Transverse Mode Coupling Instability in the CERN SPS: Comparing HEADTAIL Simulations with Beam Measurements

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Working Group A: Beam Dynamics in High-Intensity Circular Machines: theory, codes, simulations and experiments

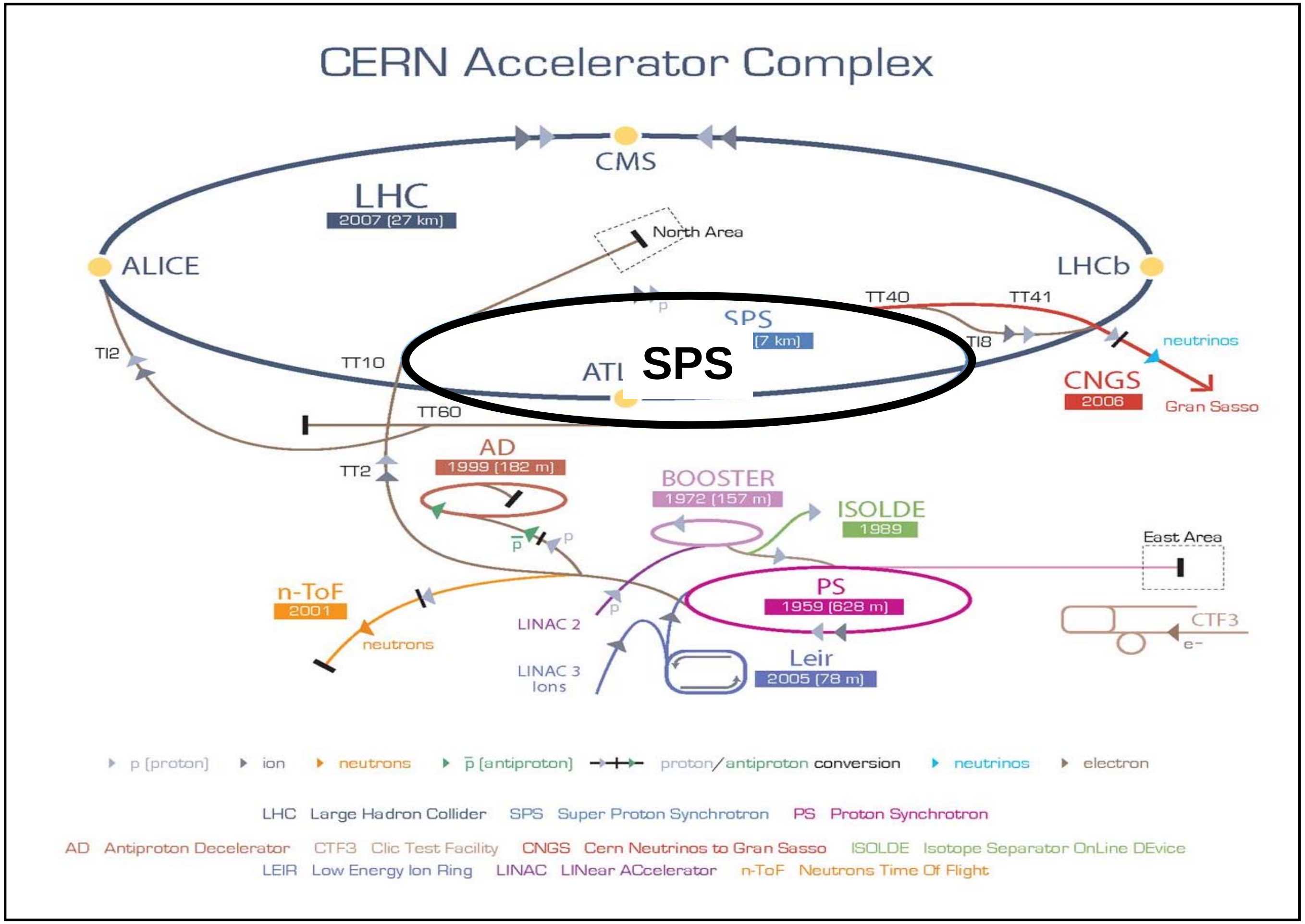
in

42nd ICFA Advanced Beam Dynamics Workshop on High-Intensity, High-Brightness Hadron Beams

Agenda

- Context
  - CERN SPS
  - Fast instability at injection
- Methods
- Results
- Outlook and perspectives

Context : CERN SPS



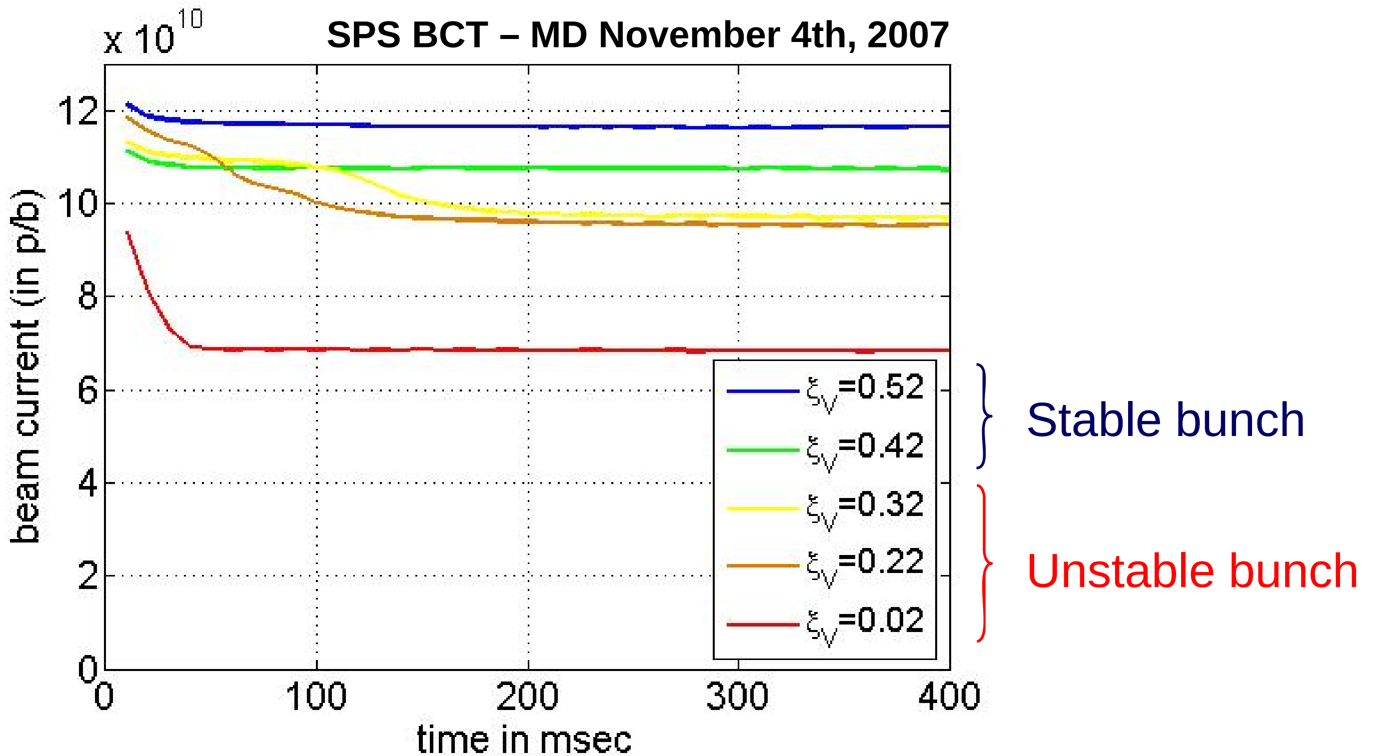
The SPS is now the last accelerator in the LHC injector chain.

Proton source → LINAC 2 → PS Booster → PS → SPS → LHC

26 GeV/c *450 GeV/c*

Context : SPS Fast Instability at injection

To stabilize the low emittance high intensity single bunch of protons at injection in the SPS, the vertical chromaticity ξ_v has to be increased.



(after bunch injection in the SPS)

Upgrade of the LHC injector complex (4 10^{11} p/b) → Need to understand this instability
→ Also, observing TMCI would a way to measure SPS impedance characteristics

Context : Is this instability a TMCI?

This instability has the characteristics of a Transverse Mode Coupling Instability (TMCI) (G. Arduini, E. Metral et al, 2007):

- very fast (less than a synchrotron period)
- travelling wave pattern in the transverse wideband pickup delta signal
- stabilized by vertical chromaticity

However, it is not enough to prove that this instability is a TMCI.
Besides, TMCI was never clearly observed with hadron beams.

