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TRACKING OF A PETRA III POSITRON BUNCH WITH A PRE-COMPUTED WAKE MATRIX DUE TO ELECTRON CLOUDS

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Overview

- Introduction, Challenges, Motivation, Idea
- Simulation of interaction beam – e-cloud
- Single bunch instability simulation
- Results for PETRA III
- Summary and conclusion

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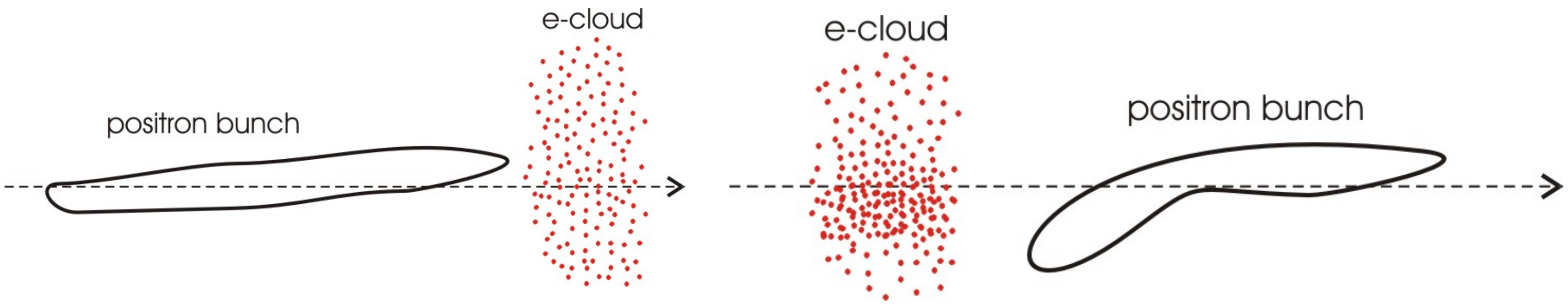
Introduction - Head – Tail instability due to e-clouds



Schematic of the single-bunch instability induced by electron cloud after some time in the storage ring.

Challenges

Fact: Presently no computational resources for a full 3D strong-strong simulation of the beam- e-cloud interaction over the time of a synchrotron period!!!

↓

Tracking with the optics matrices + the influence of the collective effects!

↓

The transverse kick on the bunch due to the e-cloud :
Lumped, on one or more points in the lattice applying a kick on the bunch

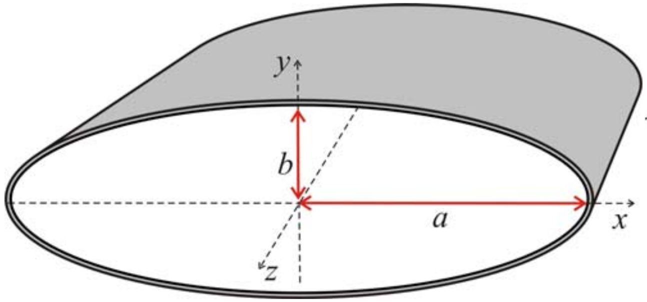
Motivation

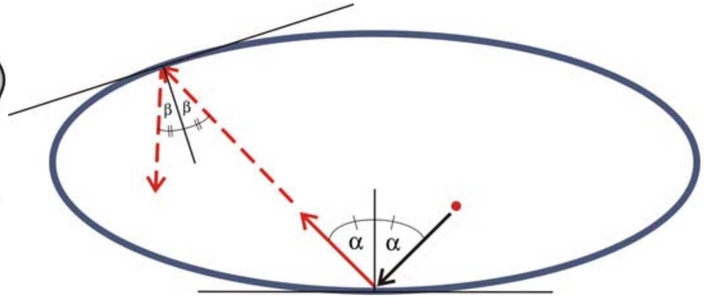
- To estimate the e-cloud effect on the beam by numerical simulation
- Simulation - fast and cheap but still to a certain extent reliable prediction of the effects

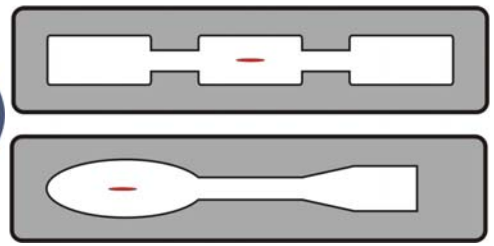
Idea

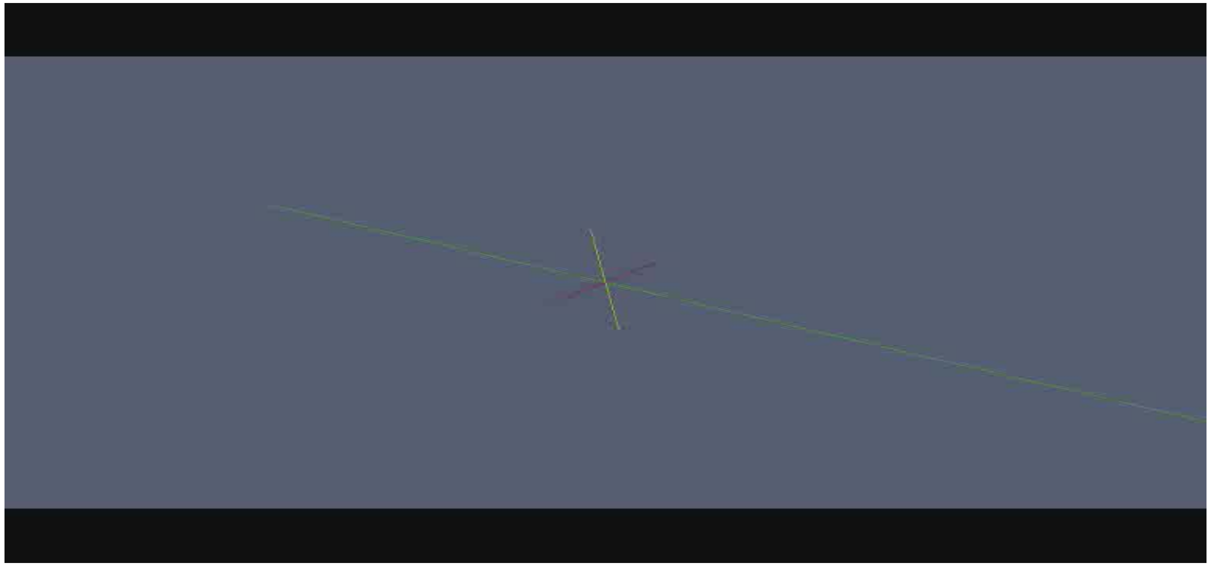
- Pre-computed wake - idea of K. Ohmi
- Tracking with the pre-computed wake matrix

Interaction: beam - e-cloud (MOEVE PIC Tracking)









Momentum of the electrons along the bunch passage (symmetry)

