Beam Dynamics Studies in the BEPCII Storage Rings

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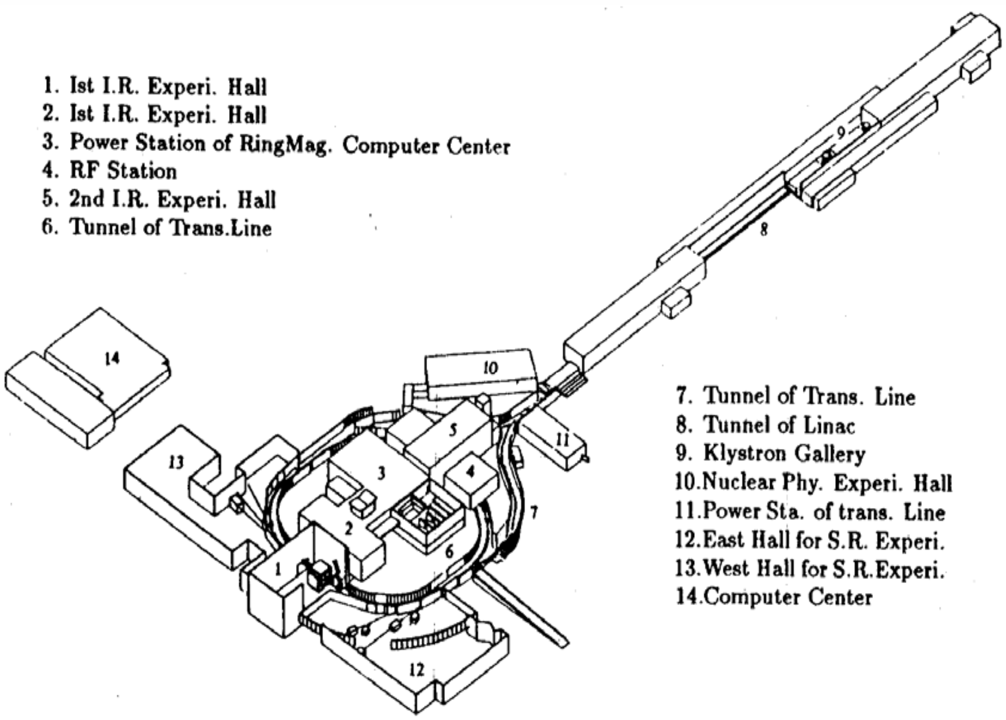
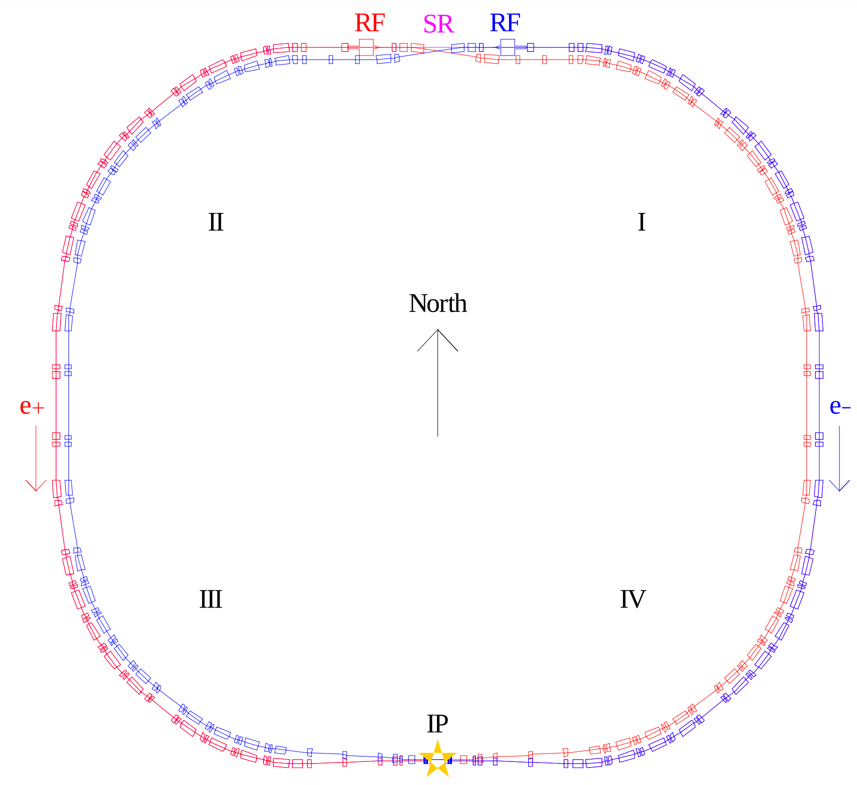
- Determination of beam parameters
- Single beam dynamics
- Beam instabilities
- Summary

1. Introduction

- BEPCII — An upgrade project of the BEPC
  - — A two-ring factory like machine
  - — Provide beam to HEP & SR





Goals of the BEPCII

Collision Mode

- **Beam energy range** — 1-2.1 GeV
- **Optimized beam energy** — 1.89 GeV
- **Luminosity** — 1×10^{33} cm^{-2}s^{-1} @1.89 GeV
- **Full energy injection** — 1-1.89 GeV

SR Mode

- **Beam energy** — 2.5 GeV
- **Beam current** — 250 mA
- **Keep the present beam lines useable**

Design Parameters of Ring (Col. Mode)

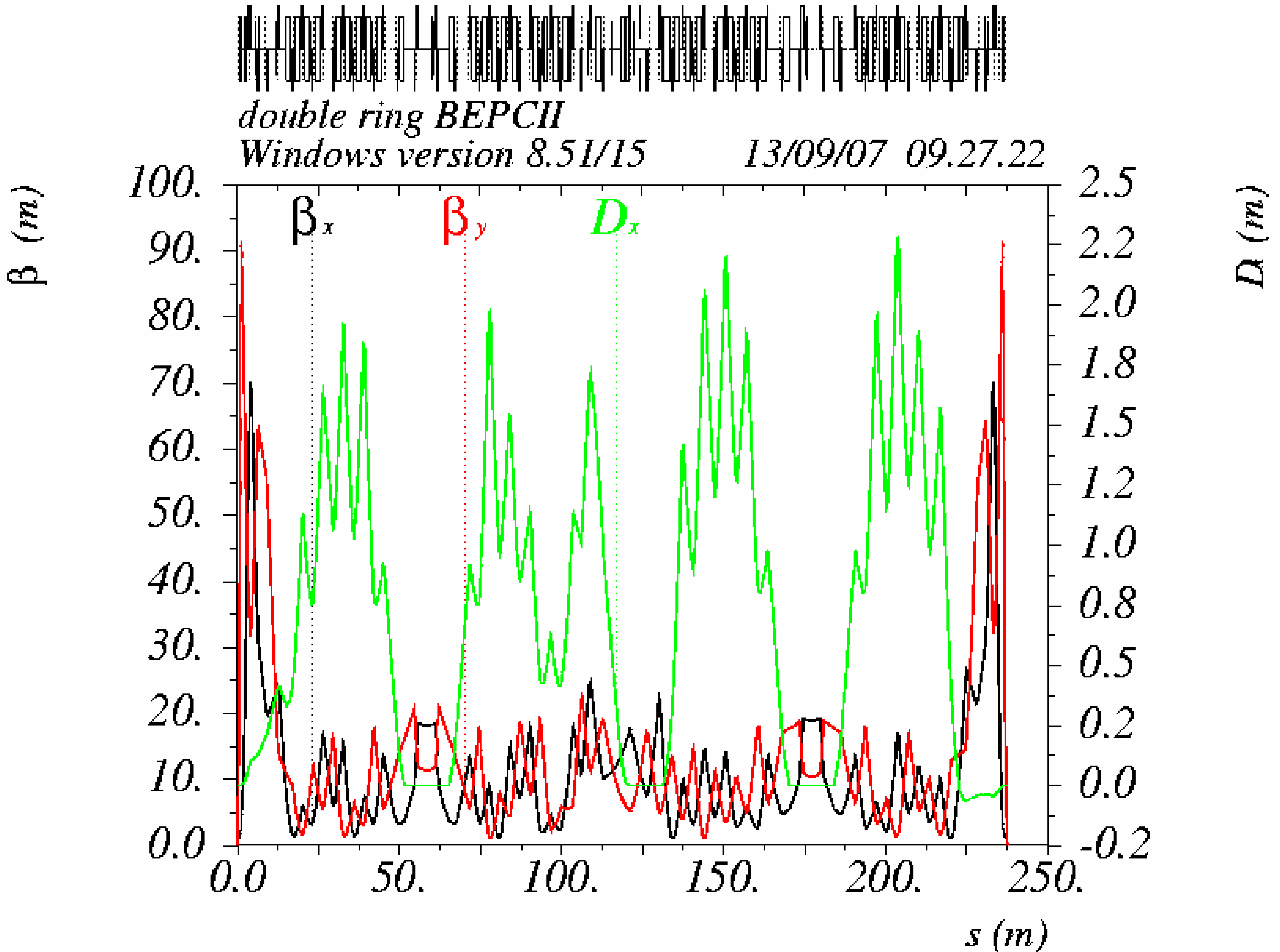
Energy	GeV	1.89
Circumference	m	237.53
Beam current	A	0.91
Bunch number		93
Bunch current	mA	9.8
Bunch spacing	m	2.4
Bunch length	cm	1.5
RF frequency	MHz	499.80
Harmonic number		396
Emittance (x/y)	nm·rad	144/2.2
β function at IP (x/y)	m	1.0/0.015
Crossing angle	mrad	±11
Design luminosity	$cm^{-2}s^{-1}$	1×10^{33}

Design Parameters of Ring (SR Mode)

Energy	GeV	2.5
Circumference	m	241.13
Beam Current	mA	250
Natural emittance	nm·rad	120
RF frequency	MHz	499.80
Harmonic number		402
RF Voltage	MV	3.0
Energy loss per turn	keV	335
SR Power	kW	84
Natural bunch length	cm	1.2
Momentum compact factor		0.016
Tune (x/y/z)		7.28/5.18/0.036
SR Damping time (x/y/z)	ms	12/12/6

Parameters of on-line lattice

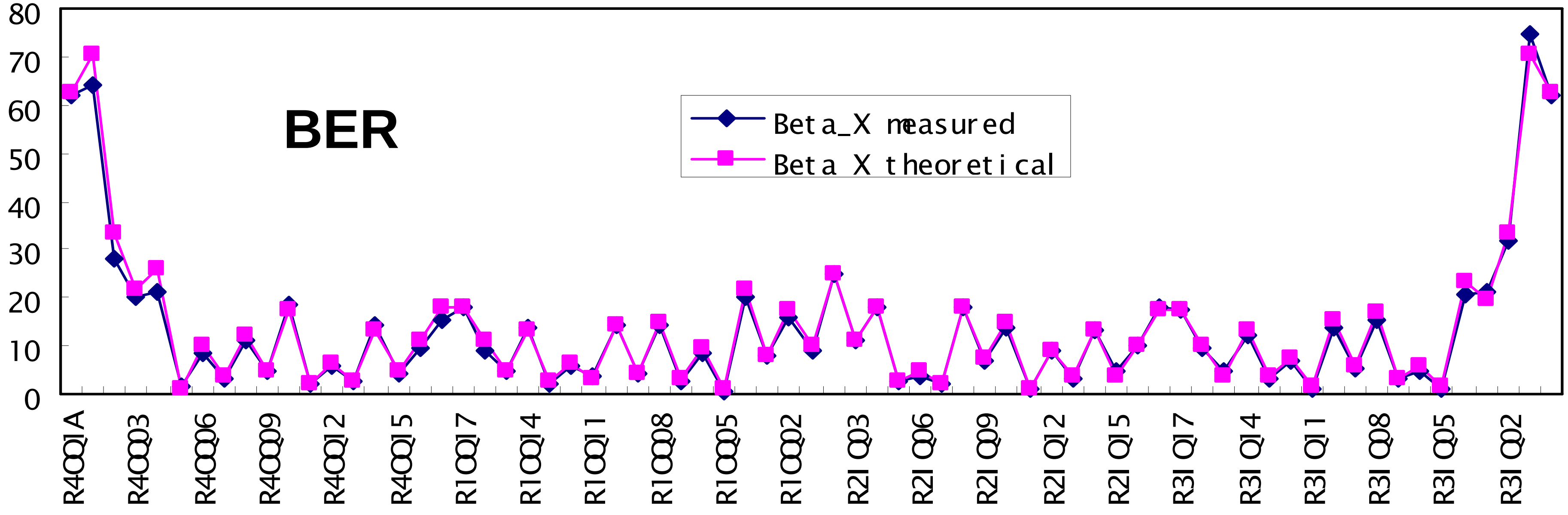
Circumference（m）	237.53
Beam energy（GeV）	1.89
RF voltage（MV）	1.5
Tune（x/y/s）	6.54/5.59/0.035
Momentum compaction factor	0.0237
Nature chromaticity（x/y）	–10.8/–20.8
Nature horizontal emittance（nm·rad）	132
Nature energy spread	5.16×10^{-4}
Nature bunch length（cm）	1.36
$\beta_{x,y}$ @ IP（m）(x/y)	1/0.015
$\beta_{x,y,\ max}$ @ IR（m）(x/y)	70.2/91.4
$\beta_{x,y,\ max}$ @ arc（m）(x/y)	24.2/23.5
$D_{x,max}$（m）	2.28

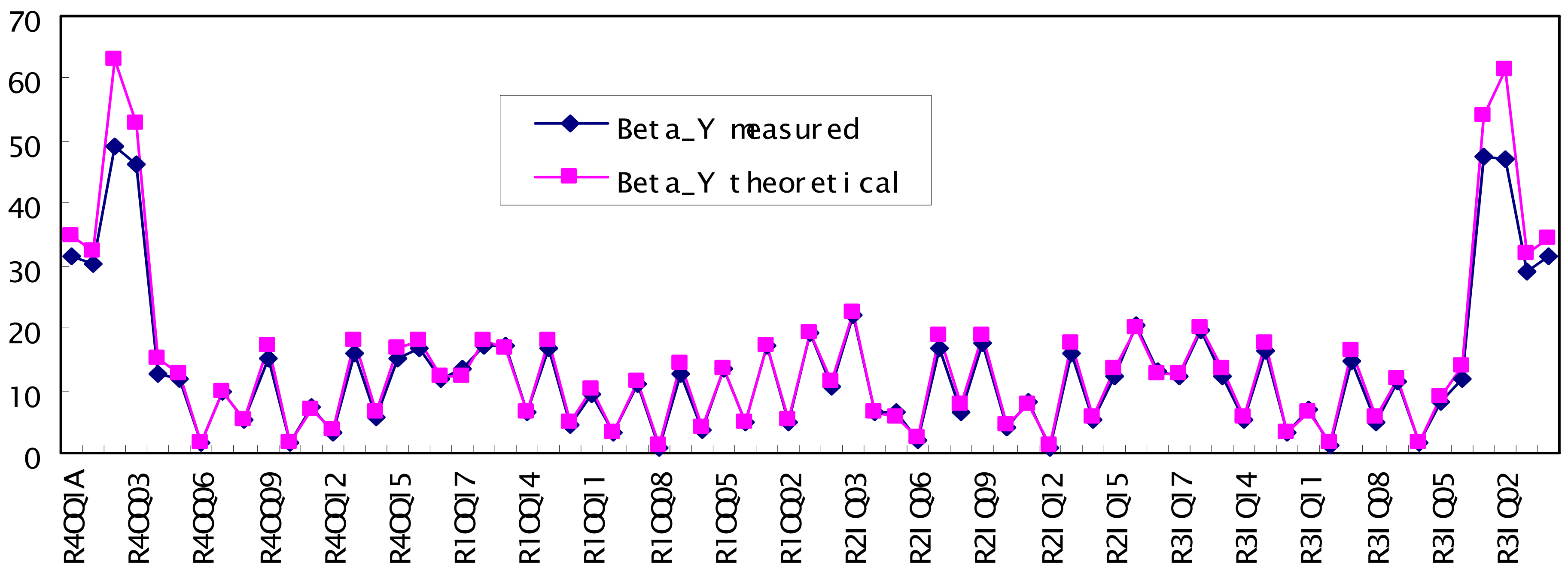


double ring BEPCII
Windows version 8.51/15
13/09/07 09.27.22
β (m)
D (m)
βx
βy
Dx
s (m)
100.
90.
80.
70.
60.
50.
40.
30.
20.
10.
0.0
2.5
2.2
2.0
1.8
1.5
1.2
1.0
0.8
0.5
0.2
0.0
-0.2
0.0
50.
100.
150.
200.
250.

