Overview of Longitudinal Beam Dynamics Simulations in the PSB

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Acknowledgements: *S. Albright, M. A. Angoletta, A. Findlay, M. Migliorati, M. Paoluzzi, E. Shaposhnikova, H. Timko and the BLonD team*

Contents

Motivation for studies

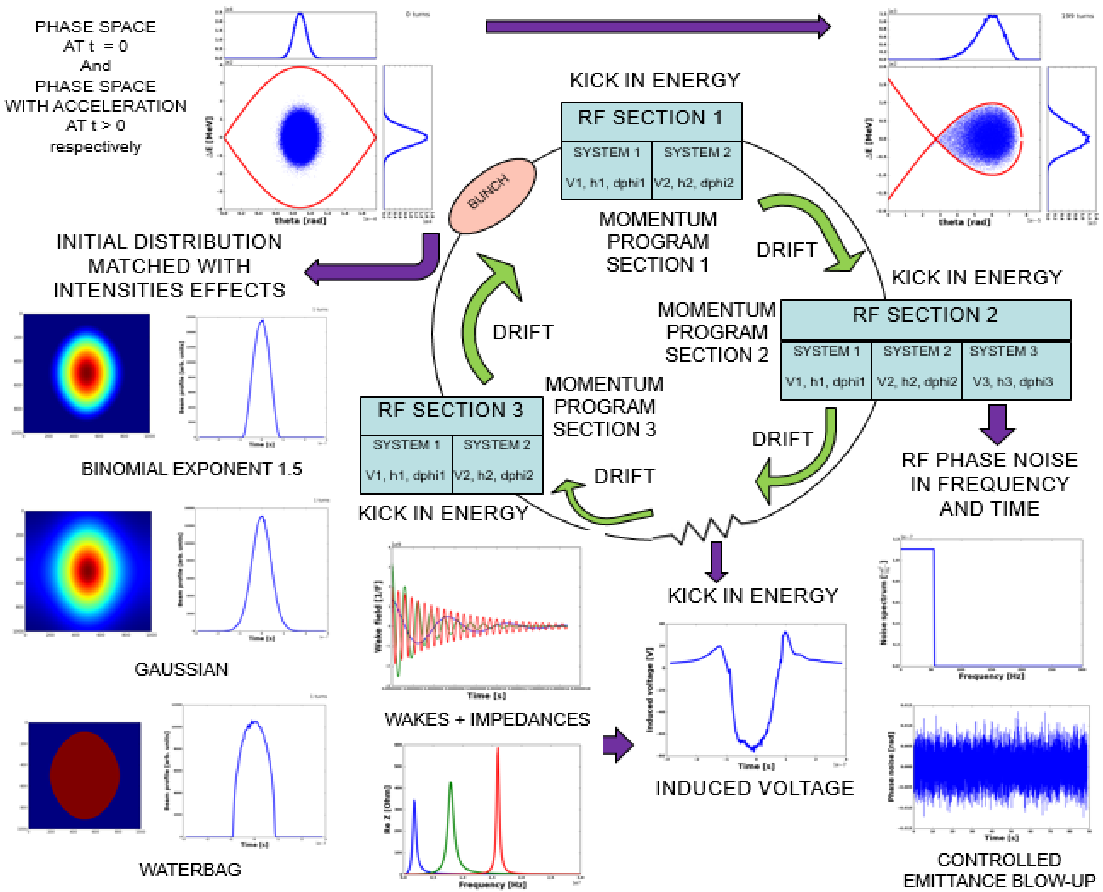
- Main changes in the PSB after LS2 affecting the longitudinal beam dynamics:
  - ➢ Higher injection energy (LINAC4) and different injection schemes.
  - ➢ Higher extraction energy (new magnet power supplies).
  - ➢ Higher acceleration rate (higher extraction energy).
  - ➢ Higher beam intensities (~2 for LHC beam)
  - ➢ New momentum programs.
  - ➢ New RF systems.
  - ➢ Different space charge effect and PSB impedance model.
  - ➢ Larger controlled longitudinal emittance blow-up required for the PS.

