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

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

emittance β-function

⇨ Traveling focus

z-dependent waist

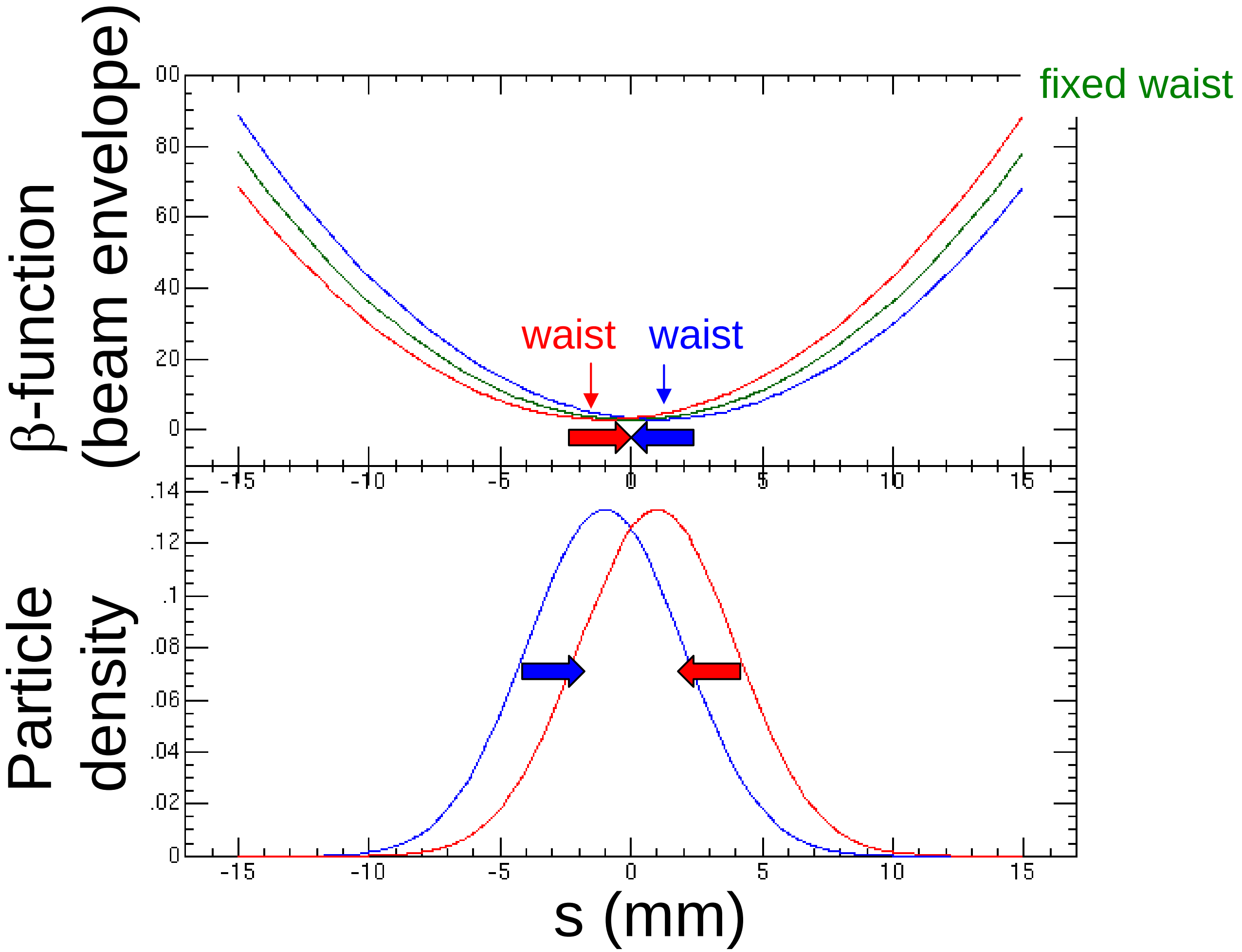
Waist locates the most density position.

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

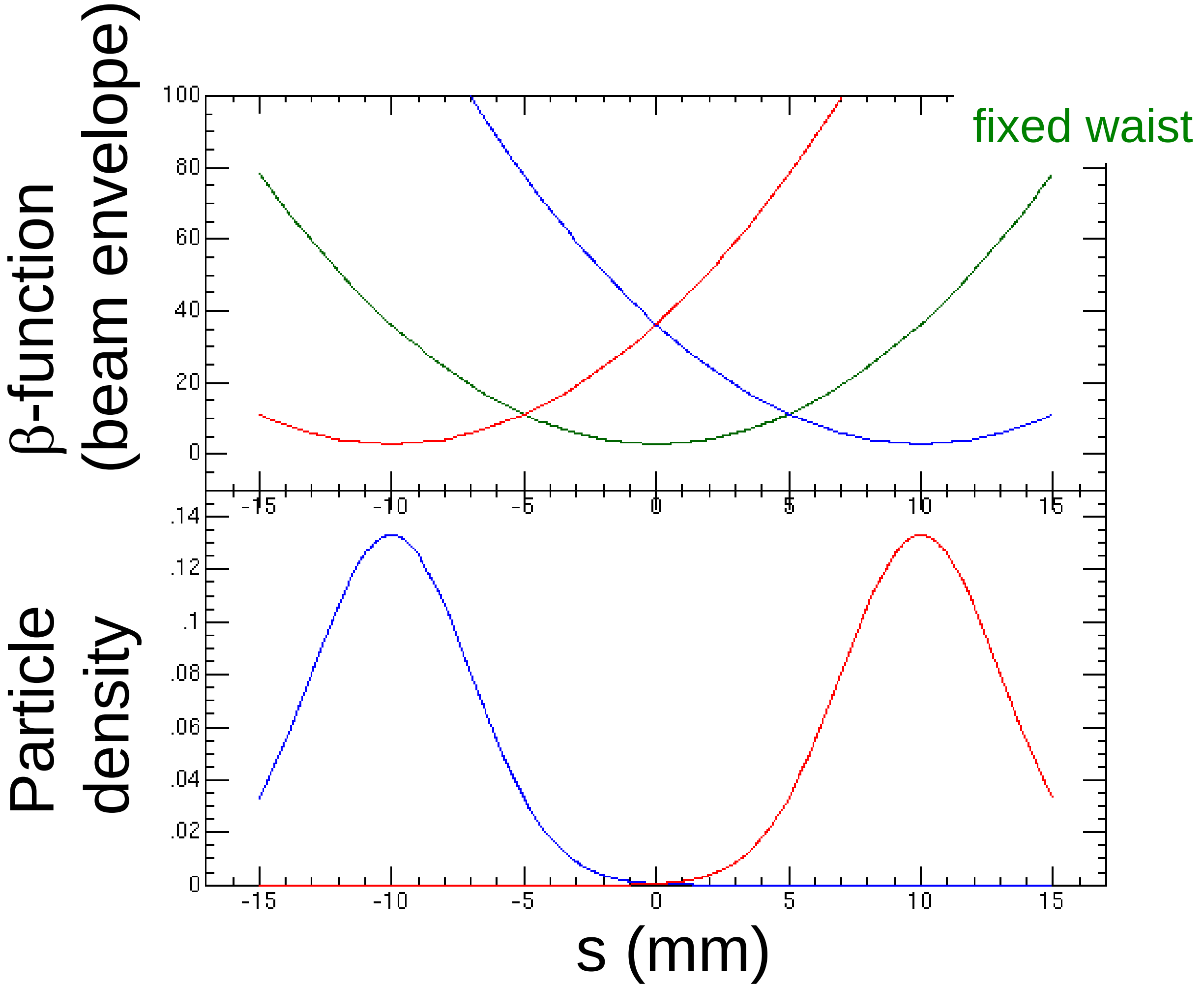
$$a = \frac{1}{2} \text{ for } z = z_1, \; a = -\frac{1}{2} \text{ for } z = z_2$$

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

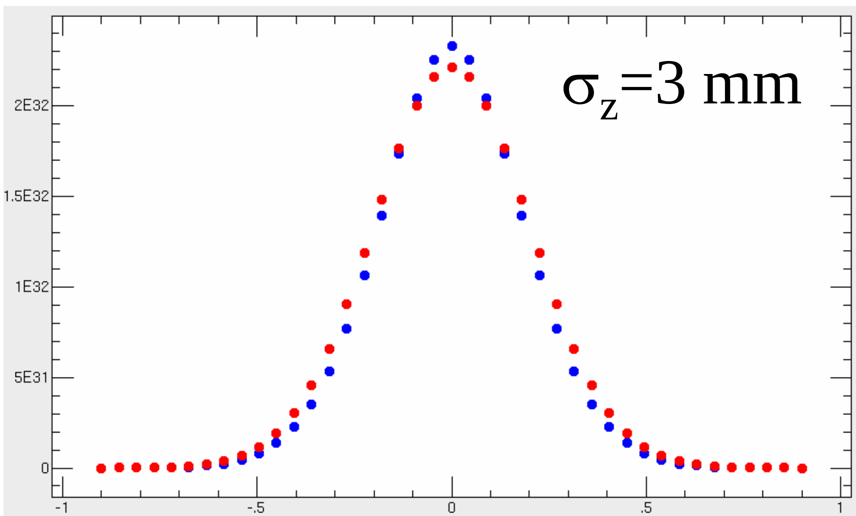


Different particles have different waist.

