E-cloud instability and incoherent emittance growth

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Acknowledgments**: *F. Zimmermann, G. Arduini, E. Metral, G. Franchetti, K. Ohmi, F. Ruggiero, G. Rumolo, D. Schulte***

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  - – Electron cloud evolution in the bunch potential
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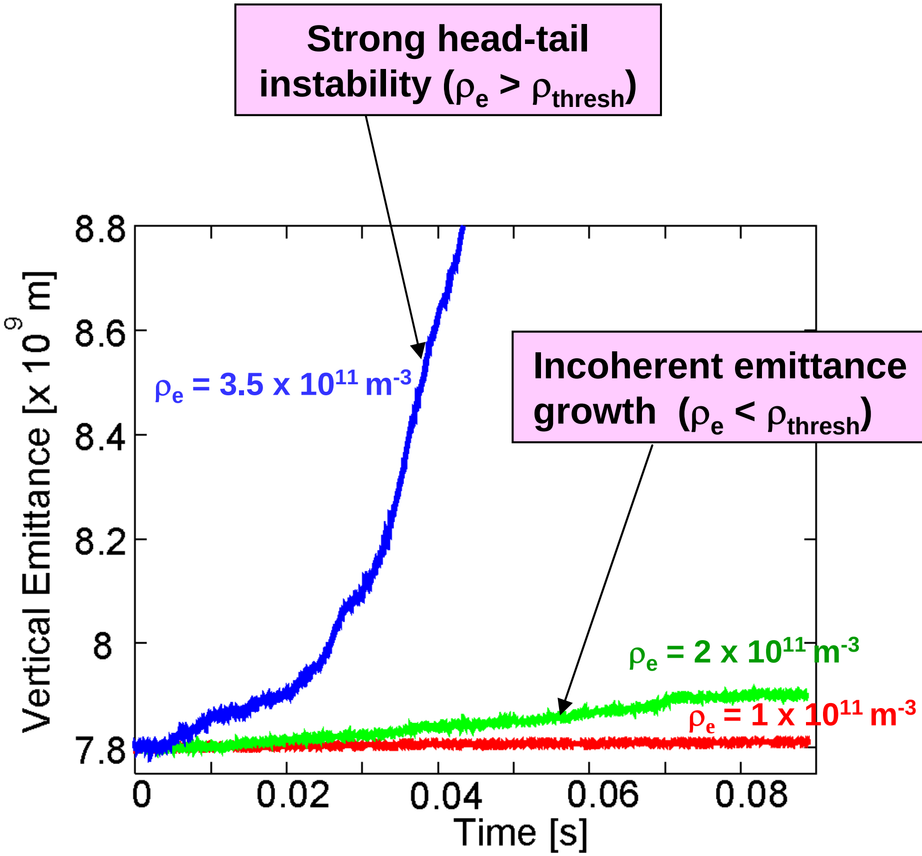
- ✓ Conclusions and outlook

CARE-THESIS-06-007, CERN-THESIS-2008-096

- ✓ Single-bunch effects below & above EC instability threshold
- ✓ Strong head-tail instability, coherent tune shift, head-tail motion and associated emittance growth.
  - During bunch passage, e- go toward beam center (pinch).
  - e- follow perturbations of beam:
    - *If displacement between head and tail, tail feels wake force.*
  - Effective short-range wake field:
    - *Single-bunch TMC Instability.*
- ✓ Incoherent emittance growth and long-term beam losses



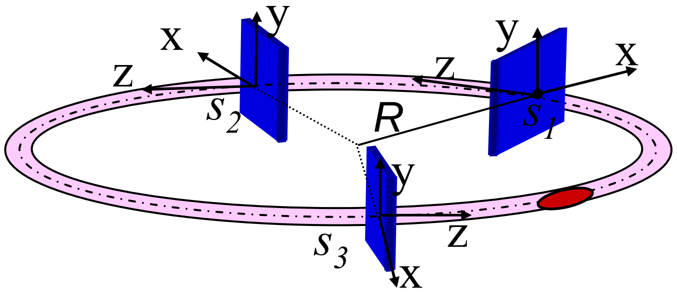
(simulations for LHC @ injection)

HEADTAIL → *CERN, 2002, G. Rumolo, F. Zimmermann, et al.*

✓ EC localized in a finite number N_k of interaction points (IPs) around the ring.

✓ EC density as input.

✓ The cloud is thin (2D).



(N_k=3)

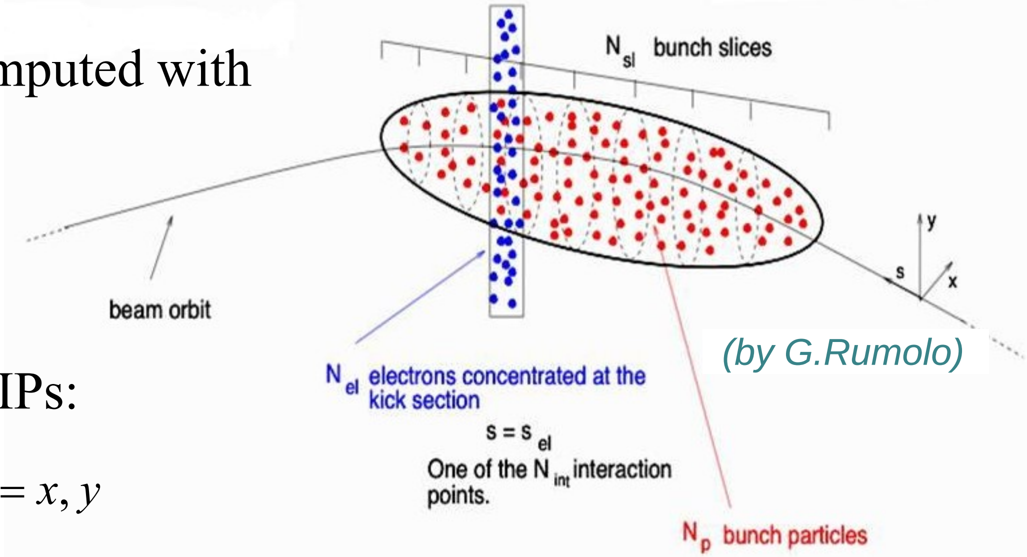
✓ Bunch divided in slices, which enter into the EC at subsequent time steps.

✓ At each time step, 2D interaction computed with PIC module:

- e- perturbed by p+ field
- p+ get a kick Δu by e- field

✓ Matrix to transport protons between IPs:

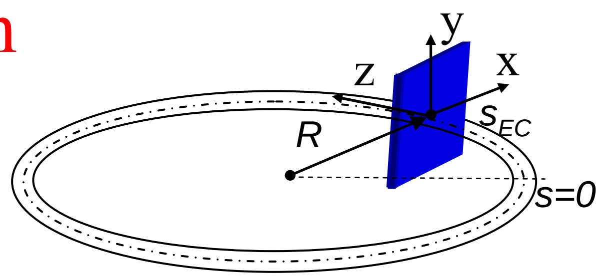
$$\begin{pmatrix} u \\ u' \end{pmatrix} = M \begin{pmatrix} u_0 \\ u'_0 + \Delta u'_{EC} \end{pmatrix} \qquad u = x, y$$

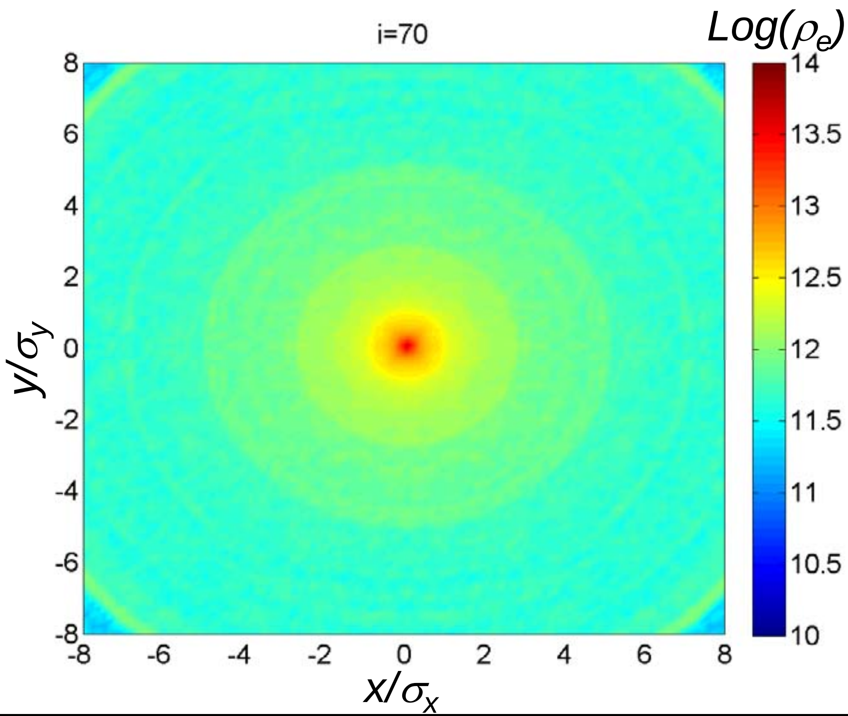


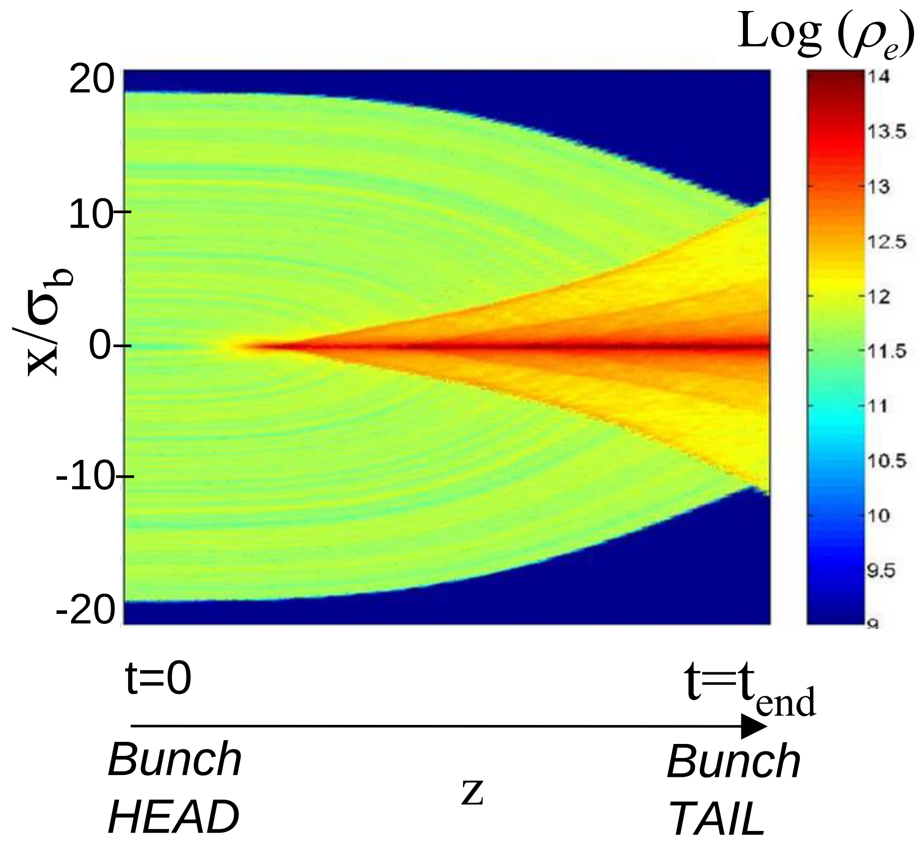
(by G.Rumolo)

