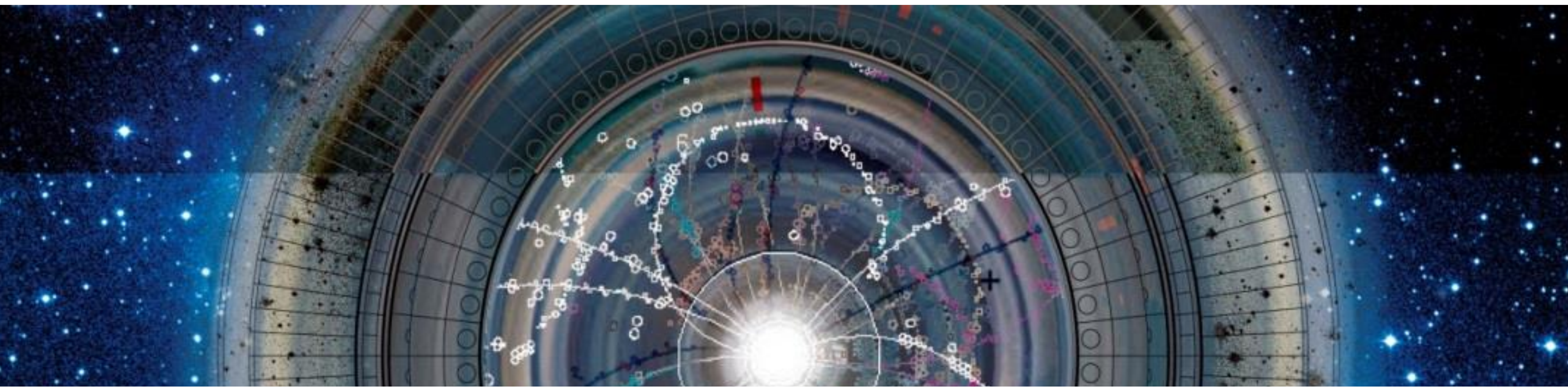


Progress of SuperKEKB

Takako Miura

on behalf of SuperKEKB and LINAC group

KEK

Contents

- **Introduction** of **SuperKEKB**
- **Strategy** of Upgrade
- Upgrade status of **Main Rings**
- Upgrade of **Injector LINAC** & **beam commissioning**
- **Damping Ring** Construction Status
- **Schedule**

Introduction of SuperKEKB

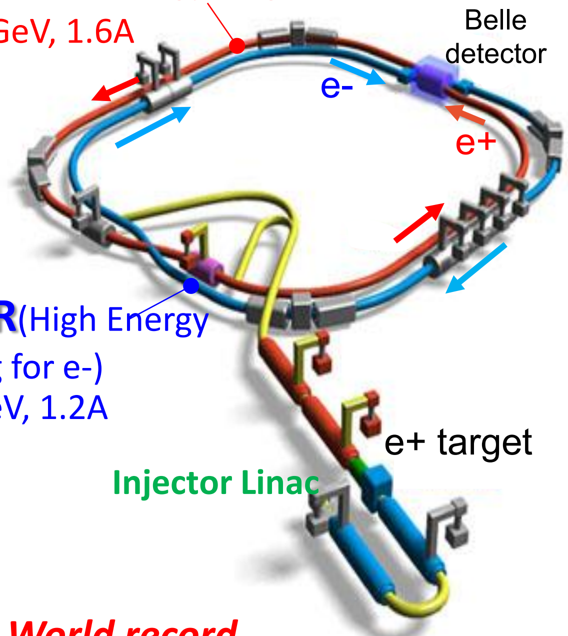
KEKB
(1999 - 2010)
e-/e+ Collider
E_{CM}=10.58 GeV : Υ(4S) resonance

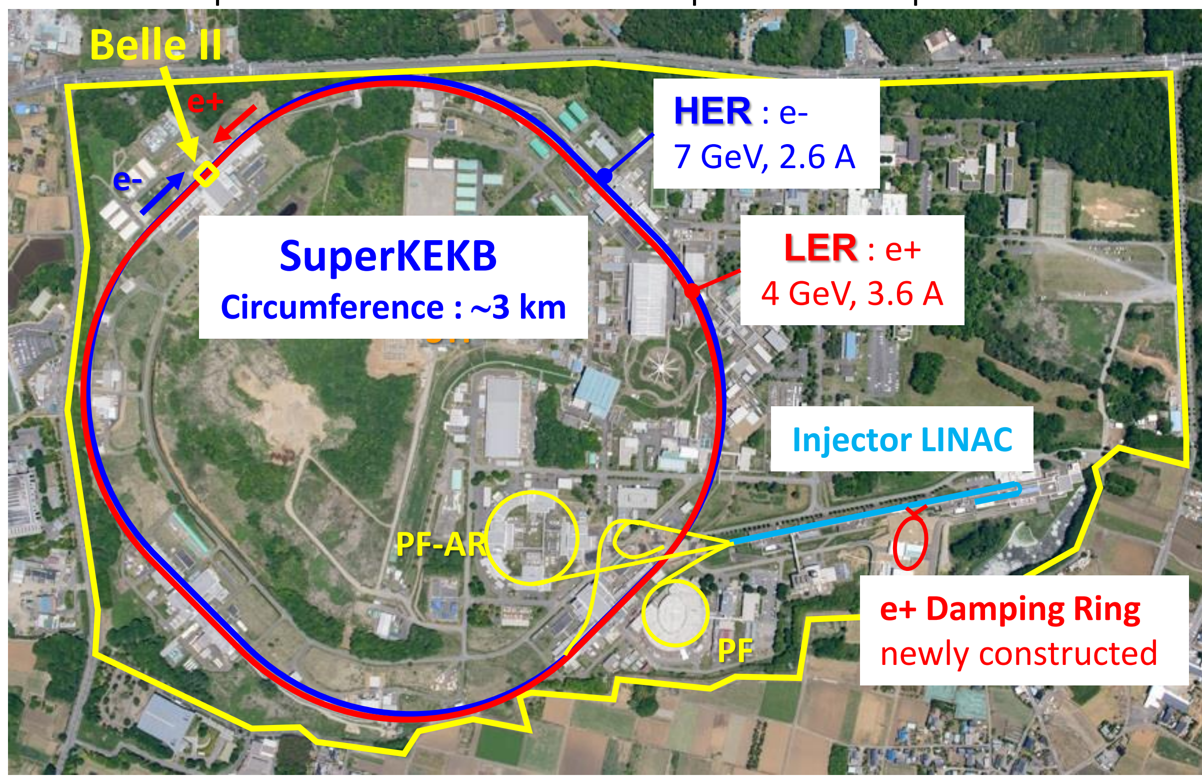
Upgrade

SuperKEKB (2016 -)
Target peak Luminosity: 8×10^{35} cm^{-2}s^{-1}

40 × ***L*** (KEKB)

KEKB tunnel is reused.
KEKB components are reused as much as possible for SuperKEKB.

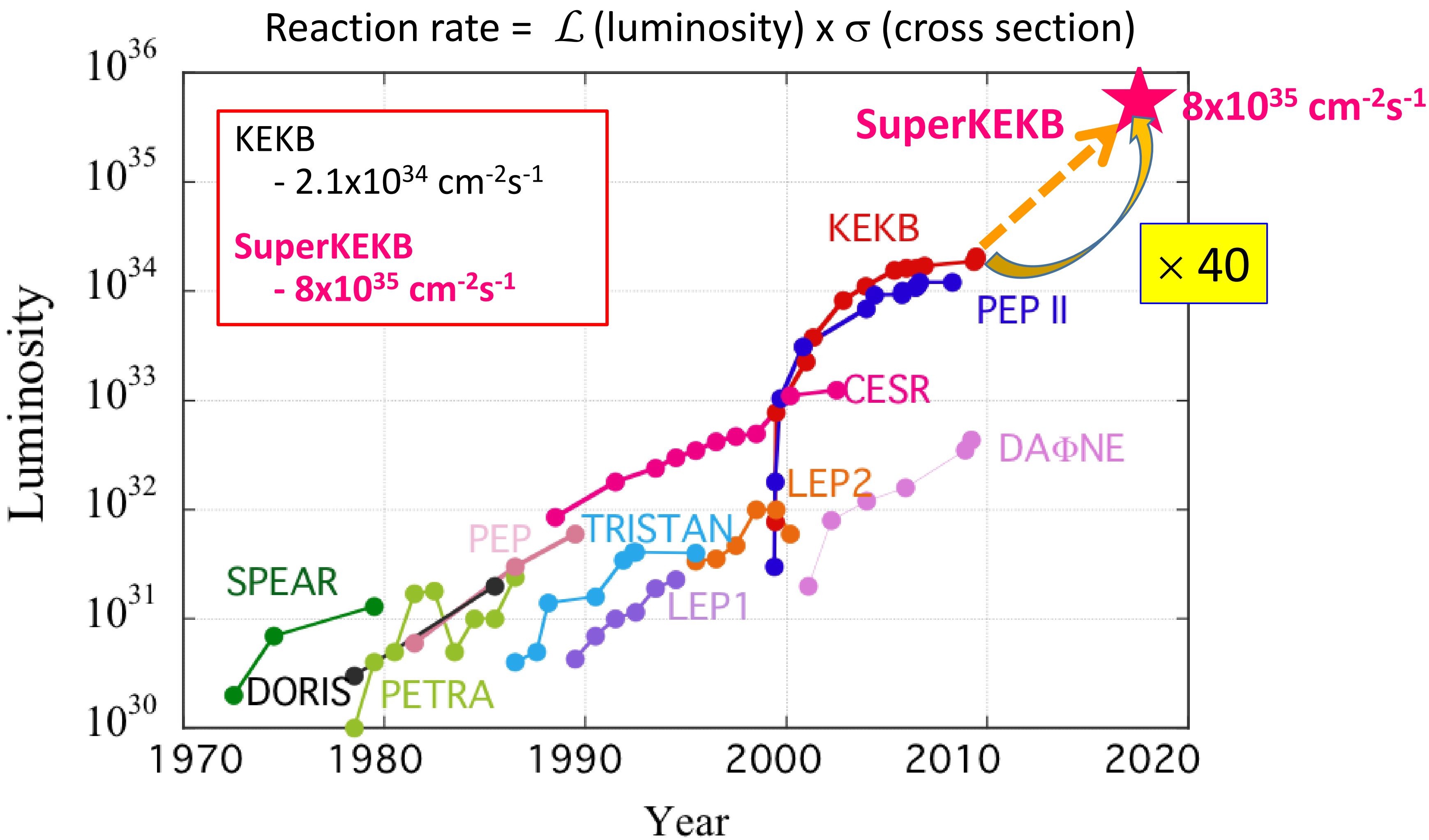




World record

Peak Luminosity
2.1×10^{34} cm^{-2}s^{-1}

Peak Luminosity History of e-/e+ colliders



Contents

How to Increase Luminosity by 40 times

Lorentz factor — Beam current — Beam-Beam parameter

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

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

Classical electron radius

Geometrical reduction factors (crossing angle, hourglass effect)

Vertical beta function at Interaction Point (IP)

	KEKB Achieved		SuperKEKB Nano-beam		
	LER	HER	LER	HER	
β_y^* [mm]	5.9	5.9	0.27	0.30	× 1/20
I [A]	1.6	1.2	3.6	2.6	× 2
ξ_y	0.129	0.090	0.088	0.081	× 1
Luminosity [cm^{-2} s^{-1}]	2.1×10^{34}		8.0×10^{35}		40 times higher

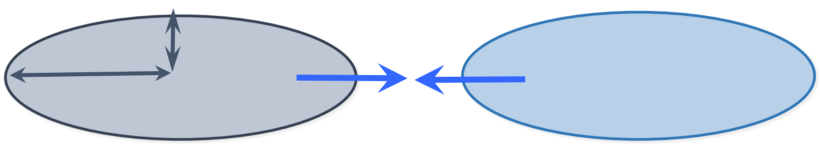
Collision Scheme

At interaction point(IP), $\beta_y^* \geq$ overlap region by "hourglass effect".

$$\boldsymbol{\beta(s) = \beta^* + \frac{s^2}{\beta^*}}$$

KEKB

head-on (w/ crab)



Overlap region = bunch length

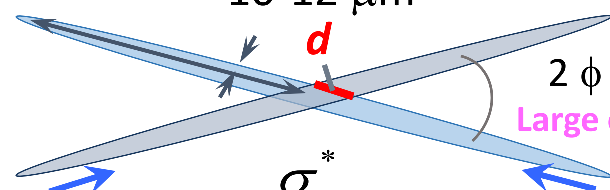
Hourglass Condition

$$\beta_y^* \geq \sigma_z \quad \sim 6 \text{ mm}$$

SuperKEKB

Nano-beam scheme

P. Raimondi



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

ϕ : Half crossing angle

Overlap region = *d*

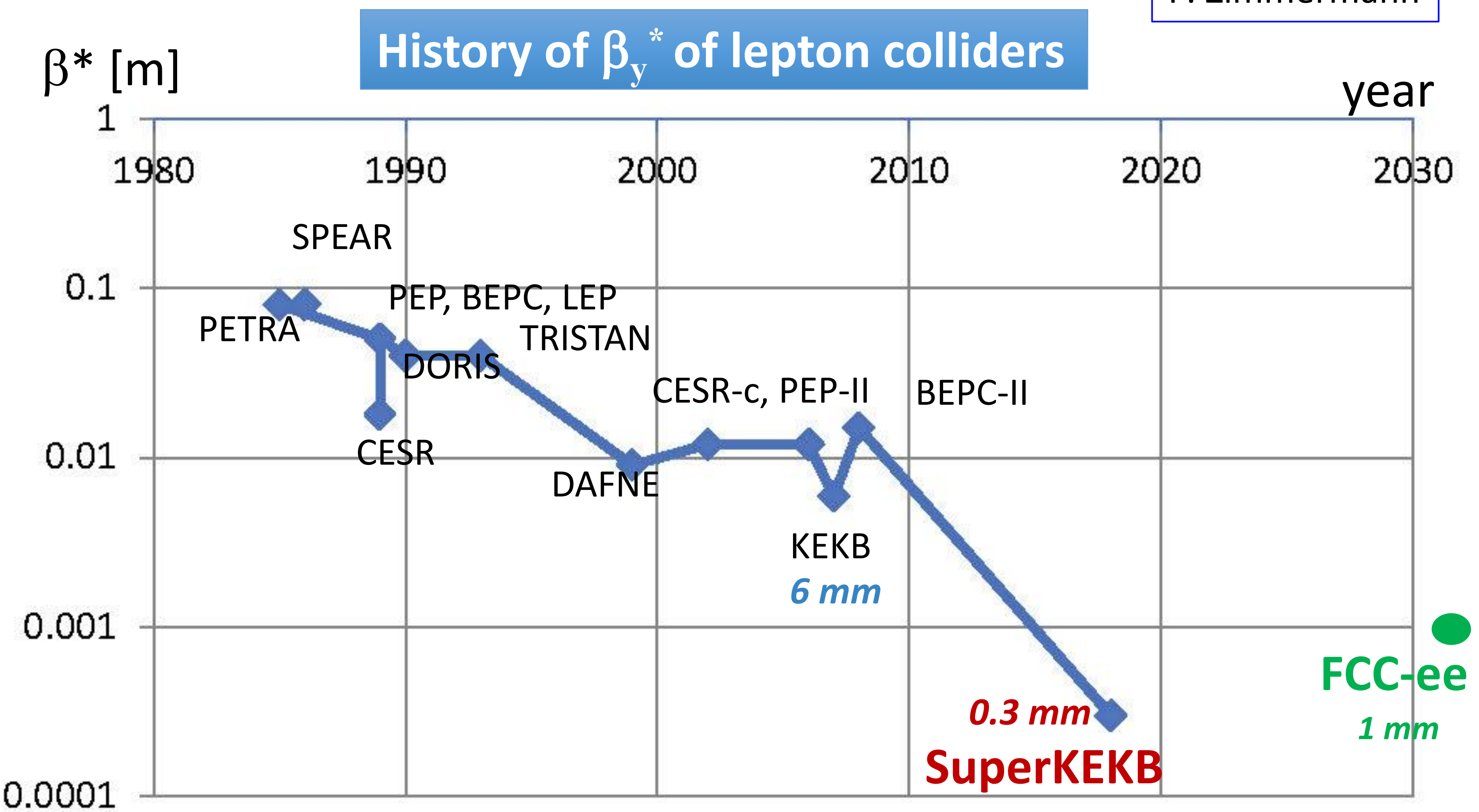
Hourglass Condition

$$\beta_y^* \geq \frac{\sigma_x^*}{\phi} \quad \sim 0.3 \text{ mm}$$

Need small horizontal beam size at IP.
→ low emittance, small β_x at IP.

