

Update on SuperKEKB Design

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June/14/2006

3rd SuperB workshop at SLAC

- Machine parameters and luminosity estimation
- Recent status of crab cavity
 - since 2nd SuperB WS (I reported at Frascati).

Luminosity

(Estimation of geometrical luminosity)

- Luminosity formula

$$L = f_{col} \int dx dy dz_1 dz_2 ds \rho_1(x, y, z_1; s) \rho_2(x, y, z_2; -s) \delta\left(s - \frac{z_1 - z_2}{2}\right)$$

$$= f_{col} \int dx dy dz_1 ds \rho_1(x, y, z_1; s) \rho_2(x, y, z_1 - 2s; -s)$$

$$s = \frac{z_1 - z_2}{2}$$

$$z_1 = -\infty \sim +\infty$$

$$z_2 = -\infty \sim +\infty$$


- Particle density

$$\rho(x, y, z; s) = \frac{N}{2\pi\sigma_x(s)\sigma_y(s)} \exp\left(-\frac{x^2}{2\sigma_x^2(s)} - \frac{y^2}{2\sigma_y^2(s)}\right) \frac{1}{\sqrt{2\pi}\sigma_z} \exp\left(-\frac{z^2}{2\sigma_z^2}\right)$$

- Beam size

$$\sigma_{x,y}(s) = \sqrt{\varepsilon_{x,y} \beta_{x,y}^* \left(1 + \frac{s^2}{\beta_{x,y}^{*2}}\right)}$$

↑ emittance
 ↑ β -function

 **Traveling focus**
 z-dependent waist

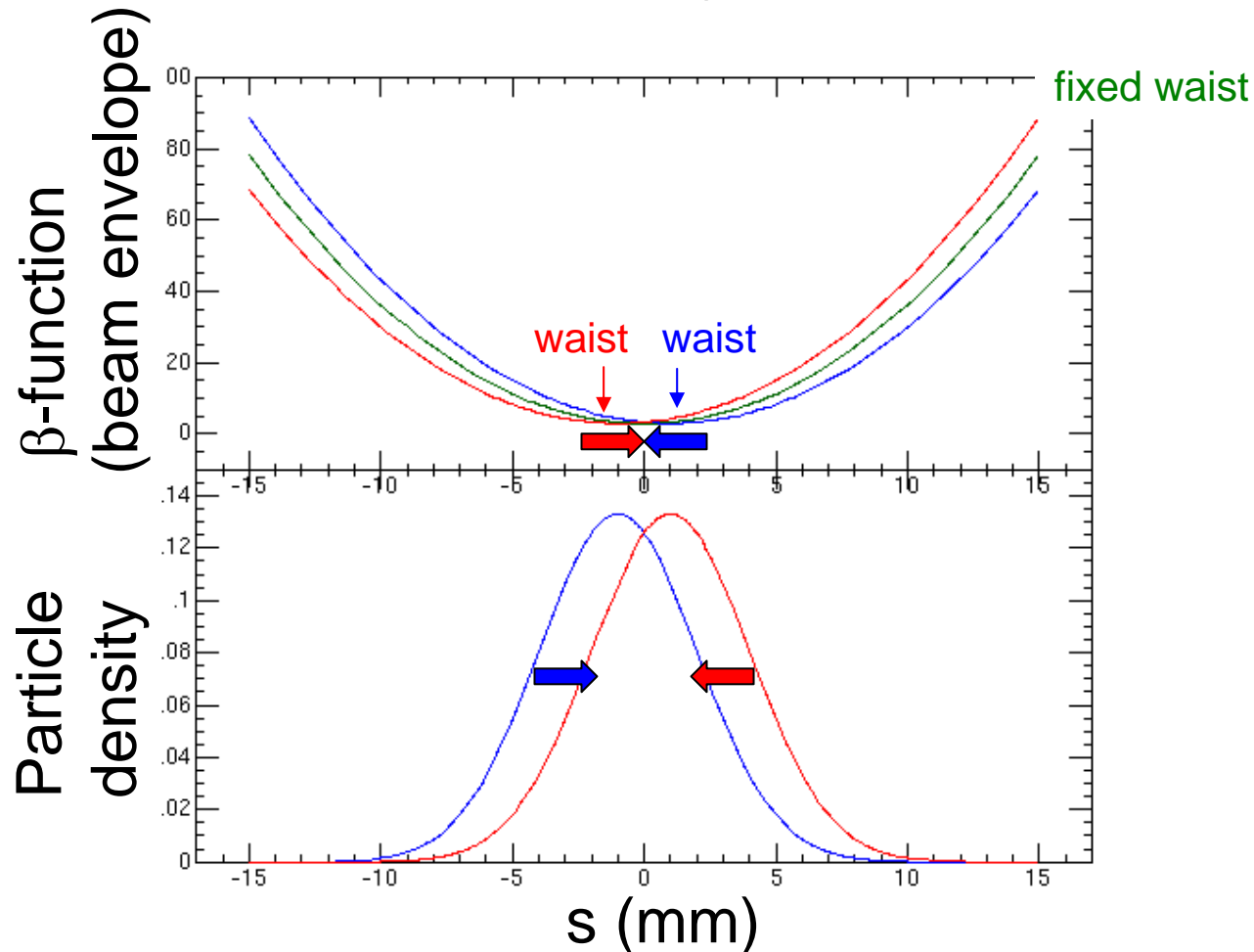
Waist locates
the most density
position.

$$\sigma_{x,y}(z; s) = \sqrt{\varepsilon_{x,y} \beta_{x,y}^* \left(1 + \frac{(s - az)^2}{\beta_{x,y}^{*2}}\right)}$$

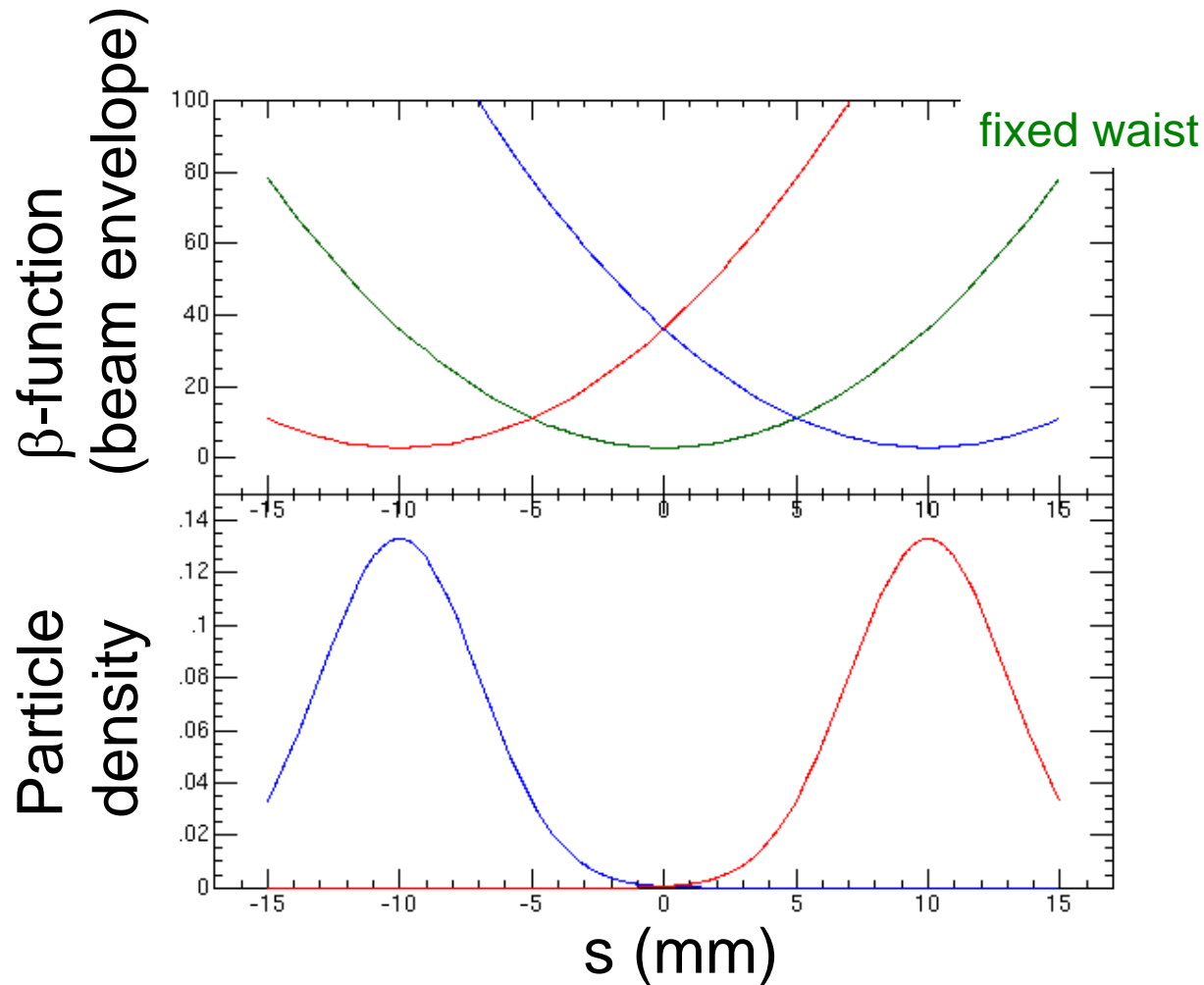
$$a = \frac{1}{2} \text{ for } z = z_1, \quad a = -\frac{1}{2} \text{ for } z = z_2$$

Traveling Focus

The particles of the head and tail of a bunch are focused in different places, so that the focus point is running from the head to the tail.



