Introduction of Accelerator

Luminosity & Collider

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Luminosity: Definition

The luminosity is the number of events produced by the collisions, per second, for events with a cross section of one square centimeter.

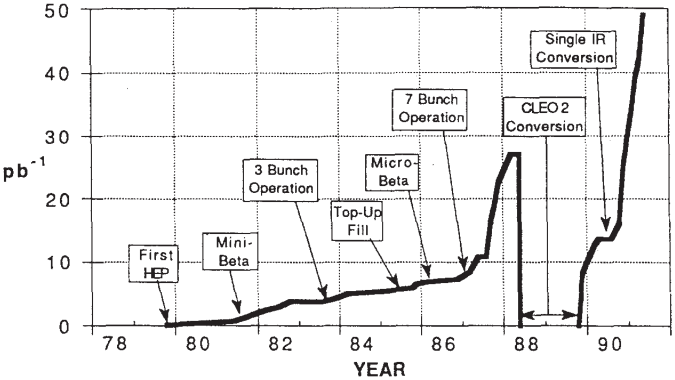
Since a typical cross section unit is one nanobarn (1 nb – $10^{-33} cm^2$), a luminosity $\mathcal{L} = 10^{33} cm^{-2} s^{-1}$ only produces one such event per second, in which case the luminosity is said to be one inverse nanobarn per second.

The figure that one quotes as luminosity is in general the peak luminosity of the machine, expressed in $cm^{-2} s^{-1}$ which mostly interests machine designers.

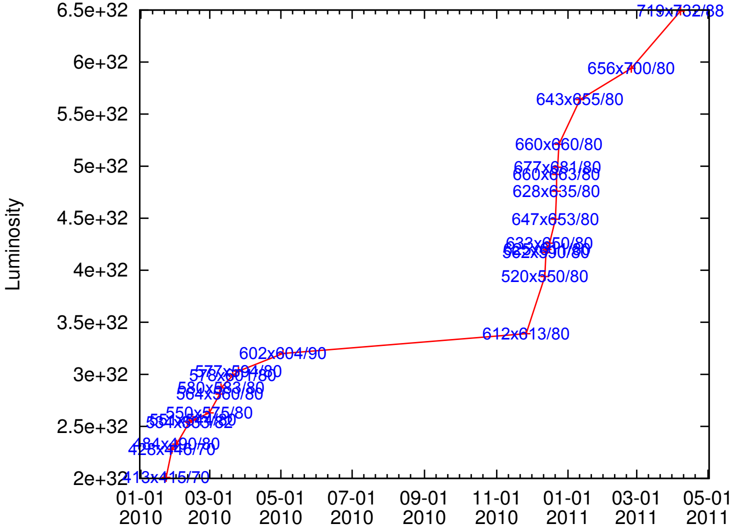
Integrated Luminosity

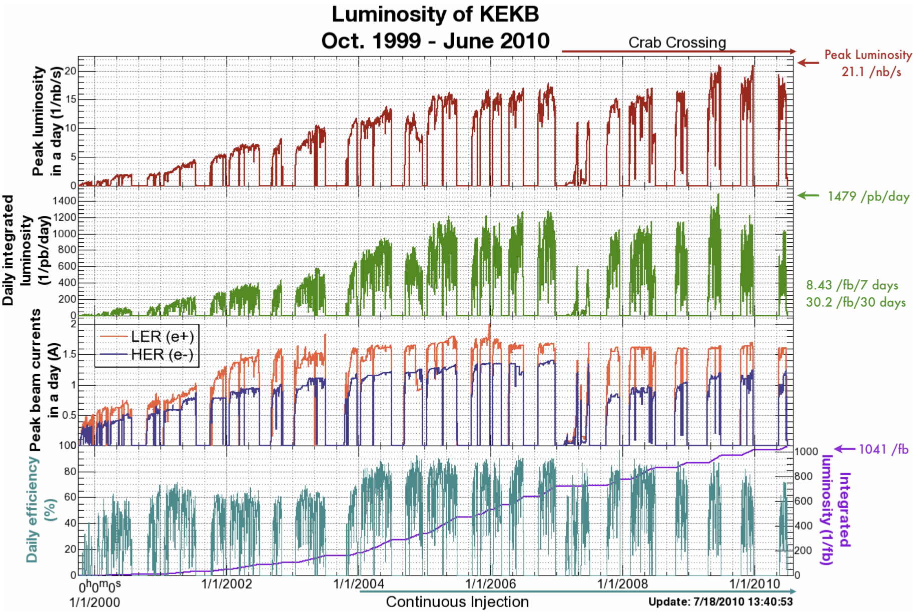
Luminosity integrated over a week , or at least several runs is what physicists are interested in; it is often measured in inverse picobarn. Note

that one inverse picobarn is one thousand times larger than one inverse nanobarn. In MKS unit: 1 pb$^{-1} = 10^{40}$ m^{-2}.



Peak luminosity of BEPCII





Luminosity of KEKB
Oct. 1999 - June 2010
Crab Crossing
Peak Luminosity 21.1 /nb/s
1479 /pb/day
8.43 /fb/7 days
30.2 /fb/30 days
1041 /fb
Peak luminosity in a day (1/nb/s)
Daily integrated luminosity (1/pb/day)
Peak beam currents in a day (A)
LER (e+)
HER (e-)
Daily efficiency (%)
Integrated luminosity (1/fb)
0h0m0s 1/1/2000
1/1/2002
1/1/2004
1/1/2006
1/1/2008
1/1/2010
Continuous Injection
Update: 7/18/2010 13:40:53

Table 1. Electron-positron circular colliders in the world. S/D = single/double ring.