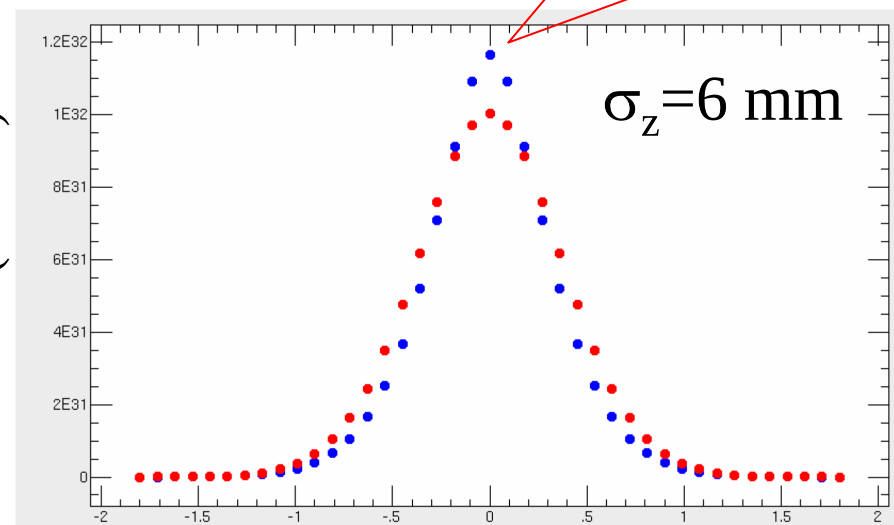
SuperKEKB
(geometrical)

$I_+ = 10$ A / $I_- = 4.4$ A ($N_b = 5000$)
N+= 1.26×10^{11} / N-= 5.5×10^{10} per bunch
$\varepsilon_x = 18$ nm
$\varepsilon_y = 0.18$ nm
$\beta_x = 20$ cm
$\beta_y = 3$ mm

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



L /Δs(cm^{-3}s^{-1})



s (cm)

Head-on: 5.33×10^{35} (ξ_y=0.25)

Traveling focus: 5.61×10^{35}

gain~ 5.3%

Hourglass effect

s (cm)

Head-on: 4.37×10^{35}

Traveling focus: 4.70×10^{35}

gain~ 7.5%

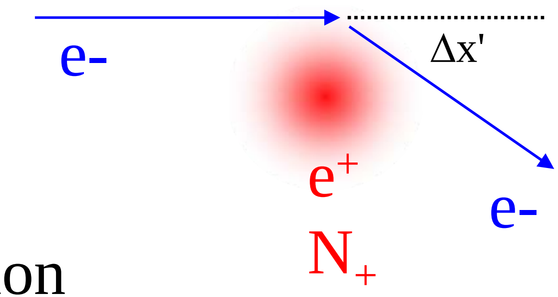
Beam-beam tune shift

- Beam-beam tune shift

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

k=1/f, f is focal length.

BB kick = Deflection by Coulomb force



- Beam-beam tune shift with beam distribution

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

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

Crossing angle: 2θ

x = zθ

- Bassetti-Erskine formula (Coulomb force)

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

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

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

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

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

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

SuperKEKB	Crab crossing		Finite crossing		
E (LER/HER)	3.5 / 8.0				GeV
I (LER/HER)	10 / 4.4				A
N (LER/HER)	1.26×10^{11} / 5.5×10^{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	$\times 10^{35}$ $cm^{-2}s^{-1}$

*1nominal tune shift *2travel 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)	$1.26 \times 10^{11} / 5.5 \times 10^{10}$				
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
ν_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	$\times 10^{35}$ cm^{-2}s^{-1}
L (S.S*3)	6.0	8.3	4.8	9.0	$\times 10^{35}$ cm^{-2}s^{-1}

*1 nominal tune shift *2 Weak-Strong simulation *3 Strong-Strong simulation

Homework

What is crab crossing

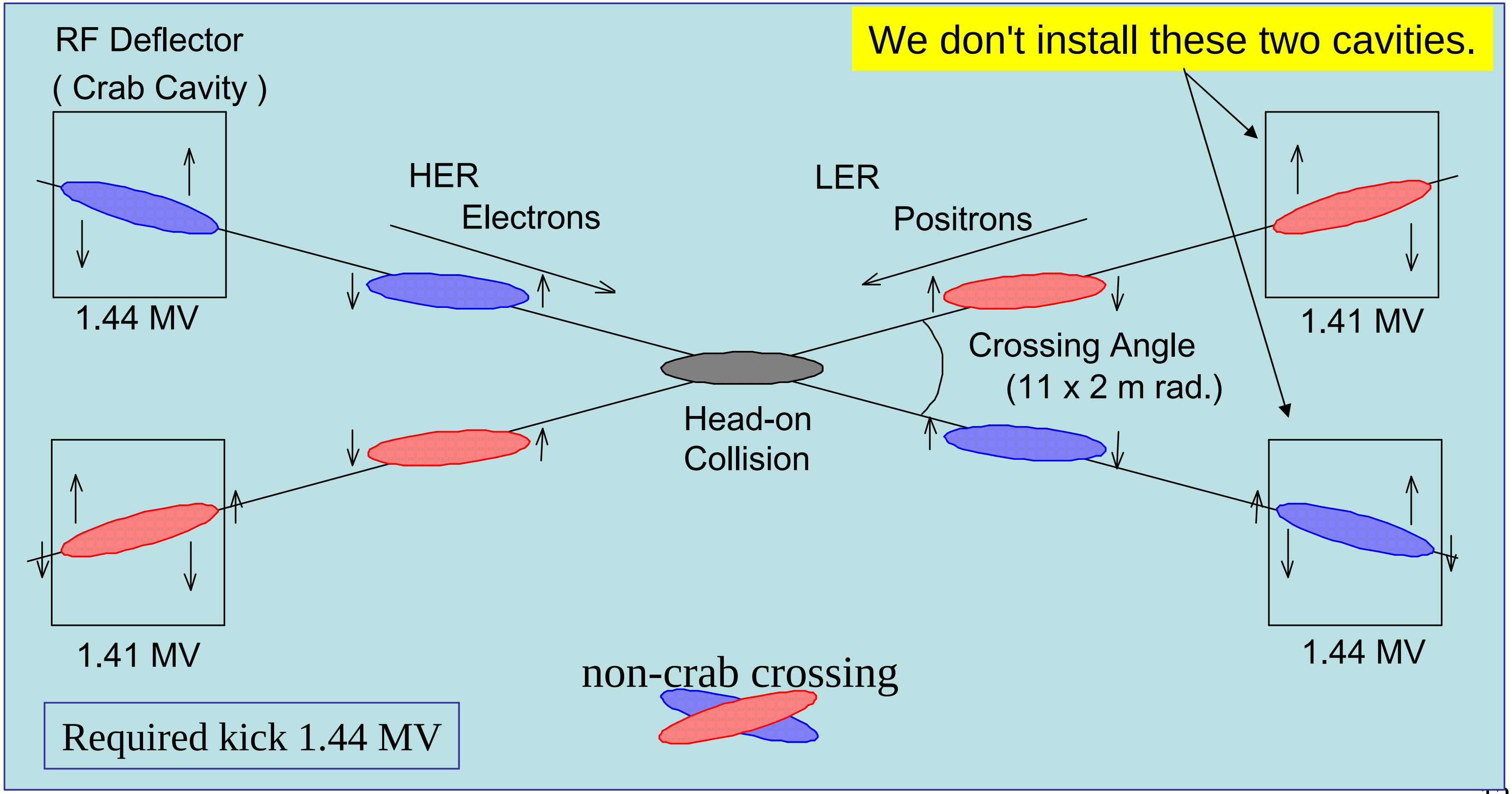
and

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)]

