LHC Injectors Upgrade

Longitudinal Beam Dynamics Simulations for PSB in the Linac4 scenario

D. Quartullo, S. Albright, E. Shaposhnikova

ACKNOWLEDGEMENTS: *M.E. Angoletta, E. Benedetto, A. Blas, V. Forte, K. Hanke, S. Hancock, A. Lasheen, M. Migliorati, B. Mikulec, J. E. Muller, M. Paoluzzi, G. Rumolo, H. Timko, C. Zannini*

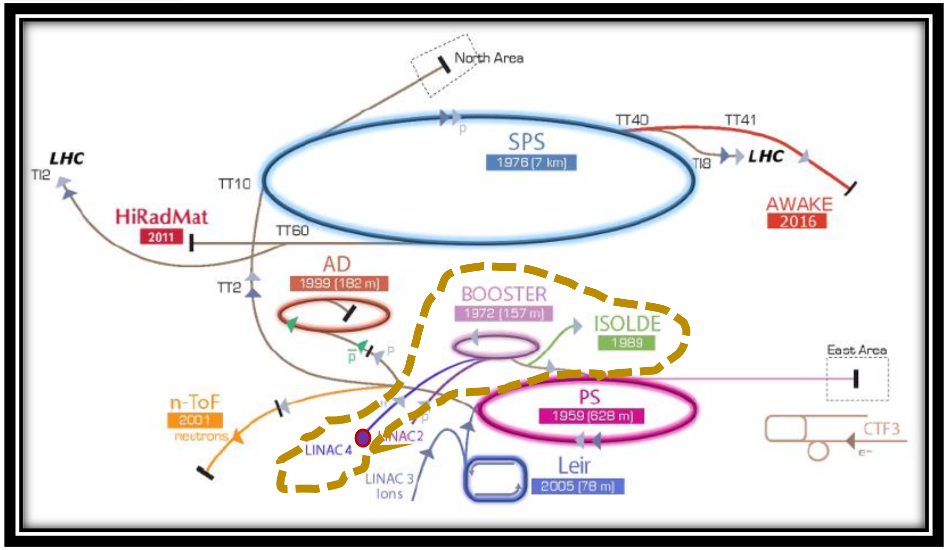
CONTENTS

- Introduction
- The CERN BLonD code
  - Main features
  - Examples of benchmarking with measurements, other code and analytical formulas
- PSB impedance
  - Space charge
  - Other contributions
- Simulations
  - ISOLDE beam
  - HL-LHC beam
    - Double RF with different second harmonic voltages
- Conclusion
- References

Introduction

- We need to analyse the situation after LS2:
  - Injection kinetic energy: 50 MeV => 160 MeV
  - Extraction kinetic energy: 1.4 GeV (**ISOLDE**) or 2 GeV (**HL-LHC**)
- Longitudinal beam dynamics simulations to predict beam stability:
  - Realistic impedance model (cavities, ...)
  - Reliable estimation of space charge - dominant impedance source

animation



Relevant PSB parameters:

$\boldsymbol{E_{kin}}$: 160 MeV → 1.4 GeV → 2 GeV

$\boldsymbol{\beta}$: 0.52 → 0.92 → 0.95

$\boldsymbol{\gamma}$: 1.17 → 2.49 → 3.13

$\boldsymbol{T_{rev}}$: 1008 ns → 570 ns → 552 ns

$\boldsymbol{f_{rev}}$: 0.99 MHz → 1.75 MHz → 1.81 MHz

$\boldsymbol{f_{sync}^{V=8kV}}$: 1.68 KHz → 0.41 KHz → 0.26 KHz

h=1 or **h**=1 & **h**=2

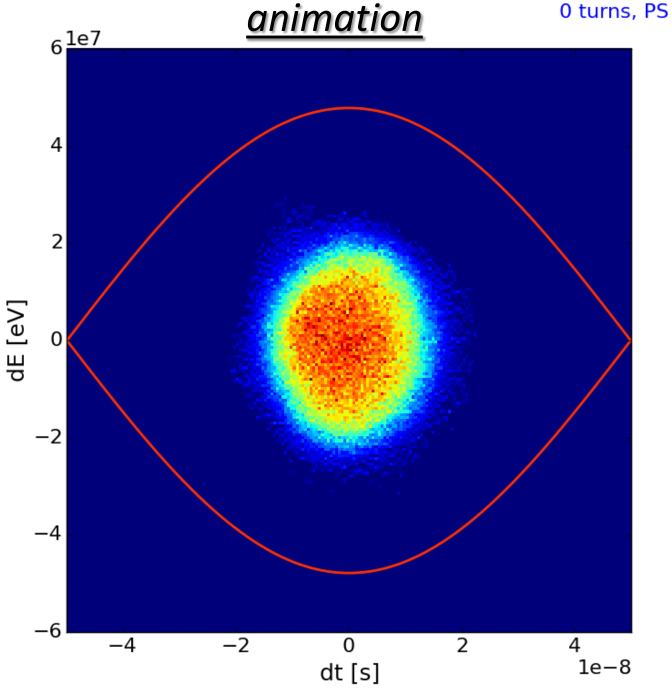
The BLonD code

- BLonD is a Beam Longitudinal Dynamics simulation code for synchrotrons developed at CERN in BE/RF group (supposed to replace Fermilab ESME) => *http://blond.web.cern.ch/*
- Main features:
  - Python and C++
  - Single and multi-bunch options
  - Acceleration, multiple RF systems, multiple RF stations
  - RF manipulations
  - Collective effects in frequency and time domain
  - Low-power level RF options (phase noise, phase loop, feedbacks...)
  - Low-beta case (introduced for PSB)
  - Monitoring, plotting, data analysis
  - Documentation

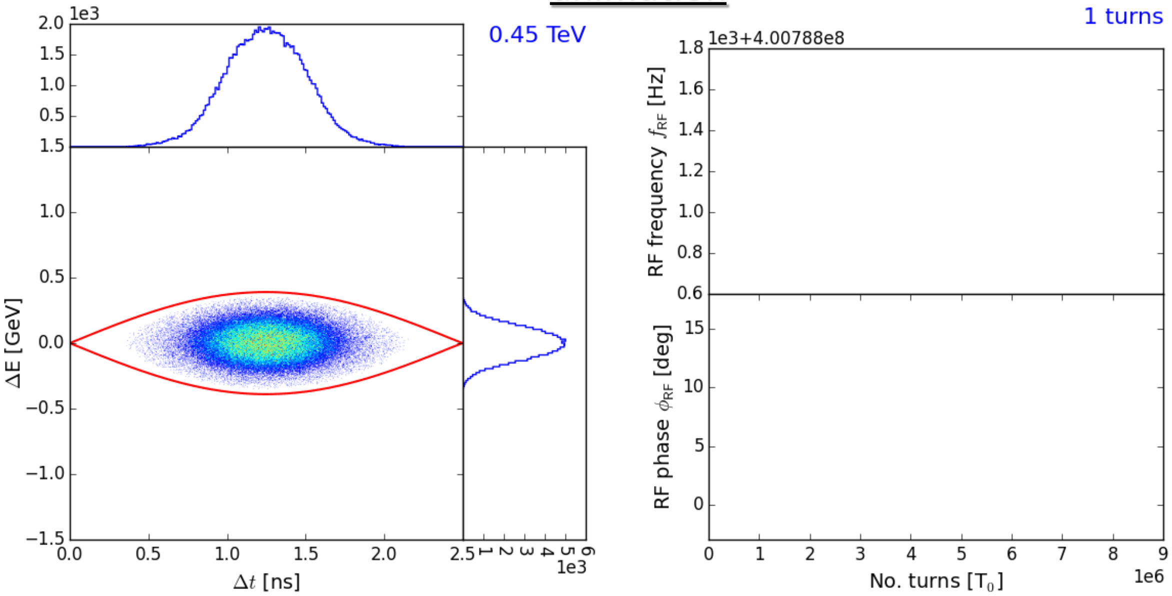
BLonD: examples of application

http://blond.web.cern.ch/content/applications

animation



animation

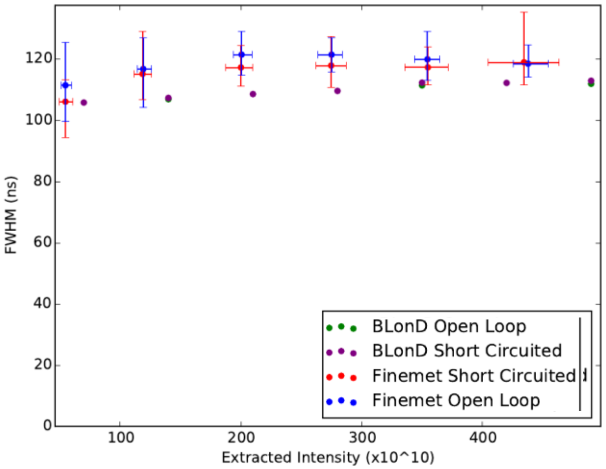


PS-to-SPS transfer, splitting + rotations (*courtesy H. Timko)*

LHC controlled longitudinal emittance blow-up during the ramp (*courtesy H. Timko*)

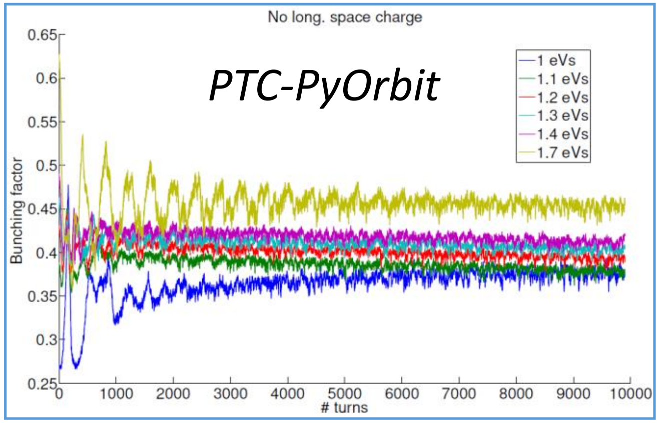
BLonD: benchmarking

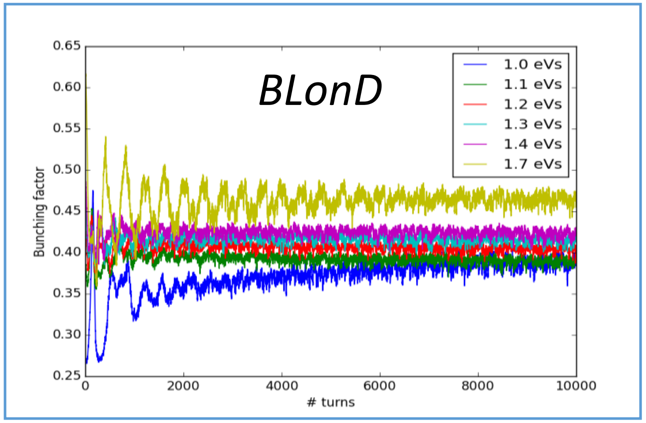
- Comparison with PSB measurements (Finemet Review, 2015)



