KEKB Status and Upgrade Plan with Crab Crossing

Second Electron-Ion Collider Workshop

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Mika Masuzawa, KEK

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1. Introduction

Beam energy

– 8GeV (electron, “HER”)

– 3.5GeV (positron, “ LER”)

Circumference

– 3016 m

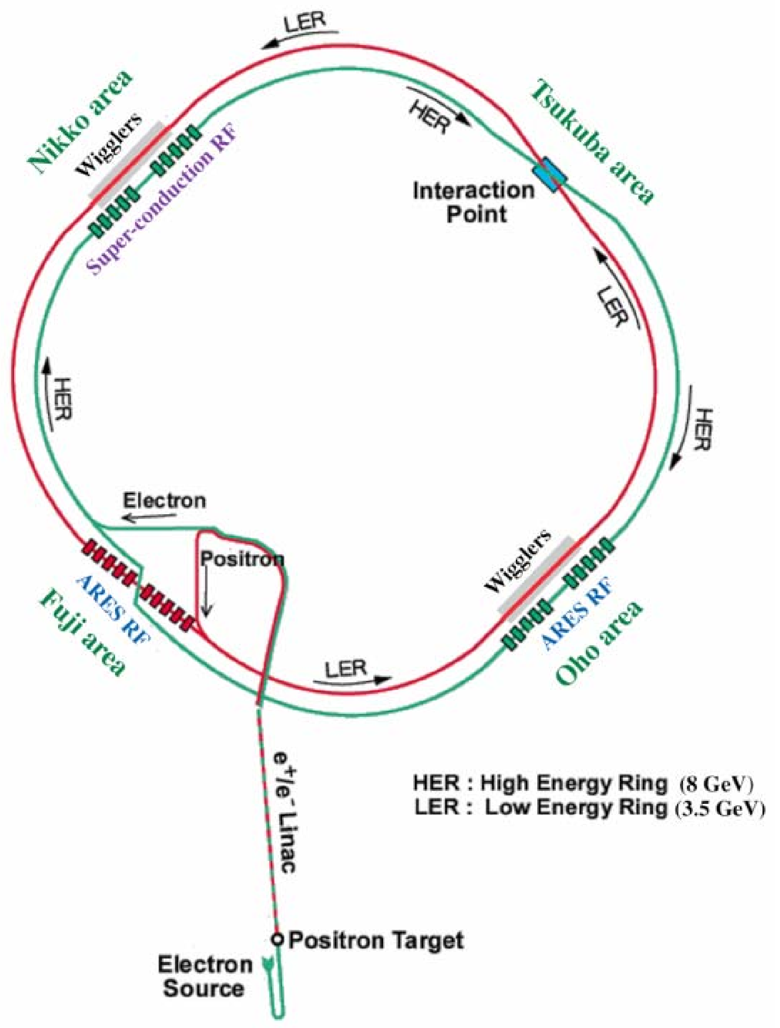
– Use TRISTAN tunnel

RF system

– f_{RF} ~ 509MHz

– ARES (LER)

– ARES+SCC (HER)



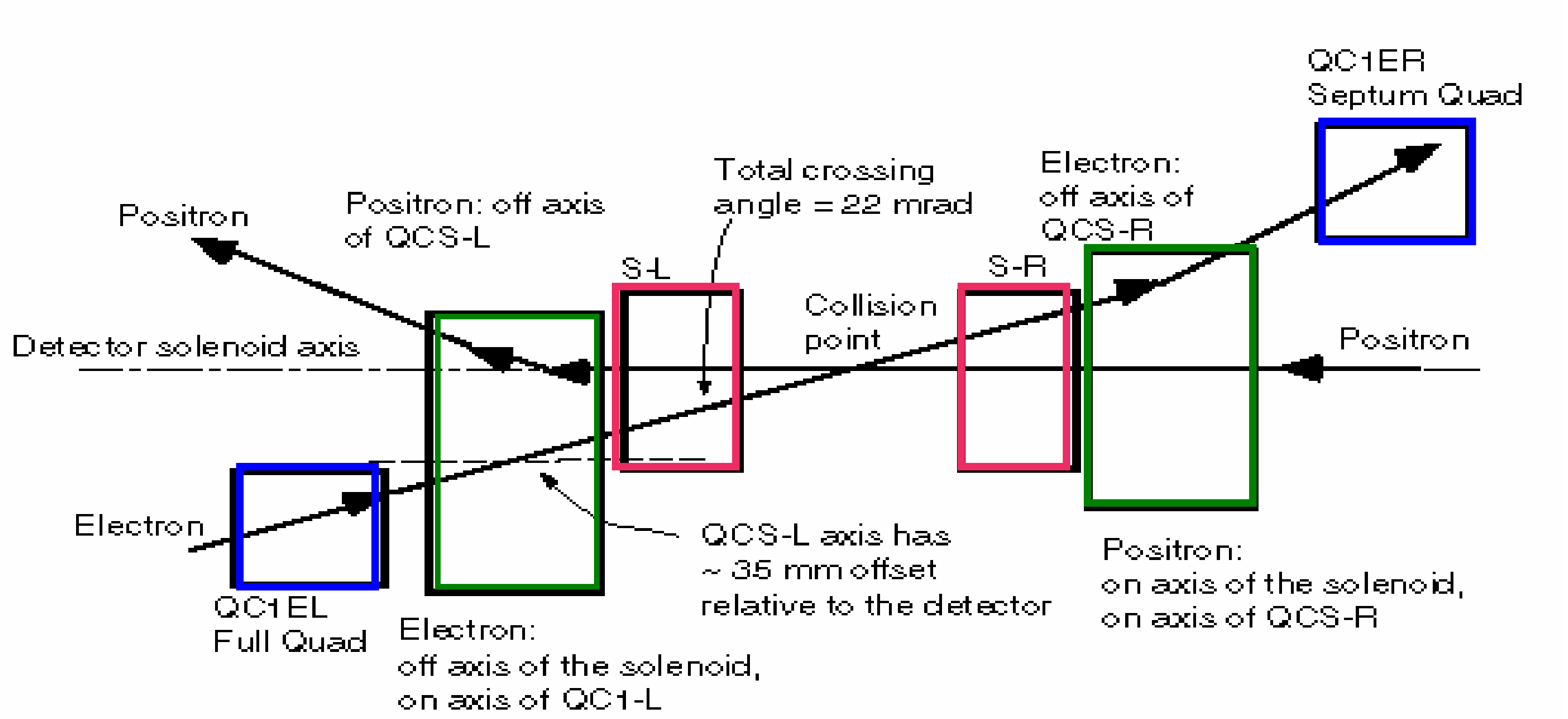
The construction of KEKB began in 1994, and was completed in November 1998. Commissioning started in Dec.1998.

Machine Parameters (12/18/2003)

Ring	LER	HER
Horizontal Emittance (nm)	18 (18)	24 (18)
Beam Current (mA)	1503 (2600)	1132 (1100)
Number of bunches	1281 (~5000)	
Bunch Current (mA)	1.17 (0.52)	0.884 (0.22)
Number of Bunch Trains	1	
Horizontal Beam Size@IP(μm) σ^*_x	103	116
Vertical Beam Size@IP(μm) σ^*_y	2.3	2.3
Emittance Ratio $\varepsilon_y/\varepsilon_x$	5.5	3.4
Beta function@IP β_x*(cm)/β_y*(cm)	59/0.58 (33/1)	56/0.7 (33/1)
Beam-beam parameters ξ_x/ξ_y	0.104/0.069 (0.039/0.052)	0.071/0.053 (0.039/0.052)
Beam lifetime at collision (minutes)	125 at 1503mA	216 at 1132 mA
Peak luminosity (/nb/s)	11.6 (10)	

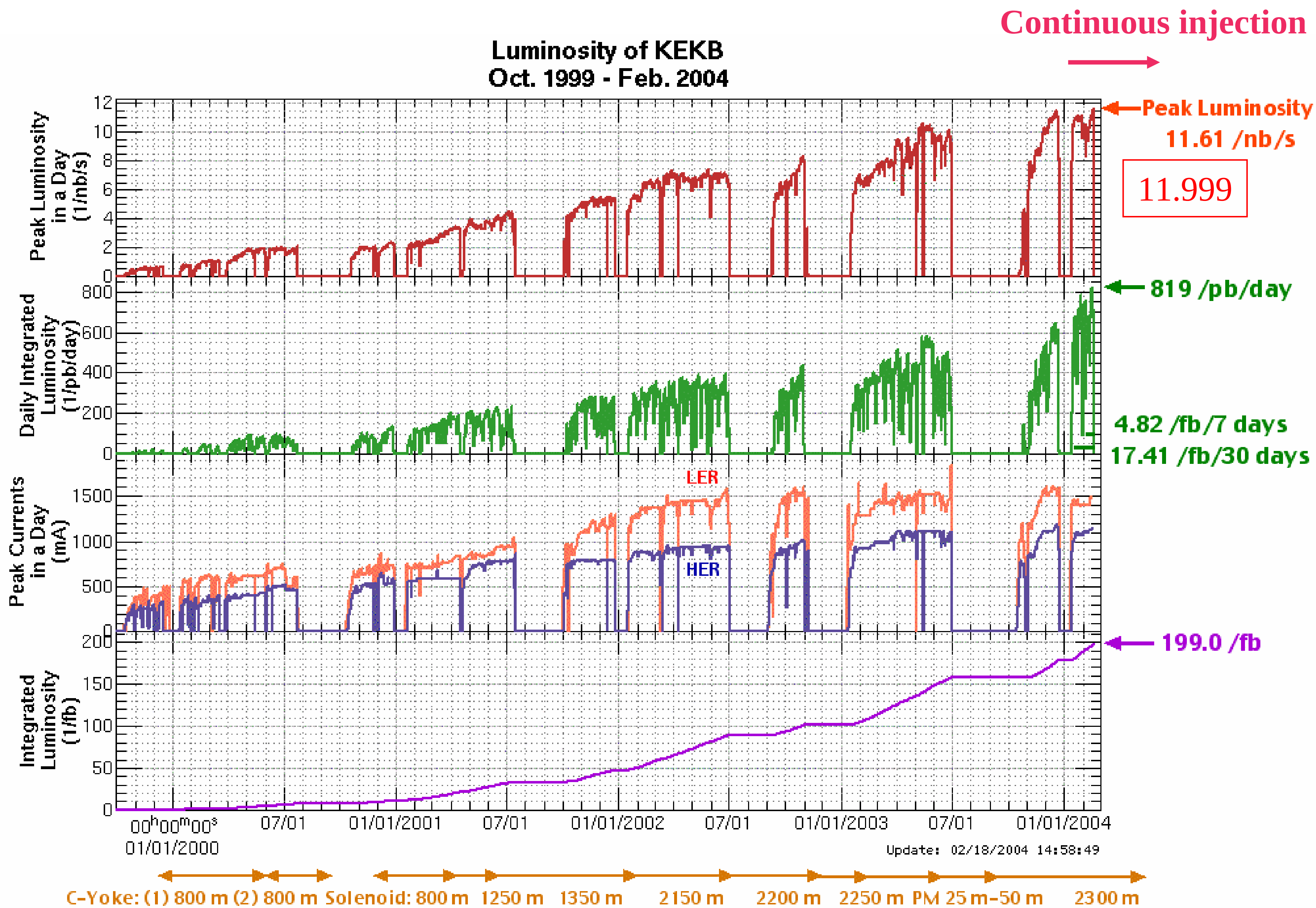
( ) Design values

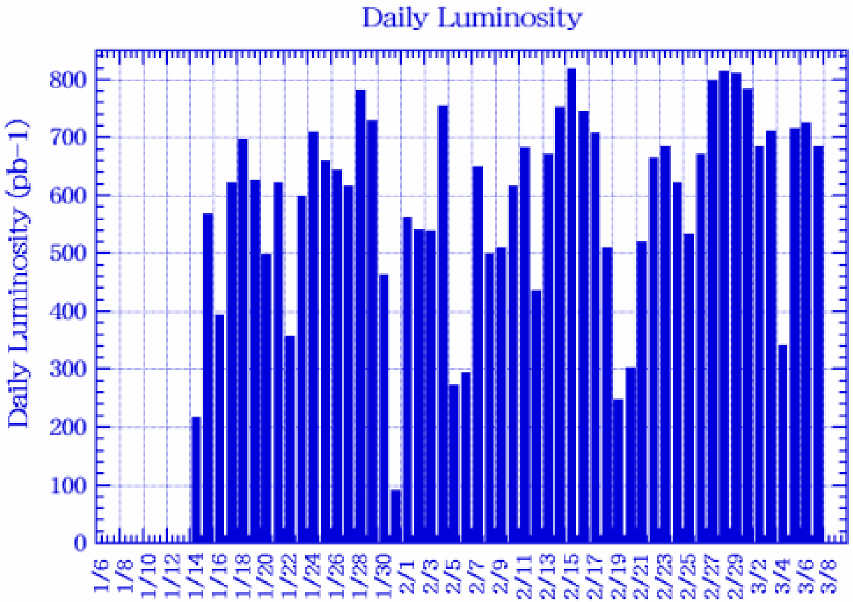
IR

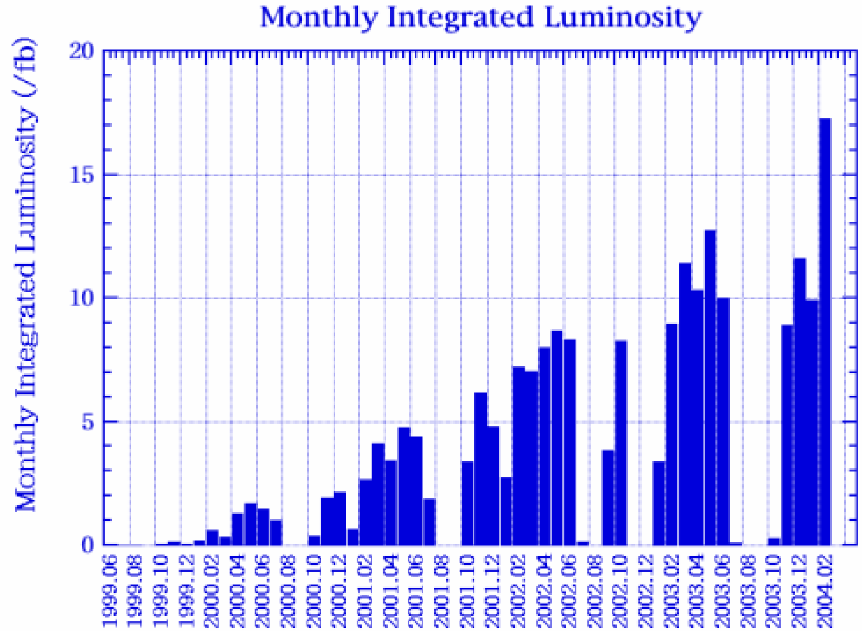


- Vertical focusing by a pair of **superconducting Q-magnet (QCSL/QCSR)**.
- Extra vertical focusing by **QC1L/R** for the electron beam.
- One beam must go off axis due to the finite crossing angle at the IP.
- To minimize the flux of SR through the IP, the incoming positron (electron) beam orbit is set on the axis of QCSL (QCSR).
- **Superconducting solenoid magnets SL/R** used for compensating the detector solenoid field.