Electron cloud evolution

- ✓ EC "pinch" in the transverse plane, during the passage of a bunch



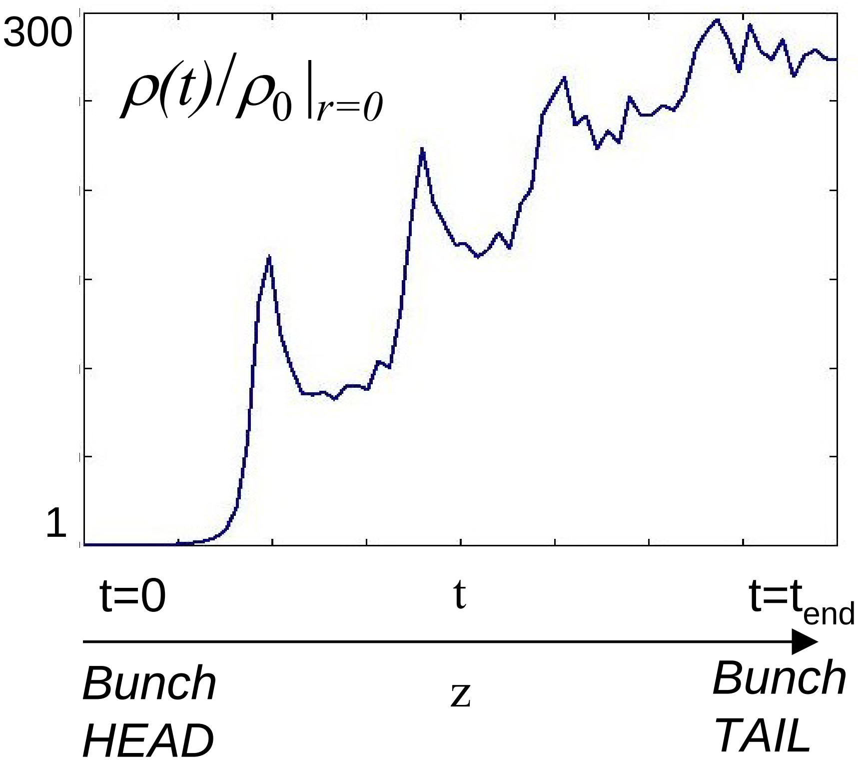


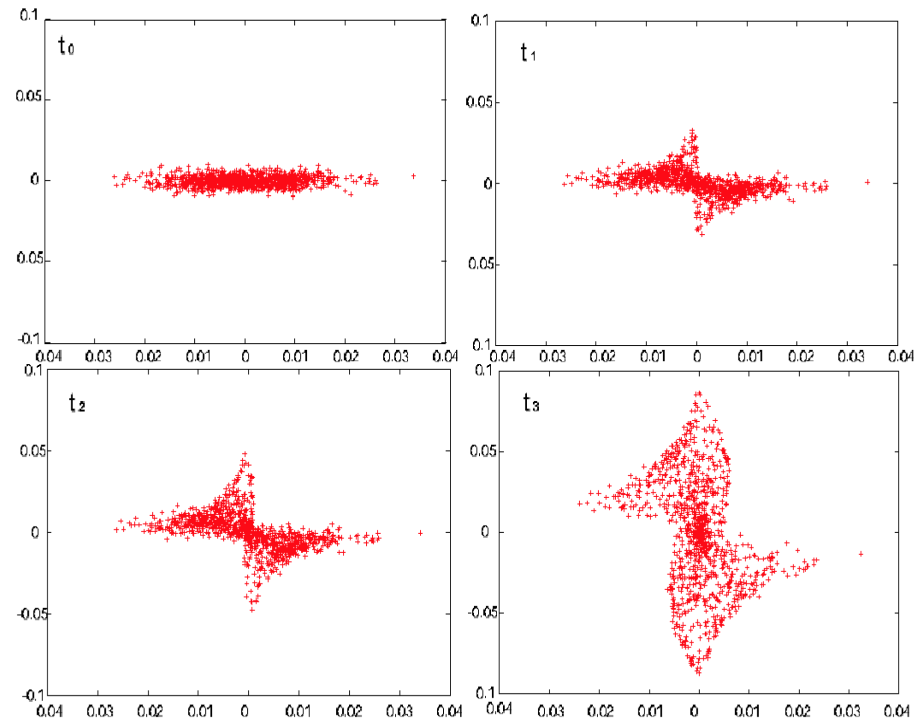


EC density in the horizontal plane vs. time

LHC @ inj, field-free region

- ✓ EC evolution at the centre of the bunch (x,y)=(0,0)
  - peaks (“linear” e^-)
  - density increase (“non linear” e^-)



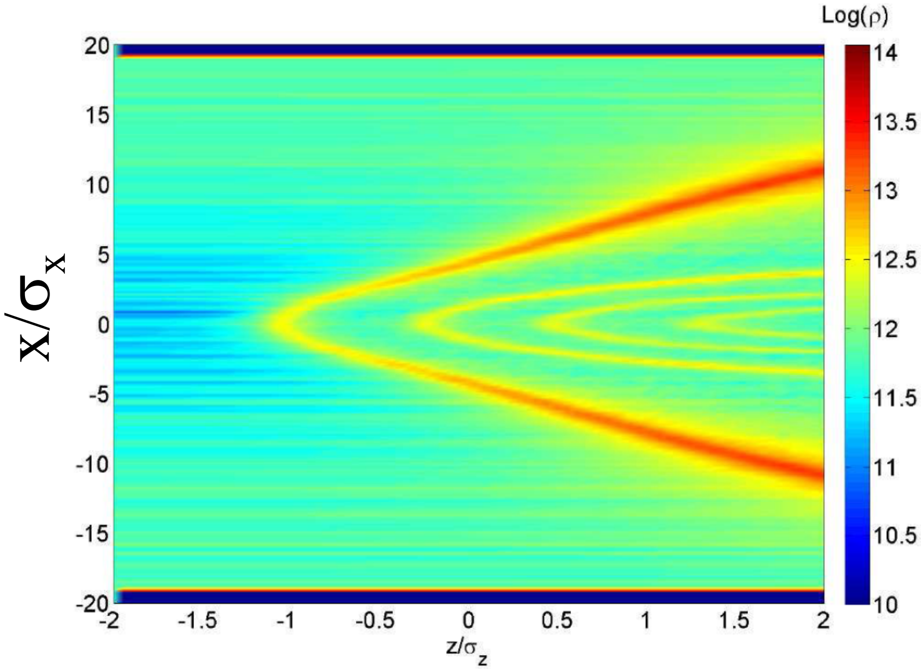


EC phase space at different times: t0=beginning, t1=first peak, t2=first valley, t3=second peak

→ EC density function of longitudinal & transverse position in the bunch

✓ EC evolution in dipole regions of LHC (@ inj energy)