Challenge to $\beta_y^* \leq 1$ mm

F. Zimmermann



Other Design Concept

Changing beam energy

KEKB SuperKEKB

- **LER (e+) : 3.5 GeV → 4.0 GeV**
  - Longer Touschek lifetime
  - Mitigation of emittance growth due to the intra-beam scattering

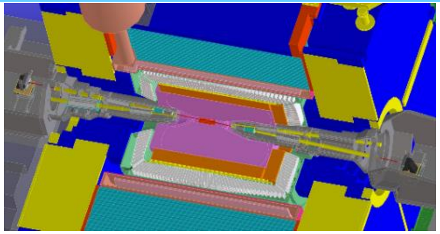
- **HER (e-) : 8.0 GeV → 7.0 GeV**
  - Lower emittance
  - Lower synchrotron radiation power

  ⇨ Despite of doubling beam current,
  KEKB beam chambers can be re-used.

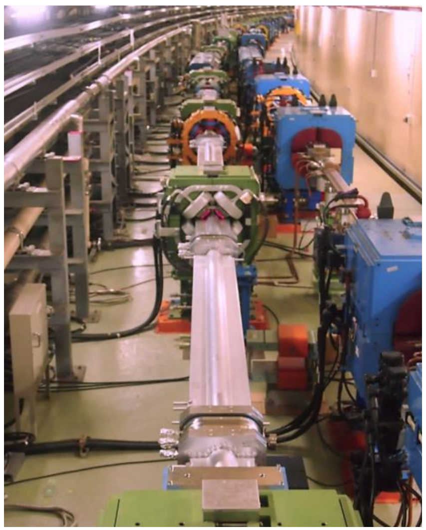
Machine Design Parameters

parameters		KEKB		SuperKEKB		units
		LER	HER	LER	HER	
Beam energy	E_b	3.5	8	4	7.007	GeV
Half crossing angle	ϕ	11		41.5		mrad
# of Bunches	N	1584		2500		
Horizontal emittance	ε_x	18	24	3.2	4.6	nm
Emittance ratio	κ	0.88	0.66	0.27	0.25	%
Beta functions at IP	β_x^*/β_y^*	1200/5.9		32/0.27	25/0.30	mm
Beam currents	I_b	1.64	1.19	3.6	2.6	A
beam-beam param.	ξ_y	0.129	0.090	0.088	0.081	
Bunch Length	σ_z	6.0	6.0	6.0	5.0	mm
Horizontal Beam Size	σ_x^*	150	150	10	11	um
Vertical Beam Size	σ_y^*	0.94		0.048	0.062	um
Luminosity	**L**	**2.1×10^{34}**		**8×10^{35}**		**$cm^{-2}s^{-1}$**

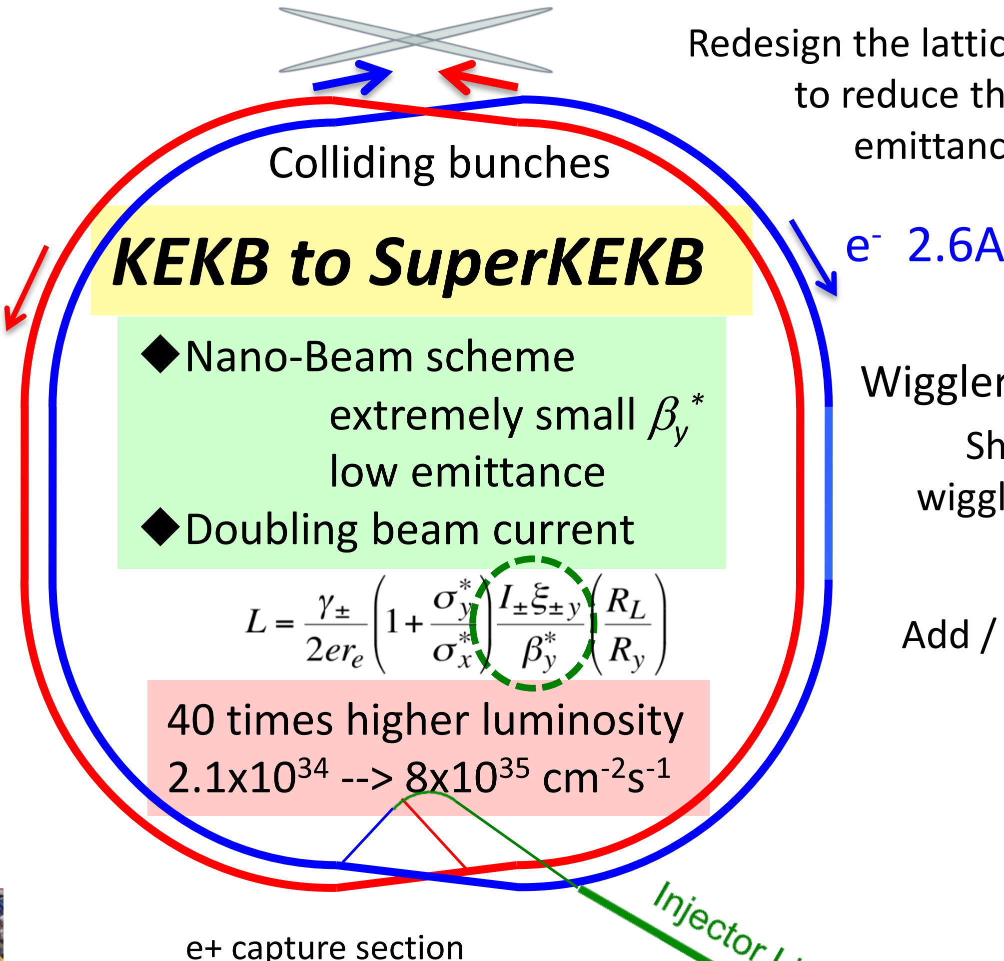
Major Upgrades toward SuperKEKB



New superconducting final focus system



TiN-coated beam pipes with antechambers



e+ capture section

Redesign the lattice to reduce the emittance

Wiggler section

Shortening wiggler cycles

Add / modify RF systems for higher beam current

Contents

- Introduction of SuperKEKB
- Strategy of Upgrade
- **Upgrade status of Main Rings**
  - **Final Focusing Magnets**
  - **Interaction Region**
  - **Magnet System**
  - **Vacuum System**
- Upgrade of Injector LINAC & beam commissioning
- e+ Damping Ring Construction Status
- Schedule

Final Focusing Magnets

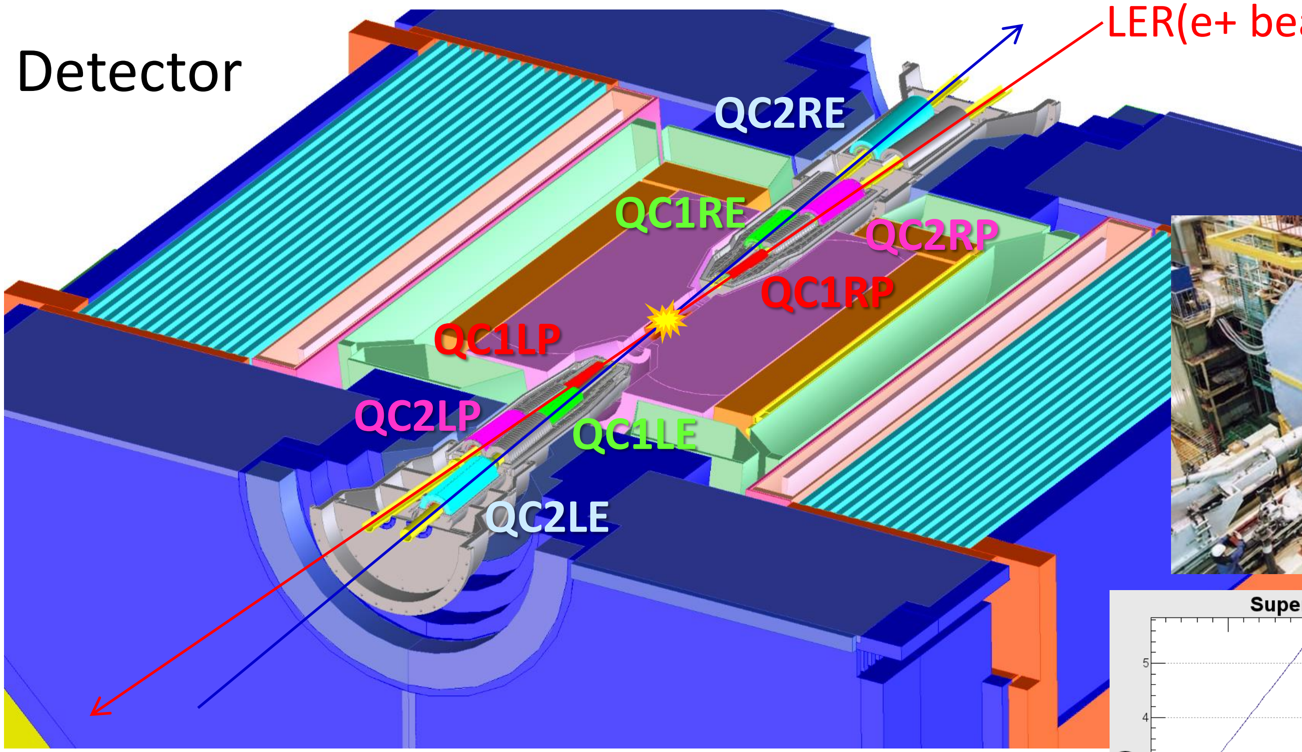
N. Ohuchi

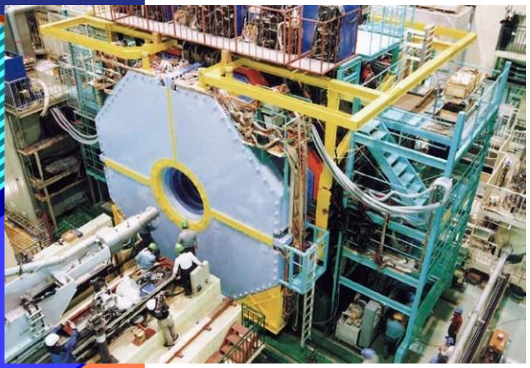
"QC" : Final focus superconducting(S.C.) magnet

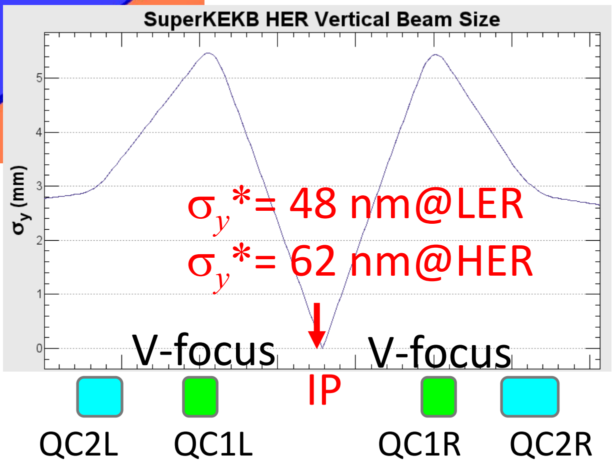
HER(e- beam)

LER(e+ beam)

Belle II Detector





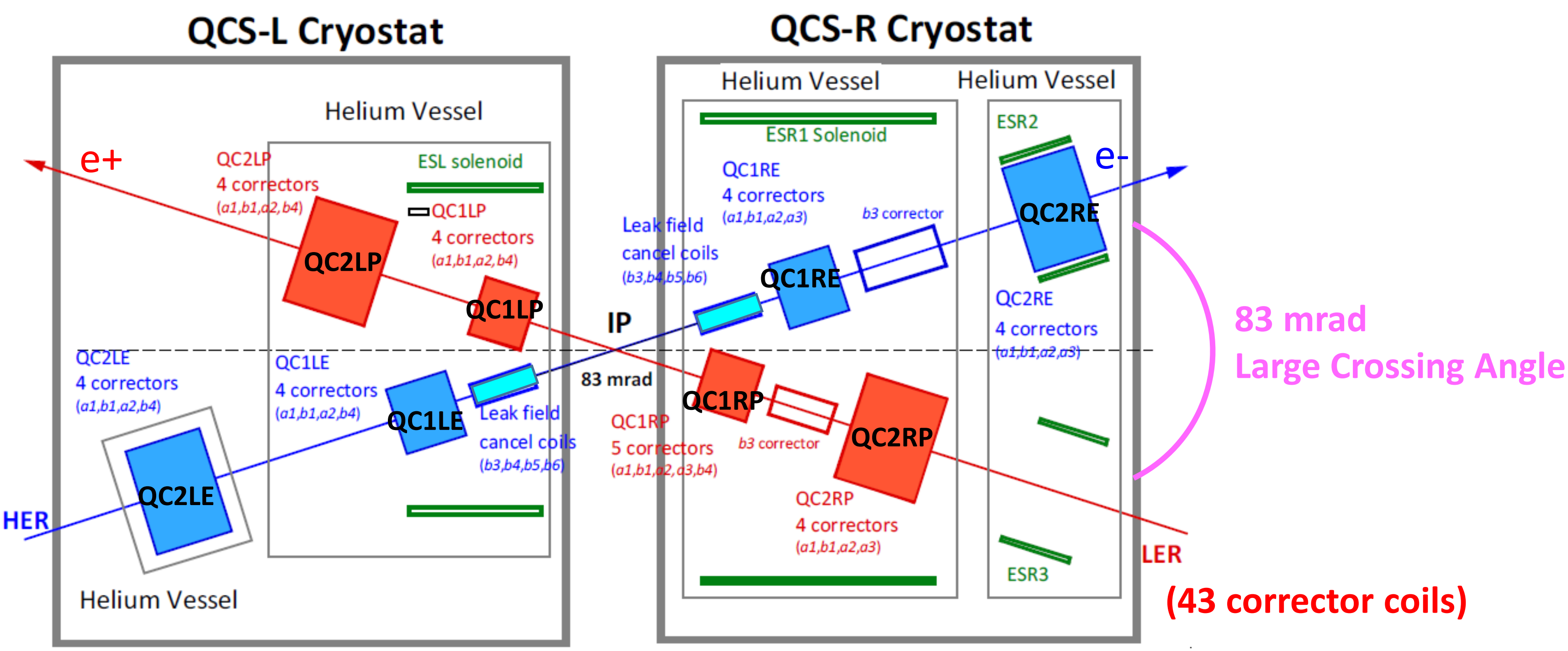


Design Constraint:
Quadrupoles need to be located as close to Interaction Point (IP) as possible. (LER L*= 0.76 m, HER: L*=1.22 m)

➡ Quadrupoles are located inside of the Belle II solenoid fields (1.5T).

