Operation of High-Luminosity Meson Factories and the Challenge to go to the Next Generation

- Operational status of B- and Φ-factories
- Present luminosity performance and limitation
- Upgrade plans, new ideas and experiments
- Next generation Super-Factories

Kazunori AKAI

KEK

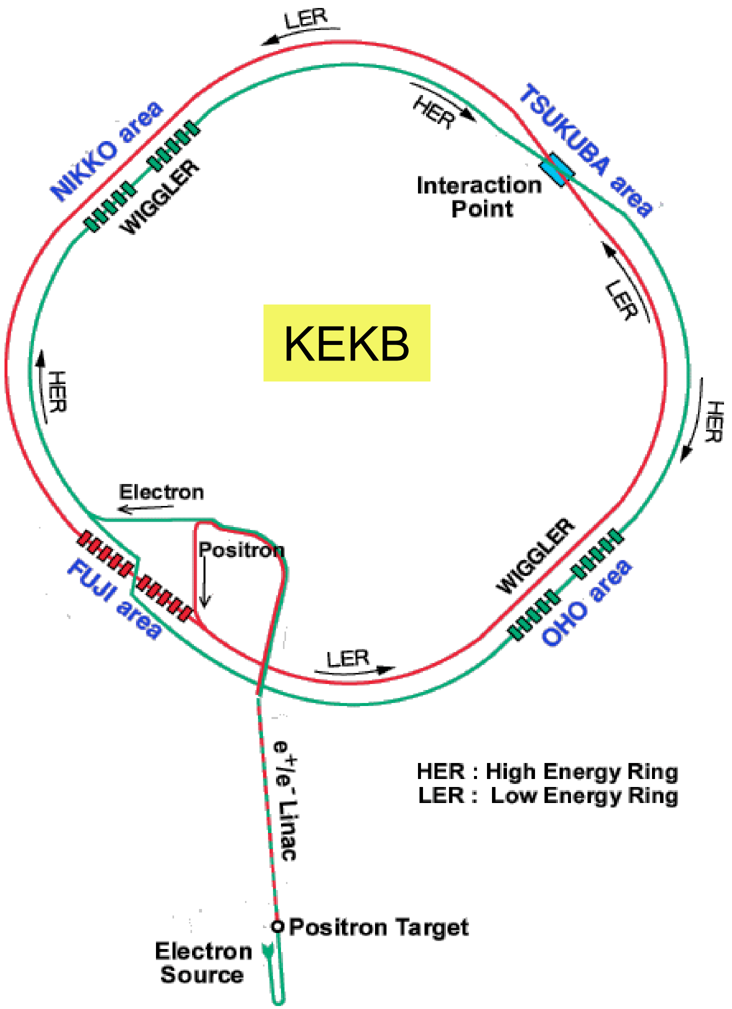
EPAC 2006, Edinburgh

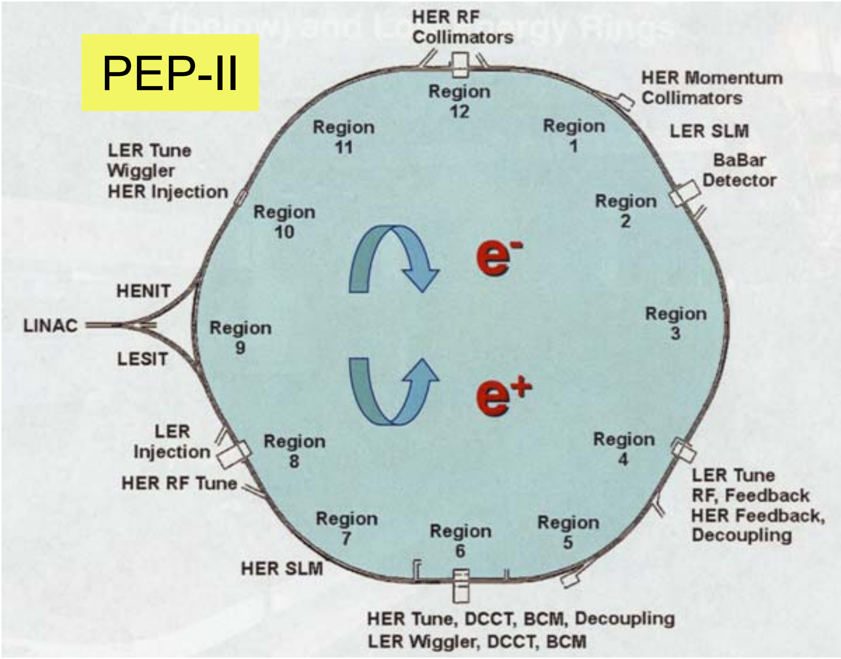
e+e- meson factories in the world

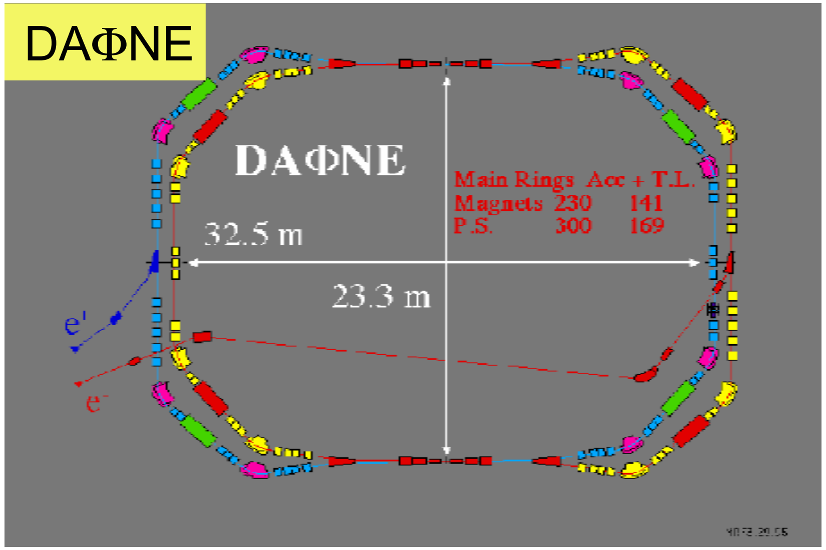
High-luminosity e+e- colliders, providing particular particles such as B, τ-c or Φ mesons at a very high rate of production

Factory	CESR	DAΦNE	PEP-II	KEKB	BEPC-II	VEPP-2000
Location	Cornell	INFN-LNF	SLAC	KEK	IHEP	BINP
Physics	B	Φ	B (asym.)	B (asym.)	τ-c	Φ
Commissioning	1979	1998	1998	1998	(2006)	(2006)
Current status	running (CESR-c)	running	running	running	construct	construct
Ring	single	double	double	double	double	single
Beam energy [GeV]	4.7~6.0	0.51/0.51	3.1/9.0	3.5/8.0	1.0~2.1	1.0
Circumference [m]	768	97.7	2200	3016	237.5	24.4
Crossing angle [mrad]	+/- 2.5~3.3	+/- 10~15	< 0.1	+/- 11	+/- 11	0
Beta_y* [cm]	1.9	1.7	1.1	0.6	1.5	10
Bunch length [mm]	20	10-25	11	7	13-15	
Beam current, e+/e- [A]	0.78	1.5/2.4	3.0/1.78	2.0/1.36	0.91/0.91	0.1+0.1
Luminosity [$\text{x}10^{32}/\text{cm}^2/\text{s}$]	12.5	1.53	108.8	162.7	10	1 (x 2IPs)
Integrated lum. [/pb] /day	73	10	786.3	1201.7		

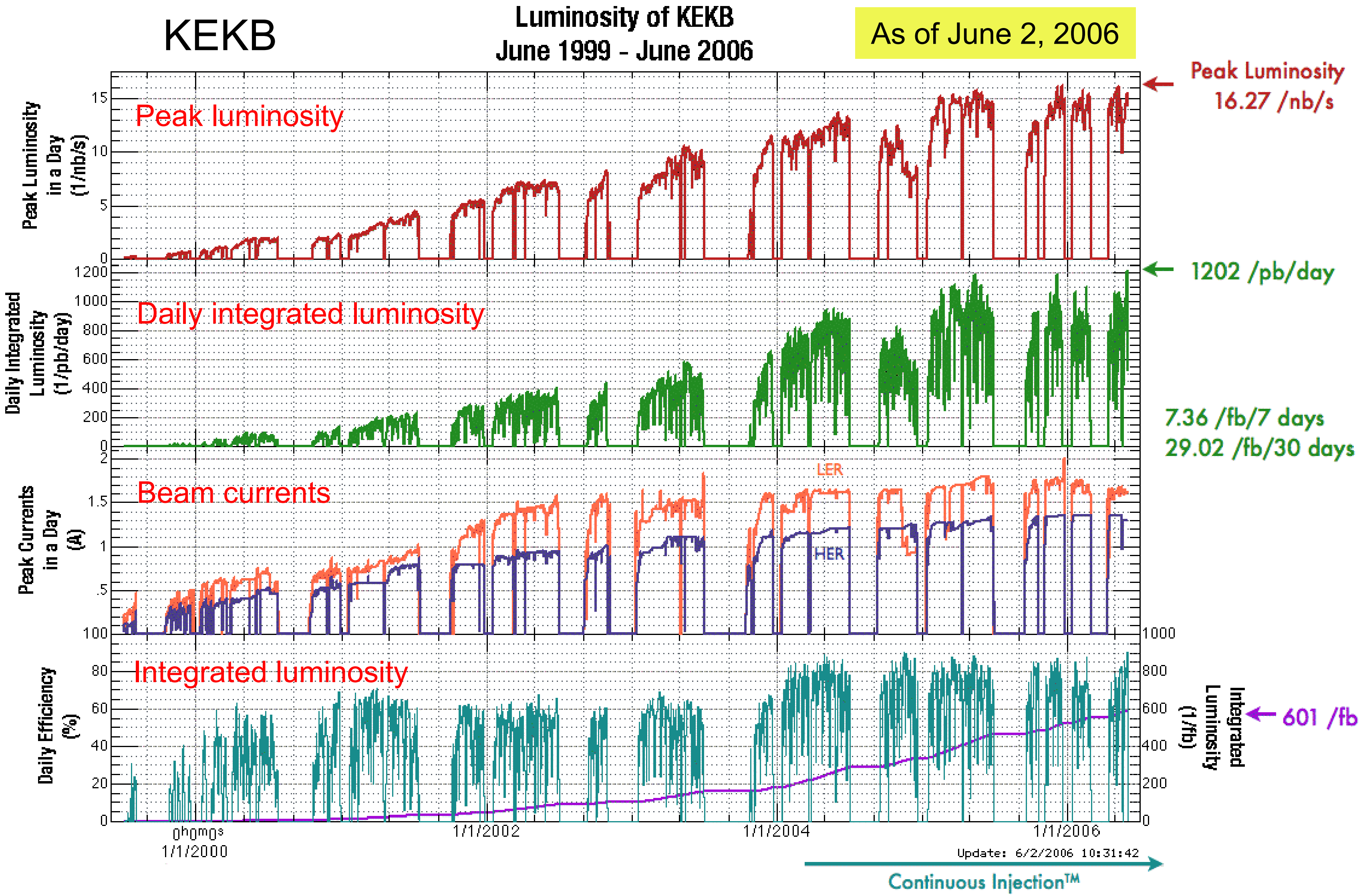
2 fb^{-1}/day by two B-factories!


