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Beam dynamics in ring and linac

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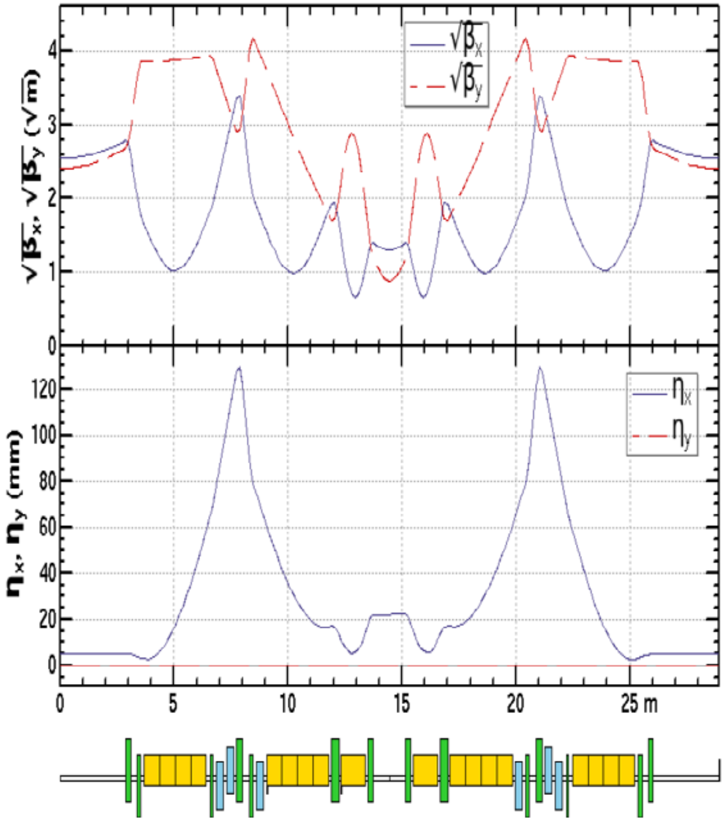
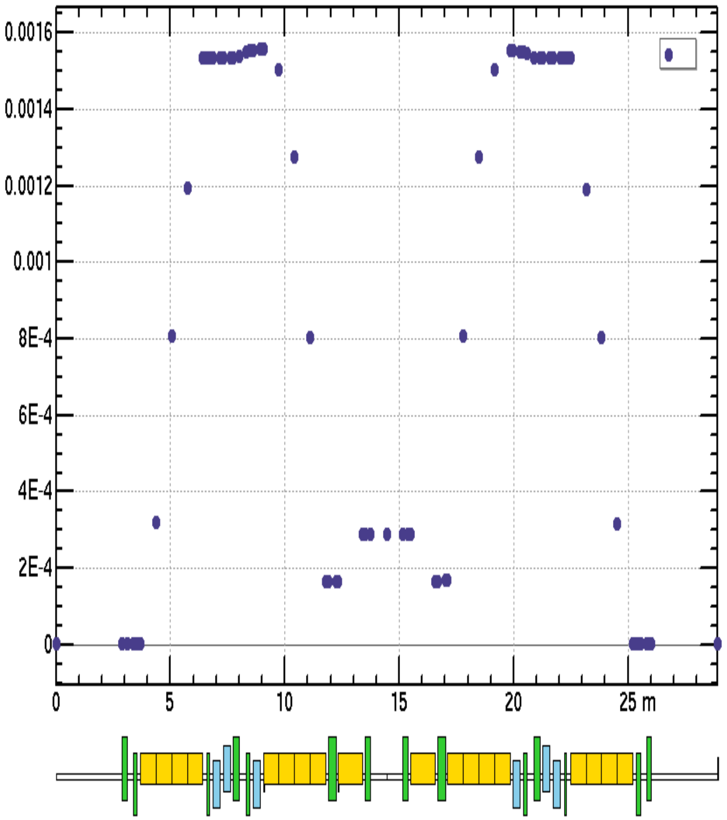
- Beam dynamics in 4 GeV light source
- Beam dynamics in ATF damping ring
- Beam dynamics in 2.5 GeV light source
- Beam dynamics in Energy Recovery Linac
- Beam dynamics in Free Electron Linac

Lattice design (by code SAD)



HMBA



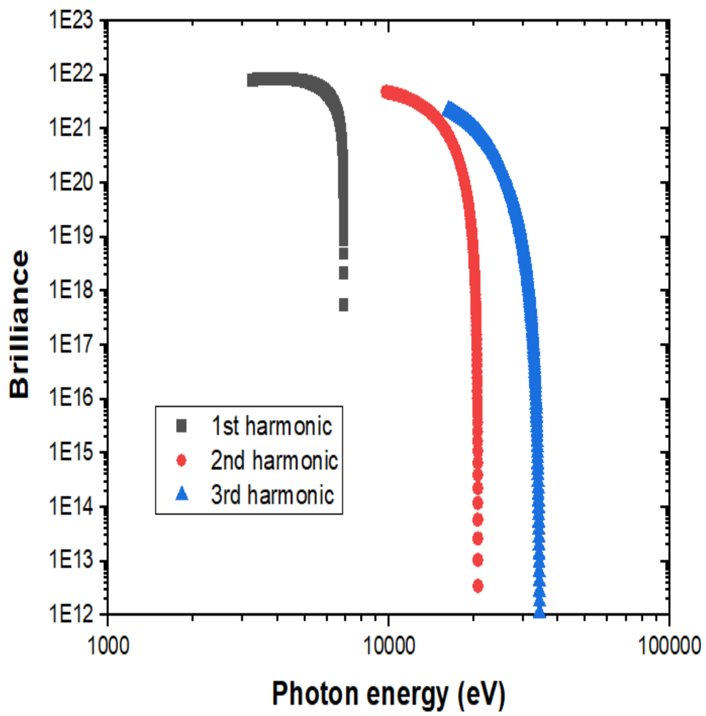
$H_x = \gamma\eta_x^2+2\alpha_x\eta_x\eta_{px}+\beta_x\eta^2_{px}$

Parameters	Value
Lattice type	HMBA
Beam energy (GeV)	4
Natural beam emittance (pm)	95
Number of cell	28
Circumference (m)	809.2
Magnetic field (T) in combined dipole	0.48
Gradient (T/m) in combined dipole	-26.3
RF frequency (MHz)	500
Harmonic number	1349
Number of cell	28
Rms energy spread	6.5×10^{-4}
Synchrotron frequency (kHz)	1.59
Beam size(x,y) at long straight section (μm)	24/7.5
Momentum compaction factor	1.4×10^{-4}
RF bucket height (%)	3.87
Energy loss per turn (MeV)	0.48
Touschek lifetime(hour) at 400 mA	3
Damping time (x/y/z)(ms)	29.7/44.4/29.4
Damping partition number (x/y/z)	1.49/1/1.5
RMS bunch length (mm)	2.68
RF voltage (MV)	2.5
Natural chromaticity(x/y)	-86.9/-76.4
Corrected chromaticity	0.1/0.1
Maximum strength (T/m^2) of sextupole	1750
Betatron tune (x/y)	64.29/22.85
Beta function (x/y)(m) in long straight section	6/6
Dispersion function(x)(cm)	
- in long/short straight section	0.6 /2.2

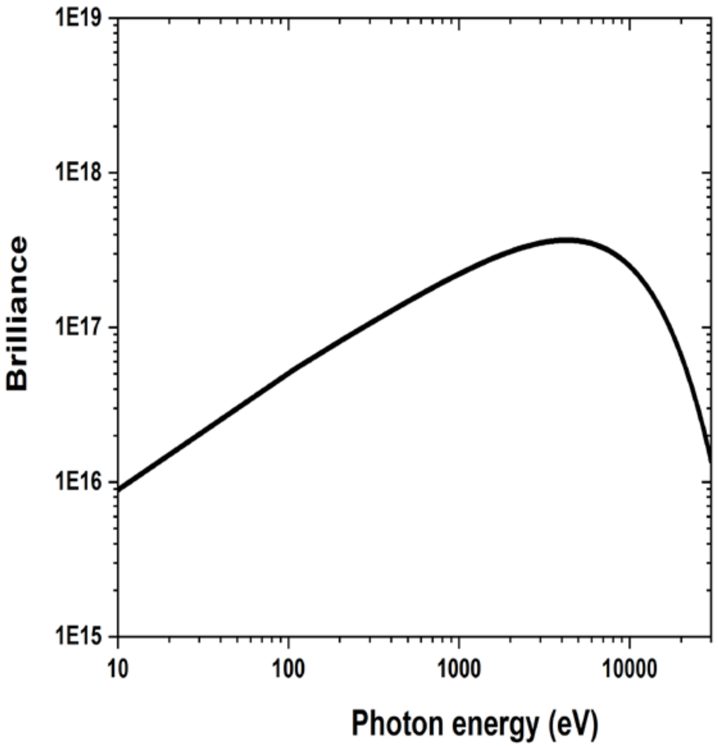
CEPC (APES) also uses code SAD for lattice design and beam simulations.

1. Beam dynamics in 4 GeV light source

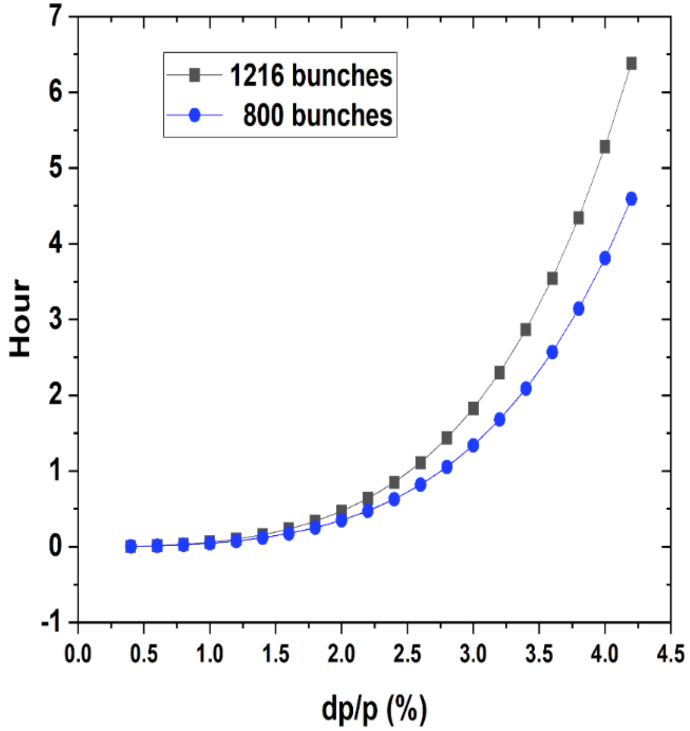
Brilliance and beam lifetime



In-vacuum undulator
(period 22mm, gap 8mm
L=4m K=1.52)



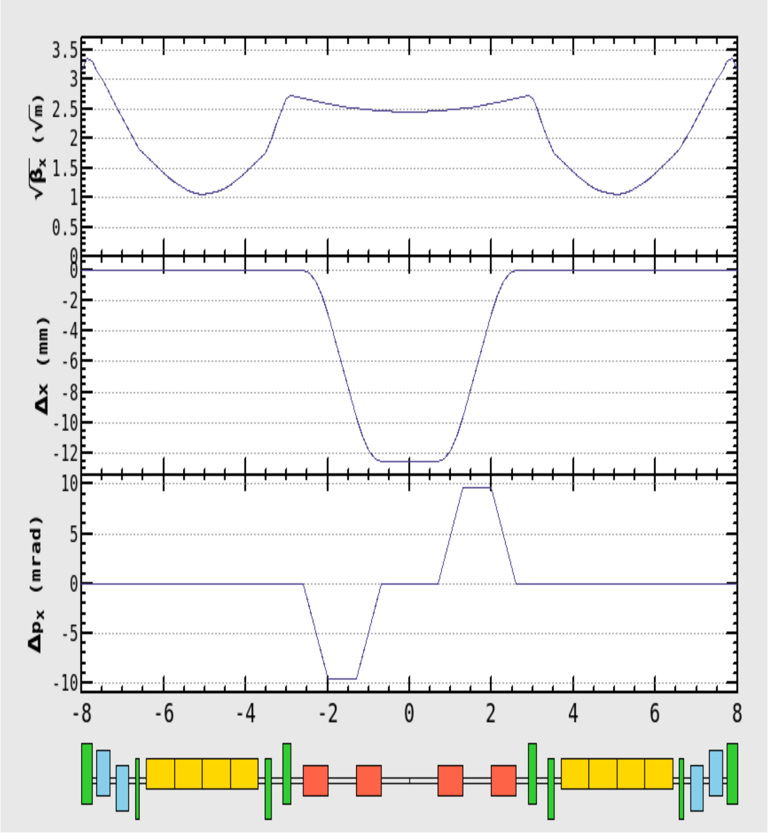
dipole



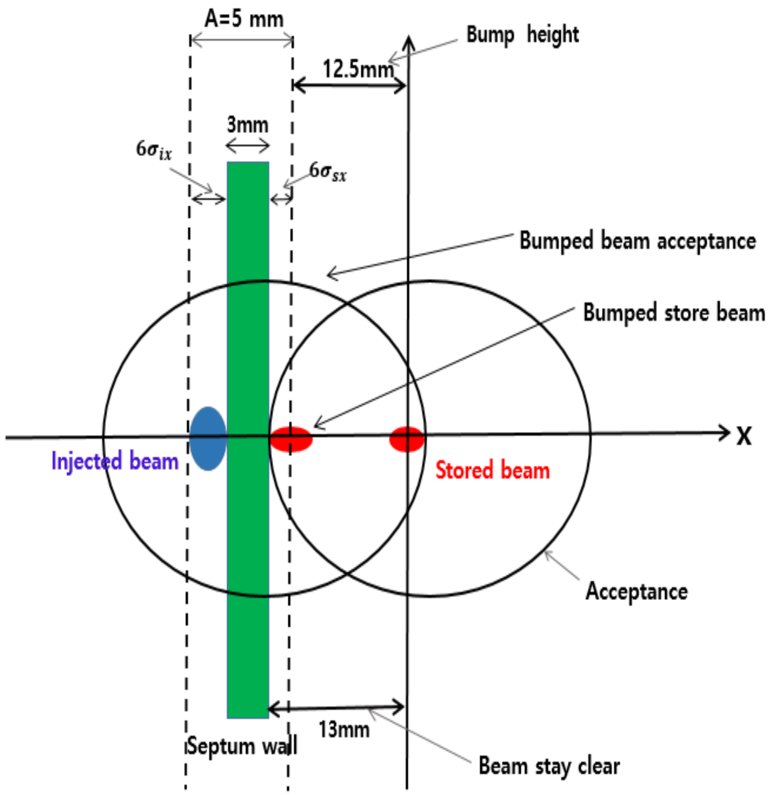
beam lifetime

1. Beam dynamics in 4 GeV light source

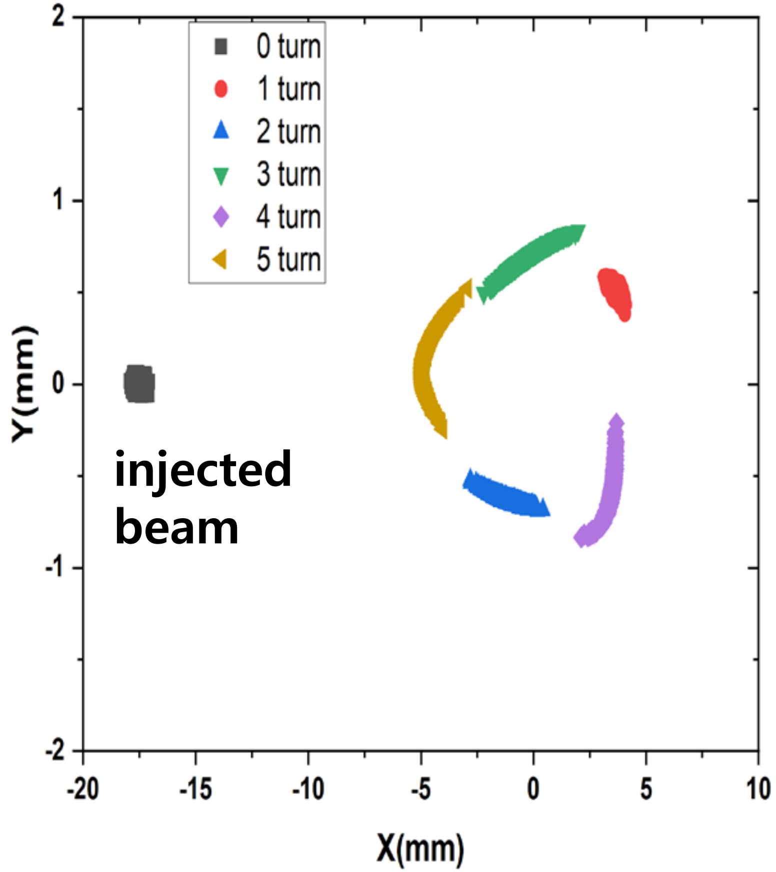
Beam injection by 4 kickers



Beta, bump height, kick angle



Horizontal space in injection scheme



Horizontal beam distribution after for 5 turns after injection

Resistive wall Wake

- **Short range longitudinal wake function**

$$W(s) = \frac{16}{a^2}\left[\frac{e^{-s/so}}{3}\cos\frac{\sqrt{3}s}{so} - \frac{\sqrt{2}}{\pi}\int_0^\infty \frac{dx\, x^2 e^{-x^2 s/so}}{x^6+8}\right]$$

- **Long range longitudinal wake function**

$$W(s) = -\sqrt{c/\sigma}/(2\pi a s^{3/2}).$$

- **Short range transverse wake function**

$$W(s) = \frac{8Zo\, c\, so}{\pi a^4}\left[\frac{-1}{12} e^{-\frac{s}{so}} \cos\left(\sqrt{3}\,\frac{s}{so}\right) + \frac{1}{4\sqrt{3}} e^{-s/so} \sin(\sqrt{3}\, s/so) + \frac{\sqrt{2}}{\pi}\int_0^\infty dx \frac{e^{-x^2 s/so}}{x^6+8}\right]$$

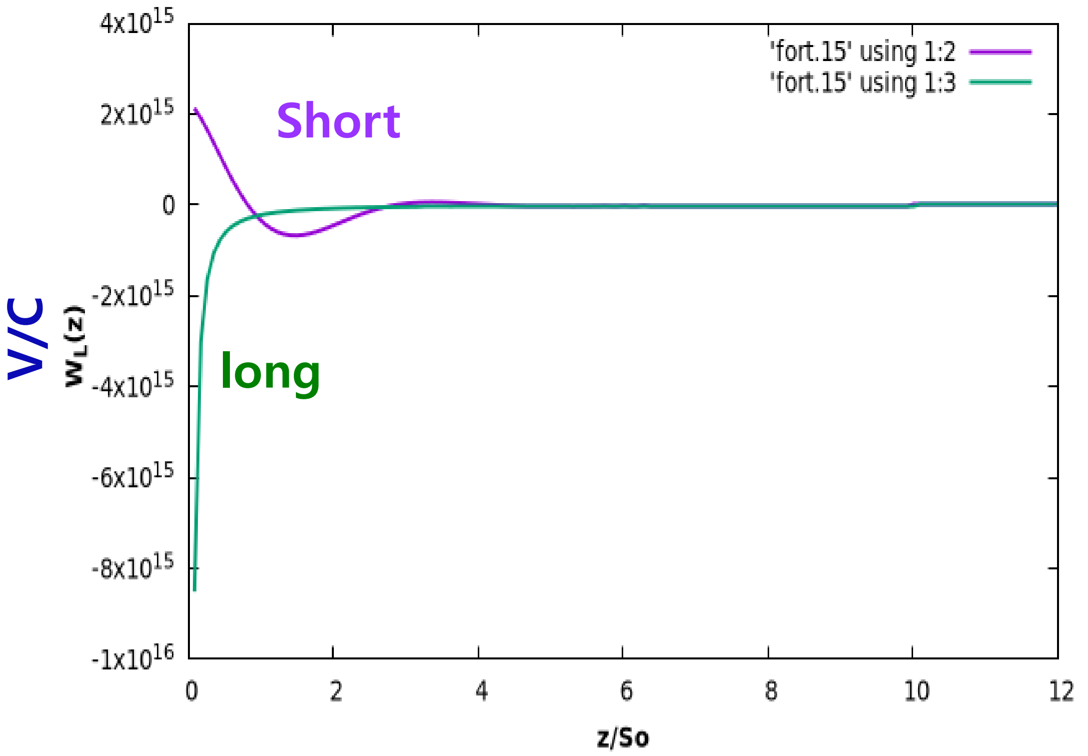
- **Long range transverse wake function**

$$W(s) = \frac{c}{\pi^{3/2} a^3}\sqrt{\frac{Zo}{\sigma s}}$$

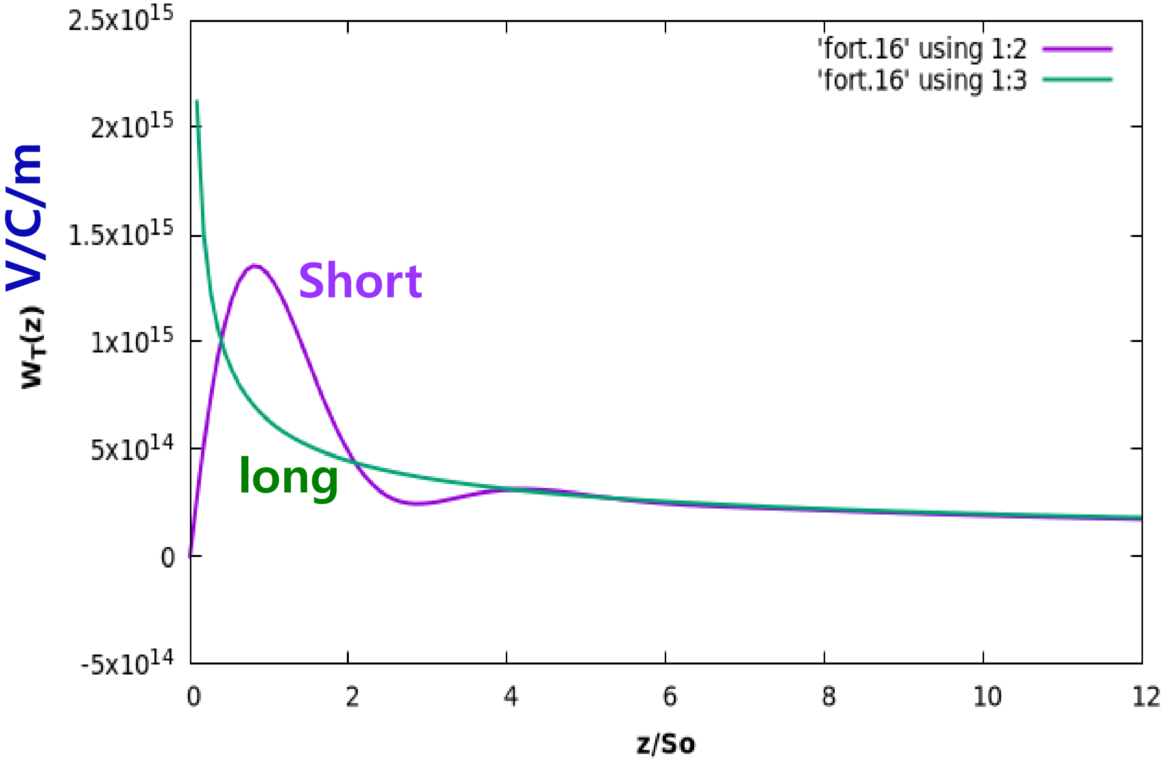
characteristic distance : $S_o=(2a^2/Z_o s)^{1/3}$