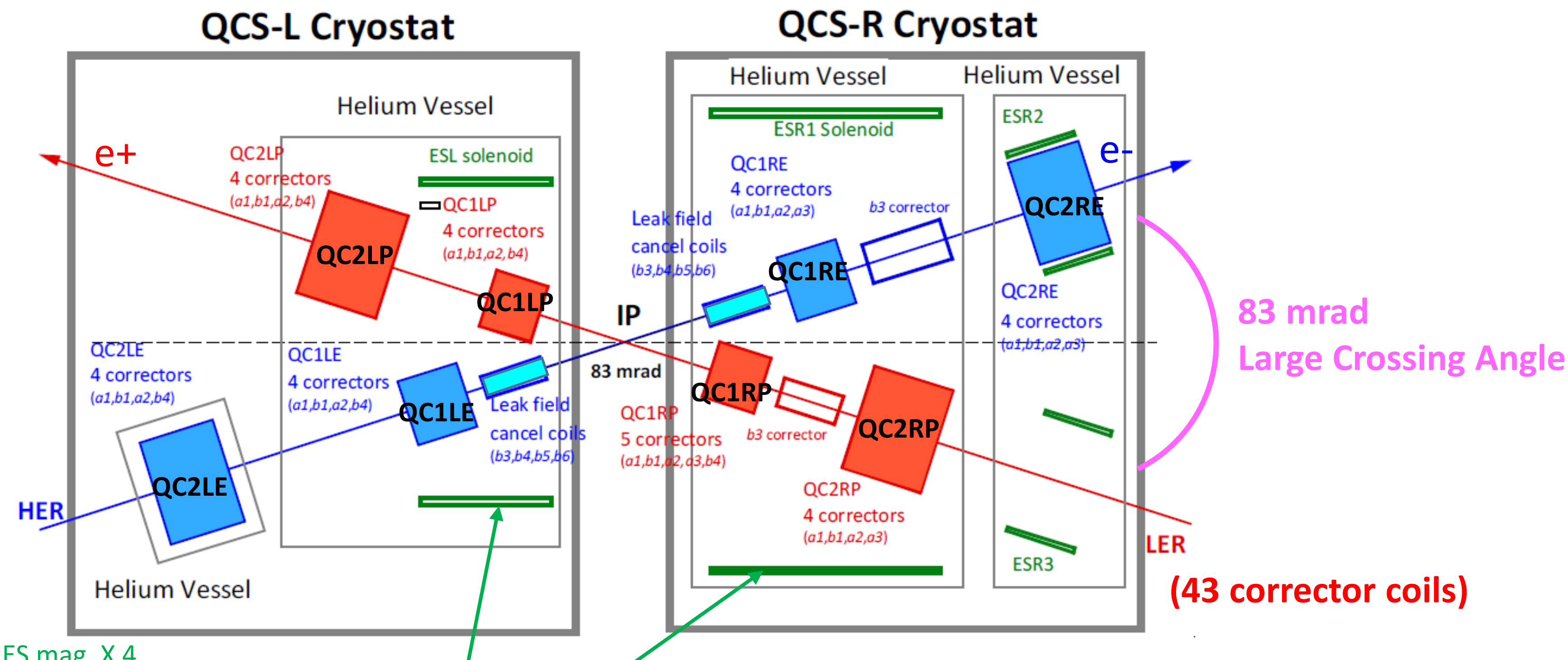
Final Focusing S.C. Magnets

N. Ohuchi



Final Focusing S.C. Magnets

N. Ohuchi



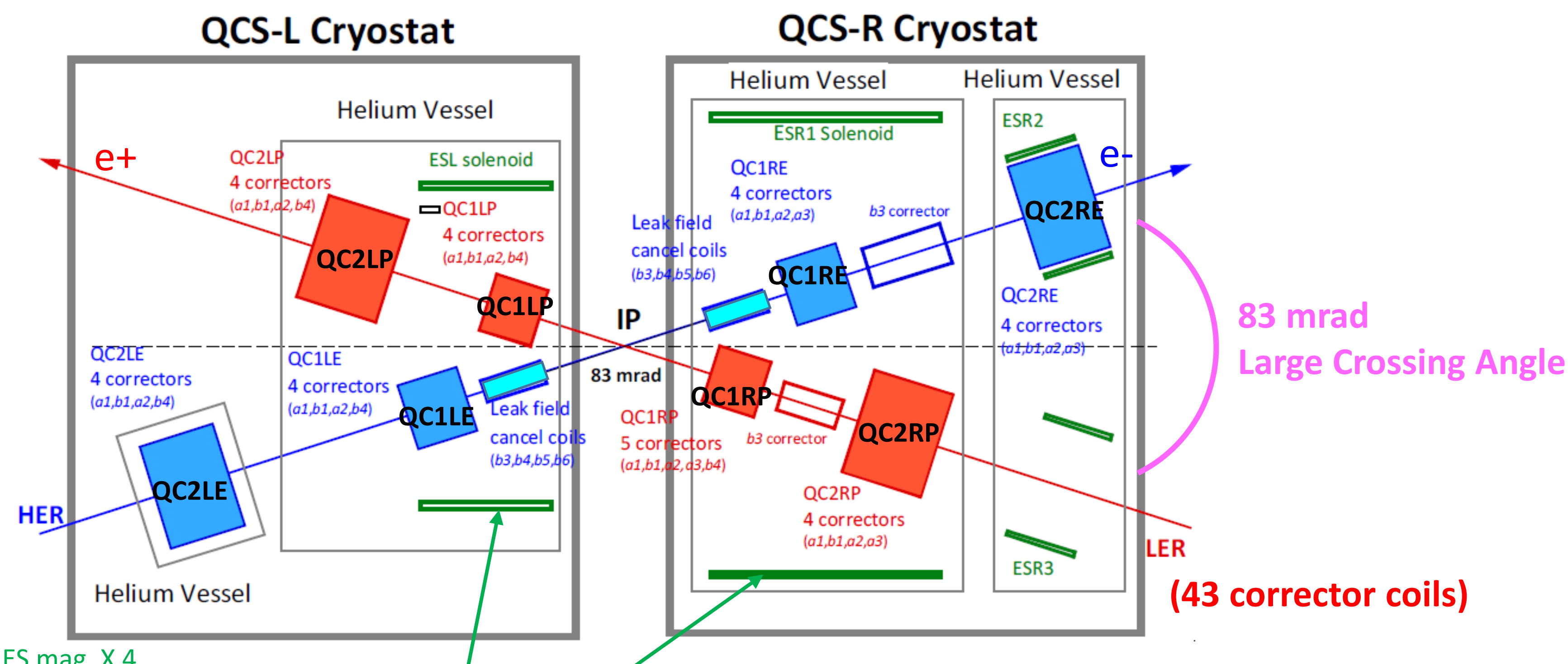
ES(L/R): Compensation solenoids
to cancel the Belle II solenoid field

Final Focusing S.C. Magnets

QC1,QC2: Final Focus Doublet

N. Ohuchi

with corrector coils : nomal&skew dipole, skew quad, sextupole, skew sextupole, octupole



ES(L/R): Compensation solenoids to cancel the Belle II solenoid field

Final Focusing S.C. Magnets

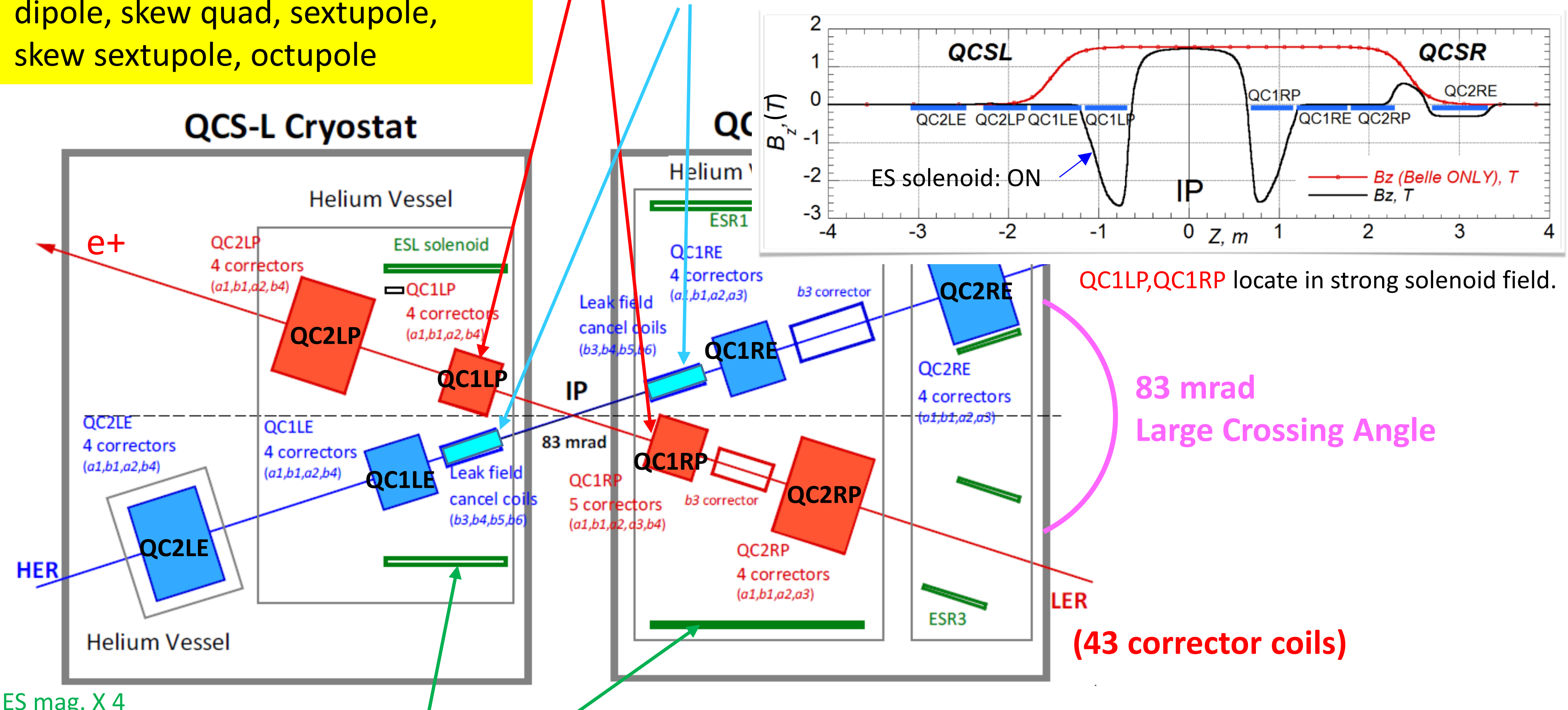
QC1,QC2: Final Focus Doublet

with corrector coils : nomal&skew dipole, skew quad, sextupole, skew sextupole, octupole

QC1LP, QC1RP : no magnetic shield (return yoke).
Leakage fields affect HER beam line.

N. Ohuchi

Cancel coils for QC1LP, QC1RP leakage fields



ES mag. X 4

ES(L/R): Compensation solenoids
to cancel the Belle II solenoid field

Final Focusing S.C. Magnets

QC1,QC2: Final Focus Doublet

with corrector coils : nomal&skew dipole, skew quad, sextupole, skew sextupole, octupole

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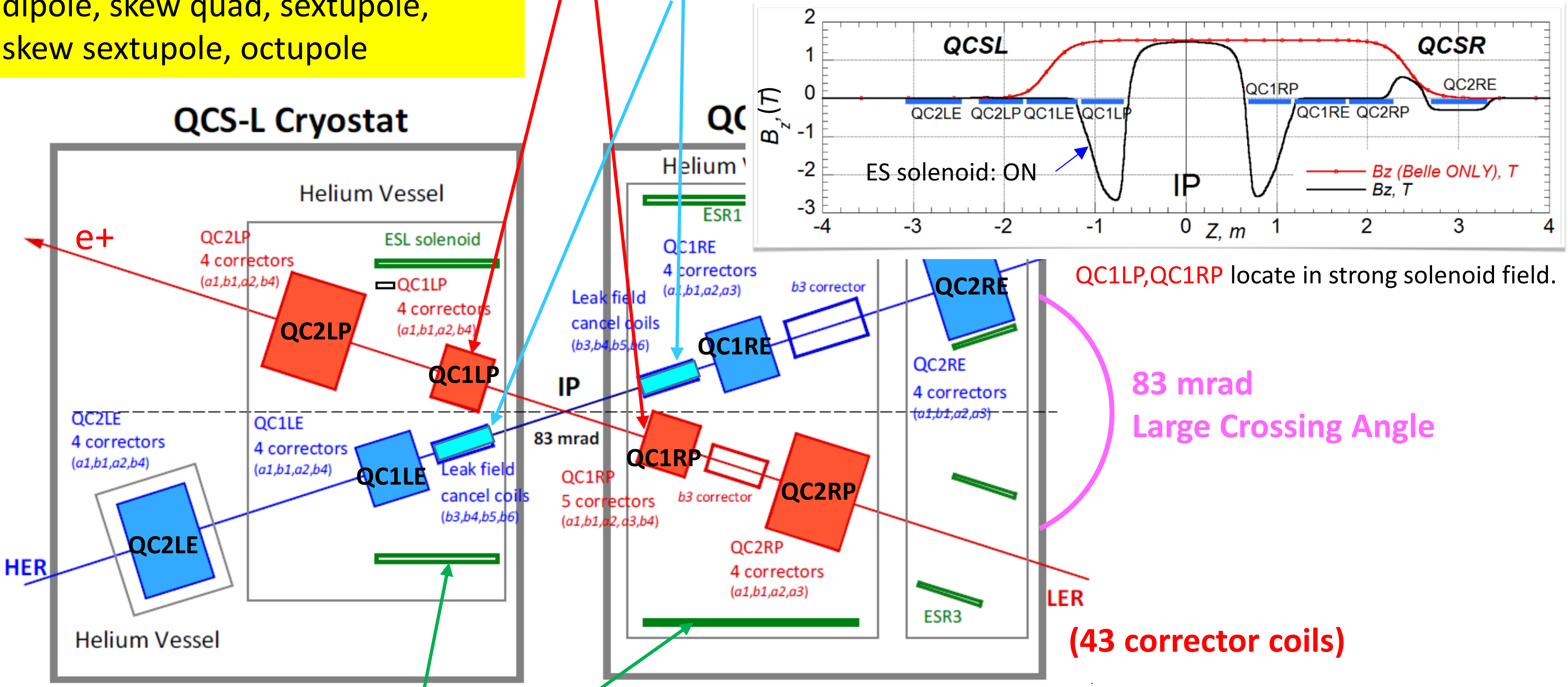


QC1LP,QC1RP locate in strong solenoid field.