Collider	Location	Scheme	Beam Energy (GeV)	Luminosity ($10^{30}cm^{-2}s^{-1}$)	Year
AdA	Frascati	S	0.25	$\sim 10^{-5}$	1962
ACO	Orsay	S	0.5	0.1	1966
Adone	Frascati	S	1.5	0.6	1969–1993
SPEAR	SLAC	S	4	12	1972–1990
VEPP-2/2M	BINP	S	0.7	13	1974–
DORIS	DESY	D	5.6	33	1974–1993
DCI	Orsay	D	1.8	2	1976–2003
PETRA	DESY	S	19	30	1978–1986
VEPP-4M	BINP	S	7	50	1979–
CESR	Cornell	S	6	1,300	1979–2002
PEP	SLAC	S	15	60	1980–1990
TRISTAN	KEK	S	32	37	1986–1994
BEPC	IHEP	S	2.2	13	1989–2005
LEP	CERN	S	46	24	1989–1994
DAΦNE	Frascati	D	0.7	150	1997–
LEP2	CERN	S	105	100	1995–2000
PEP-II	SLAC	D	3.1 / 9	12,000	1999–2008
KEKB	KEK	D	3.5 / 8	21,100	1999–2010
CESR-c	Cornell	S	1.9	60	2002–2008
VEPP-2000	BINP	S	0.5	120	2006–
BEPCII	IHEP	D	2.1	710	2007–

Beam-Beam Parameter

- the achieved beam-beam parameter ξ with collision is defined as

$$\xi_u = \frac{Nr_e}{2\pi\gamma}\frac{\beta_u^0}{\sigma_u(\sigma_x+\sigma_y)}$$

  where β^0 is nominal beta function without collision, and σ is disturbed beam size with collision.

- Do not consider the finite bunch length and finite crossing angle, the bunch luminosity can be represented as

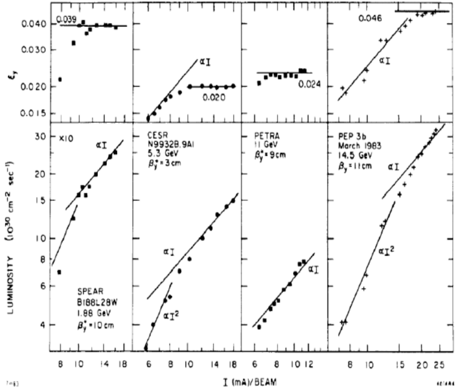
$$L = \frac{N^2 f_0}{4\pi\sigma_x\sigma_y}$$

  where σ is disturbed beam size with collision.

- when beam $\sigma_y \ll \sigma_x$, the achived ξ_y can be represented by lum,

$$\xi_y = \frac{2r_e\beta_y^0}{N\gamma}\frac{L}{f_0}$$

Beam-beam parameter in early machines



J. Seeman, “Observations of the beam–beam interaction”, 1985

Collider	Energy (GeV)	ξ_v	Nb of IP
VEPP-2M	0.5	0.050	2
DCI	0.8	0.041	2
ADONE	1.5	0.070	6
SPEAR	1.2	0.018	2
	1.9	0.056	2
	2.1	0.055	2
BEPC	1.6	0.035	2
DORIS-2	5.3	0.026	2
VEPP-4	5.0	0.050	1
KEK-AR	5.0	0.030	2
	5.0	0.045	1
CESR	4.7	0.018	2
	5.0	0.022	2
	5.3	0.026	2
	5.5	0.028	2
	5.4	0.020	2
	5.4	0.035	1
PEP	14.5	0.045	6
	14.5	0.065	2
	14.0	0.050	1
PETRA	7.0	0.014	4
	11.0	0.024	4
	17.0	0.040	4
TRISTAN	30.4	0.034	4
LEP	45.6	0.035	4

Bunch Spacing

The only one susceptible of increasing the luminosity by an order of magnitude, as requested by the new factory specifications, is the number of bunches (or its equivalent in this case, the bunch spacing around the ring). This is possible in two ways, either put more bunches in a single ring–The CESR solution–or have the two beams in two different rings, solution selected for modern factories.

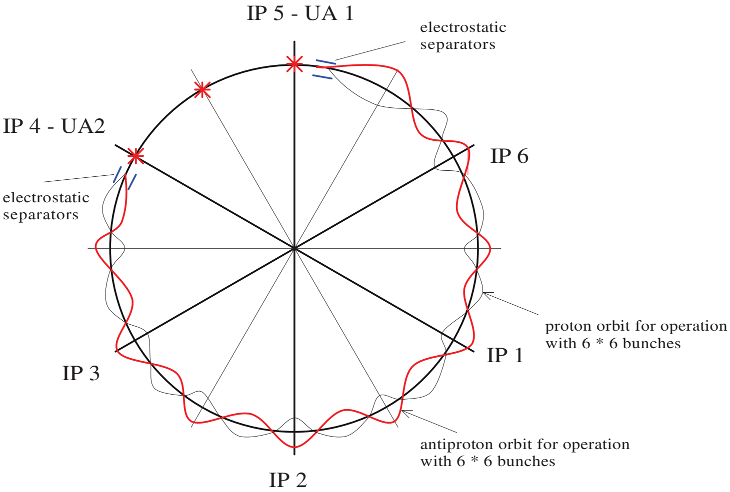
Bunch Spacing - The Pretzel Scheme

The seven bunches of CESR circulating in the same ring, cross in 14 places around the ring. If nothing was done, the tune shift induced by the beam-beam effect in each of the crossings being of the order of 0.04, the total beam-beam tune spread would be $\delta Q = 14 \times 0.04 = 0.56$ and most of the beam would probably be lost in a few turns.

The solution adopted by CESR–the so-called Pretzel scheme–is to have the two beams circulate on different orbits so that at the crossing points not used for experiments they are separated. At these parasitic crossings the beam-beam effect is considerably reduced by this separation, but it is still present so that one cannot increase the number of bunches at will.

