Accelerator Physics Issues in BEPCII

BEPCII AP Group

- Introduction
- Lattice and dynamic aperture
- Coupling impedance
- Single beam effects
- Beam-Beam interaction
- Summary

(1) Introduction

DR: multy-bunch k_{bmax}~400, k_b=1 ✍ 93

Choose large $?_x$ & optimum param.: I_b=9.75mA, $?_y$=0.04

$$L(\mathrm{cm}^{-2}\mathrm{s}^{-1}) ?\ 2.17 ?\ 10^{34}(1 ?\ R) ?_y \frac{E(GeV)k_b I_b(A)}{?^*_y(cm)}$$

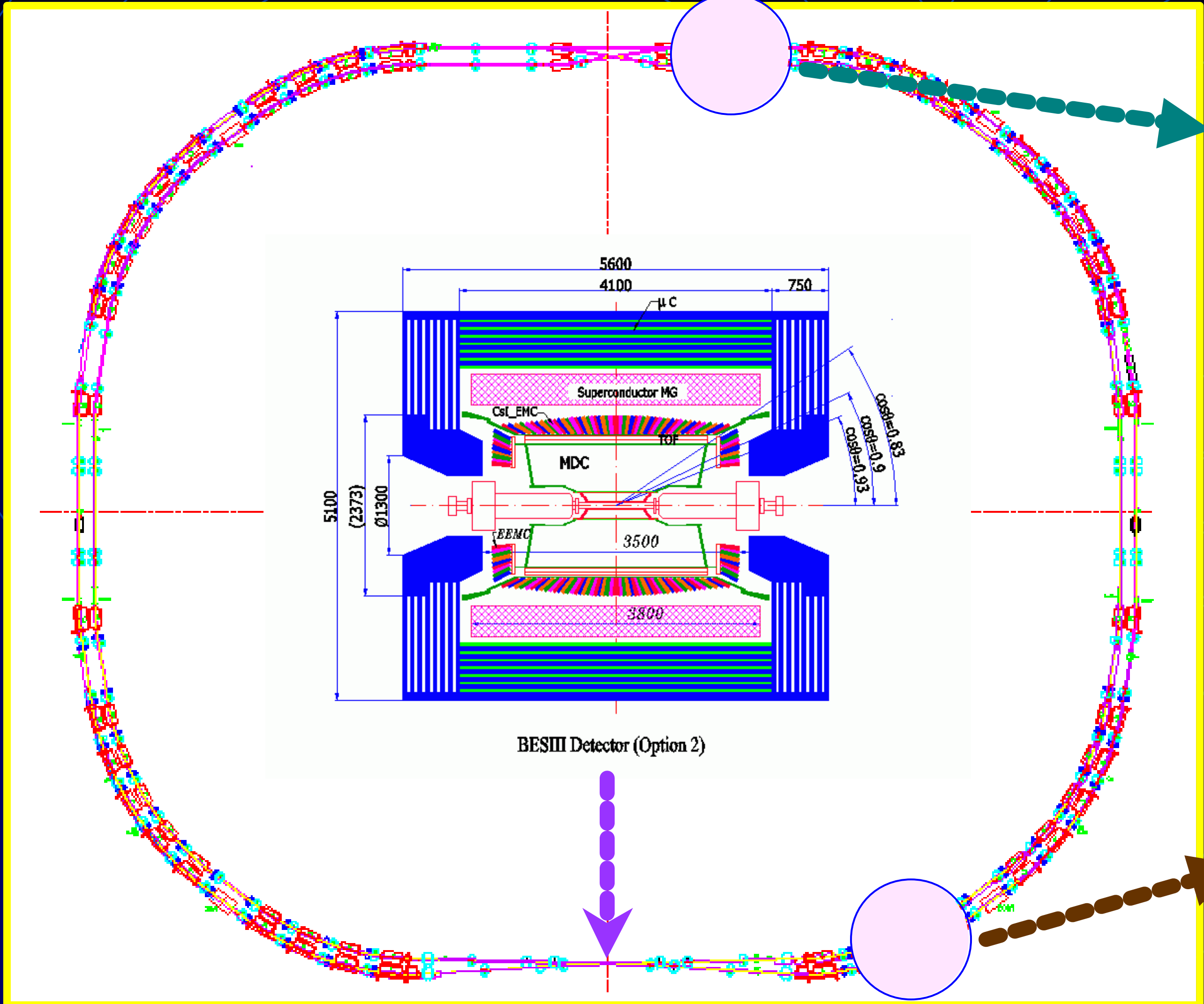
Micro-? : $?_y^*$ =5cm ✍ 1.5 cm
SC insertion quads

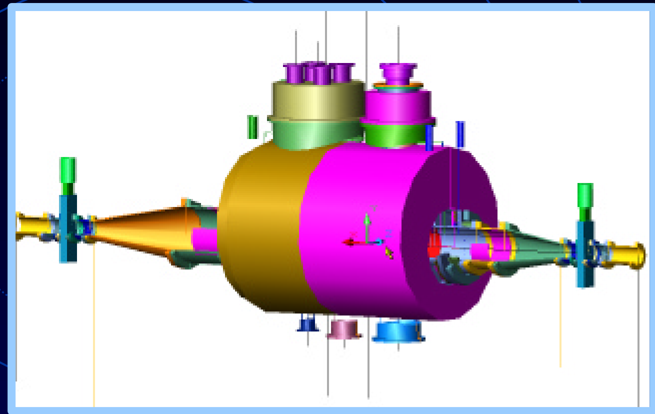
Reduce impedance +SC RF
$?_z$ =5cm ✍ <1.5cm

$(L_{BEPCII}/ L_{BEPC})_{D.R.}$=(5.5/1.5) ?93 ? 9.8/35=96

L_{BEPC}=1.0?10 ^{31} cm^{-2}s^{-1} ✍ L_{BEPCII} =1?10 ^{33} cm^{-2}s^{-1}

BEPCII: *a high luminosity double–ring collider*





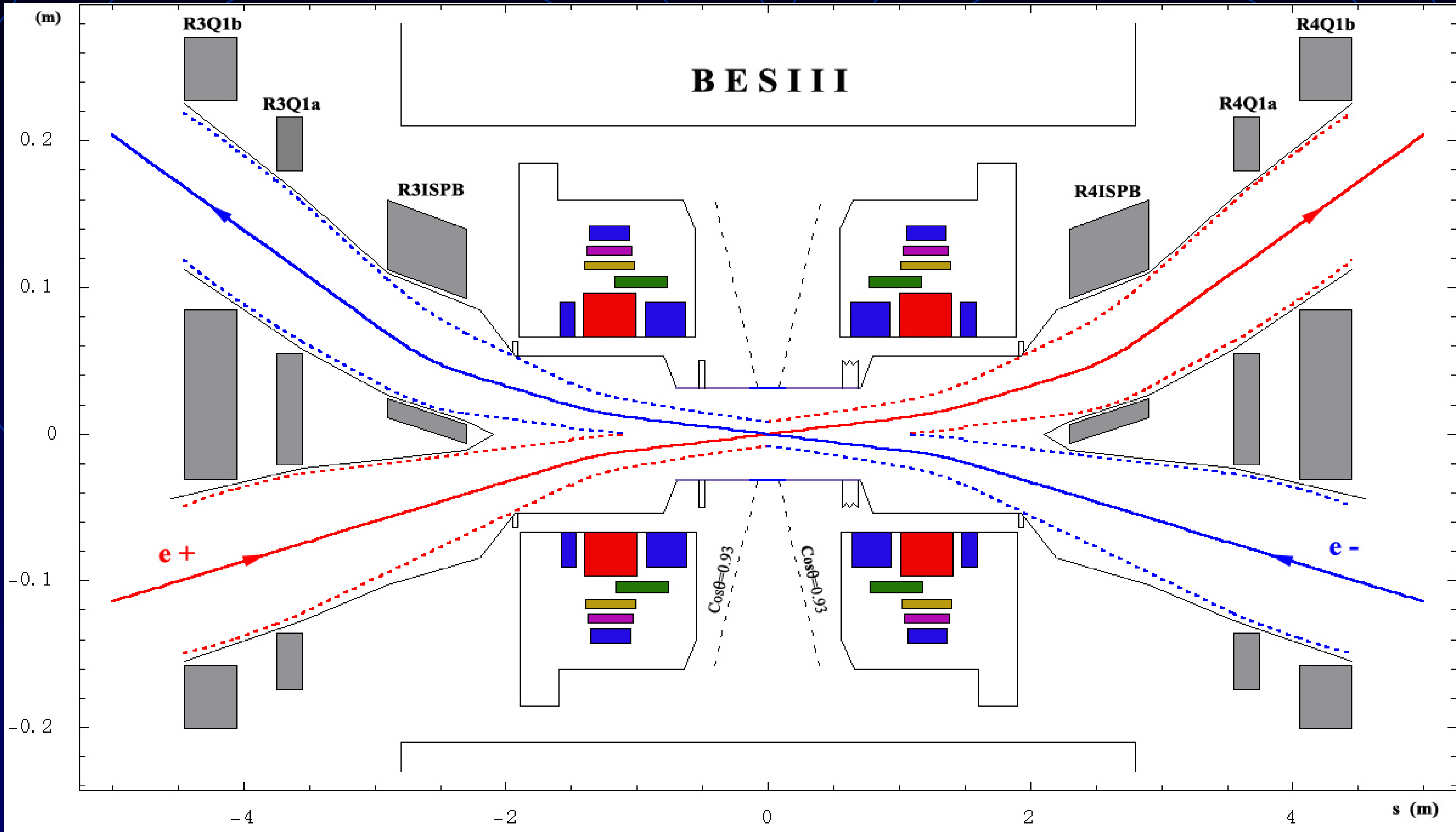
Design Goals and Main Parameters

Beam energy range	1–2 GeV
Optimized beam energy region	1.89GeV
Luminosity @ 1.89 GeV	1? 10 ^{33} cm^{-2}s^{-1}
Injection from linac	Full energy injection: E_{inj}=1.55? 1.89GeV
Dedicated SR operation	250 mA @ 2.5 GeV

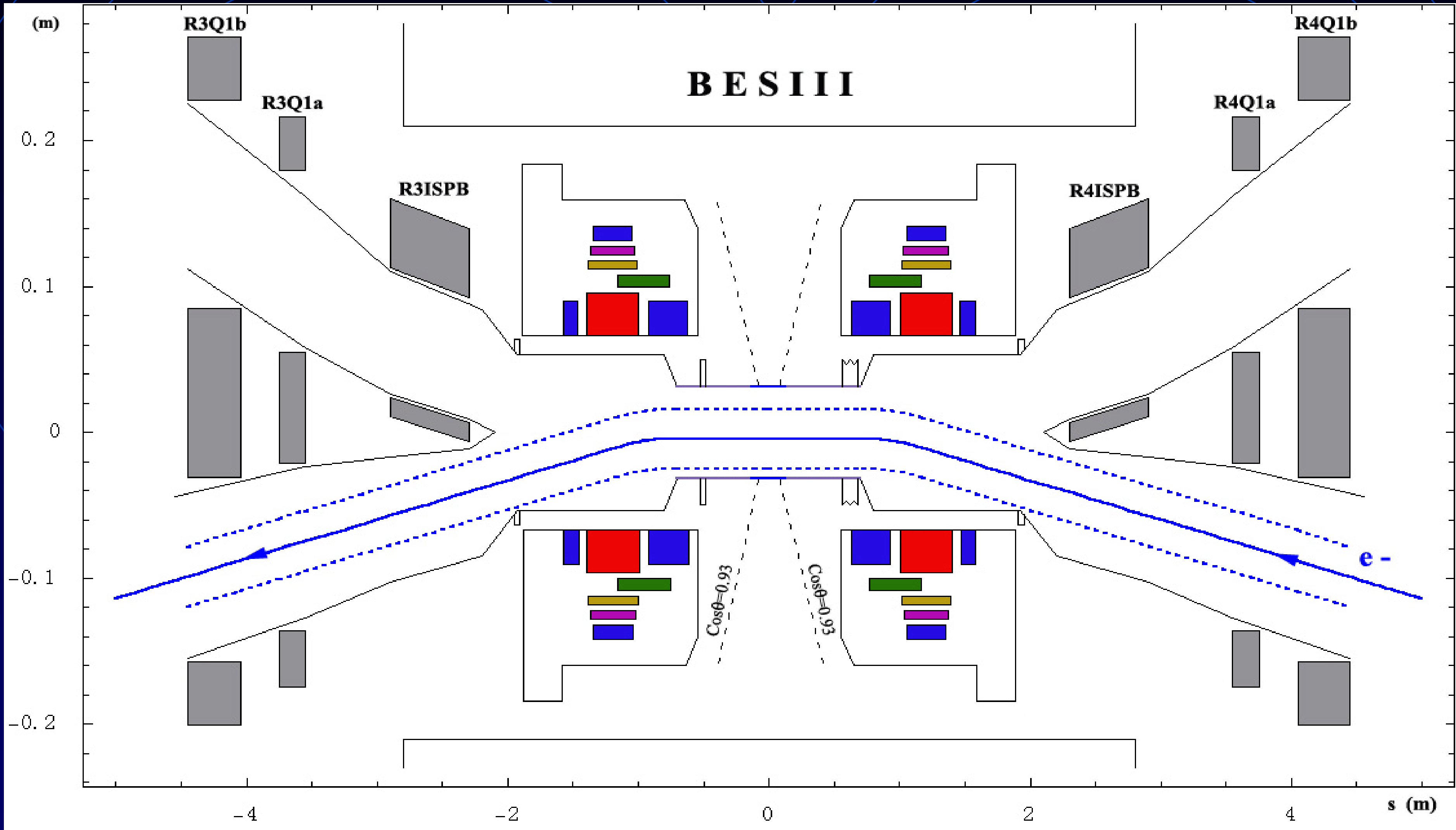
(2) The lattice and dynamic aperture

- The lattice design should meet the requirement of BEPCII as a dual-purpose machine for both HEP and SR researches, which makes BEPCII a three-ring collider: e^--ring, e^+-ring and SR-ring;
- It will provide the colliding beams of the center-mass between 2-4.2 GeV optimized at 1.89 GeV with 1? 10^{33} $cm^{-2}s^{-1}$.
- Design energy for SR is 2.5 GeV and current of 250 mA, the existing SR beam-lines should keep at their present position;
- RF frequency is chosen as 499.8Mhz(=2856? 7/40). The harmonic number of colliding and SR rings are 396 and 402, the circumference are 237.53 m and 241.13 m; The distance between the outer and inner rings is 1.18 m.

