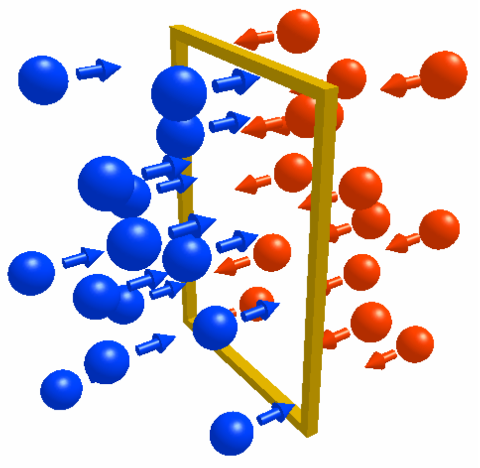
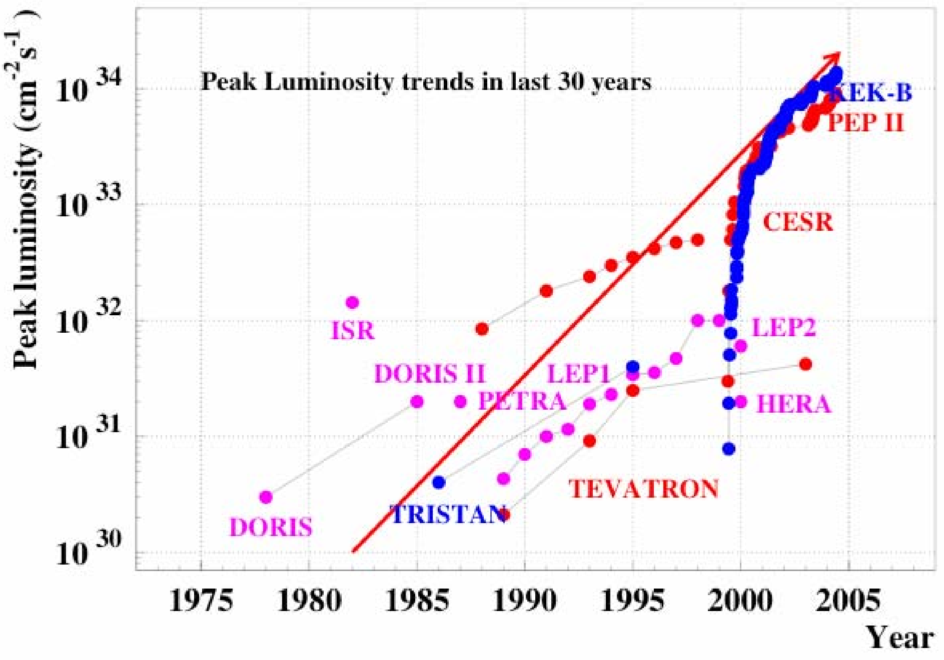
KEKB / SuperKEKB
The Luminosity Frontier



(number of events/unit time)

= (cross section) X (luminosity)



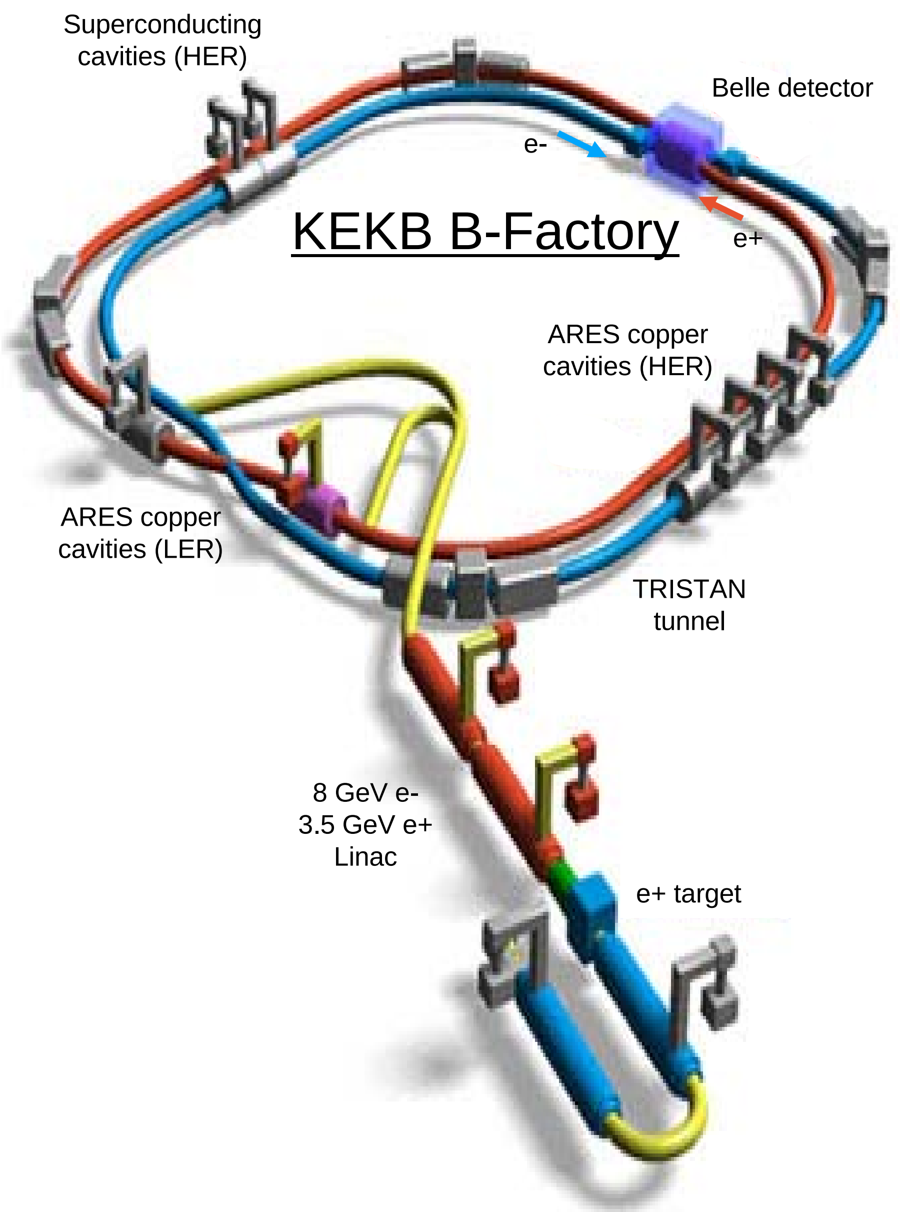
Katsunobu Oide (KEK)

Jan. 19, 2005 @ Kyoto Univ.

http://kekb.jp

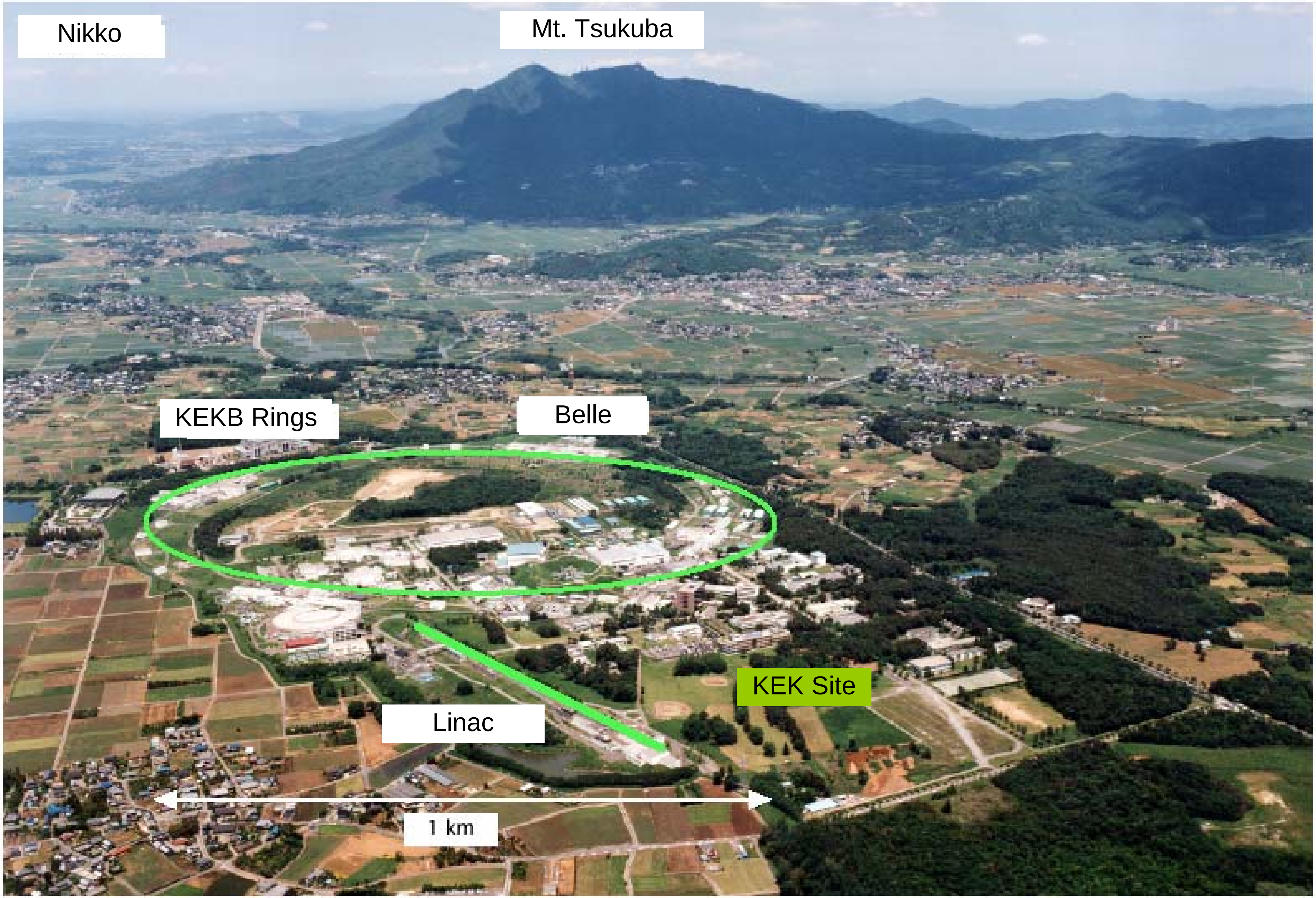
KEKB = Asymmetric Double-Ring Collider for B-Physics

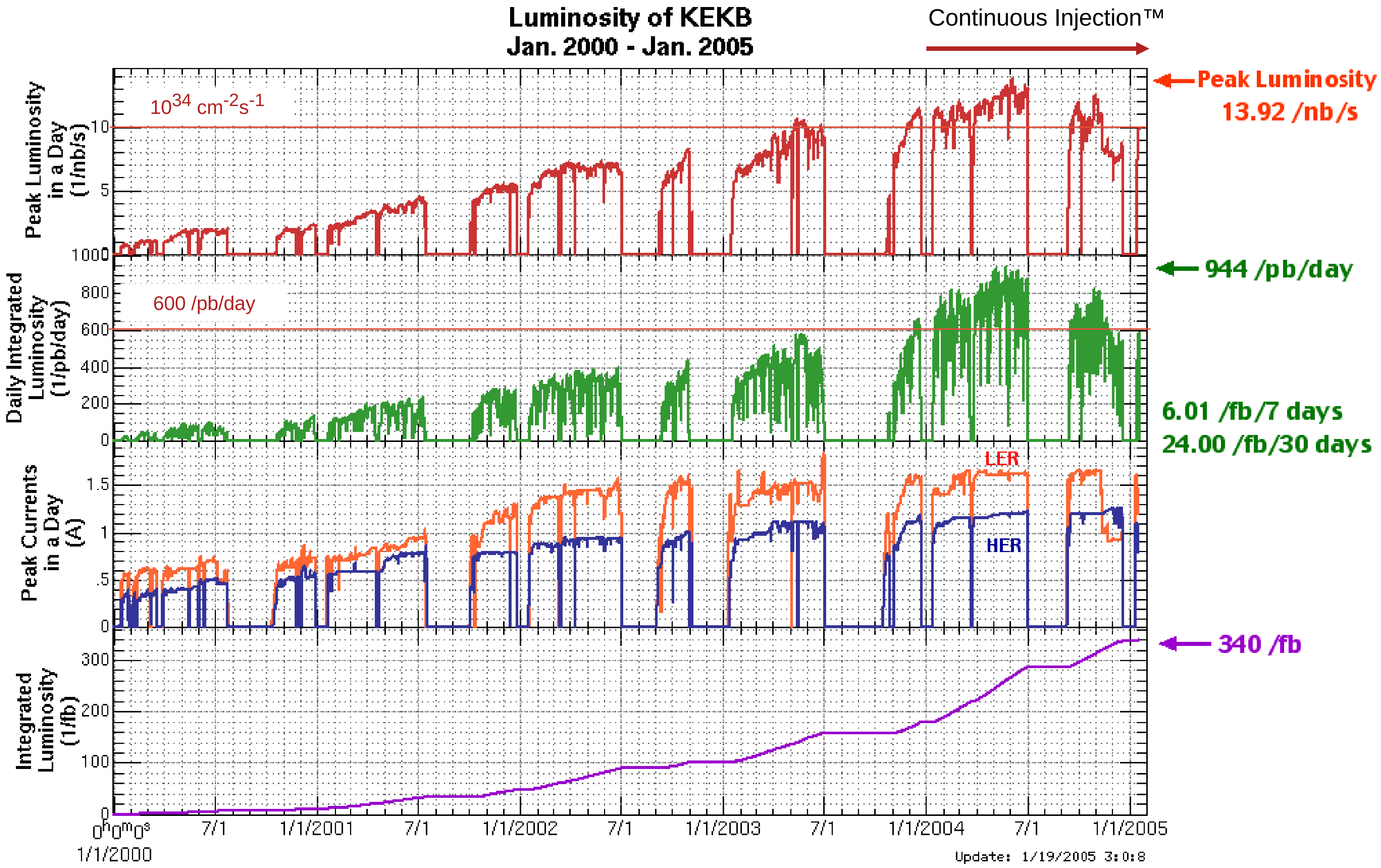
8 GeV Electron + 3.5 GeV Positron



1989:	Design work started.
1994:	Approval of the budget, construction started.
June 1995:	KEKB Design Report
Sep. 1997:	Commissioning of the injector Linac started.
Dec. 1998:	First beam at HER.
Jan. 1999:	First beam at LER.
May 1999:	Belle roll-in.
June 1999:	First event at Belle.
Apr. 2001:	World record of the luminosity, 3.4 /nb/s.
Oct. 2002:	World record of the integrated luminosity, 100 /fb.
May 2003:	Exceeded the design luminosity, 10 /nb/s.
Feb. 2004:	Exceeded 12 /nb/s & 200 /fb.
June 2004:	13.9 /nb/s & 288 /fb.
Dec. 2004:	338 /fb.