Need for more evidence to conclude:

→ analytical calculations, FEA electromagnetic simulations, bench measurements to estimate impedance and wakefields (F. Roncarolo's talk)

→ macroparticle tracking simulations and SPS beam measurements to observe resulting beam dynamics and instability thresholds

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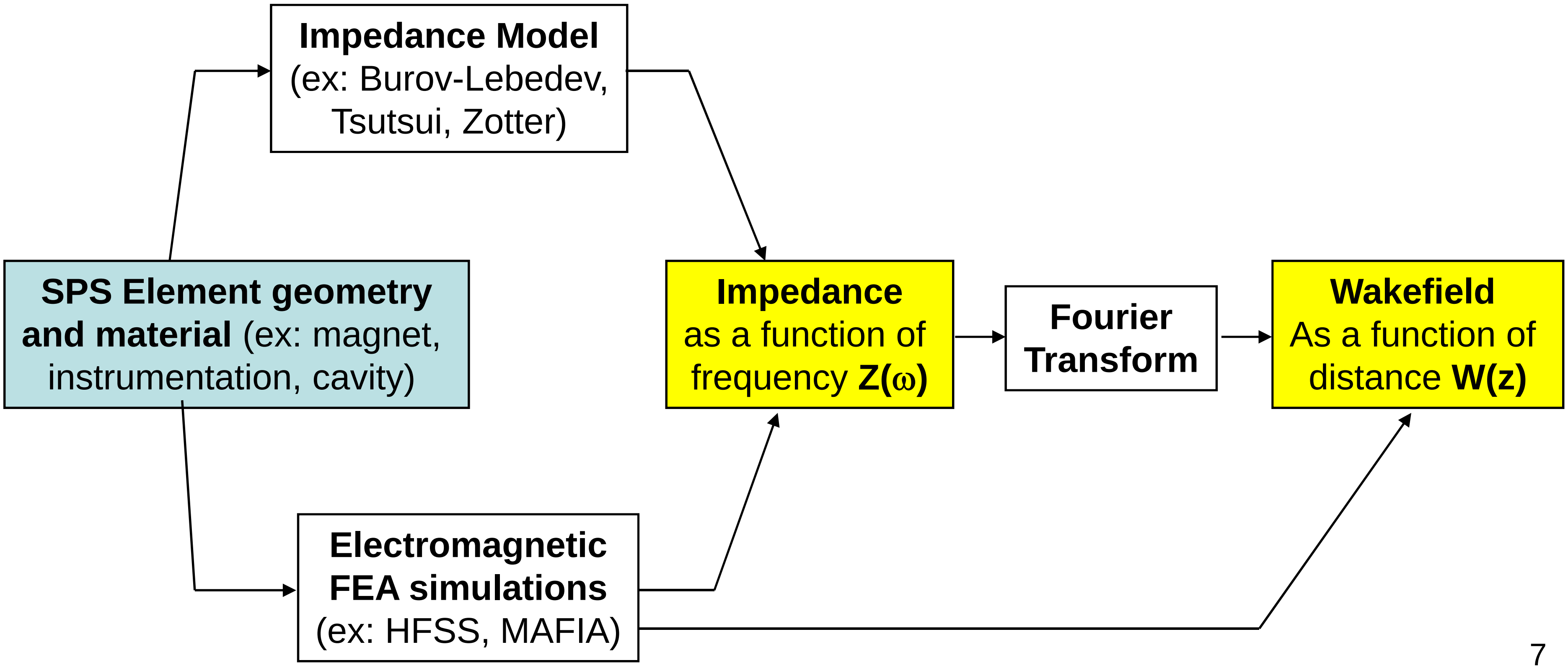
Methods: ZBASE an impedance database

ZBASE aims at keeping track of the impedance sources of the CERN machines.

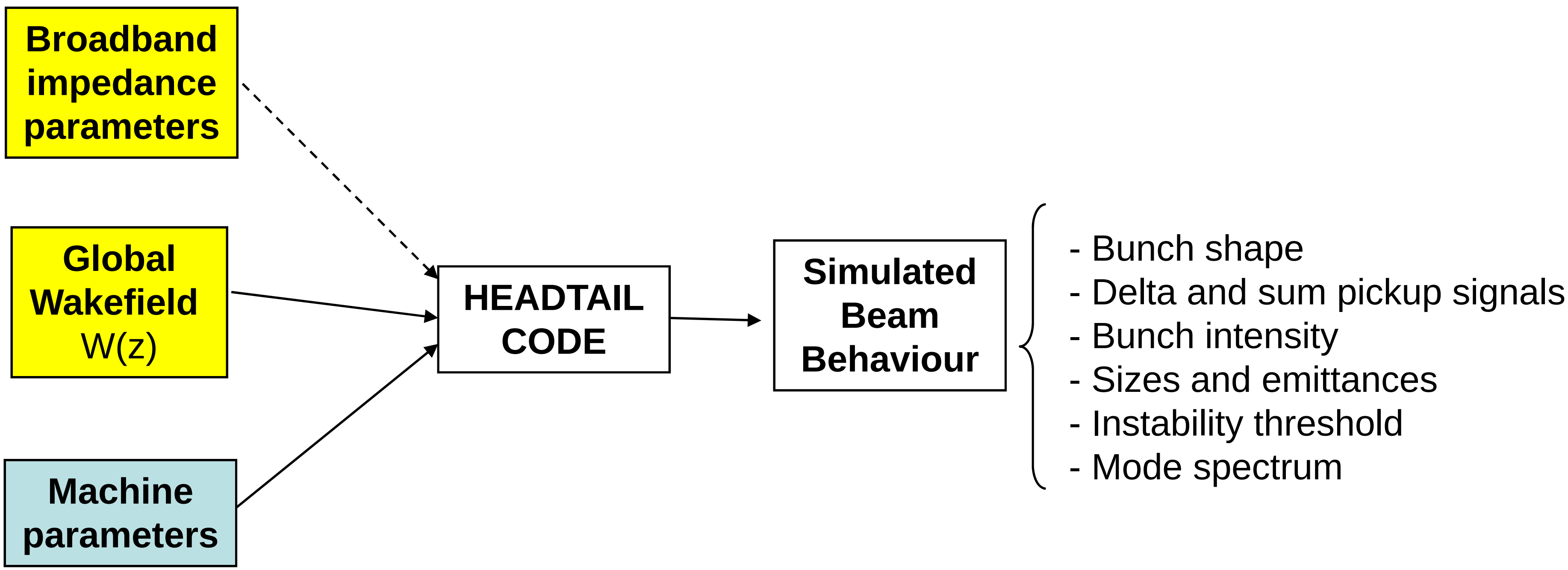
The goal is to obtain impedance and wakefield tables from input parameters thanks to simulation tools and/or analytical models.



Methods: HEADTAIL Tracking Simulations

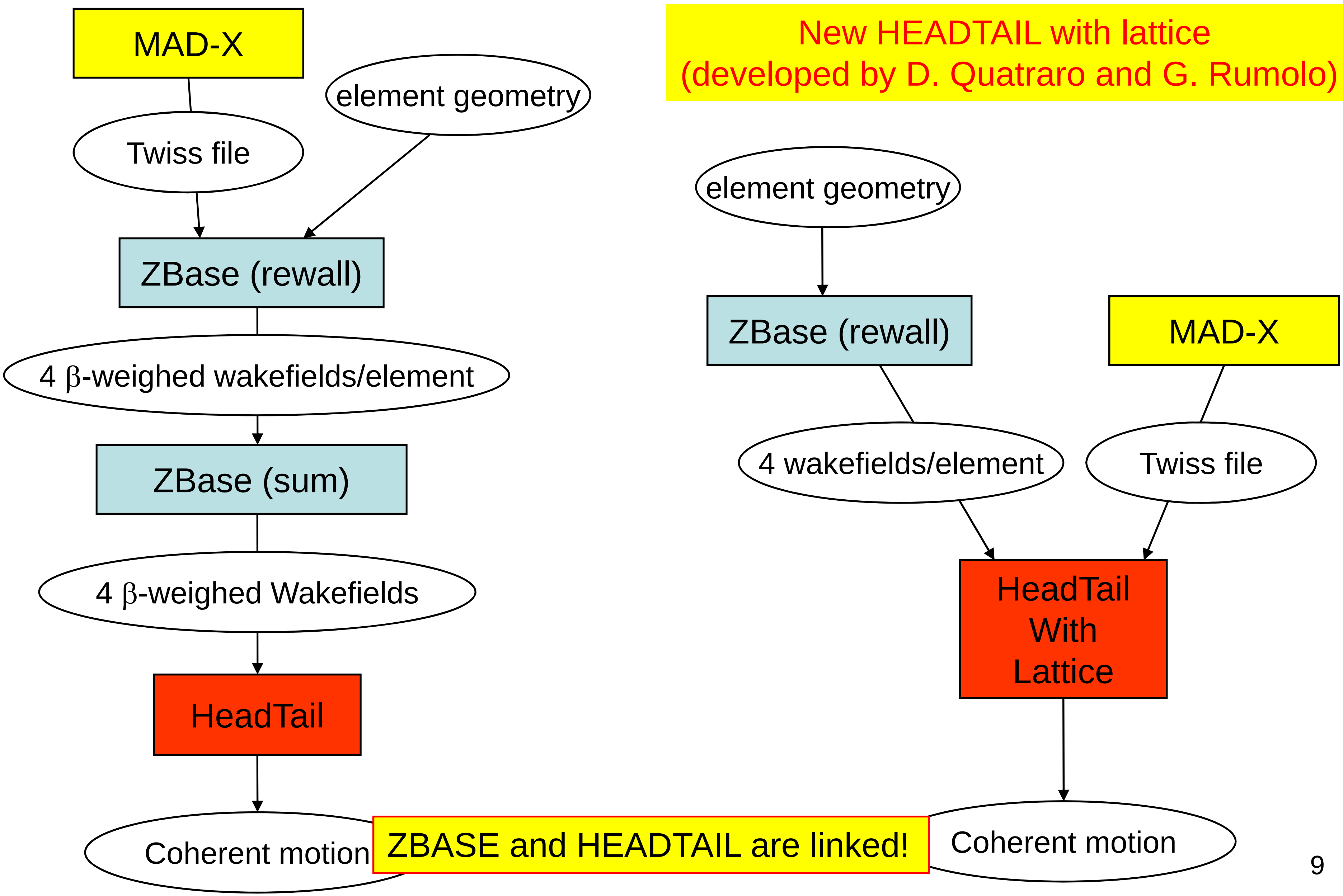
HEADTAIL (G. Rumolo, F. Zimmermann,SL-Note 2002-036-AP, CERN 2002) :

Code that simulates the interaction of a single bunch of macroparticles with disturbance phenomena (e.g. electron cloud, impedance, space-charge). Interactions are modelled by one or more kicks given at each simulated turn.