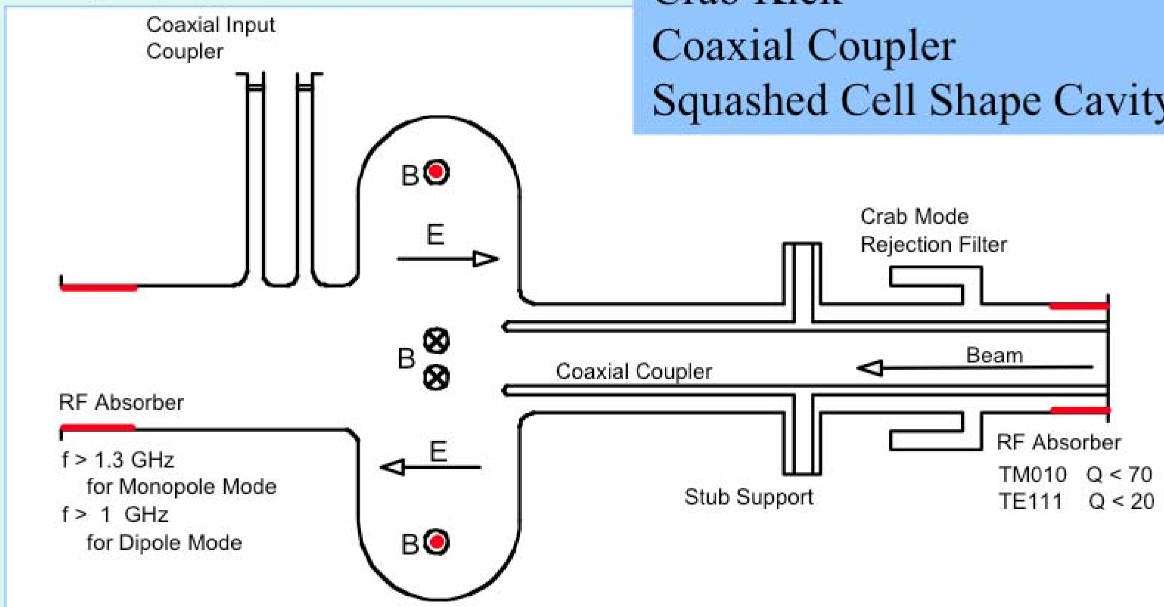
1) R.B.Palmer, SLAC-PUB-4707,1988
2) K.Oide and K.Yokoya, SLAC-PUB-4832,1989

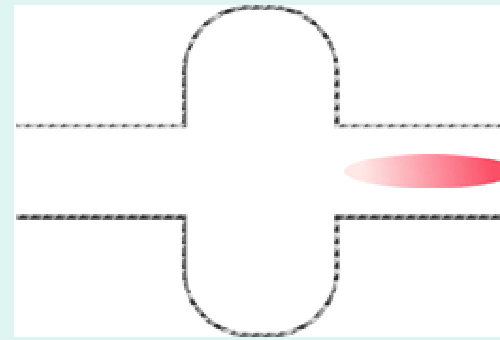


Conceptual Design of KEKB Crab Cavity

Top View

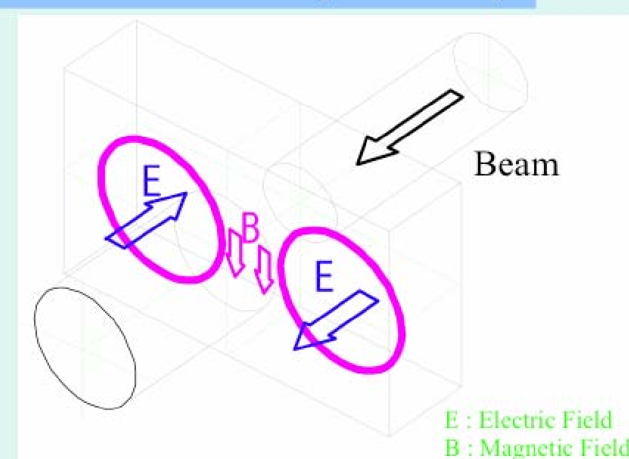
Crab Kick	TM110 B-field	1.44 MV
Coaxial Coupler	TM010, TE111	
Squashed Cell Shape Cavity	TM110*	





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:

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

Betatron phase advance

Dipole kick changes equilibrium position.

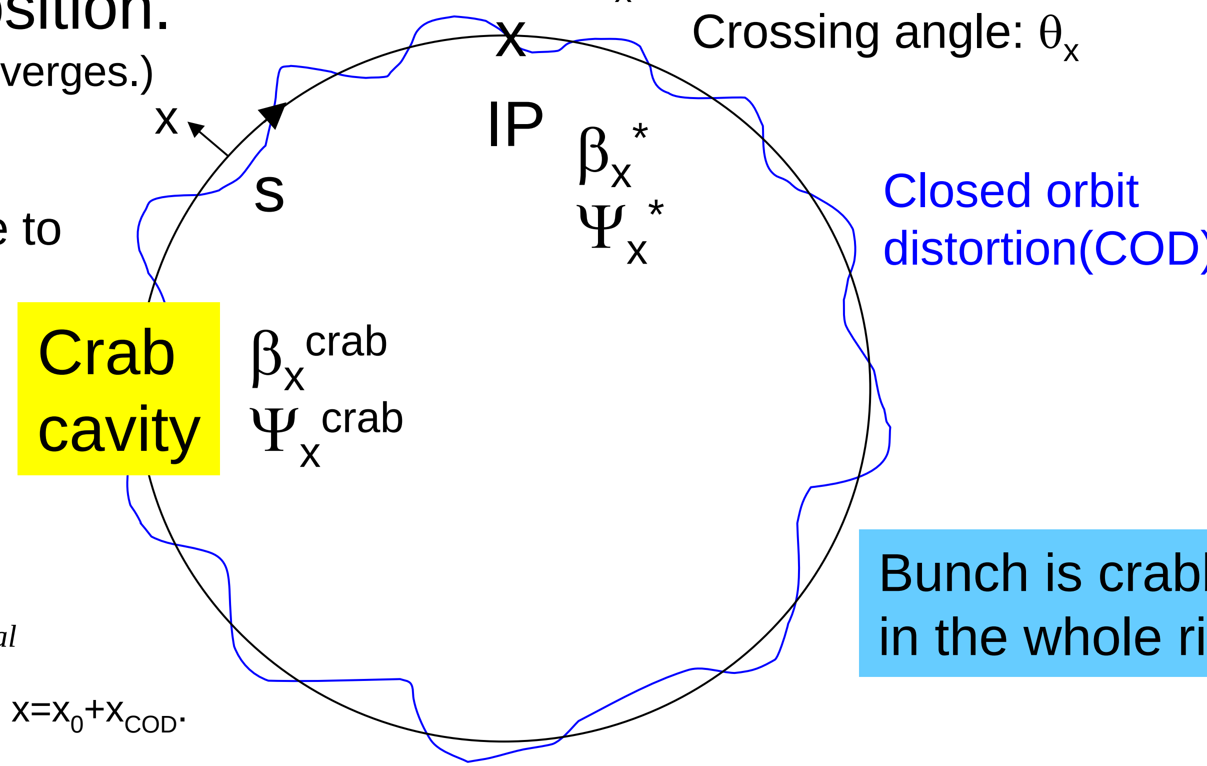
(If ν_x=integer, orbit diverges.)

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

Crossing angle: θ_x

Kick angle due to crab cavity

Θ_x^{crab}



Bunch is crabbing in the whole ring.

Betatron oscillation:

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

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

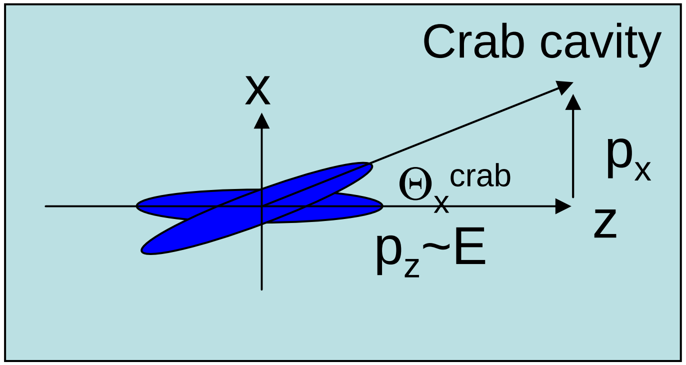
Crab crossing with a crab cavity

Transverse kick of crab cavity:

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

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

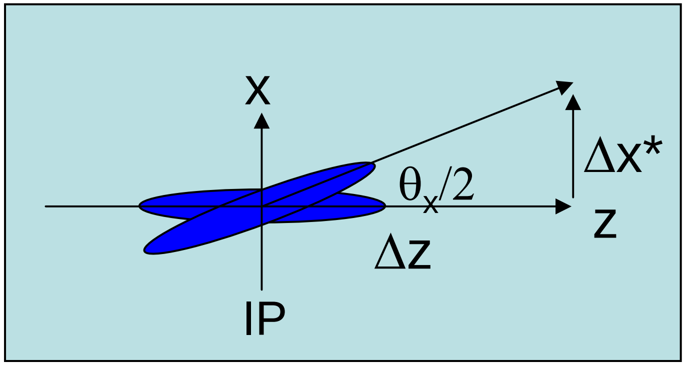
f_{rf}: rf frequency



Half crossing angle is:

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

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



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

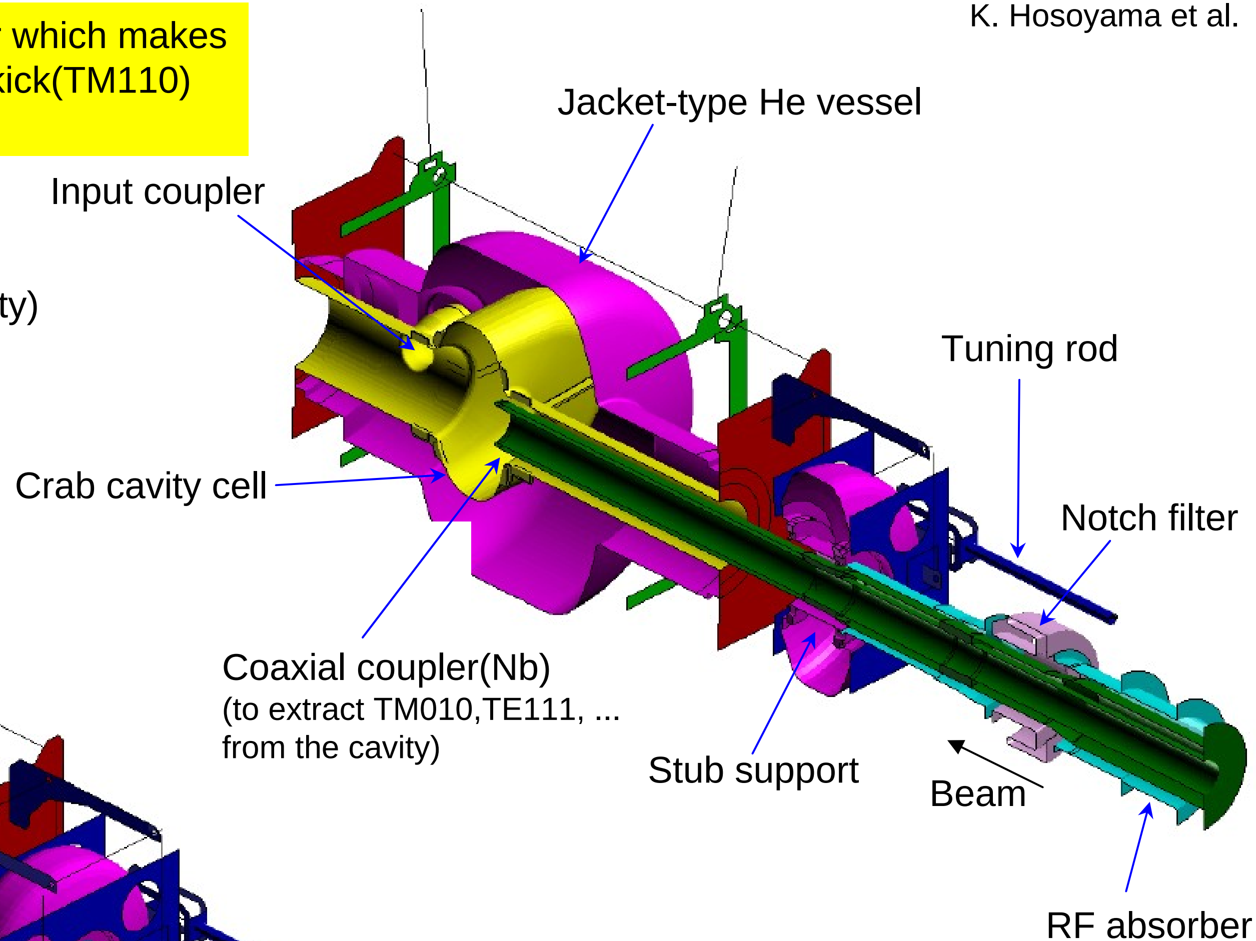
K. Hosoyama et al.

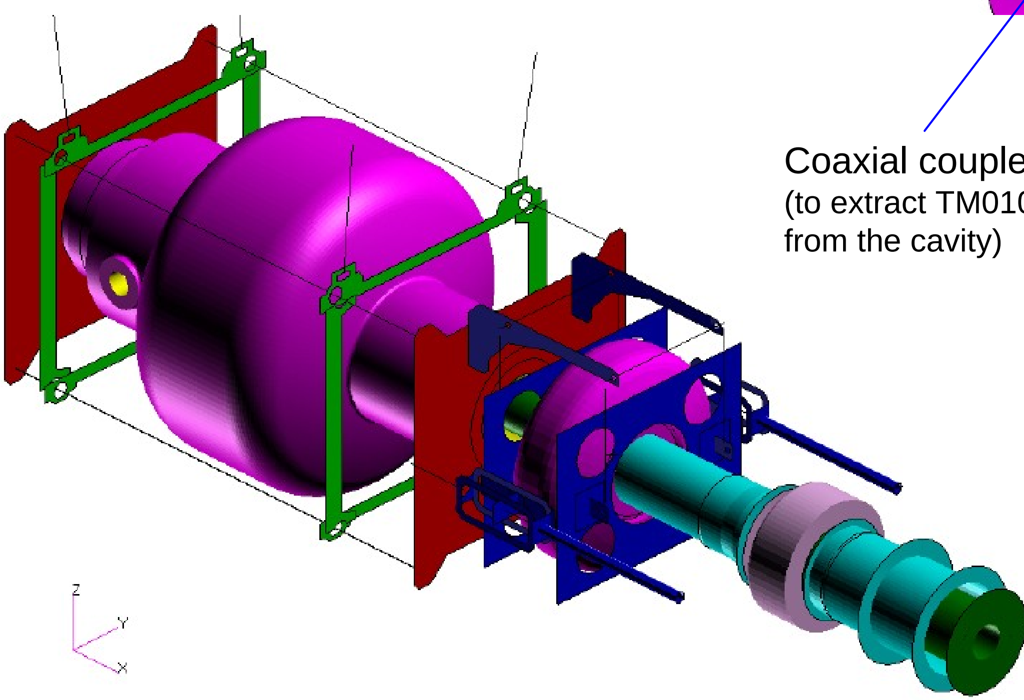
Crab cavity is the RF deflector which makes a time-dependent transverse kick(TM110) to tilt the beam.

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

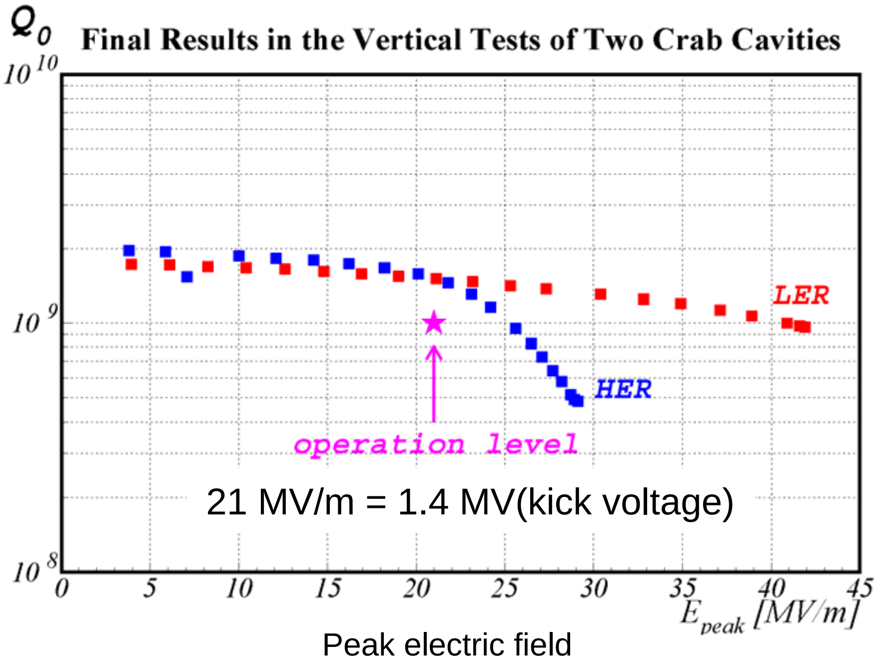
(one cavity)

