Electron cloud coherent instabilities in the SPS and SPS+

G. Rumolo, in collaboration with E. Métral, E. Shaposhnikova

CARE-HHH-APD, CARE-ELAN, EUROTeV-WP3, **Mini-Workshop ECL2**

- Background & context
- Some observations at the SPS
- Energy dependence of instability thresholds in the SPS with PS2 with HEADTAIL simulations
  - Electron cloud with fixed density
  - Self-consistent electron cloud
- Conclusions

BACKGROUND AND CONTEXT (I)

→ Known evidence:

E-cloud instability is one of the main single bunch intensity limitations in the SPS for the LHC beam.

→ How would the electron cloud instability threshold change if the injection energy into the SPS was raised to 50-70 GeV/c ?

→ Answer to this question is not clear :

⇒ Higher energy means more rigid, and therefore **more stable**, beam

⇒ At higher energy the beam gets **transversely smaller**, which enhances the pinch of the electrons as the bunch goes through them

⇒ The matched voltage is lower at higher energy, which translates into a **lower synchrotron tune** (destabilizing)

BACKGROUND AND CONTEXT (II)

The effects of a higher injection energy in the SPS

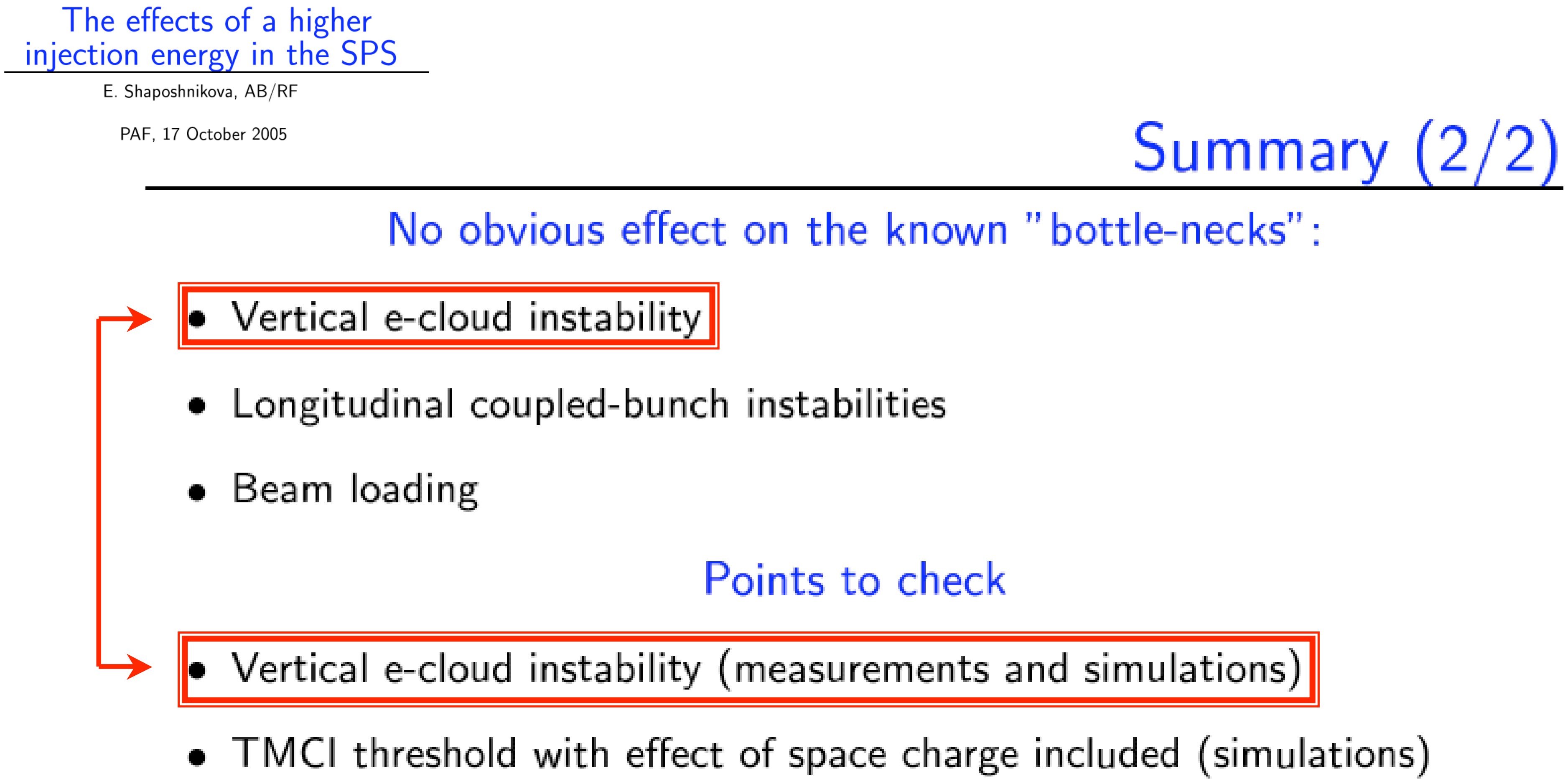
E. Shaposhnikova, AB/RF

PAF, 17 October 2005

Advantages of the increased injection energy in the SPS:

- No transition crossing for proton beams and probably light ions
- Easier acceleration of lead ions
- Smaller space change tune spread and IBS growth time (critical for nominal ions and ultimate protons, probably also for capture loss)
- Threshold increase in H-plane of coupled-bunch instabilities due to e-cloud
- TMCI threshold increase without effect of space charge
- Smaller physical transverse emittance - less injection losses
- Shorter acceleration time (10%)
- ...

BACKGROUND AND CONTEXT (III)



The effects of a higher injection energy in the SPS

E. Shaposhnikova, AB/RF

PAF, 17 October 2005

Summary (2/2)

No obvious effect on the known "bottle-necks":

- Vertical e-cloud instability
- Longitudinal coupled-bunch instabilities
- Beam loading

Points to check

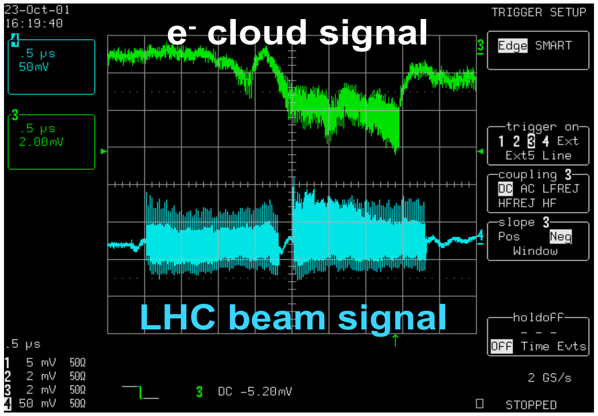
- Vertical e-cloud instability (measurements and simulations)
- TMCI threshold with effect of space charge included (simulations)

E-CLOUD IN THE SPS (I)

- Above a given threshold (~ 0.2_10^{11} p) an electron cloud builds-up along the LHC bunch train and couples subsequent bunches or the head and the tail of each bunch in the trailing edge of the batch

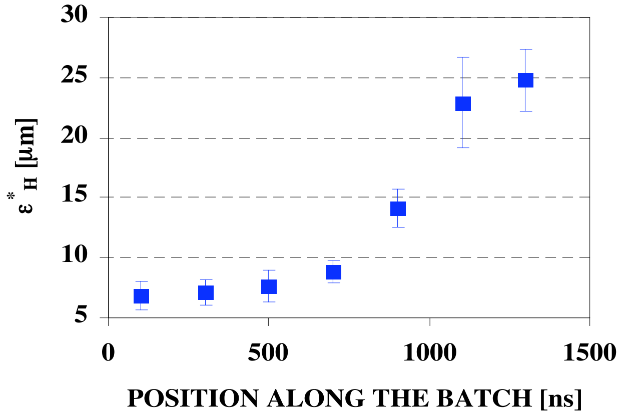
➔ instabilities

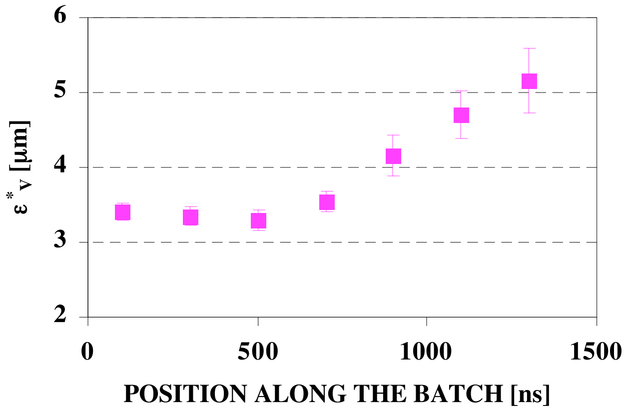
➔ blow-up of the tail of the batch.