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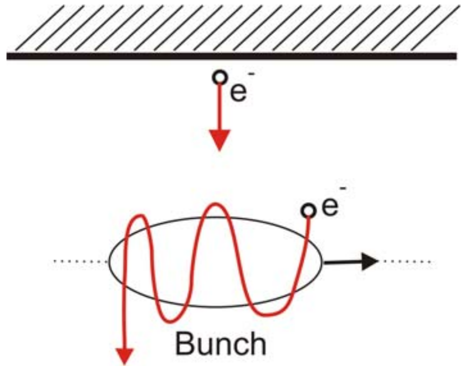
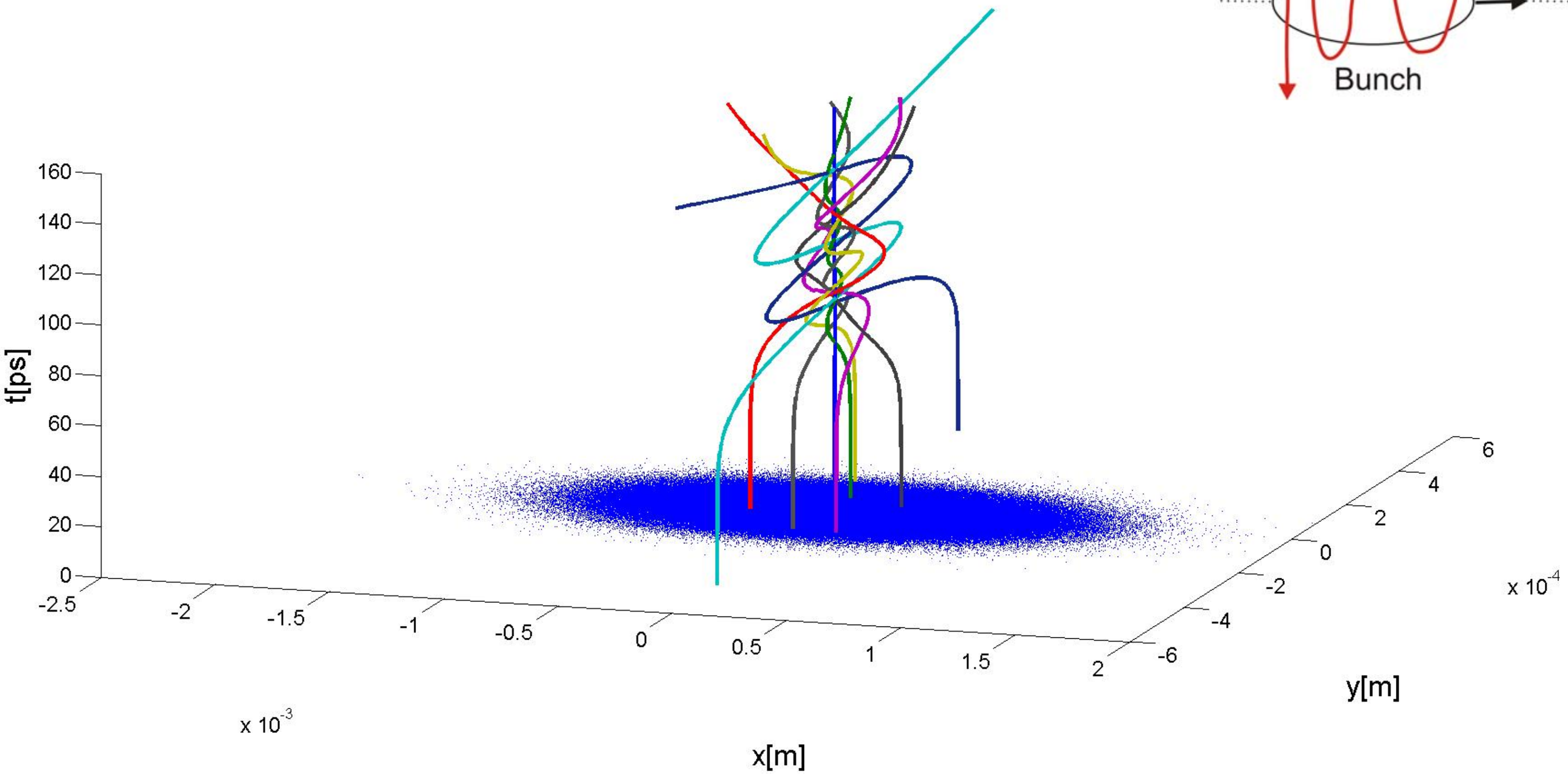
Electron trajectories
Several e-Cloud Particles





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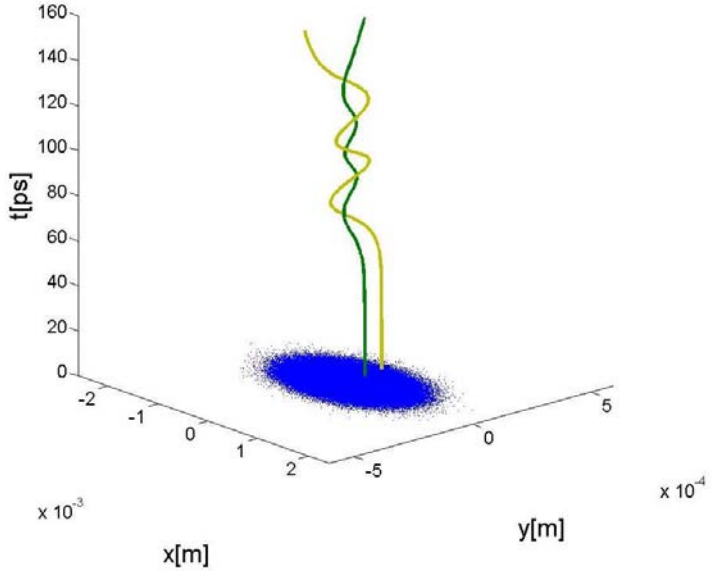
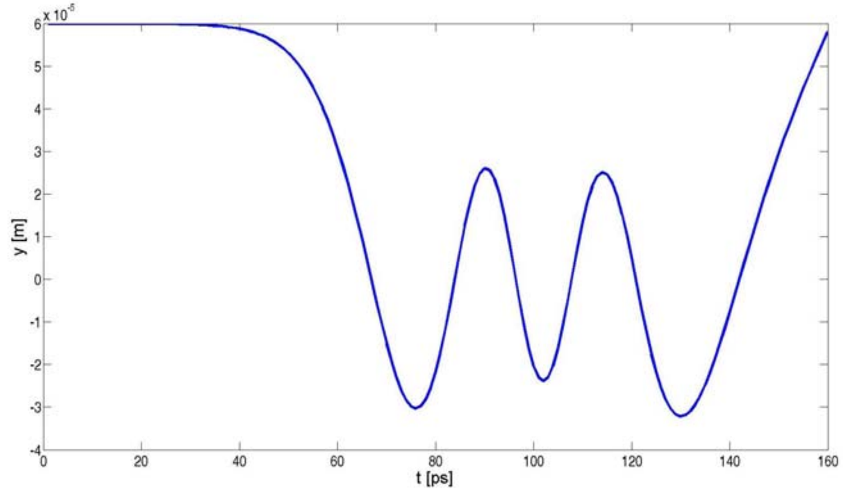
Electron trajectories



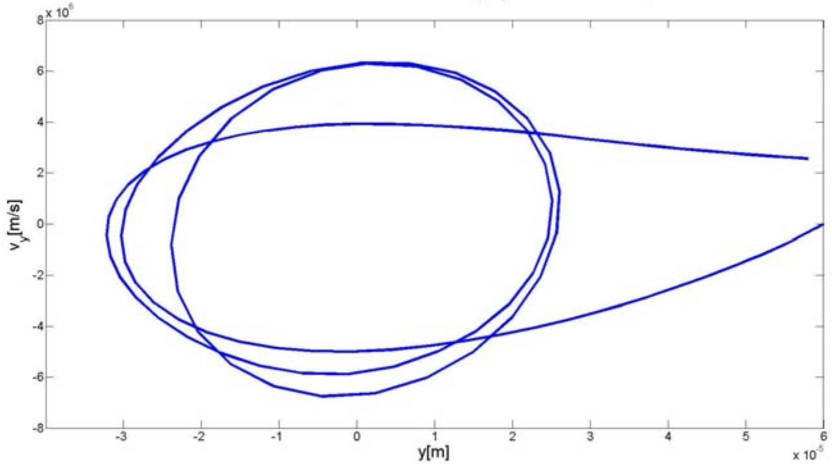


$$\omega_{e,x(y)} = \left(\frac{2\lambda_b r_e c^2}{\sigma_{x(y)}(\sigma_x + \sigma_y)} \right)^{1/2}$$

Broadband resonator model

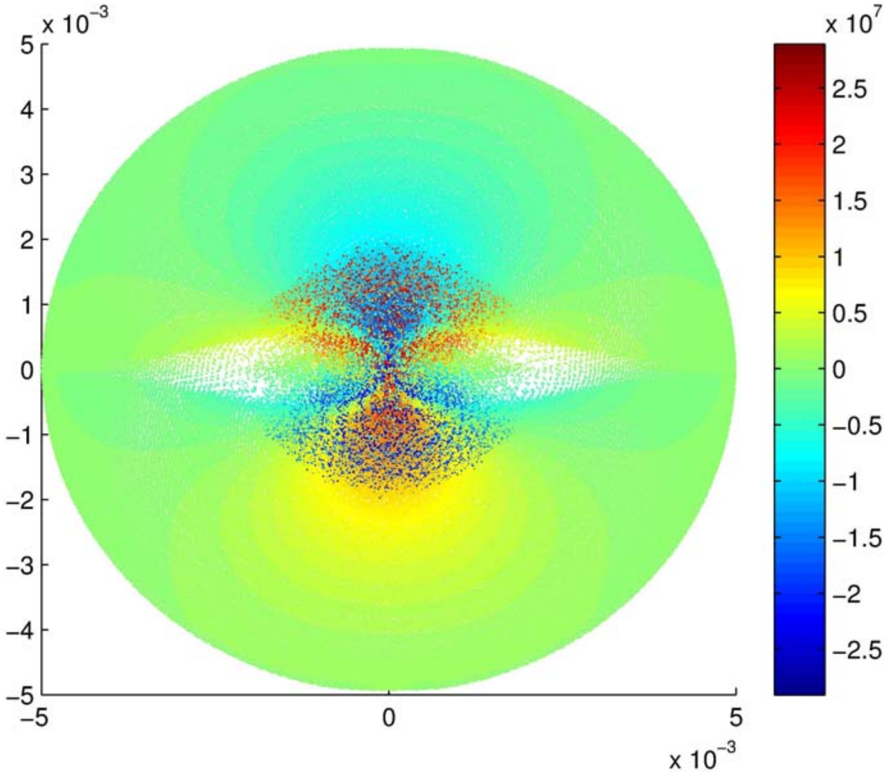
$$\omega_{c,y}^2 = \frac{2\lambda_b r_e c^2}{k_y(\sigma_x + \sigma_y)\sigma_y} \qquad \omega_{b,y}^2 = \frac{2\lambda_c r_e c^2}{\gamma k_y(\sigma_x + \sigma_y)\sigma_y}$$