IR Layout (Collision Mode)



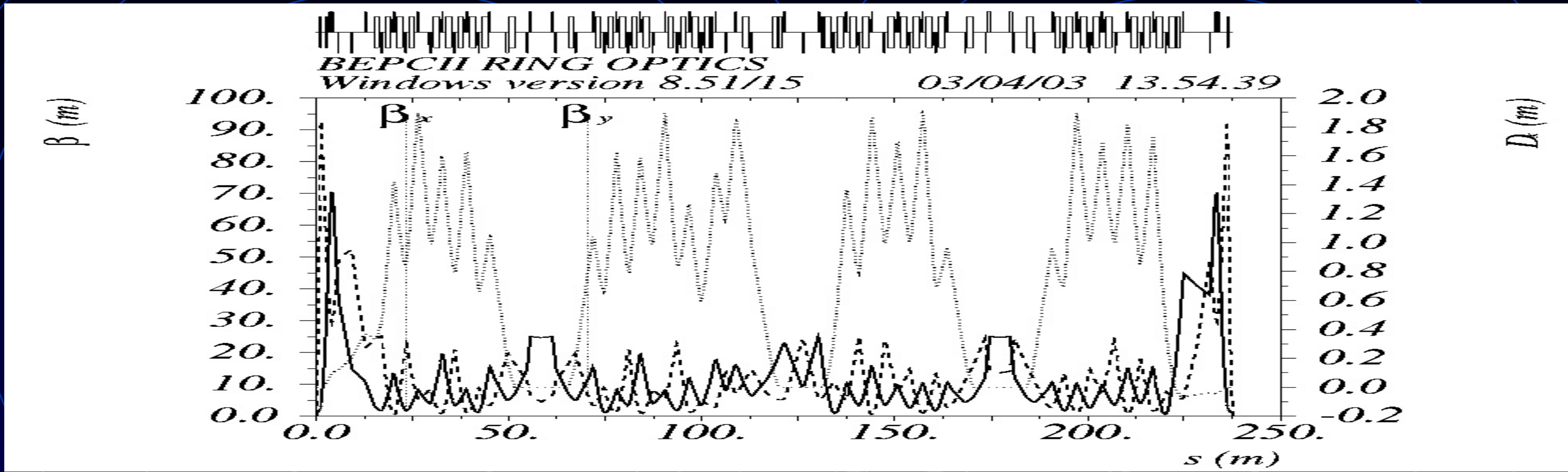
IR Layout (SR Mode)

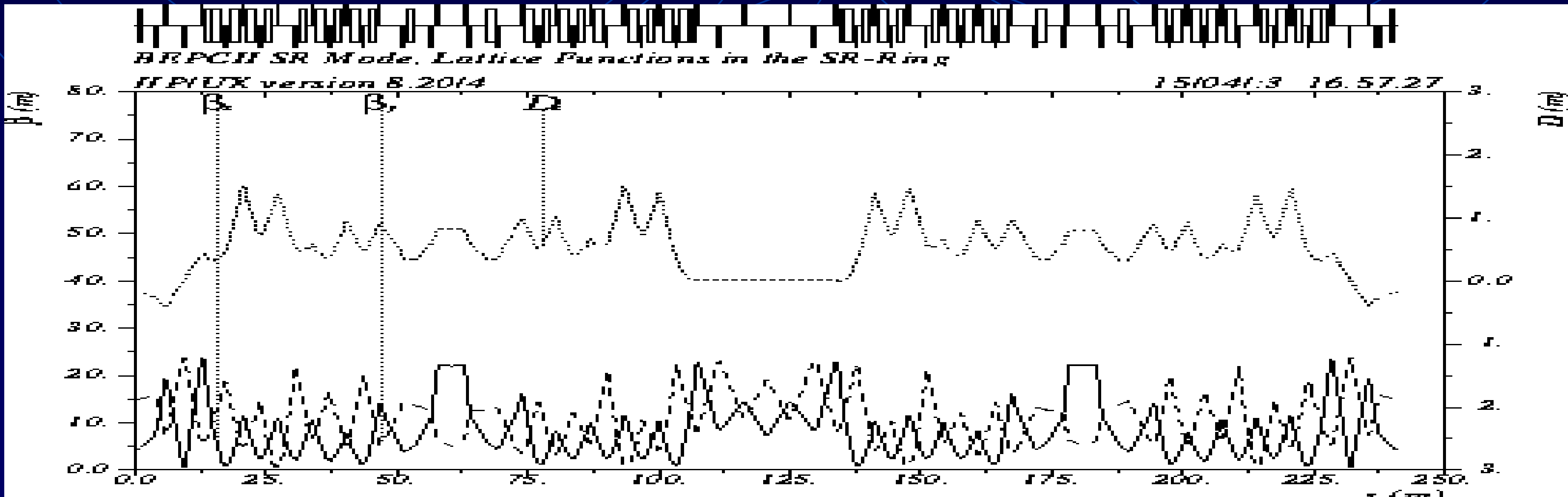


Two tune regions are studied: *?$_x$/ ?$_y$* **= 6.5/7.5 and** *?$_x$/ ?$_y$* **= 6.5/5.5. Both meet the following requirements.**

- Natural emittance ~ 140nm
- Momentum compact factor a_p~ 0.02
- ?$_x^*$ = 1m   ?$_y^*$ = 1.5cm D_x^* = 0
- ?$_x^*$_inj > 20m, D_{x_inj}=0
- ?$_x$_kicker > 6 m, ? ?$_x$_kickers=0.5
- ?$_x$_ rfc, ?$_y$_rfc < 15m and D_x_rfc=0
- ?$_x$_arc, ?$_y$_arc < 25m and D_x_arc<2.5m
- a_x =0, a_y=0 and D_x?=0 at IP and symmetric points.

Optics functions for colliding and SR modes

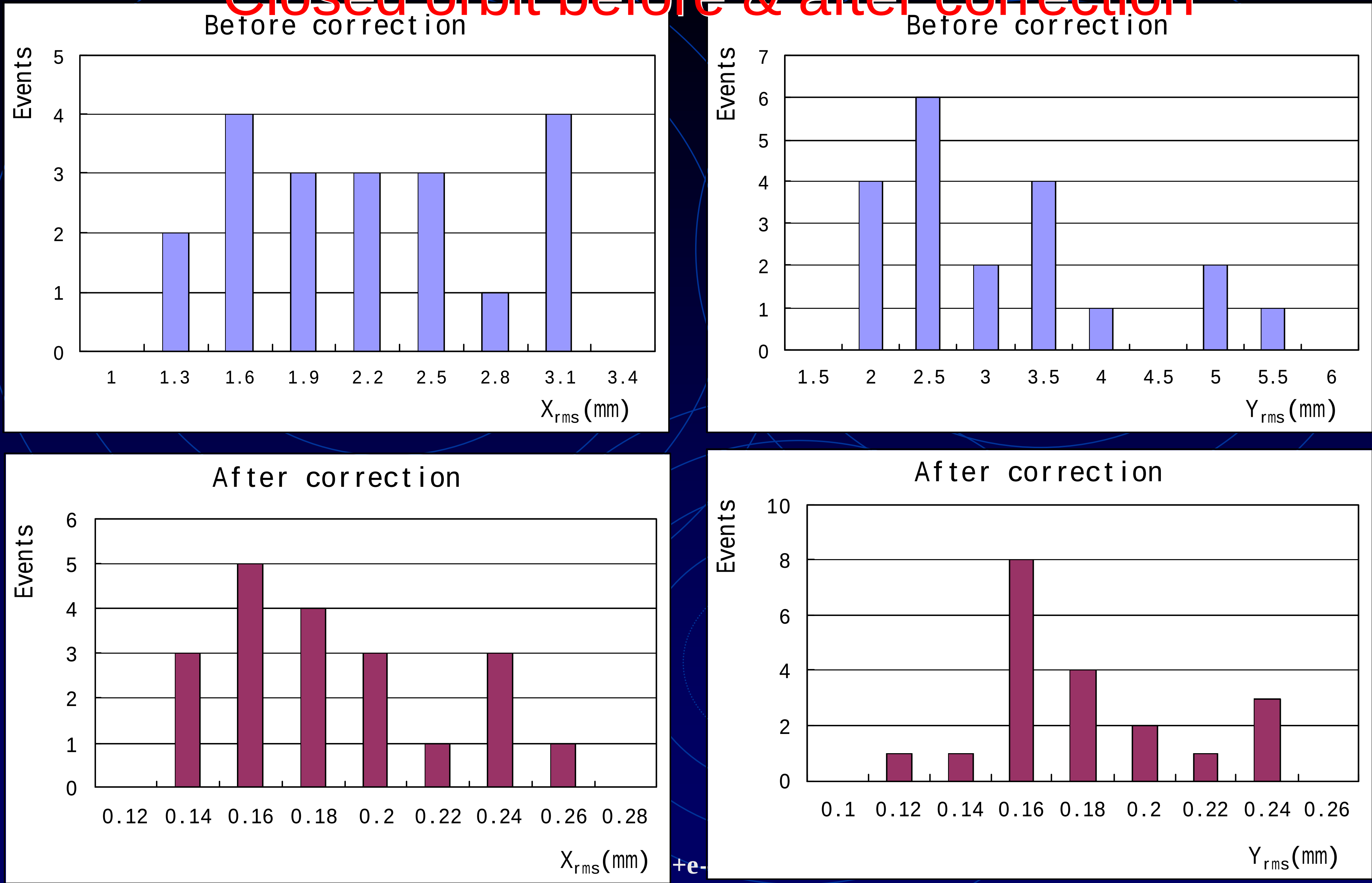




Main Parameters of BEPCII vs. BEPC

Parameters		Unit	BEPCII	BEPC
Operation energy (*E*)		GeV	1.0?2.0	1.0?2.5
Injection energy (E_{inj})		GeV	1.55?1.89	1.3
Circumference (*C*)		m	237.5	240.4
?*-function at IP ($?_x^*$/ $?_y^*$)		cm	100/1.5	120/5
Tunes ($?_x$/$?_y$/$?_s$)			6.57/7.61/0.034	5.8/6.7/0.02
Hor. natural emittance ($?_{x0}$)		mm?mr	0.14 @1.89 GeV	0.39 @1.89 GeV
Damping time ($?_x$/$?_y$/$?_e$)			25/25/12.5 @1.89 GeV	28/28/14@1.89 GeV
RF frequency (f_{rf})		MHz	499.8	199.533
RF voltage per ring (V_{rf})		MV	1.5	0.6?1.6
Bunch number (N_b)			93	2?1
Bunch spacing		m	2.4	240.4
Beam current	Colliding	mA	910 @1.89 GeV	~2?35 @1.89 GeV
	SR		250 @ 2.5GeV	130
Bunch length (cm) $?_l$		cm	~1.5	~5
Impedance $\vert Z/n\vert_0$		? ?	~?0.2	~4
Crossing angle		mrad	?11	0
Vert. beam-beam param. $?_y$			0.04	0.04
Beam lifetime		hrs.	2.7	6?8
luminosity@1.89 GeV		$10^{31}cm^{-2}s^{-1}$	100	1