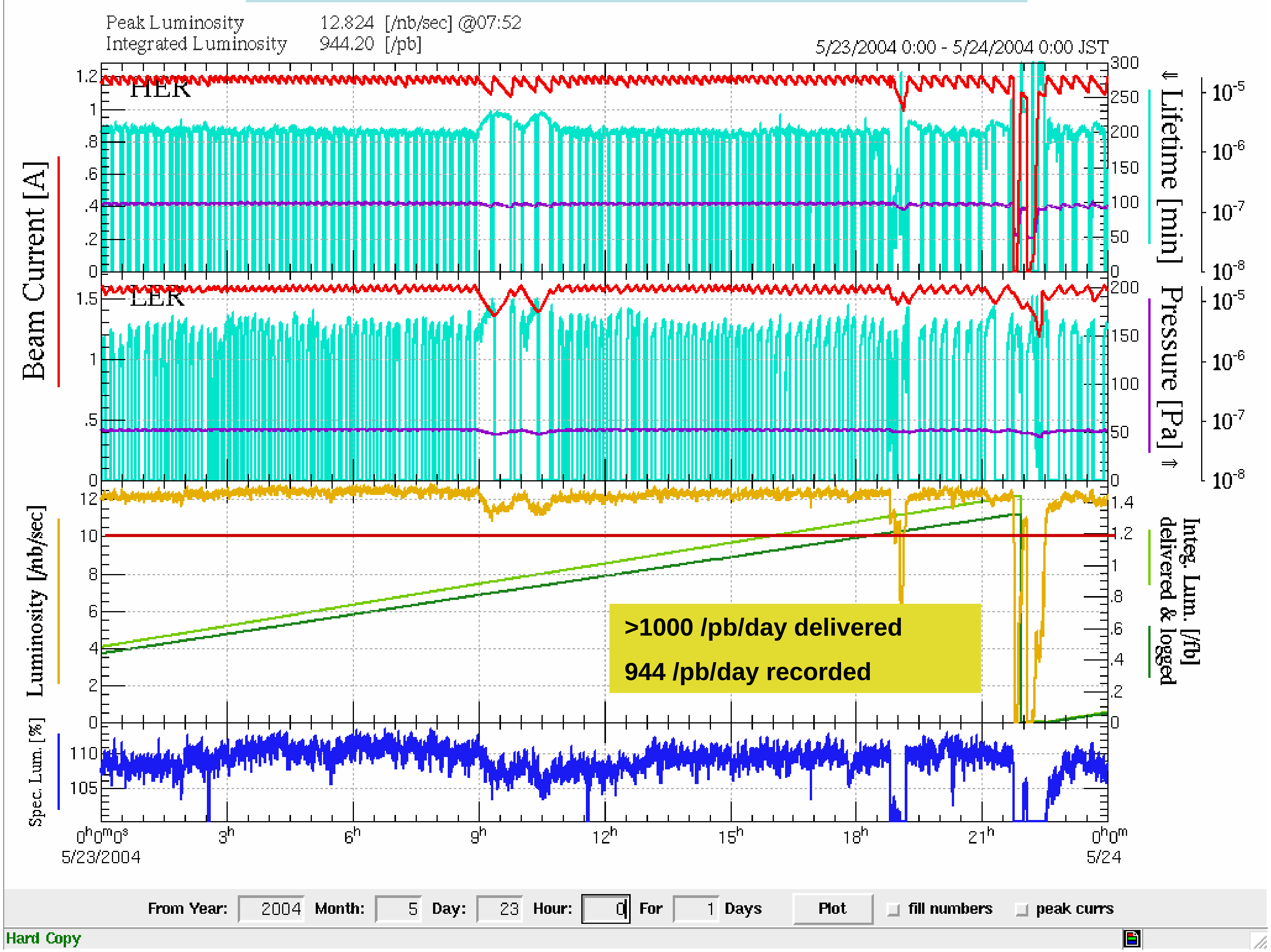
… continues rewriting own records …


Nikko
Mt. Tsukuba
KEKB Rings
Belle
KEK Site
Linac
1 km

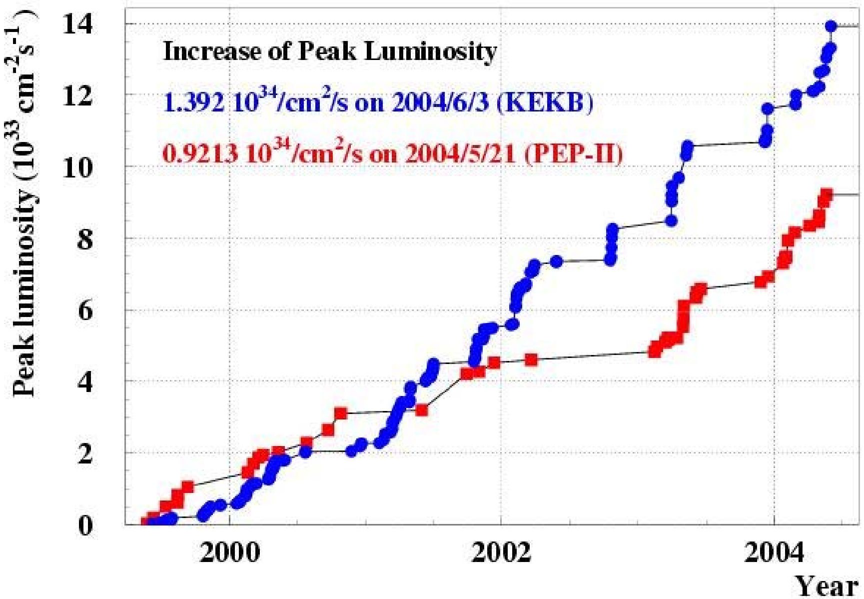


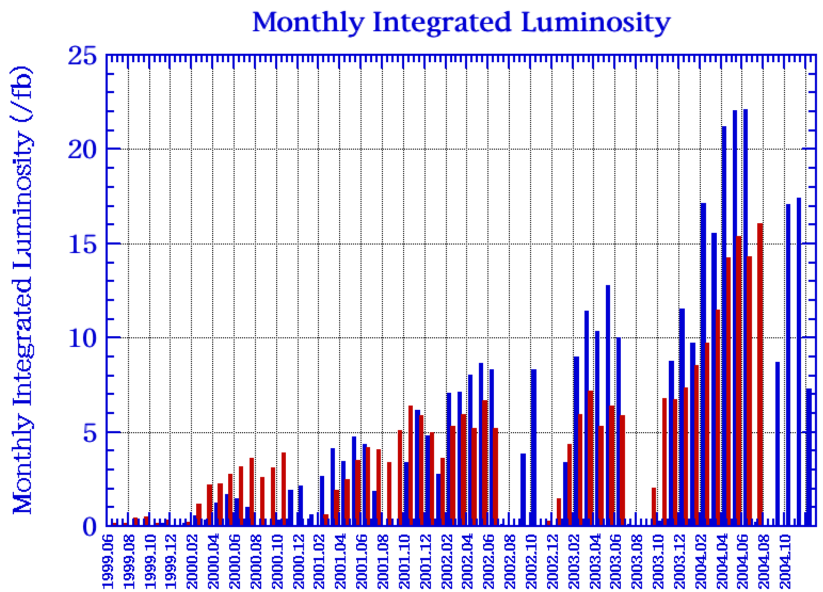
Luminosity of KEKB
Jan. 2000 - Jan. 2005
Continuous Injection™
Peak Luminosity
13.92 /nb/s
944 /pb/day
6.01 /fb/7 days
24.00 /fb/30 days
340 /fb
Peak Luminosity in a Day (1/nb/s)
10^34 cm^-2s^-1
Daily Integrated Luminosity (1/pb/day)
600 /pb/day
Peak Currents in a Day (A)
LER
HER
Integrated Luminosity (1/fb)
0h0m0s 1/1/2000
7/1
1/1/2001
7/1
1/1/2002
7/1
1/1/2003
7/1
1/1/2004
7/1
1/1/2005
Update: 1/19/2005 3:0:8

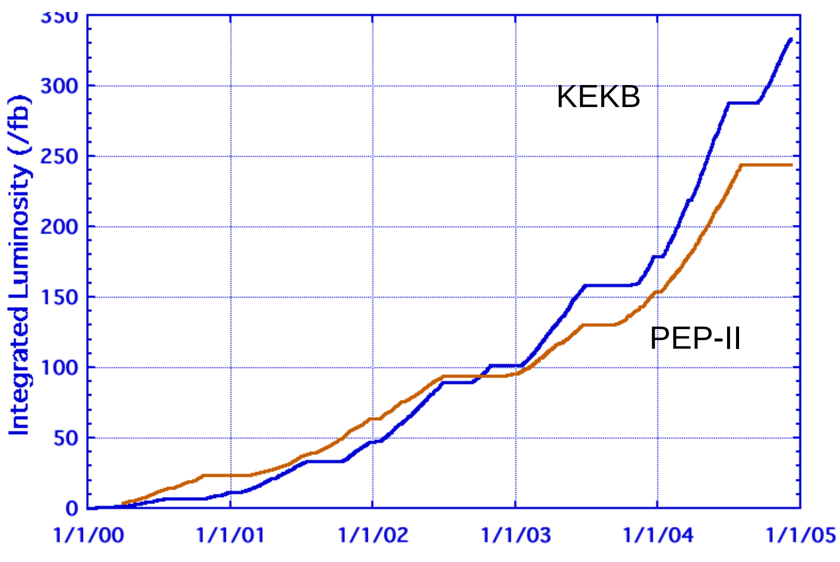
The best day 5/23/2004



The Competition



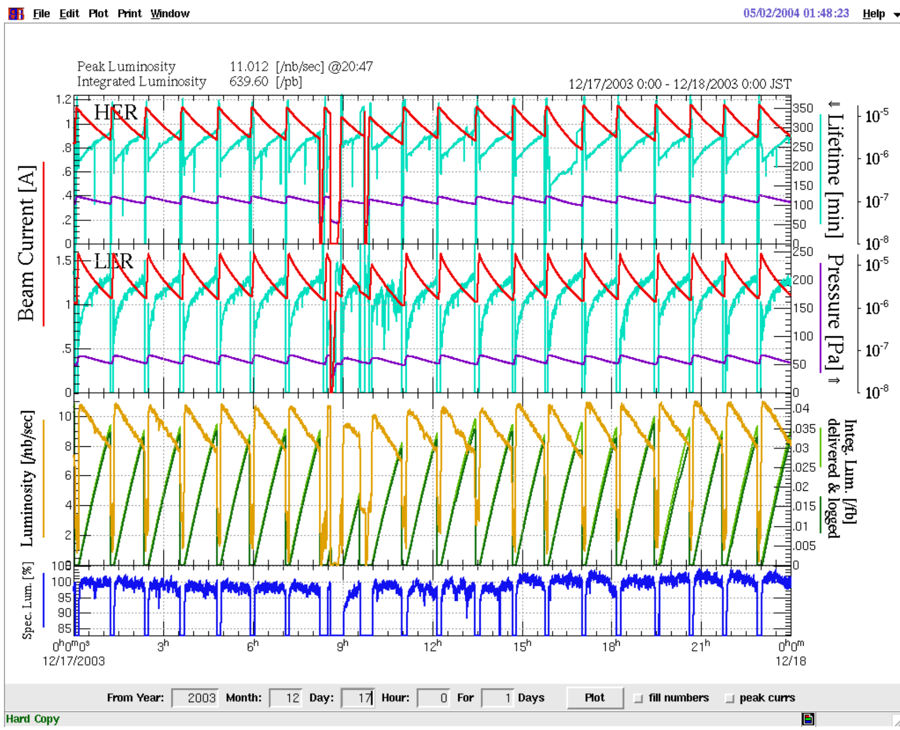




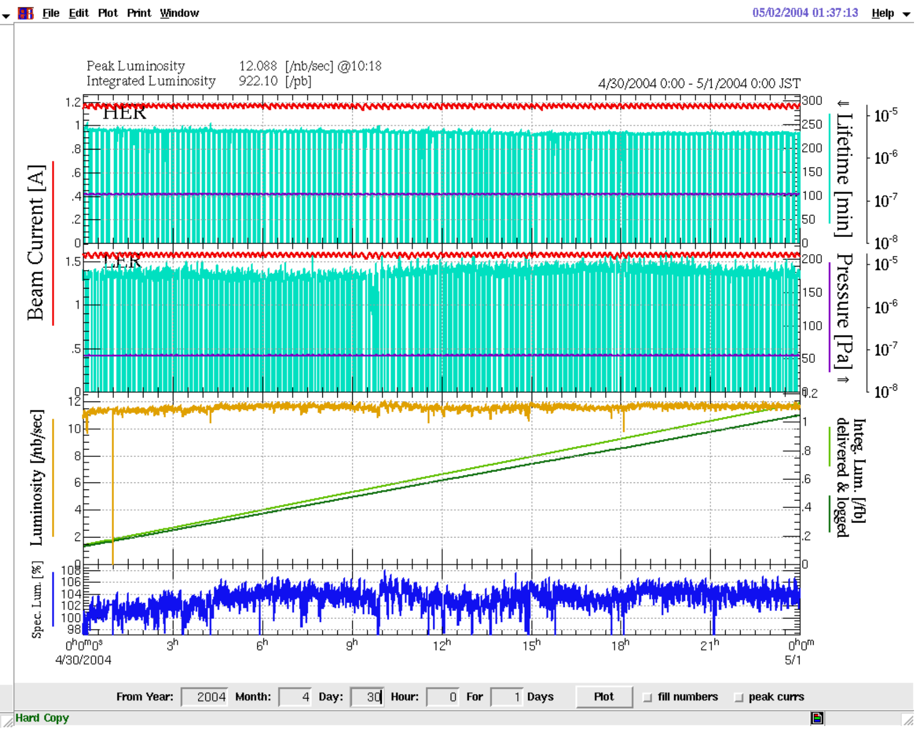
Up to now, KEKB is taking the lead over PEP-II by about 50% margin.

But cannot relax. They have a very ambitious plan to 2.4×10^{34} $cm^{-2}s^{-1}$ by 2007.

Continuous Injection Mode (CIM)



before



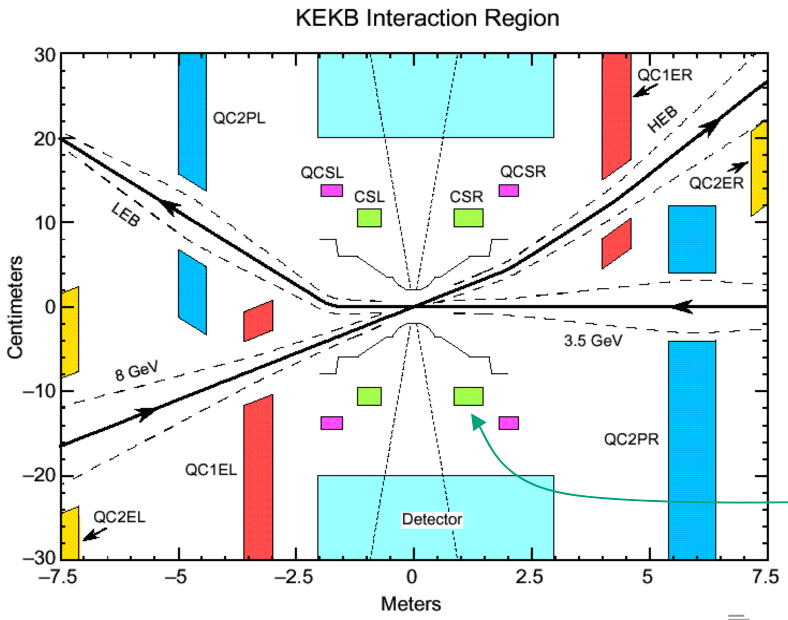
after

- Belle takes data continuously, except for veto for 3.5 msec after each injection pulse.
- 30% higher average luminosity.
- More stable operation & higher operating currents.

The machine must be tuned up as ideal, to obtain the predicted luminosity….

- Four betatron tunes
- Emittances
- Grobal orbit/optics correction
  - Measure orbit responses at BPMs (450/ring)
  - $\Delta\beta/\beta \leq 7$ %
  - $\Delta\eta_y \leq 7$ mm
  - X-y coupling
- Tuning of local parameters at the IP
  - relative orbit offsets (5) - better than 0.1σ, looking at beam-beam deflections, beam sizes, and Belle vertex
  - Vertical waists (2) ± 0.5 mm
  - vertical dispersions (4)
  - x-y coupling parameters (8)

Collision with a finite crossing angle



- Easier beam separation.
- No bend for the incoming beam (less radiation).
- No separation bends (less background).
- Simplified IR.
- Room for solenoid compensation, smaller β^*.