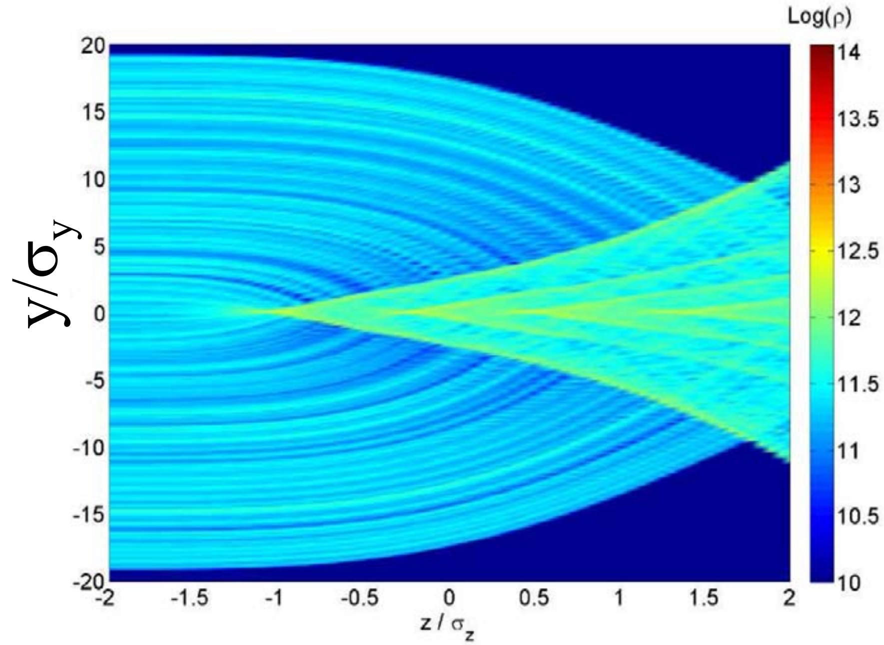
Horizontal plane



t=0 t [ns] $t=t_{end}$

Bunch HEAD z *Bunch TAIL*

Vertical plane



t=0 t [ns] $t=t_{end}$

Bunch HEAD z *Bunch TAIL*

Head-tail instability

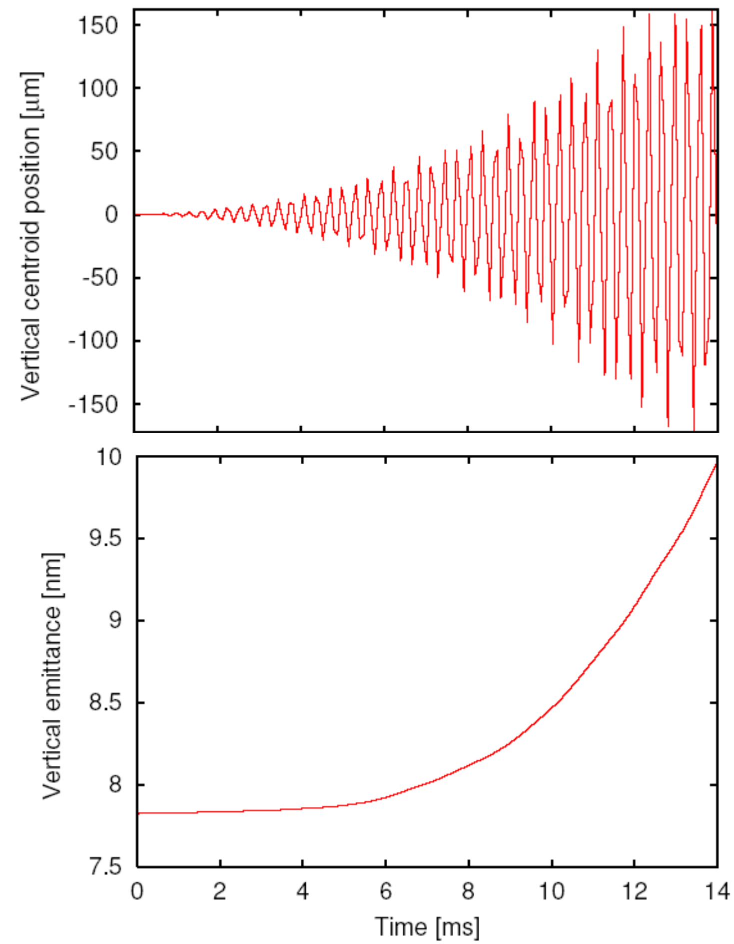
✓During the bunch passage, e- are accumulated around beam center

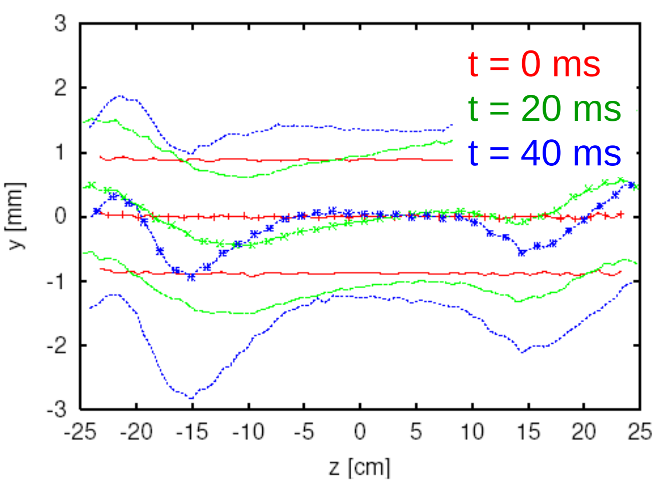
✓If offset between head and tail:

→ tail feels transverse electric field created by head

– effective short-range wake field

Vertical centroid motion and emittance growth in the the first 14 ms, at the onset of the strong head-tail instability.



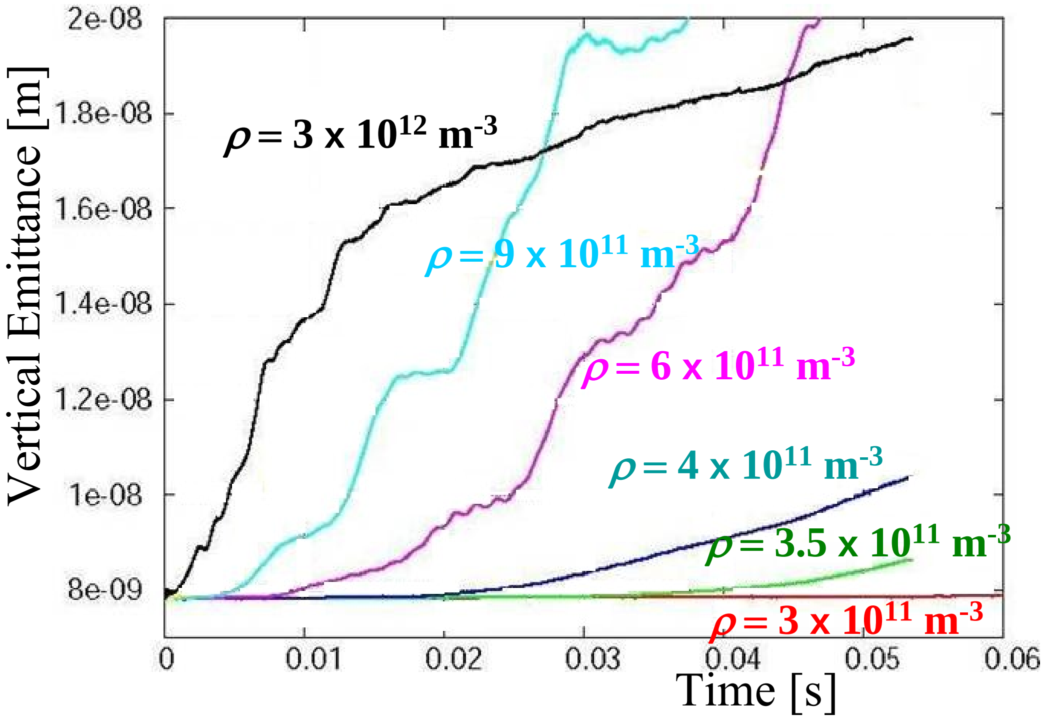


(simulations for LHC @ inj. energy, ρ_e=6 x 10^{11} m^{-3}, Q'=2, field free region)

Snapshot of the vertical bunch profile (bunch centroid and rms size) at different time steps.

✓ Dependence of beam blow-up on EC density value

(studies for LHC @ injection)



Vertical emittance vs. time, for different EC densities; chromaticity Q'=2

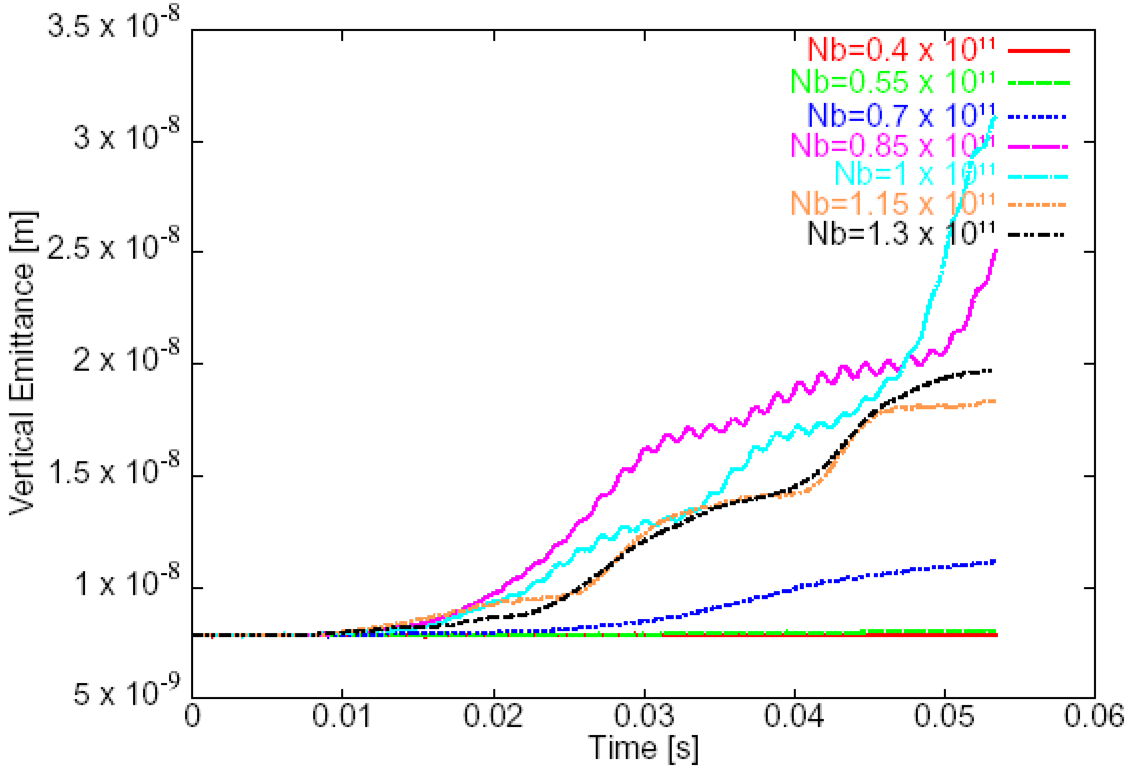
- ✓ Agrees with a 2-particles model analytical estimate of the threshold density for TMC type instability:

$$\rho^{thre} = \frac{2\gamma Q_s}{\pi r_p L \beta} \approx 4.4 \cdot 10^{11} m^{-3}$$

γ	Relativistic factor
Q_s	Synchrotron tune
r_p	Classical proton radius
L	Circumference length
β	Average β – function

