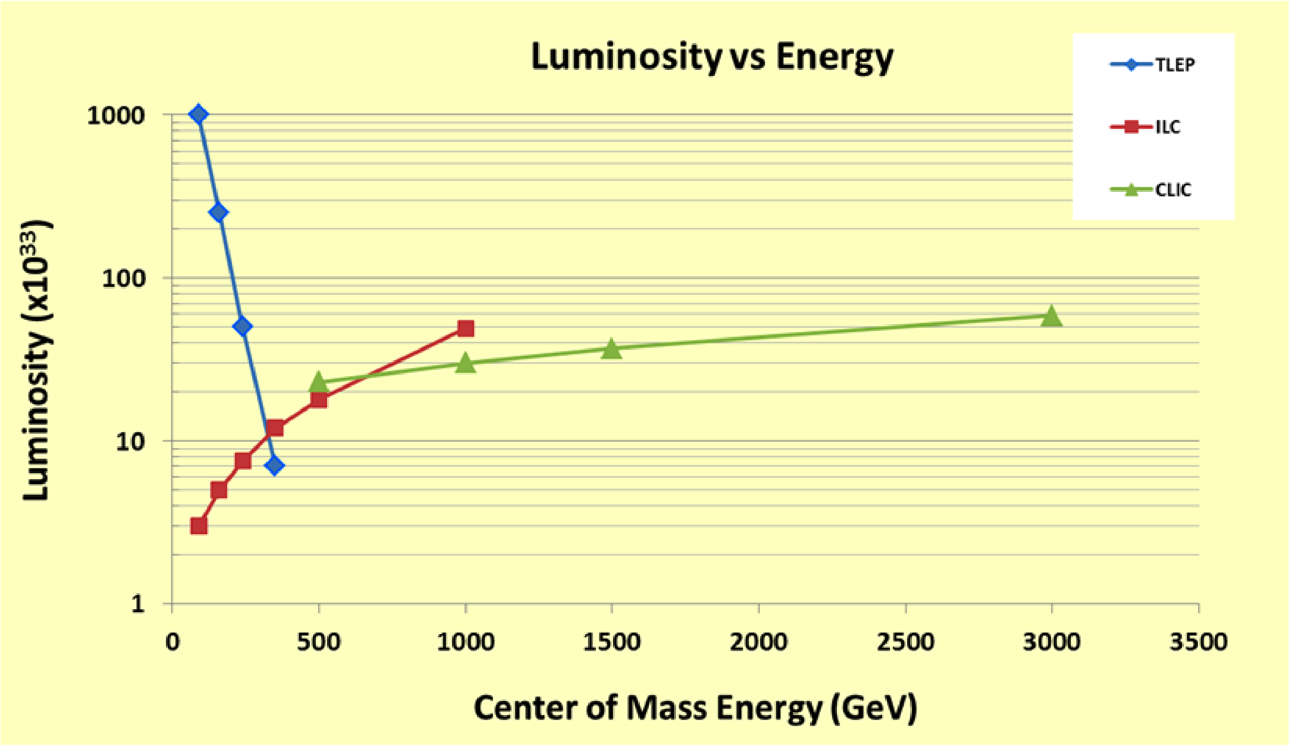
→ SuperKEKB KEK, Japan 7x 4 GeV Spring 2015!

Circular Electron Positron Collider Family

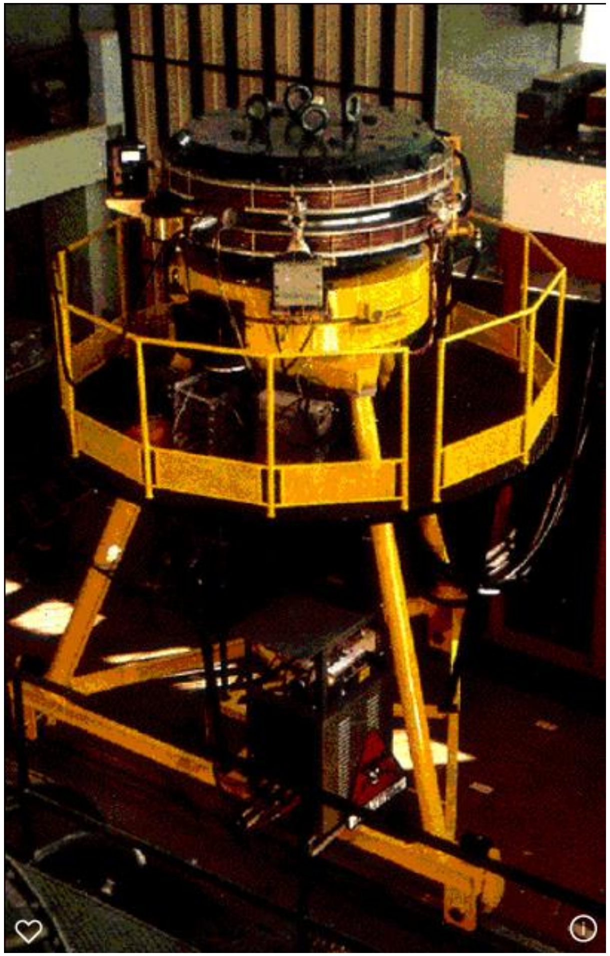


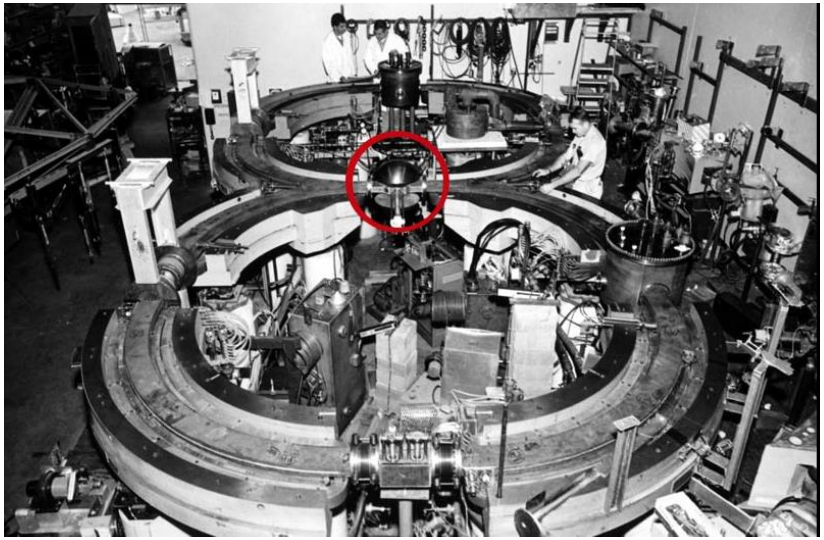
C. Biscari

Luminosity Scaling with Beam Energy (M. Zanetti)



Earliest Colliders (Early 1960's)

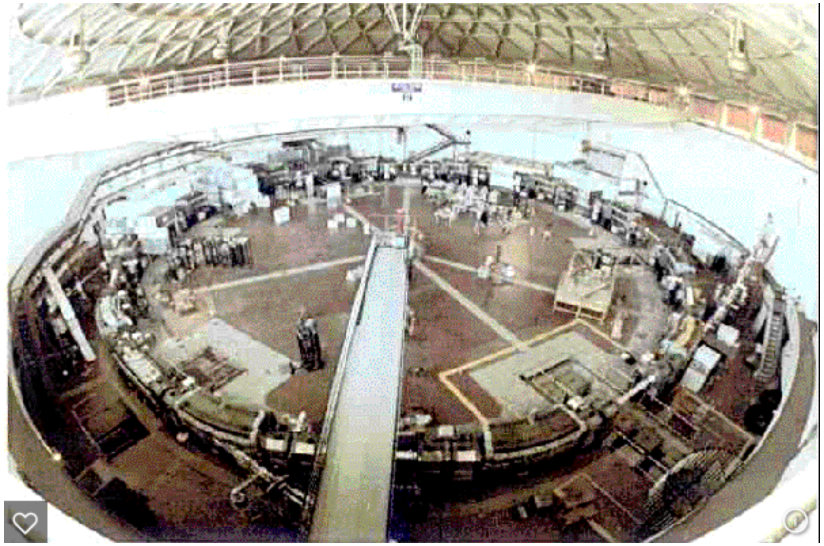




CBX e-e- Stanford
(Stored 1 Amp/per beam,
beam-beam tune shift observed))

ADA e+e- Frascati
(Touschek scattering discovered)

Low energy colliders (1970s)



ADONE Frascati
(Longitudinal feedback,
adjustable damping partitions)

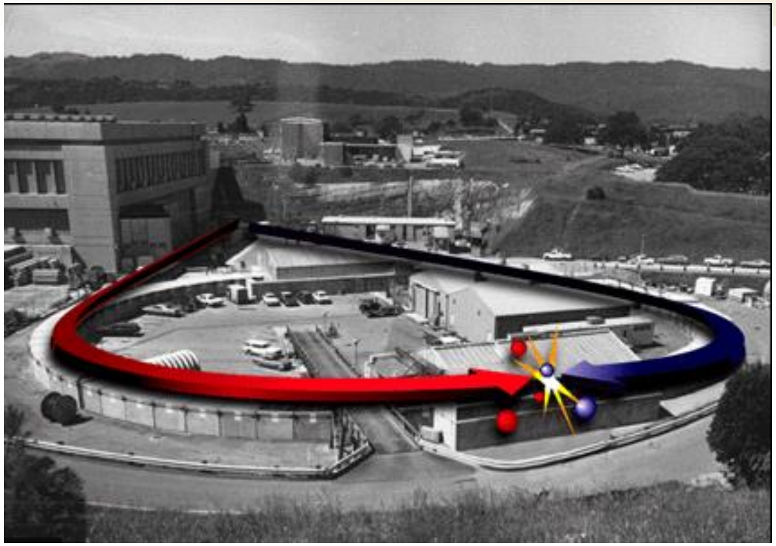
ACO Orsay
(Ring based FEL studies)

Intermediate Energy Colliders (1980s)

PEP, SLAC
(Three bunches per beam,
Mitigations for head-tail
microwave instability)

PETRA, DESY
(Seven cell RF cavities,
Positron pre-damping ring)

Phi-Tau-Charm Colliders



SPEAR
(Flexible
Lattice)

DAFNE
(Crab waist)

VEPP-2000
(Round beams)

BEPC-I&II
(SC RF)

Asymmetric Energy B Factories (1998-2010)

PEP-II, SLAC
(1722 bunches,
3 Amps stored,
Top-up injection,
bunch feedback)

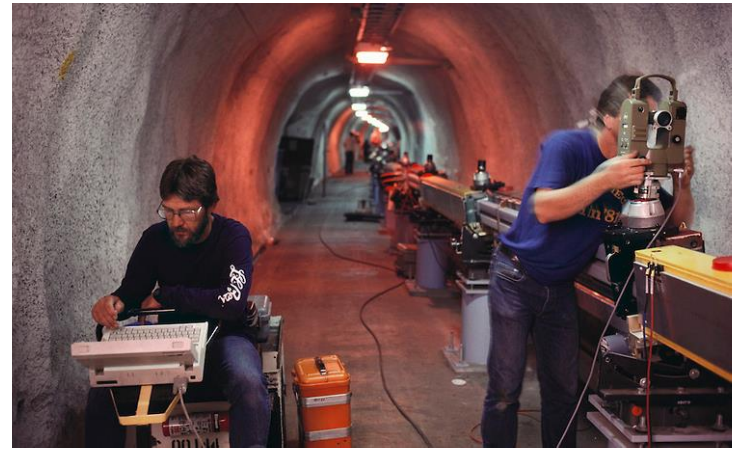
KEKB, KEK
(Low emit lattice,
record luminosity,
ARES RF cavities,
Crab cavities)

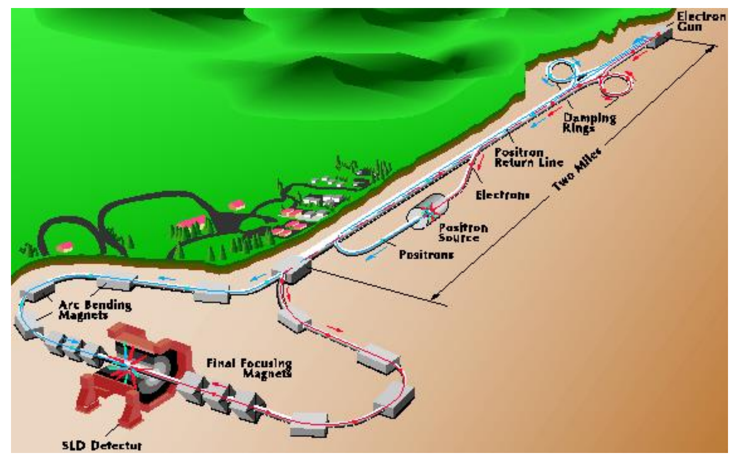
Z Colliders

Table 2 : LEP Performance Parameters

Parameter	Design (55 / 95 GeV)	Achieved (46 / 98 GeV)	
Bunch current	0.75 mA	1.00 mA	
Total beam current	6.0 mA	8.4 / 6.2 mA	
Vertical beam-beam parameter	0.03	0.045 / 0.083	
Emittance ratio	4.0 %	0.4 %	× 10
Maximum luminosity	16 / 27 10^{30} cm^{-2}s^{-1}	23 / 100 10^{30} cm^{-2}s^{-1}	× 1.4 / 3.7
IP beta function b_x	1.75 m	1.25 m	
IP beta function b_y	7.0 cm	4.0 cm	