J.-M. Jimenez

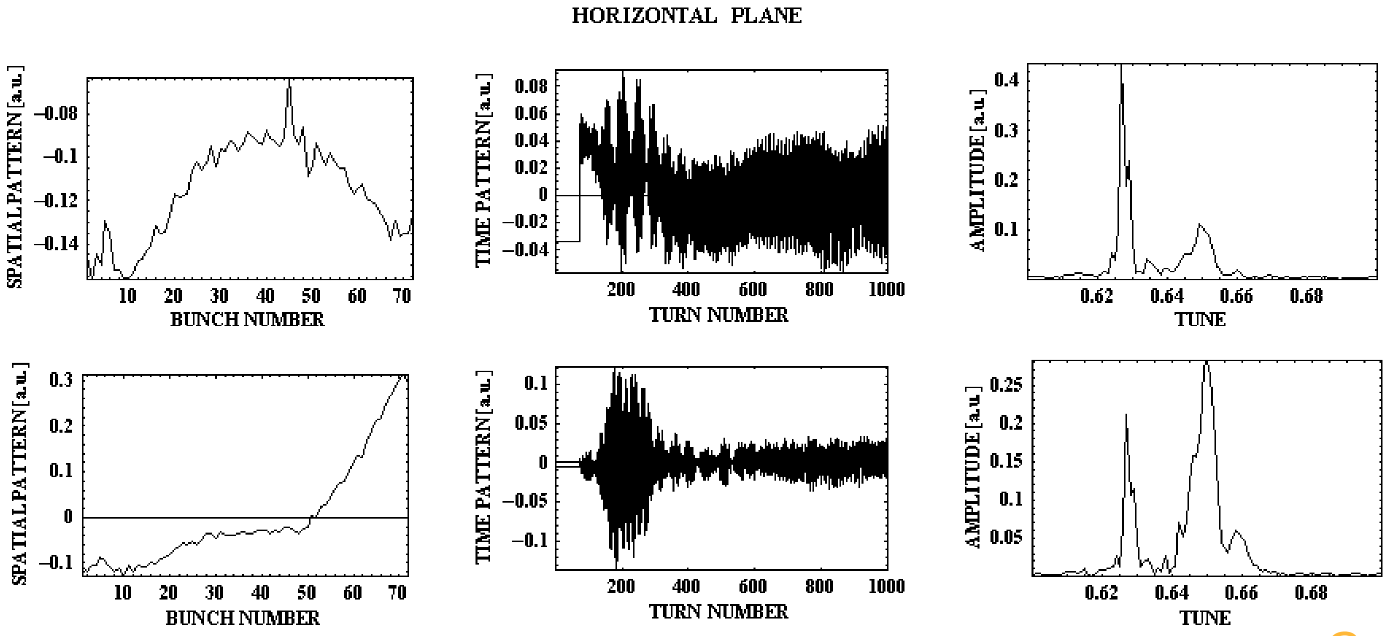
G. Arduini





E-CLOUD IN THE SPS (II)

Horizontal plane



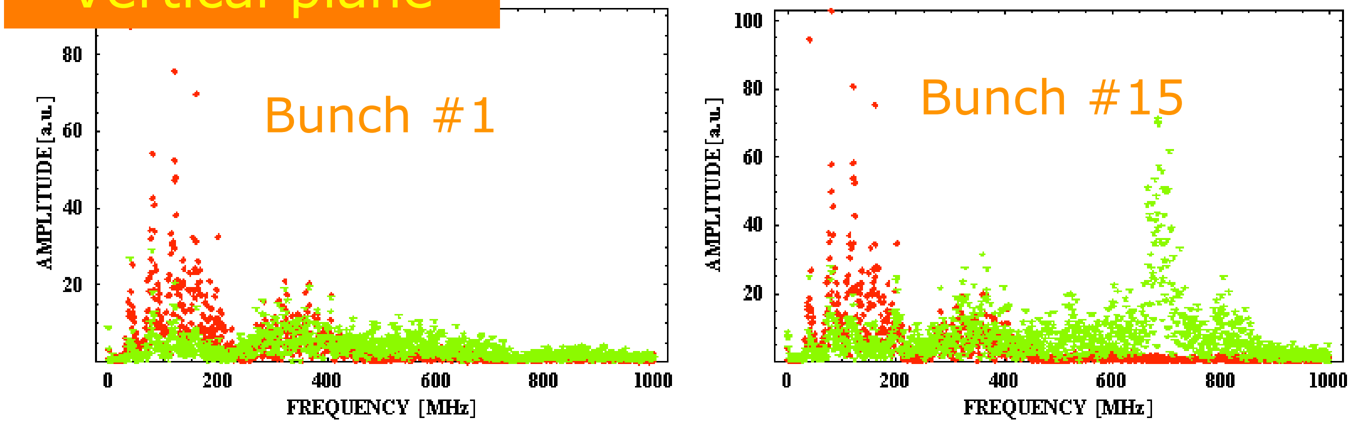
τ~ γ

G. Arduini

- Low order (~1-2 MHz) CB-mode
- Cures: Transverse feedback (bandwidth 0–20 MHz).

E-CLOUD IN THE SPS (III)

Vertical plane



G. Arduini

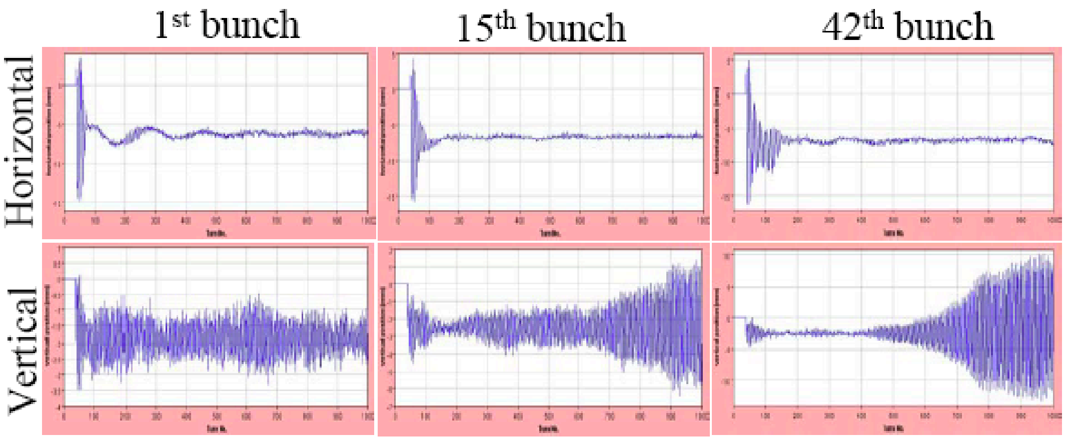
- Single bunch instability (~700 MHz) affecting trailing bunches.
- Cures: ($\xi_V > 0.4\text{-}0.5$) ➔ large tune spread. How far can we go above the nominal intensity?
- How does it change with energy?
- We might need to reconsider the optimum longitudinal parameters for the transfer (larger longitudinal emittance?)

E-CLOUD IN THE SPS (IV)

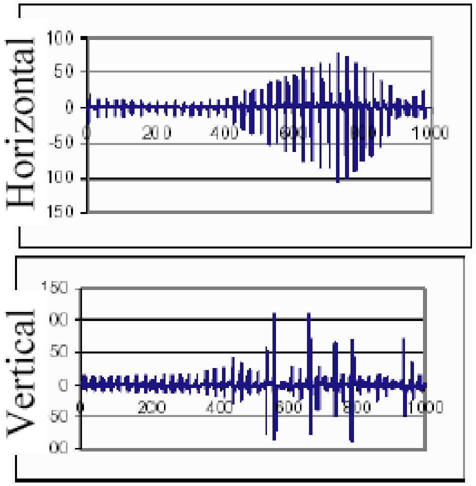
EC effects observed on LHC–beam in SPS :

- ✓ Horizontal coupled-bunch instabilities
- ✓ Vertical single-bunch instabilities

E. Benedetto



Bunch centroid motion vs. # turns for bunches at different position in the train. *BPM measurements in SPS with LHC-type bunch during Scrubbing run 2006 ($Q_V'\sim 0$). Courtesy V. Kain*



Snapshot of bunch position in a train.
Measurements during Scrubbing'01. Courtesy K.Cornelis

HORIZONTAL PLANE (CBI): ENERGY DEPENDENCE

Electron cloud

- Coupled-bunch instability in H-plane at different energies.