2. Determination of beam parameters

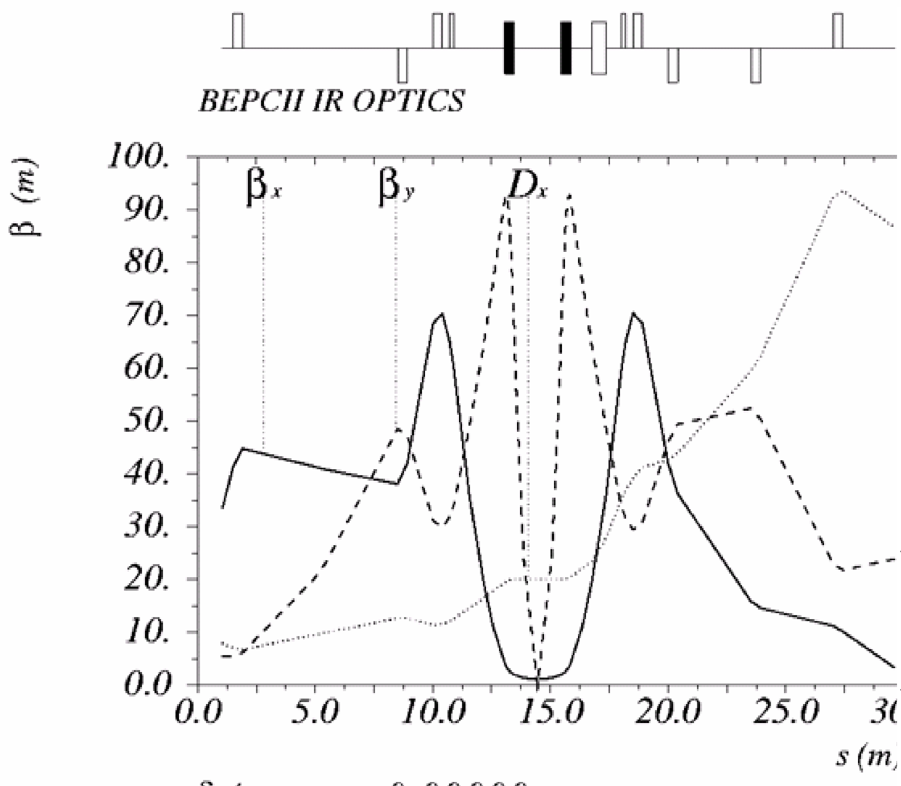
- β functions and transverse tunes
  - Optics correction with LOCO, based on the measured response matrix.
  - COD correction with response matrix.
  - Measured with the method of tune modulation. (β in arcs and β* at the IP)

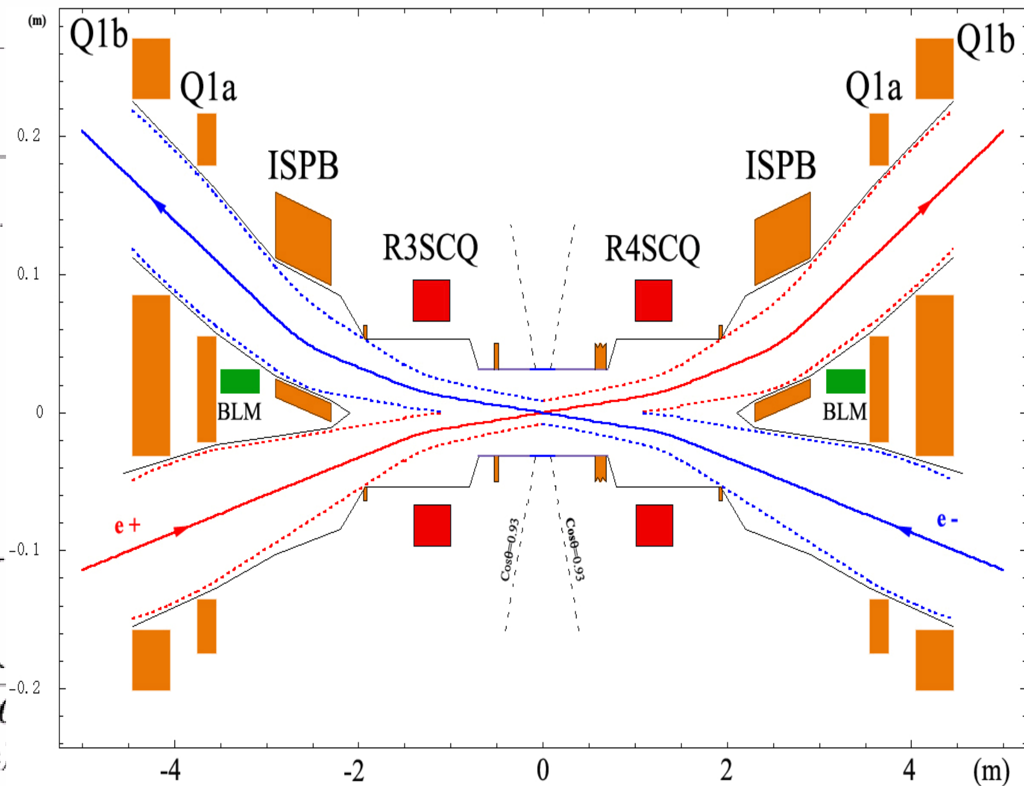

BER
Beta_X measured
Beta_X theoretical
80
70
60
50
40
30
20
10
0
R4OQ1A
R4OQ03
R4OQ06
R4OQ09
R4OQ12
R4OQ15
R1OQ17
R1OQ14
R1OQ11
R1OQ08
R1OQ05
R1OQ02
R2IQ03
R2IQ06
R2IQ09
R2IQ12
R2IQ15
R3IQ17
R3IQ14
R3IQ11
R3IQ08
R3IQ05
R3IQ02


Beta_Y measured
Beta_Y theoretical
70
60
50
40
30
20
10
0
R4OQ1A
R4OQ03
R4OQ06
R4OQ09
R4OQ12
R4OQ15
R1OQ17
R1OQ14
R1OQ11
R1OQ08
R1OQ05
R1OQ02
R2IQ03
R2IQ06
R2IQ09
R2IQ12
R2IQ15
R3IQ17
R3IQ14
R3IQ11
R3IQ08
R3IQ05
R3IQ02

β functions at the IP

- Thick lens model
- Tune modulation method
- Horizontal bending effect of the SCQ near the IP included





- Formulae

$$\bar{\beta}_y = \pm\frac{2}{\Delta kl}\left[\cot(2\pi Q_y)(1-\cos(2\pi\Delta Q_y)) + \sin(2\pi\Delta Q_y)\right]$$

$$\bar{\beta}_x = \pm\frac{2}{\left(\Delta kl + \frac{\theta}{\rho}\right)}\left[\cot(2\pi Q_x)(1-\cos(2\pi\Delta Q_x)) + \sin(2\pi\Delta Q_x)\right]$$

$$\bar{\beta}_y = \left\{\frac{L_0\sin^2(k_0 l)}{k_0^2 l} + \frac{k_0 l - \sin(k_0 l)\cos(k_0 l)}{2k_0^3 l} + \frac{L_0^2[k_0 l + \sin(k_0 l)\cos(k_0 l)]}{2k_0 l}\right\}\cdot\frac{1}{\beta_y^*}$$

$$+\frac{k_0 l + \sin(k_0 l)\cos(k_0 l)}{2k_0 l}\cdot\beta_y^*$$

$$= C_1\cdot\frac{1}{\beta_y^*} + C_2\cdot\beta_y^*$$

$$\bar{\beta}_x = \left\{\frac{L_0\sinh^2(k_0 l)}{k_0^2 l} - \frac{k_0 l - \sinh(k_0 l)\cosh(k_0 l)}{2k_0^3 l} + \frac{L_0^2[k_0 l + \sinh(k_0 l)\cosh(k_0 l)]}{2k_0 l}\right\}\cdot\frac{1}{\beta_x^*}$$

$$+\frac{k_0 l + \sinh(k_0 l)\cosh(k_0 l)}{2k_0 l}\cdot\beta_x^*$$

$$= D_1\cdot\frac{1}{\beta_x^*} + D_2\cdot\beta_x^*$$

$$\beta_y^* = \frac{\bar{\beta}_y - \sqrt{\bar{\beta}_y^2 - 4C_1C_2}}{2C_2}$$

$$\beta_x^* = \frac{\bar{\beta}_x - \sqrt{\bar{\beta}_x^2 - 4D_1D_2}}{2D_2}$$

- Results

	β_x (m)	β_y (m)
SCQW-1*	1.293	60.87
SCQE-1	3.661	60.60
IP-1	0.983	0.0171
SCQW-2	2.202	62.45
SCQE-2	3.658	62.12
IP-2	0.986	0.0167

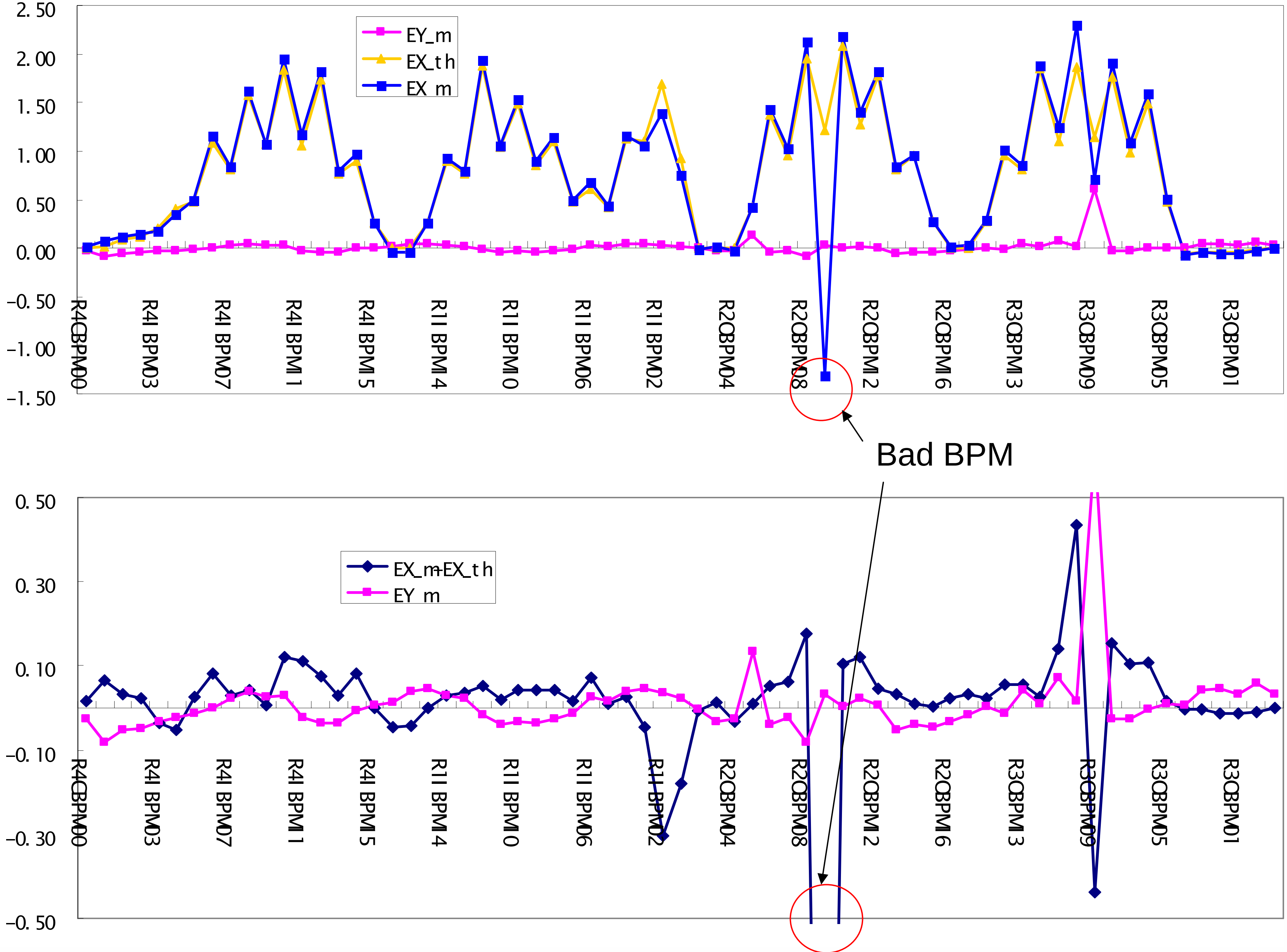
*** 1 and 2 mean the measurements at different time**

• Transverse tunes

- After the optics corrections with response matrix, measured tunes are close to the nominal values.

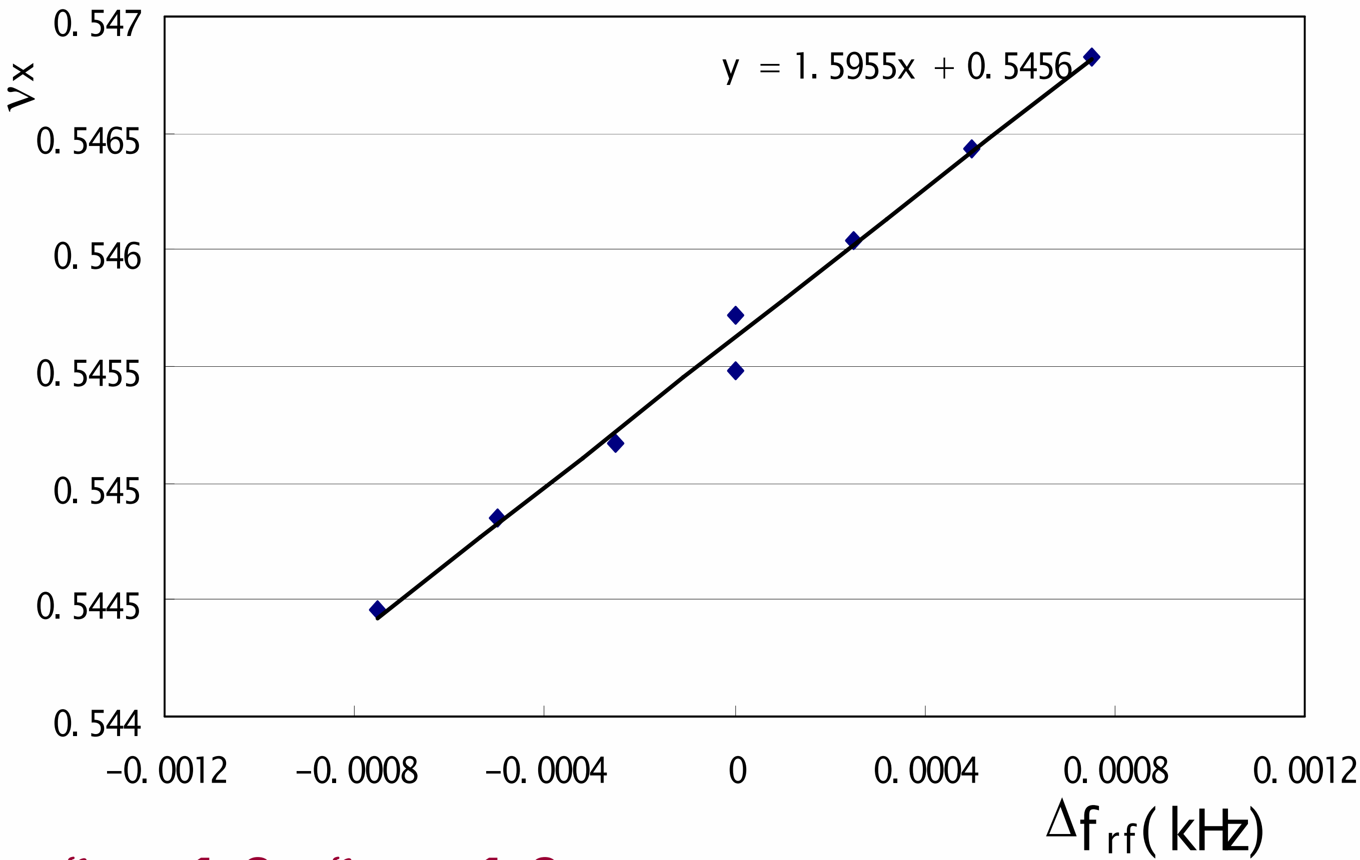
	Nominal	Measured (BER)	Measured (BPR)
ν_x	6.54	6.544	6.540
ν_y	5.59	5.559	5.596

- Dispersion function
  - — Measured with the method of RF frequency shift.
  - — Small difference between measured and theoretical dispersions at most BPMs.



2.50
2.00
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
EY_m
EX_th
EX_m
Bad BPM
0.50
0.30
0.10
-0.10
-0.30
-0.50
EX_m-EX_th
EY_m

- Chromaticity

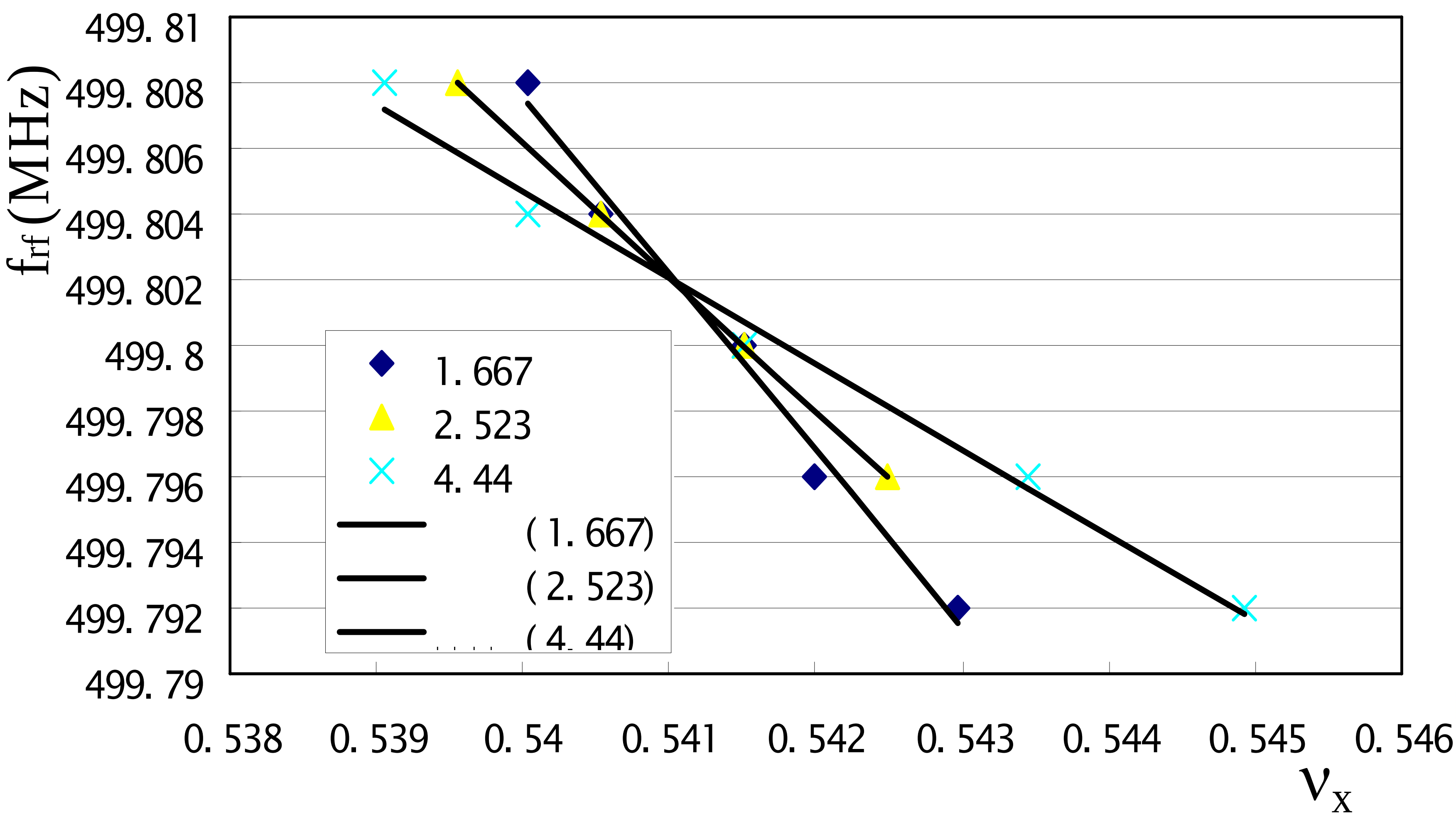


$\xi_x \sim 1.6, \;\; \xi_{x0} = 1.0$

Chromaticity measured at the 1st stage of commissioning

Nominal ξ_x/ξ_y	**Meas. ξ_x/ξ_y**	**Nominal ξ_x/ξ_y**	**Meas. ξ_x/ξ_y**
-5.0/-5.0	-5.33/-5.02	-1.0/-1.0	-1.28/-0.82
-3.0/-3.0	-3.19/-2.46	+1.0/+1.0	+1.05/+0.95
-2.0/-2.0	-2.33/-0.89	+5.0/+5.0	+4.50/+3.28
Natural ξ_{x0}/ξ_{y0}	-11.7/-10.4	**Meas. ξ_{x0}/ξ_{y0}**	-10.33/-10.07