Traveling Focus

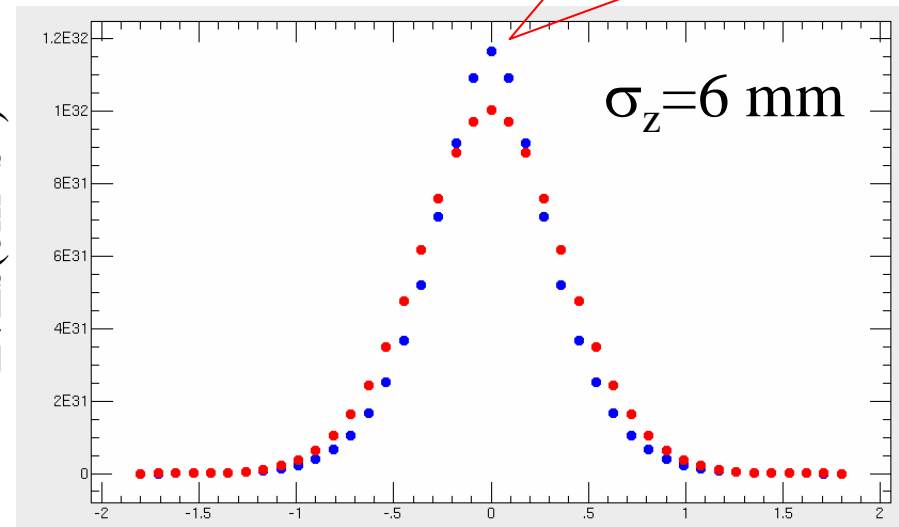
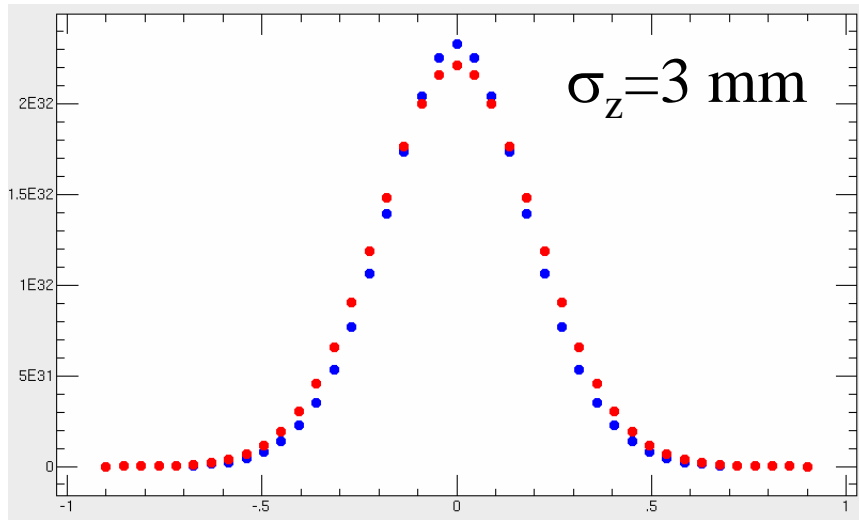


Different particles have different waist.

SuperKEKB (geometrical)

$I_+ = 10 \text{ A} / I_- = 4.4 \text{ A} (N_b = 5000)$
 $N_+ = 1.26 \times 10^{11} / N_- = 5.5 \times 10^{10} \text{ per bunch}$
 $\epsilon_x = 18 \text{ nm}$
 $\epsilon_y = 0.18 \text{ nm}$
 $\beta_x = 20 \text{ cm}$
 $\beta_y = 3 \text{ mm}$

At $s=0$,
beam-beam
is relaxed for TF.



Head-on: 5.33×10^{35} ($\xi_y = 0.25$)
 Traveling focus: 5.61×10^{35}
 gain ~ 5.3%



Hourglass
effect

Head-on: 4.37×10^{35} s (cm)
 Traveling focus: 4.70×10^{35}
 gain ~ 7.5%

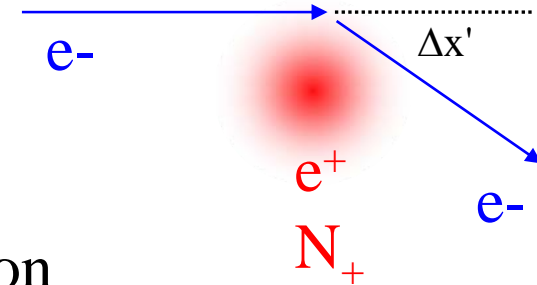
Beam-beam tune shift

- Beam-beam tune shift

$$\xi_{x,y} = \frac{\beta_{x,y}}{4\pi} k_{x,y} \begin{cases} \Delta x' = -k_x x & \Delta x' = -\frac{N_+ r_e}{\gamma_-} F_x \\ \Delta y' = -k_y y & \Delta y' = -\frac{N_+ r_e}{\gamma_-} F_y \end{cases}$$

$k=1/f$, f is focal length.

BB kick = Deflection by Coulomb force



- Beam-beam tune shift with beam distribution

$$\xi_x = \frac{r_e}{4\pi\gamma_-} \int dz \rho_+(z) \beta_x(s) \frac{\partial F_x}{\partial x} \bigg|_{x=z\theta, y=0} \delta\left(s - \frac{z}{2}\right)$$

Crossing angle: 2θ

$$\xi_y = \frac{r_e}{4\pi\gamma_-} \int dz \rho_+(z) \beta_y(s) \frac{\partial F_y}{\partial y} \bigg|_{x=z\theta, y=0} \delta\left(s - \frac{z}{2}\right)$$

$x = z\theta$

- Bassetti-Erskine formula (Coulomb force)

$$F = F_y + iF_x$$

$$= \frac{2\sqrt{\pi}}{\Sigma} \left[w\left(\frac{x+iy}{\Sigma}\right) - \exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}\right) w\left(\frac{x/\kappa + iky}{\Sigma}\right) \right]$$

$$\Sigma = \sqrt{2(\sigma_x^2(s) - \sigma_y^2(s))}$$

$$\kappa = \sigma_y(s)/\sigma_x(s)$$

$$w(z) = \exp(-z^2) \{1 - \operatorname{erf}(-iz)\}$$

$$\frac{\partial F_x}{\partial x} \bigg|_{y=0} = \frac{4}{\Sigma^2} \left\{ 1 - \kappa \exp\left(-\frac{x^2}{2\sigma_x^2}\right) \right\} - \frac{4\sqrt{\pi}}{\Sigma^3} x \operatorname{Im} \left[w\left(\frac{x}{\Sigma}\right) \right] + \frac{2\sqrt{\pi}}{\Sigma} \left(\frac{x}{\sigma_x^2} \right) \exp\left(-\frac{x^2}{2\sigma_x^2}\right) \operatorname{Im} \left[w\left(\frac{\kappa}{\Sigma} x\right) \right]$$

$$\frac{\partial F_y}{\partial y} \bigg|_{y=0} = -\frac{4}{\Sigma^2} \left\{ 1 - \frac{1}{\kappa} \exp\left(-\frac{x^2}{2\sigma_x^2}\right) \right\} - \frac{4\sqrt{\pi}}{\Sigma^3} x \operatorname{Re} \left[iw\left(\frac{x}{\Sigma}\right) \right] + \frac{2\sqrt{\pi}}{\Sigma} \left(\frac{2x}{\Sigma^2} \right) \exp\left(-\frac{x^2}{2\sigma_x^2}\right) \operatorname{Re} \left[iw\left(\frac{\kappa}{\Sigma} x\right) \right]$$

SuperKEKB	Crab crossing		Finite crossing		
E (LER/HER)	3.5 / 8.0				GeV
I (LER/HER)	10 / 4.4				Å
N (LER/HER)	1.26x10 ¹¹ / 5.5x10 ¹⁰				
n _b	5000				
ε _x	18	9.0	6.0	6.0	nm
ε _y	0.18	0.045	0.06	0.06	nm
β _x [*]	20	20	10	5	cm
β _y [*]	3	3	1	0.5	mm
σ _x [*]	60	42	25	17	μm
σ _y [*]	0.73	0.37	0.25	0.17	μm
σ _z	3	3	6	6	mm
θ _x	0 (30)	0 (30)	30	30	mrad
ξ _{x0} ^{*1}	0.196	0.395	0.042	0.022	
ξ _{y0} ^{*1}	0.267 (0.241 ^{*2})	0.758	0.197	0.169	
L _{geometrical}	5.3(5.6 ^{*2})	15	9.1	12	x10 ³⁵ cm ⁻² s ⁻¹

^{*1}nominal tune shift ^{*2}travel focus

In the real machine,

Finite crossing scheme degrades luminosity due to nonlinear terms.

To alleviate this,
we introduce crab crossing or crab waist.

See ohmi-san 's talk(Beam-beam simulations)

SuperKEKB	Crab crossing		Crab waist		
E (LER/HER)	3.5 / 8.0				GeV
I (LER/HER)	10 / 4.4				A
N (LER/HER)	1.26x10 ¹¹ / 5.5x10 ¹⁰				
n _b	5000				
ε _x	18	9.0	6.0	6.0	nm
ε _y	0.18	0.045	0.06	0.06	nm
β _x [*]	20	20	10	5	cm
β _y [*]	3	3	1	0.5	mm
σ _z	3	3	6	6	mm
θ _x	0 (30)	0 (30)	30	30	mrad
v _s	0.025	0.025	0.01	0.01	
ξ _{x0} ^{*1}	0.196	0.395	0.042	0.022	
ξ _{y0} ^{*1}	0.267	0.758	0.197	0.169	
L (W.S ^{*2})	6.1	8.0	6.7	10	x10 ³⁵ cm ⁻² s ⁻¹
L (S.S ^{*3})	6.0	8.3	4.8	9.0	x10 ³⁵ cm ⁻² s ⁻¹

