Final Focus & Injection

Experiences at KEKB/SuperKEKB

FCC Kick-off Meeting

Feb 13, 2014 @ Genève Univ.

K. Oide (KEK)

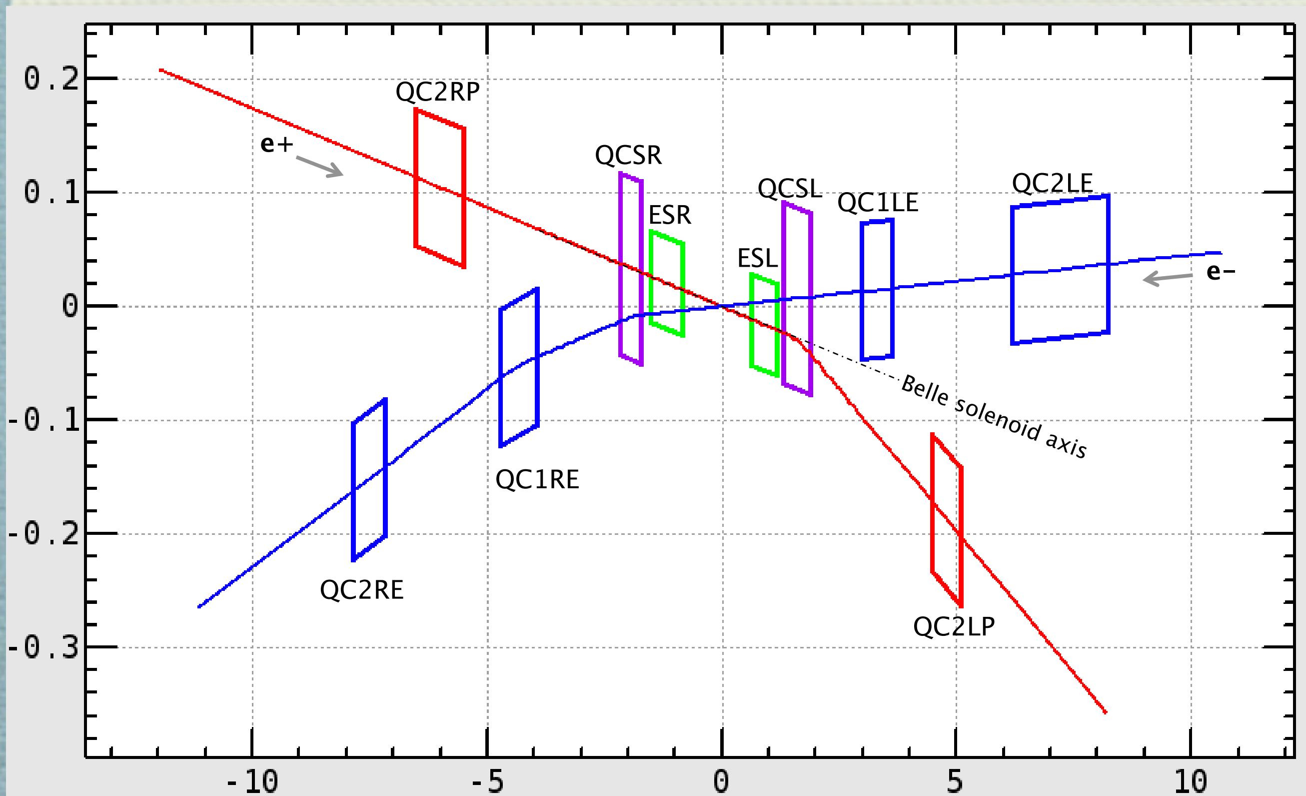
Thank Y. Ohnishi, N. Ohuchi, M. Satoh, F. Zimmermann, and all who provided the materials.

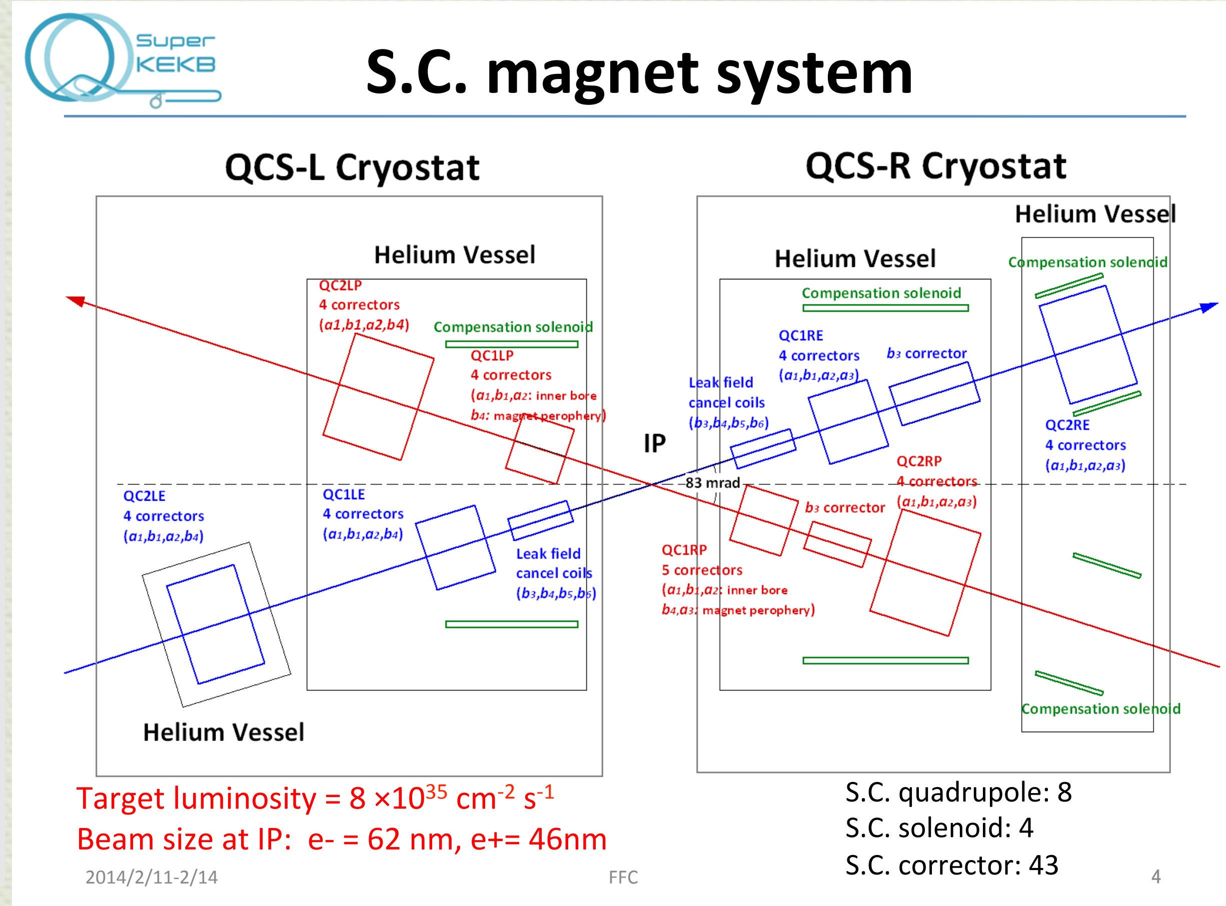
Parameter comparison

Rings	TLEP Z	TLEP tt	KEKB LER / HER	SuperKEKB LER / HER	
Beam energy	46	175	3.5 / 8	4 / 7	GeV
Circumference	100		3		km
Current / beam	1.45	0.0066	$\sim$ 1.6/1.3	3.6 / 2.6	A
Bunches / beam	16700	98	$\sim$ 1500	2500	
Particles / bunch	1.8	1.4	$\sim$ 0.67/0.54	0.90 / 0.65	10^{11}
Hor. emittance	29	2	18 / 24	3.2 / 5	nm
Ver. emittance	60	2	$\sim$ 150	10 / 15	pm
$\varepsilon_y/\varepsilon_x$	0.2	0.1	$\sim$ 0.8/0.6	0.27	%
β_x^*	500	1000	$\sim$ 1200	32 / 25	mm
β_y^*	1	1	$\sim$ 6	0.27 /0.3	mm
Bunch length σ_z	2.6	1.5	8 / 6	6 / 5	mm
Momentum spread w/BS	6	19	9 / 7	7 / 6	10^{-4}
Half crossing angle	?	?	11	41.5	mead
Beam-beam ξ_x	0.031	0.092	$\sim$ 0.12/0.13	0.003	
Beam-beam ξ_y	0.030	0.092	$\sim$ 0.13/0.09	0.09	
Luminosity / IP	28	1.8	2.1	80	10^{34}