E. Benedetto, G. Rumolo, D. Schulte, F. Zimmermann, PRST-AB 8, 124402 (2005)

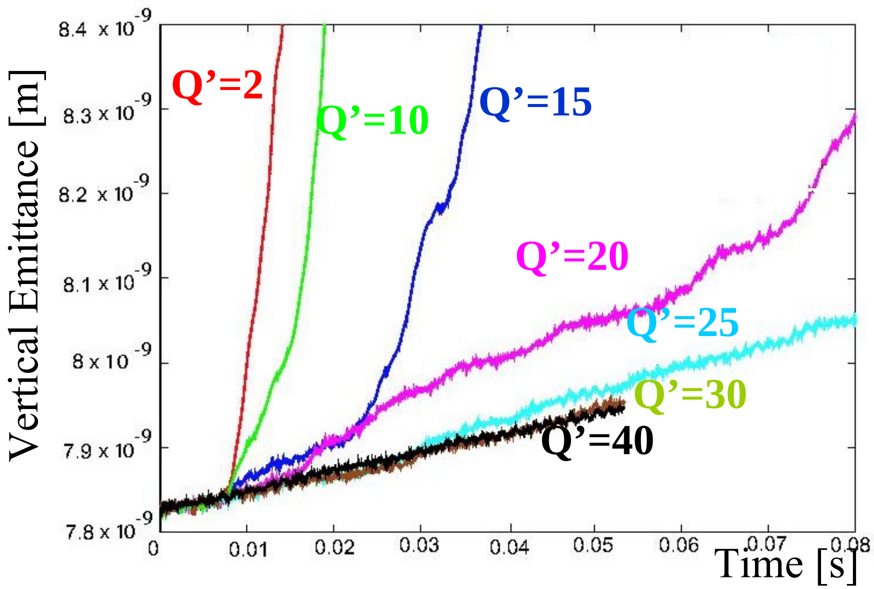
✓ Dependence on bunch intensity



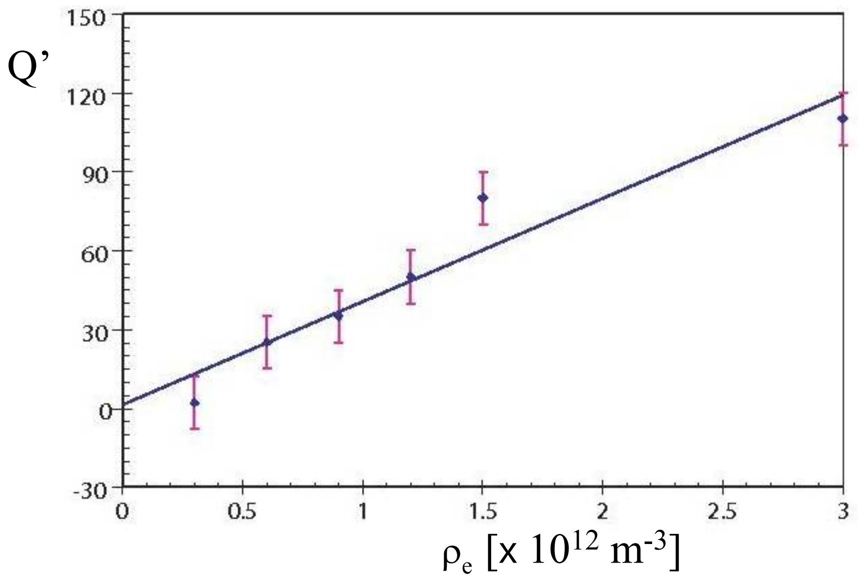
✓ At half nominal bunch intensity (green curve) → below threshold of the fast head-tail

Vertical emittance vs. time, varying bunch intensity; (LHC @ inj), ρ_e=6 x 10^{11} m^{-3}, chromaticity Q'=2

Vertical emittance vs. time, for different chromaticities (ρ_e= 6 x 10^{11} m^{-3})



Chromaticity vs. e- density, needed to cure head-tail instability.

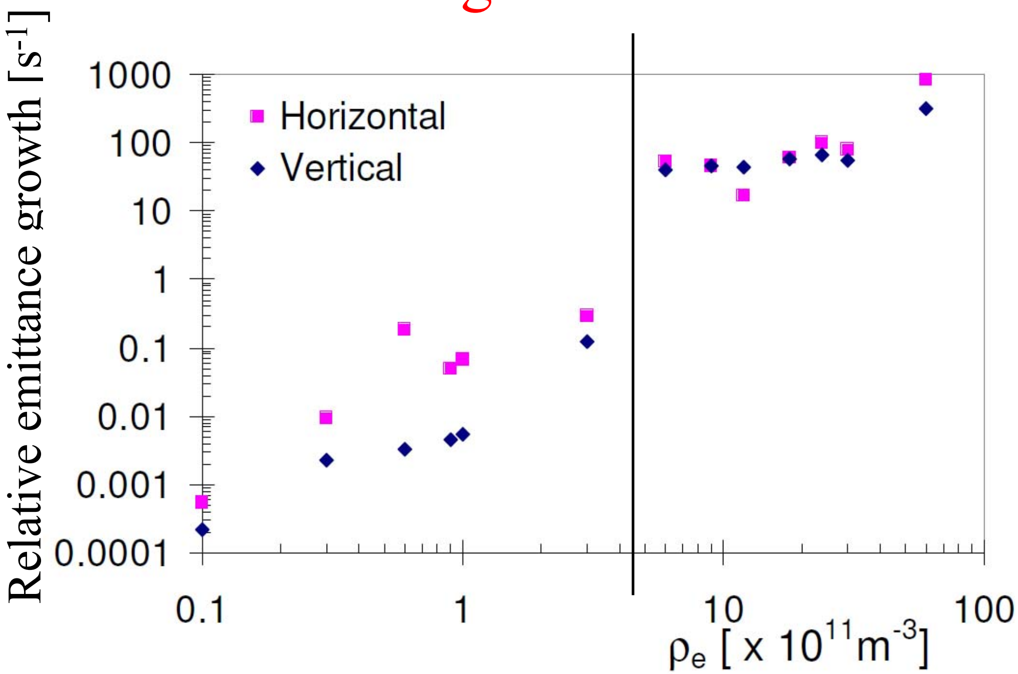


- ✓ Chromaticity cures head-tail instability *(in agreement w. observations)*
- ✓ Incoherent emittance growth below head-tail instability threshold
  - numerical noise or physical effect ?

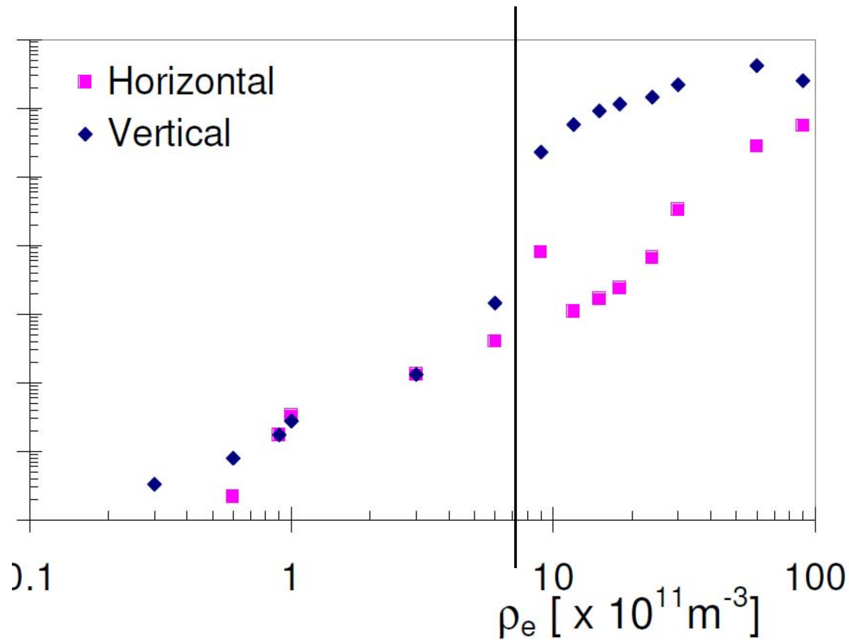
Simulation of head-tail instability

(Simulations for LHC @ inj. energy, 10 kicks/turn, Q'=2)

✓ Field free regions



✓ Dipole field regions



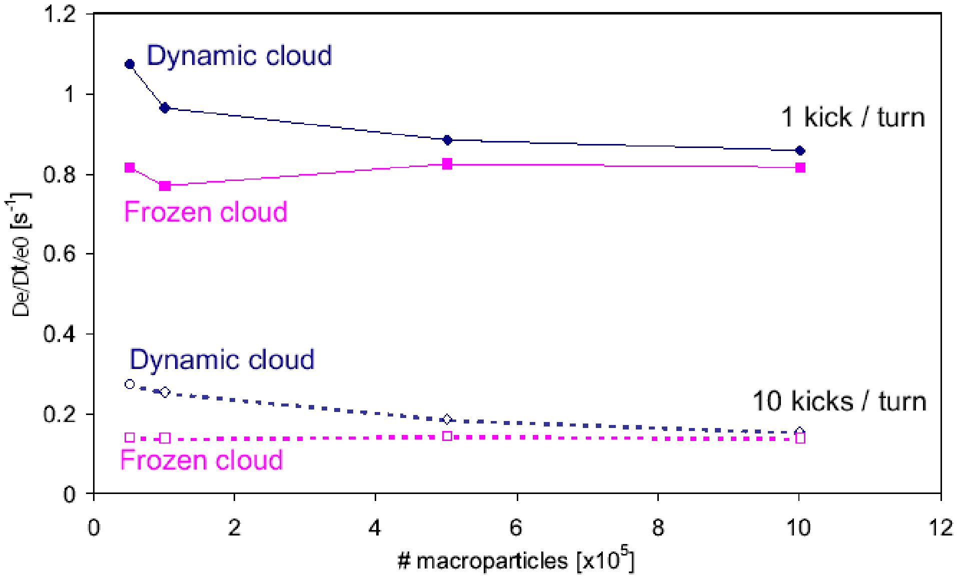
- ✓ Clear threshold in both planes.
- ✓ Emittance growth below threshold.

- ✓ Clear threshold in the vertical plane.
- ✓ No instability in the horizontal plane.