Measurements with $\mathbf{1.1 \times 10^{11}}$ ppb (*G. Arduini et al.*)

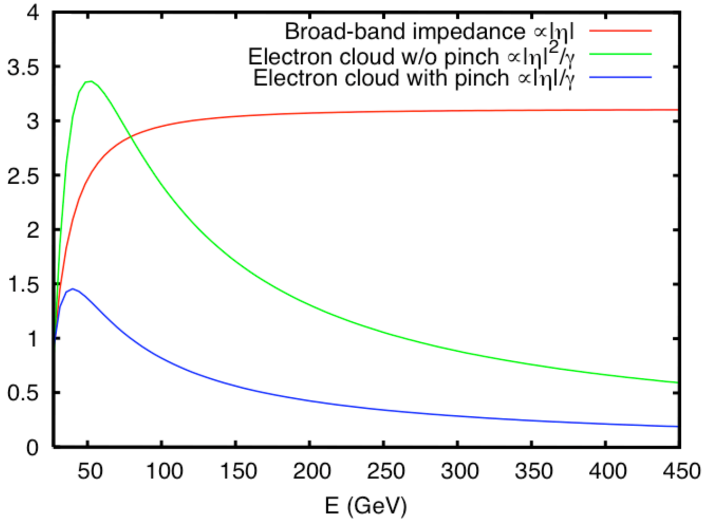
Momentum [GeV/c]	Growth time [turns]
26	300-400
55	800-900
450	6000

$\Rightarrow$ Instability growth rate $\sim \mathbf{1}/\gamma$

ENERGY DEPENDENCE OF SINGLE BUNCH INSTABILITY THRESHOLDS: TMCI AND ECI

→The effect on the TMCI and ECI threshold has been studied

„Simulation Study on the Energy Dependence of the TMCI Threshold in the CERN-SPS“,
G. Rumolo, E. Métral, E. Shaposhnikova, EPAC‘06, Edinburgh



Unlike the conventional broad band impedance driven TMCI, the ECI threshold seems to scale like $\propto|\eta|^a/\gamma$ (models by E. Métral, F. Zimmermann)

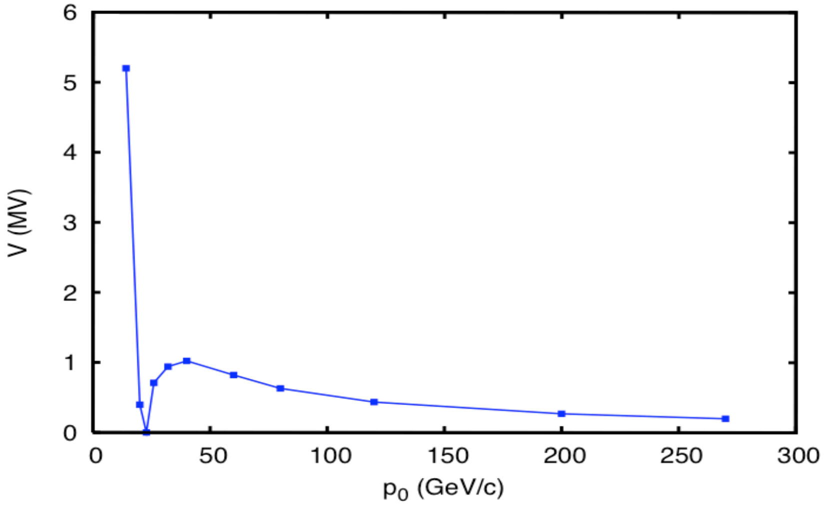
→ Preliminary HEADTAIL simulations showed stronger instability at 60 GeV/c than at 26 GeV/c ⇒ **Detailed threshold study needed!**

ENERGY DEPENDENCE OF SINGLE BUNCH INSTABILITY THRESHOLDS: MAIN ASSUMPTIONS

- Nominal (LHC) beam parameters at injection:
  - Longitudinal emittance $\varepsilon_z = 0.35$ eVs - unchanged
  - Bunch length $\sigma_z = 0.3$ m
  - Normalised transverse emittances: $\sim\varepsilon_{x,y} = 3.0$ µm
- Beam energy swept over a large range (14-270 GeV/c)
- Bunches are always matched to their buckets
- Source of the instability:
  - Electron cloud with density of 10^{12} m^{-3} (average value) and concentrated in the MBB dipoles
  - Electron cloud distribution as generated with ECLOUD

MAIN IMPLICATIONS OF THE ASSUMPTIONS

- Longitudinal emittance 0.35 eVs and rms bunch length 0.3 m:
  - * Matched voltage scales like $|\eta|/\gamma$ and is re-adjusted for the simulations at different energies



- Normalised transverse emittances: ~3.0 μm implies that transverse beam sizes scale like $\gamma^{-1/2}$

MODEL WITH UNIFORM E-CLOUD
- FULL OVERVIEW ON THE PARAMETERS -

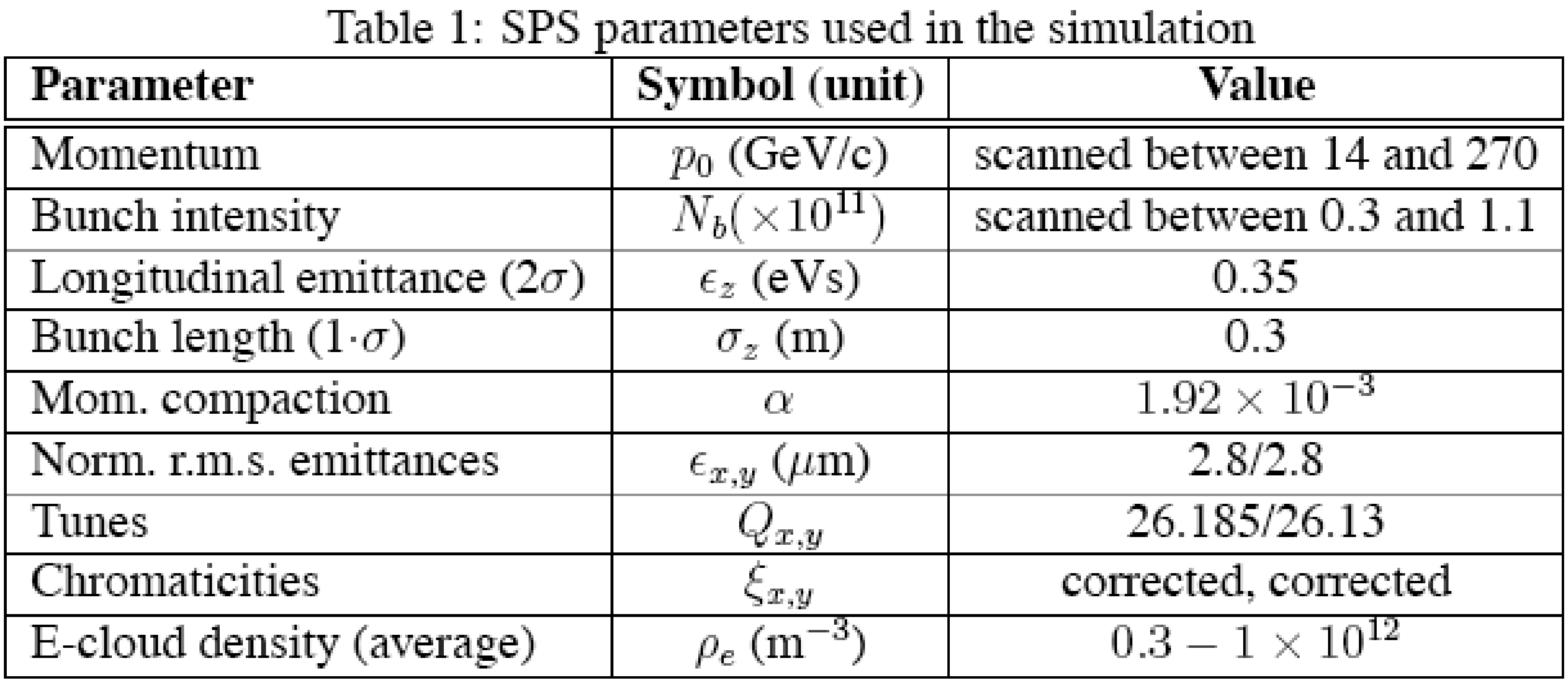
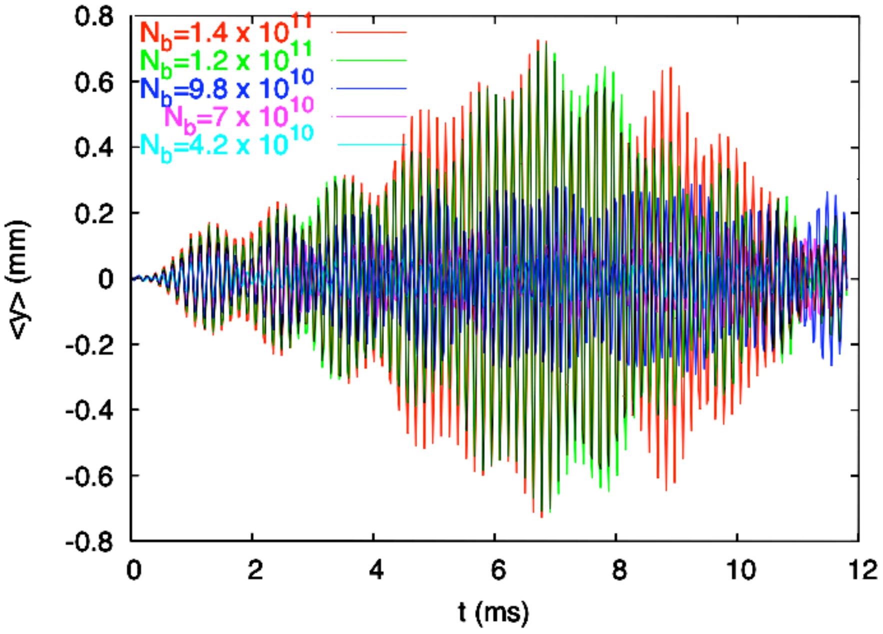