TLEP: FCC-ACC-SPC-0004

Final Focusing Quads

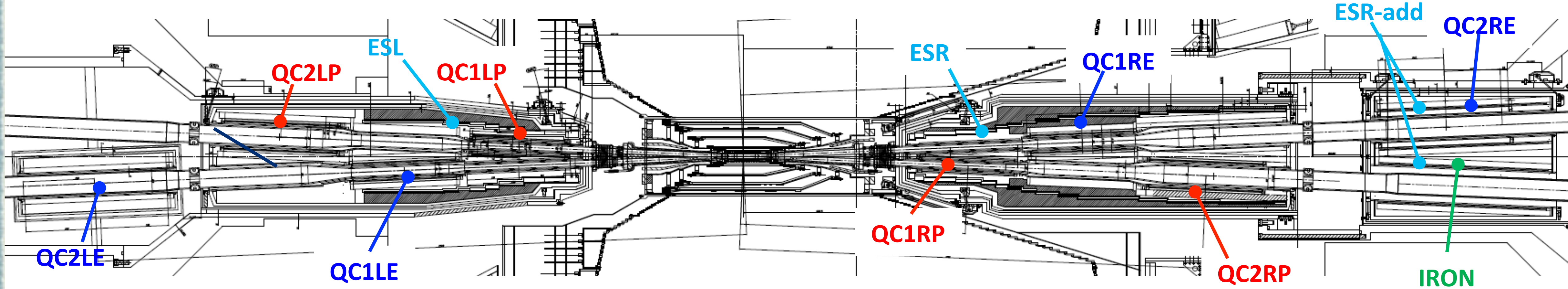




KEKB:
Common final quads
with medium crossing angle
11 mrad x 2

SuperKEKB:
Separate final quads
with large crossing angle
41.5 mrad x 2

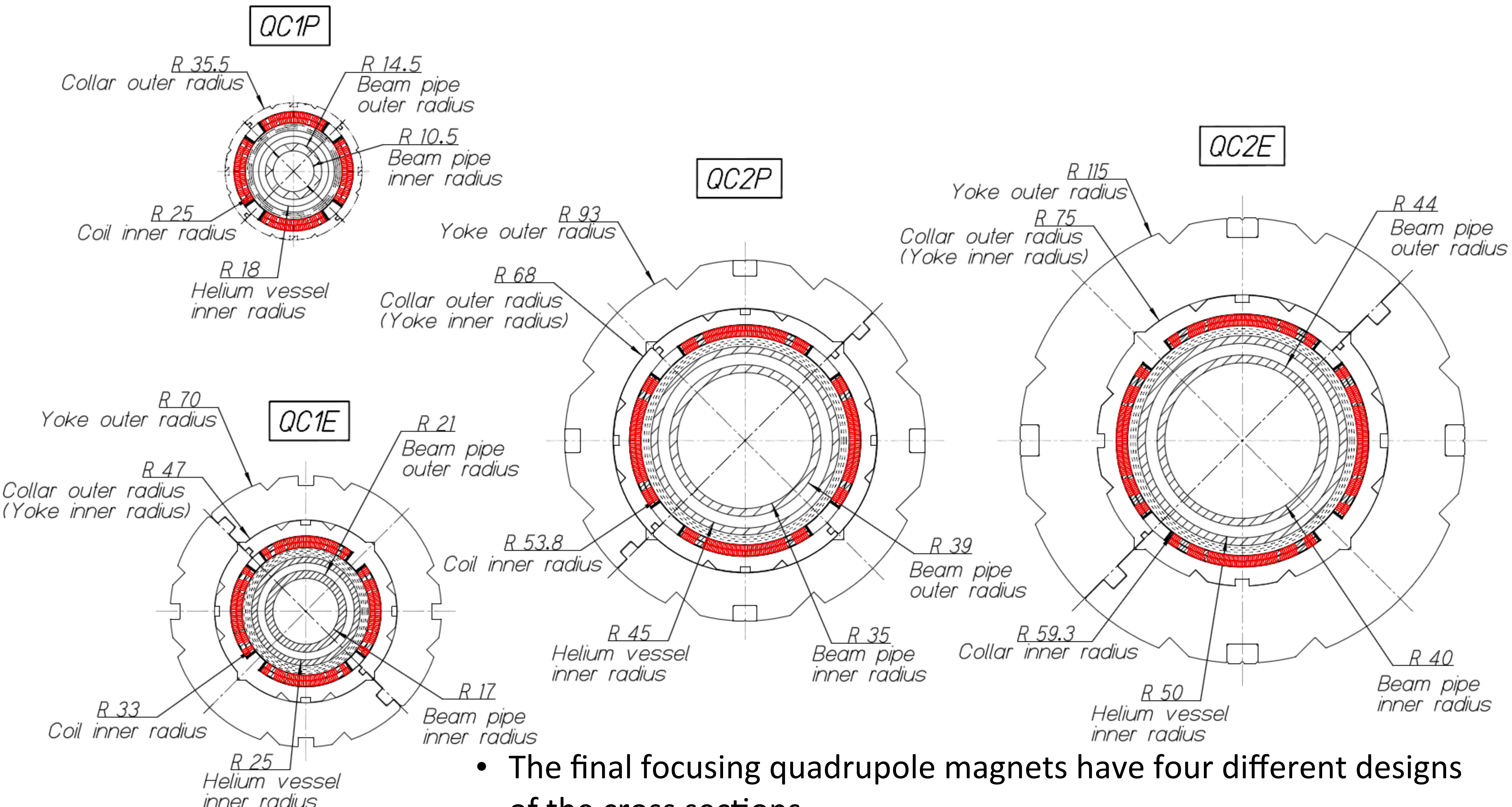
S.C. magnets in SuperKEKB IR



	Integral field gradient, (T/m)·m Solenoid field, T	Magnet type	Z pos. from IP, mm	θ, mrad	ΔX, mm	ΔY, mm
QC2RE	13.58 [32.41 T/m × 0.419m]	**Iron Yoke**	2925	**0**	**-0.7**	**0**
QC2RP	11.56 [26.28 × 0.410]	**Permendur Yoke**	1925	**-2.114**	**0**	**-1.0**
QC1RE	26.45 [70.89×0.373]	**Permendur Yoke**	1410	**0**	**-0.7**	**0**
QC1RP	22.98 [68.89×0.334]	**No Yoke**	935	**7.204**	**0**	**-1.0**
QC1LP	22.97 [68.94×0.334]	**No Yoke**	-935	**-13.65**	**0**	**-1.5**
QC1LE	26.94 [72.21×0.373]	**Permendur Yoke**	-1410	**0**	**+0.7**	**0**
QC2LP	11.50 [28.05 × 0.410]	**Permendur Yoke**	-1925	**-3.725**	**0**	**-1.5**
QC2LE	15.27 [28.44×0.537]	**Iron Yoke**	-2700	**0**	**+0.7**	**0**

N. Ohuchi

Cross section of four quadrupoles

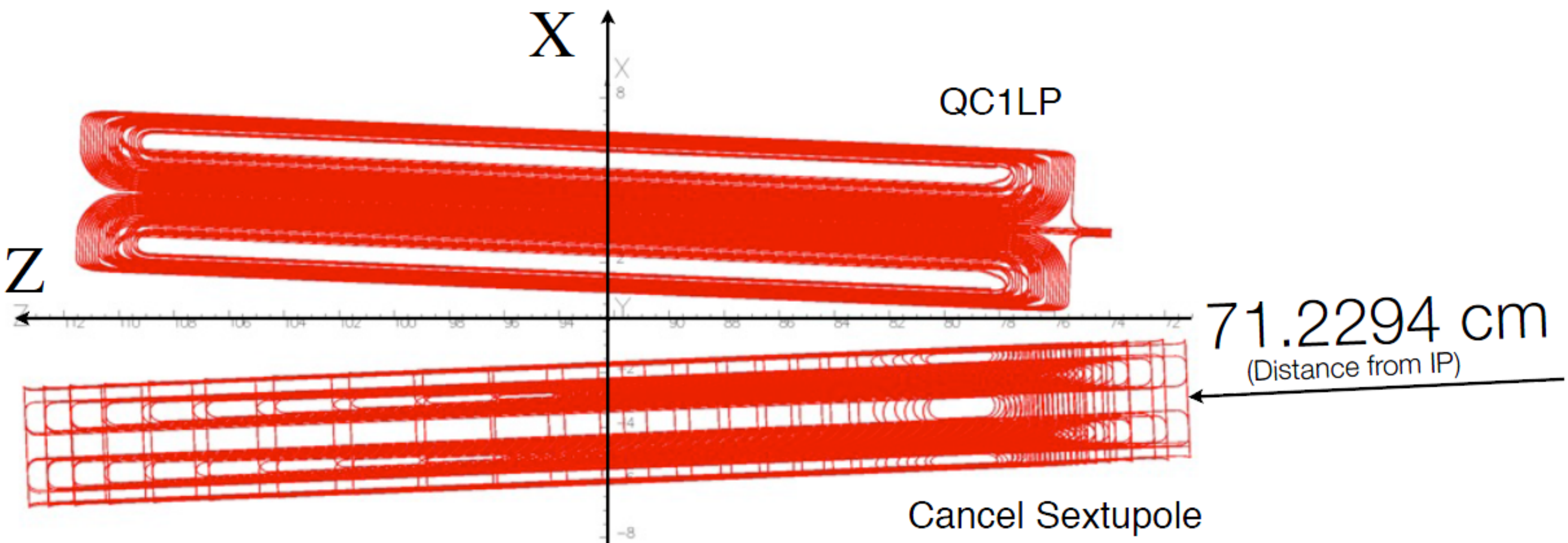


- The final focusing quadrupole magnets have four different designs of the cross sections.
  - QC1P has the smallest inner radius of 25 mm.
  - QC2E has the largest inner radius of 59.3 mm.

N. Ohuchi

SC leak field cancel coils

- The leak field cancel coils are now designed and constructed by BNL under the US-Japan research collaboration program.
- The field model is constructed with the collaboration between BNL and KEK.

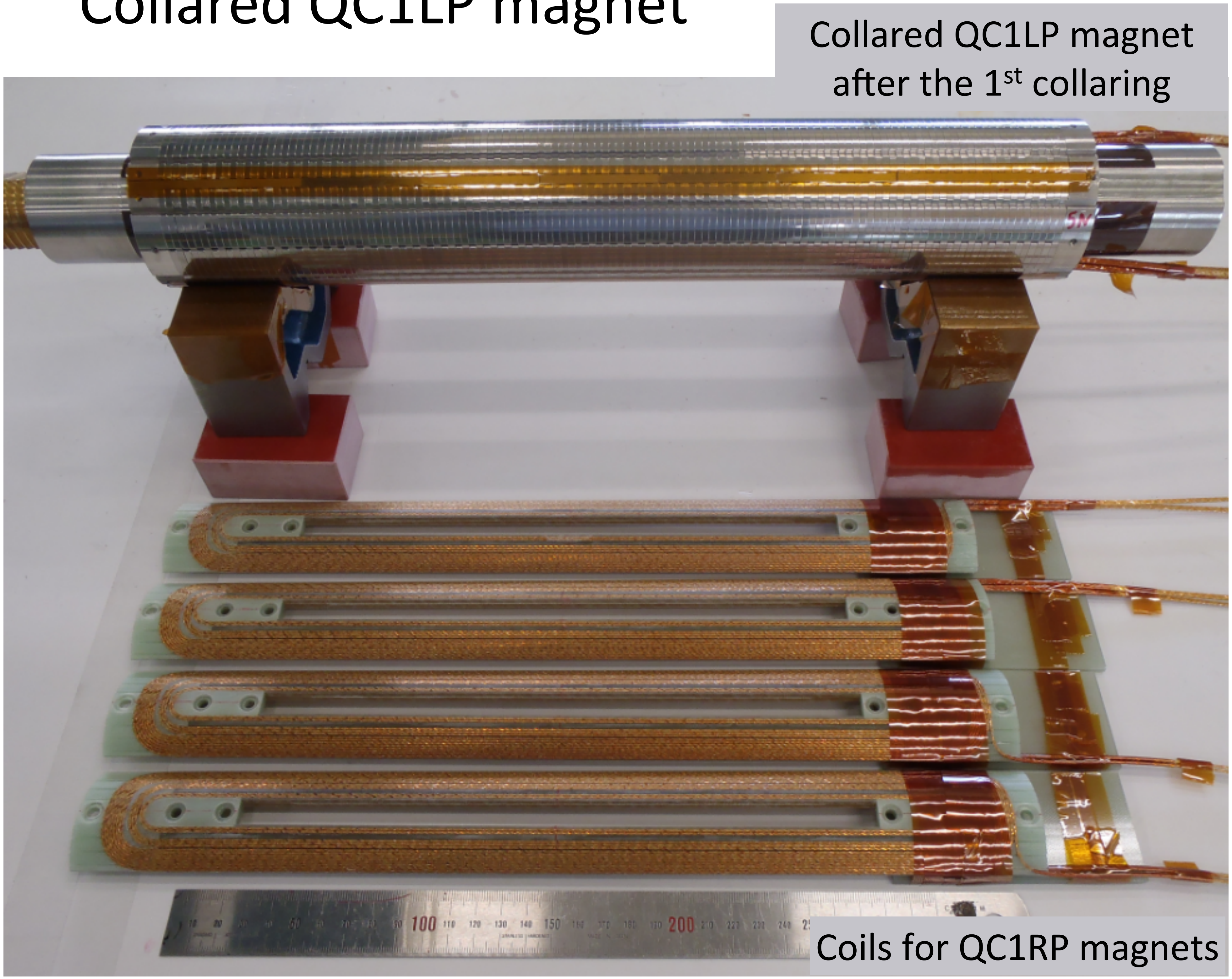


Cancel coil designed by B. Parker [BNL]
Sextupole cancel coil : 2 layer serpentine coils

N. Ohuchi

Production of quadrupole

Collared QC1LP magnet

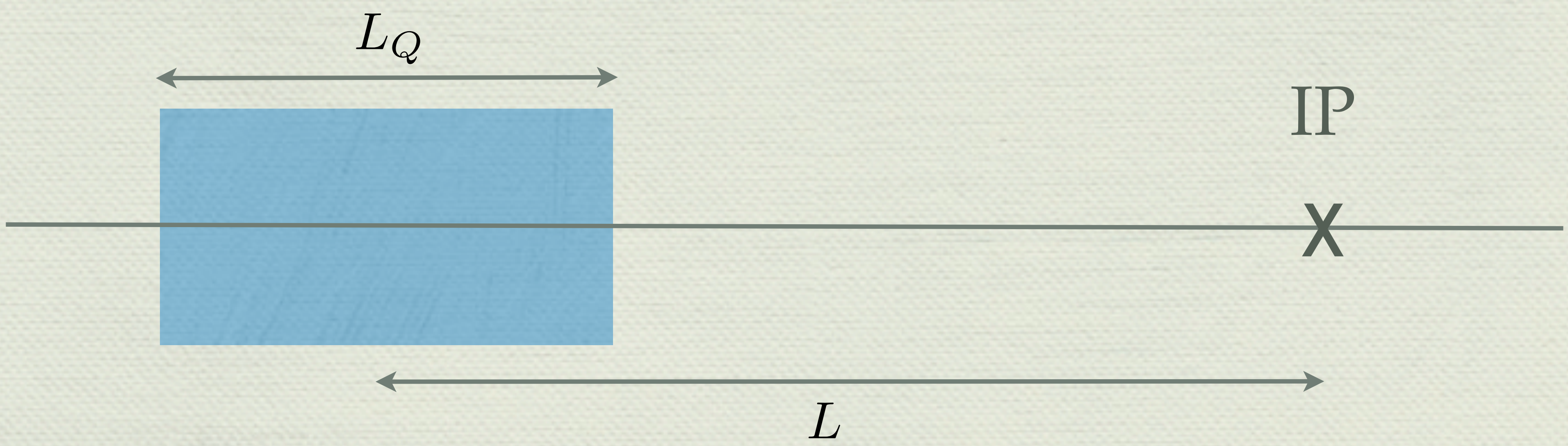


QC1LP field quality after collaring

@ R = 10 mm	a_n	b_n
n=1	-0.1	-0.4
2	0.0	**10000**
3	-0.5	5.4
4	-0.0	-1.9
5	0.8	-3.6
6	-0.4	-0.3
7	0.8	0.8
8	-0.4	0.7
9	-0.2	-0.4
10	0.4	-0.1