LEP, CERN
(high beam energy 104 GeV
Pretzel orbit, concrete dipoles)



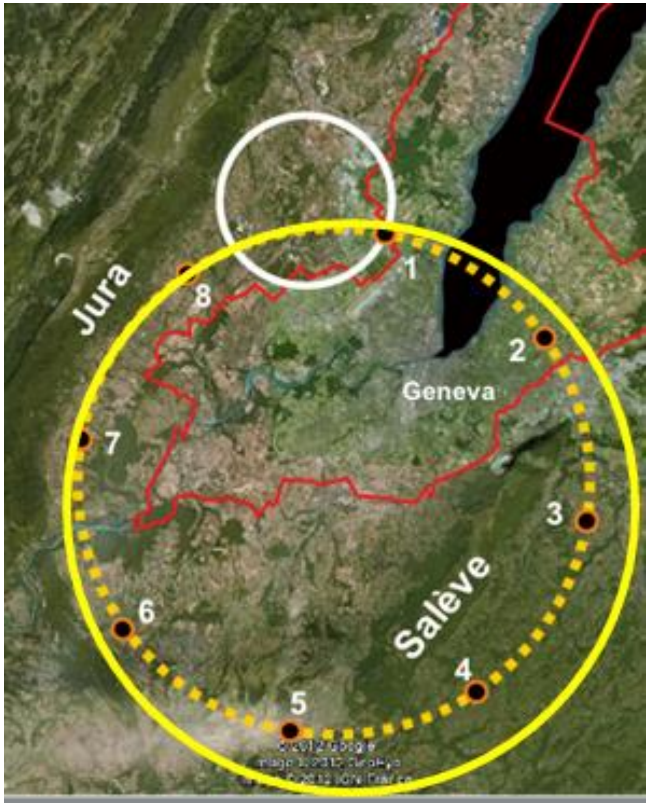


SLC, SLAC
(First linear collider,
BNS damping, e- polarization at IP)

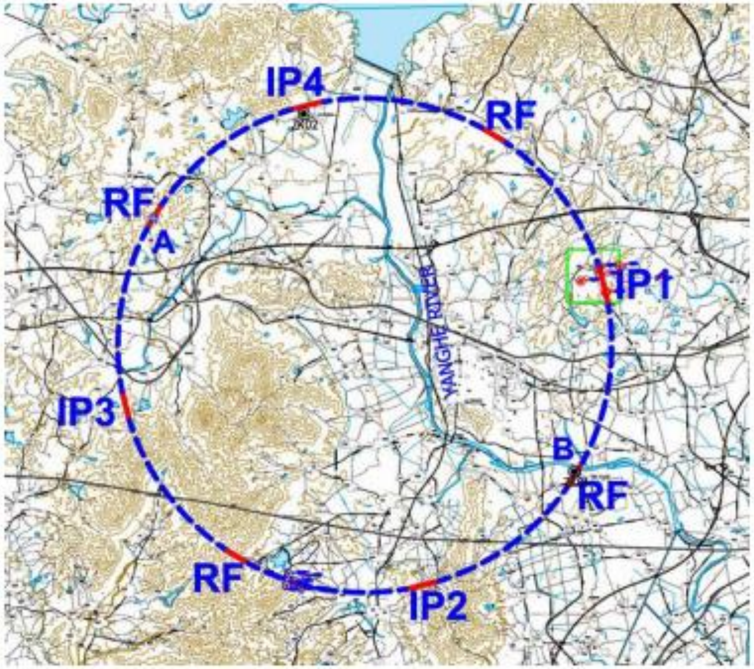
SuperKEKB nearing completion

(nano-beam emittances, mm level IP vert betas)

Future New e+e- Colliders (Higgs, Top)



FCCee



: A hypothetical location of the CEPC ring on the Qinghuangdao area

CEPC

How to get more luminosity?

Luminosity equation

$$L = 2.17 \times 10^{34} \frac{n \xi_y E I_b}{\beta_y^*}$$

Parameters:

ξ_y	Vertical beam-beam parameter
I_b	Bunch current (A)
n	Number of bunches
β_y^*	IP vertical beta (cm)
E	Beam energy (GeV)

Answer:

Increase	I_b
Decrease	β_y^*
Increase	ξ_y
Increase	n

General Observations e+e- Colliders (1)

Lattices:

x-y chromatic coupling in the IR is important: → skew sextupoles.

Sextupole and skew quadrupole coupling corrections in IR

More studies of IR error tolerances needed.

Instabilities:

More work on e-cloud to allow more bunches.

Beam-Beam Calculations:

Need mores studies of non-linear beam dynamics.

Parasitic crossing studies

Beam lifetimes:

Short beam lifetimes expected in the next collider (~10 minutes) with continuous top-off needed.

General Observations Lepton e+e- Colliders (2)

Tunes:

For best collisions: ν_x = ~0.505, ν_y = 0.512-0.518,

Crab cavities:

Crab cavities tilt bunches as expected at IP.

Expected luminosity gains not, so far, fully achieved.

Must include dynamic beta effects with respect to ring apertures.

Crab cavity trip rates need some additional study.

Large Piwinski Angle:

Works in a collider.

Allows ν_x >0.505

Crab waist:

Crab waist can potentially improve the luminosity.

Effects of crab sextupoles on dynamic aperture needs work.

Round beams:

Initial beam tests look promising.

Additional tolerance studies are needed.

Interaction Point Design

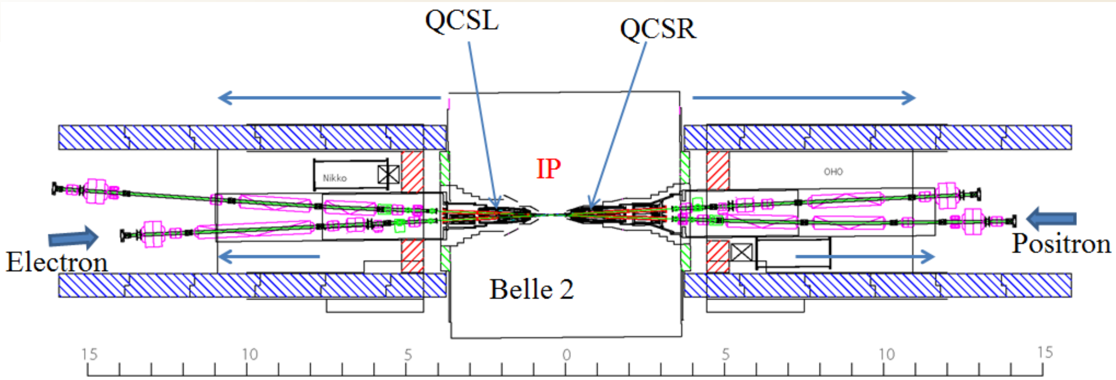
Key issues: 1 mm to 300 micron scale βy^*, large betas in IR quadrupoles, quadrupoles inside the detector, collision feedback, vacuum chamber design, magnet tolerances, alignment and jitter tolerances, crab cavities, crab waist

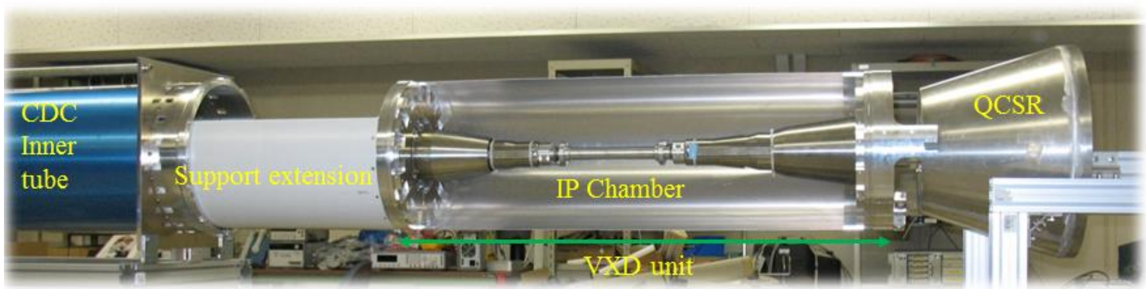
Test accelerators/facilities: SuperKEKB, CESR-TA, PETRA-3, vibration stabilization facility

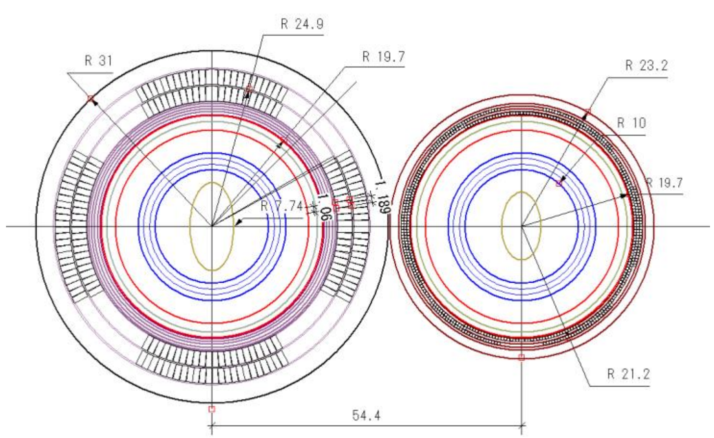
Technologies:

- 100+ Hz IP dither feedback on luminosity
- Superconducting magnets
- Permanent magnets
- Power supply stability
- Vibration control
- Non-linear optics

SuperKEKB Interaction Region







Superconducting quadrupoles
In the interaction region
Two beam passages
Need to shield stray fields.

Magnet inner radius=22 mm,
Outer radius=27.86 mm
Magnet current=1622 A
Field gradient=80.63 T/m

Machine Detector Interface

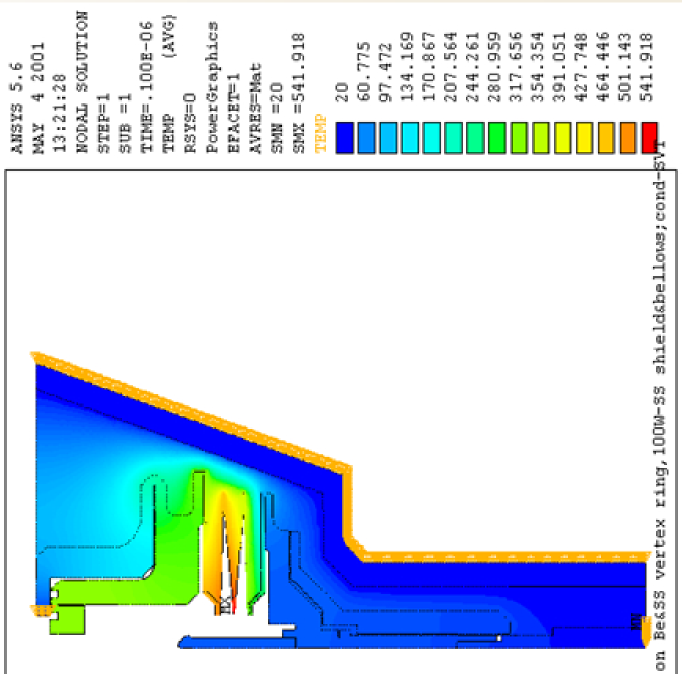
Key issue: Synchrotron radiation backgrounds, lost particle backgrounds, SR heating of vacuum chambers, radiation damage/lifetime of detectors, sensor occupancy, luminosity measurement.