BLonD main features (1/2)

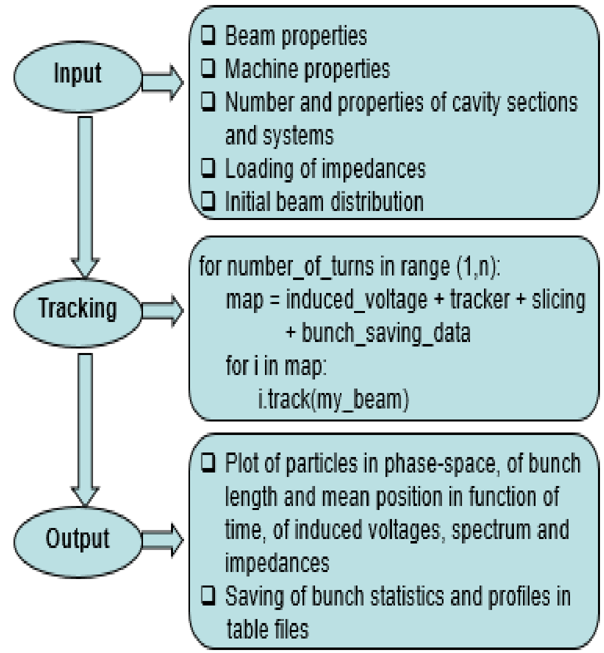
- BLonD is a Beam Longitudinal Dynamics simulation code for synchrotrons developed at CERN in the RF group: https://blond.web.cern.ch/
- All machines in the LHC injection chain have been simulated with BLonD (SPS was the first one, Refs [1], [2]).
- Main features:
  - Python and C++
  - Single and multi-bunch options
  - Acceleration, multiple RF systems, multiple RF stations in the ring
  - Various RF manipulations (splitting, rotation, slip-stacking…)
  - Collective effects in frequency and time domain (multi-turn wakes)
  - Ring periodicity
  - Low-power level RF options (loops, beam and cavity-based feedbacks...)
  - Emittance BUP with phase noise or modulation
  - Monitoring, plotting, data analysis

BLonD main features (2/2)

♦ Example of model adopted and code capabilities



♦ Code diagram



Longitudinal equations of motion

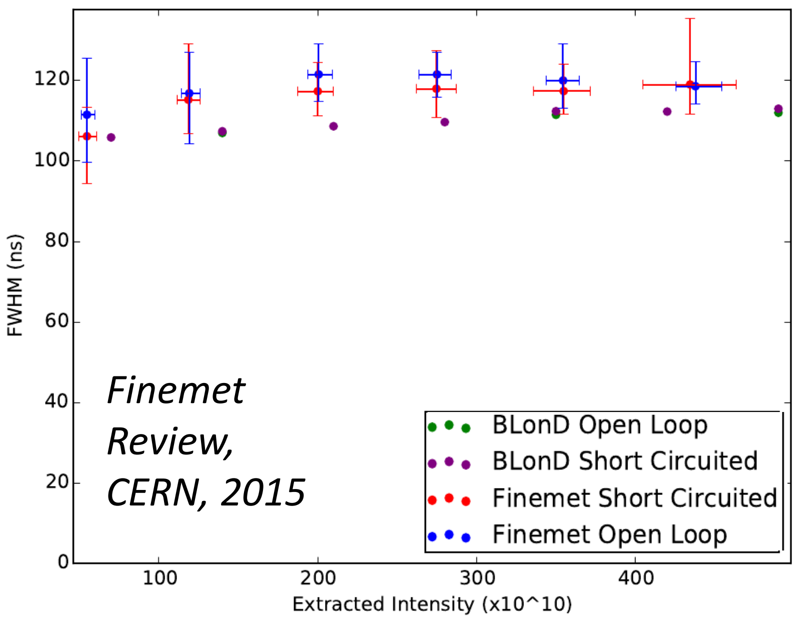
$$\Delta E^{(n+1)} = \Delta E^{(n)} + q \sum_i V_i \sin\left(\omega_{i,rf}^{(n)} \Delta t^{(n)} + \varphi_{i,rf}^{(n)}\right) - \beta_s^{(n+1)} c \left(p_s^{(n+1)} - p_s^{(n)}\right) + E_{ind}^{(n)}(\Delta t^{(n)})$$

$$\Delta t^{(n+1)} = \Delta t^{(n)} + T_{rev}^{(n+1)} \eta^{(n+1)} \delta^{(n+1)} \qquad \delta \doteq \frac{\Delta p}{p_s} = \frac{\Delta E}{\beta_s^2 E_s} \qquad \Delta E^{(n)} \doteq E^{(n)} - E_s^{(n)} \qquad \Delta t^{(n)} \doteq t^{(n)} - \sum_{k=1}^{n} T_{rev}^{(n)}$$