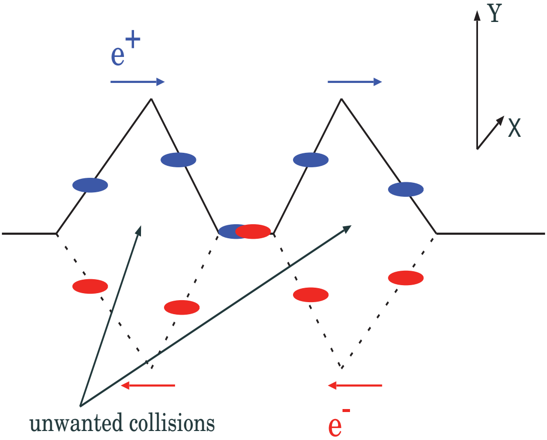
Moreover, each of the beams have to be accommodated in a smaller part of the vacuum chamber and the nonlinear optics are severely complicated by the requirement to 'comfortably' install two beams on two different trajectories inside the same vacuum chamber.

Beam separation with a Pretzel scheme



Short bunch trains in LEP

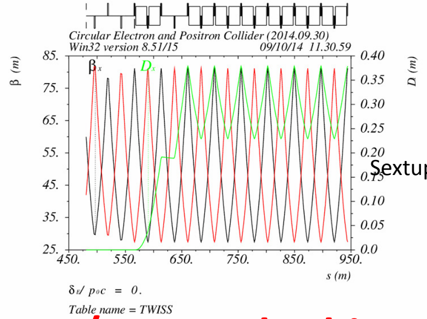
To avoid a separation around the whole machine, the bunches can be arranged in so-called trains of bunches following each other closely. In that case a separation with electrostatic separators is only needed around the interaction regions. Such a scheme was used in LEP in the second phase.



Issues with pretzel orbit

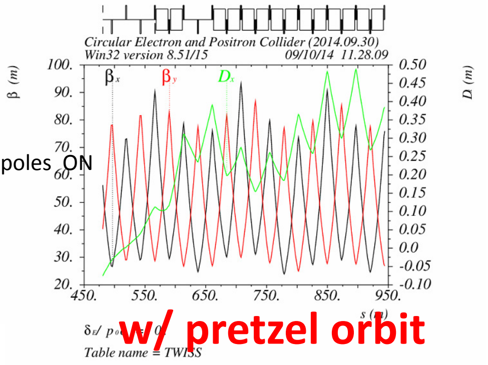
➤ Pretzel orbit has effects on:

- Beta functions, thus tune
- Dispersion function, thus emittance
- Dynamic aperture



w/o pretzel orbit

Sextupoles ON



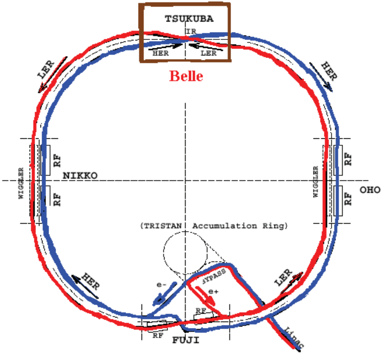
w/ pretzel orbit

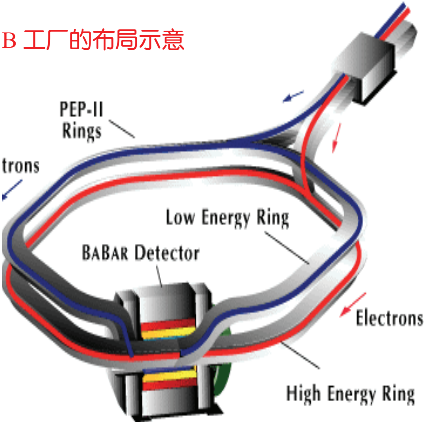
Bunch Spacing - The Double-ring Collider

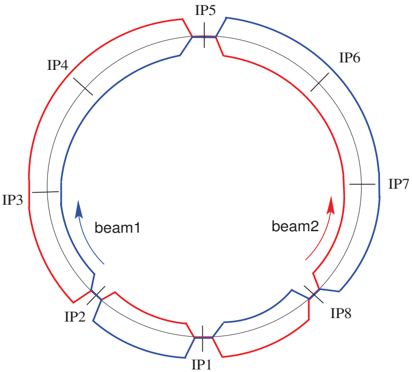
With the two beams each installed in their own vacuum chamber, the beams only see each other in the interaction area, the limitation to the number of bunches is now in the separation scheme in the interaction area.

The obvious disadvantage is the cost of the installation of two rings instead of one. Also some specific problems have to be solved: the mechanical and magnetic stability of the two rings have to be carefully checked in order to avoid that the two beams move or vibrate at the collision point where the beam sizes are only a few microns. The double ring makes it possible to avoid collisions in the arcs.

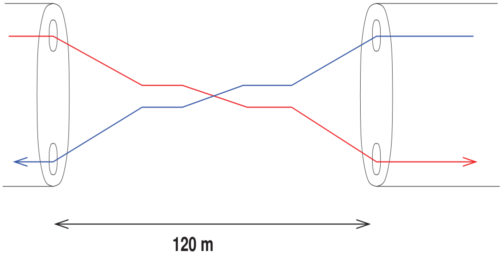
KEKB 和 PEPII 两个 B 工厂的布局示意图







Schematic layout of the LHC collision points and beams



Cross over between inner and outer vacuum chamber in the LHC (schematic)

Interaction Region

To achieve high luminosity low beta values are required at the interaction point.

The assembly of elements used to achieve this, starting from the regular lattice, is called the interaction region. It usually includes, starting from the interaction point: a quadrupole doublet, a matching section, a dispersion suppressor, and a set of skew quadrupoles in order to compensate the effect of the detector solenoid.