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





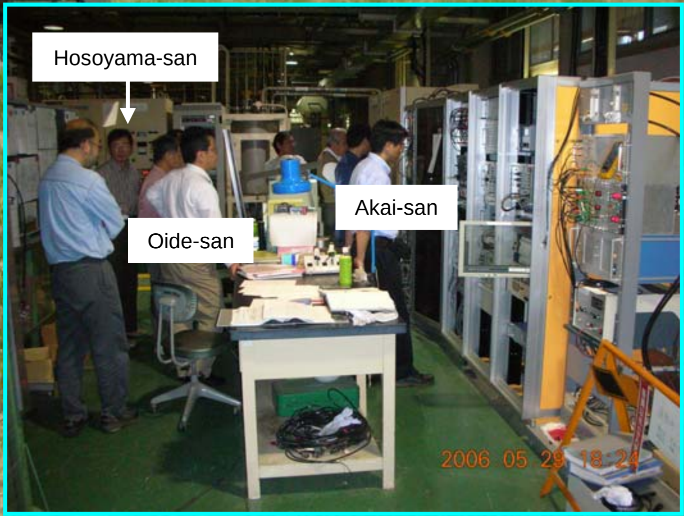
Results of Q-value at the vertical test for the crab cavities



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

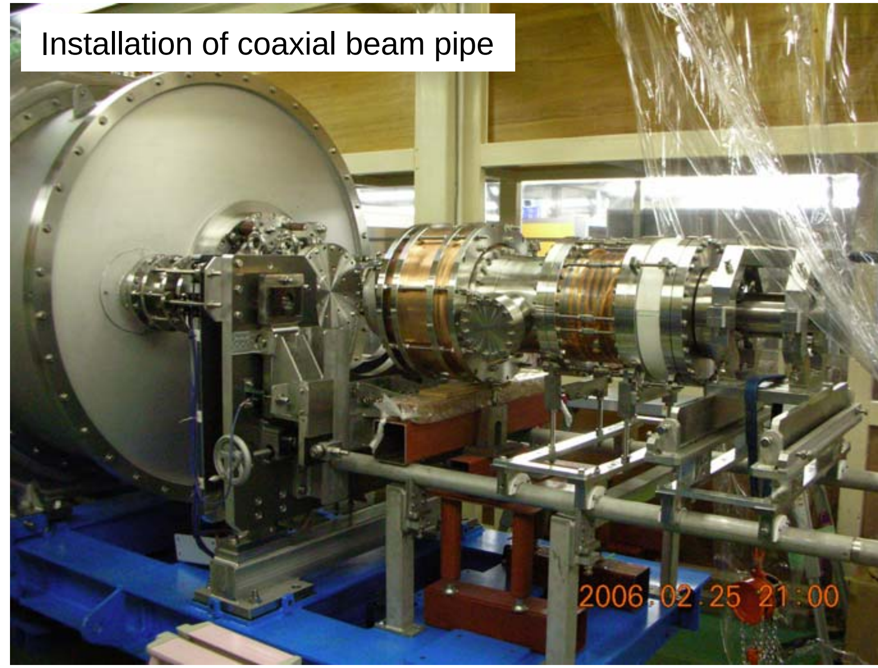
HER cavity is worse performance than that of LER, however it satisfies the requirement.

Horizontal test of crab cavity



Assembly of the first crab cavity.

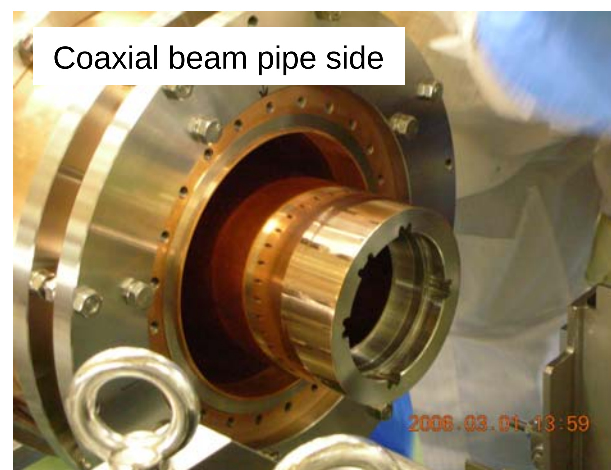
Coaxial beam pipe assembly



Installation of coaxial beam pipe

Installation was very difficult !

Cavity side



Coaxial beam pipe side

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

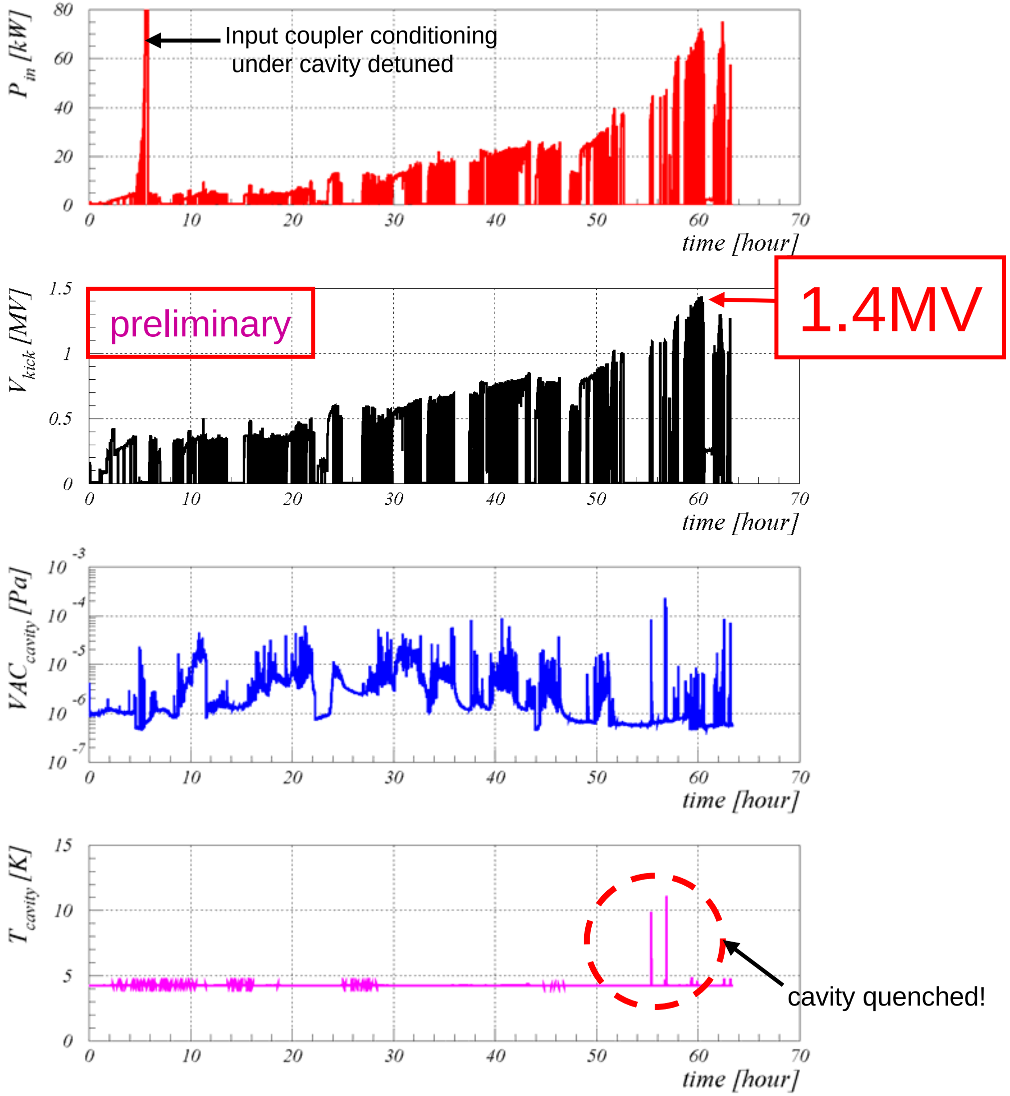
The cavity was moved for the horizontal test.