FWHM bunch length at PSB extraction for various intensities, full ramp simulation **=> very good agreement (< 10 ns)** (slightly more blow-up measured)

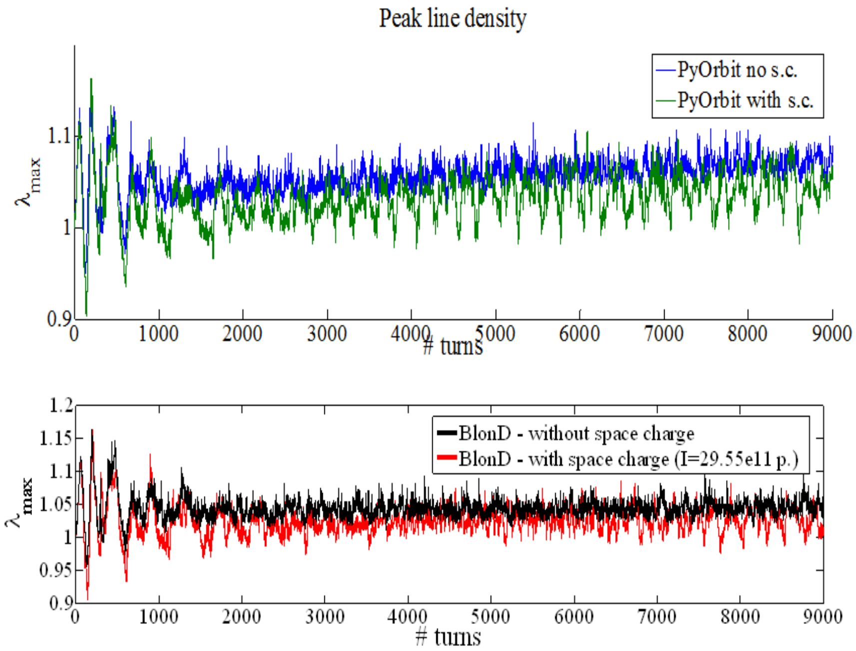
- Benchmarks against the PIC code PTC-PyOrbit (V. Forte and D. Quartullo)





PSB simulations at 160 MeV in double RF and no space charge **=> good agreement**

BLonD: benchmarking (PTC-PyOrbit)

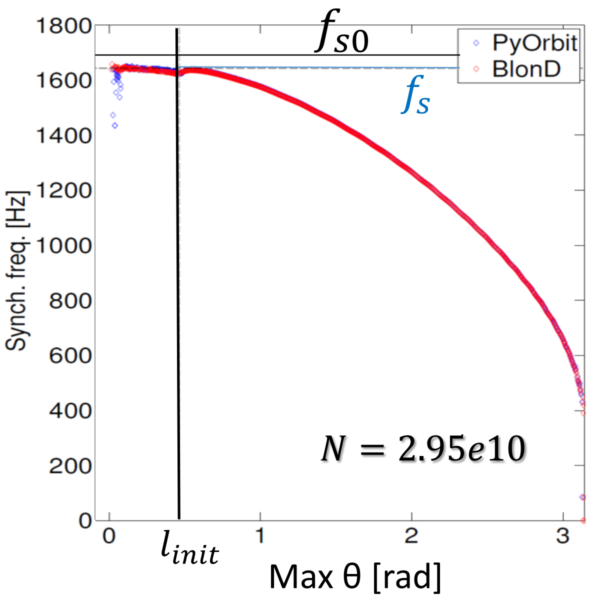


PSB simulations at 160 MeV with *space charge* in a double RF system

PSB simulations at 160 MeV with space charge in a double RF system

$\Rightarrow$ **Also good agreement**

(Blond is less noisy?)



$$f_s = f_{s0}\sqrt{1 - \frac{3\,e\,N f_{rev}}{\pi^2\,h\,V}\left(\frac{C}{l}\right)^3\left[\frac{Z}{n}\right]_{SC}}$$

Syncrotron frequency distribution for a matched parabolic bunch with space charge below transition => ***perfect agreement***

CONTENTS

- *Introduction*
- *The CERN BLonD code*
  - *Main features*
  - *Examples of benchmarking with measurements, other code and analytical formulas*
- *PSB impedance*
  - *Space charge*
  - *Other contributions*
- *Simulations*
  - *ISOLDE beam*
  - *HL-LHC beam*
    - *Double RF with different second harmonic voltages*
- *Conclusion*
- *References*

Space charge impedance at 160 MeV: rough estimations

- First estimation, on-axis potential

Impedance free space

$$\frac{Z_{SC}}{n} \overset{(*)}{=} \frac{Z_0\, g}{2\,\beta\,\gamma^2} = \frac{Z_0}{2\,\beta\,\gamma^2}\left(1 + 2\log\frac{b}{a}\right) = 795.8\ \Omega$$

- Second estimation, average potential over $\sigma_{x,y}$

$$\frac{Z_{SC}}{n} \overset{(*)}{=} \frac{Z_0}{2\,\beta\,\gamma^2}\left(0.5 + 2\log\frac{b}{a}\right) = 663.7\ \Omega$$

(*) formulae valid for round uniform beam in circular chamber

$\sigma_{x,y} \approx 5.5\ \mathrm{mm}$
30 mm is the lowest half-height of all the PSB chambers

⇩

b = radius chamber = 30 mm
$a = 2\,\sigma_{x,y}$ = radius beam = 11 mm

- Third estimation, using measurement (S. Hancock et al.) g(100 MeV) = 2 and rescaling

Norm. transverse emittance

$$a(E_k) \propto \frac{\sqrt{\epsilon_N}}{\sqrt{\beta(E_k)\gamma(E_k)}}$$

$$\frac{Z_{SC}}{n} = \frac{Z_0}{\beta\,\gamma^2}\left\{1 + \frac{1}{2}\ln\frac{\beta\,\gamma}{\beta\,\gamma(100\ MeV)}\right\} = 595.5\ \Omega$$

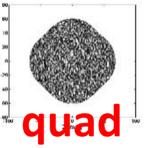
=> Too wide range, more accurate estimation was needed!

Space charge impedance at 160 MeV: more accurate calculations

- The code LSC developed at SLAC [7] was used

MAIN INPUT:

- Gaussian transverse distribution
- ring divided in 211 parts according to chamber cross-section



- σ_X, σ_Y

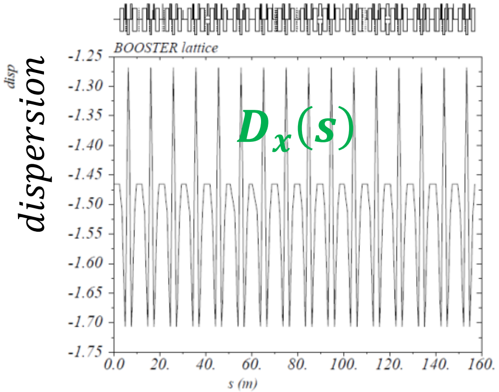
$$\nabla^2 \boldsymbol{E} - \frac{1}{c^2}\frac{\partial \boldsymbol{E}}{\partial t} = \frac{\nabla\rho}{\varepsilon_0} + \mu_0 \frac{\partial \boldsymbol{J}}{\partial t}$$

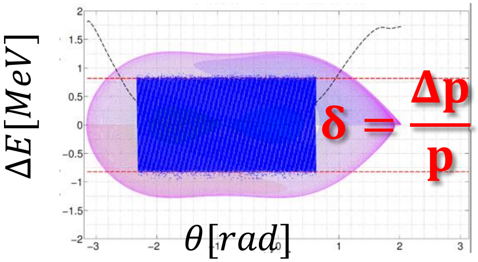
LSC

OUTPUT:

- Z/L averaged over 1 σ

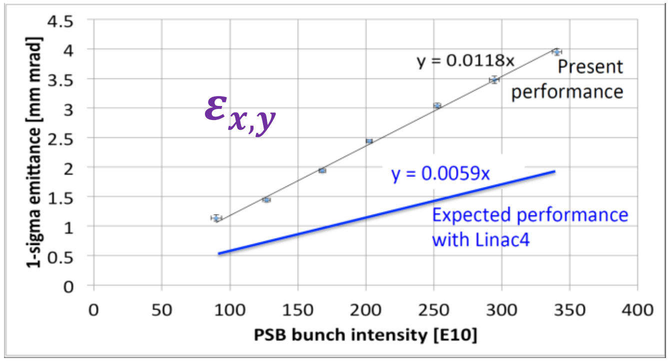
$$\frac{Z}{n} = \sum_{i=1}^{211} L_i \left(\frac{Z}{n\,L}\right)_i = \boxed{\mathbf{633.14\ \Omega}}$$