KEKB
LER
HER
TSUKUBA area
NIKKO area
WIGGLER
Interaction Point
LER
HER
HER
Electron
Positron
FUJI area
WIGGLER
OHO area
LER
e+/e- Linac
HER : High Energy Ring
LER : Low Energy Ring
Positron Target
Electron Source

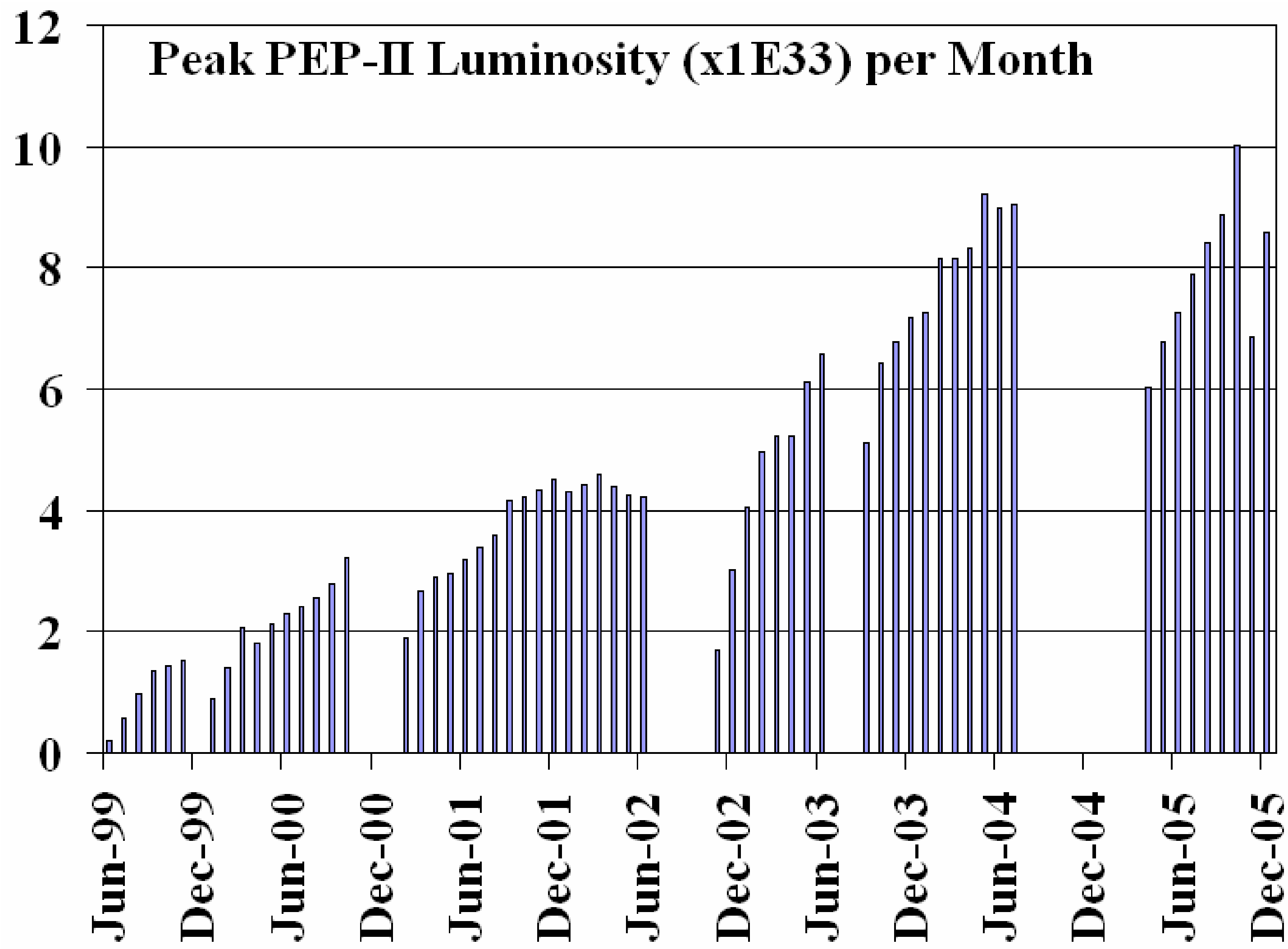

PEP-II
HER RF Collimators
HER Momentum Collimators
LER SLM
BaBar Detector
Region 12
Region 11
Region 1
LER Tune Wiggler HER Injection
Region 10
Region 2
HENIT
LINAC
LESIT
Region 9
Region 3
e-
e+
LER Injection
Region 8
HER RF Tune
Region 4
LER Tune RF, Feedback HER Feedback, Decoupling
Region 7
Region 6
Region 5
HER SLM
HER Tune, DCCT, BCM, Decoupling
LER Wiggler, DCCT, BCM


DAΦNE
DAΦNE
Main Rings Acc + T.L.
Magnets 230 141
P.S. 300 169
32.5 m
23.3 m
e+
e-

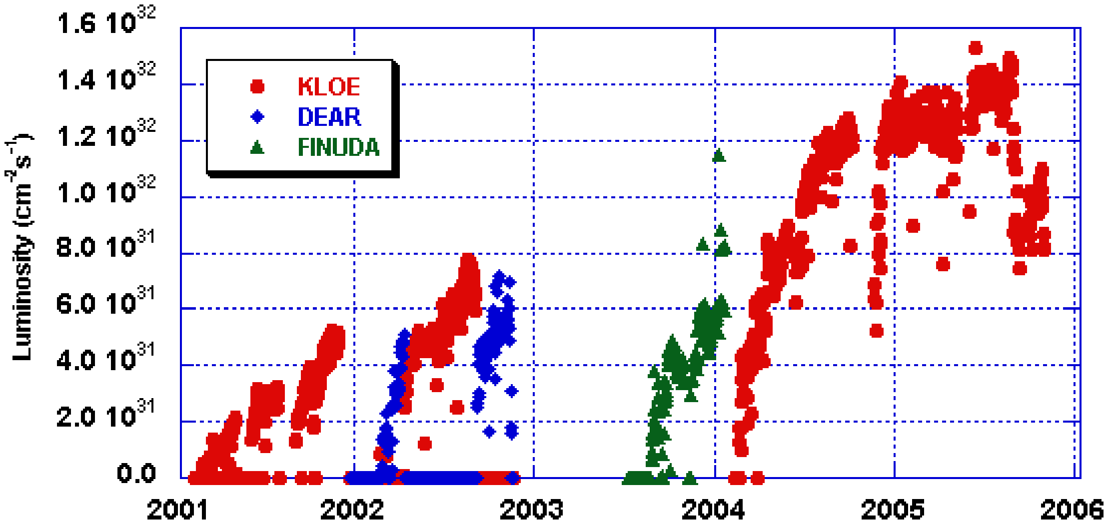
KEKB



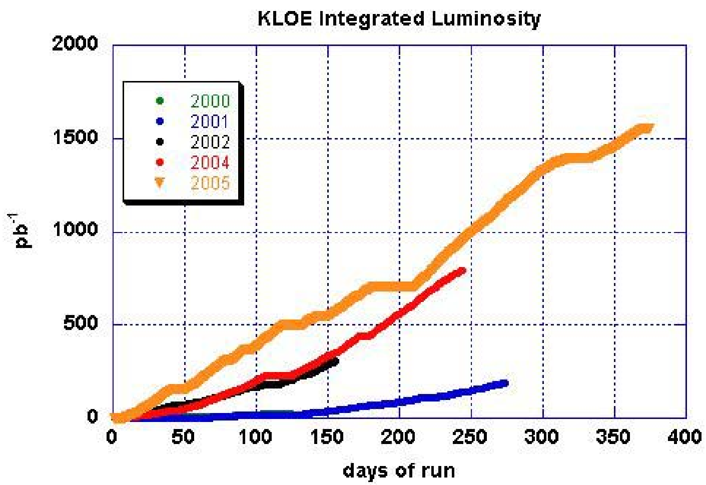
Luminosity of KEKB
June 1999 - June 2006
As of June 2, 2006
Peak luminosity
Daily integrated luminosity
Beam currents
Integrated luminosity
Peak Luminosity in a Day (1/nb/s)
Daily Integrated Luminosity (1/pb/day)
Peak Currents in a Day (A)
Daily Efficiency (%)
Integrated Luminosity (1/fb)
LER
HER
Peak Luminosity 16.27 /nb/s
1202 /pb/day
7.36 /fb/7 days
29.02 /fb/30 days
601 /fb
1/1/2000
1/1/2002
1/1/2004
1/1/2006
Update: 6/2/2006 10:31:42
Continuous Injection™


Peak PEP-II Luminosity (x1E33) per Month
12
10
8
6
4
2
0
Jun-99
Dec-99
Jun-00
Dec-00
Jun-01
Dec-01
Jun-02
Dec-02
Jun-03
Dec-03
Jun-04
Dec-04
Jun-05
Dec-05