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

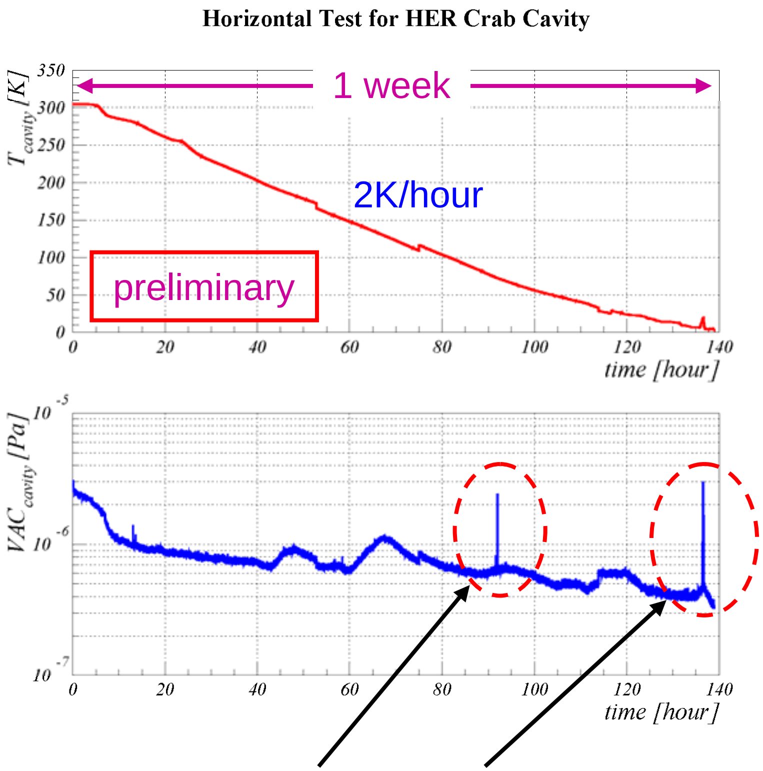
operation level (1.4MV)

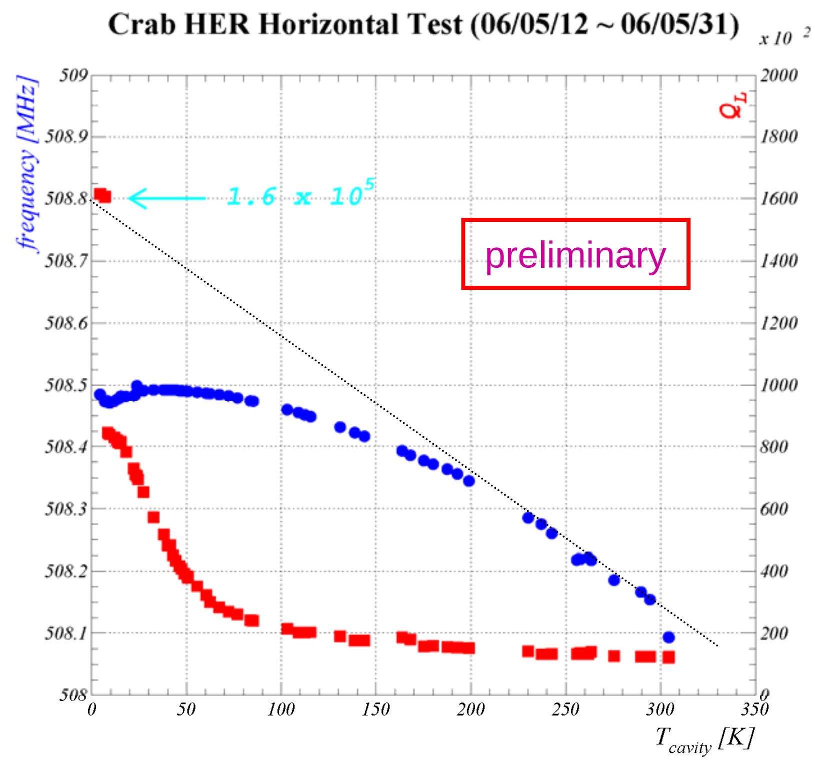
on June/8 by C.W.!!!

Crab cavity cool-down toward 4K

The cavity was cooled down very slowly.