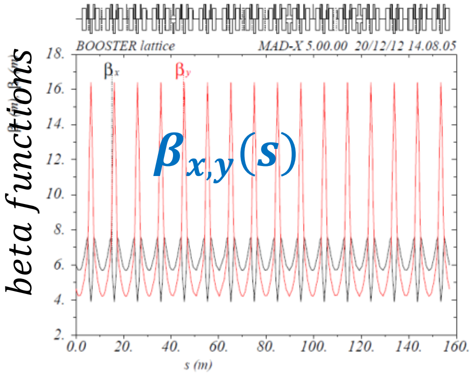




$$\sigma_x(s) = \sqrt{\varepsilon_x\, \beta_x(s) + D_x^2(s)\delta^2}$$

$$\sigma_y(s) = \sqrt{\varepsilon_y\, \beta_y(s)}$$

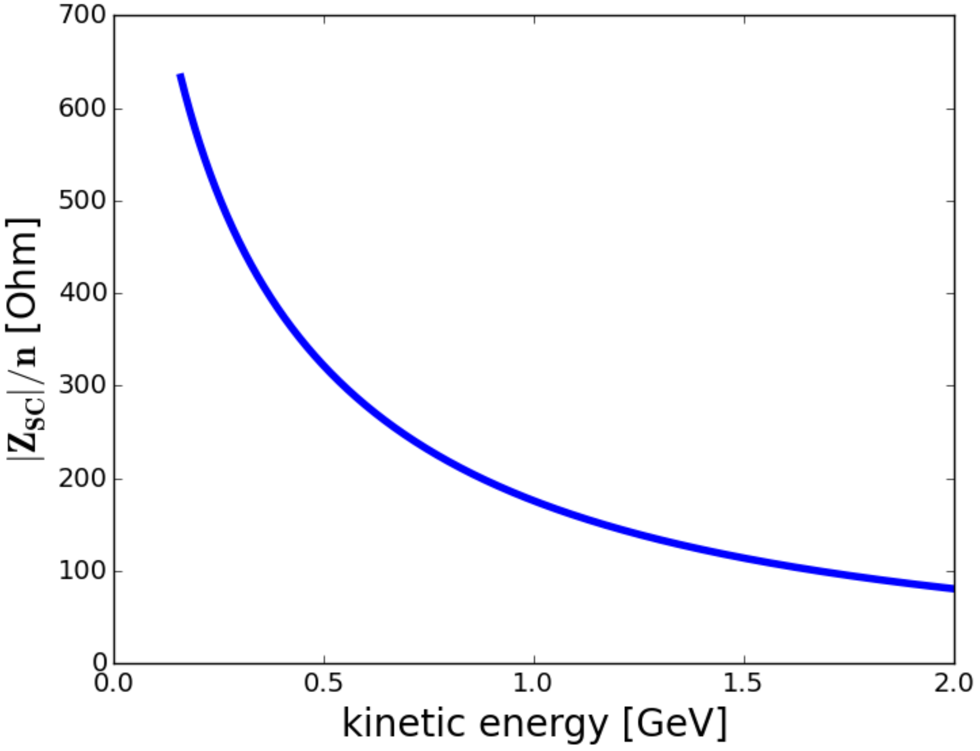




Space charge impedance during cycle

- Scaling based on value at 160 MeV of 633.14 Ohm => used in all simulations

$$\frac{|Z_{SC}|}{n}(E_k) = \frac{Z_0}{\beta(E_k)\gamma(E_k)^2}\left(1.2 + \frac{1}{2}\ln\frac{\beta(E_k)\gamma(E_k)}{\beta(160\,MeV)\gamma(160\,MeV)}\right)$$



Factor 8 change during cycle, but the SC effect is reduced much less due to bunch length reduction!

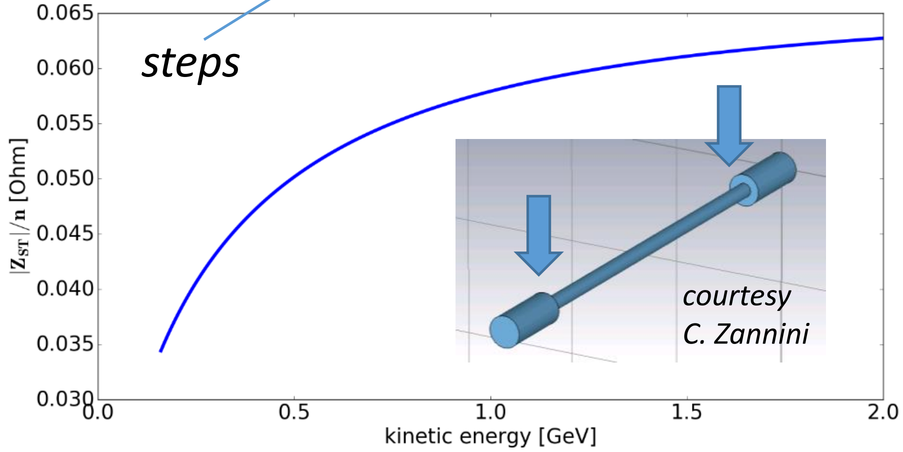
PSB impedance model

Space charge +

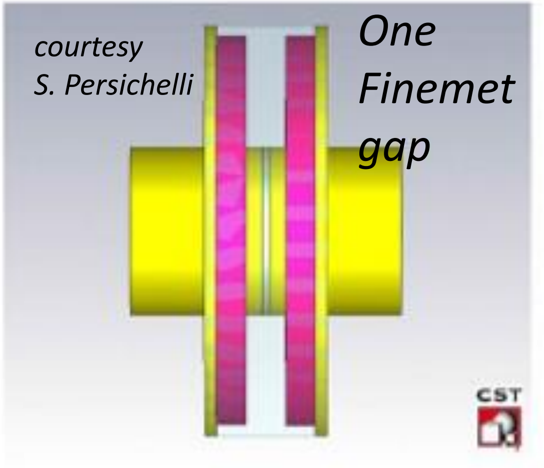
- Finemet cavities
- Extraction kickers
- Extraction kicker cables
- KSW magnets
- Resistive wall
- Steps (beam pipe discontinuities)

Impedances in red depend on the beam energy!

Negligible compared to SC!

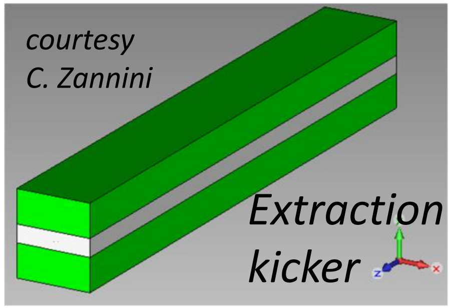


courtesy C. Zannini



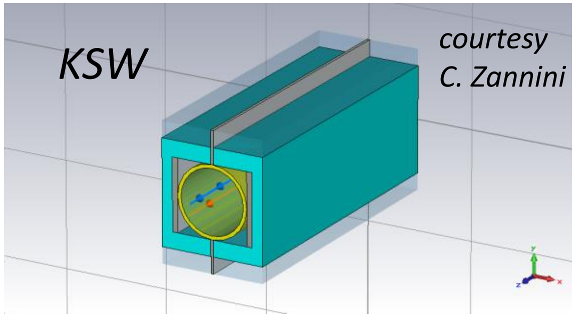
courtesy S. Persichelli

One Finemet gap



courtesy C. Zannini

Extraction kicker



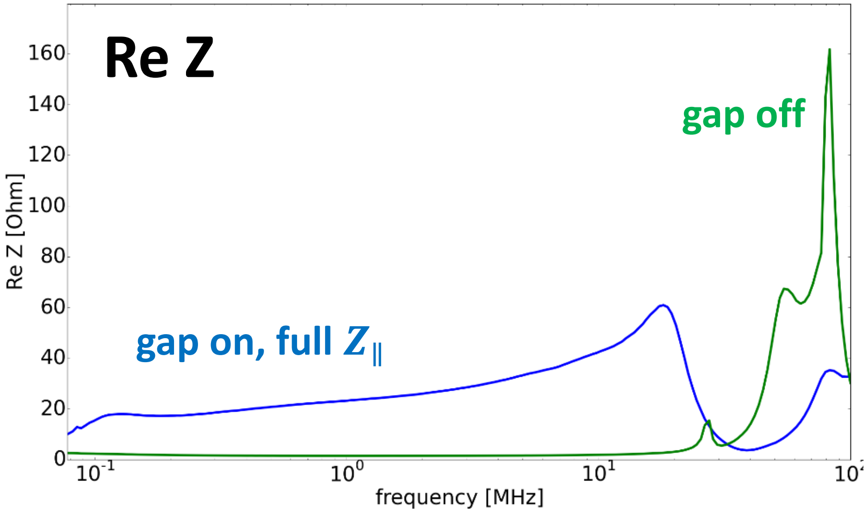
KSW

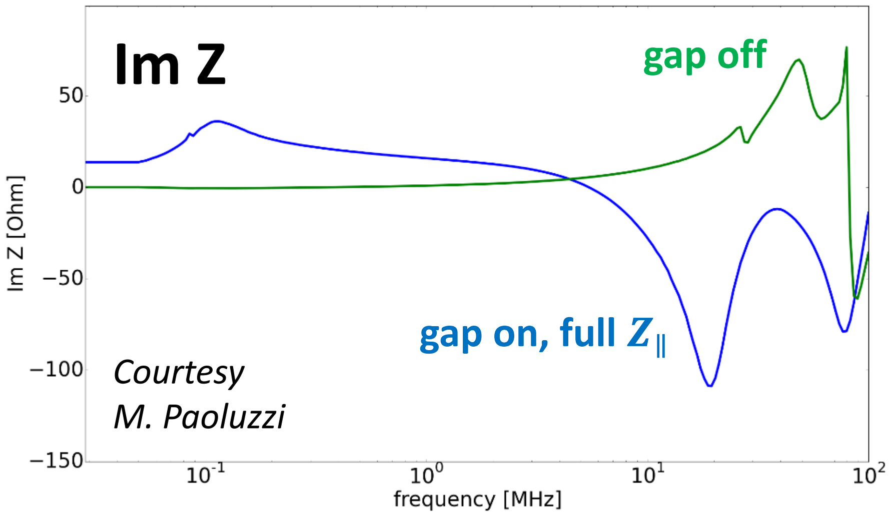
courtesy C. Zannini

Finemet cavities impedances

- Three Finemet cavities (36 gaps) will be installed in each ring for total V of 24 kV
- Three possible configurations:
  - **Short circuited gap off (green), gap on with open loop (blu), gap on with closed loop (next slide)**

no cavity feedbacks *with cavity feedbacks*



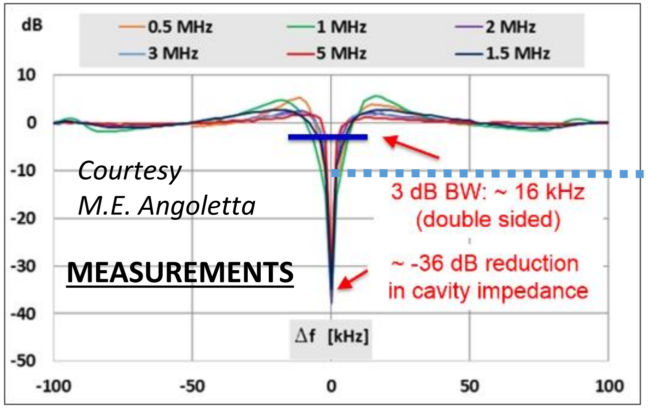


Courtesy M. Paoluzzi

- f_{rev} varies from 0.99 MHz to 1.81 MHz → **short circuited impedance is very small for beam!**
- No dependence on the beam energy