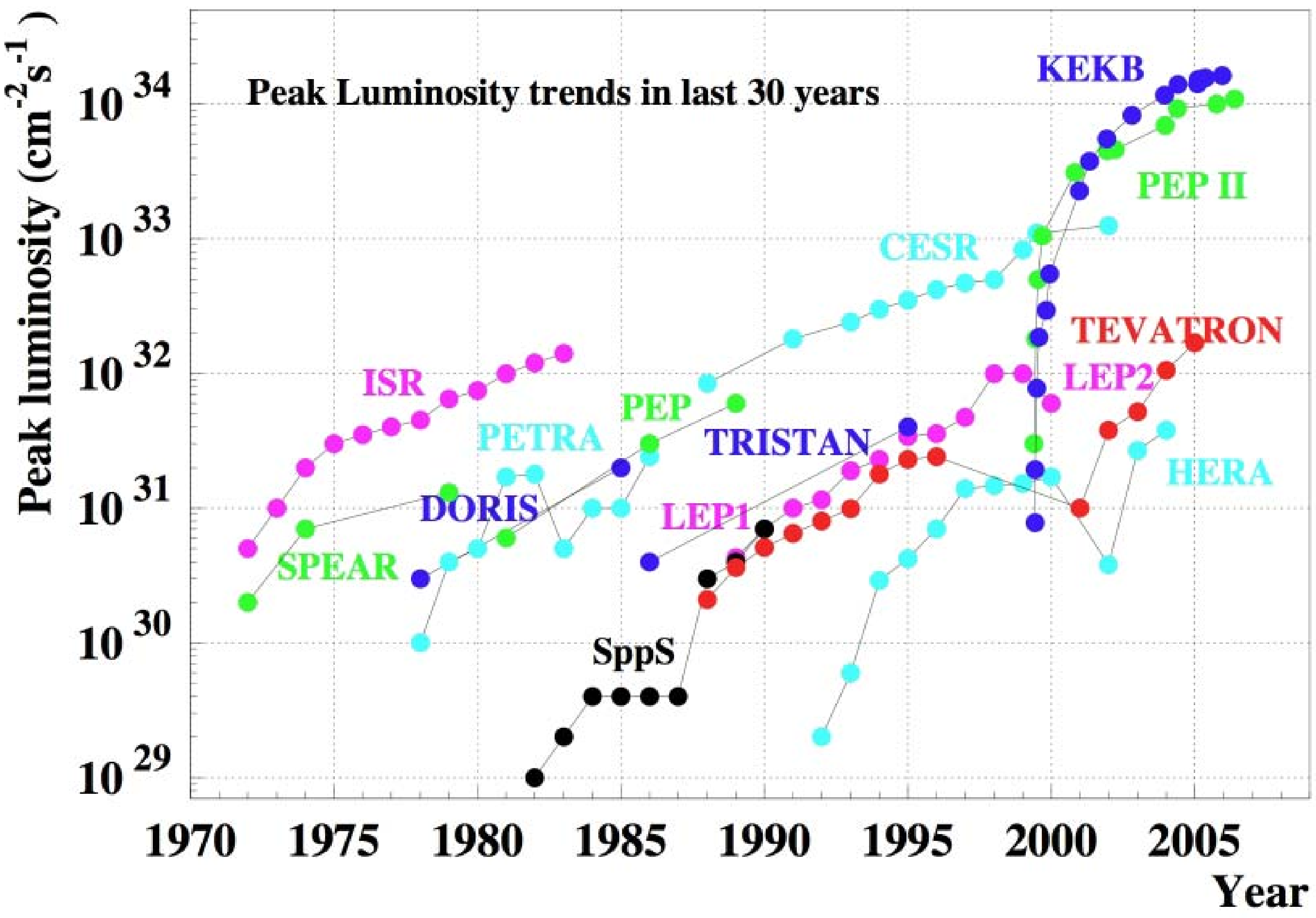
DAΦNE luminosity summary since 2001



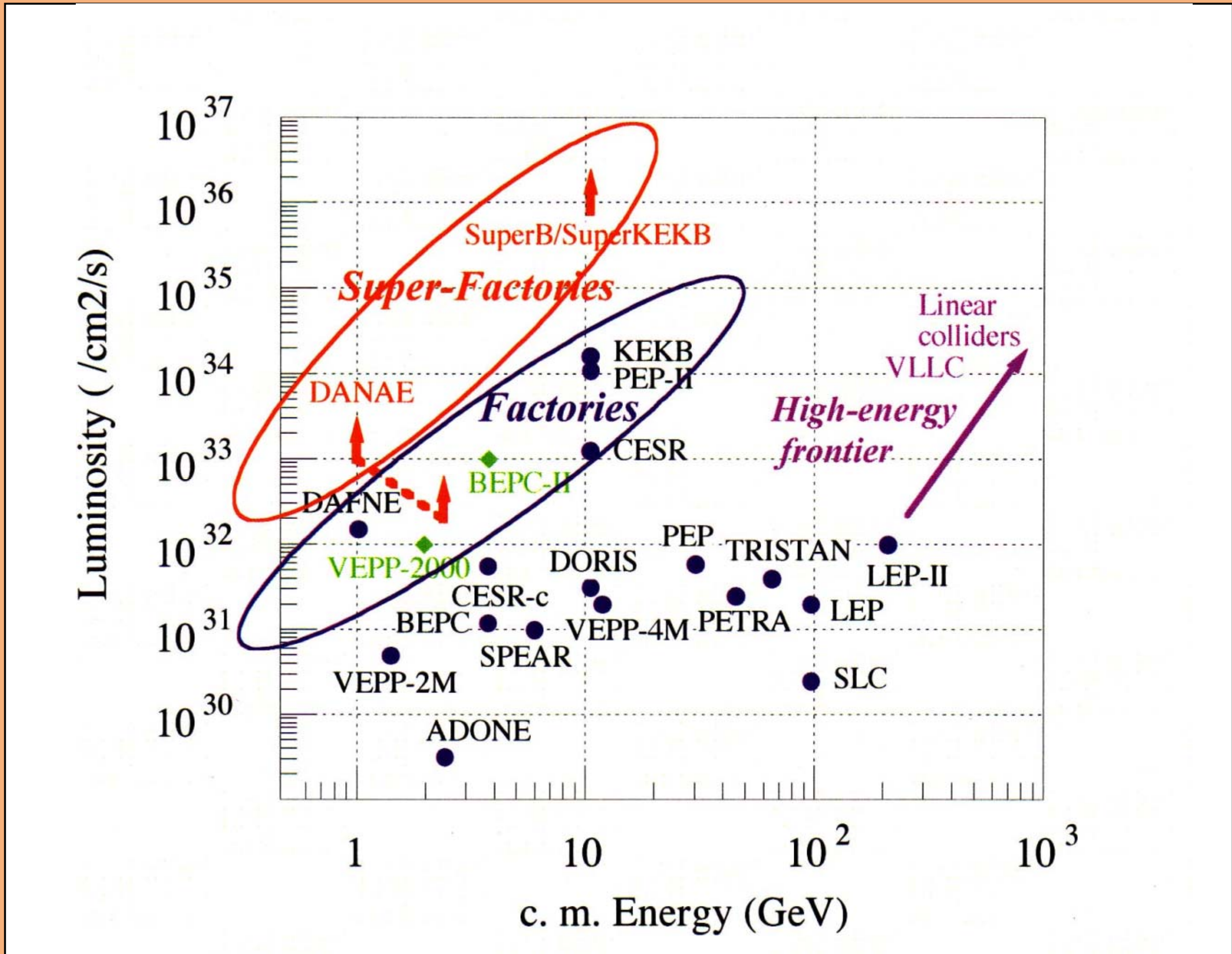
The last points with lower ***L*** refer to the KLOE off-energy operation.



Peak luminosity trends in 30 years



Luminosity and energy of e+e- colliders



Luminosity foumula

For a flat beam, short bunch collider:

$$L = \frac{\gamma}{2er_e}\left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_{beam}\xi_y}{\beta_y^*}\frac{R_L}{R_{\xi_y}}$$

Lorentz factor

Beam current

Beam-Beam parameter

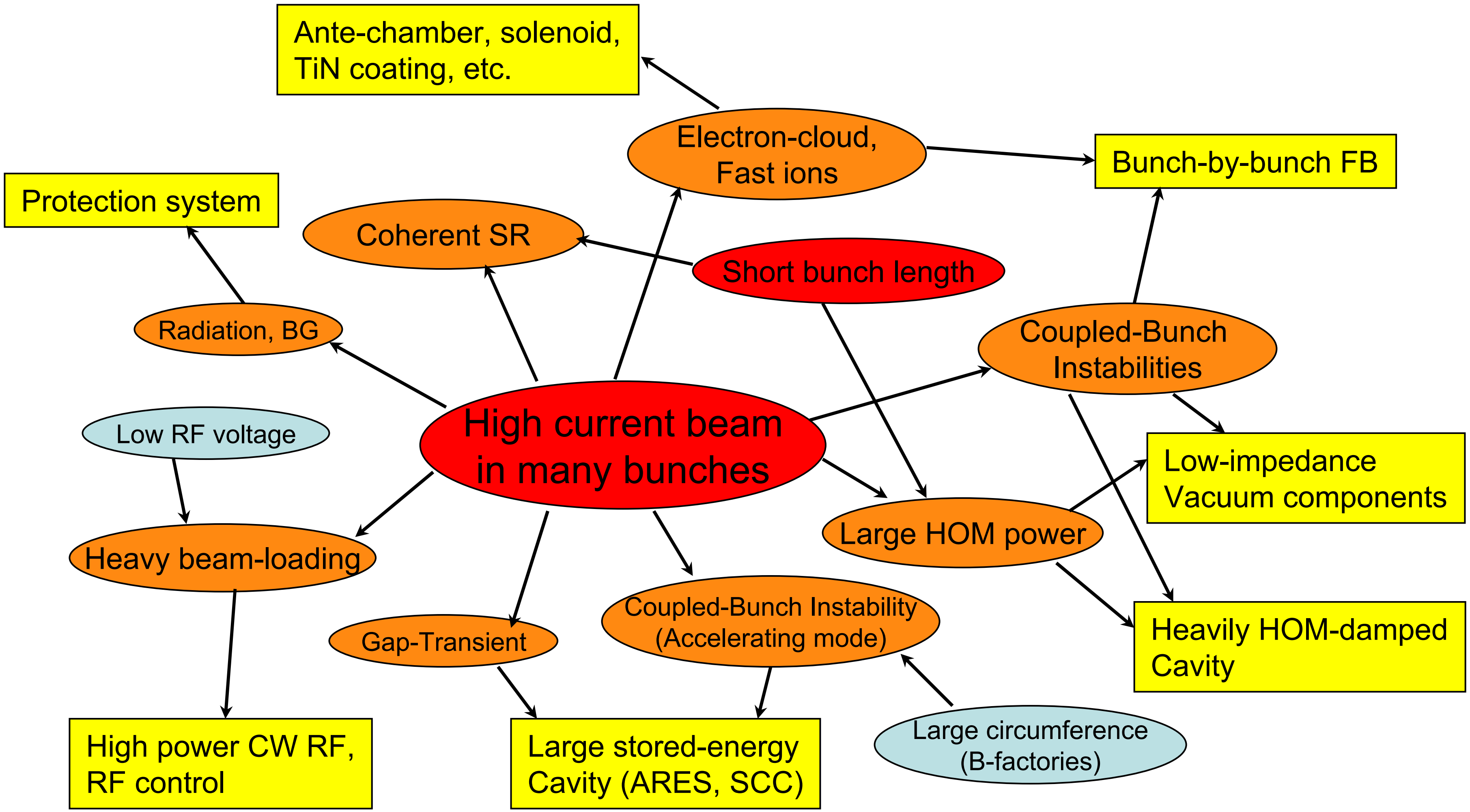
Geometrical reduction factors (crossing angle, hourglass effect)

$$\sigma_s \le \beta_y^*$$

Vertical beta function at IP

Beam aspect ratio at IP

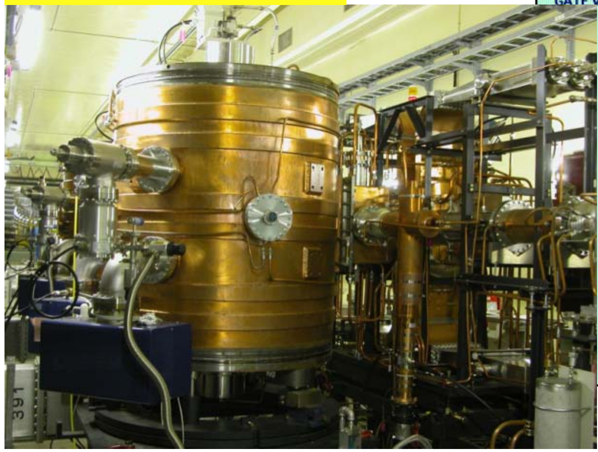
High beam current and Challenges



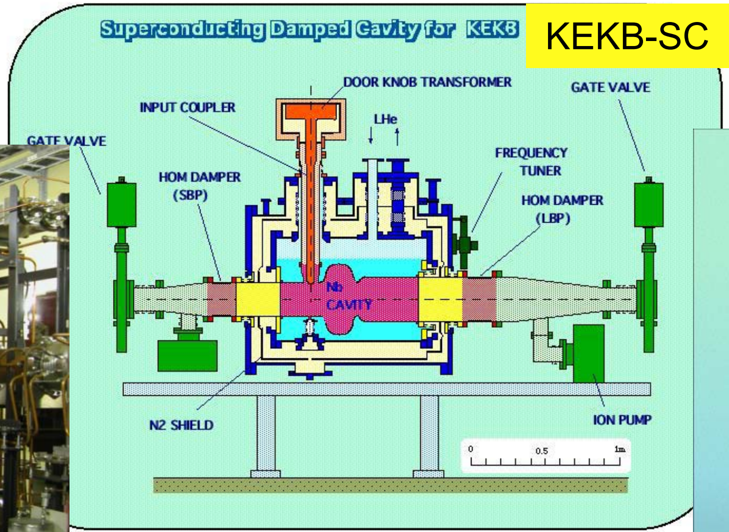
Hardware with high beam currents

- Requirements for RF system
  - Large amount of RF power per cavity to provide to beams
  - Very low HOM impedance to avoid CBI
  - Cure for the CBI drivenby the accelerating mode (B-factories)
- RF system for high current beams of several amperes has come to a standard technology.
  - HOM power 5 ~ 15 kW/cavity
  - Beam power 25 ~ 400 kW/cavity
  - Highest e+ beam current: 3A (PEP-II)
  - Highest e- beam current: 2.4A (DAΦNE)
  - Highest beam current in SC cavities: 1.36A (KEKB)

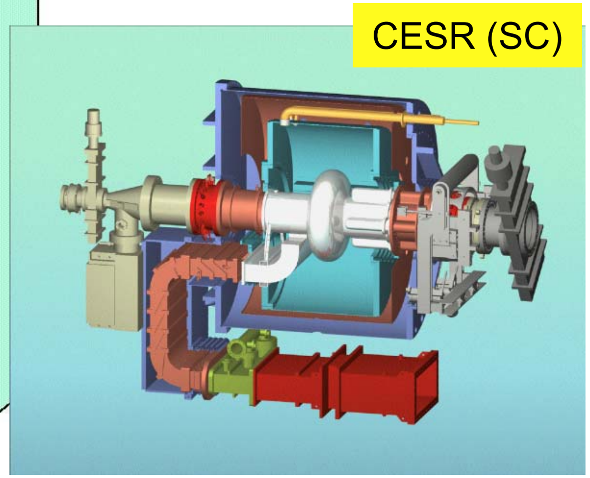
KEKB-NC (ARES)



KEKB-SC



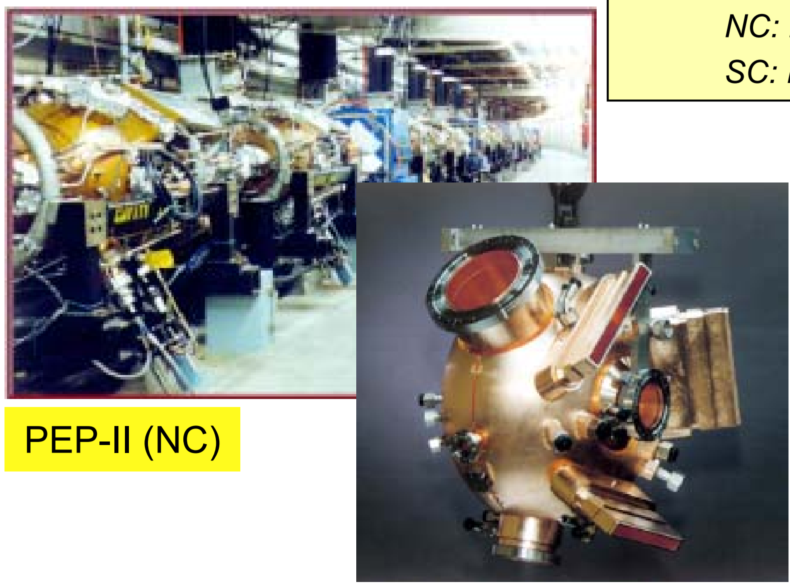
CESR (SC)