Resistive wall Wake

Short and long range longitudinal wakes

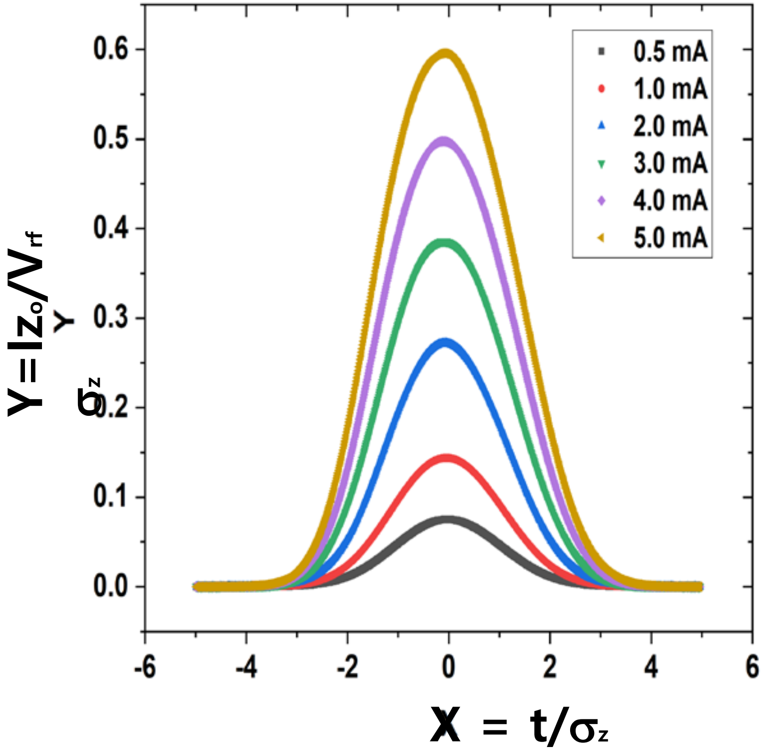


Short and long range transverse wakes

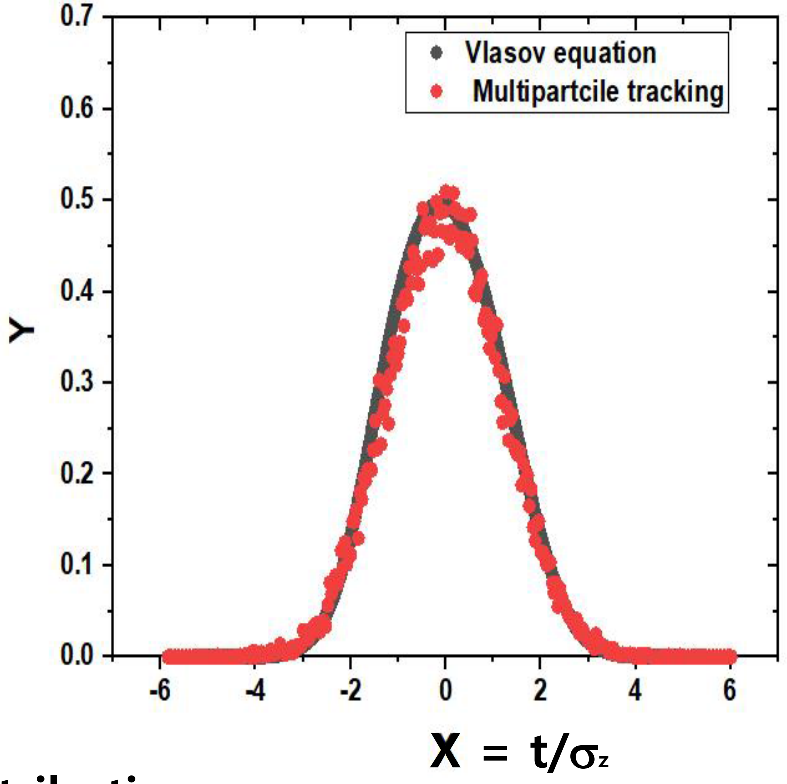


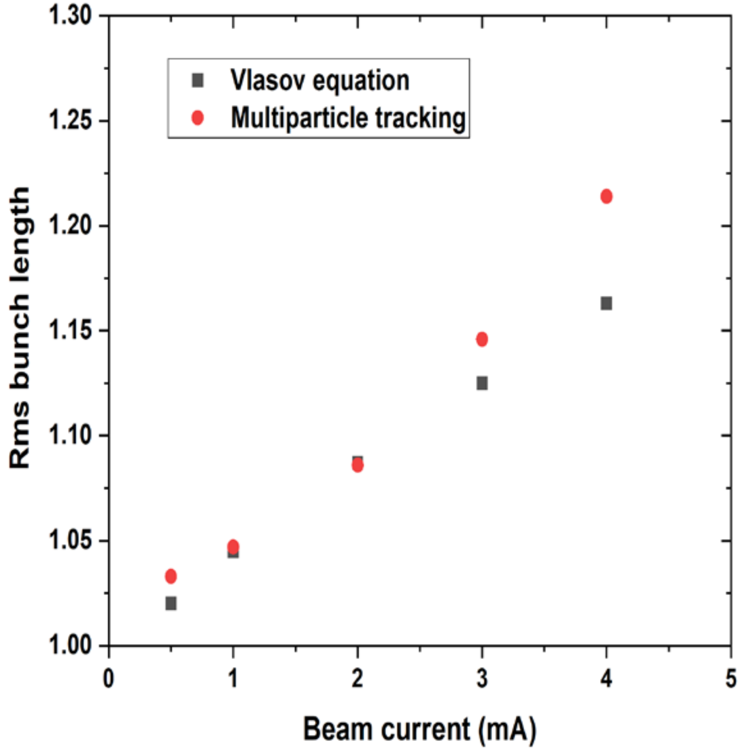
$S_o=(2a^2/Z_o s)^{1/3}$

Potential well distortions due to Resistive wall Wake



Calculated longitudinal beam distributions





Calculated bunch length for the different beam currents

Resistive wall Wake

Muilparticle tracking (binning method)

Longitudinal wake (for i^th macroparticle)

$$W_o(z_i(n)) = -\frac{eN_b}{N_p} \sum_j^{z^i(n)<z^j(n)} N_j W_o'(z^i(n) - z^j(n))$$

wake between different bins (z^i and z^j)

$$-\frac{eN_b}{N_p} \sum_j^{z_i(n)<z_j(n)} W_o'(z_i(n) - z_j(n))$$

wake between macroparticle in a same bin

Transverse wake (for i^th macroparticle)

$$W_i^x(z_i(n)) = -\frac{eN_b}{N_p} \sum_j^{z^i(n)<z^j(n)} \bar{x}^j(n) N_j W_T(z^i(n) - z^j(n))$$

N_b : bunch population, N_p : number of macroparticles

$\bar{x}^j$ **: average horizontal or vertical displacements of the preceeding particles**

Muilparticle tracking simulation (x,x',y,y',z,ε)

$$\epsilon_i(n) = \epsilon_i(n-1) - \frac{2T_o}{\tau_d}\epsilon_i(n-1) + 2\sigma_{\epsilon o} \sqrt{\frac{T_o}{\tau_d}} r_{1i}(n) + V'_{rf} z_i(n-1) + W(z_i)(n),$$

$$z_i(n) = z_i(n-1) + \frac{\alpha c T_o}{E_o}\epsilon_i(n),$$

$$V'_{rf} = 2\pi\nu_{rf}\hat{V}_{rf}[1-(U_o/\hat{V}_{rf})^2]^{1/2}.$$

$$x_i(n) = M_{11}[\epsilon_i(n)]x_i(n-1) + M_{12}[\epsilon_i(n)]x'_i(n-1)(1-\frac{T_o}{\tau_x}) + \sqrt{\frac{2\epsilon_z\beta_x T_o}{\tau_x}} r_{1i}(n) + M_{12}[\epsilon_i(n)]\frac{W_i^x(n-1)}{E_o},$$

$$x'_i(n) = M_{21}[\epsilon_i(n)]x_i(n-1) + M_{22}[\epsilon_i(n)]x'_i(n-1)(1-\frac{T_o}{\tau_x}) + \sqrt{\frac{2\epsilon_z T_o}{\beta_x\tau_x}} r_{2i}(n) + M_{22}[\epsilon_i(n)]\frac{W_i^x(n-1)}{E_o},$$

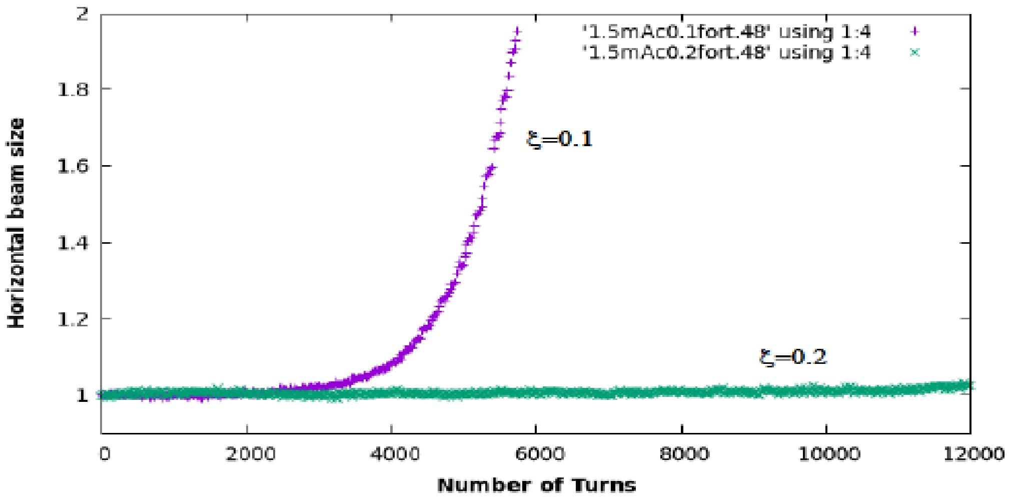
$$M(\epsilon) = \begin{bmatrix} cos2\pi Q_x(\epsilon) & \beta_x sin2\pi Q_x(\epsilon) \\ -1/\beta_x sin2\pi Q_x(\epsilon) & cos2\pi Q_x(\epsilon) \end{bmatrix},$$

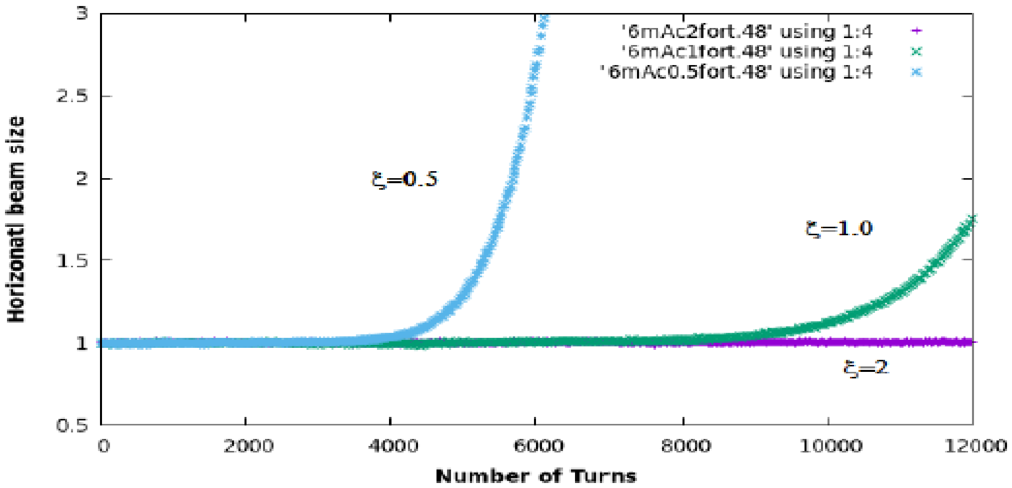
$Q_x(\varepsilon) = Q_x(1+\varepsilon\xi/Eo)$ (ξ : chromaticity)

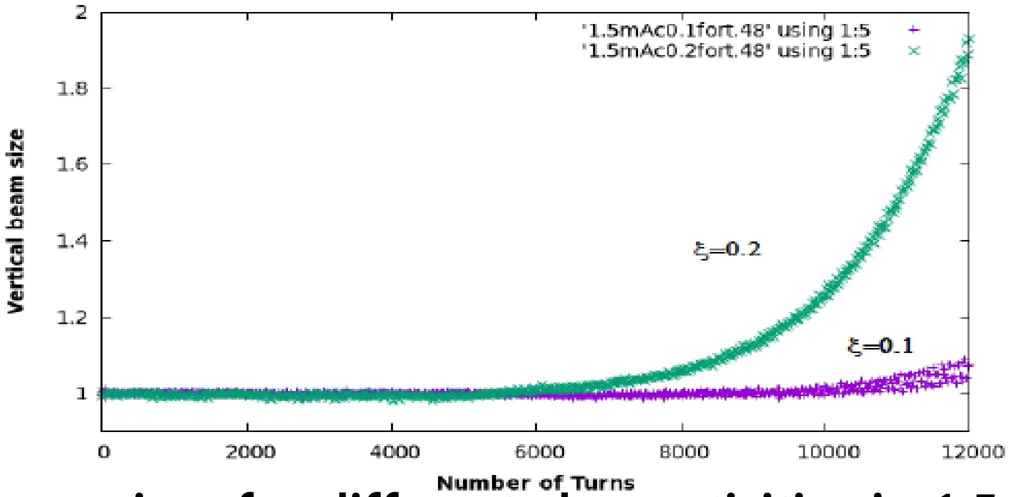
1. Beam dynamics in 4 GeV light source

Resistive wall Wake

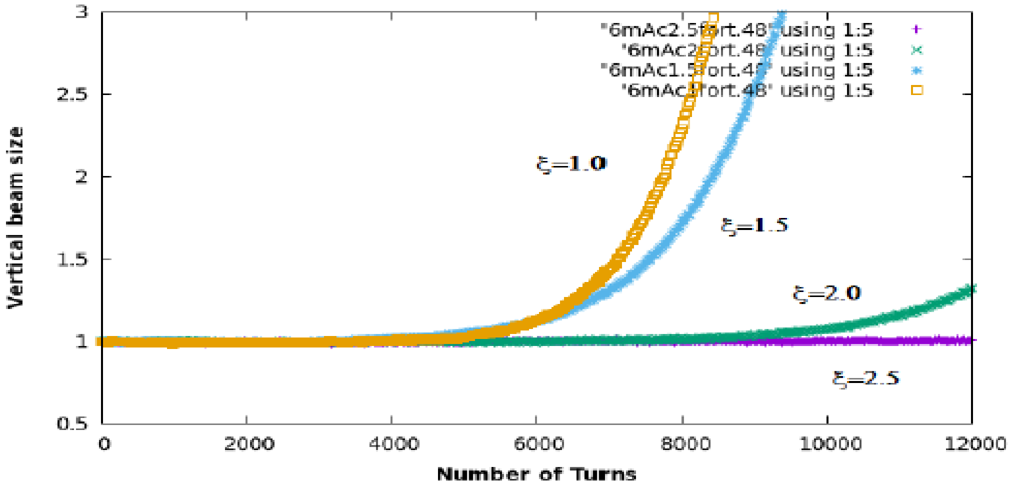
Beam sizes due to chromaticity







beam sizes for different chromaticities in 1.5 mA

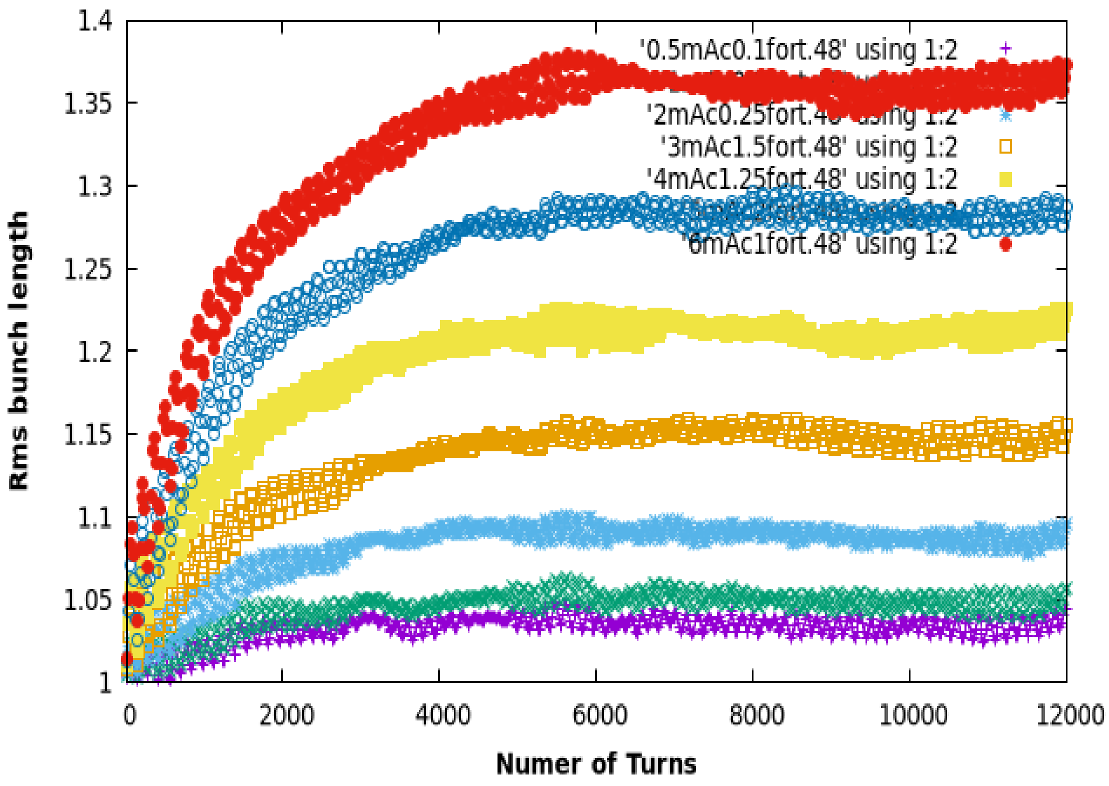


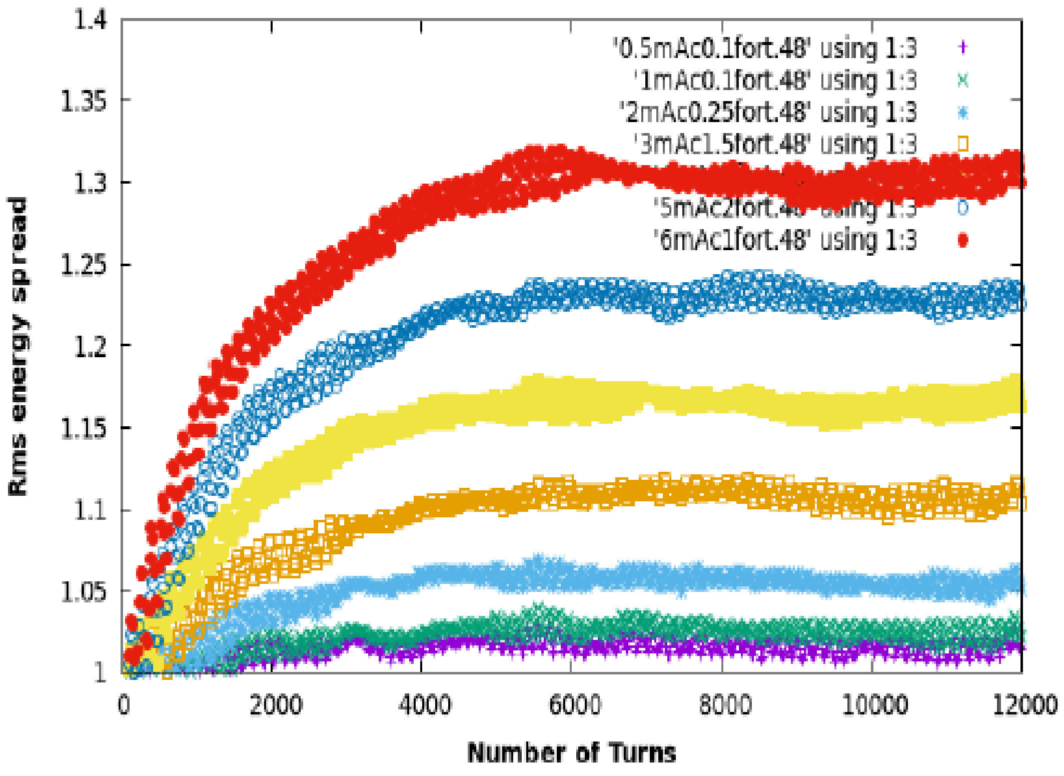
beam sizes for different chromaticities at 6 in mA