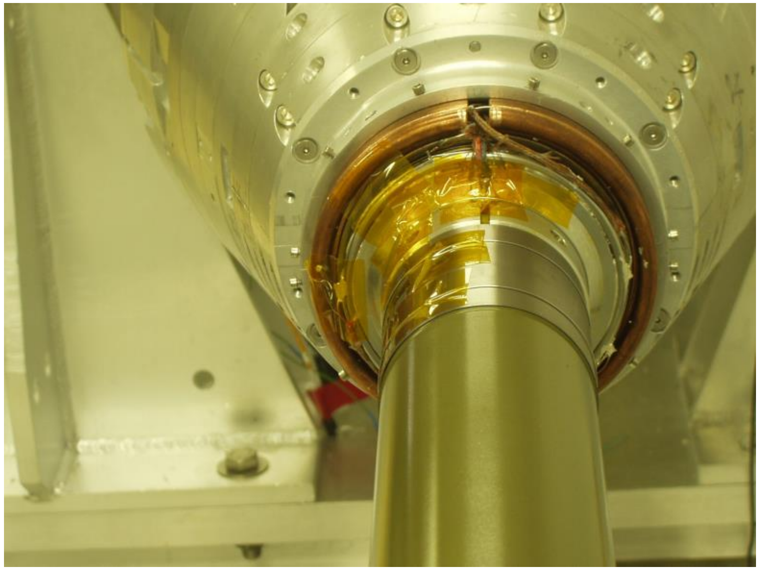
Test accelerators/facilities: SuperKEKB, LHC, lab tests of high power vacuum chambers, lab tests of detector lifetime

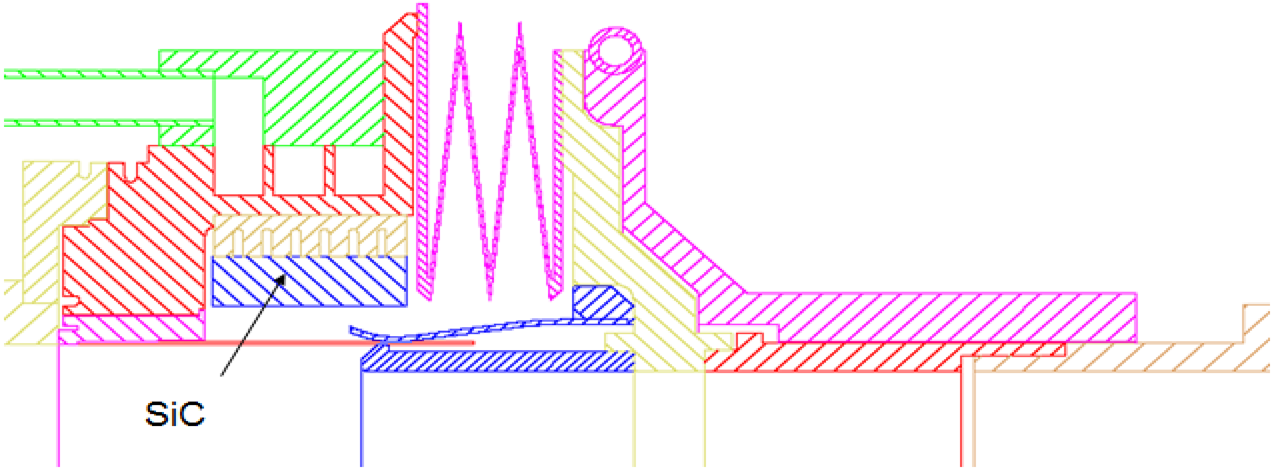
Technologies:

- IP vacuum pumping
- Advanced masking
- Rapid luminosity feedback
- Detector design

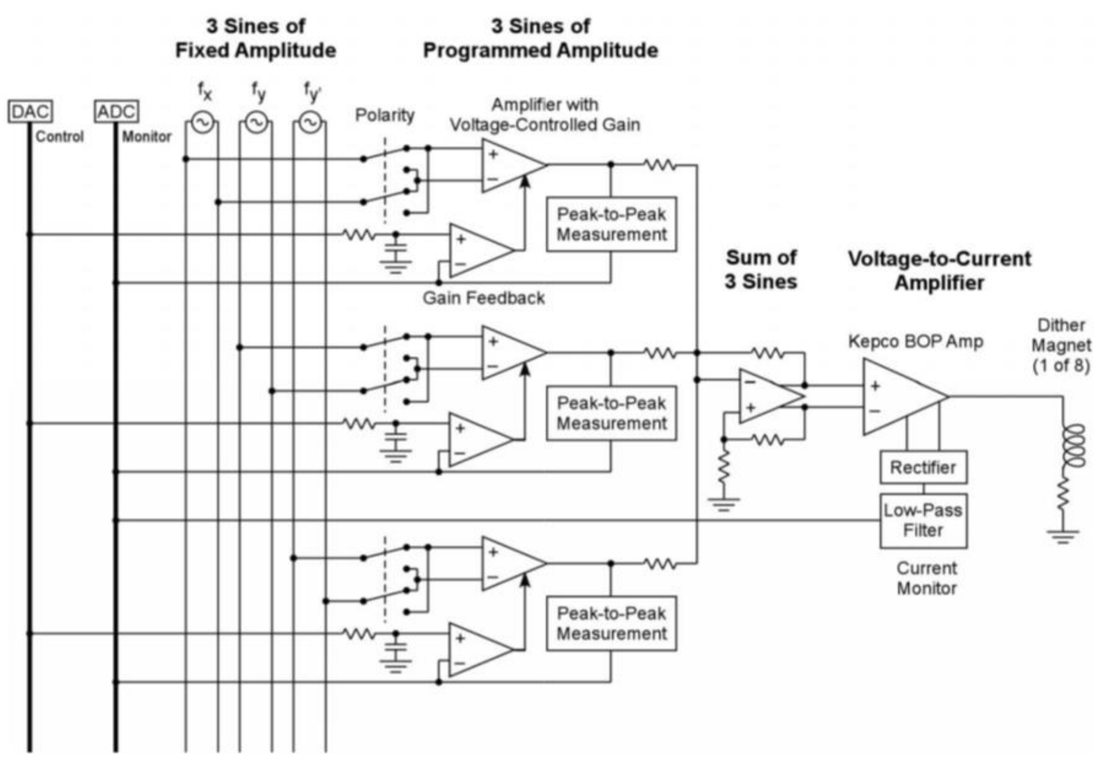
IP Vertex Be Chamber Bellows Cooling (PEP-II, 5 Amps)

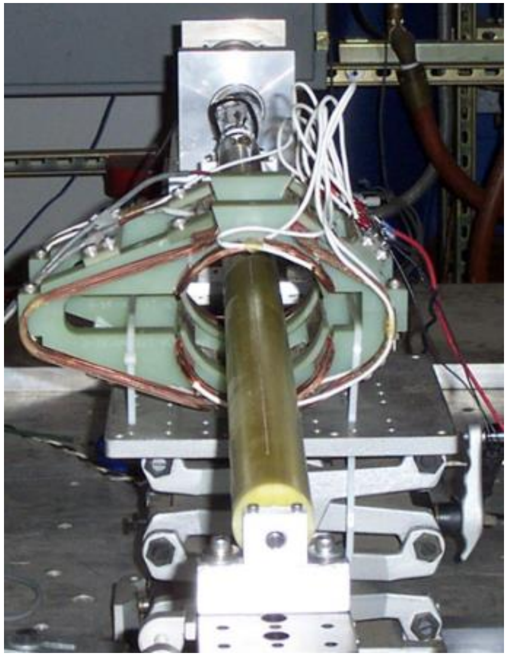


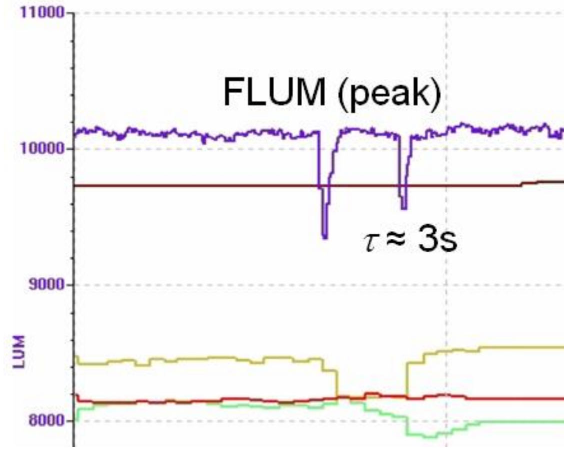




SuperKEKB Fast Dither Feedback (Wienands, Funakoshi)







Low Emittances

Key issue: Component tolerances, vibration control, emittance measuring hardware, active feedbacks, field nonlinearities.

Test accelerators/facilities: SuperKEKB, PETRA-3, CESR-TA, NSLS-II, lab tests of x-ray size monitors

Technologies:

300 to1 emittance tuning techniques

Coherent Synchrotron Radiation CSR simulations and measurements

Fast Ion Instability FII simulations and measurements

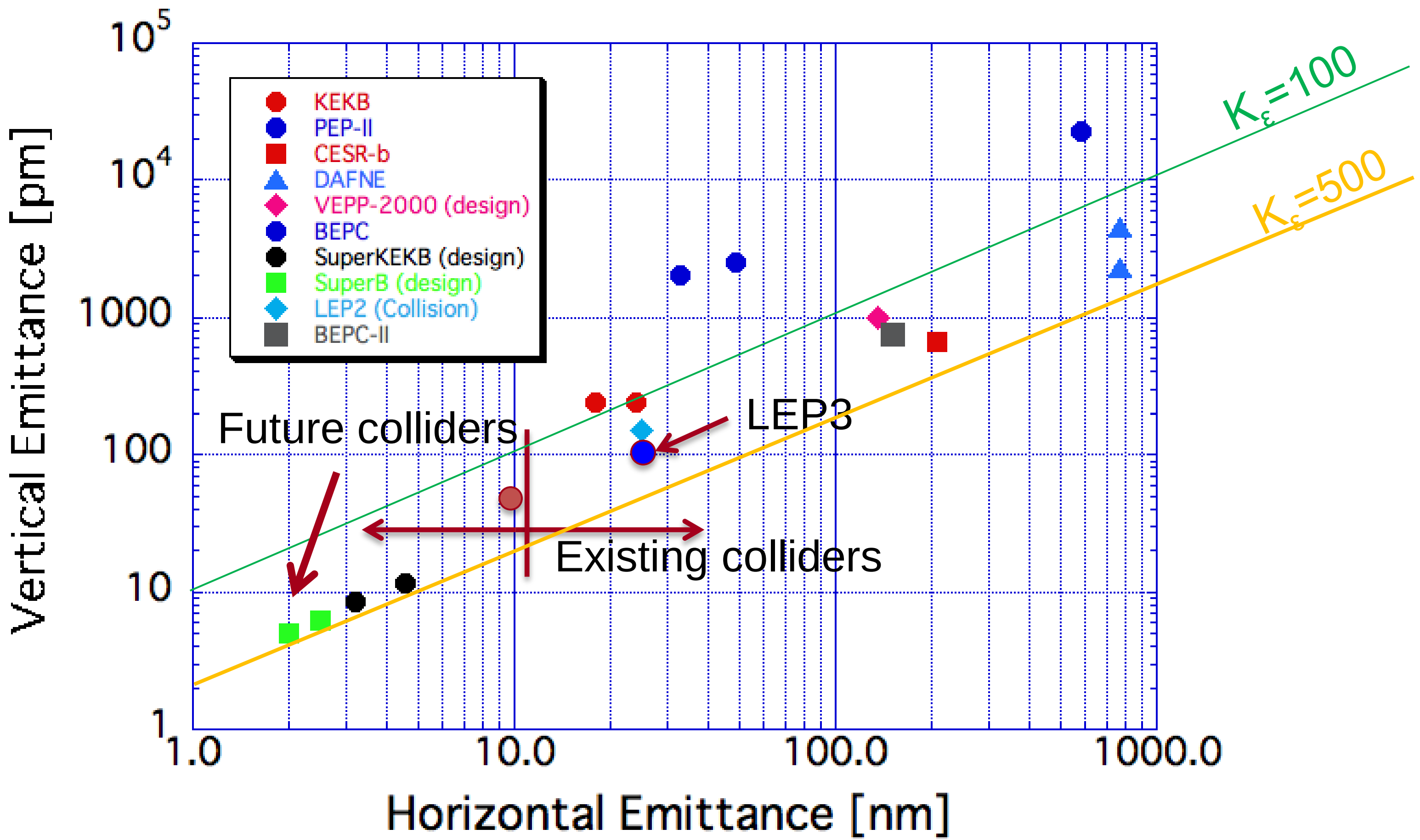
Intra-Beam Scattering IBS simulations and measurements

Electron Cloud Instability ECI simulations and measurements

Effects of spin rotators.