Heavily HOM-damped single-cell cavities

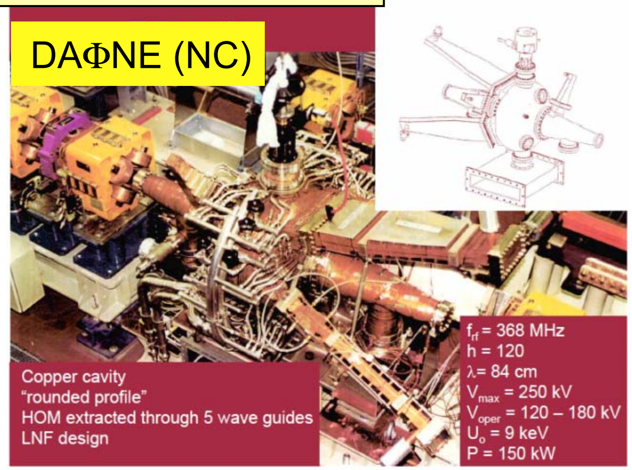
NC: KEKB, PEP-II, DAΦNE, VEPP-2000

SC: KEKB, CESR, BEPC-II



PEP-II (NC)

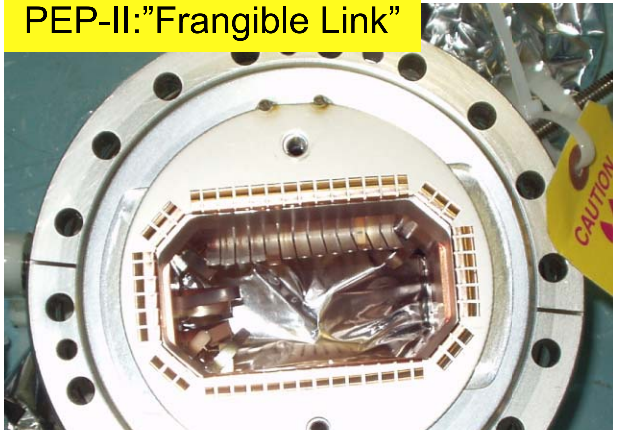
DAΦNE (NC)



Hardware with high beam currents (cont'd)

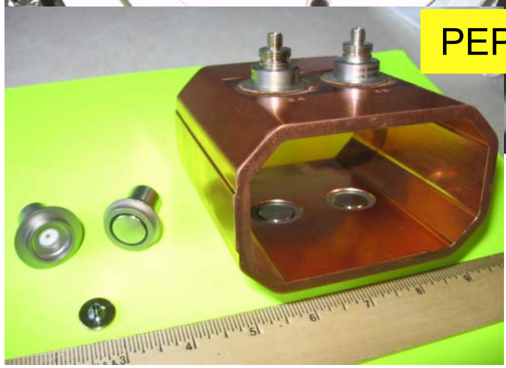
- Beam duct vacuum components
  - Heating due to HOM and SR, damage by direct hit of beams
  - Elaborate works to solve problems and to improve beam duct components such as Masks (collimators), bellows, HOM absorbers, etc.

PEP-II:"Frangible Link"

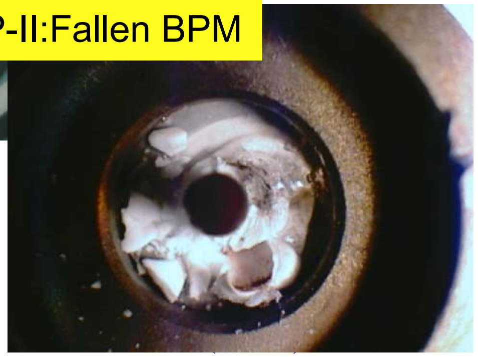


Troubles caused by high beam currnts

KEKB: QC4RE Bellows



PEP-II:Fallen BPM



KEKB: Movable Mask Head

R&D for improvement of vacuum components

Masks, bellows, GVs, HOM dampers, ante-chambers, etc.

N. Kurita

PEP-II:Q4/Q5 Bellows layout (Fall 2006)

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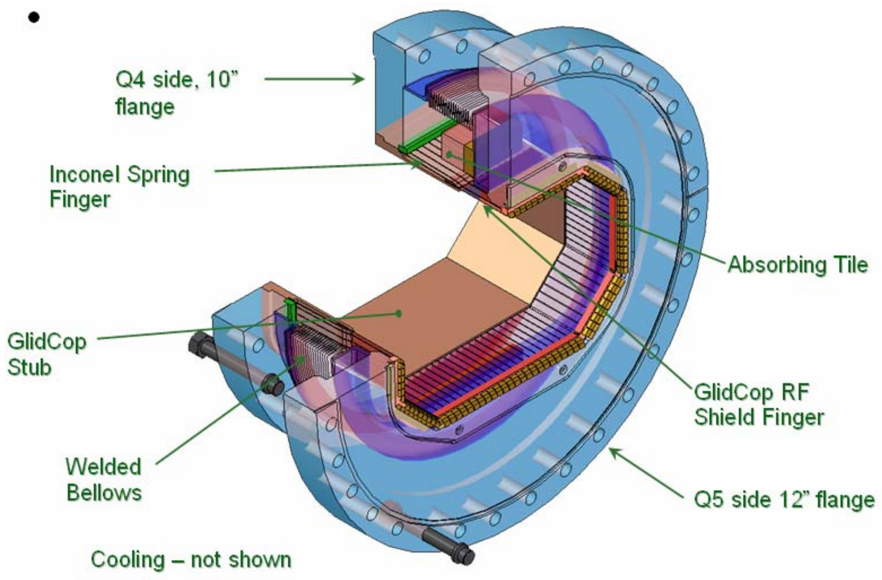
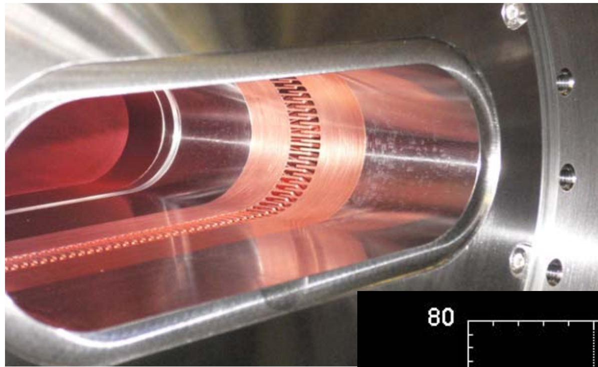
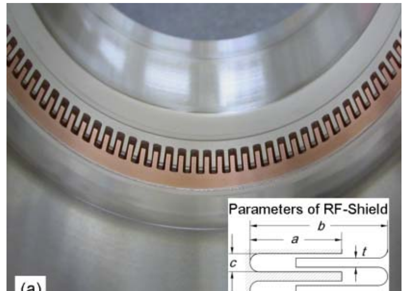
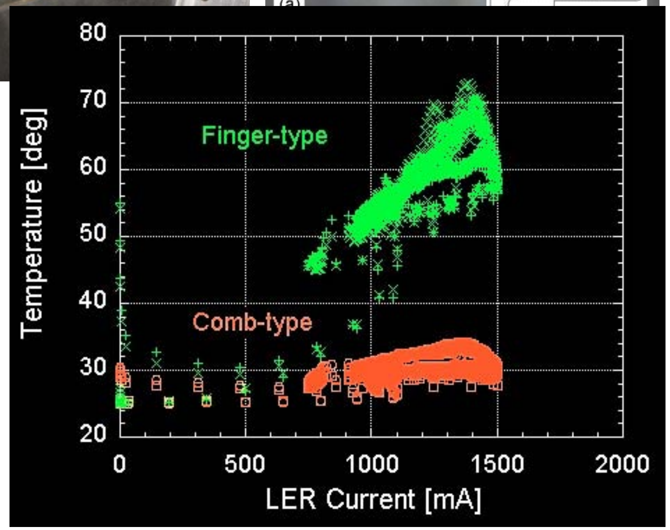








KEKB: Comb-type Bellows

Y. Suetsugu

Hardware with high beam currents (cont'd)

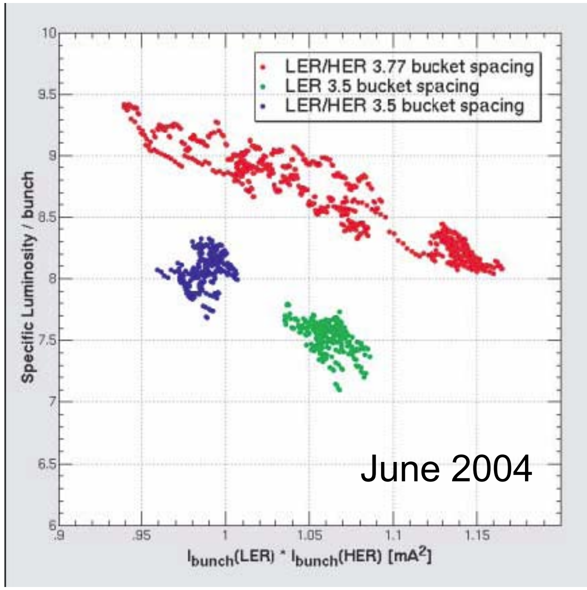
- Bunch-by-bunch feedbacks
  - Transverse
  - Longitudinal (not used in KEKB)
  - High damping rate and short bunch spacing
- Protection
  - Fast beam abort system
  - Beam loss monitors, RF monitors etc.
- Linac with higher injection rate

Single-bunch current and More bunches

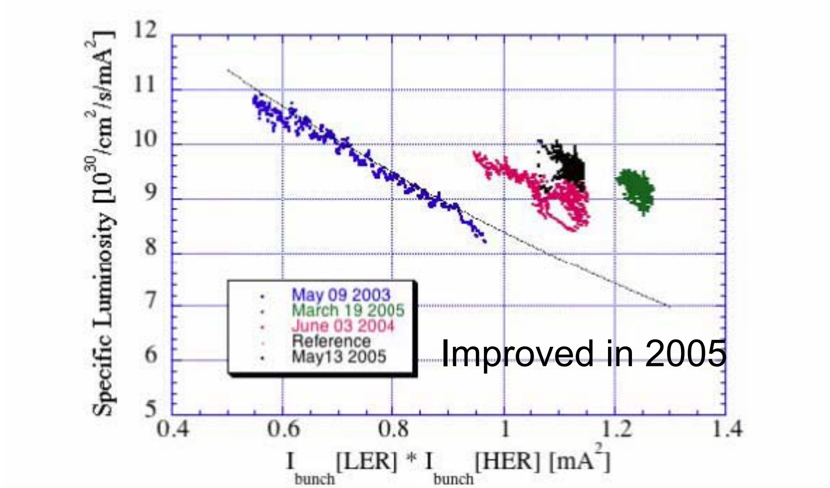
- Single-bunch current can be limited by:
  - Saturation of beam-beam parameters
  - Microwave instability
  - From the point of view of HOM power
- Shorter bunch spacing:
  - Blowup or oscillation caused by electron-cloud
  - Requirements for bunch-by-bunch feedback
- Increase of the number of bunches is desired to increase luminosity, but failed in some cases.

Shorter bunch spacing in KEKB

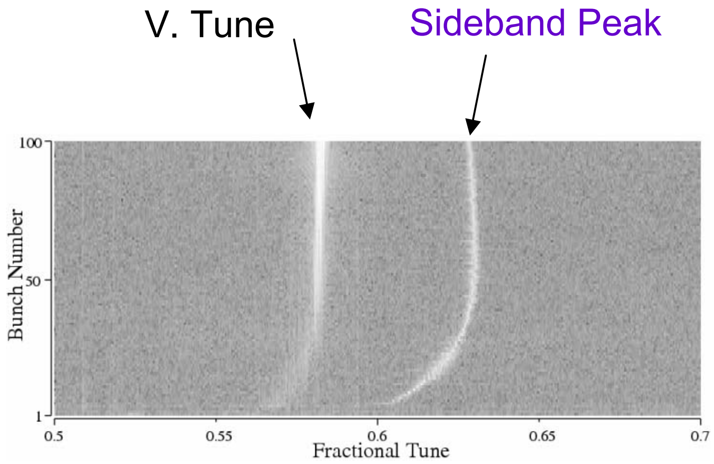
- Specific luminosity significantly drops at a shorter bunch spacing due to e-cloud.
  - No ante-chambers in KEKB (except for test ones).
  - The length of solenoid windings has been increased.
  - Now OK with 3.5 bucket spacing, but still degrades with 3.27 spacing.
  - The effect of increasing the solenoid length now seems to be saturating.