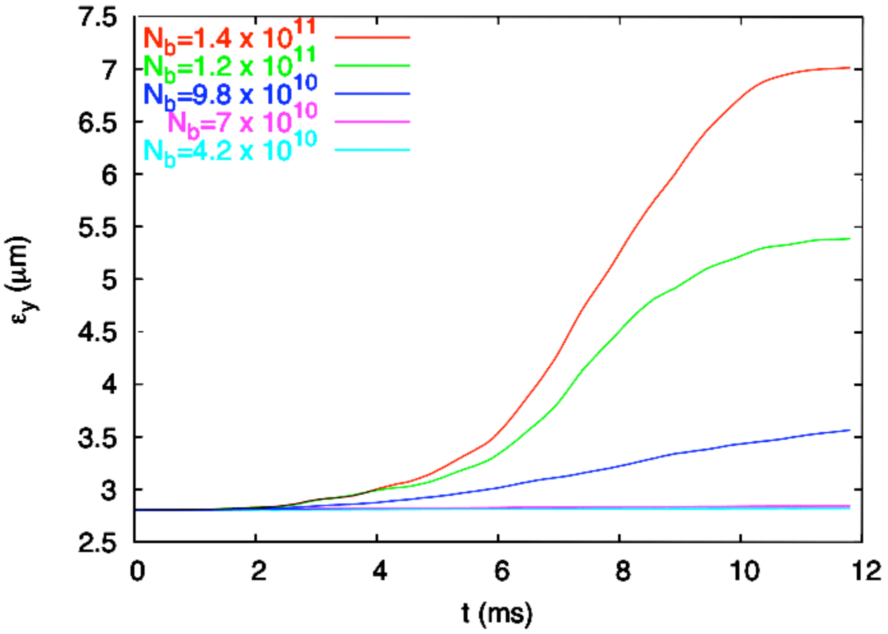
Table 1: SPS parameters used in the simulation

Parameter	Symbol (unit)	Value
Momentum	p_0 (GeV/c)	scanned between 14 and 270
Bunch intensity	$N_b(\times 10^{11})$	scanned between 0.3 and 1.1
Longitudinal emittance (2σ)	ϵ_z (eVs)	0.35
Bunch length ($1 \cdot \sigma$)	σ_z (m)	0.3
Mom. compaction	α	1.92×10^{-3}
Norm. r.m.s. emittances	$\epsilon_{x,y}$ (μm)	2.8/2.8
Tunes	$Q_{x,y}$	26.185/26.13
Chromaticities	$\xi_{x,y}$	corrected, corrected
E-cloud density (average)	ρ_e (m^{-3})	$0.3 - 1 \times 10^{12}$

Model with uniform E-cloud (II)

Centroid and emittance evolution



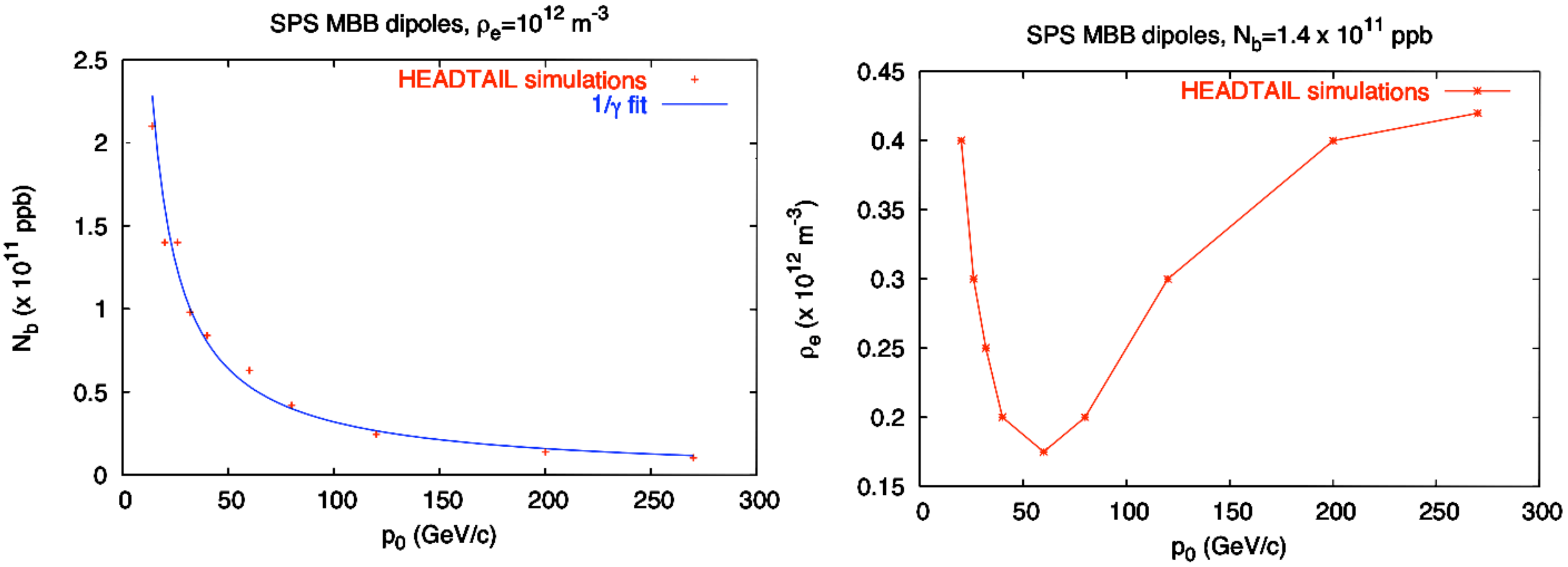


Example at 40 GeV/c:

→ There is a coherent motion of the bunch with threshold at around 8 x 10^{10}

→ simulations are in dipole field regions, the instability appears in the vertical plane.

MODEL WITH UNIFORM E-CLOUD (III)
OVERVIEW ON THE INSTABILITY THRESHOLDS



Instability thresholds as:

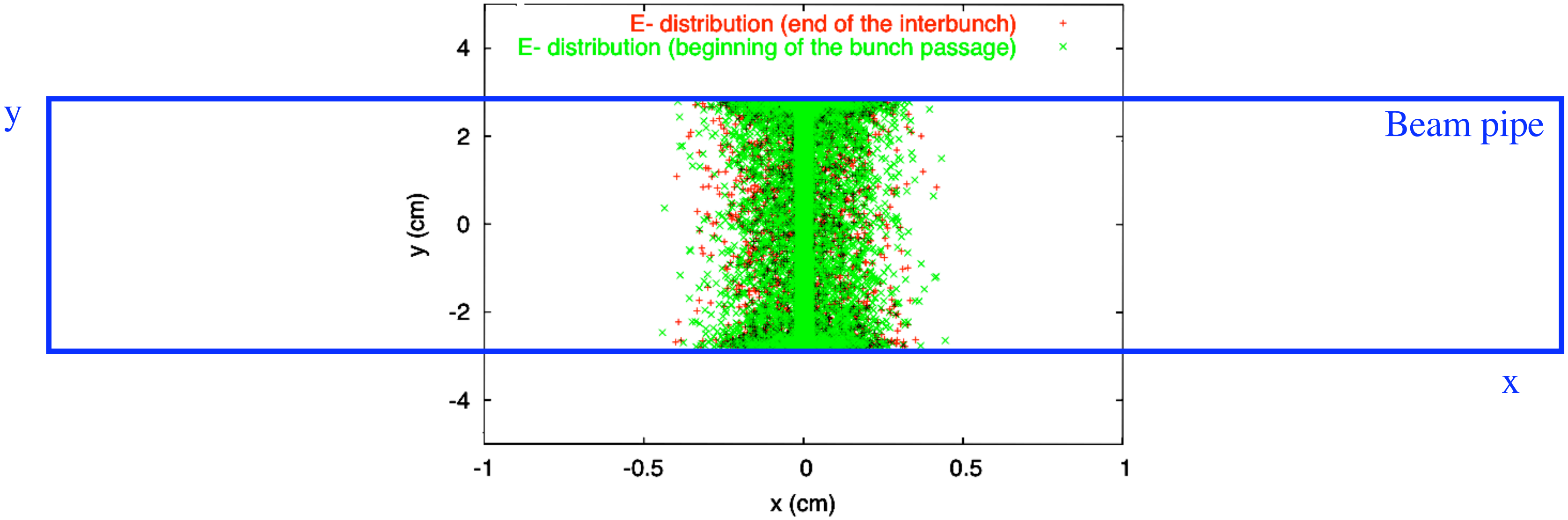
- Bunch intensity when the e-cloud density is fixed → **decreases with energy!**
- E-cloud density when the bunch intensity is fixed → it does not change by a large amount

MODEL WITH SELF-CONSISTENT E-CLOUD
UPGRADE OF HEADTAIL

The electron distribution used in HEADTAIL has been so far a uniform distribution in the beam pipe or a single- or two-stripe distribution to better fit the real distribution in a dipole field region.