1. Beam dynamics in 4 GeV light source

Resistive wall Wake

Bunch length and energy spread vs beam current

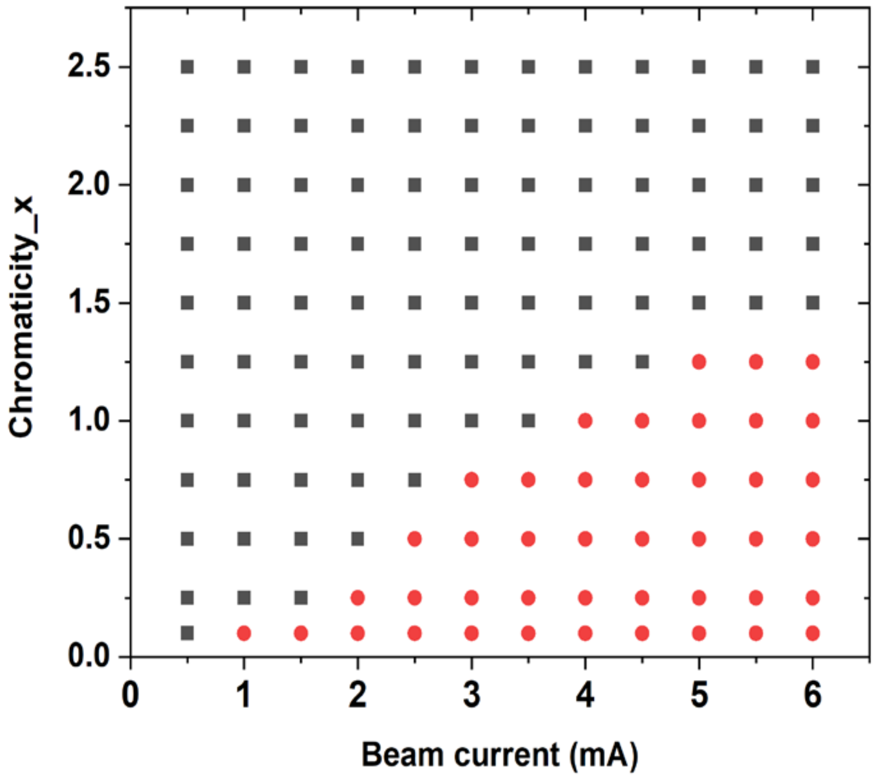


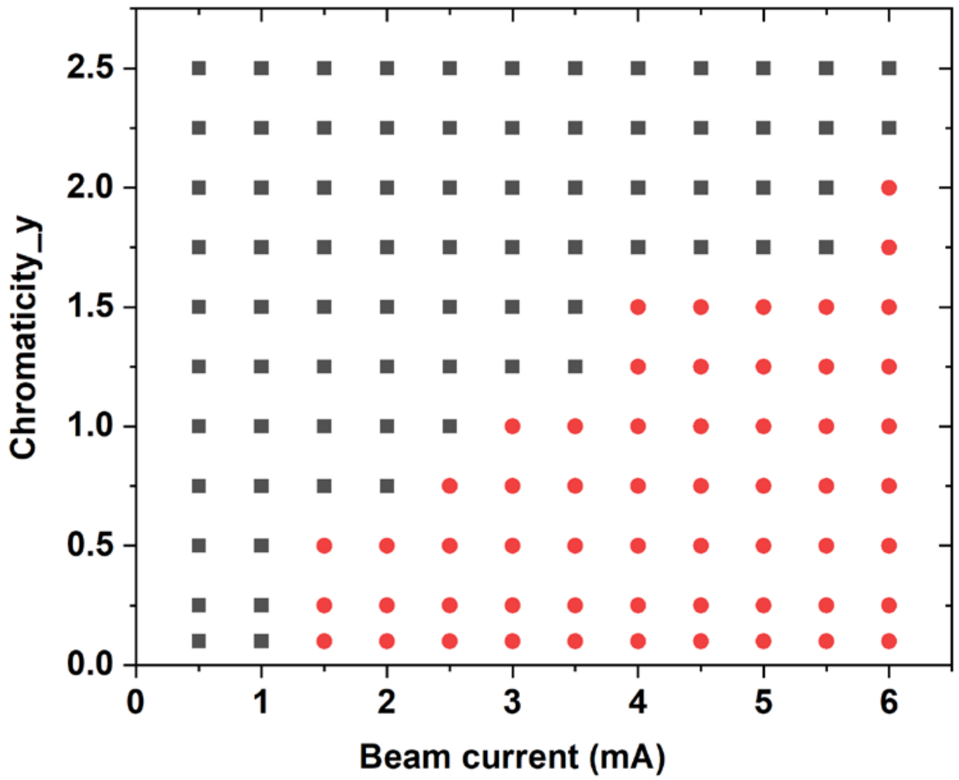


Bunch length and energy spread for the different beam currents (6mA to 0.5mA)

Resistive wall Wake

Transverse instability at chromaticities for different beam currents





Black and red dots indicate that the beam size is not increased and increased due to the wake, respectively.

1. Beam dynamics in 4 GeV light source

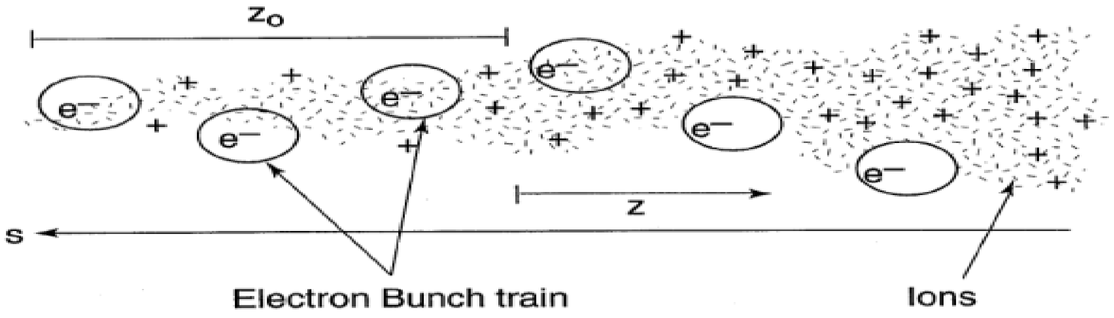
Fast-ion instability

■ In electron storage rings, **residual gas molecules can be ionized by the beam. The resulting positive ions are trapped in the electric field of the beam**, and accumulate to high density. → **The fields of the ions can then drive beam instabilities.**

■ While electrons move rapidly on the time scale of a single bunch passage, ions move relatively slowly. The dynamical behaviour is then somewhat different.

■ If a storage ring is uniformly filled with electron bunches, then ions accumulate over many turns. This leads to the well-known phenomenon of ion trapping, which is usually solved by including "gaps" in the fill pattern.

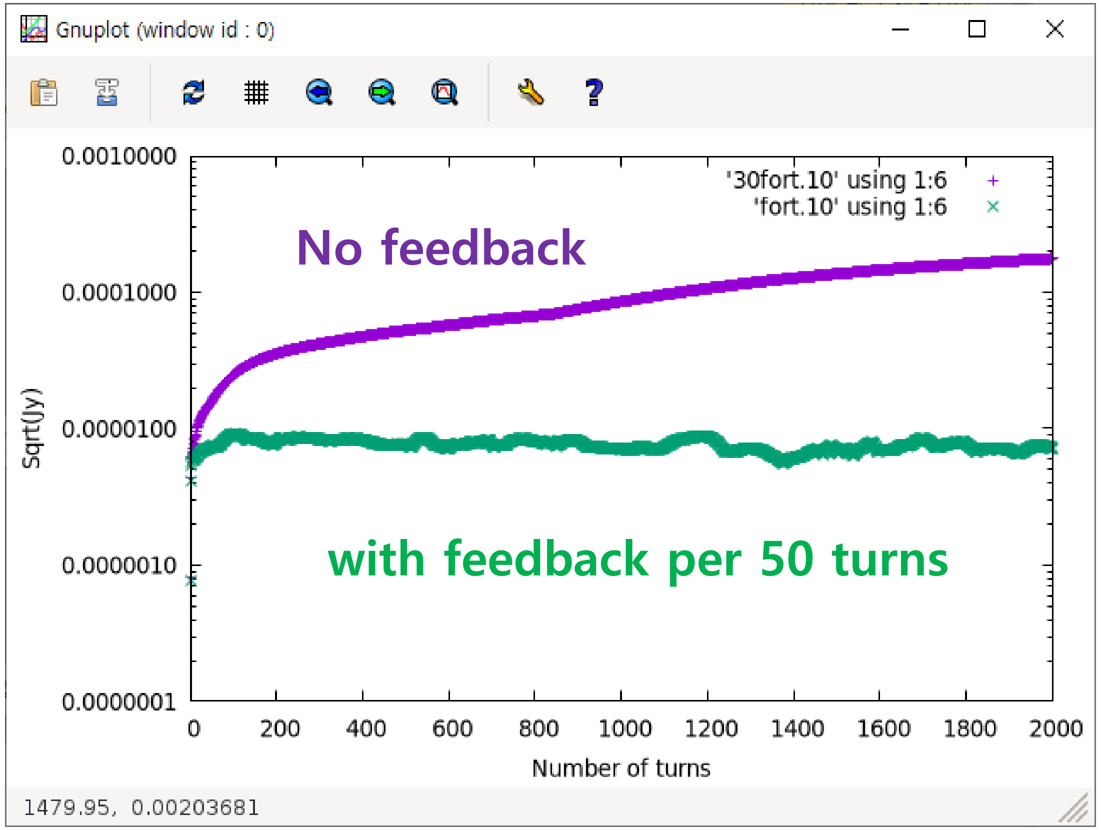
■ Under certain conditions, sufficient ions can accumulate in the passage of a small number of bunches to drive an instability, known as the "fast ion instability".

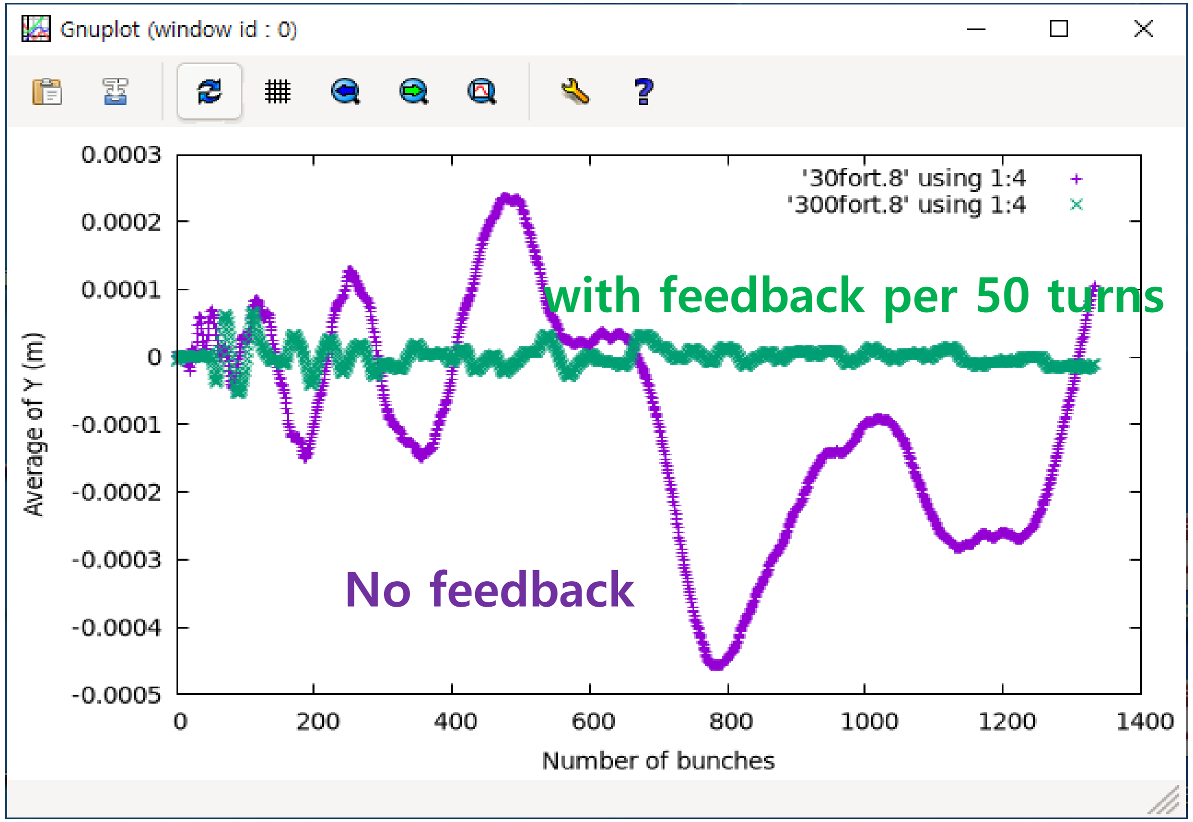


1. Beam dynamics in 4 GeV light source

Fast-ion instability

1332 bunches 400 mA 0.1 nT





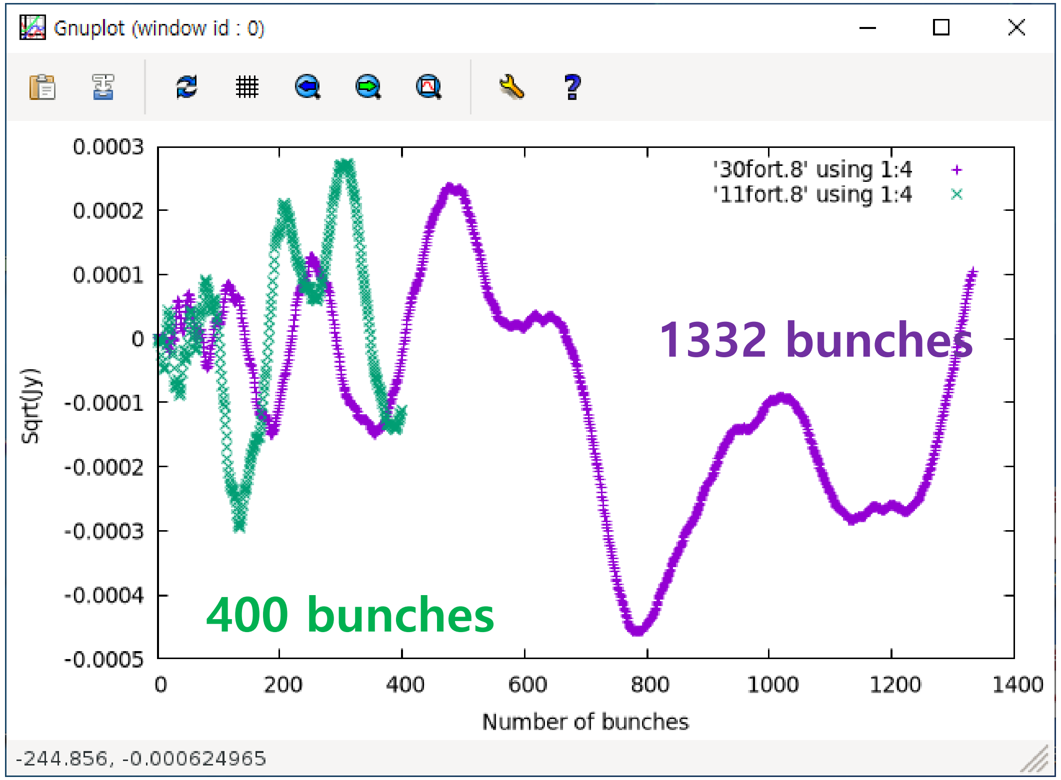
Vertical oscillation amplitude of the bunch centroid is half of the Courant–Synder invariant