^{*1}nominal tune shift

^{*2}Weak-Strong simulation ^{*3}Strong-Strong simulation

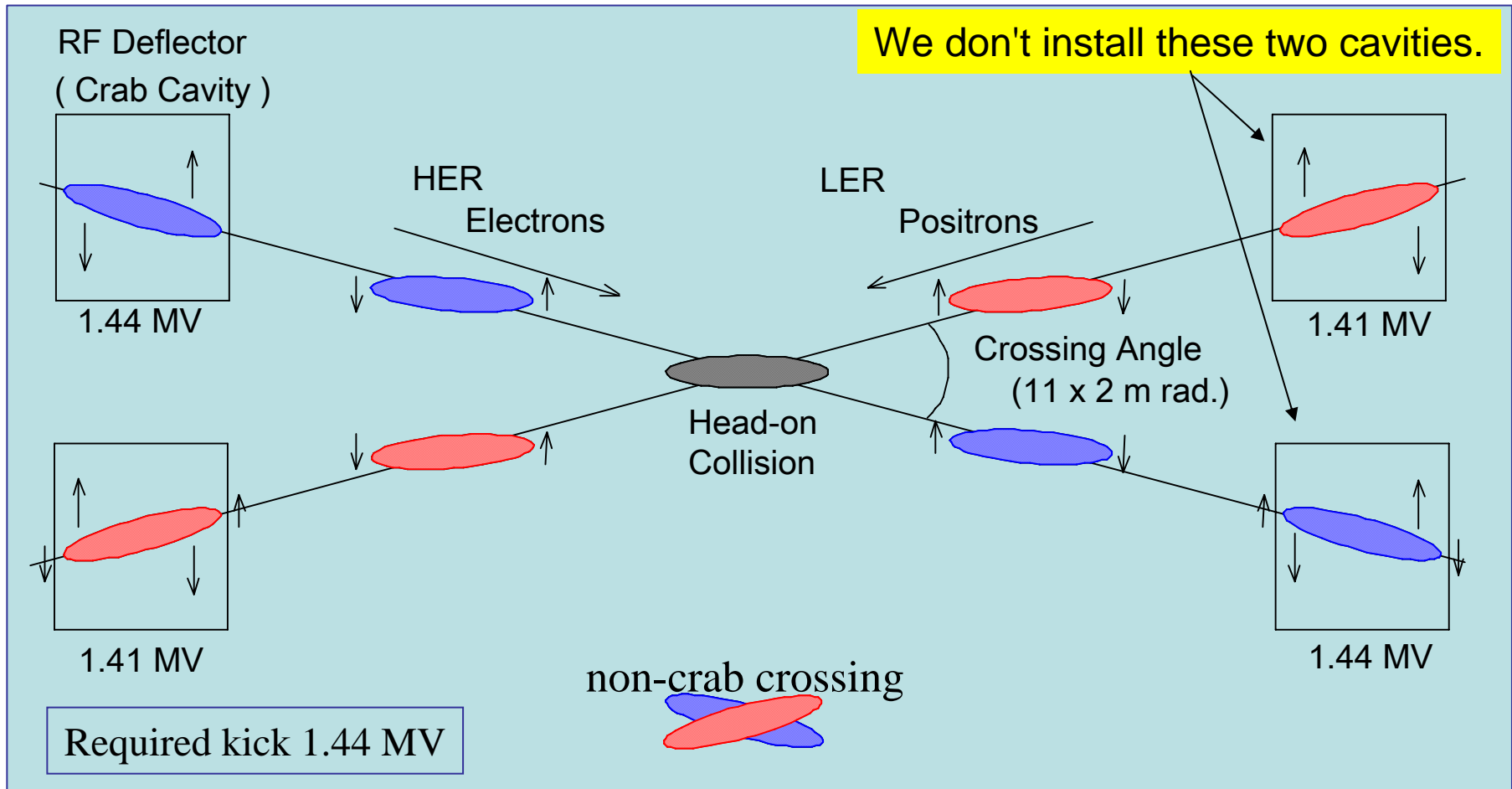
Homework

What is crab crossing
and
Recent status of the crab cavity

KEKB Crab Crossing

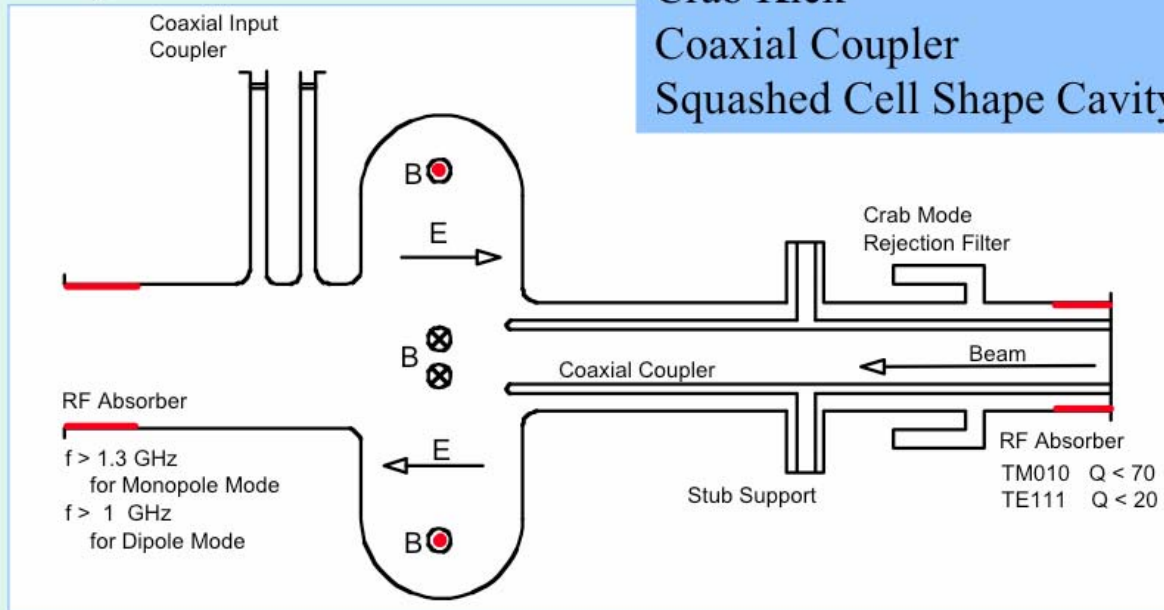
The crab crossing scheme allows a large crossing angle collision without introducing any synchrotron-betatron coupling resonances. ^{1, 2)}

- 1) R.B.Palmer, SLAC-PUB-4707,1988
- 2) K.Oide and K.Yokoya, SLAC-PUB-4832,1989



Conceptual Design of KEKB Crab Cavity

Top View



Crab Kick

Coaxial Coupler

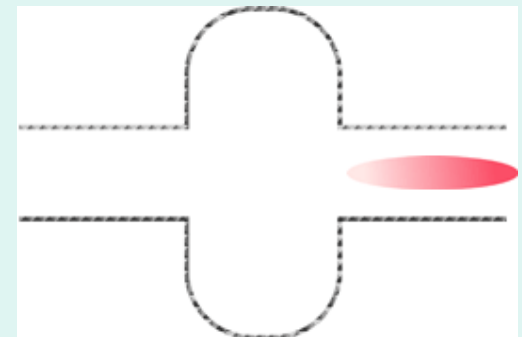
Squashed Cell Shape Cavity

TM110 B-field

1.44 MV

TM010, TE111

TM110*

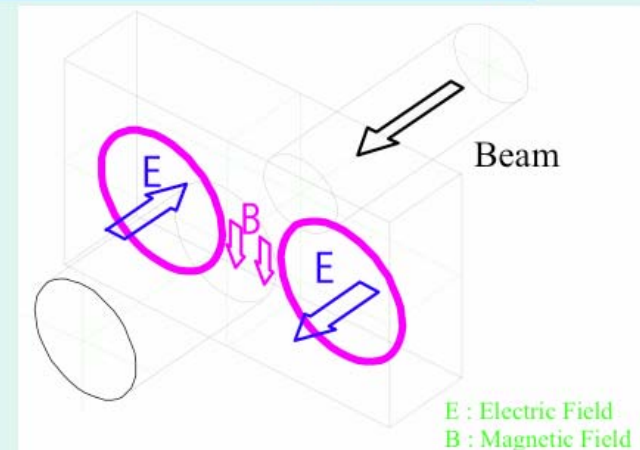


We use TM110 to make horizontal kick.

Squashed Cell Shape Cavity

⇒ The squashed cell shape cavity scheme was studied extensively by Akai at Cornell in 1991 and 1992 for CESR-B under KEK-Cornell collaboration.

We adopted this design as “base design”!



Crab crossing with a crab cavity

x-position at IP induced by kick with a crab cavity:

$$x^* = \frac{\sqrt{\beta_x^* \beta_x^{crab}}}{2 \sin \pi \nu_x} \cos(\pi \nu_x - |\psi_x^* - \psi_x^{crab}|) \cdot \Theta_x^{crab} = \frac{\sqrt{\beta_x^* \beta_x^{crab}}}{2} \Theta_x^{crab}, \quad \text{if } \Delta\psi_x = \psi_x^* - \psi_x^{crab} = \frac{\pi}{2} + n\pi$$

Betatron phase advance

Dipole kick changes equilibrium position.

(If ν_x =integer, orbit diverges.)

Kick angle due to crab cavity

Θ_x^{crab}

Crab cavity

β_x^{crab}
 Ψ_x^{crab}

$dx^*/dz = \tan(\theta_x/2)$

IP

β_x^*
 Ψ_x^*

Crossing angle: θ_x

Closed orbit distortion(COD)

Betatron oscillation:

$$\frac{d^2 x}{ds^2} + kx = f_{external}$$

If $f_{external}$ is independent on x , $x = x_0 + x_{COD}$.

Bunch is crabbing in the whole ring.

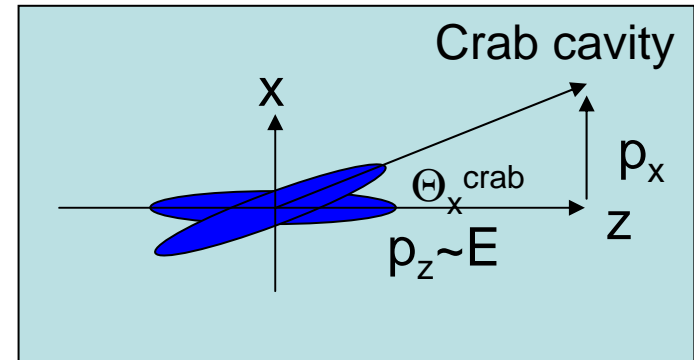
Crab crossing with a crab cavity

Transverse kick of crab cavity:

$$\frac{dp_x}{dt} = ecB \quad z = ct$$

$$\Theta_x^{crab} = \frac{p_x}{E} = \frac{eV_{\perp} \sin(2\pi f_{rf} z/c)}{E}$$

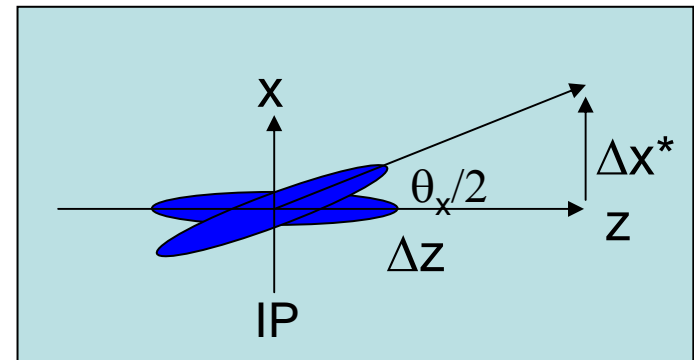
f_{rf} : rf frequency



Half crossing angle is:

$$\tan \frac{\theta_x}{2} = \frac{dx^*}{dz} = \frac{\sqrt{\beta_x^* \beta_x^{crab}}}{2} \frac{d\Theta_x^{crab}}{dz} \Big|_{z=0}$$

$$= \frac{2\pi f_{rf} eV_{\perp} \sqrt{\beta_x^* \beta_x^{crab}}}{2c(E/e)}$$



Deflecting voltage of the crab cavity:

$$V_{\perp} = \frac{2c(E/e)}{2\pi f_{rf} \sqrt{\beta_x^* \beta_x^{crab}}} \tan \frac{\theta_x}{2}$$

Requirement for the crab cavity at KEKB

KEKB	LER	HER	
E	3.5	8	GeV
f_{rf}	509		MHz
θ_x	22		mrad
β_x^*	0.59	0.56	m
β_x^{crab}	45	250	m
V_{\perp}	1.4	1.4	MV

We have achieved 1.4 MV at horizontal test on June/8/2006.