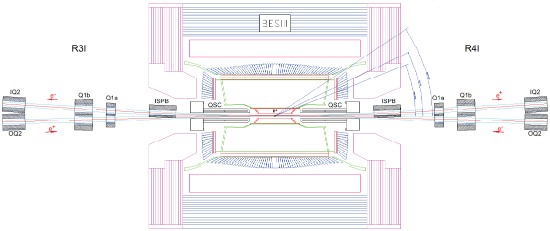
In the case of double rings a set of beam separators is required. When the separation is made in the vertical plane a vertical dispersion matching is required. In the case of the B-factory this must be done separately for two different energies, and with elements common to the two beams close to the interaction point. The solutions proposed should be transparent enough that the experimenter can understand, measure, and correct possible imperfections.

Interaction Region – Chromaticity

The very strong quadrupoles required in low-betas will focus more low energy particles of the beam than high-energy ones. This effect (the chromaticity induced by the low-beta optics) must be corrected to prevent head-tail instabilities. This correction is made using sextupoles, which reduce the dynamic aperture.

Detector forward acceptance

By pushing the quadrupoles closer and closer to the interaction point one increases the solid angle where the detector is blind, which makes the interpretation of events more uncertain. Quadrupoles with minimum transverse dimensions are therefore favored. This explains the choice of permanent magnet quadrupoles in some designs.

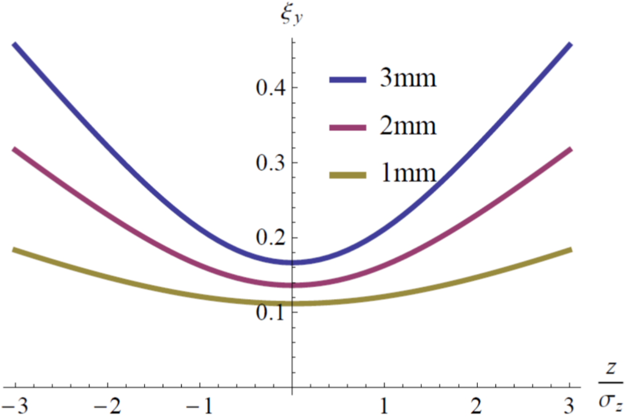


Low-beta Section – Detector masking

The detector must be protected from stray radiation to avoid excessive background. Two sources of background must be considered: the synchrotron radiation and the circulating beam interaction with the residual gas or the vacuum chamber. Their effect is analyzed using tracking programs which include routines to describe the secondary particle production when the incident particle hits an obstacle.
The result of the study is a set of masks placed at convenient positions, close to the interaction point, to stop the incident particles.

Bunch Length

In order that all particles cross at the waist of the low beta, the bunch length must be short compared to the value of β^*.



The effective beam-beam parameter versus the particle's longitudinal offset for different bunch length. The nominal ξ_y is 0.1 and $\beta_y^* = 1mm$ assumed.

How to Achieve High Luminosity - Ordinary

For flat lattices with $\sigma_y^*/\sigma_x^* \ll 1$ and $\epsilon_y/\epsilon_x \ll 1$, the luminosity

$$\mathcal{L} = f_0 \frac{\pi\gamma^2}{r_e^2} \frac{\epsilon_{x0}}{\beta_y^*} \xi_x \xi_y S$$

where,

- f_0, the revolution frequency; r_e, the classical electron raidus; γ, the relativistic factor
- ϵ_{x0}, the natural emittance; β_y^*, the vertical beta function at IP
- ξ_x/ξ_y, the beam-beam parameter
- S, the luminosity geometrical suppression factor

Since ξ_x/ξ_y are generally limited to values < 0.05, high luminosity requires:

- short bunches
- small β_y^*, the so-called "mini-beta insertion"
- large horizontal emittance

Summary from Oide's talk at 2005 2nd Hawaii SuperBF Workshop

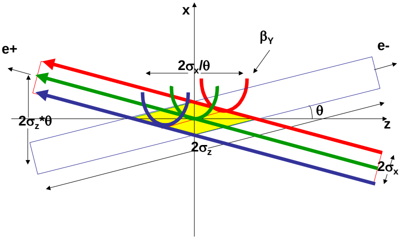
- Present design of SuperKEKB hits fundamental limits in the beam-beam effect and the bunch length (HOM & CSR).
- Higher current is the only way to increase the luminosity.
- Many technical and cost issues are expected with a new RF system.
- **We need a completely different collider scheme.....**

Crab Waist in 3 Steps

1. Large Piwinski's angle $\Phi = tg(\theta)\sigma_z/\sigma_x$

2. Vertical beta comparable with overlap area $\beta_y \approx \sigma_x/\theta$

3. Crab waist transformation $y = xy'/(2\theta)$



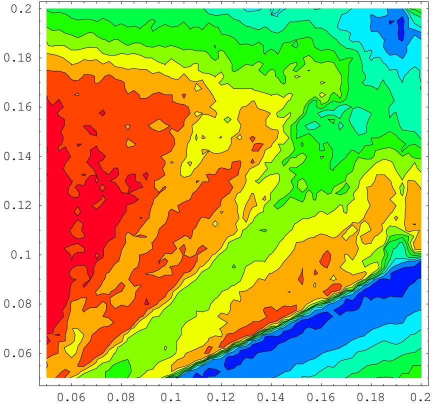
Crabbed waist is realized with a sextupole in phase with the IP in X and at $\pi/2$ in Y

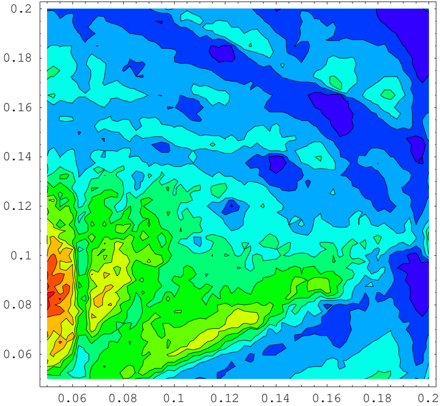
1. *P.Raimondi, 2° SuperB Workshop, March 2006*