$$J_y = [\gamma y^2 + 2\alpha y y' + \beta y'^2]/2$$

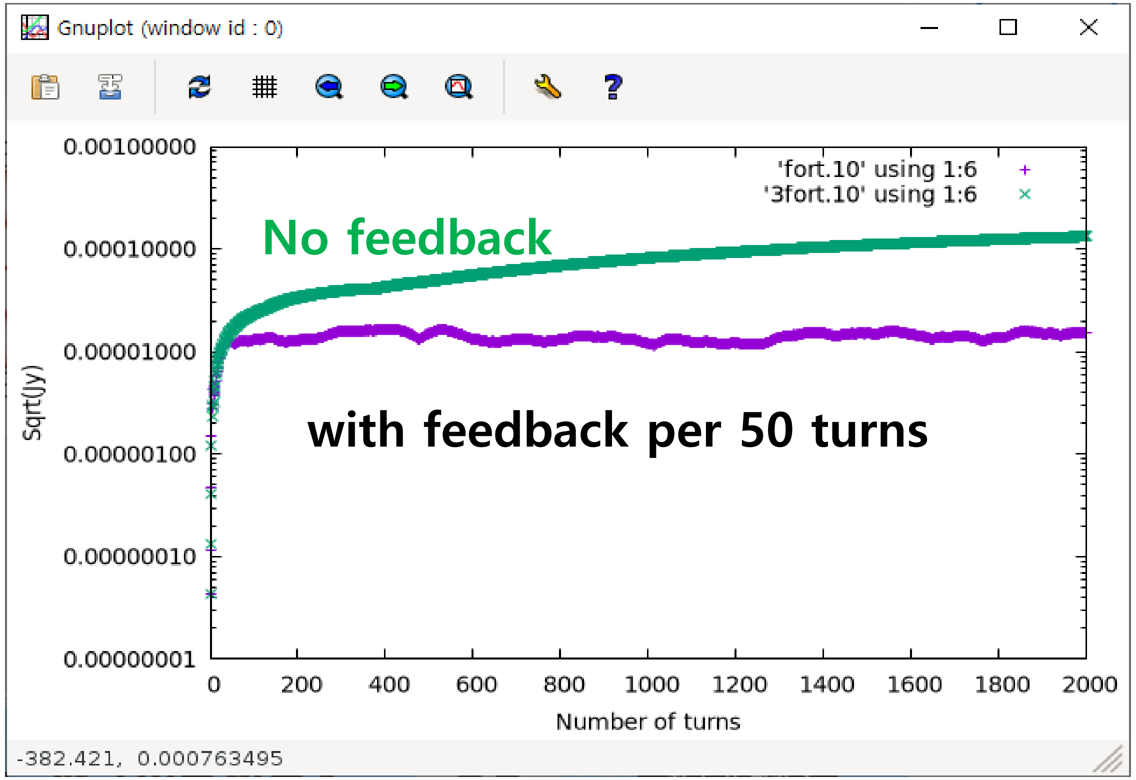
Fast-ion instability

400 mA and 0.1 nT

1 train case of 1332 and 400 bunches

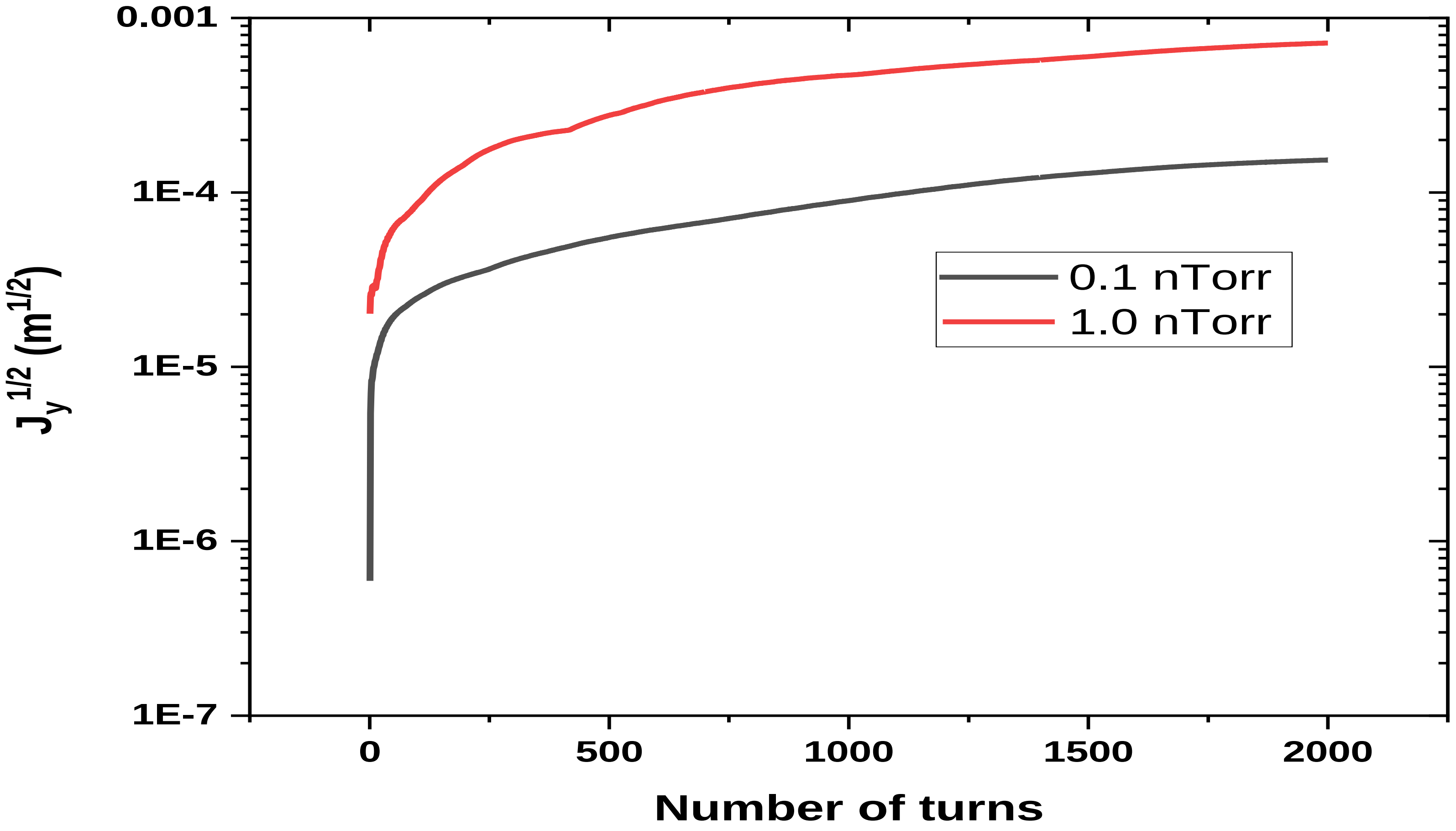


400 bunches with 4 trains (233 buckets are empty between trains)



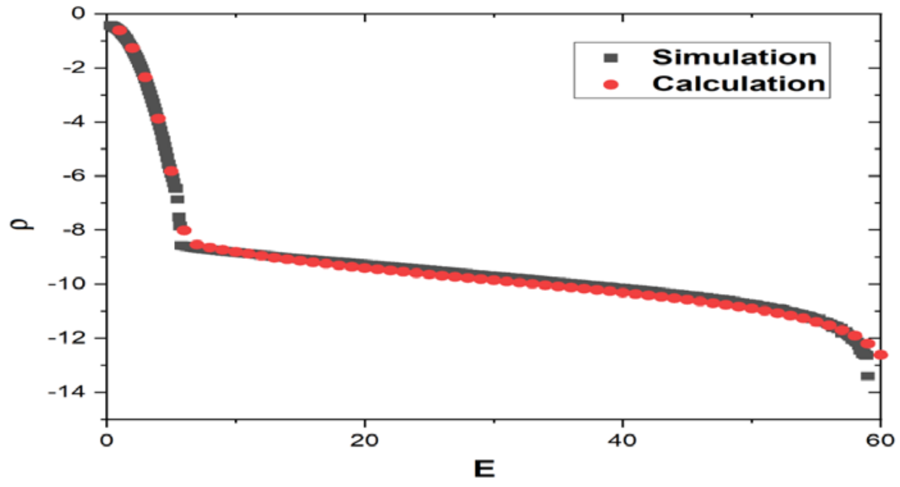
Fast-ion instability

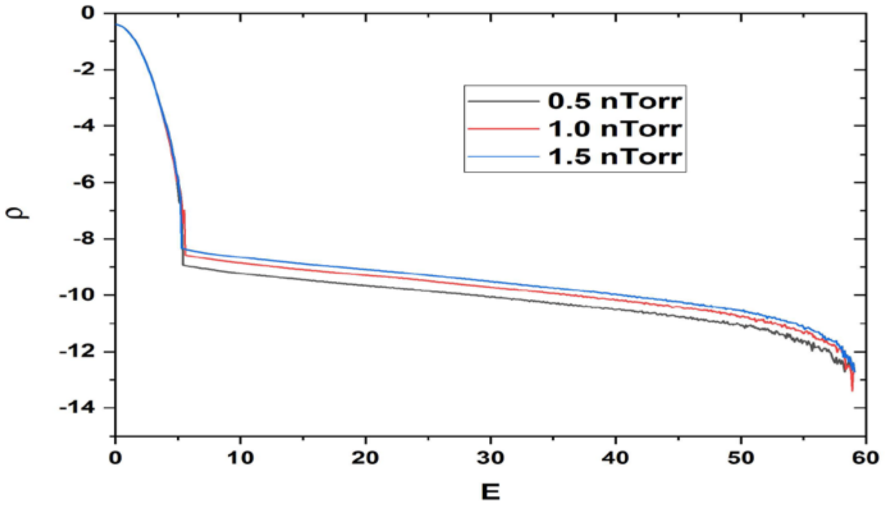
400 mA



1. Beam dynamics in 4 GeV light source

Beam tail distribution due to beam-gas Bremsstrahlung





$$\rho(\mathrm{E}) = \frac{1}{\pi}\int \mathrm{dK}\cos(\mathrm{KE})\exp\left[-\frac{\mathrm{K}^2}{2} + \frac{\mathrm{N}\tau_\epsilon}{2}\hat{f}\left(\frac{\mathrm{K}}{\mathrm{E}_0\sigma_\epsilon^0}\right)\right]$$

Simulation result

Energy aperture	1 nTorr	1.5 nTorr
2.5 %	41.1 h	28.1 h
3.0 %	44.6 h	29.3 h
3.87%	48.5 h	33.1 h

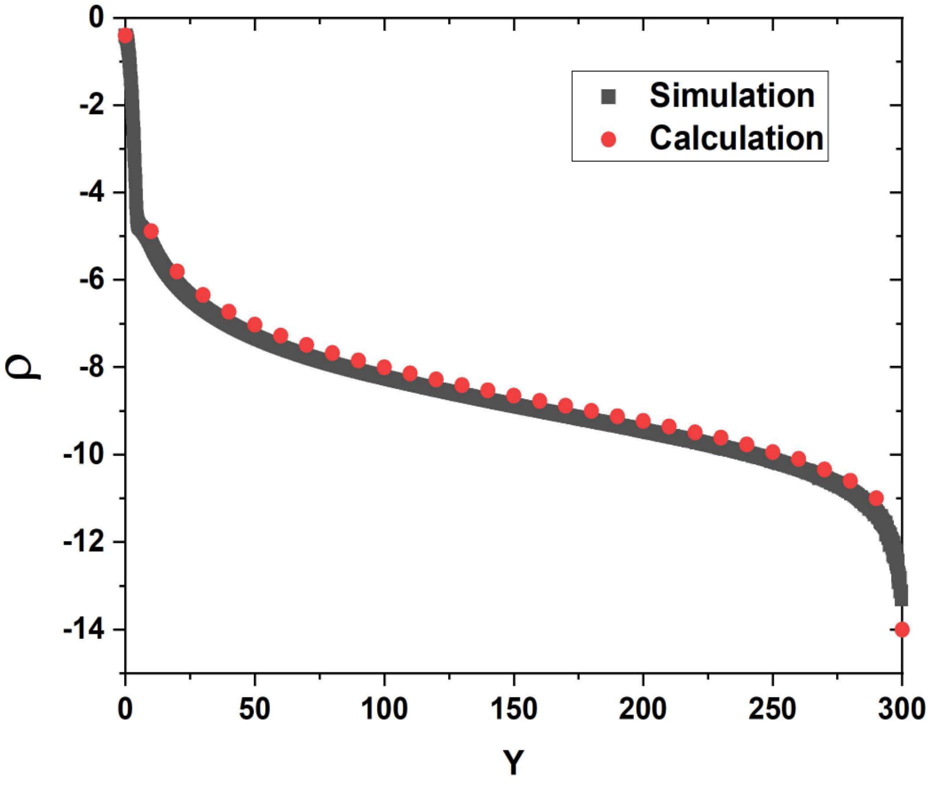
Calculation result

Energy aperture	1 nTorr	1.5 nTorr
2.5 %	43.7 h	29.1 h
3.0 %	45.7 h	30.5 h
3.87%	49.4 h	32.9 h

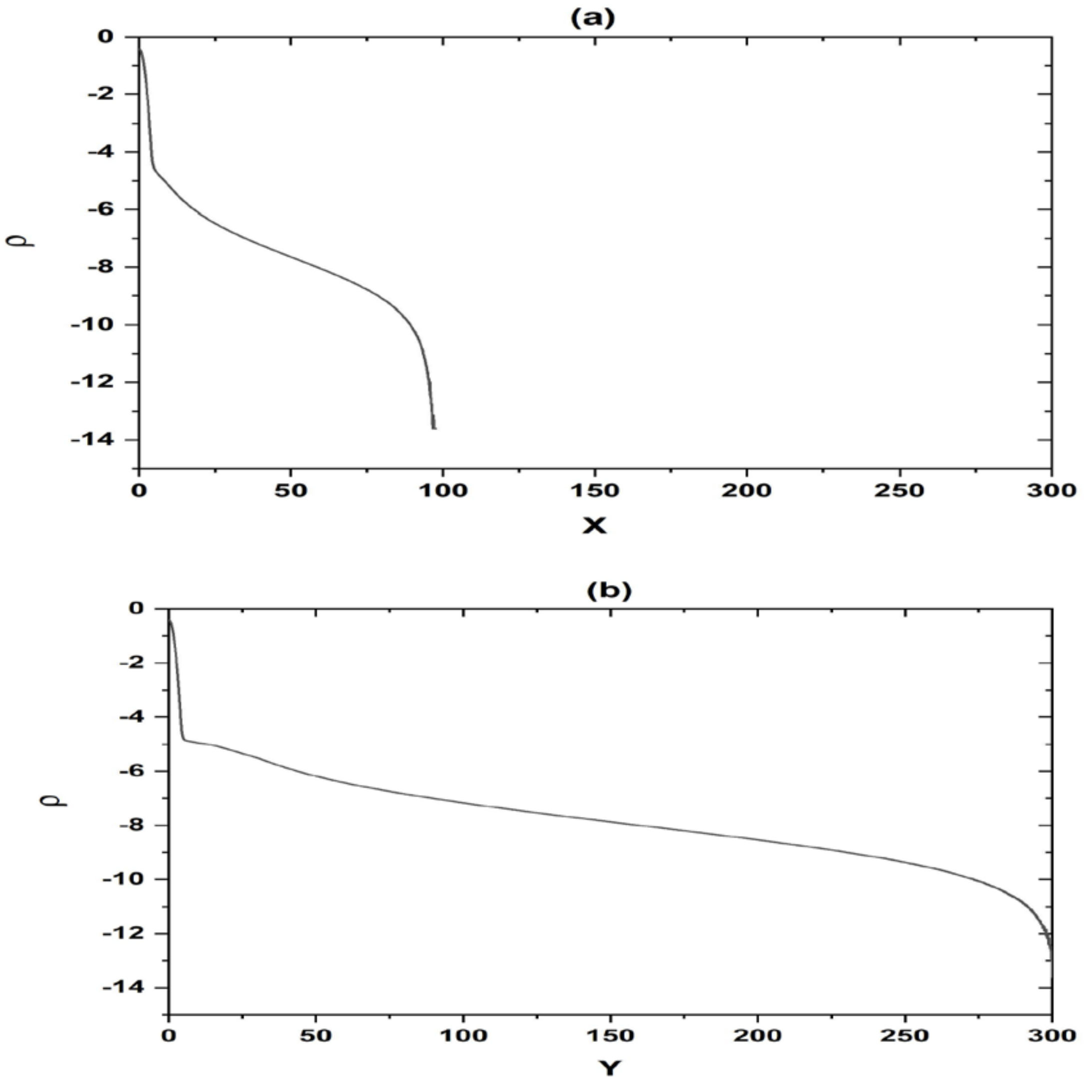
Both simulation and calculation results agree well.

1. Beam dynamics in 4 GeV light source

Beam tail distribution due to beam-gas scattering

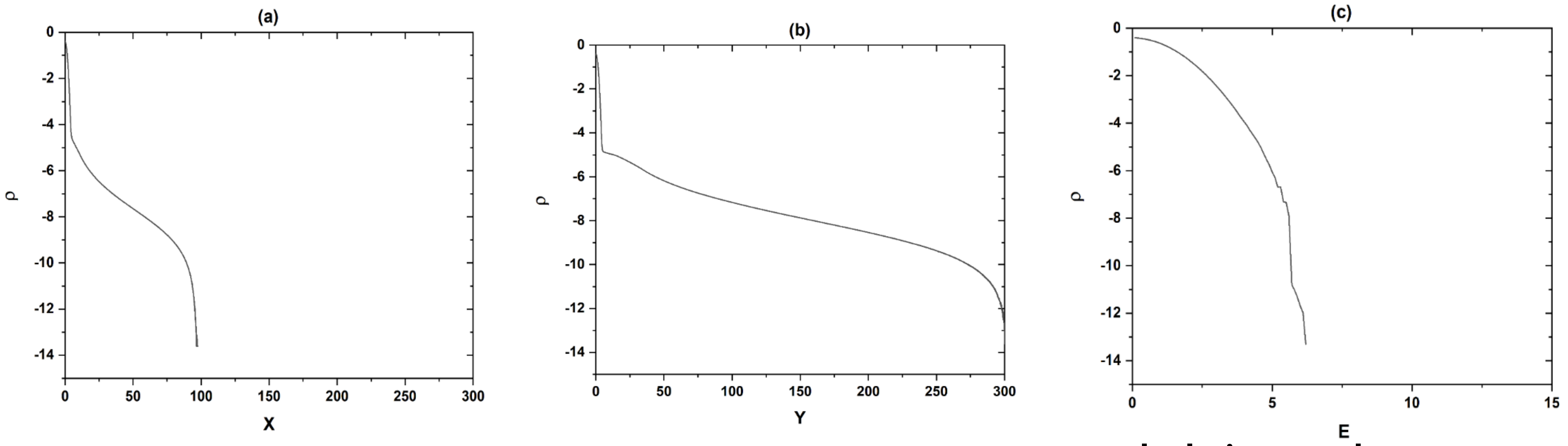


$$\rho(\mathrm{X}) = \frac{1}{\pi}\int \mathrm{dK}\cos(\mathrm{KX})\exp\left[-\frac{\mathrm{K}^2}{2} + \mathrm{N}\tau\hat{f}\left(\frac{\mathrm{K}}{\sigma'_x}\right)\right]$$



1. Beam dynamics in 4 GeV light source

Beam tail distribution due to intra-beam scattering



Simulation result

Vertical aperture	300 σy	400 σy	500 σy
Residual gas scattering	21.2 h	37.5 h	58.8 h
Intra-beam scattering	1.6 h	2.5 h	3.6 h

calculation result

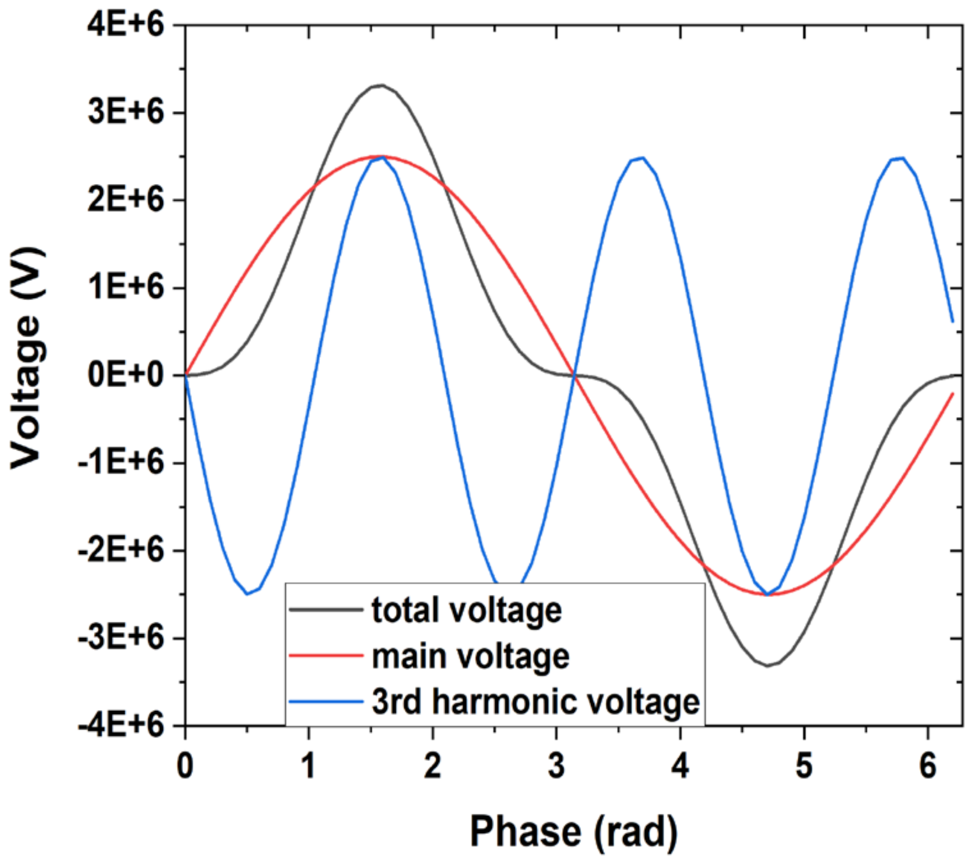
Vertical aperture	300 σy	400 σy	500 σy
Residual gas scattering	21.7 h	38.7 h	60.5 h
Intra-beam scattering	1.67 h	2.87 h	4.3 h

Both simulation and calculation results agree well.