Effects of beam-beam interaction on spin

Comparison of Emittances of Colliders



Courtesy of F. Zimmermann, H. Burkhardt and Q. Qin

Vertical rms IP spot sizes in nm

LEP2	3500
KEKB	940
SLC	500
FCC	***250***
CEPC	***150***
ATF2, FFTB	73 (*35*), 77
SuperKEKB	*50*
ILC	*5 – 8*
CLIC	*1 – 2*

β_y^*:
5 cm→
1 mm

F. Zimmermann

Lattice and Dynamic Aperture Calculations

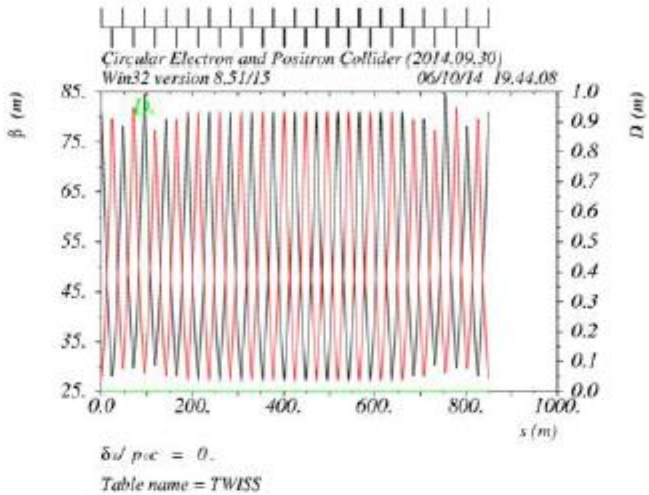


Figure 4.2.3: The beta functions and dispersion function of a short straight section in the CEPC ring.

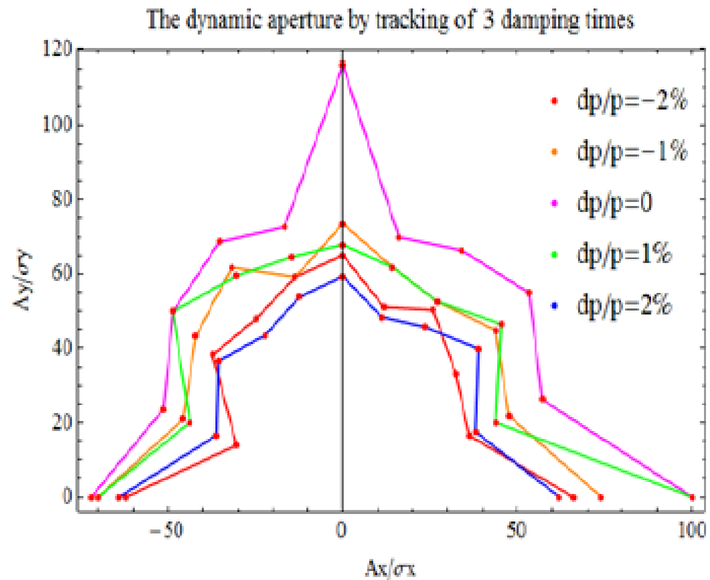
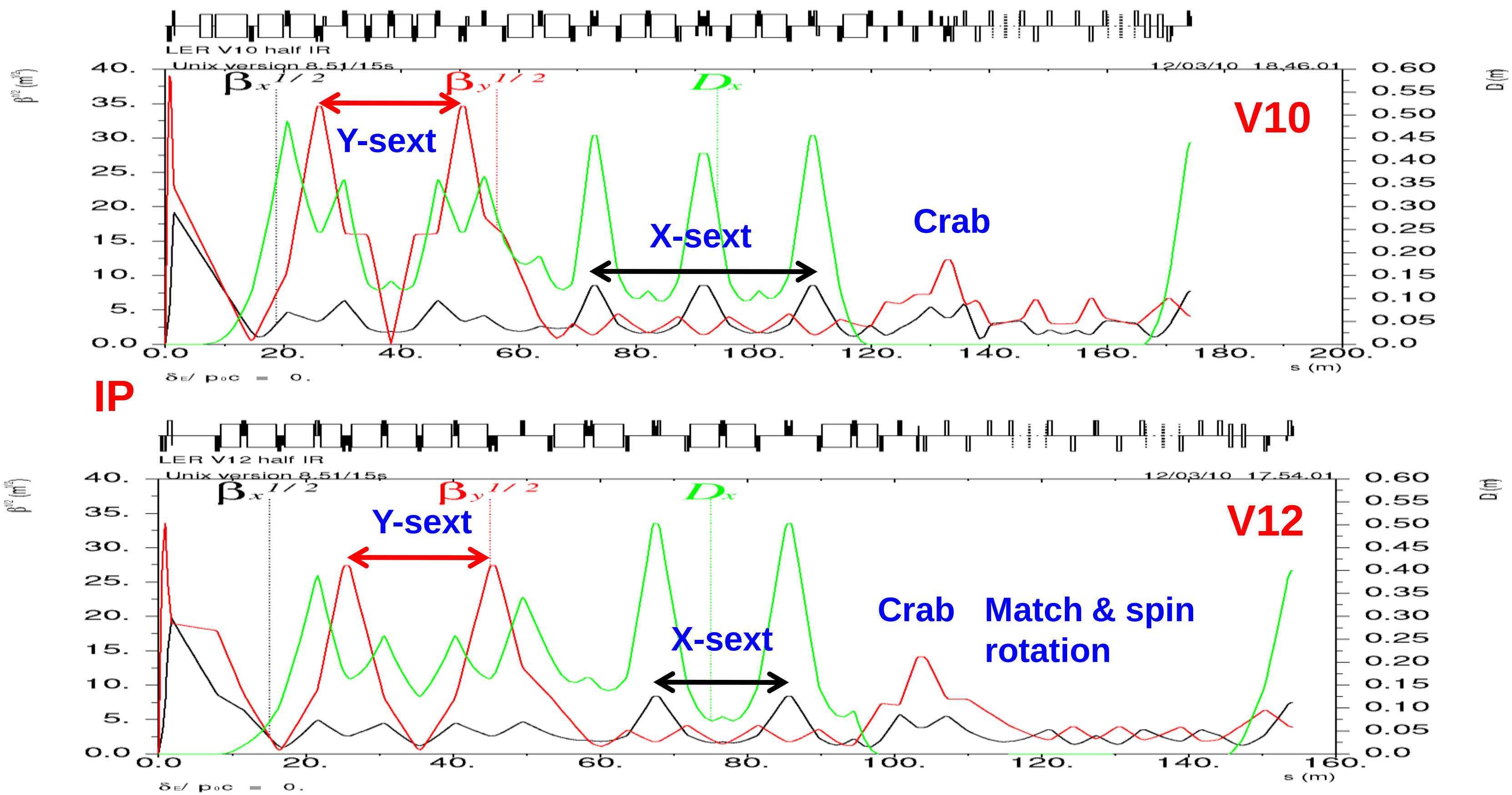


Figure 4.2.4: The dynamic aperture of the CEPC ring.

Chao, Cai)

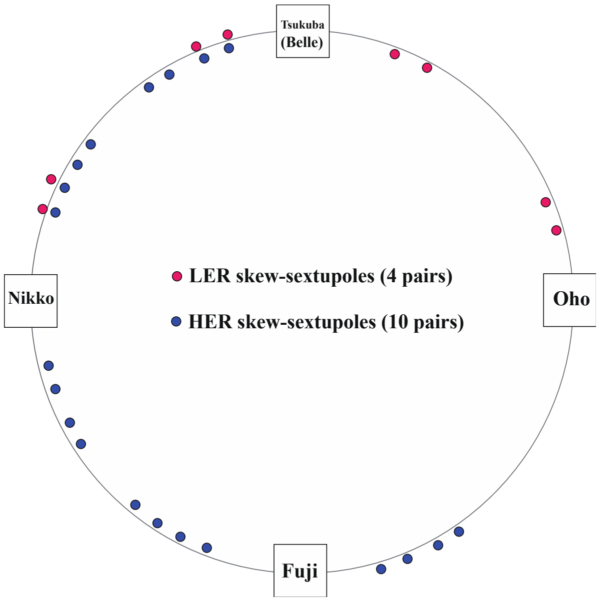
SuperB LER FF optics

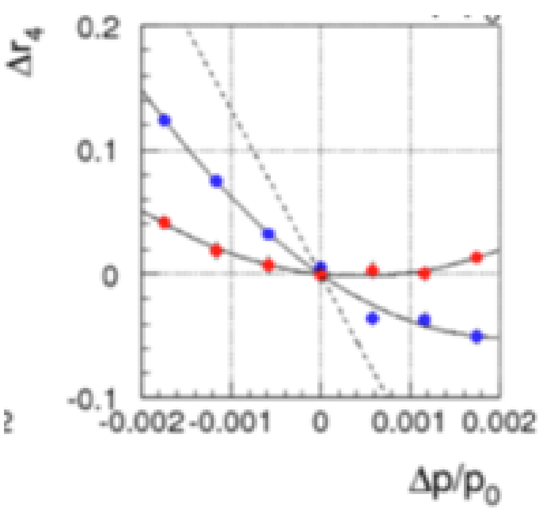
- **Similar layout as in HER except that matching section is shorter to provide space for spin rotator optics.**



(Cai, Ramondi, Biagini)

KEKB: Chromaticity of x-y coupling at IP





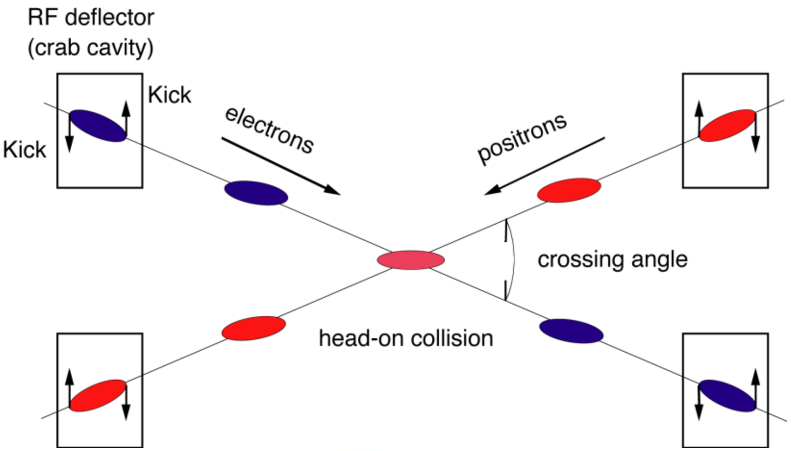
Ohmi, Cai, et al. showed that the linear chromaticity of x-y coupling parameters at IP could degrade the luminosity, if the residual values, which depend on machine errors, are large.

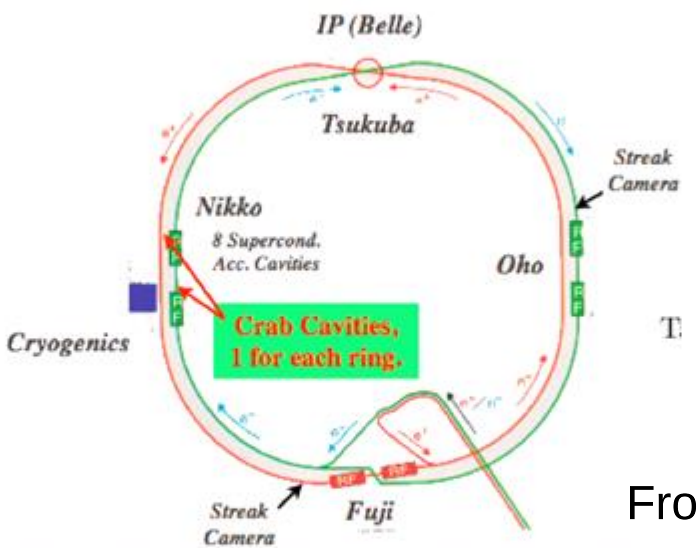
To control the chromaticity, skew sextupole magnets were installed during winter shutdown 2009.

The skew sextuples are very effective to increase the luminosity at KEKB.

The gain of the luminosity by these magnets is ~15%.