2. *P.Raimondi, D.Shatilov, M.Zobov, physics/0702033*

Simulation Result in DAΦNE

Lum. vs. Tune





Crab ON => 0.6/θ

$L_{max} = 2.97 \times 10^{33}\ cm^{-2}s^{-1}$

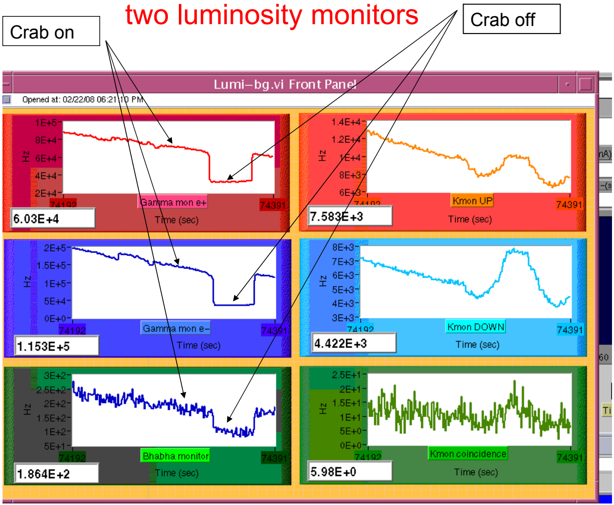
$L_{min} = 2.52 \times 10^{32}\ cm^{-2}s^{-1}$

Crab OFF

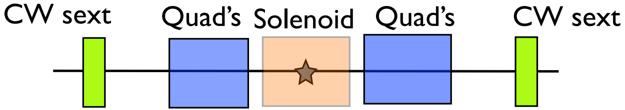
$L_{max} = 1.74 \times 10^{33}\ cm^{-2}s^{-1}$

$L_{min} = 2.78 \times 10^{31}\ cm^{-2}s^{-1}$

Success of Crab-Waist Scheme



Crab waist and IR nonlinearity



$$\mathcal{M}_{IR} = e^{-axy^2} e^{-H_{Q's}} e^{-H_{Sol}} e^{-H_{BB}} e^{-H_{Sol}} e^{-H_{Q's}} e^{-axy^2}$$

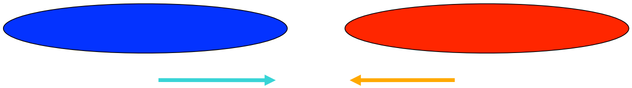
$$\nparallel$$

$$e^{-H_{Q's}} e^{-H_{Sol}} e^{-xp_y^2/2\phi} e^{-H_{BB}} e^{-xp_y^2/2\phi} e^{-H_{Sol}} e^{-H_{Q's}}$$

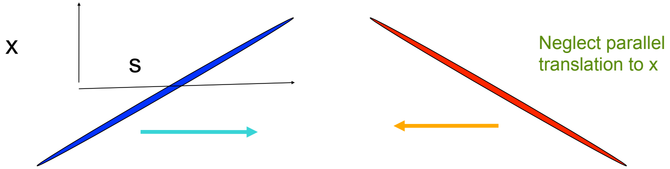
- Strong dynamic aperture degradation is seen by crab sextupole installation (H. Koiso).
- We do not know how to handle the nonlinear terms of Q's and Solenoid located at very high β.
- Crab waist is an option in (the) future for Super KEKB.

Nano-beam scheme

- KEKB with crab cavity targeted a high beam-beam parameter >0.1.



- SuperKEKB goes toward Low emittance, low beta, moderate beam-beam parameter <0.1

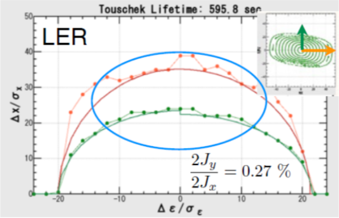


Parameters of SuperKEKB, CEPC, LHC and FCC

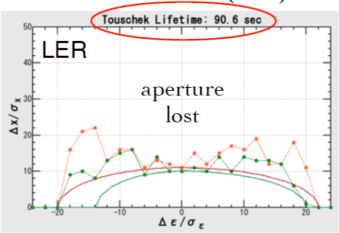
	SuperKEKB		CEPC	FCC-ee	LHC	FCC-hh
circumference (L[m])	3016		54,000	100,000	26658	100000
energy (E[GeV])	4(e+)	7(e-)	120	120	7,000	50,000
emittance (ε_x [nm])	3.2	4.6	1	0.9	0.5	0.041
emittance (ε_y [nm])	0.0086	0.012	0.001	0.5		
β_x^*[m]	0.032	0.025	0.8	1.2	0.55	0.55
β_y^*[m]	0.00027	0.0003	0.003	0.0012	0.55	0.55
rms bunch length [m]	0.006	0.005	0.001	0.001	0.0755	0.0755
bunch population N_p (10^{10})	9.0	6.5	3.9	6	11.5	10
number of bunches	2500	2500	48	1046	2808	13338
bunch spacing [ns]	4	4	3750	320	50	25
crossing angle/2 [mrad]	41.5		0	0-10	0.15	-
luminosity (10^{34} cm^{-2}s^{-1})	80		2	10	1	10

Difficulty in the Nano-Beam scheme

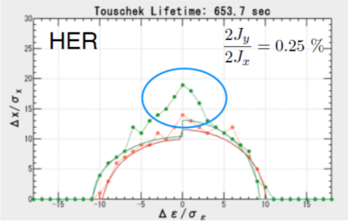
w/o beam-beam

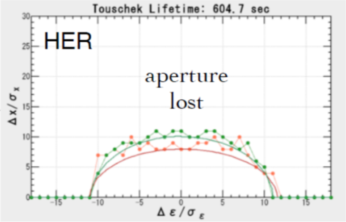


with beam-beam (W-S)



Transverse aperture is reduced significantly.