Finemet impedance: FB closed loop

- ➢ Reduction of $Z_{\parallel}$ at specific longitudinal harmonics
- ➢ Well-width as large as possible to reduce $Z_{\parallel}$ at $h\, f_{rev} \pm f_s$ ($f_s < 2$ kHz)

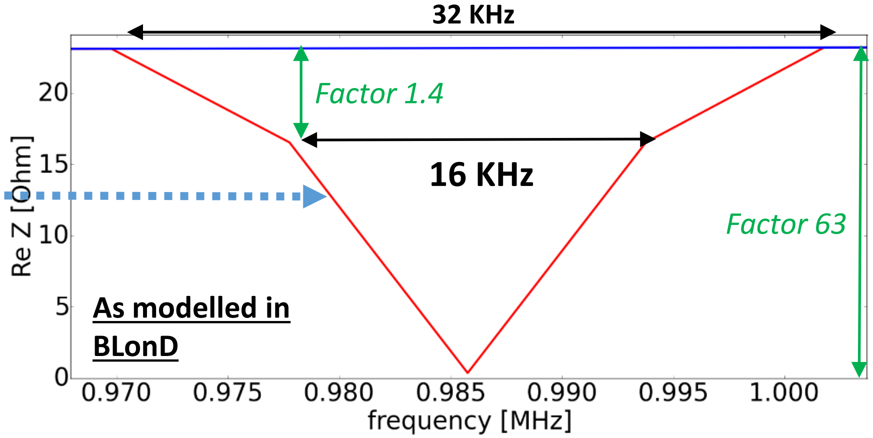


Courtesy M.E. Angoletta

MEASUREMENTS

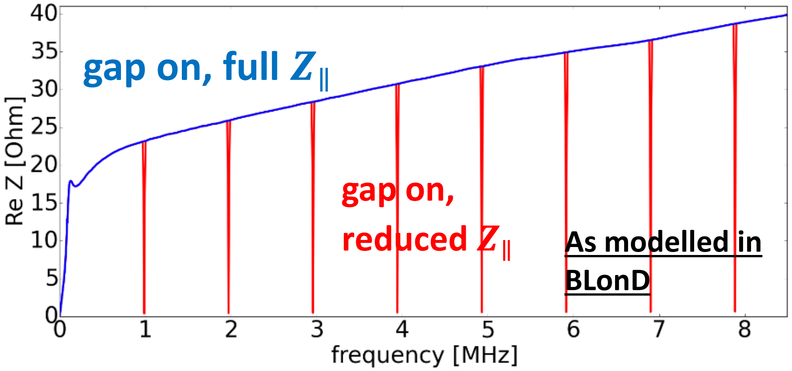
3 dB BW: ~ 16 kHz (double sided)

~ -36 dB reduction in cavity impedance



As modelled in BLonD

- ➢ Longitudinal harmonics affected: from 1 to 8 and maybe more

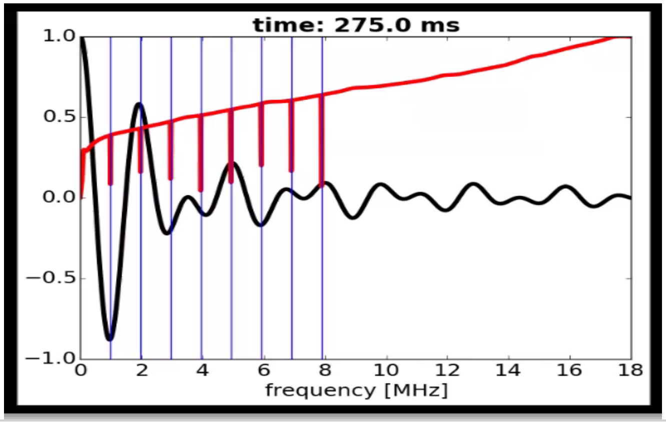


gap on, full $Z_{\parallel}$

gap on, reduced $Z_{\parallel}$

As modelled in BLonD

Finemet impedance at injection energy

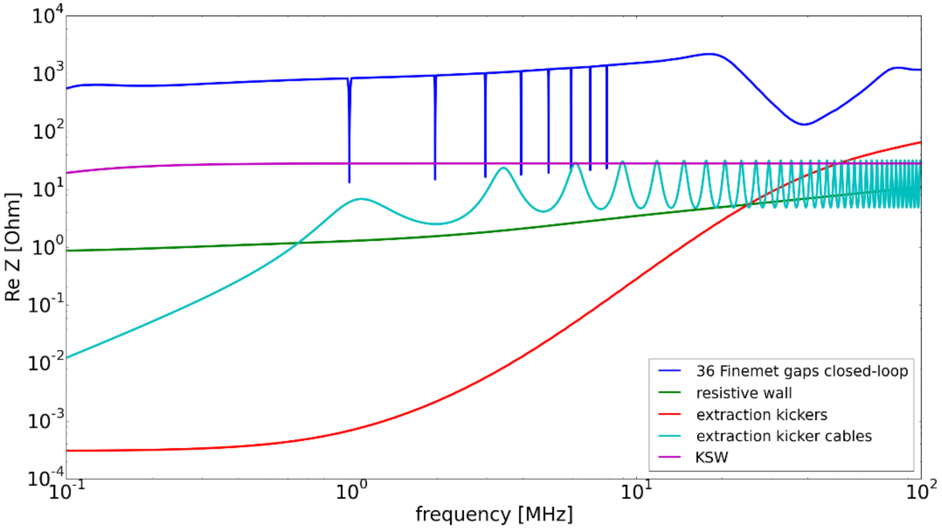


animation

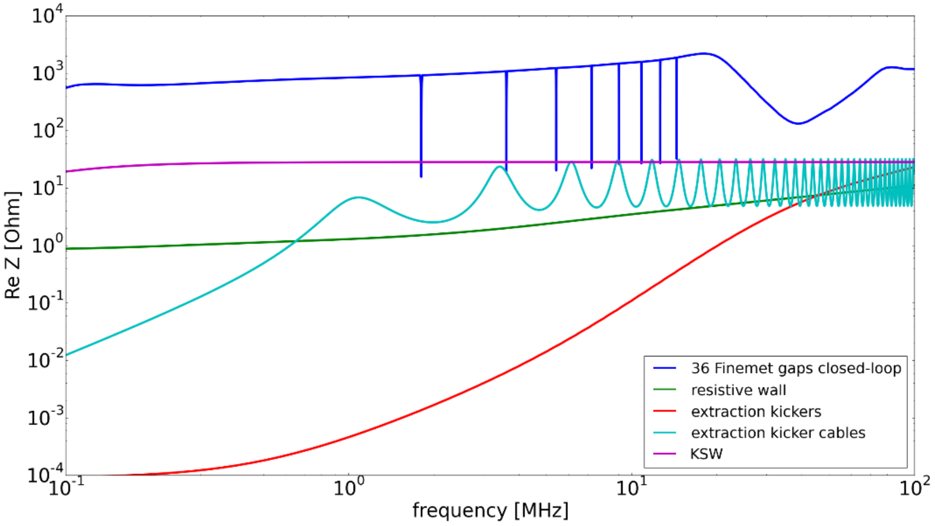
Finemet impedance and bunch spectrum during ramp

Complete PSB impedance model (real part in log scale)