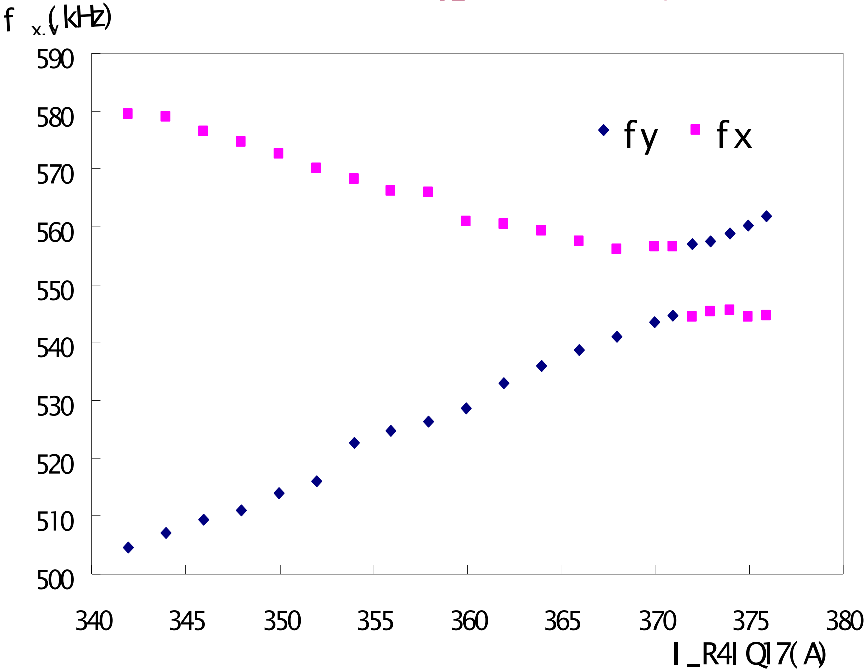
• Optimized RF frequency



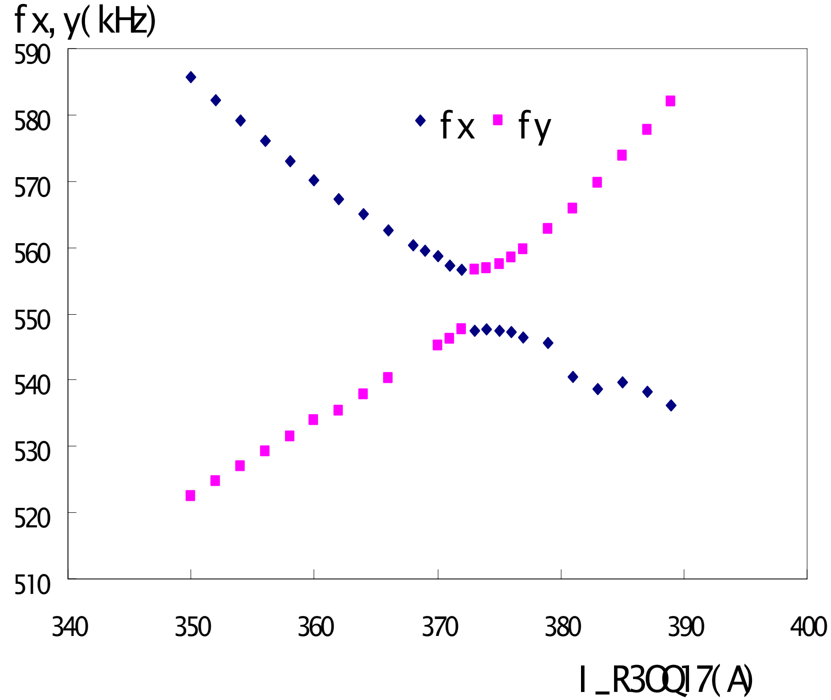
• Transverse coupling

- Adjusted with the vertical bump in sextupoles
- Measured with tune split method
- Method using response matrix is under way

BER: κ ~ 1.24%



BPR: κ ~ 1.02%



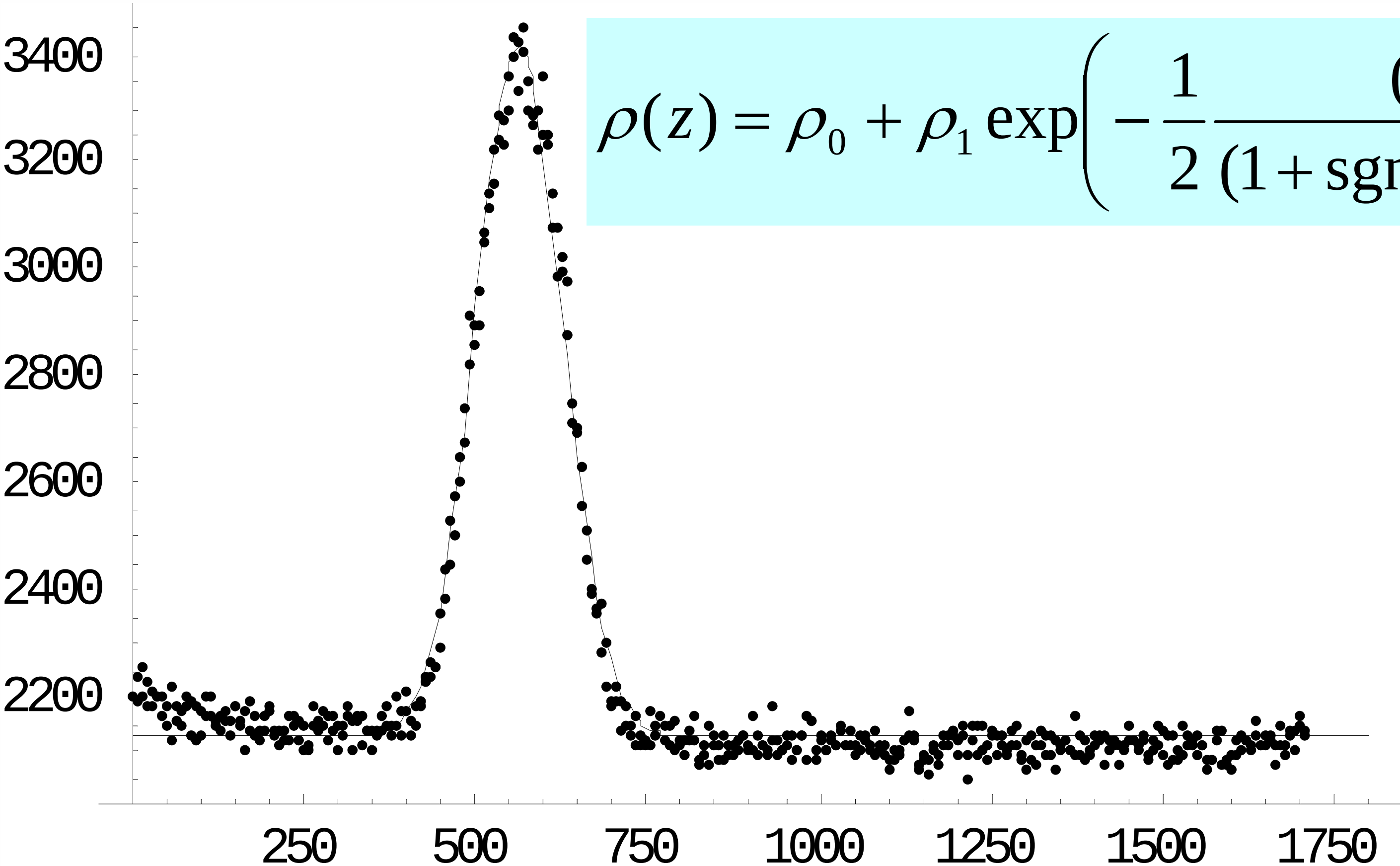
3. Single Beam Dynamics

- Bunch lengthening
- Tune variation vs. bunch current
- Impedance
- Beam lifetime

• Bunch lengthening

- Bunch length in BER/BPR measured with streak camera.
- Single bunch stored in BER/BPR, respectively, in bunch length measurement.
- Keep V_{rf} fixed, measure the bunch length vs. bunch current.

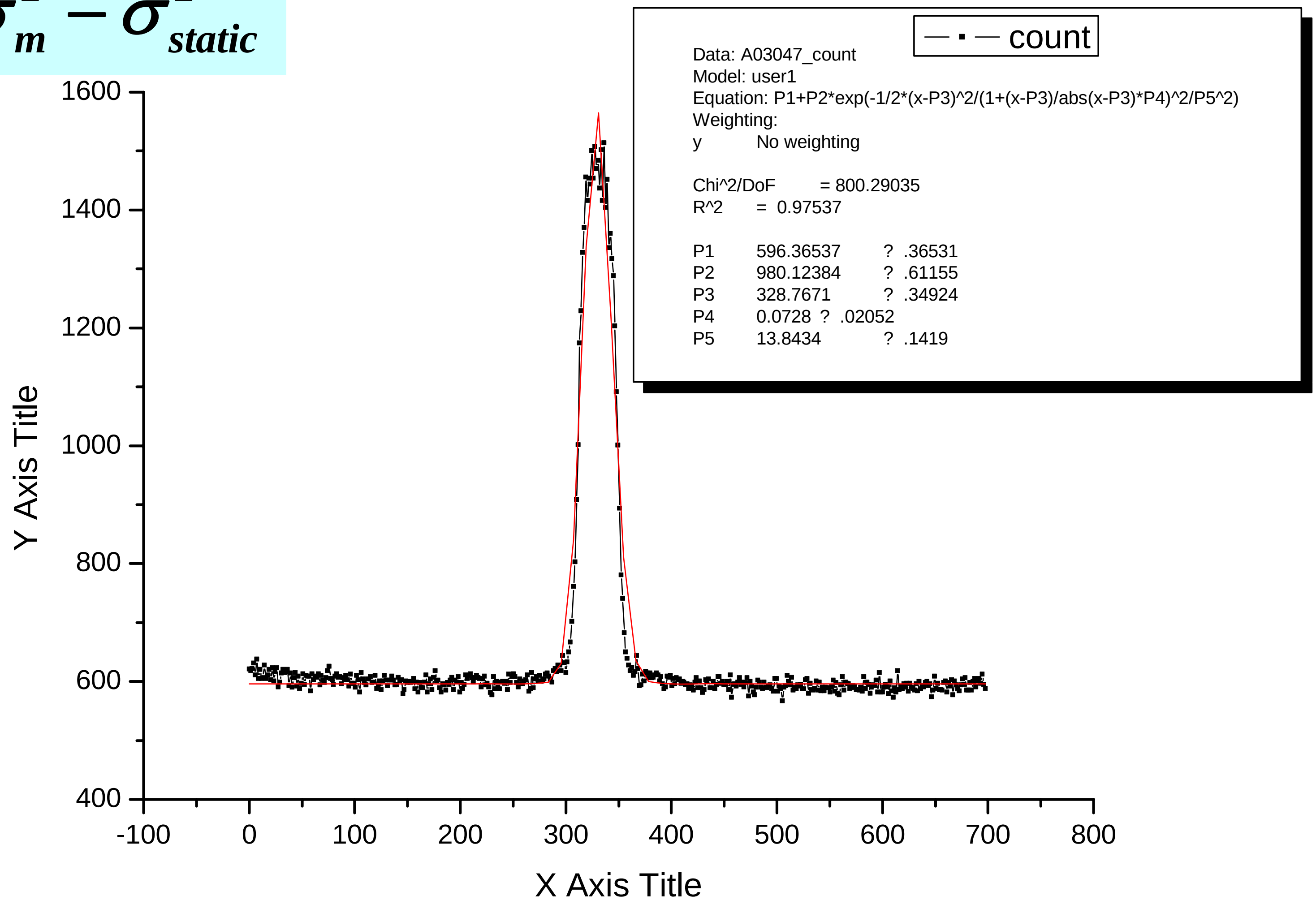
- Bunch length fitting



$$\rho(z) = \rho_0 + \rho_1 \exp\left(-\frac{1}{2} \frac{(z-\bar{z})^2}{(1+\mathrm{sgn}(z-\bar{z})A)^2 \sigma_z^2} \right)$$