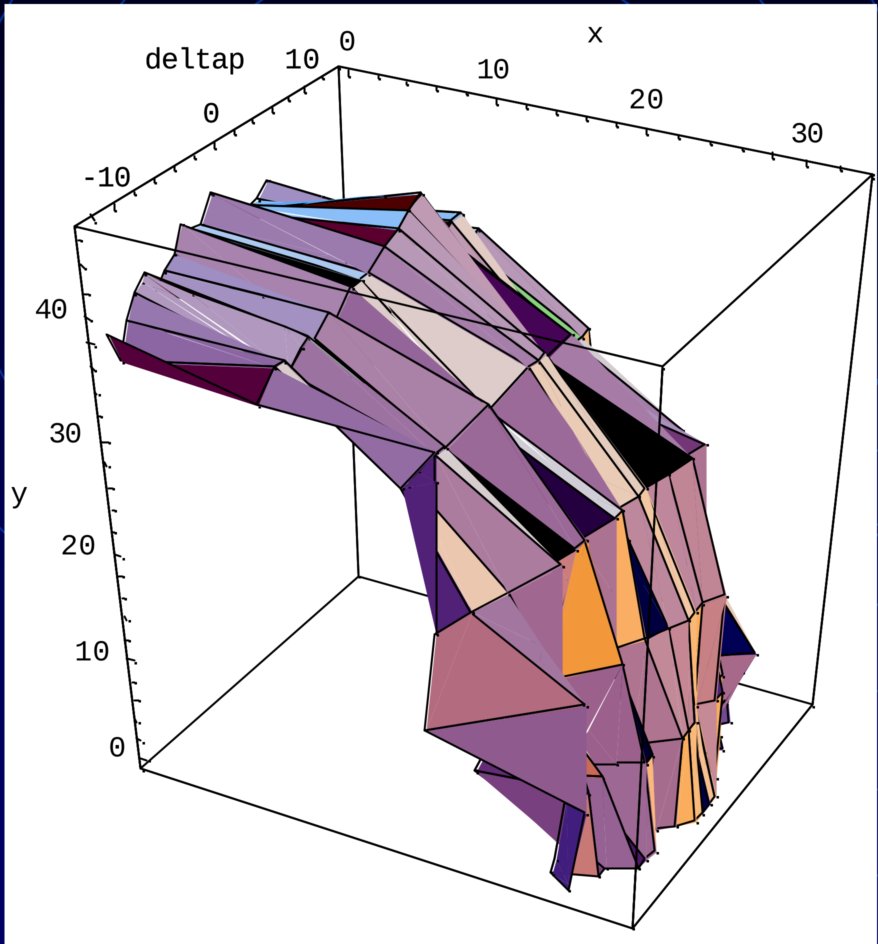
Closed orbit before & after correction

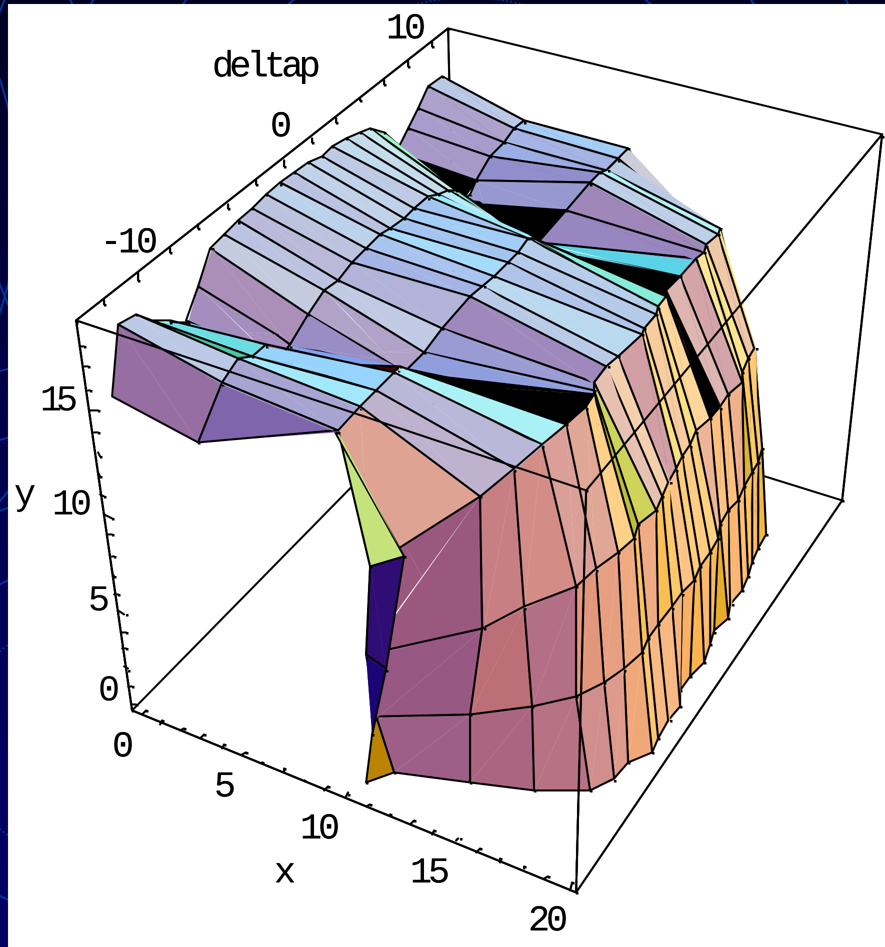


Summary of orbit correction

	Before correction	After correction
X_{ip} (mm)	-1.7 ~ +1.3	-0.21 ~ +0.19
Y_{ip} (mm)	-0.30 ~ +0.26	-0.20 ~ +0.36
X ?$\_{ip}$ (mrad)	-0.85 ~ +1.1	-0.09 ~ +0.15
Y?$\_{ip}$ (mrad)	-13.5 ~ +8.0	-1.2 ~ +1.3
X_{max} (mm)	6.4	0.56
Y_{max} (mm)	7.8	0.83
X_{rms} (mm)	2.1	0.18
Y_{rms} (mm)	2.9	0.17
NO. of H-COR(aver, max)		21, 27
NO. of V-COR(aver, max)		25, 33
K_0 of H-COR(aver, max) (mrad)		0.35, 0.58
K_0 of V-COR(aver, max) (mrad)		0.30, 0.49

The dynamic aperture without/with errors





(3) Coupling Impedance

- Broad band impedance ? bunch lengthening, TMCI
- Narrow band impedance ? coupled bunch instability
  - To minimize the impedance
- Special problems due to intensive beam with short bunch length: Trapped modes & HOM heating
  - Avoid trapped mode

Limit on Longitudinal Broadband Impedance

1) Bunch Lengthening due to PWD

$$\left(\frac{?_l}{?_{l0}}\right)^3 ? \left(\frac{?_l}{?_{l0}}\right) ? I_b \frac{e?_p}{4?E?_{s0}^2}\left(\frac{R}{?_{l0}}\right)^3 \frac{Z}{n}\Big|_0 ? 0$$

I_b=9.8mA, $(?_l - ?_0)/?_0$ <10%$_-$? Z/n? 0.65? (*L*=83nH)

2) Microwave instability threshold

$$I_{th} ? \frac{\sqrt{2?}\,?_p \frac{E}{e} ?_{e0}^2 ?_{l0}}{R\left|\frac{Z}{n}\right|_{eff}}$$

if I_{th}>9.8mA, $?_{l0}$=1.3cm

$\left|\frac{Z}{n}\right|_{eff}$? 0.97?

Threshold on transverse broadband impedance much higher

Limit on narrow band impedance

From Coupled bunch Instabilities

- **Assuming on resonance and growth rate equal to SR damping**

Longitudinal

$$crit ? (\frac{f}{GHz})(\frac{\mathrm{Re}\,Z}{k?})e^{?(2?f?_{l}/c)} ? 0.49$$

Transverse

$$crit ? (\frac{\mathrm{Re}\,Z}{k?\ /\mathrm{m}})e^{?(2?f?_{l}/c)} ? 21.5$$

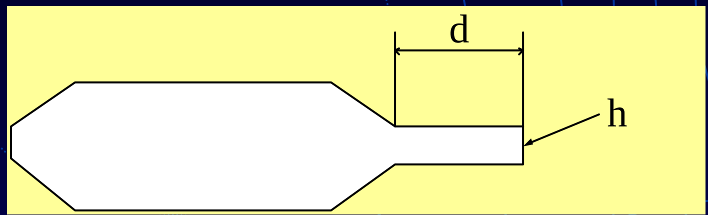
- **To control the HOM impedance below the threshold, or to import feedback system to cure the instability.**

Main Impedance generating components per ring

Components	Number of items
RF cavity	1
BPM	68
Bellows	67
flanges	200
Mask	~40
Pumping slots	~2 (DIP+LP)
Taper	8
Injection kicker	2
IR chamber	1
Feedback kicker	2
Y-shape	2
X-cross	1
Collimator	3

Simple rules for low impedance in engineering design

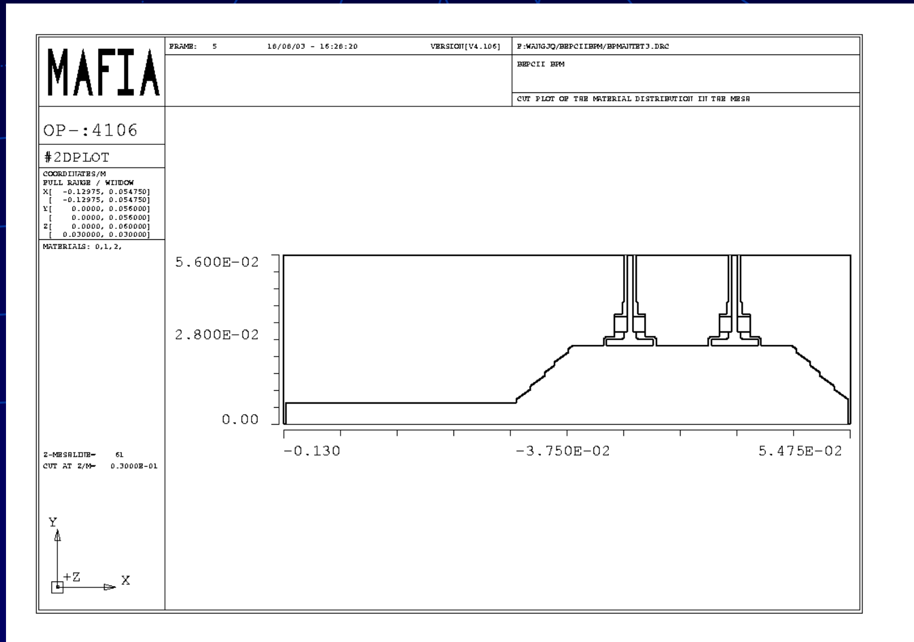
- Taper, mask: shallow slop <10?, i.e. 1:5.
- Antechamber: d>h i.e. thickness>1.5cm.



- Bellows: with RF-finger shielding
- BPM: PEPII style button (? 1.5cm, w=1mm)
- Pumping port: longitudinally narrow (w<5mm)
  slots with RF screen grid
- Avoid trapped mode: avoid recess structure

BPM

- BEPCII: Adopt the design similar to PEPII's.
  Optimize the radius of the button and the cut width to avoid the modes trapped: taking button *a*=7.5mm *w*=1mm.
- To avoid TE_{10} mode propagating to BPM, a photon stopper put near the BPM.



Simulation results

For 68 BPMs,

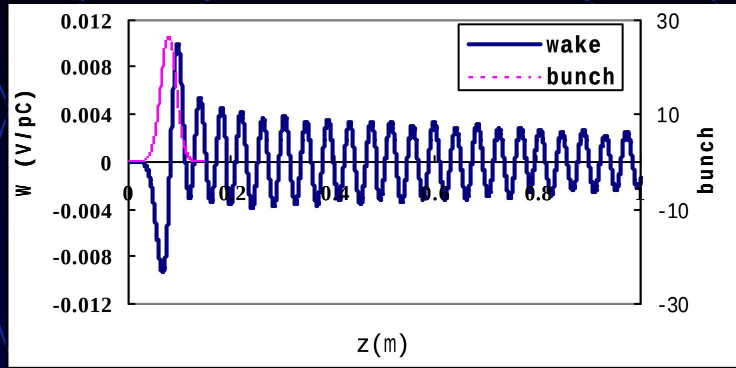
L=6.5nH, k_l=0.15V/pC

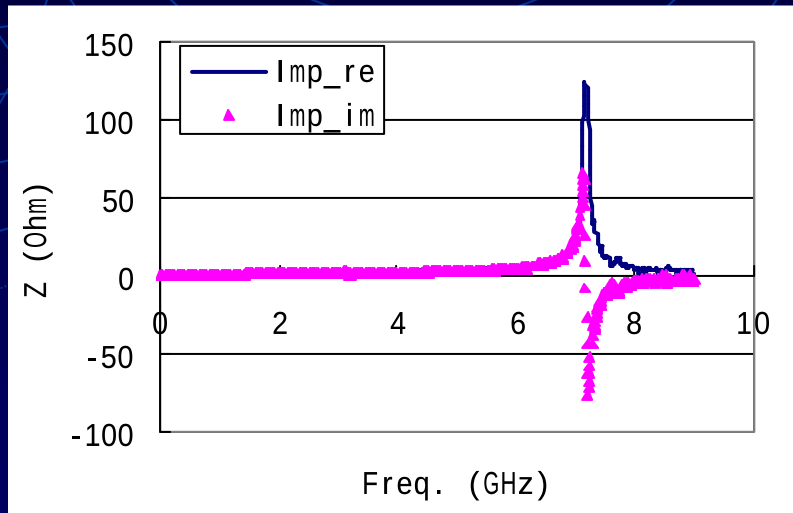
One peak at

~7.2GHz, Z=120?