@160 MeV



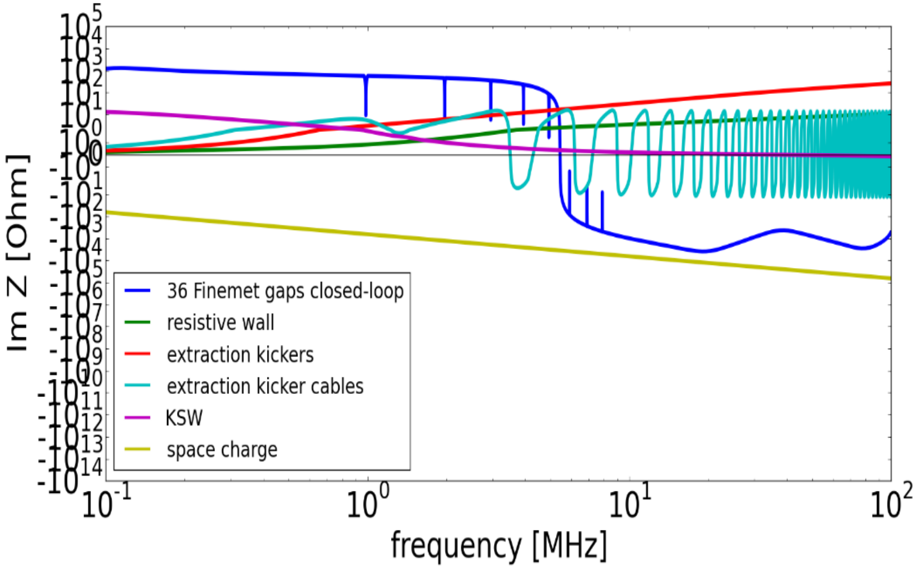
@ 2 GeV



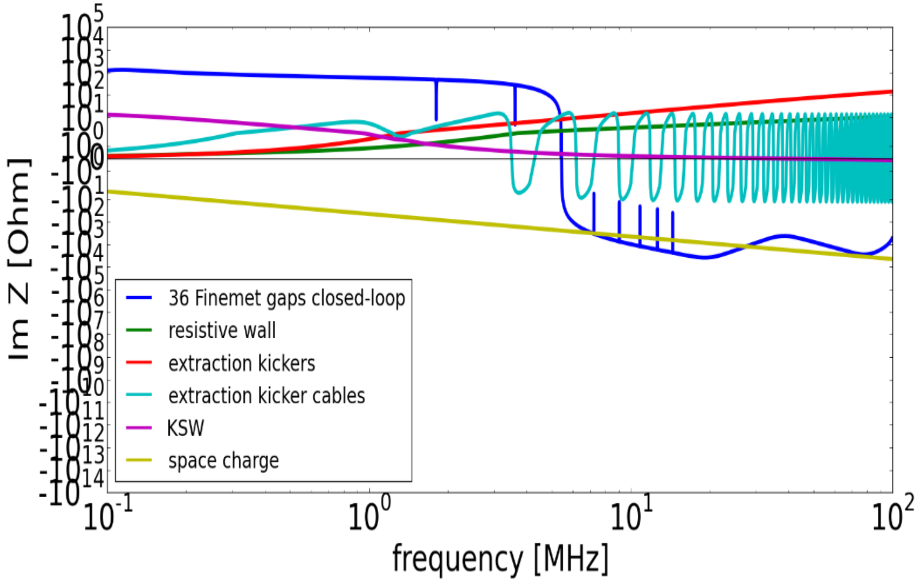
- The 36 gaps open-loop Finemet impedance dominates the other contributions
- **Importance of closed-loop impedance reduction:** impedance comparable to the other four contributions at the affected frequencies
- Simulations were done for $f < f_{max}$ = 100 MHz determined by available Finemet impedance measurements

Complete PSB impedance model (imaginary part in log scale)

@ 160 MeV

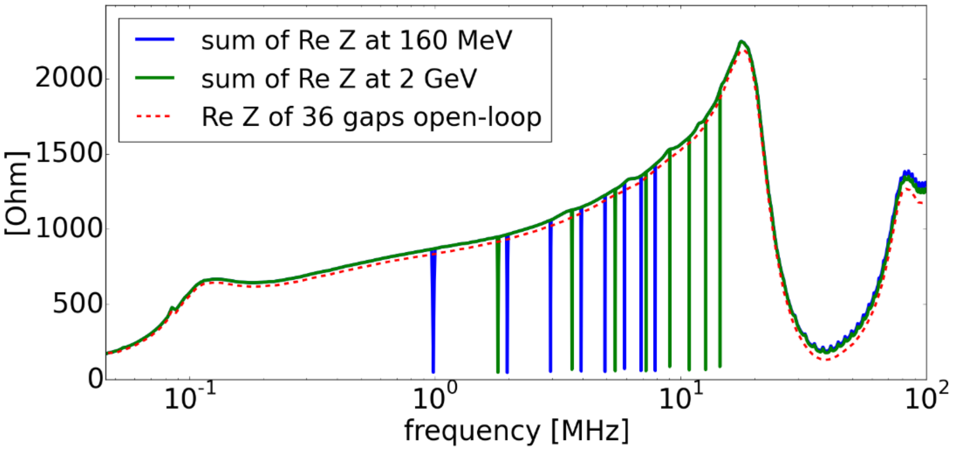


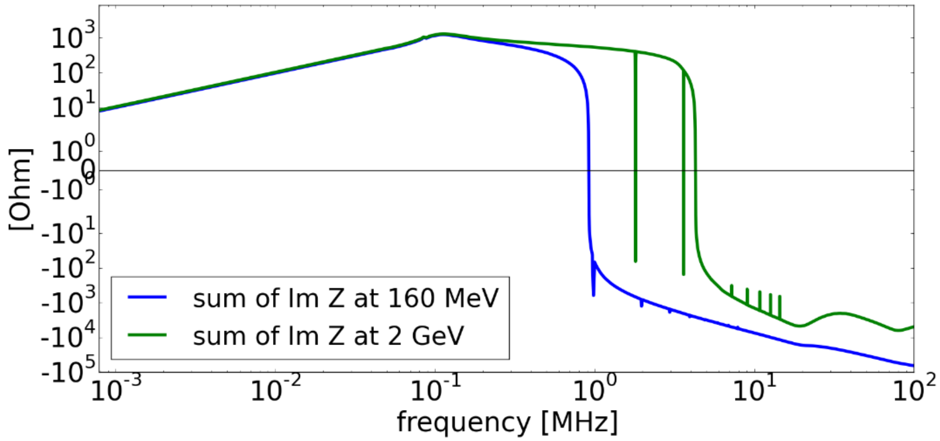
@ 2 GeV



- The space charge slope decreases by factor 8 at 2 GeV
- Again the closed-loop cavity feedback reduces the Finemet impedance to values comparable to the other contributions

Sum of all the impedances



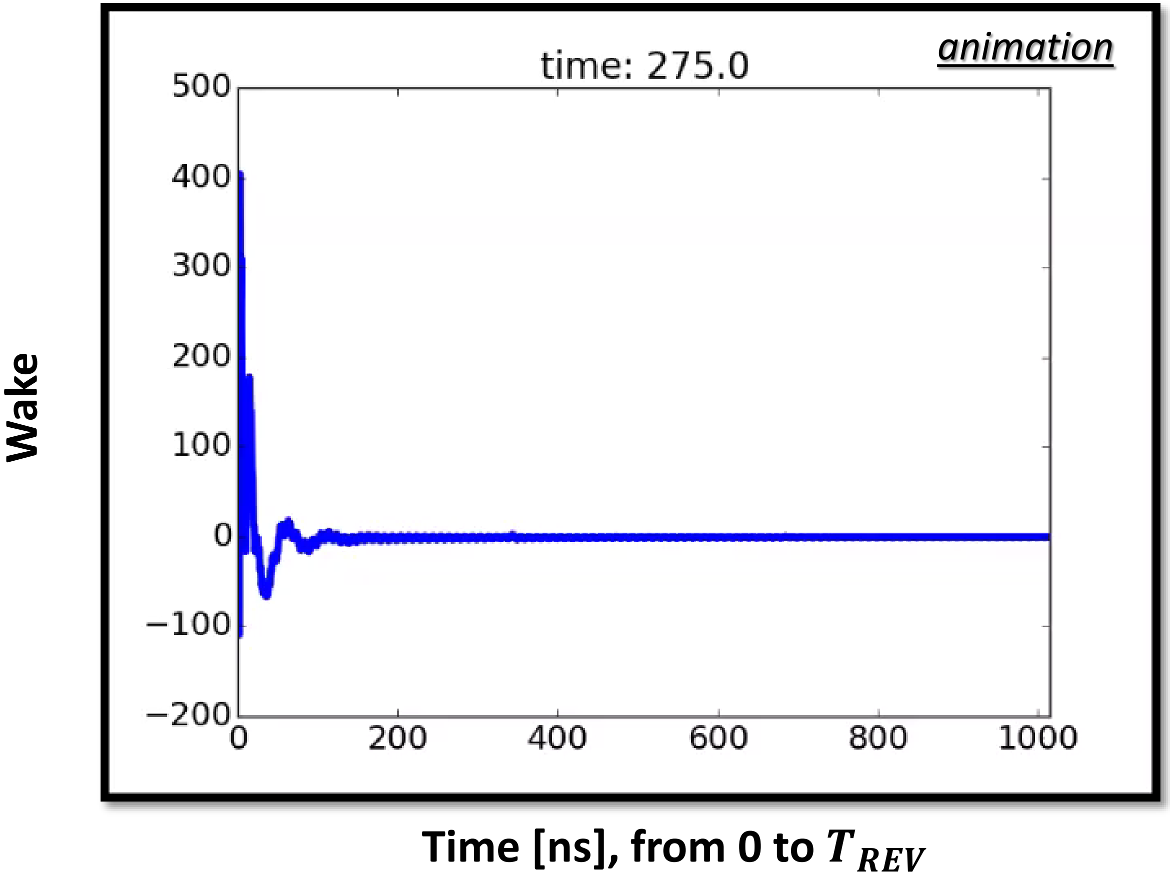


- ➢ The Finemet real part impedance dominates all the other contributions which can be considered as a 'perturbation' of it slightly dependent on energy

- ➢ At injection and extraction energies the space charge impedance dominates all the other components above ~1 MHz and ~4 MHz respectevely

PSB longitudinal wake

- Only one turn wake is important (unlike situation for ferrite cavities with wake lasting >100 turns)



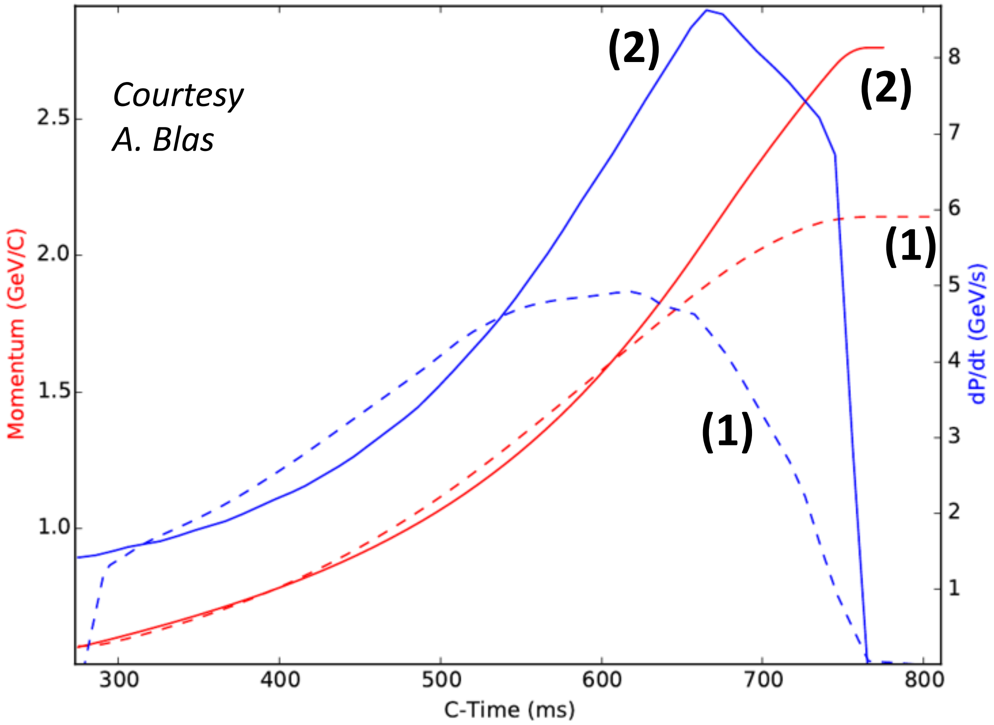
No Robinson instability mechanism and faster simulations (no memory wake)!