So, the merits were obvious, but was that safe enough?

- What about the synchrotron-betatron coupling?

$$H \approx f\left(x + \frac{x'z}{2} + \theta_x z,\ y + \frac{y'z}{2} \right) \delta(s - nC)$$

z: longitudinal position in a bunch, θ_x: horizontal half corssing angle

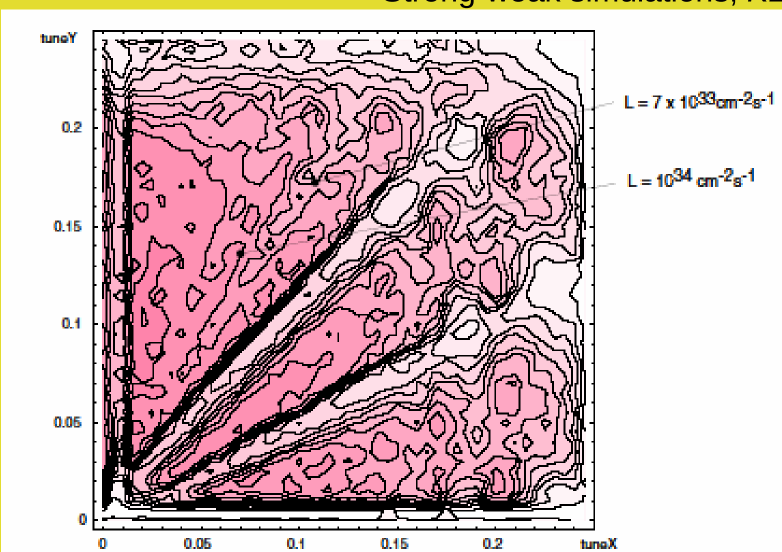
Collision with a finite crossing angle

Synchrotron-betatron couplings are inevitable for a beam-beam interaction anyway, even with a head-on collision.

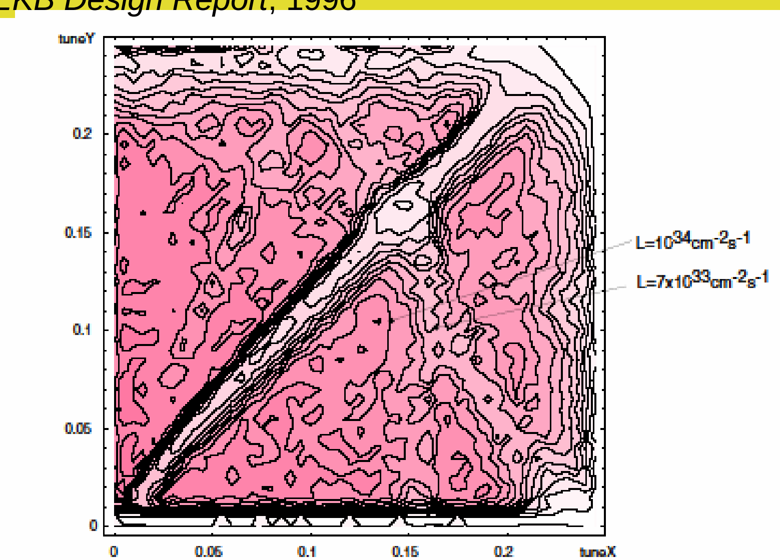
$$f_y \approx \frac{4\pi\xi_y}{\beta_y^*}\left(y+\frac{y'z}{2}\right)^2\left(1-\frac{(x+\theta_x z)^2}{2\sigma_x^{*2}}\right)\delta(s-nC)+\text{higher orders}$$

The relative magnitude of the crossing angle term is about same as the original term.

Strong-weak simulations, *KEKB Design Report*, 1996



Crossing



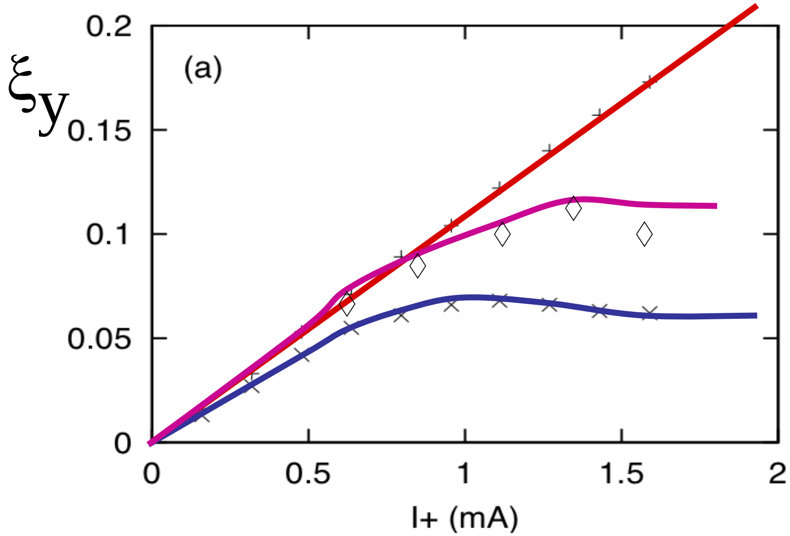
Head-on

Crossing angle is manageable, if we choose the tunes.

Crab crossing in the near future

- Crab crossing will boost the beam-beam parameter up to 0.14!

K. Ohmi



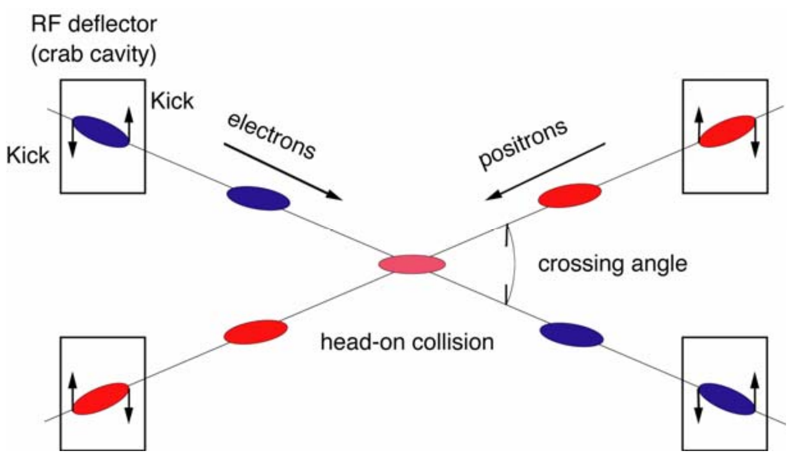
(Strong-weak simulation)

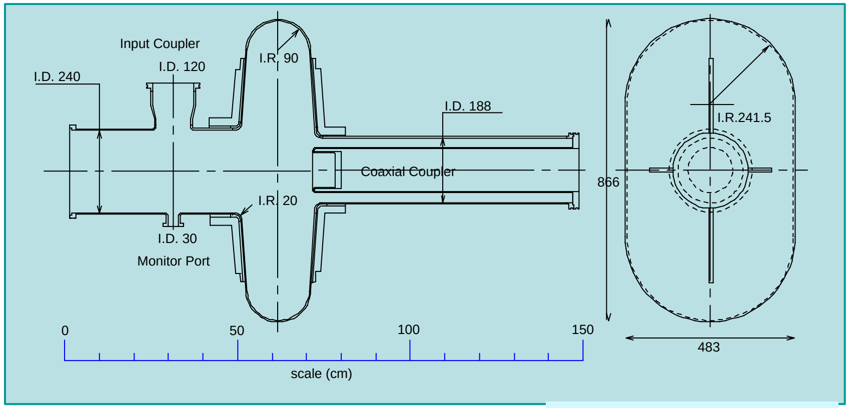
Head-on(crab)

(Strong-strong simulation)

crossing angle 22 mrad

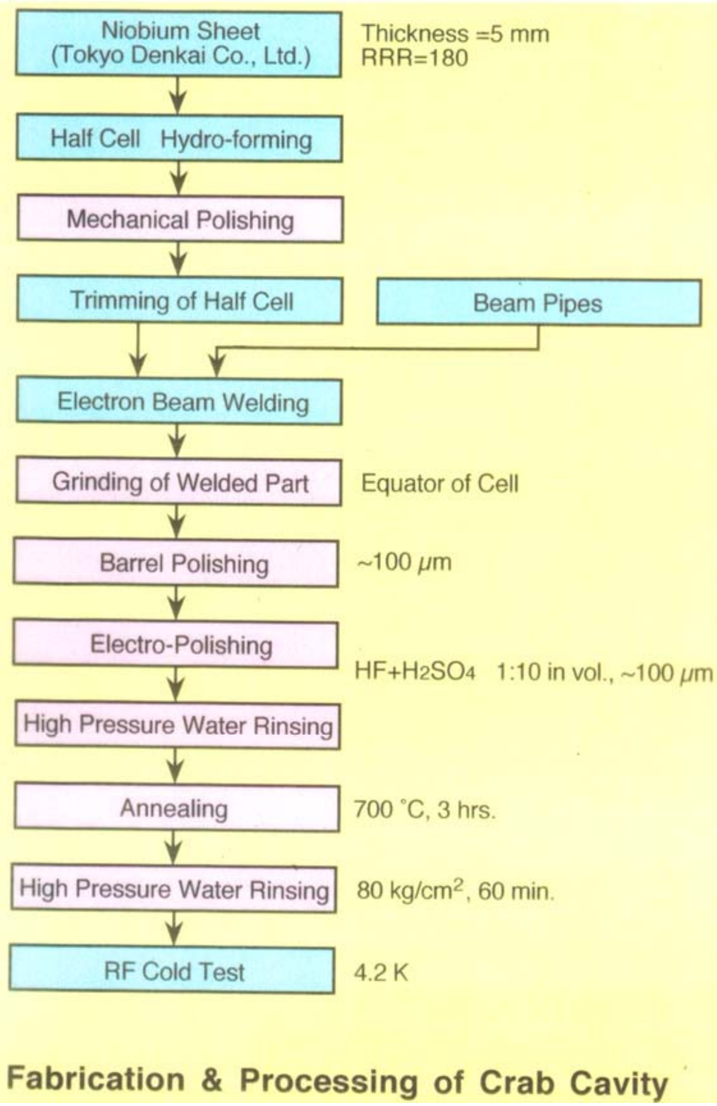
- Superconducting crab cavities are under development, will be installed in KEKB in early 2006.