Superconducting crab cavity for KEKB

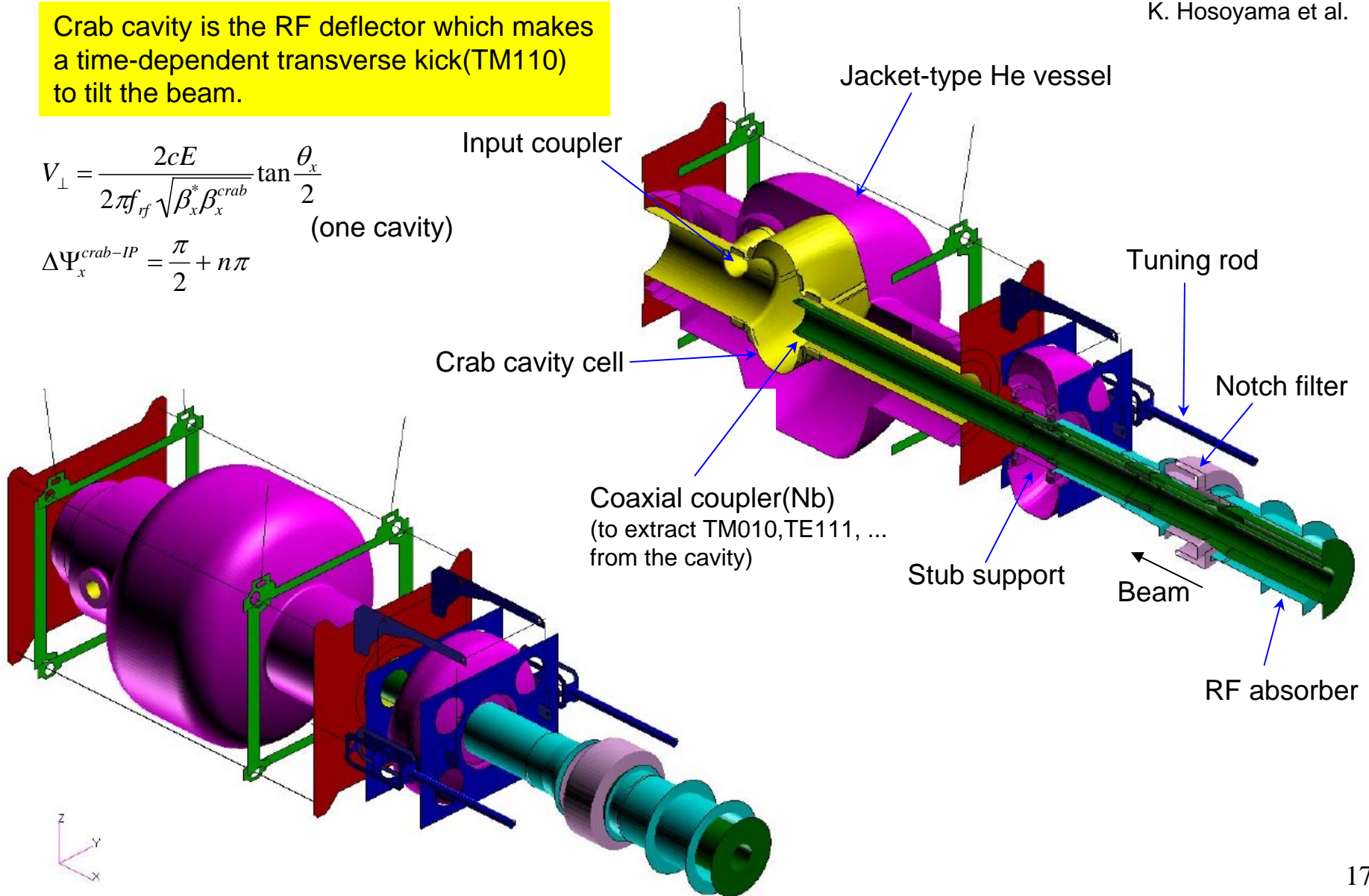
K. Hosoyama et al.

Crab cavity is the RF deflector which makes a time-dependent transverse kick(TM110) to tilt the beam.

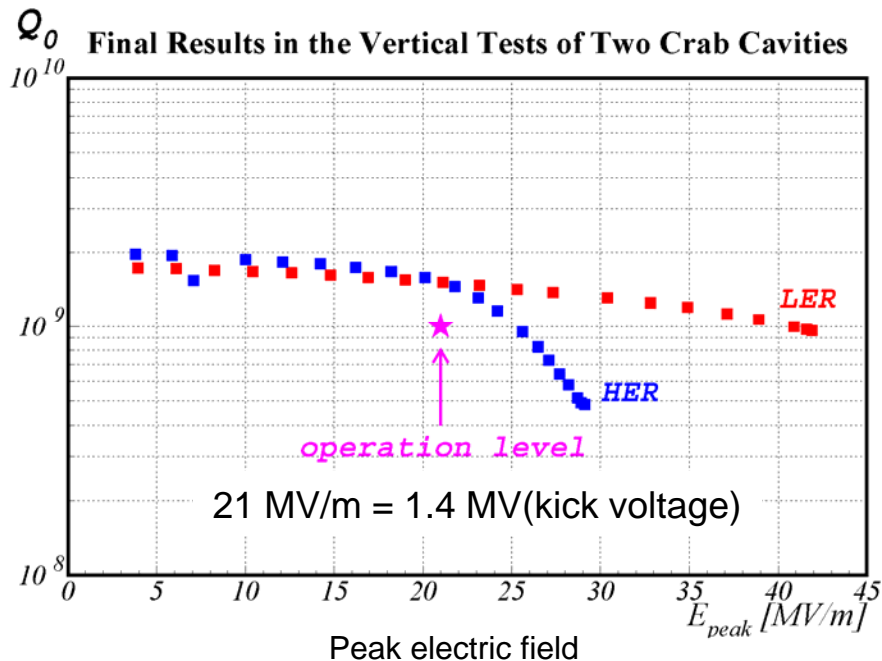
$$V_{\perp} = \frac{2cE}{2\pi f_{rf} \sqrt{\beta_x^* \beta_x^{crab}}} \tan \frac{\theta_x}{2}$$

(one cavity)

$$\Delta \Psi_x^{crab-IP} = \frac{\pi}{2} + n\pi$$



Results of Q-value at the vertical test for the crab cavities



LER cavity has achieved the best performance for the peak electric field.

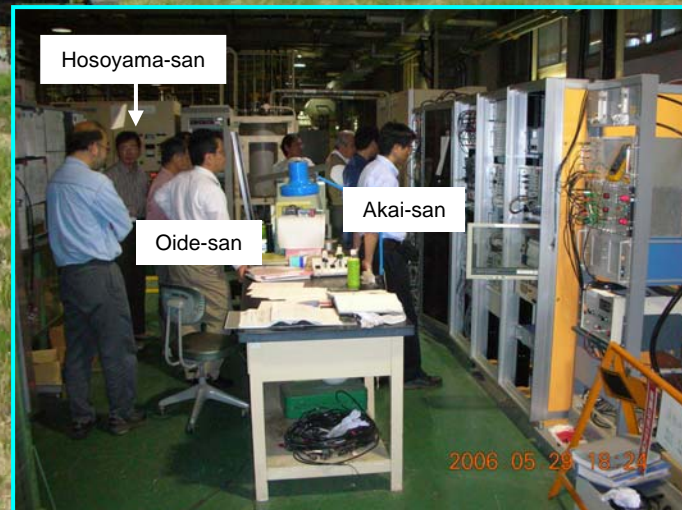
HER cavity is worse performance than that of LER, however it satisfies the requirement.