CONTENTS

- *Introduction*
- *The CERN BLonD code*
  - *Main features*
  - *Examples of benchmarking with measurements, other code and analytical formulas*
- *PSB impedance*
  - *Space charge*
  - *Other contributions*
- *Simulations*
  - *ISOLDE beam*
  - *HL-LHC beam*
    - *Double RF with different second harmonic voltages*
- *Conclusion*
- *References*

Cycles

Two different momentum programs



Courtesy
A. Blas

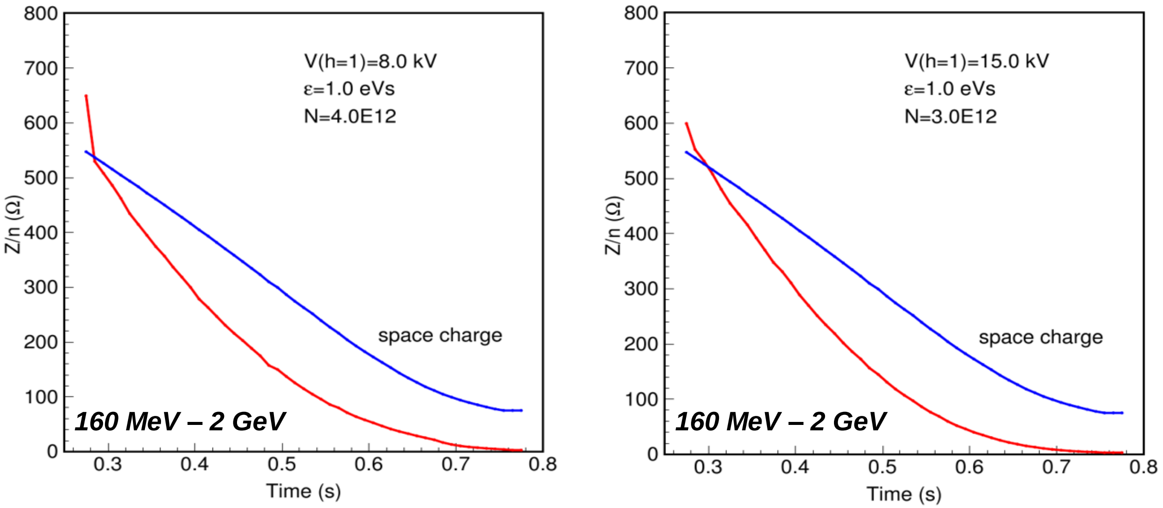
1. **160 MeV -> 1.4 GeV (ISOLDE)**
   - **N = 1.6e13 at injection**
     - Single RF: h=1, V=15 kV
     - Double RF: h=1, V=12 kV
       h=2, V=6 kV
2. **160 MeV -> 2 GeV (HL-LHC)**
   - **N = 3.6e12 at injection**
     - Single RF: h=1, V=8 kV
     - Double RF: h=1, V=8 kV
       h=2, V=4 kV

- *Cycle length = 1.2s (the same as now)*
- *Injection-extraction: C275 -> C775*
- *Faster acceleration than now for HL-LHC beams (and faster deceleration at the end)*
- *Injection at* $\dot{B}>0$

- No longitudinal painting at injection in simulations
- Bunch emittance = 1 eVs after filamentation
- Costant voltages along the ramp

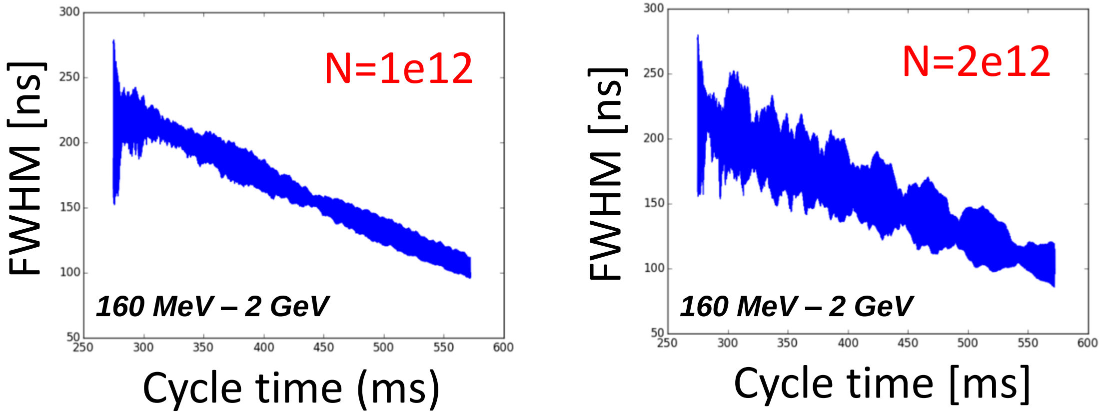
Landau damping in a single RF

- **Loss of Landau damping (LLD) in single RF for both HL-LHC and ISOLDE beams ISOLDE**



- ***Landau damping in a single RF is lost for the whole cycle above ~3e12***

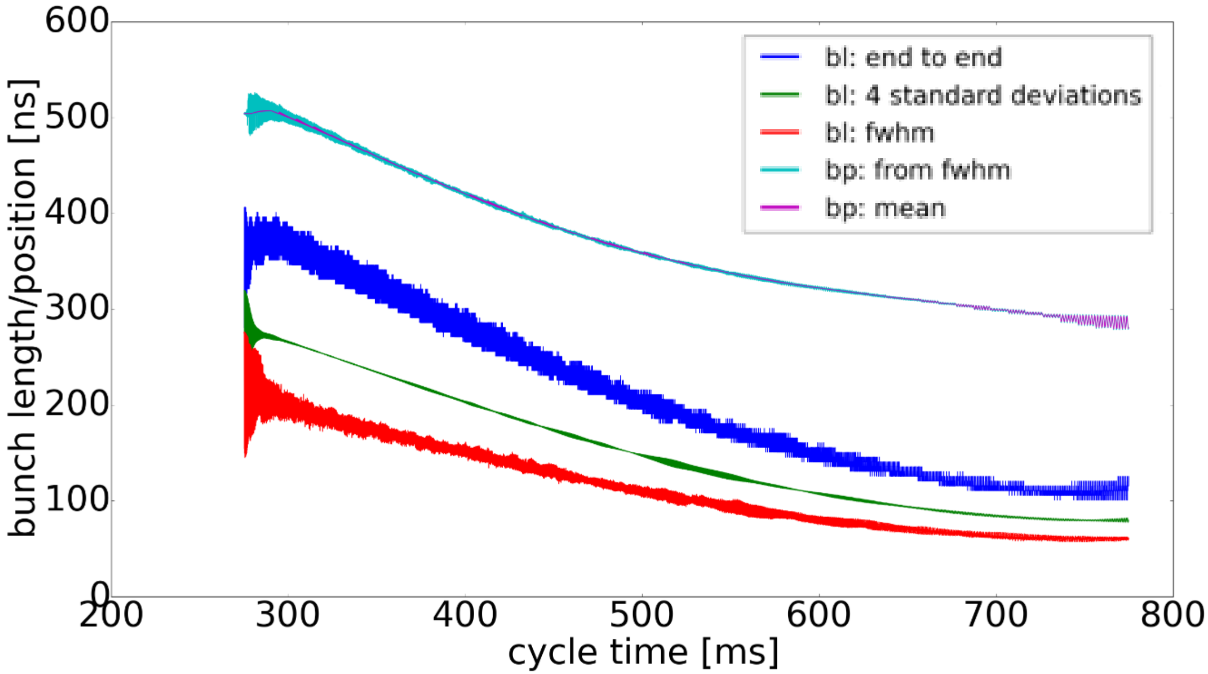
- **Simulations at 15 kV using a kick show Landau damping is lost between 1e12 and 2e12**



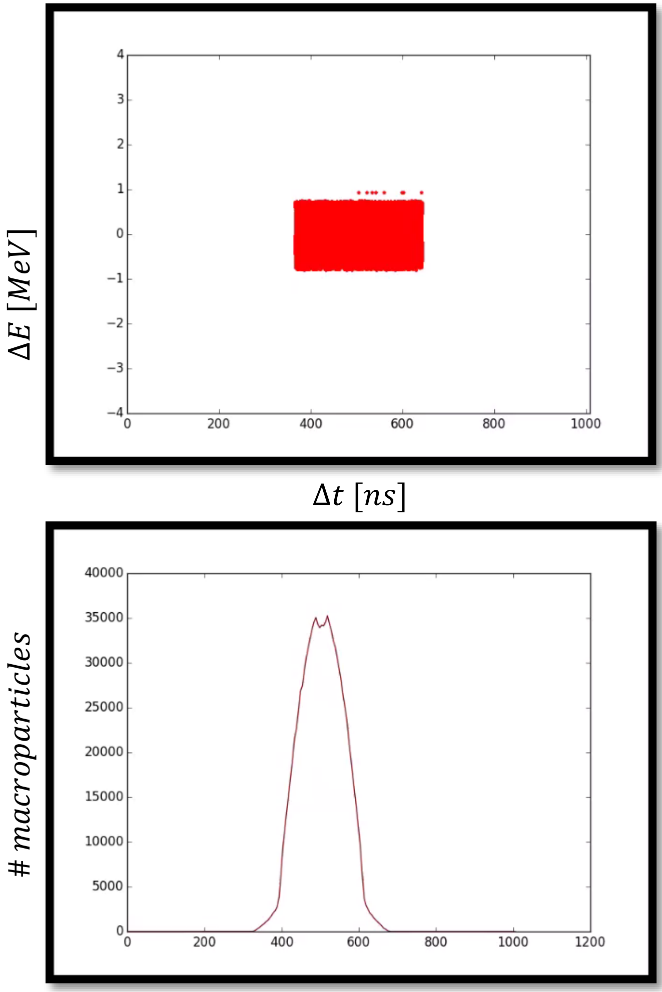
- ***Good agreement with analytical prediction***
- ***Oscillations will be damped by phase loop***