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





Due to the adjustment of the helium flow

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

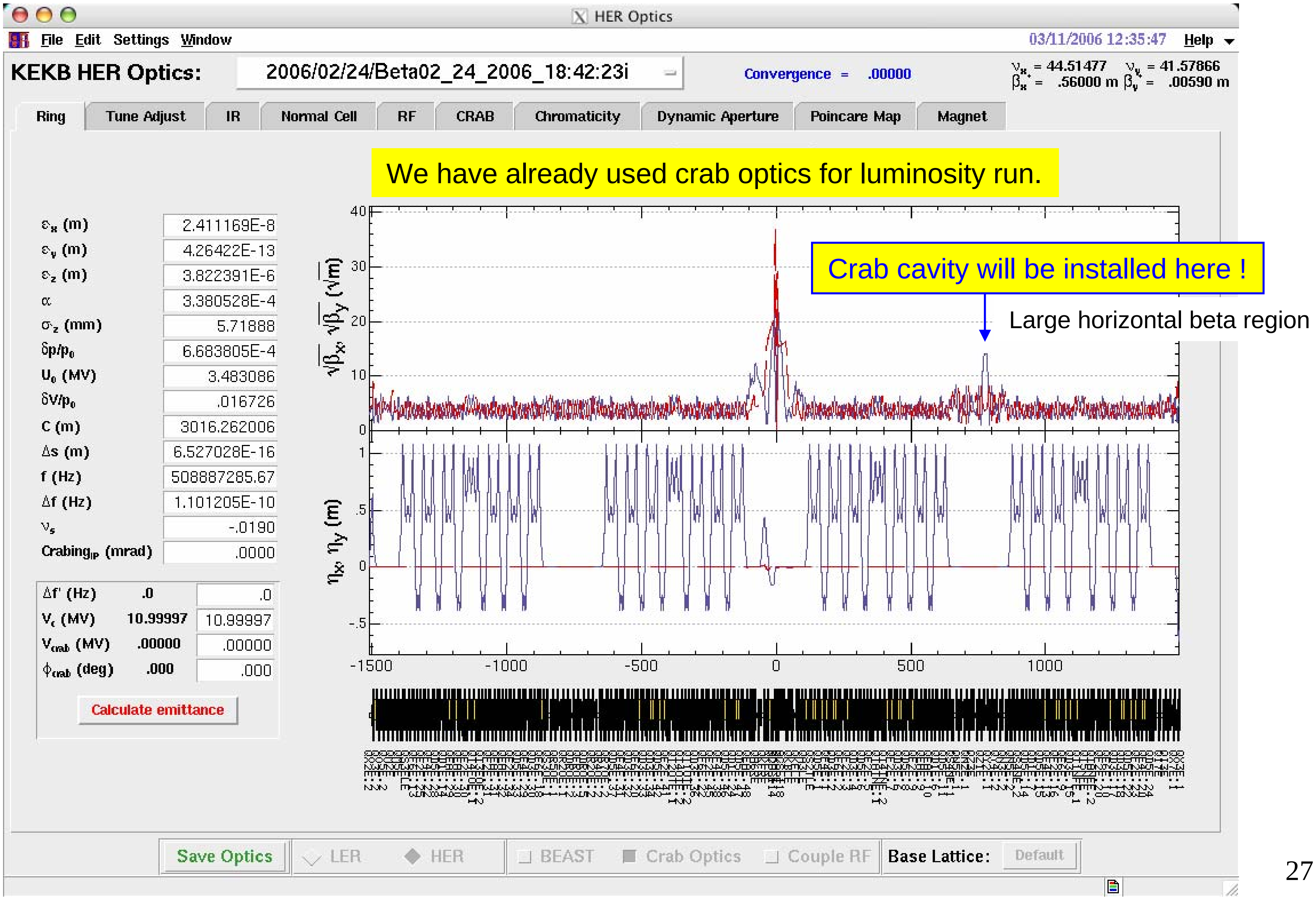
Near future plan

- 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



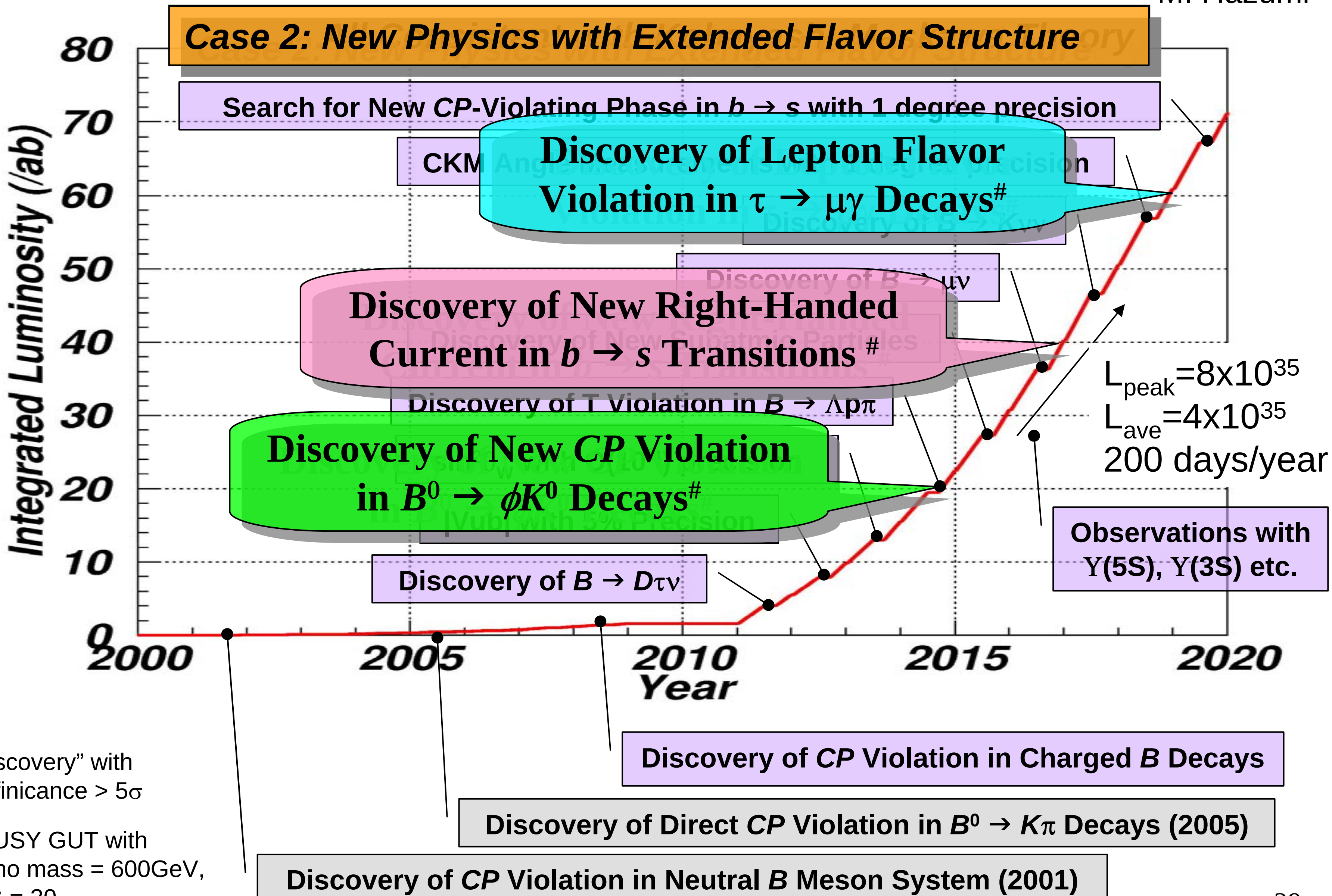
Summary

- 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

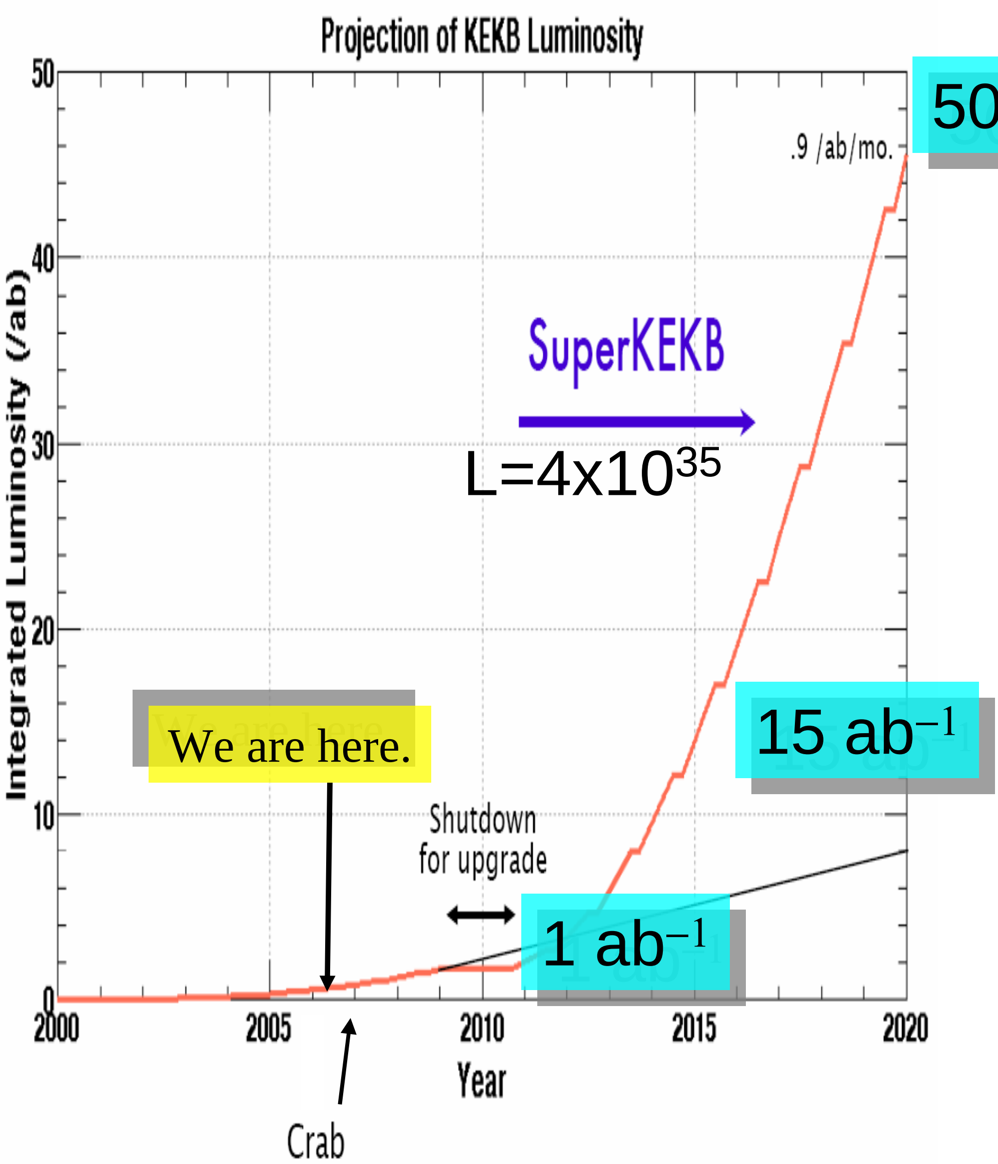


"Discovery" with sigfinicance > 5σ

SUSY GUT with gluino mass = 600GeV, tanβ = 30

Backup slides

Projection of integrated luminosity and expected discoveries at SuperKEKB



Discoveries of $B \to K\nu\nu$

Discovery of new *CP* violation in $B^0 \to \phi Ks$

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

Discoveries at SuperKEKB and required integrated luminosities (discovery = significance > 5σ)

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

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

** Assuming WA values as of August 2005.

*** Guestimation assuming $Br=4x10^{-7}$, full rec. eff. = 0.1%, and no background. Need simulation studies.

Luminosity

- Luminosity formula (well-known)

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

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)

Beam-beam parameter
(Strength of interaction between colliding beams)
0.055 (KEKB)→ 0.19 (SuperKEKB)

It correlates with many things.

Limited by beam-beam effect

Lorentz factor

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

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

Classical electron radius

Beam size ratio
1 ~ 2 % (flat beam)

Vertical beta function
(Focal depth)
6.5 mm/6.2 mm (KEKB)
→ 3 mm/3 mm(SuperKEKB)

Limited by bunch length

Luminosity
1.63x10^{34} cm^{-2}s^{-1} (KEKB)
→ 4.0x10^{35} cm^{-2}s^{-1} (SuperKEKB)

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

Limited by HOM, CSR

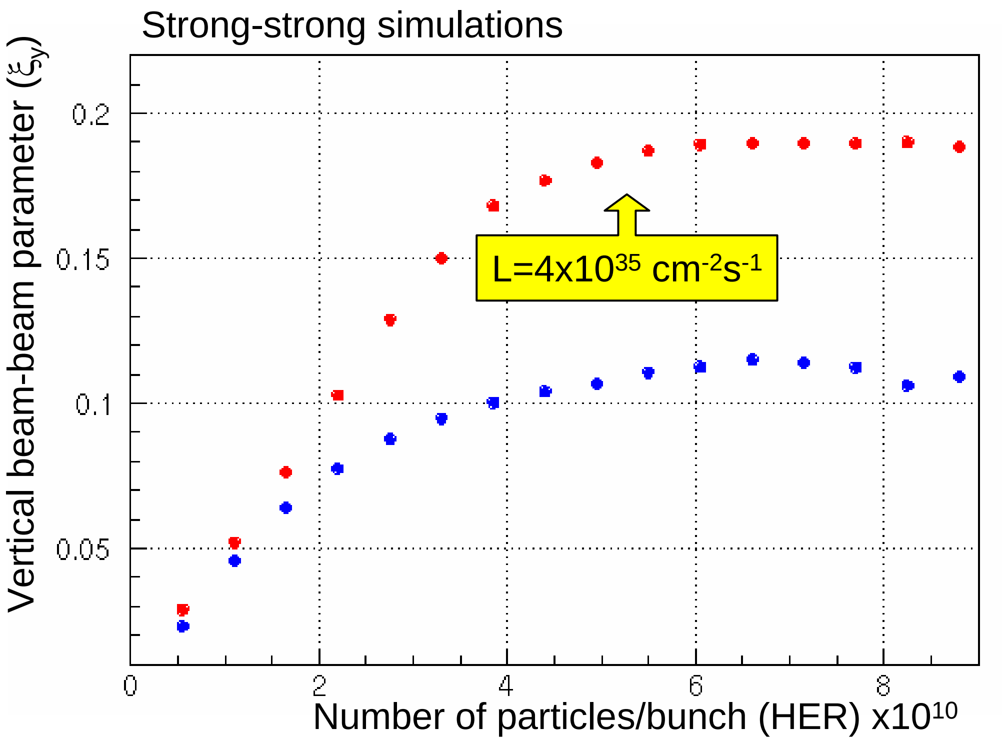
Luminosity is proportional to beam currents, beam-beam and inverse of vertical beta function at IP.