83 mrad Large Crossing Angle

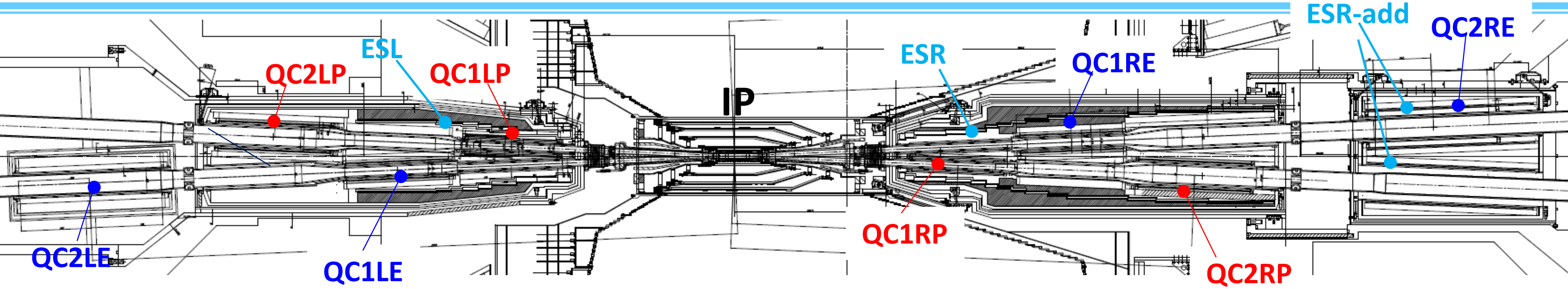
(43 corrector coils)

ES mag. X 4

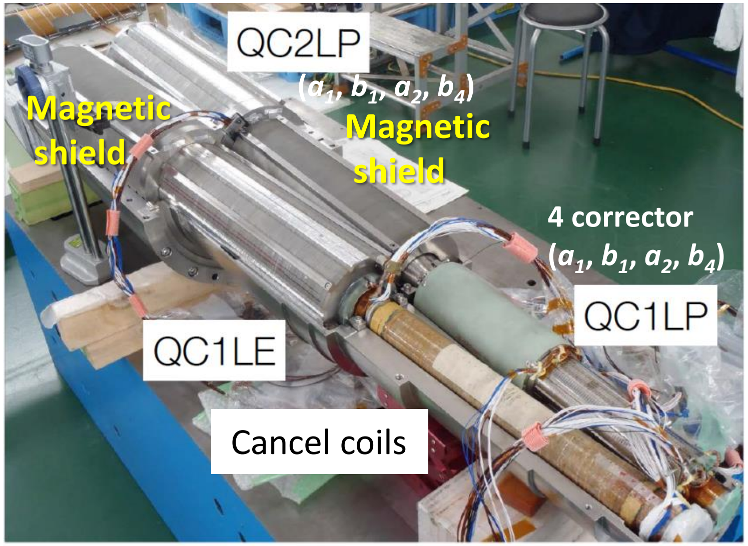
ES(L/R): Compensation solenoids to cancel the Belle II solenoid field

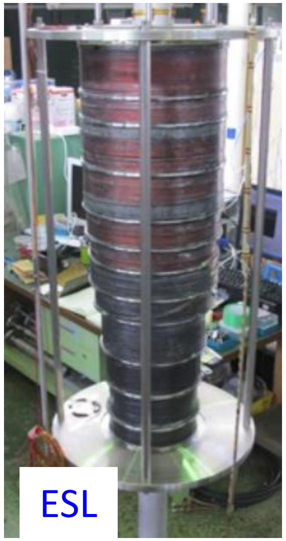
Minimization of higher multipole fields is crucial for wide dynamic aperture.
➡ Final focus magnets were carefully designed.

Final Focusing S.C. Magnets (Construction Status)

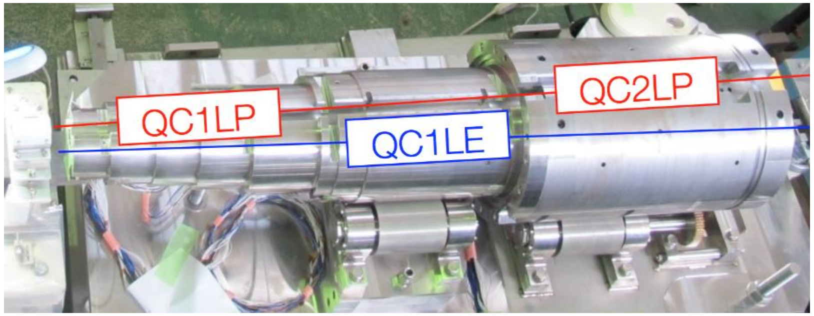


Left side S.C. magnets





Assemblies of all quadruple magnets were completed.



4K cold test of left-side magnets was performed.
Sufficient performance for beam operation was confirmed.
Left-side cryostat will be completed soon. (Right-side: end of 2015)

N. Ohuchi

Interaction Region (IR)

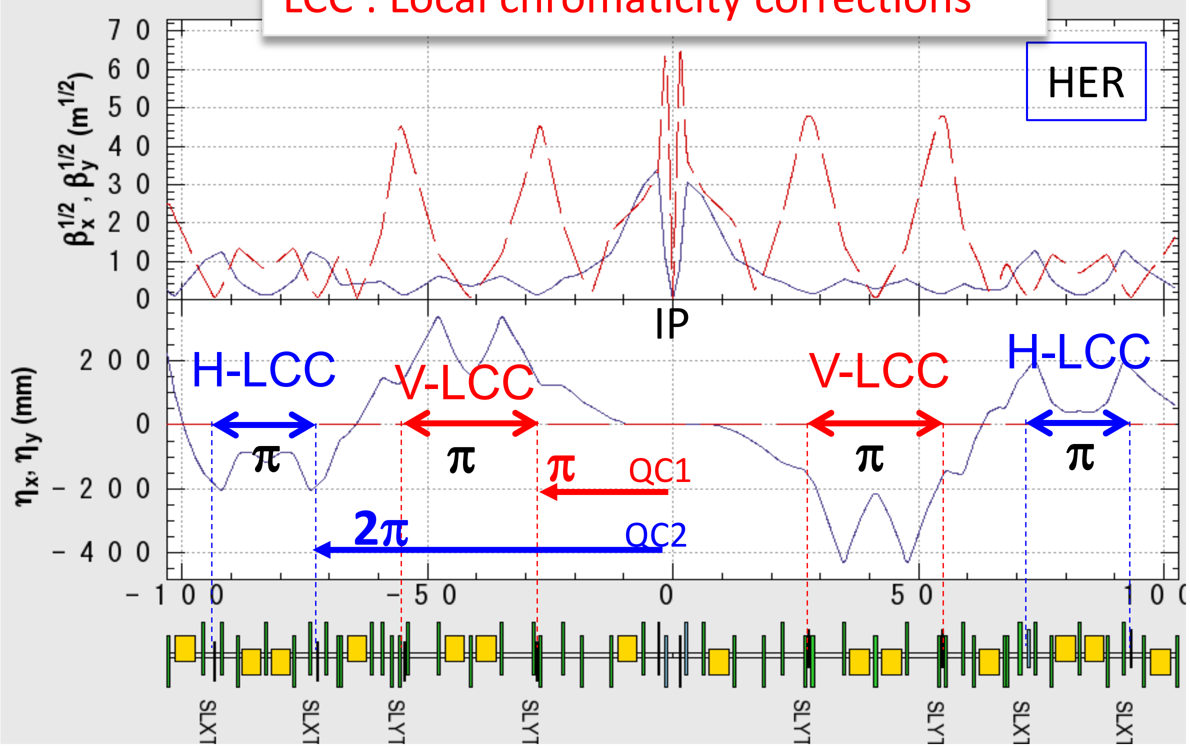
Natural Chromaticity

	KEKB		SuperKEKB	
	LER	HER	LER	HER
Horizontal	-72	-70	-105	-171
Vertical	-123	-124	-776	-1081

Y. Ohnishi, A. Morita

~80% in vertical chromaticity is induced by “Final Focus”.

LCC : Local chromaticity corrections

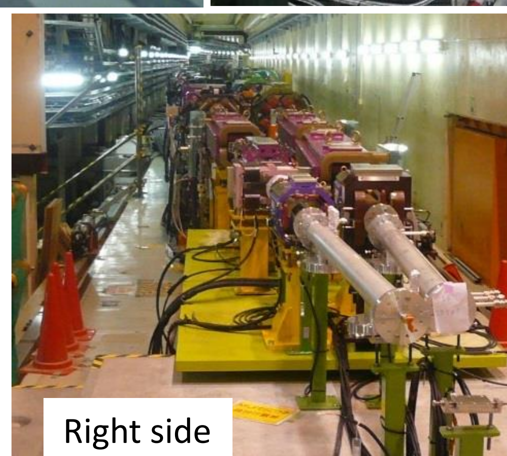


Ver./Hori. LCC are adopted to correct large chromaticity near final focus in the both rings.

Construction Progress in Interaction Region

Large crossing angle & Local chromaticity correction

➡ 320 m beam lines around interaction region were entirely reconstructed.



M. Masuzawa

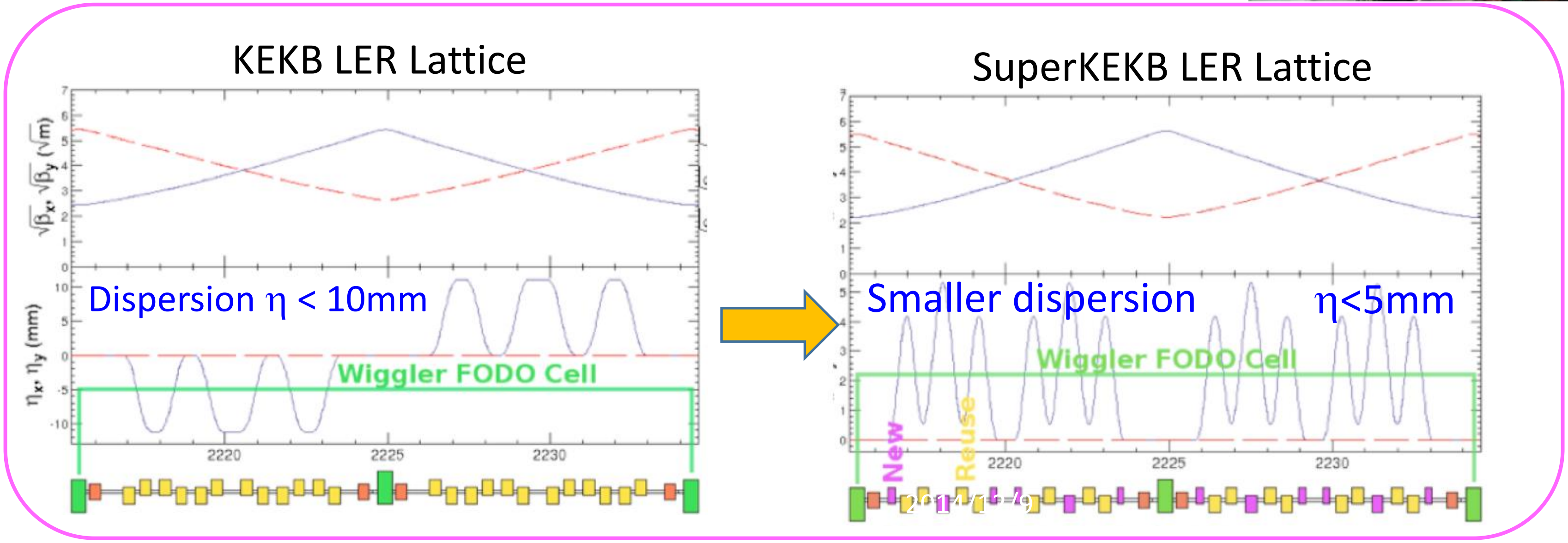
Magnet System (Wiggler Magnets)

M. Masuzawa

Wiggler magnets have been installed in the both rings for

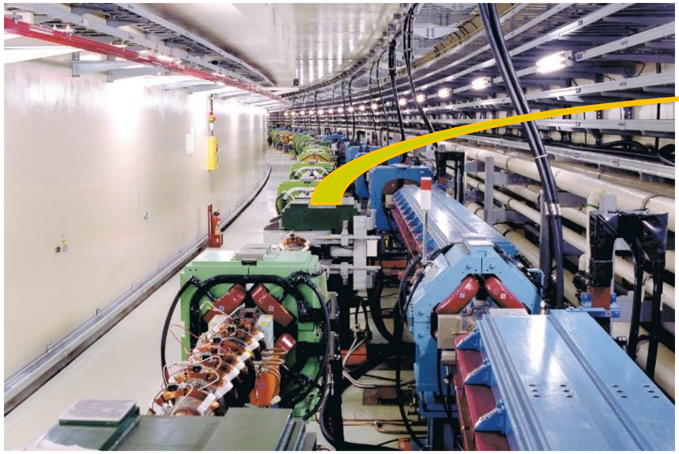
- **Shortening of radiation damping time**
- **Reduction of Emittance**

LER : Shortening wiggler cycles



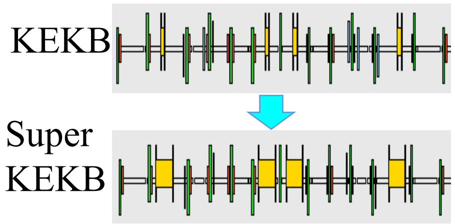
Magnet System (LER Dipoles in arc)

LER dipole magnets in arc are replaced with longer ones for low ε_x.



LER bend in arc

L_{Bend}: 0.89 m → 4 m



M. Masuzawa

$$\varepsilon_x \propto \frac{1}{2\pi\rho^2} \oint H(s)\, ds$$

$$H(s) = \gamma_x \eta_x^2 + 2\alpha \eta_x \eta'_x + \beta_x \eta'^2_x$$

ρ : curvature of dipole magnets
α, β, γ : twiss parameters
η : dispersion

Progress of magnet system

Most of magnets have been already installed.

Integrated testing with power supplies is in progress.

2nd alignment will be started soon.

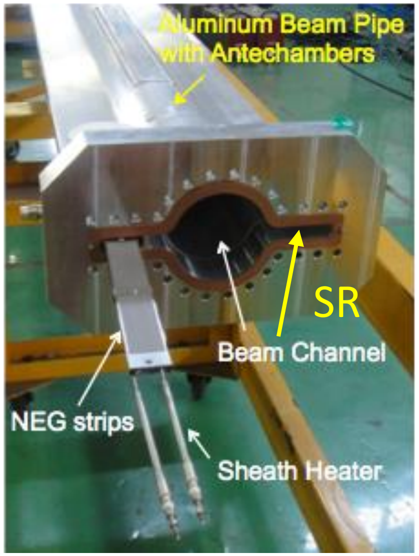
Vacuum System

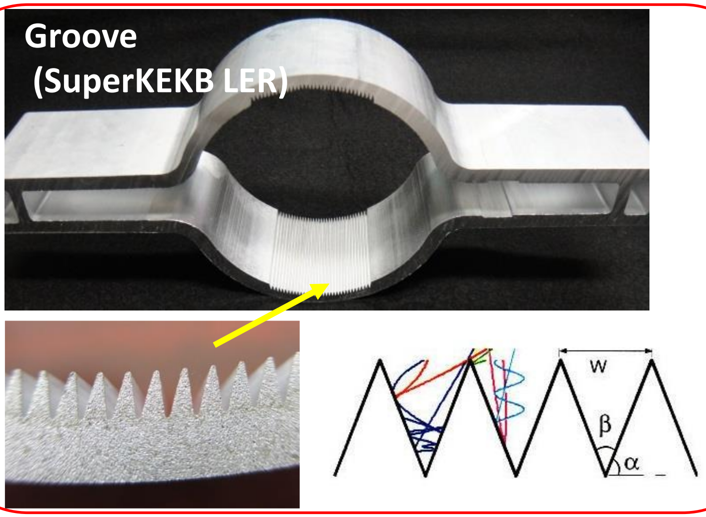
Effects of the electron cloud in LER (e+) are more serious than KEKB. Various countermeasures to prevent emittance growth due to head-tail instability are necessary.