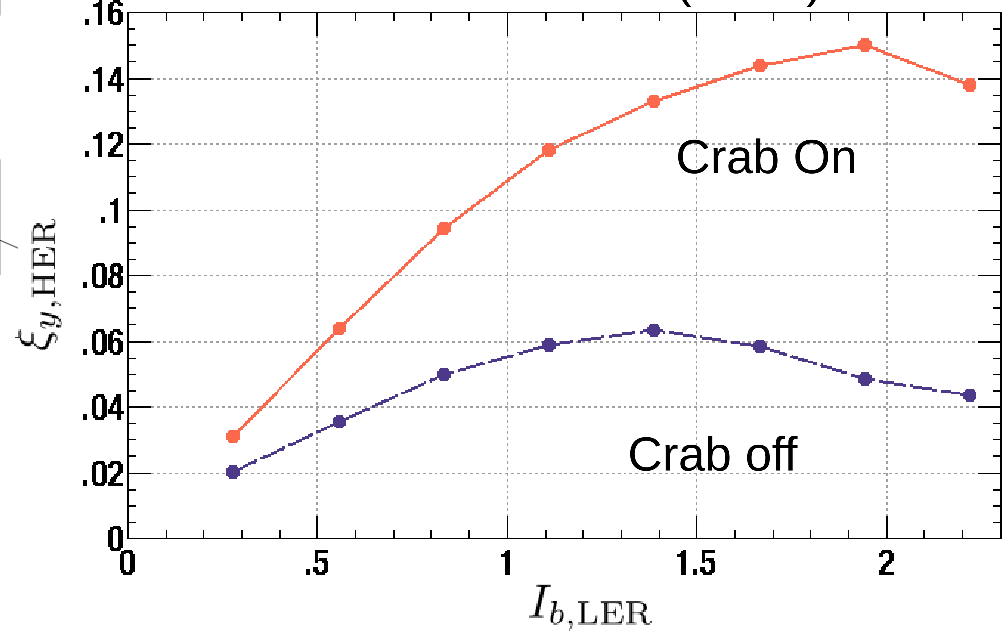
Crab Cavities in KEKB at 2 x 11 mrad crossing





* 1 crab cavity per ring.

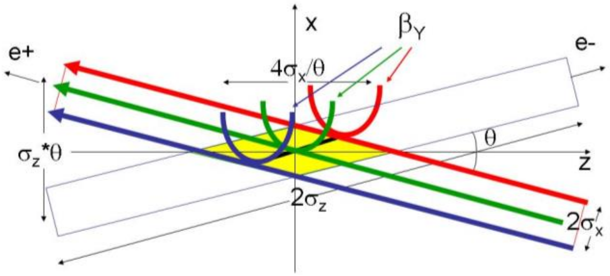
(Ohmi)



From simulation BB Parameter increases 0.06 → 0.15

(Funakoshi)

Crabbed Waist Scheme



Sextupole — β_x, β_y

IP — β_x^*, β_y^*

(Anti)sextupole — β_x, β_y

$$\Delta\mu_y = \frac{\pi}{2} \qquad \Delta\mu_y = \frac{\pi}{2}$$

$$\Delta\mu_x = \pi \qquad \Delta\mu_x = \pi$$

Sextupole strength

$$K = \frac{1}{2\theta}\frac{1}{\beta_y^*\beta_y}\sqrt{\frac{\beta_x^*}{\beta_x}}$$

Equivalent Hamiltonian

$$H = H_0 + \frac{1}{2\theta}xp_y^2$$

$$\boxed{\beta_y = \beta_y^* + \frac{(s - x/\theta)^2}{\beta_y^*}}$$

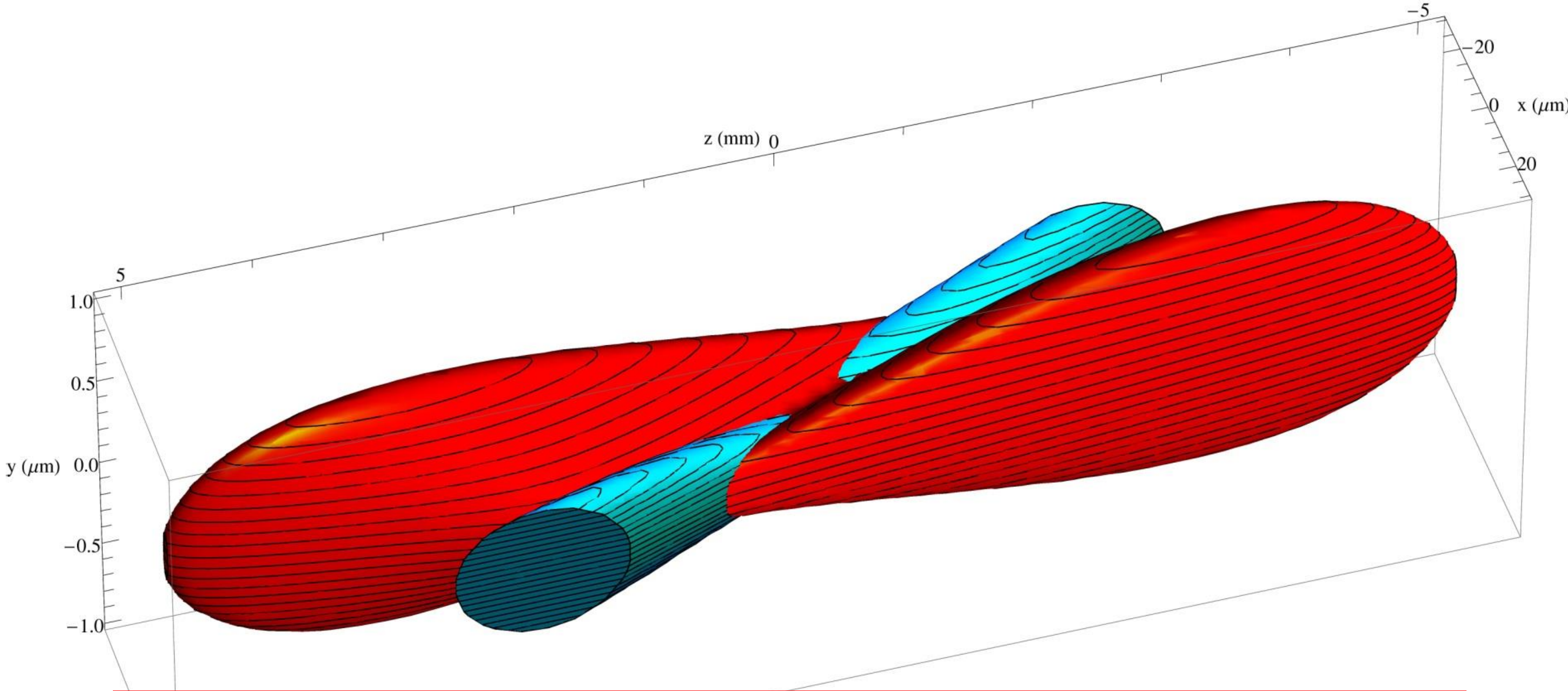
DAFNE Crab Waist:

1. Small emittance ε_x
2. Large Piwinski angle $\Phi >> 1$
3. Larger crossing angle θ
4. Longer bunch length σ_z
5. Strong nonlinear elements (sextupoles)

(Zobov)

How the crabbed waist works

Crab sextupoles OFF: Waist line is orthogonal to the axis of the beam



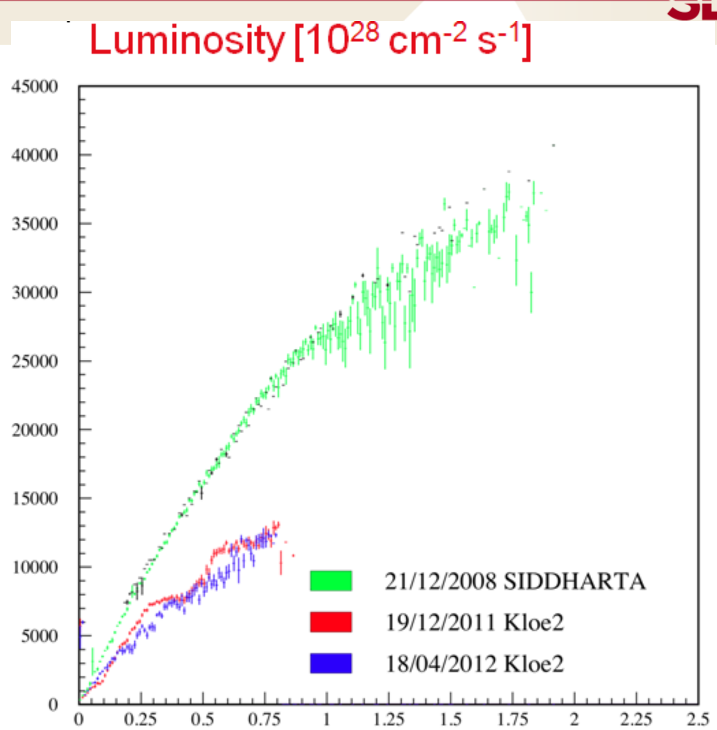
All particles in both beams collide in the minimum β_y region, with a net luminosity gain

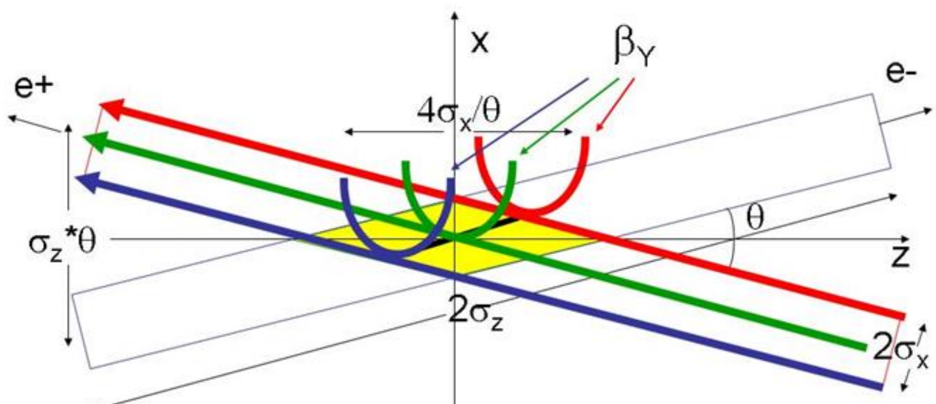
Crab sextupoles ON: Waist moves parallel to the axis of other beam: maximum particle density in the overlap between bunches

Plots by E. Paoloni

Frascati: DAFNE: Large Piwinski angle and crab waist

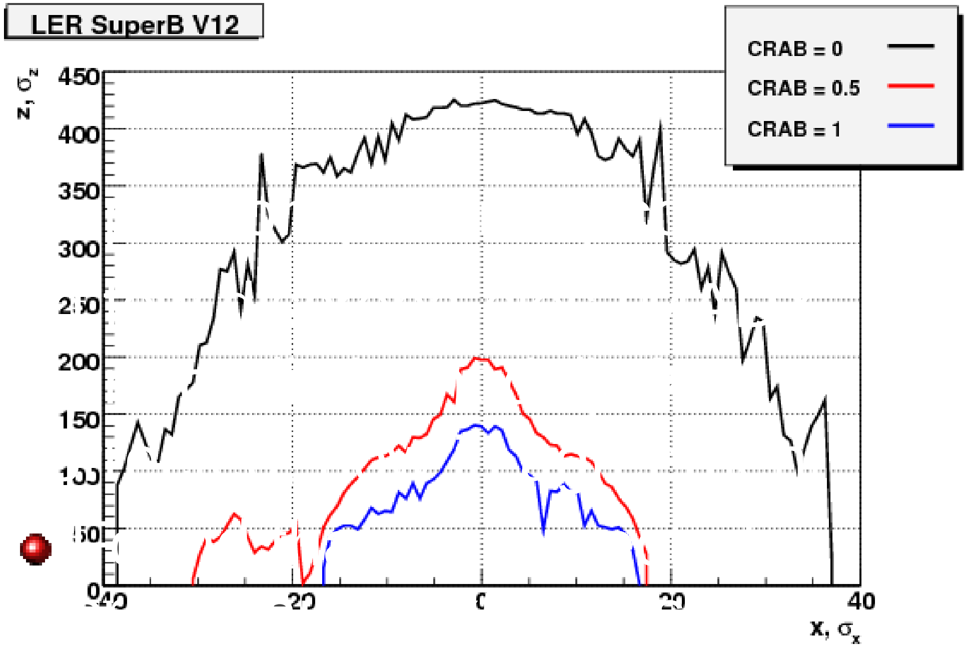
Energy per beam	510 [MeV]
Machine length	97 [m]
Max. beam current (KLOE run)	2.5(e-) 1.4(e+) [A]
N of colliding bunches	100
RF frequency	368.67 [MHz]
RF voltage	200[kV]
Harmonic number	120
Bunch spacing	2.7[ns]
Max ach. Luminosity (SIDDHARTA run)	$4.5 \cdot 10^{32}$ [$cm^{-2}s^{-1}$]

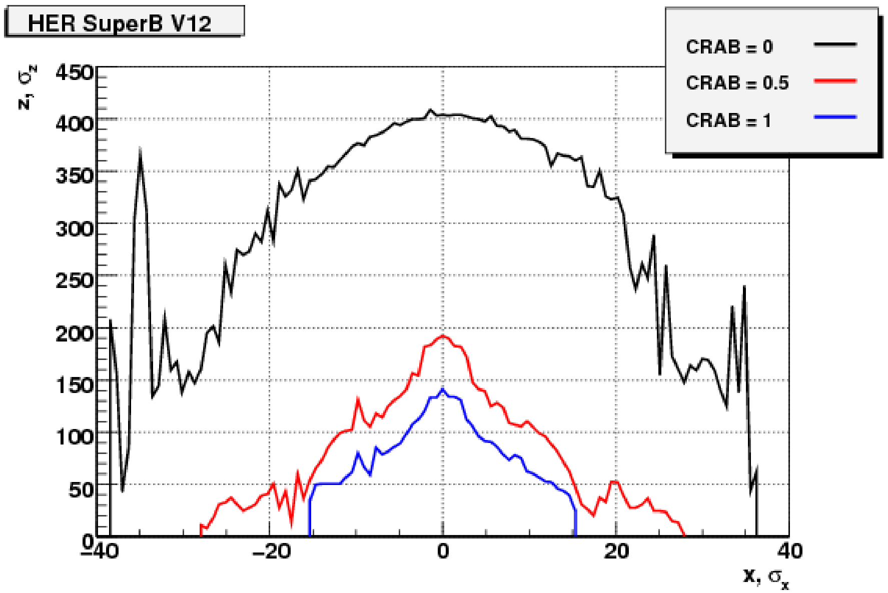




DAFNE will run for luminosity for at least the next two to three years.