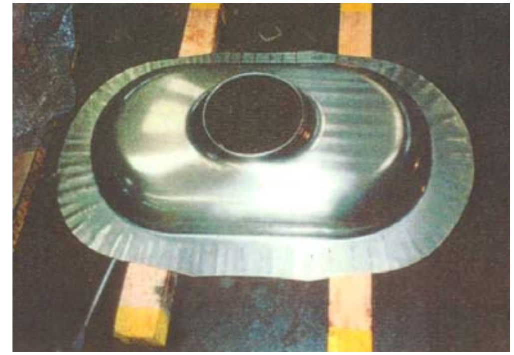


K. Hosoyama, et al

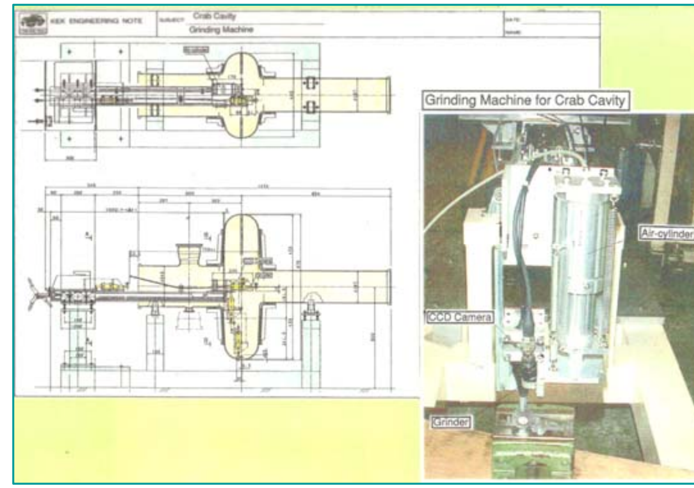
Fabrication & Processing 1



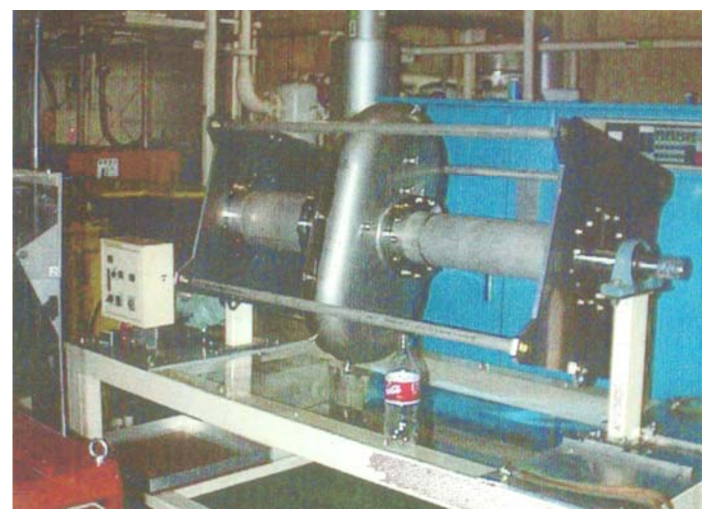
Hydro-forming



Nb Half Cell

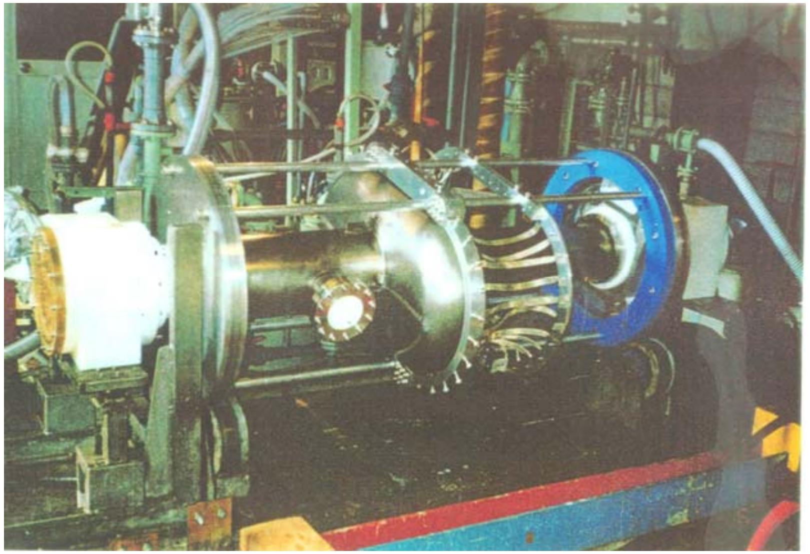


Grinding of Welding Part

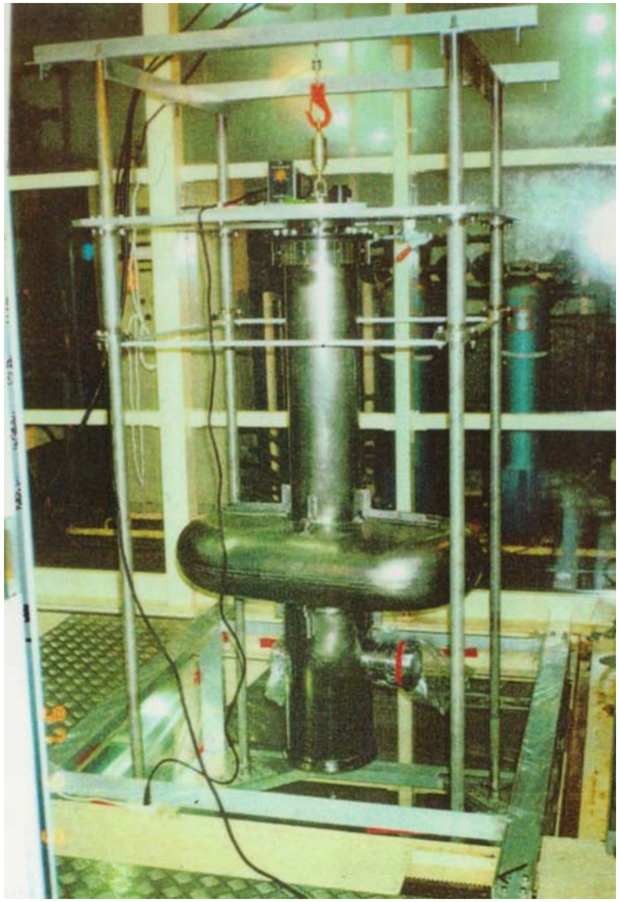


Barrel Polishing

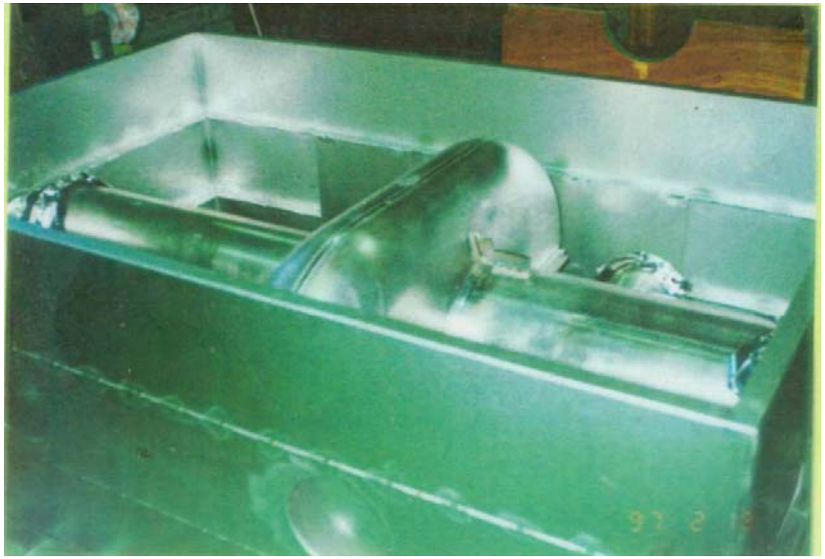
Fabrication & Processing 2



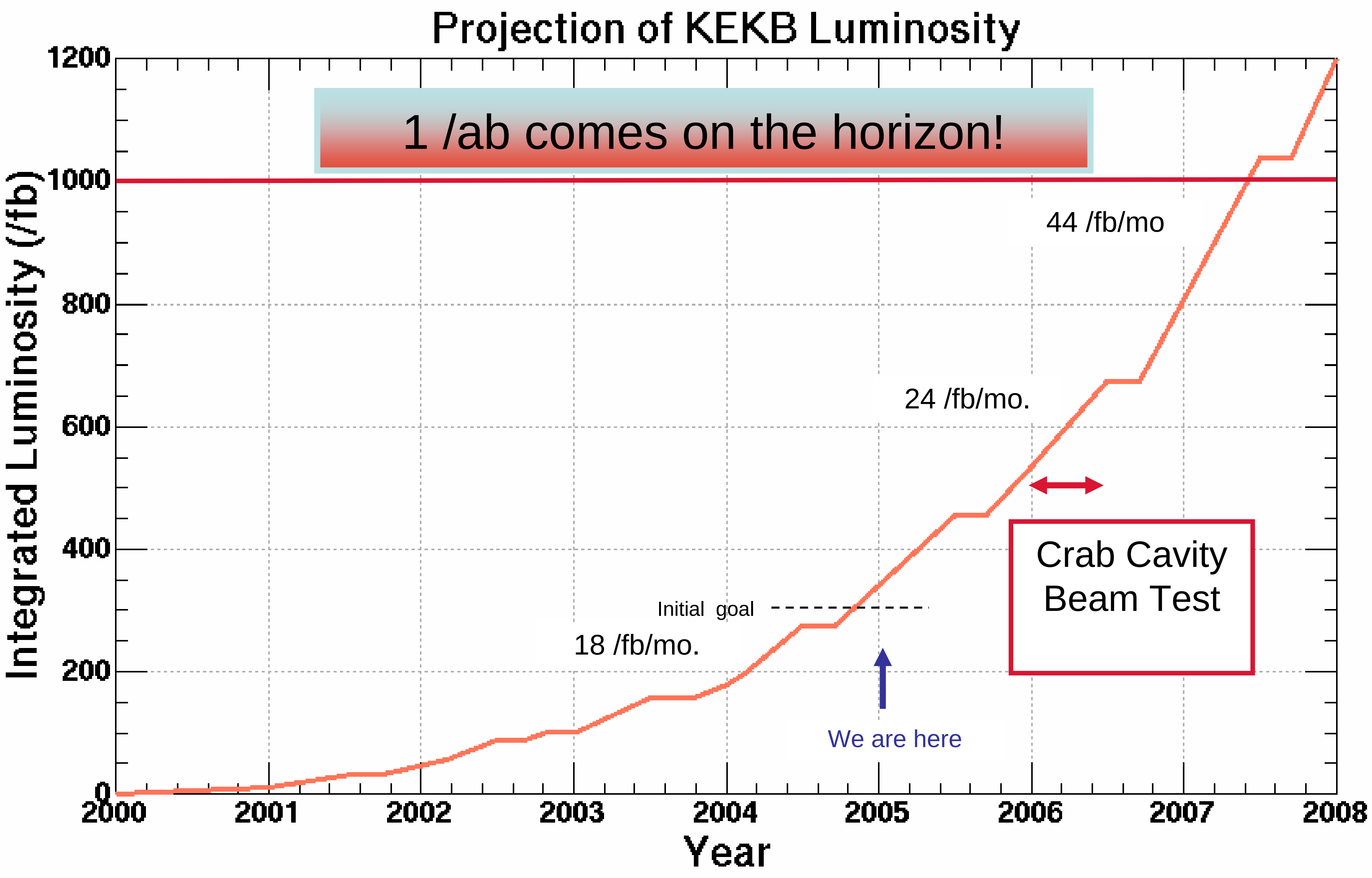
Electro-Polishing



High Pressure Water Rinsing
by 80 bar Ultra-Pure water

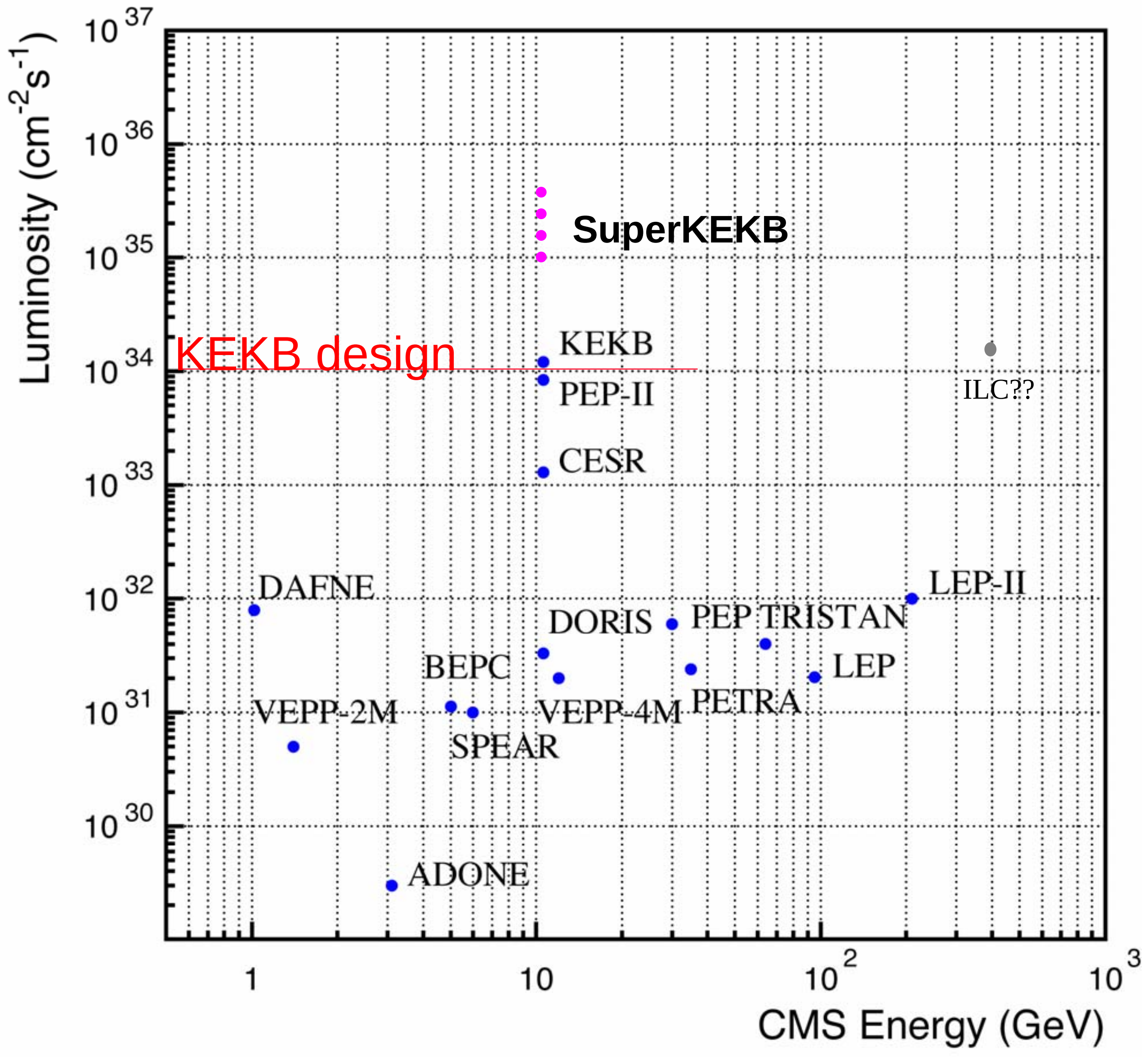


Annealing at 700^0C for 3 hours



Projection of KEKB Luminosity
1 /ab comes on the horizon!
44 /fb/mo
24 /fb/mo.
Crab Cavity
Beam Test
Initial goal
18 /fb/mo.
We are here
Integrated Luminosity (/fb)
Year
0
200
400
600
800
1000
1200
2000
2001
2002
2003
2004
2005
2006
2007
2008

SuperKEKB, the next step



Three factors to determine luminosity:

Stored current:

1.2/1.65 A (KEKB)

→ 4.1/9.4 A (SuperKEKB)

Beam-beam parameter:

0.057 (KEKB)

→ 0.14 (SuperKEKB)

Lorentz factor

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\left(\frac{R_L}{R_y}\right)$$

Classical electron radius

Beam size ratio

Geometrical reduction factors due to crossing angle and hour-glass effect

Luminosity:

0.14×10^{35} cm^{-2}s^{-1} (KEKB)

2.5×10^{35} cm^{-2}s^{-1} (SuperKEKB)

Vertical β at the IP:

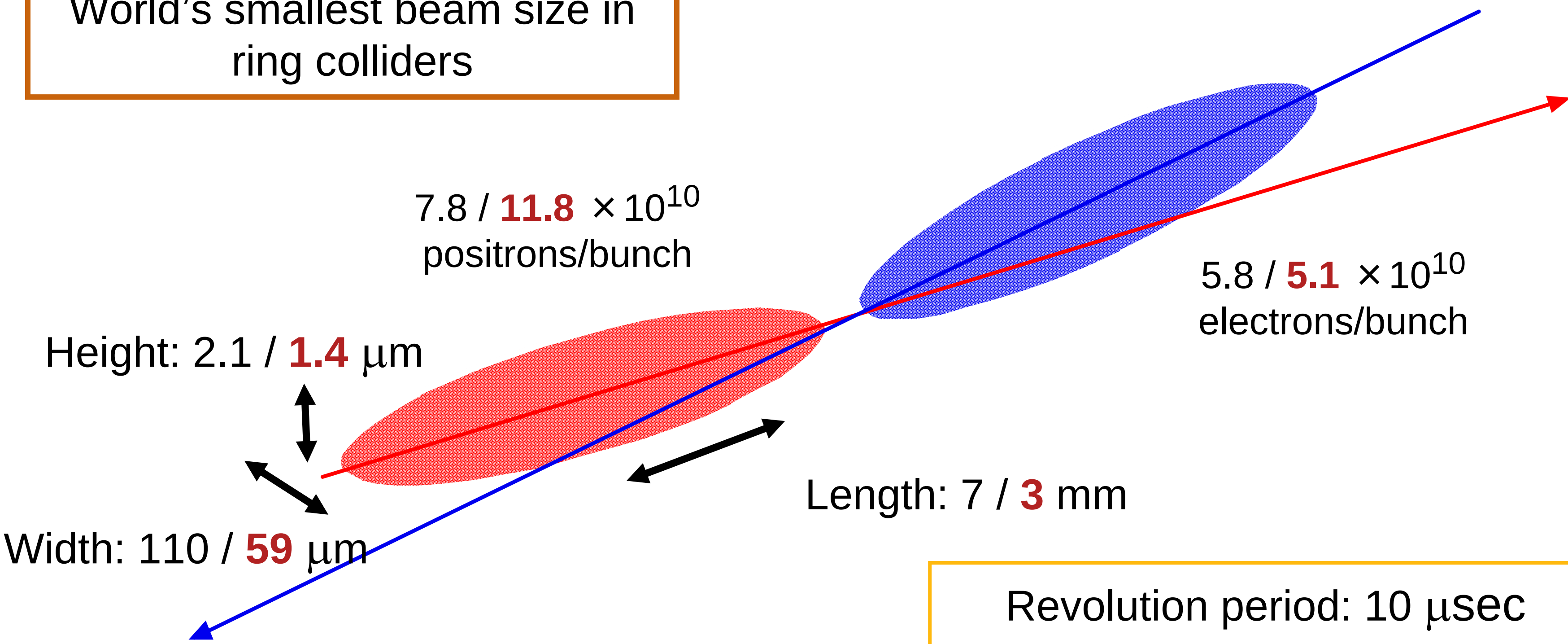
5.2/6.5 mm (KEKB)

→ 3.0/3.0 mm (SuperKEKB)