For 68 BPMS, Z=8.2k ?

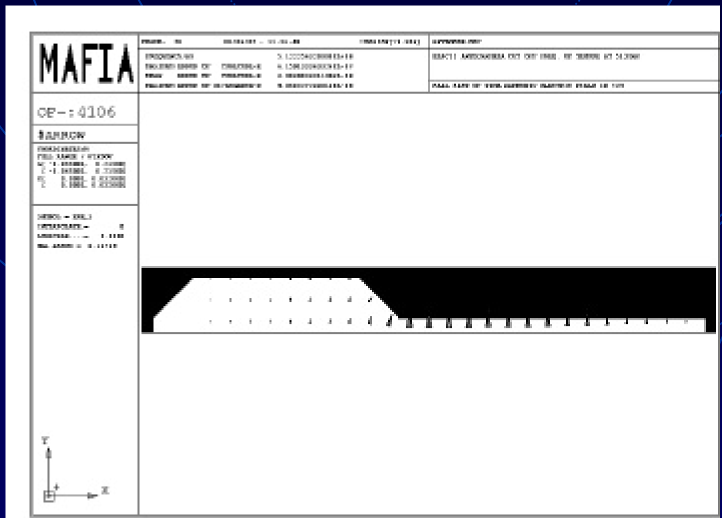
<Accepted value 11.3 k ?



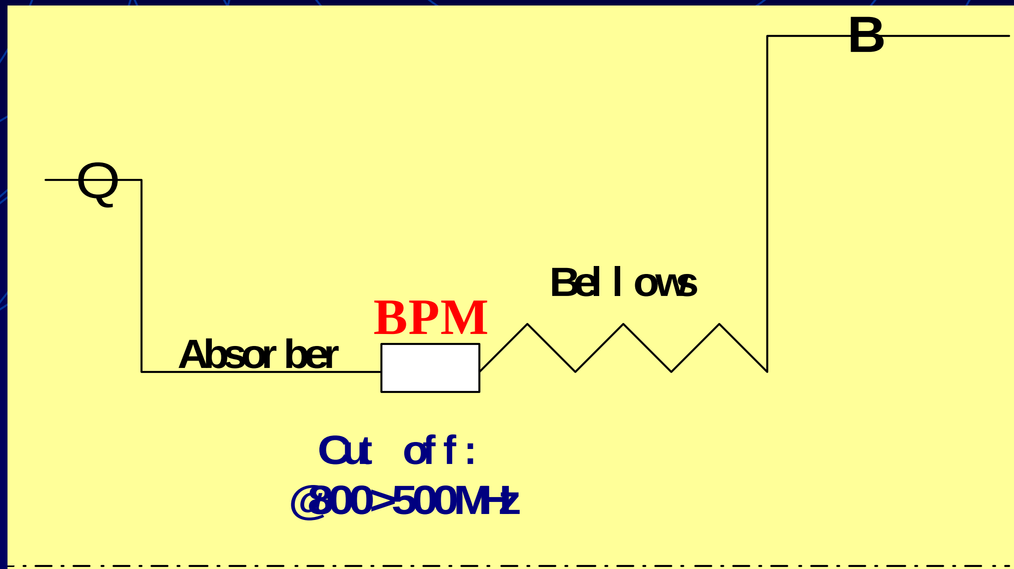


TE_{10} mode issues

To avoid TE_{10} mode, which may affect the vertical beam offset signal, BPM installed in the narrowest part, whose cut off freq. is higher than BPM processing freq. of 500MHz.



TE_{10} mode



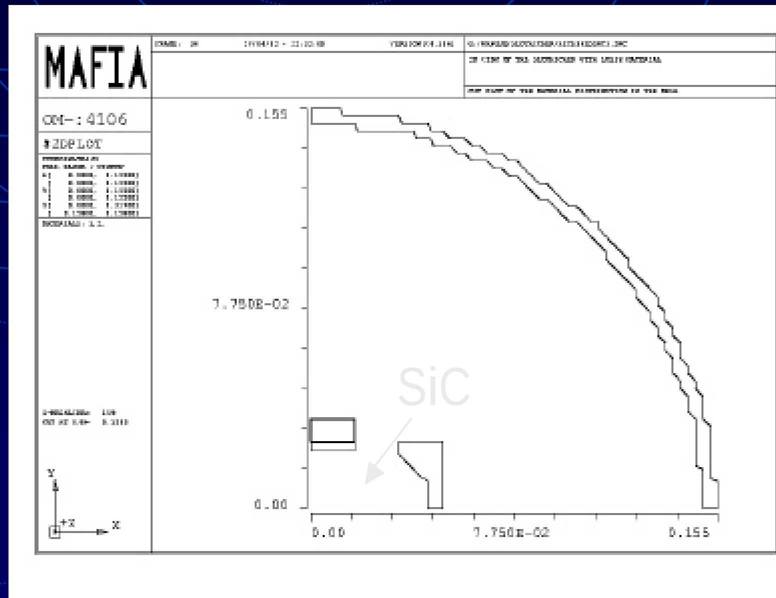
Injection kicker

Slotted-pipe kicker (DELTA, SPEARIII) is chosen

Continues image current across the top and bottom of the chamber

✍ ✍ **impedance small, k_l=0.014V/pC.**

- **HOMs possibly trapped due to the coaxial structure of the kicker chamber and the vacuum tank.**
- **Possible ways to damp HOMs:**
  - ✍ **Absorber SiC**
  - ✍ **Antenna.**



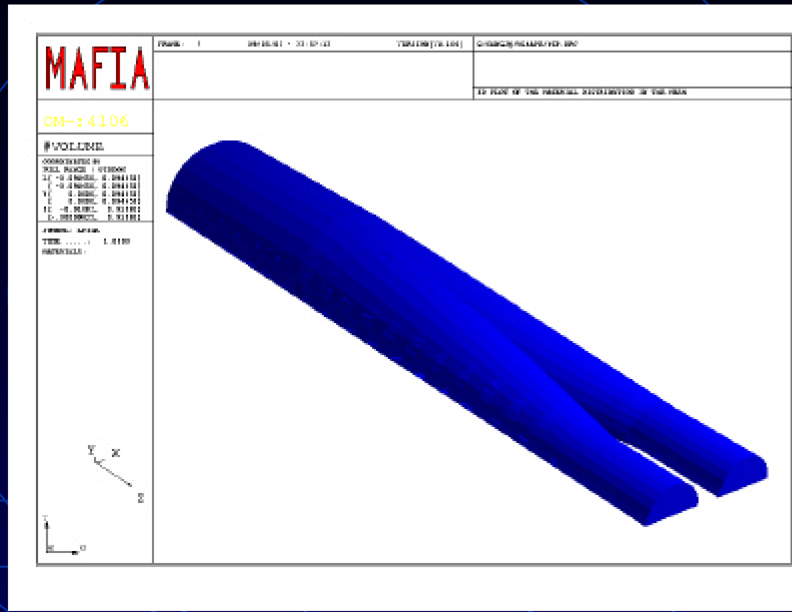
Y-Shape

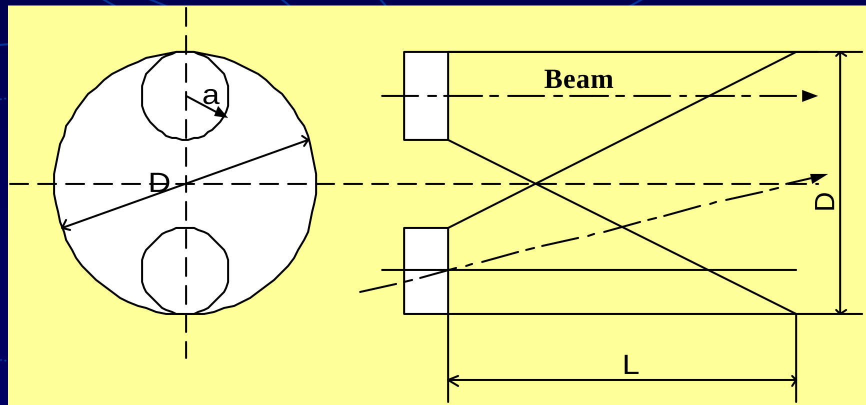
- Two Y-shapes recombine e^+ and e^- rings
- Smooth tapering structure is being studied.
- A simple mode

? 107mm=> ? 78mm

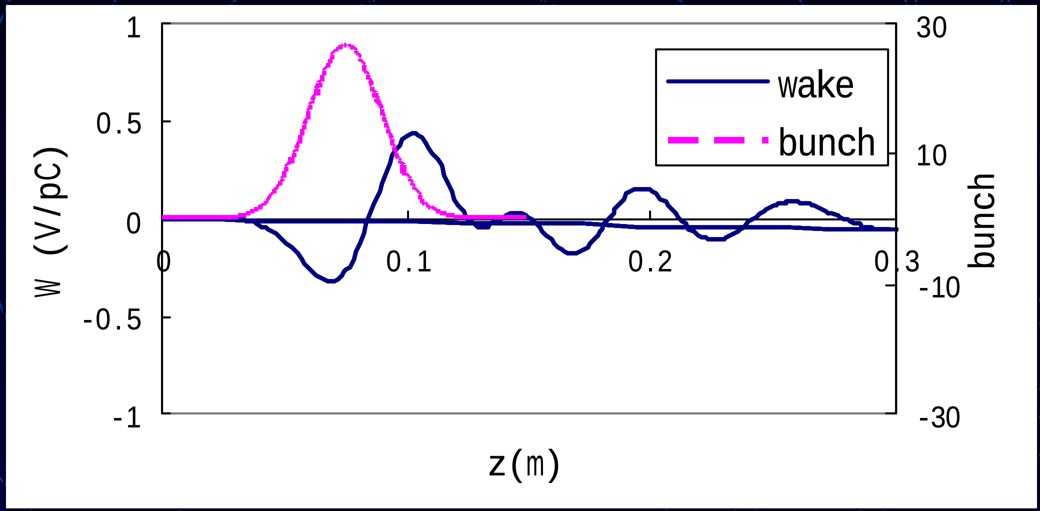
With 1:10 taper (L=0.27m)

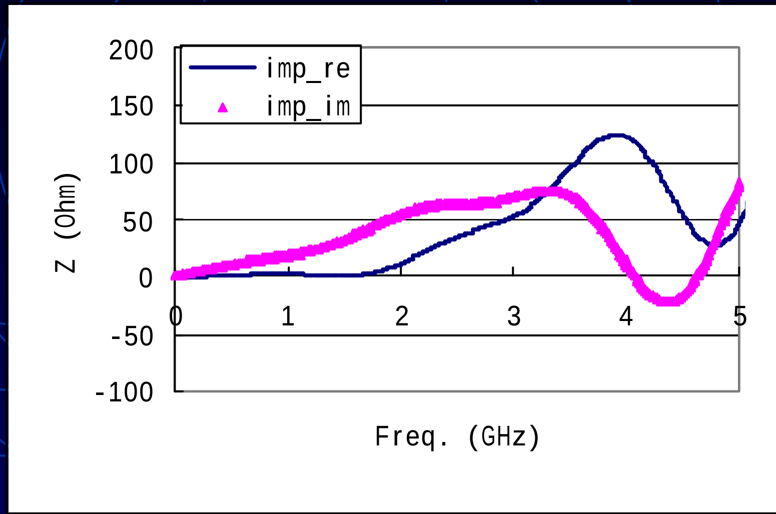
was used to estimate impedance.





Simulation results





k_l=0.095V/pC, L~ 1.1nH. P_{HOM}~ 1.4kW for 2 beams.

No trapped modes (longitudinally)

Cooling channel should be installed around the Y-chrotch

Comparison of P_{HOM} between BEPCII, KEKB and PEPII

$$P_{HOM} ? k_l (eN_b)^2 n_b f_{rev} ? k_l I_b^2 n_b / f_{rev} ? I_b^2 n_b C$$

	BEPCII	PEPII (LER)	KEKB (LER)
Ring current (mA)	910	2140 (1800)	2600 (1454)
Bunch current (mA)	9.8	1.29 (2.27)	0.52 (1.23)
Bunch length (cm)	1.5	1.0	0.4
Bunch number	93	1658 (792)	5000 (1184)
Circumference (m)	237.5	2200	3016
$I^2 n_b C$ (10^6)	2.12	6.1 (9.0)	4.1 (5.4)

BEPCII: Bunch length longer, k_l smaller, P_{HOM} smaller

The parasitic loss in BEPCII smaller compared with KEKB and PEPII ? feasible referring their experiences.

Further study on HOM heating is under way.

Resistive Wall

Aluminum: antechamber, octagon=54mm, *b*=26mm. 70% in total length,

racetrack shape , a=60mm, b=27mm , 30% in total length

1) Longitudinal impedance: Small

2) Transverse resistive wall impedance

$$Z_{?\,x} \; ? \; 0.7 ? 10^{8}(1 ? i)/\sqrt{?}$$

$$Z_{?\,y} \; ? \; 1.4 ? 10^{8}(1 ? i)/\sqrt{?}$$

Transverse impedance gives the dominant contribution to the total impedance at low frequency. Stability of beam will be studied later.