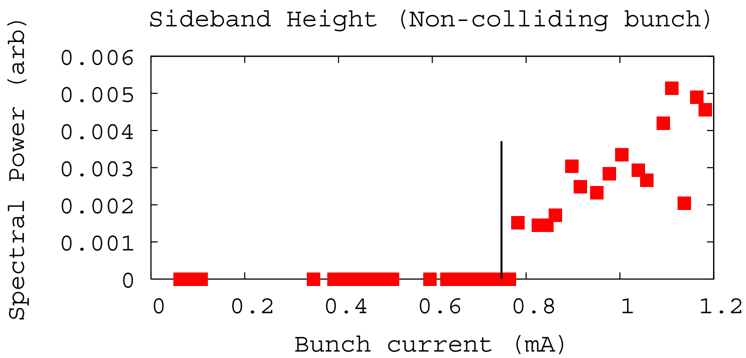
Y. Funakoshi et al.

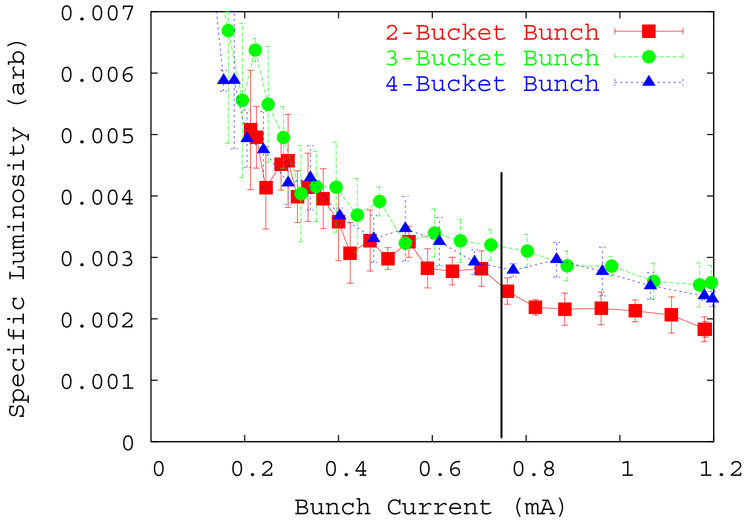


Electron cloud in KEKB



J. Flanagan et al.





- Observation of synchrotron sideband of vertical tune --> TMCI (strong head-tail) due to e-cloud
- Correlation of the sideband, vertical blowup and specific luminosity drop for a shorter bunch spacing has been clearly observed.

Single bunch current and More bunches (cont'd)

- PEP-II
  - Anomalous vacuum pressure rise, luminosity drop and horizontal blowup along the bunch train were observed.
  - The number of bunches has been successfully increased: by4 --> by3 --> by2.
    - Solenoid windings + improved operation parameters? + scrubbing?
  - The e-cloud now does not seem to limit the performance.
- DAΦNE
  - The e+ current has been limited below 1.4A after 2003 shut down. The suspect that the fast horizontal instability is caused by e-cloud is supported by a large positive tune shift, anomalous pressure rise, agreement with simulation.
  - Bunch lengthening and vertical blowup due to microwave instability are observed, particularly in the electron ring.

Remove Ion Clearing Electrodes in e^- Wigglers

C. Milardi

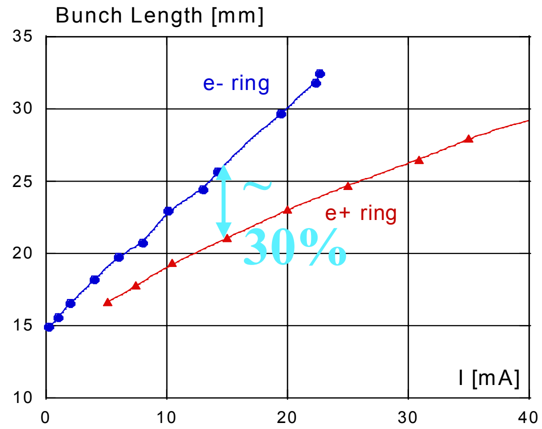
MOTIVATION:

- Impedance of the DAFNE Main Rings:

$$\left(\frac{Z}{n}\right)_0 \approx 1\Omega \quad e^-$$

$$\left(\frac{Z}{n}\right)_0 \approx 0.54\,\Omega \quad e^+$$

mainly due to ICE in WGLs



- Impedance affects bunch length:

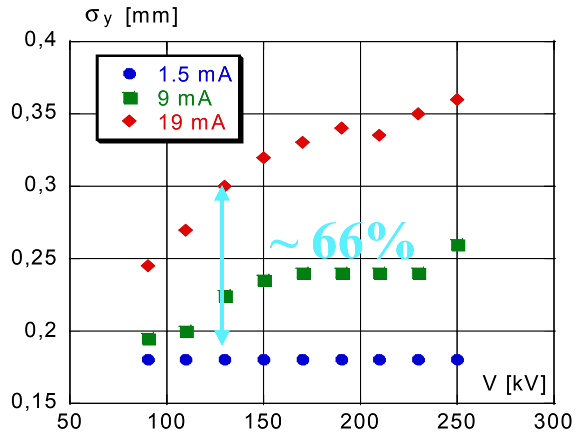
$$\left(\frac{\sigma_z}{R}\right) \approx \left(\frac{2}{\pi}\right)^{1/6} \xi^{1/3} \left(\frac{Z}{n}\right)_o^{1/3} \qquad \xi = \frac{\alpha_c I}{\nu_s^2 (E/e)} = \frac{2\pi I}{h V_{RF} \cos\phi_c}$$

$\sigma_z^- \approx 2.7\text{cm}$

$\sigma_z^+ \approx 2\text{ cm}$ measured @ I_b ~ 15 mA

- Impedance affects vertical beam size as well

e^- Vertical Size Blow f(V_{RF}, I_b)



Optics and beam-beam issues

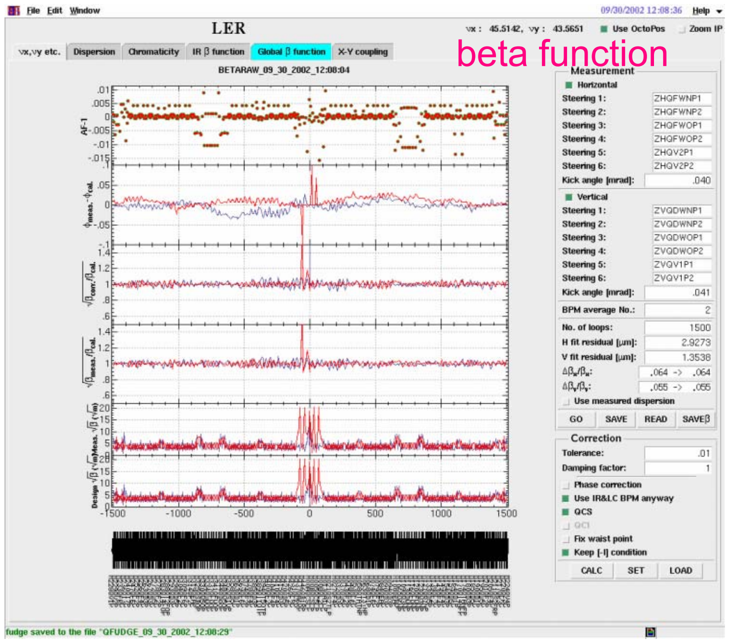
- Requirements for a large beam-beam parameter ξ_y and small β_y^*
  - High performance and precise control of linear optics and orbits
  - Keeping the optimum collision condition
  - Suffeciently long lifetime by a wide dynamic aperture
  - Wiggler magnets to increase the damping rate
  - These are more stringent for a lower energy beam
- Large beam-beam parameters ξ_y and small β_y^* achieved in the factories are mainlyattributed to:
  - Precise measurement and correction of linear optical functions
    - Beta function, dispersion, coupling correction
  - Improvements of non-linear dynamics
    - Sextupoles and octupoles
    - Local chromaticity correction near the IP
  - Non-interleaved sextupole pairs with a 2.5π lattice (KEKB)
  - Moving close to a half horizontal tune (KEKB and PEP-II)
  - Continuous tuning of machine conditions and working points

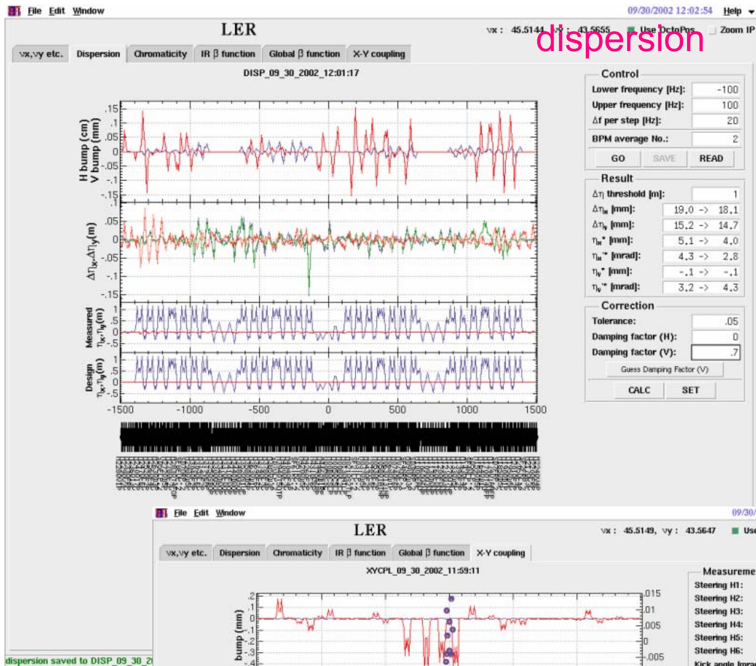
Tuning procedure at KEKB

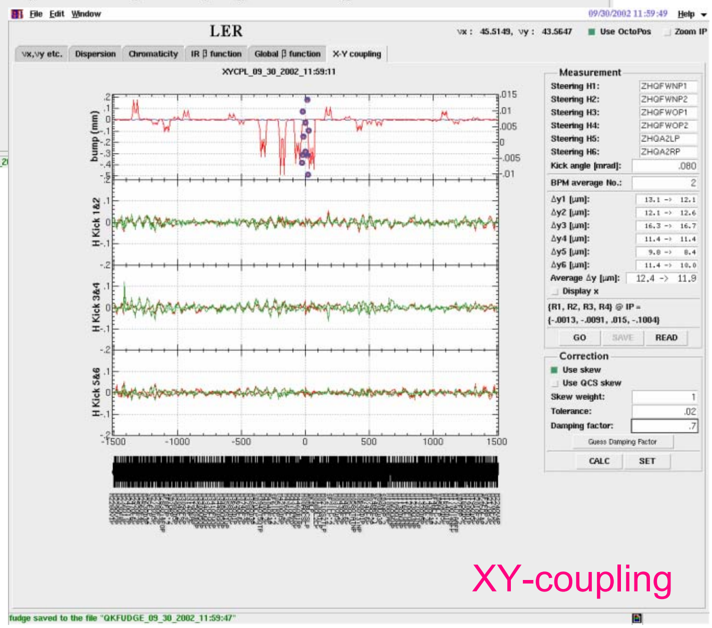
Category	Item	Measurement	Correction	Accuracy (typical)	Frequency (typical)
Ring optics correction	X-Y coupling	H-steering ---> V-orbit	skew-Q Bump orbit @sextupole	~3%	/ week
	dispersion	RF frequency ---> orbit	Bump orbit @sextupole	~10mm	/ week
	global-beta	steering ---> orbit	Q (fudge factor)	~5% ~50mrad	/ week
Ring feedbacks	COD	orbit	steering	~50μm	/ 20 sec
	tune	pilot bunch tune	Q (at Fuji)	~0.0001	/ 20 sec
Collision Feedbacks	transverse	orbit near IP	steering		/ 10 sec
	longitudinal	Vertex from Belle	RF phase		/ 3min
	beam size	SR interferometor	Bump orbit @sextupole		/ 20 sec
Collision Tuning	coupling & dispersion@IP	(optimizing luminosity)	Bump orbit @sextupole		/ shift
	waist position	(optimizing luminosity)	Final Q fudge		/ shift

Optics measurement and correction

H. Koiso et al







Interactive procedure of
measurement + analysis + correction

Knobs:

- Local bumps at sextupoles
- Fudge factors for quads/skews

Works very well !

