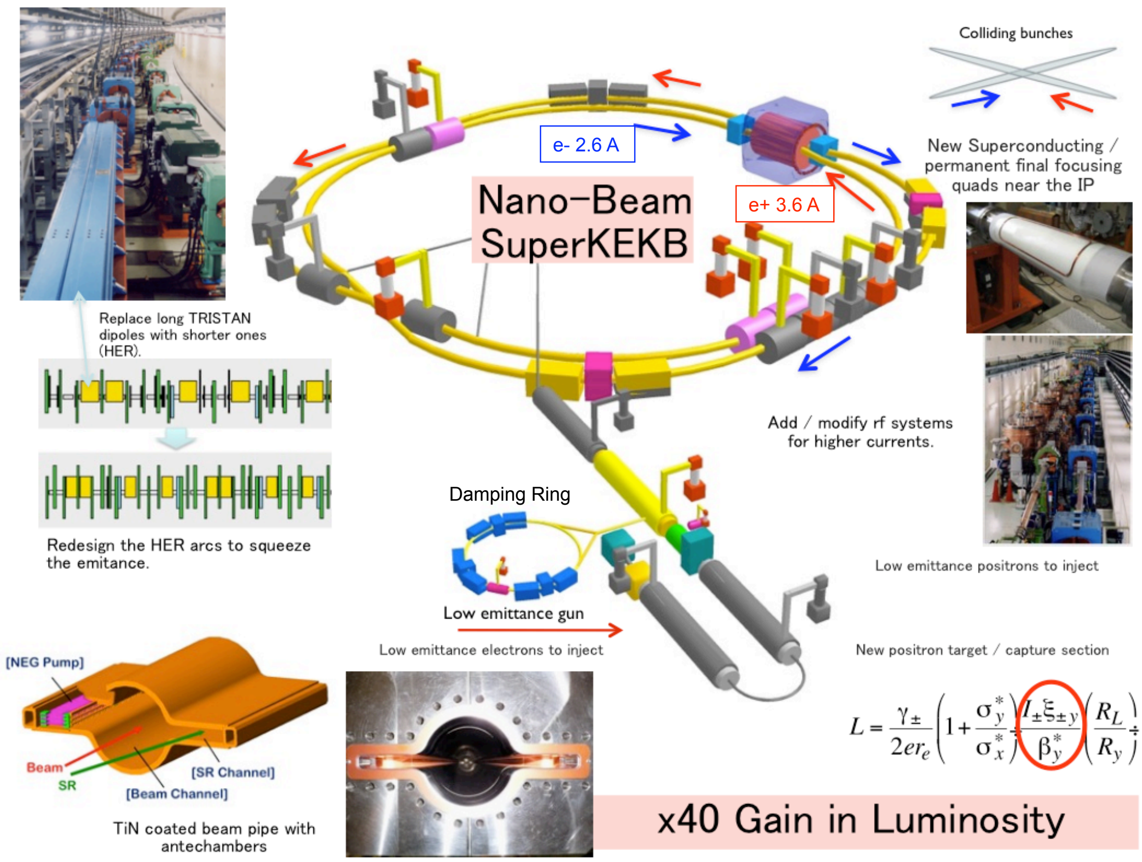
Machine Parameters

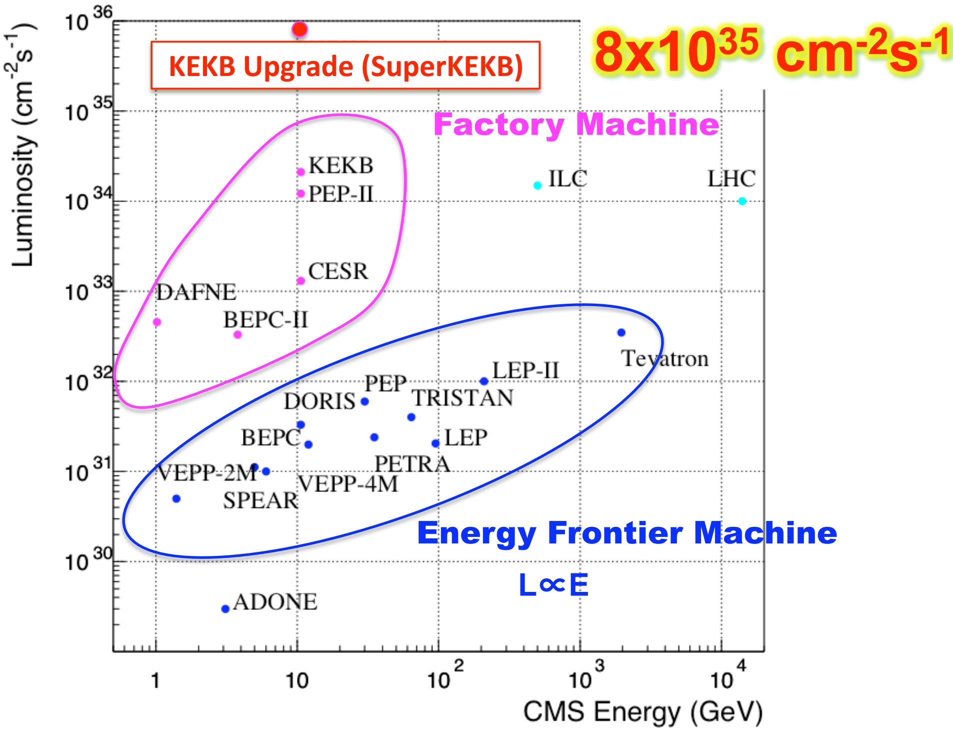
Y. Ohnishi

The 15th KEKB Review

Feb/15-17/2010



Luminosity of Collider



Comparison of Parameters

	KEKB Design	KEKB Achieved : with crab	SuperKEKB Nano-Beam
Energy (GeV) (LER/HER)	3.5/8.0	3.5/8.0	**4.0/7.0**
β_y^* (mm)	10/10	5.9/5.9	**0.27/0.41**
ε_x (nm)	18/18	18/24	**3.2/2.4**
σ_y(μm)	1.9	0.94	0.059
ξ_y	0.052	0.129/0.090	**0.09/0.09**
σ_z (mm)	4	~ 6	6/5
I_{beam} (A)	2.6/1.1	1.64/1.19	**3.6/2.62**
$N_{bunches}$	5000	1584	2503
Luminosity (10^{34} cm^{-2} s^{-1})	1	2.11	**80**

Beam Energy

- In SuperKEKB, the beam energy is changed to decrease the effect of the **intra-beam scattering in LER**, especially to make longer **Touschek lifetime**.
- **LER**: 3.5 GeV → **4 GeV**
- **HER**: 8 GeV → **7 GeV**
- In HER, the lower beam energy makes lower emittance.

Luminosity

$$L = \frac{\gamma_\pm}{2er_e} S \cdot \left(\frac{I_\pm \xi_{y\pm}}{\beta^*_{y\pm}} \right) \cdot \frac{R_L}{R_{\xi y\pm}}$$

If $\sigma_x^* = \sigma_{x+}^* = \sigma_{x-}^*$ and $\sigma_y^* = \sigma_{y+}^* = \sigma_{y-}^*$, $S = 1+\sigma_y^*/\sigma_x^*$ (aspect ratio of the beam size at IP).

Three fundamental parameters to determine the luminosity.

where

$$\xi_{y\pm} = \frac{r_e \beta^*_{y\pm} N_\mp}{2\pi\gamma_\pm \sigma^*_{y\mp}\left(\sigma^*_{x\mp} + \sigma^*_{y\mp}\right)} R_{\xi y\pm}$$

Target Luminosity is 8×10^{35} $cm^{-2}s^{-1}$ in SuperKEKB.