Examples of benchmarking: with measurements

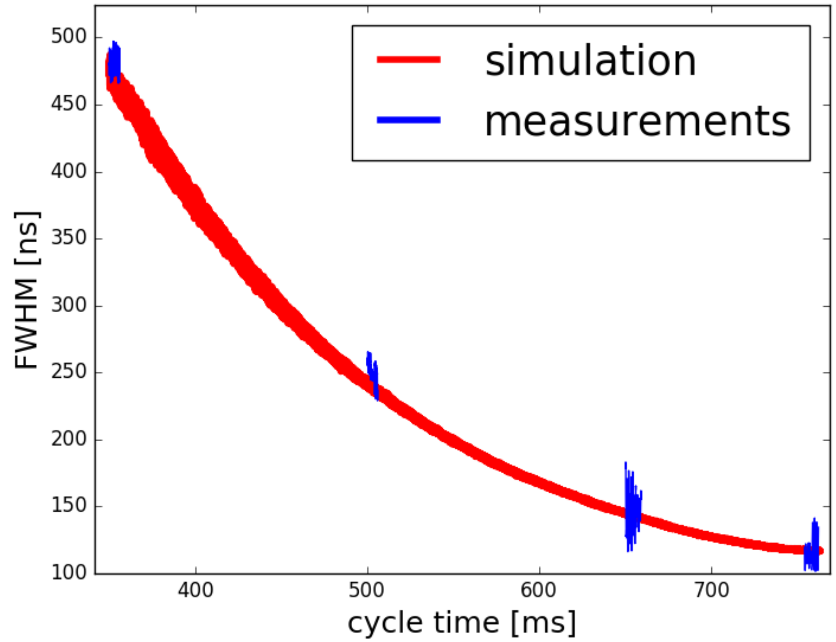
- Comparison with PSB measurements => **good agreement**

Bunch length at PSB extraction



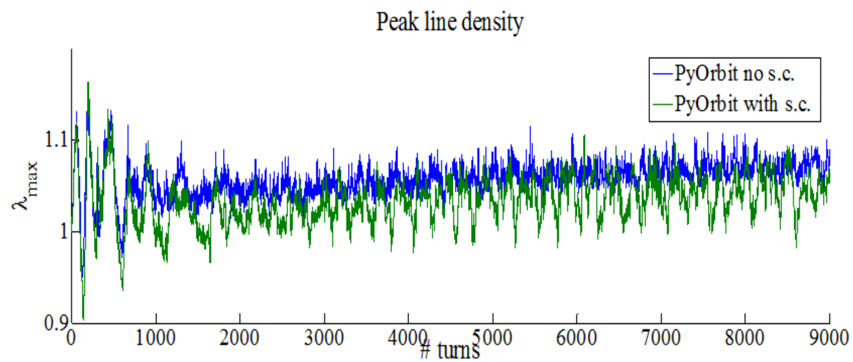
FWHM bunch length for various intensities based on full ramp simulation

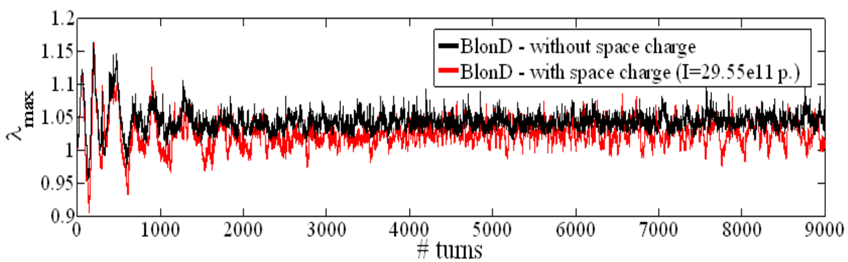
Bunch length during ramp, $N = 5 \times 10^{12}$