Present performance limitations and Near-term upgrade

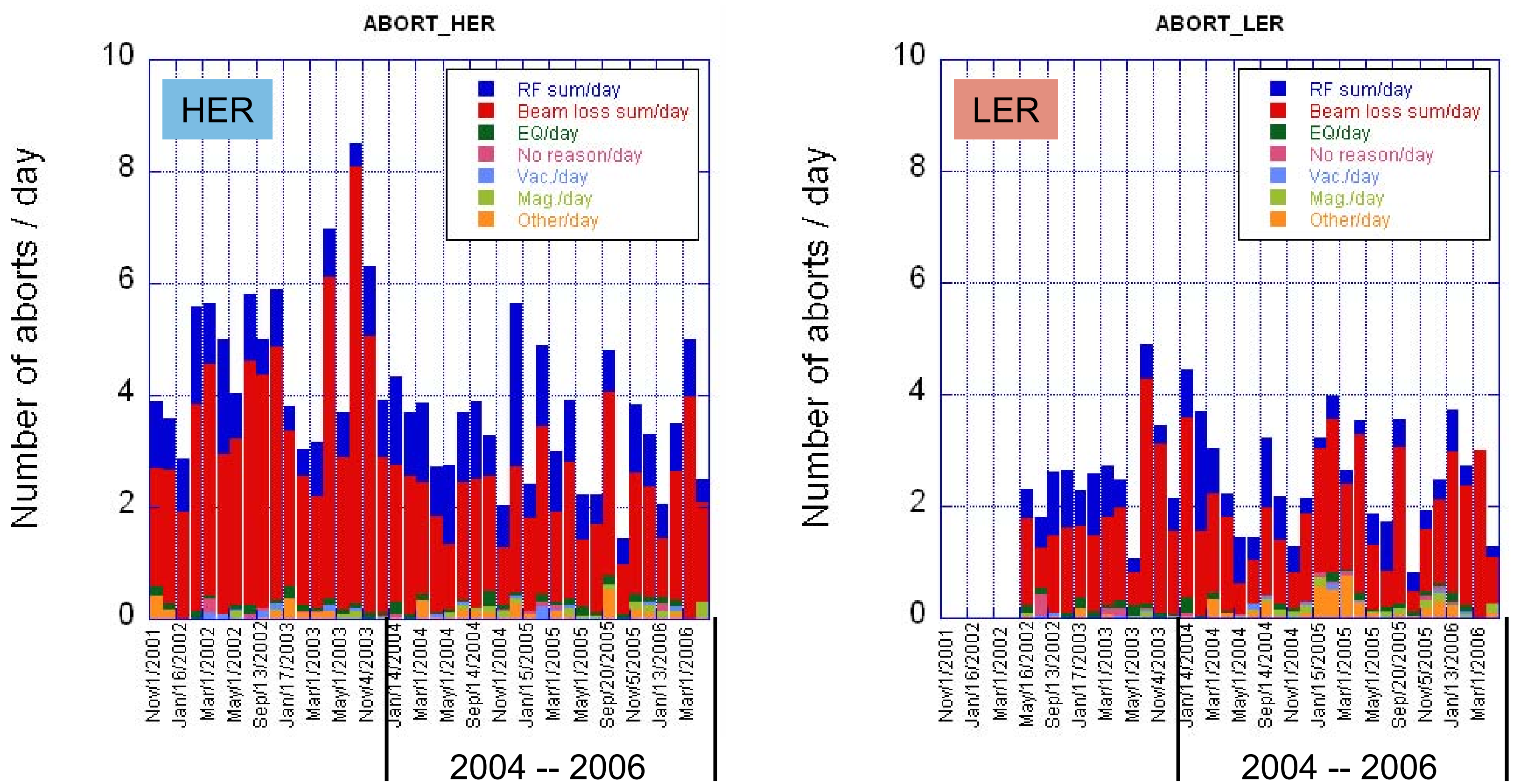
Factory	Present limitations	Cause	Near-term improvements	Expected results
KEKB	spec. lum. Drop (e+ > 1.8A)	electron-cloud (& beam-beam?)	ante-chambers? more solenoids?	
	e- current (1.3A)	heating	improve beam duct components	e- current up (1.5A?)
		crossing angle	crab crossing or crab waist	ξ_y up
PEP-II	beam currents	RF power HOM heating	more RF stations repair & improve BPMs replace IR beam ducts	e+ current up to 4A e- current up to 2.2A
			improve optics/orbit correction	β_y reduce to 8.5mm ξ_y up by 10%
DAΦNE	e+ current (1.5A)	fast instability due toelectron cloud	scrubbing?	
	bunch lengthening & vert. blow up	microwave instability	remove ion-clearing electrodes, negative alpha?	reduce impedance avoid bunch lengthening
			new injection kickers	beam currents up stable beam at injection

Integrated luminosity

- A high ratio of the average to peak luminosity is also important for the factories.
- Continuous injection
  - 20-40% daily luminosity increase in PEP-II and KEKB
  - Also effective for DAFNE/KLEO
- Reduce the number of beam aborts
- Long-term stable operation

KEKB beam abort statistics

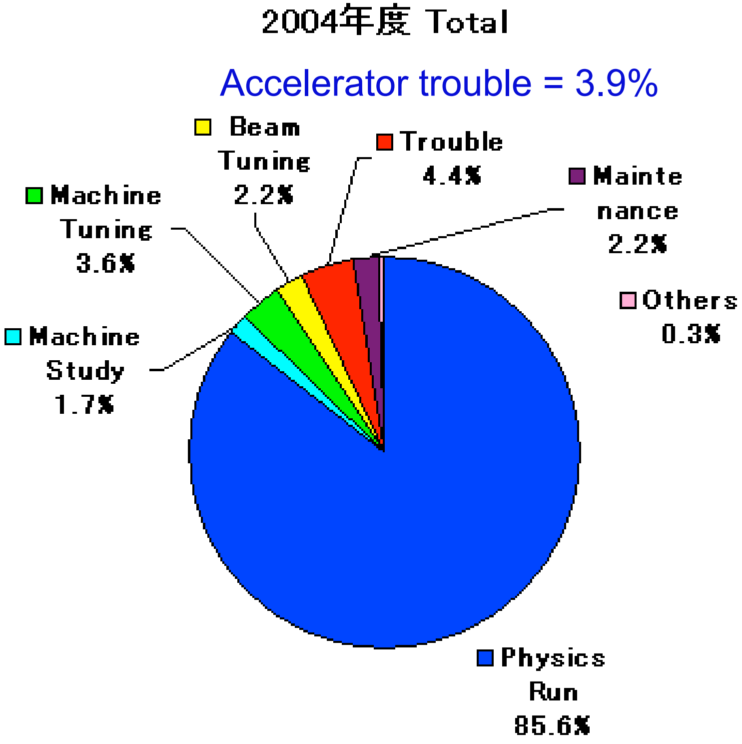
H. Ikeda



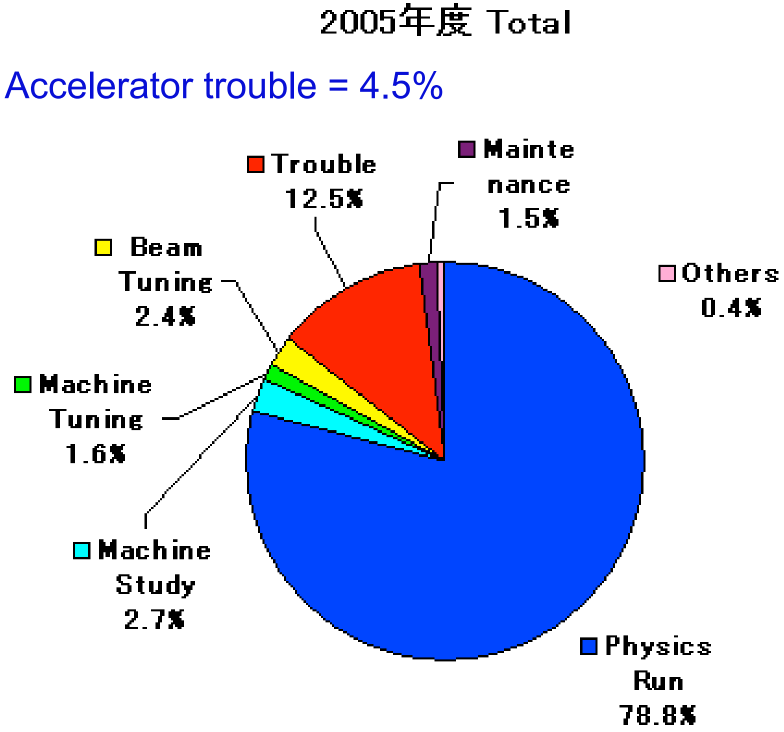
- Average number of beam aborts during three years (from 2004 to 2006) is three times /day (HER) and twice /day (LER).
- 60% is caused by beam loss and 28% by RF trips.

KEKB operation statistics

FY2004



FY2005

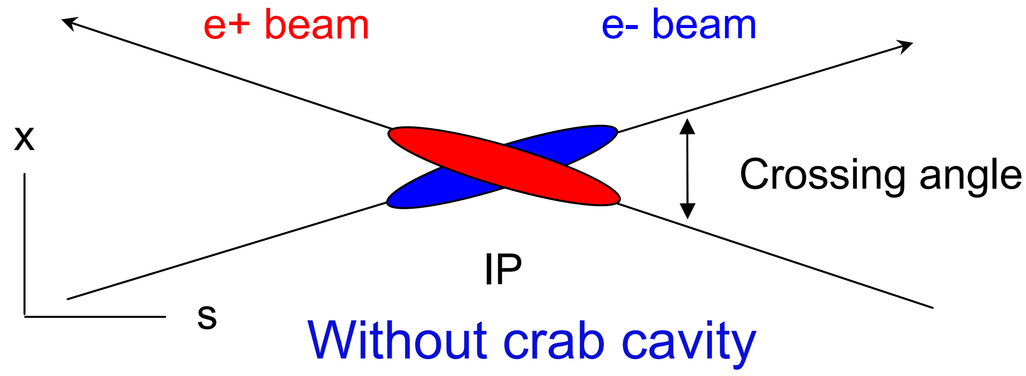


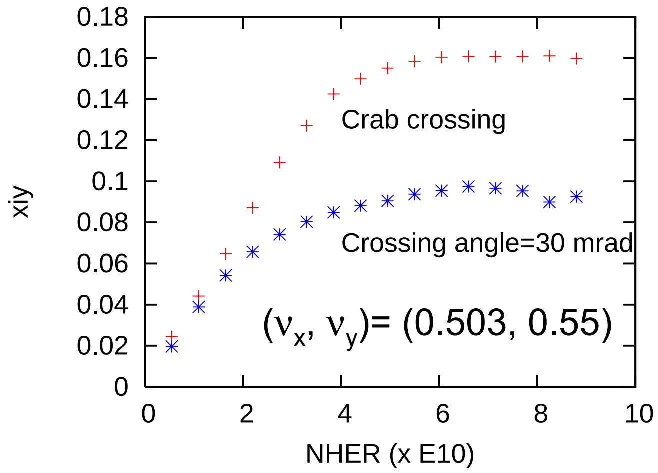
Next generation Super-Factories

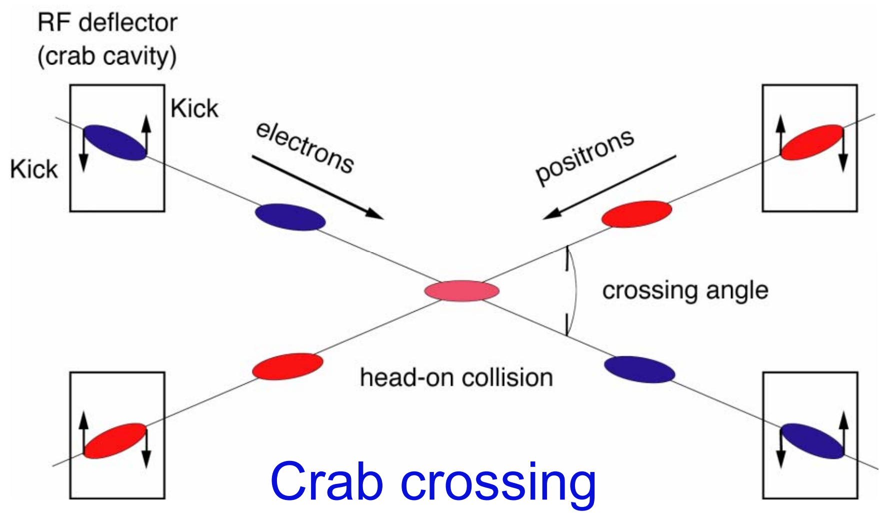
- Innovative ideas and experiments to drastically increase the luminosity
  - Crab crossing experiment
  - Crab waist
  - Strong RF focus
  - Negative alpha experiment
- Super factories proposed or being investigated
  - Super ϕ-factory
  - Super B-factories