Now, need to use Wakefield output from ZBASE as input to HEADTAIL

Methods: Two options to link ZBASE wakefields to HEADTAIL



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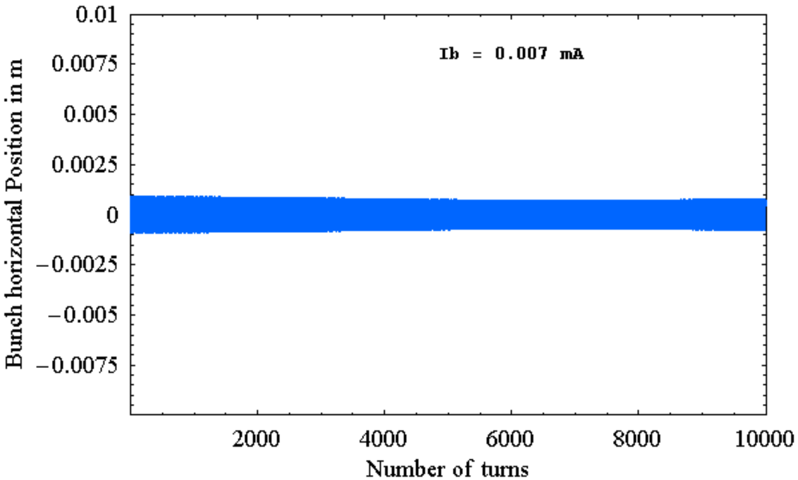
Results: HEADTAIL simulations for the BroadBand impedance case

HEADTAIL simulated coherent
bunch transverse position at a BPM location

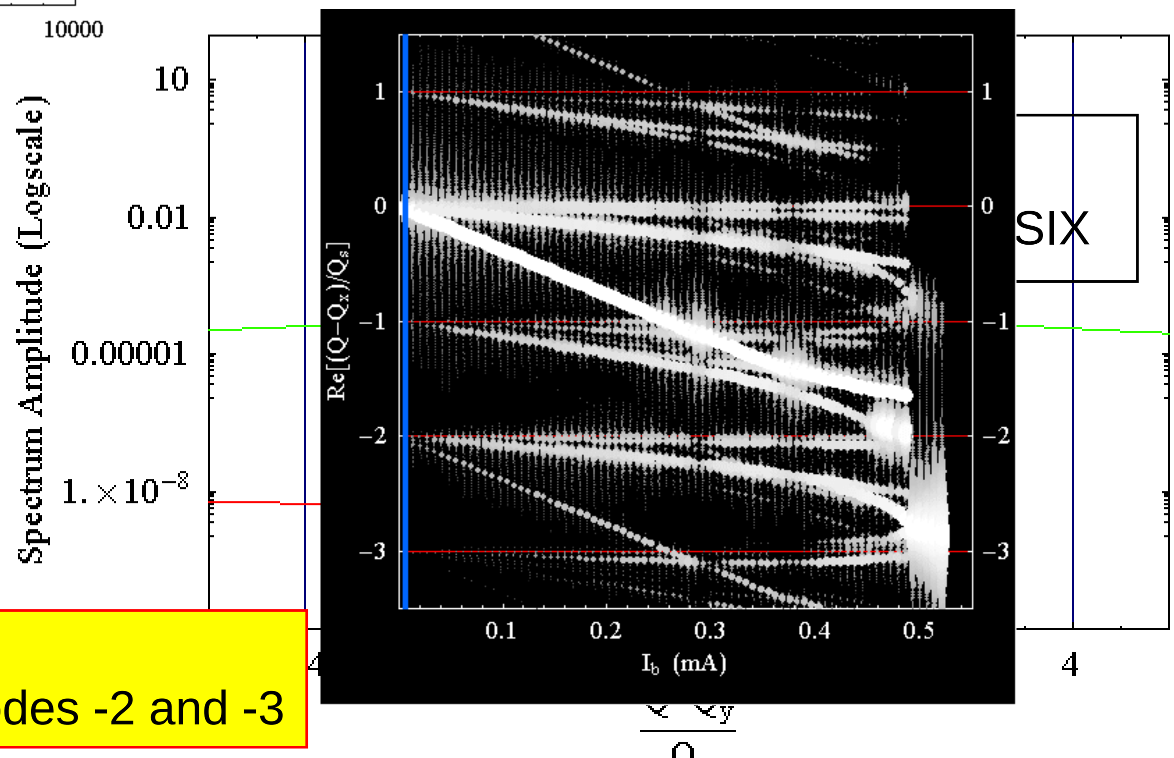


HEADTAIL simulation parameters:
- Broadband impedance
- Round beam pipe
- No space charge, no spread, no chromaticity
- Linear longitudinal restoring force

See also our talk at Beam'07

FFT
or
SUSSIX

HEADTAIL Simulated mode spectrum

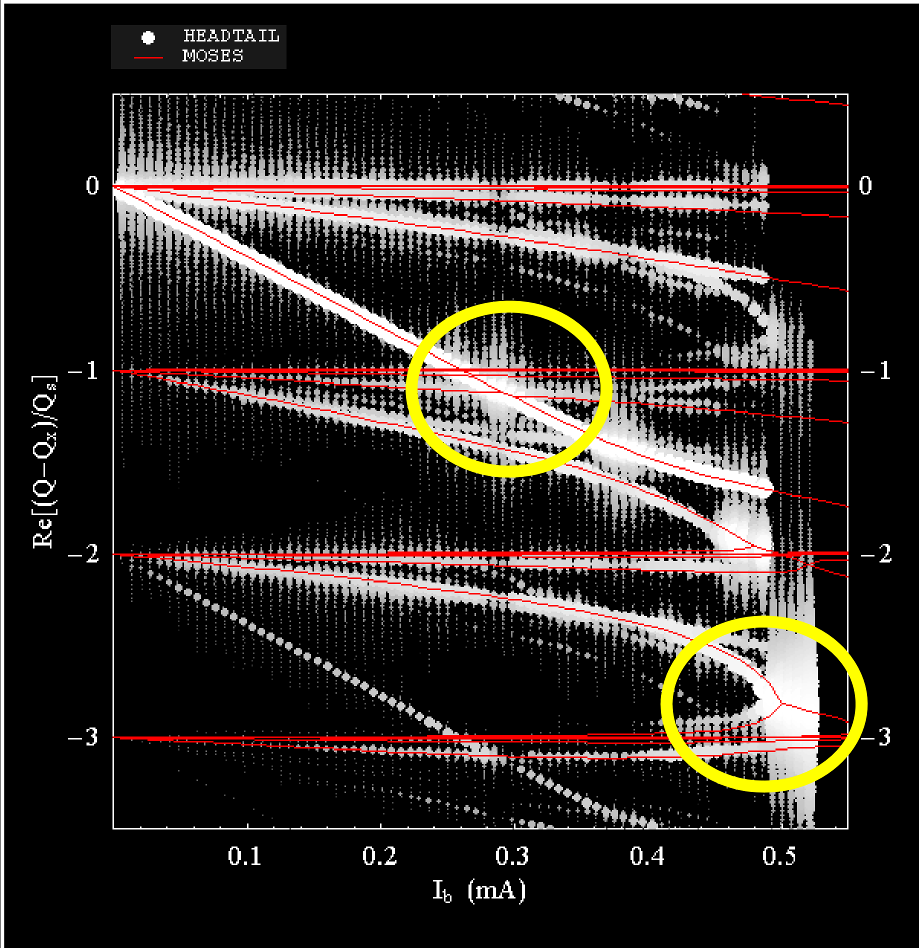


HEADTAIL predicts a TMCI:
coupling between transverse modes -2 and -3

Results: MOSES calculations for the BroadBand impedance case

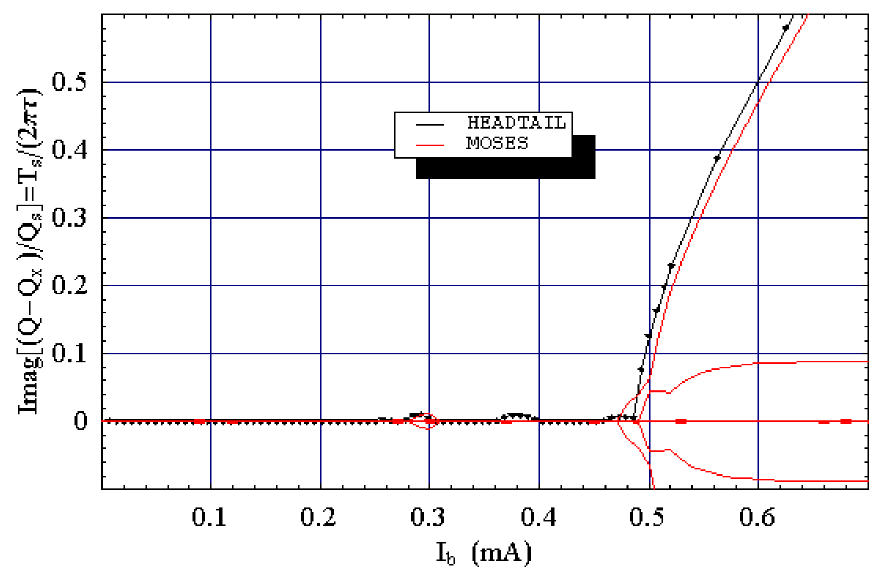
MOSES and HEADTAIL mode spectra Vs current