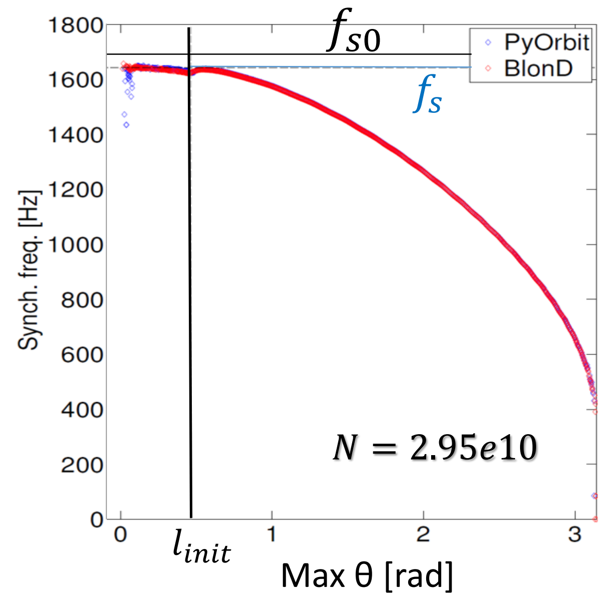


Acceleration in single RF with full impedance model. Measurements: significant shot-to-shot variations in bunch length.

Examples of benchmarking: with another code PTC-PyOrbit







PSB simulations at 160 MeV with space charge in a double RF system
⇒ ***Also good agreement***

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

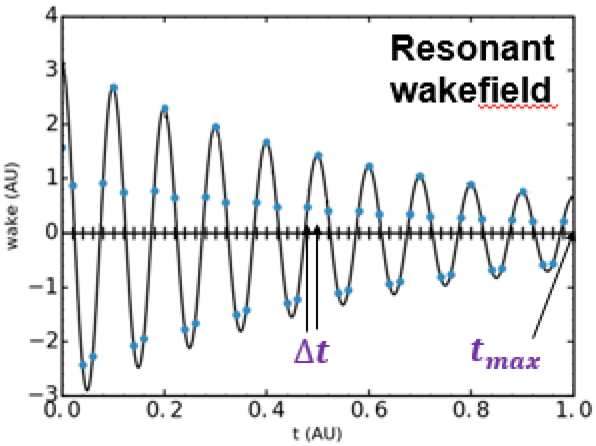
Syncrotron frequency distribution for a matched parabolic bunch with space charge below transition
=> ***Perfect agreement***

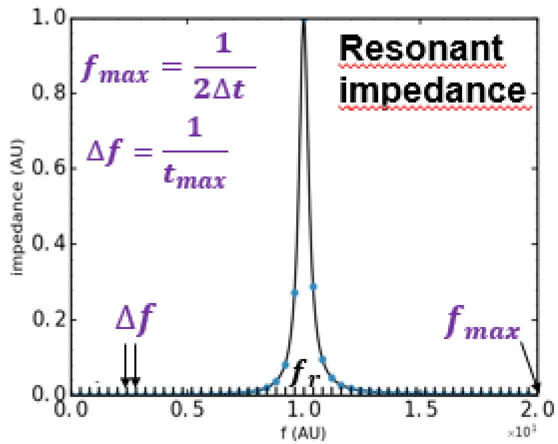
Refs [3], [4]

Examples of benchmarking: with Music code (1/3)

- BLonD and MuSiC (M. Migliorati' code) similarities:
  - Macro-particle models used to treat high number of particles
  - Same longitudinal equations of motion for single-particle dynamics

- BLonD and MuSiC differences:
  - MuSiC calculates the exact V_{ind} in time domain from wakes generated by resonant impedances. Only parameter: # macroparticles N_M
  - Slicing of the beam profile in BLonD, V_{ind} in time or frequency domain. Parameters: N_M, f_{max} (or Δt), Δf (or t_{max}).





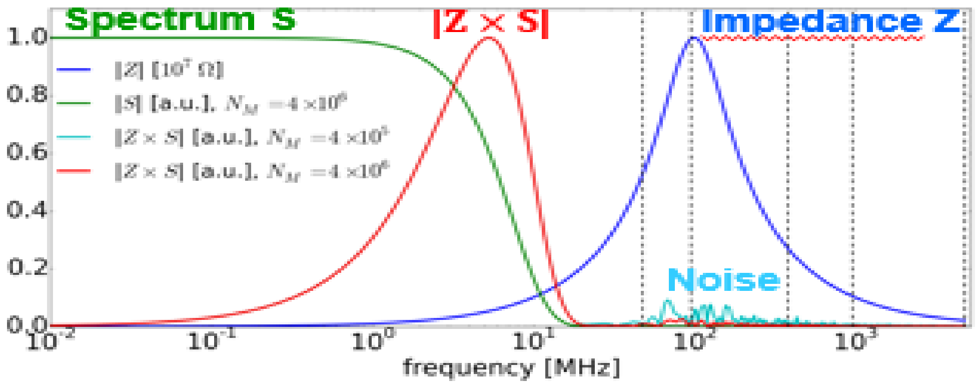
$$V_{ind}(\phi_i) = \frac{Q_{tot}}{N_M} \sum_{j=1}^{N_M} w_{\parallel}(\phi_i - \phi_j)$$