2. Machine Performance




Daily Luminosity
Daily Luminosity (pb−1)
0
100
200
300
400
500
600
700
800
1/6
1/8
1/10
1/12
1/14
1/16
1/18
1/20
1/22
1/24
1/26
1/28
1/30
2/1
2/3
2/5
2/7
2/9
2/11
2/13
2/15
2/17
2/19
2/21
2/23
2/25
2/27
2/29
3/2
3/4
3/6
3/8


Monthly Integrated Luminosity
Monthly Integrated Luminosity (/fb)
0
5
10
15
20
1999.06
1999.08
1999.10
1999.12
2000.02
2000.04
2000.06
2000.08
2000.10
2000.12
2001.02
2001.04
2001.06
2001.08
2001.10
2001.12
2002.02
2002.04
2002.06
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2002.10
2002.12
2003.02
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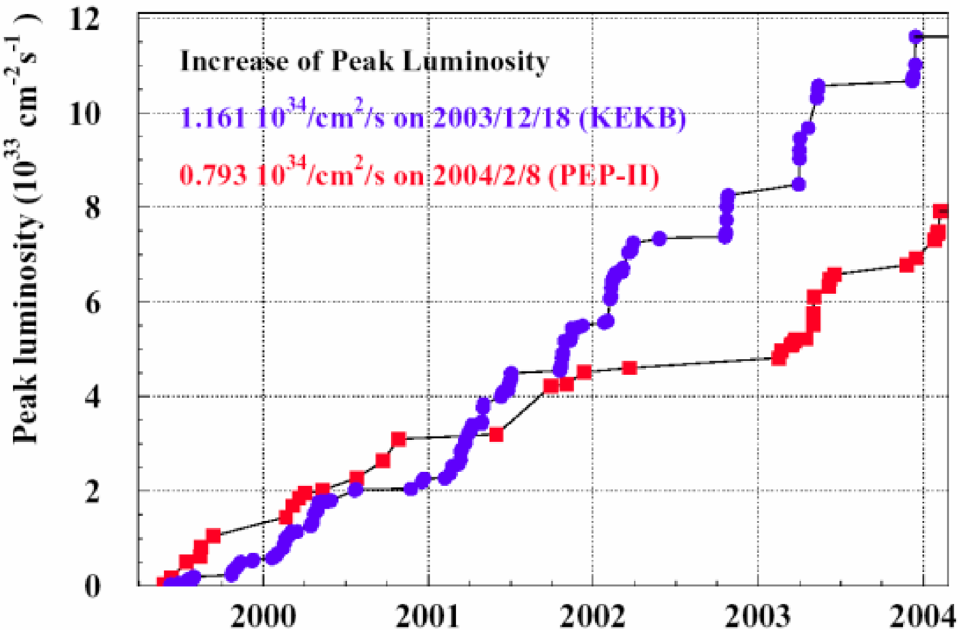
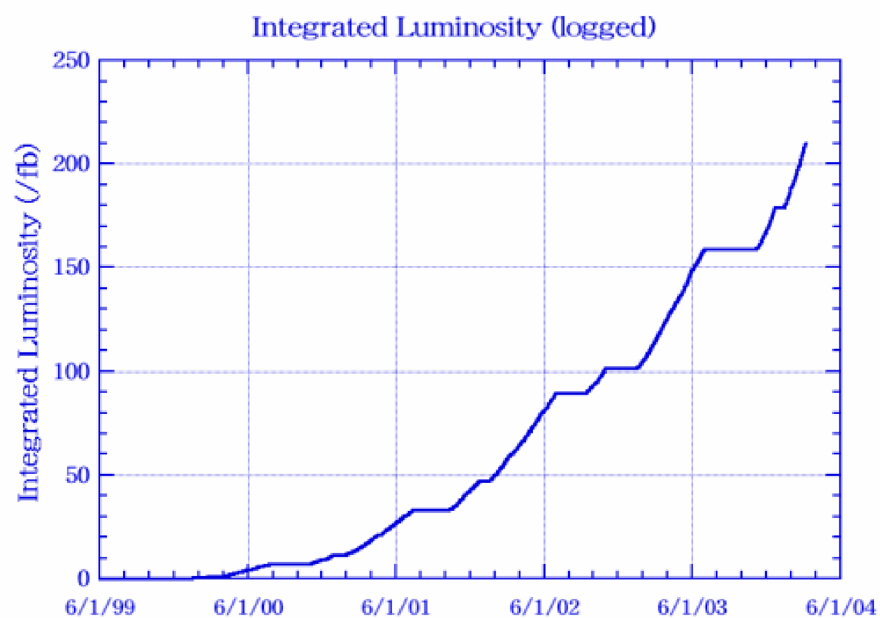
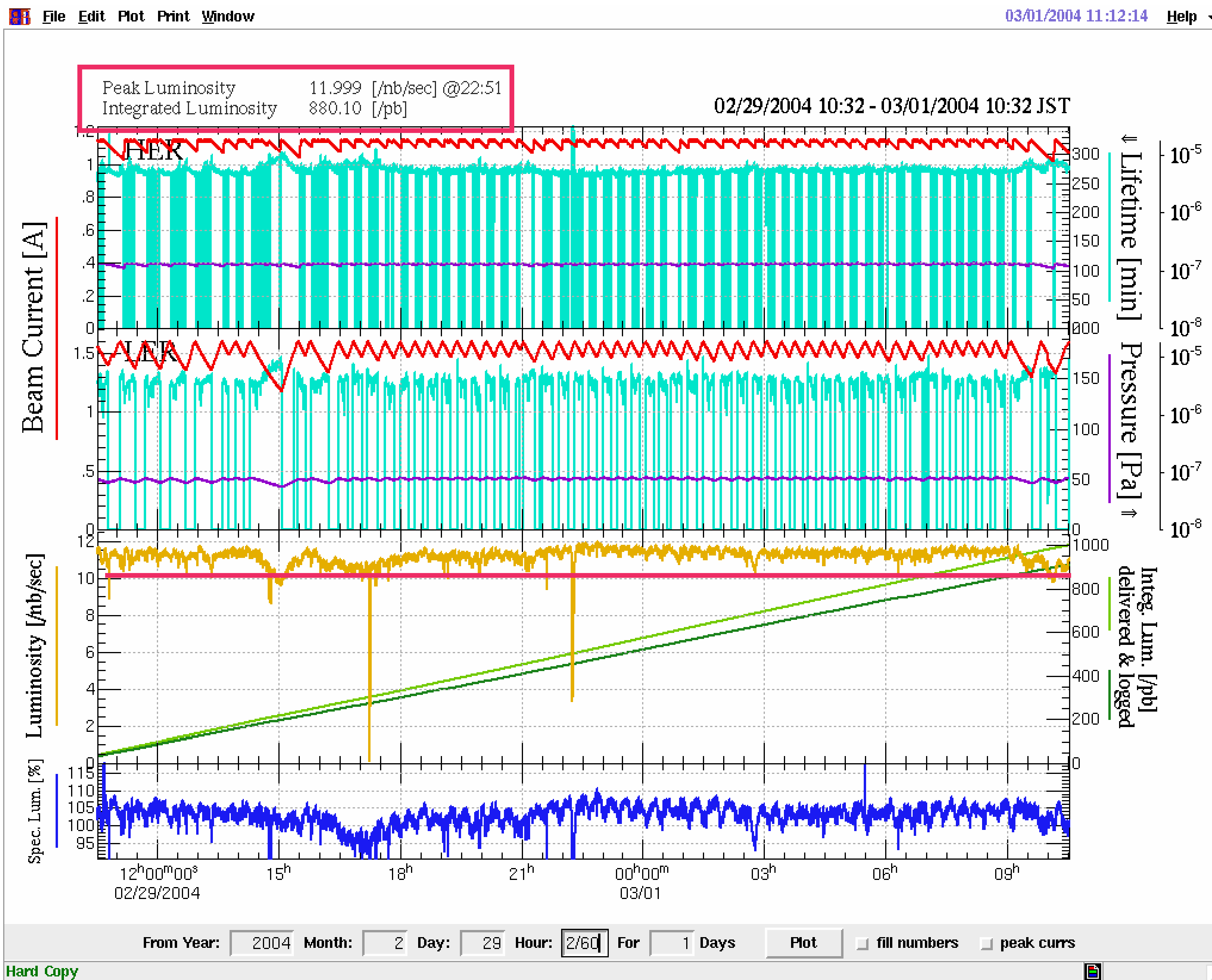
2003.06
2003.08
2003.10
2003.12
2004.02


Increase of Peak Luminosity
1.161 10^34/cm^2/s on 2003/12/18 (KEKB)
0.793 10^34/cm^2/s on 2004/2/8 (PEP-II)
Peak luminosity (10^33 cm^-2 s^-1)
0
2
4
6
8
10
12
2000
2001
2002
2003
2004


Integrated Luminosity (logged)
Integrated Luminosity (/fb)
0
50
100
150
200
250
6/1/99
6/1/00
6/1/01
6/1/02
6/1/03
6/1/04

Best 24 hours



3. Key Issues for High Luminosity

The history of the KEKB commissioning has been a struggle with issues such as:

A) High beam currents

- Problems with hardware components
- Instability

B) Single beam blowup due to the electron cloud instability

- Solenoid winding

C) Beam-beam blowup

- Tune survey
- Optics corrections
- Other tuning knobs (X-Y coupling at IP etc.)

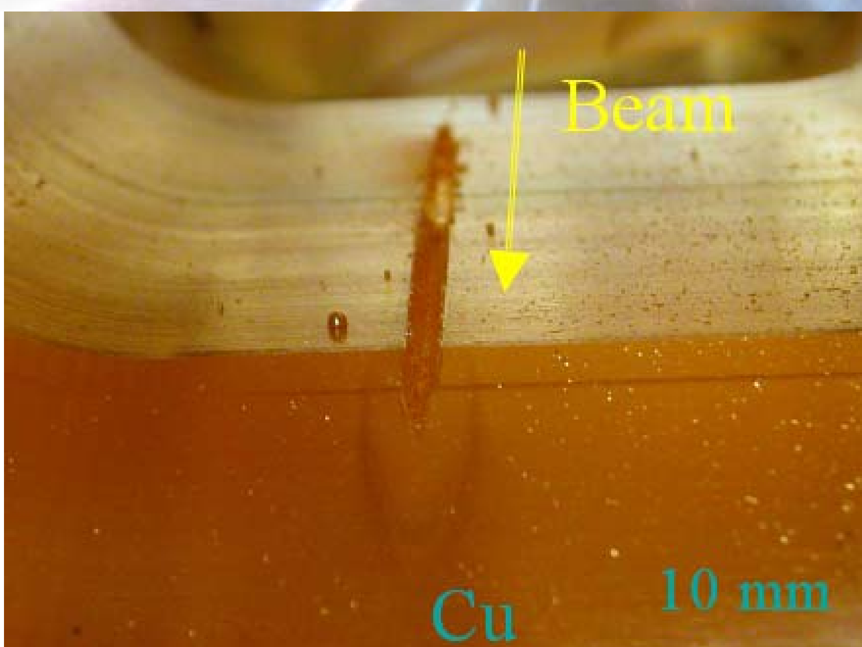
A) Problems due to High Beam Currents

Problems with vacuum components

- HOM heating and damage
  - Bellows, gate valves
- Arcing of components due to HOMs or wall currents
  - Movable masks, RF shield at injection septum
- Direct damage by beam
  - Movable masks, beam abort chamber
- Heating and vacuum leak due to SR
  - IR chambers, Helico-flex gaskets