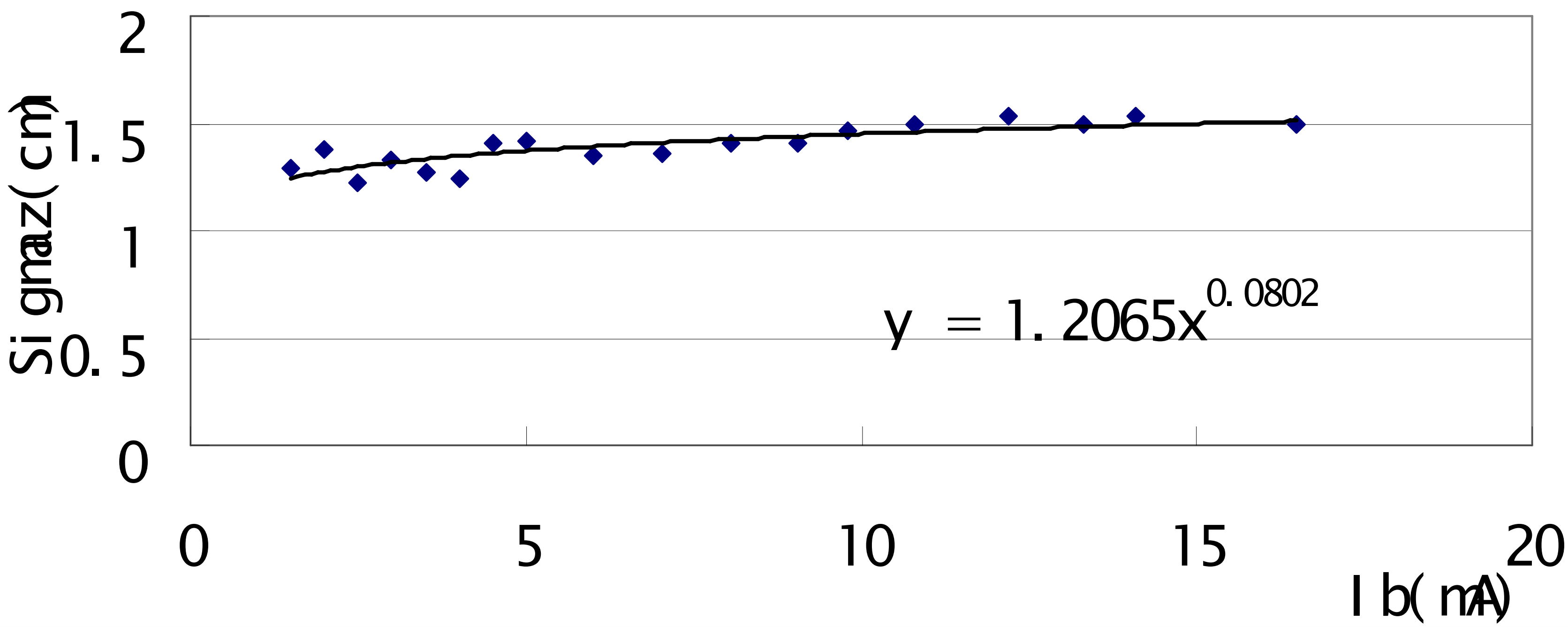
Static image measured and reduced by

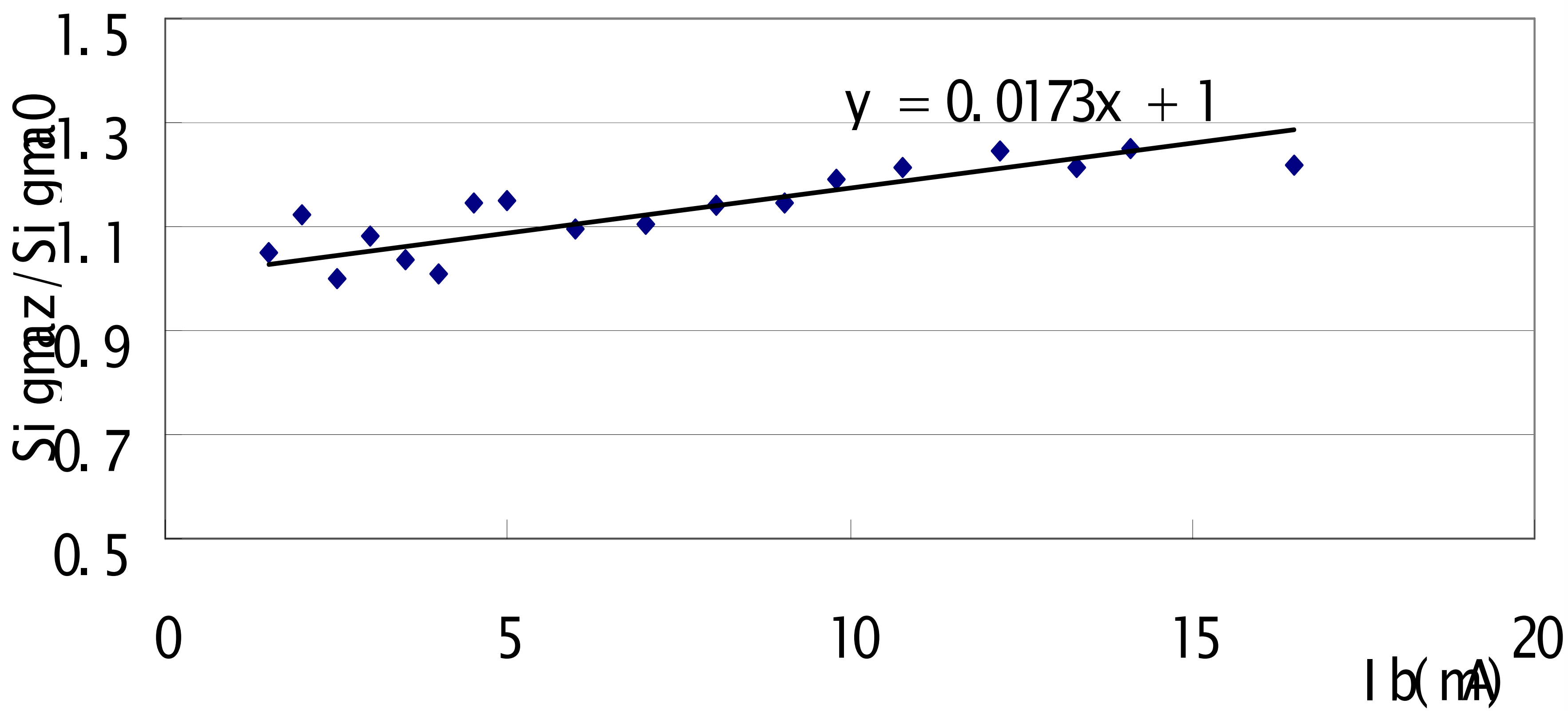
$$\sigma_l = \sqrt{\sigma_m^2 - \sigma_{static}^2}$$



- Results of bunch lengthening

BPR





$$L_{ave} = 118\text{nH} \Rightarrow |Z/n|_0 = 0.94\ \Omega$$

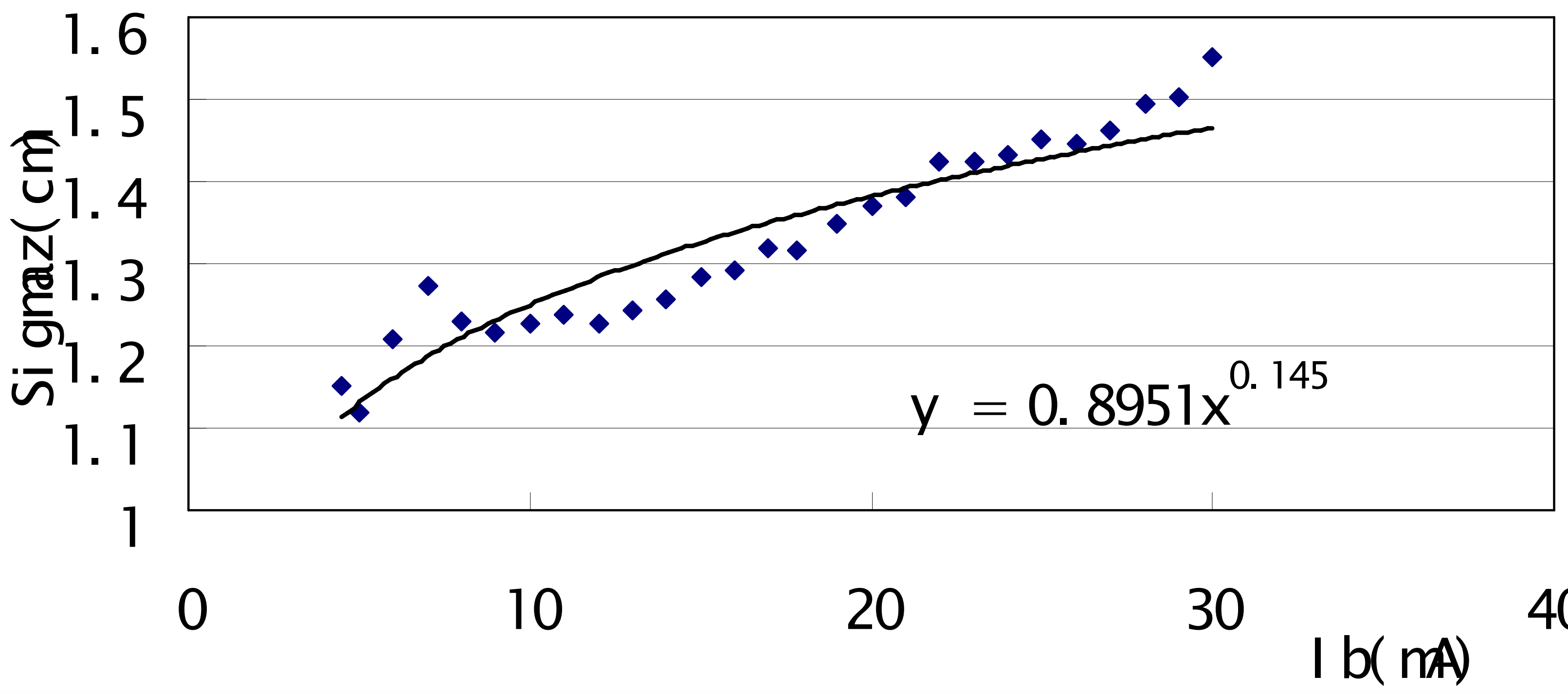
- According to

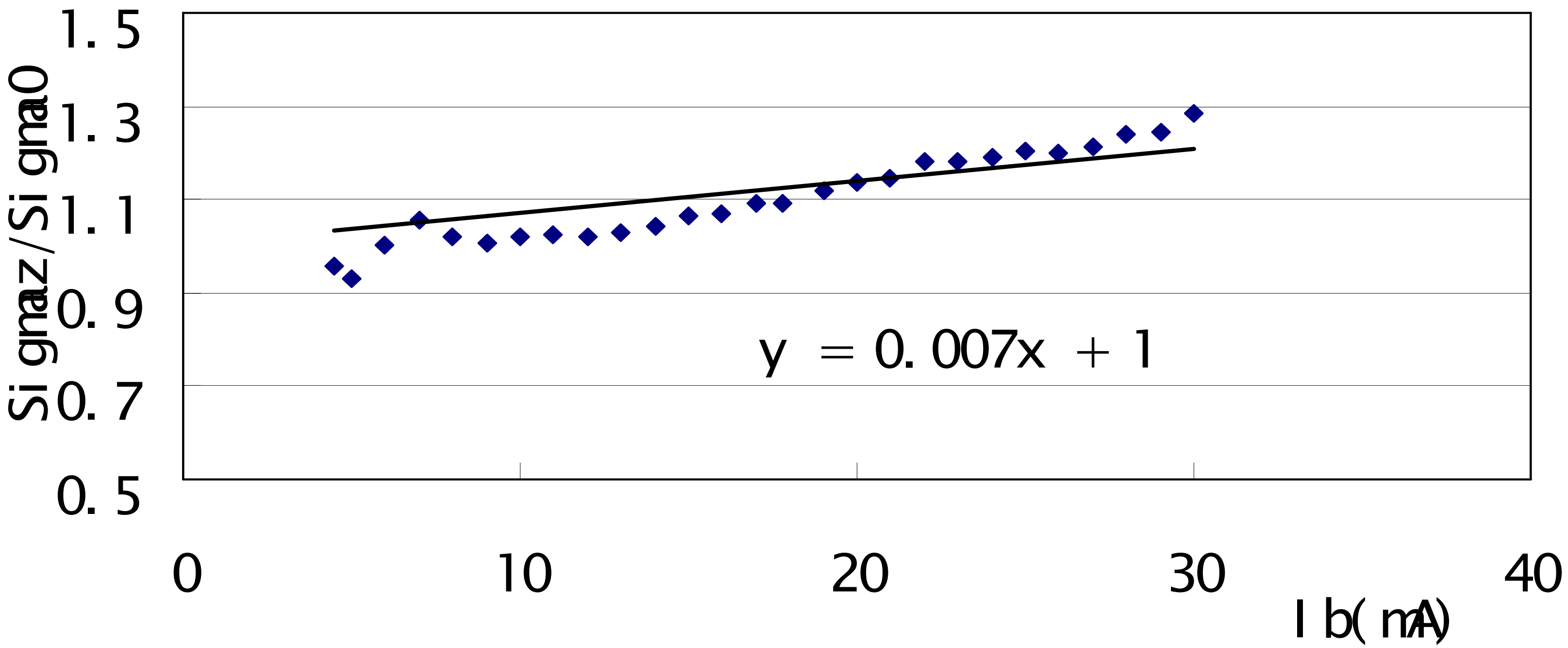
$$\frac{\sigma_l}{\sigma_{l0}} \approx 1 + \frac{e\alpha_p I_b \omega_0 L}{8\sqrt{\pi}\nu_s^2 E}\left(\frac{R}{\sigma_{l0}}\right)^3$$

we get

$$\boldsymbol{\frac{\sigma_l}{\sigma_{l0}} \approx 1 + 0.0185 I_b} \Rightarrow \boldsymbol{y = 1 + 0.0173x}$$

BER

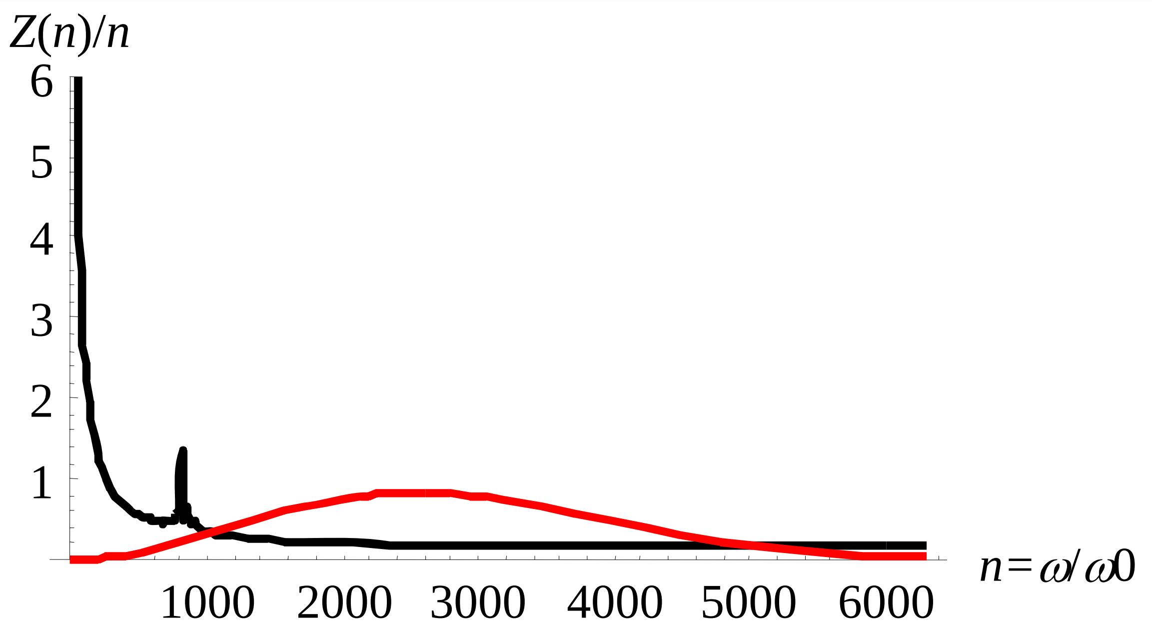




$$L_{ave} = 32.1\text{nH} \Rightarrow |Z/n|_0 = 0.25\ \Omega$$

$$\frac{\sigma_l}{\sigma_{l0}} = 1 + 0.0053 I_b \quad \Rightarrow \quad y = 1 + 0.007x$$

• Design estimation on impedance



L = 29 nH, $|Z/n|_0$ = 0.2 Ω

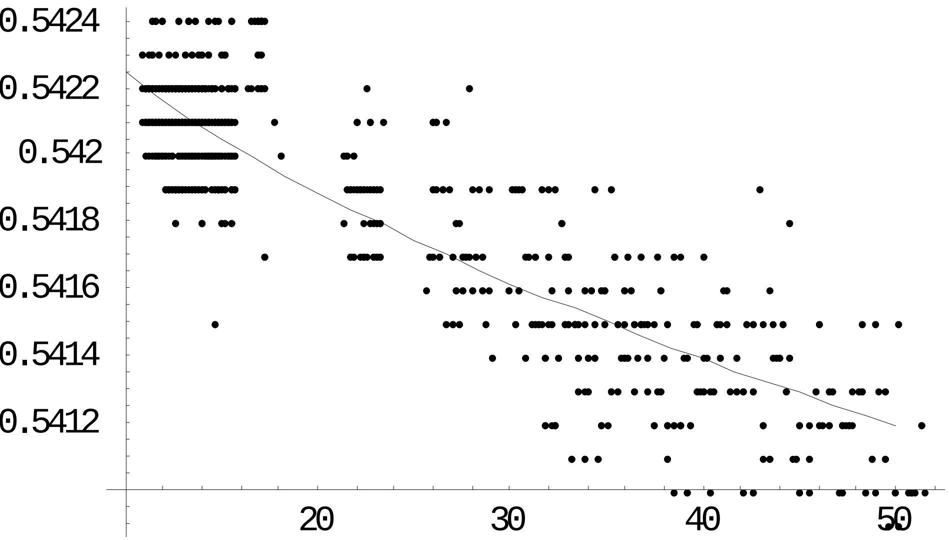
• Tune variation vs bunch current

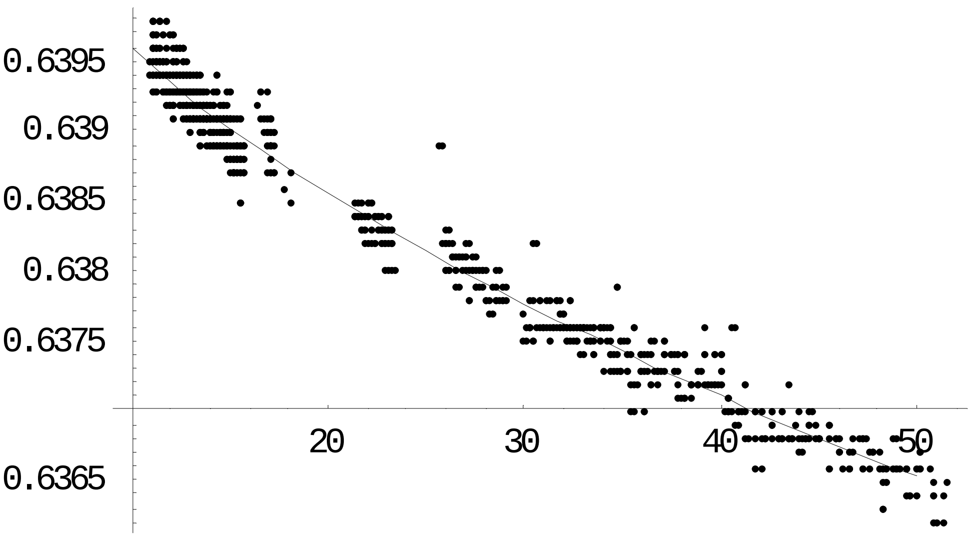
- Betatron tunes vary with single bunch current
- Effective impedance can be got from the tune variation

$$\frac{d\nu_\perp}{dI} = \frac{R}{4\sqrt{\pi}(E/e)\sigma_l}\overline{\beta}_\perp Z_{\perp,eff}$$

$$Z_{\parallel,0} = \frac{b^2}{2R} Z_{\perp,eff}$$

BPR:

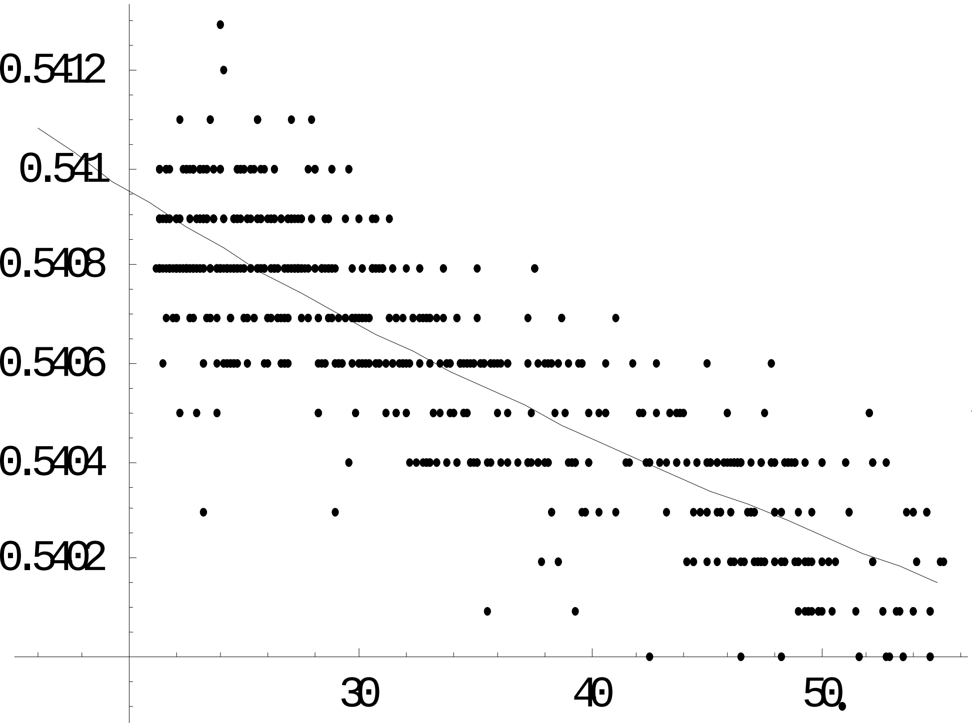


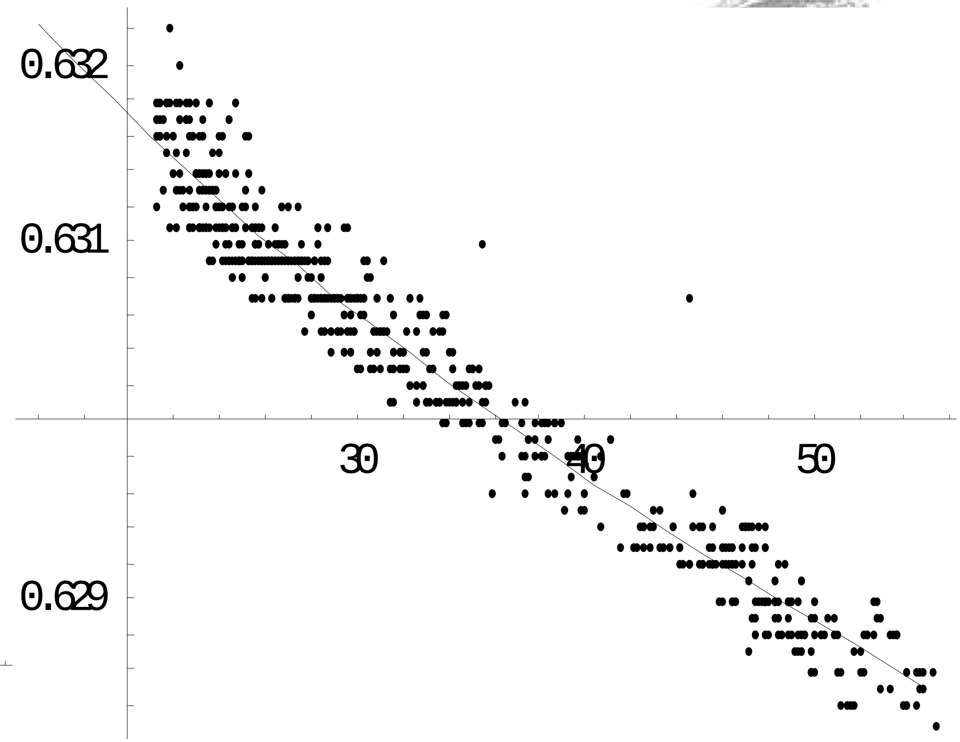


Hori. tune vs. bunch current
$|Z/n|_0 \sim 1.38 \pm 0.021\ \Omega$

Vert. tune vs. bunch current
$|Z/n|_0 \sim 0.81 \pm 0.004\ \Omega$

BER:





Hori. tune vs. bunch current

$|Z/n|_0 \sim 1.43 \pm 0.032\ \Omega$

Vert. tune vs. bunch current

$|Z/n|_0 \sim 1.15 \pm 0.014\ \Omega$

• Estimated impedance

➢ Bunch lengthening ⇒

BPR: $|Z/n|_0$ =0.94Ω, BER: $|Z/n|_0$ =0.25Ω

➢ Tune variation ⇒

BPR & BER: $|Z/n|_0$ ~ 1.0 Ω

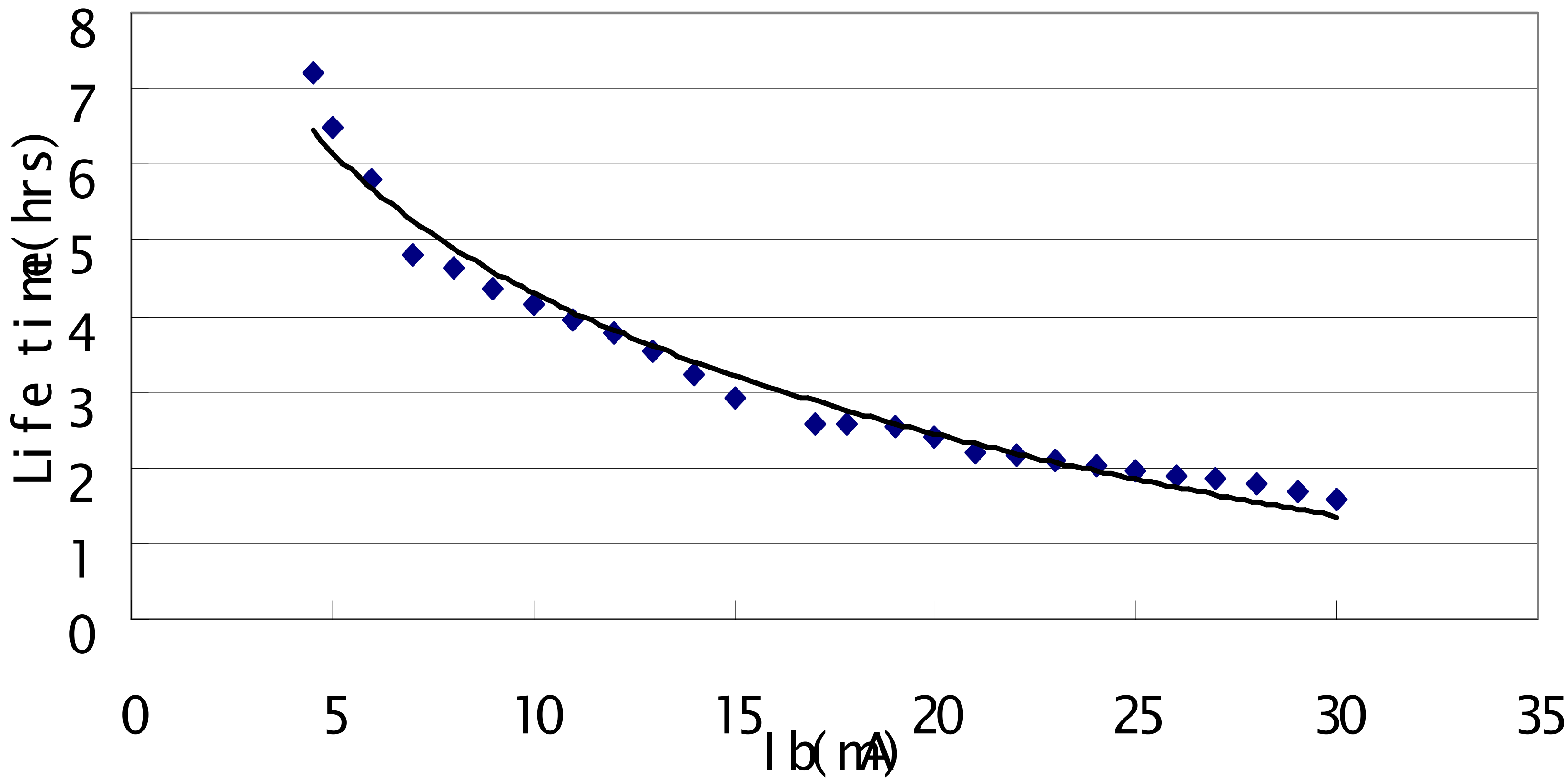
• Beam Lifetime

- Single bunch beam lifetime in both rings measured for several times under different machine conditions
- Multi-bunch beam lifetime observed with different beam current, together with vacuum pressure
- Some calculations done on beam lifetime

• Observations

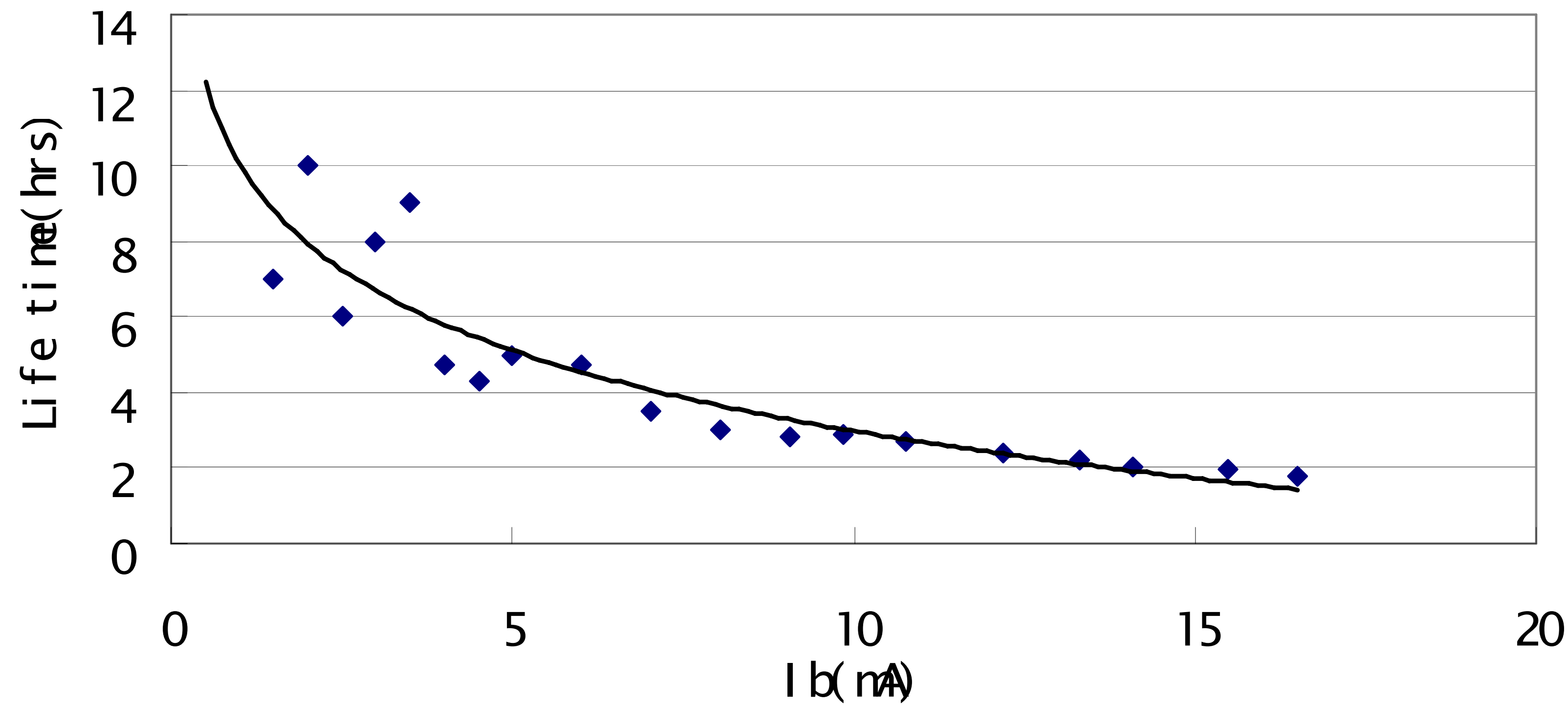
- BER: I_b = 4.5 ~30 mA, V_{rf} = 1.69 MV

  ν_s = 0.0344

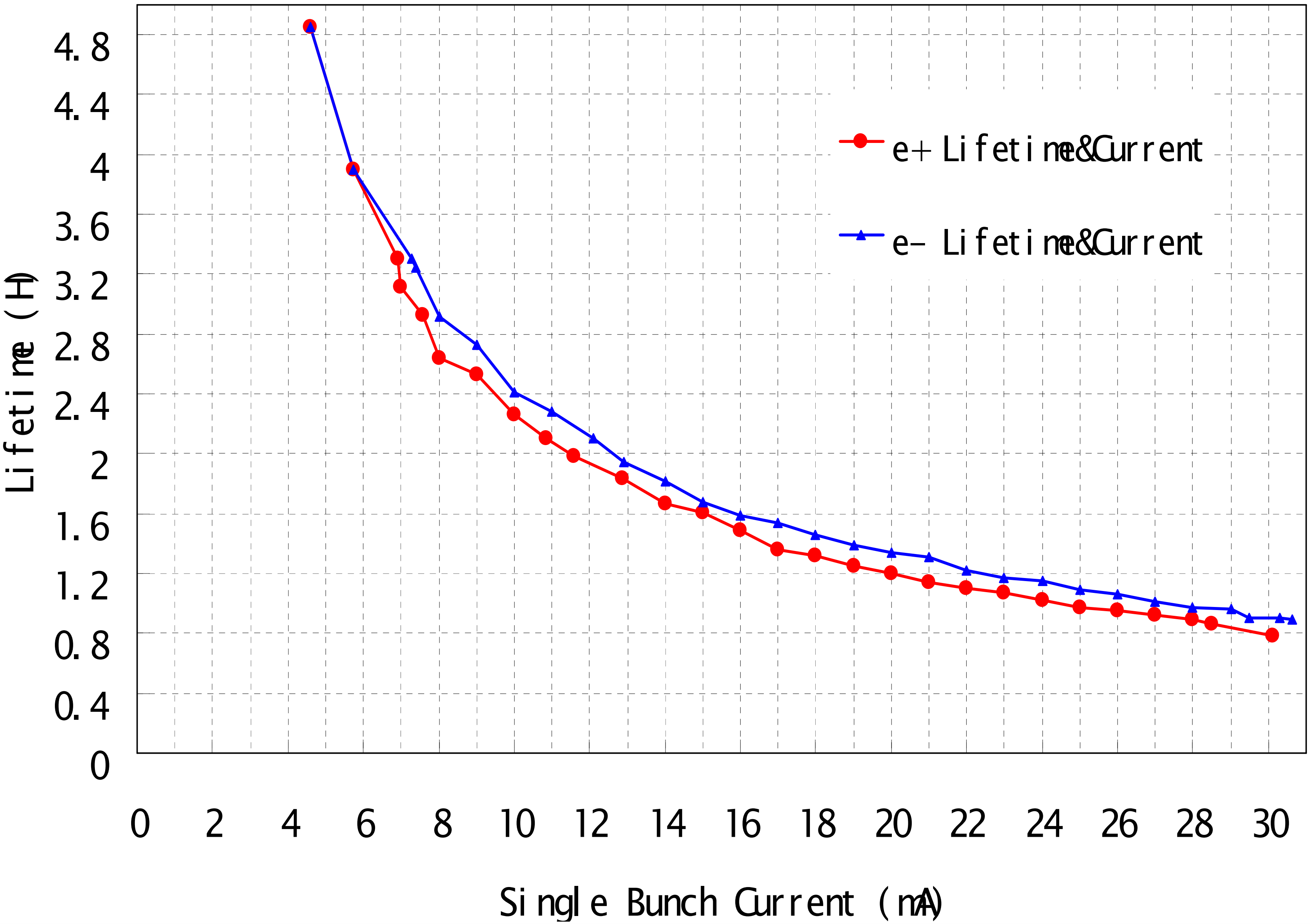


- BPR: I_b = 1.5 ~ 16.5 mA, V_{rf} = 1.61 MV,

  ν_s = 0.0334



Single bunch lifetime



- Beam lifetime:

$$\frac{1}{\tau} = -\frac{1}{N}\frac{dN}{dt}$$

Without beam collision:

$$\frac{1}{\tau} = \frac{1}{\tau_g} + \frac{1}{\tau_q} + \frac{1}{\tau_t}$$

Long enough

• Touschek lifetime

- Got from single bunch lifetime, say, the lifetime of 1mA ~ Touschek lifetime
- Similar in BER & BPR, we get

τ_t =10 hrs @1mA

- In the BEPCII design book, the calculated

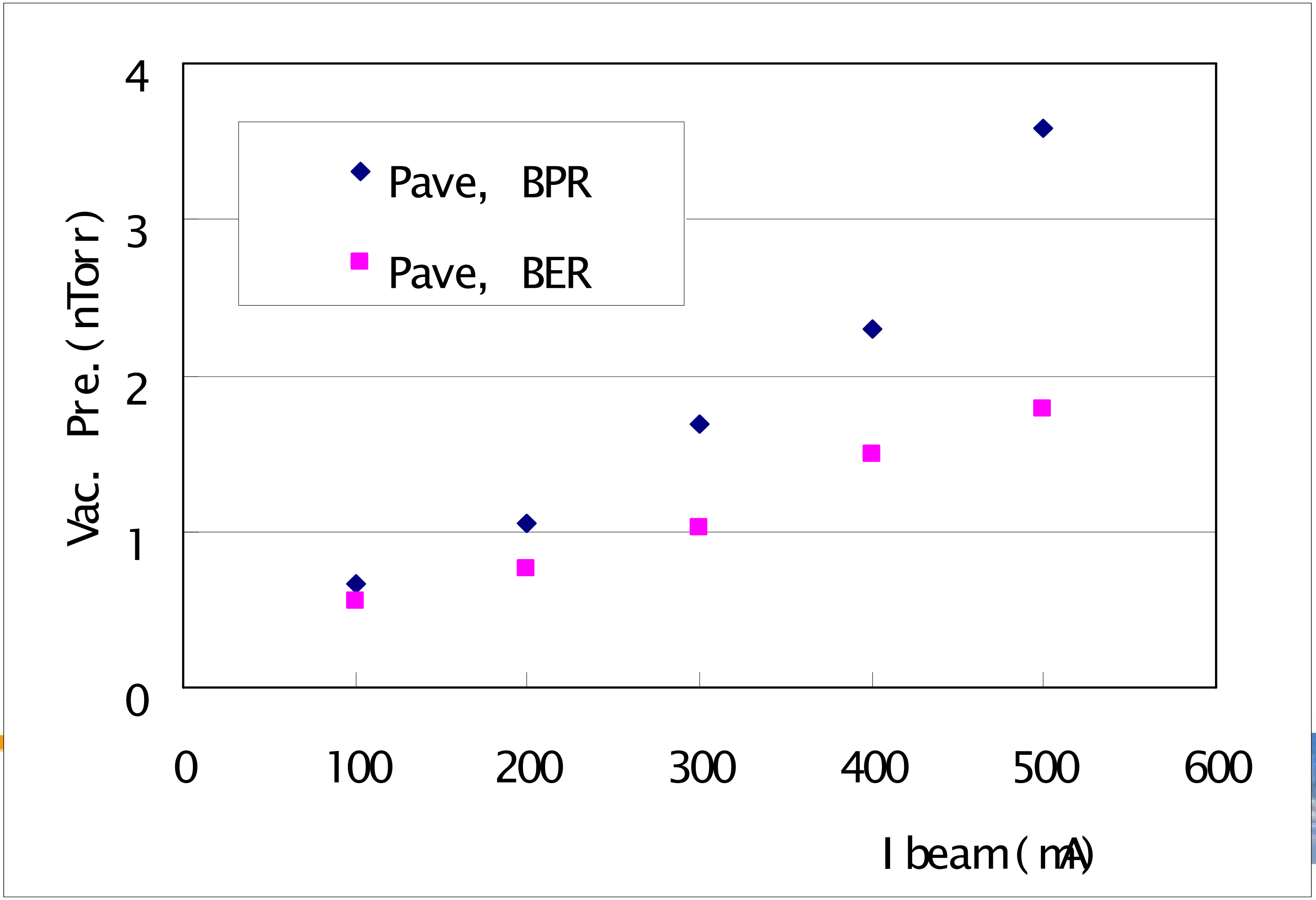
τ_t =7.1 hrs @9.8mA

• Beam-gas lifetime

- In the BPR, <p > = 0.178 nTorr @1mA
- The residual gas consists of 70%CO and 30%H_2 in the BPR.
- BER: 70%H_2 + 30%CO
- The calculated beam-gas lifetime is 146 hrs @1mA in BPR
- The calculated total lifetime @1mA is 43 hrs, >> 10 hrs !