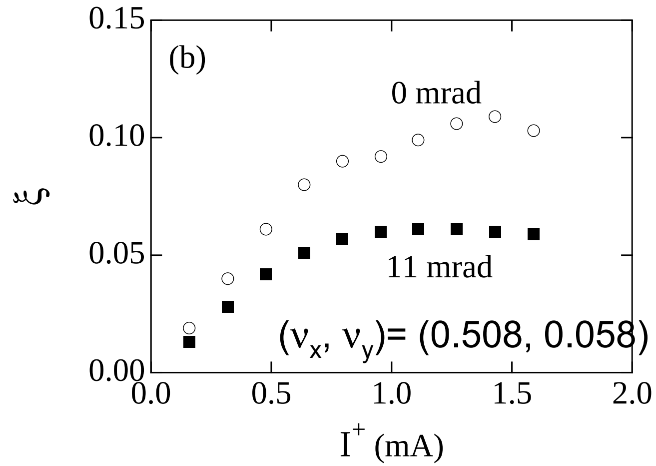
Crab crossing

K. Ohmi





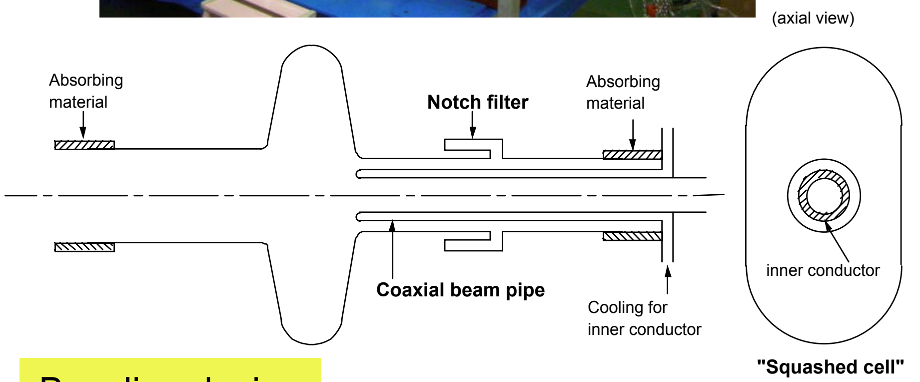




KEKB superconducting crab cavity

Assembly in a cryostat

Placed into horizontal test pit



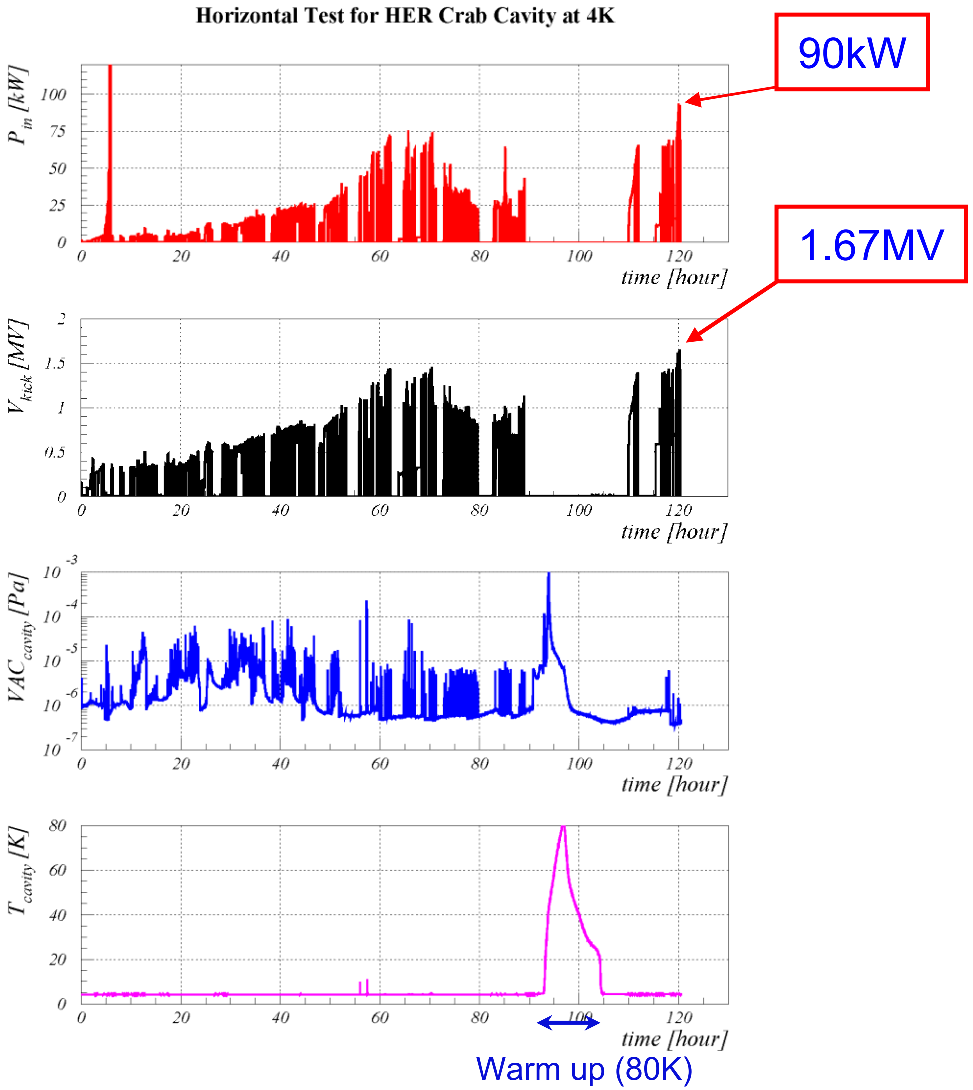
Baseline design

Squashed Crab cavity for B-factories

(K. Akai et al., Proc. B-factories, SLAC-400 p.181 (1992).)

Horizontal test of first crab cavity

May-June 2006



Achieved 1.67 MV kick voltage.
(Required kick is 1.4 MV.)

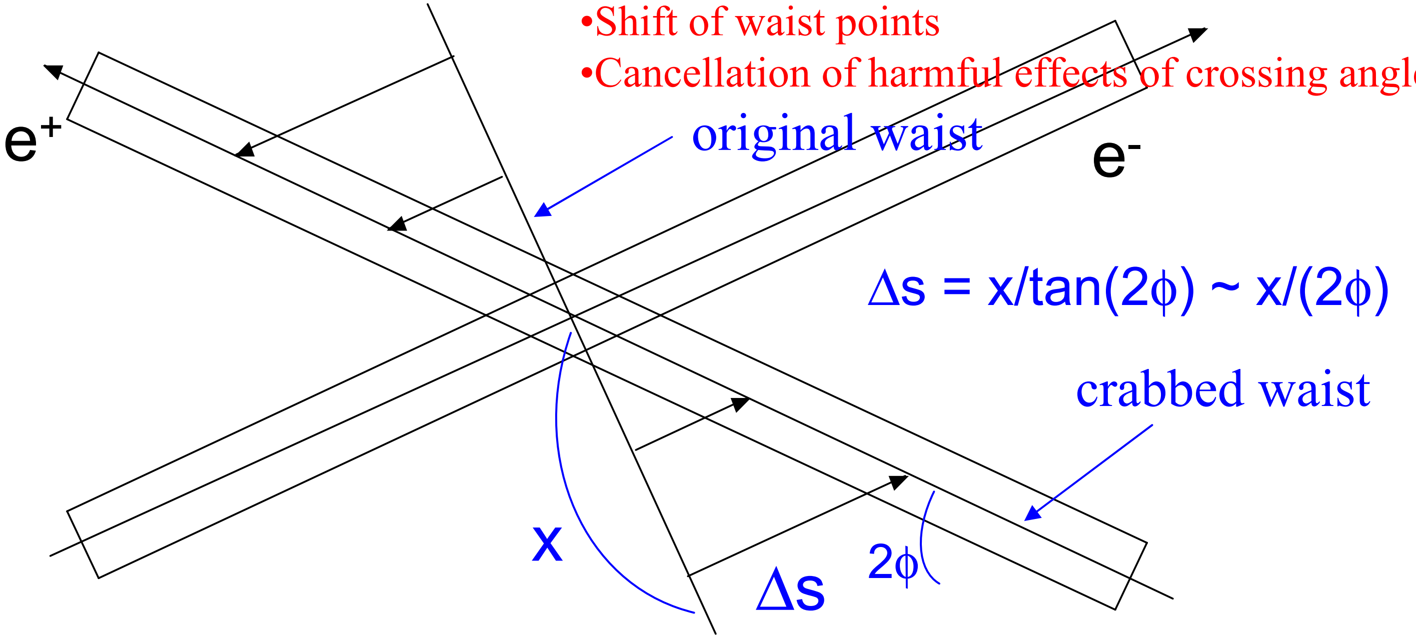
- To be improved
  - Resonance frequency correction
  - Mechanical stiffness
  - Wider tuning range
  - Allignment of coaxial pipe
- Re-assembly of the HER Crab cavity and test
- Assembly of the LER Crab cavity and test
- Installation into KEKB and experiment of crab crossing (hopefully, winter 2006)

Crab waist

P. Raimondi
SuperB workshop @LNF

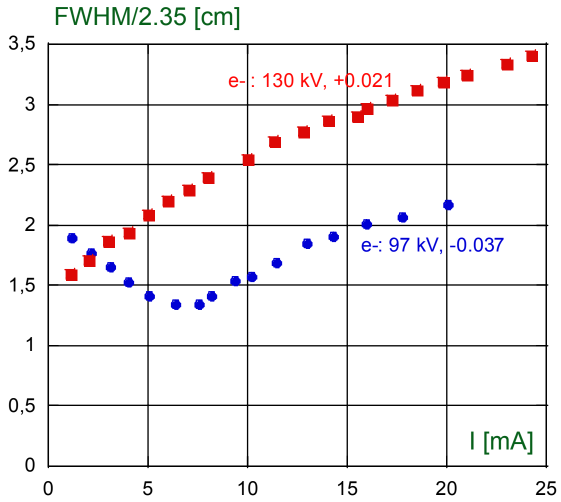
Basic scheme
- crossing angle
- small x size
- crab waist

- Smaller area of interaction
  - -> effectively short bunch
  - -> very small β_y^*(hourglass)
  - -> smaller emittance is needed to keep ξ_y high
- Smaller beam-beam tuneshift (Hor.)
  - Cancellation of main and long range force
- Still crab waist is needed.
  - Shift of waist points
  - Cancellation of harmful effects of crossing angle



Short bunch length

- Strong RF Focus A. Gallo et al, 2004
  - A high momemtum compaction factor together with a high RF gradient provide a modulation of bunch length
  - Short bunch at IP, while keeping a longer bunch at places where high-impedance components are located
- Negative alpha experiment