Y. Ohnishi, “Optics Issues”, 18th KEKB Review, 2014

◆ Scaling of final quads (cont'd)

$$L_0 = \frac{c_f B\rho}{c_Q B_0}\sqrt{\frac{2J_{x,y}}{\beta^*_{x,y}}}$$

$$L > \frac{L_0}{2}\left(1 + \sqrt{1 + 4\frac{\beta^{*2}_{x,y}}{L_0^2}}\right)$$

$$\xi_y = \frac{c_f L}{\beta^*_y}$$

Rings	SuperKEKB LER	TLEP Z	TLEP tt	
Beam energy	4	46	175	GeV
$B\rho$	13.3	153	584	Tm
B_0	0.7	⇐		T
$c_f \equiv k_1 L$	1.56	⇐		
$c_Q \equiv L_Q/L$	0.35	0.35	0.7	
β^*_x	32	500	1000	mm
β^*_y	0.27	1	1	mm
$2J_x$	3.7	⇐		μm
$2J_y$	10	0.87	0.23	nm
L_0	0.935	2.65	3.58	m
L	0.935	2.74	3.84	m
L_Q	0.33	0.96	2.69	m
b	10	7.4	7.4	mm
ξ_y	5,400	4,200	6,000	

$J_{x,y}$ assumes similar injected beams.

Similar level of difficulty!

If TLEP uses a chromaticity correction similar to SuperKEKB, the resulting momentum acceptance will be similar, about ±1.4%.

K. Oide, "Final Focus & Injection", FCC Kick-off Meeting, 2014


S363
S269
S251
S023
S266
S048
山海关区
G1
秦皇岛市
高能所
G102
抚宁县
S267
G205
S365
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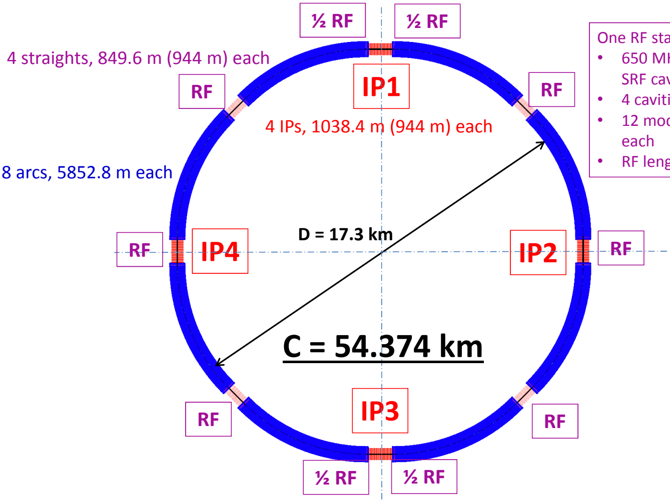
© 2013 Mapabc.com
Image © 2013 TerraMetrics
Google earth

CEPC Lattice Layout (September 24, 2014)

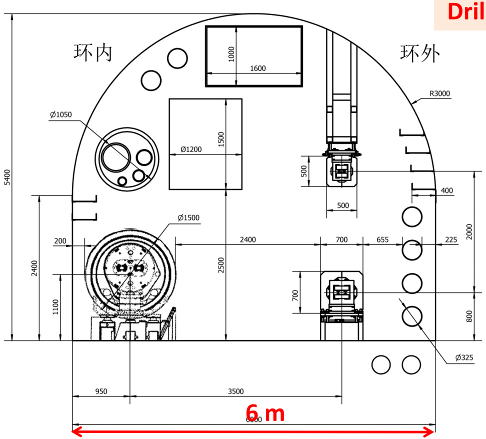


One RF station:

- 650 MHz five-cell SRF cavities;
- 4 cavities/module
- 12 modules, 10 m each
- RF length 120 m

Tunnel Cross Section – SPPC + CEPC Magnets

Drill/Blast Method



LHC Tunnel – Magnet Section

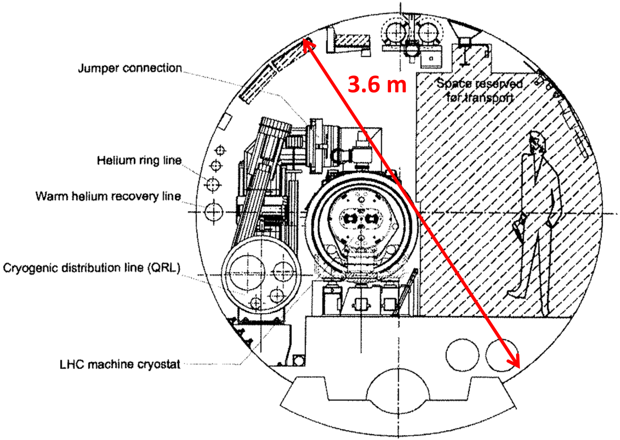
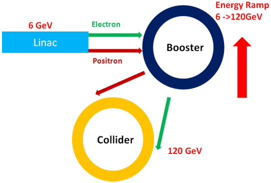


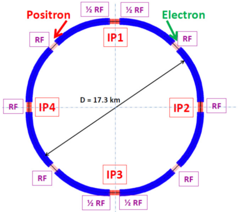
Figure 11.1: Transverse cross-section of the LHC tunnel