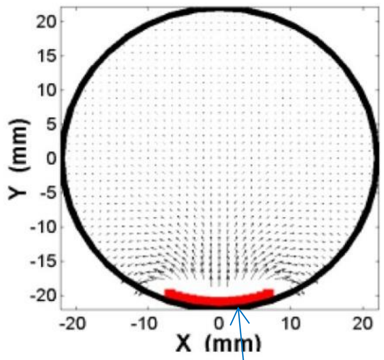
Drift section	Antechamber(Al) +TiN Coating + Solenoid (50G)
Q and Sx mag.	Antechamber(Al) +TiN Coating
Bend section	Antechamber(Al) +Groove+ TiN Coating
Wiggler section	Antechamber(Cu) +Clearing electrode

<Suppression rate> Antechamber:1/5, Solenoid:1/50, Groove:1/4, Electrode:1/100
TiN: 3/5 (Cu), 1/50 (Al)

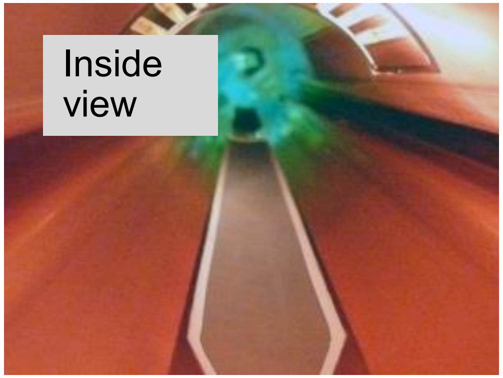
Arc Section







Clearing Electrode
(+500V)



Almost all beam pipes in LER have been already replaced with new ones.

Y. Suetsugu

Beam Lifetime

Y. Funakoshi

	KEKB (design)		KEKB (operation)		SuperKEKB Design	
	LER	HER	LER	HER	LER	HER
Radiative Bhabha	21.3h	9.0h	6.6h	4.5h	28min.	20min.
Beam-gas	45h[a)]	45h[a)]			24.5min.[b)]	46min. [b)]
Touschek	10h	-			10min.	10min.
Total	5.9h	7.4h	~2.2h	~3.3h	6min. [c)]	6min. [c)]
Beam current	2.6A	1.1A	1.6A	1.1A	3.6A	2.6A
Loss Rate	0.12mA/s	0.04mA/s	0.23mA/s	0.11mA/s	10mA/s	7.2mA/s

a) Bremsstrahlung
b) Coulomb scattering, sensitive to collimator setting
c) w/o beam-beam effect

Revolution freq~100kHz

For compensation of the particle loss
4nC@25Hz 2.9nC@25Hz
injection rate are required.

Low emittance and high current injection beams are necessary.

➡ ***LINAC is a key component of SuperKEKB.***

Contents

- Introduction of SuperKEKB
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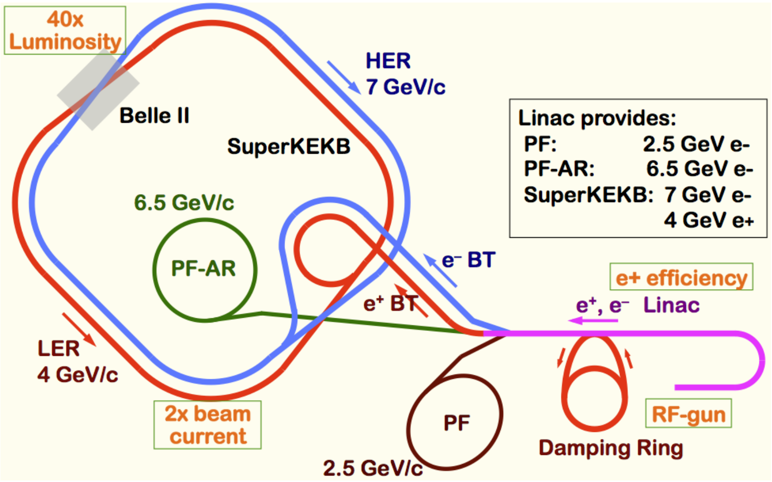
- **Upgrade of Injector LINAC & beam commissioning**
  - **Low emittance e- Gun System**
  - **Positron Capture Section**
- e+ Damping Ring Construction Status
- Schedule

LINAC Beam Parameters

	for KEKB		for SuperKEKB	
	e+	e-	e+	e-
Energy	3.5 GeV	8.0 GeV	4.0 GeV	7.0 GeV
Bunch charge	Primary e-10nC →1 nC	1 nC	Primary e-10nC → 4 nC	5 nC
Num. of Bunch / Pulse	2	2	2	2
Norm.Emittance (γβε)	2100 (mm·mrad)	100 (mm·mrad)	100/20 (Hor./Ver.) (mm·mrad)	50/20 (Hor./Ver.) (mm·mrad)
Energy spread	0.125%	0.125%	0.1%	0.1%
Repetition rate	50 Hz		50 Hz	



0.3nC ×1
5nC × 1
5nC × 2
4nC × 2

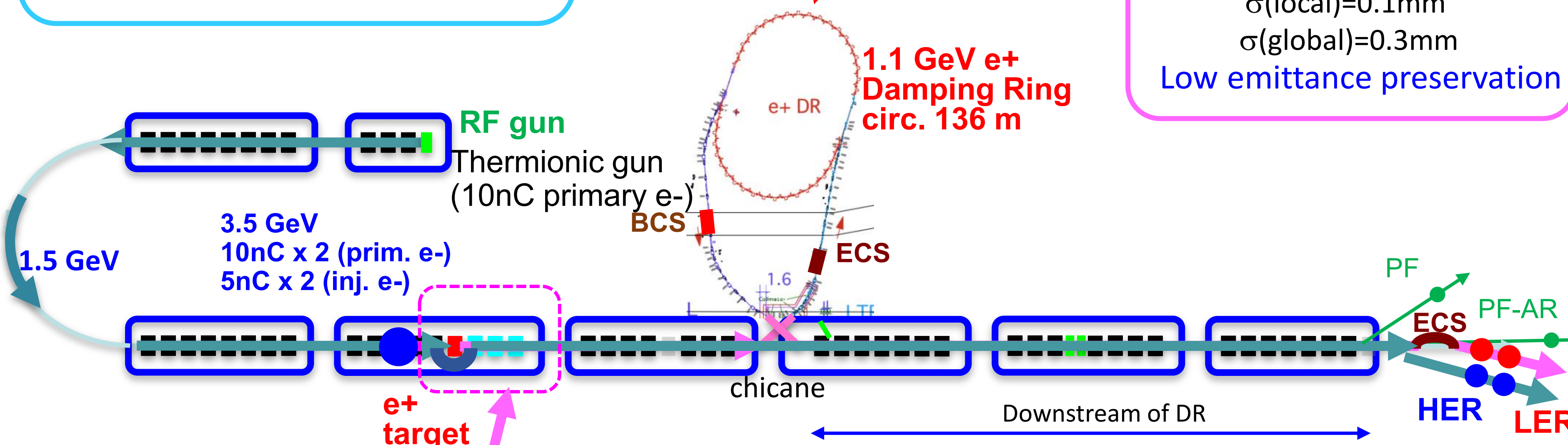
Beam modes are switched in pulse to pulse for 5-rings including Damping Ring (DR).

Major Upgrades of Injector LINAC

Photo-cathode RF gun system
< e- beam>
Low emittance ($\gamma\varepsilon \leq 20$ mm·mrad)
high bunch charge ($\geq$ 5nC)

Positron Damping Ring (DR)
Low emittance e+ beam

Alignment error tolerance
σ(local)=0.1mm
σ(global)=0.3mm
Low emittance preservation



- RF phases are switched for each beam energy
- Pulsed Quads & Pulsed Steering Magnets are installed for switching the optics for each mode

Positron Capture Section
- Flux concentrator (FC)
- Large aperture S-band accel. Structures (LAS)

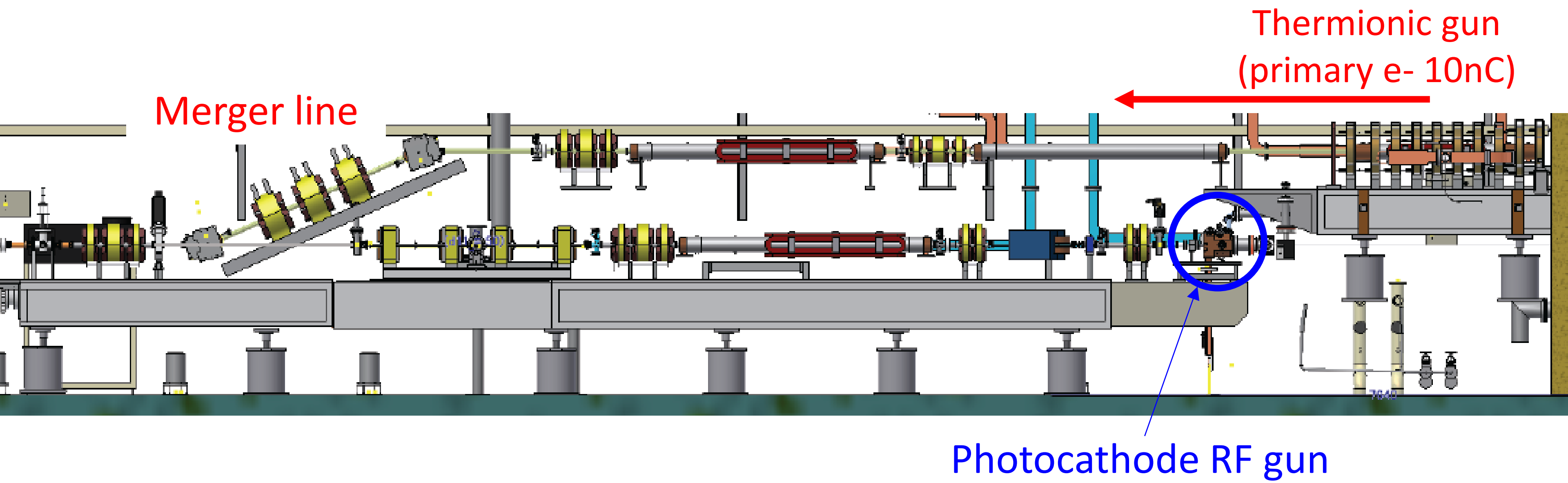
4 times higher e+ yield

Event Timing System and Pulsed Modules
- Synchronization for 5-rings including DR.

Layout of Electron Guns

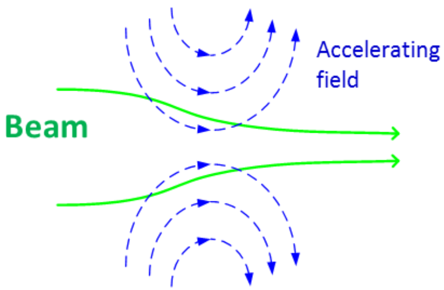
- Thermionic electron gun are located upstairs to produce ~10 nC primary electrons for positron production.

- Photocathode RF gun for low emittance e- production is located on the straight line.

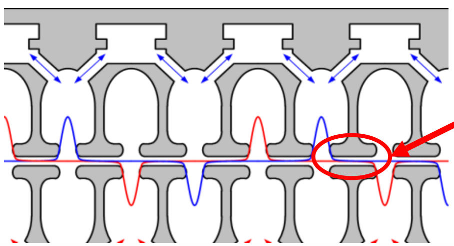


Quasi Traveling Wave Side Couple RF GUN

Strong focusing force using accelerating field

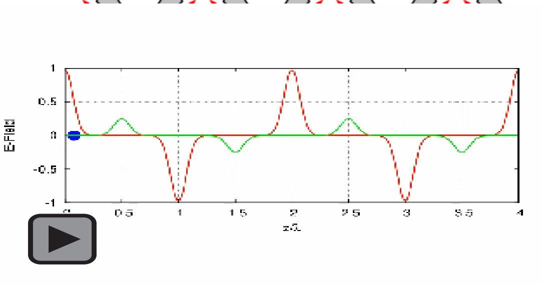


=> Strong focus



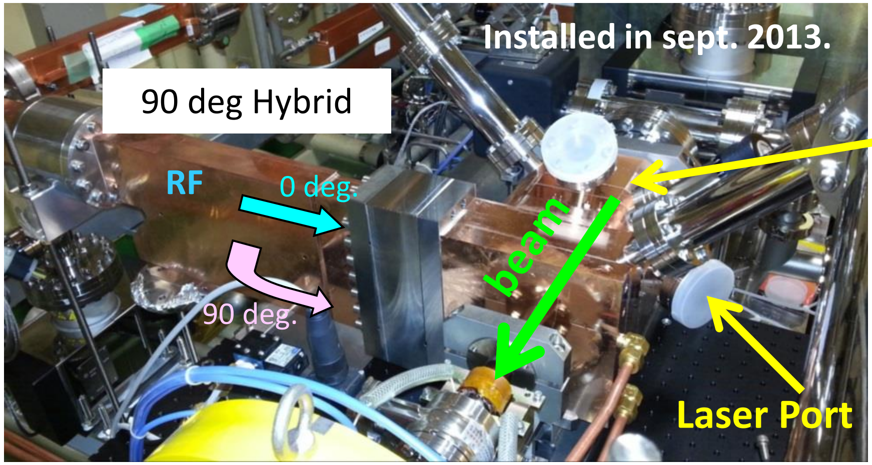
QTW type is adopted to make drift space short.

Drift space = no focus field



QTW is made by two standing waves with 90deg phase difference.

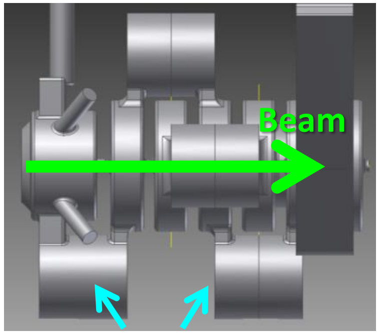
Quasi traveling wave (QTW) side couple RF gun



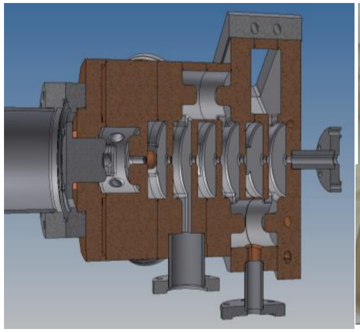
QE=1 × 10^{-4} @266nm
Long lifetime

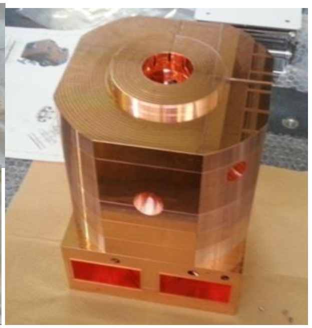
Incident angle: 60deg to the cathode surface.