Horizontal test of crab cavity

Mt. Tsukuba

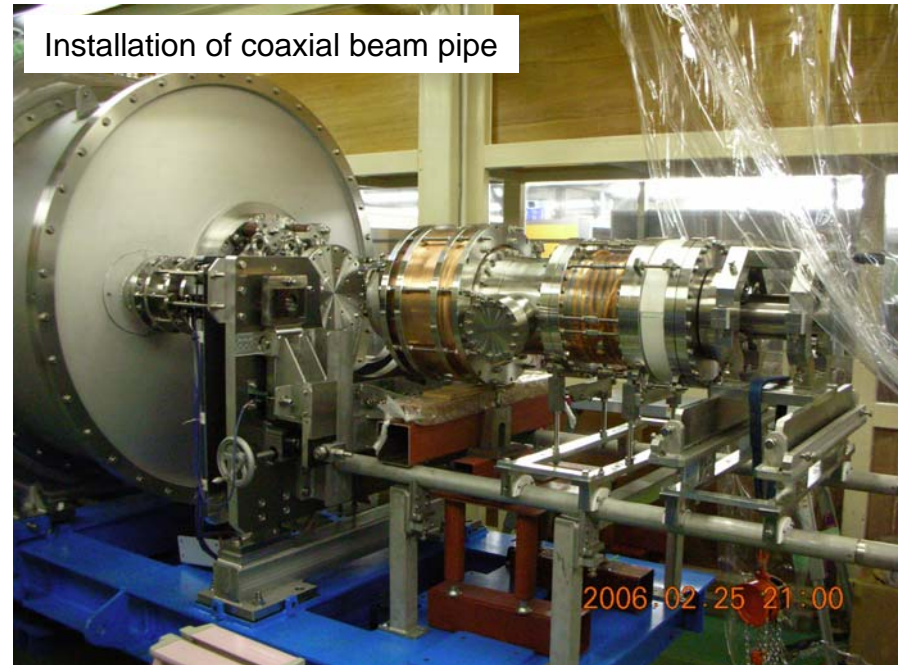


HER Crab cavity

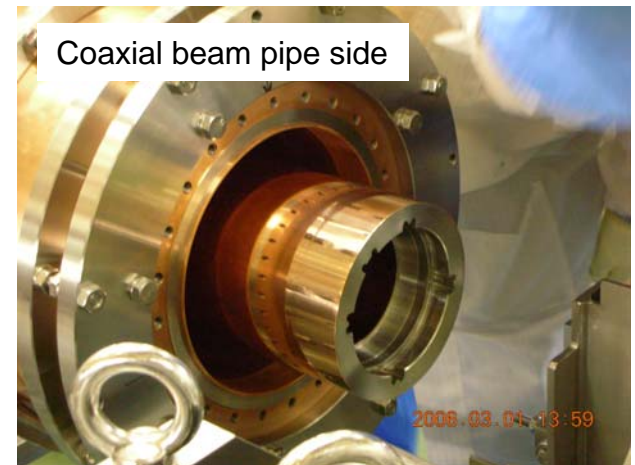


Assembly of the **first** crab cavity.

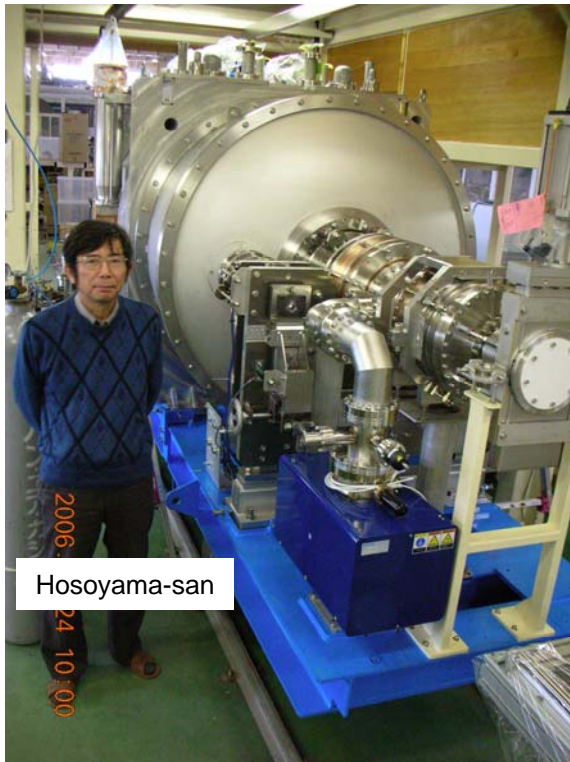
Coaxial beam pipe assembly



Installation was very difficult !



Assembly of HER crab cavity has been done on April 21!



The cavity was moved for the horizontal test.

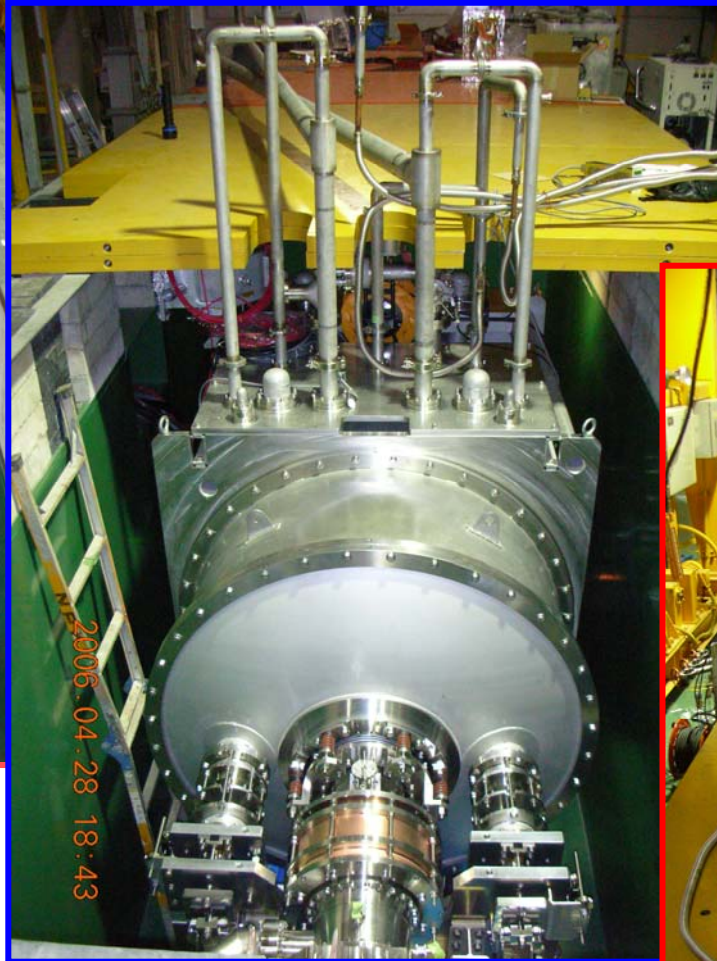


Experimental site

Installation of the crab cavity in the test stand



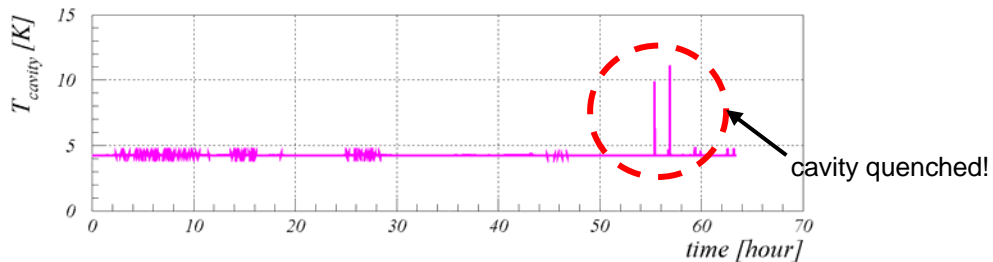
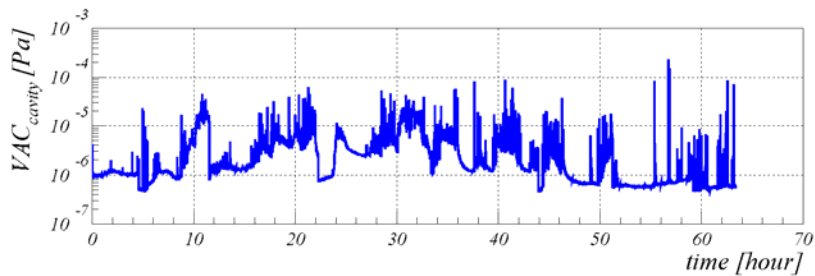
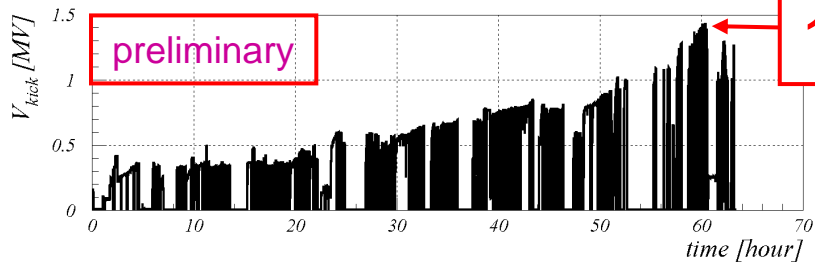
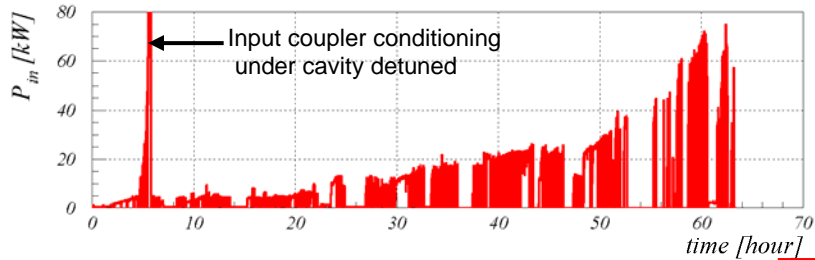
Connection of the transfer line of helium



Iron shield for radiation



Horizontal test of HER crab cavity



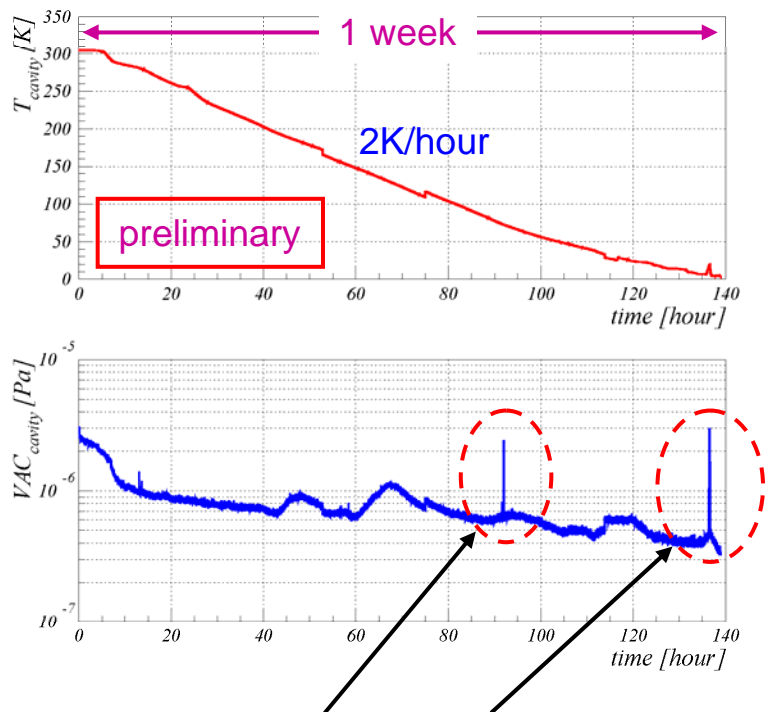
We finally achieved
operation level (1.4MV)
on June/8 by C.W.!!!