Emittance growth below density threshold

✓ HEADTAIL-ws (“weak-strong” or “Frozen cloud” approx)

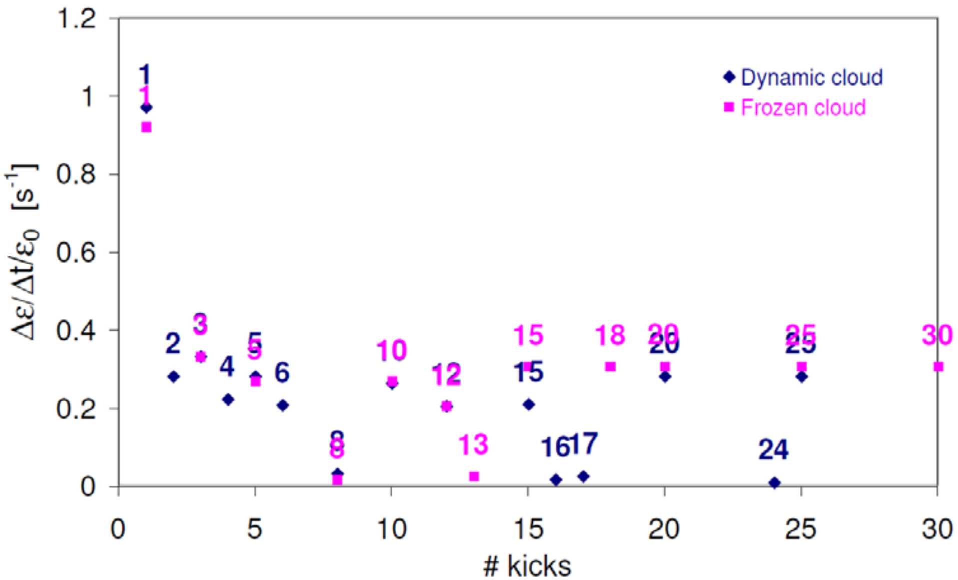
- EC potential (z-dependent) computed only at 1st interaction
- Used for successive turns
- Speeds-up simulations
- Valid for study of incoherent effects only!



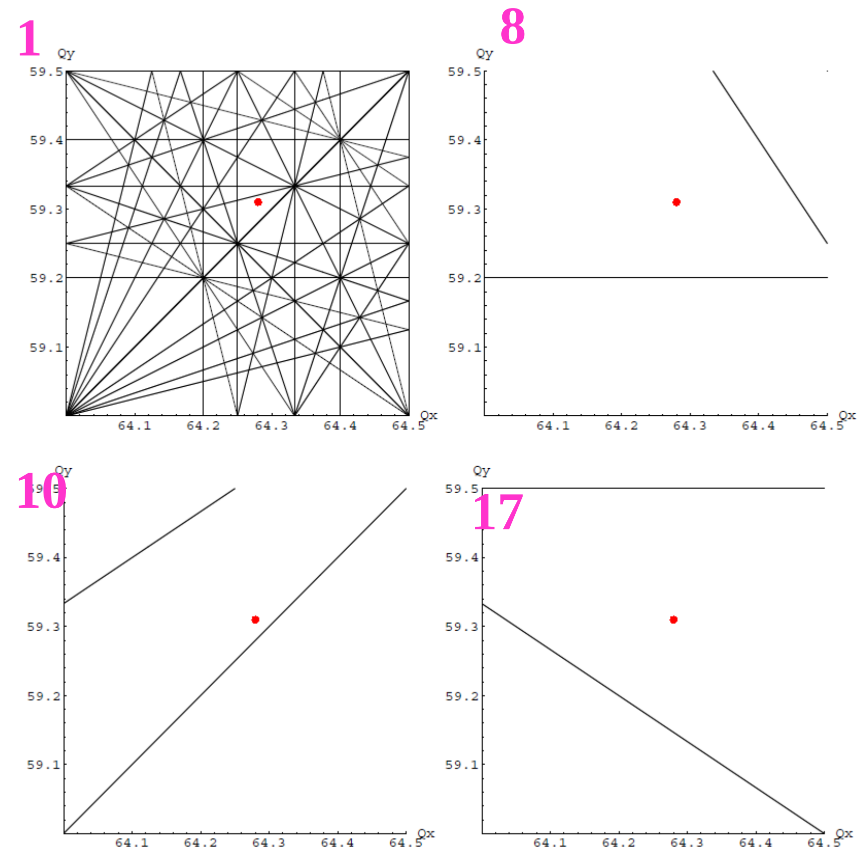
Emittance growth rate vs. # of macroparticles, for 1 (top) and 10 kicks/turn (bottom lines); Simulation results for dynamic (blue) and frozen cloud (magenta) are compared.

✓ dependence # kicks/turn!

✓ Non-monotonic dependence on # of kicks



Horizontal emittance growth vs # kicks



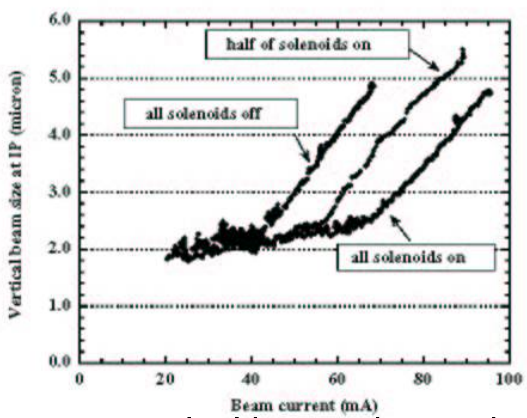
✓ Persisting emittance growth below threshold TMCI

– NOT ONLY numerical noise

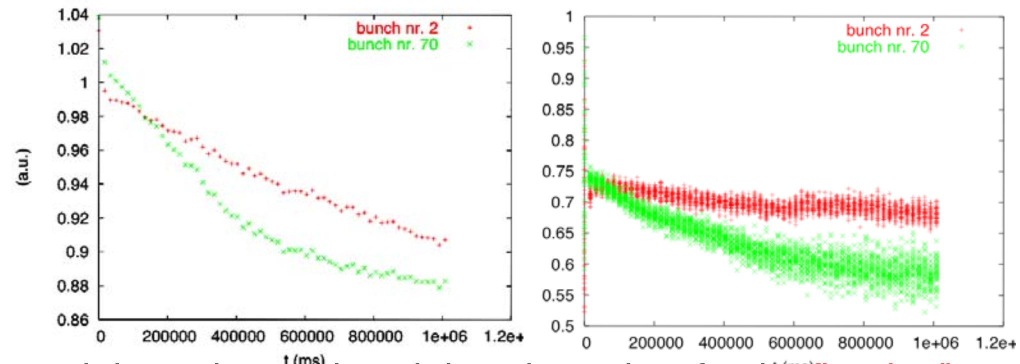
– resonance crossing and trapping or scattering

– Combined effect of :

- Synchrotron motion
- Incoherent tune shift induced by EC (with pinch effect)
- Resonances, excited by external nonlinearities or e-cloud itself (in the simulations depend on e-cloud "kicks" number and position)



KEKB, Vertical beam size vs. beam Intensity (H.Fukuma, ECLOUD'02)

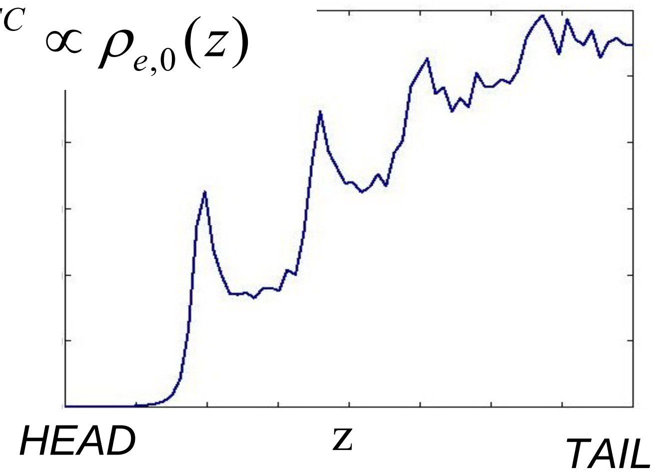


Bunch intensity and bunch length vs. time for the first (red) and last (green) bunch in a train.

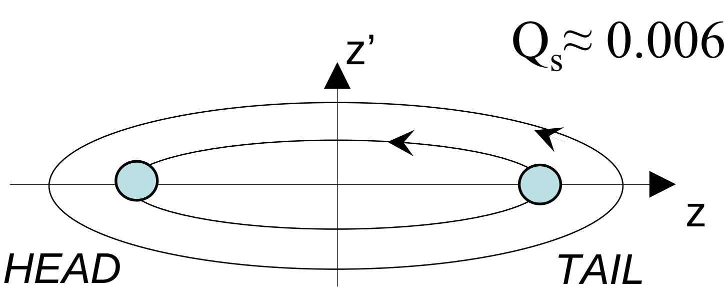
Measurements in SPS with LHC-type bunch, MDs (coast) 26th Aug'04. (G.Rumolo, CARE-HHH Workshop, March'06, GSI)

- ✓ Tune shift function of z

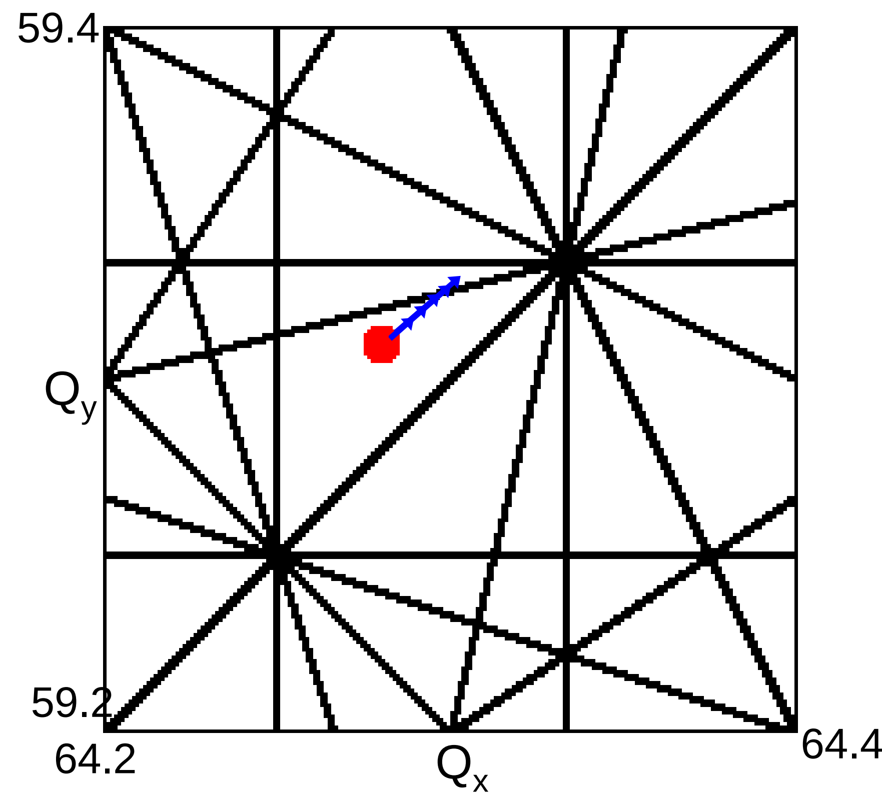
$$\Delta Q_u^{EC} \propto \rho_{e,0}(z)$$