7 cell, 13.5 MeV@design
Norm. ε: 5.5 mm-mrad @5 nC (by simulation)
This RF gun can generate e- up to 10 nC



coupling cavities

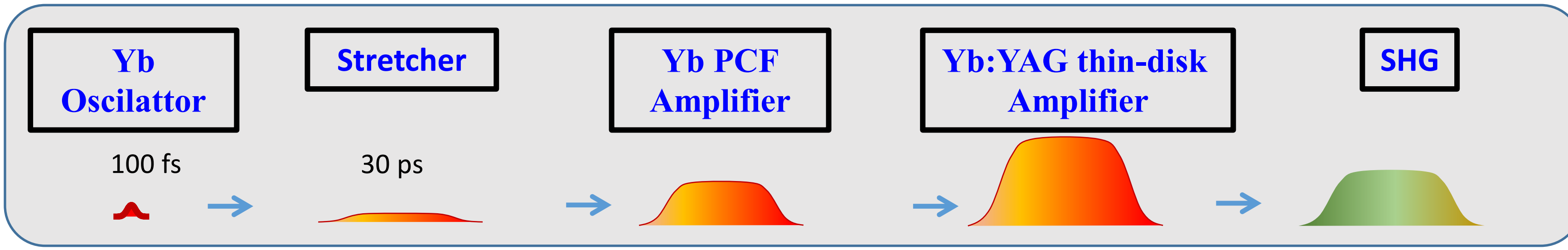


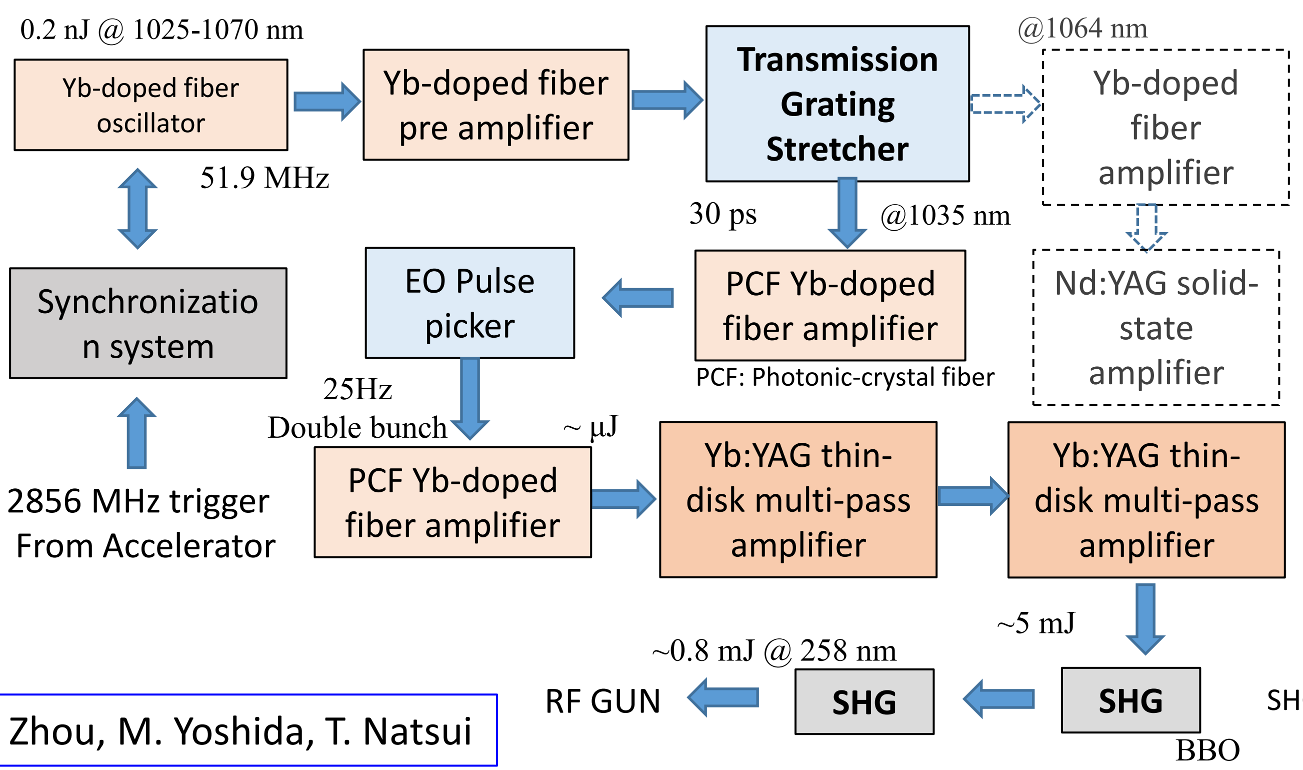


T.Natsui, M.Yoshida

Yb:YAG Laser System for RF-Gun

Yb:YAG (1025-1070 nm) broad band →Pulse shape manipulation is possible.





2 bunch, 25 Hz achieved (limited by thermal effect)

Final goal is 50 Hz.

SHG: Second harmonic generator

X. Zhou, M. Yoshida, T. Natsui

Beam Commissioning of RF Gun

Operation Condition

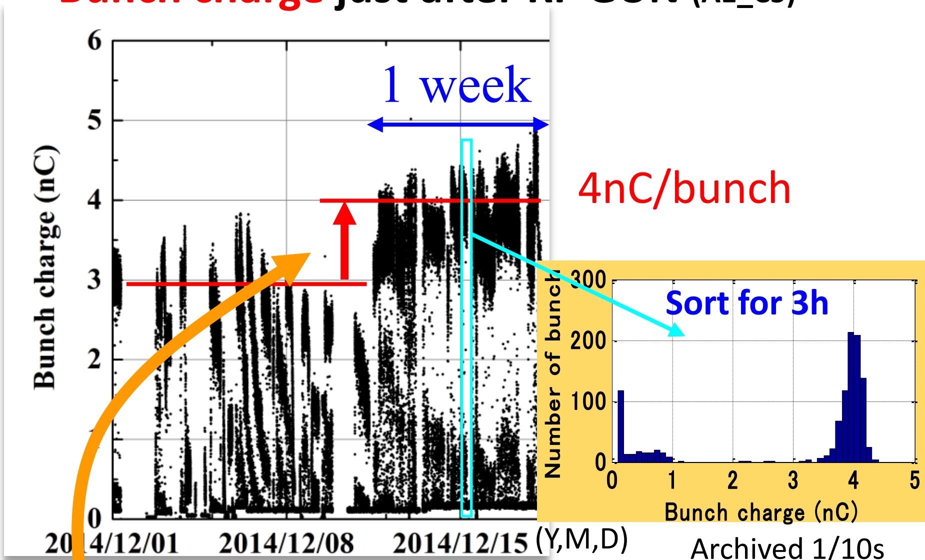
- Laser: 2bunch, 25 Hz
- RF gun acc. voltage: limited to 6.5 MV by breakdown (13.5 MV@design)

Target : 5nC

$\gamma\beta\varepsilon_x$=50 mm·mrad, $\gamma\beta\varepsilon_y$=20 mm·mrad @ LINAC end

$\gamma\beta\varepsilon_x$, $\gamma\beta\varepsilon_y$ = 10 mm·mrad @ Gun

Bunch charge just after RF GUN (A1_C5)



Archived 1/10s

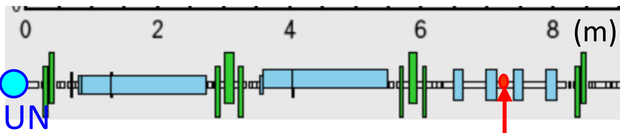
Bunch charge stability depends on the laser stability.

Yb:YAG Thin-disk cooling by soldering Cu plate was Improved.

R. Zhang, TUPWA071

Laser power increased and stability was also improving.

Emittance measurement by Quad-scan

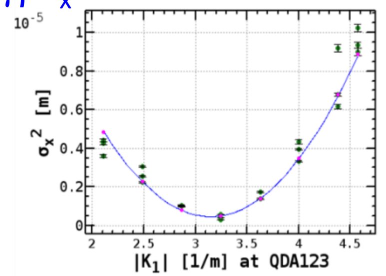


Bunch charge: 3nC@Screen

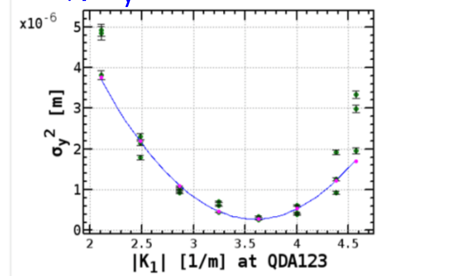
Beam size was measured shot by shot.

=> Position jitter is not included

$\gamma\beta\varepsilon_x$=49.2 mm·mrad±10%



$\gamma\beta\varepsilon_y$=26.2 mm·mrad±10%



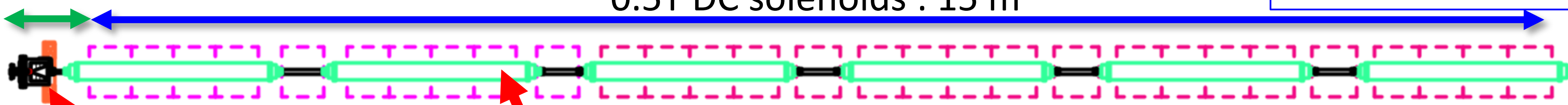
- Measured emittances were higher than target values.
- Higher horizontal emittance is due to laser incident angle.

Need high acc. voltage of RF gun for small emittance

Positron Capture Section

T. Kamitani, L. Zang

0.5T DC solenoids : 15 m



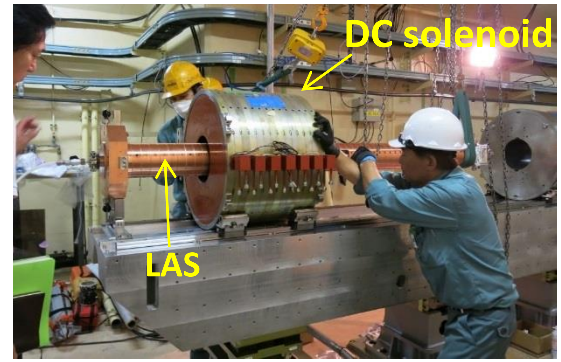
FC : Flux concentrator

Large energy acceptance

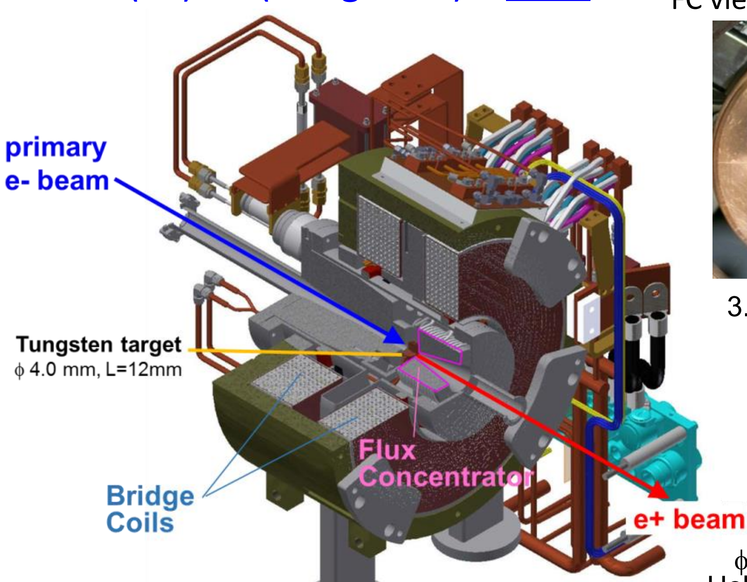
LAS : Large aperture S-band accel. Structures

Aperture ϕ20mm → ϕ 30mm

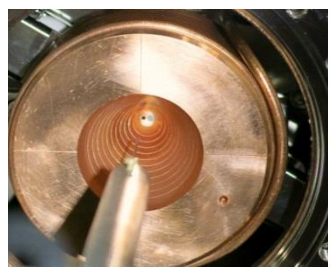
Large transverse acceptance



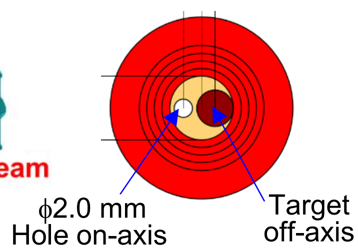
Solenoid field at e+ production target = 3.5T(FC)+1T(Bridge coil) = 4.5 T

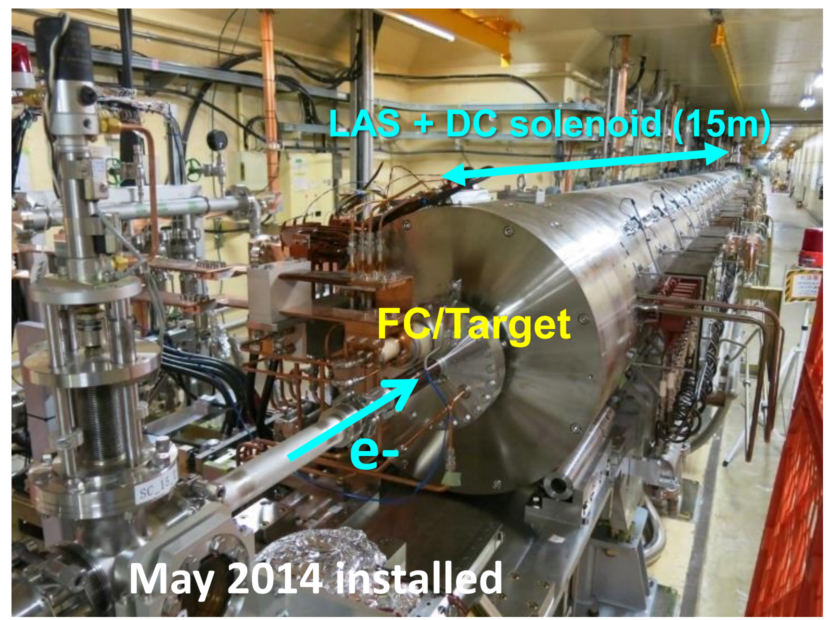


FC viewed from downstream



3.5T@12kA, 6μs (half sine)