Total charge; Number of macro-particles; Longitudinal coordinate; Single particle longitudinal wake

Refs [5], [6]

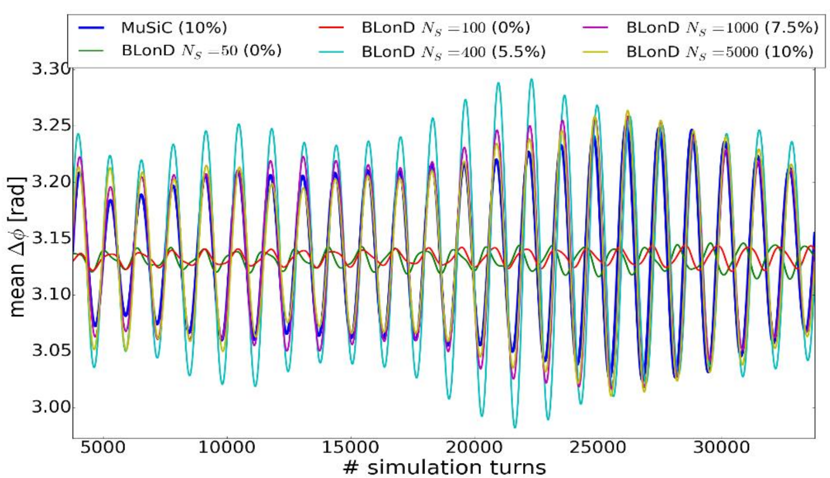
Examples of benchmarking: with Music code (2/3)

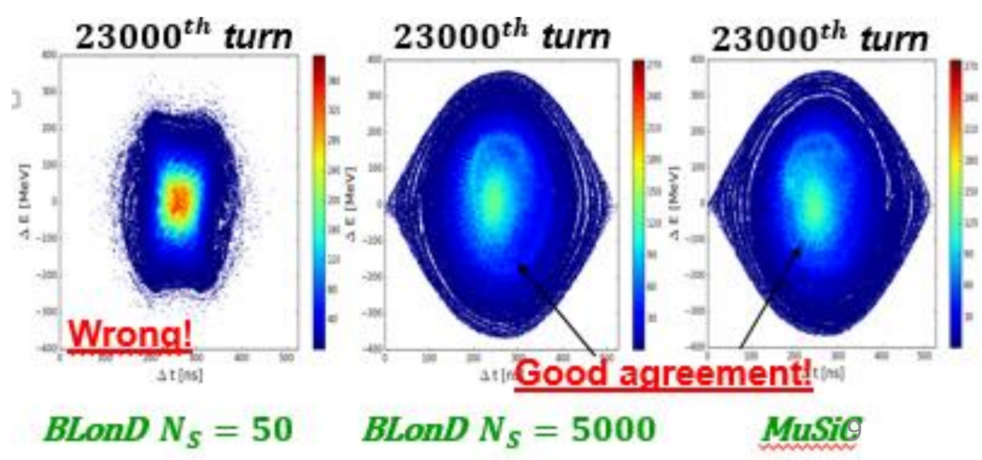
- **FIRST EXAMPLE: short-range wake field**
  - ➢ Broad-band resonator impedance with f_r higher than the bunch spectrum cut-off frequency is difficult to simulate in BLonD: fixed N_M, physical contributions are lost if f_{max} is too low and noise is included if f_{max} is too high.



- ➢ With high intensity effects: simulations should show filamentation, possible losses and later equilibrium in phase space.