Damaged vacuum components

Damaged RF shield fingers



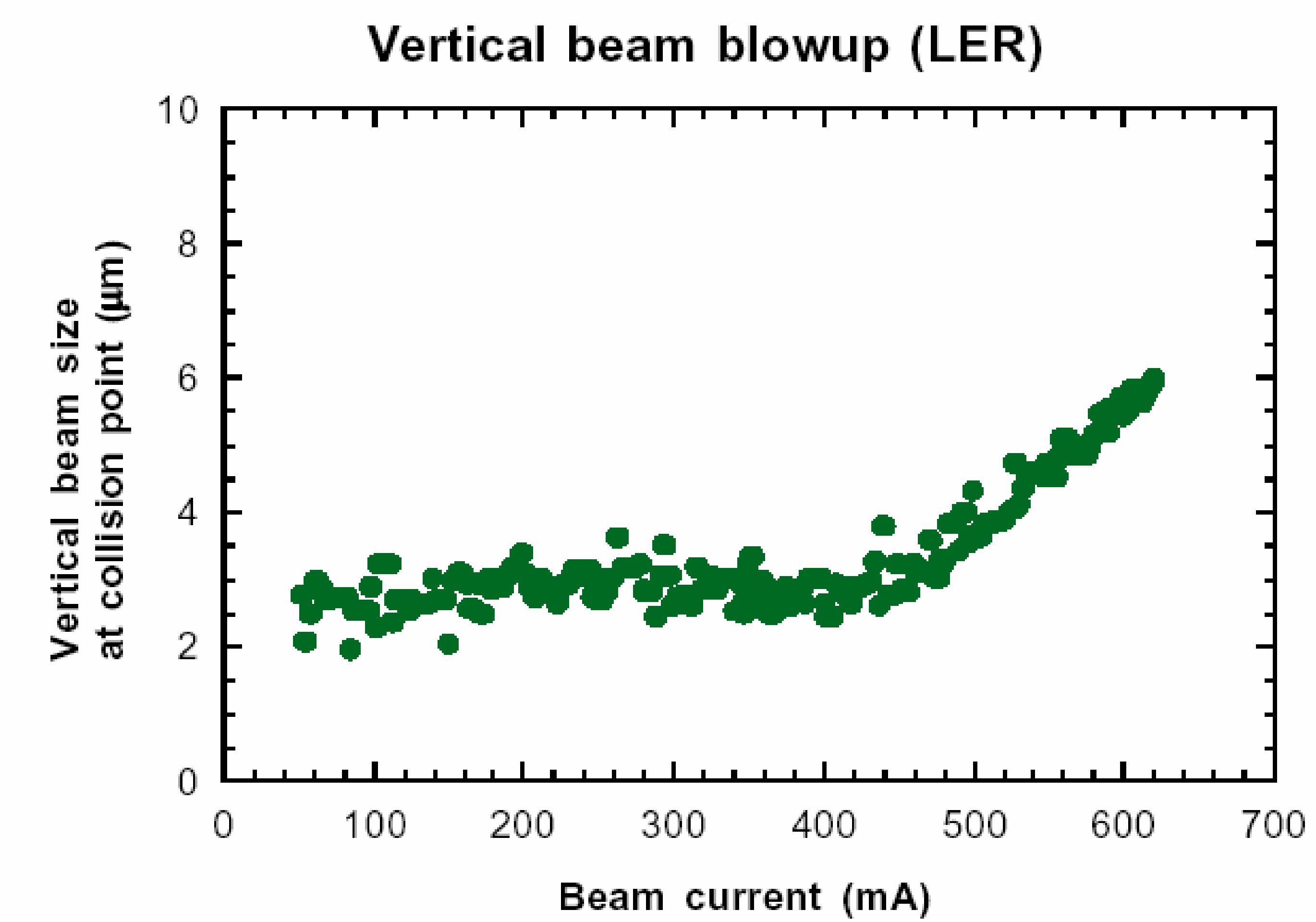
Damaged movable mask

A) Problems due to High Beam Currents

Instability sources

- Fast ion (electron ring)
  - Serious at high vacuum pressures
  - Can be suppressed by bunch-by-bunch FB
- Electron cloud (positron ring)
  - Can be suppressed by solenoid field
- RF cavity
  - Beam current is not limited by instabilities due to RF cavity.
  - We use -1 mode damper (with comb-filter) to suppress instability from the fundamental mode.
  - We do not need longitudinal bunch-by-bunch FB.
- Others
  - Dust trapping

B) Single beam blowup due to the electron cloud instability



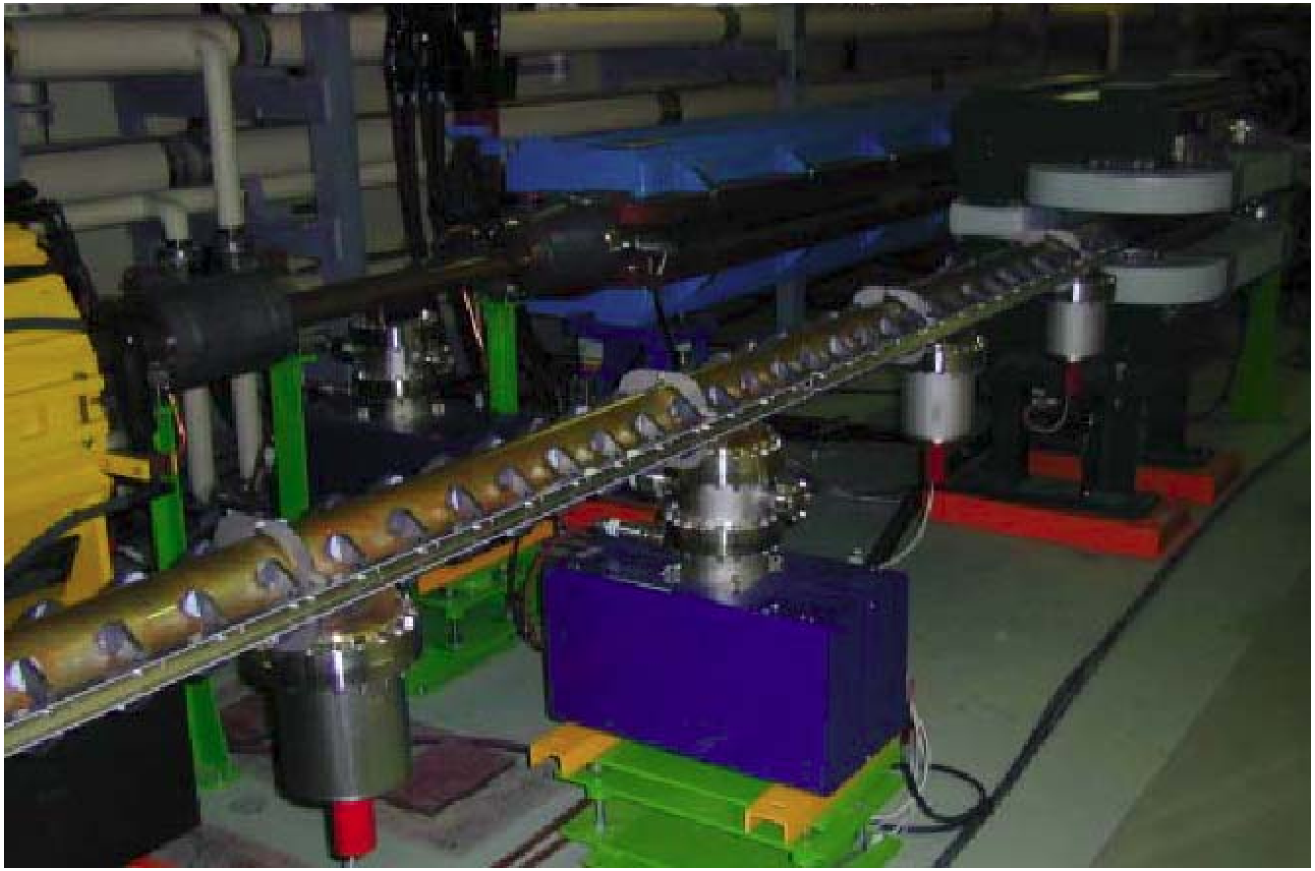
H.Fukuma ECOULD2002
http://wwwslap.cern.ch/collective/ecloud02/

Electron Cloud (EC)

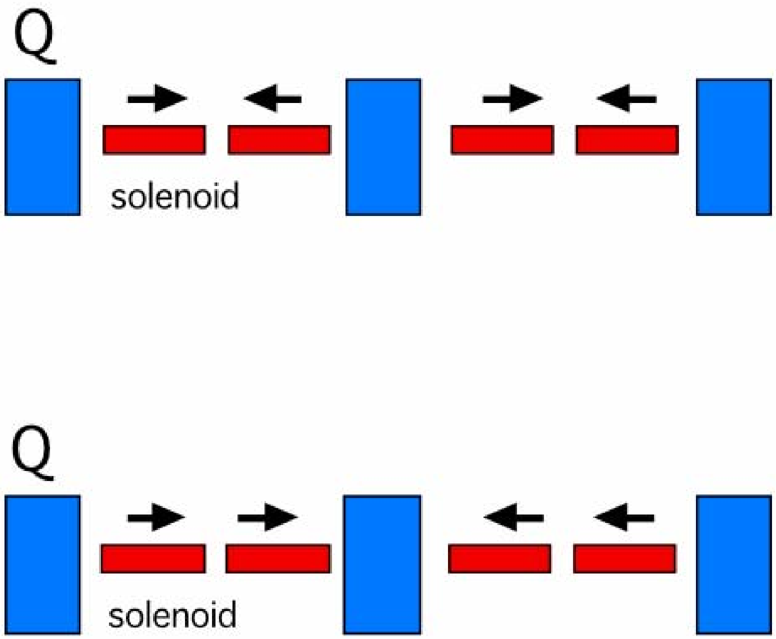
1999/4	Single beam blowup was observed by SR monitor.
1999/10	Electron cloud hypothesis was proposed by K.Oide.
1999/11	C-yoke permanent magnets were installed in attempt to cure the blowup problem.
2000/3	Additional C-yoke magnets were installed.
2000/5	Head-tail instability model by K.Ohmi & F.Zimmermann was proposed.
2000/9	C-yoke magnets were replaced by solenoid magnets (~2800 sections).
2000/12	Effectiveness of the solenoids in improving luminosity was confirmed.
2001/1	1950 additional solenoid magnet sections were installed.
2001/9	3450 additional solenoid magnet sections were installed.
2001/11	Peak luminosity reached 5.5 nb/s.

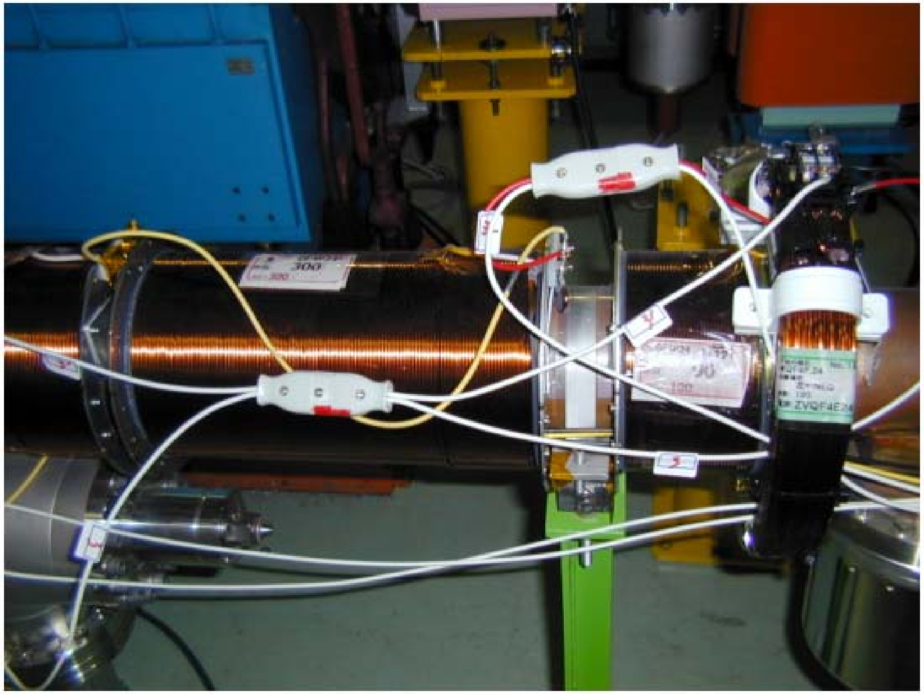
H.Fukuma ECOULD2002
http://wwwslap.cern.ch/collective/ecloud02/