Beam-Beam Parameter

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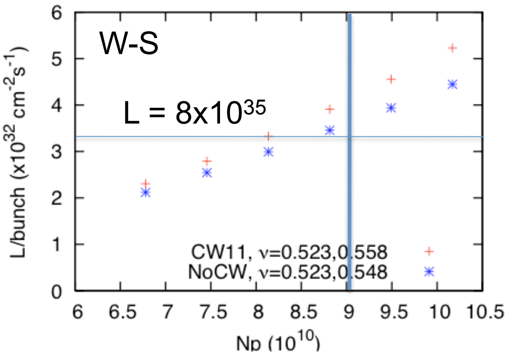
Beam-Beam Parameter

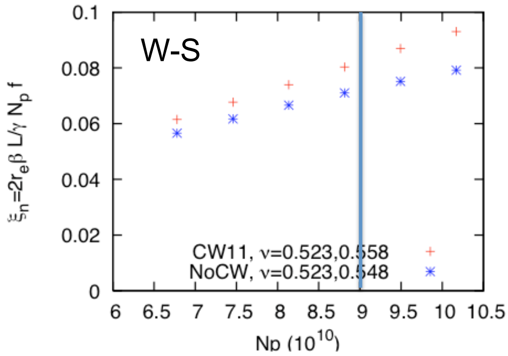
- The maximum value of the beam-beam parameter is assumed to be **0.09 in SuperKEKB**.
- The beam-beam parameter of 0.09 has been achieved in KEKB.
- The horizontal beam-beam parameter becomes very small in the nano-beam scheme. ξ_x~0.0028
- Dynamic effects is also small since the small horizontal beam-beam parameter and the horizontal betatron tune is far from 0.5.

Beam-Beam Simulation

- Beam-beam simulation gives 8×10^{35} $cm^{-2}s^{-1}$
- Difference between with and without the crab-waist is not so large.



LER



LER

Vertical Beta Function at IP

	KEKB Design	**KEKB Achieved : with crab**	**SuperKEKB Nano-Beam**
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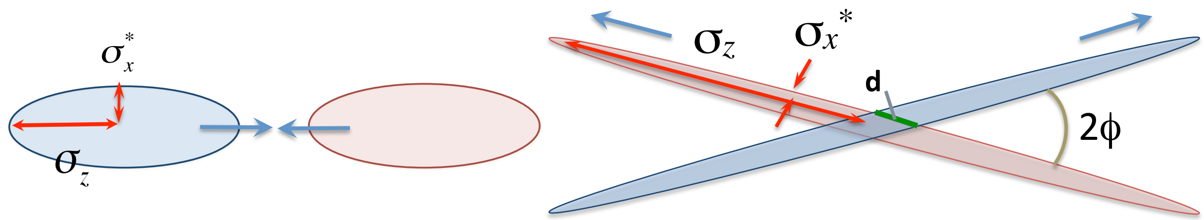
Vertical Beta Function at IP

- By using the modern technique, the vertical beta function can be squeezed to be a few hundred micron at most.
  - β_y^* ~ 1/20 of KEKB
- Hourglass effect (HG) is a serious problem to squeeze the beta function in the head-on collision.
- In order to satisfy HG, a collision of narrow beams with a large crossing angle is adopted. This is "***nano-beam scheme***".
- However, dynamic aperture (DA) will be reduced because of the nonlinear fringe, and kinematic terms in the interaction region (IR), and also strong sextupoles.