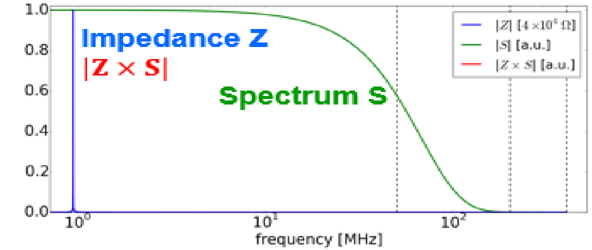
- **RESULTS (BLonD in frequency domain):**





Examples of benchmarking: with Music code (3/3)

- **SECOND EXAMPLE: long-range wake field**
  - Narrow-band resonator impedance with f_r lower than the bunch spectrum cut-off frequency is difficult to simulate in BLonD: wakefield can couple multiple revolution turns and f_{max} and Δf (or Δt and t_{max}) are not easily defined.



- **If $f_r = pf_0 + mf_s, p \in \mathbb{N}, m \in \mathbb{Z}$, then Robinson instability** can be observed.

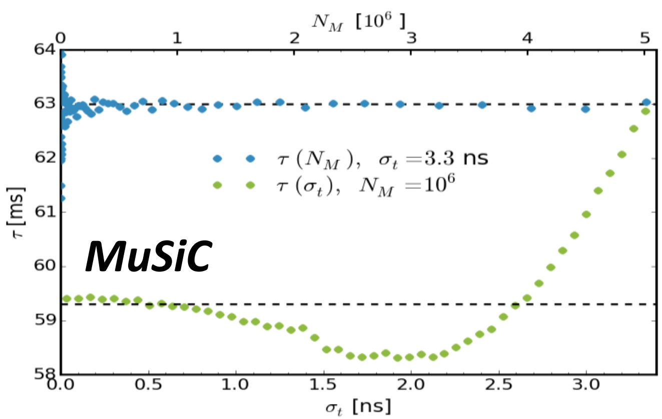
- **Growth-rate for a Gaussian bunch:**

$$\frac{1}{\tau_a} = \frac{-\pi\eta e^2 N_P}{E_0 T_0^2 \omega_s} \sum_{m=\pm 1} m\, x\, \mathrm{ReZ}(x) G_m(x\sigma_t)$$

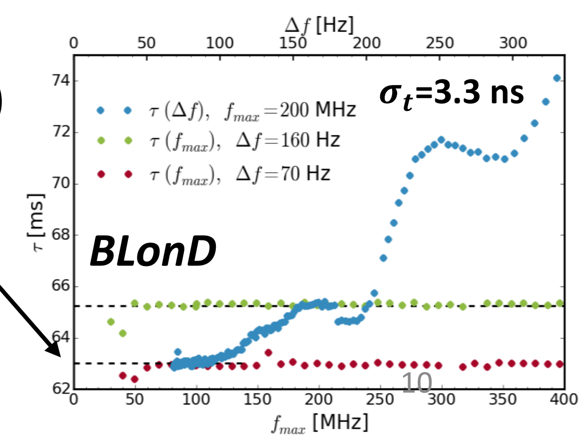
Form factor / *Modified Bessel function of first kind*

$$G_m(s) = \frac{2e^{-s^2}}{s^2} I_m(s^2) \qquad x = pf_0 + mf_s$$

- $\tau_a \approx$ **59.3 ms** and the instability growth time τ from MuSiC and BLonD should converge to τ_a for short bunches (no Landau damping effect).



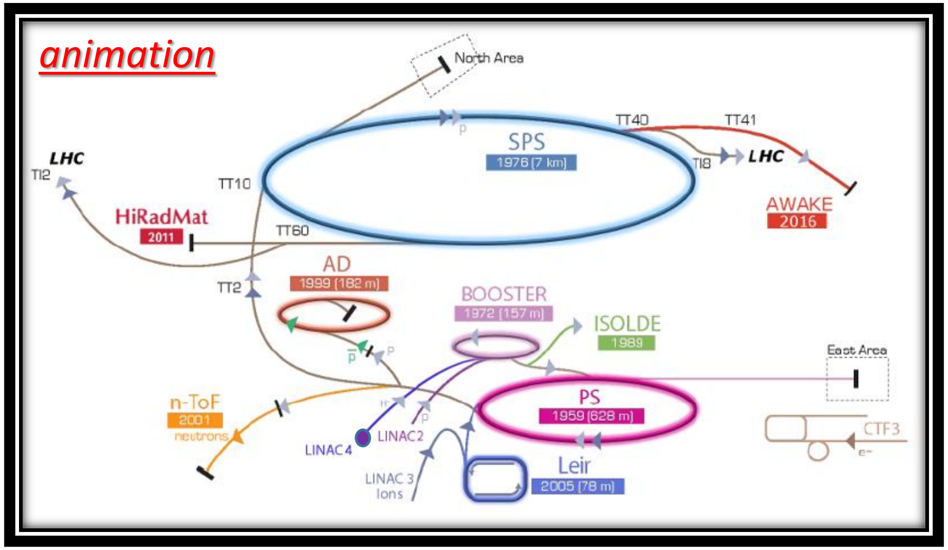
RESULTS (BLonD time domain)
=> Good agreement