See also our talk at Beam'07



HEADTAIL and MOSES parameters:
- Broadband impedance
- Round beam pipe
- No space charge, no spread, no chromaticity
- Linear longitudinal restoring force

MOSES and HEADTAIL growth rate Vs Current



HEADTAIL and MOSES predict a TMCI for broadband impedance model

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Results : a more realistic impedance model

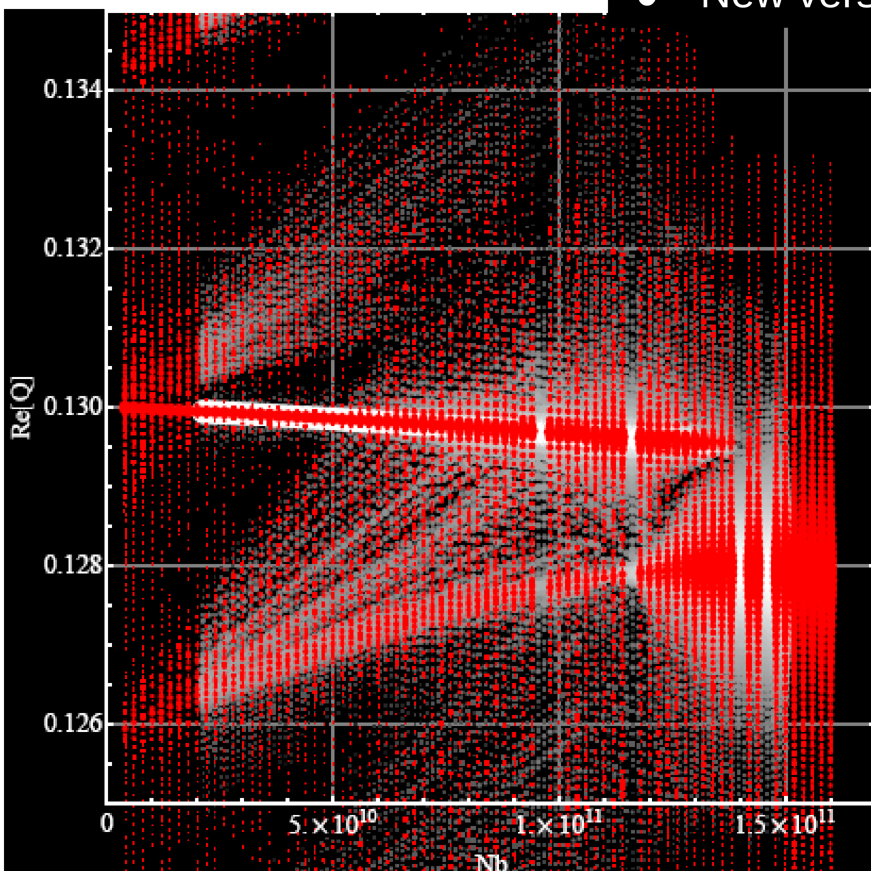
SPS kickers' transverse Resistive Wall impedance is taken into account (Zotter-Metral model).

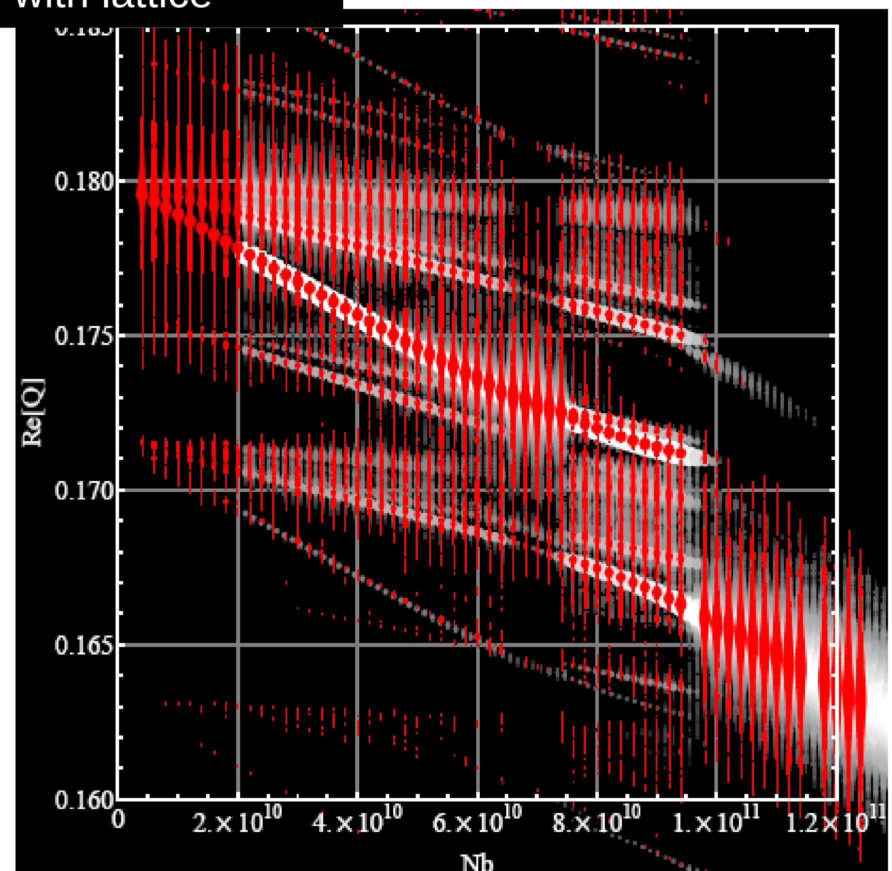
According to analytical calculations, these 20 kickers represent about 40 % of the measured impedance