• Multi-bunch beam lifetime

- Beam current: 100mA, 200mA, 300mA, 400mA and 500mA for both BER & BPR



• BPR beam lifetime @ 500mA

- 500mA*500mA collision observation
- Bunch current ~5mA
- Average vacuum pressure = 3.58 nTorr
- 70%CO + 30%H_2 in residual gas
- Beam-gas lifetime calculated ~7.3 hrs
- Touschek lifetime ~2.0 hrs@5mA
- Beam-beam lifetime ~6.0 hrs
- Calculated beam lifetime ~1.24 hrs
- Observed beam lifetime ~1.12 hrs when collision

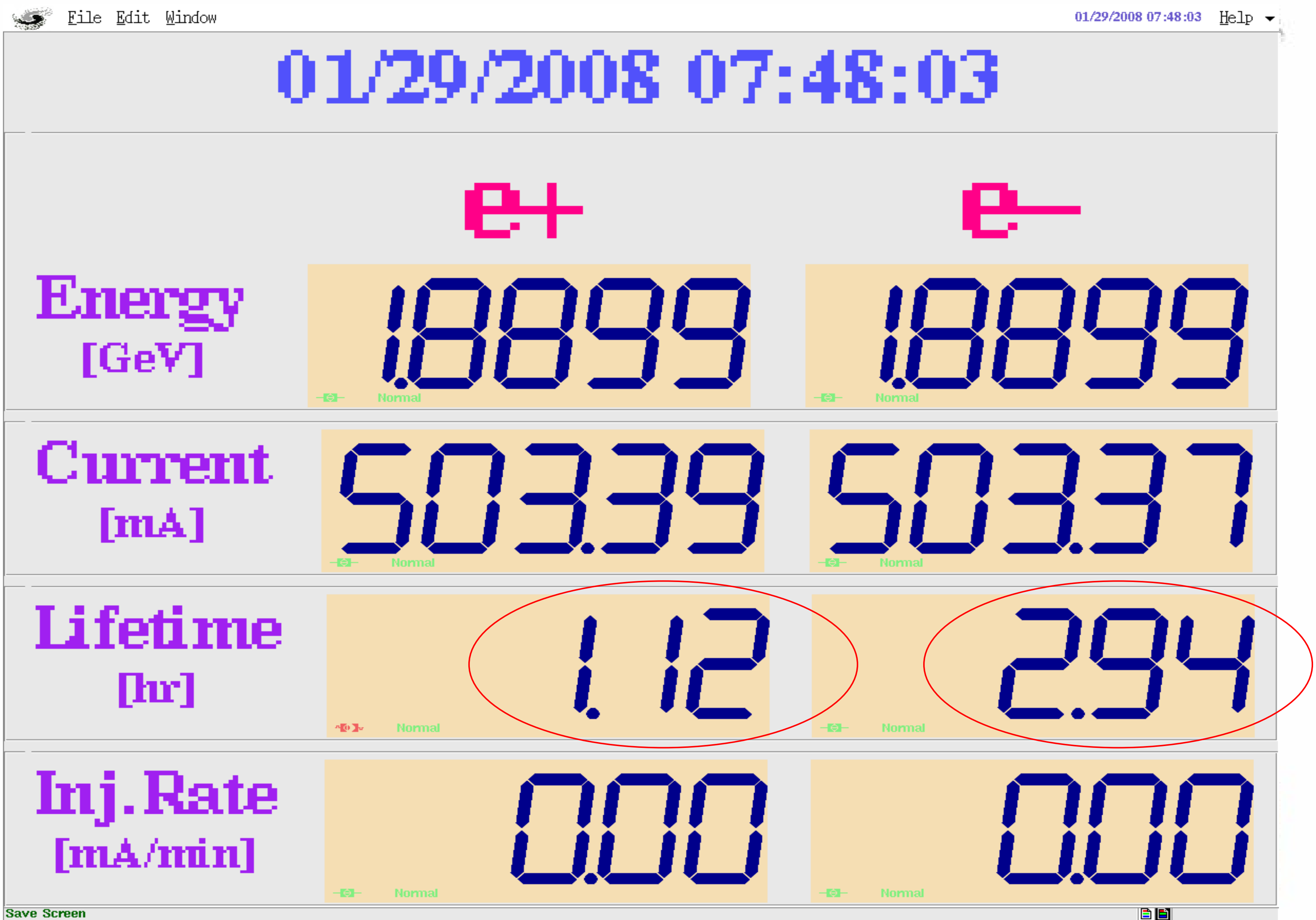
• BER beam lifetime @ 500mA

- <p> = 1.79 nTorr
- Calculated beam-gas lifetime ~33hrs@500mA, 30%CO+70%H_2
- Touschek lifetime ~2.0hrs@5mA
- Calculated beam lifetime ~1.44hrs
- Observed beam lifetime ~3hrs@500 mA when collision

◆ **Observed lifetime of e+ beam agrees well as the expected value, but e- beam doesn't**

◆ **Vacuum needs to improve further.**

Beam collision at 500mA in both rings

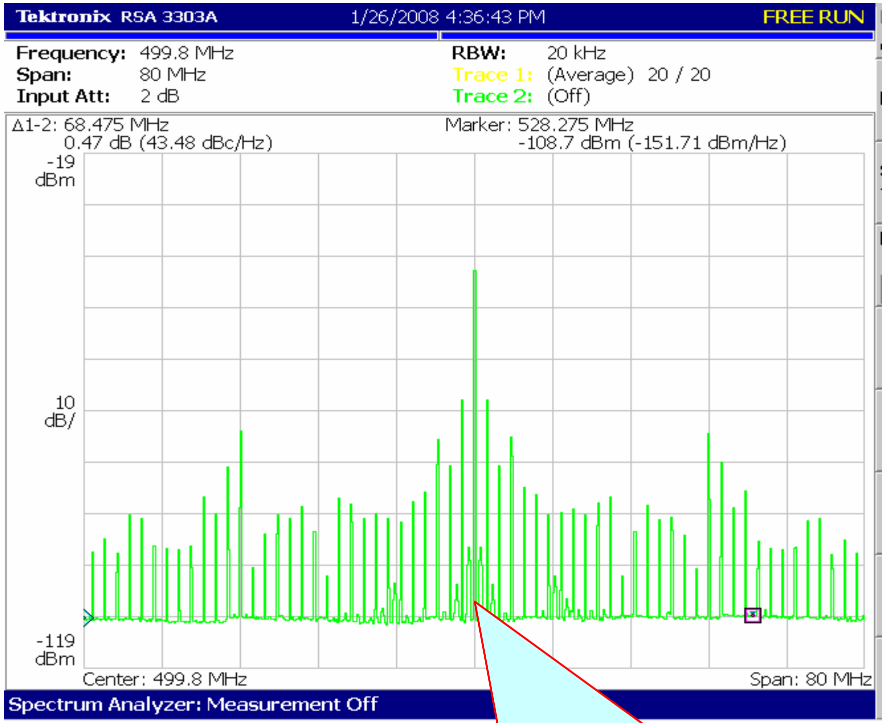


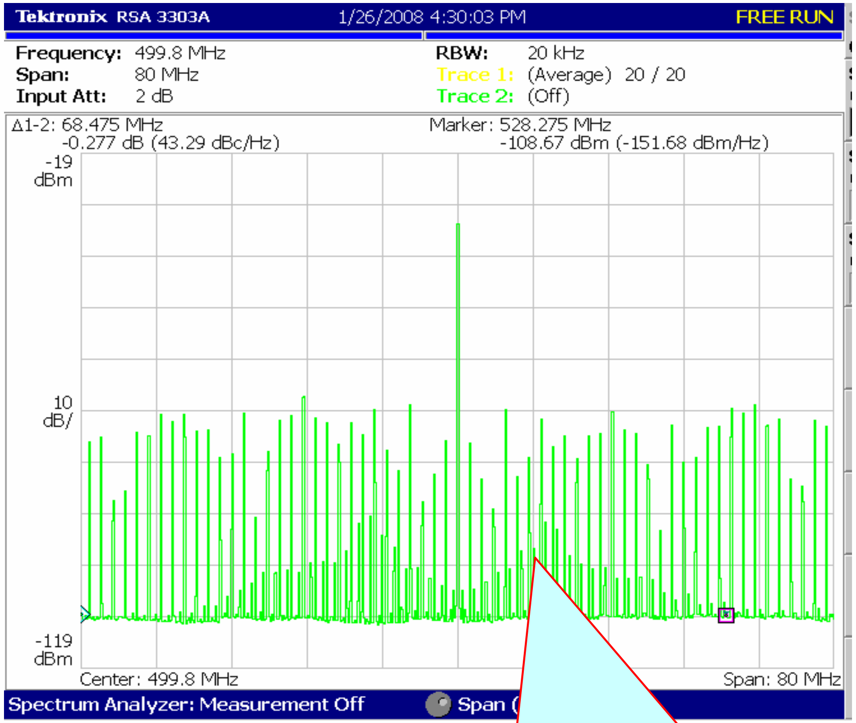
4. Beam Instabilities

- Single bunch — Bunch lengthening
- Electron cloud — Observed clearly in the positron ring
  — beam blow-up, bunch oscillation, etc.
  — preliminary analyses