Contents

PSB parameters under study

- Situation after LS2:
  - Injection kinetic energy: 50 MeV => 160 MeV
  - Extraction kinetic energy: 1.4 GeV (ISOLDE) or 2 GeV (HL-LHC), now 1.4 GeV
  - Same cycle duration as now (1.2 s) => Higher acceleration rate
  - RF systems: narrow-band ferrite => broad-band Finemet (Refs [7], [8], [9])
- Longitudinal simulations to predict beam stability: (Refs [10], [11], [12], [13])
  - Realistic impedance model (cavities, ...)
  - Reliable estimation of space charge (dominant impedance source)
  - Realistic LLRF feedbacks modeling
  - h=1 or h=1 & h=2



Relevant PSB parameters after LS2

E_{kin}: 160 MeV → 1.4 GeV → 2 GeV
β: 0.52 → 0.92 → 0.95
γ: 1.17 → 2.49 → 3.13
T_{rev}: 1008 ns → 570 ns → 552 ns
f_{rev}: 0.99 MHz → 1.75 MHz → 1.81 MHz
$f_{sync}^{V=8kV}$: 1.68 KHz → 0.41 KHz → 0.26 KHz

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

$\sigma_{x,y} \approx 5.5$ 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!

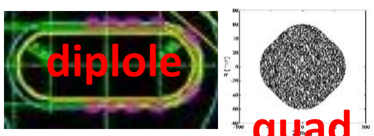
Ref [14]

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

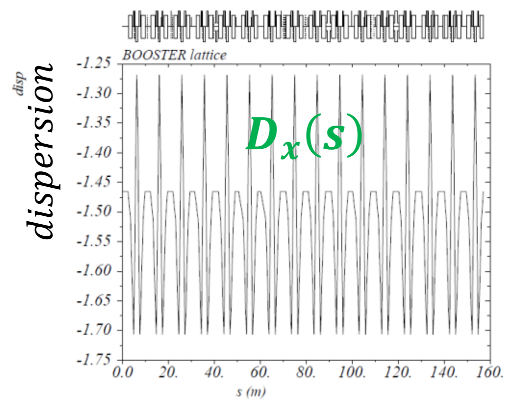
$$\nabla^2 \boldsymbol{E} - \frac{1}{c^2}\frac{\partial \boldsymbol{E}}{\partial t} = \frac{\nabla\rho}{\varepsilon_0} + \mu_0 \frac{\partial \boldsymbol{J}}{\partial t}$$

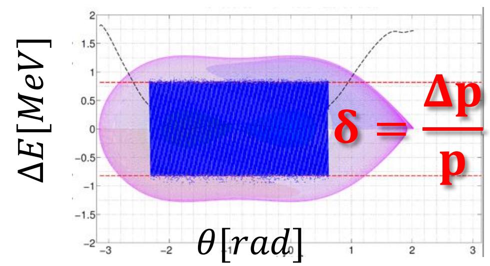
LSC

OUTPUT:

- Z/L averaged over 1 σ

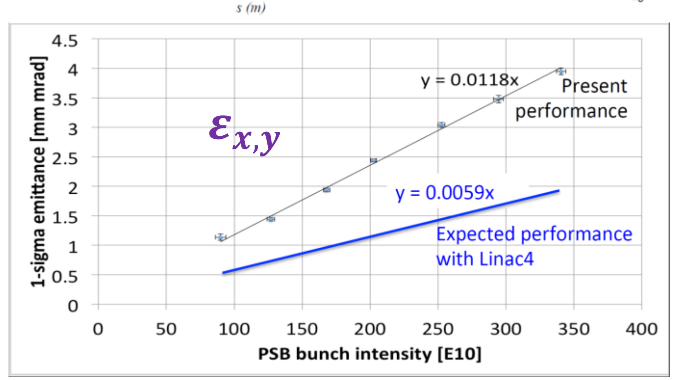
$$\frac{Z}{n} = \sum_{i=1}^{211} L_i \left(\frac{Z}{n\,L}\right)_i = \mathbf{633.14\ \Omega}$$