Colliding Bunches at KEKB / **SuperKEKB**

Hor. Crossing Angle 22 / **30** mrad

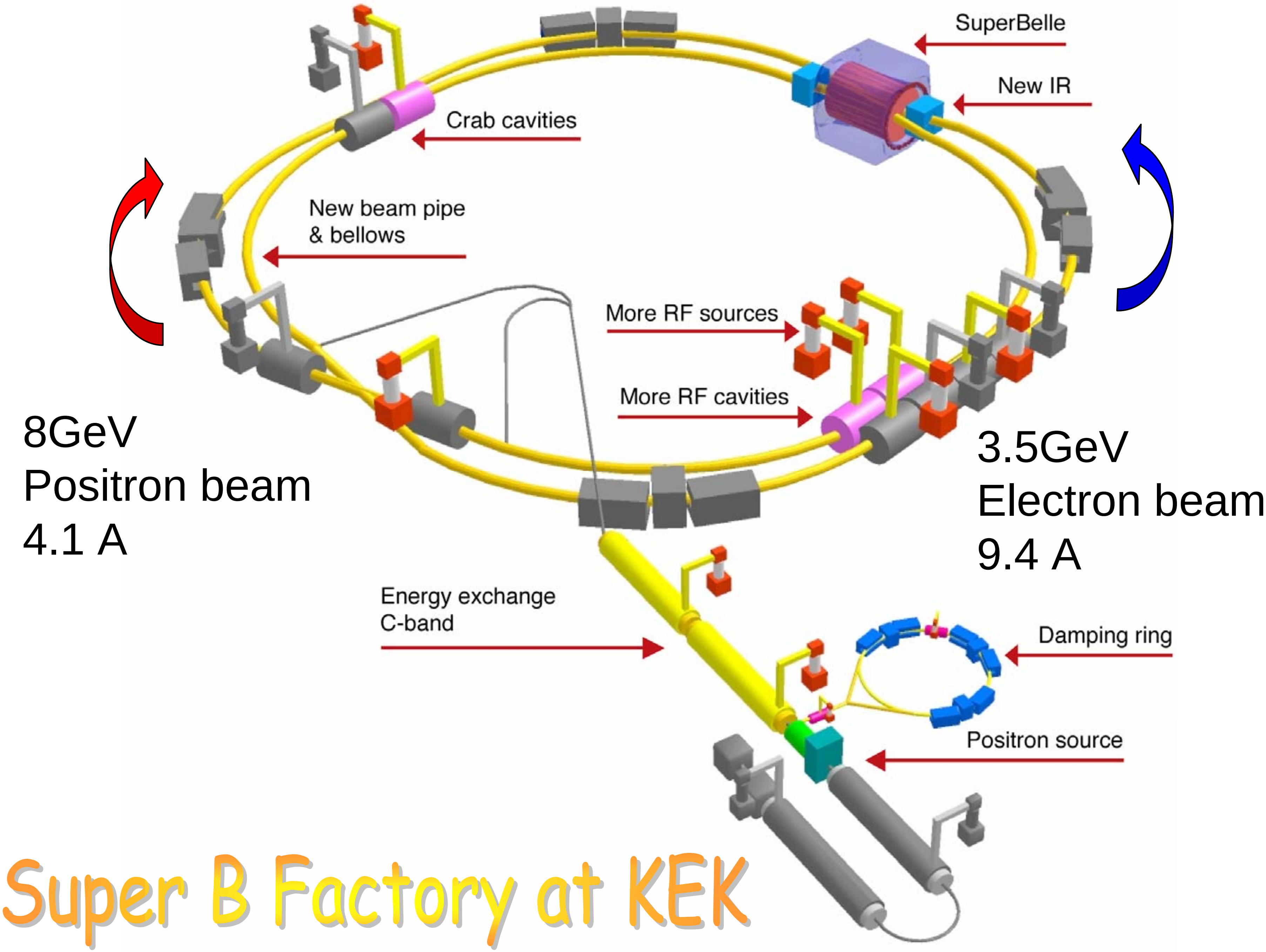
World's smallest beam size in ring colliders



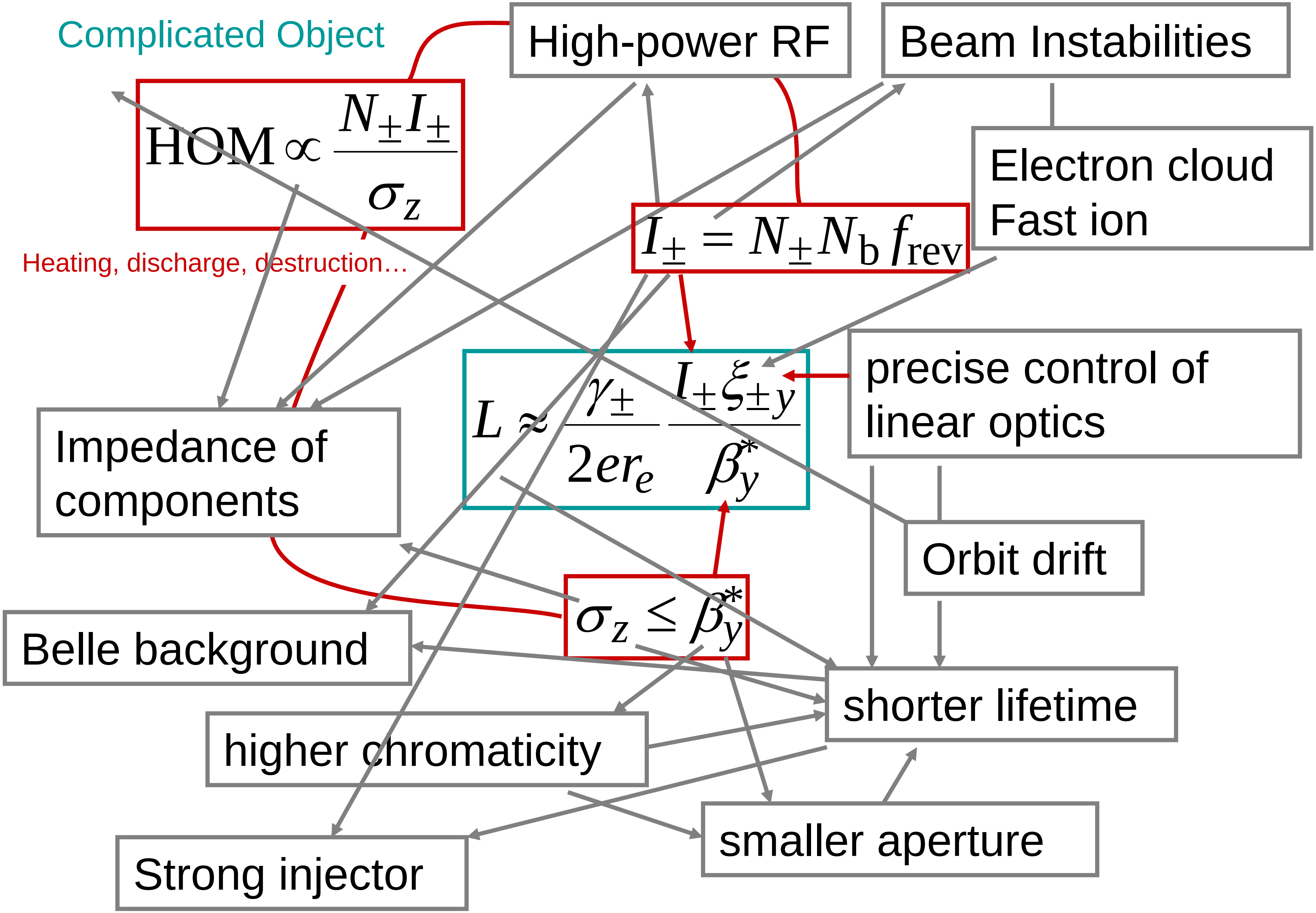
Revolution period: 10 μsec

1293 / **5018** bunches / beam

6 - 8 / **2** ns bunch spacing



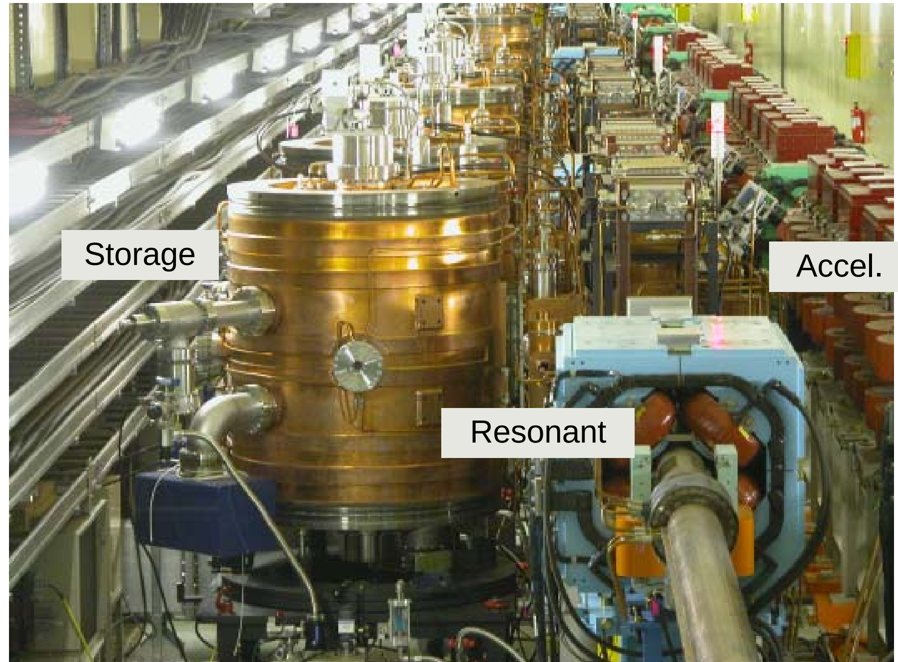
Super B Factory at KEK

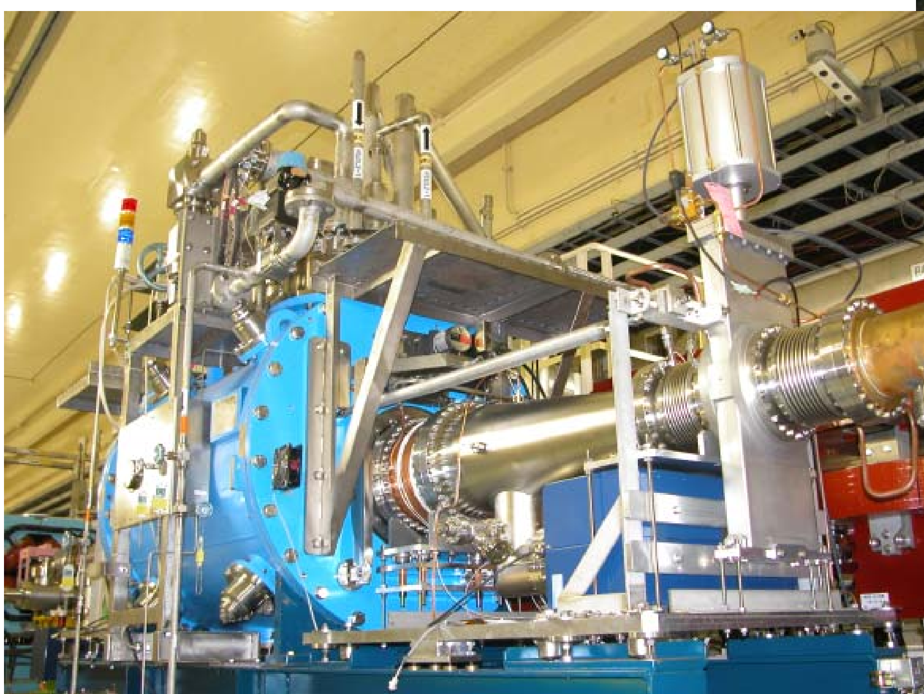


Complicated Object
High-power RF
Beam Instabilities
$\mathrm{HOM} \propto \frac{N_{\pm} I_{\pm}}{\sigma_z}$
Electron cloud
Fast ion
$I_{\pm} = N_{\pm} N_{\mathrm{b}} f_{\mathrm{rev}}$
Heating, discharge, destruction…
$L \approx \frac{\gamma_{\pm}}{2 e r_e} \frac{I_{\pm} \xi_{\pm y}}{\beta_y^*}$
precise control of
linear optics
Impedance of
components
Orbit drift
$\sigma_z \leq \beta_y^*$
Belle background
shorter lifetime
higher chromaticity
smaller aperture
Strong injector

ARES Cavity

- Passive stabilization with huge stored energy.
- Eliminates unnecessary modes by a coupling of 3 cavities.
- Higher order mode dampers and absorbers.
- No need for longitudinal bunch-by-bunch feedback.
- No transverse instability arises from the cavities.





Superconducting Cavity

- World’s highest current, 1.2 A.
- Input coupler has been operated up to 380 kW.
- Ferrite HOM absorber working at 10 kW.

ARES upgrade for SuperKEKB

- **Larger detuning**

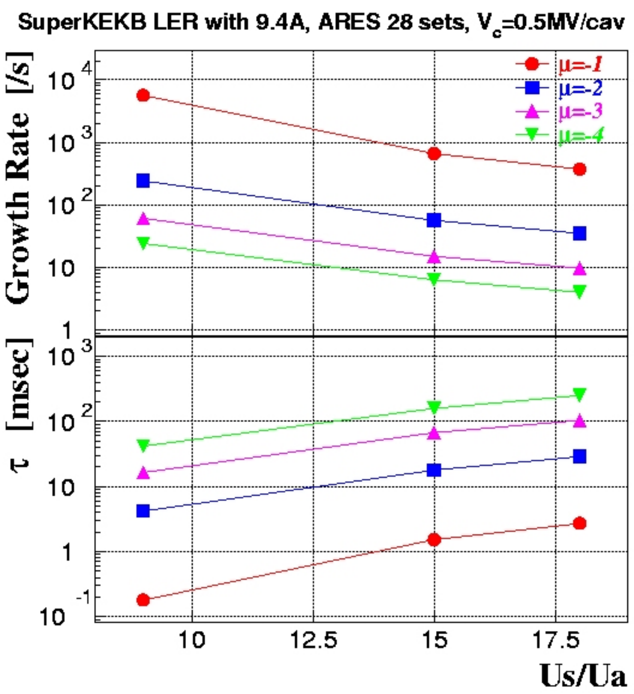
⇒ Change energy ratio : Us/Ua = 9 →15

Small modification on the window size of A-cav

-1 mode growth time :0.3 ms to 1.6 ms.

Then the -1 (and -2) modes related to the fundamental mode will be suppressed by a FB system in the RF control system.

(need bunch-by-bunch FB to suppress ARES HOM & 0/π mode instability)



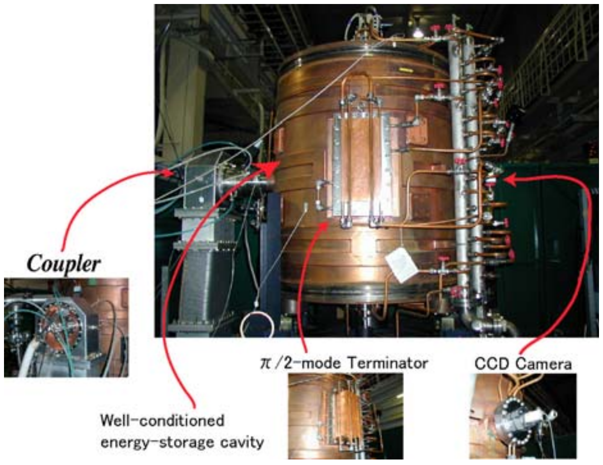
- **Higher HOM power**

Upgrade of HOM damper

- **Higher input RF power**

400 kW/cavity -> 800 kW/cavity

R&D of input coupler using new test-stand.



Talks by Kageyama, Abe

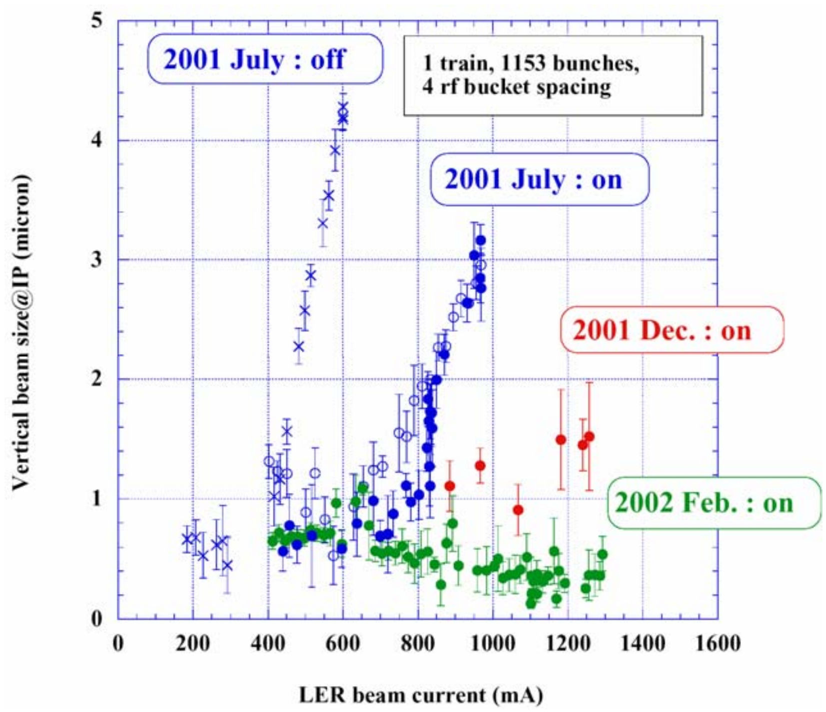
Superconducting Cavity

SuperKEKB challenges:
The expected power load to the HOM absorber is 50 kW/cavity at 4.1 A,
(even) with a larger beam pipe of 220 mmϕ.