→ We could improve the model by using as an input the real distribution of electrons as it comes out of the build up ECLOUD code

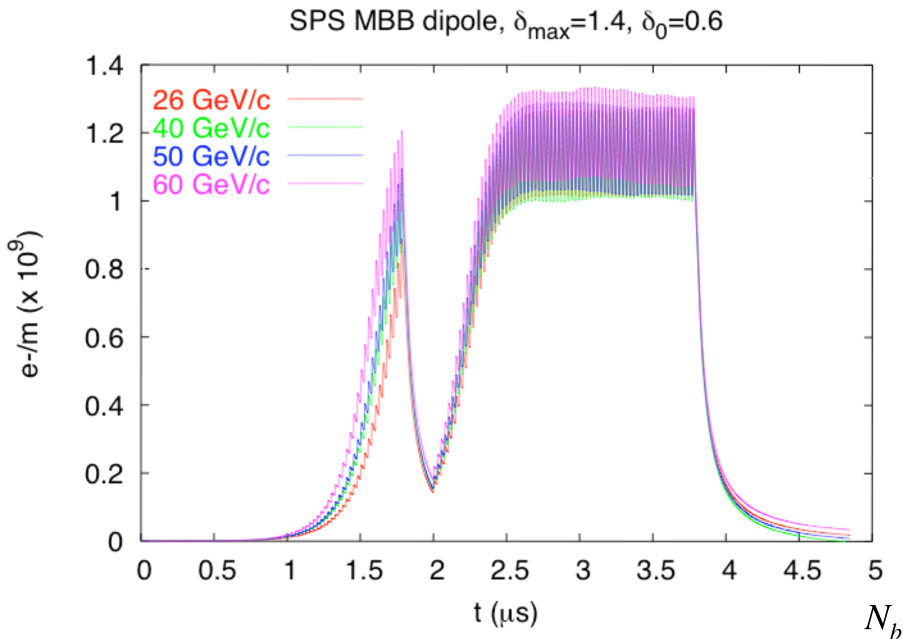
→ The electron distribution at the very beginning of a bunch passage is saved into a file from an ECLOUD run and subsequently fed into HEADTAIL. **This model is more self-consistent!**



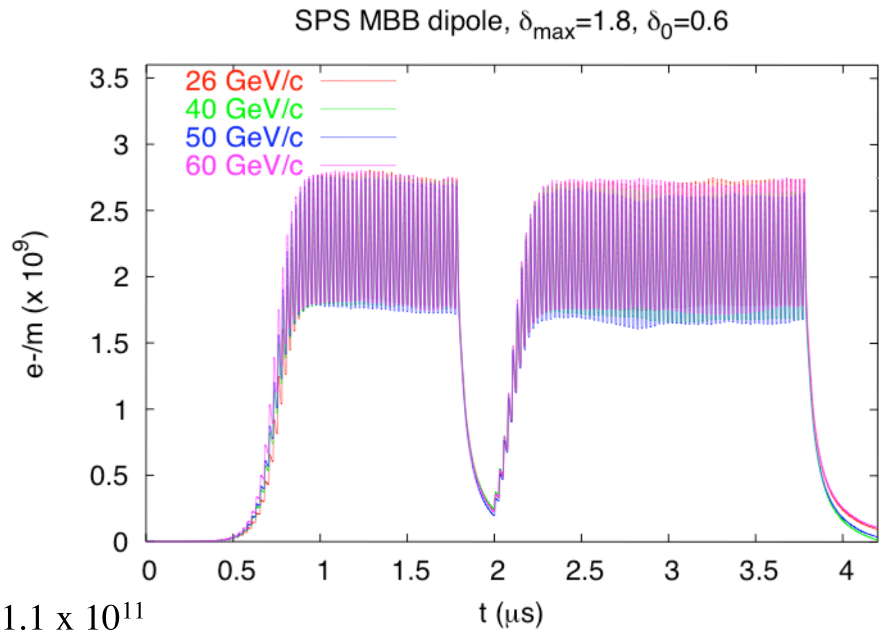
MODEL WITH SELF-CONSISTENT E-CLOUD (II)

→ The build up simulations show a very weak dependence of the saturated electron density on the beam energy (i.e. transverse beam sizes).

→ Changing δ_{max} from 1.4 to 1.8 the value of saturated density about doubles.



SPS MBB dipole, δ_{max}=1.4, δ_0=0.6



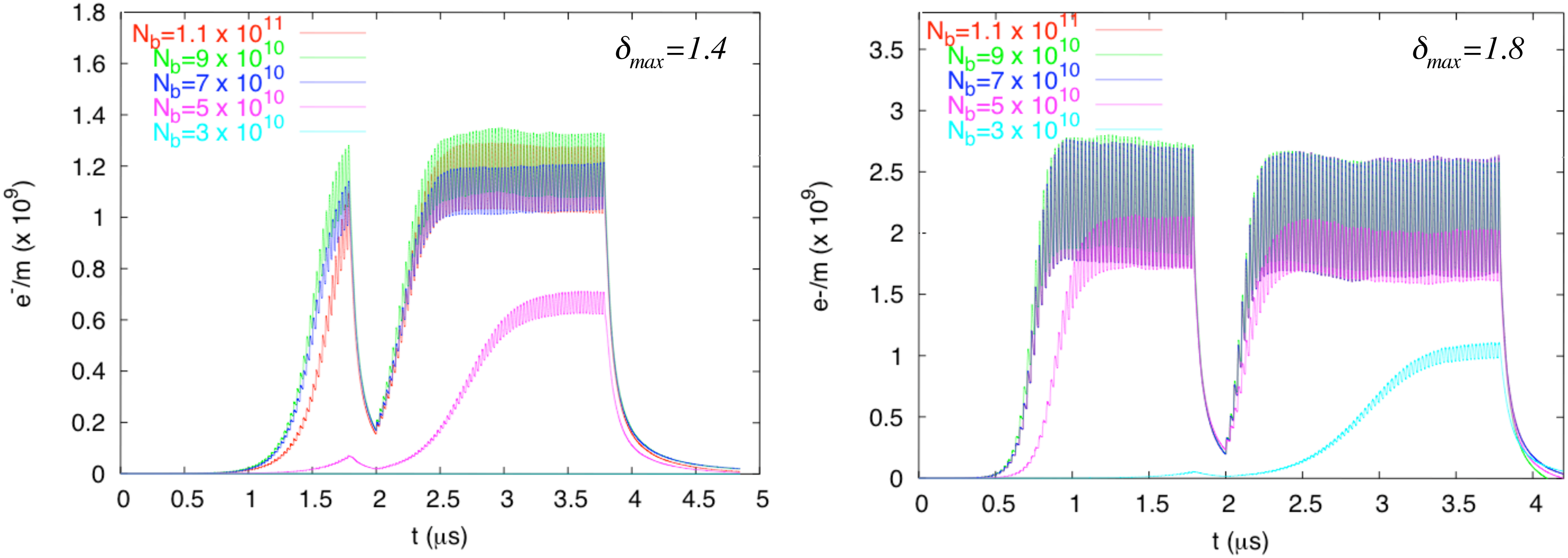
SPS MBB dipole, δ_{max}=1.8, δ_0=0.6

N_b=1.1 x 10^{11}

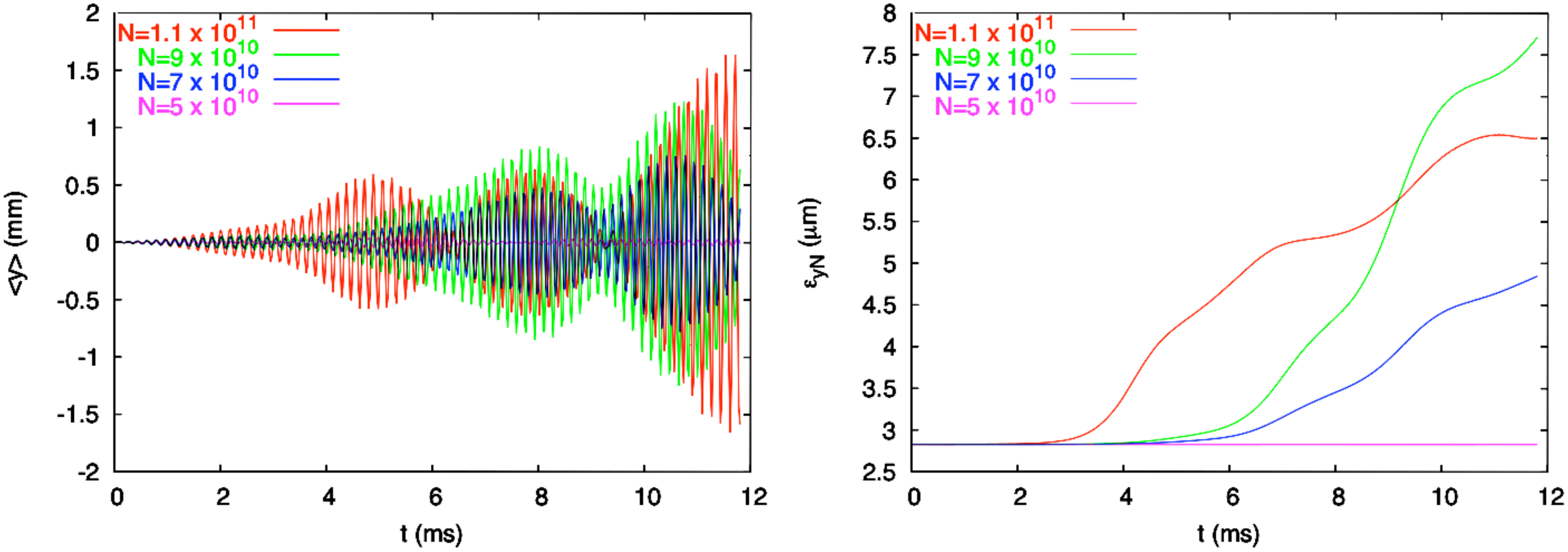
MODEL WITH SELF-CONSISTENT E-CLOUD (III)

→ The dependence of the saturated electron density on the beam intensity is plotted for two values of the δ_{max}

→ When $\delta_{max}=1.4$ the threshold for the e-cloud build up is at around 4 x 10^{10}.