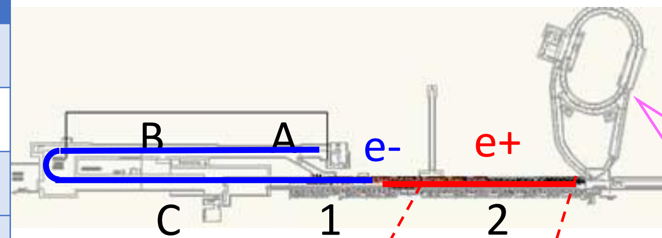




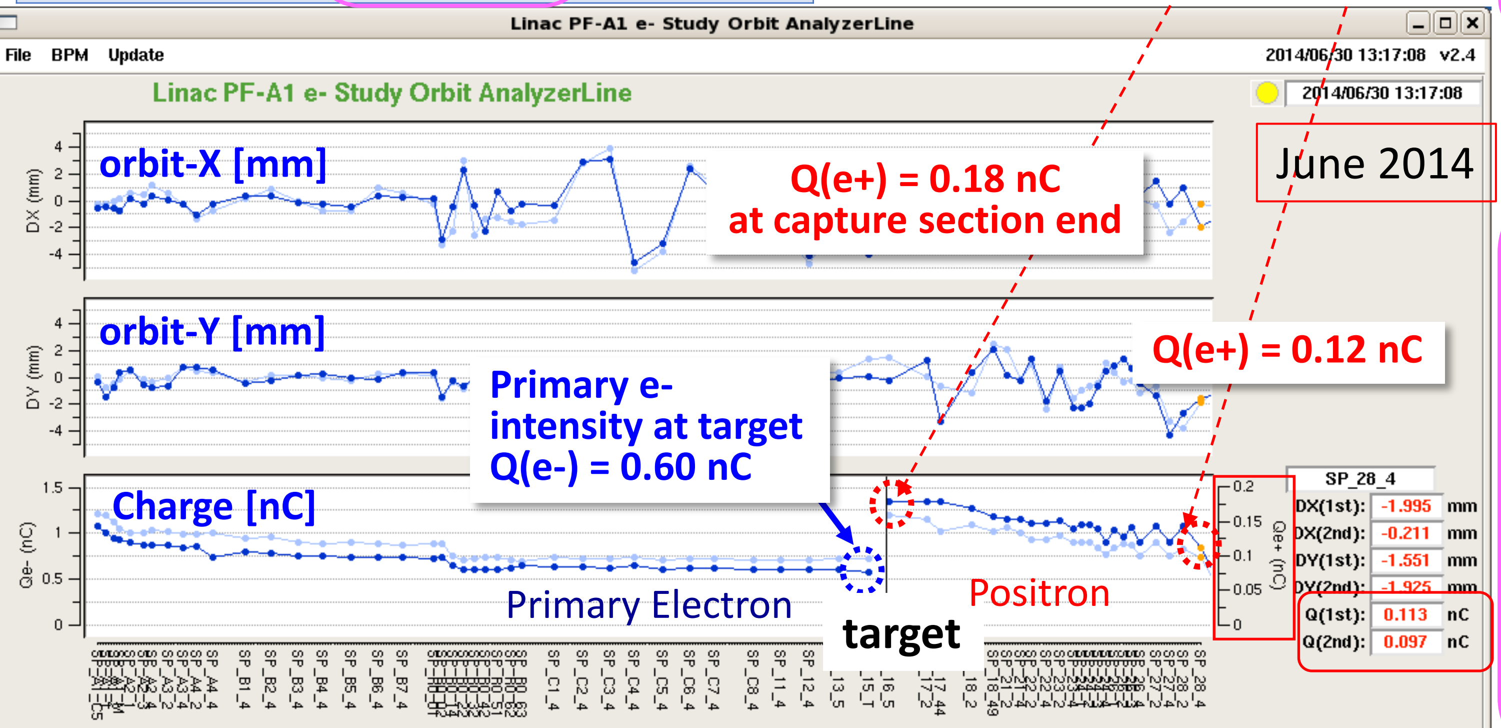
Positron beam commissioning @June 2014

T. Kamitani

	Design	6/2014
Flux Concentrator	12 kA	6.4 kA
Bridge Coil	600 A	600 A
DC Solenoids	650 A	370 A
Acc Field	14, 12MV/m	10, 12MV/m



Ye+ > 40 % is necessary at DR entrance.



Commissioning with design parameters will be started from Oct. 2015.

At least, 2 times higher Ye+ is expected by simulation

e+ yield (Ye+) = e+ charge (Qe+) / primary e- charge (Qe-)

Ye+@Jun.2014 = 30 % at capture section end, 20% at the end of Sector2

Contents

- Introduction of SuperKEKB
- Strategy of Upgrade
- Upgrade status of Main Rings
- Upgrade of Injector LINAC & beam commissioning
- **e+ Damping Ring Construction Status**
- Schedule

Positron Damping Ring

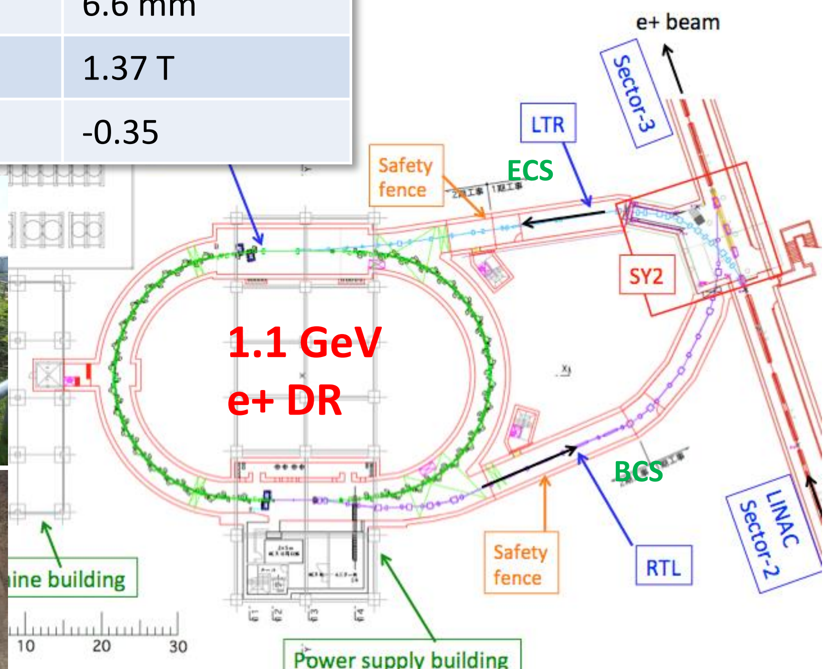
M. Kikuchi

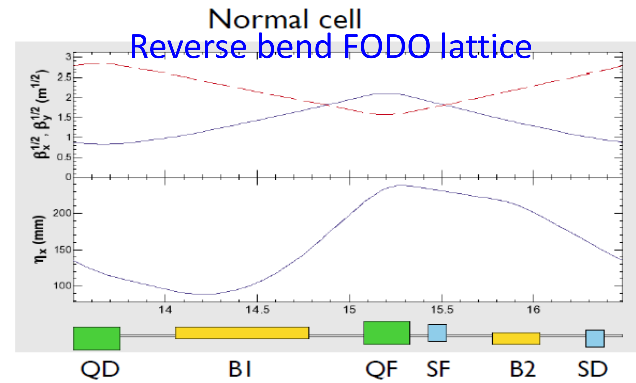
Energy	1.1 GeV
No. of bunches	4
Circumference	135.5 m
damping time	10.87 ms
Store time	40 ms
Ext. emittance (H/V) ($\gamma\beta\varepsilon_H$ / $\gamma\beta\varepsilon_V$)	42.5/3.15 nm (91.3/6.8 um)
RF voltage	1.4 MV
Bunch length	6.6 mm
Bend field	1.37 T
Bend angle ratio B2/B1	-0.35

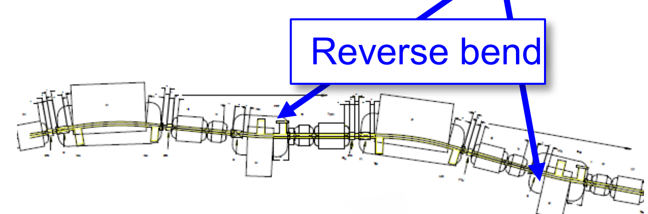
Reverse-bend FODO lattice

- shorter damping time (10.8 ms)
- large momentum aperture (1.5%)
- easy to get low momentum compaction (0.0144)

Emittance is damped from 1400 nm to 43 nm in 40 ms.

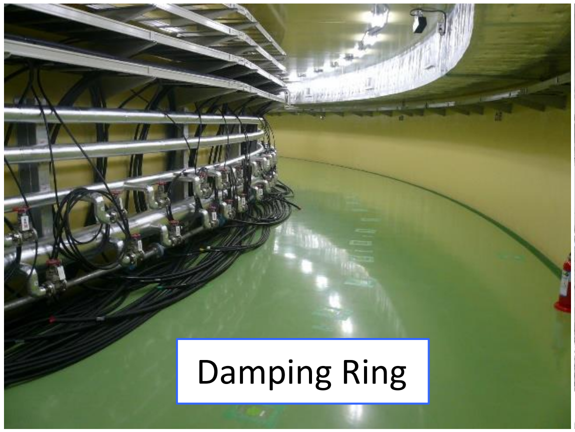






Construction Status of Damping Ring

Installation of magnets will start in June of 2015.



Magnets installation in transport line(LTR and RTL) is almost completed.

LTR(LINAC to DR)
RTL(DR to LINAC)

Contents

- Introduction of SuperKEKB
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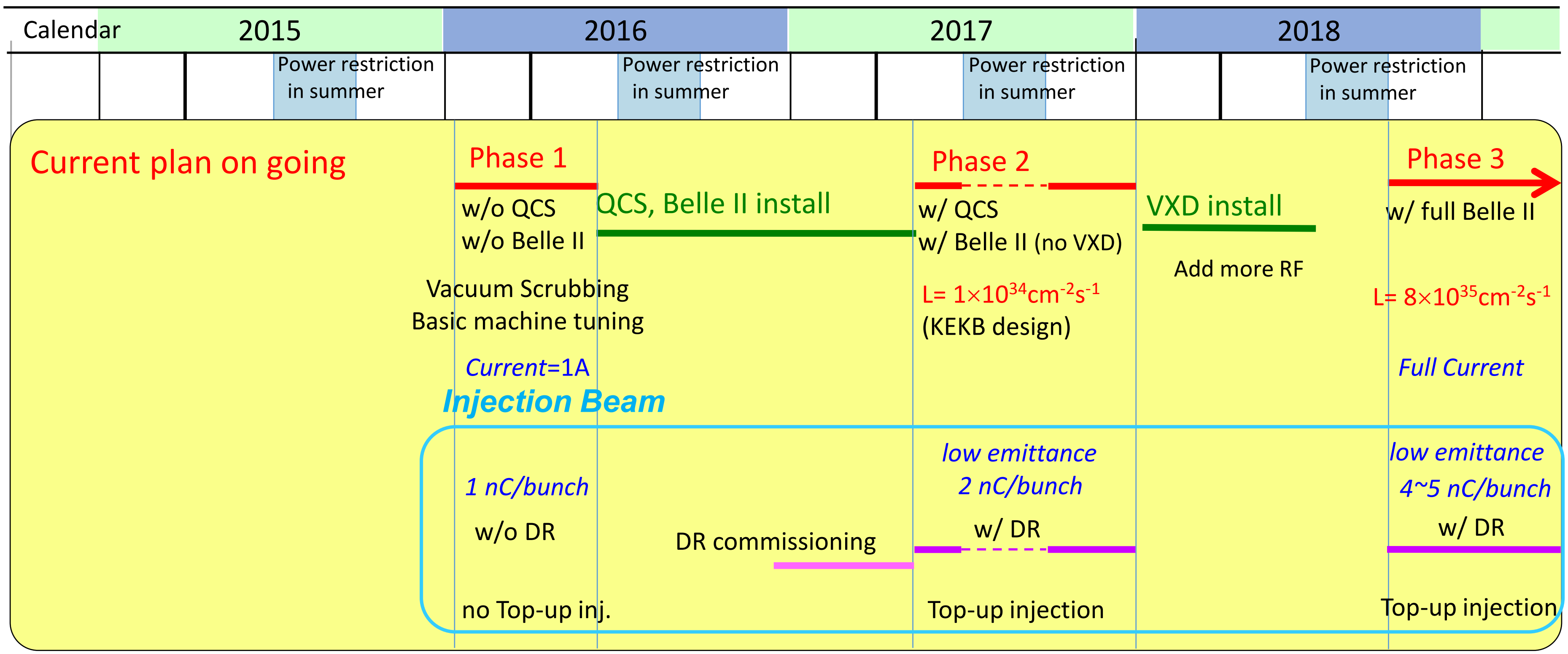
- Schedule

SuperKEKB Schedule

SuperKEKB commissioning is divided into three stages. (phase1, phase2, phase3)



Presentation List for SuperKEKB

Main Ring

WEYB3 **Interplay of Beam-Beam, Lattice Nonlinearity, and Space Charge**, D. Zhou
Invited Talk

MOPHA056 **LLRF Control System**, T.Kobayashi

MOPHA054 **Interaction Point Orbit Feedback**, Y.Funakoshi

MOPHA055 **Timing System**, H.Kaji

Injector LINAC

MOPHA059 **Control System**, M.Satoh

TUPTY008 **Commissioning**, M.Satoh

TUPJE003 **Quasi-Traveling Wave RF Gun**, T. Natsui

TUPWA071 **Laser System**, R. Zhang

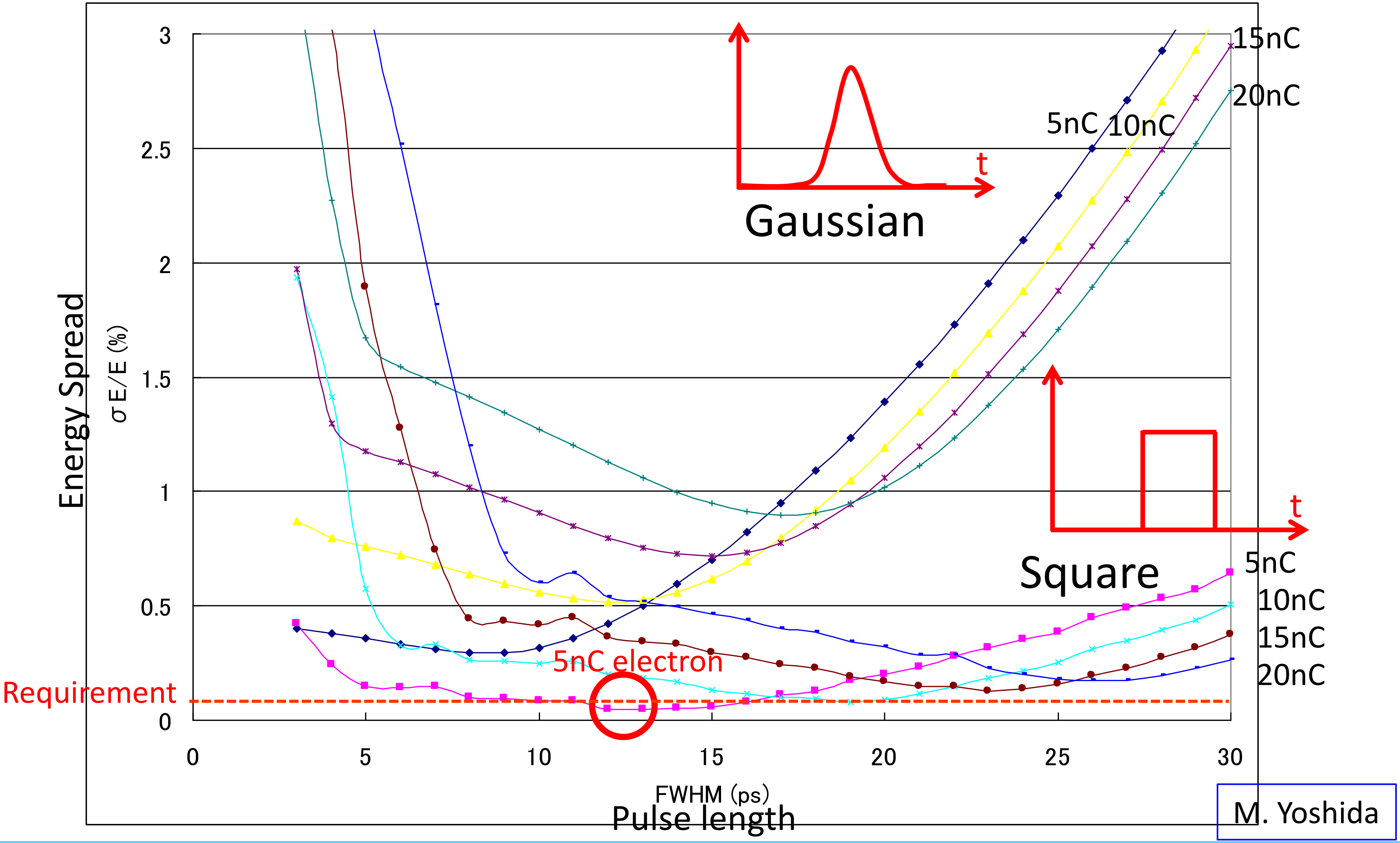
MOPWA053 **Emittance Preservation**, S. Kazama

Thank you for your attention.