Crab cavity cool-down toward 4K

The cavity was cooled down very slowly.

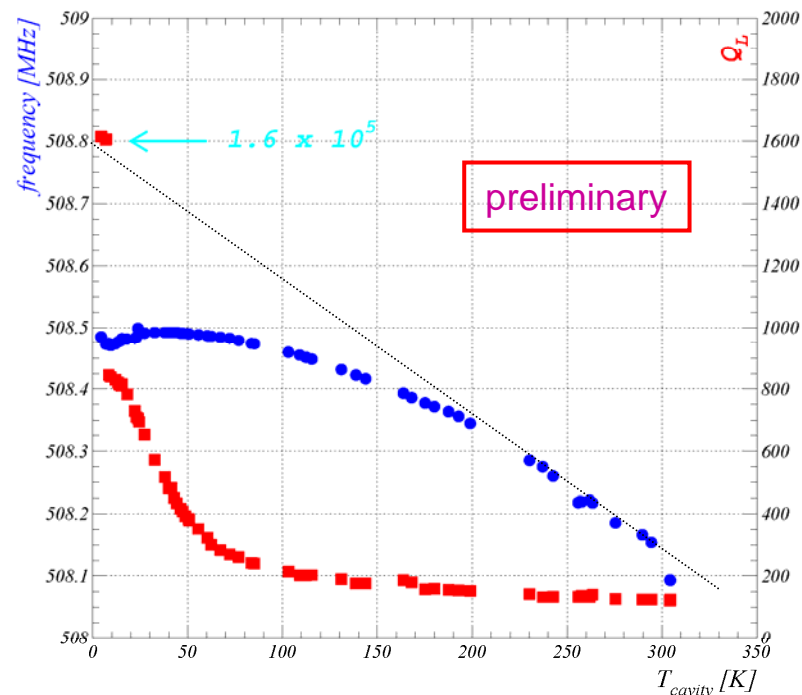
Horizontal Test for HER Crab Cavity



Due to the adjustment of the helium flow

The resonant frequency was lowered by about 300kHz than the operation frequency(508.8MHz).
Now we are investigating the reason.

Crab HER Horizontal Test (06/05/12 ~ 06/05/31) $\times 10^{-2}$



The loaded Q value measured by network analyzer was 1.6×10^5 .
It was consistent with the estimation (2×10^5) by HFSS.
In high power test, the loaded Q value was 1.7×10^5 .

What needs to be fixed

- Discrepancy between resonant frequency and operation frequency is about 300kHz.
- Range of tuner position is smaller than that of expected.
- Tuner feedback stability



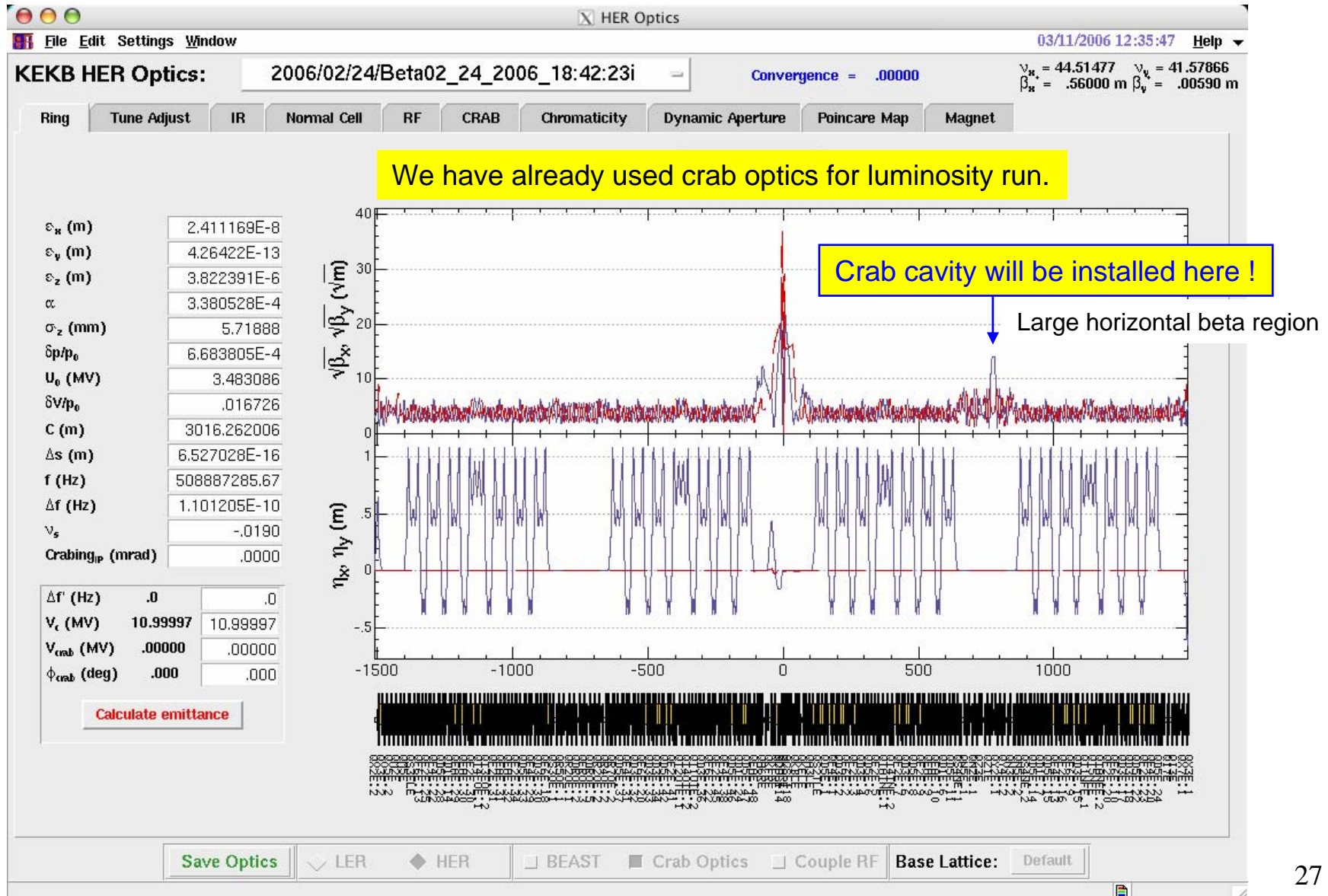
Near future plan

- Tuner reforming
- Cavity pre-tuning
- HPR for the cavity
- Re-assembly of the HER crab cavity
- Assembly of the LER crab cavity

Two crab cavities will be ready for the installation to the tunnel in the end of this year(hopefully).

Please wait ...

Optics for crab cavity

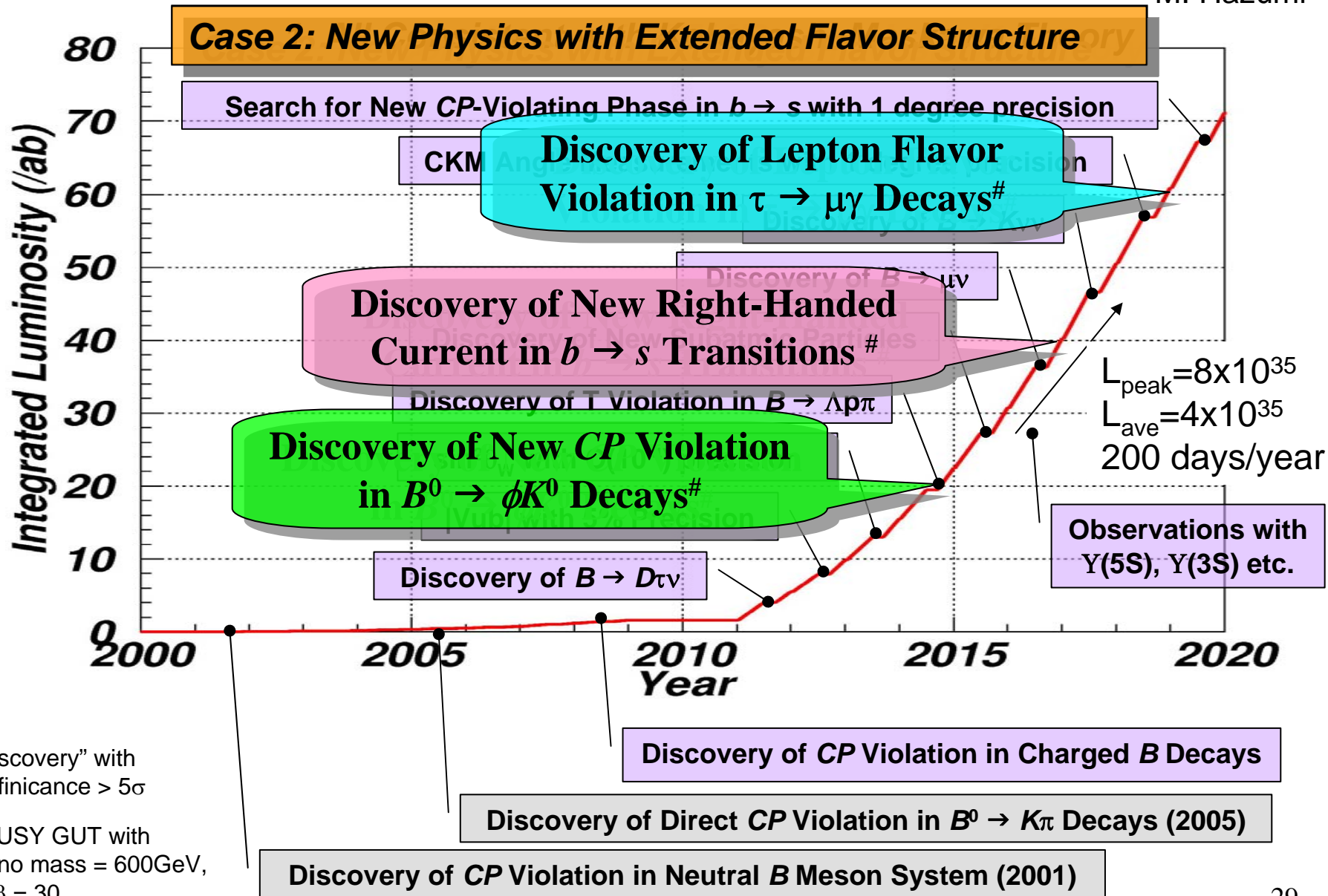


Summary

- Machine parameters are reconsidered.
- Both of crab crossing and crab waist are hopeful to achieve higher luminosity.(→BB simulation)
 - Extremely small beta has to be achieved for the crab waist.
- Traveling focus provides luminosity gain about 5-7%.
- In case of crab crossing, better betatron tune is 0.503/.55, however it might be prevented by physical aperture around IR due to dynamic effects.(→IR issues)
 - Other things such as electron cloud, CSR, etc. should be also solved at SuperKEKB.
- Crab cavity is assembled successfully and have been operated at the horizontal test.
- Required deflecting voltage of 1.4 MV has been achieved.