CEPC Design – Guidelines

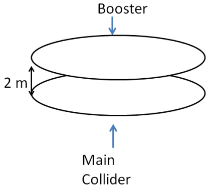
- Build an underground tunnel for a Higgs factory
- Use the same tunnel for a future *pp* collider:
  - The tunnel cross section should be big enough to accommodate an *e+e-* collider, a booster and a *pp* collider
  - The straight sections should be long enough to accommodate large detectors and complex collimation systems of a *pp* collider
  - It should allow to run both *e+e-* and *pp* experiments simultaneously
  - Within the budget limit, the tunnel circumference should be made as large as possible
- Keep options open for:
  - Super Z
  - *e-p* and *e-A* colliders
  - Light source
  - XFEL

Injectors

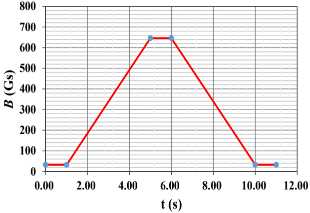




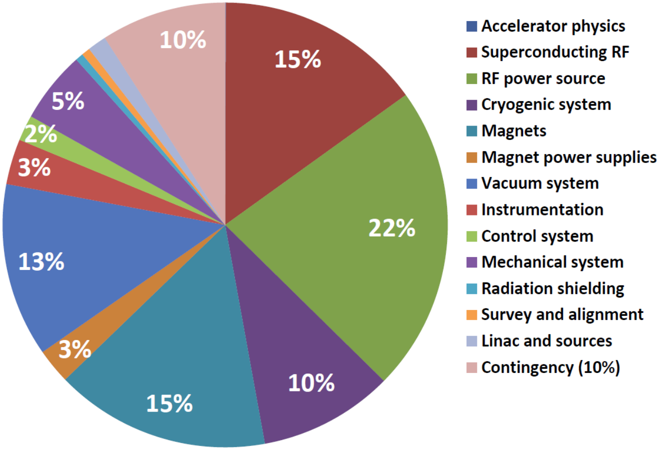
Top-up Full-energy Injection



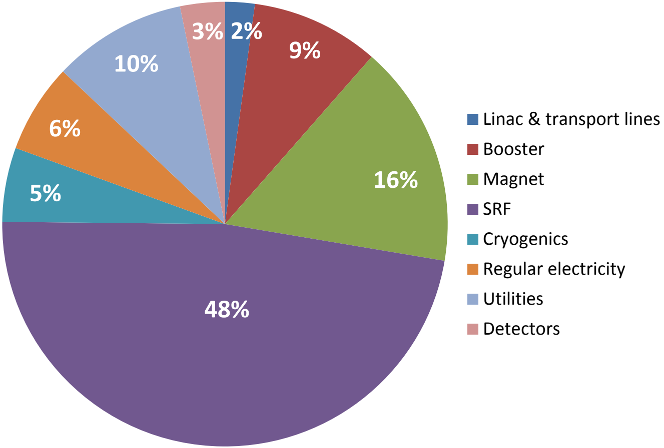
Booster Cycle (0.1 Hz)



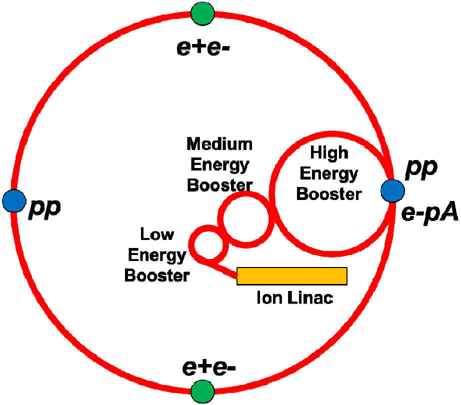
CEPC Relative Cost Estimate



Relative Power Consumption



Upgrade to SPPC



Main Technical Challenges for SPPC

- Accelerator technology
  - SC magnet (increasing performance and decreasing costs)
  - Synchrotron radiation and beam screen (reducing power consumption)
  - Collimation (machine protection)
- Accelerator physics
  - IR design, low β_y^* , dynamic aperture
  - Synchrotron radiation, heat load and radiation damage lifetime
  - Beam-beam
  - e-cloud
  - Impedance and instabilities
  - Ground motion
  - MDI and background
  - Machine reliability
  - Cooling
- Non-technical:
  - Government strategic plan for S/T investment
  - Support from both HEP and non-HEP scientists

CEPC-SPPC

Preliminary Conceptual Design Report

March 2015

300 authors

from 57 institutions

in 9 countries

The CEPC-SPPC Study Group

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- **Pre-CDR is easy**
- **CDR is hard. Because we leave all hard things to CDR!**
- **A long worklist (total 37) by Weiren Chou**

Weiren Chou[16] (周为仁), Xiaohao Cui[1] (崔小昊), Changdong Deng[1] (邓昌东),

Yadong Ding[1] (丁亚东), Haiyi Dong[1] (董海义), Jiajia Dong[8] (董甲甲),

Lan Dong[1] (董岚), Yuhui Dong[1] (董宇辉), Zhe Duan[1] (段哲), Jingzhou Fan[5] (范荆洲),

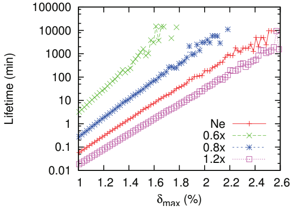
Huiping Geng[1] (耿会平), Dianjun Gong[1] (宫殿军), Li Gong[46] (龚丽),

Lingling Gong[1] (龚玲玲), Alfred Goshaw[26], Chen Gu[5] (顾晨), Lili Guo[8] (郭莉莉),

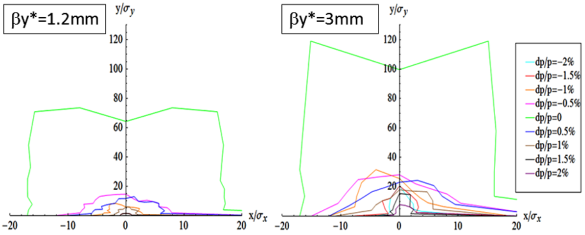
Yan Guo[47] (郭雁), Yuanyuan Guo[1] (郭媛媛), Ramesh Gupta[14] (古拉梅),