N. Ohuchi

Scaling of final quads



$$k_1 = \frac{B' L_Q}{B\rho} = c_f / L \qquad \text{(inverse focal length)}$$

$$L_Q = c_Q L$$

$$B' b = B_0 \qquad \text{(pole tip field)}$$

$$b > \max(\sqrt{2\beta_{x,y} J_{x,y}}) \qquad \text{(required acceptance)}$$

$$\beta_{x,y} = \beta^*_{x,y} + \frac{L^2}{\beta^*_{x,y}}$$

$$\xi_y = k_1 \beta_y \qquad \text{(vertical chromaticity)}$$

$$L_0 = \frac{c_f B\rho}{c_Q B_0} \sqrt{\frac{2J_{x,y}}{\beta^*_{x,y}}}$$

$$L > \frac{L_0}{2}\left(1 + \sqrt{1 + 4\frac{\beta^{*2}_{x,y}}{L_0^2}}\right)$$

$$\xi_y = \frac{c_f L}{\beta^*_y}$$

A measure of difficulty in chromaticity correction

Scaling of final quads (cont'd)

$$L_0 = \frac{c_f B\rho}{c_Q B_0}\sqrt{\frac{2J_{x,y}}{\beta^*_{x,y}}}$$

$$L > \frac{L_0}{2}\left(1+\sqrt{1+4\frac{\beta^{*2}_{x,y}}{L_0^2}}\right)$$

$$\xi_y = \frac{c_f L}{\beta^*_y}$$

Rings	SuperKEKB LER	TLEP Z	TLEP tt	
Beam energy	4	46	175	GeV
$B\rho$	13.3	153	584	Tm
B_0	0.7	$\Leftarrow$		T
$c_f \equiv k_1 L$	1.56	$\Leftarrow$		
$c_Q \equiv L_Q/L$	0.35	0.35	0.7	
β^*_x	32	500	1000	mm
β^*_y	0.27	1	1	mm
$2J_x$	3.7	$\Leftarrow$		μm
$2J_y$	10	0.87	0.23	nm
L_0	0.935	2.65	3.58	m
L	0.935	2.74	3.84	m
L_Q	0.33	0.96	2.69	m
b	10	7.4	7.4	mm
ξ_y	5,400	4,200	6,000	

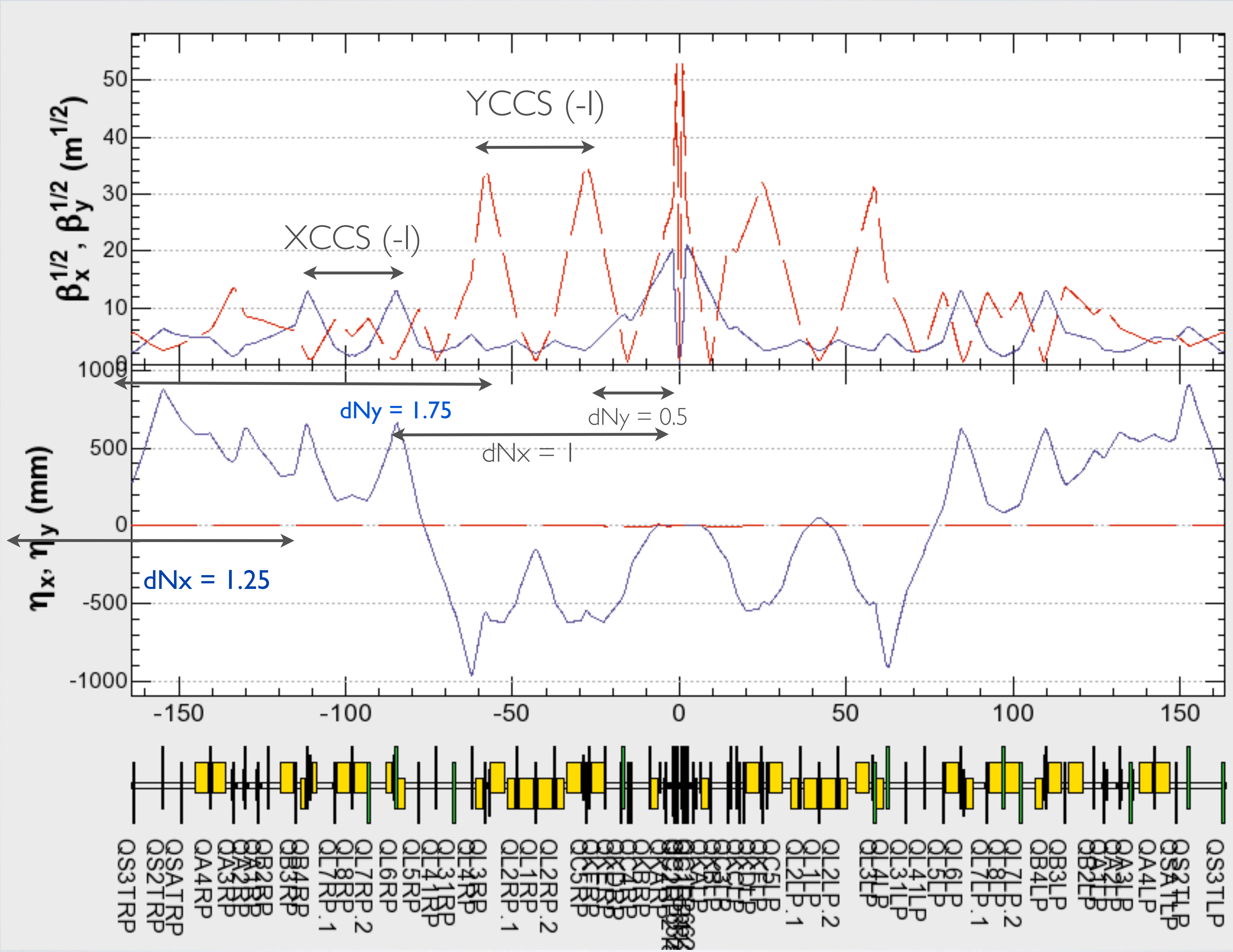
$J_{x,y}$ assumes similar injected beams.

Similar level of difficulty!

If TLEP uses a chromaticity correction similar to SuperKEKB, the resulting momentum acceptance will be similar, about ±1.4%.

LER (Semi-)Local Chromaticity Correction

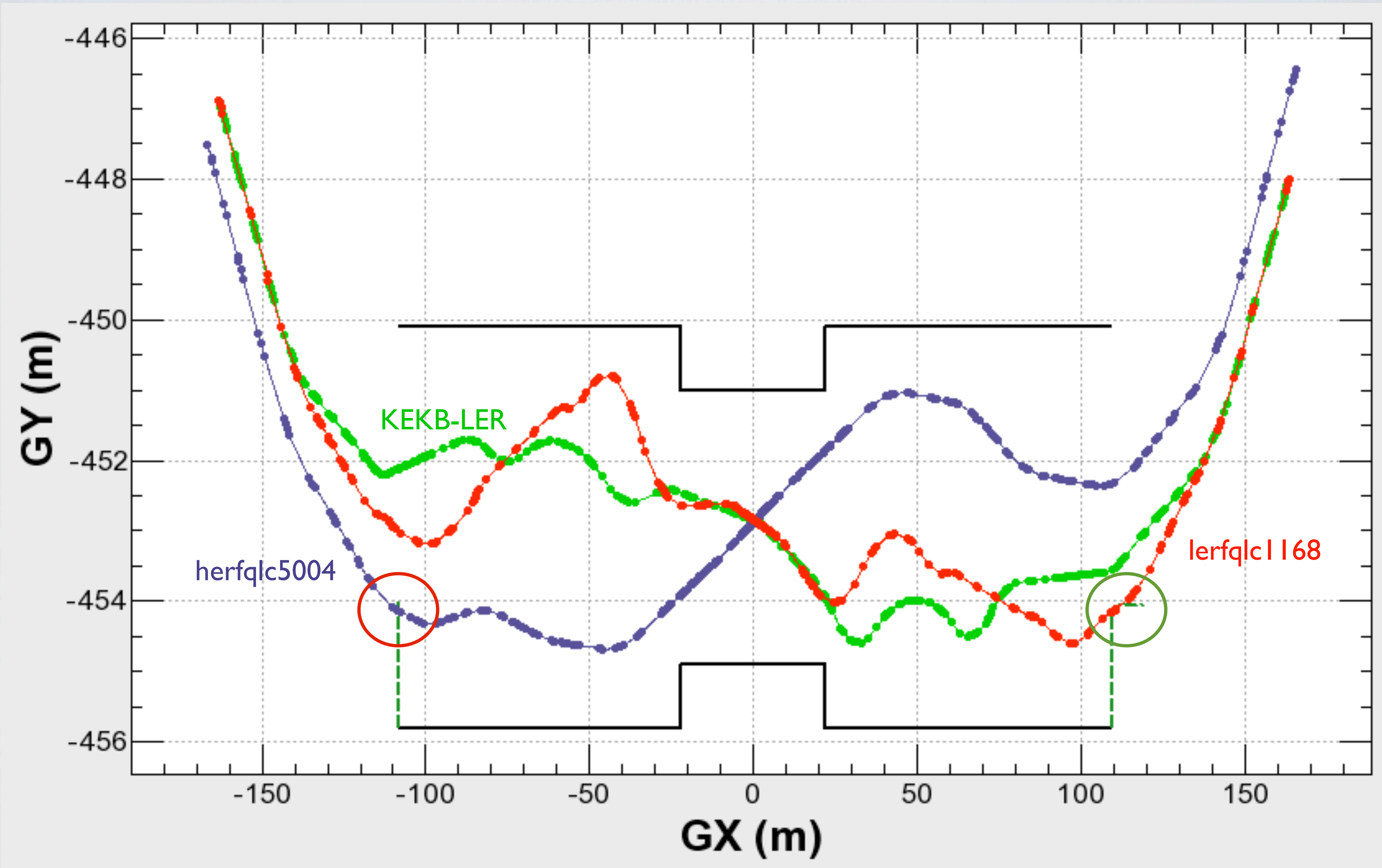
K. Oide



lerfqlc_Oide_1168.sad

LER 2-family LCCS

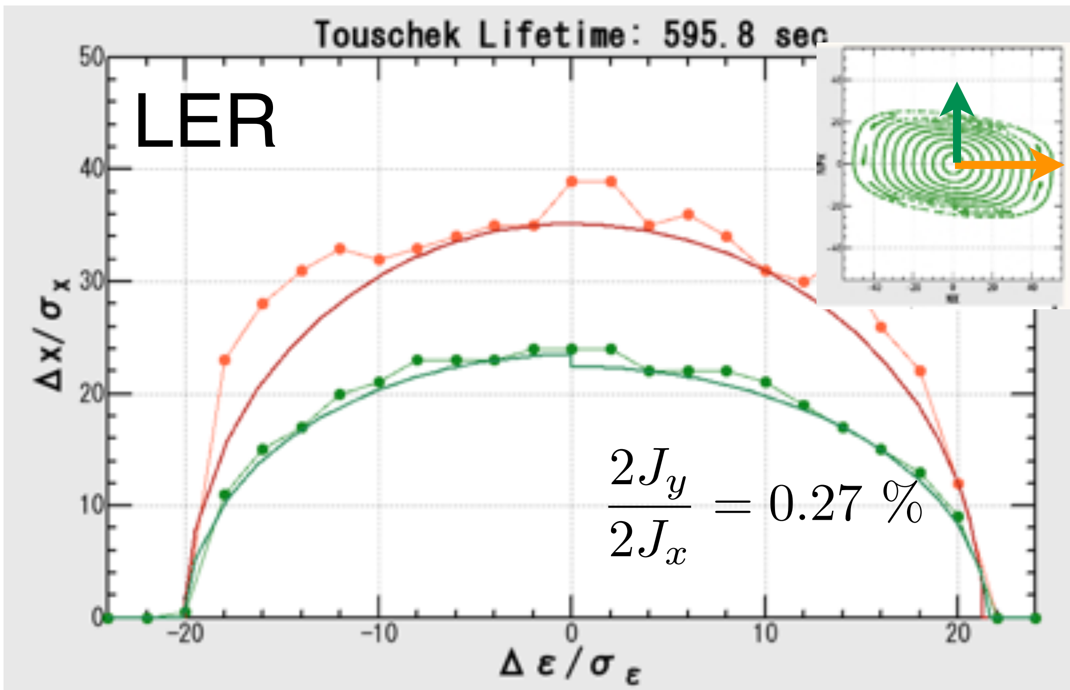
- Such a local CCS wiggles the orbit around the IP -