$$W_1(z)[\mathrm{m}^{-2}] = cR_S/Q \sin\left(\frac{\omega_c}{c} z\right) \quad cR_S/Q = \frac{\gamma \omega_b^2 \omega_c}{\lambda_b r_c c^3} L$$

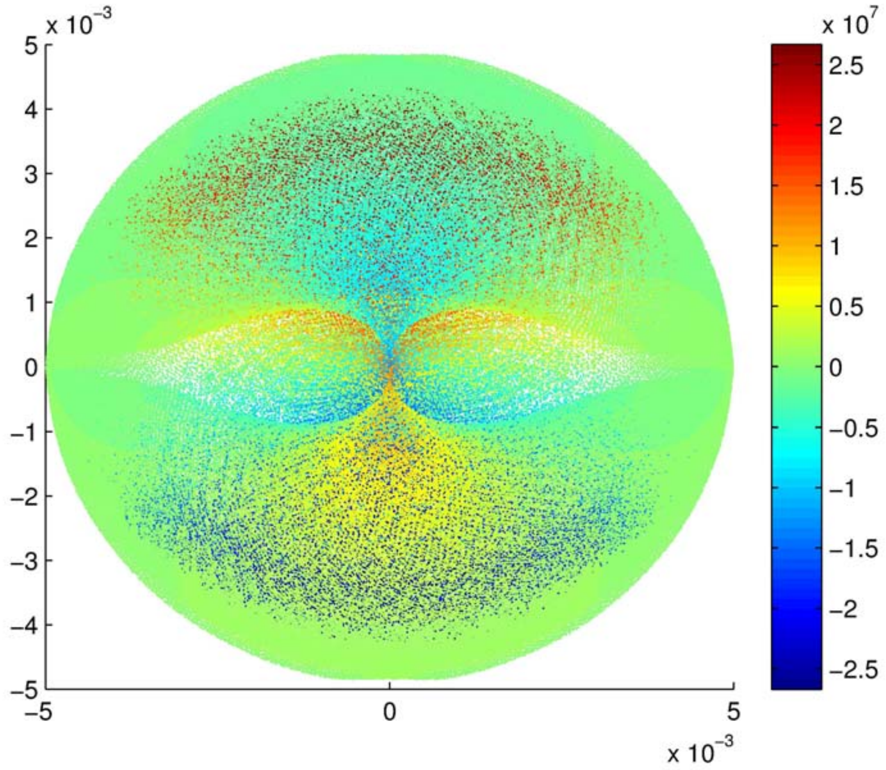


K. Ohmi, F. Zimmermann, E. Perevedentsev, Phys. Rev. E 65, 16502 (2002)

Electron velocity - vertical component (m/s)

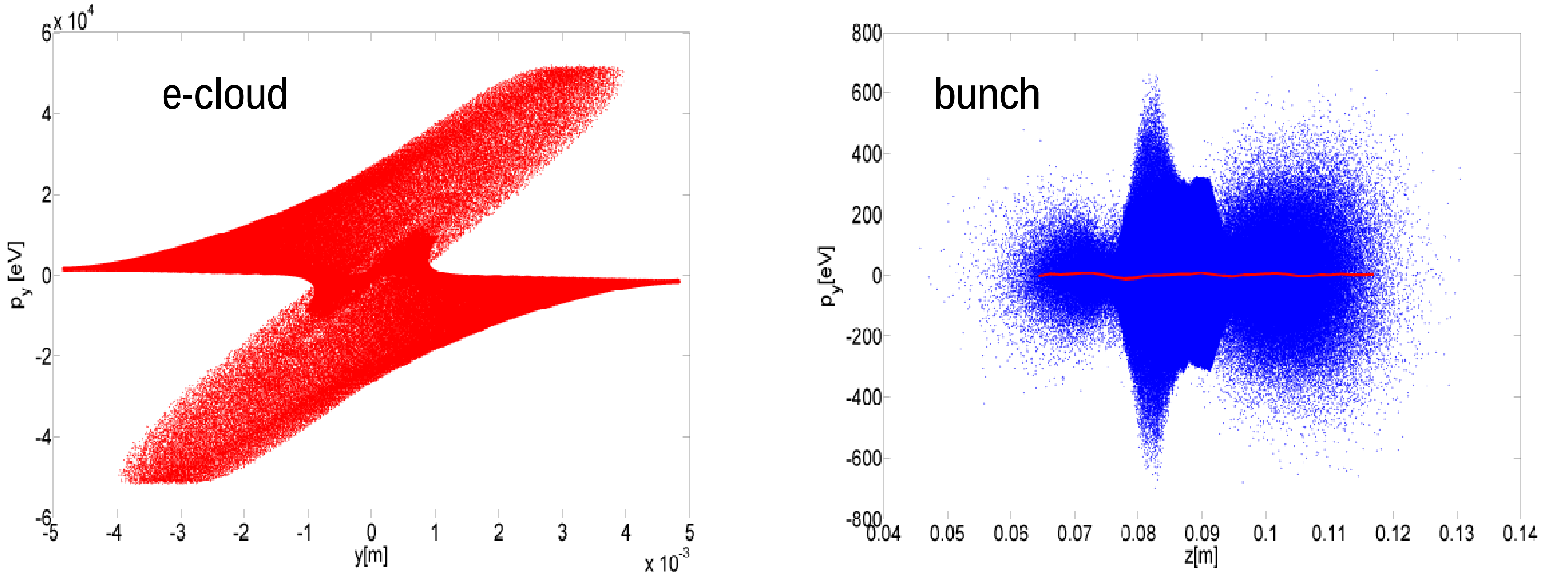


During the bunch passage



After the bunch passage

After the interaction…



Vertical phase-space of the e-cloud after bunch passage (left), vertical momentum along the bunch length (right).