Dynamic aperture studies with crab waist (SuperB studies)

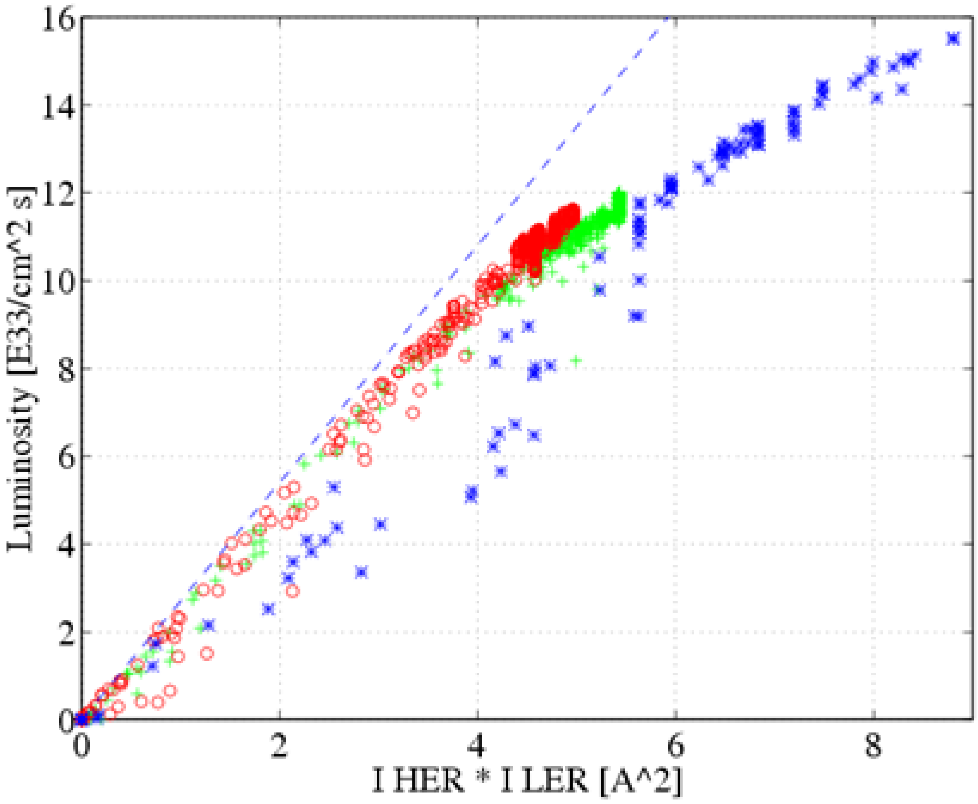




Piminov, Chancé

K. Ohmi

Luminosity and Beam-Beam Interaction



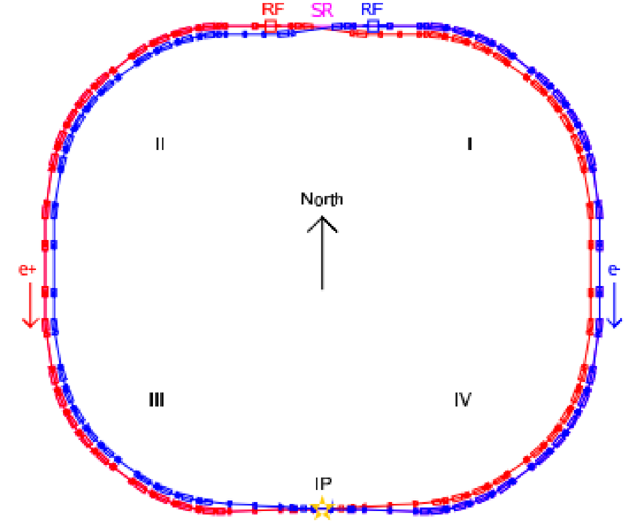
PEP-II Luminosity versus $N^{+} \times N^{-}$

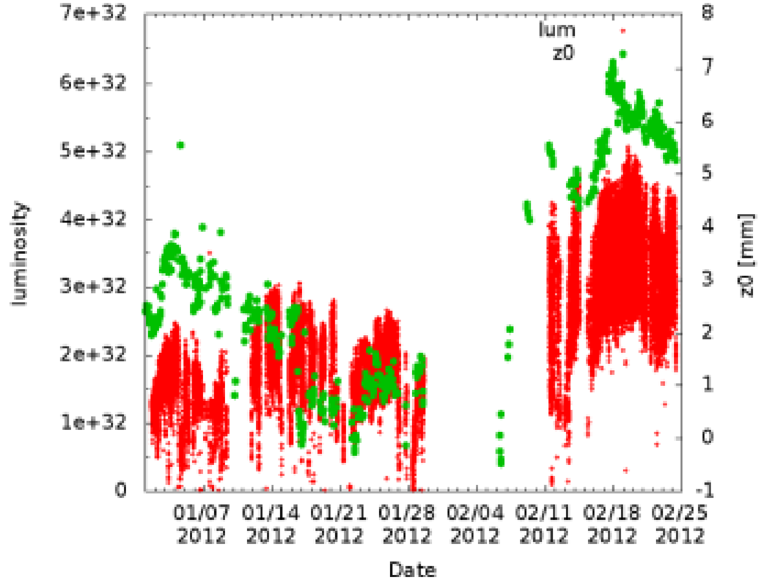
IHEP: BEPC-II: Crossing angle and new sextupole families

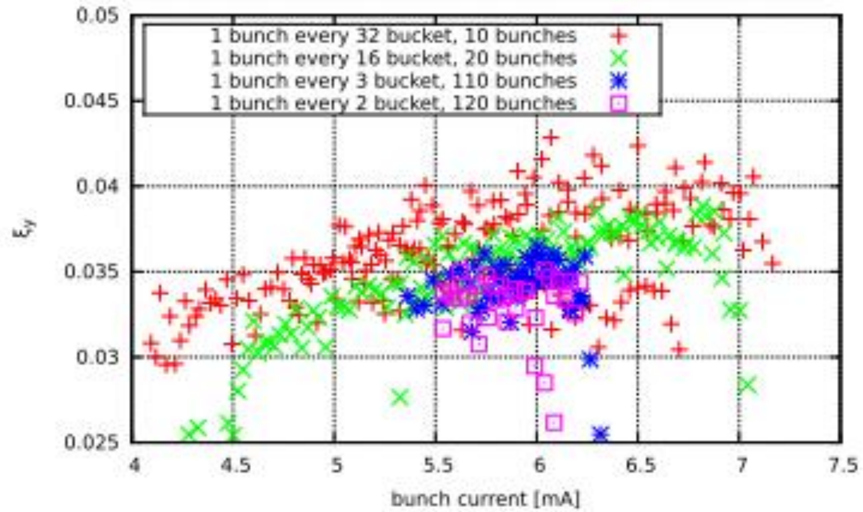
SLAC

Energy	1.89 GeV	ν_s	0.034
Beam Current	910 mA	α_p	0.024
Bunch Current	9.8 mA	σ_{z0}	0.0135 m
Bunch Number	93	σ_z	0.015 m
RF Voltage	1.5 MV	Emittance	144 nmrad
β_x^*/β_y^*	1.0/0.015 m	Coupling	1.5%
ν_x/ν_y	6.53/5.58	ξ_y	0.04
Crossing Angle	2×11 mrad	$\tau_x/\tau_y/\tau_z$	3.0e4/3.0e4/1.5e4 turns

- z0 and lum in 2010-2011
- z0 and lum in 2011-2012





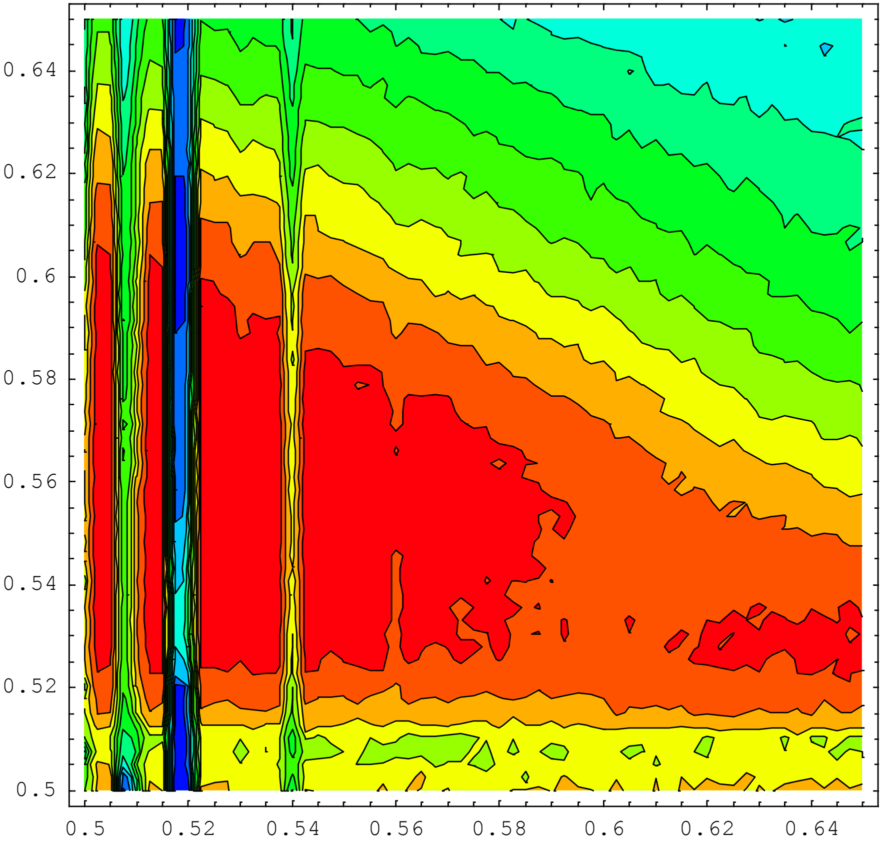


BEPC-II will run for luminosity for the next ~five years, then look at upgrades.

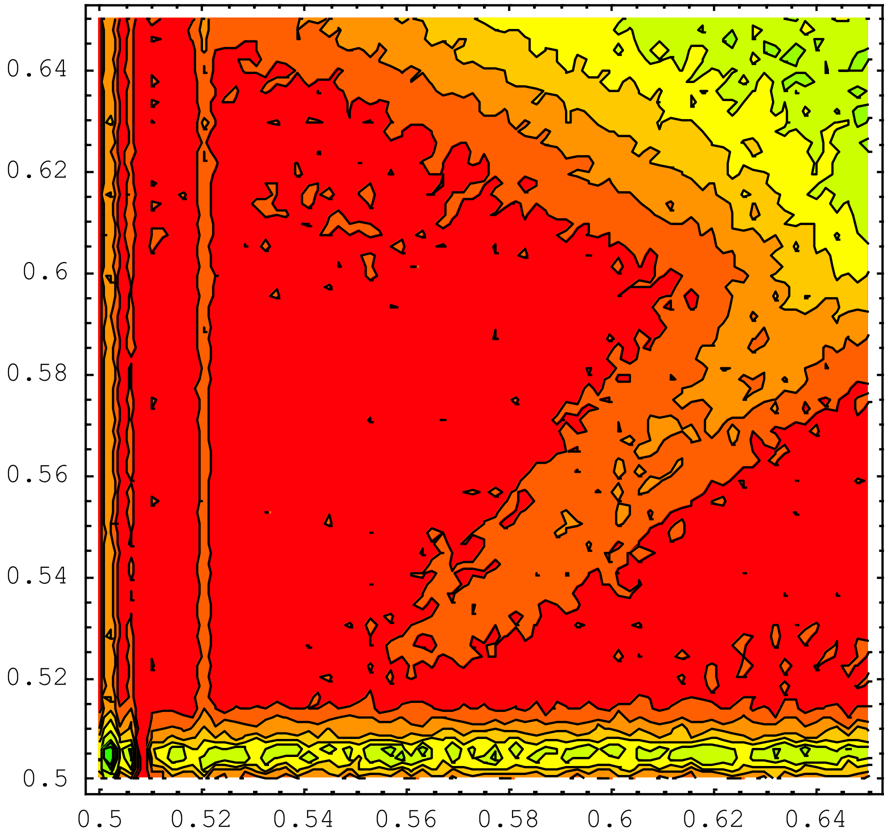
Simulations: Beam-beam tune plane scan

Shatilov

CDR, $\xi_y = 0.17$



CDR2, $\xi_y = 0.097$



Crab waist gives better performance.
Synchro-betatron resonances are still present.