1

Lifetime & Aperture



More than 2.0% energy acceptance and $40\sigma_y$ in vertical direction is required. But now,



References

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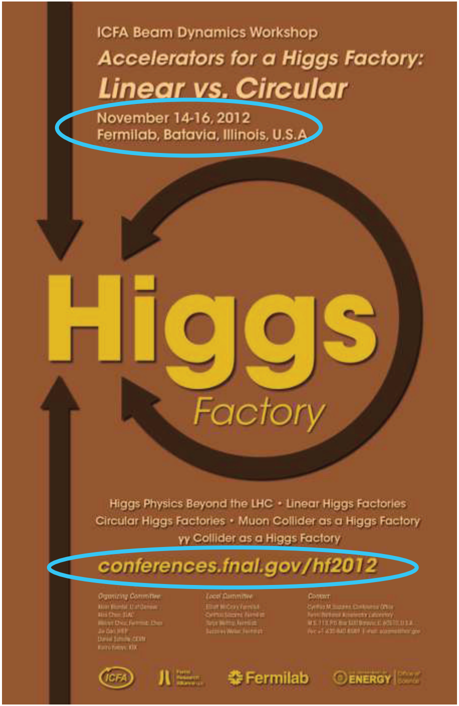
- Werner Herr, CAS, 2009
- M. Zobov,
- K. Oide, RAST,
- W. Chou, CEPC-SPPC Study Group Meeting, 2015-05
- H. Geng, CEPC-SPPC Study Group Meeting, 2015-05

Backup


ICFA Beam Dynamics Workshop
Accelerators for a Higgs Factory:
Linear vs. Circular
November 14-16, 2012
Fermilab, Batavia, Illinois, U.S.A
Higgs
Factory
Higgs Physics Beyond the LHC • Linear Higgs Factories
Circular Higgs Factories • Muon Collider as a Higgs Factory
γγ Collider as a Higgs Factory
conferences.fnal.gov/hf2012
Organizing Committee
Local Committee
Contact
ICFA
Fermilab
ENERGY

The World HEP Landscape Planning – a Circle?

2001 Snowmass → **2004** → **After 4th of July 2012**

2001 Snowmass

- Linear e+e-
  - Cold (TESLA)
  - Warm (NLC/JLC)
- Circular e+e-
- VLHC
- Muon collider

2004

- **Cold Linear e+e- (ILC)**

After 4th of July 2012

- Linear e+e-
  - ILC
  - CLIC
  - X-band klystron based
- Circular e+e-
  - Fermilab site filler
  - LEP3 and TLEP
  - SuperTRISTAN
  - China Higgs Factory (CHF)
  - VLLC
- Muon collider
- Photon cillider
  - ILC-based
  - CLIC-based
  - SAPPHiRE
  - SLC-type
  - ERL-based

3

W. Chou, "Higgs Factory R&D and Facilities", Snowmass Preparation Mini-Workshop, 2013

(1) Linear e^+e^- Collider as a Higgs Factory (cont.)

- Advantages:
  - Extensive design and prototyping work have been done
  - Key technologies are in hand after large investment for R&D.
  - There exist well-organized international collaborations led respectively by the ILC GDE and CLIC Collaboration (now combined in the Linear Collider Collaboration)
  - Important step towards high energy e+e- collisions
  - Polarized beams (e- 80%, e+ 30%)
  - A front runner (in terms of readiness)
- Challenges:
  - High cost
- Specific issues:
  - ILC
    - FFS
    - Positron source for a Higgs factory needs 10 Hz operation of the e- linac for e+ production, or the use of an unpolarized e+ beam as a backup scheme
  - CLIC
    - Accelerating structure
    - Industrialization of major components
    - From CDR to TDR

W. Chou, "Higgs Factory R&D and Facilities", Snowmass Preparation Mini-Workshop, 2013

(2) Circular e^+e^- Collider as a Higgs Factory (cont.)

- Advantages:
  - At 240 GeV and below, a higher luminosity than a linear collider when the ring size is sufficiently large
  - Based on mature technology and rich experience
  - Some designs can use existing tunnel and site
  - More than one IP
  - Tunnel of a large ring can be reused as a pp collider in the future
- Challenges:
  - Beamstrahlung limiting beam life time requires lattice with large momentum acceptance
  - RF and vacuum problem from synchrotron radiation
  - A lattice with low emittance
  - Efficiency of converting wall power to synchrotron radiation power
  - Limited energy reach
  - No comprehensive study; design study report needed.

W. Chou, “Higgs Factory R&D and Facilities”, Snowmass Preparation Mini-Workshop, 2013

(3) Photon Collider as a Higgs Factory (cont.)

- Advantages:
  - Allow access to CP property of the Higgs
  - Lower beam energy (80 GeV per e- beam to generate 63 GeV γ beam)
  - High polarization in the colliding γ beams
  - No need for e+ beam
  - 160 GeV e- linac has a lower cost w.r.t. a 240 GeV linear e+e- collider
  - Can be added on a linear e+e- collider
- Challenges:
  - Physics not as comprehensive as a 240 GeV e+e- collider would be.
  - Background problem
  - Complex IR design
  - No comprehensive study.; design study report needed.
- Specific issues:
  - ILC-based
    - Optical cavity
  - CLIC-based
    - Laser can piggy-back on the Livermore LIFE fusion project. (But the project schedule is unknown.)
  - Recirculating linac-based:
    - Polarized low emittance e- gun

W. Chou, "Higgs Factory R&D and Facilities", Snowmass Preparation Mini-Workshop, 2013