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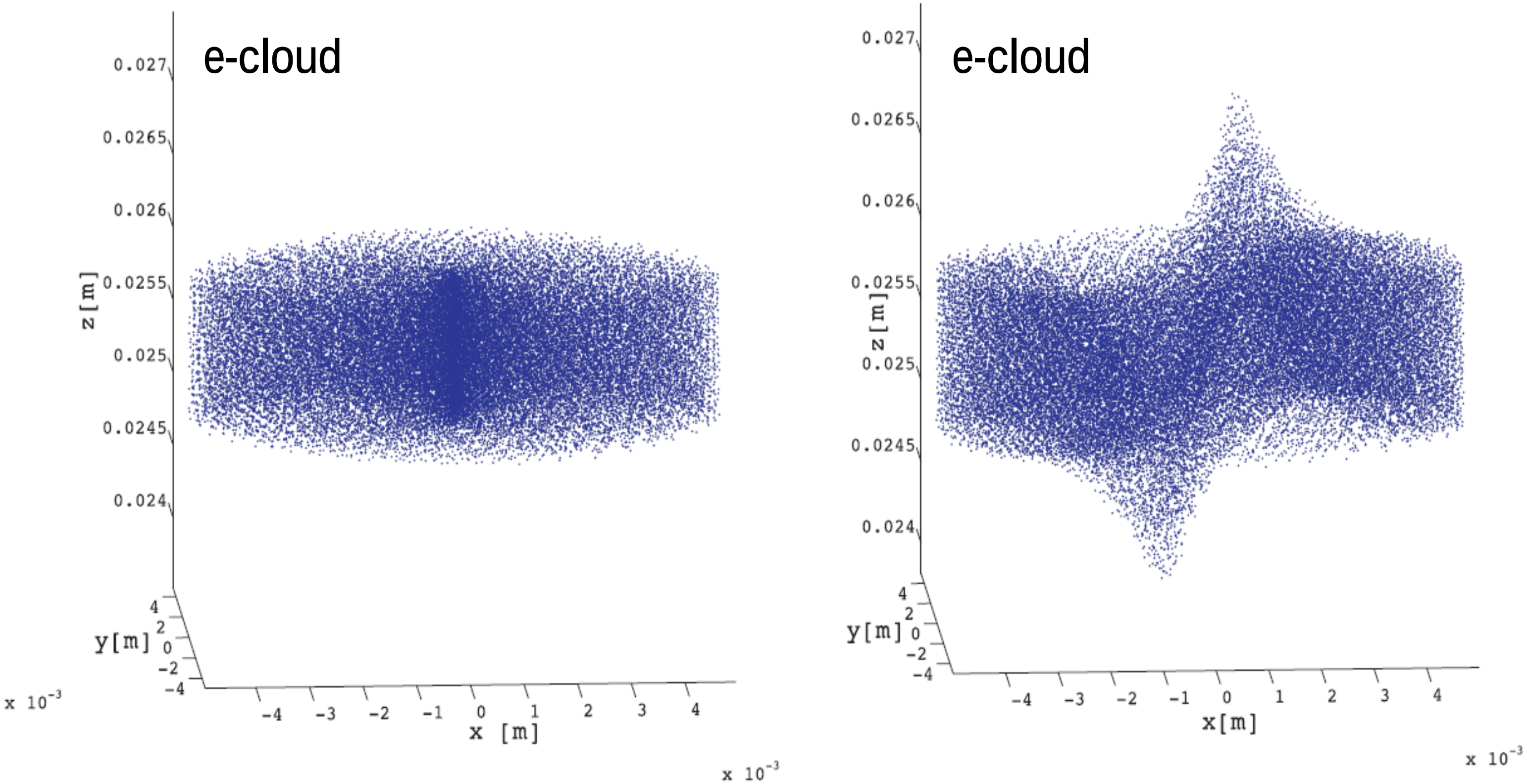
Interaction: beam - e-cloud with and w/o dipole field



Electron distribution after the interaction with the bunch w/o dipole field (left) and with dipole field (right).

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Single bunch instability simulation

- Wake matrix by detailed beam – e-cloud interaction simulations with MOEVE PIC Tracking - idea of K. Ohmi
- Tracking with “PEWKT” by K.Ohmi –Input: Wake Matrix with the transversal kick due to the e-cloud interaction

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Dipole kick from the e-cloud (head-tail)

A particle at a longitudinal position z_j in the tail of the bunch receives a dipole kick $\Delta p_y(j,i)$ from the e-cloud perturbed by a preceding slice i $(z_i > z_j)$ with an off-set Δy_i .

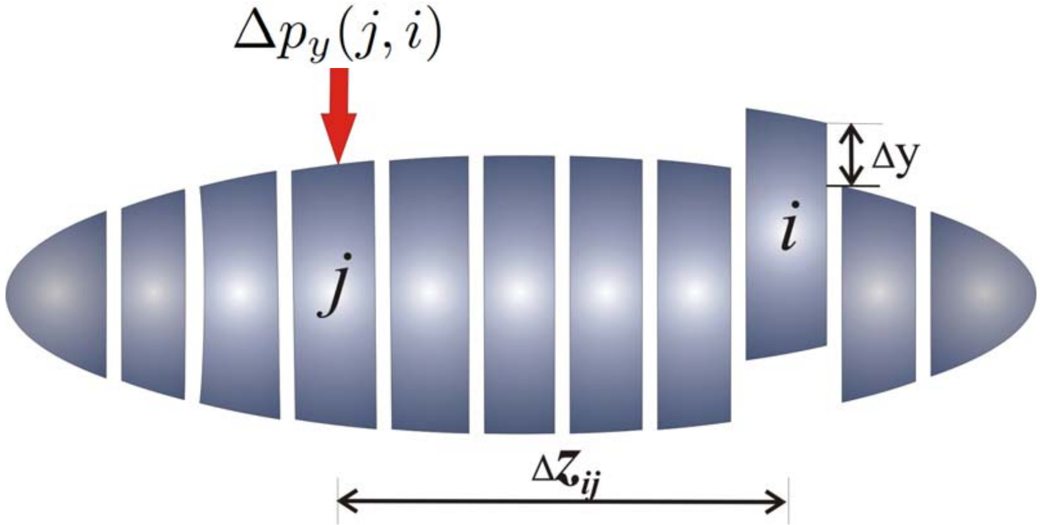
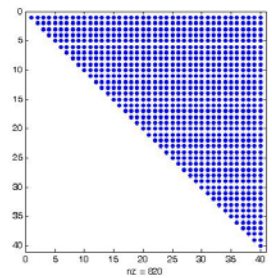


Fig.1: Slicing the 3D bunch in M longitudinal slices and introducing an offset $\Delta y \le \sigma_y$ in the transversal plane for each slice at the time.



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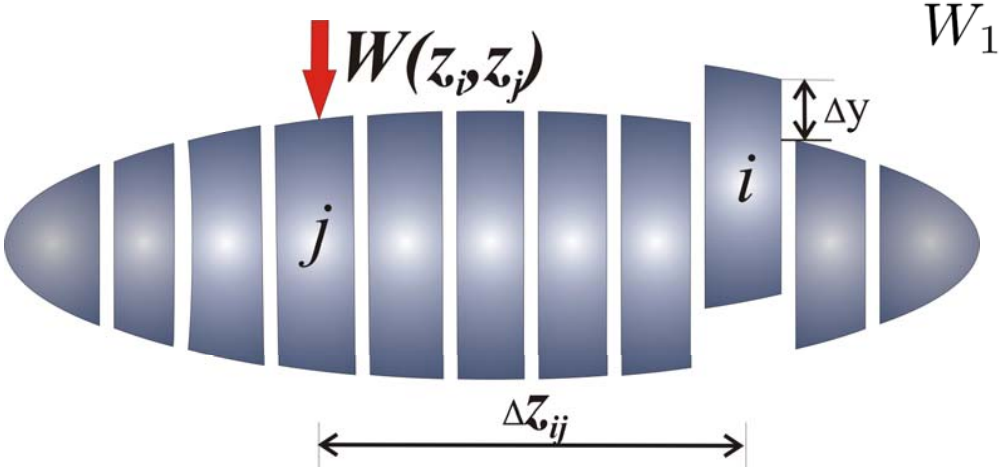
Entries of the wake matrix W_1

Perform M MOEVE PIC Tracking simulations of the interaction where each of the slices $i = 1, \ldots, M$ has an off-set at a time which is responsible for inducing a dipole kick $\Delta p_y(i, j)$ on the following $j = i, \ldots, M$ slices $(z_i > z_j)$



The entries of the wake matrix:

$$W_1(z_j, z_i) = \frac{\gamma \Delta p_y(j, i)}{p_b r_e \Delta y_i N_i} [1/\mathrm{m}^2]$$

Δy_i - The value of the offset of i

N_i - Particles in the off-set slice

p_b - Longitudinal impulse of the bunch

r_e - Classical radius of electron

γ - Lorentz factor of the beam

$\Delta p_y(j, i)$ - Change of the transverse impulse of j

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Tracking of a single bunch with a wake matrix

- With the tracking program PEWKT[1] of K. Ohmi we track the bunch through the linear optics of the storage ring while at each turn the M slices of the bunch receive a kick according to the pre-computed wake matrix.

Main Assumptions:

- - The kick on the slice j is a superposition of the kicks induced by all the slices $i = 1, \ldots, j-1$ ahead of the slice j.
- - The transverse kick scales linearly with the off-set Δy_i until $\Delta y \leq \sigma_y$

[1] K. Ohmi. Particle-in-cell simulation of beam-electron cloud interactions. In PAC, 2001, volume 3, pages 1895–1897, 2001.