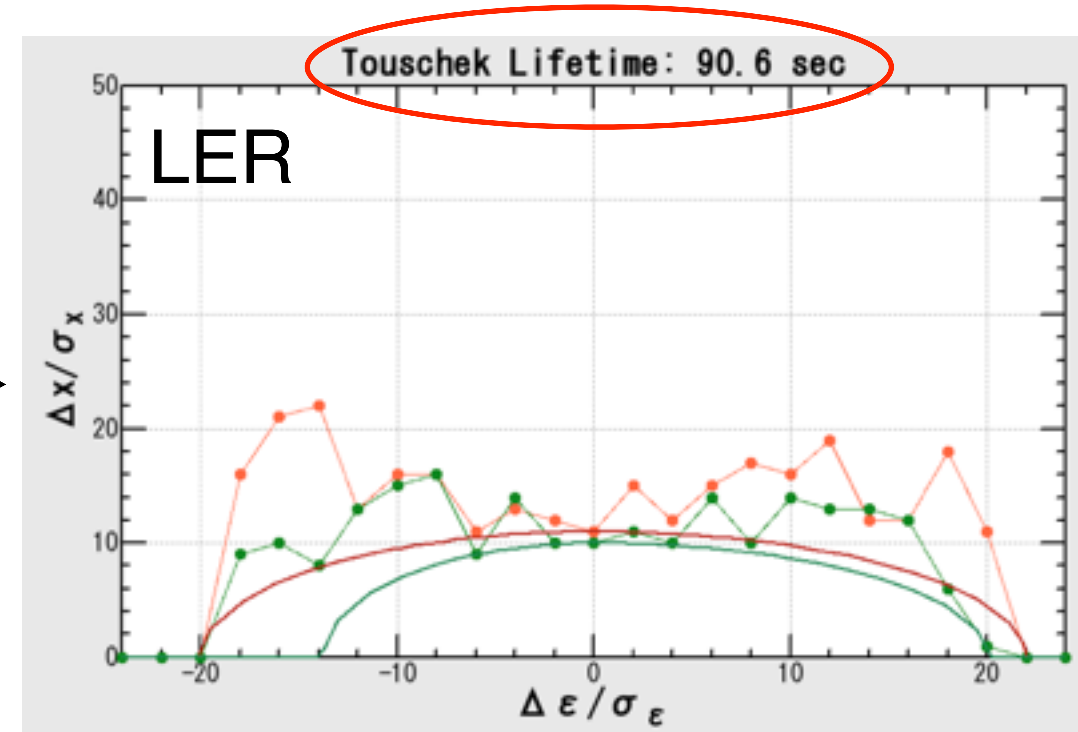


The design of CCS must be matured before the tunnel.

Reduction of dynamic aperture due to beam-beam

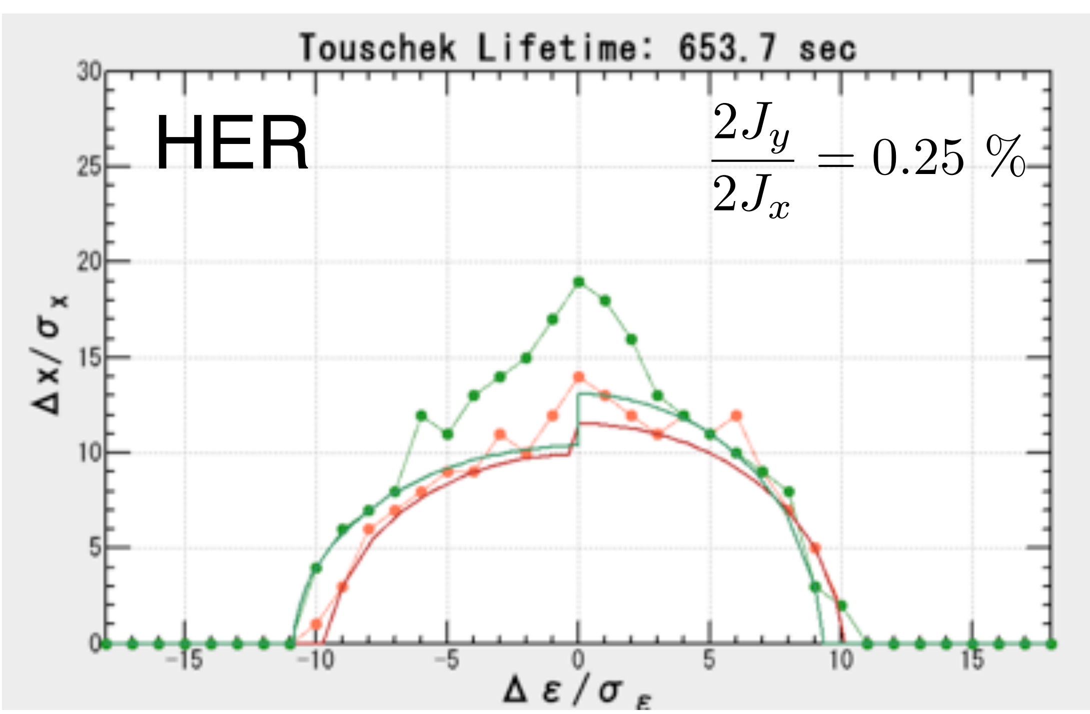
w/o beam-beam | **with beam-beam**

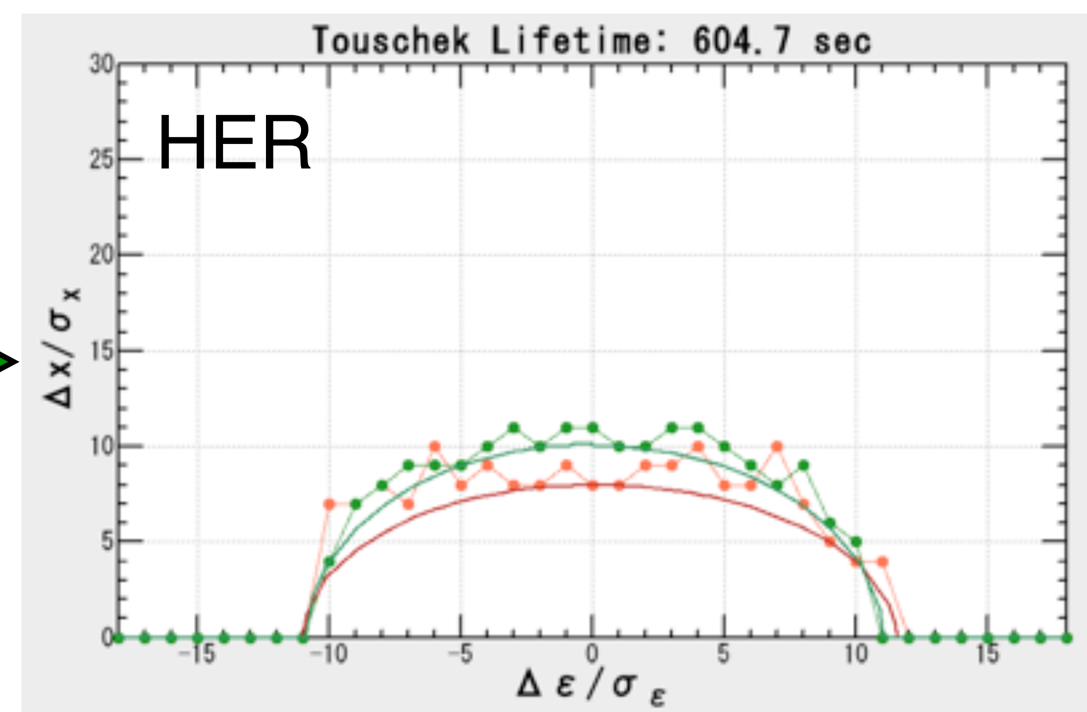




$\Delta p/p = \pm 1.4\%$

Transverse aperture reduces significantly.

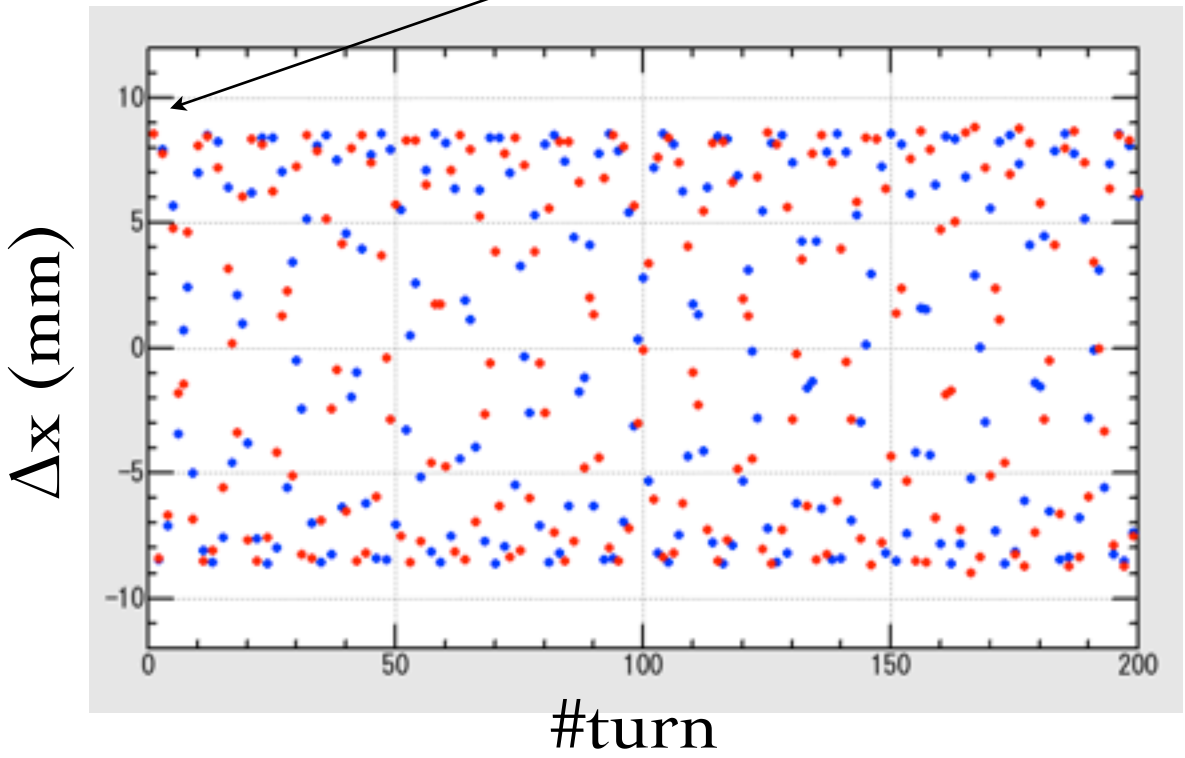




Y. Ohnishi, A. Morita, H. Sugimoto, H. Koiso

Tracking simulation: beam-beam effect

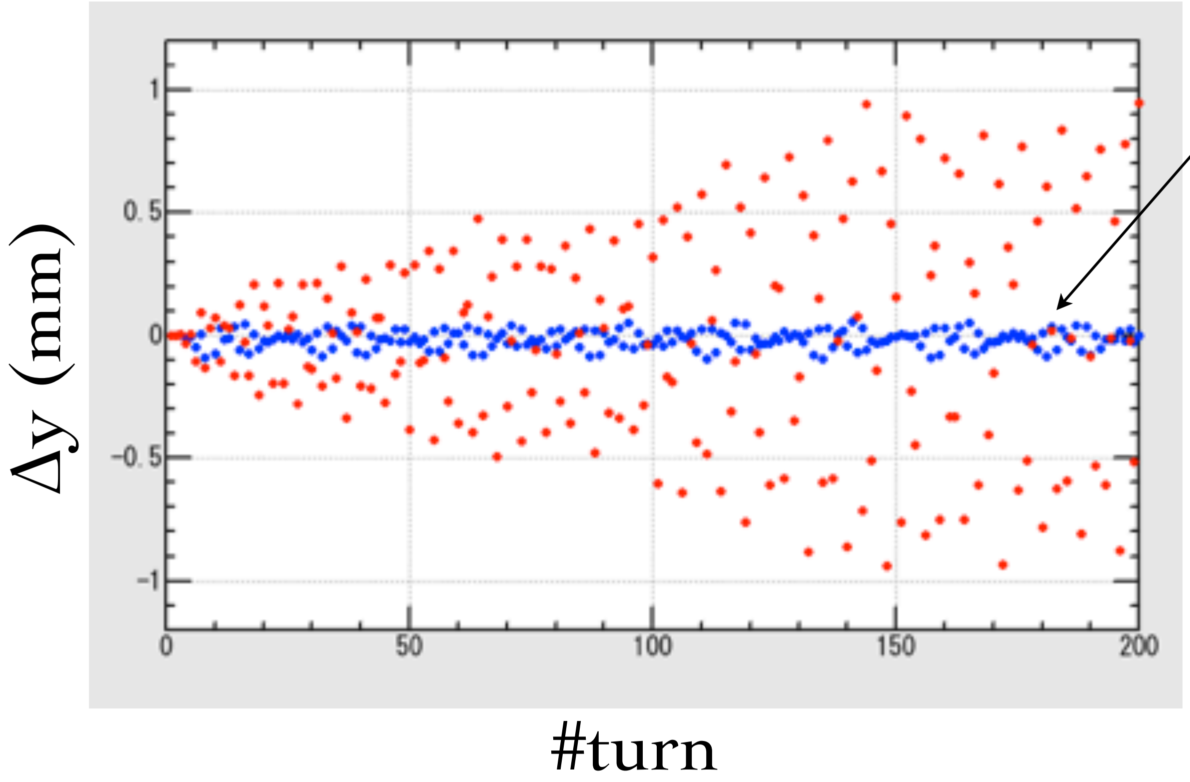
Initial orbit is **15 sigmas** in the horizontal direction and **0** for the vertical direction



blue: no beam-beam

red: with beam-beam

Horizontal betatron oscillation is stable for both cases.