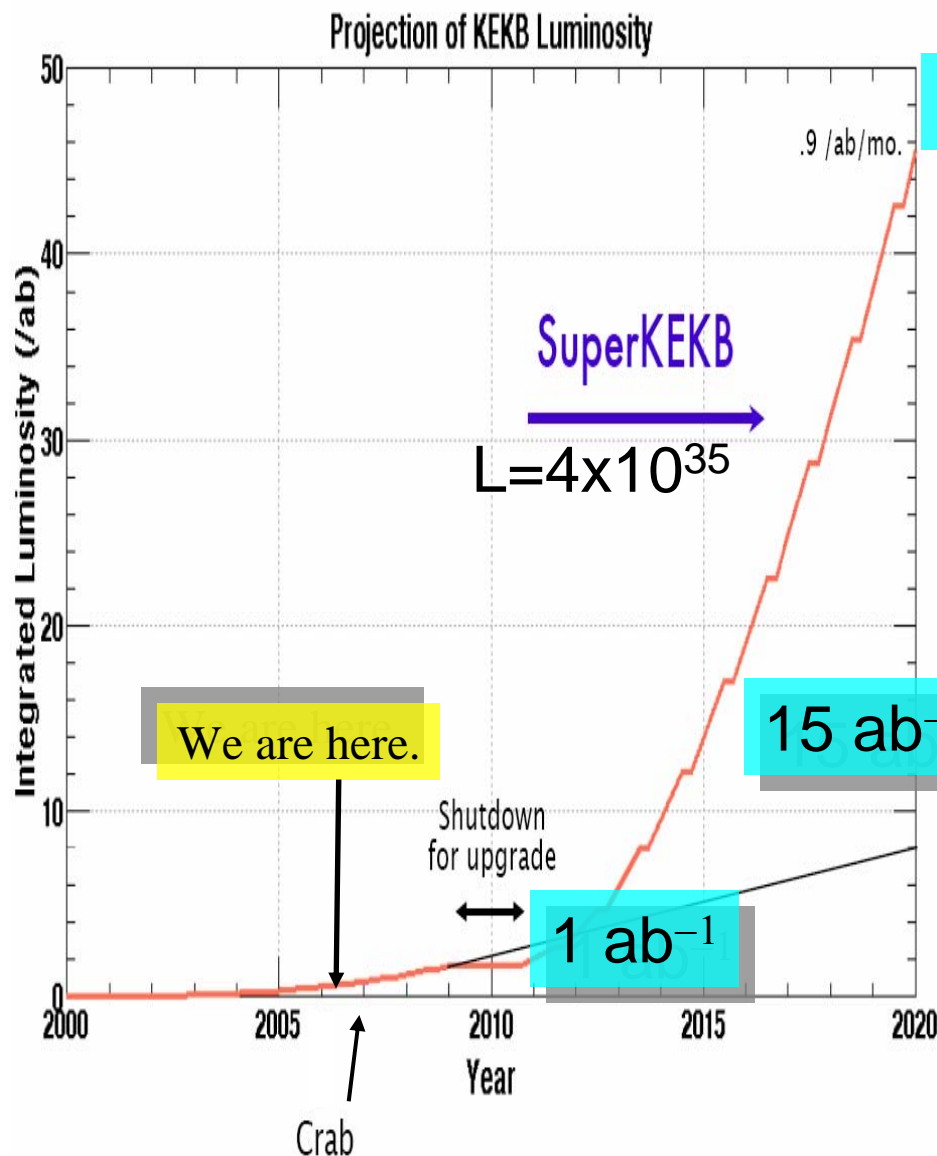
Major achievements expected at SuperKEKB

M. Hazumi



Backup slides

Projection of integrated luminosity and expected discoveries at SuperKEKB



Discoveries of
 $B \rightarrow K \nu \nu$

Discovery of
new CP violation
in $B^0 \rightarrow \phi K_s$

Discoveries of
 $B^0 \rightarrow D \tau \nu, \tau \nu$

Discoveries at SuperKEKB and required integrated luminosities (discovery = significance $> 5\sigma$)

Item	Integrated luminosity (ab^{-1})	New physics
$B \rightarrow \tau \nu$	0.5	charged Higgs
$B \rightarrow D \tau \nu$	1*	charged Higgs
New CP violation in $B^0 \rightarrow \eta' K_S$	10**	SUSY breaking, extra dimension, GUT, baryogenesis/leptogenesis
New CP violation in $B^0 \rightarrow \phi K_S$	15**	SUSY breaking, extra dimension, GUT, baryogenesis/leptogenesis
$B \rightarrow \mu \nu$	30***	SUSY MFV
$B \rightarrow K \nu \nu$	50*	EW baryogenesis, dark matter, SUSY

* From SuperKEKB. Estimations will be updated in Autumn 2006.

** Assuming WA values as of August 2005.

*** Guestimation assuming $\text{Br}=4 \times 10^{-7}$, full rec. eff. = 0.1%, and no background. Need simulation studies.

Luminosity

- Luminosity formula (well-known)

The diagram shows the luminosity formula $L = \frac{N_{e+} N_{e-} f}{4 \pi \sigma_x^* \sigma_y^*} R_L$ with arrows pointing from descriptive labels to each variable. The labels are: 'Number of particles/bunch (e+)' for N_{e+} , 'Number of particles/bunch (e-)' for N_{e-} , 'Collision frequency' for f , 'Horizontal beam size at IP' for σ_x^* , 'Vertical beam size at IP' for σ_y^* , and 'Luminosity reduction due to geometrical effect' for R_L .

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

Number of particles/bunch (e+)

Number of particles/bunch (e-)

Collision frequency

Luminosity reduction due to geometrical effect

Horizontal beam size at IP

Vertical beam size at IP

Luminosity

- Luminosity formula for machine design

Beam current

1.8/1.35 A (KEKB) → 9.4/4.1 A (SuperKEKB)

It correlates with many things.

Lorentz factor

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

Classical electron radius

Beam size ratio
1 ~ 2 % (flat beam)

Beam-beam parameter

(Strength of interaction between colliding beams)
0.055 (KEKB) → 0.19 (SuperKEKB)

Limited by beam-beam effect

Geometrical factor
due to hour-glass effect
and crossing angle
0.8 ~ 1 (short bunch)

Luminosity

$1.63 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ (KEKB)
→ $4.0 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$ (SuperKEKB)

Vertical beta function

(Focal depth)

6.5 mm/6.2 mm (KEKB)
→ 3 mm/3 mm (SuperKEKB)

Limited by
bunch length

Bunch length ($\sigma_z < \beta_y^*$)
~7 mm (KEKB) → 3 mm (SuperKEKB)

Luminosity is proportional to beam currents, beam-beam and inverse of vertical beta function at IP.

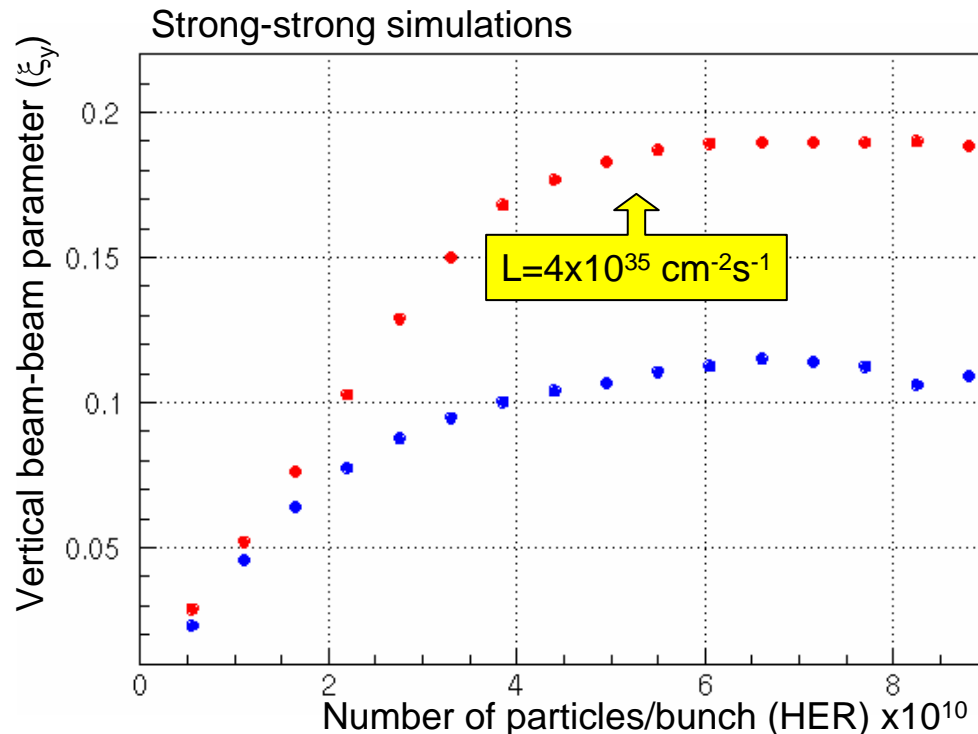
Limited by HOM, CSR

Lattice parameters w/o and w/ beam-beam effect

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	130	nm
Horizontal beta at IP	β_x^*	20	1.9	cm
Vertical beta at IP	β_y^*	3	2.4	mm
Horizontal beam size	σ_x^*	69	50	mm
Vertical beam size	σ_y^*	0.73	1.0	mm
Bunch length	σ_z	3	3	mm
Crossing angle (30 mrad crab crossing)	θ_x	0	0	mrad
Luminosity reduction	R_L	0.86	0.82	
ξ_x reduction	R_{ξ_x}	0.99	0.98	
ξ_y reduction	R_{ξ_y}	1.11	1.16	
Reduction ratio	R_L/R_{ξ_y}	0.78	0.70	
Horizontal beam-beam (estimated with S-S simulation)	ξ_x	0.152	0.030	
Vertical beam-beam (estimated with S-S simulation)	ξ_y	0.215	0.187	
Luminosity	L	4.0×10^{35}		$\text{cm}^{-2}\text{s}^{-1}$