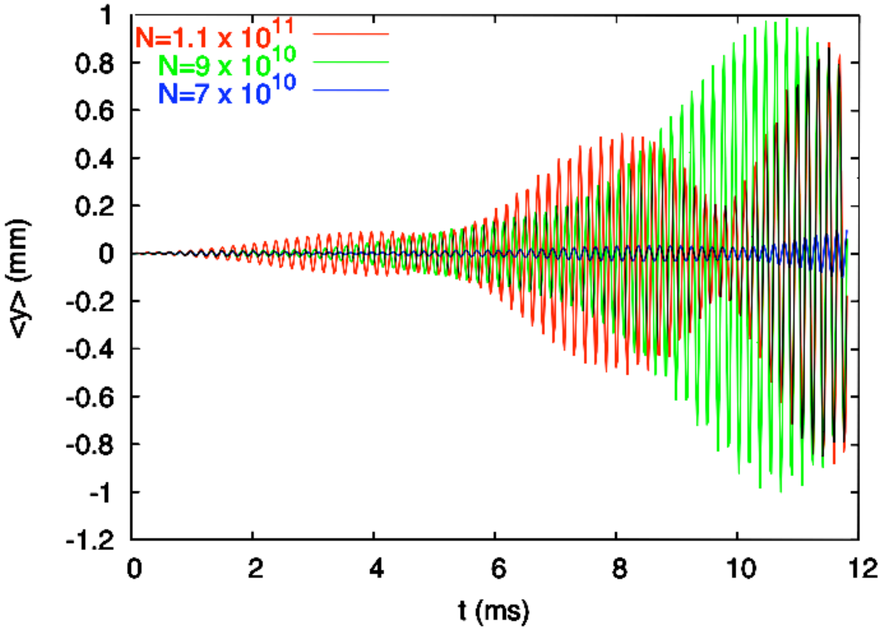
MODEL WITH SELF-CONSISTENT E-CLOUD (IV)

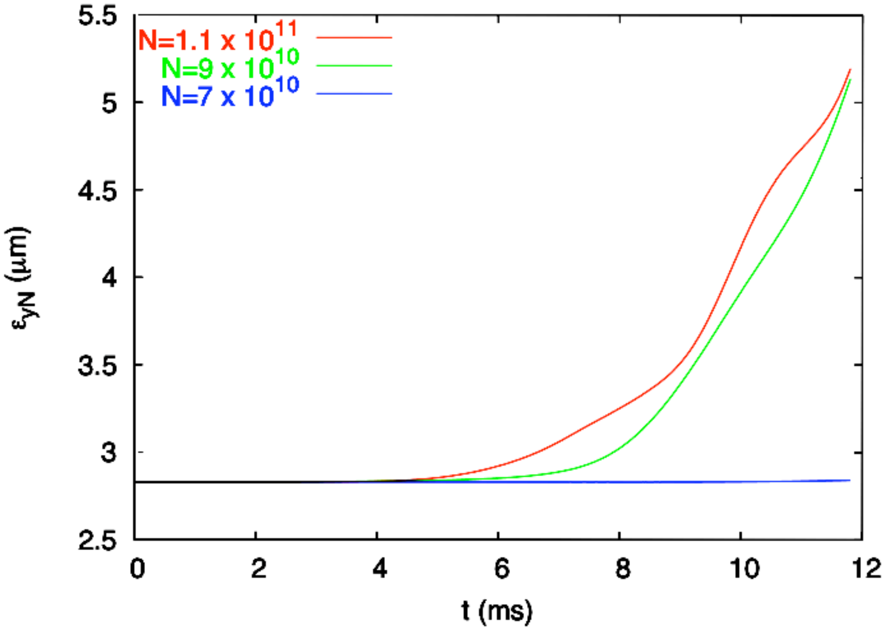


Example at 50 GeV/c and **δ_{max}=1.8 :**

→ The instability occurs in a very similar fashion to the case with electrons uniformly distributed inside the beam pipe. **The threshold is lower than the one previously computed!!**

MODEL WITH SELF-CONSISTENT E-CLOUD (V)

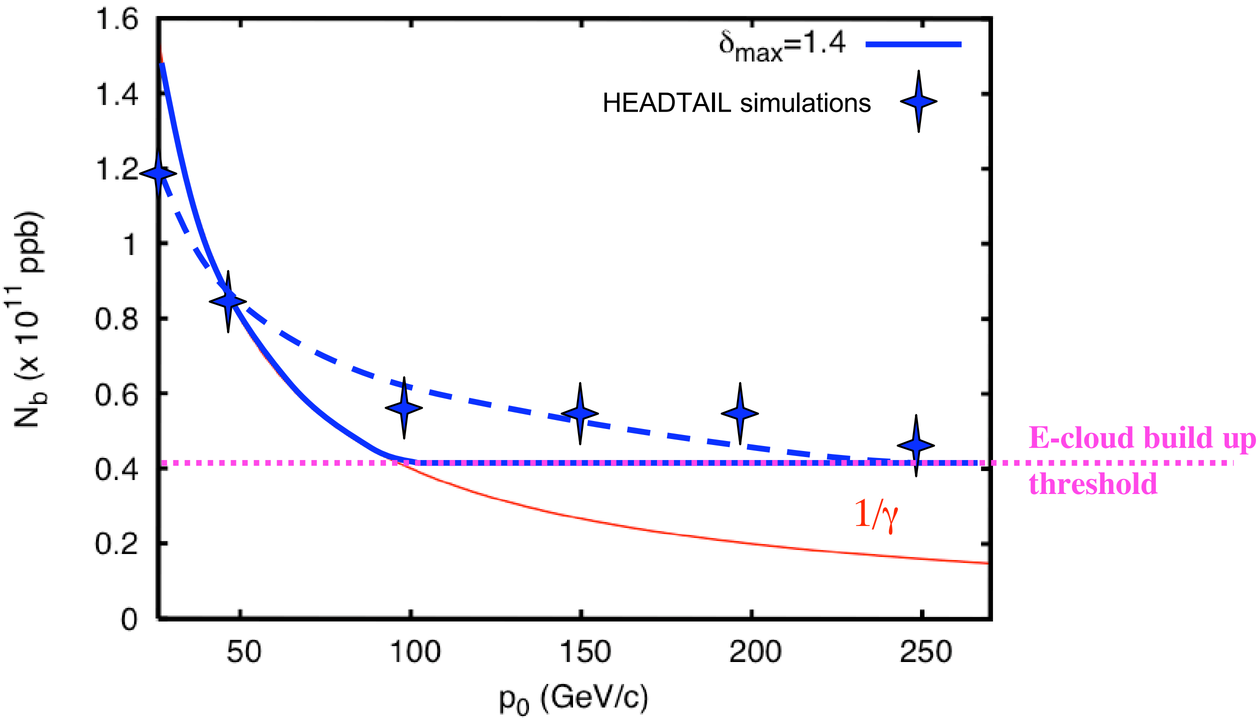




Example at 50 GeV/c and δ_{max}**=1.4:**

→ The threshold is about 8 x 10^{10} ppb.