Impedance Budget of BEPCII Storage Ring

Component	Number of items	Inductance L (nH)	Loss factor k_l (V/pC)	HOM power (kW) (I_b= 9.8mA, N_b= 93)
SRF	1		~0.69	4.74
Resist. wall			0.11	0.78
BPM	68	3.3	0.08	0.57
Bellows	67	0.48	0.02	0.14
RF seals	200	3.0	0.003	0.02
Mask	40	2.8	0.06	0.42
Pumping ports		0.5		
Taper	8	4.4	0.05	0.35
Injection kicker	2	0.8	0.04	0.28
Y-shape	2	2.2	0.19	1.34
X-cross	1	0.8	0.03	0.21
IR	1	0.8	0.01	0.07
Collimator	3	3.81	0.06	0.42
Feedback kicker	2	6.0	0.44	2.82
Total		28.9	1.76	12.5

Summary of impedance study

- Total impedance: L~29nH, i.e. Z/n~0.23? . P_{HOM}~12.5 kW;
- It's possible to control the impedance under the threshold of bunch lengthening and microwave instability, provided the beam duct built smoothly. (Experiences from DA? NE, CESR, KEKB, PEPII etc.);
- R&D should be carried out for key components such as kickers, IR chamber. Work together with design engineering team to minimize the impedance;
- Bench measurement of impedance will be carried out.

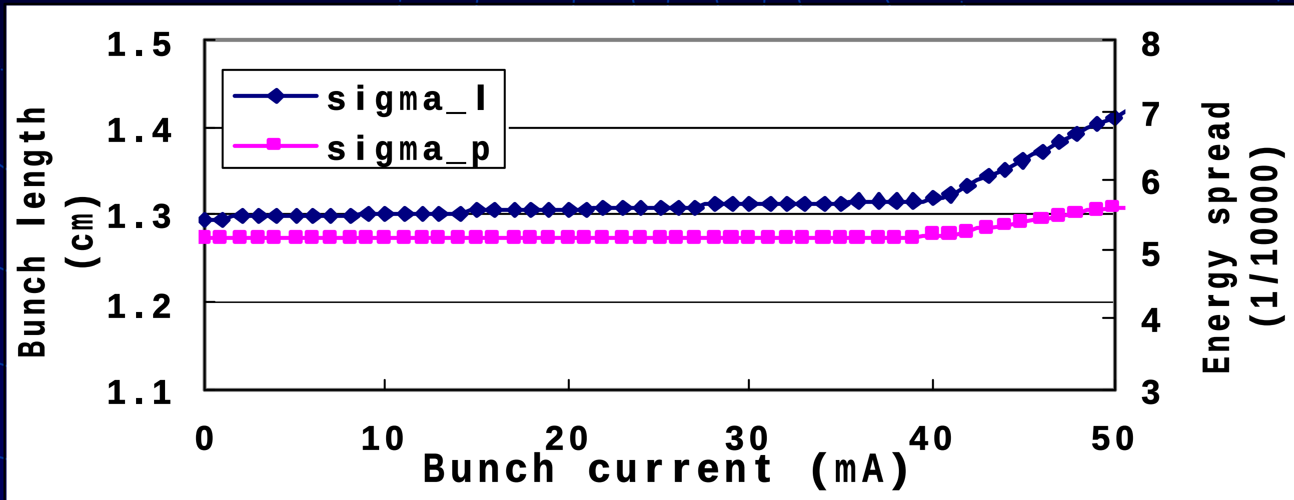
(4) Collective Effects in BEPCII

- Single Bunch Instability
- Coupled bunch Instability
- Ion effects in the Electron Ring
- Electron Cloud Instability in Positron Ring
- Beam lifetime and average luminosity

4.1 Single Bunch Collective Effects

From the broadband impedance model (e.g. Hefeits-bane model) , the effective longitudinal impedance:

$|Z_{//}/n|_{eff}$~0.24? => I_{th}~36mA Bunch lengthening ~ 5%



Bunch lengthening calculated with $|Z/n|_{eff}$

A scheme with negative momentum compaction factor to reduce bunch length is being studied.

4.2 Coupled Bunch Instability

4.2.1 Coupled Bunch Instability Due to HOM of SCC

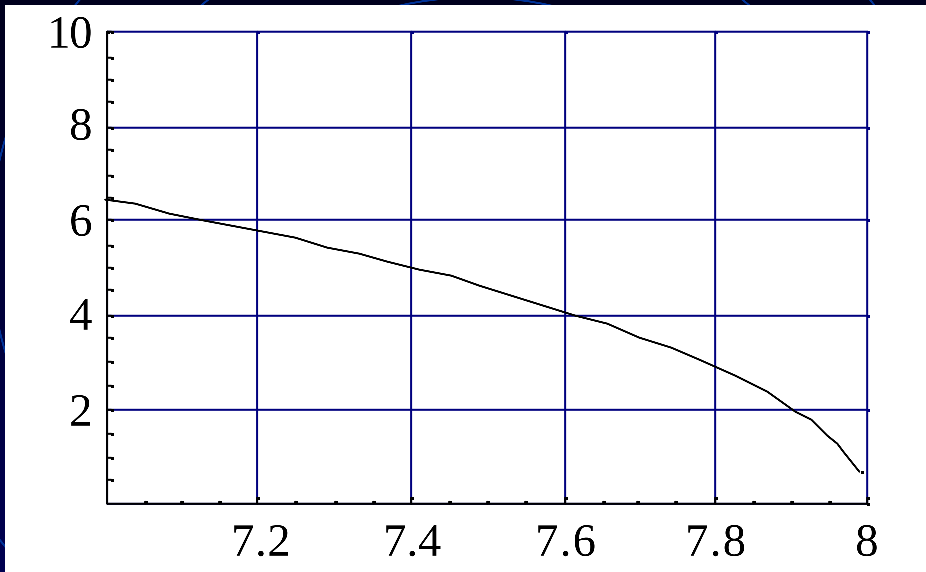
M = 99, I_b = 9.8mA, the most unstable mode

		Growth time (ms)		Growth time (ms)
Longitudinal	a = 1	$?_1$ = 12.8 $?_2$ = 13.7 $?_3$ = 13.9	a = 2	$?_1$ = 304 $?_2$ = 323 $?_3$ = 338
Transverse	a = 0	$?_1$ = 26.6 $?_2$ = 29.0 $?_3$ = 30.0	a = 1	$?_1$ = 1076 $?_2$ = 1165 $?_3$ = 1229

For 93 bunches, similar results obtained with multi-bunch simulation.

4.2.2 Resistive Wall Instability

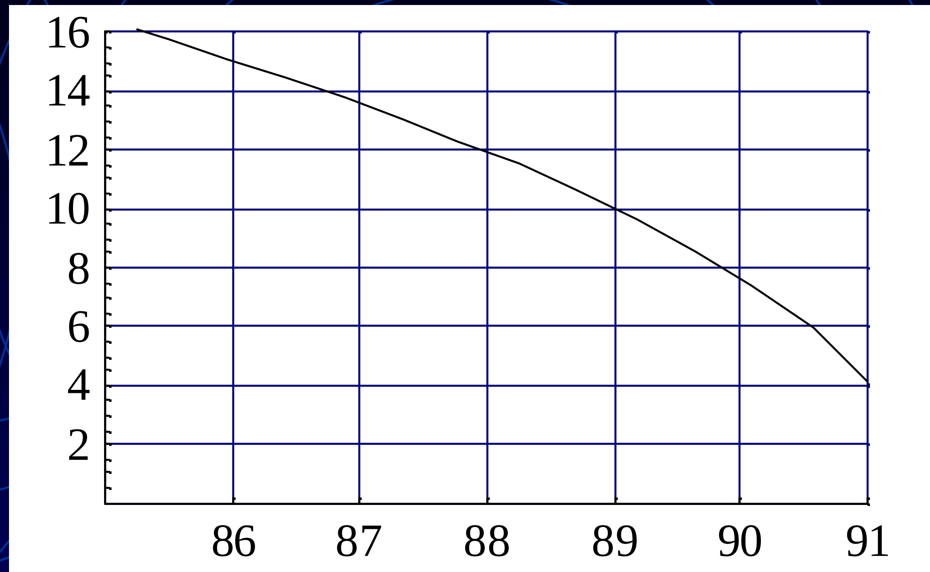
? (ms)



$?_y$

Growth time vs. transverse tune

? (ms)



mode

Growth time vs. unstable mode

- **For $?_x/?_y$ = 6.53/7.58, ?=4.3ms**
- **At $?_y$=*7.9*, the most unstable mode has growth time of 1.5ms, which require the feedback system of damping time of 1ms.**

4.2.3 Ion Effects

- **Ion trapping**

$$\left|\cos(?_i l_{train} / c) ? \frac{1}{2} ?_i T_g \sin(?_i l_{train} / c)\right| ? 1$$

Possible method to eliminate ion trapping

- **Partially filling the beam in the RF buckets.**
- **Install cleaning electrode.**

With ~6 bunches absent, the ions is not trapped. Detailed simulation is being done.

Fast Beam-Ion Instability (FBII)

Ions created during a single revolution of the beam could potential causes instability:

$$\frac{1}{?_e} ? \frac{1}{?_c} \frac{c}{2\sqrt{2} l_{train} (? \tilde{?}_i)_{rms}}$$

Growth rate:

Coherent ion freq. $\tilde{?}_i$ $=2.8?10^7\ s^{-1}$, $? \tilde{?}_i$ $=1.38?10^7\ s^{-1}$

$?_e$=3ms => FBII should be damped with feedback system.

shorter bunch trains may be helpful.

4.2.4 Electron Cloud Instability

Rough estimation of ECI

1) Coupled Bunch Instability

With the saturated EC density:

$$?_{e,CB} \; ? \; \frac{?? \, _{?} h_x h_y L_{sep}}{2 r_e N_b c^2}$$

2) Single Bunch Instability

$$?_{e,thr} \; ? \; \frac{2?? \, _s}{?? \, _y r_e C}$$

? $= N_b r_e |W_y| ß\ _y / 16?\ Q_s$, ? > 1 **unstable.**

ECI Parameters of a few Storage rings

	BEPCII	KEKB	PEPII
Beam energy(GeV)	1.89	3.5	3.1
Bunch population $N_b(10^{10})$	4.84	3.3	9
Bunch spacing L_{sep}(m)	2.4	2.4	2.5
Rms bunch length $?_z$(m)	0.015	0.004	0.013
Rms bunch sizes $?_{x,y}$(mm)	1.18,0.15	0.42,0.06	1.4,0.2
Chamber half dimensions $h_{x,y}$(mm)	60,27	47	45, 25
Slippage factor ? (10^{-3})	22	0.18	1.3
Synchrotron tune Q_s	0.033	0.015	0.03
Circumference C(km)	0.24	3.0	2.2
Average beta function(m)	10	15	18
$?_{CB}$ (ms)	**0.03**	**0.06**	**0.01**
TMCI threshold $?_e[10^{12}m^{-3}]$	**22.7**	**0.5**	**1**

- $?_{e,CB}$: the same level as B-factories.
  - Similar specification on feedback to cure the CB.
- EC density threshold higher than B-factories
  - TMCI in BEPCII due to EC may not be stronger.

To control ECI

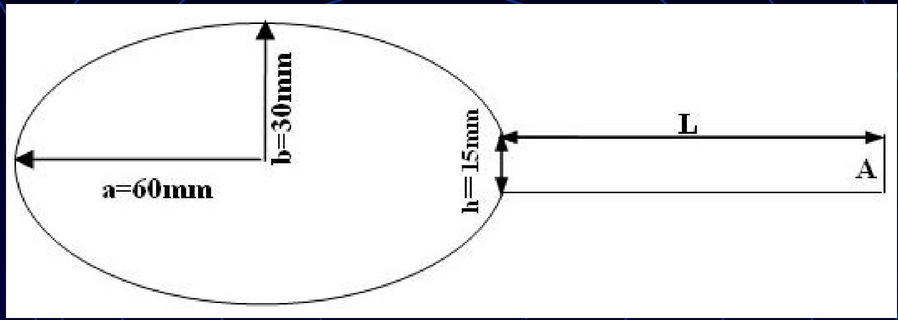
To guarantee the beam performance against ECI, precaution methods successfully adopted in PEPII and KEKB is considered in BEPCII design.