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	$R_{\xi x}$	0.99	0.98	
ξ_y reduction	$R_{\xi y}$	1.11	1.16	
Reduction ratio	$R_L/R_{\xi y}$	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}		$cm^{-2}s^{-1}$

Dynamic effect

Head-on and finite-crossing collision



Head-on (crab-crossing)

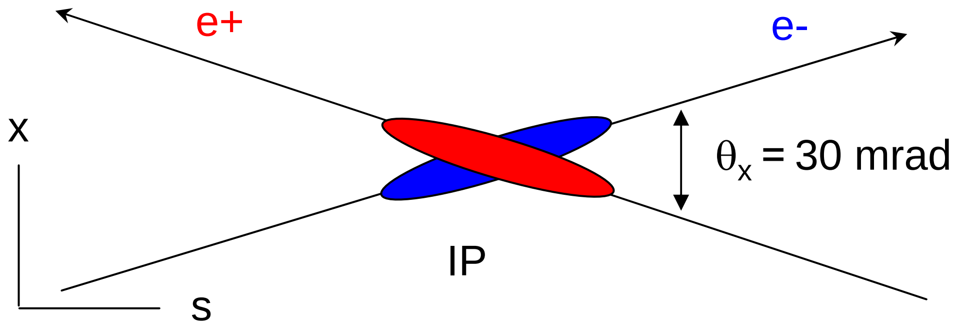
ν_x/ν_y = .503/.550

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.

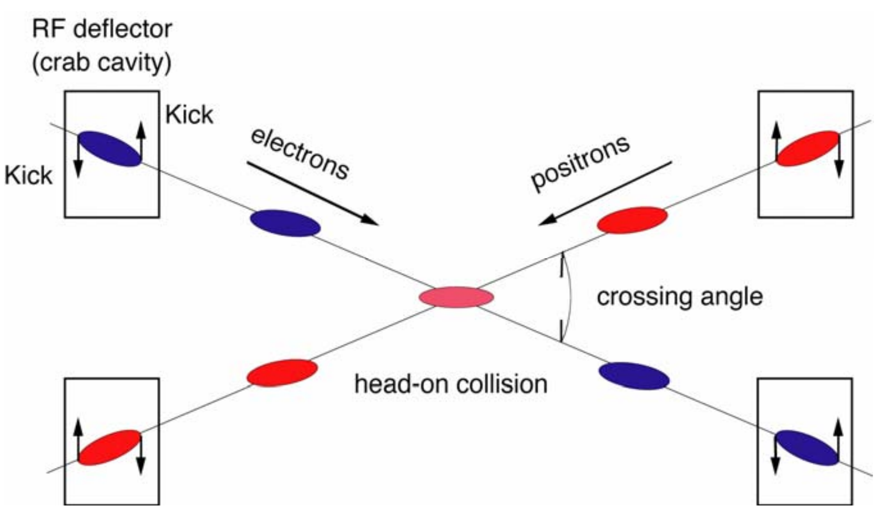
Head-on collision with crab cavity

Finite-crossing collision without crab cavity

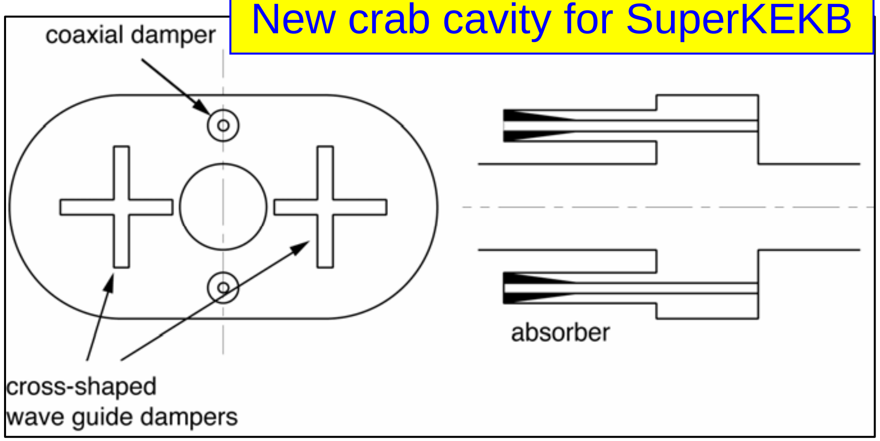


Crab cavity tilts the beam to make head-on collision.

Development of crab cavity applicable for high beam current(~10 A)



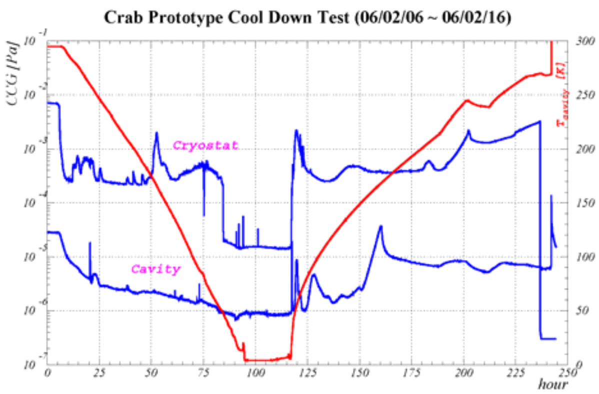
New crab cavity for SuperKEKB



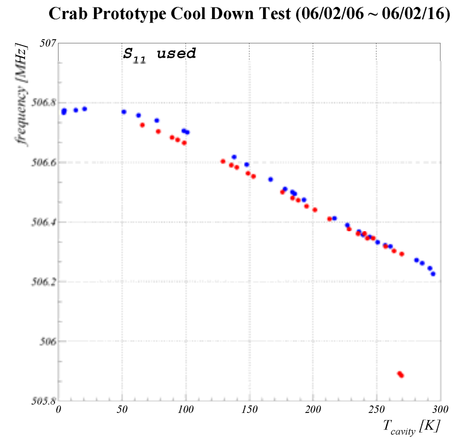
This is different from the cavity will be installed at KEKB.

Cold test of porototype crab cavity

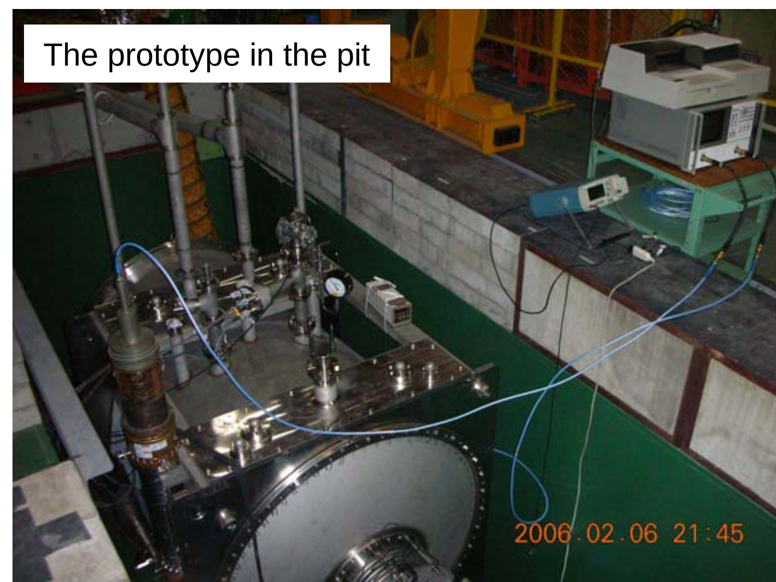
Time variation of the cavity and cryostat vacuum



The temperature dependence of the frequency



The cold test was done !



The prototype in the pit

Traveling focus

Traveling focus (in longitudinal direction)

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

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

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

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)

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

Swap z and x in the left

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

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

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.

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