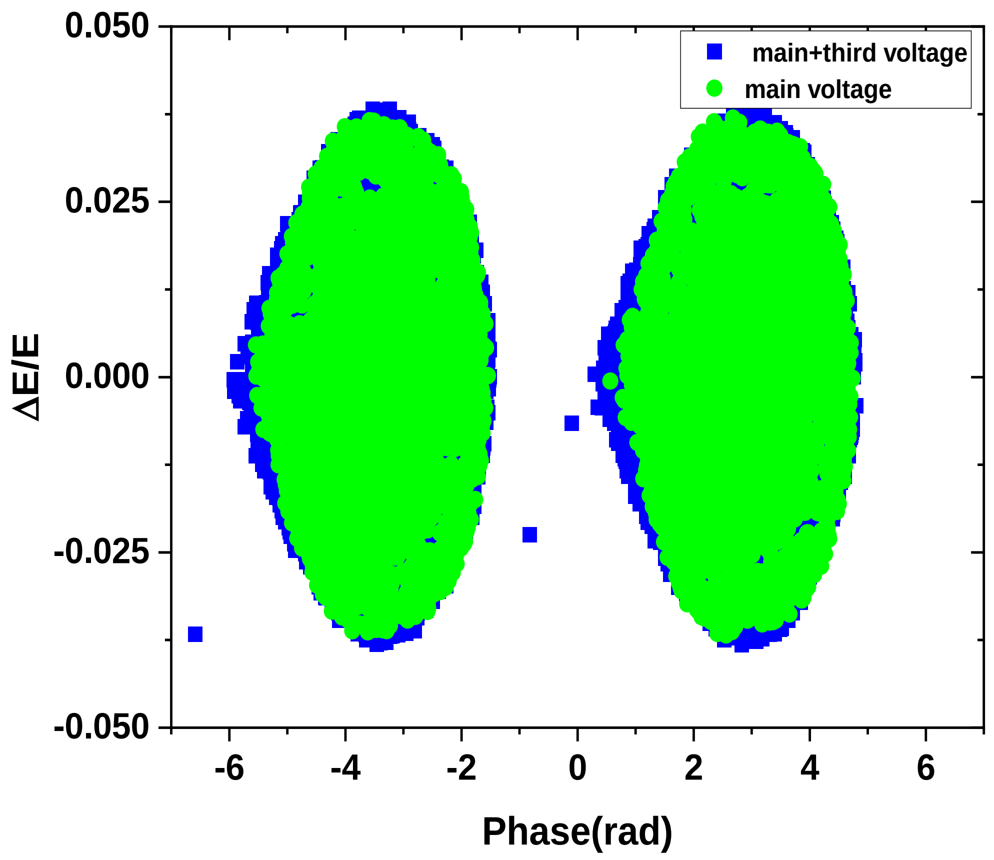
Total beam lifetime : 3.2 hour for 400 mA and 1 nTorr

1. Beam dynamics in 4 GeV light source

Bunch-lengthening due to 3rd harmonic cavity (1.5 GHz)



Rf voltages seen by a bunch for bunch lengthening



RF buckets with with and without third-harmonic voltage for bunch lengthening

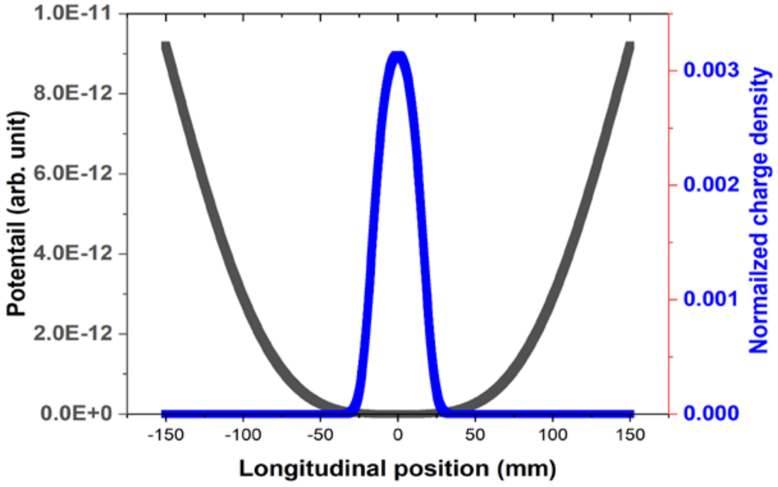
1. Beam dynamics in 4 GeV light source

Bunch-lengthening due to 3rd harmonic cavity

$V_{3rd\ rf} / V_{M\ rf} = 0.32$
$\phi_{3rd} = 1.047$ rad

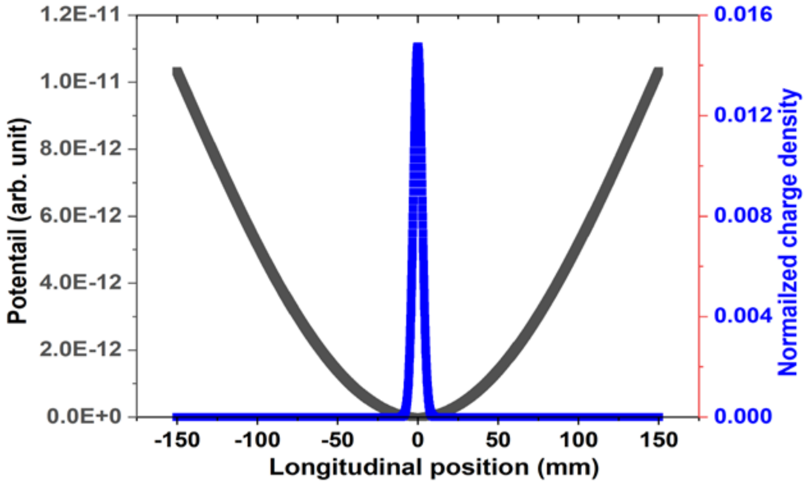
bunch-lengthening : factor of 3.5

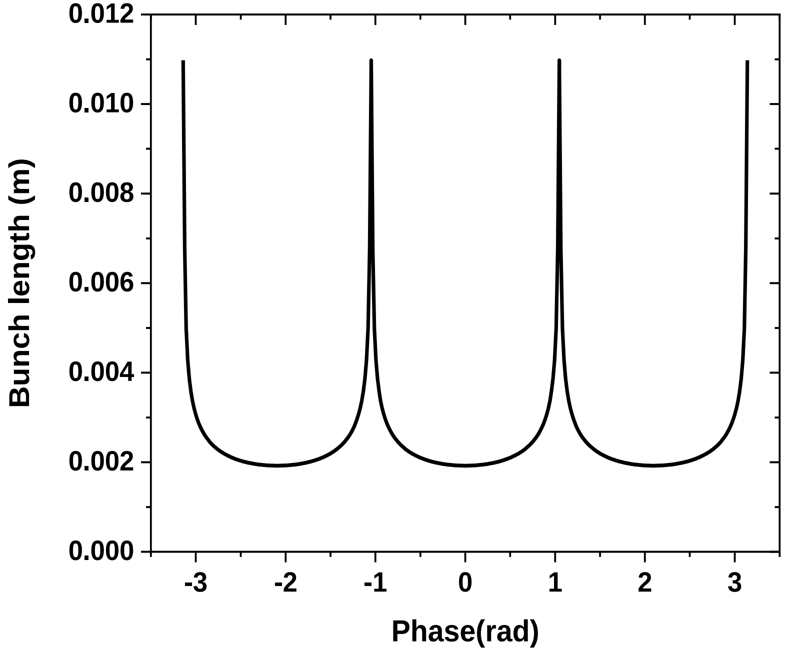
with harmonic cavity



Potential-Well and longitudinal beam distributions

without harmonic cavity





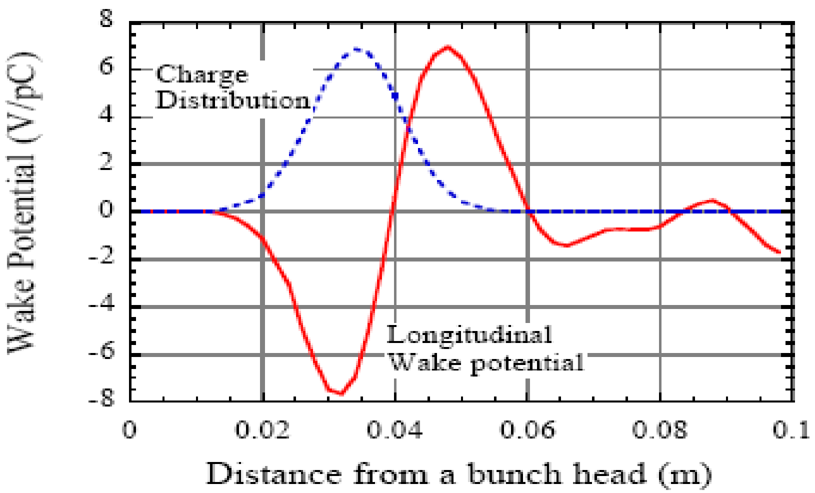
Bunch length as a function of phase angle in 3rd harmonic cavity

2. Beam dynamics in ATF damping ring

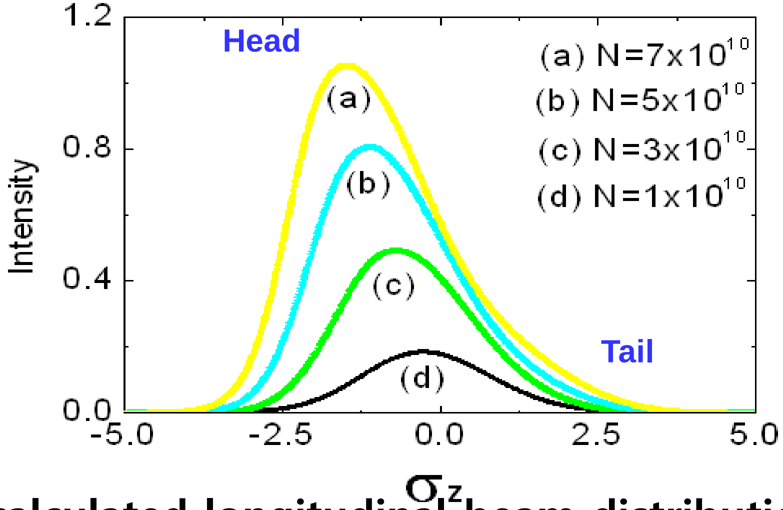
Impedance estimation of damping ring

Main contributions to the longitudinal impedance

Components	Type	Number	$\lvert\frac{Z_{\parallel}(w)}{n}\rvert$ (Ω)	L(nH)	Code used
BPM	Button-type	96	0.064	4.8	MAFIA
Bellows	Normal type with $\phi = 24$ mm	56	0.02	1.568	ABCI
	Elliptic type with $\phi = 24$ mm $\times 12$ mm	8	0.0058	0.46	MAFIA
	External kicker with radius = 30 mm	1	0.01411		ABCI
	External kicker with raduis = 15 mm	1	0.01017		ABCI
Masks	Wiggler	8	0.00096	0.0713	MASK30
	Straight section	8	0.047	3.544	MAFIA
Tapers	Length(= 120 mm), angle(= 10.3°)	2	0.0093	0.70	MAFIA
	Length(= 170 mm), angle(= 10.3°)	2	0.008	0.602	MAFIA
Septum		1	0.0082	0.6224	ABCI
Injection kicker	taper part	1	0.0015	0.1203	ABCI
	step part	1	0.00008	0.0063	ABCI
RF cavitity	With tapers	2	0.03144	0.687	ABCI
RF absorber	With SiC with $\sigma = 80$ and $\varepsilon = 16$	4	0.0089	0.671	MAFIA
Total			0.23	13.9	



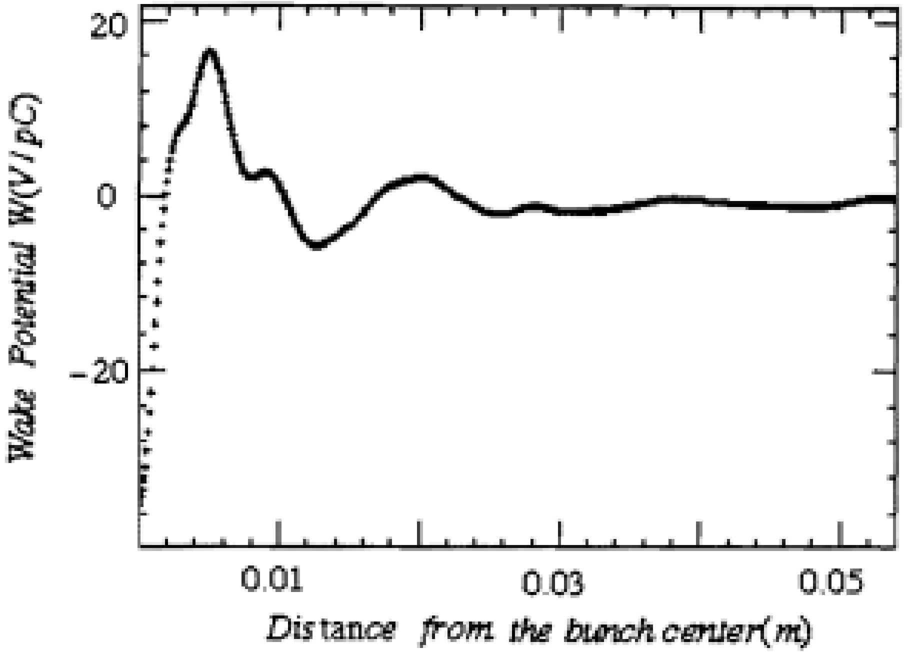
longitudinal wake potential of a 6.8 mm Gaussian bunch



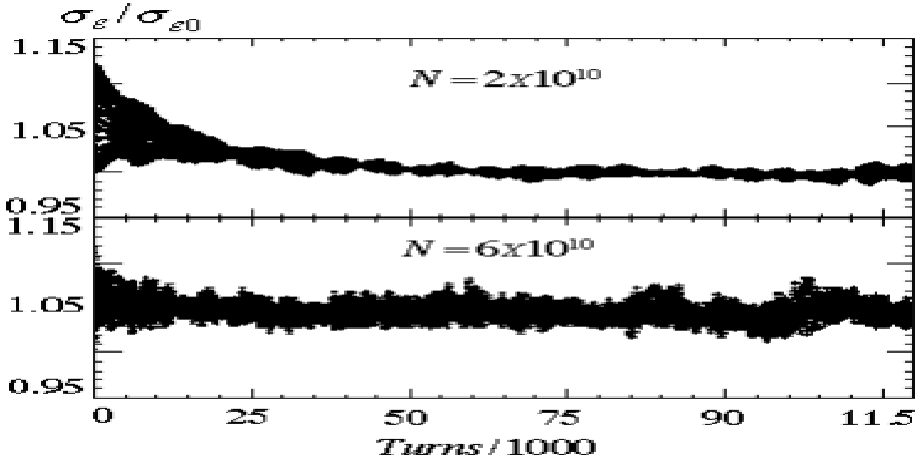
calculated longitudinal beam distributions due to potential well distortion

2. Beam dynamics in ATF damping ring

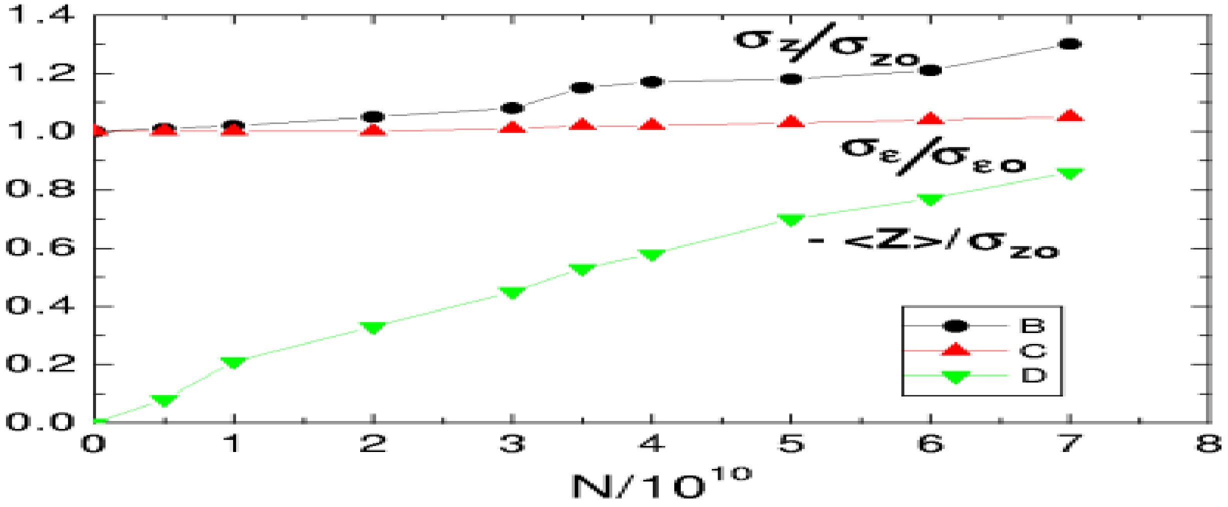
longitudinal instability



Longitudinal wake potential for 2 rf cavities in damping ring



Rms energy spread vs turn number.

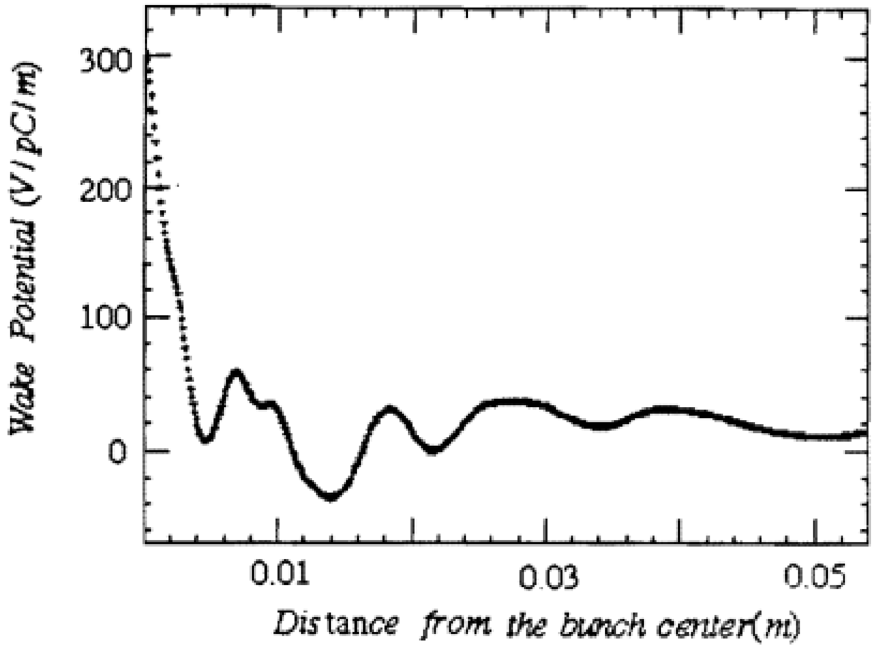


threshold instability : N=3.3 × 10^{10}

2. Beam dynamics in ATF damping ring

Transverse instability

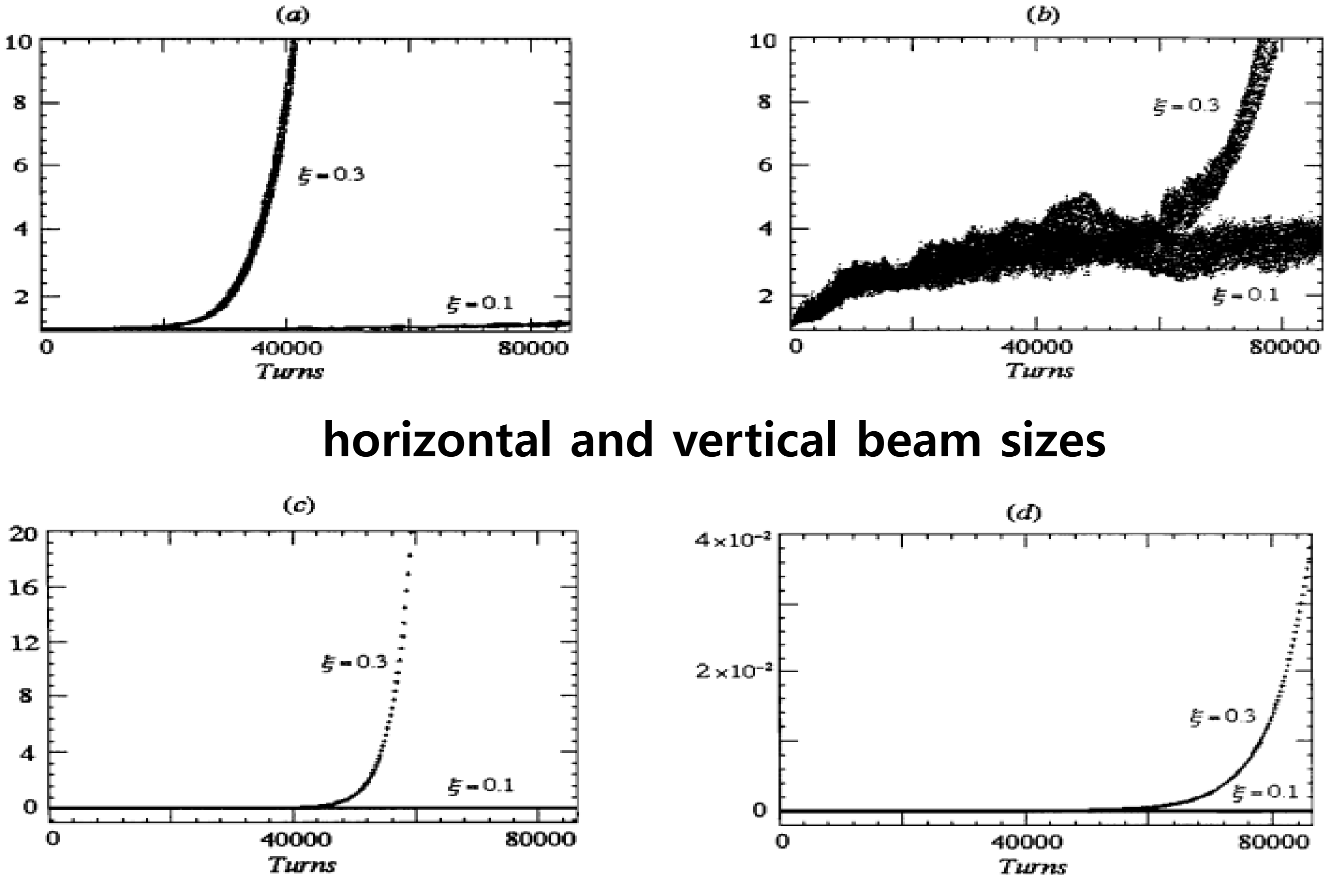
head-tail effect occuring at positive chromaticity



Transverse wake potential for two cavities

Charge bunch is a Gaussain with an rms of 1mm.
Parts on front of bunch center (z < 0) are discarded.