HOM damper upgrade may be needed.

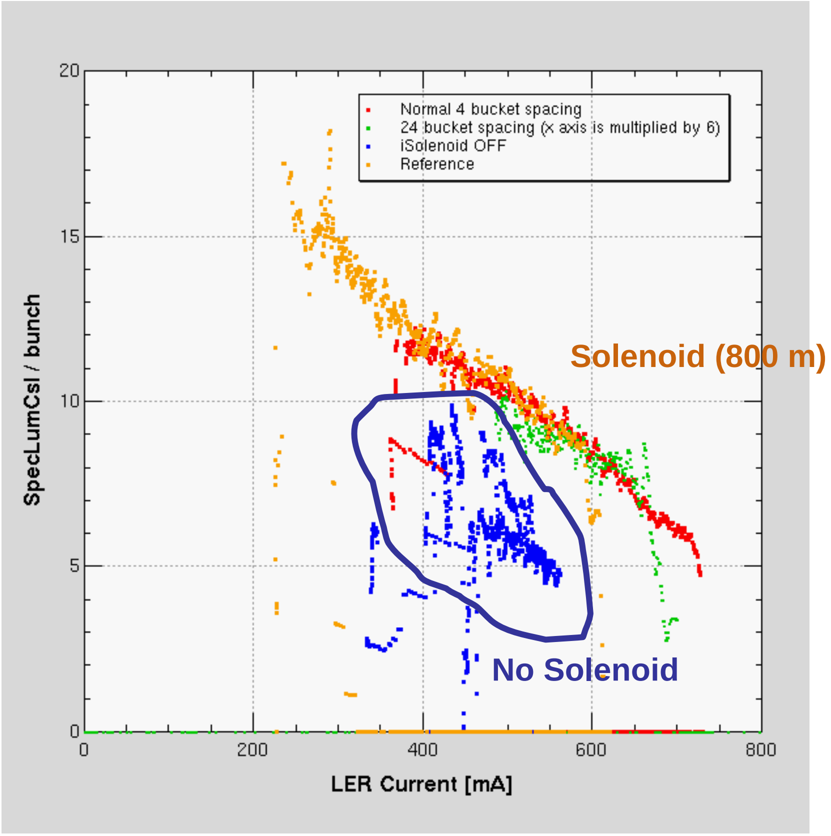
Talk by Mitsunobu

Electron cloud



Blow-up of the vertical beam size in LER has been suppressed by more solenoid windings.

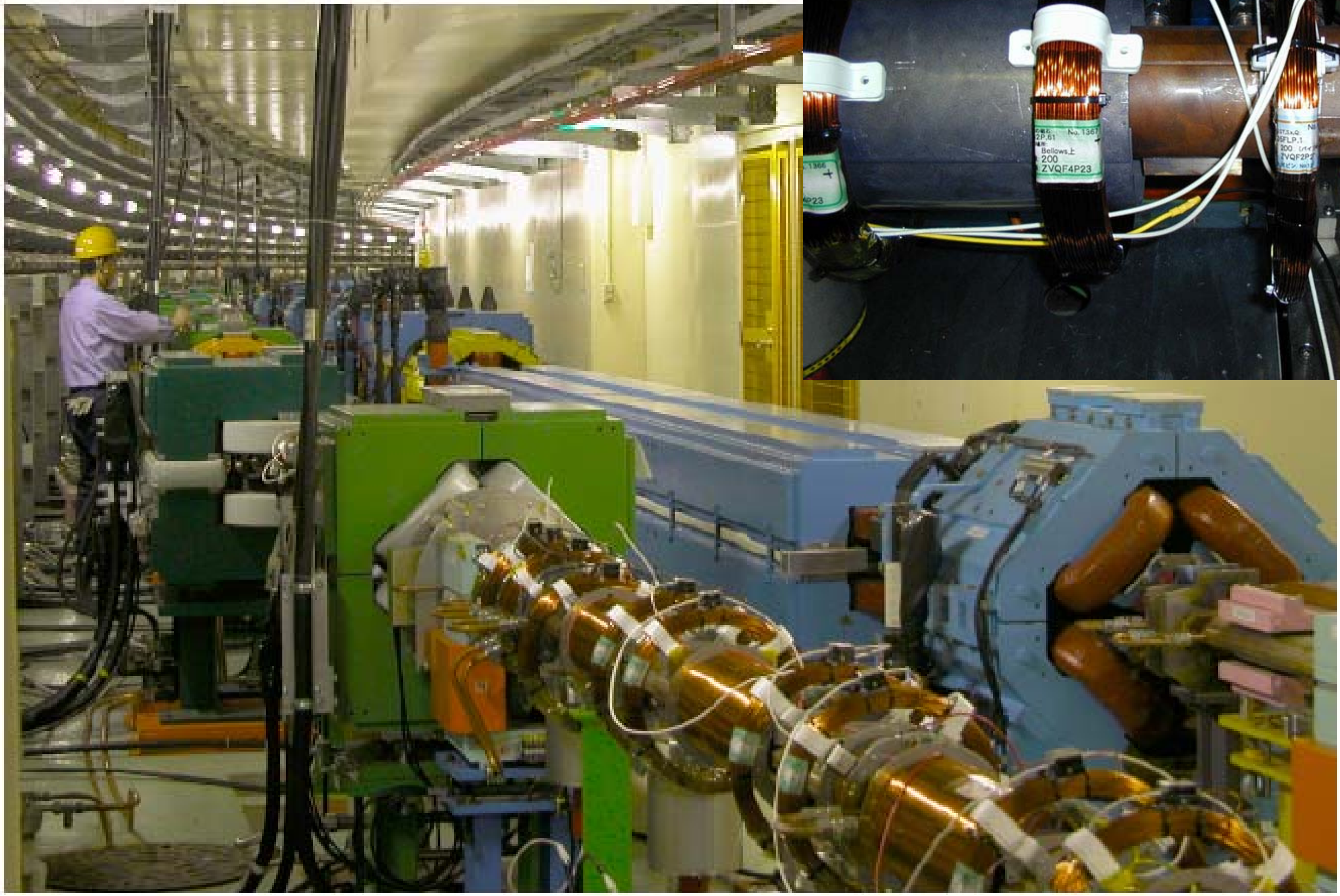
The coverred length of solenoids reached 2,300 m, raised the threshold to 1.8 A.



Specific luminosity vs. LER current.

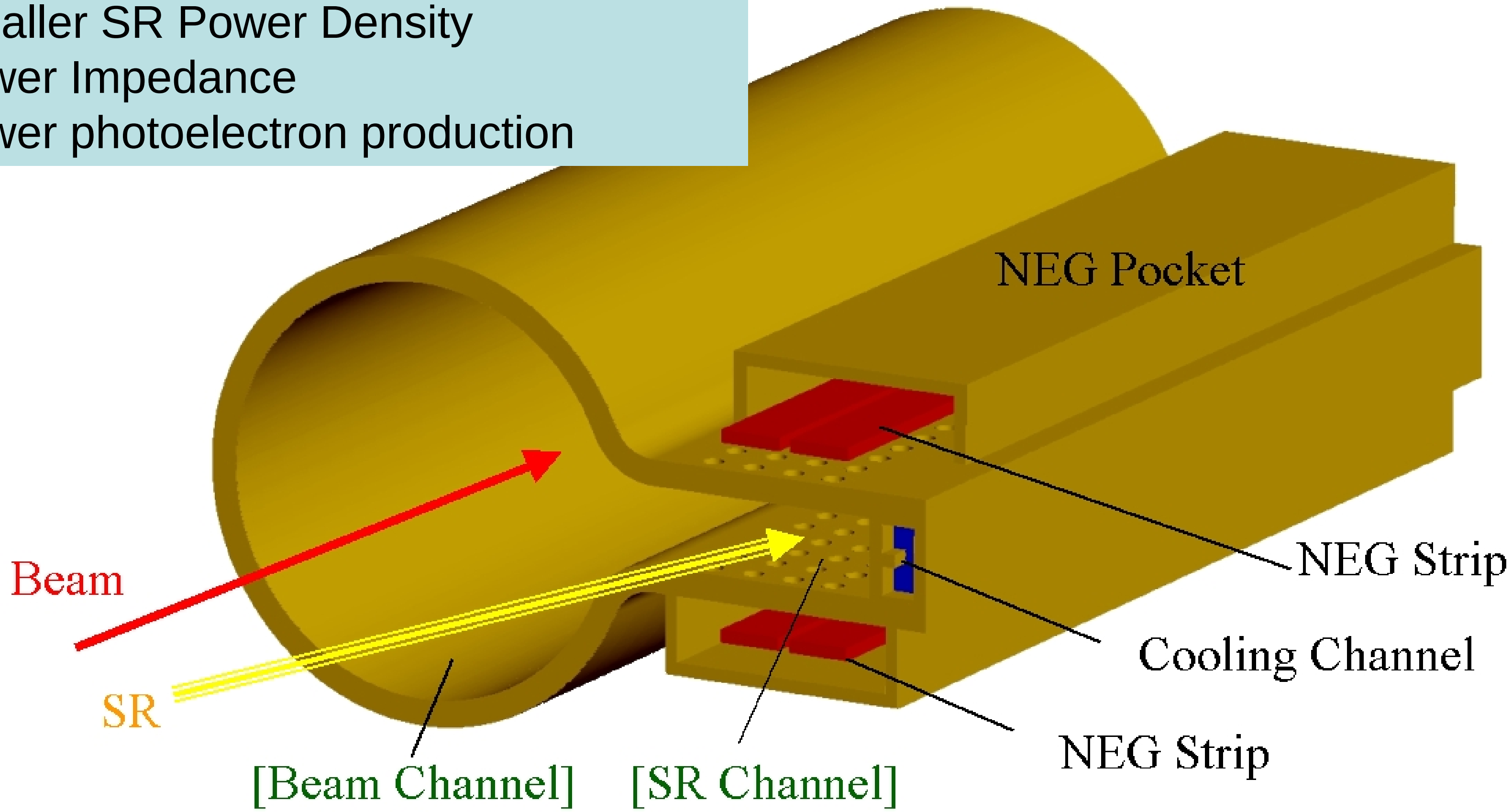
Solenoids are just so effective.

Winding more solenoids in the LER



Vacuum components: Antechamber-type copper duct

Smaller SR Power Density
Lower Impedance
Lower photoelectron production



Prototype ducts were installed in the LER (Jan.2004)

Talk by Suetsugu

Fight for High Current

- High luminosity always requires high stored current.

- The history of KEK was a history of fight against high current, which caused

    Heating of components, by synchrotron light and higher order modes

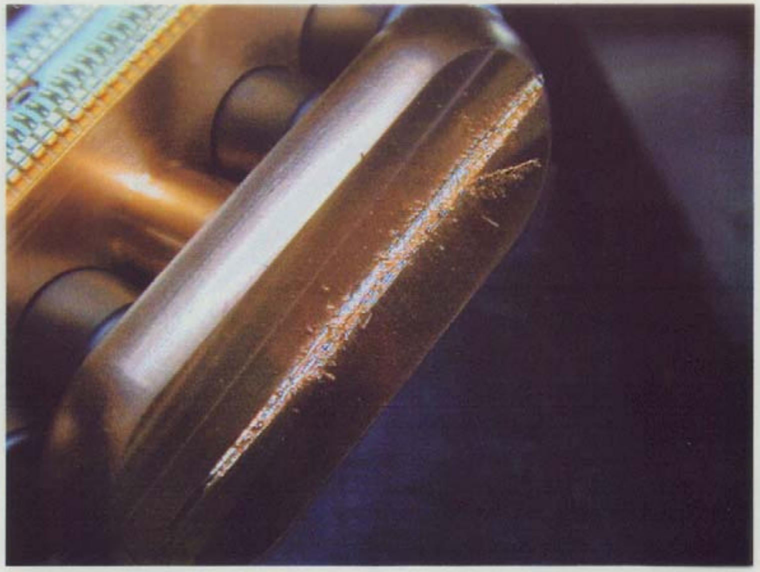
    Discharge and melt down

    Vacuum leak

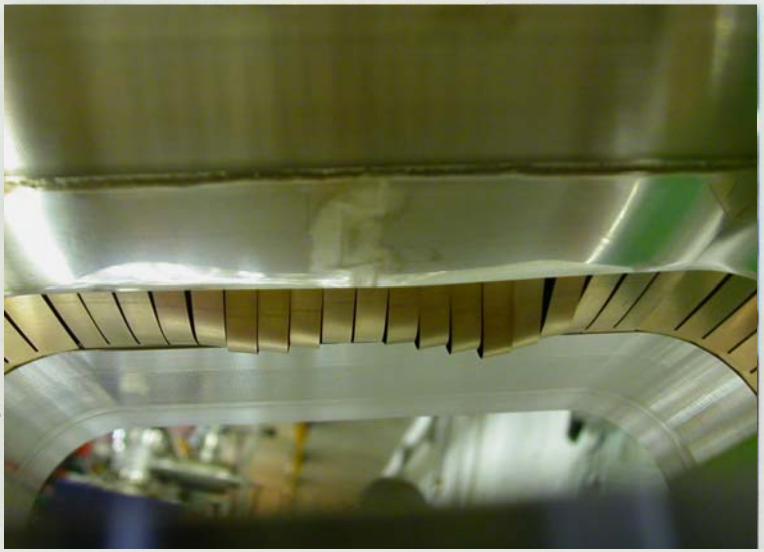
    Damage on Belle detectors

- Endless upgrades of components have been done on vacuum chambers/movable masks/bellows/pumps/abort windows, etc.

- Machine protection system with fast beam abort has been developed to reduce the possible damage.