Simulations: ISOLDE beam in a single RF

15 kV, N=1.6e13



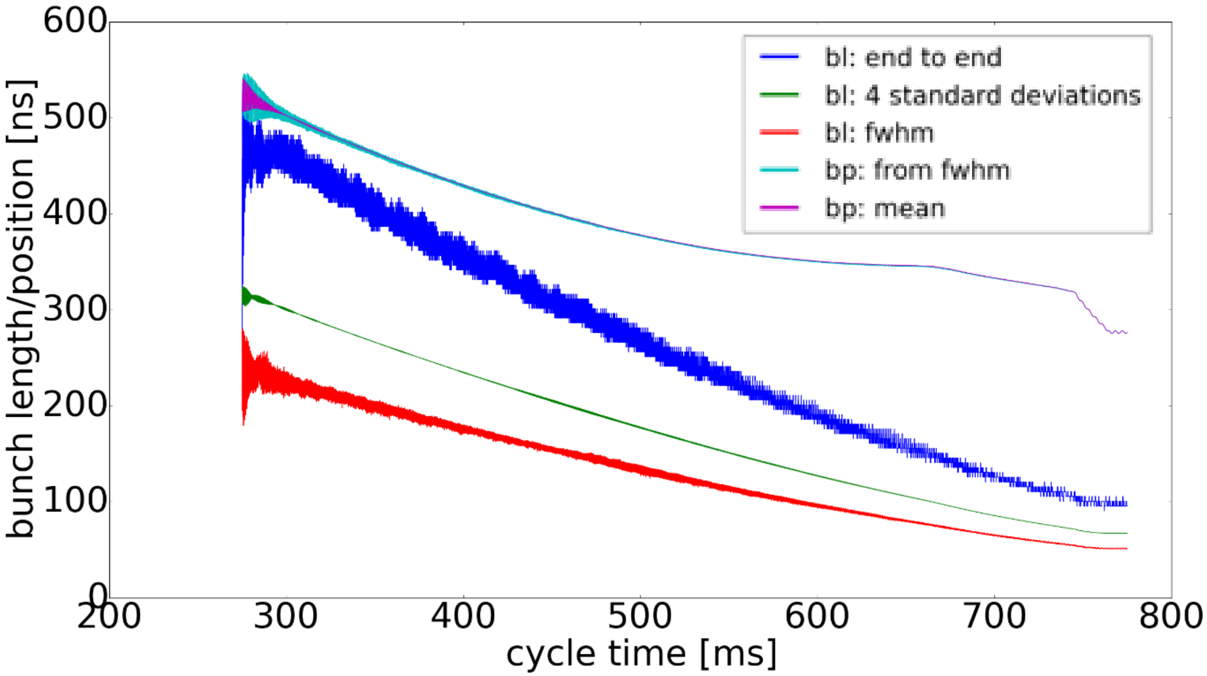
animations



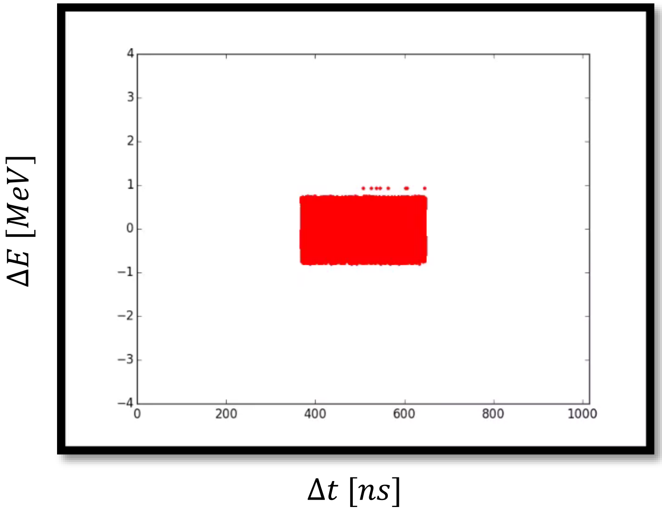
- ***Some dipole and quadrupole oscillations at the end of the ramp (noisy $\dot{B}$), but no losses***

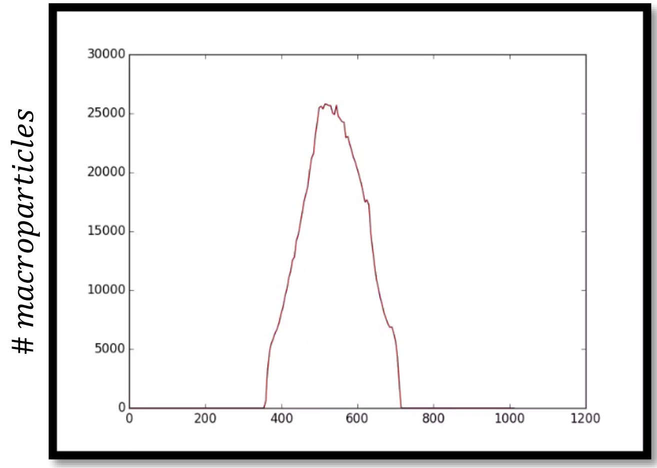
Simulation: HL-LHC beam in a single RF

8 kV, N = 3.6e12



animations

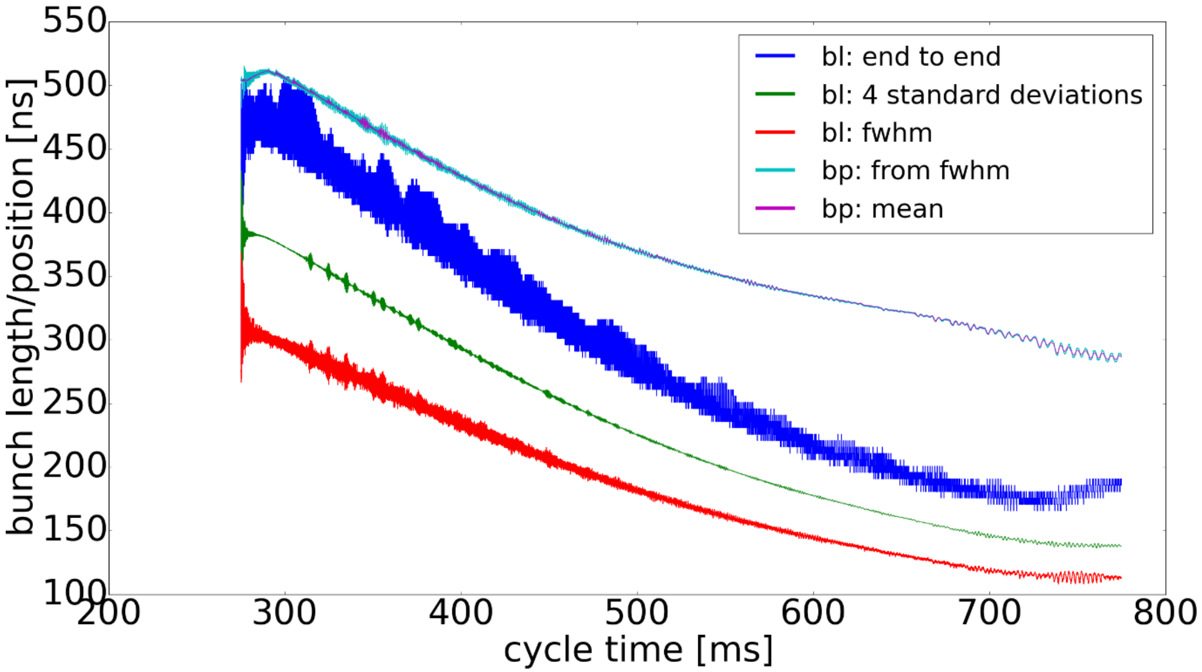




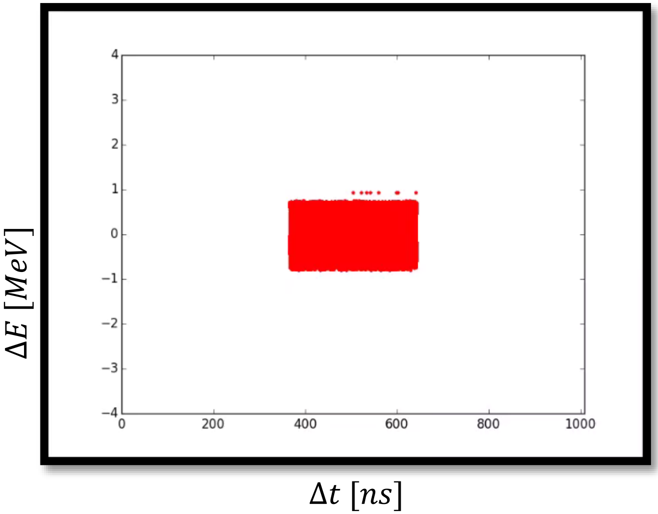
- ***No dipole and quadrupole oscillations (different $\dot{B}$ and lower intensity), also no losses***