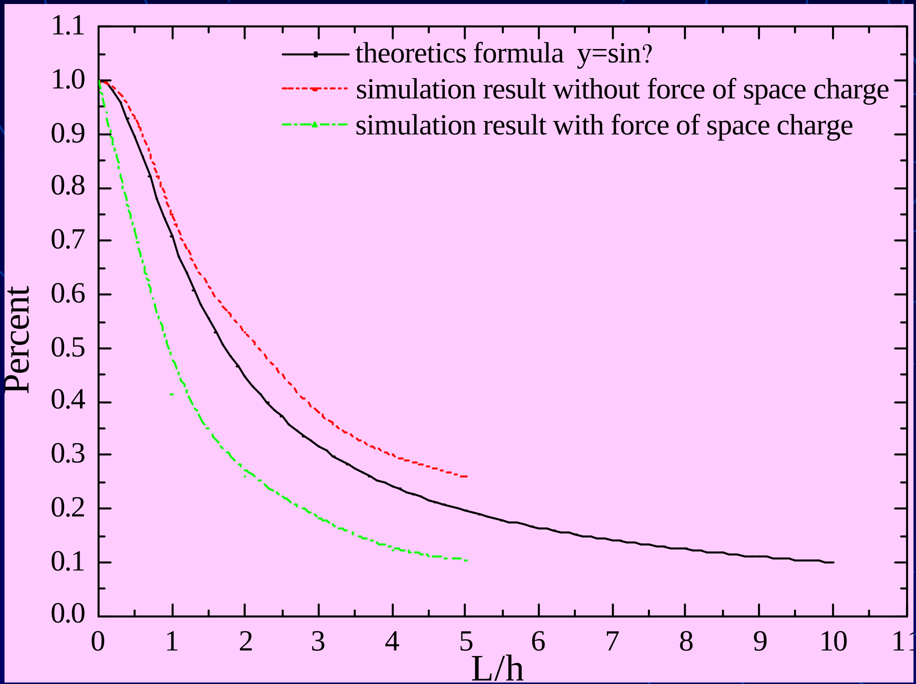
- Antechamber
- TiN coating of the inner surface
- Solenoid winding (as backup)
- Clearing electrode (R&D)

  - Simulation study being done

Consideration on the antechamber geometry

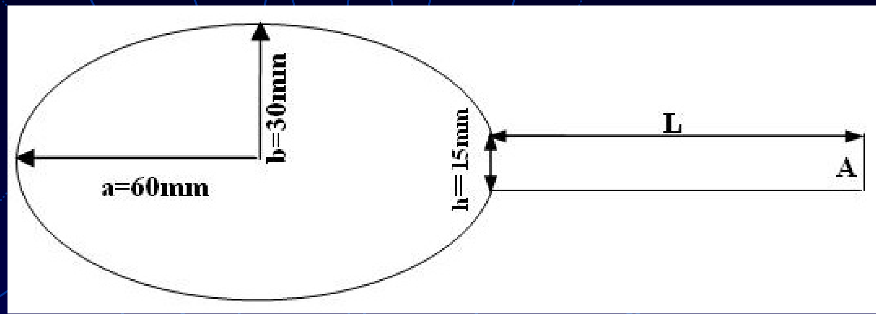
1) h=15mm, 99.5% out
2) L>5* h, <10% PE drift into beam duct

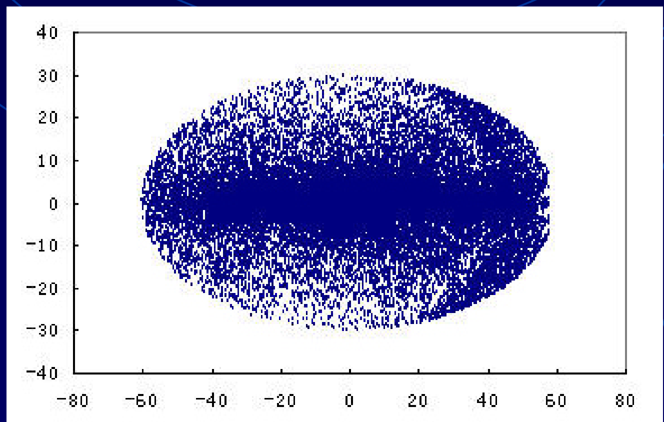


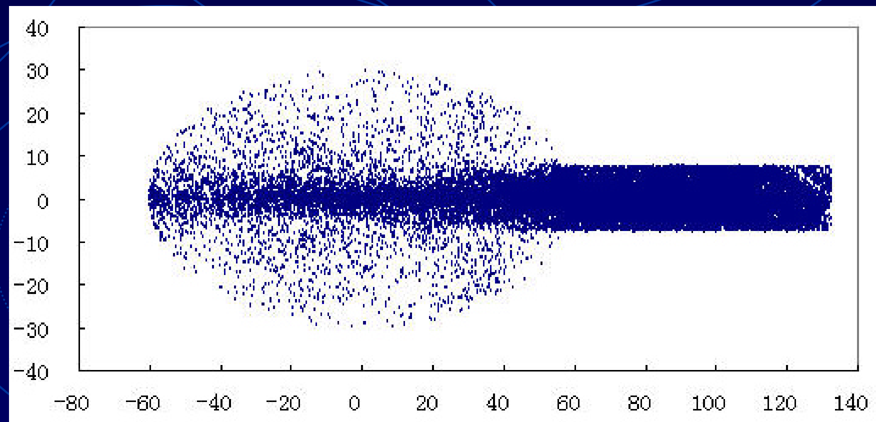


3) Photon absorber in the antechamber:
>5*h from beam duct
Photon reflection rate reduced: <1/10
PEY reduced ~1/5

A code has been developed (Y. Liu) to study the effect of antechamber against ECI, based on Ohmi's model

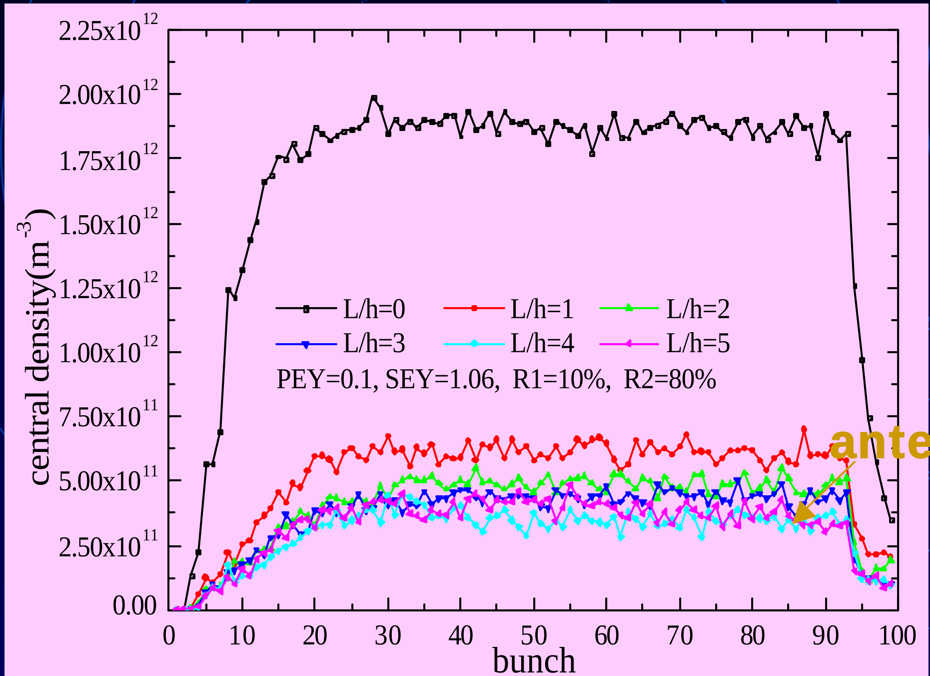




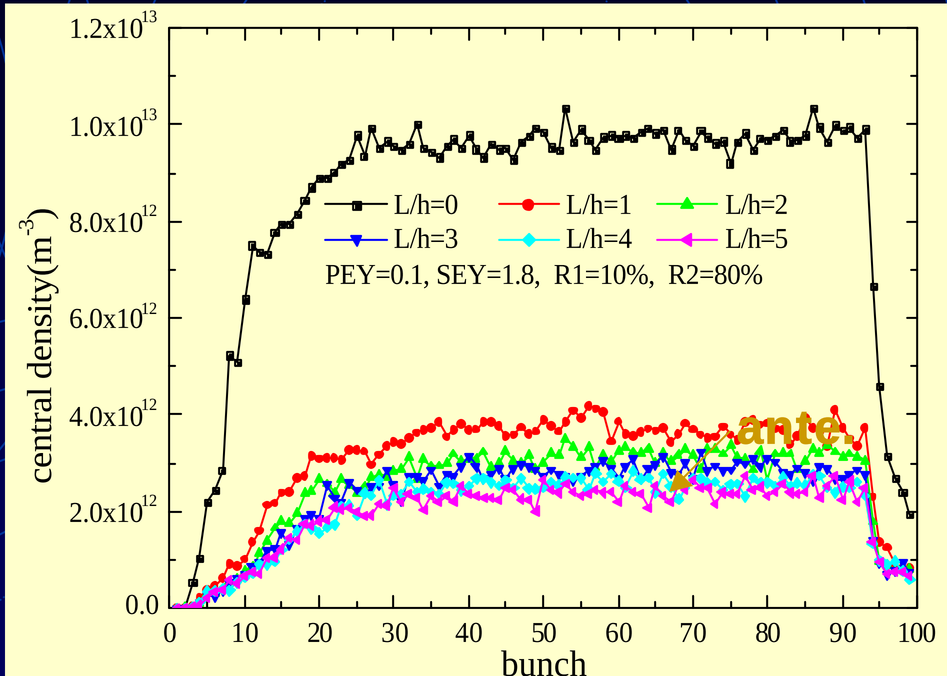


Comparison of EC w/o antechamber and TiN

With TiN

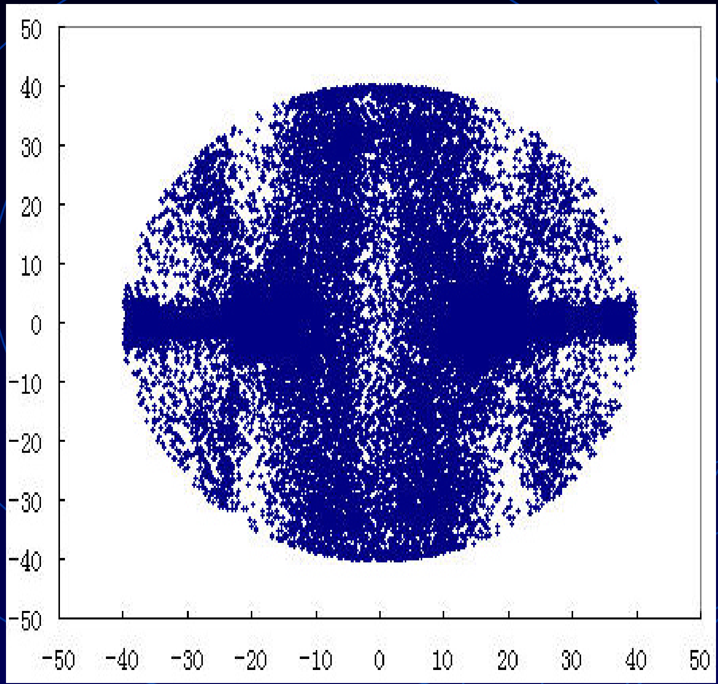


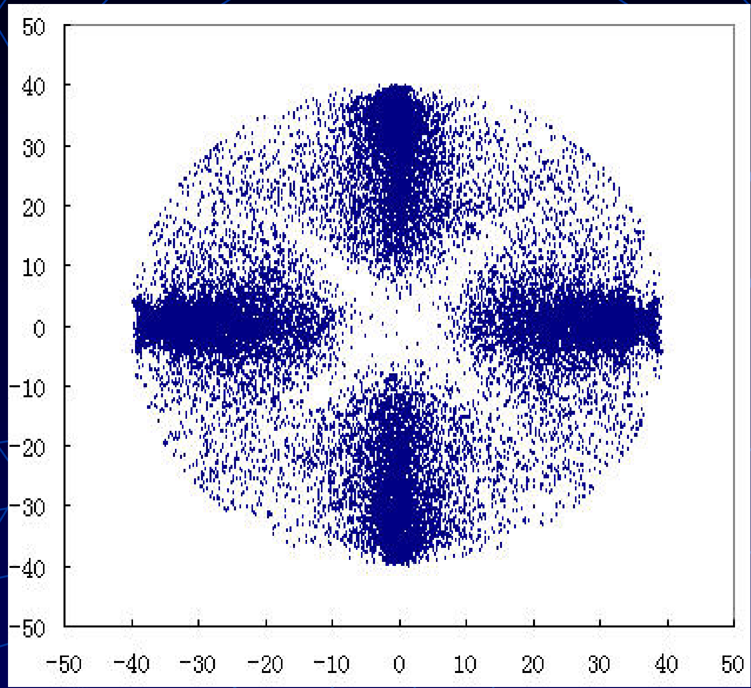
Without TiN



- With antechamber, EC density about 5 times lower;
- With TiN, EC density 5 times lower.

EC in magnetic fields





- EC density at the beam pipe center significantly reduced in B,Q,S magnet field;
- Advantages in BEPCII: more than ½ space in arc occupied by magnets.