	SuperKEKB		KEKB
Natural chromaticity	**LER: ξ_x/ξ_y = -104/-789**	⇔	**LER: ξ_x/ξ_y = -72/-123**
	HER: ξ_x/ξ_y = -187/-853		**HER: ξ_x/ξ_y = -70/-124**

Collision Scheme

High Current Scheme / Nano-Beam Scheme



High Current Scheme

Head-on

overlap region = bunch length

Hourglass requirement

$$\beta_y^* \geq \sigma_z \quad \text{~5 mm}$$

Nano-Beam Scheme

Half crossing angle: ϕ

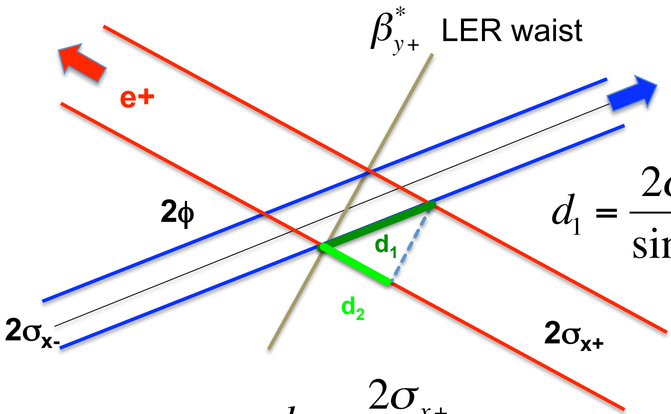
overlap region (≠ bunch length)

$$d = \frac{\sigma_x^*}{\phi}$$

Hourglass requirement

$$\beta_y^* \geq \frac{\sigma_x^*}{\phi} \quad \text{~200-300 } \mu\text{m}$$

Hourglass Requirements for Nano-Beam



$$d_1 = \frac{2\sigma_{x+}}{\sin 2\phi}$$

There are two kinds of hourglass requirements.

$$d_2 = \frac{2\sigma_{x+}}{\tan 2\phi}$$

Hourglass (HG) requirement:

$$\beta^*_{y-} \geq \max\left(\frac{2\sigma_{x+}}{\sin 2\phi}, \frac{2\sigma_{x-}}{\tan 2\phi}\right)$$

$$\beta^*_{y+} \geq \max\left(\frac{2\sigma_{x-}}{\sin 2\phi}, \frac{2\sigma_{x+}}{\tan 2\phi}\right)$$

Beta Function at IP

- Machine parameters are chosen to be insensitive to the HG effect.
- The vertical beta function:

$$\beta^*_{y-} = \underline{410} \geq \max\left(\frac{2\sigma_{x+}}{\sin 2\phi}, \frac{2\sigma_{x-}}{\tan 2\phi}\right) = \max(244,186)\ \mu m$$

$$\beta^*_{y+} = \underline{270} \geq \max\left(\frac{2\sigma_{x-}}{\sin 2\phi}, \frac{2\sigma_{x+}}{\tan 2\phi}\right) = \max(187,243)\ \mu m$$

- The vertical beta functions in both rings satisfy the HG requirement.
- To squeeze β_y^*, low emittance and low β_x^* are needed.

$$\beta^*_y \geq \frac{\sigma^*_x}{\phi}$$

Beam Current

	KEKB Design	KEKB Achieved : with crab	SuperKEKB Nano-Beam
Energy (GeV) (LER/HER)	3.5/8.0	3.5/8.0	**4.0/7.0**
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$N_{bunches}$	5000	1584	2503
Luminosity (10^{34} cm^{-2} s^{-1})	1	2.11	**80**

Beam Current

- In order to achieve the target luminosity, the beam current in nano-beam scheme becomes **twice of KEKB**.
- The highest beam current is 2 A in LER and 1.4 A in HER at the KEKB operation.
  - 1.8 A in LER / 1.35 A in HER at physics run
- In SuperKEKB, the design beam currents are **3.6 A for LER** and **2.62 A for HER.**
- Number of bunches is **2503** to get the suitable density of the overlap region.
  - Bunch current becomes 1.44 mA in LER and 1.05 mA in HER.

Luminosity gain is $1(\xi_y)$ x $20(1/\beta_y^*)$ x $2(I)$ = 40 times of KEKB.
Then, we get 8×10^{35} cm^{-2}s^{-1}

Crossing Angle

- The full crossing angle is **83 mrad** in SuperKEKB.
- Separation of two beams is necessary to put final focusing magnets closer to IP as much as possible. This affects the magnet design and the dynamic aperture.
- The angle between the solenoid axis and the beam line is 41.5 mrad, respectively. This angle is determined by optimization of the vertical emittance generated by SR from the solenoid fringe.