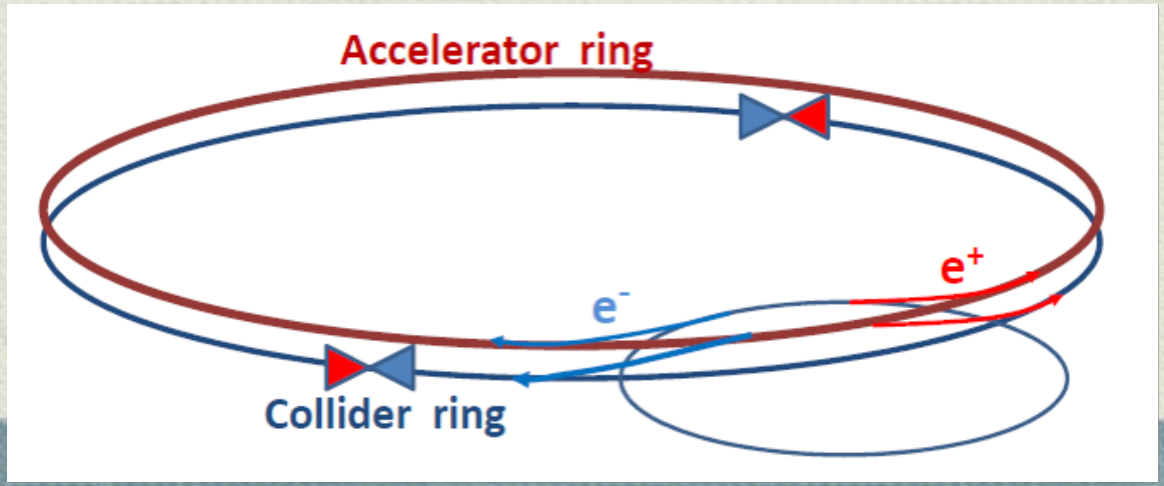
The vertical oscillation exists for the case w/o beam-beam, since there is a X-Y coupling.

Vertical betatron oscillation is unstable when beam-beam effect is included.

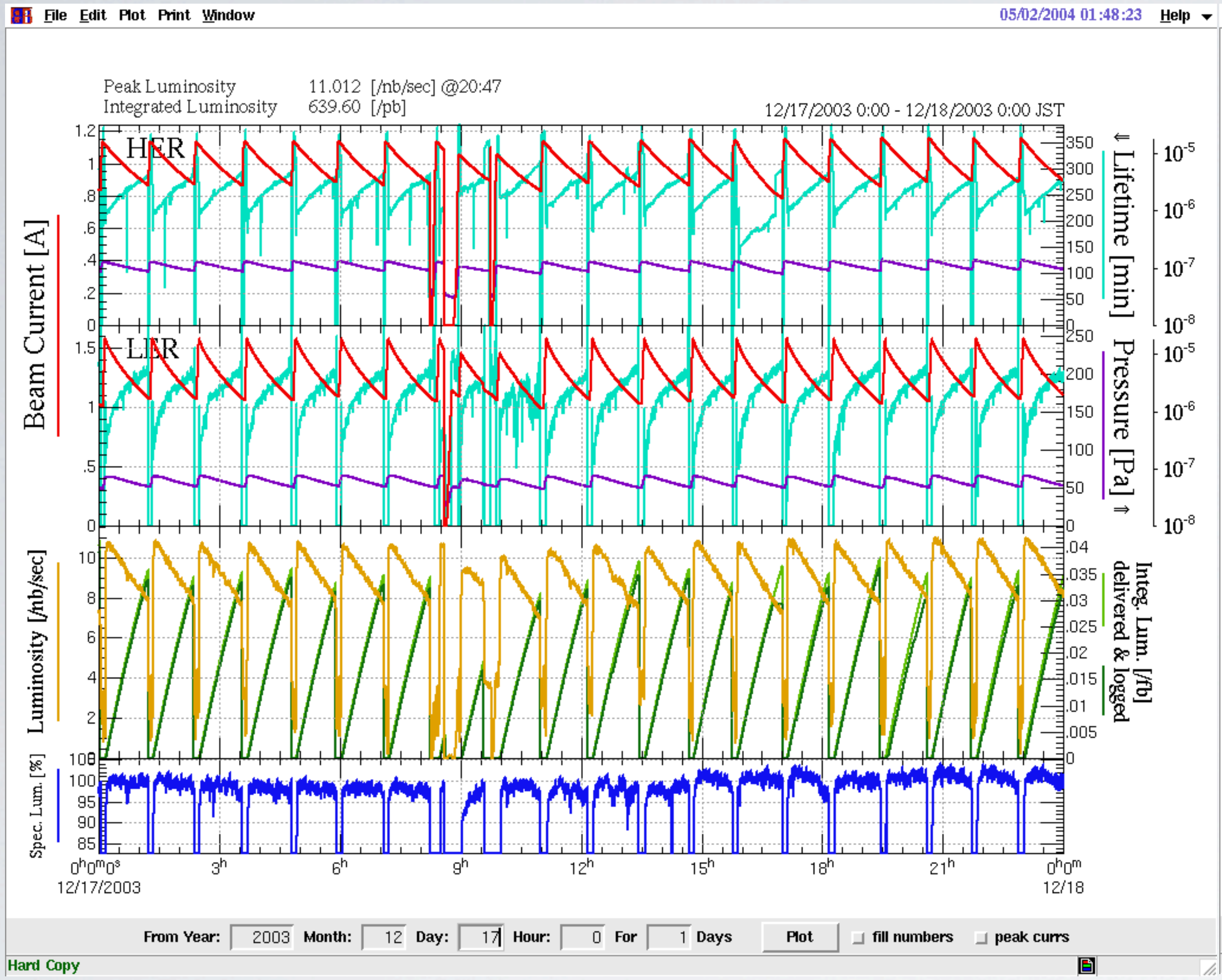
Injection parameters for top-up

Rings	TLEP Z	TLEP t	KEKB LER / HER	SuperKEKB LER / HER	
Beam energy	46	175	3.5 / 8	4 / 7	GeV
Current / beam	1.45	0.0066	$\sim 1.6/1.3$	3.6 / 2.6	A
Stored Charge / beam	484	2.2	16 / 13	36 / 26	μC
Lifetime	~ 400	~ 30	~ 100	$\sim 3.3/6.7$	min
Injection rate / beam	20	1.2	2.7 / 2.2	180 / 65	nC/s
Linac charge / beam	~ 4	~ 2	1 / 2	8 / 4	nC/pulse
Linac rep./beam	30	30	< 5	< 25	Hz
Synchrotron inj. duty / beam	17	< 2	–	–	%

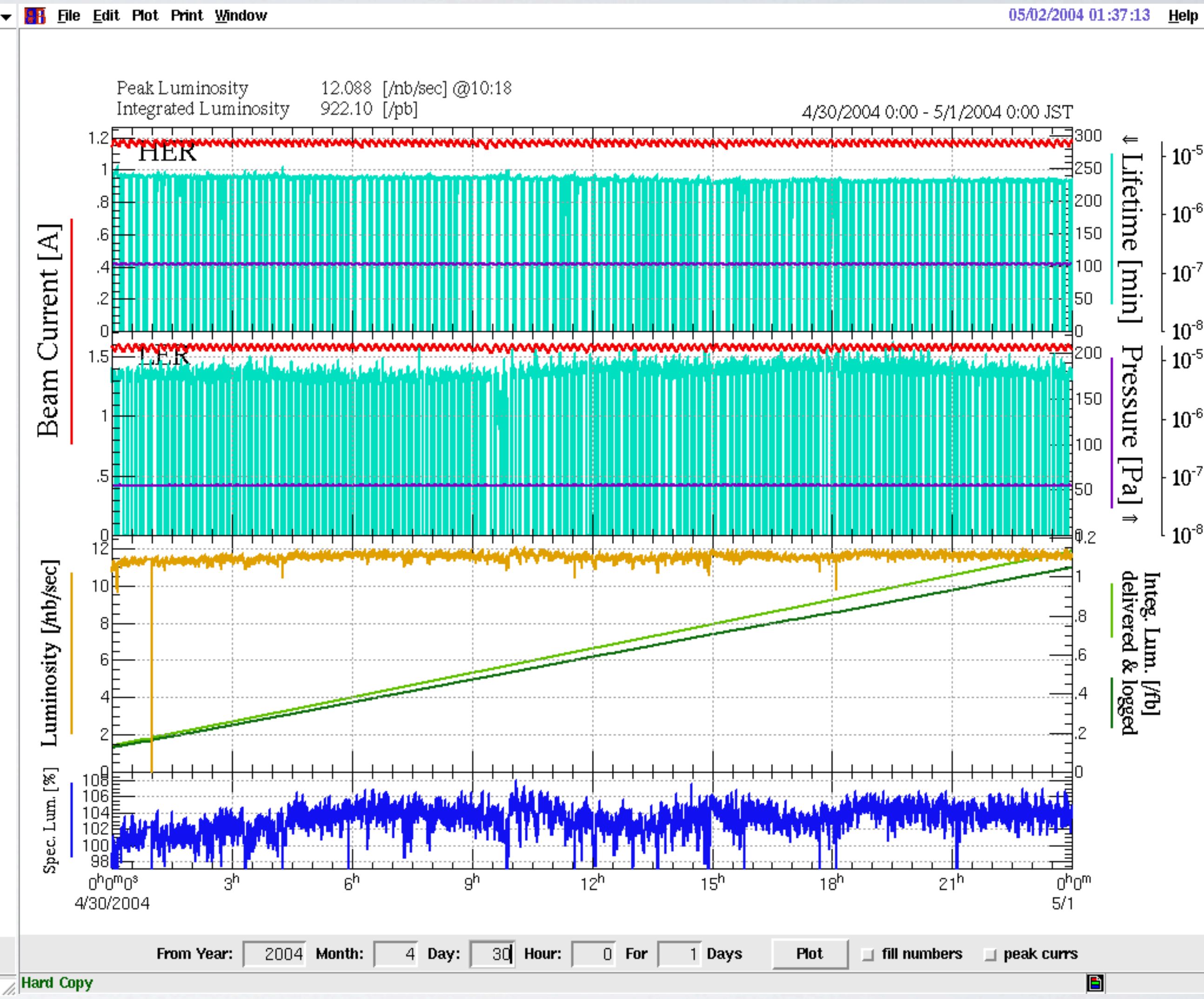
- TLEP Z may require an injector comparable to SuperKEKB.
- The synchrotron dedicates 17% per beam for its injection from the linac in the case of TLEP Z.
- The intensity imbalance between bunches in the collider rings should be estimated.