C-yoke permanent magnets

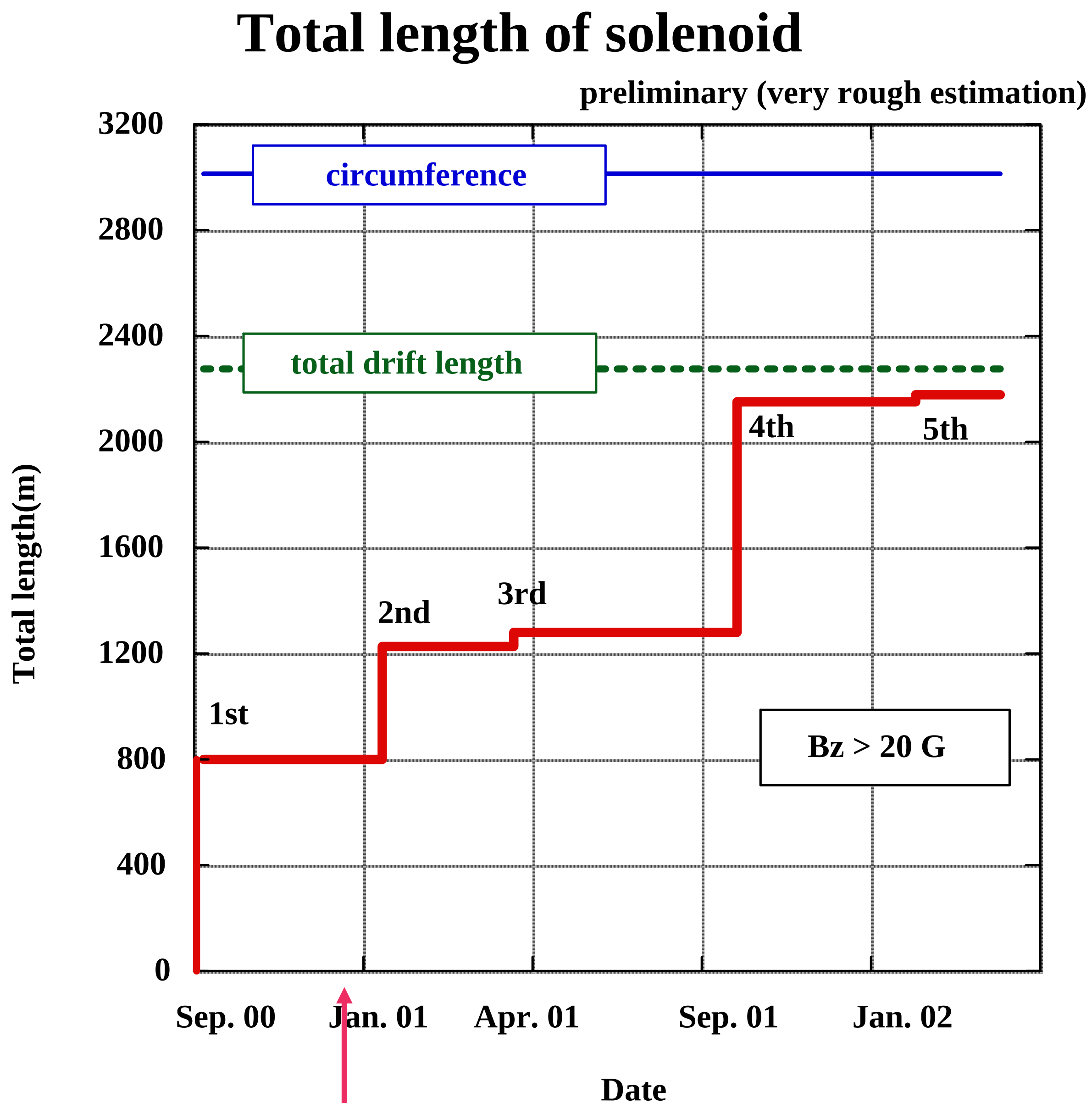


Electron-cloud-suppression solenoids



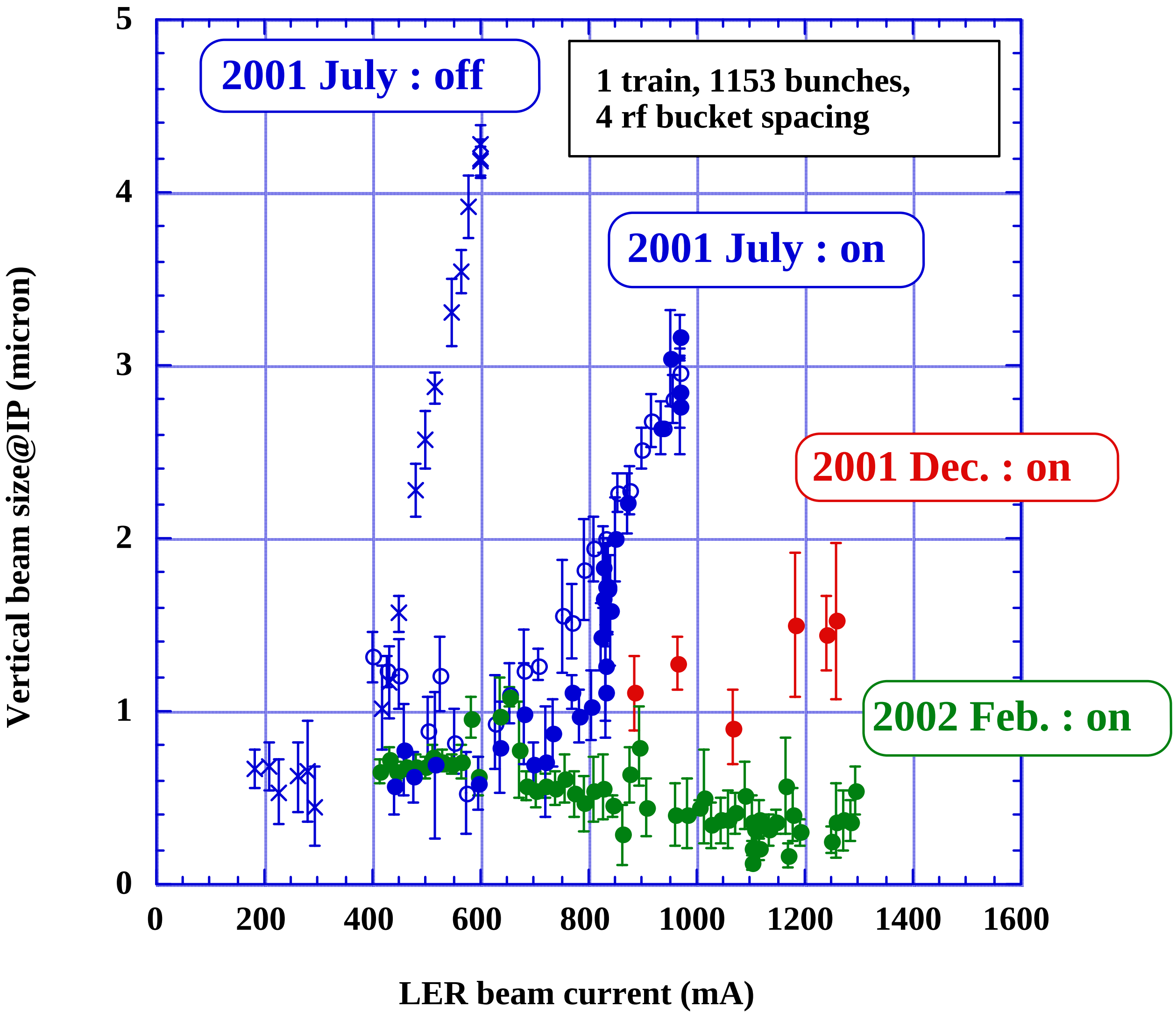


Electron-cloud-suppression solenoids

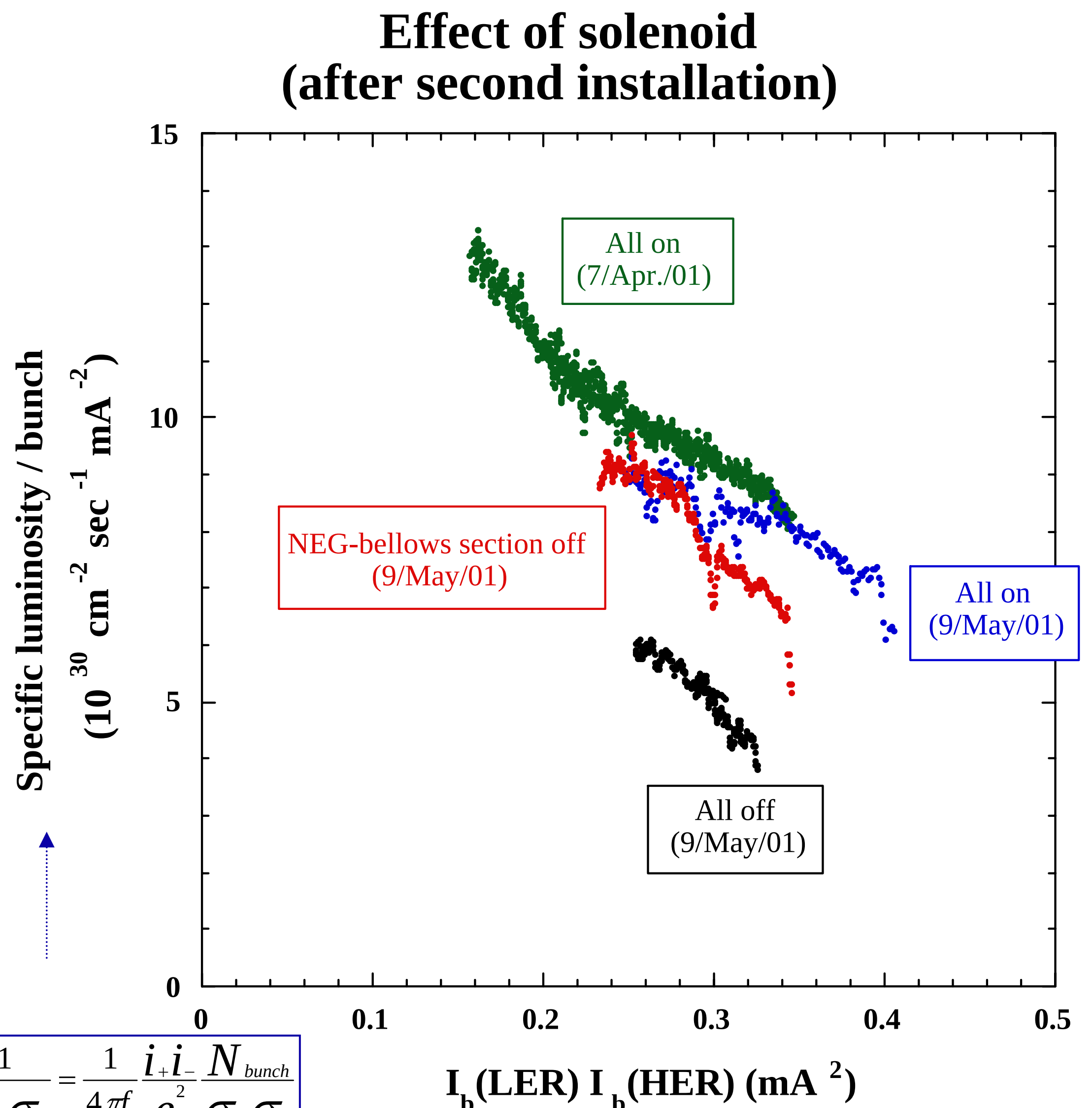


Effect on luminosity confirmed

LER Beam size (σ_y)



Effect of solenoids on luminosity



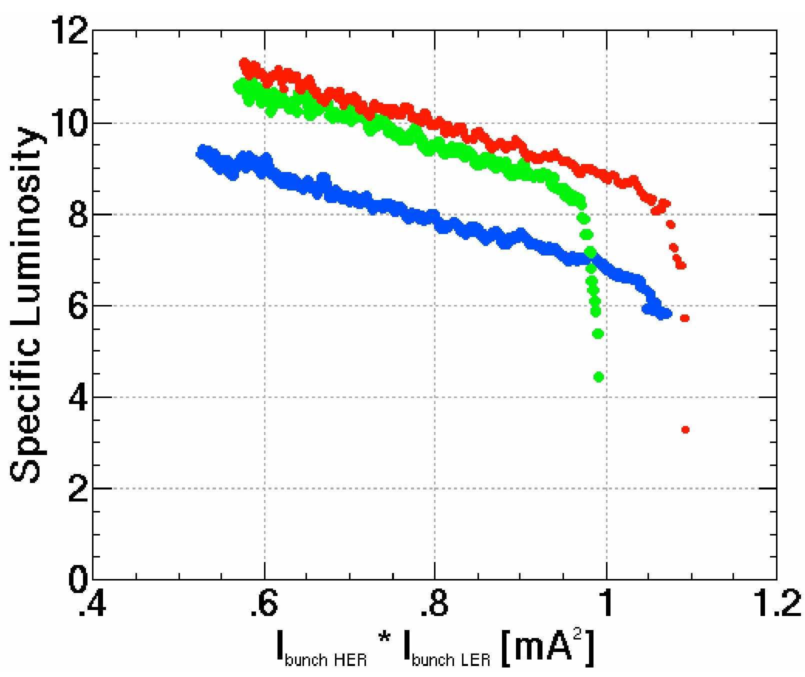
$$L = \frac{1}{4\pi N_{bunch} f} \frac{I_+ I_-}{e^2} \frac{1}{\sigma_x \sigma_y} = \frac{1}{4\pi f} \frac{i_+ i_-}{e^2} \frac{N_{bunch}}{\sigma_x \sigma_y}$$

$$Spec.Lum/bunch = \frac{L}{i_+ i_- N_{bunch}}$$

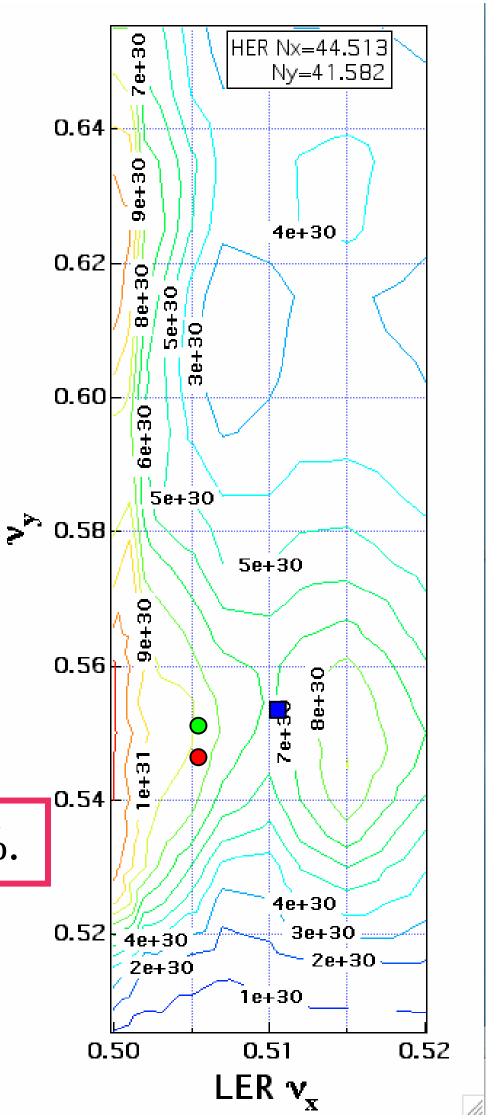
C) Beam-Beam Blowup

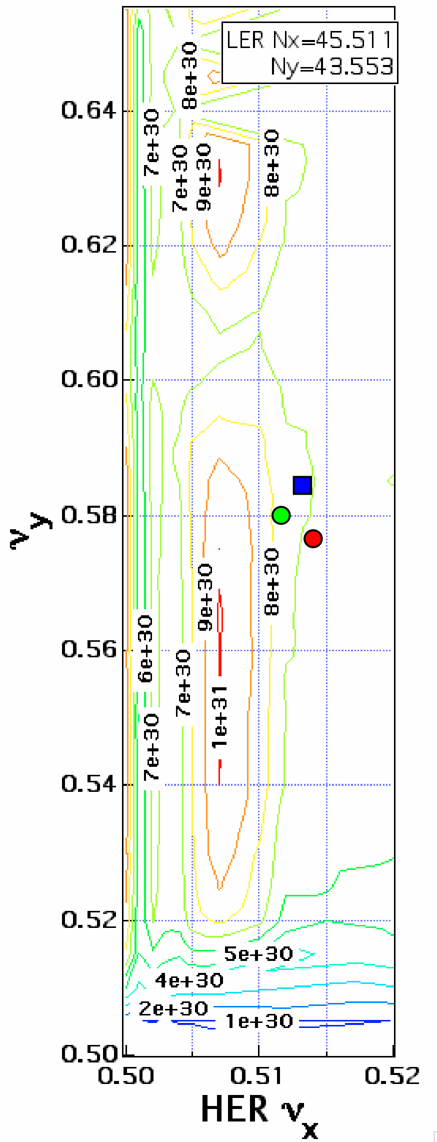
- Tune survey
  - Both simulations and surveys in real machine
  - Horizontal tunes very close to the half-integer
  - Need very fine control of tunes
- Optics correction (global correction)
  - β functions
  - Dispersion
  - X-Y coupling
- Collision tuning knobs
  - Waist points
  - X-Y coupling at IP
  - Dispersions at IP
  - Orbit feedback around IP

Choice of Betatron Tunes & Specific Luminosity



Specific luminosity was improved by 25%.