Emittance

$$\varepsilon_x = \frac{c_\gamma \gamma^2}{J_x} \frac{1}{2\pi\rho_0^2} \oint_{Bend} H ds$$

$$\beta_y^* \geq \frac{\sigma_x^*}{\phi}$$

(η_x:dispersion)

$$H = \gamma_x \eta_x^2 + 2\alpha_x \eta_x \eta'_x + \beta_x \eta'_x$$

- Redesign of arc cells to make low emittance
  - 2.5 π non-interleaved sextupole cell (-I' connection)
    - chromaticity is corrected and nonlinear kick is cancelled.
  - **LER (4 GeV)**
    - Longer bending radius is adopted.
  - **HER (7 GeV)**
    - Number of cells increases to reduce dispersion.

Emittance

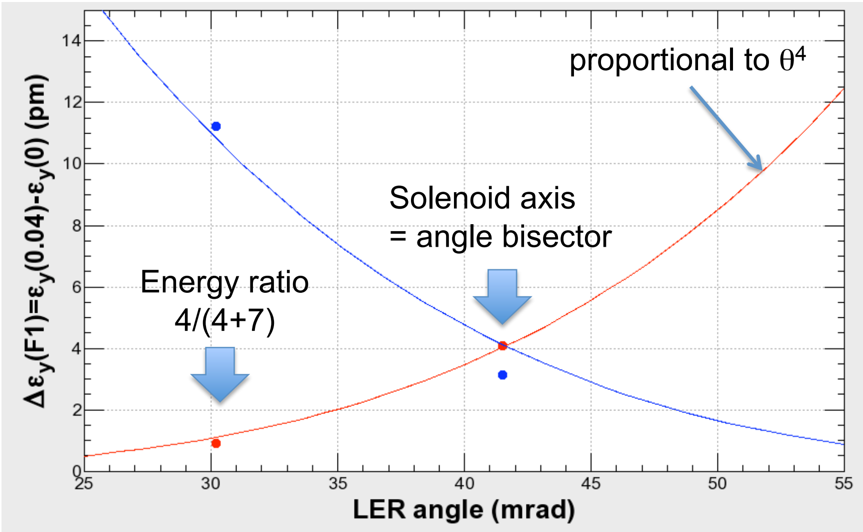
- Local chromaticity correction (LCC) is necessary to correct large chromaticity generated in the vicinity of IP.
- However, the LCC generates some emittance to make dispersion region.
- The emittance generation at the LCC should be reduced as much as possible. This is a trade-off between DA and emittance.

Emittance

- In SuperKEKB, the horizontal emittance is **3.2 nm in LER** and **2.4 nm in HER**, respectively.
  - 2.7 nm in LER and 2.3 nm in HER at the zero beam current
- Coupling parameter of 0.4 % in LER and 0.35 % in HER are assumed. (challenging!)
- Vertical emittance induced by SR from solenoid fringe field can not be ignored. (suggested by E. Perevedentev)
- In order to suppress it, rate of change of Bz should be reduced and/or decrease angle between the solenoid axis and the beam axis.
- Machine error also should be reduced and corrected.