10.2 mA



horizontal and vertical beam sizes

horizontal and vertical center-of-mass motion

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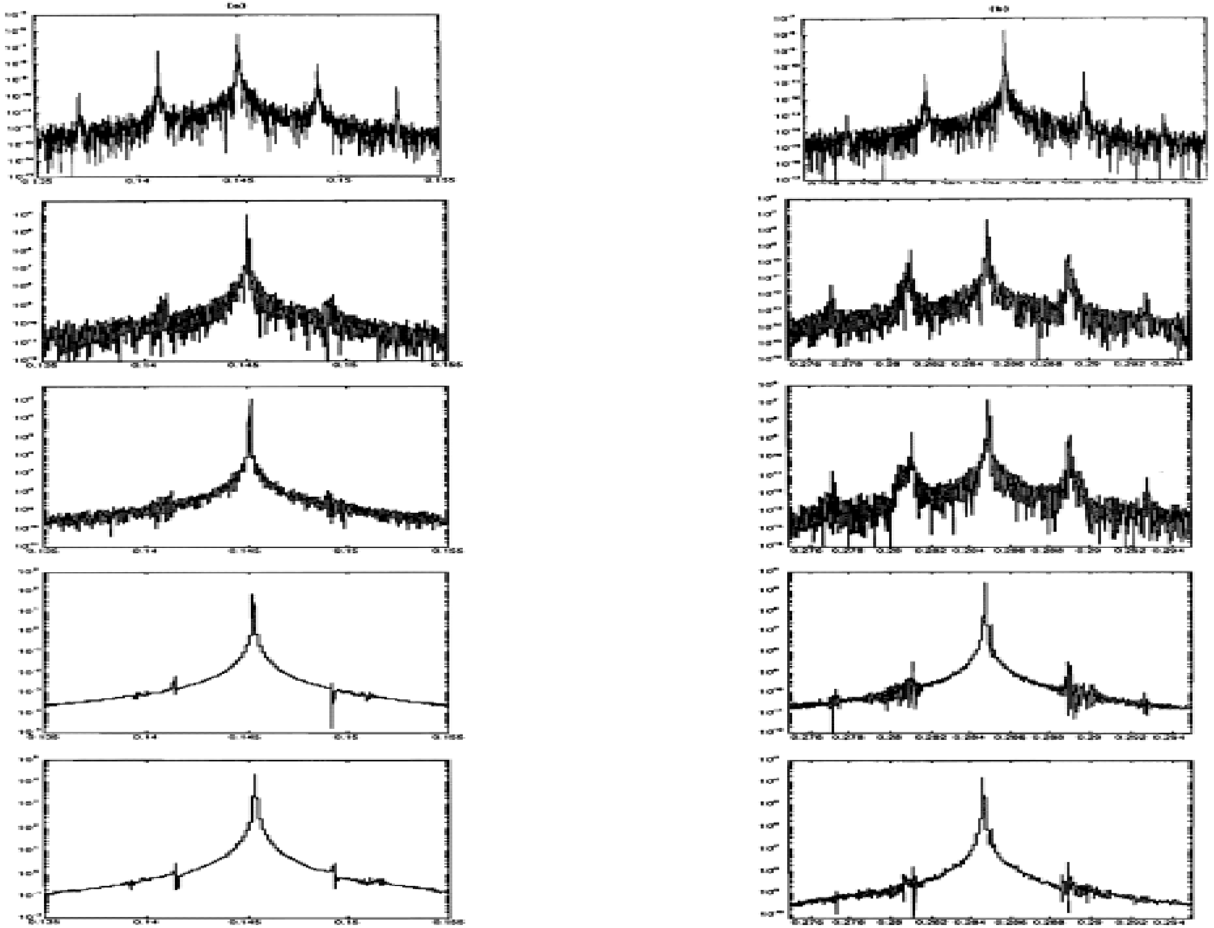
Transverse instability

Fourier Transform of mean horizontal and vertical positions of the beam for different beam currents

m=0 mode has shifted to higher tunes as the beam currents increase.
Mode m=-1 and mode m=1 are shown clearly.

Chromaticity : 0.1
Q_x=0.145, Q_y=0.285
ω_s= 1 x 10^{-3}.



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3. Beam dynamics in 2.5 GeV light source

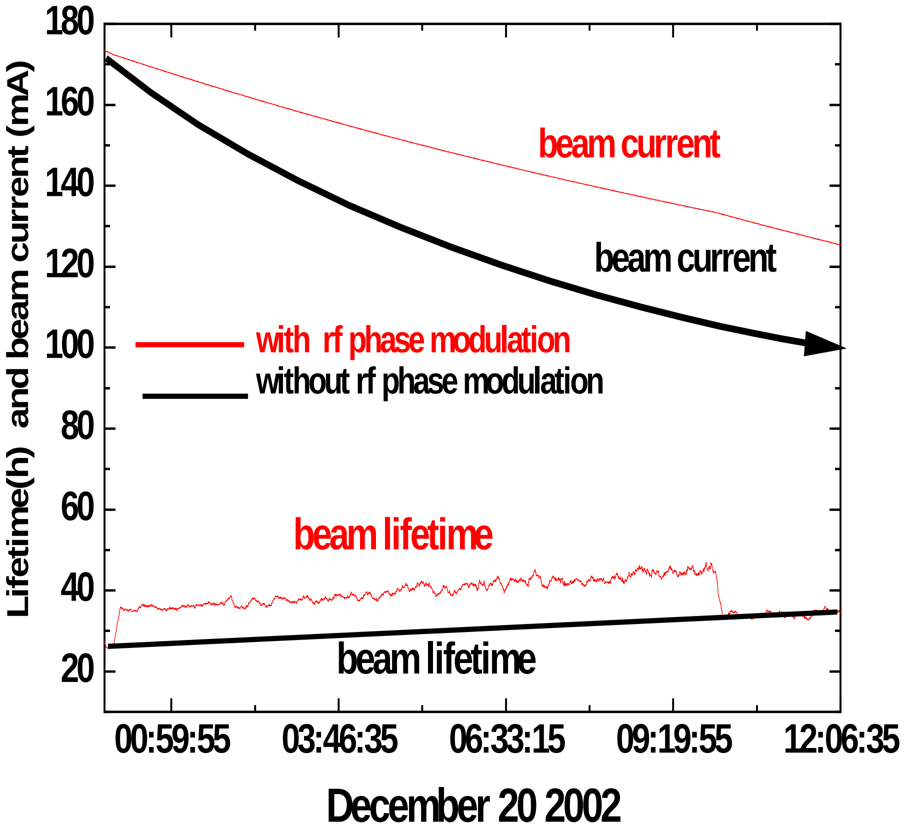
RF phase modulation

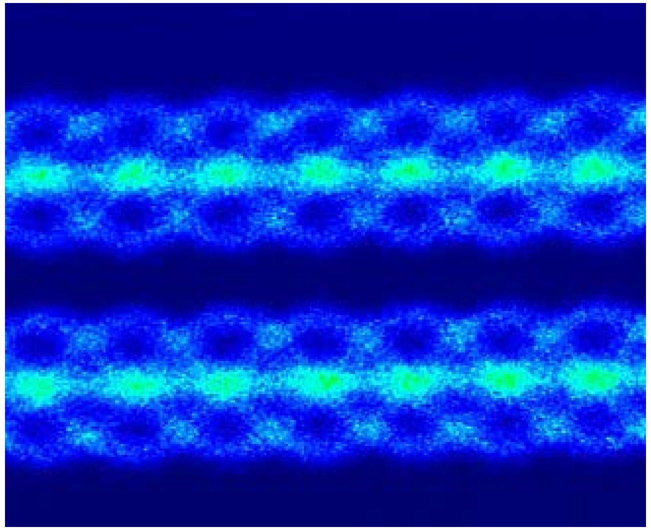
increased beam lifetime by a factor of 1.5
by bunch-lengthening

$$V_{rf} = \overline{V_o} \cos(\phi_o - \omega_{rf}\tau + \phi_m)$$

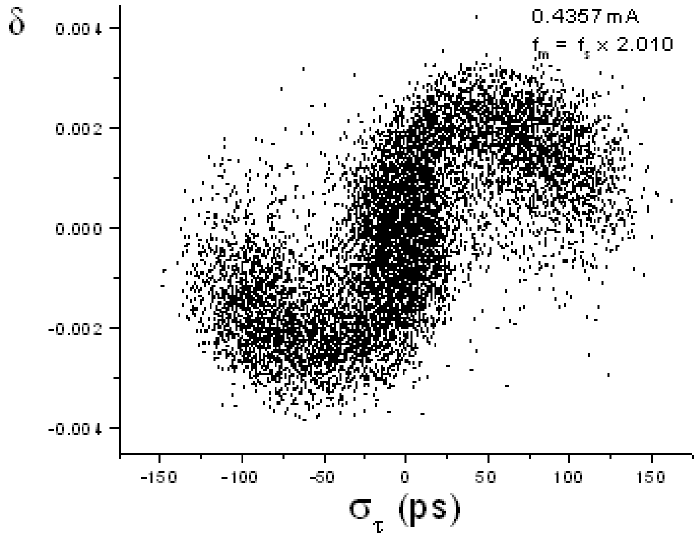
$$\phi_m = \phi_{mo} \cos(\omega_m T_o)$$

$(\phi_{mo} = 5 \text{ deg.}\ ,\ \omega_m = 2 \times 9.34 \text{ kHz})$





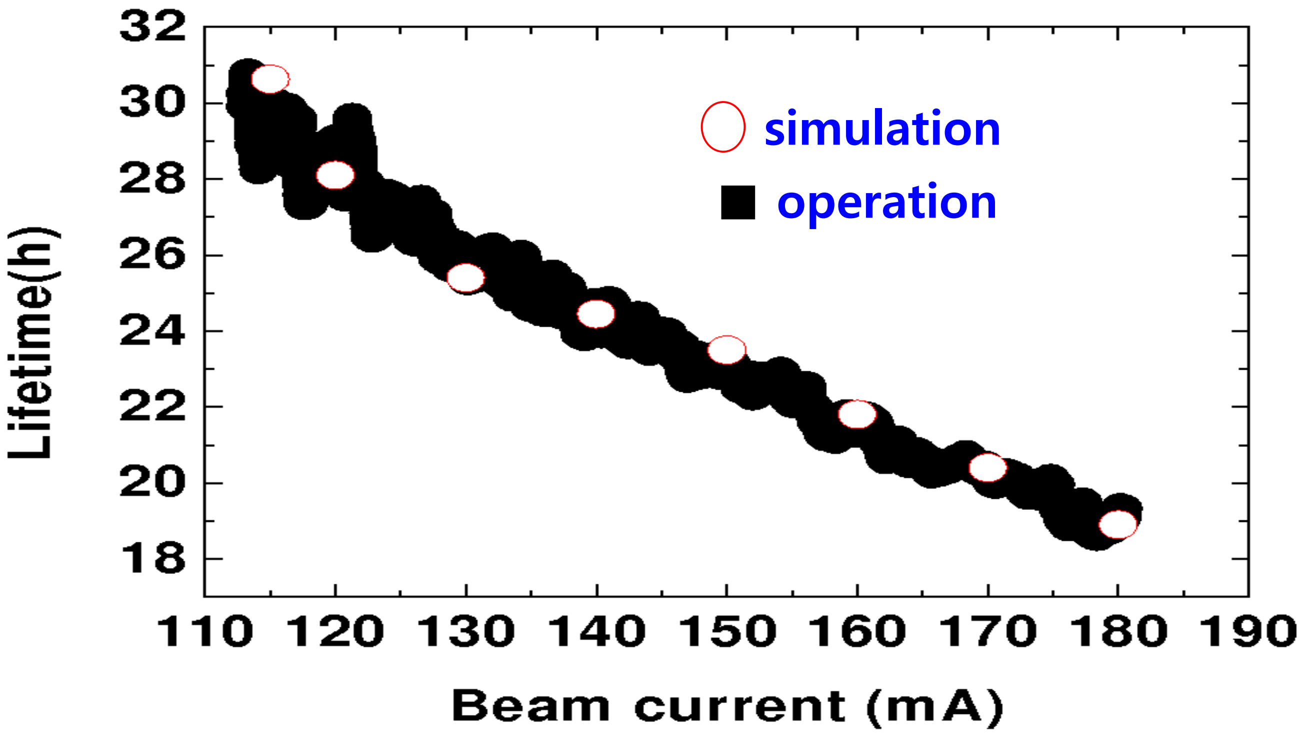
Streak camera image
of the RF phase modulation



simulation result
of the RF phase modulation

3. Beam dynamics in 2.5 GeV light source

Operation and simulation beam lifetimes



From the simulation results

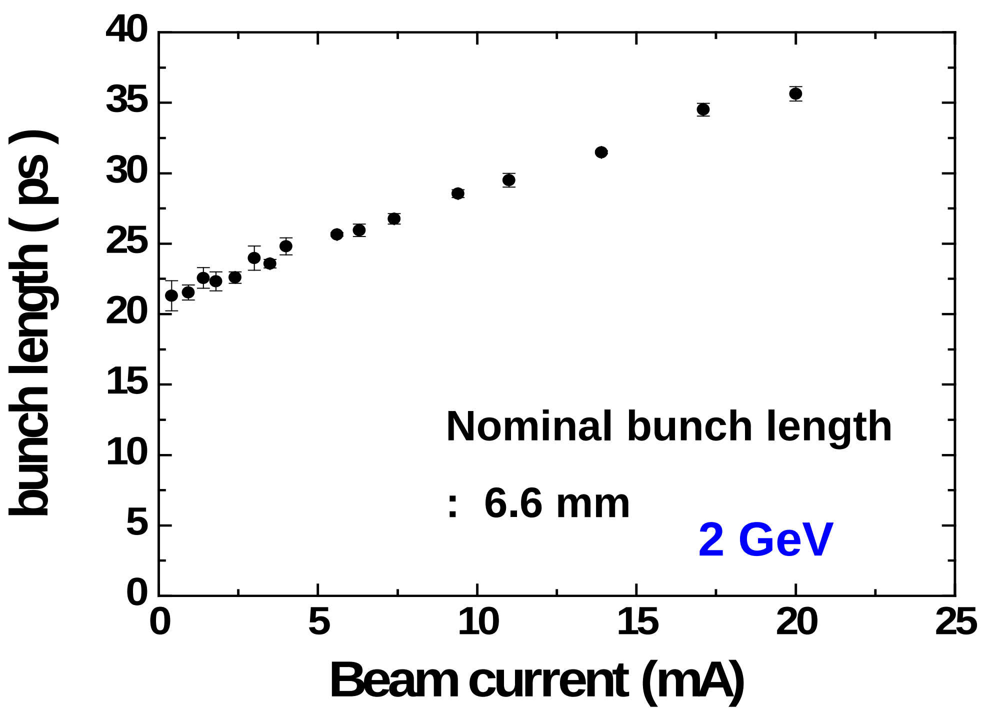
Beam-gas scattering lifetime : 290 h

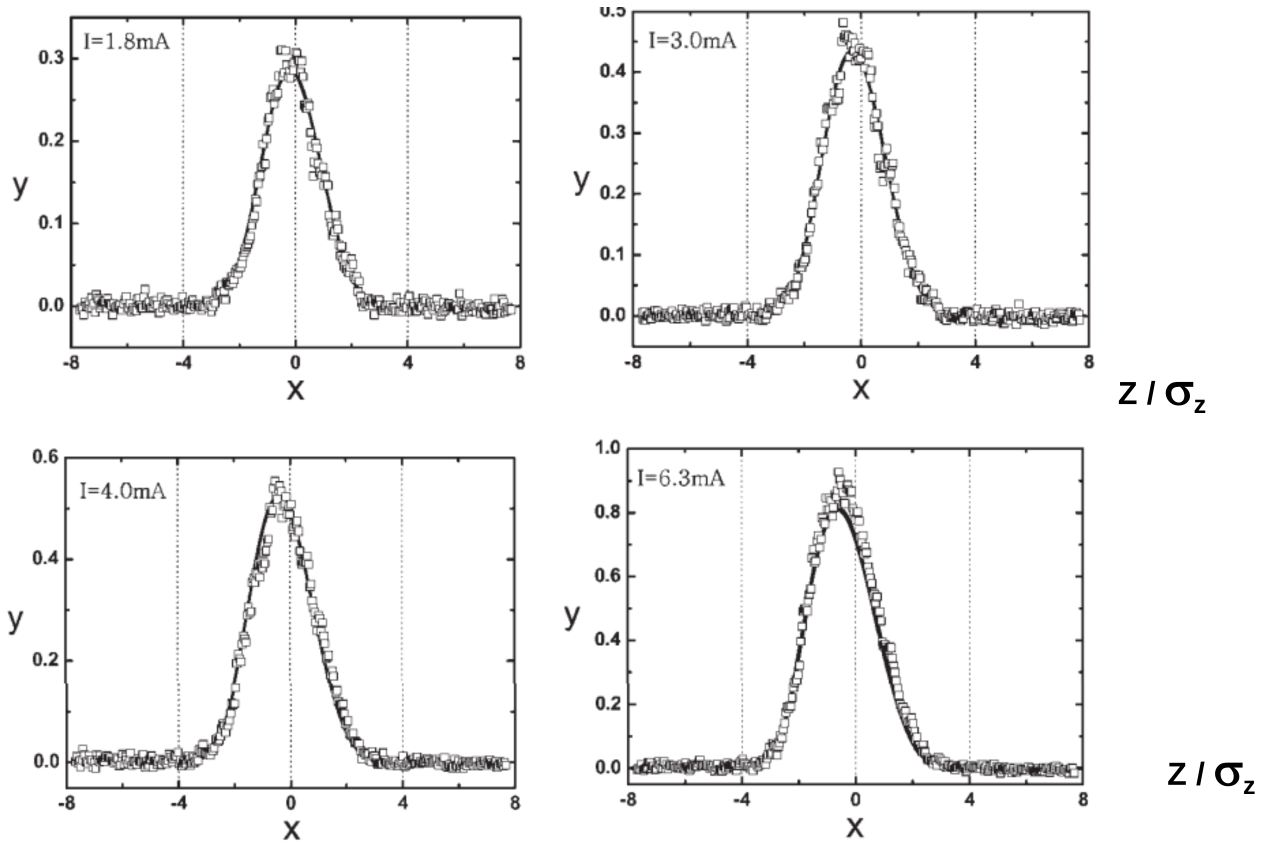
Beam-gas Bremsstrahlung lifetime : 460 h

Touscheck lifetime : 18 h

3. Beam dynamics in 2.5 GeV light source

Estimation of ring impedance from bunch-lengthening





Resistive impedance : R= 743 Ω ± 84Ω

Inductive impedance : L= 13.7 nH ± 3.5 nH

Measured bunch shapes (squares) and their fits (black lines) to the Haissinski solution of a series R+L impedance

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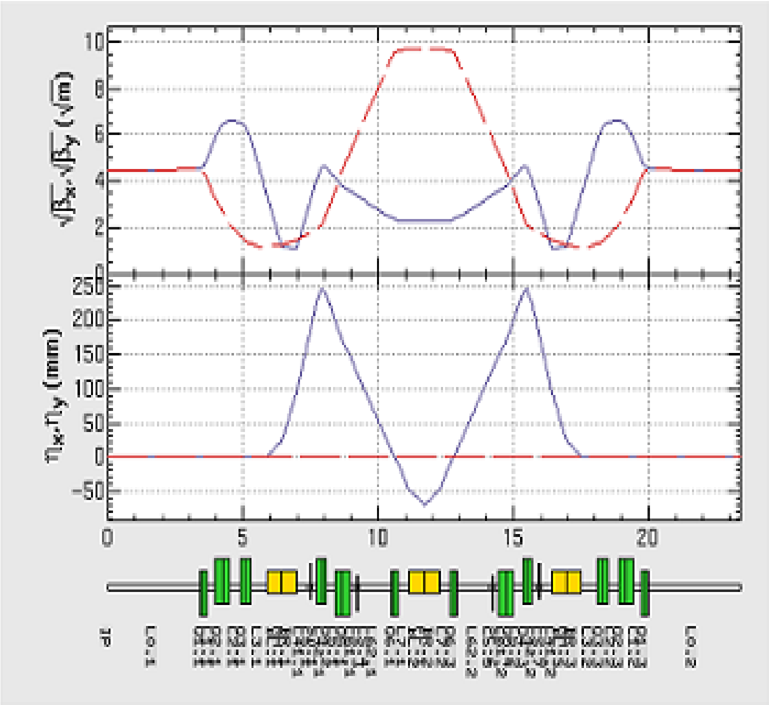
3. Beam dynamics in 2.5 GeV light source