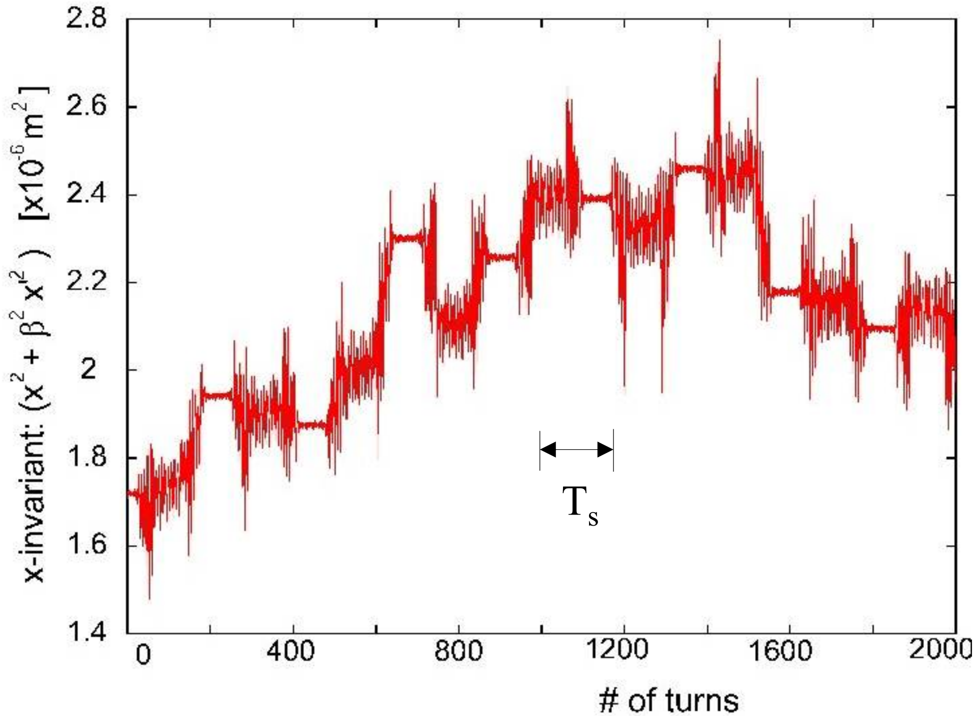
- ✓ Synchrotron motion



Protons at high synchrotron amplitude can cross a resonance back and forward.



✓ When a particle cross a resonance…

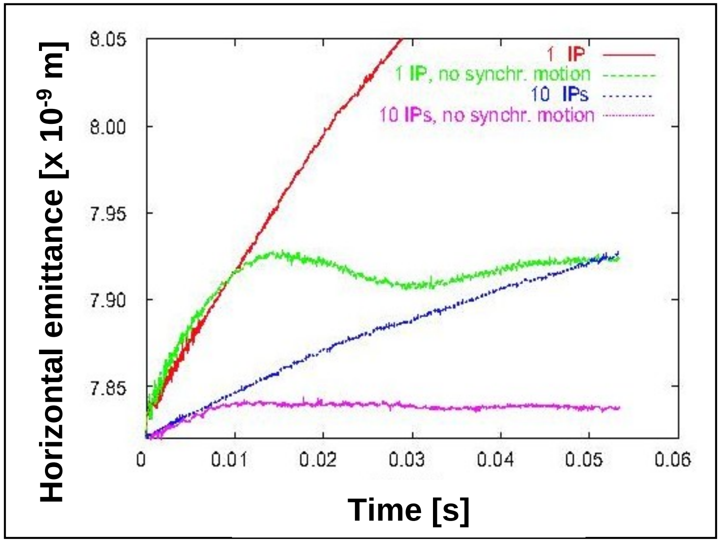


Horizontal action vs. time of a proton at large synchrotron amplitude (from HEADTAIL simulations)

…its oscillation amplitude varies (cfr. random walk)

⇓

net increase of beam rms size and emittance

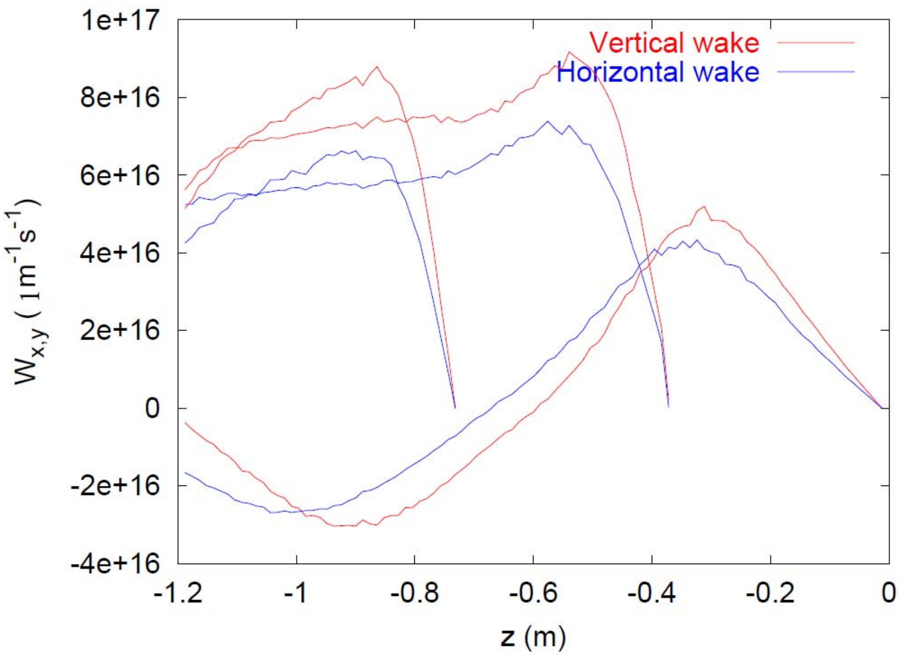


E. Benedetto, G. Franchetti, F. Zimmermann, PRL 97, 3, 034801 (2006)

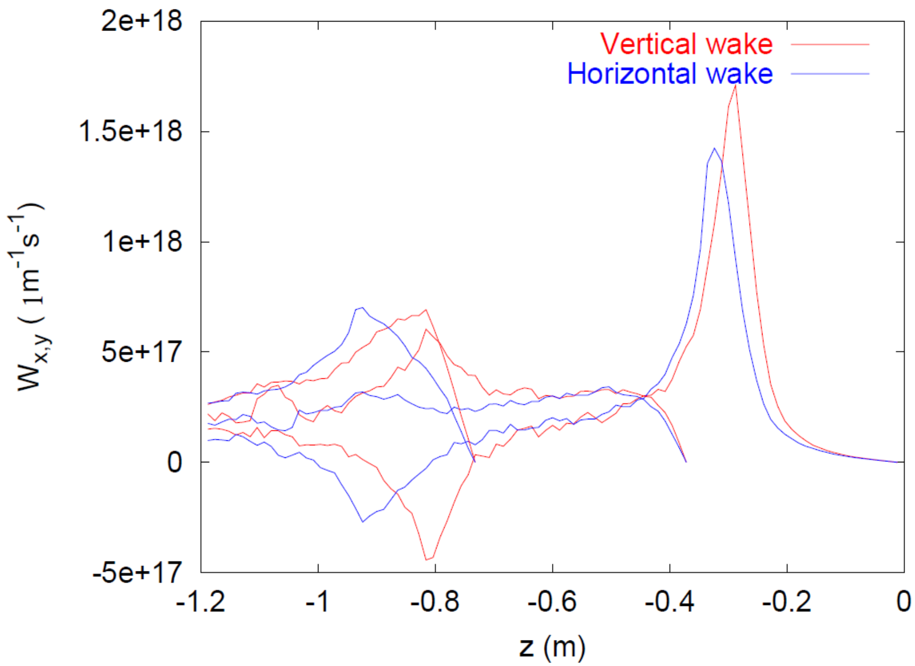
EC “wake field”

✓ Wake field depends on pinch effect

Wake fields averaged on the transverse beam cross section



Wake fields calculated on the axis



Different bunch sections at z = 0, at z ≈ 0.4 and at z ≈ 0.8 transversely displaced to compute wake field induced on the following part of the bunch.