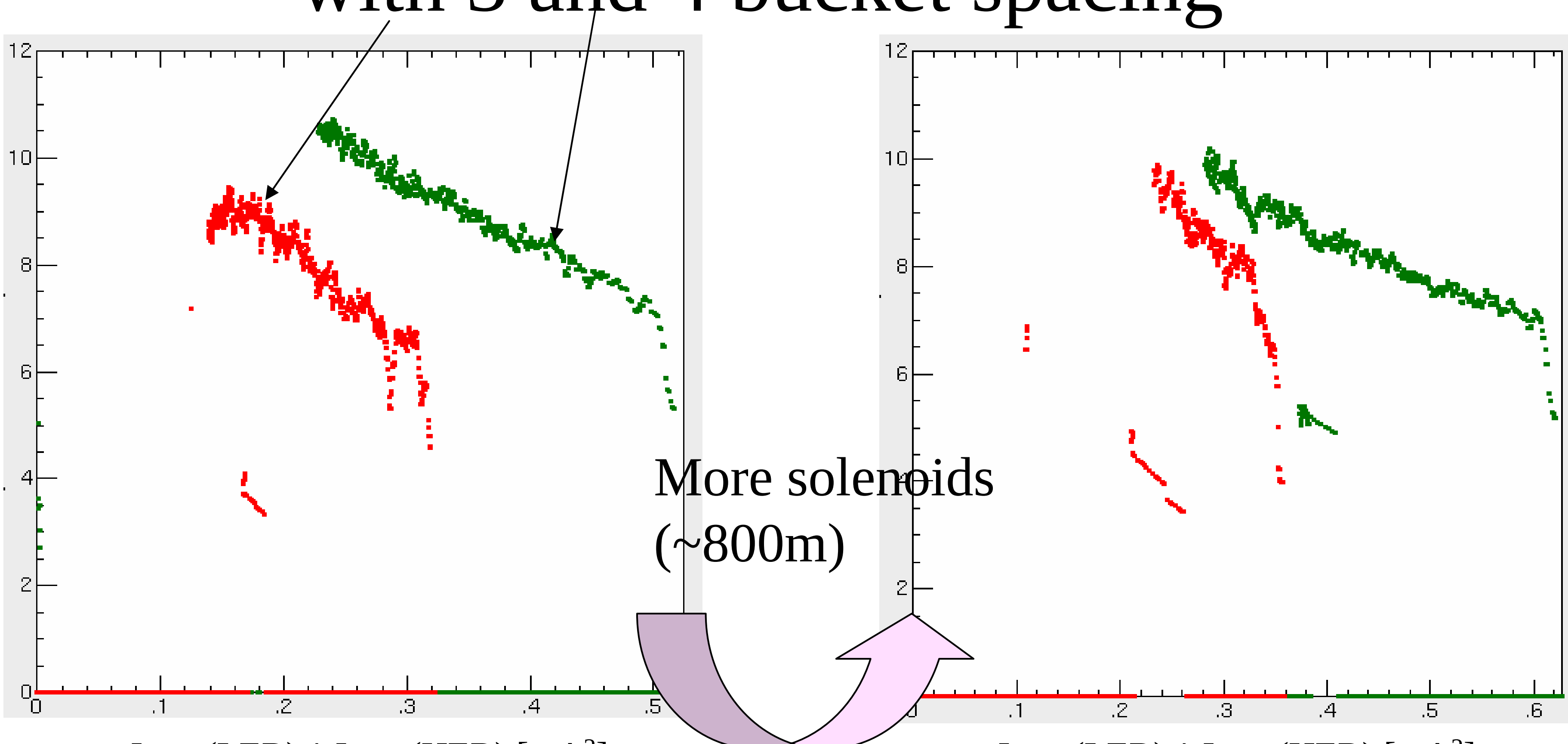
■ 10/29/2002
● 5/9/2003
● 12/18/2003

Simulations M.Tawada, et al.

Bunch-spacing problem

- Observations
  - The specific luminosity depends on the bunch spacing.
  - A longer bunch spacing gives a higher specific luminosity.
- Cause of the problem
  - Not understood.

Comparison of specific luminosity/bunch with 3 and 4 bucket spacing



I_{bunch}(LER) * I_{bunch}(HER) [mA^2] I_{bunch}(LER) * I_{bunch}(HER) [mA^2]

$$L = \frac{1}{4\pi N_{bunch} f} \frac{I_+ I_-}{e^2} \frac{1}{\sigma_x \sigma_y} = \frac{1}{4\pi f} \frac{i_+ i_-}{e^2} \frac{N_{bunch}}{\sigma_x \sigma_y}$$

$$Spec.Lum/bunch = \frac{L}{i_+ i_- N_{bunch}}$$

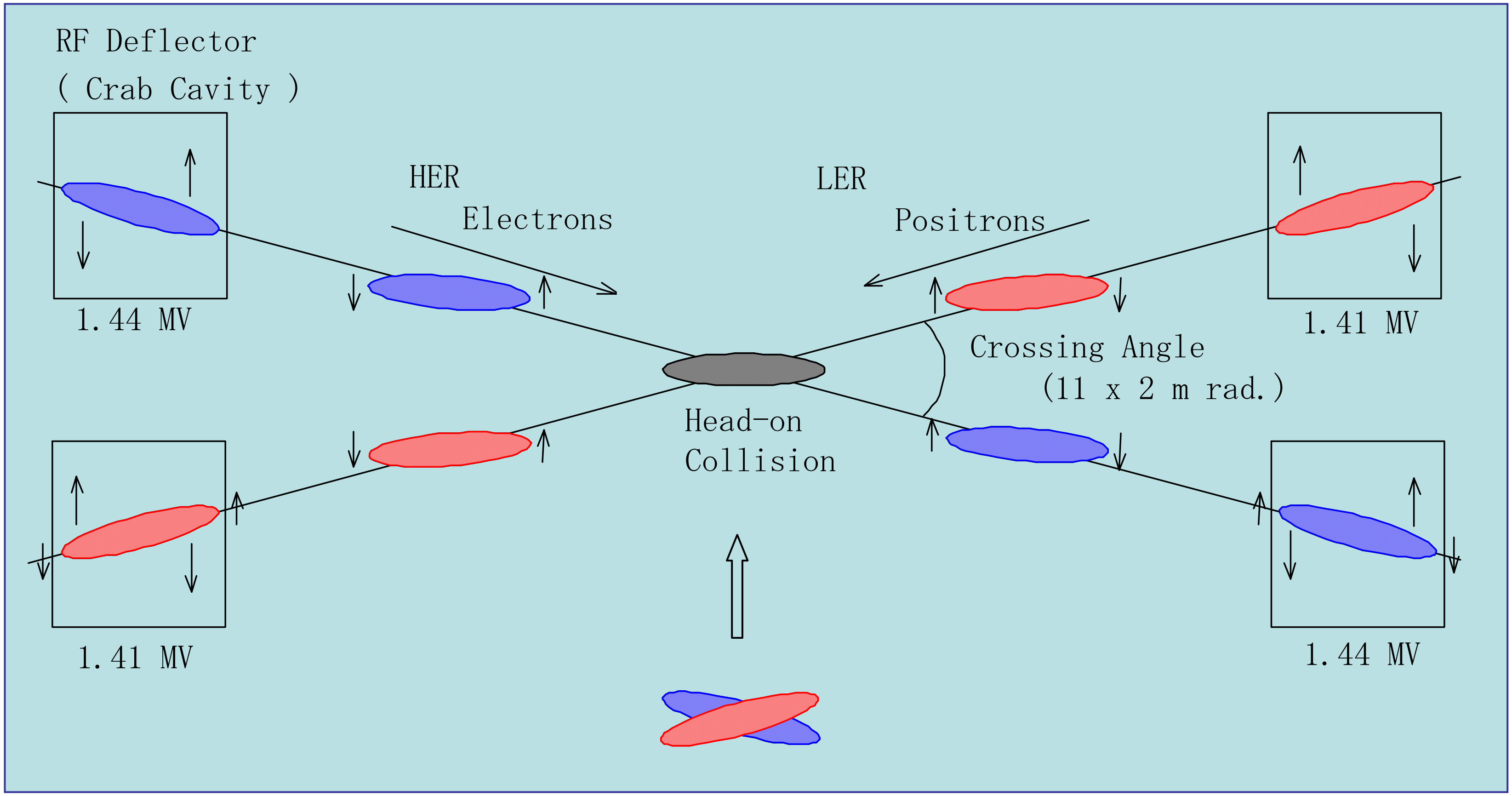
4. Upgrade Plan with Crab Crossing

Role of Crab Cavity

	KEKB		*Super-KEKB*	
Strategy	Backup scheme		Adopted as baseline	
Ring	LER	HER	LER	HER
Beam energy (GeV)	3.5	8.0	3.5	8.0
Beam current (A)	2.6	1.1	9.4	4.1
RF frequency (MHz)	508.887		508.887	
Crossing angle (mrad)	±11		±15	
βx* (m)	0.33	0.33	0.2	0.2
βx, crab (m)	20	100	100〜200	300〜400
Required kick (MV)	1.41	1.44	1.10 〜 0.78	1.45 〜 1.26

The design luminosity of 1.0 x10^{34} cm^{-2} s^{-1} has been achieved without crab crossing.

Crab crossing scheme



Palmer for LC (1988)
Oide and Yokoya for storage rings :Phys,Rev.A40,315(1989)

Recent simulations by Ohmi showed significant increase of luminosity with crab crossing.

Crossing angle

Transformation from lab. Frame to head-on frame.

(ϕ: half crossing angle)

$$x^* = \tan\phi\, z + [1 + h_x^* \sin\phi]\, x$$

$$p_x^* = (p_x - h\tan\phi)/\cos\phi$$

$$y^* = y + h_x^* \sin\phi\, x$$

$$p_y^* = p_y^* / \cos\phi$$

$$z^* = z/\cos\phi + h_z^* \sin\phi\, x$$

$$p_z^* = p_z - p_x \tan\phi + h\tan^2\phi$$

$$h = p_z + 1 - \sqrt{(p_z+1)^2 - p_x^2 - p_y^2}$$

Linear part

$$\begin{pmatrix} 1 & 0 & 0 & 0 & \tan\phi & 0 \\ 0 & 1/\cos\phi & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/\cos\phi & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/\cos\phi & 0 \\ 0 & -\tan\phi & 0 & 0 & 0 & 1 \end{pmatrix}$$

Oide and Yokoya for storage rings (1989)

Transverse kick by Crab Cavity

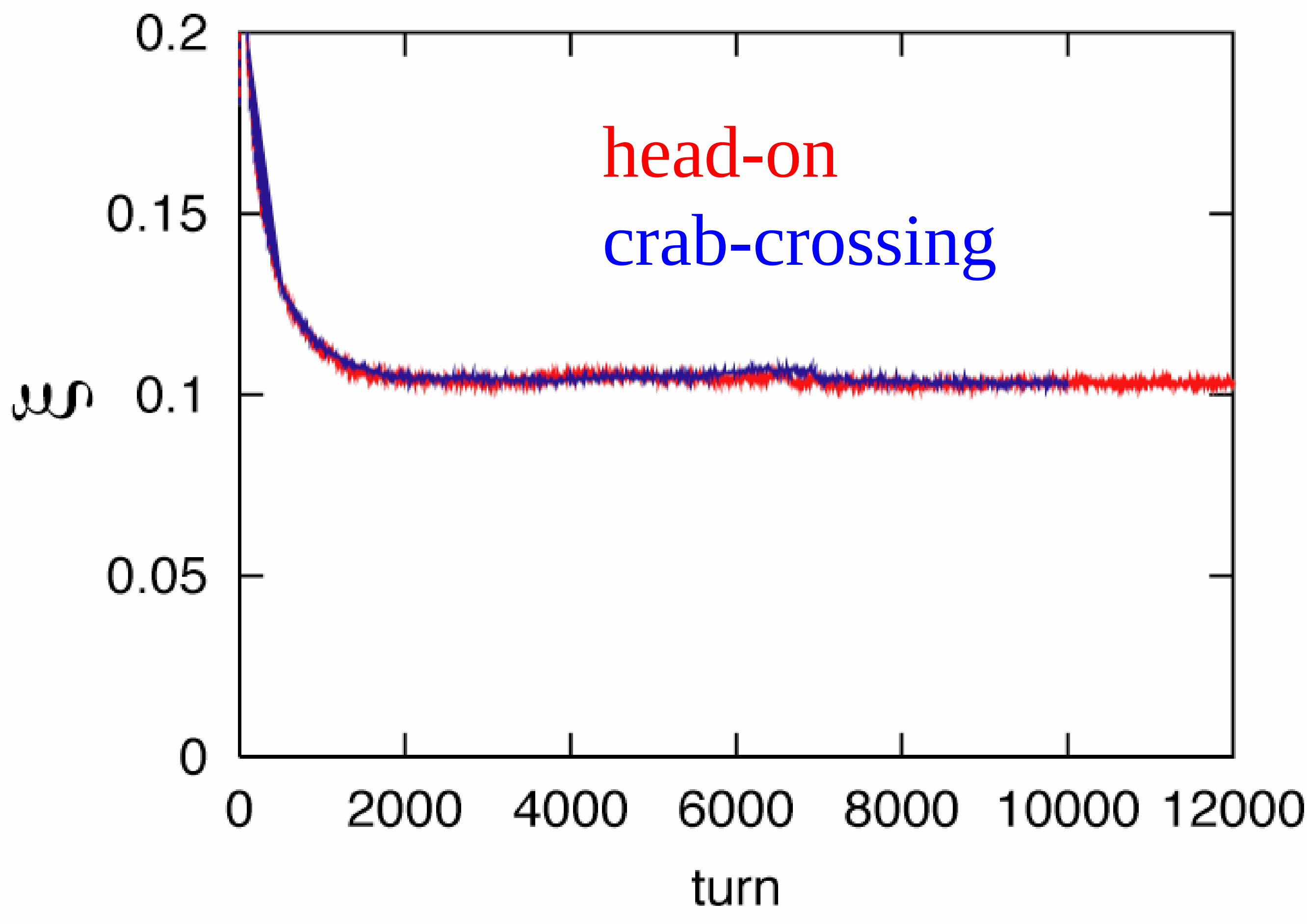
$$\begin{pmatrix} 1 & 0 & 0 & 0 & \tan\phi & 0 \\ 0 & 1/\cos\phi & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/\cos\phi & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/\cos\phi & 0 \\ 0 & -\tan\phi & 0 & 0 & 0 & 1 \end{pmatrix} \bullet \begin{pmatrix} 1 & 0 & 0 & 0 & \zeta_x & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & -\zeta_x & 0 & 0 & 0 & 1 \end{pmatrix}$$