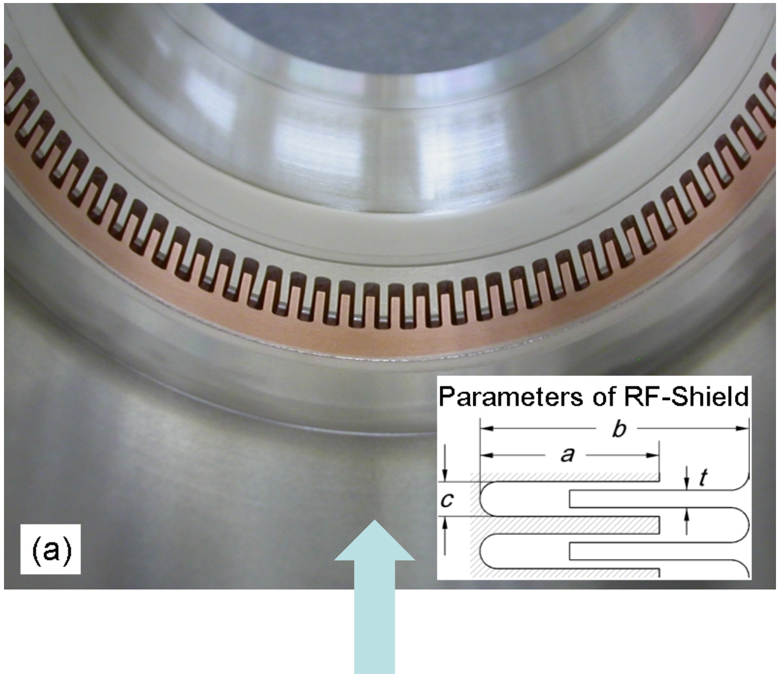


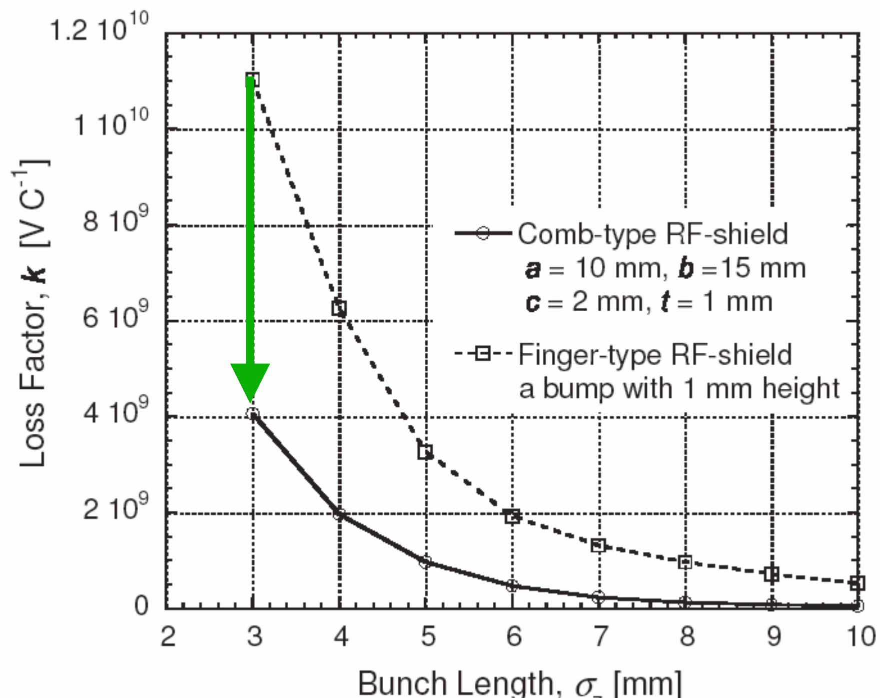
Heavy groove on the surface of a copper movable mask in HER.



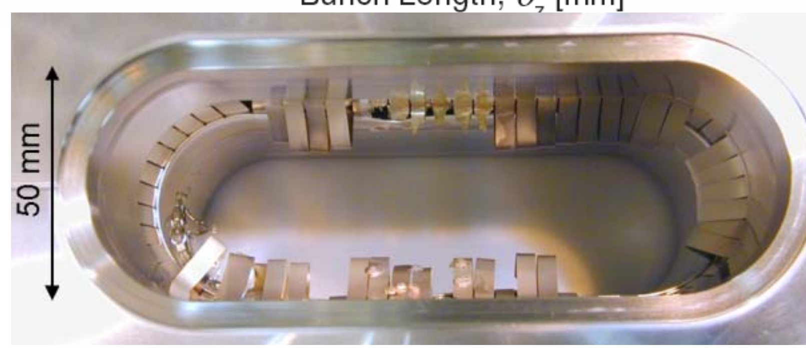
Thermal deformation of the fingers for rf shield of bellows.

Vacuum components:
Bellows chamber with comb type RF-shield





- High thermal strength
- Low impedance
- No sliding contact on the surface facing the beam



Comb-type bellows were installed in the LER (2004).

Talk by Suetsugu

C-Band Klystrons

	S-band	C-band		
Parameters	KEKB	1-st prototype	2m-structure	Unit
total length	2.072	1.082	2.0	m
number of regular cells	54	54	108	
regular cell length (d)	35.0	17.5	17.5	mm
disk thickness (t)	5.0	2.5	2.5	mm
disk iris diameter (2a)	24.95 - 20.90	12.48 - 10.45	14.03 - 10.54	mm
cavity diameter (2b)	83.0 - 82.0	41.5 - 41.0	42.0 - 41.0	mm
group velocity (v_g/c)	1.4	1.9 - 1.0	2.8 - 1.0	%
shunt impedance	57	75 - 85	67 - 85	MΩ/m
Q factor	13700	9690	9700	
RF power in cells	30 - 15	34 - 15	59 - 15	
Field gradient	21	41.2 - 39.0	42.5 - 38.1	
Filling time	462	234	376	
Attenuation constant	0.302	0.434	0.696	

Table 11.3: Accelerating section characteristics

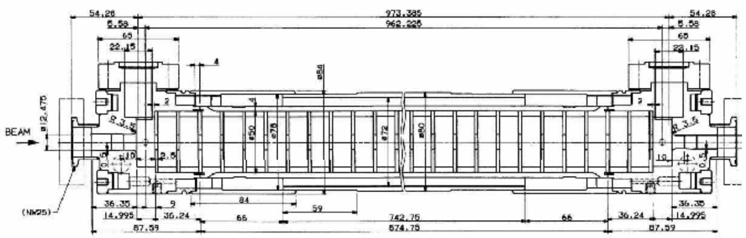
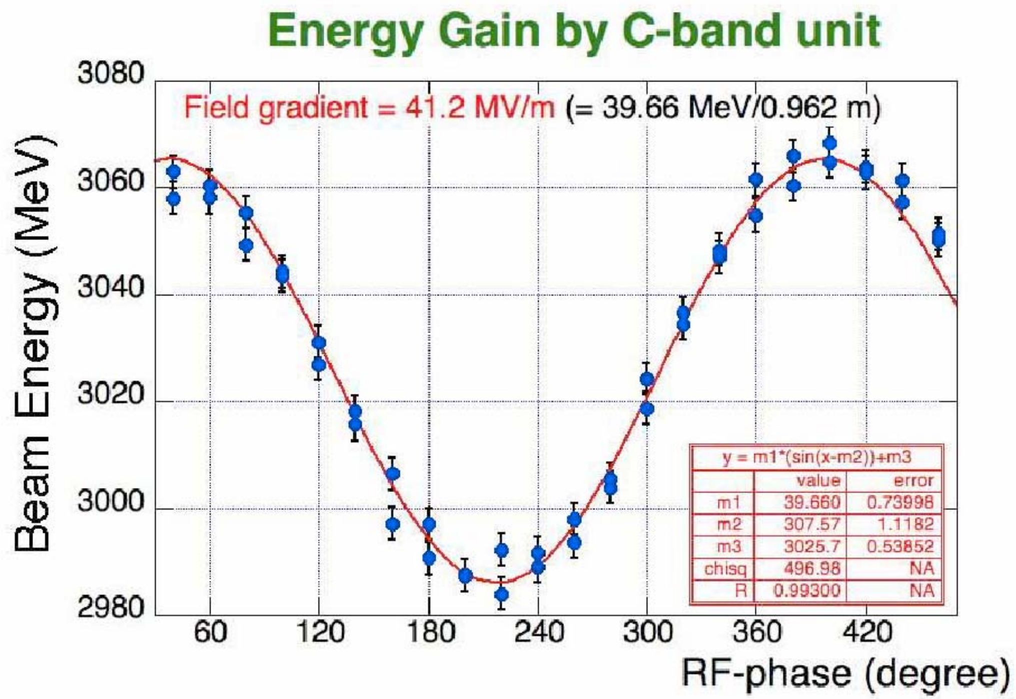


Figure 11.7: C-band 1m-long accelerating section (1-st prototy

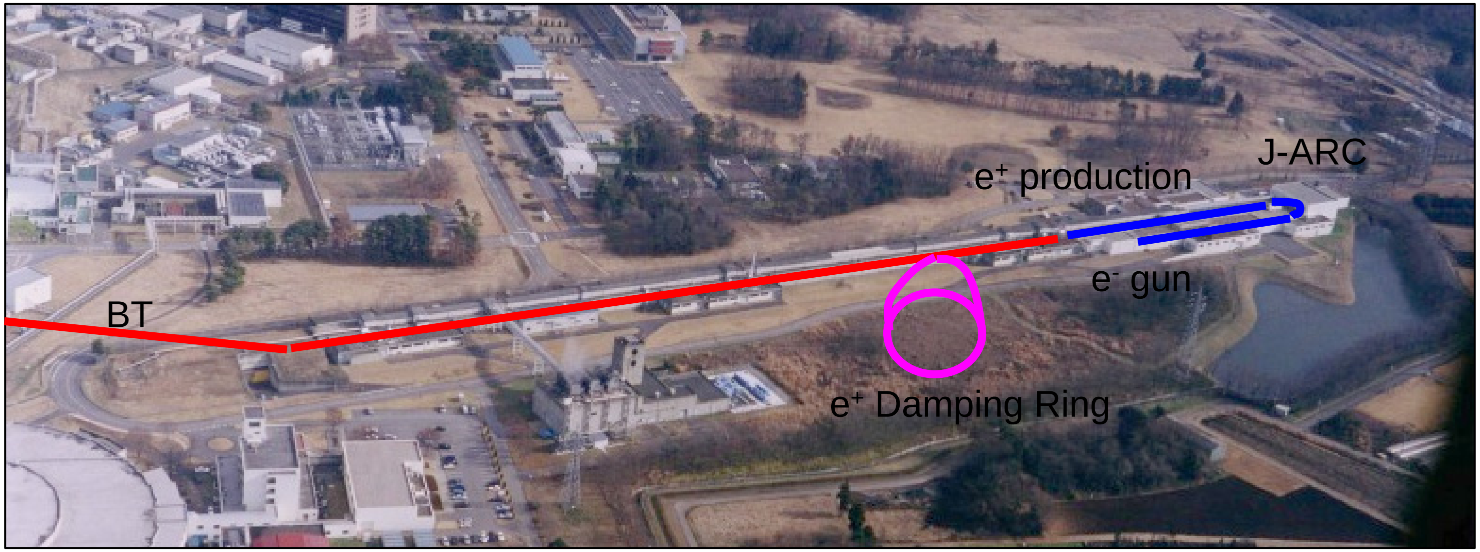
Prototype C-band structure installed and tested at linac using actual beam (2003). Measured field gradient of 41 MV at 43 MW agrees with expectation.



Talk by Kamitani

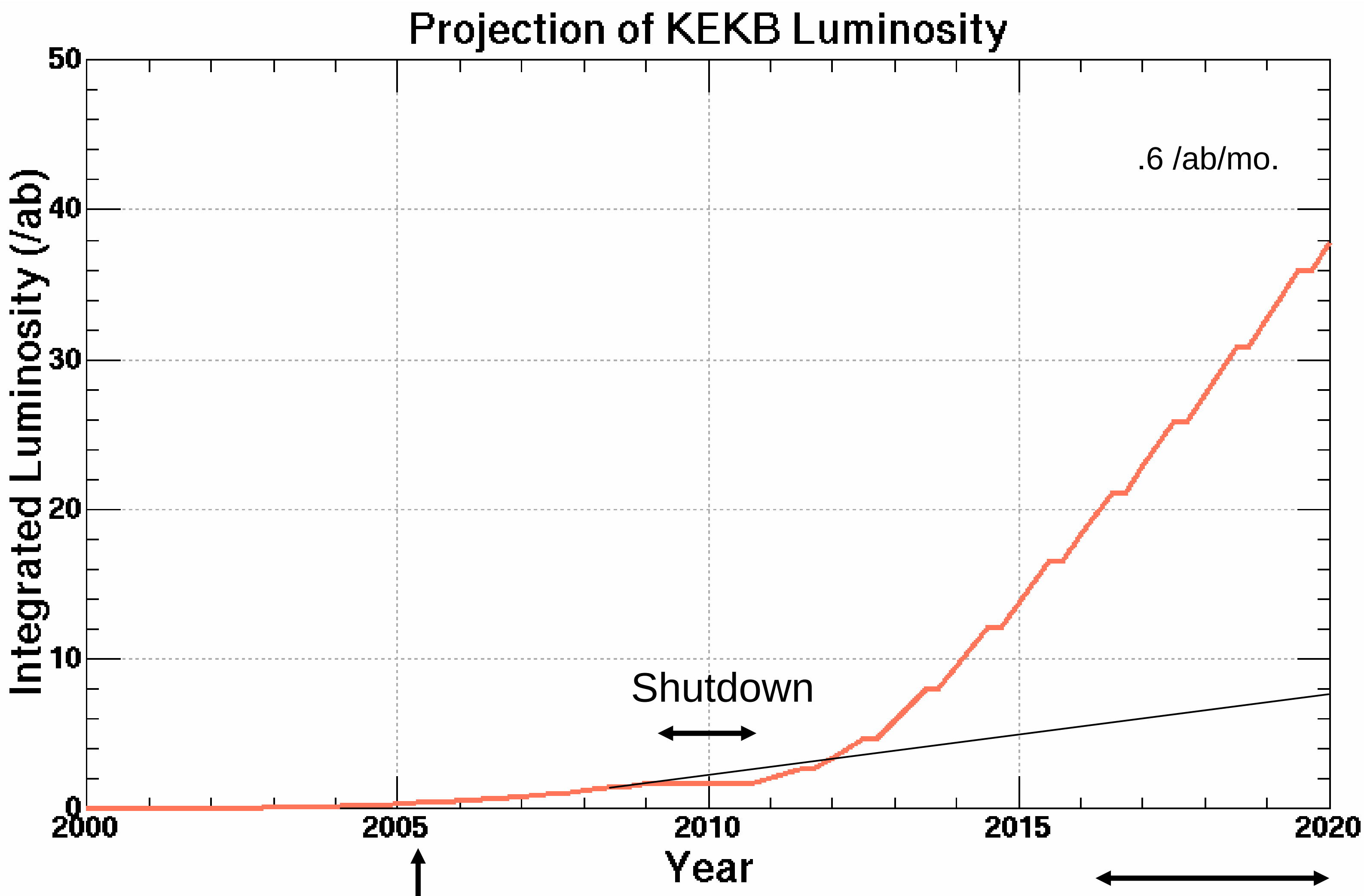
Damping Ring

- Positron emittance needs to be damped, to pass reduced aperture of C-Band section and to meet IR dynamic aperture restrictions.
  - Electron DR may be considered later to reduce injection backgrounds in physics detector, but for now only positron DR considered.
- Damping ring located downstream of positron target, before C-Band accelerating section.