Horizontal mode spectrum

- Classical 1 kick approximation
- New version with lattice

Vertical mode spectrum

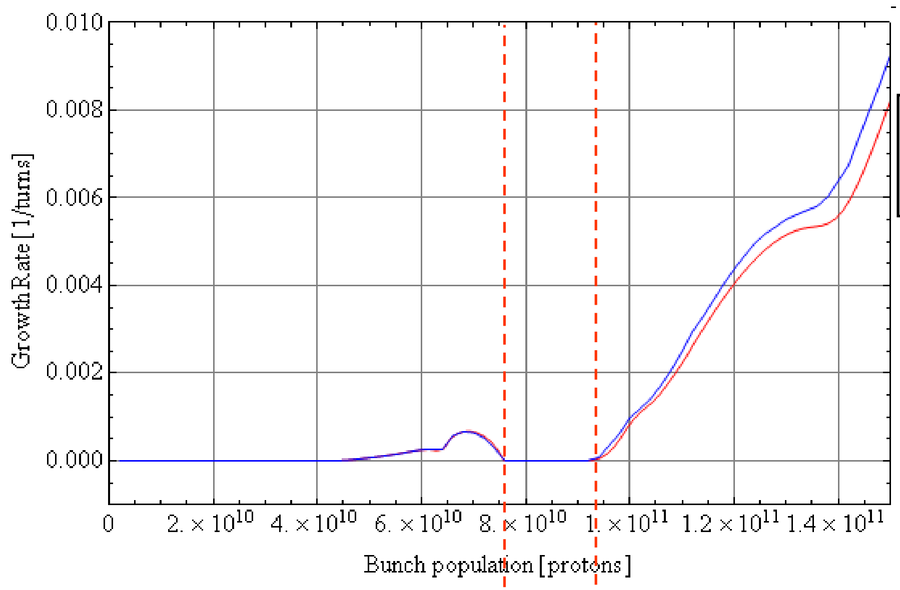




Very good agreement between 1 kick and version with lattice

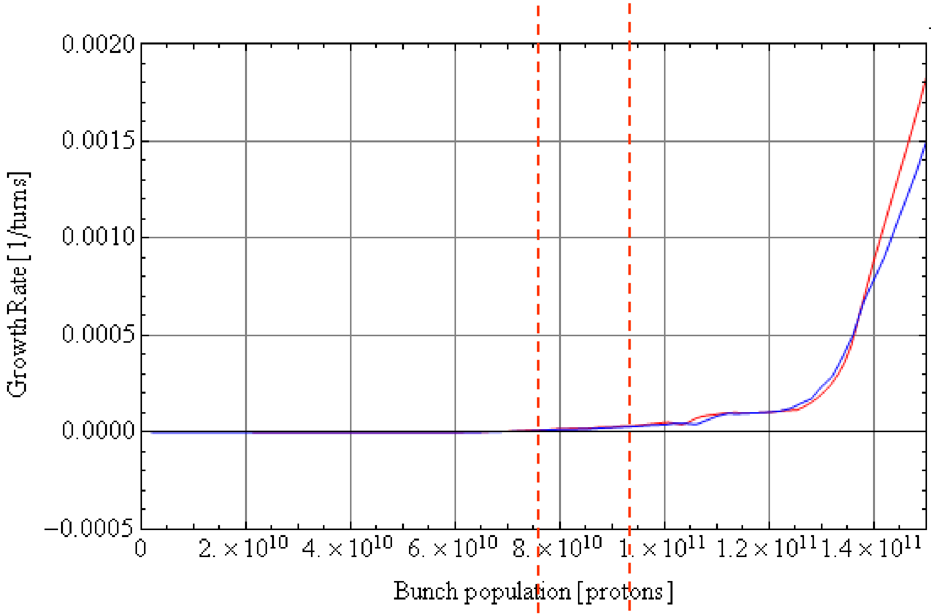
Results : more realistic impedance model

Vertical growth rate



Classical 1 kick approximation
New version with lattice

Horizontal growth rate



There is a beam current range around 8e10 p/b where the vertical motion is stable Wheras the horizontal motion is slightly unstable.

Next steps:

- include space charge
- include other impedance sources

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    - Proton losses
    - Tune shift
    - Growth rate
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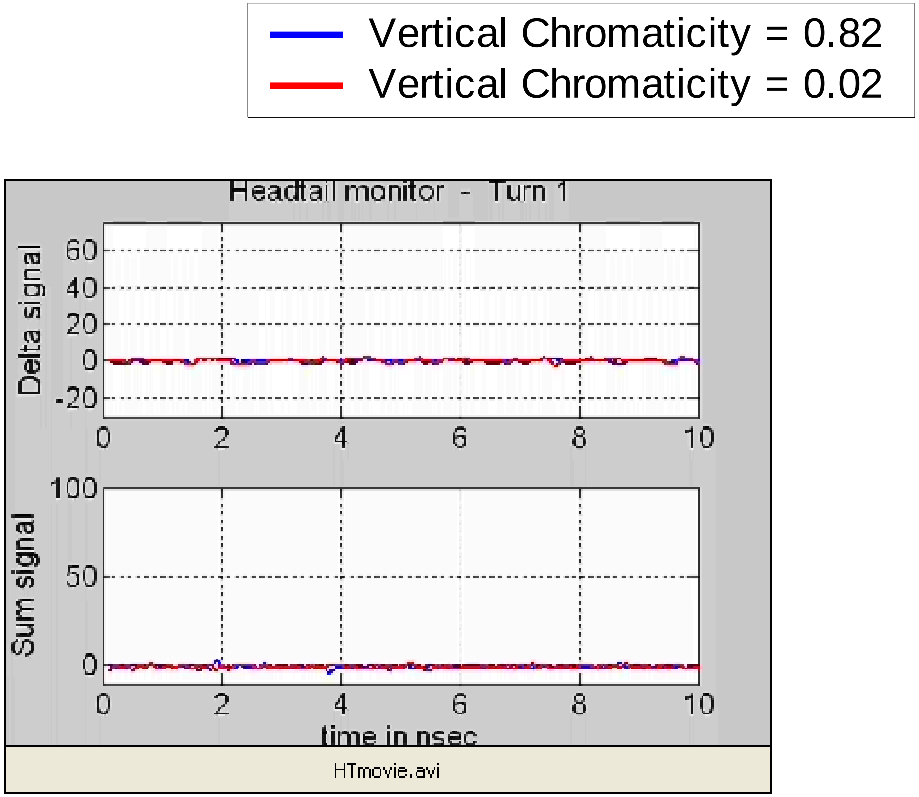
Results: Check for known instability characteristics

Measurement conditions

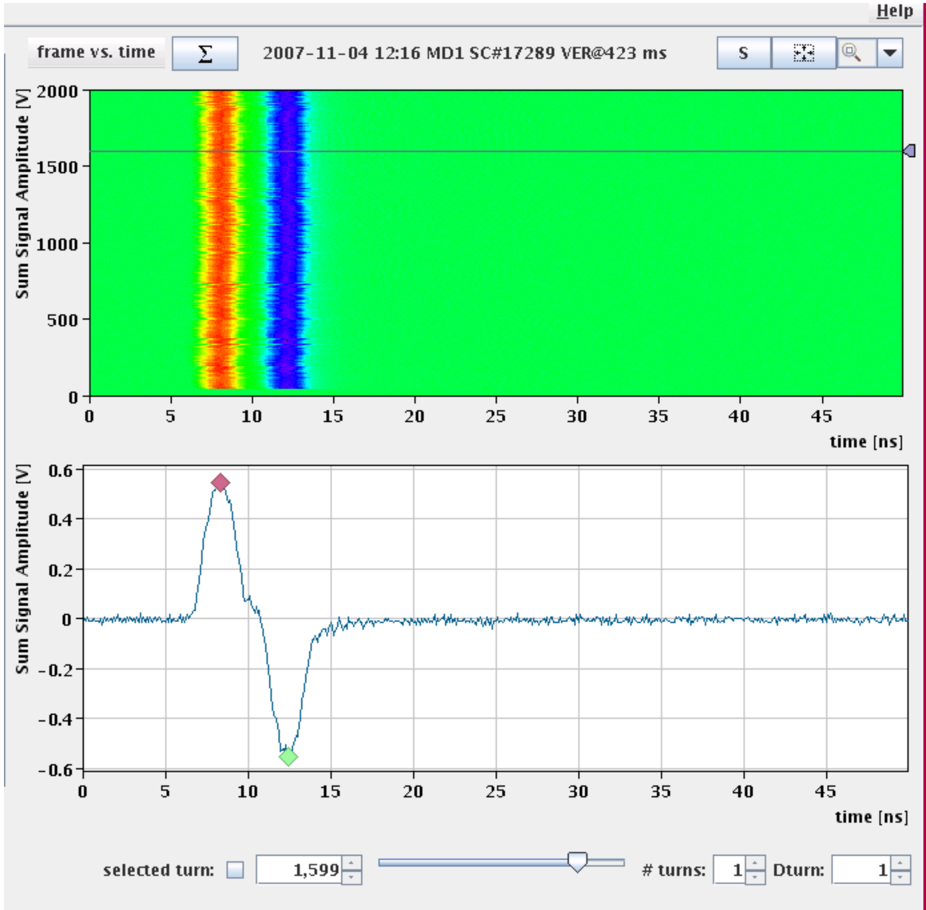
- Single LHC-type-bunch, except low longitudinal emittance (< 0.2 eVs)
- Positive vertical chromaticity as low as possible
- High horizontal chromaticity
- Octupoles used to « correct » amplitude detuning and non linear chromaticity
- Attempt to match RF voltage, but oscillation remain.
- Instrumentation: BCT, Qmeter, Headtail monitor, 2 BBQ, WCM.

HeadTail monitor data (Nov 4th 2007)
High bunch population: 1.2 10^{11} p/b
→ Above threshold