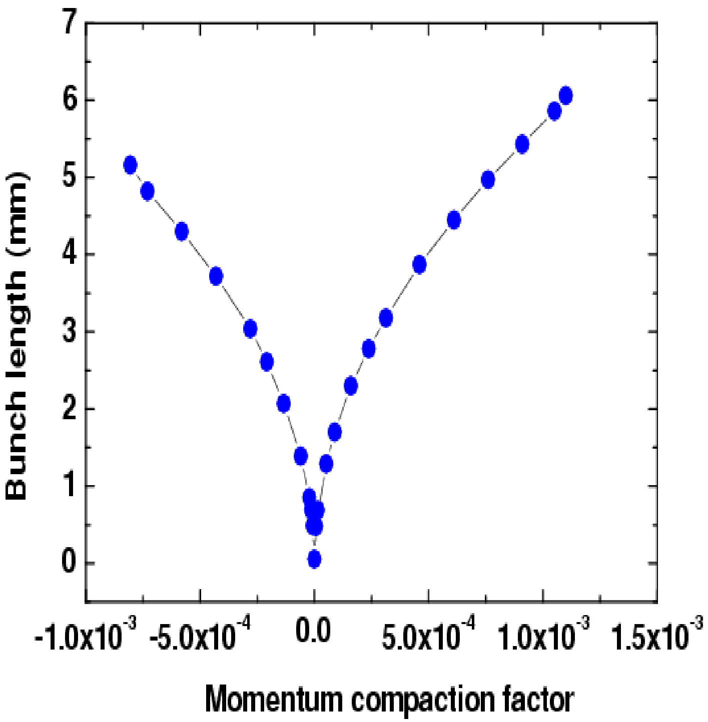
Lattice design for short-bunch length

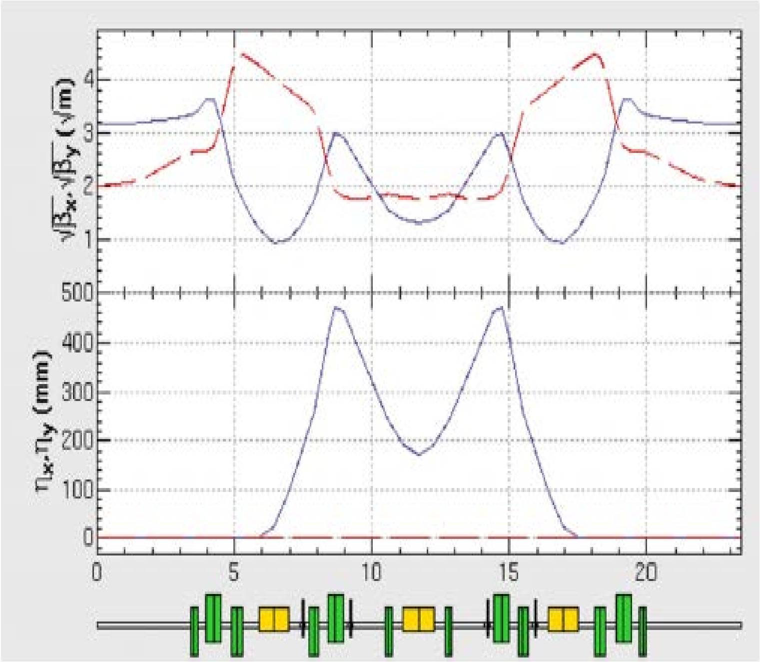


Lattice for

1 ps bunch length

Bunch length vs momentum compaction factor



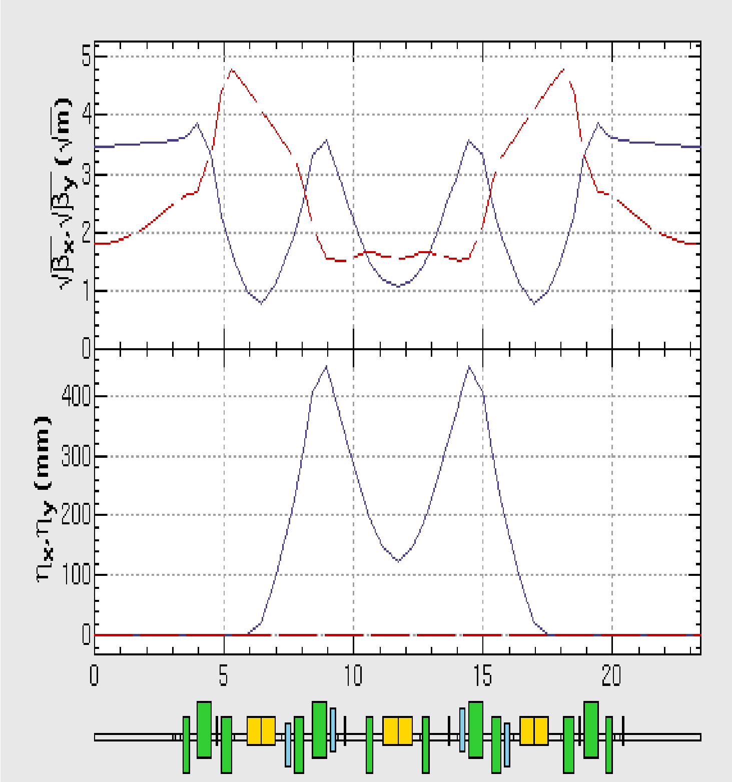


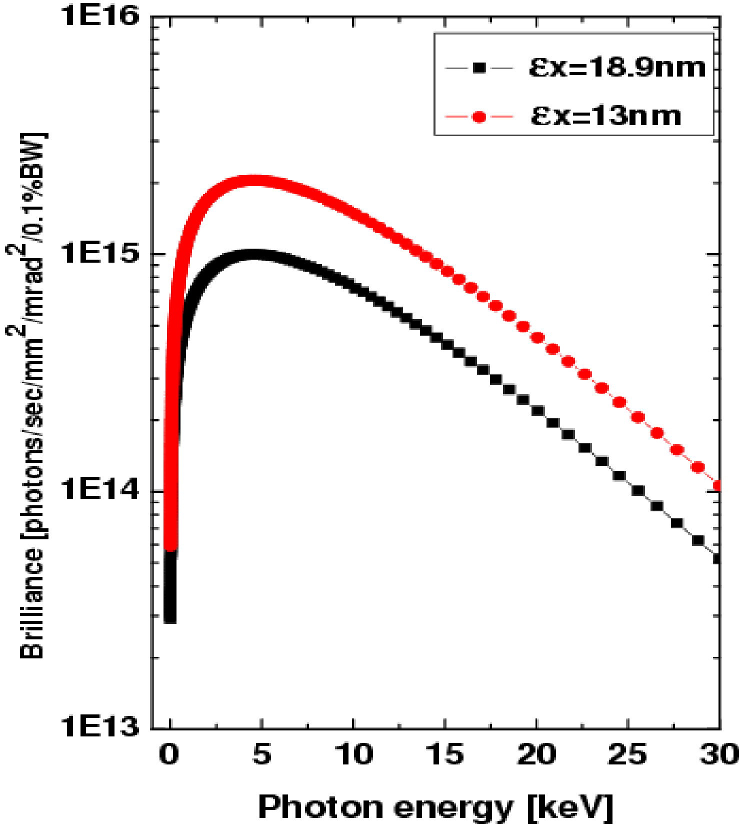
Lattice for
28 ps nominal bunch length

3. Beam dynamics in 2.5 GeV light source

Lattice design for a lower emittance

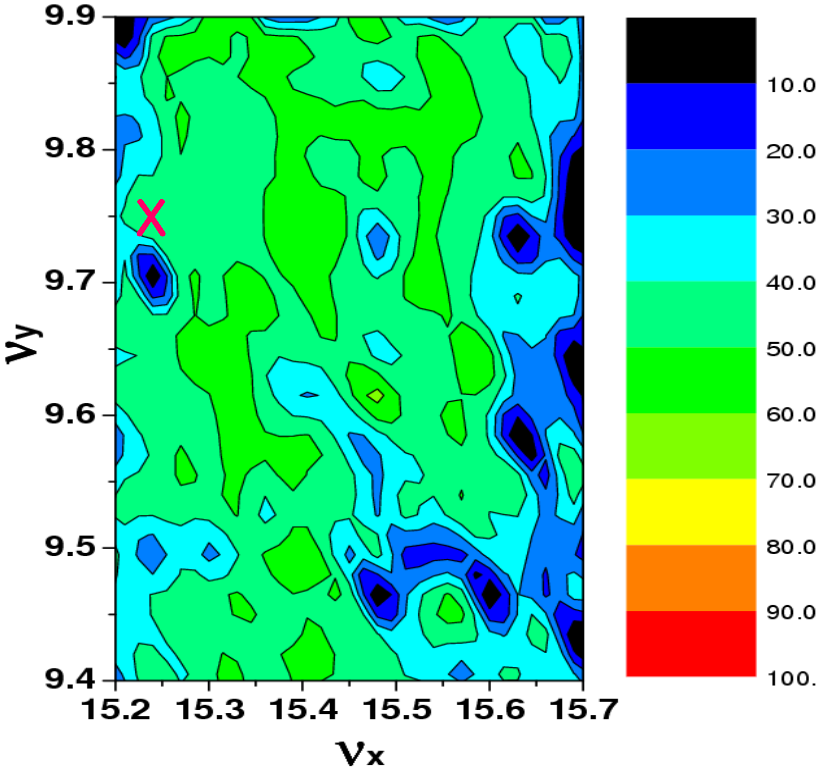
ε = 13 nm (cf : 18.9 nm @ 2.5 GeV)





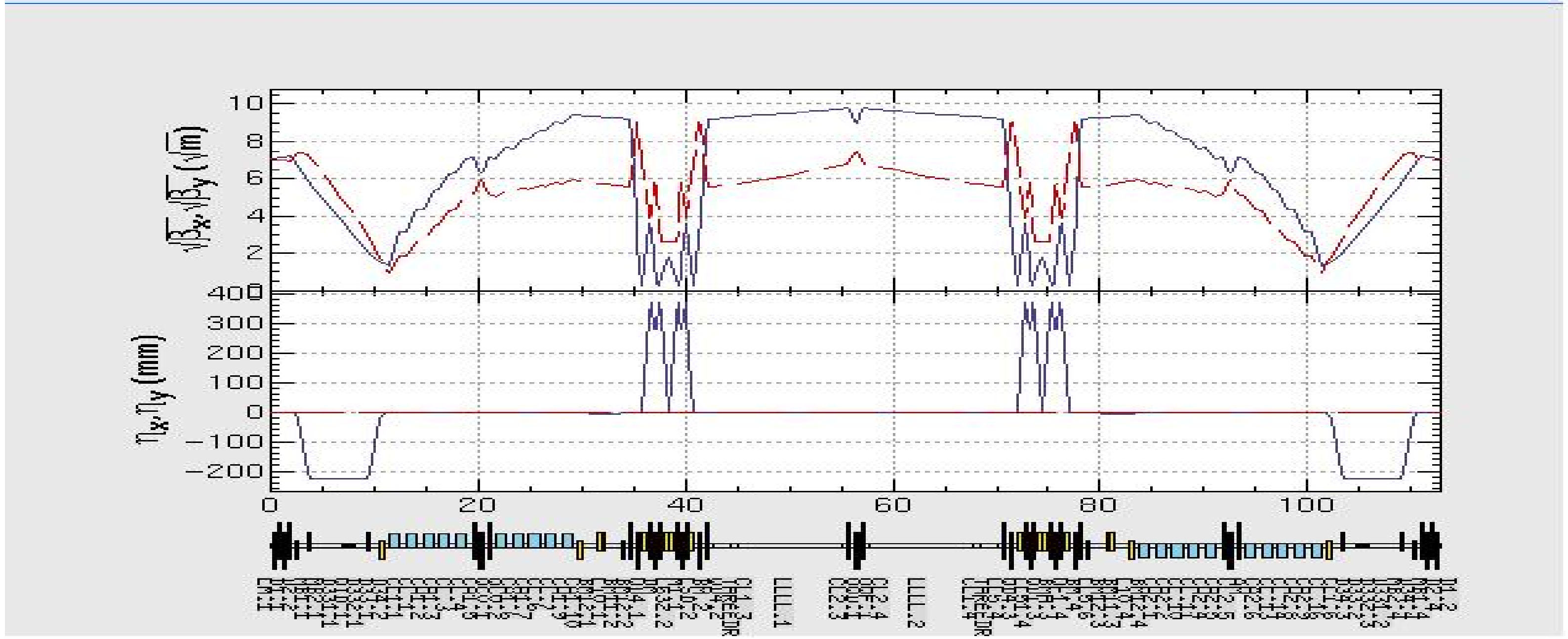
dipole

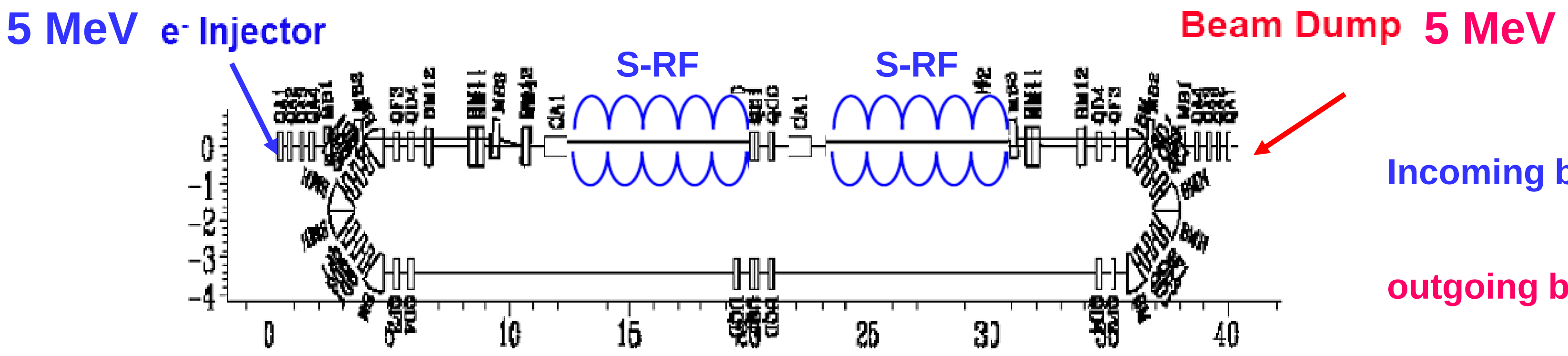
Tune survey for large dynamic aperture

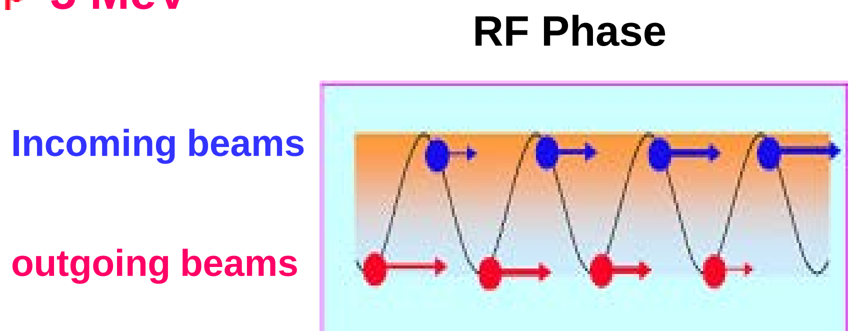


4. Beam dynamics in Energy Recovery Linac

Lattice from merger to beam dump







4. Beam dynamics in Energy Recovery Linac

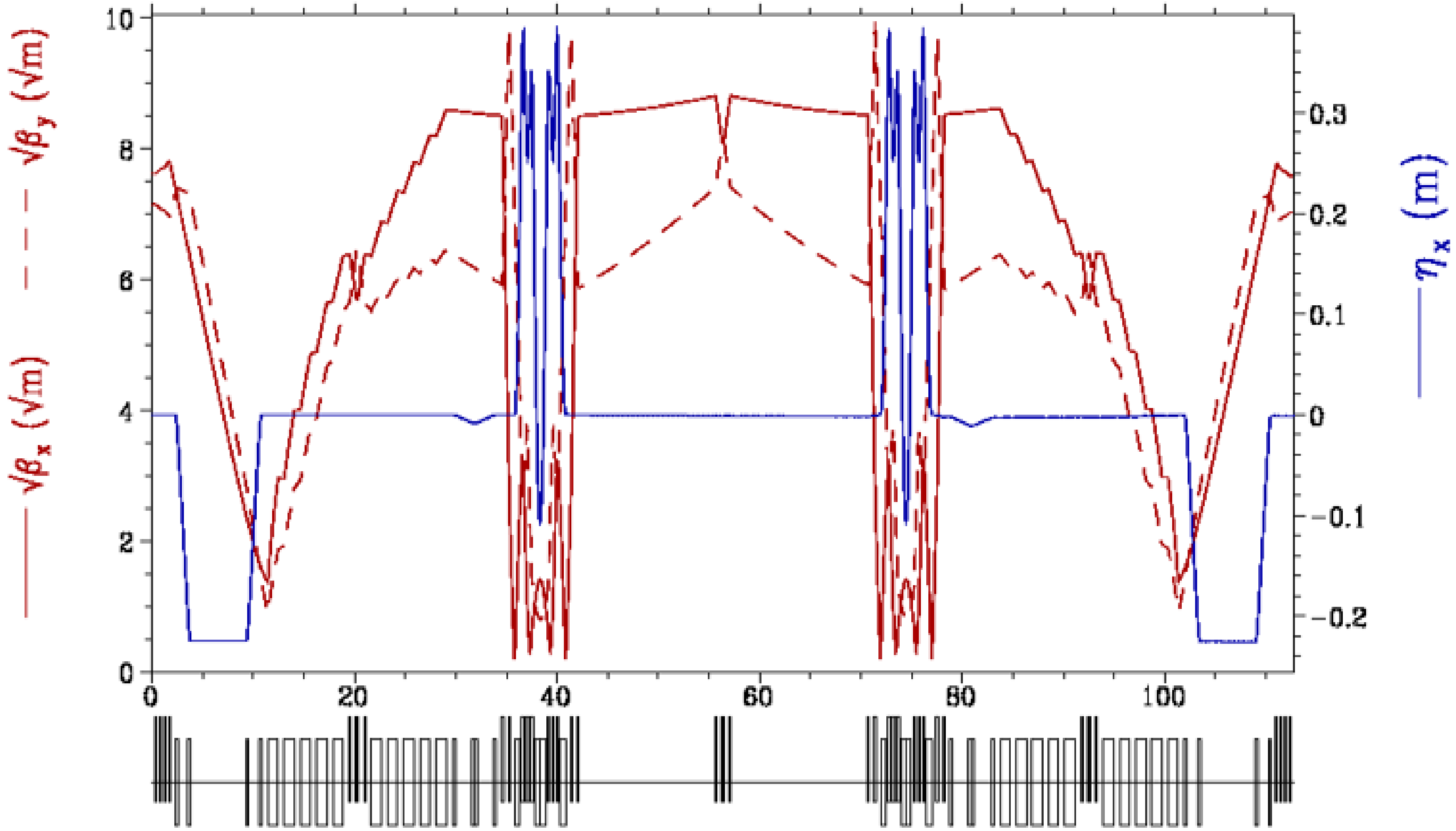
Main parameters

Beam energy	: 205 MeV	Average beam current	: 100 mA
Bunch charge	: 77 pC	Injection beam energy	: 5 MeV
RF frequency	: 1.296 GHz	Harmonic number	: 320
Rms bunch length	: 1 ps	Rms energy spread	: 3 x10^{-4}
Number of rf cavity units	: 10	RF cavity length	: 1 m
RF cavity gradient	: 20 MV /m	Momentum compaction	: 10^{-5}
Normalized emittance (x/y)	: 0.1 / 0.1 mm mrad		
Length of Bends	: 60 cm	Length of quadrupole	: 15cm/20cm