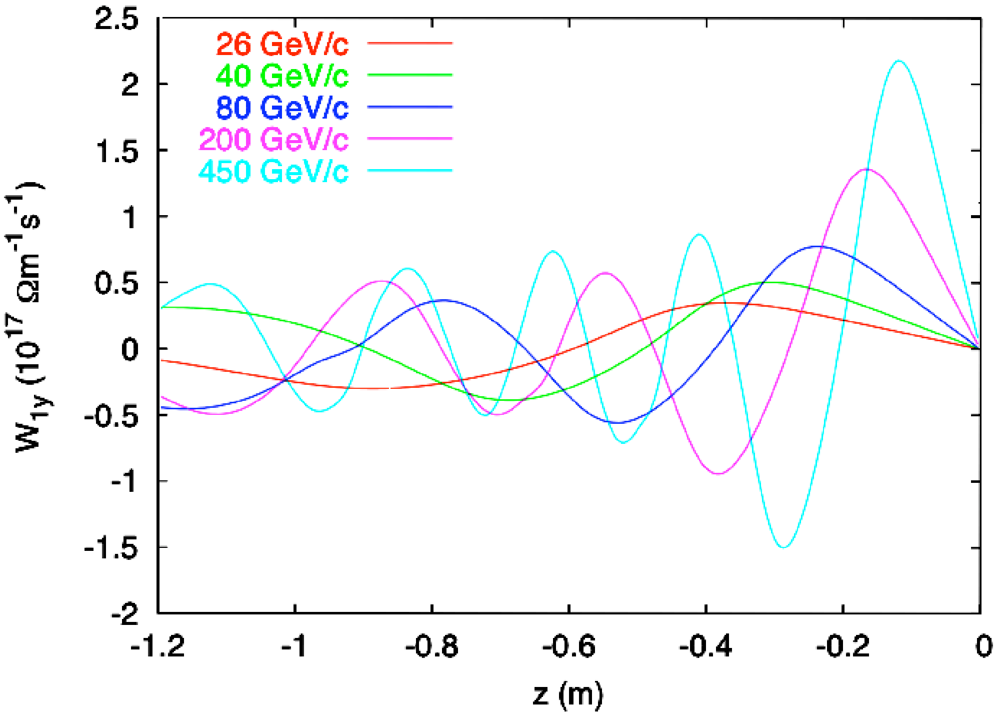
MODEL WITH SELF-CONSISTENT E-CLOUD (VI)



For δ_{max}=1.4 the instability threshold decreases like 1/γ till it levels off at the value of the build up threshold

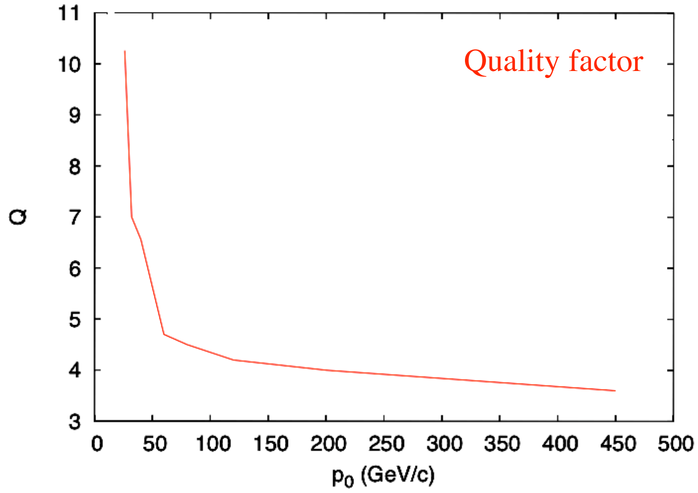
→ For momenta > ~100 GeV/c, e-cloud build up and instability thresholds become equal.

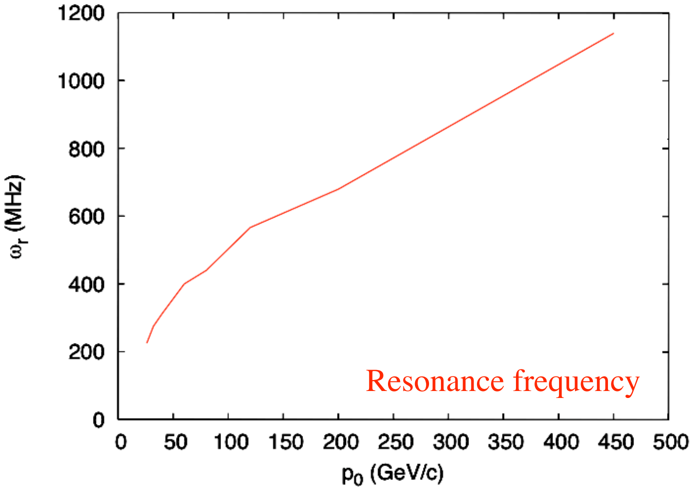
E-CLOUD WAKE FIELDS
IS ECI ALSO A TYPE OF TMCI?

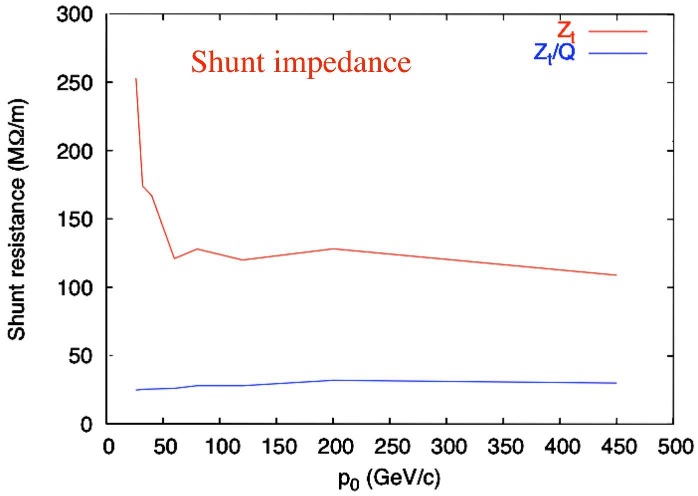


The electron cloud dipole wake field (as trailing from the bunch head) can be evaluated at different energies and the expected thresholds can be compared with the prediction from the TMCI theory.

E-CLOUD WAKE FIELDS (II)







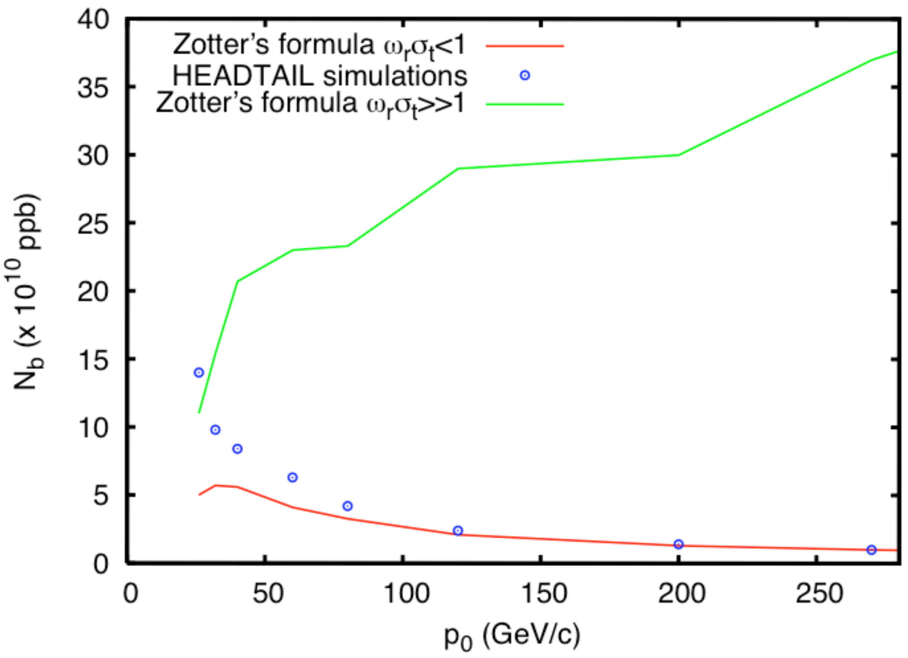
→ Broad-band impedance parameters as extrapolated from a fit using the e-cloud wake fields at different energies

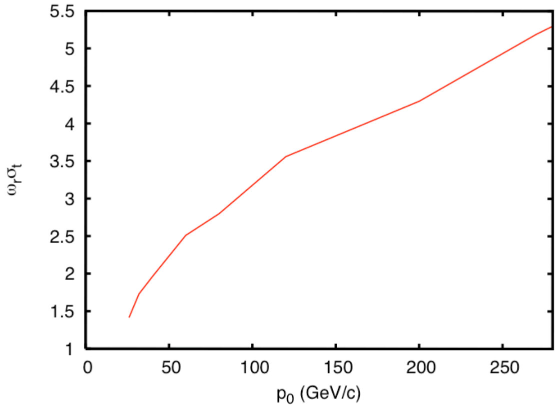
→ Q decreases and levels off

→ w_r increases

→ Z_t decreases and levels off, but Z_t/Q is constant

E-CLOUD WAKE FIELDS (III)





The broad-band model applied to the electron cloud does not seem to explain satisfactorily the observed behavior...

$$N_b = \begin{cases} \dfrac{3.75}{\sqrt{2}} \dfrac{Q^2 Q_y |\eta| \omega_r}{Z_t c e} \cdot \epsilon_z [\mathrm{eVs}] & \text{if } \omega_r \sigma_z / c \gg 1 \\ 11.25\pi \cdot \dfrac{Q Q_y |\eta| c^2}{\omega_r^2 \sigma_z^3 Z_t e} \cdot \epsilon_z [\mathrm{eVs}] & \text{if } \omega_r \sigma_z / c \leq 1 \end{cases}$$

COUNTERMEASURES (I):
REDUCING THE CHAMBER SIZE…

The table shows the average electron cloud central density (m^{-3}) for nominal beam current (1.1×10^{11}) at 50 or 70 GeV/c