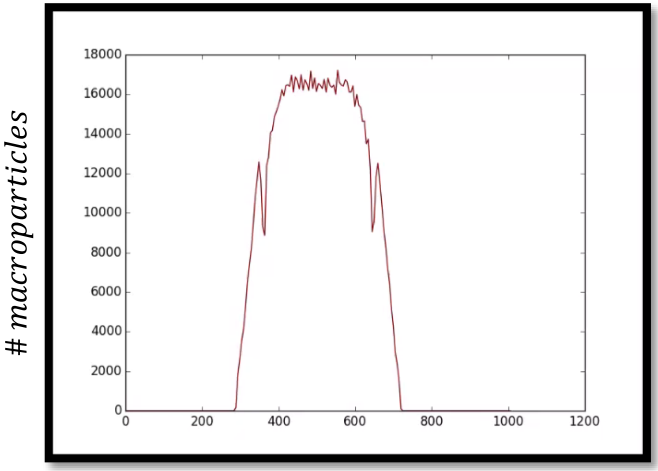
Simulation: ISOLDE beam in a double RF

12 kV + 6 kV, N = 1.6e13



animations

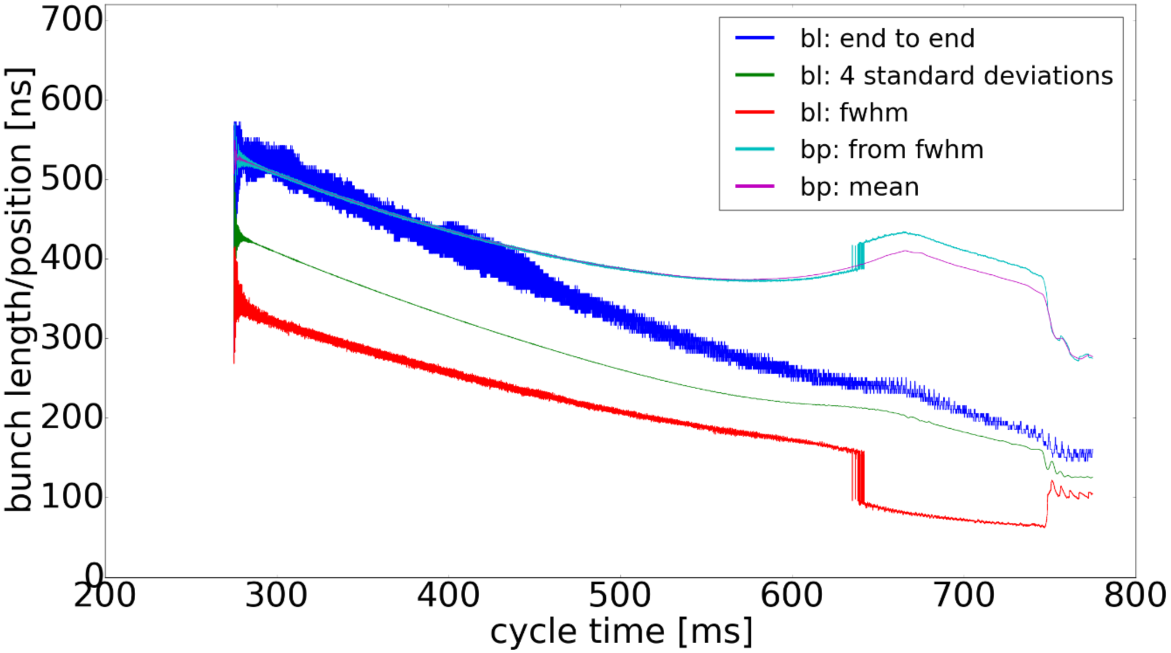




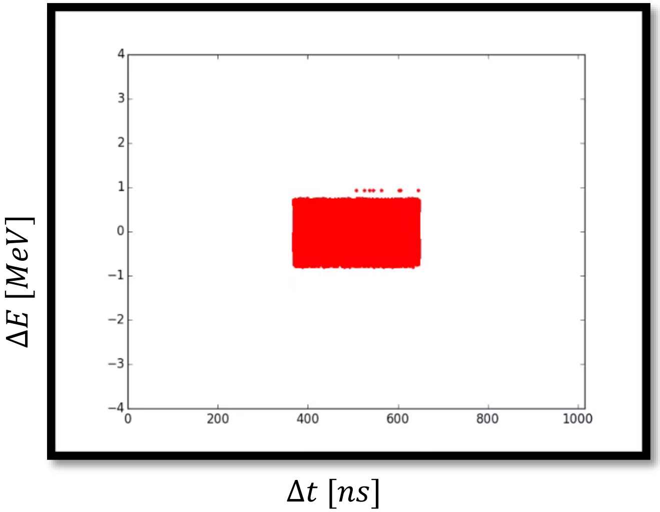
- ***Some dipole and quadrupole oscillations at the end of the ramp but no losses***
- ***Phase for bunch lengthening mode without considering intensity effects***

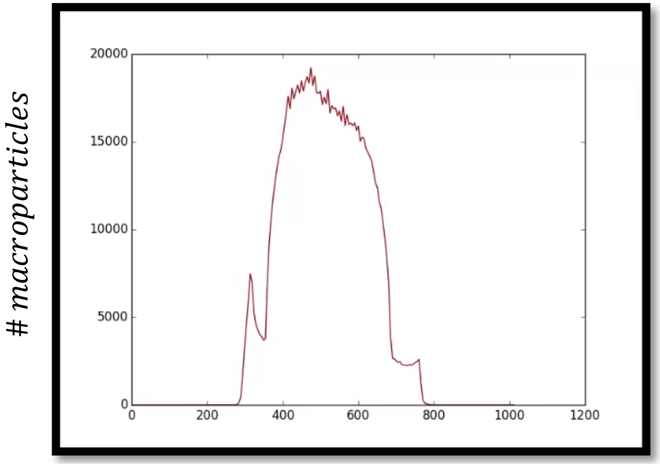
Simulation: HL-LHC beam double RF

8 kV + 4 kV, N = 3.6e12



animations



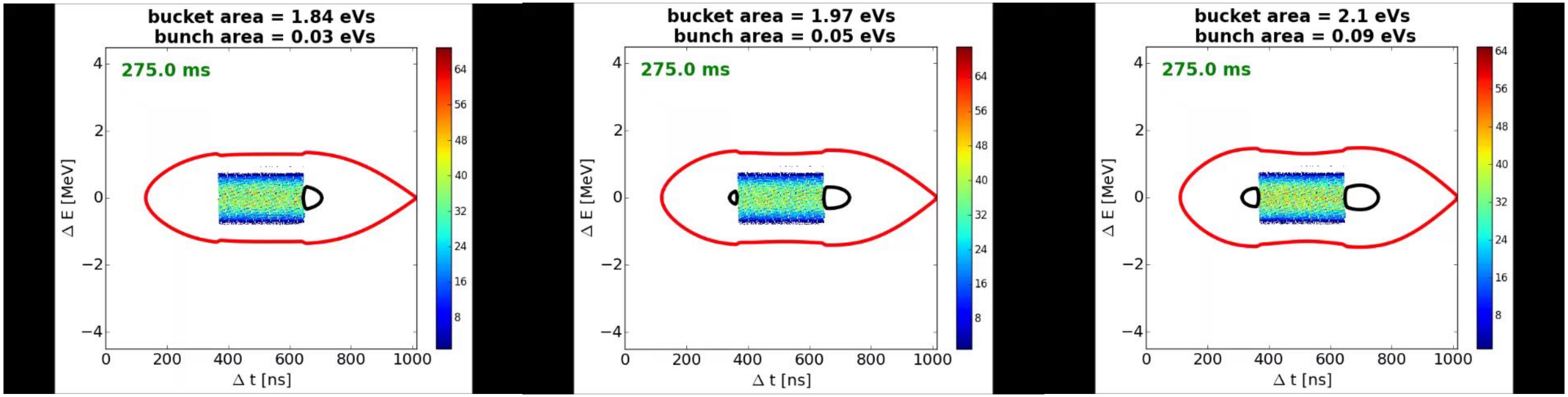


- ***Still no losses***
- ***Phase for bunch lengthening mode without considering intensity effects***
- ***High peak in line density and high deceleration at the end of the ramp produces strong filamentation***

HL-LHC beams in double RF

red => separatrix, black => Hamiltonian curve corresponding to matched bunch

V = 8 + 4 *animations* **V = 8 + 6** **V = 8 + 8**



- The second voltage starts to decrease linearly at C705
- Phase of second RF in bunch lengthening mode again creating peaks towards the end of the ramp leading to strong filamentation (also because of high deceleration)
- Bunch splitting and merging for the 8+6 and 8+8 cases; bunch emittance too small
- The bucket and bunch areas increase as the second harmonic voltage goes up
- No particle loss

Conclusion

- *The BLonD code has been developed at CERN and recently updated to low energy rings. It has been used to simulate longitudinal beam dynamics of the PSB beams in the Linac4 scenario*
- *Several benchmarks with measurements, analytical formulae and the PIC code PTC-PyOrbit give the code sufficient reliability*
- *The complete PSB longitudinal impedance model has been used with careful estimations of the dominant sources: space charge and Finemet impedances*
- *Simulations of HL-LHC and ISOLDE beams show no particle loss for maximum assumed intensities*
- *Dipole and quadruple oscillations at the end of the ISOLDE ramp maybe due to a noisy momentum program*

Next steps

- *Phase-loop in simulations*
- *Study of effect of noise in momentum program*
- *Double RF operation*
  - ❑ *phase optimisation through cycle taking into account intensity effects*
- *Study of controlled emittance blow-up*

References

1) *LHC Injectors Upgrade, Technical Design Report, Volume I: Protons, 2014*
2) *S. Albright, D. Quartullo and E. Shaposhnikova, Longitudinal beam stability in the PSB: Studies, simulations and measurements. Finemet Review, CERN, 2015*
3) *BLonD code, http://blond.web.cern.ch/*
4) *V. Forte, E. Benedetto, A. Lombardi, D. Quartullo, Longitudinal injection studies for the PSB at 160 MeV (to be published)*
5) *D. Quartullo, S. Albright and E. Shaposhnikova , Longitudinal dynamics simulations of CERN PS Booster beams in the Linac4 scenario, CERN-ACC-NOTE-2016 (to be published)*
6) *D. Quartullo and V. Forte, Longitudinal space charge simulations with BLonD at injection in the CERN PS Booster. EuCARD2/Xbeams Workshop on Space Charge, Oxford, 2015*
7) *L. Wang and W. Li, Analysis of the longitudinal space charge impedance of a round uniform beam inside parallel plates and rectangular chambers, PRST-AB, 2015*
8) *C. Zannini and G. Rumolo, Updated status of the PSB impedance model, MSWG, 2015*

LHC Injectors Upgrade

THANK YOU FOR YOUR ATTENTION!

CERN