Top-up at KEKB (2004-)



a day before top-up



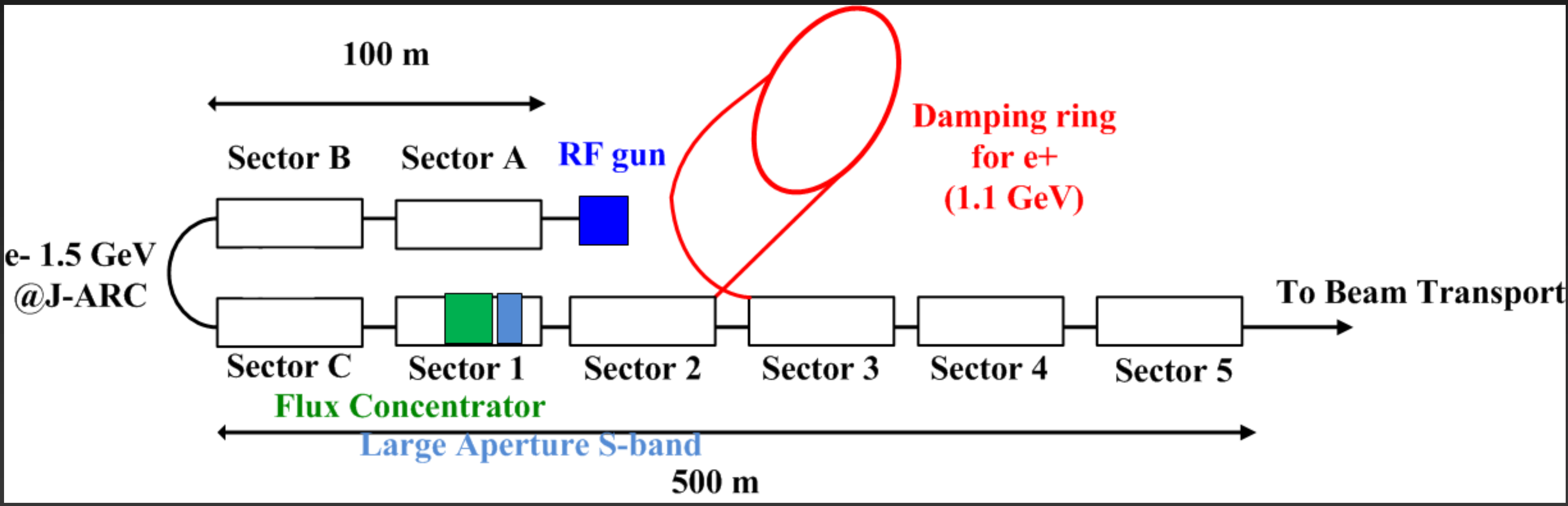
a day after top-up

- Top-up improved the integrated luminosity from 640 pb/day to 920 pb/day in 2004 (eventually reached 1480 pb/day in 2009).
- Machine becomes more stable and less aborts, as the stored beam current is nearly constant.
- Thus the luminosity tuning became easier.

Upgrade Items for Injector

- New low emittance photo-cathode rf gun
- New positron source (Flux concentrator)
- Damping ring for positron
- Low emittance preservation

M. Satoh



e- Linac Beam Parameters

M. Satoh

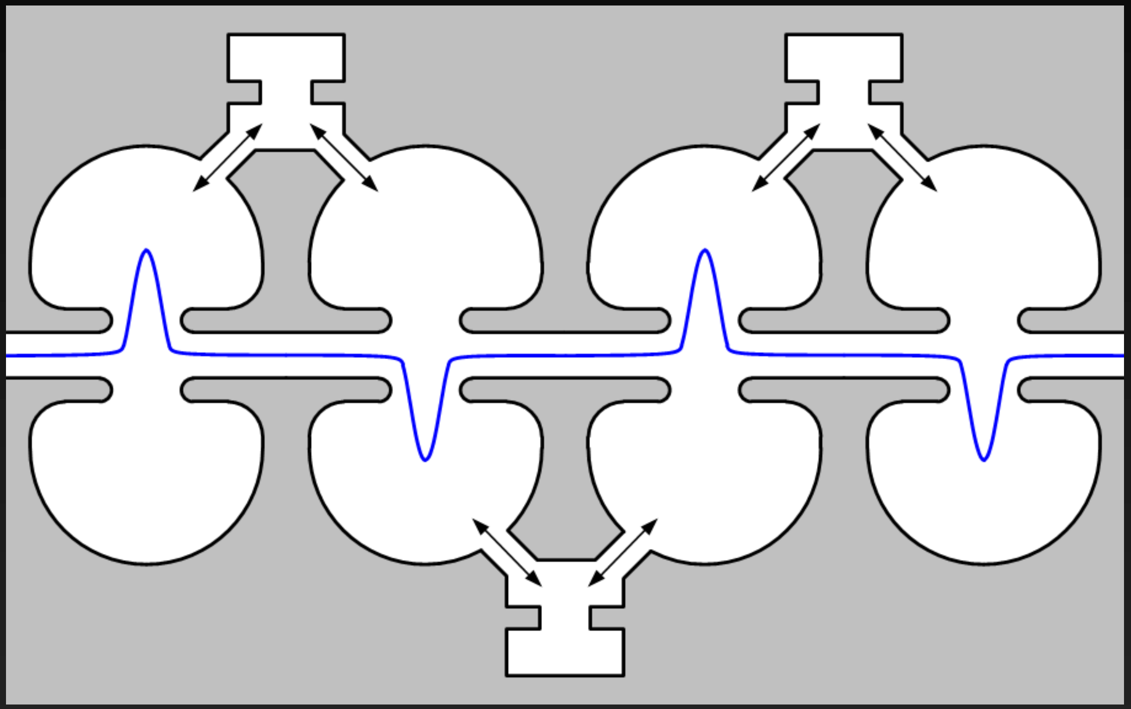
	SuperKEKB	KEKB
Energy (GeV)	7.0	8.0
HER stored current (A)	2.6	1.1
HER beam lifetime (min.)	6	200
Maximum beam repetition (Hz)	50	50
Max. # of bunch in an rf pulse	2	2
Emittance (mm·mrad)	50/20 (Hor./Ver.)	100
Charge (nC)	5	1
Energy spread (%)	0.08	0.05
Bunch length σz (mm)	1.3	1.3
Damping ring	-	-
Simultaneous top-up injection	4 rings (SuperKEKB e-/e+, PF, PF-AR)	3 rings (KEKB e-/e+, PF)

e+ Linac Beam Parameters

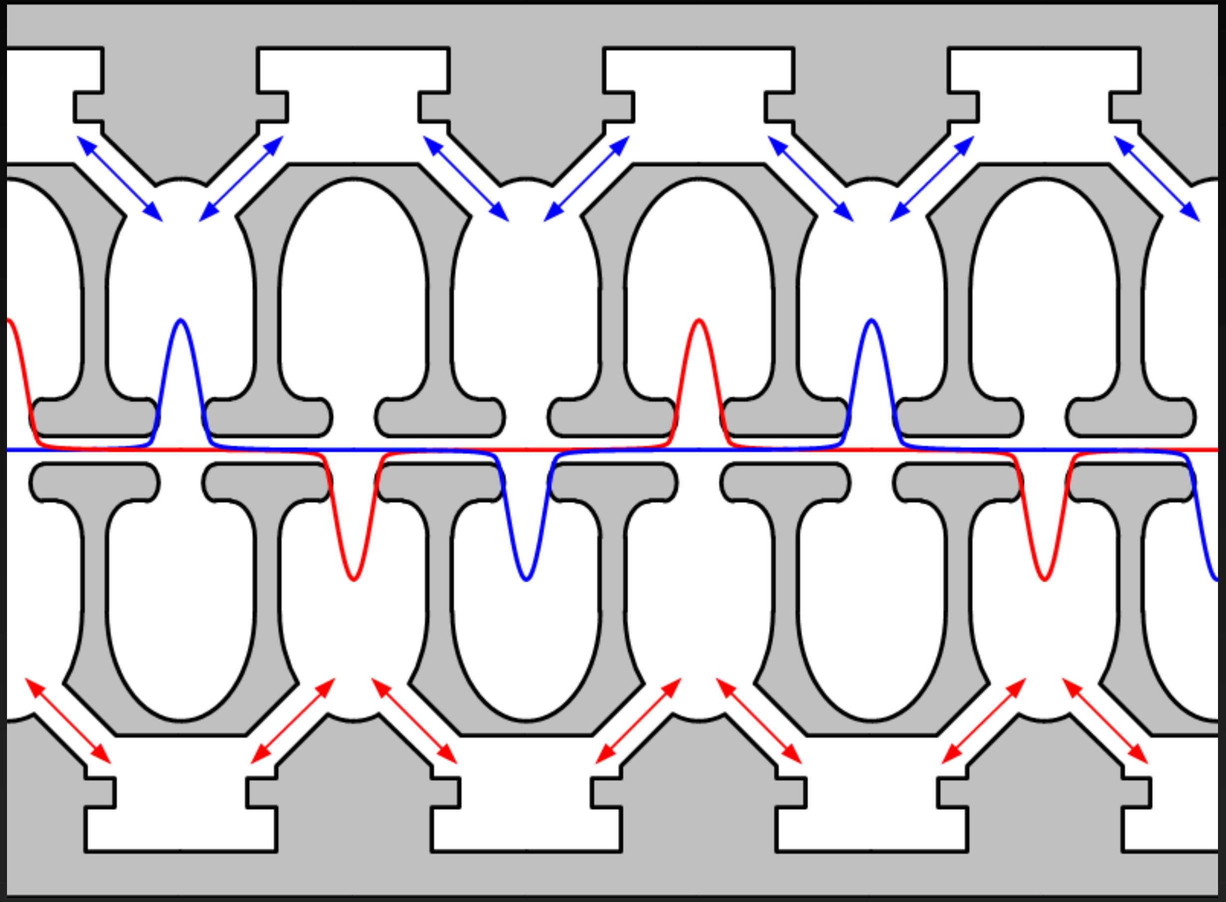
M. Satoh

	SuperKEKB	KEKB
Energy (GeV)	4	3.5
LER stored current (A)	3.6	1.6
LER beam lifetime (min.)	6	133
Maximum beam repetition (Hz)	50	50
Max. # of bunch in an rf pulse	2	2
Emittance (mm·mrad)	100/20 (Hor./Ver.)	2100
Charge (nC)	4	1
Energy spread (%)	0.07	0.125
Bunch length σz (mm)	0.7	2.6
Damping ring	○	-
Simultaneous top-up injection	4 rings (SuperKEKB e-/e+, PF, PF-AR)	3 rings (KEKB e-/e+, PF)

Structure of the quasi traveling wave cavity



Normal side coupled cavities

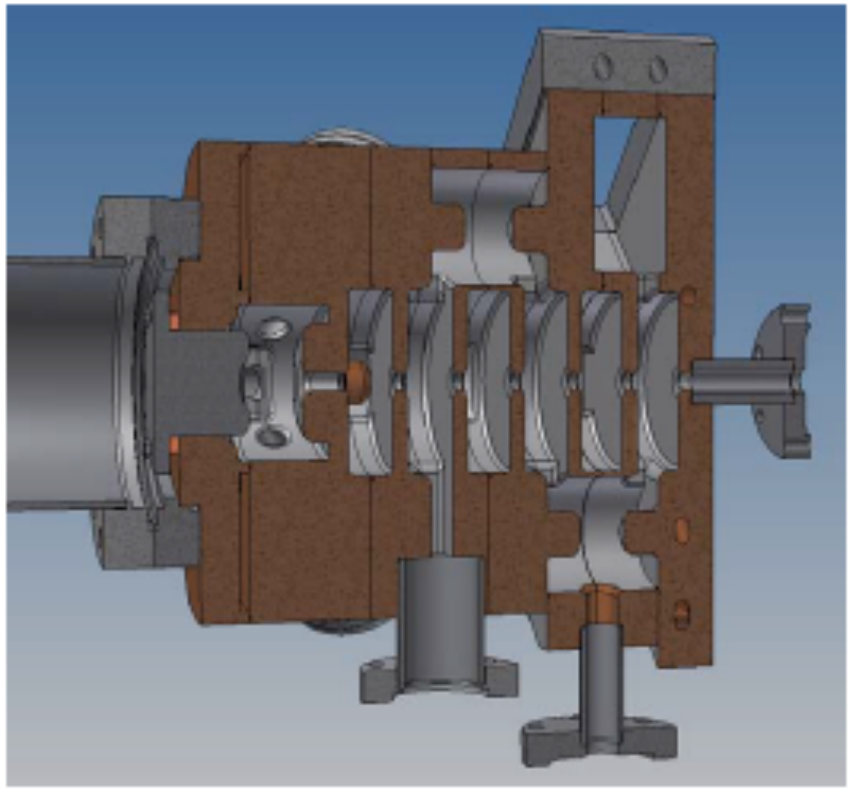


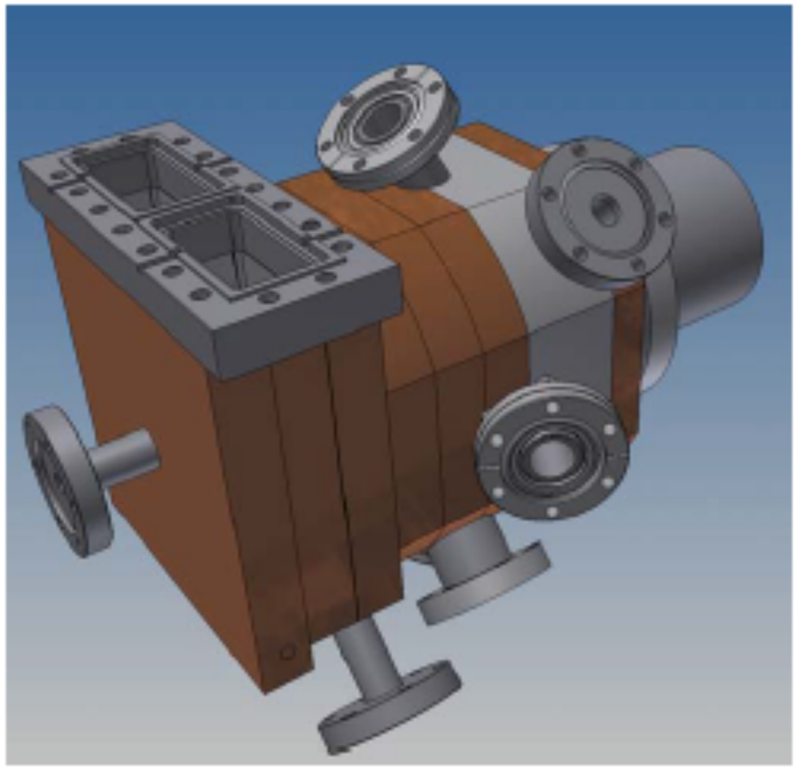
Quasi traveling wave side coupled cavities