→ The beam is unstable in all the cases with electron cloud! (threshold is about 1.5×10^{12} m^{-3})

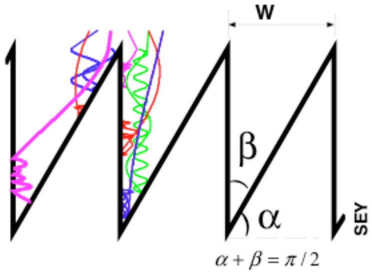
δ_{max} size	1.3	1.4	1.6
nominal	2×10^{12}	2.5×10^{12}	4×10^{12}
0.75 x		1.5×10^{12}	3×10^{12}
0.5 x			1.5×10^{12}

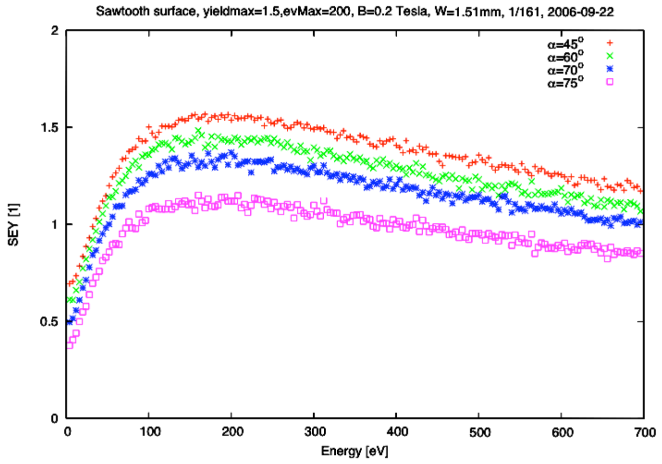
COUNTERMEASURES (II):
REDUCING THE δ_{MAX} OR ACTING ON BEAM PARAMETERS

- If **δ_{max} <1.3** there is **no electron cloud** and therefore, no instability for the nominal LHC beam (even keeping the present pipe size!)

  → Efficient scrubbing, NEG coating on surfaces

  → Grooved surfaces seem to reduce the SEY (example, courtesy W. Bruns)



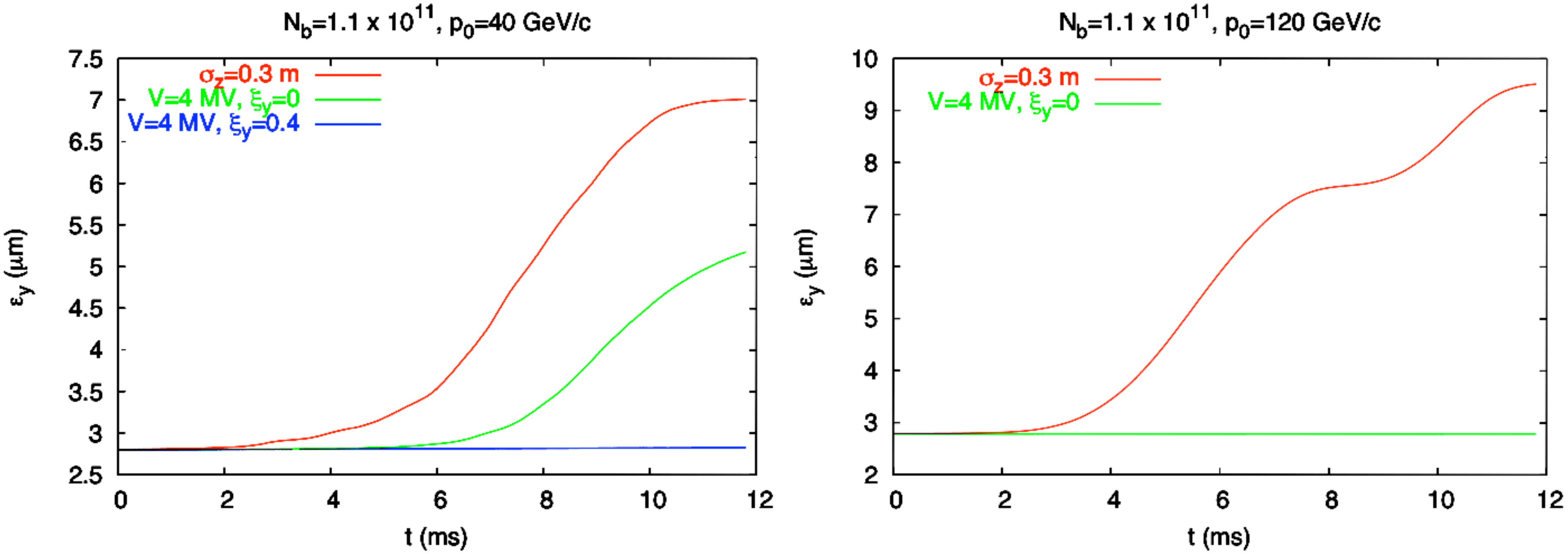


- Perhaps injecting into the SPS with a **higher longitudinal emittance**?

CONCLUSIONS & OUTLOOK

- E-cloud single bunch instability in the vertical plane is presently an intensity limitation in the SPS
- The scaling of ECI thresholds with energy, as predicted by HEADTAIL simulations, is not favorable under conservation of longitudinal emittance and normalized transverse emittances
- This can be overcome by
  - suppressing the e-cloud (smaller chamber radii, NEG or grooved surfaces)
  - injecting into the SPS with larger ε_z
- The broad-band impedance model for the ECI does not satisfactorily explain the scaling law found in simulations
- Ongoing or planned:
  - **Benchmark with experiments** (attempted once in the SPS in October 2006, but no effect observed due to the high voltage during ramp)
  - **Benchmark with another ECI code** (PEHTS, K. Ohmi, KEK)
  - Look for **mode coupling** when crossing the ECI threshold

CHANGING ASSUMPTIONS: V=4 MV

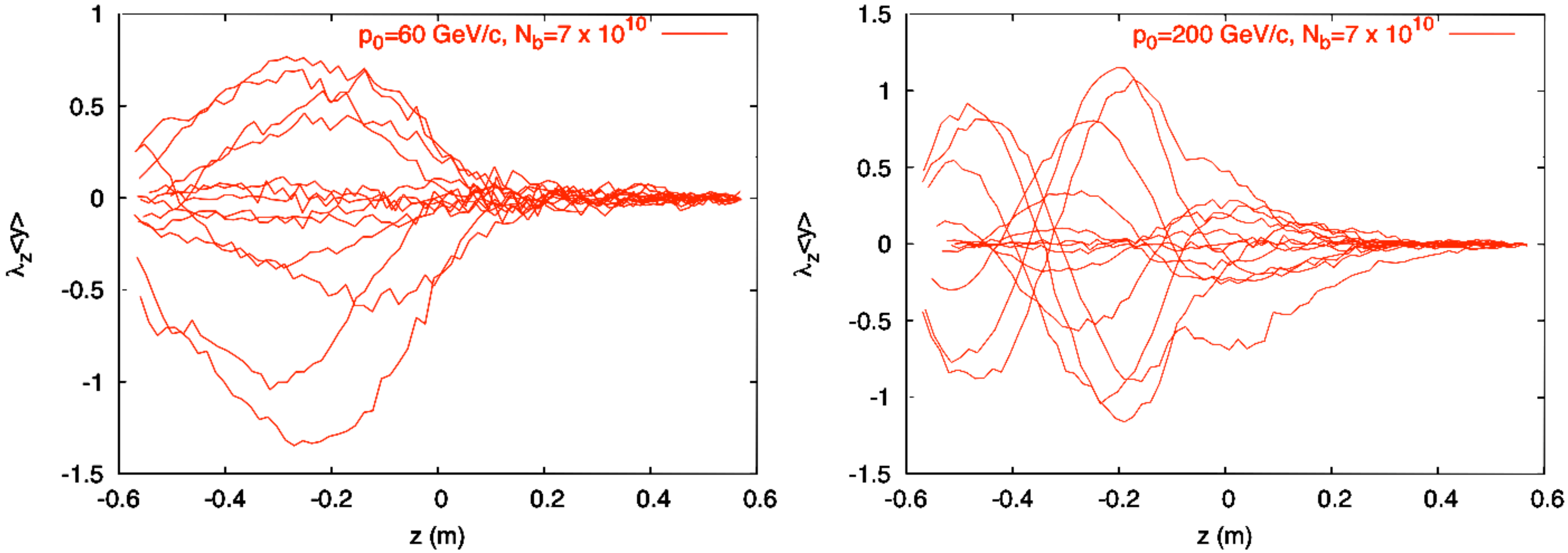


Stronger voltage makes the beam more stable:

→ At 40 GeV/c 1.1 x 10^{11} ppb is less unstable than in matched condition and it is completely stabilized by a 0.4 units of vertical chromaticity.

→ At 120 GeV/c 1.1 x 10^{11} ppb is stable even with zero chromaticity.

CENTROID MOTION ALONG THE BUNCH



The coherent motion appears along the bunch with a typical TMCI pattern.

Example ↪ The figures above are superimposed snapshots of the centroid motion along the bunch at different times for the 60 and 200 GeV/c cases.