Vertical Emittance originated from Solenoid Fringe

Crossing angle = LER angle + HER angle = 83 mrad



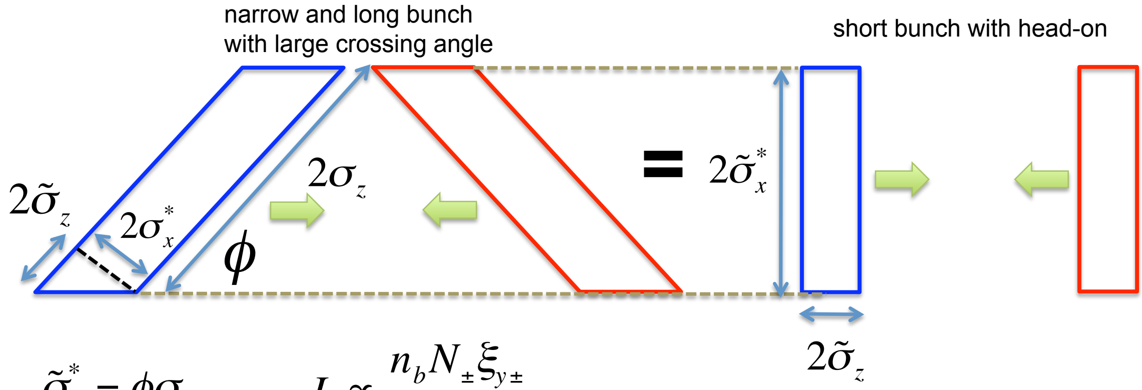
We choose 41.5 mrad and the contribution of solenoid fringe is ~4 pm.

Bunch Length

- In SuperKEKB, the bunch length is **6 mm in LER** and **5 mm in HER** which are similar to the present KEKB.
- The "bunch length" means a value includes intra-beam scattering and wake field from the ring impedance **at the design beam current**.

Nano-Beam Scheme

Head-on Frame



$$\tilde{\sigma}_x^* = \phi\sigma_z$$

$$\tilde{\sigma}_z = \frac{\sigma_x^*}{\phi}$$

$$L \propto \frac{n_b N_\pm \xi_{y\pm}}{\beta_y^*}$$

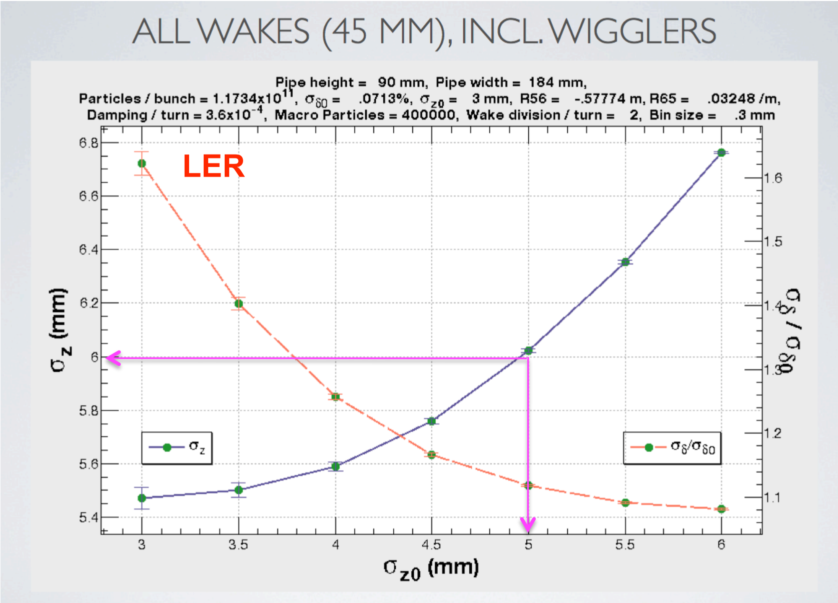
$$\xi_{y\pm} \cong \frac{r_e}{2\pi\gamma_\pm} \frac{N_\mp}{\phi\sigma_z} \sqrt{\frac{\beta_y^*}{\varepsilon_y}}$$

Bunch Length

- When we adopt a longer bunch length, particle density of the overlap region is decreased.
- In order to retrieve the particle density, we have to decrease the coupling parameter or increase the bunch current.
- Therefore, shorter bunch is preferable to relax these parameters.
- However, the shorter bunch implies beam instabilities such as CSR.
- The bunch length of 5~6 mm is acceptable for CSR.