Crossing-angle term

Crab-cavity term

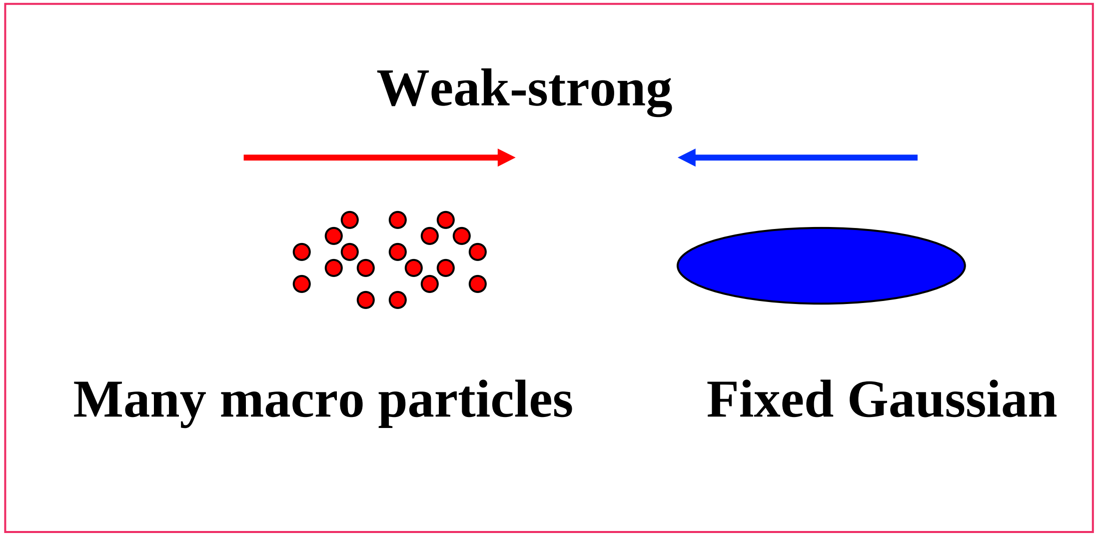
Crab cavity makes z dependent dispersion $\zeta_x = -\phi$ at the IP, which cancels the crossing angle effect ($\phi << 1$).

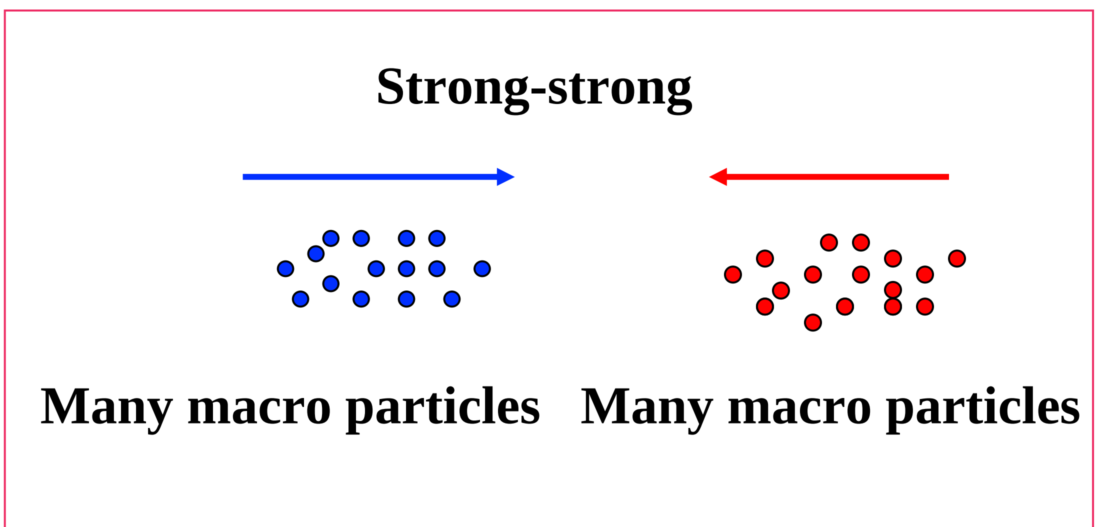
Simulation
Head-on vs. crab-crossing (K.Ohmi)



Crab crossing restores the full luminosity of a head-on collision.

Simulation model





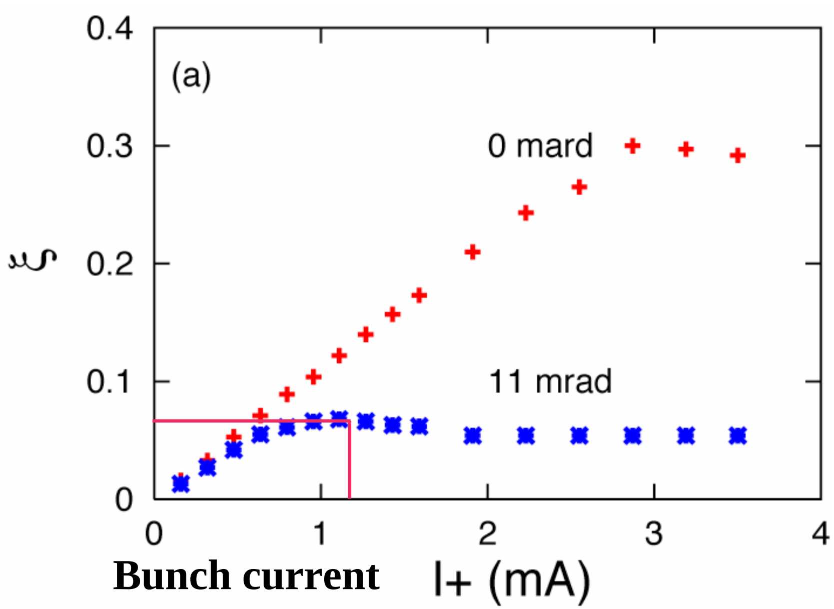
K.Ohmi

'Simulation of beam-beam effects in a circular e+e- collider'

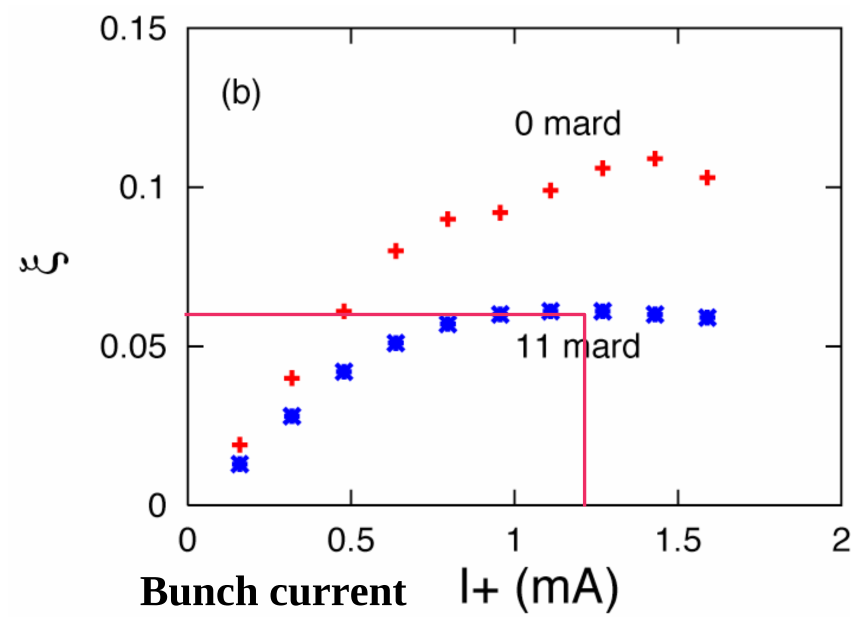
Phys.Rev.E62 (7287)2000

Crab-crossing simulation
0-mrad vs. 11-mrad crossing angle (K.Ohmi)

Weak-Strong model



Strong-Strong model



- Beam-beam limit is ~0.06 for 11 mrad half-crossing angle (both models agree well).
- 0-mrad (head-on) collision gives a higher ξ_y.
- Beam-beam limit for 0-mrad crossing depends on the model.

Parameters for 11 mrad crabbing

Specification of Crab Cavity

- Transverse kick: 1.44MV(HER)/1.4MV(LER)

IP horizontal β Function

- βip = 0.56m(HER)/0.59m(LER) — 0.33m(HER)/0.33m(LER)

Required Optics Parameter at Cavity Position

- $\Delta\nu$x(Crab Cavity-IP) = 2n$\pi \pm \pi$/2
- βcrab = 200m(HER)/40m(LER) — 100m(HER)/20m(LER)
- ηx = η'x = 0

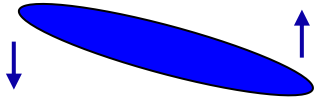
$$V = \frac{cE\tan\varphi}{\omega_{rf}\sqrt{\beta^{*}_{x}\beta_{x,crab}}}$$

V:voltage
E:Beam energy
β_x^*: *beta-function at the IP*
β_x: *cra beta-function at the crab cavity*
φ:*half crossing angle at the IP*
ω_{rf}:*the rf frequency of the cavity*

(A.Morita MAC2004)

Hardware for Crabbing (design)

- The TM110 mode is used to create time-dependent horizontal rotational kicks to beam bunches.
- The TM110 mode is trapped within the cavity, while the other unwanted modes are extracted from the cavity module.



Crab Cavity

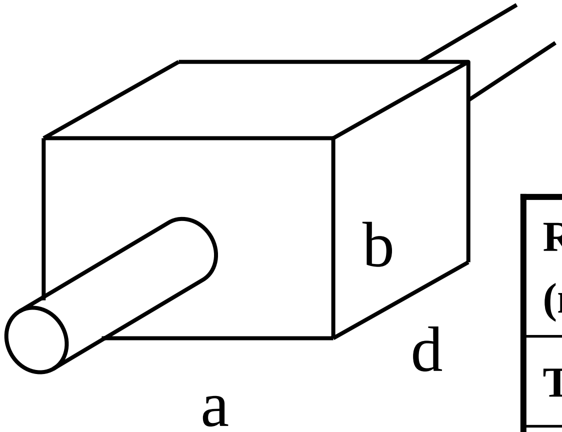
Damping unwanted parasitic modes

- **Accelerating cavities**
  - **Operating mode (TM010) is the lowest frequency mode.**
  - **Any parasitic mode (HOM) has higher frequency than the operating mode.**
  - **Wave guides or beam pipe with cut-off frequency higher than the operating mode can damp all HOM's. (ARES, SCC, PEP-II cavity, etc)**

- **Crab cavity**
  - **Operating mode (usually TM110) is NOT the lowest frequency mode.**
  - **Frequency of several parasitic modes can be lower than (or close to) the crabbing mode.**
  - **Special cure is needed for the damping of parasitic modes.**

(K.Akai MAC2004)

Analogy with rectangular cavity



$$f_{n,m,l} = c\sqrt{\left(\frac{n}{2a}\right)^2 + \left(\frac{m}{2b}\right)^2 + \left(\frac{l}{2d}\right)^2}$$

Rectangular (n-m-l)	**Cylindrical**	**Beam coupling**	**Mode**
TM1-1-0	**TM010**	**monopole-like**	**Accelerating mode**
TM2-1-0	**TM110(H)**	**dipole-like**	**Crabbing mode**
TM1-2-0	**TM110(V)**	**dipole-like**	**Unwanted crabbing**
TE0-1-1	**TE111(H)**	**dipole-like**	**Lowest TE-like**
TE1-0-1	**TE111(V)**	**dipole-like**	**Lowest TE-like**
TM3-1-0	**-**	**monopole-like**	
TM4-1-0	**-**	**dipole-like**	
TE0-2-1	**TE211**	**quadrupole-like**	

(K.Akai MAC2004)

Squashed cell

- Extremely polarized cell

  Large eccentricity where horizontal size is about twice the vertical size (a ~2b).

  ⇒Frequency of the unwanted crabbing mode increases.