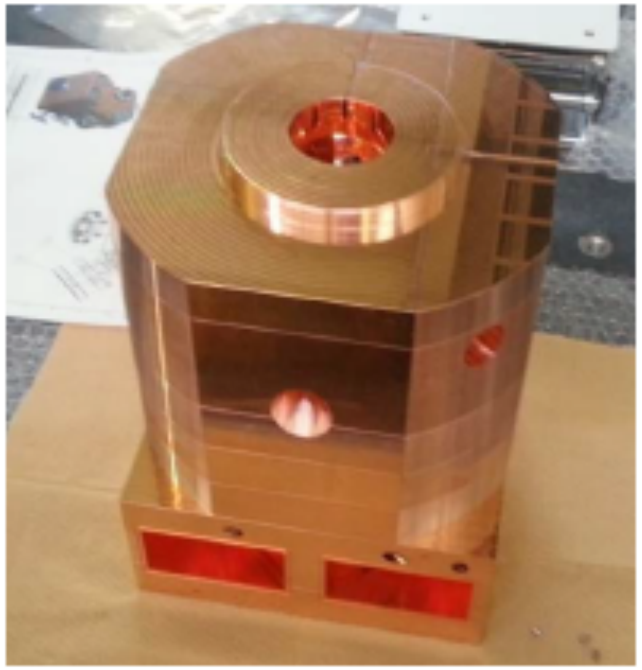
The close nose makes focus field. Our DAW RF gun is using this focus field. Side coupled cavity also can be made the close nose. But, long drift space is problem. One solution is to use tow standing wave cavity.

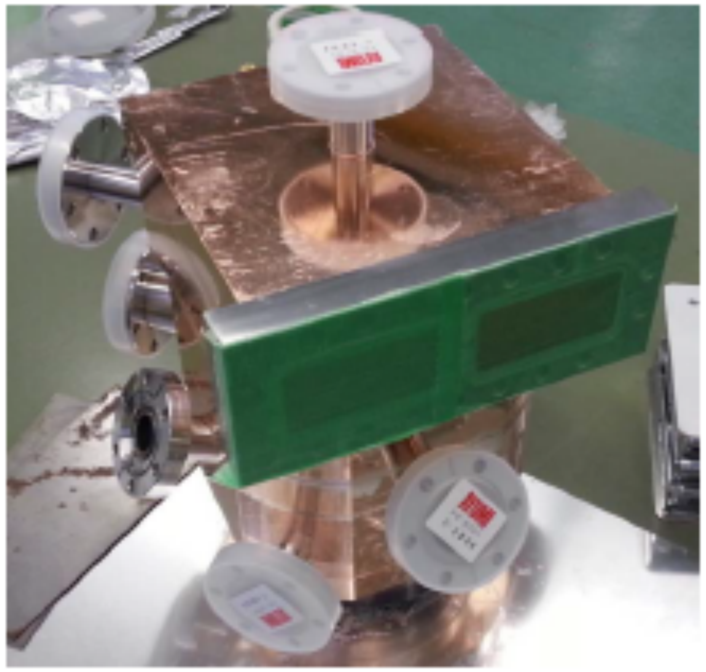
T. Natsui, ICFA Mini-Workshop on Commissioning of SuperKEKB and e+e– Colliders.

Mechanical design and manufacturing







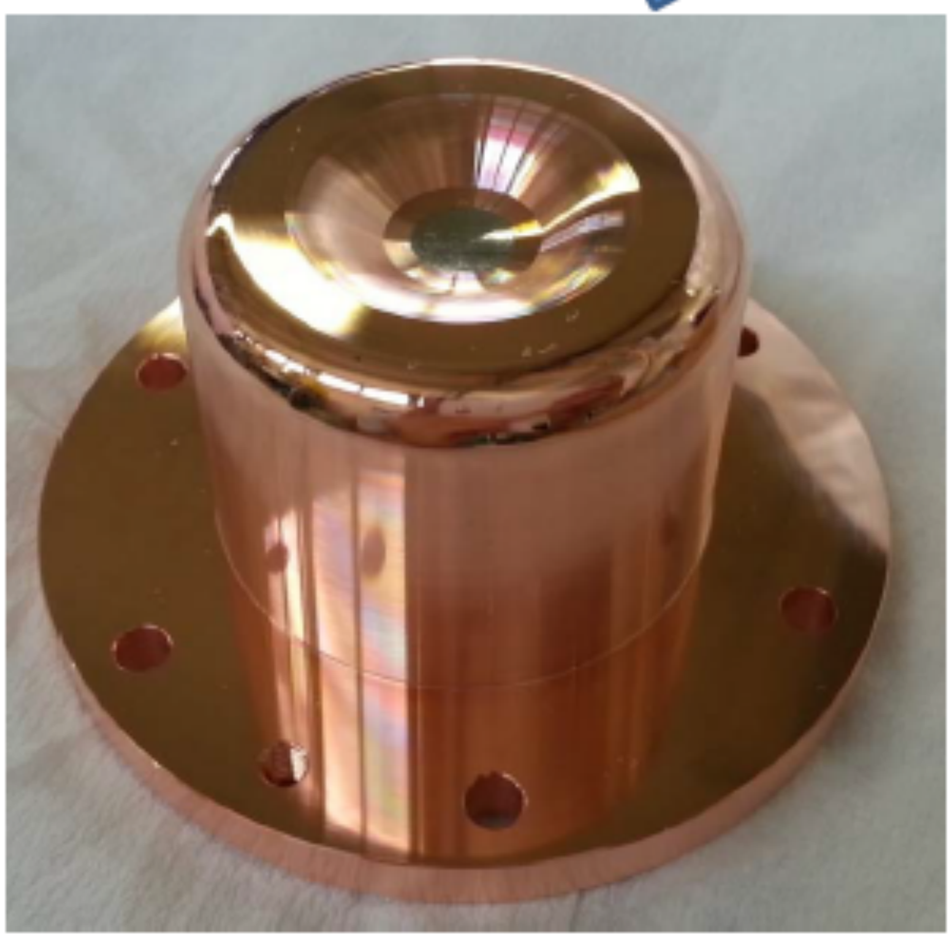


T. Natsui, ICFA Mini-Workshop on Commissioning of SuperKEKB and e+e– Colliders.

Photo-cathode material

Ir_5Ce

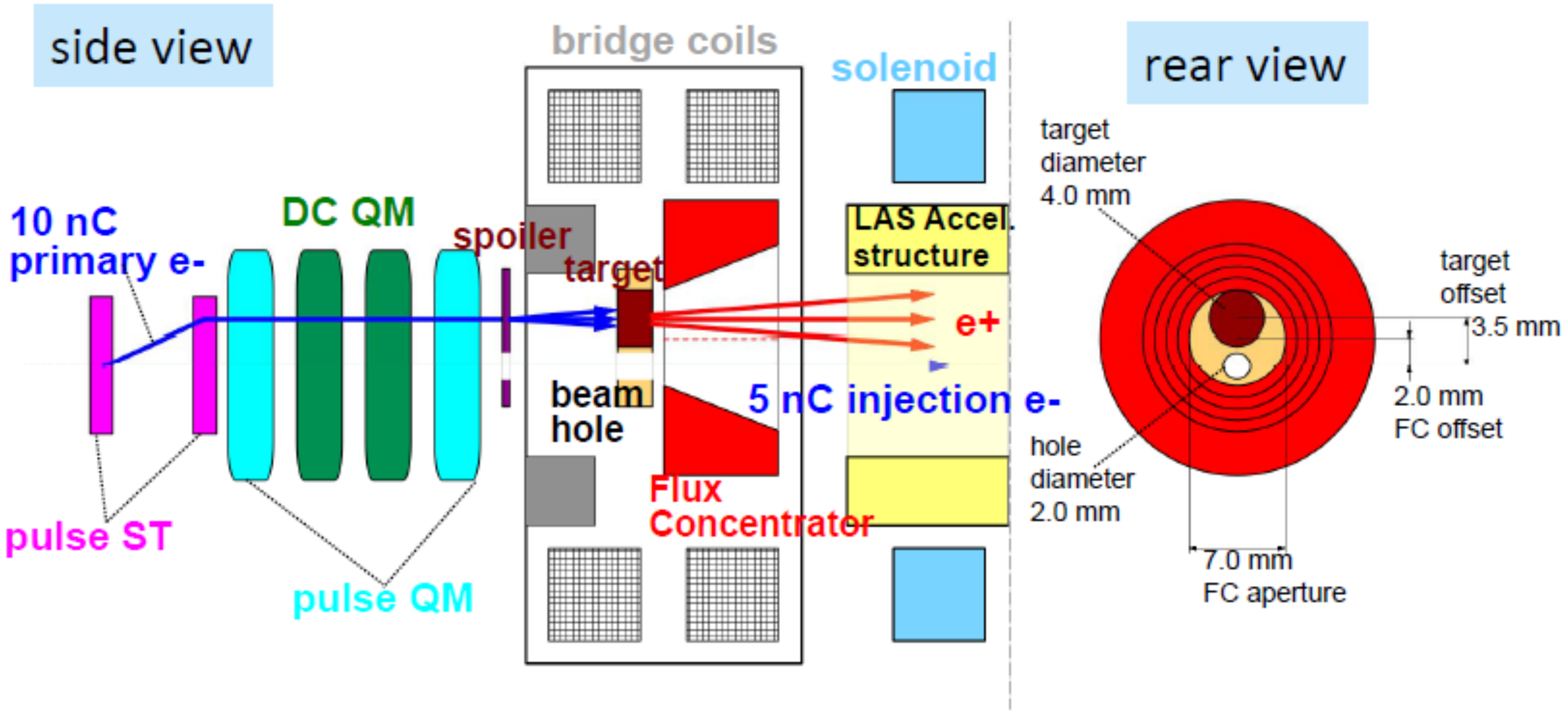
High charge 5 nC ⟺ Long term operation



- Metal composite cathode
- Solid (not thin film)
- High quantum efficiency 10^{-4} at room temperature
- Low work function
- Robust in bad vacuum condition