✓ Broadband impedance model for the electron cloud

K.Ohmi, F.Zimmermann, E.Perevedentsev, Phys. Rev. E 65, 016502 (2002).

$$W_{x,y}(z) = \left(\frac{cR_s}{Q}\right)\frac{\omega_R}{\bar{\omega}}e^{\alpha z/c}\sin\left(\frac{\bar{\omega}}{c}z\right)$$

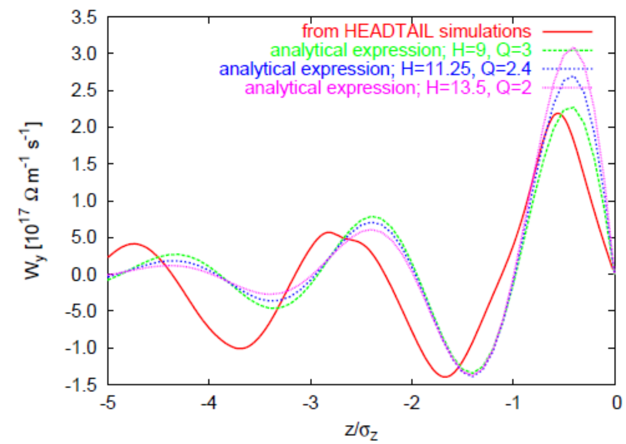
$$\omega_R = \sqrt{\frac{2r_e c^2}{\sigma_{x,y}(\sigma_x+\sigma_y)}}\sqrt{\frac{N_b}{\sqrt{2\pi}\sigma_z}}\frac{1}{\sqrt{k}}$$

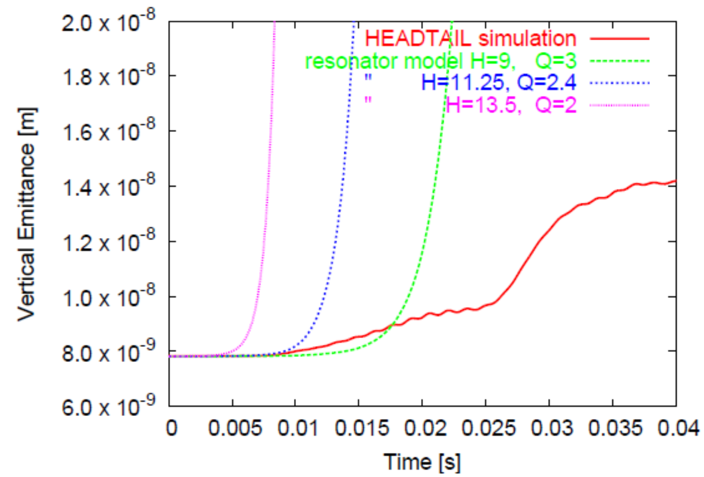
$$\left(\frac{cR_s}{Q}\right) = H_{enh}\frac{2^{3/2}\lambda_c r_e^{1/2}\,C}{\sigma_{x,y}^{3/2}(\sigma_x+\sigma_y)^{3/2}k^{3/2}\sqrt{\frac{N_b}{\sqrt{2\pi}\sigma_z}}}$$

$$\omega_r = 2\pi\times 1.199\ \mathrm{GHz}$$

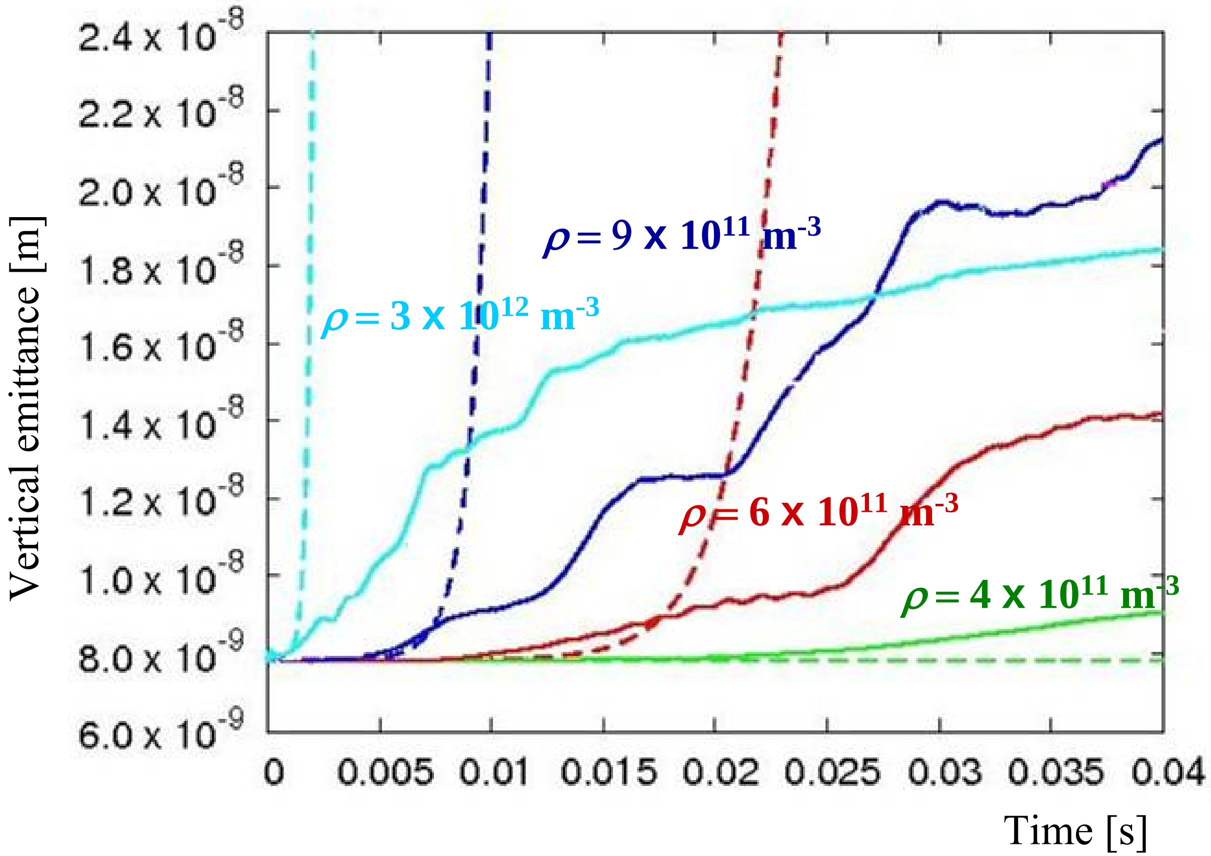
$$Q = 3 \qquad H_{enh} = 9$$

$$Z_t = 115.3\ \mathrm{M}\Omega/\mathrm{m}$$





✓ Broadband impedance model for the electron cloud



Emittance vs. time for different EC densities: comparison between resonator model (dotted line) and HEADTAIL PIC module (full line).

✓ Fair agreement at the onset of the instability only

Conclusions

Conclusions

- ✓ Single-bunch instabilities and emittance growth induced by EC
- ✓ Simulations above the strong instability threshold
  - Dependence on different parameters
  - Threshold in agreement with analytical models
  - Chromaticity as a cure for EC-TMC Instability (in agreement with measurements)
  - Dipole field
  - Comparison w. broad-band resonator model (agrees at the onset)
- ✓ Slow emittance growth mechanism
  - not only numerical noise
  - resonance crossing and trapping or scattering mechanism
  - HEADTAIL(weak-strong) and e-MICROMAP successfully benchmarked
- ✓ Very important to model:
  - Electron cloud pinch inducing incoherent tune shift
  - Accelerator lattice, non-linearities and e-cloud location in the ring

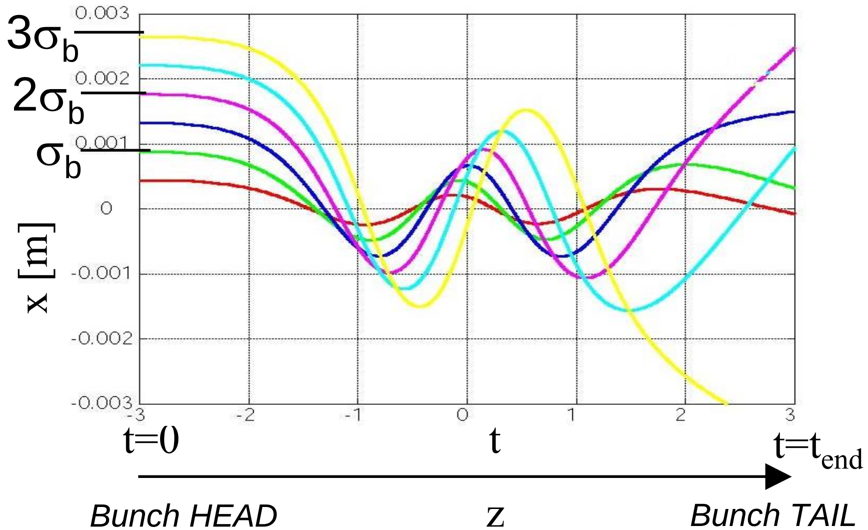
Back-up Slides

✓ e^- motion during the passage of a proton bunch (Gaussian shape):

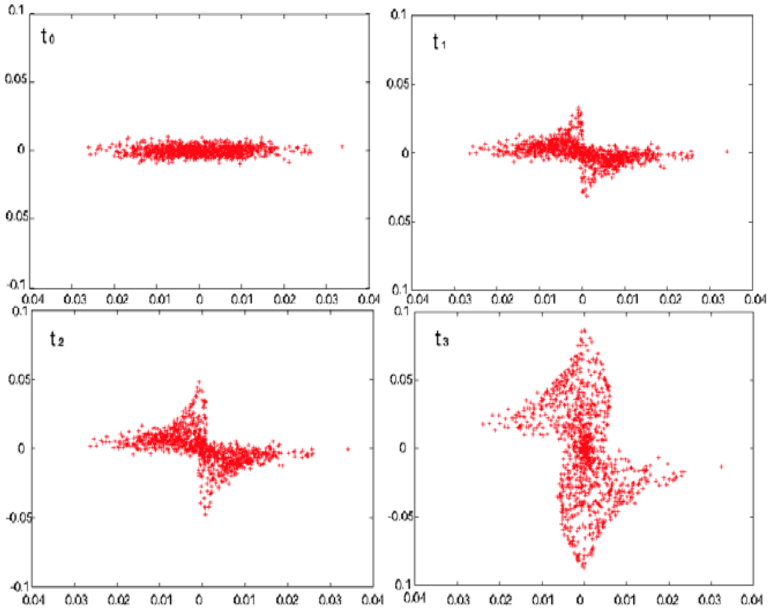
- $x \ll \sigma_x$ ⇨ harmonic oscillations (~ 2)

$$\omega_e = \sqrt{\lambda_b(z) r_e c^2 / \sigma_r^2} \approx 2\pi \cdot 1.2\, GHz$$

- $x \gg \sigma_x$ ⇨ non-linear oscillations ($x > 12\sigma_x$, e^- perform less then ¼ oscillat.!!!)



Position vs. time of e^- starting from different initial amplitudes.