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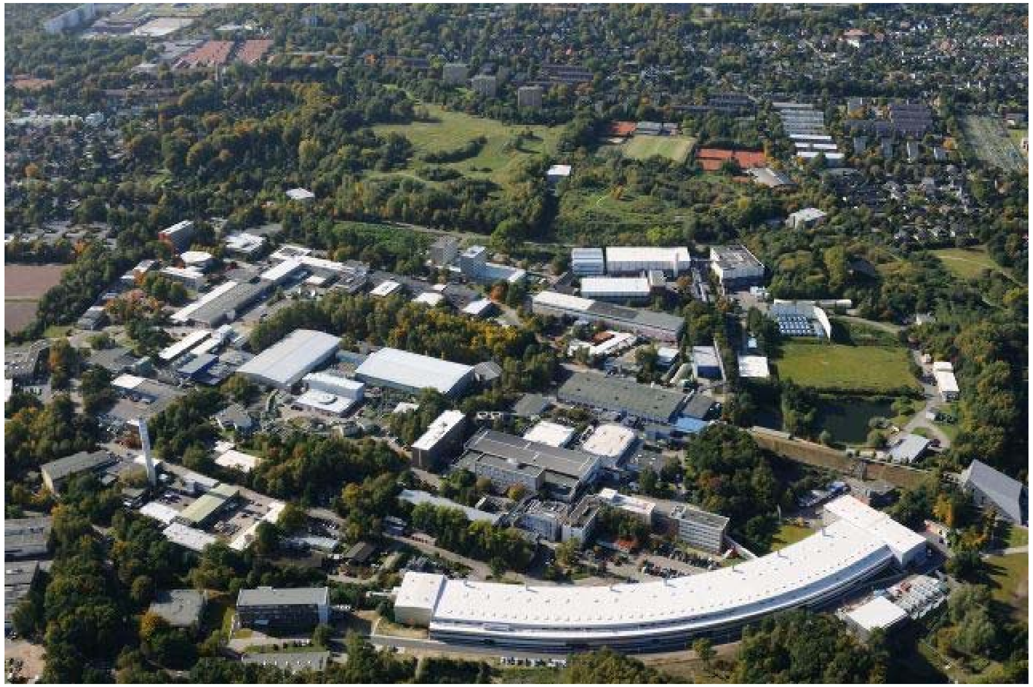
Results for PETRA III



Aerial view of October 6, 2008
Photo: http://petra3-project.desy.de/buildings/photos/october_2008/aerial_views/index_eng.html

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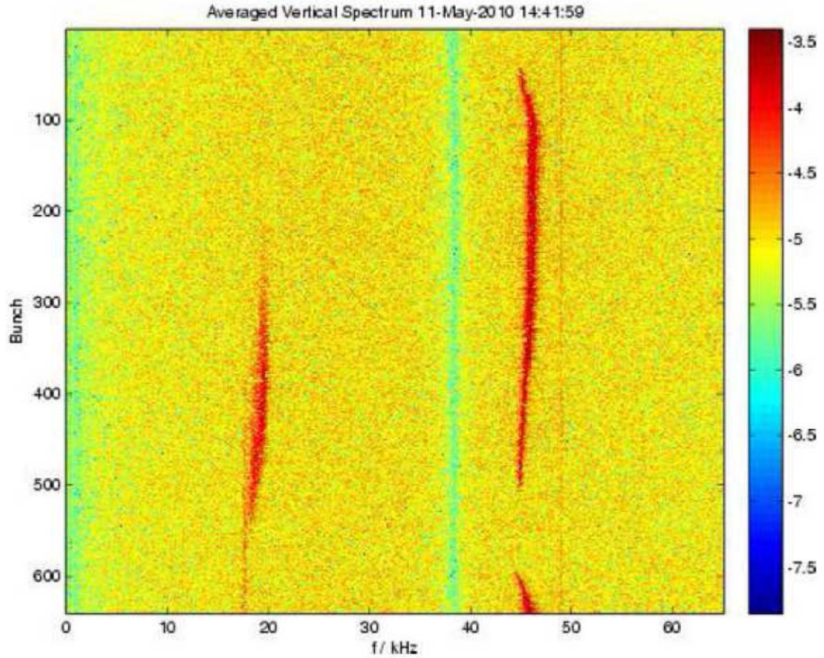
PETRA III - synchrotron machine running with positrons in a top up operation with I=100mA

Parameter	Symbol	PETRA III
Circumference	L	2304 m
Beam energy	E_b	6 GeV
Length (rms)	σ_z	12 mm
Emittance	ϵ_x ϵ_y	1nm 0.01nm
Synchrotron tune	ν_s	0.049
Betatron tune	$\nu_{x(y)}$	36.13/30.29
Radiation Damping	horizontal vertical longitudinal	19.75 ms 19.75 ms 9.84 ms
Momentum compaction factor	α	1.2010^{-4}
RF Frequency	RF	499.564 MHz

Table 1: PETRA III machine parameters. Designed for 960 and 40 bunches with equidistant spacing of 8 and 192 ns.



Vertical tune spectra of each of the 640 bunches with 8ns spacing, measured on May 11, 2010[1]. The total beam current was 62mA.
Courtesy of R.Wanzenberg.

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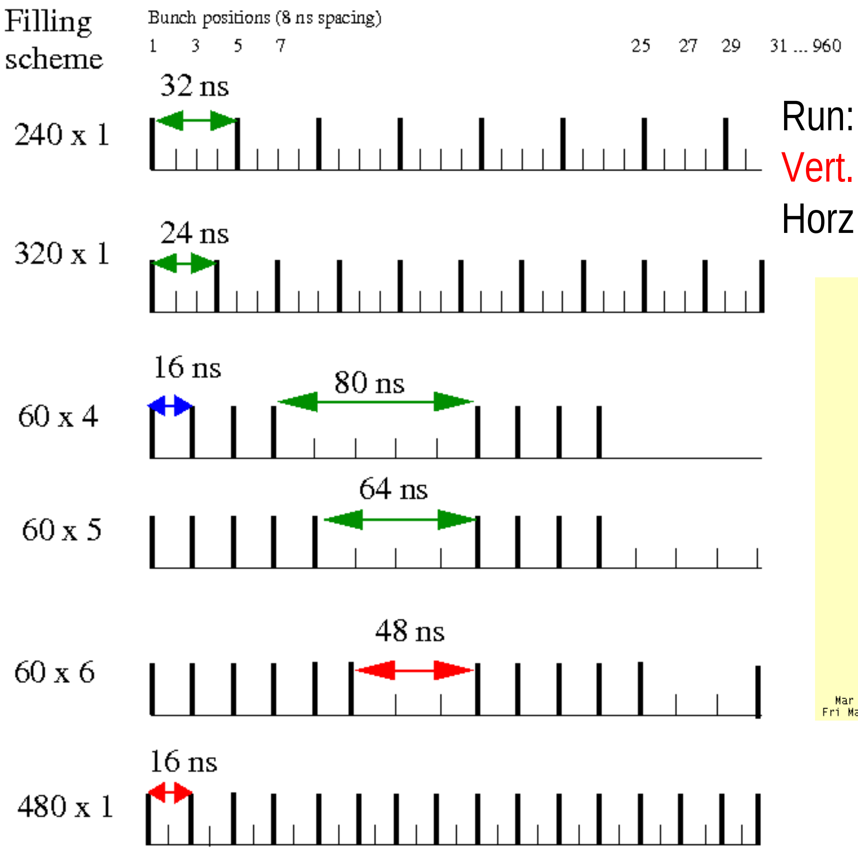
Different filling schemes of the machine:



Courtesy of R. Wanzenberg.

Run: 480 x 1 Beam Scrubbing, March 3 / 4, 2012

Vert. Emittance ~140 pm rad (for 20 h), than dropping to 97 pm rad

Horz. Emittance Starting at 1.0 nm rad Increasing to 1.8 nm rad

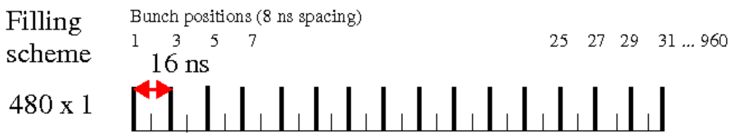
Green: total current (100 mA)

Red: vertical emittance (scale 0 … 150 pm rad)

Blue: Number of bunches (480)

Black: horizontal emittance (scale 0 … 6 nm rad)

Simulation of a single bunch stability for the bunch of the 480 x 1 run:



Starting vertical emittance: ε_y=20 pm rad

Beam Current	I	100 mA
Beam Charge	Q	769 nC
Bunch Charge	Q_b	1.6 nC
Positrons per Bunch	N_b	10^{10}
Mean β function	$\beta_{x/y}$	15 m
Transverse	σ_x	122.47 μm
beam size (rms)	σ_y	17.321 μm

e-cloud:

- uniform distribution,
- density: ρ_e=1 10^{11}, 5 10^{11}, 2 10^{12}, 5 10^{12} [N_e/m^3]
- Beam pipe radius: 5mm length: 10mm
- Represented by unit charges

positron bunch:

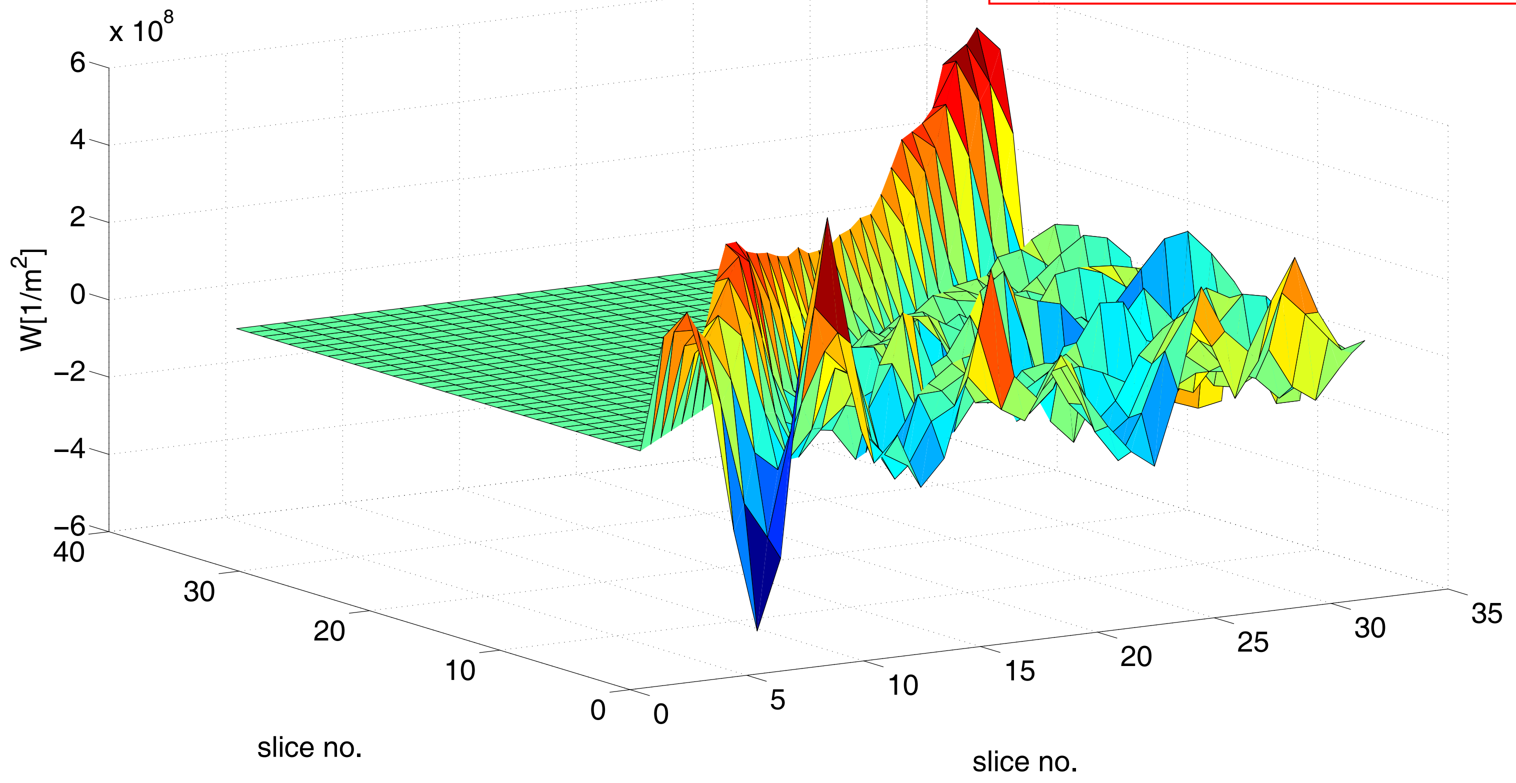
- represented by 10^6 macro-particles;
- Gaussian distribution;
- longitudinally spreads from $-3\sigma_z$ to $+3\sigma_z$
- virtually sliced in M = 40 slices*

The time step used for the interaction simulation is 1 ps.

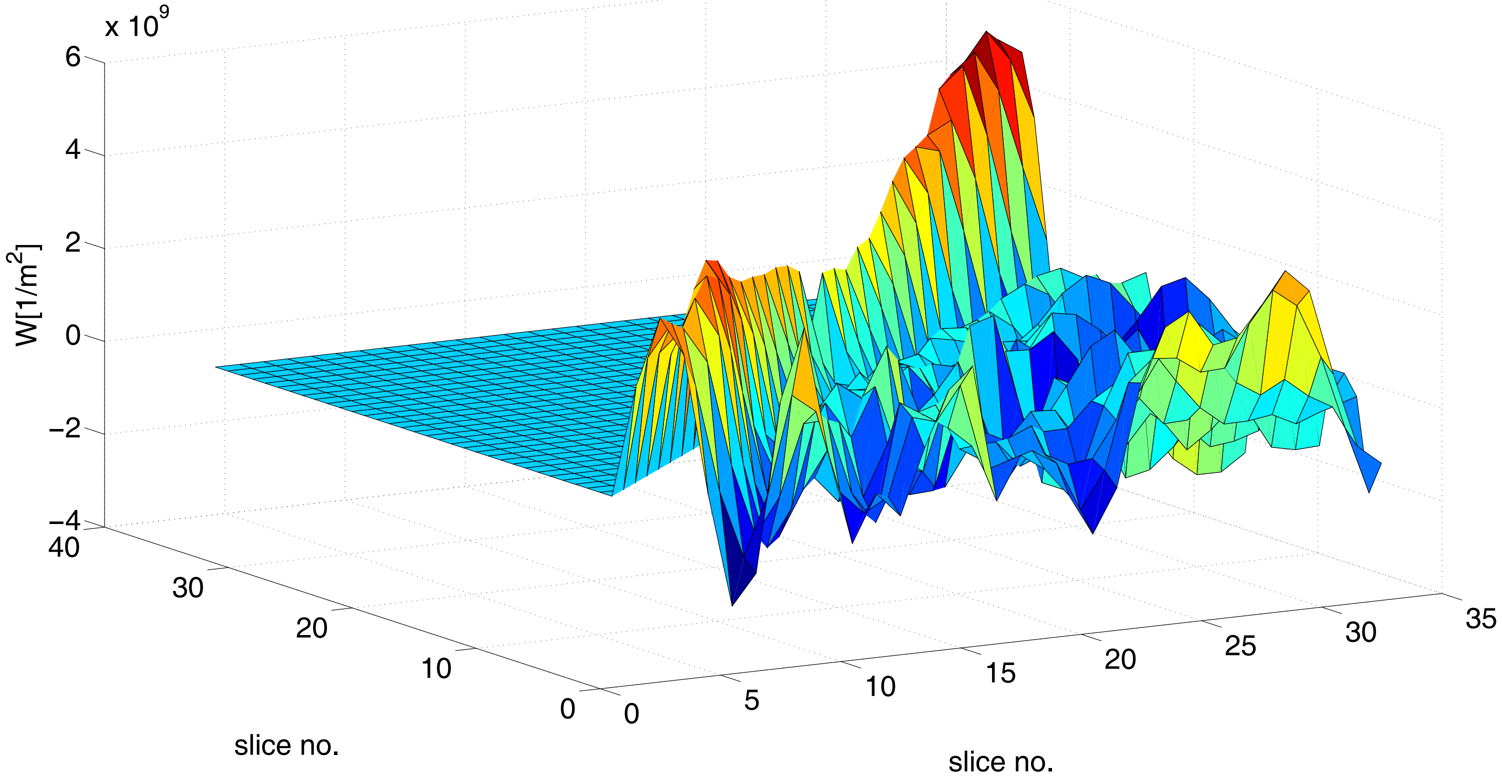
** The thickness of the slices in the lab frame corresponds to the time which the electrons on the beam axis need to change their vertical position for one σ_y.*