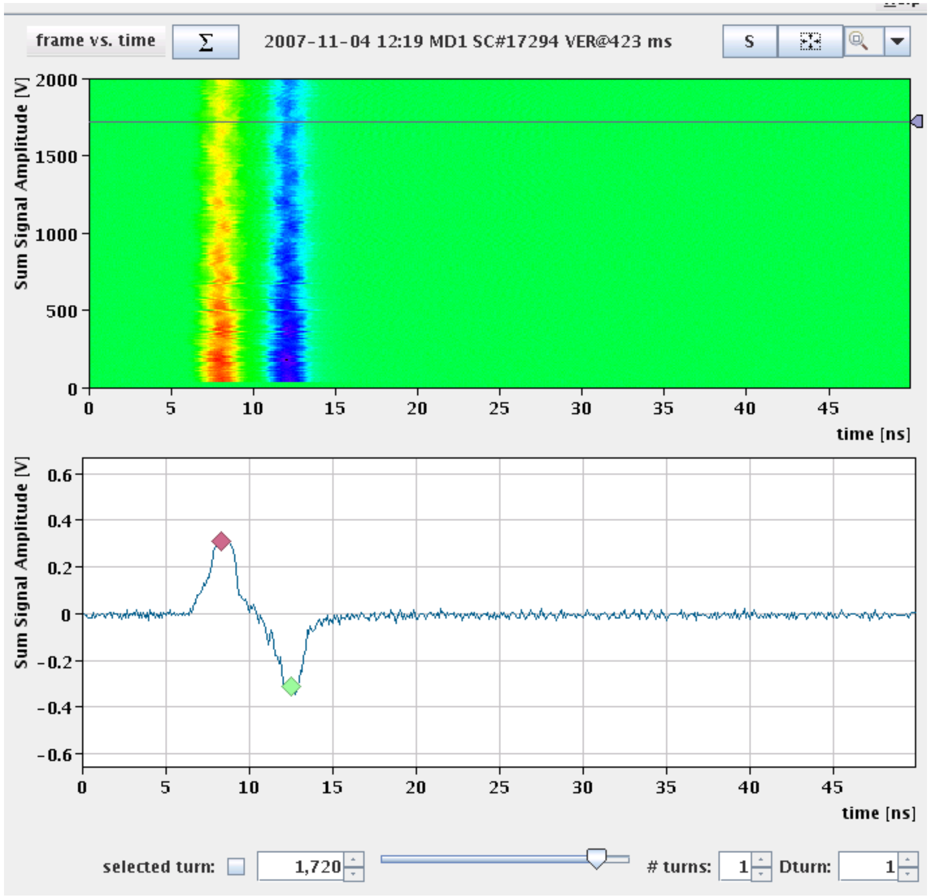


Results : Check for instability characteristics

Sum signal - Vertical chromaticity = 0.82



Sum signal - Vertical chromaticity = 0.02



→ Fast losses, damped by chromaticity, travelling wave pattern → TMCI?

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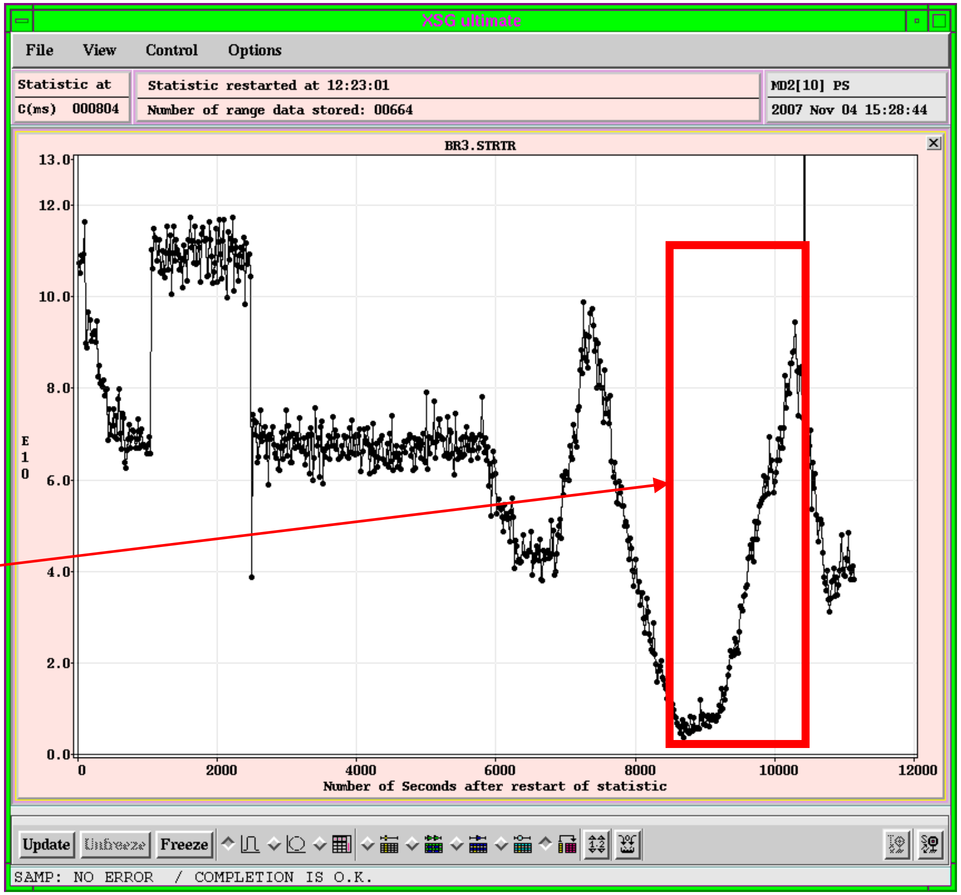
Results : Intensity scan

Intensity scan performed by shaving the beam in the PS Booster

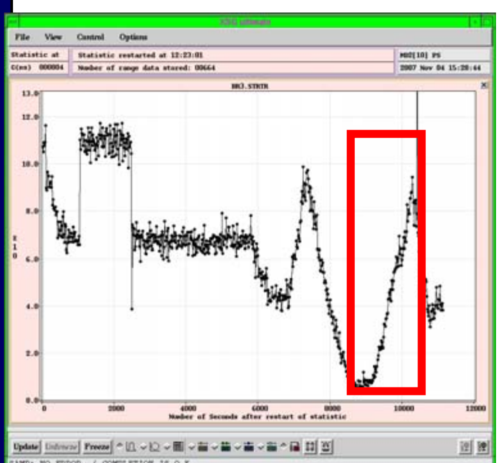
Intensity scan discussed
in the next slides (~20 minutes)

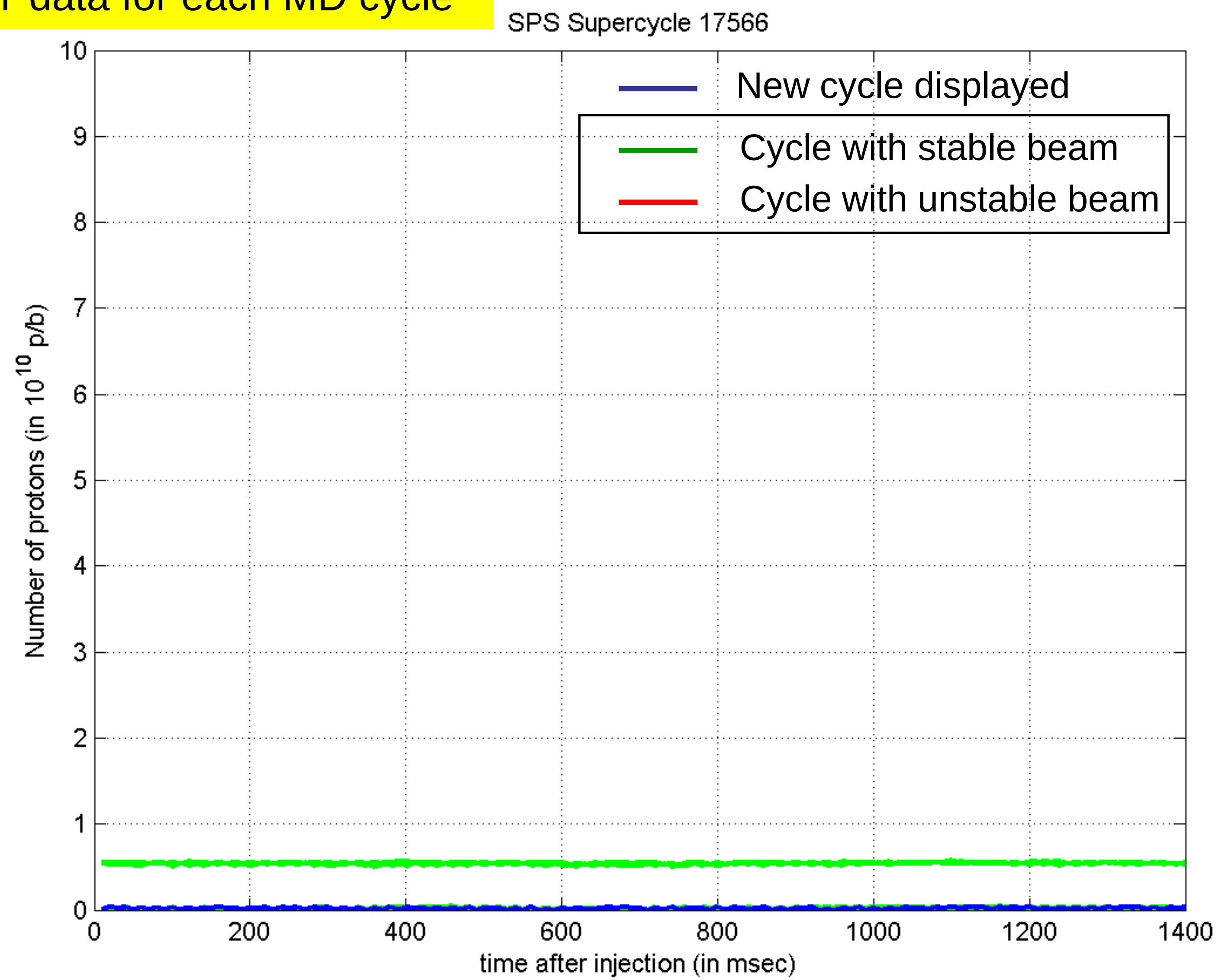


Results : Intensity scan

BCT data for each MD cycle

Intensity scan
On Nov 4th 2007:

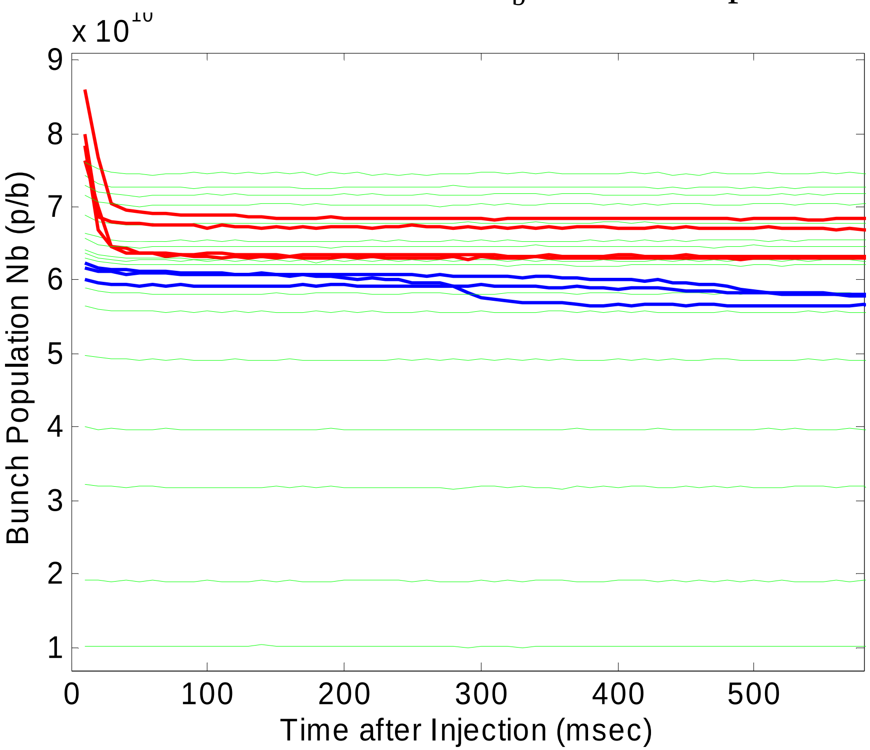




Results: Comparing measured and simulated loss patterns

SPS Measurements (Nov 4th 2007)

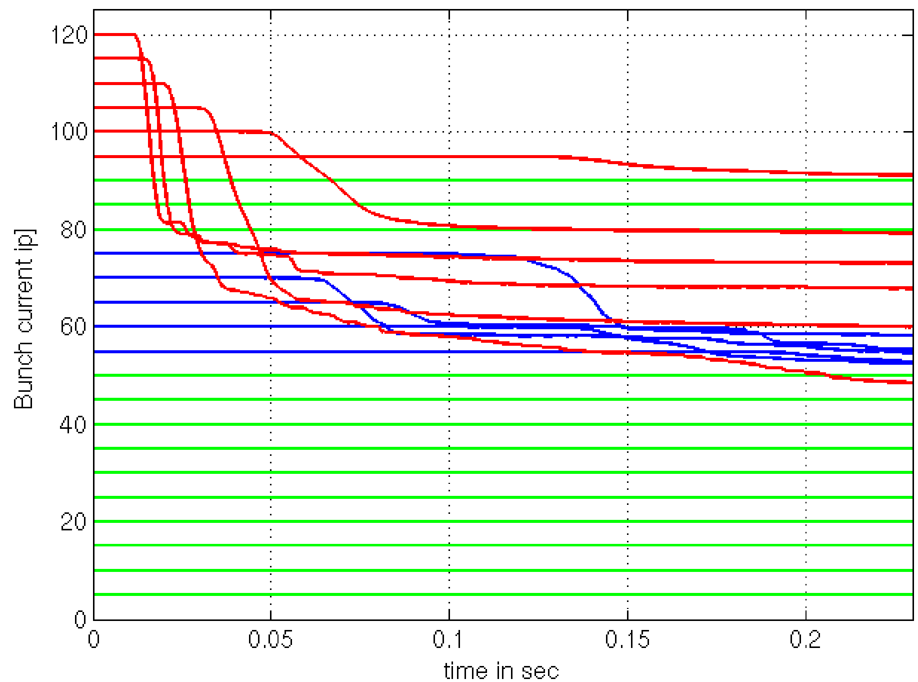
- Stable beam → $N_b \in [0; 6]$ & $[6.3;7.6]\ 10^{10}$ p
- Unstable beam → $N_b \in [6; 6.3]\ 10^{10}$ p
- Unstable beam → $N_b > 7.6\ 10^{10}$ p



0.2 sec

HEADTAIL simulations

- Stable beam → $N_b \in [0; 5]$ & $[8;9]\ 10^{10}$ p
- Unstable beam → $N_b \in [5.5; 7.5]\ 10^{10}$ p
- Unstable beam → $N_b > 9.5\ 10^{10}$ p



0.2 sec

→ Similar « double threshold » between simulations and experiments → TMCI?

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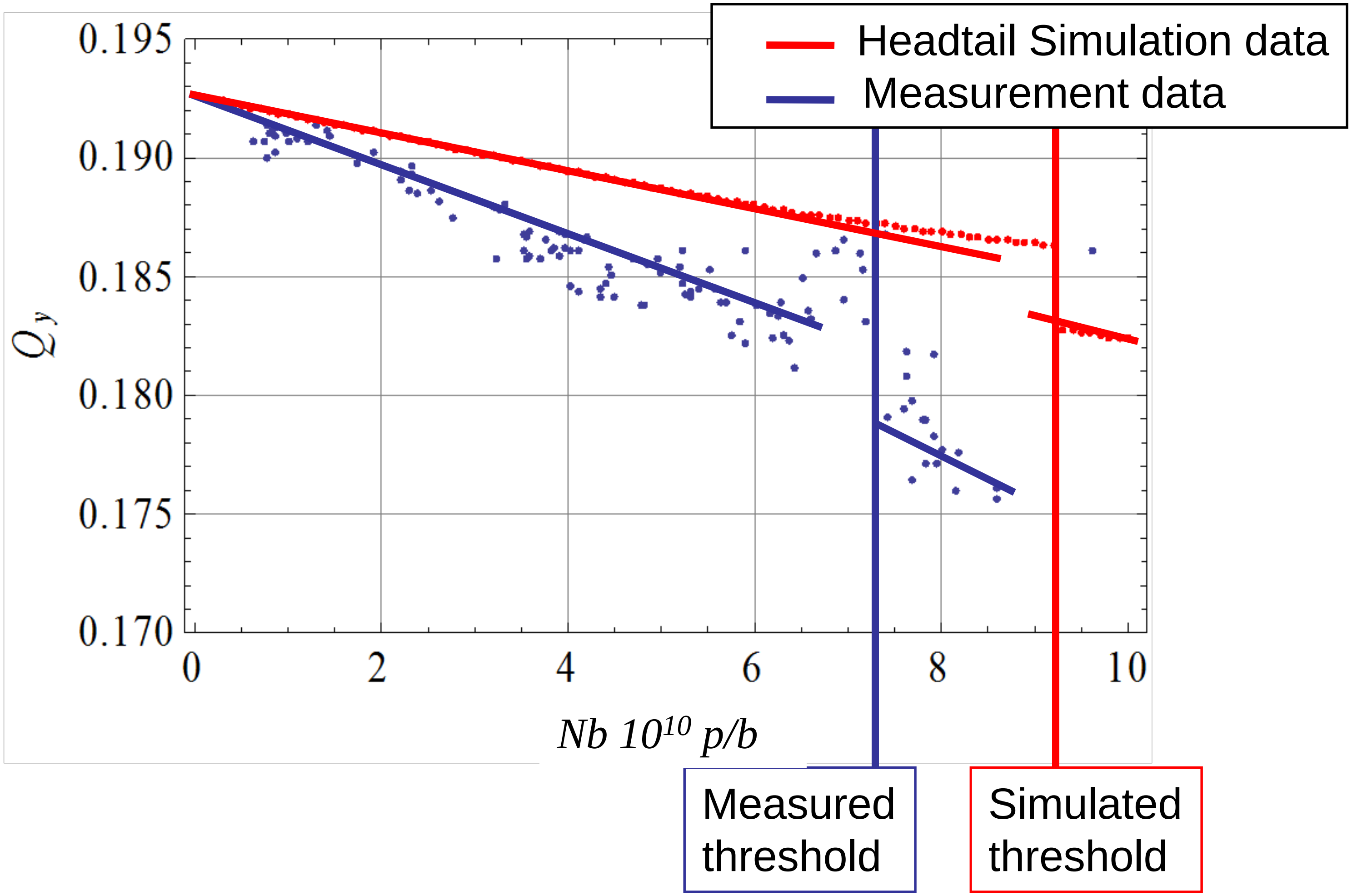
Results : Simulated vs measured Vertical tune shift

Vertical Tune spectrum as a function of bunch population



→ Similar tune step between simulations and experiments → TMCI?