Dynamic
effect

Head-on and finite-crossing collision



Head-on (crab-crossing)

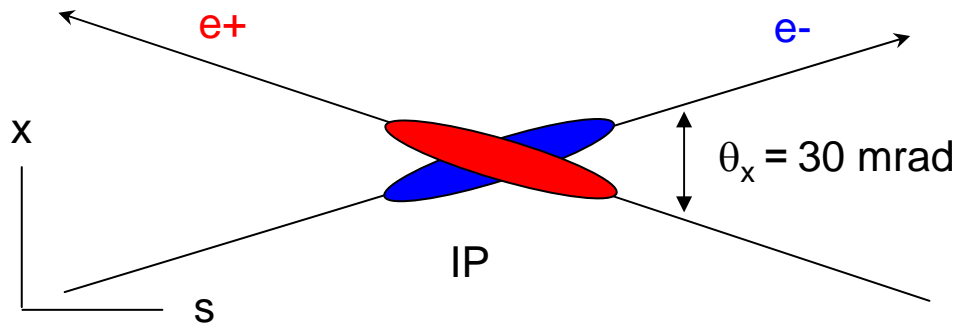
$$v_x/v_y = .503/.550$$

Crossing angle: 30 mrad

- Head-on collision will boost the beam-beam parameter up to 0.19.
- Crab cavity is one of the most important components, because it can realize head-on collision.

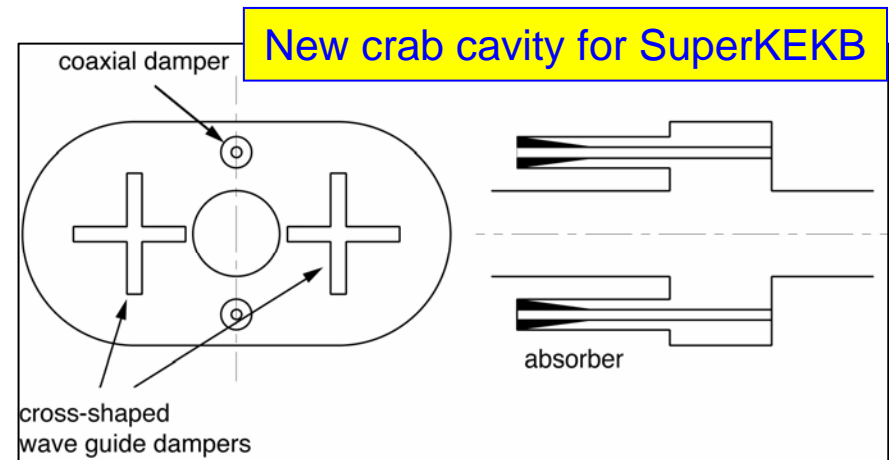
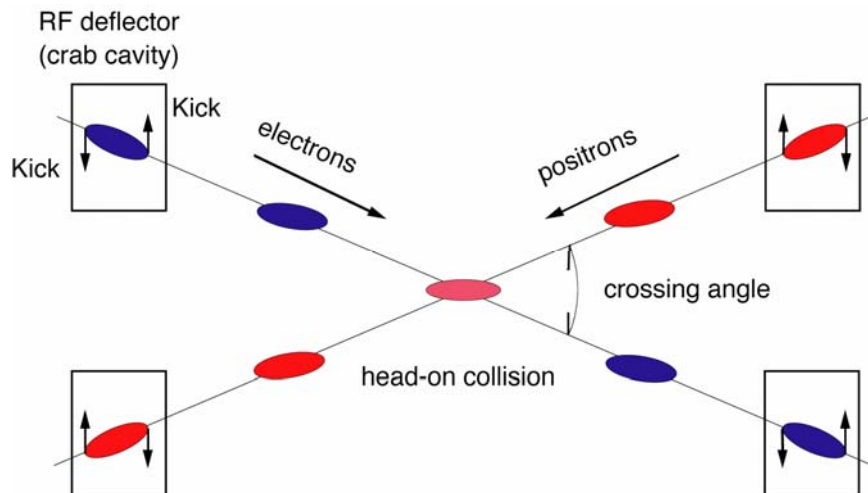
Head-on collision with crab cavity

Finite-crossing collision without crab cavity



Crab cavity tilts the beam to make head-on collision.

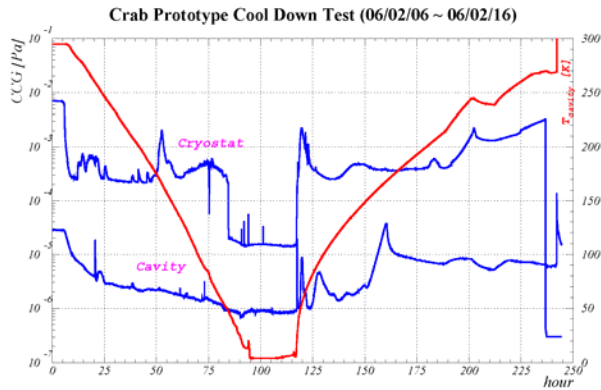
Development of crab cavity applicable for high beam current ($\sim 10 \text{ A}$)



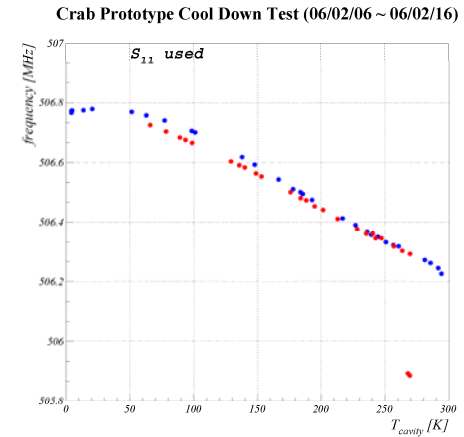
This is different from the cavity will be installed at KEKB. 37

Cold test of porototype crab cavity

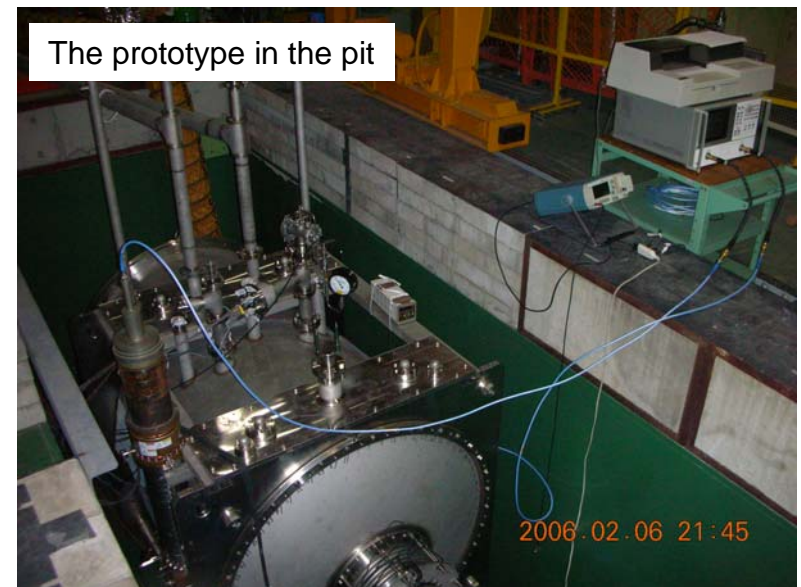
Time variation of the cavity and cryostat vacuum



The temperature dependence of the frequency



The cold test was done !



Traveling focus

Traveling focus (in longitudinal direction)

$$H_{\pm} = \frac{a}{2} z p_y^2$$

$$y = y + \frac{\partial H_{\pm}}{\partial p_y}$$

$$= y + a z p_y$$

$$\begin{pmatrix} y \\ p_y \end{pmatrix} = \begin{pmatrix} 1 & az \\ 0 & 1 \end{pmatrix} \begin{pmatrix} y \\ p_y \end{pmatrix}$$

Transformation of Twiss parameters:

$$\begin{pmatrix} \beta & \alpha \\ \alpha & \gamma \end{pmatrix} = \begin{pmatrix} 1 & az \\ 0 & 1 \end{pmatrix} \begin{pmatrix} \beta & 0 \\ 0 & 1/\beta \end{pmatrix} \begin{pmatrix} 1 & az \\ 0 & 1 \end{pmatrix}^T = \begin{pmatrix} \beta + az^2/\beta & az/\beta \\ az/\beta & 1/\beta \end{pmatrix}$$

Waist point moves along z position.

$$\beta(z) = \beta + \frac{az^2}{\beta}$$

Crab waist (Traveling focus in transverse plane)

$$H_{\pm} = \frac{a}{2} x p_y^2 \quad \text{Swap z and x in the left}$$

$$y = y + \frac{\partial H_{\pm}}{\partial p_y}$$

$$= y + a x p_y$$

$$\begin{pmatrix} y \\ p_y \end{pmatrix} = \begin{pmatrix} 1 & ax \\ 0 & 1 \end{pmatrix} \begin{pmatrix} y \\ p_y \end{pmatrix}$$

Transformation of Twiss parameters:

$$\begin{pmatrix} \beta & \alpha \\ \alpha & \gamma \end{pmatrix} = \begin{pmatrix} 1 & ax \\ 0 & 1 \end{pmatrix} \begin{pmatrix} \beta & 0 \\ 0 & 1/\beta \end{pmatrix} \begin{pmatrix} 1 & ax \\ 0 & 1 \end{pmatrix}^T = \begin{pmatrix} \beta + ax^2/\beta & ax/\beta \\ ax/\beta & 1/\beta \end{pmatrix}$$

Waist point moves along x position.

$$\beta(x) = \beta + \frac{ax^2}{\beta}$$