- Relatively short cell length (small d)

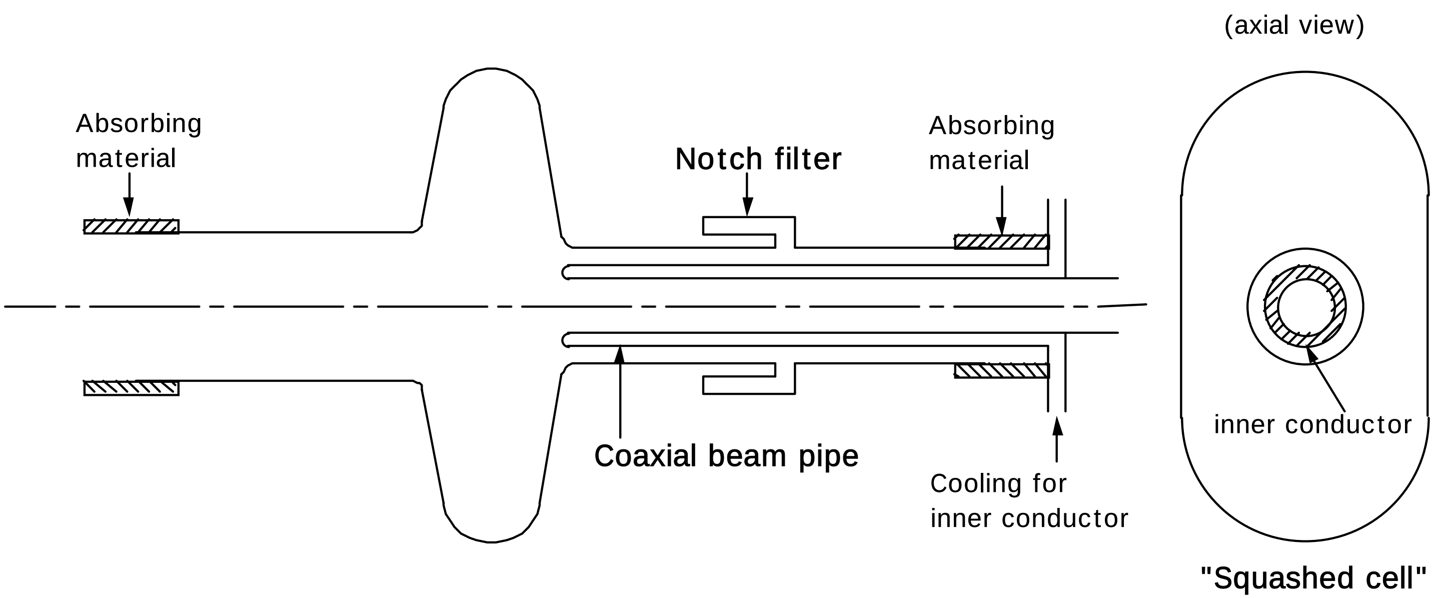
  ⇒The frequencies of lowest TE-like parasitic modes increase.

Frequencies of all parasitic modes except the accelerating mode can be made higher than the crabbing mode.

(K.Akai MAC2004)

Crab Cavity Design for KEKB

- Squashed cell
- Coaxial coupler is used as a beam pipe

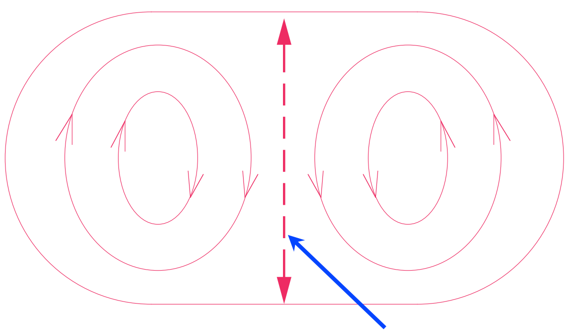


Squashed Crab cavity for B-factories

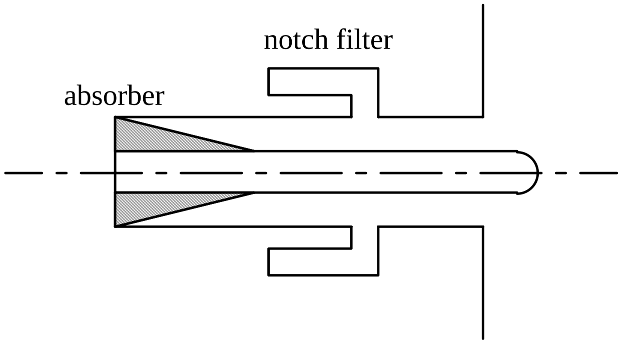
(K. Akai et al., Proc. B-factories, SLAC-400 p.181 (1992).)

Coaxial coupler with notch filter

- **Monopole mode (including the Lower Freq. Mode)**
  - **Couples strongly and propagates in the coaxial line as TEM wave and can be guided out.**
- **Crabbing mode**
  - **Couples as dipole-like, but does not propagate in the coaxial line, if the cut-off frequency of TE11 mode is higher than the crabbing frequency.**
  - **Possible asymmetry or misalignment causes monopole-like coupling, which propagates in the coaxial line as TEM. A notch filter is attached to reject the TEM-coupled crabbing mode back to the cavity.**



Possible location to attach coaxial coupler



(K.Akai MAC2004)

Crab crossing experiment at KEKB

		Original cavity
KEKB (LER) β crab=40m V_{kick}=1.47MV	No. of cavities	1
	Growth time (horizontal)	36ms
	Growth time (longitudinal)	96ms
	Total HOM power	23kW
KEKB (HER) β crab=200m V_{kick}=1.51MV	No. of cavities	1
	Growth time (horizontal)	33ms
	Growth time (longitudinal)	415ms
	Total HOM power	6kW

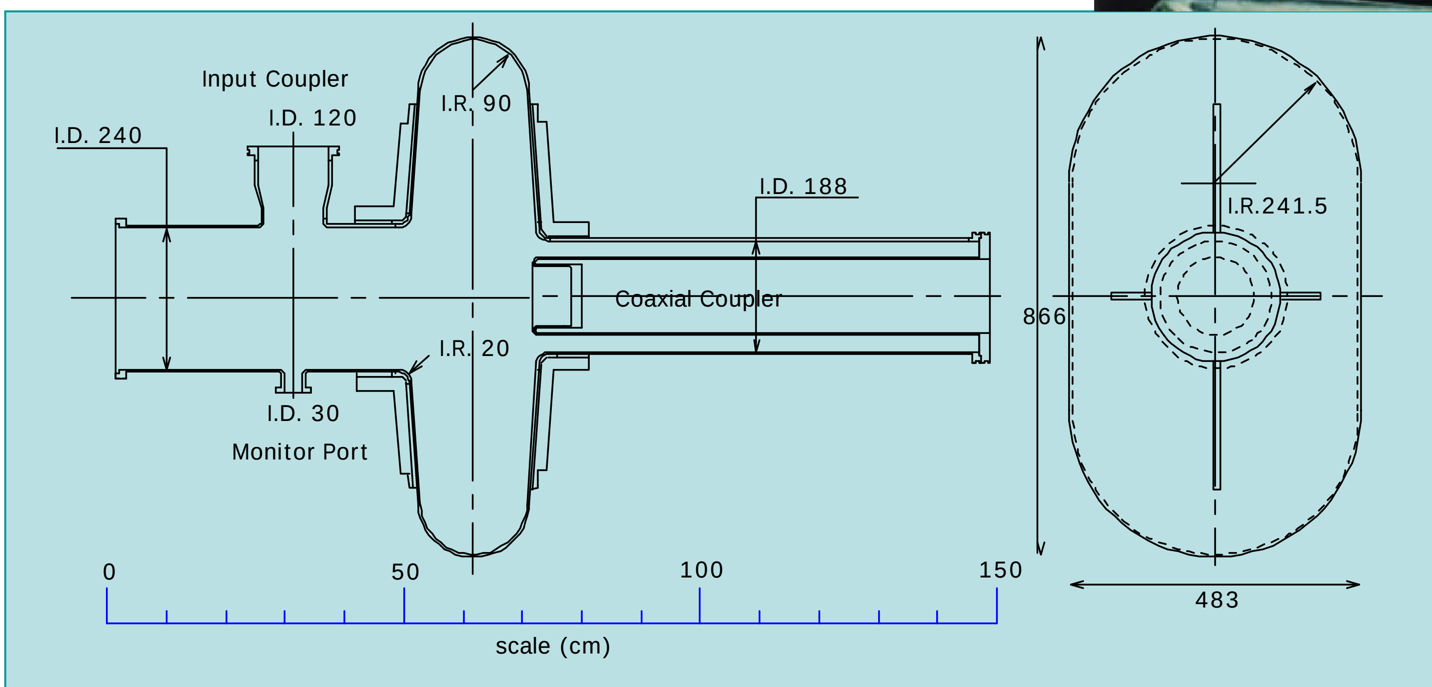
The crab crossing experiment in KEKB is planned in FY 2005.
The original crab cavity will be used for the experiment.

(K.Akai MAC2004)

Superconducting Crab Cavity

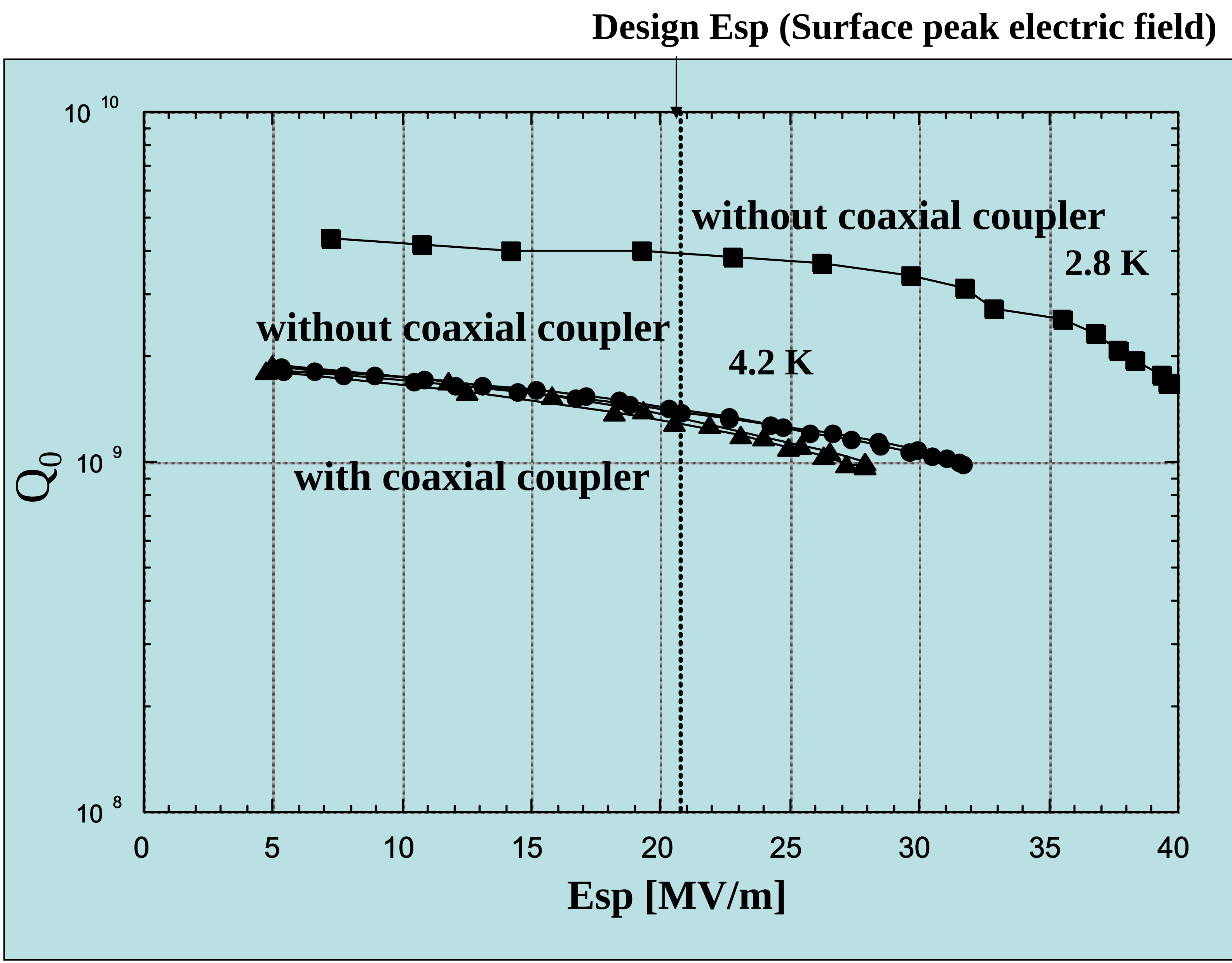
Crab Cavity Group

KEK Crab Cavity R&D Group
K. Hosoyama, K. Hara, A. Kabe,
Y. Kojima, Y. Morita, H. Nakai
A. Honma, A. Terashima, K. Nakanishi
MHI
S. Matsuoka, T. Yanagisawa



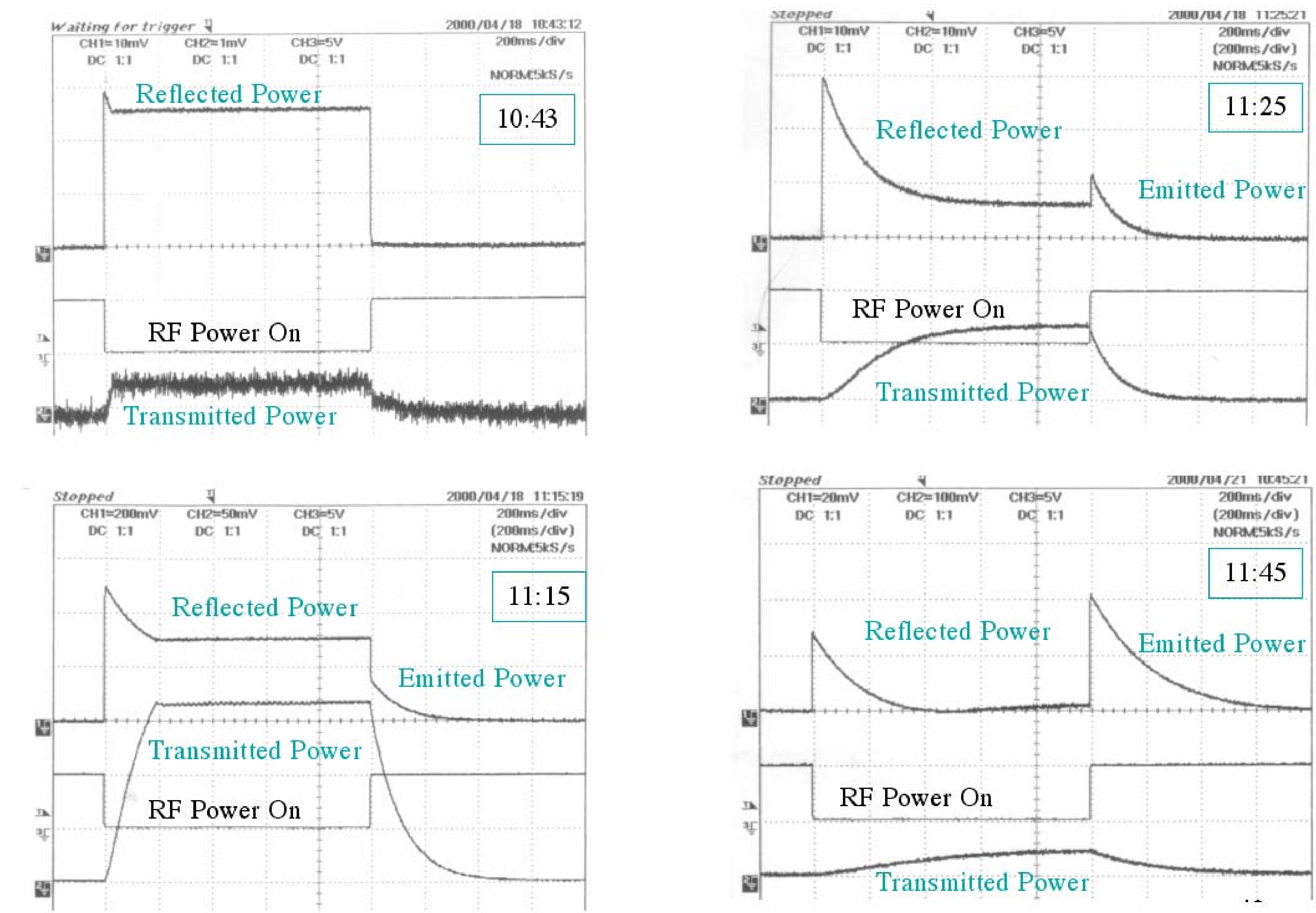
K.Hosoyama (MAC 2004)