Wake matrix computed by MOEVE-PIC TRACK

e-cloud density ρ_e =5 10^{11} [N_e/m^3]



e-cloud density $\rho^e = 5\ 10^{12}\ [N_e/m^3]$



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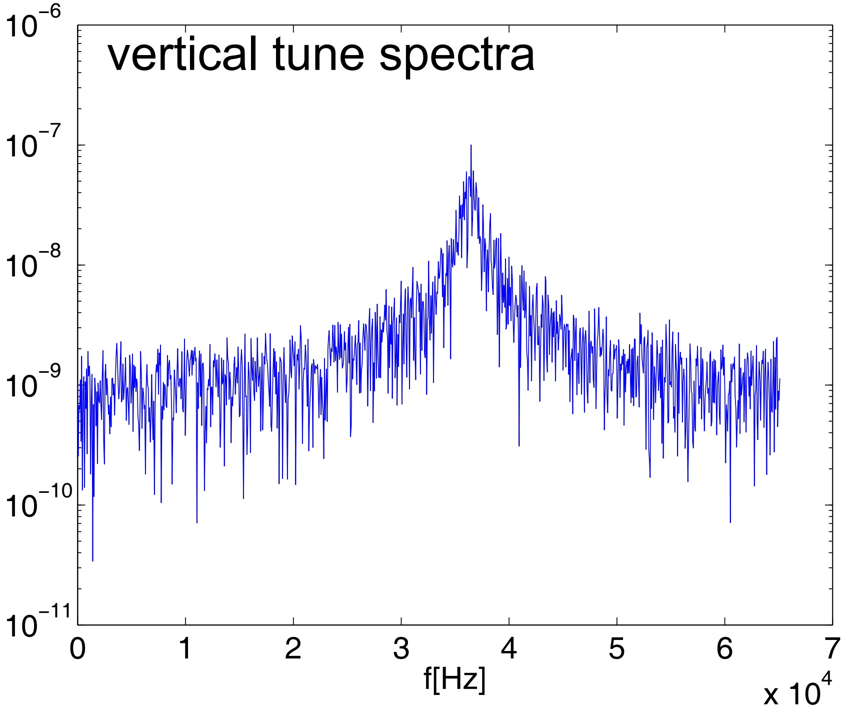
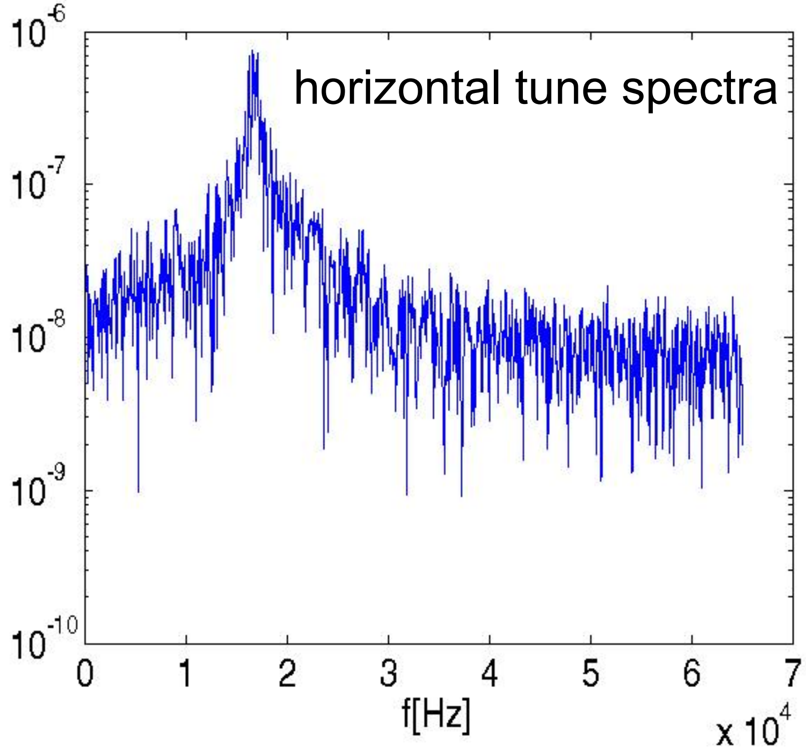
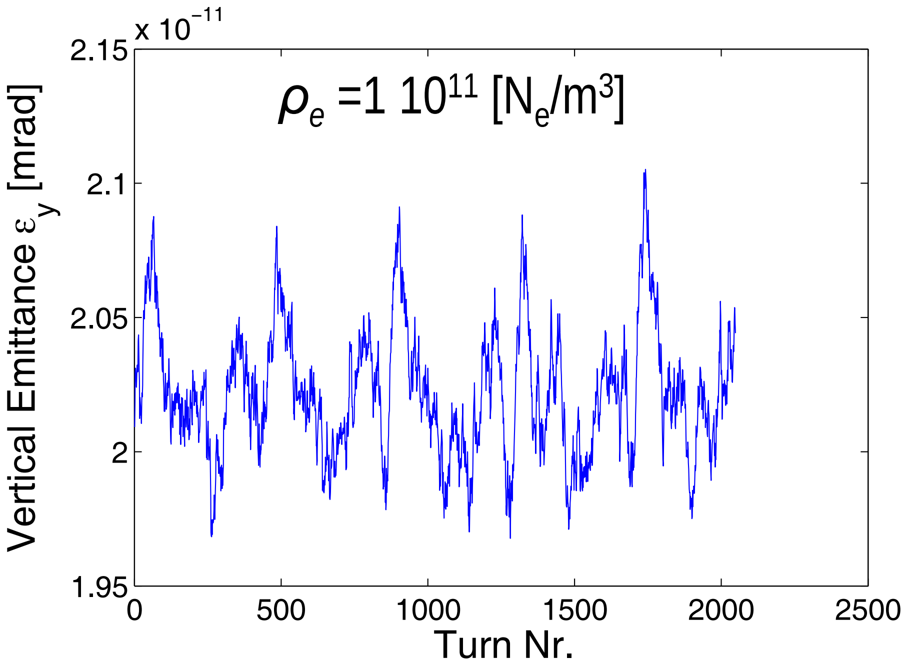
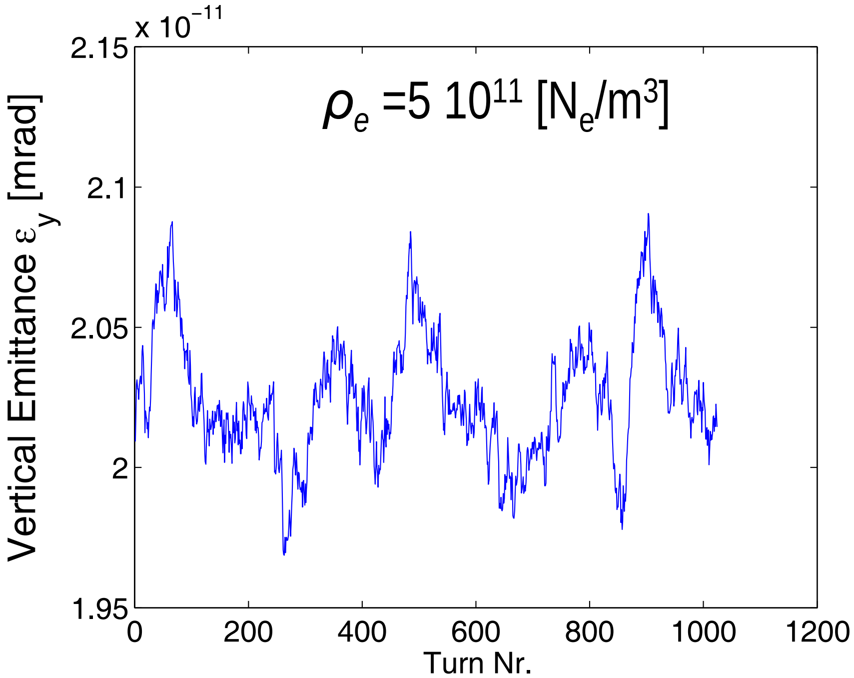
Tune spectra for e-cloud density ρ_e =5 10^{11} [N_e/m^3]





Vertical emittances… e-cloud density < threshold: $\rho_e = 1.4\ 10^{12}\ [N_e/m^3]$*