KLOE nominal optics $\alpha_c \sim$ 0.02

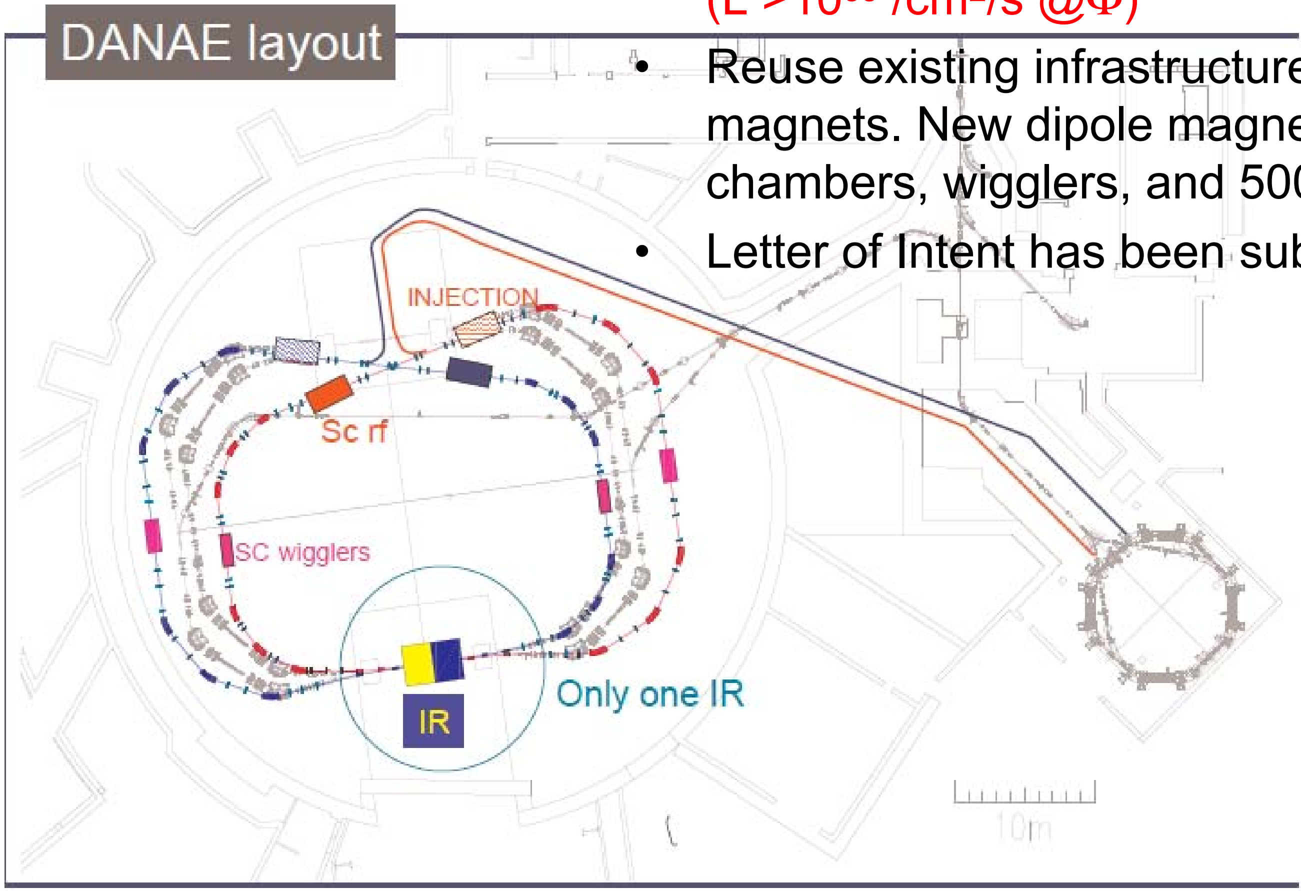
e^- L_b versus stored current for:

α_c = 0.02 red squares

α_c = - 0.036 blue dots

DAΦNE upgrade to DANAE

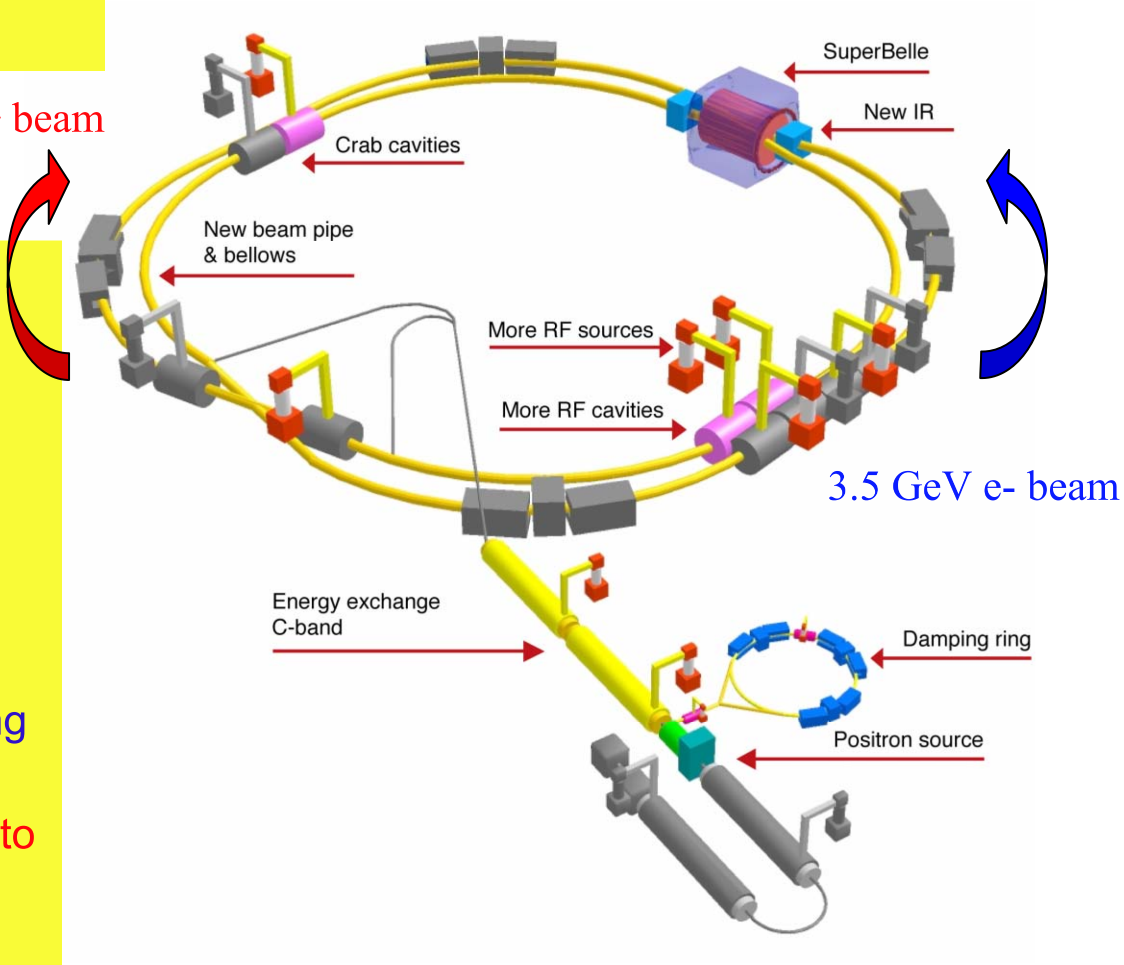
- DAfne New with Adjustable Energy
- Energy upgrade (2.4GeV) + Luminosity upgrade ($L > 10^{33}$ /cm²/s @Φ)
- Reuse existing infrastructures, buildings and magnets. New dipole magnets, new vacuum chambers, wigglers, and 500MHz RF needed.
- Letter of Intent has been submitted.



SuperKEKB

L = 8.25×10³⁵ /cm²s

- More beam current
  - LER/HER = 1.6A/1.3A → 9.6A/4.1A
- Squeeze βy*
  - βy*= 6mm → 3mm
  - σz= 6mm → 3mm
- Beam-beam parameter
  - ξy=0.05 → 0.14 by adopting crab-crossing
  - Discusstion is going on as to crab waist to be used instead of crab crossing?

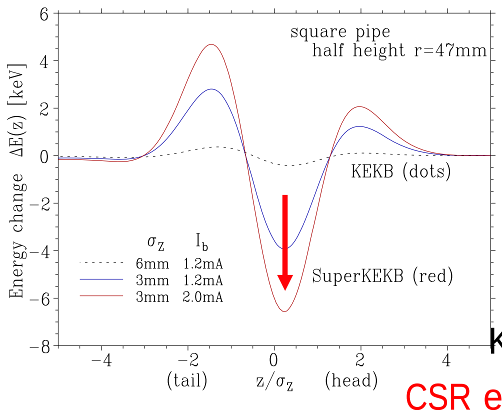


CSR in SuperKEKB

T. Agoh

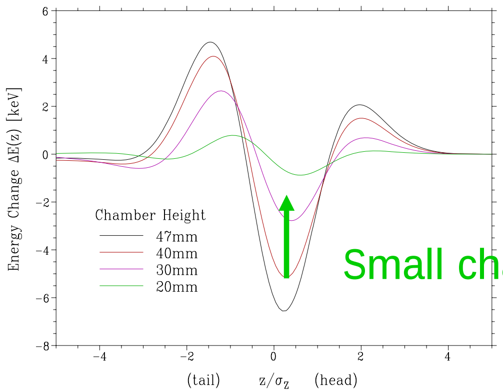
Energy change due to CSR

(Longitudinal wakefield for a single bend)



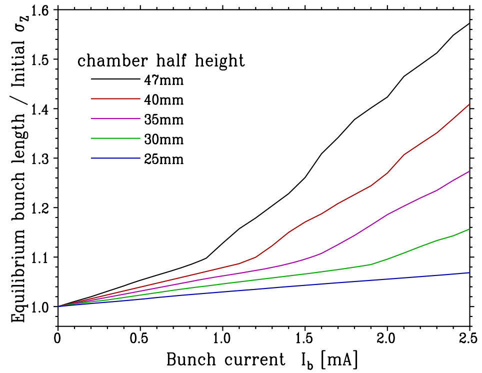
KEKB → SuperKEKB

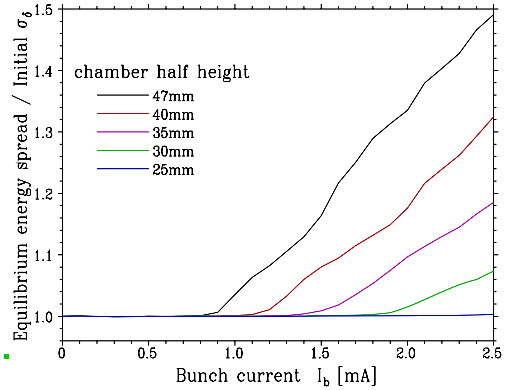
CSR effect is 14 times larger



Small chambers suppress CSR.

Bunch length (upper) and energy spread (lower) vs. Bunch current





We will make new vacuum chamber to suppress electron cloud effect.

SuperB

- SuperB workshops
  - 3 SuperB workshops held in Nov. 2005 and March 2006 @INFN-LNF, and June 2006 @SLAC.
  - Conceptual Design Report will be prepared by the end of 2006.
- Present design concept
  - Crab waist
  - Very low emmitance rings, similat to the ILC-DR
  - Very small β_y* by adopting the ILC Final Focus
  - Beam currents are comparable to those of the present factories.
- Extensive simulation work is progressing to studythe beam-beam effects and the dynamic aperture with this scheme and to make a set of design parameters.

Raimondi

Sigx*	μm	2.67
Etax	mm	0.0
Sigy	nm	12.6
Betx	mm	9.0
Bety	mm	0.080
Sigz_IP	mm	6.0
Sige_IP		1.3e-3
Sige_Lum		0.9e-3
Emix	nm	0.8
Emiy	nm	0.002
Emiz	μm	8.0
Cross_angle	mrad	2*25
Sigz_DR	mm	6.0
Sige_DR		1.3e-3
Np	10e10	2.3
Nbunches		6000
DR_length	km	3.0
Damping_time	msec	20
Nturns_betwe_coll		1
Collision freq	MHz	600
$L_{singleturn}$	1e36	1.2
$L_{multiturn}$	1e36	1.0

- **Defined a parameters set based on ILC-like parameters**
- **Same DR emittances**
- **Same DR bunch length**
- **Same DR bunch charges**
- **Same DR damping time**
- **Same ILC-IP betas**
- **Crossing Angle and Crab Waist to minimize BB blowup**

ξ_y~0.045
I(HER)~1.4A (7GeV)
I(LER)~2.5A (4GeV)

Summary

- Recent e+e- colliders have been operating at very high luminosities, generating enormous amount of mesons like "Factories", which have lead to a number of physics discoveries.

- As a result of successful operation of KEKB, PEP-II and DAΦNE, extended upgrades of them to next-generation "Super-Factories" are being investigated, aiming at nearly two orders of magnitude higher luminosity than the present factories.