4. Beam dynamics in Energy Recovery Linac

Lattice design

Momentum compaction factor : 10^{-5}



4. Beam dynamics in Energy Recovery Linac

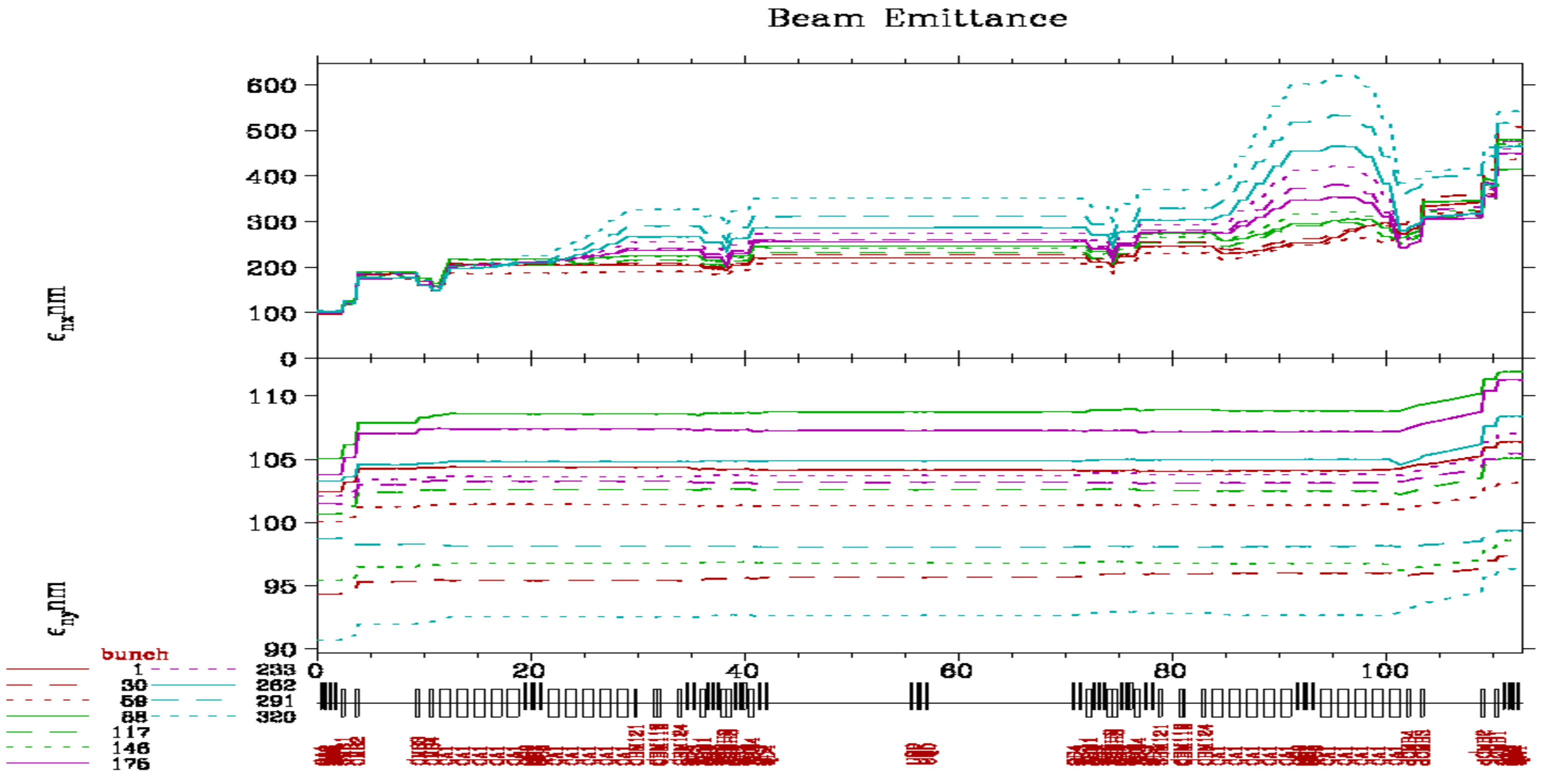
Beam tracking for 320 bunches with cavity HOMs

$q=37pC$, $\sigma_z = 1$ psec, $\varepsilon_{nx}=0.1$ mm mrad

R/Q=23.8x10^4, fr=2.57535x10^9, Q=5x10^4

R/Q=8.69x10^4, fr=1.8722x10^9, Q=7x10^4

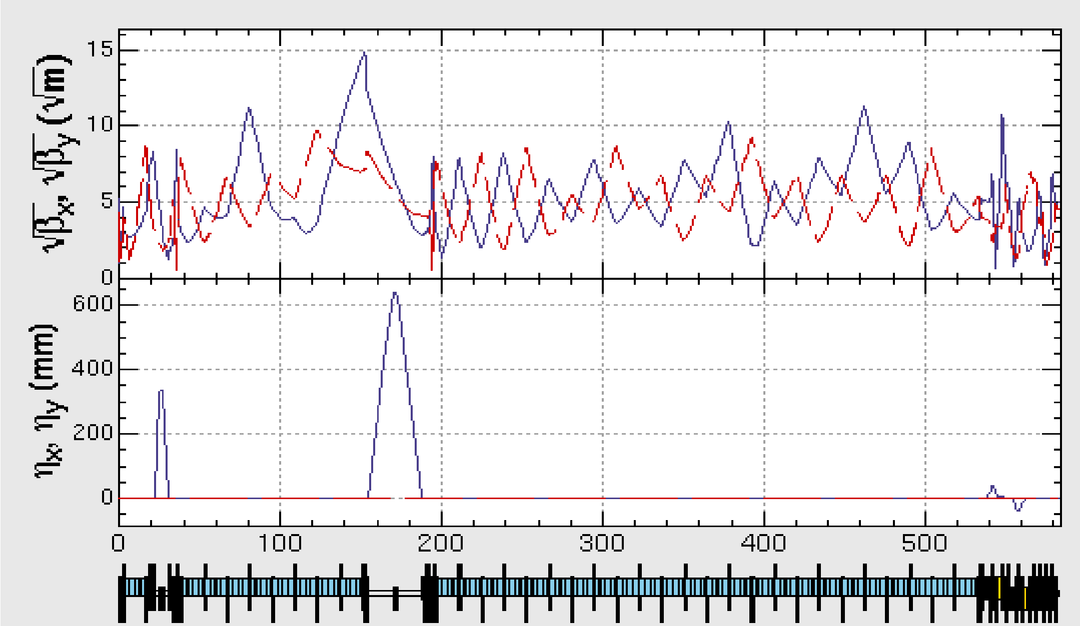
R/Q=6.54x10^4, fr=1.8643x10^9, Q=5x10^4

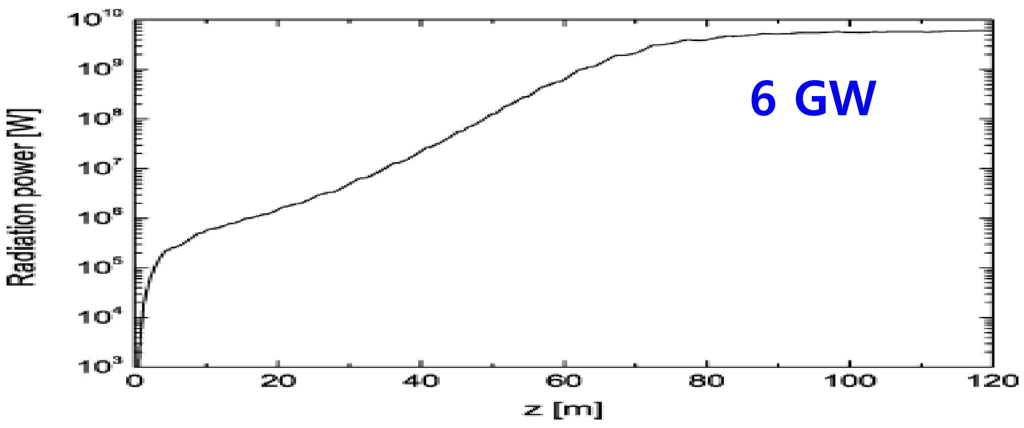


increased by factor of ~5

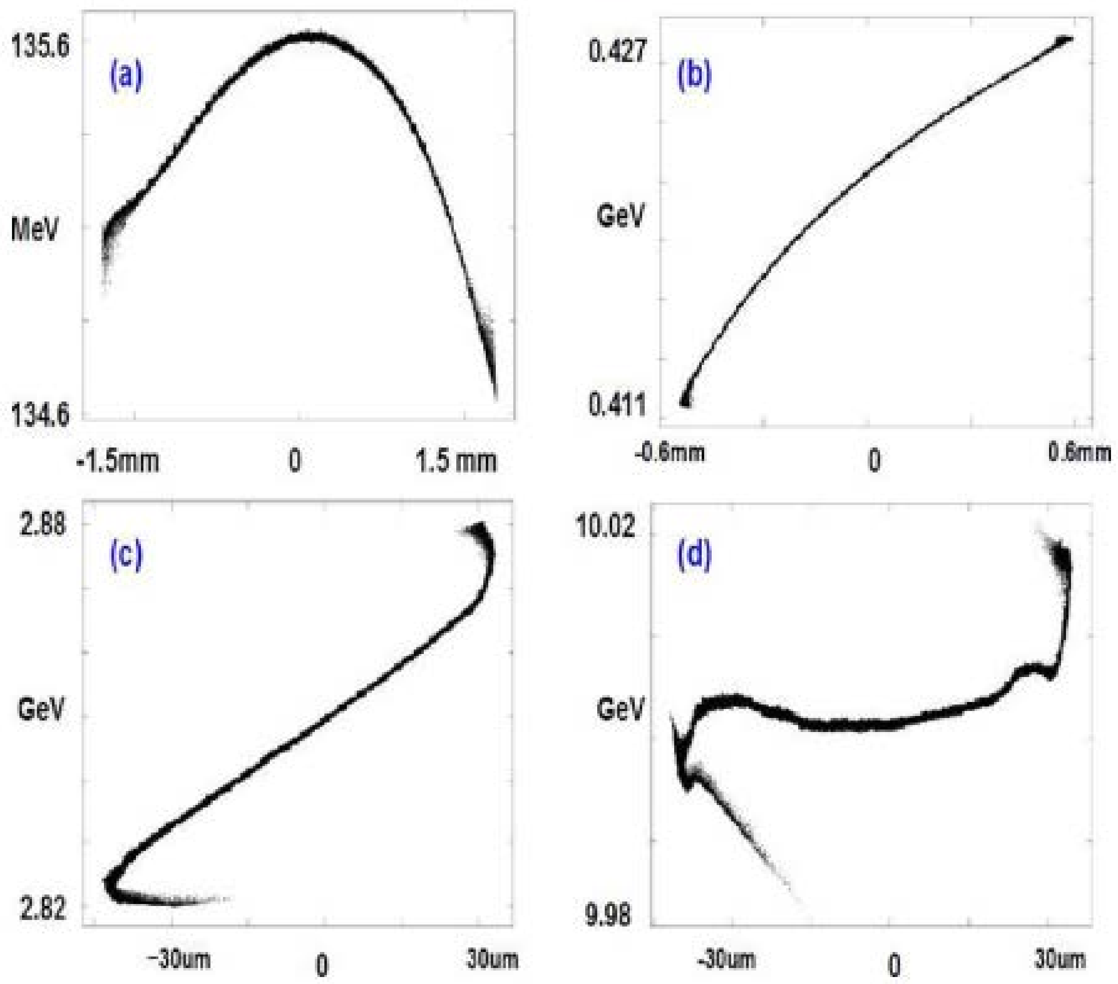
5. Beam dynamics in Free Electron Linac

Lattice for 10 GeV linac



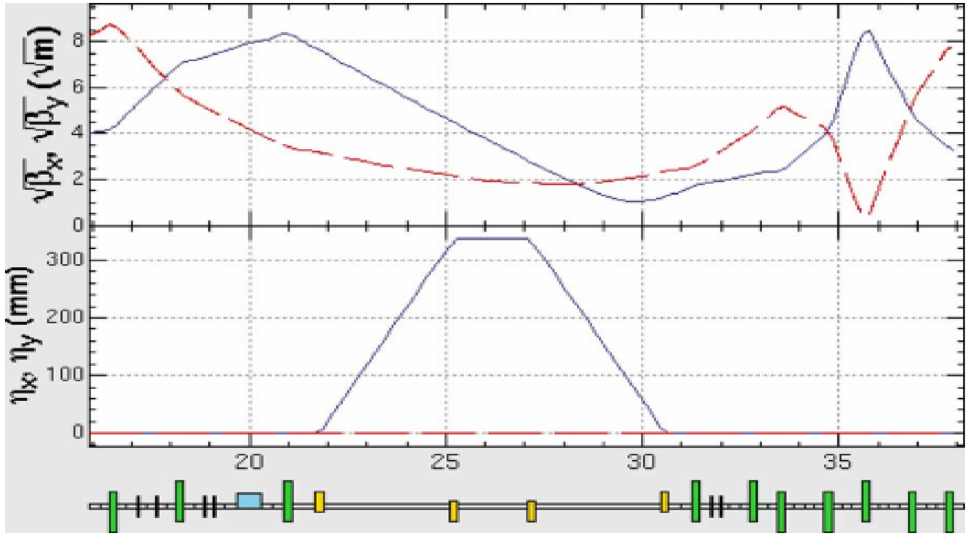


Radiation power as a function of the undulator length.

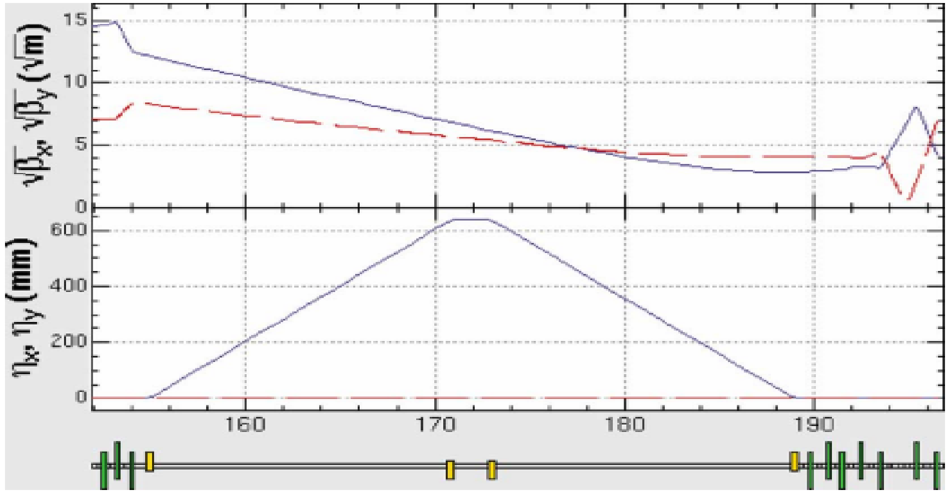


Longitudinal beam distributions (a) from the injector, (b) from the BC1, (c) from the BC2 , (d) from the entrance of undulator.

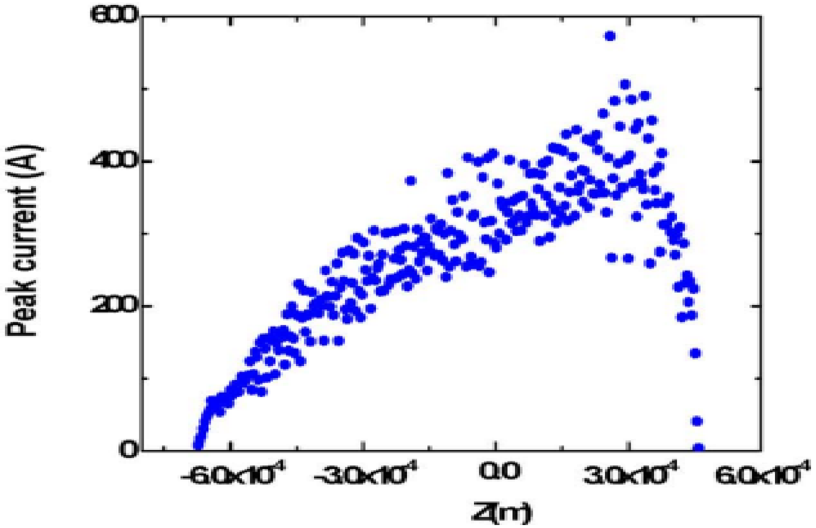
5. Beam dynamics in Free Electron Linac



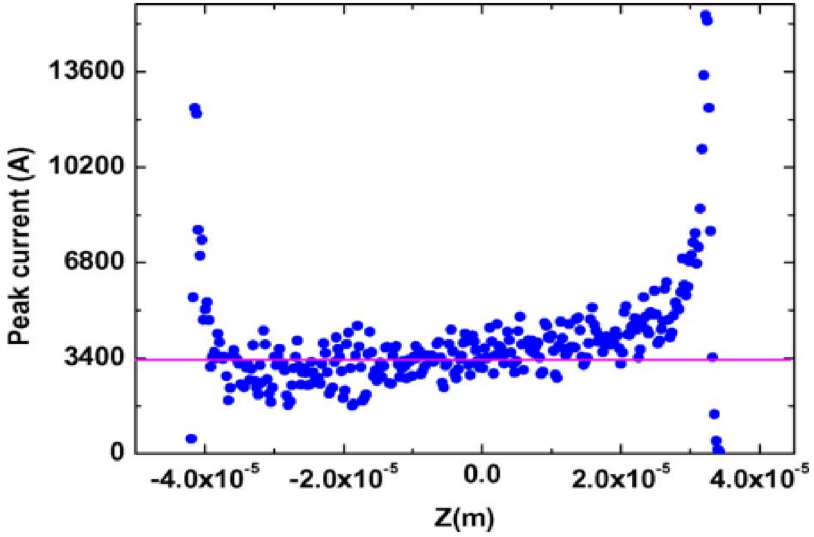
Optics for 1st bunch compressor



Optics for 2nd bunch compressor

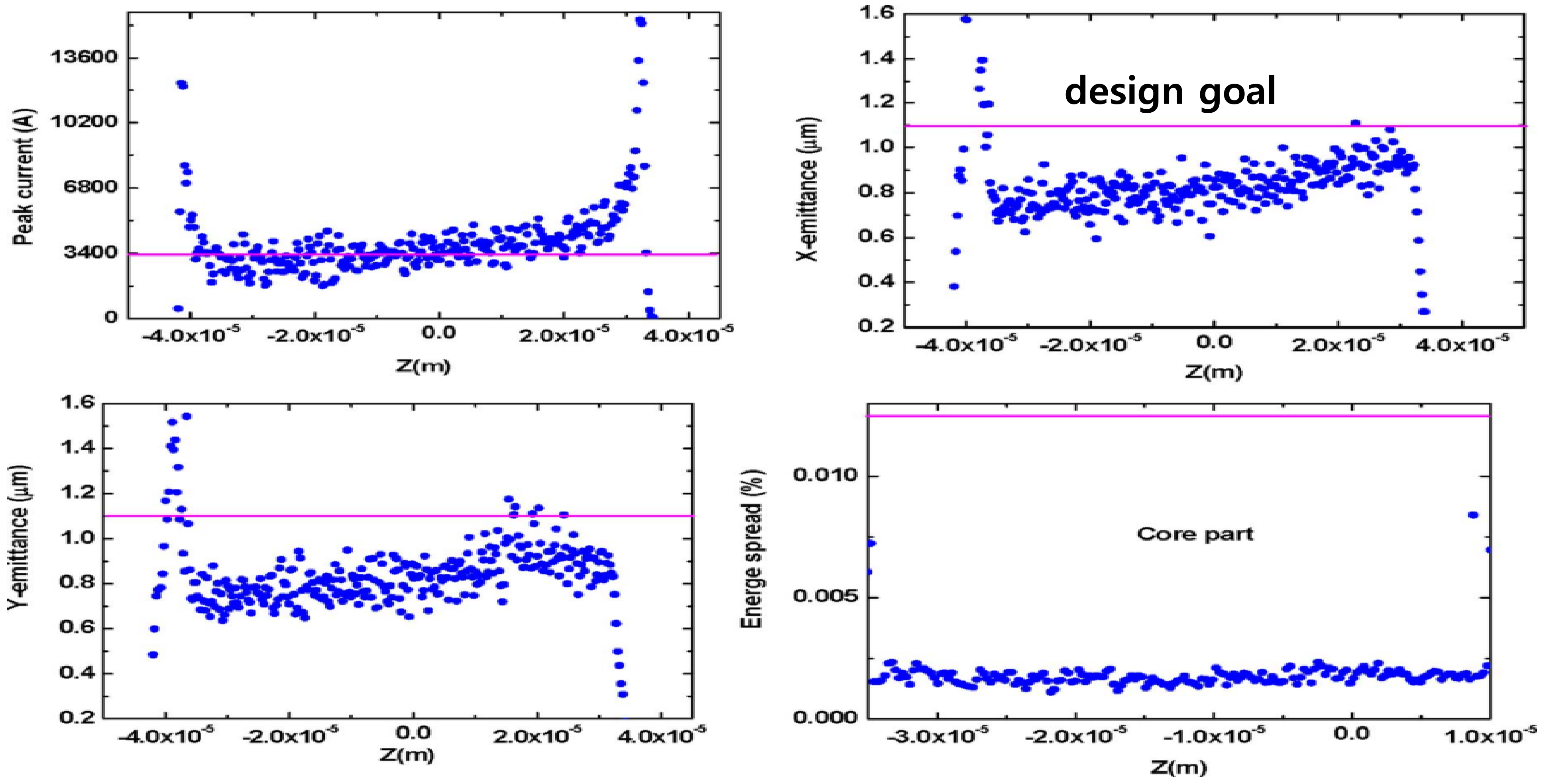


peak beam current in 1st bunch compressor.



peak beam current in 2nd bunch compressor.

5. Beam dynamics in Free Electron Linac



slice beams at the entrance of the undulator at 10 GeV

Summary

■ We showed beam dynamics studies in ring and linac.

■ Existing R&D items on beam dynamics and diagnostics with IHEP

○ Beam instabilities with Prof. Haisehng Xu
: invited (Feb. 24) to KU and visited (June. 24) to IHEP

○ are discussing with Prof. Yanfeng Sui on beam measurements for commissioning in HEPS.

○ We have an oral talk on “resistive wall instabilities in CEPC” in 2024 International workshop on High Energy CEPC (Oct. 22-24)

○ .....