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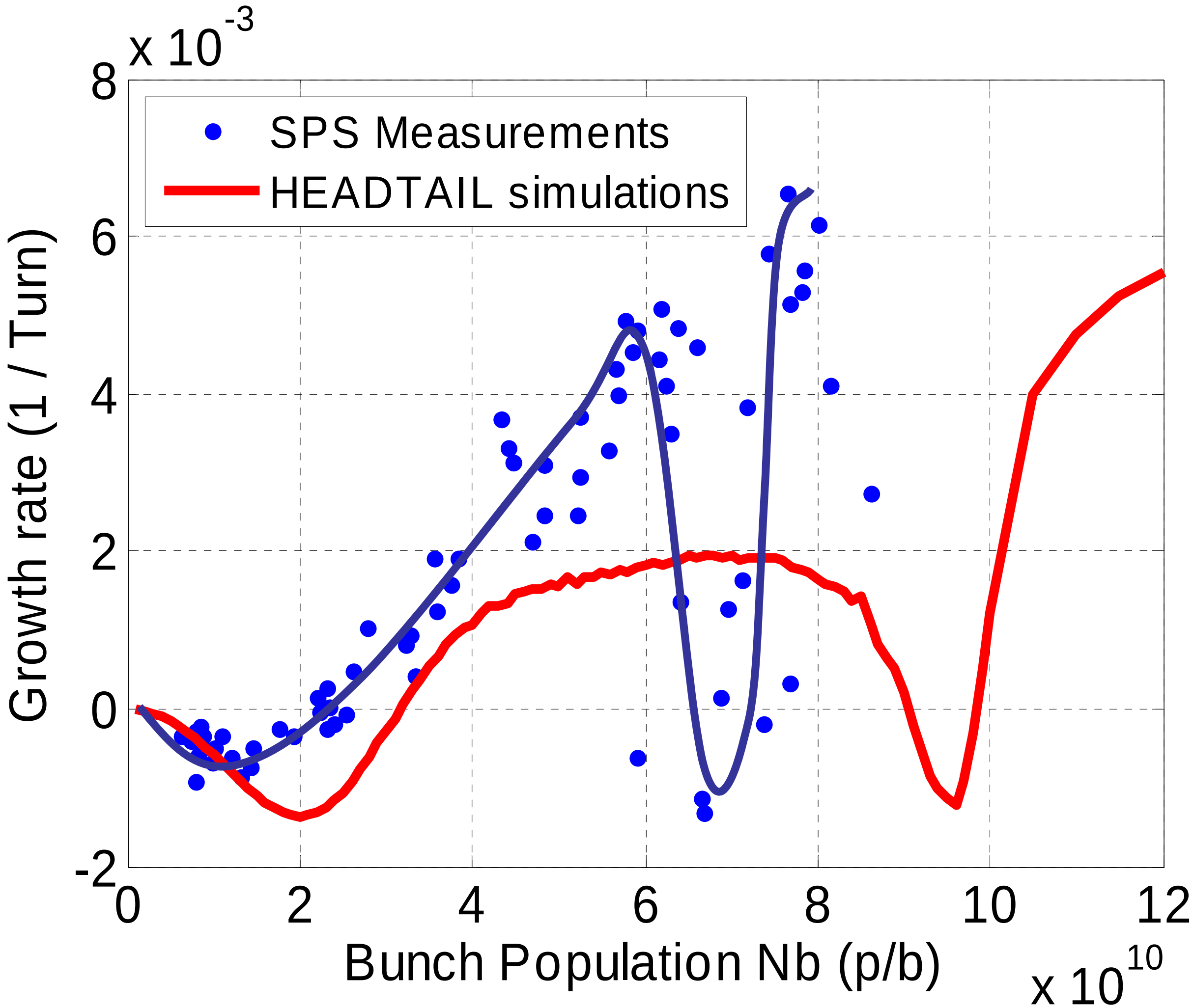
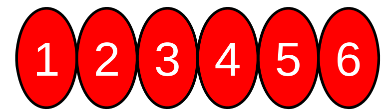
Results : Vertical growth rate



→ Similar growth rate pattern between simulations and experiments → TMCI?

Outlook

- Analysis of **loss pattern with bunch current**, **vertical growth rate** and **vertical tune shift** give more weight to the assumption that there is a TMCI at injection in SPS.



- HEADTAIL with lattice is benchmarked with the classical version of HEADTAIL.

- ZBASE is now linked to HEADTAIL, and we can use more realistic wakefields from analytical models or FEA simulations.

Perspectives

- Improve the SPS impedance model (ZBASE)
  - Add all simulated and measured SPS elements (B. Spataro and F. Caspers)
  - Get simulations with 1 wire displaced, and 2 wires to get both dipolar+quadrupolar and dipolar impedance.
- More realistic HEADTAIL simulations:
  - Space charge, amplitude detuning, etc.
- Carry on analysis and experiments in the SPS
  - 2008 first SPS MDs not very conclusive so far (analysis ongoing)
  - Control longitudinal parameters from the PS
  - Check for a horizontal instability in the intermediate vertical stable region
  - Analyse the Fourier spectrum of the Headtail monitor signal
  - 2 pickups at 90°

Acknowledgments

PS Booster, PS, SPS operators and supervisors, MD coordinator

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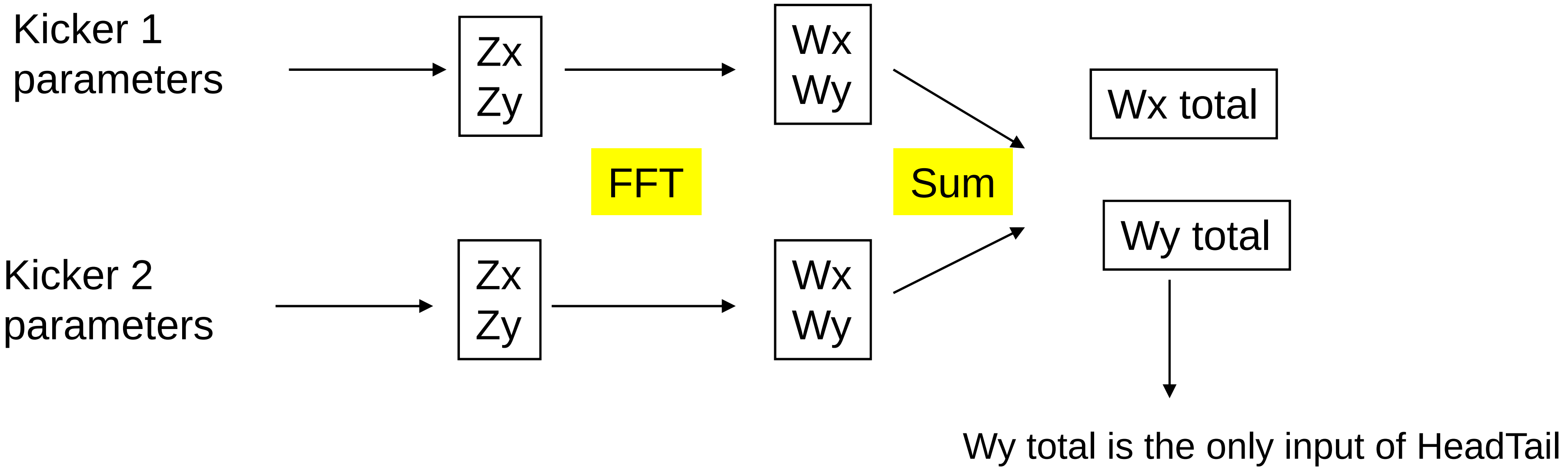
Giulia Papotti
Lenny Rivkin
Federico Roncarolo
Bruno Spataro
Bruno Zotter

Thank you very much for your attention!

Zbase

- Wake field from all the kickers come from Hubert Medina's work on zbase :



<u>Issue:</u> This calculation only works if all kickers are vertical

Zbase

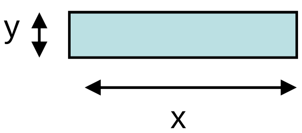
- Case of summing a horizontal and a vertical kicker:

$$Fx = K * (Wx_{dip} * x_{coherent} + Wx_{quad} * x_{incoherent})$$

$$Fy = K * (Wy_{dip} * y_{coherent} + Wy_{quad} * y_{incoherent})$$

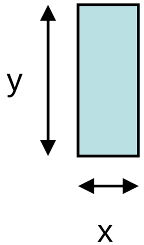
For specific geometries, Wxdip, Wydip, Wxquad, Wyquad can be obtained from the round case

Horizontal
Kicker 1



$Wxdip = 0.4\ W^{round1}$
$Wxquad = -\ 0.4\ W^{round1}$
$Wydip = 0.8\ W^{round1}$
$Wyquad = 0.4\ W^{round1}$

Vertical
Kicker 2



$Wxdip = 0.8\ W^{round2}$
$Wxquad = 0.4\ W^{round2}$
$Wydip = 0.4\ W^{round2}$
$Wyquad = -\ 0.4\ W^{round2}$

Wxquad, Wyquad and Wxdip can not be obtained from Wydip alone

$Wxdip = 0.8\ W^{round2} + 0.4\ W^{round1} \neq 0.5\ Wydip$
$Wxquad = 0.4\ W^{round2} - 0.4\ W^{round1} \neq -\ 0.5\ Wydip$
$Wydip = 0.4\ W^{round2} + 0.8\ W^{round1} =$ Wydip
$Wyquad = -\ 0.4\ W^{round2} + 0.4\ W^{round1} \neq 0.5\ Wydip$