L (red) = 1. ·10^{36}

High Current Effects

Key issues: Beam stability, high power RF, high power vacuum components, AC wall efficiency, injector capabilities, I> 1 A.

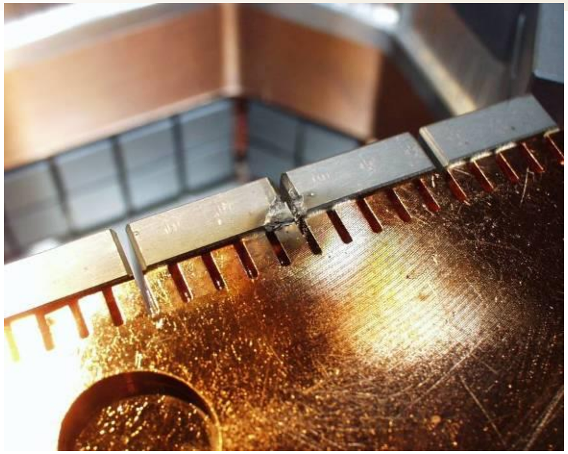
Test accelerators/facilities: SuperKEKB, CESR-TA

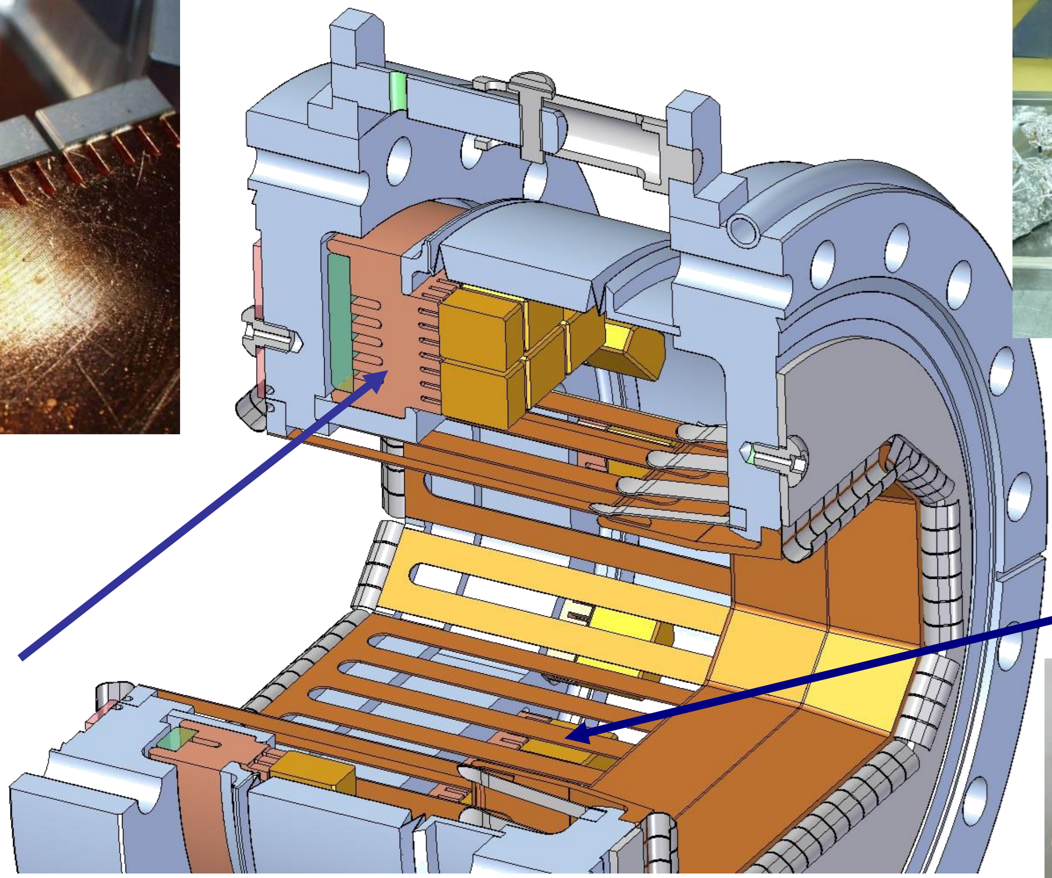
Technologies:

- Better bunch feedbacks
- Electron cloud instability control
- Intra-beam scattering mitigations
- Fast ion instability mitigations
- More efficient klystrons
- High power cavities
- Longitudinal beam feedback

New transverse kicker electrodes (SLAC, KEK)

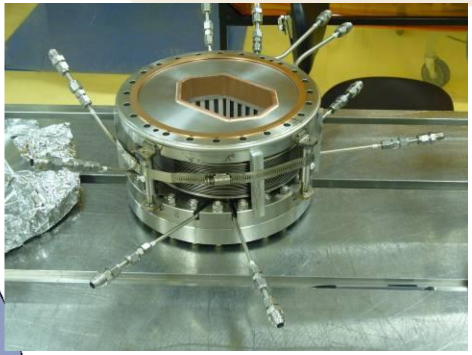
HOM Absorbing Bellows

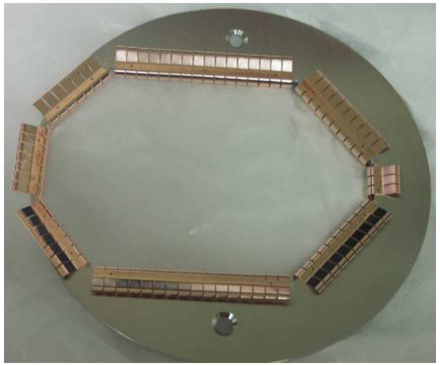




HOM tiles

Shield fingers



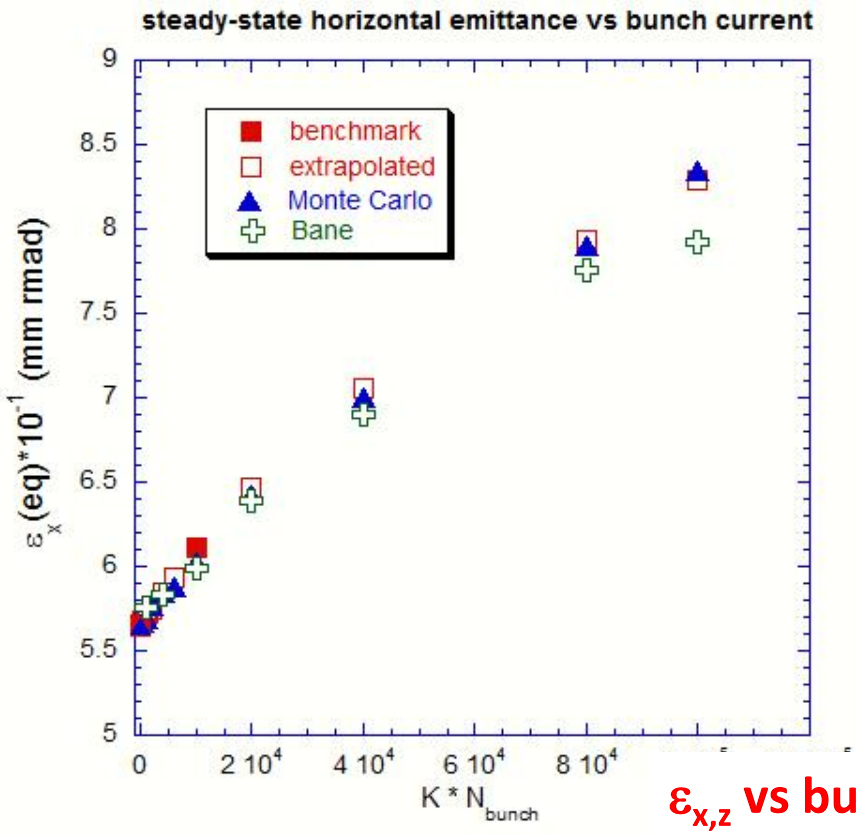


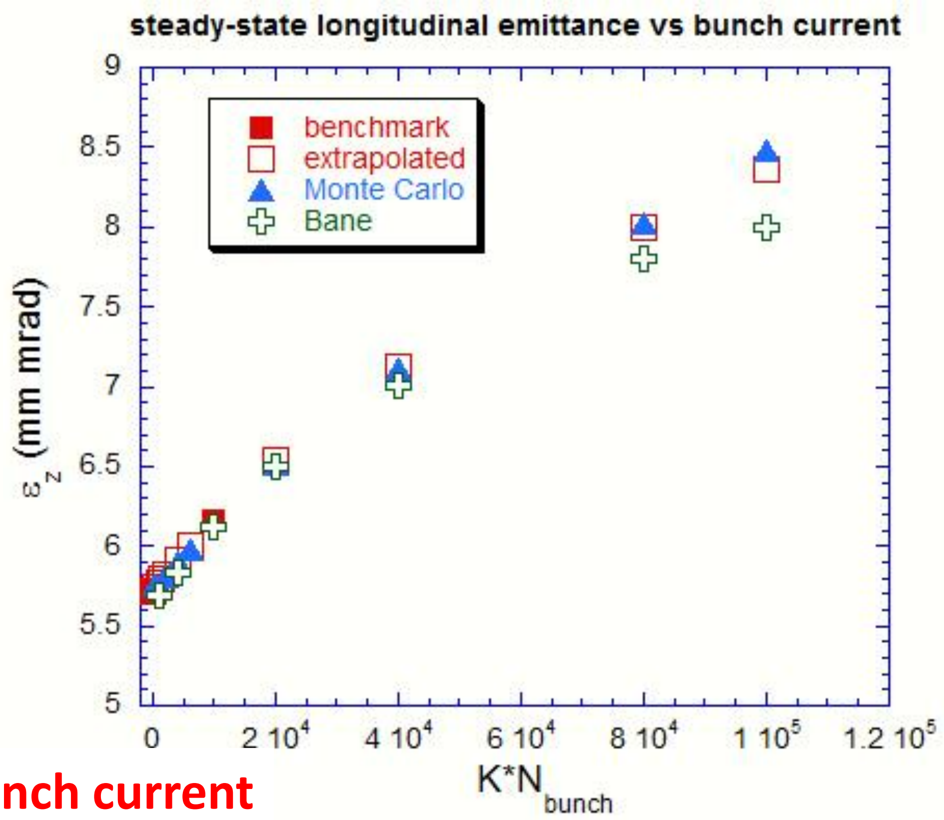
Intra Beam Scattering

Boscolo, Chao, Demma

Three methods used, all in good agreement:

- Allows for emittance growth rates estimate and for emittance time evolution estimate
- 6D MonteCarlo → more accurate, all of above, will include non-gaussian tails