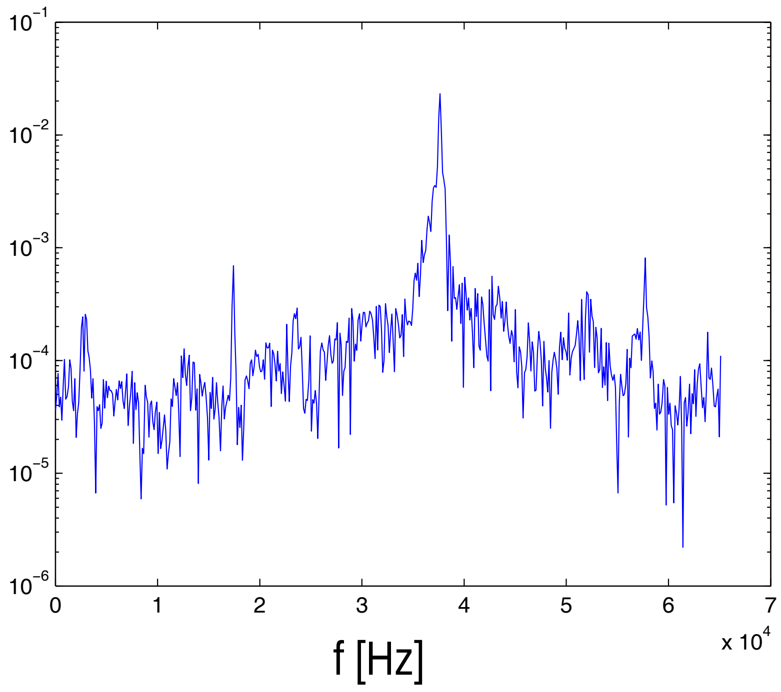


*computed by R.Wanzenberg accoding the expression from: K. Ohmi: Electron Cloud Effect in Damping Rings of Linear Colliders 31st ICFA Advanced Beam Dynamics Workshop on Electron-Cloud Effects "ECLOUD'04"

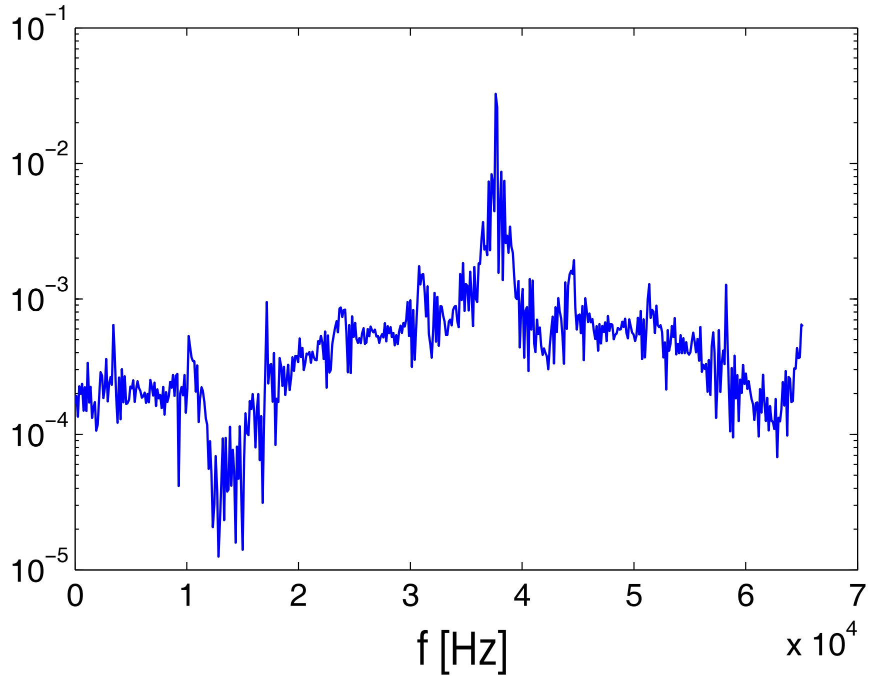
Vertical tune spectra

e-cloud density > threshold: ρ_e =1.4 10^{12} [N_e/m^3]

ρ_e =2 10^{12} [N_e/m^3]



ρ_e =5 10^{12} [N_e/m^3]



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Vertical emittances…

Run: 480 x 1 Beam Scrubbing, March 3 / 4, 2012
Vert. Emittance ~140 pm rad (for 20 h),
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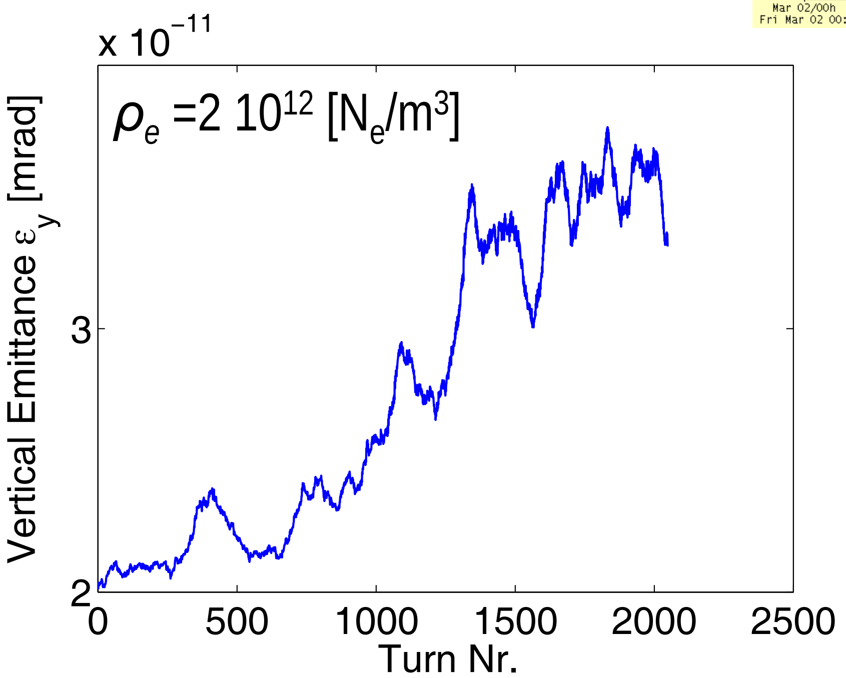

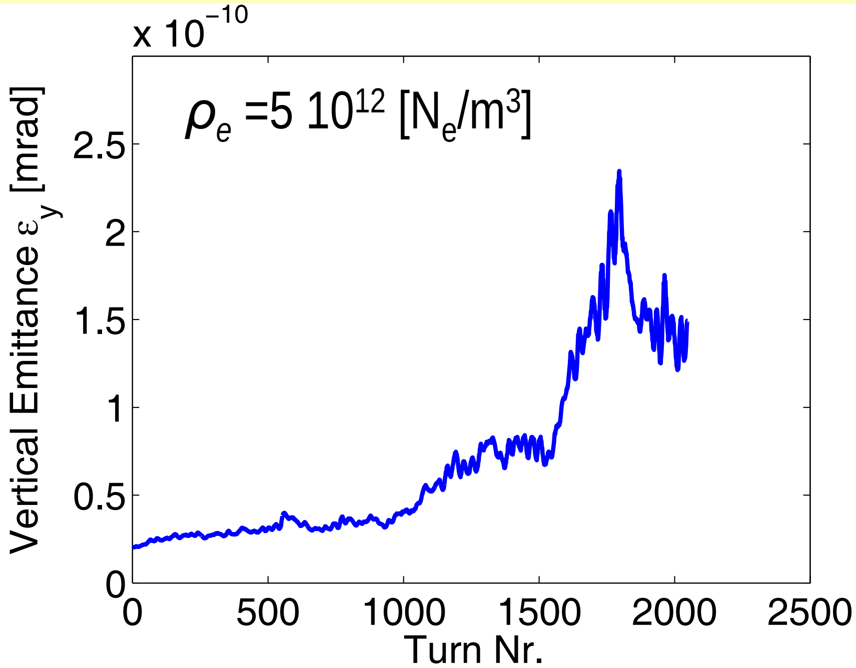

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Summary and conclusion

- 3D computation of single-bunch induced electron-cloud wake fields
- Simulation of single bunch instabilities due to the interaction with the electron clouds by tracking with a 2D Wake-Function.
- Investigation of the stability for different beam and cloud parameters
- The tracking simulation using the pre-computed wake matrix for the given bunch was able to predict the instability.
- As in the measurements the simulation for e-cloud densities above threshold show also sidebands in the betatron tune spectra.
- The simulated emittance growth seems realistic, even more the emittance from the simulation with $\rho_e = 5 \cdot 10^{12}$ N^e/m^3 seems to match the measured long time emittance (~140 pm) from the run with 480 bunches.
- Although further validation of the procedure is needed it seems that such a simulation may also be used to numerically estimate the threshold e-cloud density.

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Acknowledgment

We would like to thank K. Ohmi for letting us use his program and R. Wanzenberg for sharing his knowledge with us regarding e-cloud effects in the PETRAIII ring.