Back-up slides

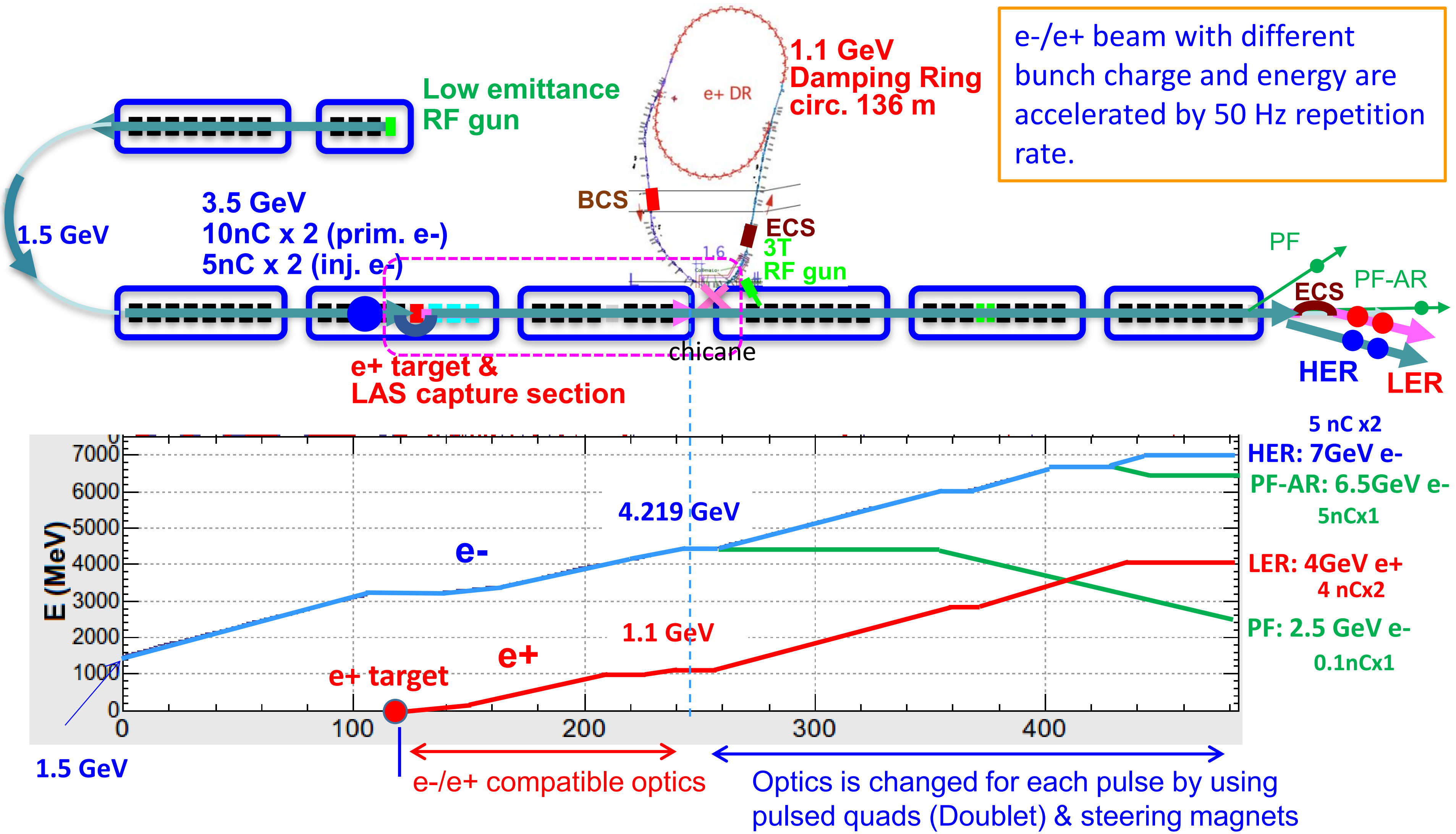
Why need longitudinal pulse-shape manipulation?

Energy spread of 0.1% is required for SuperKEKB synchrotron injection.

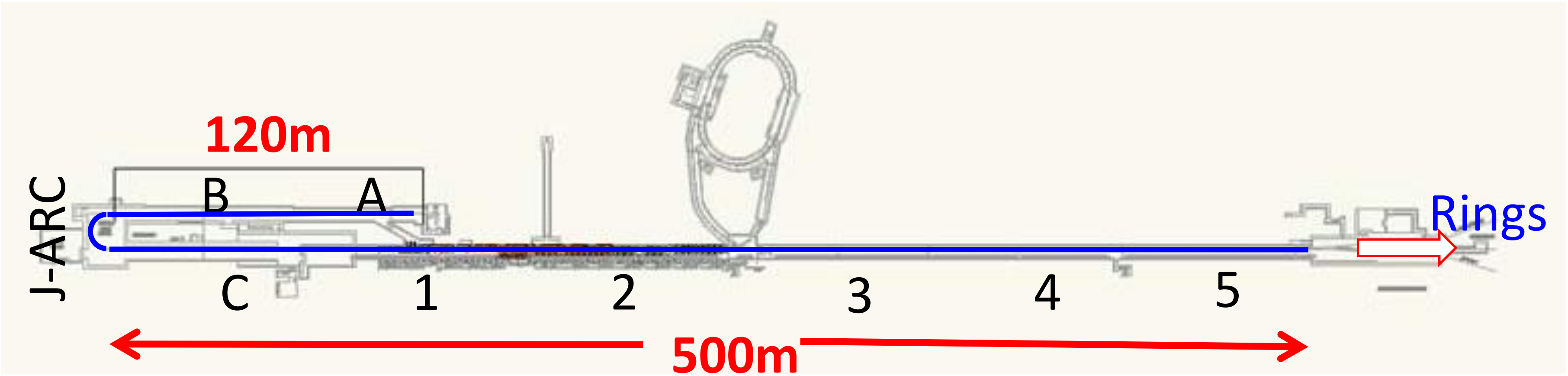


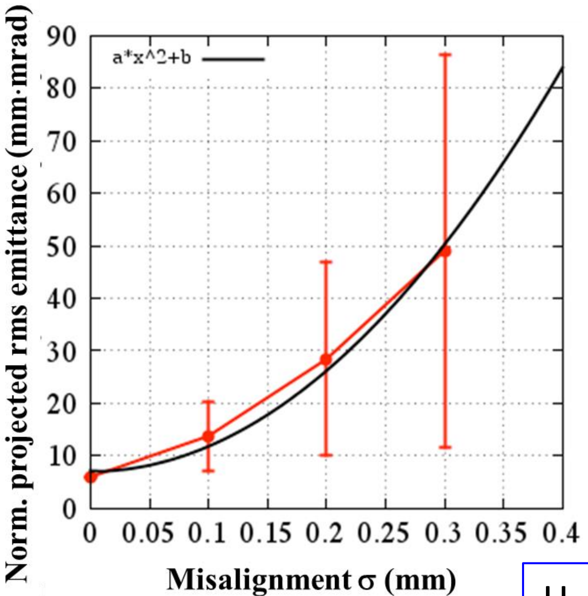
LINAC Beam Acceleration Scheme

e-/e+ beam with different bunch charge and energy are accelerated by 50 Hz repetition rate.



Alignment Requirement





H. Sugimoto

$\sigma < 0.1$ mm: $\beta\gamma\varepsilon$ 20 mm·mrad is almost satisfied.

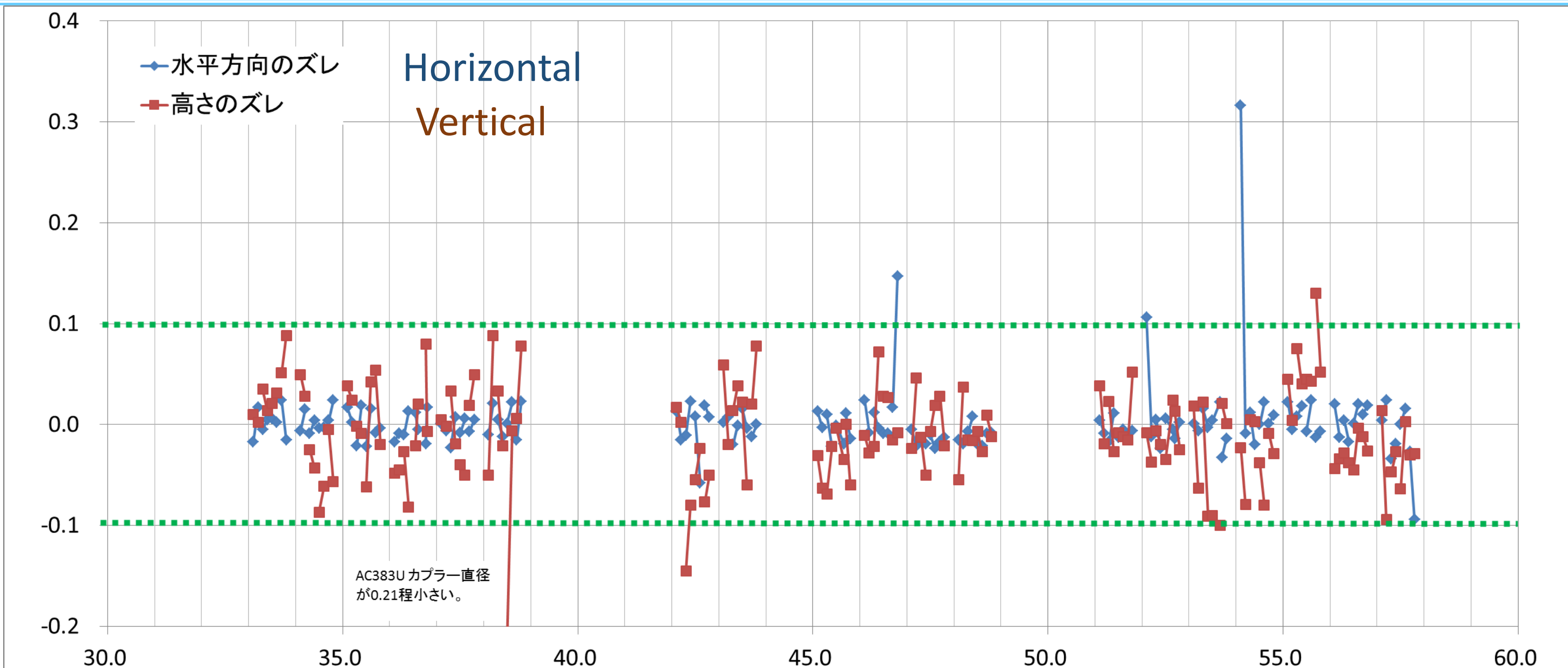
$\sigma > 0.1$ mm: emittance preservation is required by some methods.

Requirement

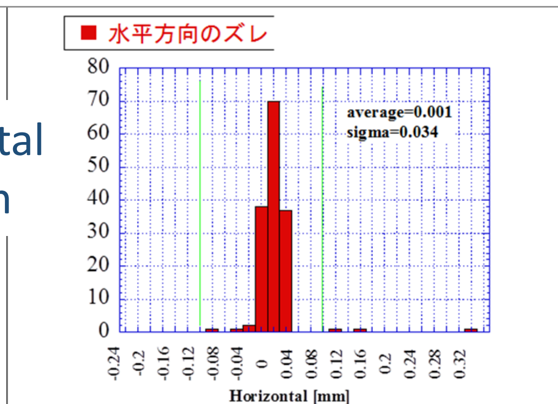
Local $\sigma < 0.1$mm

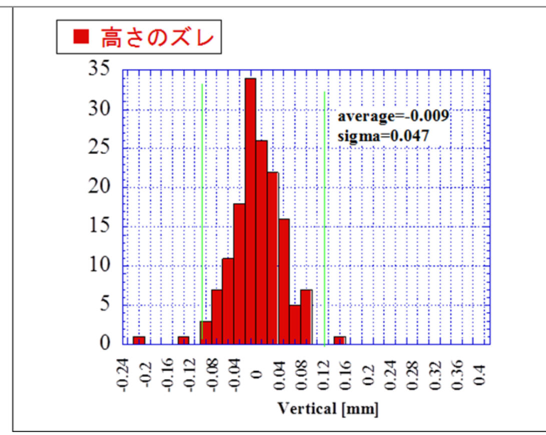
Global $\sigma < 0.3$mm

Hard ware alignment on a girders in sector 3 - 5



Horizontal
σ=34μm





Vertical
σ=47μm

T. Higo

Floor Movement in a Half Year

straight laser of 500m + Position Detector (PD)

T. Suwada

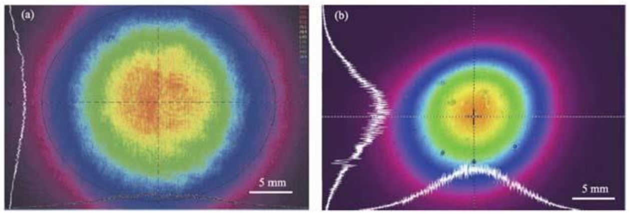
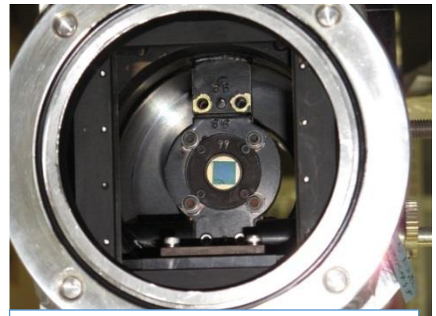
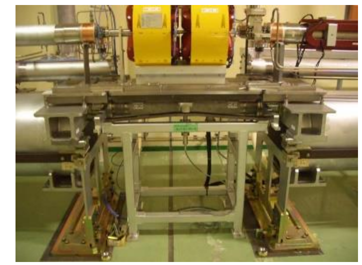


FIG. 5. Intensity profiles of the laser beam at (a) $z = 0$ m and (b) $z = 500$ m. Scale bars are 5 mm.



4-segmented silicon PD (dia.=10mm)

At expansion joint in tunnel, large movement is observed.



T. Higo