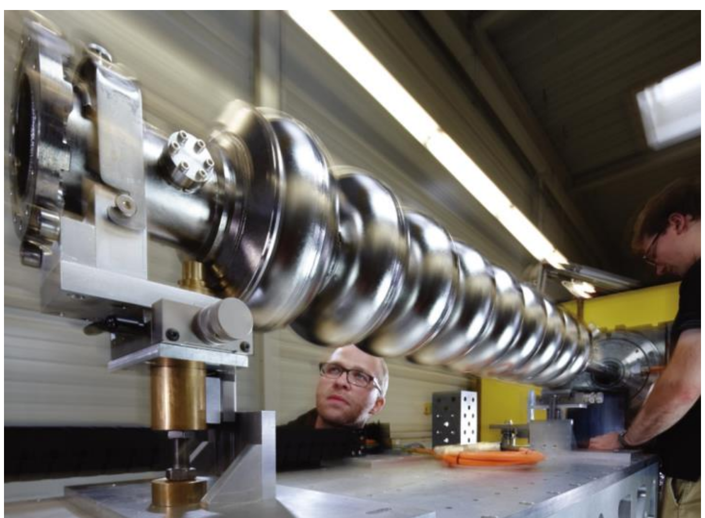


$\varepsilon_{x,z}$ vs bunch current

RF Systems

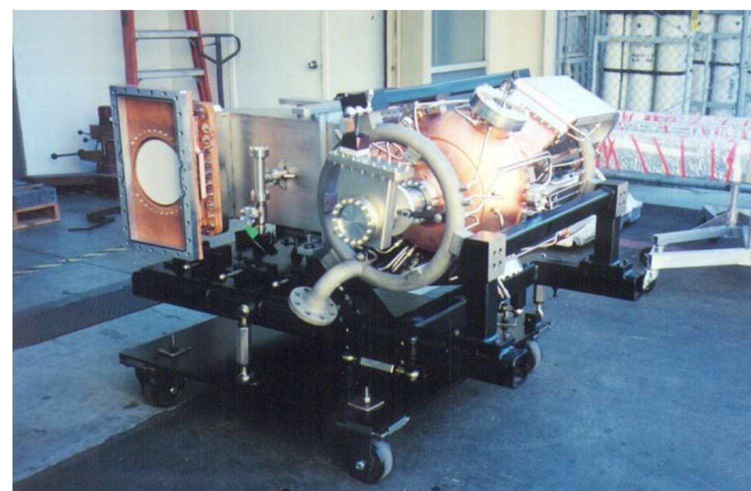
KEKB

LEP



ILC

PEP-II



High Beam Power Recipe

Higher currents and shorter bunches lead directly to much higher wake-field effects

- HOM power and CSR

Vacuum chamber impedances must be minimized

- Causes bunch lengthening
- Hard to do a lot better than present B-factories

All components must be water-cooled

- Again, difficult to do much better than present B-factories

SR power levels increase with higher beam currents causing higher total beam losses

- More RF power needed to restore the lost beam energy – more plug power

RF System Overall for FCC/CEPC

An RF system based on about 700 MHz SC cavity technology seems reasonable.

- ongoing R&D at BNL, CERN, ESS for 704 MHz cavities and components
- RF wall-plug to beam efficiency around 55 % (w/o cryogenics)

Open questions and R&D necessary

- fundamental power couplers: R&D ongoing
- HOM damping scheme: study needed
- low level RF & feedback requirements: study needed
- construction and testing cost are an issue.

Butterworth, Jensen, etc

Longitudinally Polarized e- Beam at the Interaction Point

Key issue: Injected polarization, beam lifetime, polarization lifetime, spin rotators, polarization measurements, effect on IP optics, beam-beam effect on polarization.

Technologies:

- Siberian snakes
- Solenoidal rotators
- Beam-beam depolarization diagnostics
- Spin manipulation in the Damping Ring and Linac.
- e- polarized source

Longitudinal Polarization at the Interaction Point with Vertical in the ARCs needing Spin Rotation (SuperB)

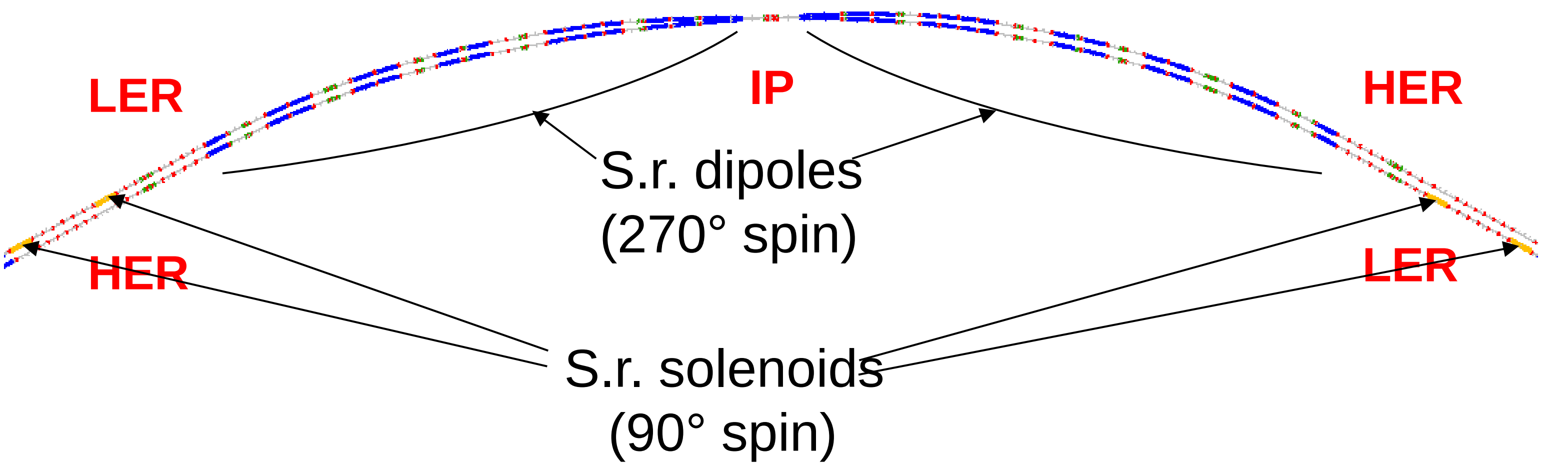
90° spin rotation about *x* axis

- 90° about *z* followed by 90° about *y*

“flat” geometry => no vertical emittance growth

Solenoid scales with energy => LER more economical

Solenoids are split & decoupling optics added.



Wienands)

Beam Lifetime

CEPC-FCC:

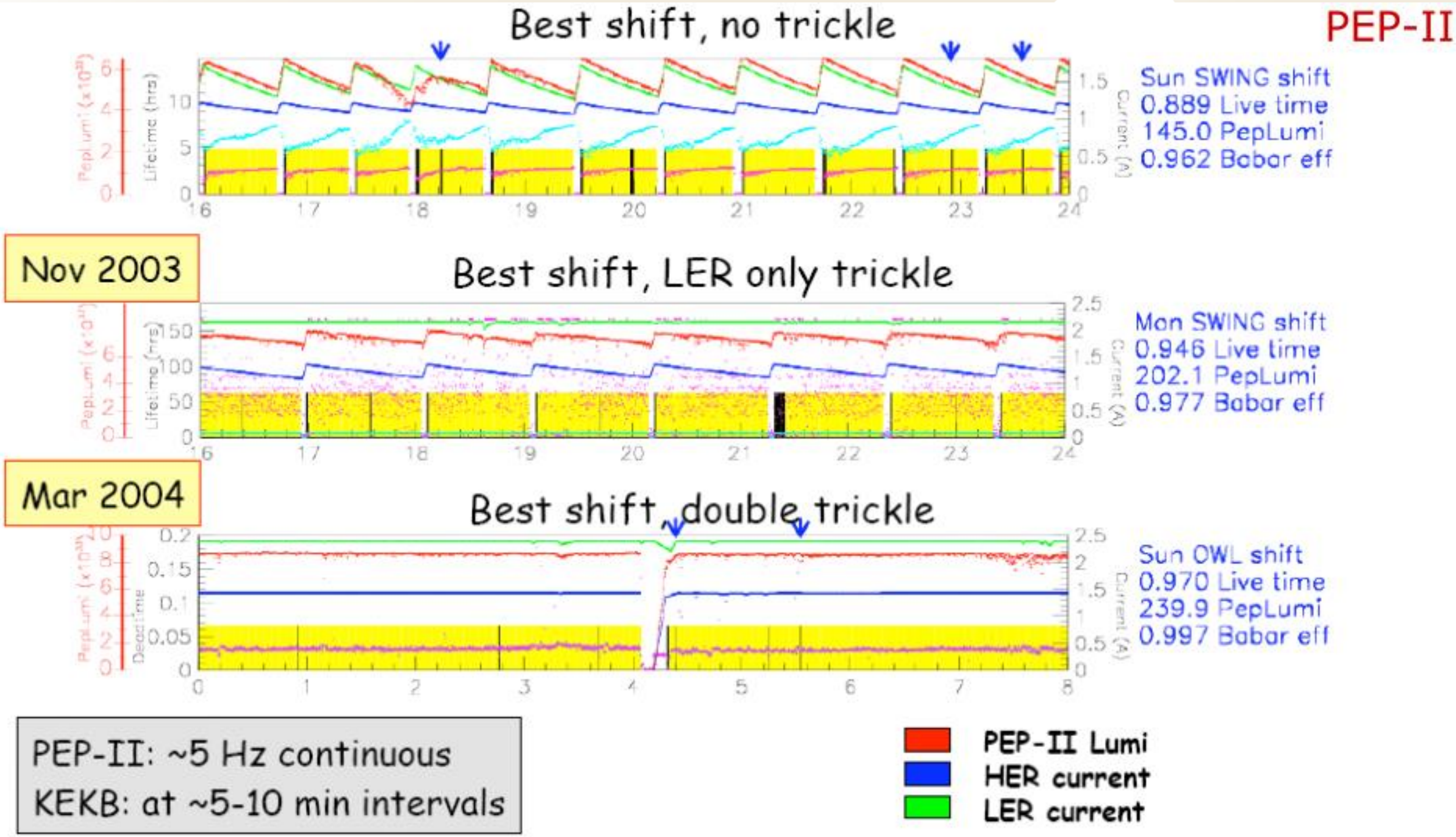
Lifetime limit due to beam-beam, luminosity (Bhabha), beamstrahlung, Touschek, and vacuum.

τ_{beam}~16 minutes

SuperKEKB: τ~6-10 minutes!

Required: Full energy and Top-Up Injection.

Top-Up or Continuous Injection In PEP-II



PEP-II: ~5 Hz continuous
KEKB: at ~5-10 min intervals

U. Wienands

"Synchrotron" as a CEPC-FCC Top-Up Injector

Top-up injection = 50 bunch / pulse

Cycle rate = 3 Hz

Injection rate: 1 Hz e+, 1 Hz e-, 1 Hz e- to make e+

Particles per injection:4 x 10^9 / pulse over 50 bunches

with 90% injection efficiency

→ 8 x 10^7 /bunch → means low instability effects and RF.

Bunch injection controller: Tailor the charge of each bunch

Magnet laminations same as AC transformers.

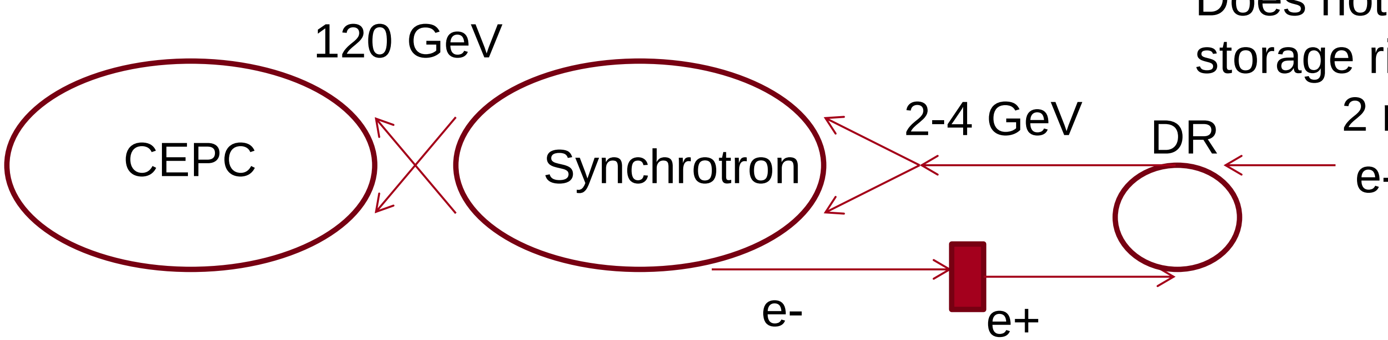
Injection kicker pulse length = 183 μsec (= 53 km)

Kickers = 13 stronger than PEP-II but 7 times slower.

Ring path length = 183 μsec (53 km)

→ Luminosity stays within 0.12% of the peak.

Cornell synchrotron: 768 m
Sine wave-magnet excitation
0.2 GeV to 12 GeV in
8.3 msec at 60 Hz.
Does not affect CESR
storage ring operation just
2 m away.



Conclusions

e+e- colliders have had a spectacular history.

Very mature knowledge base on which to design the next accelerator.

Many new accelerator physics and technology discoveries and solutions were found over the years. We need to continue to pursue new R&D and required technologies to make the next round of colliders viable.

Any new large accelerator should have a bold but achievable energy-physics reach.

Every geographical region should design to world high energy physics goals while making use of local advantages.