Summary of the simulations on ECI

method	PEY	SEY	EC ? (m^{-3})	? (ms)	?
No ante.	0.1	1.8	6.2? 10^{13}	0.003	2.89
With ante.	0.001	1.8	3.1? 10^{12}	0.040	0.17
TiN only	0.1	1.066	1.7? 10^{13}	0.020	0.81
ante+TiN	0.001	1.066	3.5? 10^{11}	0.530	0.015
Ante+TiN+ Clear.	0.001	1.066	1.2? 10^{11}	1.400	0.0058

With antechamber+TiN: Coupled bunch inst. damped by feedback, no TMCI instability occurs

Summary of growth time of coupled bunch instabilities

	HOM	Resistive	FBII	ECI
Tran. (ms)	26.6	4.3	3	0.5
Long. (ms)	12.8			

- Transverse instability much faster than SR Damping: feedback system required
- Longitudinal instability same level as SR Damping: feedback system as a backup
- For SR mode, bunch current and total beam current lower, instabilities weaker than colliding mode.

2.3.5 Beam Lifetime

Beam loss mechanism: 1) beam-beam bremsstrahlung,
2) beam-gas scattering,
3) Touschek effect.

	Beam-gas	Touschek	Beam-beam	Total
Lifetime	26 hrs	7.1 hrs	5.1 hrs	3.0hrs

P= 8? 10^{-9} torr with 80% H_2 and 20% CO,
V_{rf}=1.5MV, Energy acceptance =0.7%

Average luminosity

- The luminosity lifetime is half of the beam lifetime.

  $?_L$ =1.5 hours.

- The average luminosity is

$$\langle L \rangle ? \frac{?_0^{t_c} L(t)dt}{t_c ? t_f} ? L_0 ?_L \frac{1 ? e^{?t_c/?_L}}{t_c ? t_f}$$

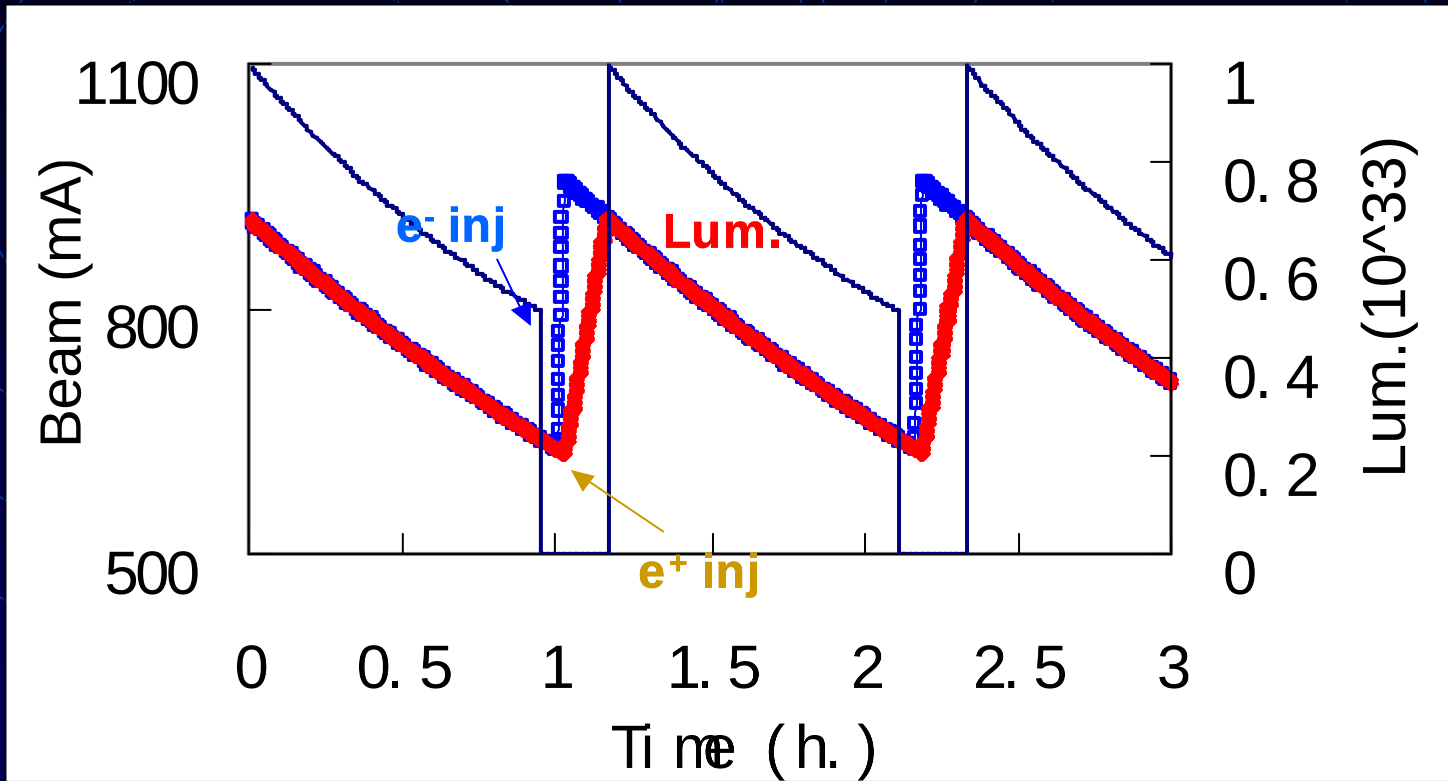
t_f — refilling time (injection time+mode switch)

t_c — collision time, or time for physics

L_0 — peak luminosity

Top-off injection

t_f ? 0.2 hours, t_c = 1.0 hours $<L>_{max}=6.0\times10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$



Operation chart

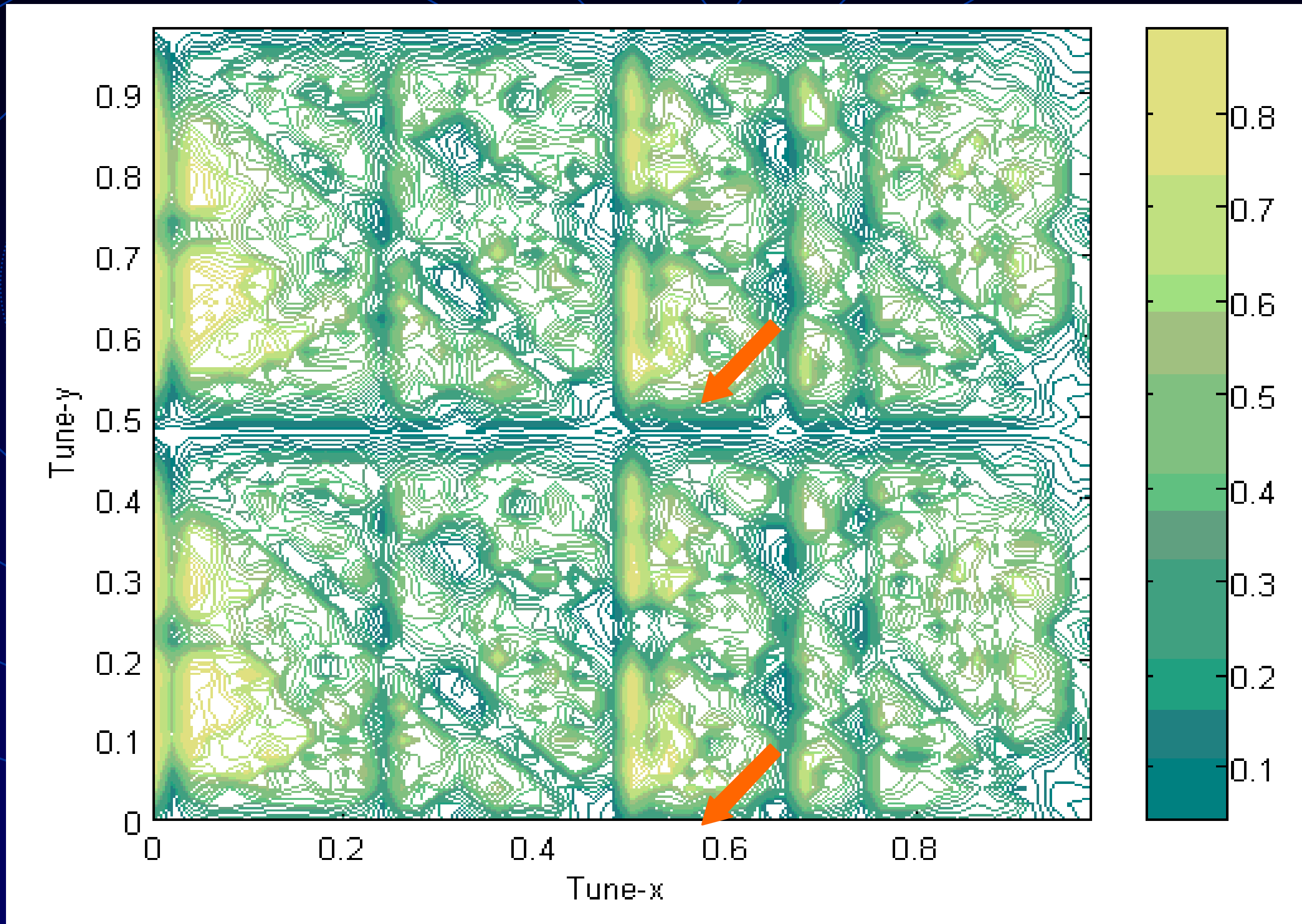
Summary of single beam effects

- With the present impedance budget, $?_l$ <1.5cm.
- Coupled bunch instabilities due to HOMs and resistive wall can be damped with the feedback system.
- Gap is needed to avoid ion trapping, FBII in e-ring should be damped with feedback system.
- For ECI in e+ ring, antechamber (TiN coated) is adopted to reduce EC. R&D on other methods (solenoid, clearing electrode) is under way.
- Normal beam lifetime is about 3.1 hours. With top-off injection the average luminosity > $6.0\times10^{32}cm^{-2}s^{-1}$.

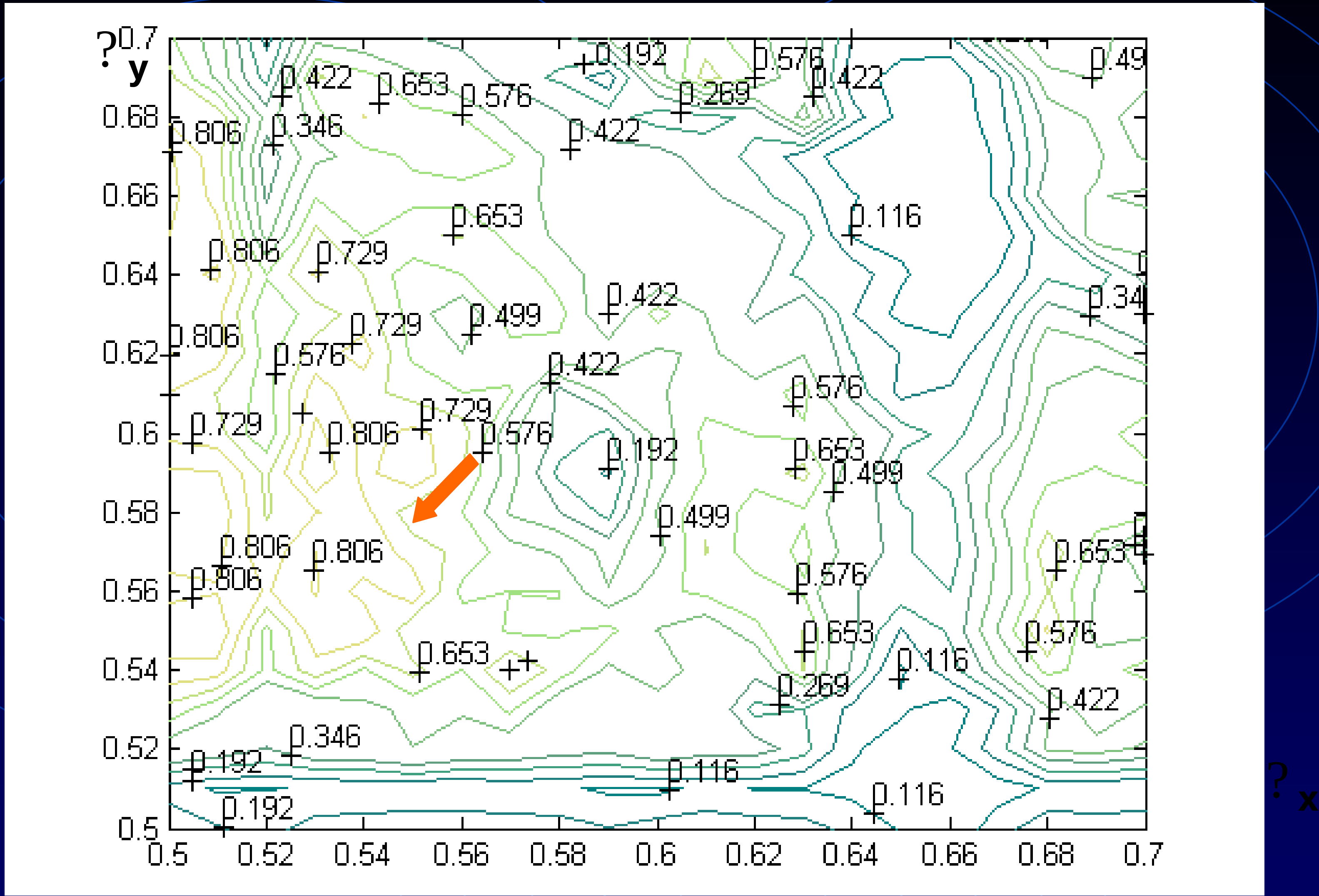
(5) Beam-Beam Interaction

- Using code BBC (Beam-Beam interaction with a Crossing angle) developed by K.Hirata.
- BBC is a weak strong simulation code in 6-dimensional phase space including the effect of crossing angle.
- The effect of a finite bunch length was taken into account by dividing a strong bunch into 5 slices longitudinally.
- The weak bunch is represented by 50 randomly generated macro particles, with Gaussian distribution in 6-dimensional phase space.
- The simulation was done for more than 5 radiation times.