Talk by Kikuchi

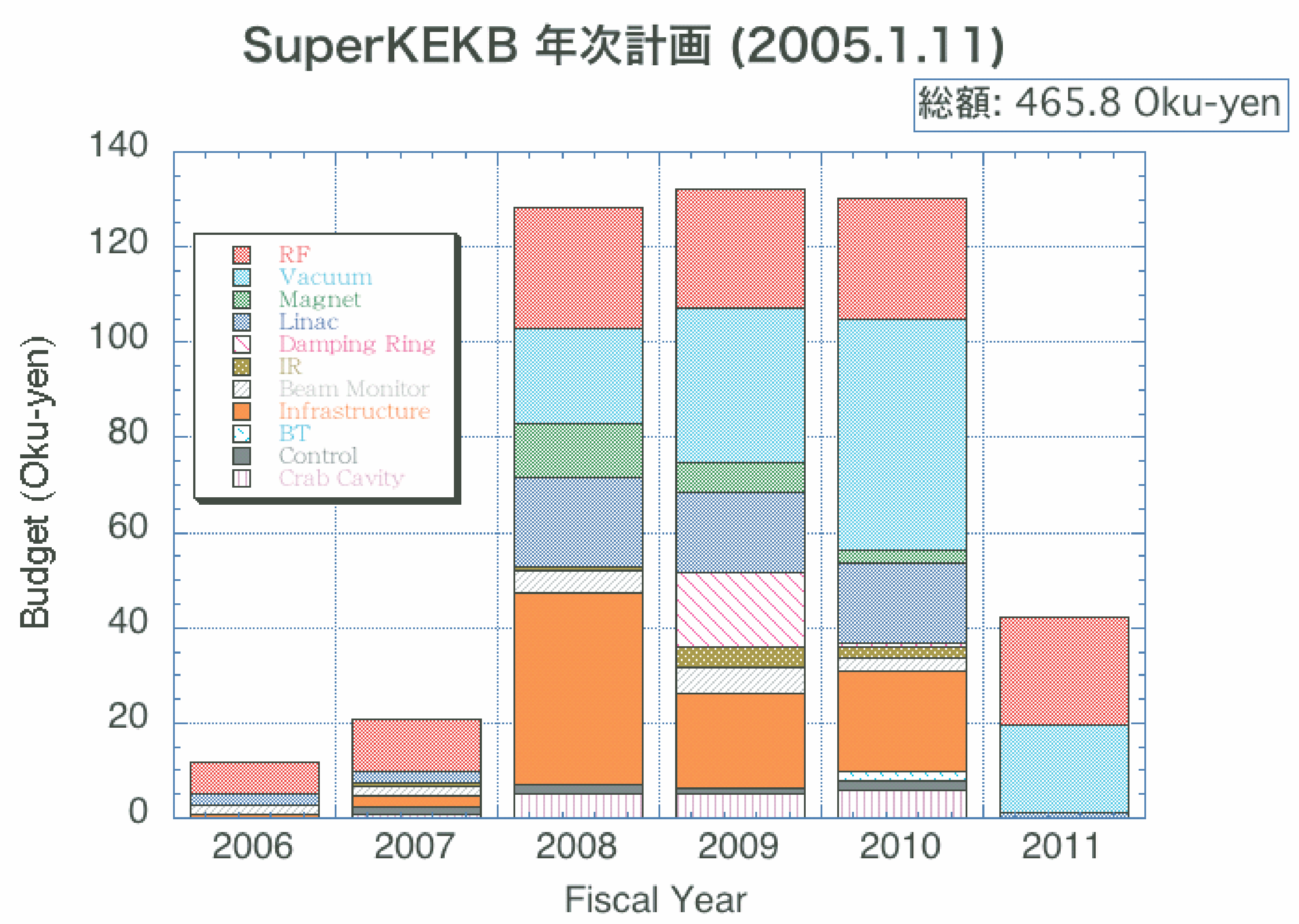
How long should we run?



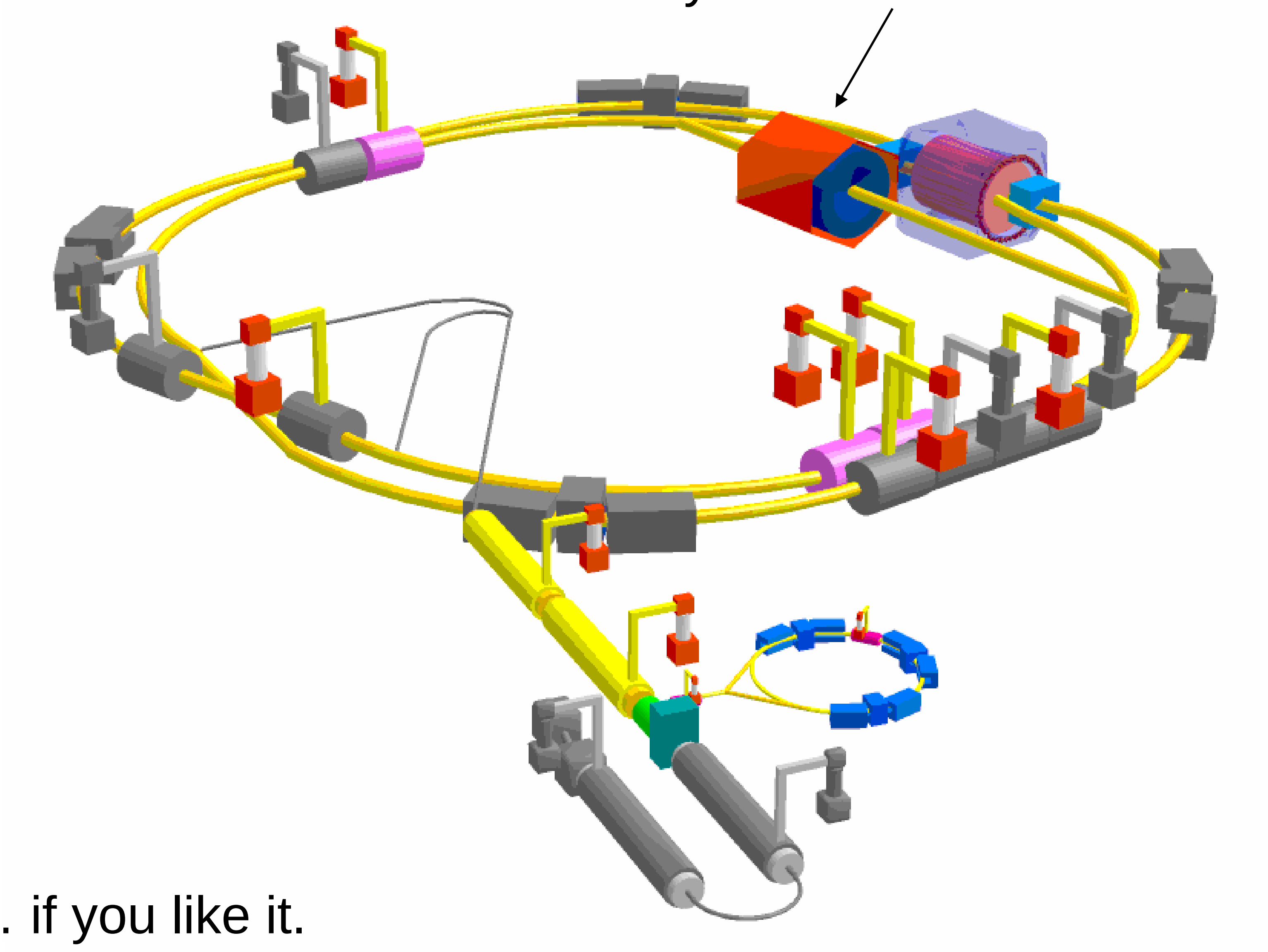
Crab

Data doubling period > 4 yrs = unhealthy

How much do we need?



We may invite another detector.



… if you like it.

Summary

- KEKB has been the front runner on the luminosity frontier.
- 1 /ab will be reached around 2007.
- A technically feasible design of SuperKEKB for $2.5 \times 10^{35} cm^{-2} s^{-1}$ has been done.

Luminosity*:

$$L = \frac{N_+ N_- f}{4\pi\sigma_x^* \sigma_y^*} R_L$$

Geometrical reduction factors (σ_z, β^*, θ_x, ε_x, …)

Beam-beam tune shift parameter*:

$$\xi_{\pm x,y} = \frac{r_e}{2\pi\gamma_\pm} \frac{N_\mp \beta_{x,y}^*}{\sigma_{x,y}^* \left(\sigma_x^* + \sigma_y^*\right)} R_{x,y}$$

Beam current:

$$I_\pm = N_\pm e f$$

Luminosity rewritten:

$$L = \frac{\gamma_\pm}{2 e r_e} \left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right) \frac{I_\pm \xi_{\pm y}}{\beta_y^*} \left(\frac{R_L}{R_y}\right)$$

$$L \approx \frac{\gamma_\pm}{2 e r_e} \frac{I_\pm \xi_{\pm y}}{\beta_y^*}$$

(flat beam, short bunch)

*Assume both beams have the same sizes and β^*s.

A jacket-type magnetic shield for the Crab Cavity.

The magnetic shield is made by 3mm thick permalloy sheet by spinning and forming. The cell and beam pipe parts can divide into two peaces and assemble around the crab cavity.

Parameters for SuperKEKB

		bare lattice	with beam-beam	unit
Beam current (LER/HER)	I	9.4/4.1	9.4/4.1	A
Beam energy (LER/HER)	E	3.5/8.0	3.5/8.0	GeV
Emittance	ε_x	24	77	nm
Horizontal beta at IP	β_x*	20	4.5	cm
Vertical beta at IP	β_y*	3	2.3	mm
Horizontal beam size	σ_x*	69	59	μm
Vertical beam size	σ_y*	0.7	1.4	μm
Beam size ratio	$r = \sigma_y^*/\sigma_x^*$	1	2.4	%
Crossing angle	θ_x	0	0	mrad
Luminosity reduction	R_L	0.86	0.81	
ξ_x reduction	$R_{\xi x}$	0.99	0.97	
ξ_y reduction	$R_{\xi y}$	1.11	1.17	
Horizontal beam-beam	ξ_x	0.137	0.041	
Vertical beam-beam	ξ_y	0.218	0.108	
Reduction ratio	$R_L/R_{\xi y}$	0.78	0.70	
Luminosity	L	4×10^{35}	2.4×10^{35}	$cm^{-2}s^{-1}$

Machine Parameters (June 3, 2004)

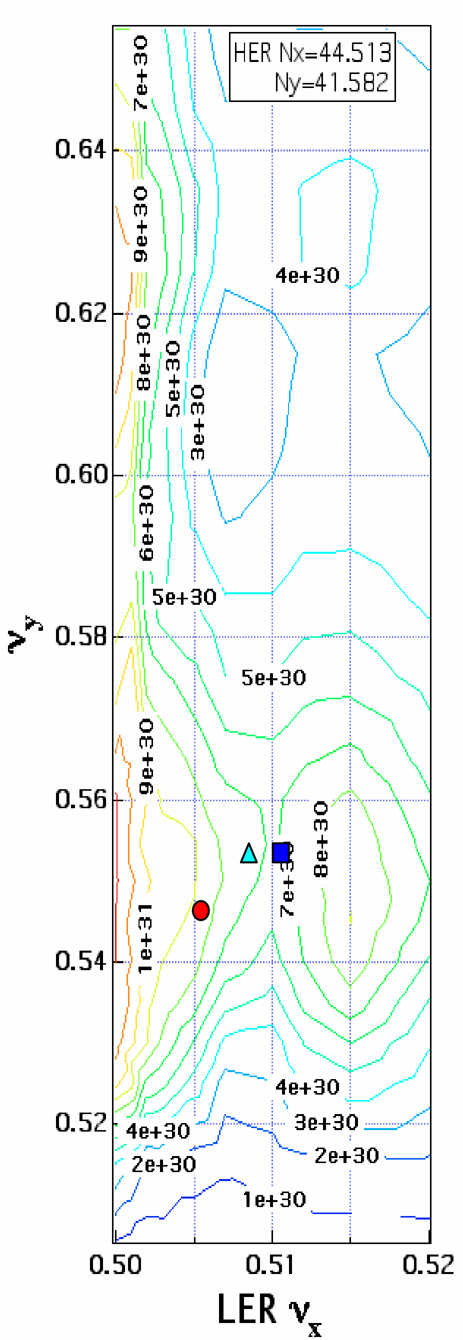
Table 1: Machine parameters of KEK, comparing to the design values.

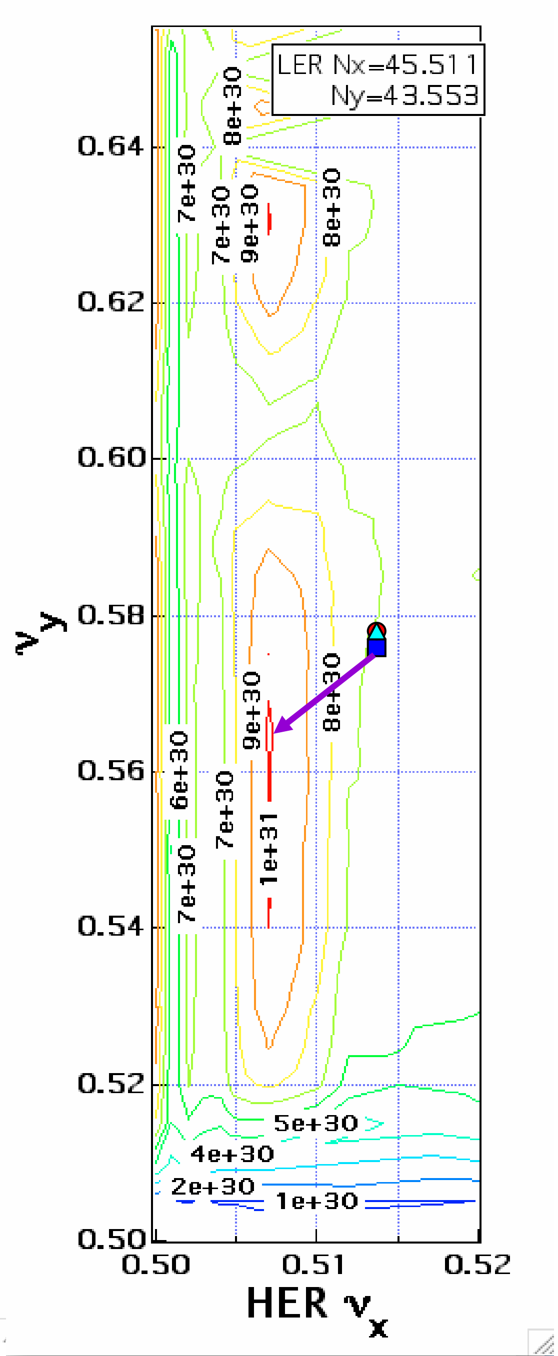
Date	6/7/2004 LER	6/7/2004 HER	Design LER	Design HER	
Current	1.58	1.19	2.6	1.1	A
Bunches	1289		5000		
Bunch current	1.2	0.92	0.52	0.22	mA
Spacing	1.8-2.4		0.6		m
Emittance ε_x	18	24	18	18	nm
β_x^*	59	56	33	33	cm
β_y^*	0.52	0.65	1	1	cm
Hor. Size @ IP	103	116	77	77	μm
Ver. Size @ IP	2.1	2.1	1.9	1.9	μm
Bunch length	8	6	4	4	mm
Beam-beam ξ_x	.107	.075	.039	.039	
Beam-beam ξ_y	.070	.057	.052	.052	
Ave. pressure	80	130	100	100	nPa
Lifetime	160	220	220	440	min.
Luminosity	13.92		10		/nb/s
$\int$Lum/day	944		~600		/pb
$\int$Lum/7 days	5.94		–		/fb
$\int$Lum/30 days	24.00		–		/fb
$\int$Lum, total	271/5 years		100/3 years		/fb

Machine parameters

Parameters		LER/HER	Unit
Beam energy	E	3.5/8.0	GeV
Beam current	I	9.4/4.1	A
Particles/bunch	N	1.18 ´10^{11}/ 5.13 ´10^{10}	
Number of bunches	n_b	5018	
Circumference	C	3016.26	m
Bunch spacing	σ_b	0.6	m
Horizontal β at IP	β_x	200	mm
Vertical β at IP	β_y	3	mm
Bunch length	σ_z	3	mm
Radiation loss	U_0	1.23/3.48	MeV/m
Horizontal beam-beam	ξ_x	0.137	
Vertical beam-beam	ξ_y	0.14	

Talk by Ohnishi





Tune Survey

Simulation by M. Tawada

- ■ 10/29/2002
- ▲ 4/2/2003
- ● 5/9/2003

Reducing LER ν_x from 0.510 to 0.506 increased the luminosity by 20% in 2003, as the simulation predicted.

20% more luminosity is expected by reducing HER ν_x from 0.513 to 0.507.