EC phase space at different times: t0=beginning, t1=first peak, t2=first valley, t3=second peak

Parameters LHC @ injection (simulations ‘06)

# of macro-electrons	NEL	10^5
# of macro-protons	NPR	3×10^5
# of slices	$NBIN$	70
# of grid points	N_g	128×128
size of the grid	σ_g	$10\ \sigma_x \times 10\ \sigma_y$
extension of the bunch in z		$\pm 2\ \sigma_z$
# of Interaction Points	n_k	10

For LHC at injection energy, the same numbers have been chosen, although the real vacuum chamber extends for $\pm 24\sigma_b$. To mantain the same ratio of beam dimension to cell size, the number of grid point should have been at least doubled in both directions, increasing considerably the computational time. Simulations shows that assuming $\pm 10\sigma_b$ grid extension does not introduce big discrepancies with respect of the real chamber size simulations, for the studies of fast instability. Considering a computational grid smaller than the real chamber dimension is even more necessary for simulations of LHC beam at top energy, where the rms beam size is about 4 time smaller than the beam dimension at injection.

When using a simulation chamber different than the real one, attention should be paid in setting the electric boundary conditions and in the studies of electron cloud incoherent effects, where the contribution of electrons far from the beam to the tune shift at the end of the bunch is important.

ε_N=3.75 μm

electron cloud density	ρ_e	6×10^{11} m
bunch population	N_b	1.1×10^{1}
beta function	$\beta_{x,y}$	100 m
rms bunch length	σ_z	0.115 m
rms beam size	$\sigma_{x,y}$	0.884 mm
rms momentum spread	$\delta_{\rm rms}$	4.68×10^{-4}
synchrotron tune	Q_s	0.0059
momentum compaction factor	α_c	3.47×10^{-4}
circumference	C	26659 m
nominal tunes	$Q_{x,y}$	64.28, 59.31
chromaticity	$Q'_{x,y}$	2, 2
space charge		no
magnetic field		no
linear coupling		no
average dispersion	D	0 m
relativistic factor	γ	479.6
particle momentum	p	450 GeV/c
cavity voltage	V	8 MV
cavity harmonic number	h	35640

✓ Benchmark between:

HEADTAIL-ws *(CERN)*:

field computed with PIC module

- real EC distribution

e-MICROMAP *(GSI space-charge code)*:

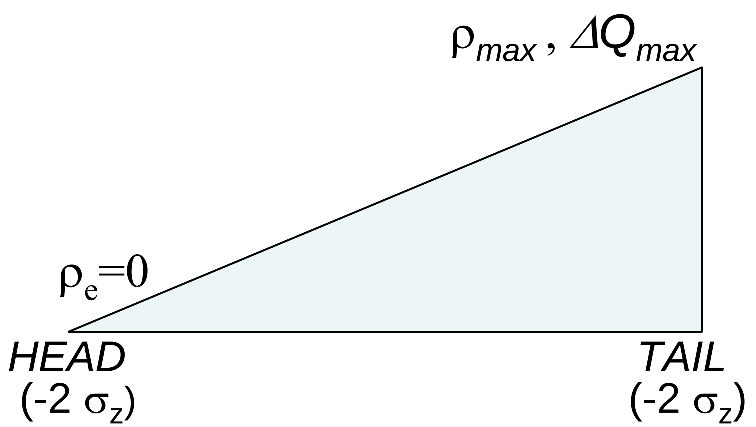
analytical expression to compute the field

- approximate EC distribution
- PIC noise avoided

CARE-HHH collaboration w. G.Franchetti, GSI

✓ Simplified model

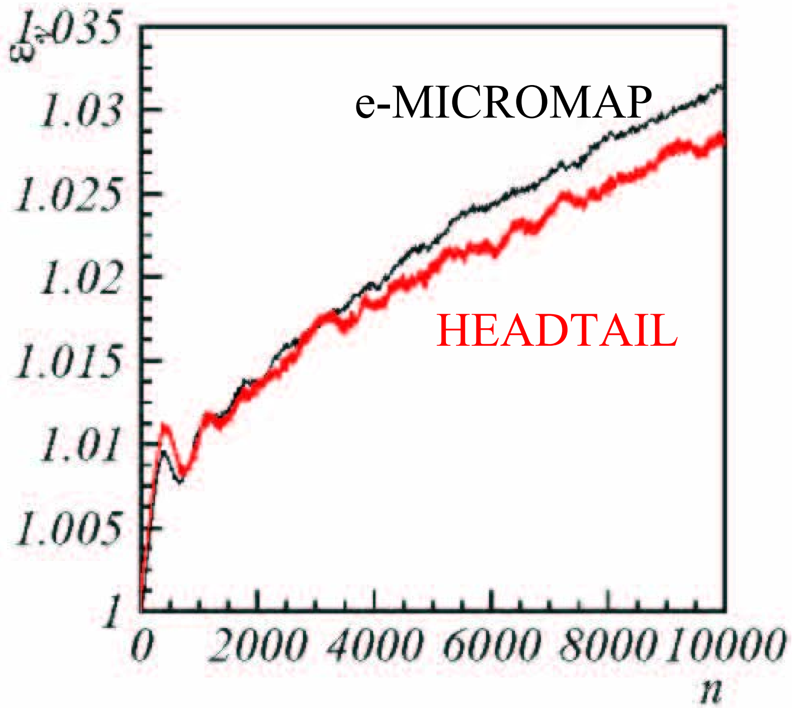
- circular symmetry
- Gaussian beam (σ_b)
- EC Gaussian distribution ($\sigma_e = f\ \sigma_b$)
- EC density linearly increasing in z
- linearized synchrotron motion



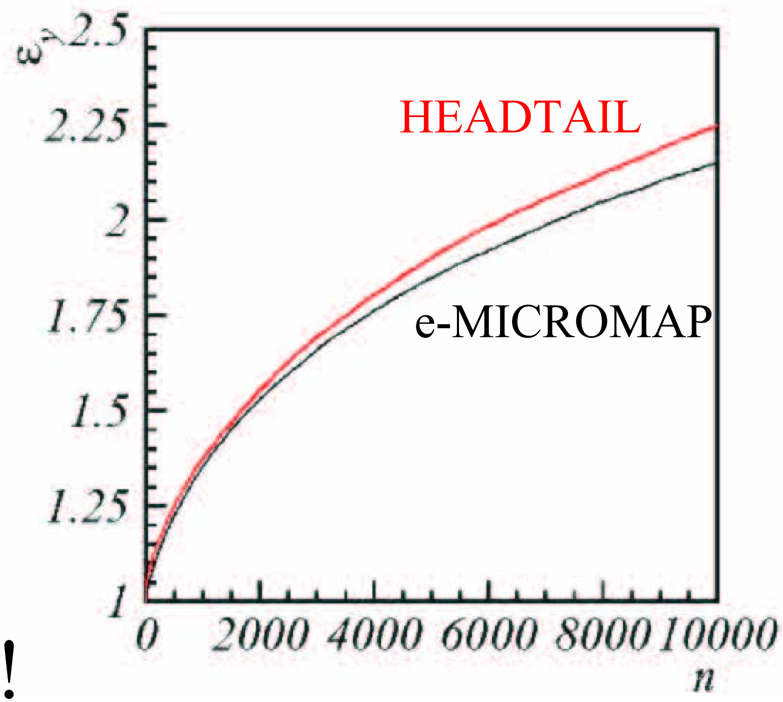
✓ Benchmark with simplified model

Relative emittance vs. number of turns, for 2 different EC densities (different ΔQ_{max})

$\sigma_e = 0.5\ \sigma_b$, $\Delta Q_{max} = 0.04$



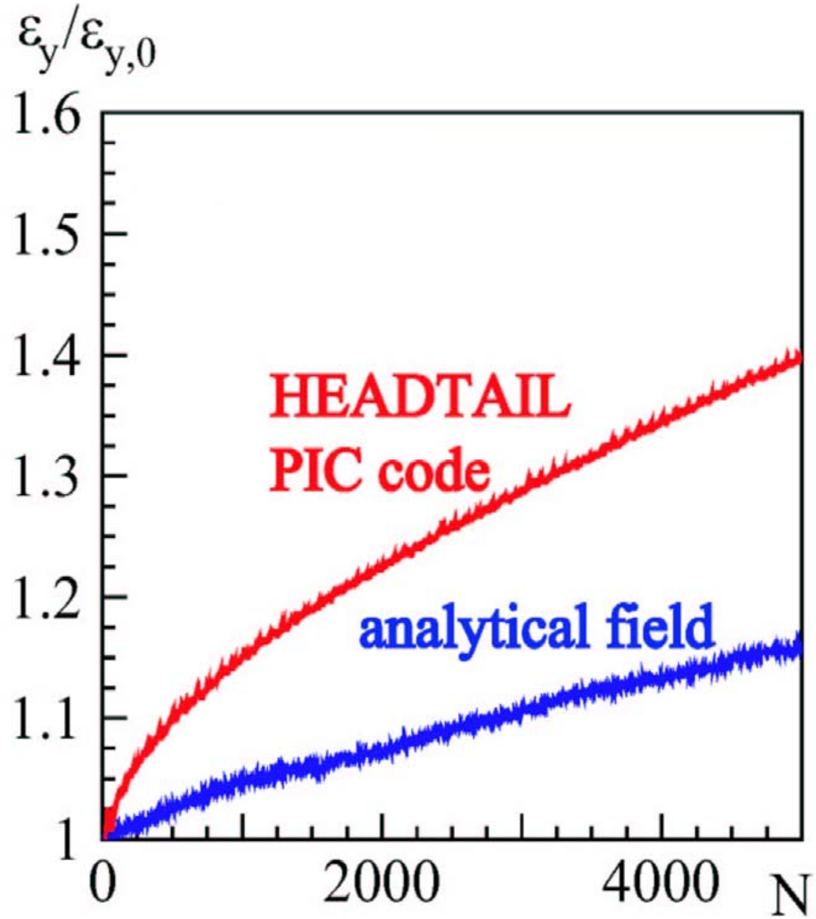
$\sigma_e = 1\ \sigma_b$, $\Delta Q_{max} = 0.1$



✓ very good agreement !

- ✓ Benchmark with EC "pinch"

- ✓ Analytical model approx:
  - – longitudinally: real EC-density
  - – transversely: Gaussian cloud
    - $\sigma_{EC}(t{=}0) = \sigma_{beam}$
    - $\rho\ \pi R^2 = \text{const}$
    - $\Delta Q_{max}{=}0.13$



Under-estimation of electron charge !!!

✓ qualitatively good agreement