Observation on coupled bunch instability

Spectrum distribution

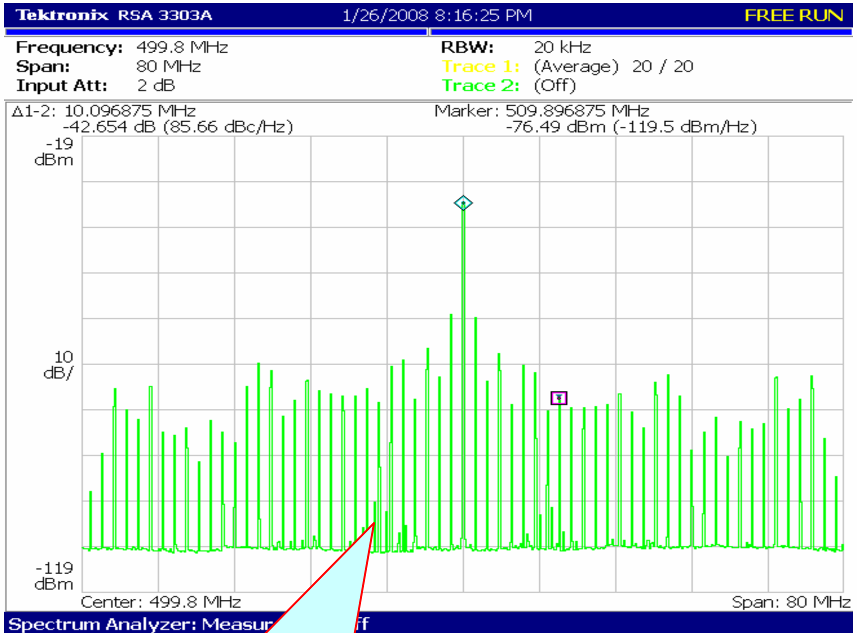


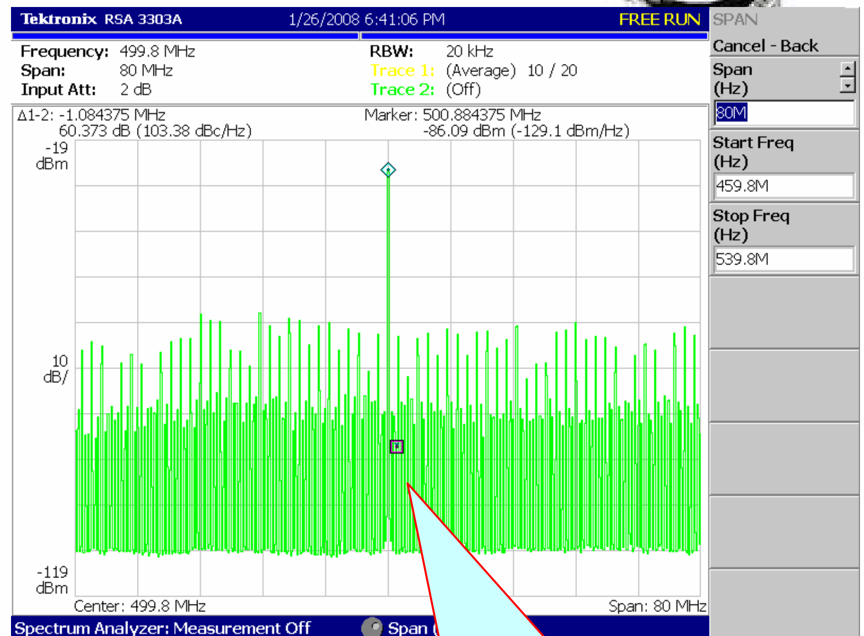


e– beam: 99-bunch, uniform filling
4 RF buckets spacing
ΣI_b= 40mA

e+ beam: 99-bunch, uniform filling
4 RF buckets spacing
ΣI_b= 40mA

Sidebands of positron beam

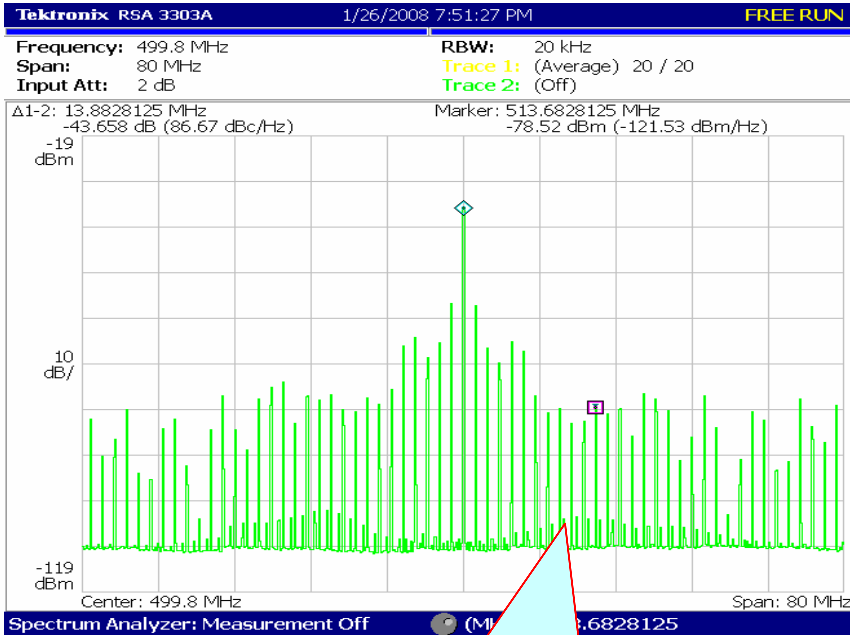


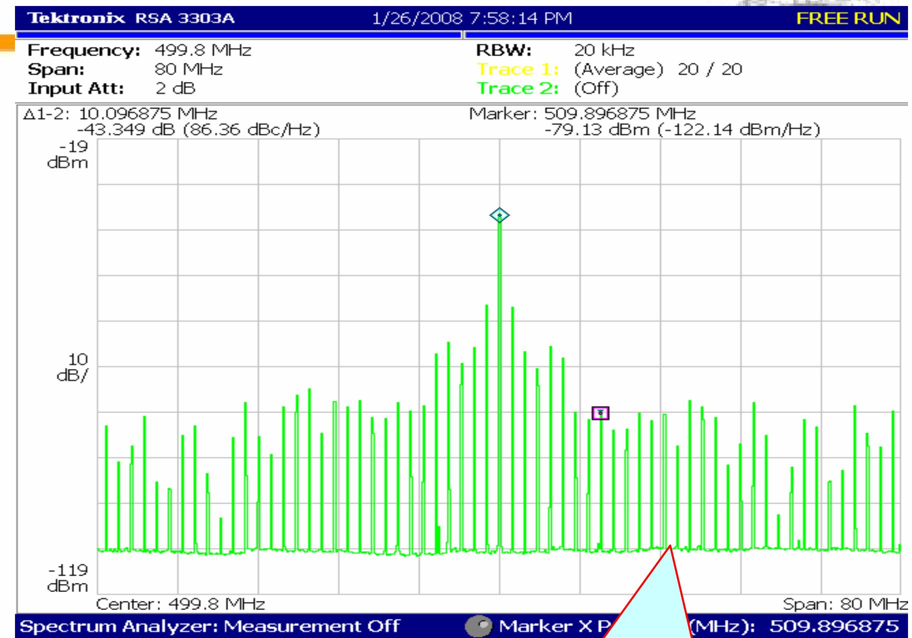


99-bunch
uniform filling
4 RF buckets spacing
ΣI_b = 35mA, I_{th} ~ 35mA

99-bunch
uniform filling
4 RF buckets spacing
ΣI_b = 100mA

Sidebands of positron beam



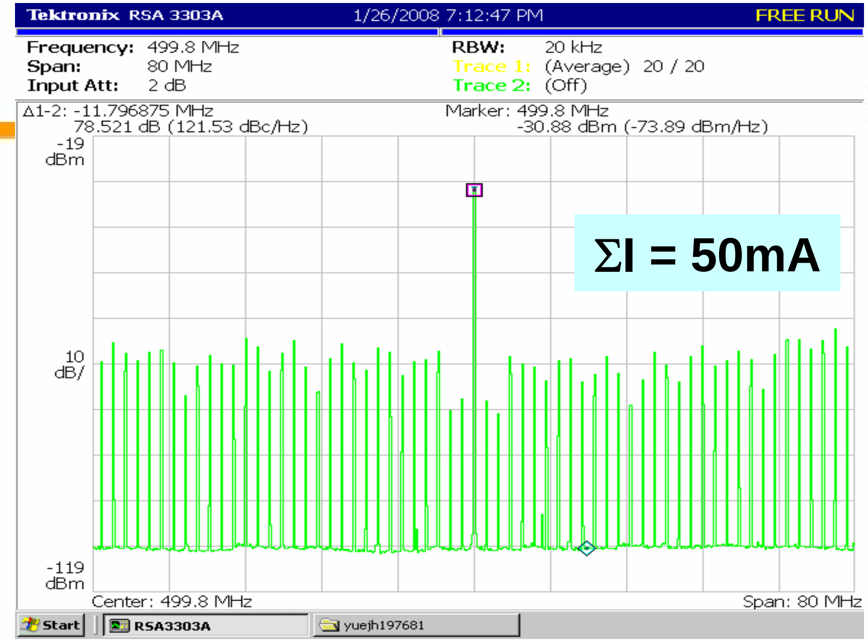


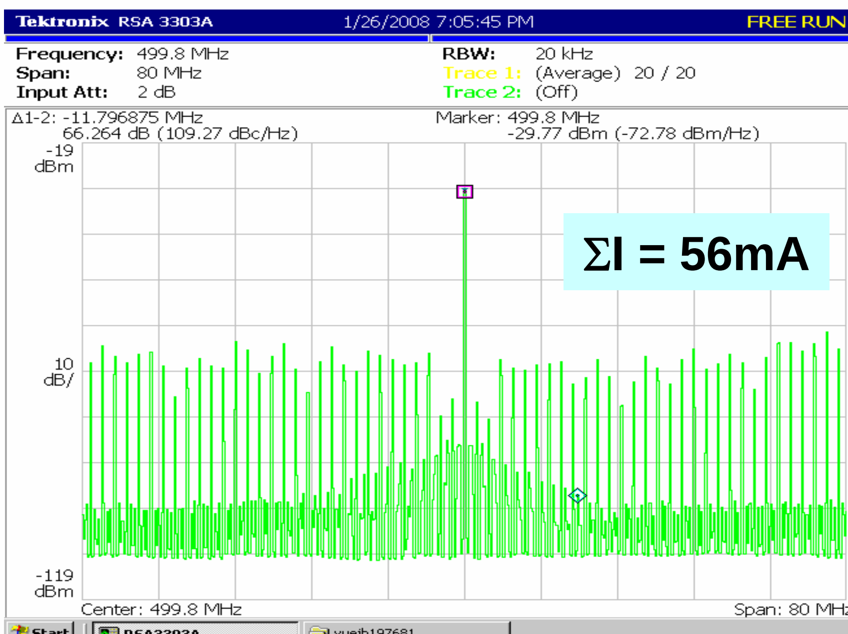
198-bunch
uniform filling
2 RF buckets spacing
ΣI_b = 31mA, I_{th} = 29~31mA

198-bunch
uniform filling
2 RF buckets spacing
ΣI_b = 28.9mA

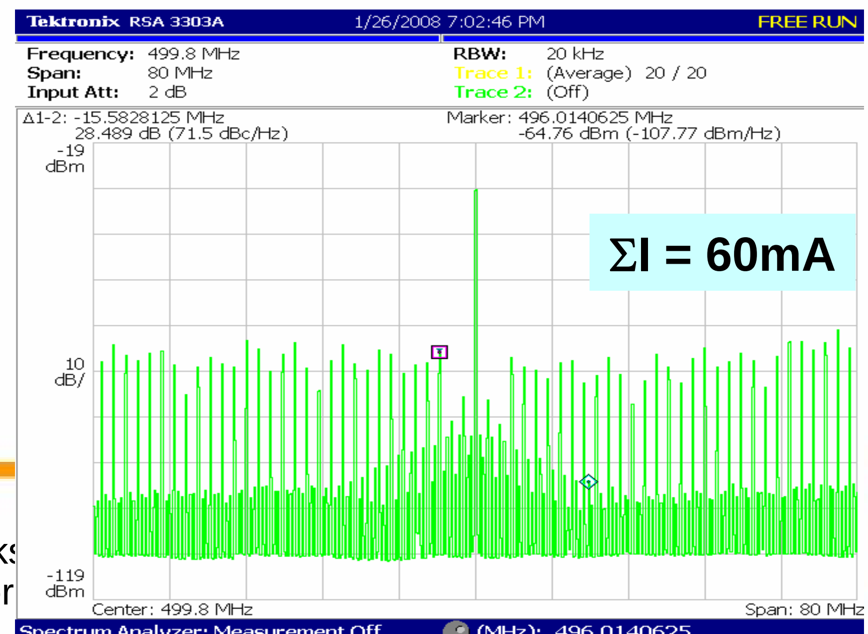
Positron beam:

48 bunches
uniform filling
bunch spacing: 8 RF buckets





orks
ctor

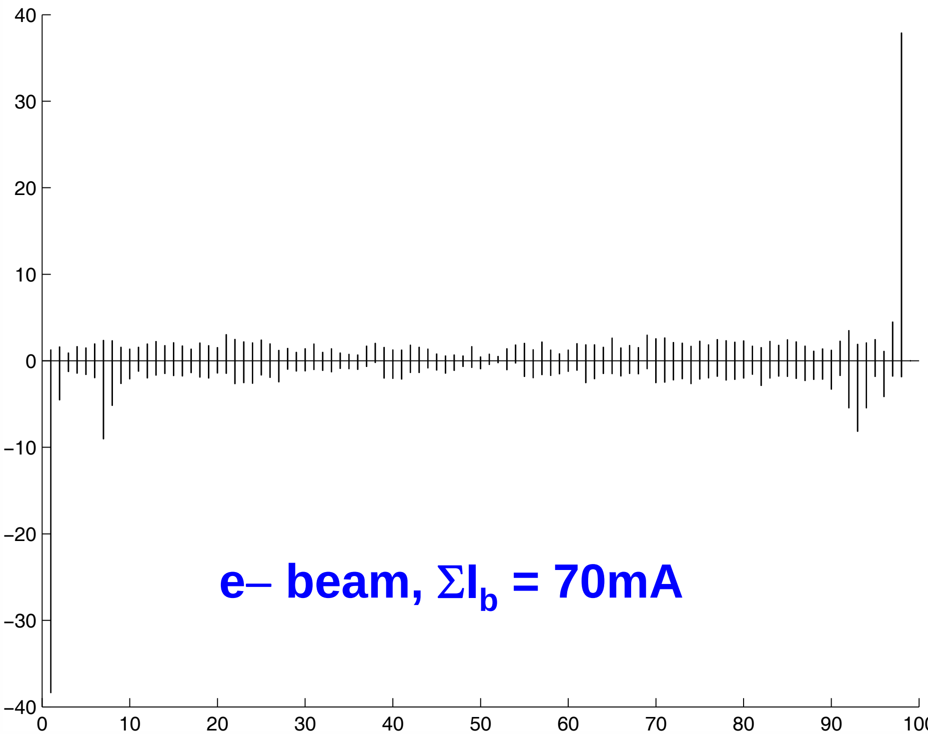


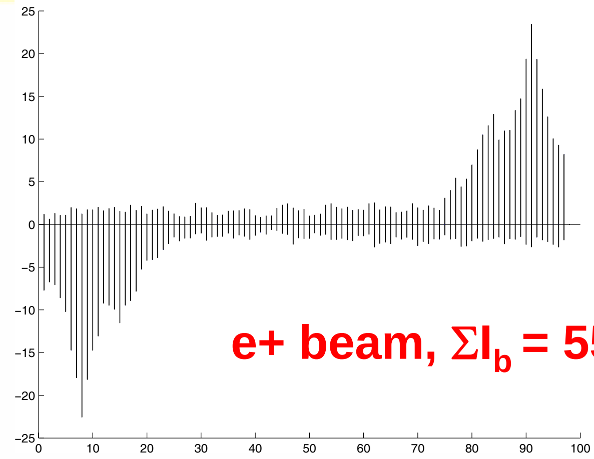
Threshold current of ECI in e+ ring

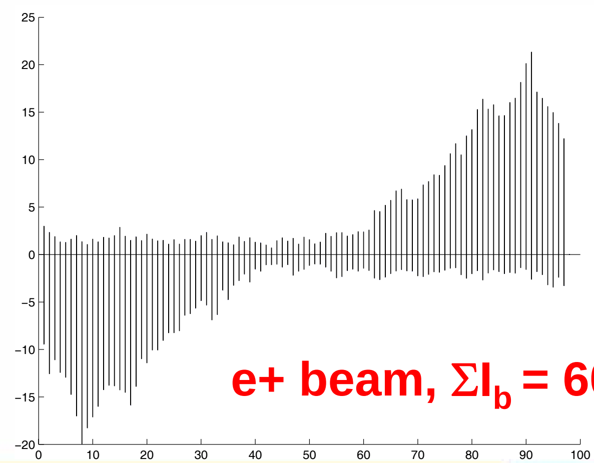
Bunch No.	Bunch spacing (RF bucket)	I_b (mA)	I_{th} (mA)
48	8	~1.0	~50
99	4	~0.35	~35
198	2	~0.15	~30

Mode distribution comparison

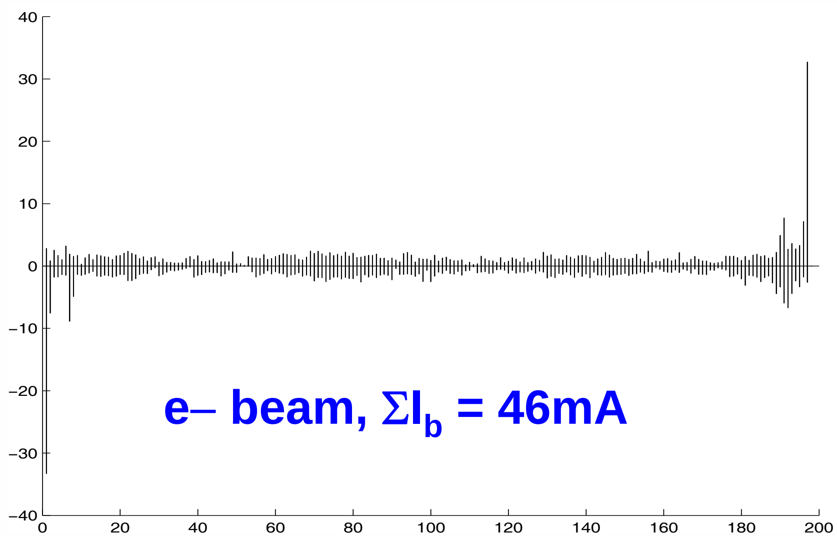
Same filling pattern:
99 bunches with 4 RF buckets spacing

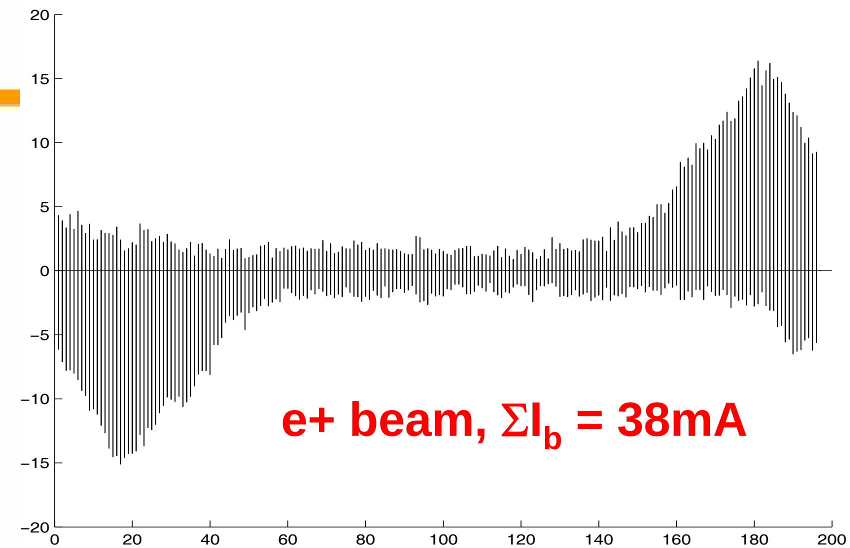




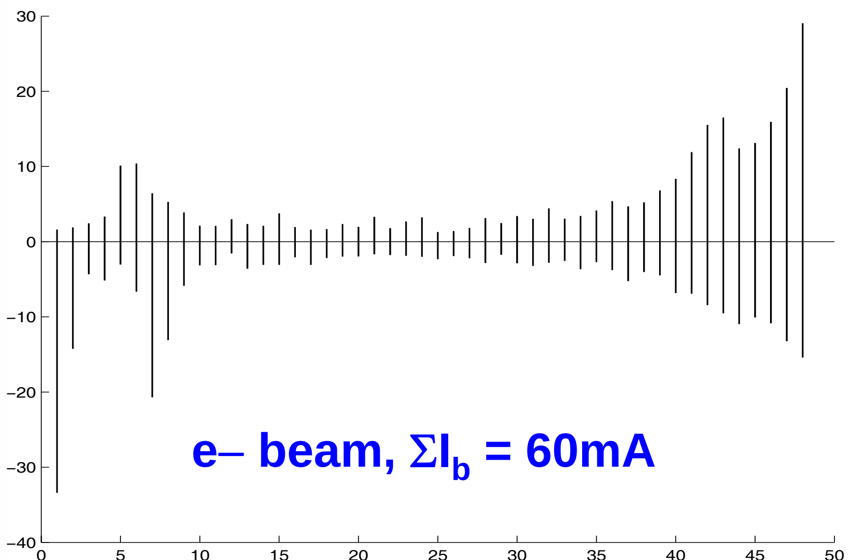


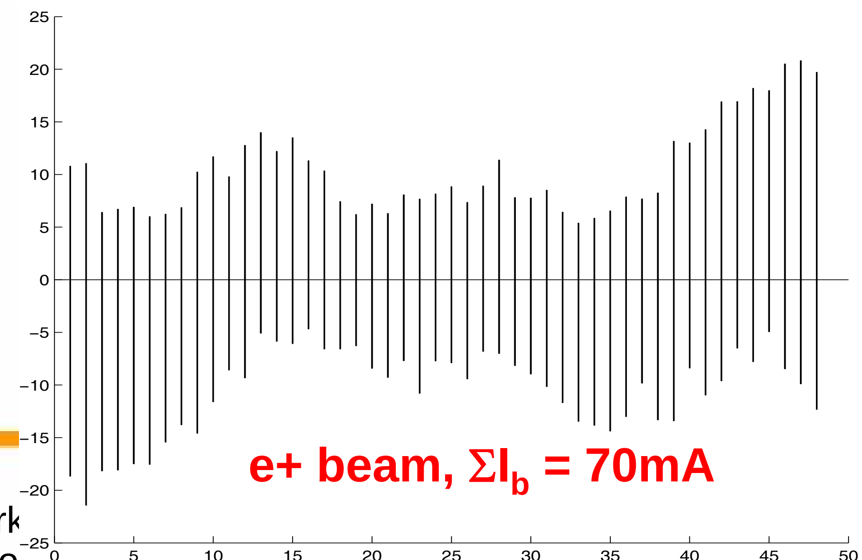
Filling pattern: 198 bunches with 2 RF buckets spacing



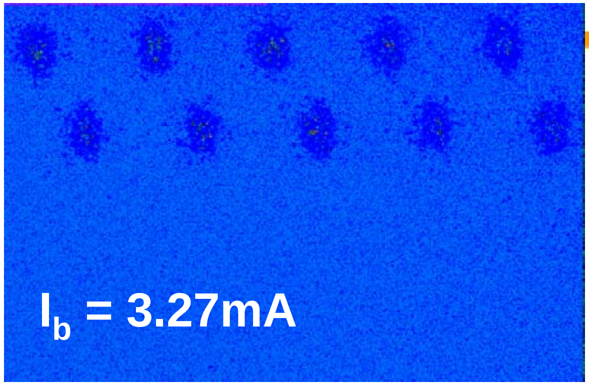


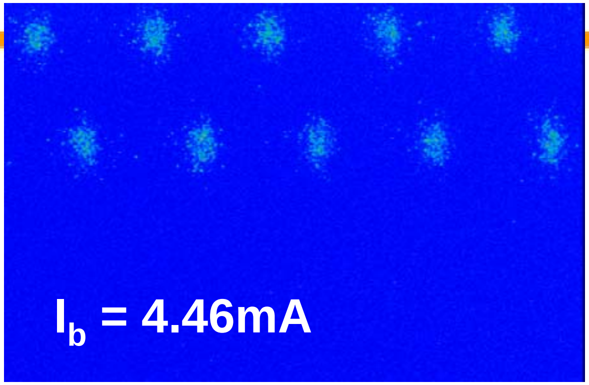
Filling pattern: 50 bunches with 4 RF buckets spacing