Test Result of KEKB Crab Cavity #1



K.Hosoyama (MAC 2004)

Multipacting in Crab Cavity with Coaxial Coupler



K.Hosoyama (MAC 2004)

Crab cavity R&D, production

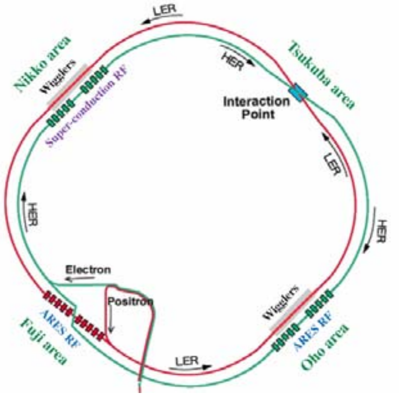
Fabrication and Surface Treatment
RF Performance Test with a Coaxial Coupler

- Multipacting could be overcome by RF process.

We have established these techniques!

K.Hosoyama (MAC 2004)

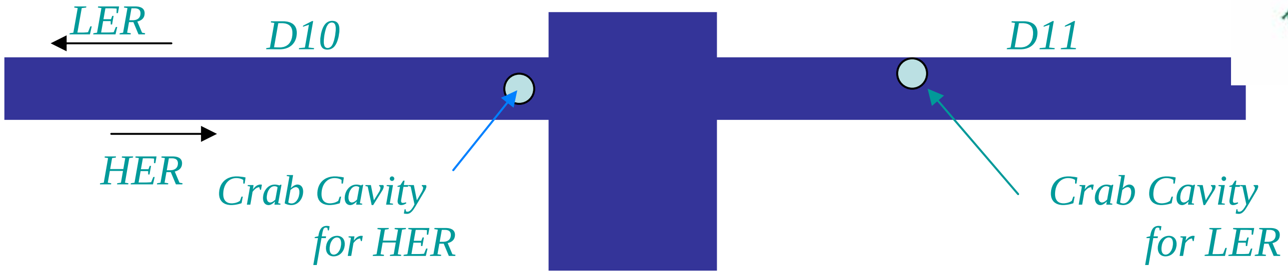
Crab Cavity Installation Plan

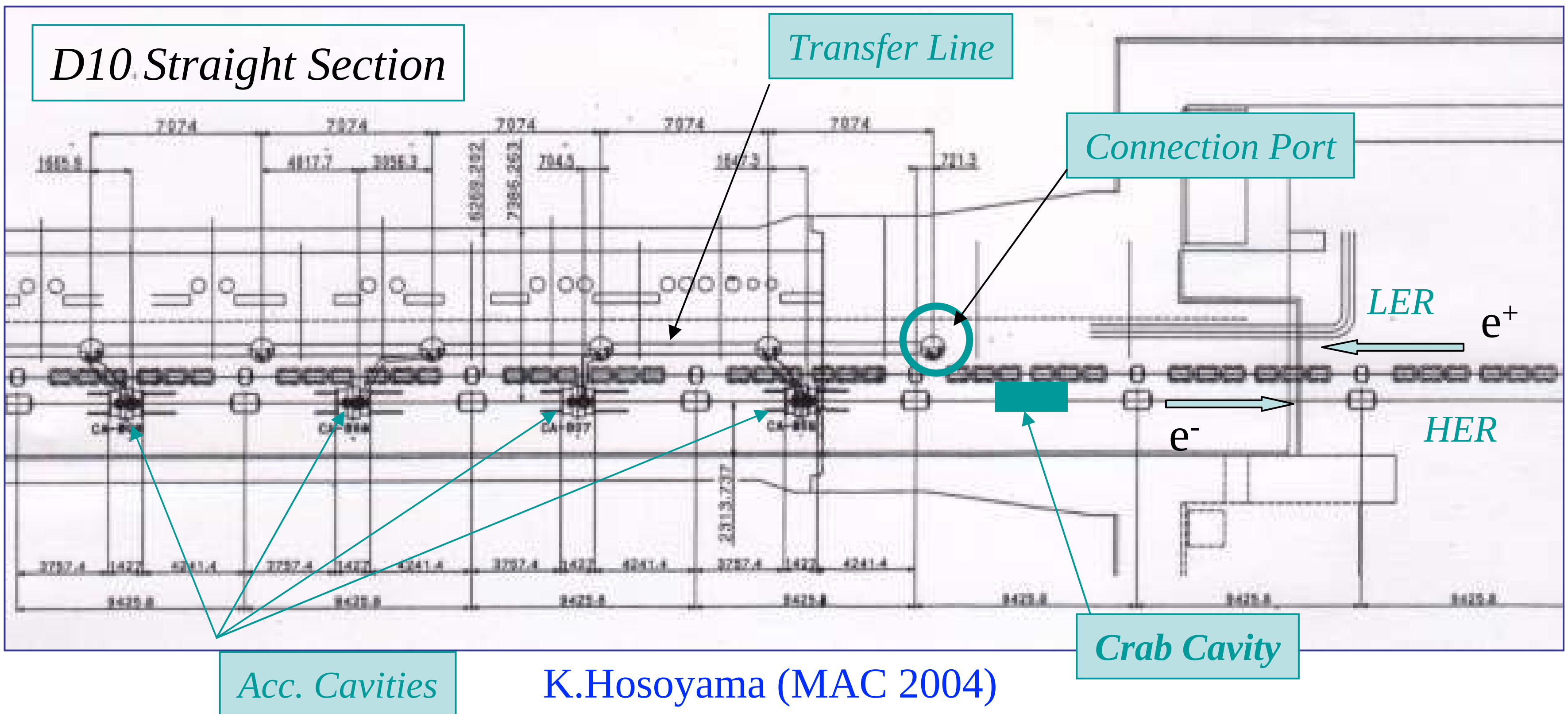


Both crab cavities will be installed in the Nikko straight section because:

–There is some space for both rings.

–Cryogenic system is available.





K.Hosoyama (MAC 2004)

Crab Cavity Installation in JFY 2005 (April 2005-March 2006)

Test Plan

- Install one cavity in either the HER or the LER at the end of 2005.
- Check hardware and modify if necessary.
- Install another crab cavity in the other ring in the summer of 2006.
- Beam will be crabbed throughout the entire ring.

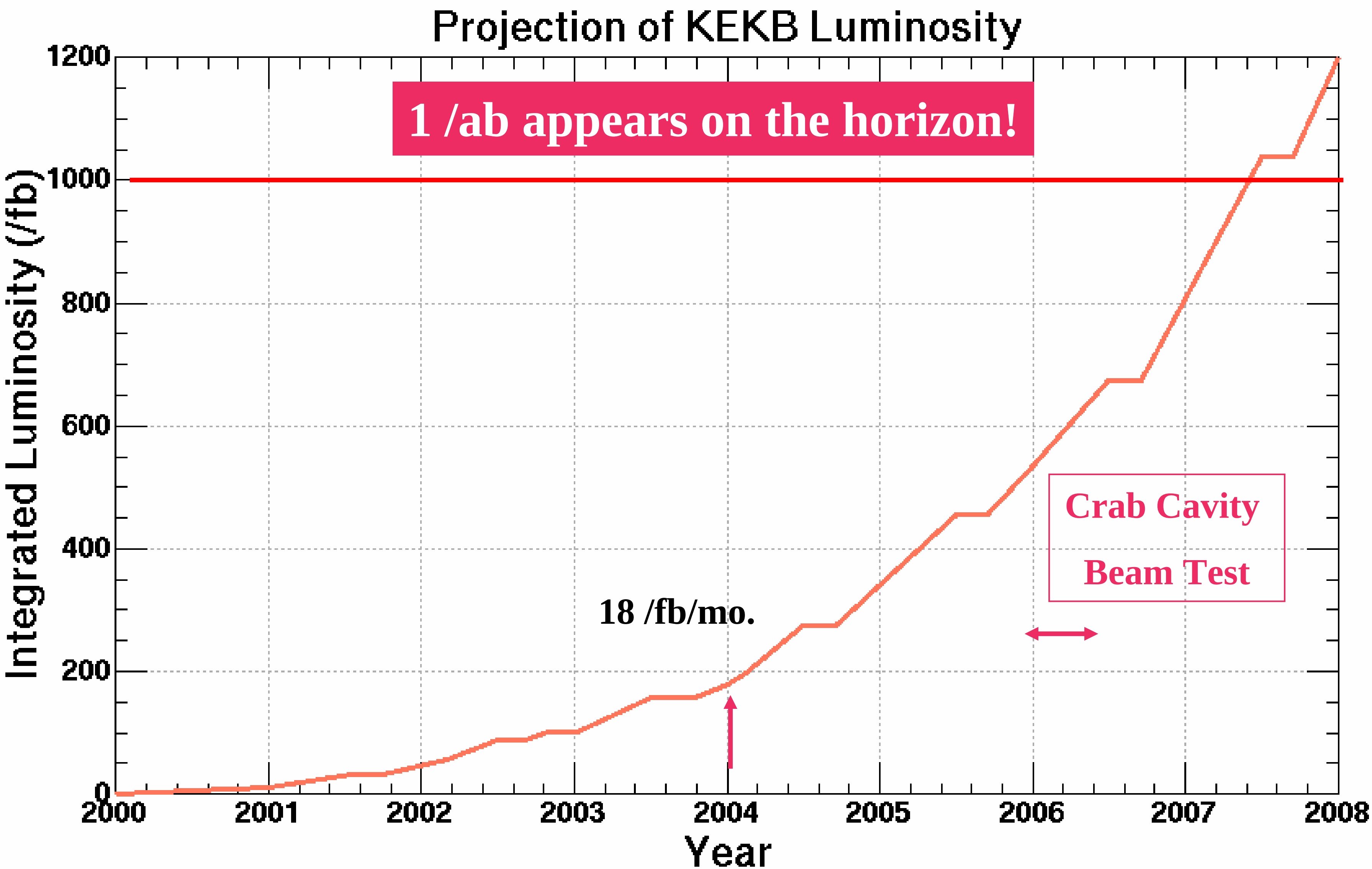
⇒What will happen? HOM, RF cavity?

⇒If everything is OK, luminosity doubles (?)

5. Summary

- KEKB has achieved its design luminosity of $1 * 10^{34}$ cm^{-2} s^{-1} without crab crossing.
- Crab cavities are planned to be installed in both rings by summer 2006.
  - Hardware preparation is going well.
  - A doubling of the luminosity is hoped for.

KEKB Luminosity Projection



(K.Oide MAC2004)

•Some numbers related to ECE at KEKB LER

Photons emitted in a bend

$$N_\gamma = \frac{5}{2\sqrt{3}}\alpha\gamma\frac{l}{\rho}$$ **= 4.1 /positron/bend**

Photons emitted in a bend / bunch

$N_\gamma N_{e^+}$ **=1.3 x 10^{11}**

Number of photoelectrons / bunch

$N_\gamma N_{e^+} Y_{pe}$ **= 1.3 x 10^{10}**

Electric field by the bunch at the wall

$$E = \frac{eN_b}{2\pi\varepsilon_0\sigma_b}\frac{1}{a}$$

Momentum kick at the wall

$$\Delta p / c = eE\frac{\sigma_b}{c}\frac{1}{c} = 2r_e m_e N_b \frac{1}{a}$$ **= 1.8 keV/c**

Velocity change

$$\beta = \frac{p}{E} = \frac{p}{\sqrt{p^2 + m_e{}^2}}$$ **= 0.0037**

Kinetic energy

$T = E - m_e$ **= 3.5 eV**

Traversal time of electron

$$\tau = \frac{2a}{\beta c}$$ **= 85 ns**

ρ = 15.9 m, l = 0.89 m,
Energy = 3.5 GeV,
N_{e+} = 3.1 10^{10}, σ_b = 6 mm,
a = 47 mm

H.Fukuma ECOULD2002
http://wwwslap.cern.ch/collective/ecloud02/

•Main source of synchrotron radiation(SR)

Main bend

Total length : 0.9m x 107 = 96m (3.2% of circumference)

Radiation power : 2.1MW at design current of 2.6A

SR emitted by bend starts to hit the vacuum duct at 0.4m apart from the exit of the bend.

Wiggler

Total length : 105m (3.5% of circumference)

Radiation power : 1.9MW

H.Fukuma ECOULD2002
http://wwwslap.cern.ch/collective/ecloud02/

Higher Current:

- More rf power, cooling, injector, …
- More HOM heating (more bunches)
- Beam Instabilities
- Electron clouds, fast ions, …

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

Head-on collision:

- Parasitic crossing for large number of bunches
- Background due to separation bends

Crossing angle:

- degrades ξ_y, < 0.06
- restored by crab crossing

$$\sigma_z \leq \beta_y^*$$

Smaller β_y^*:

- Smaller physical/dynamic aperture
- Shorter lifetime, more background, …

Shorter σ_z:

- More HOM heating
- Coherent synch. rad.
- Shorter lifetime, more background