Tracking Simulation of Bunch Stability

The 14th KEKB Review (Oide's talk)



LER
E = 3.5 GeV
I_b = 1.87 mA

[E = 4 GeV
I_b = 1.44 mA
in the latest
parameter]

No significant bunch lengthening is found in HER.

Machine Parameters of SuperKEKB

2010/Feb/08

(): zero current parameters		LER	HER	
Emittance	ε_x	3.2(2.7)	2.4(2.3)	nm
Coupling	$\varepsilon_y/\varepsilon_x$	0.40	0.35	%
Beta Function at IP	β_x^* / β_y^*	32 / 0.27	25 / 0.41	mm
Horizontal Beam Size	σ_x^*	10.2(10.1)	7.75(7.58)	μm
Vertical Beam Size	σ_y^*	59	59	nm
Bunch Length	σ_z	6.0(4.9)	5.0(4.9)	mm
Half Crossing Angle	ϕ	41.5		mrad
Beam Energy	E	4	7	GeV
Beam Current	I	3.60	2.62	A
Number of Bunches	n_b	2503		
Energy Loss / turn	U_0	2.15	2.50	MeV
Total Cavity Voltage	V_c	8.4	6.7	MV
Energy Spread	σ_δ	8.14(7.96)x10^{-4}	6.49(6.34) x10^{-4}	
Synchrotron Tune	ν_s	-0.0213	-0.0117	
Momentum Compaction	α_p	2.74x10^{-4}	1.88x10^{-4}	
Beam-Beam Parameter	ξ_y	0.0900	0.0875	
Luminosity	L	8x10^{35}		cm^{-2}s^{-1}

Parameter Consideration

- In SuperKEKB, the luminosity performance depends on the lattice performance significantly.
- Especially, Touschek lifetime becomes serious in the nano-beam scheme due to lack of DA.
- Target lifetime is 600 sec in both rings. The large DA in the momentum direction is necessary.
- Transverse aperture is also necessary for the "***betatron injection***". If enough transverse aperture cannot be kept, "***synchrotron injection***" should be considered. The emittance of the injected beam should be small, therefore e+ damping ring (DR) and RF-gun are considered.

Requirement of Injection Aperture

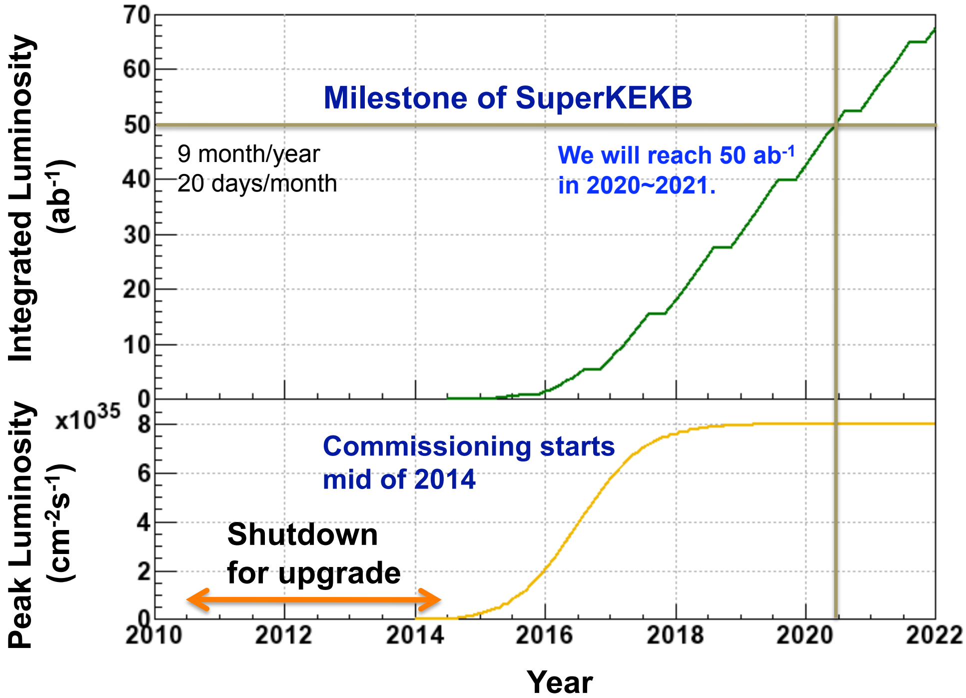
In case of the betatron injection:

Item		LER	HER	unit
Energy	E	4	7	GeV
Horizontal	Ax	5.11×10^{-7}	3.77×10^{-7}	m
	Injection error $2J_x$	4.19×10^{-7}	3.32×10^{-7}	m
Vertical	Ay	1.1×10^{-8}	1.46×10^{-8}	m
	Injection error $2J_y$	0	0	m
Longitudinal	$\Delta p/p_0$	0.21	0.24	%

Parameter Consideration (cont'd)

- Emittance
  - LCC with small emittance
  - wiggler design in LER (change from KEKB)
- Coupling parameter
  - small coupling parameter ~0.4 % is challenging.
  - optimization of solenoid field (small rate of change of Bz)
  - reduction of machine error
- Dynamic aperture
  - Touschek lifetime and injection aperture
- Crab-waist is an option of the baseline design.
  - Synchro-beta resonance is not so serious without the crab-waist.
  - Particle with transverse oscillation (e.g. injected beam) collides at a position of large beta (away from a **waist**) is stable or unstable ?
  - Need to check by tracking simulation with beam-beam kick.

Plan of Luminosity Upgrade

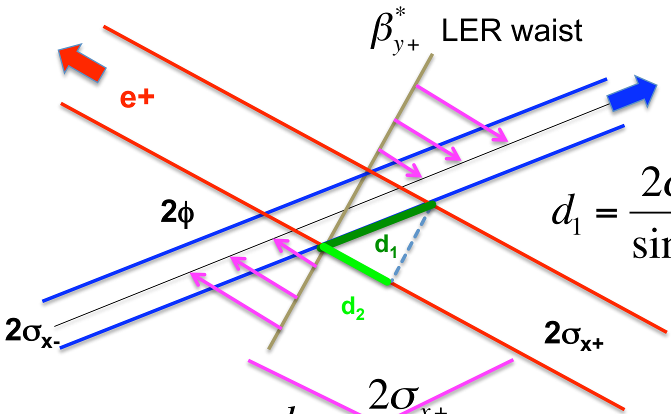


BACKUP SLIDES

Beam Parameters

		KEKB		Nano-beam	
		LER	**HER**	**LER**	**HER**
Energy	GeV	3.5	8	4	7
Beam current	A	1.8	1.4	3.60	2.62
Bunch length	mm	6~7	6~7	6	5
No. bunches		1584		2503	
Energy loss/turn	MV	1.64	3.48	2.15	2.50
Radiation Loss	MW	2.95	4.87	7.74	6.55
Loss factor, assumed	V/pC	-	-	35	40
Parasitic Loss	MW	-	-	1.82	1.10
Total Beam Power	MW	~ 3.5	~ 5.0	9.56	7.65
RF Voltage	MV	8.0	13~15	8.4	6.7

Hourglass Effect for Nano-Beam



$$d_1 = \frac{2\sigma_{x+}}{\sin 2\phi}$$

There are two kinds of hourglass requirements.

$$d_2 = \frac{2\sigma_{x+}}{\tan 2\phi}$$

If crab-waist is available, we can omit it.

Hourglass (H.G) requirement without crab-waist:

$$\beta^*_{y-} \geq \max\left(\frac{2\sigma_{x+}}{\sin 2\phi}, \frac{2\sigma_{x-}}{\tan 2\phi}\right)$$

$$\beta^*_{y+} \geq \max\left(\frac{2\sigma_{x-}}{\sin 2\phi}, \frac{2\sigma_{x+}}{\tan 2\phi}\right)$$