T. Natsui, ICFA Mini-Workshop on Commissioning of SuperKEKB and e+e– Colliders.

e+/e- beam switching at target

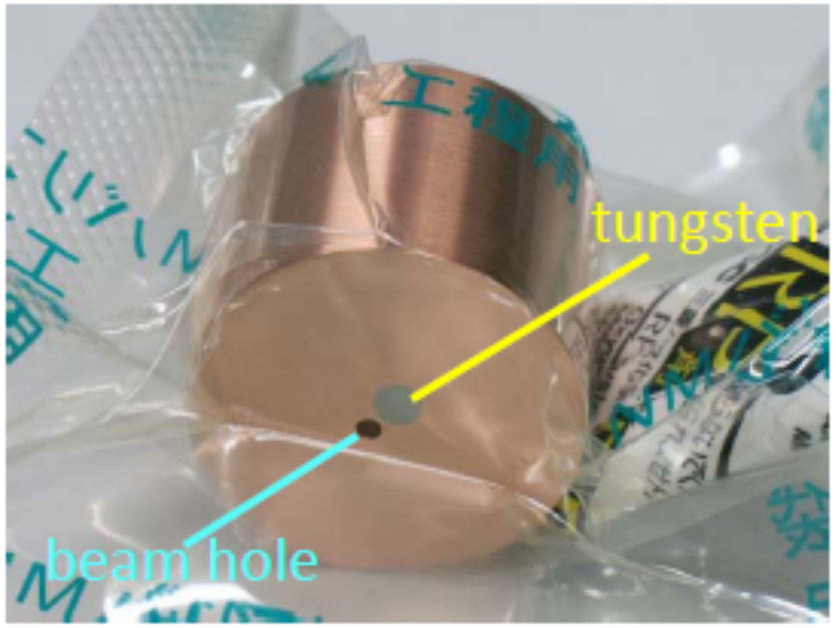


Two possible schemes of beam switching by orbit bump

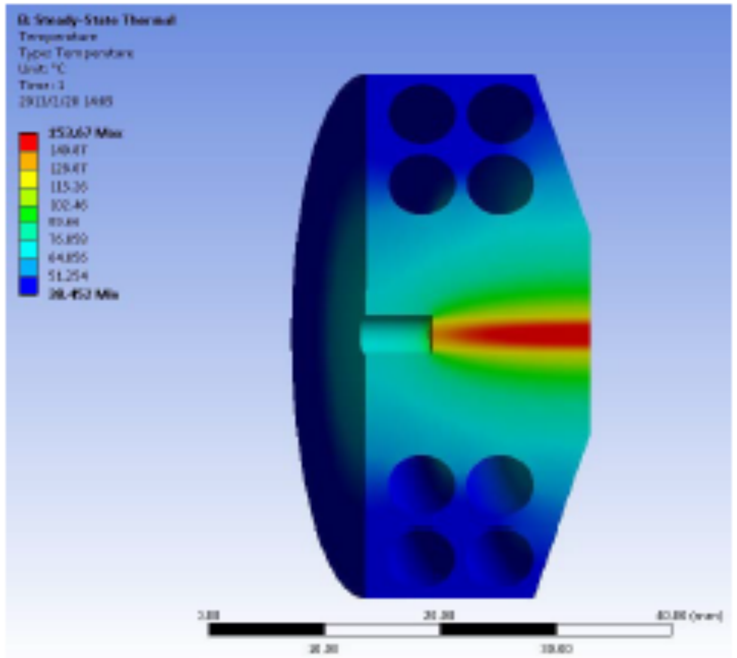
1) e+ on-axis, e- offset
   -> e- emittance growth by solenoid kick induced orbit excursion
2) e- on-axis, e+ offset
   -> e+ yield degradation (50% -> 10%)

we take this scheme.

positron production target

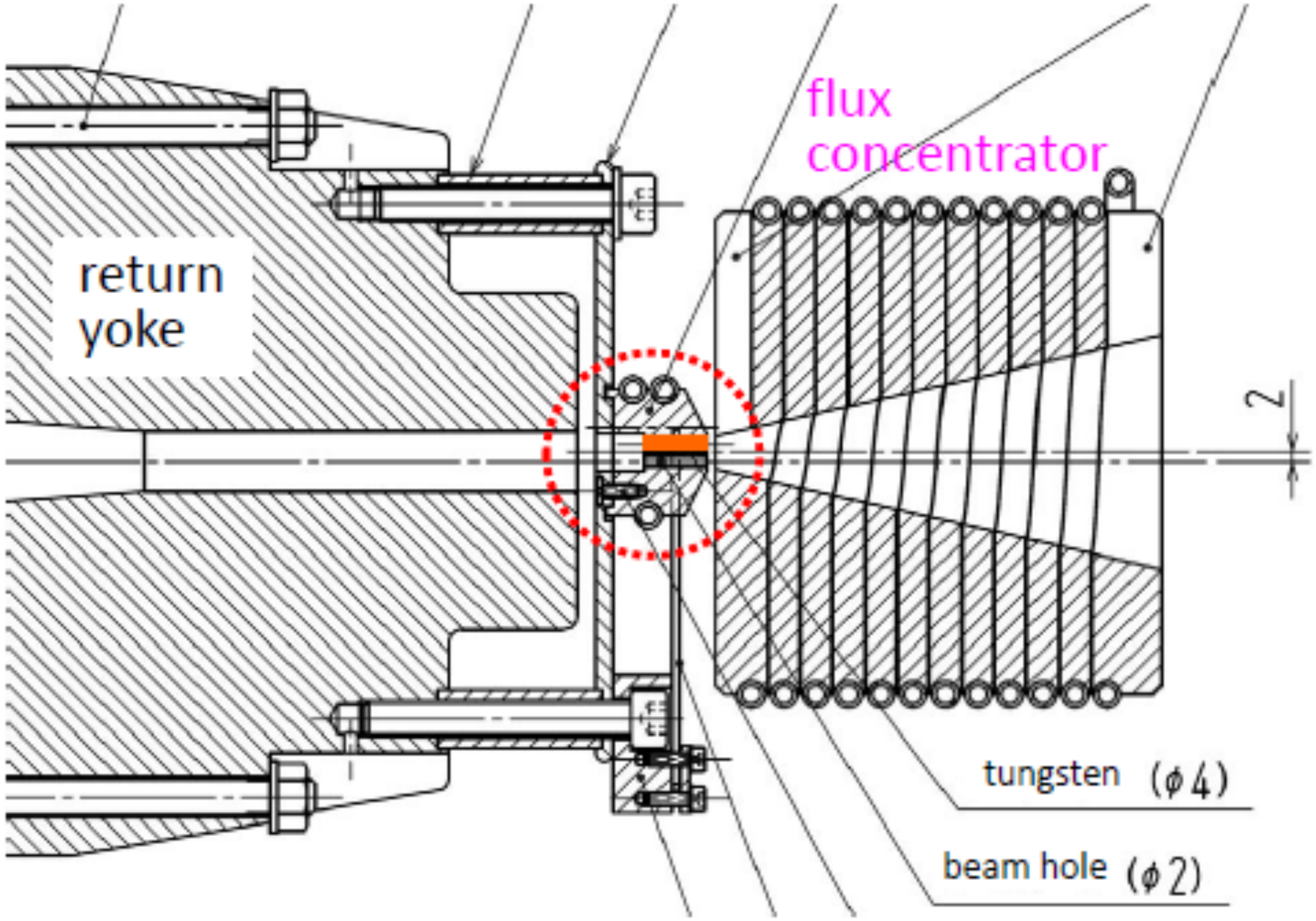


target core before processing



heat distribution in target

- target material:
  tungsten 14 mm thick (= 4.0 X_0)
- tungsten + copper body bonded by hot isostatic pressing (HIP)

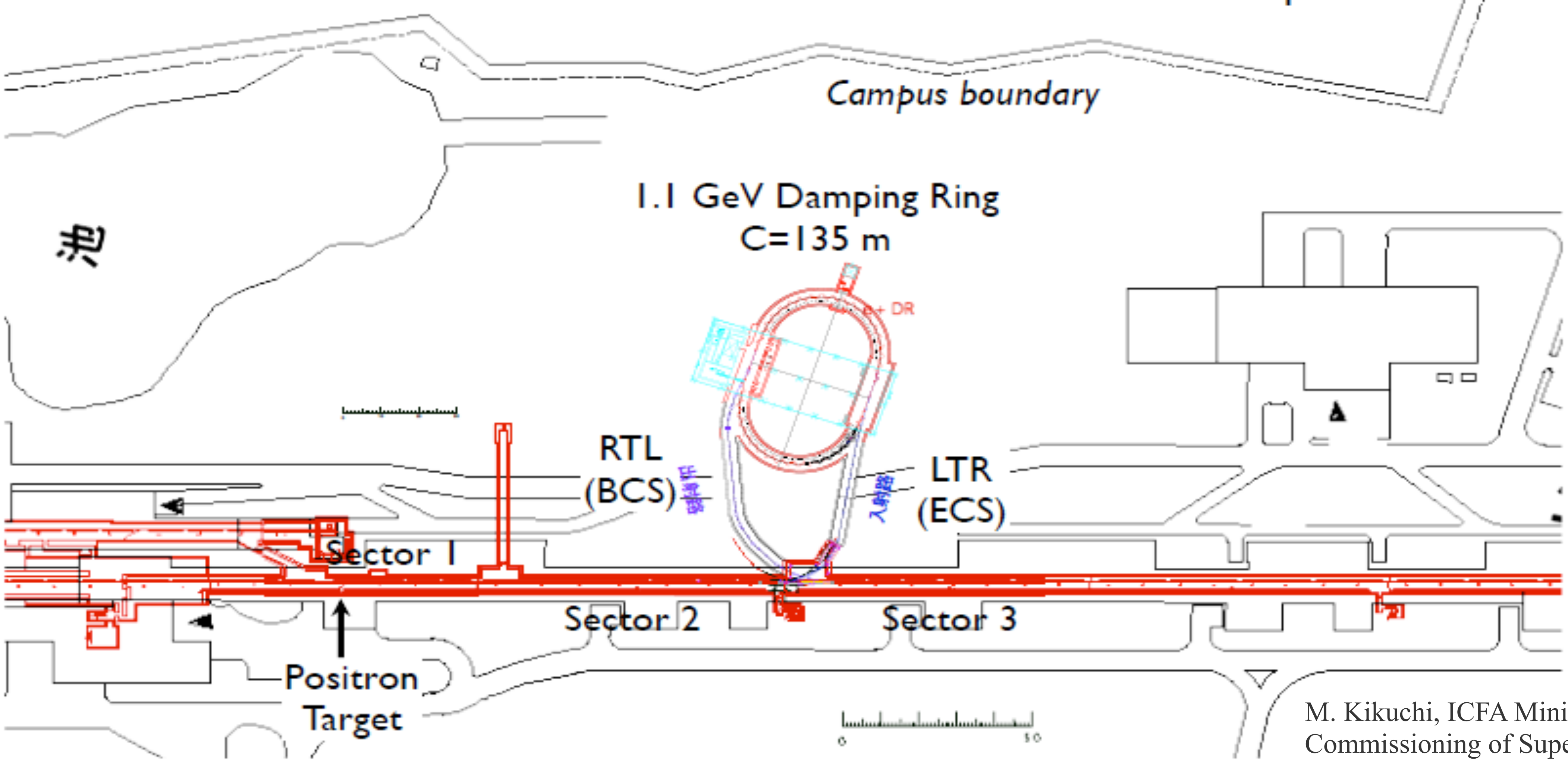


Layout of the System

- Positron target at sector1-4
- Extract from Linac at 1.1GeV
- Store 2 Linac pulse each having 2 bunches (96 ns apart)
- Circumference to accommodate 2 linac pulse + kicker rise/fall time (100 ns)
- After 2 linac-pulse, re-inject to the Linac
- LTR line with ECS
- RTL line with BCS
- Note the DR is near to the campus boundary

- Requirement from Radiation safety

Maximum particle loss rate:
1 % in injection straight
0.2% in arc (point loss)
for 8 nC/pulse at 25 Hz



M. Kikuchi, ICFA Mini-Workshop on Commissioning of SuperKEKB and e+e– Colliders.

DR: Ring Parameters

Parameters of the Damping Ring

Energy	1.1	GeV
No. of bunch trains/ bunches per train	2 / 2	
Circumference	135.5	m
Maximum stored current*	70.8	mA
Energy loss per turn	0.091	MV
Horizontal damping time	10.9	ms
Injected-beam emittance	1400	nm
Equilibrium emittance(h/v)	41.4 / 2.07	nm
Coupling	5	%
Emittance at extraction(h/v)	42.5 / 3.15	nm
Energy acceptance	± 1.5	%
Energy spread	0.055	%
Bunch length	6.5	mm
Momentum compaction factor	0.0141	
(νx, νy νz)	(8.24, 7.265, -0.025)	
Number of normal cells	32	
Cavity voltage for 1.5 % bucket-height	1.4	MV
RF frequency	509	MHz
Chamber inner width / height	44 / 24 with antechamber	mm
Bore diameter of magnets	44	mm

* 8 nC/bunch

- 8 nC/bunch (16 nC/pulse) is an 'ultimate' goal
- The hardware design is based on this value.

$$\theta_1 = 0.277 \quad \theta_2 = -0.097$$

$$(B_1 = 1.367\ \mathrm{T} \quad B_2 = -1.24\ \mathrm{T})$$

M. Kikuchi, ICFA Mini-Workshop on Commissioning of SuperKEKB and e+e– Colliders.

- # Summary (final focus)
- The final focus system for TLEP will have the same level of the chromaticity (=measure of difficulty) as SuperKEKB.
- If we apply the SuperKEKB's design concept to TLEP, the resulting momentum acceptance, may become the same level, ie., ±1.4%, which is not sufficient for TLEP tt.
- Thus we need some breakthroughs on top of SuperKEKB's optics design for TLEP tt.
- # Summary (injector)
- The performance of SuperKEKB injector (e- guns, e+ source, damping ring) basically matches to the requirements of TLEP, except for polarization.
- More study is necessary for the synchrotron.