Beam-beam tune scan

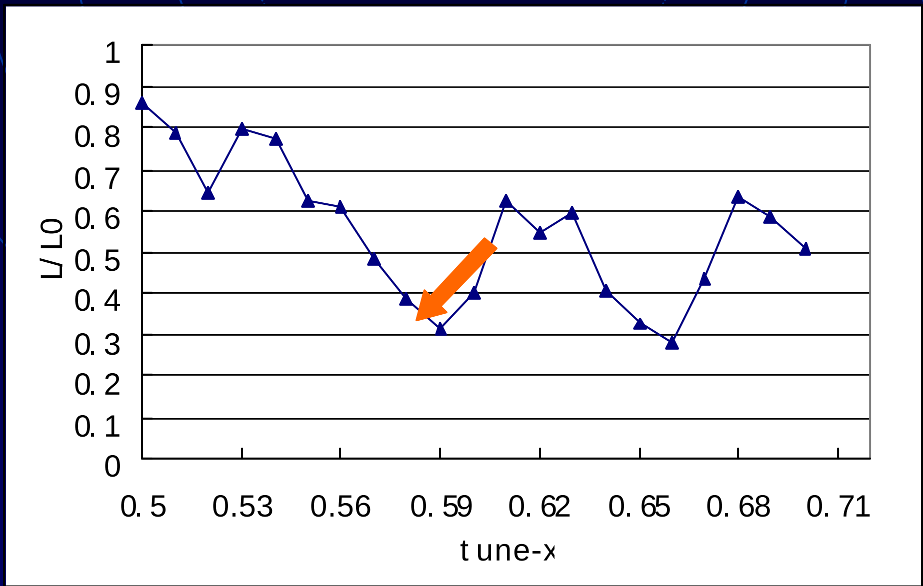


Luminosity survey with a crossing angle of $?_c$=11mrad☞2

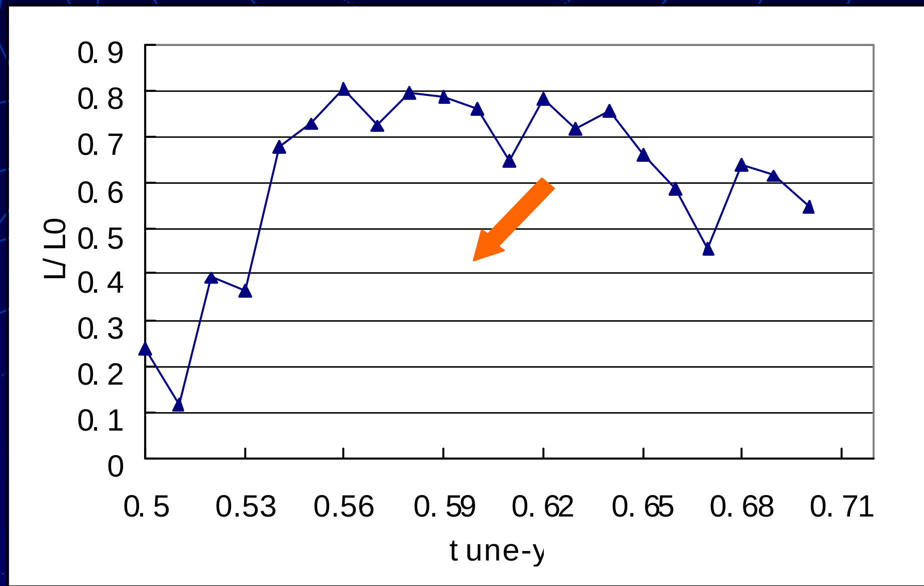


Luminosity survey with a crossing angle of ?$_c$=11mrad☞2

The high luminosity region is around ? $_x$= 0.53 , ?$_y$= 0.58. These tune values are chosen as designed working points. The crossing angle of *11 mrad* induces some reduction of the luminosity, as well as the region of the high luminosity.

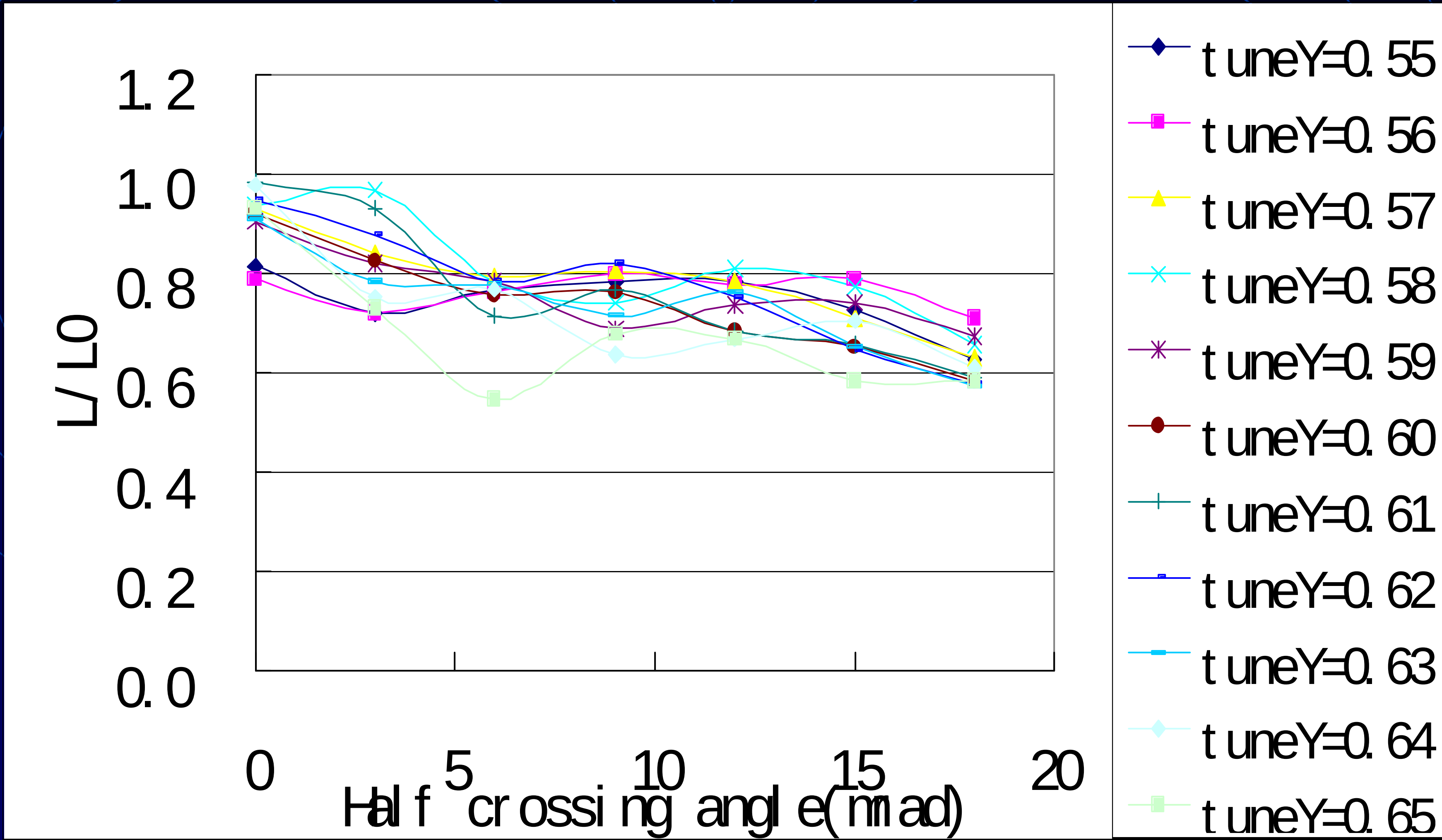


?$_y$=0.58

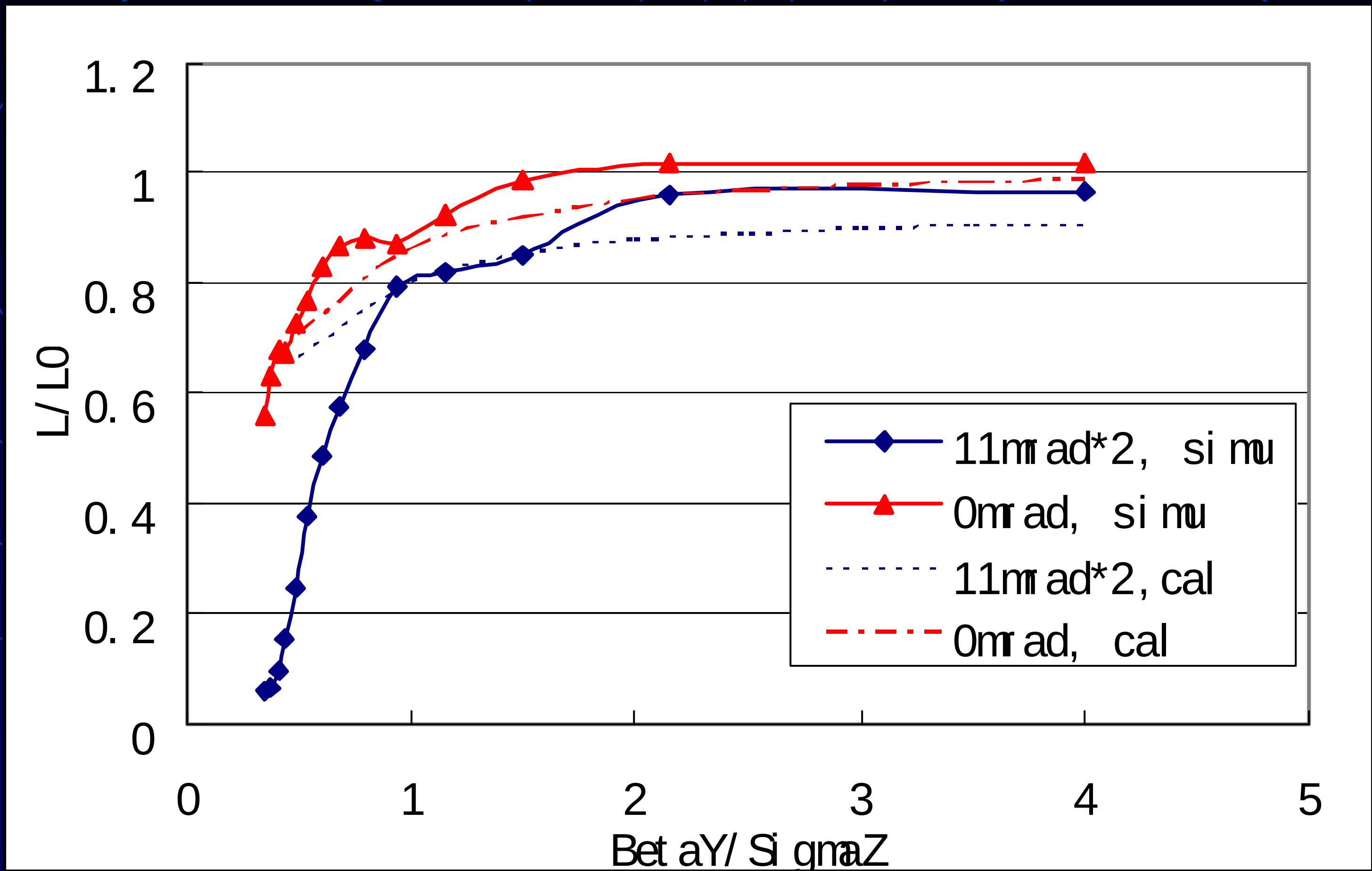


?$_x$=0.53

Crossing angle effect



Finite bunch length effects (L vs. β_y^*/σ_z)



Summary of beam-beam effects

- To choose the horizontal tune close (above) to half integer is a good choice to get the higher luminosity;
- The luminosity reduction factor due to hour glass effects and crossing angle is about 80%;
- The designed value of ?y=0.04 is reasonable and reachable for $?_c$=11mrad☞2;
- Some further simulation should be done, including the coherent beam beam effects by strong-strong simulations.

(5) Summary

- Lattice and dynamics: optimized;
- Coupling impedance: investigated;
- Single beam effects: studied;
- Beam-Beam interaction: simulated;
- Design goal: feasible;
- Further study: needed!

Thank You for Attention