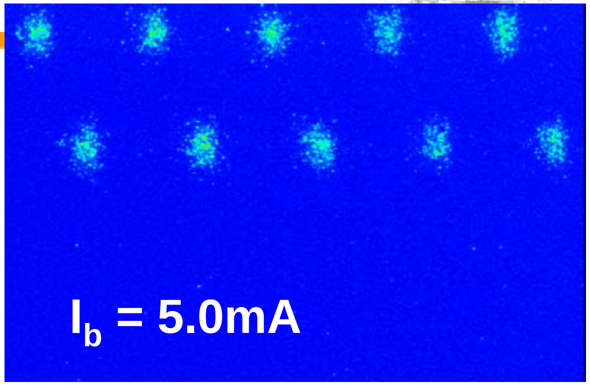


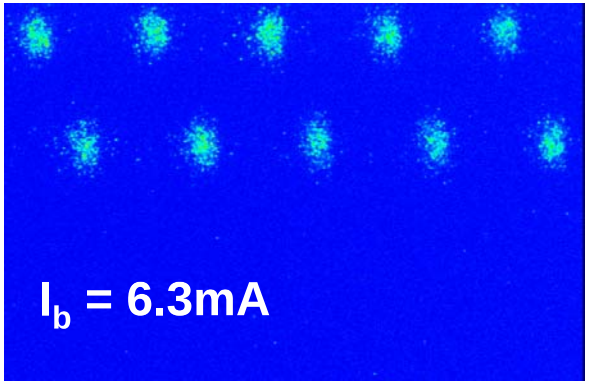


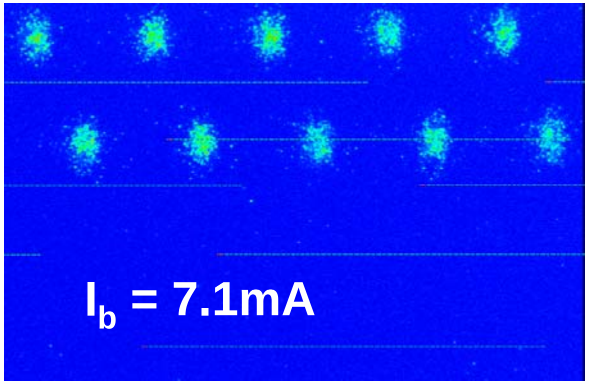
Observations on the vertical bunch size with streak camera

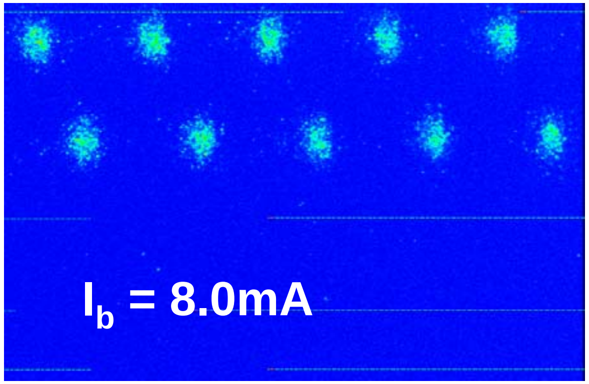


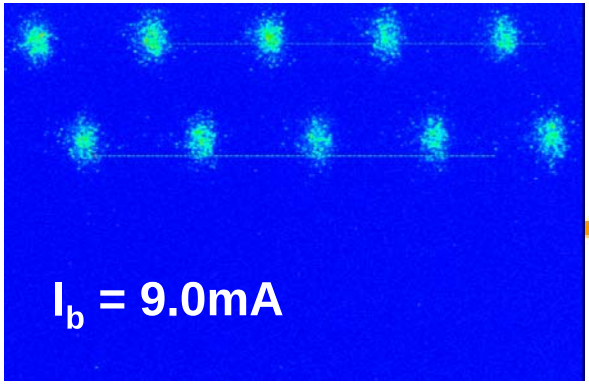






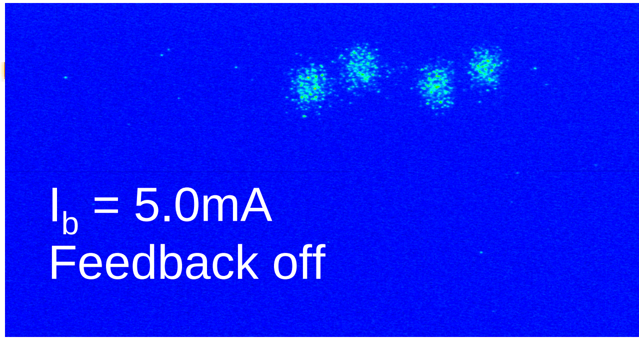


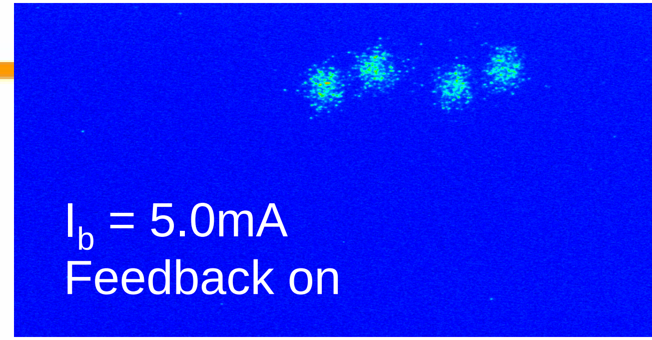


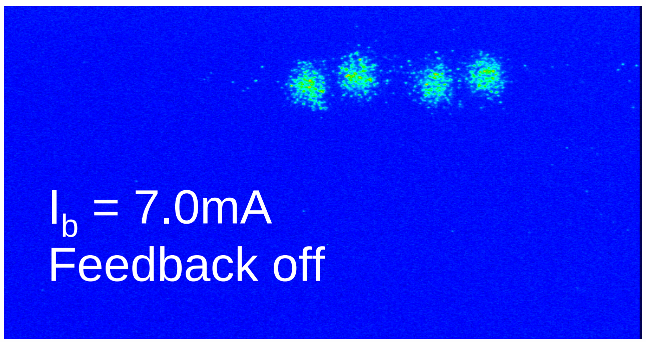


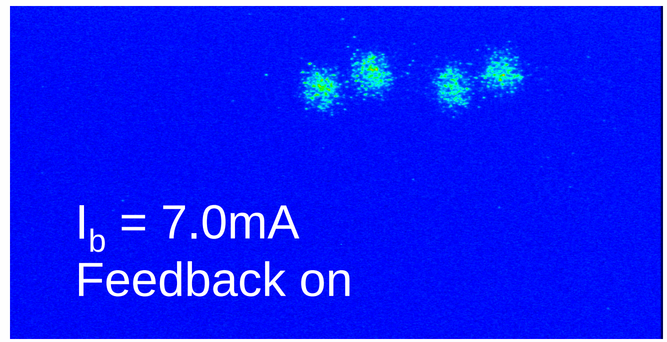
No blow-up in single bunch case when I_b increases

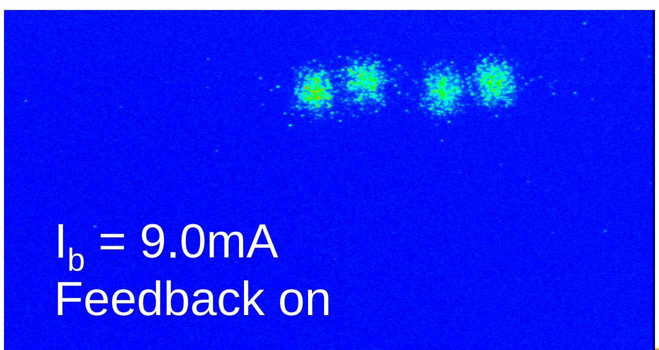
Positron bunch train (8 bunches, S_b = 8ns) case with different I_b





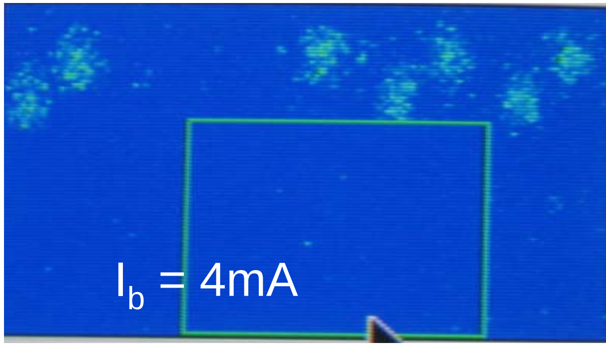


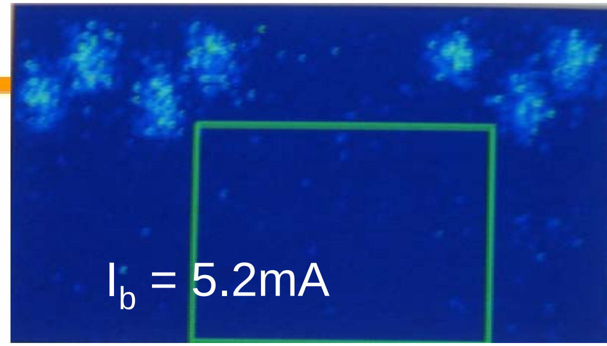


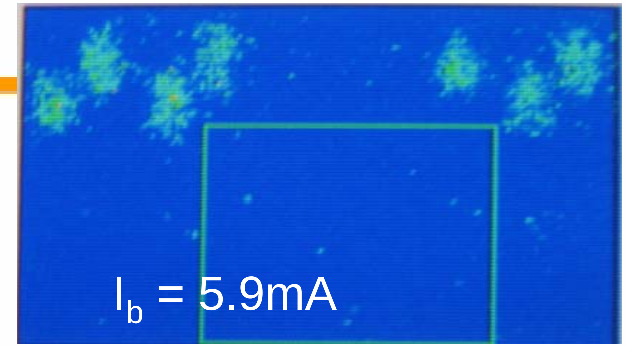


Vertical blow-up is not clearly
Feedback has no effect to the blow-up.

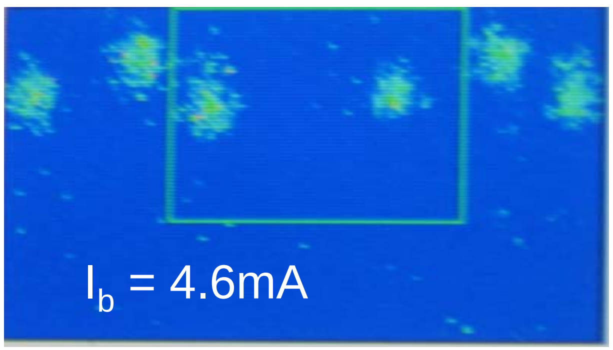
N_b = 93, bunch spacing = 4 RF buckets

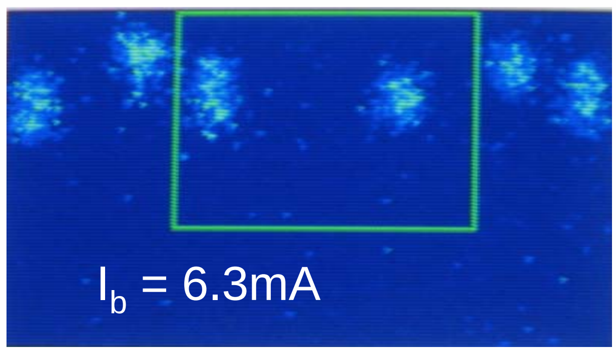


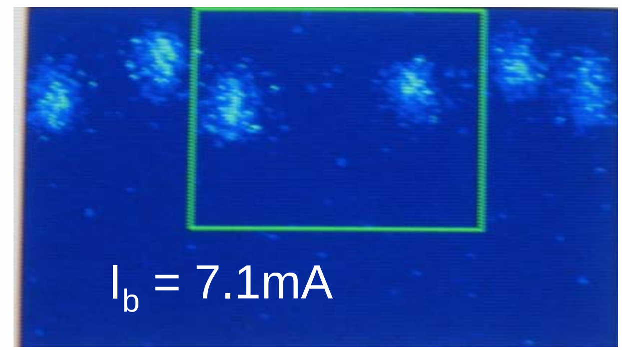


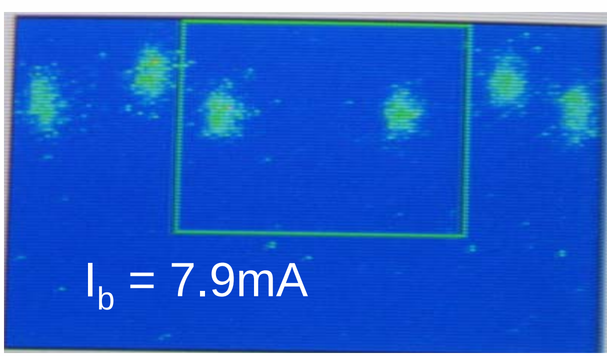


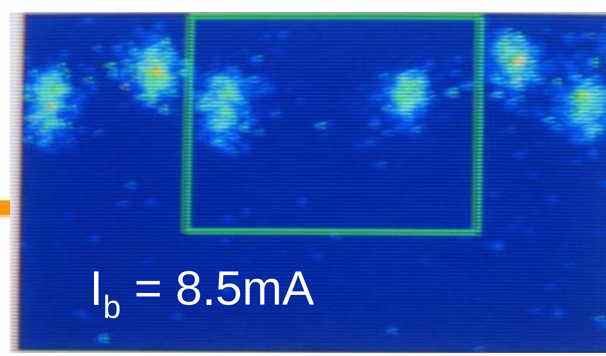
N_b = 63, bunch spacing = 6 RF buckets





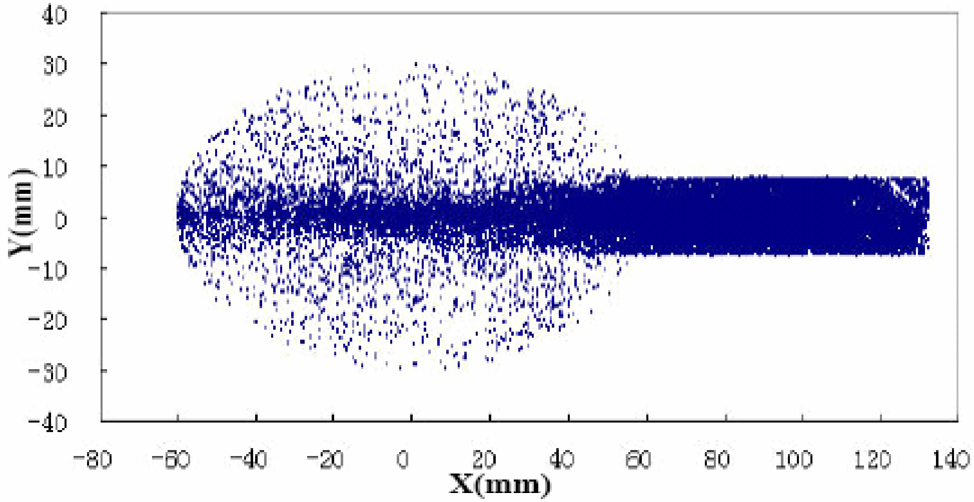


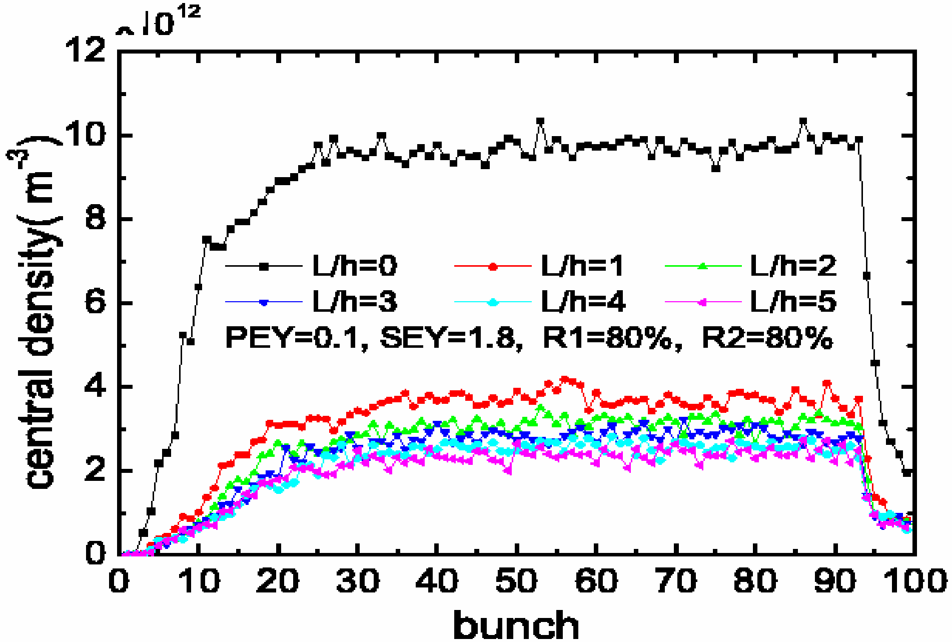




No clear blow-up in vertical between the head and tail bunches

- ECI Simulation results





5. Summary

- The two rings of the BEPCII reached their design parameters after optics corrections.
- Single and multi-bunch beam phenomena are understood by experimental studies.
- Collective effects, such as ECI, are observed and analyses are under way.
- Understanding the machine with more experiments is necessary.

Thanks for your attentions!