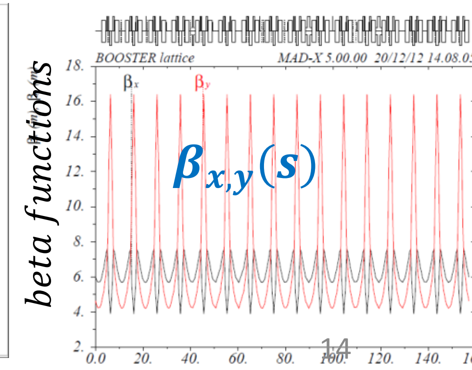




$$\sigma_x(s) = \sqrt{\varepsilon_x\, \beta_x(s) + D_x^2(s)\delta^2}$$

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



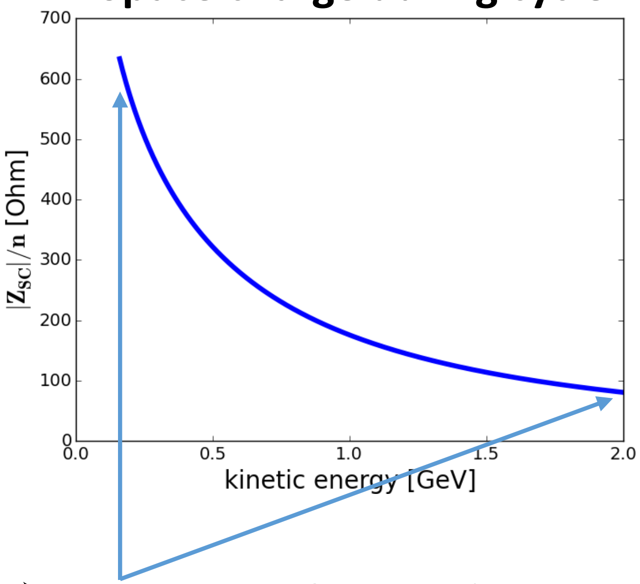


Space charge impedance during cycle

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

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

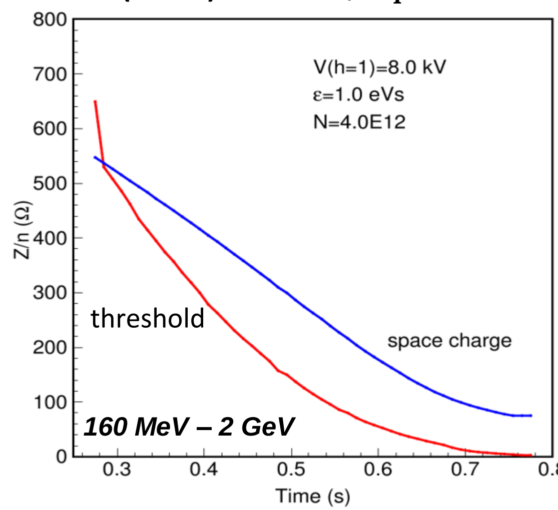
Space charge during cycle



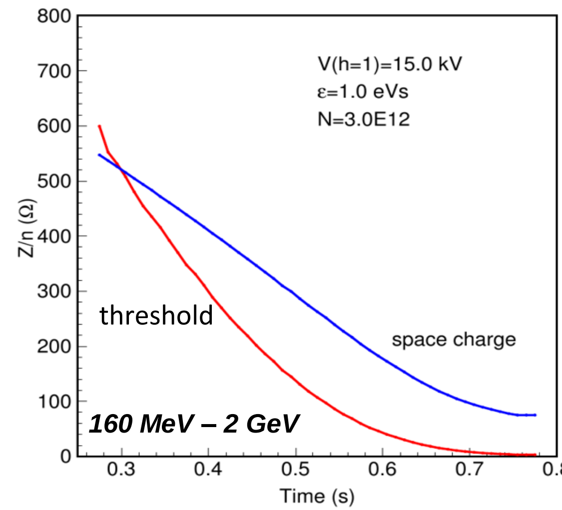
- ***Factor 8 reduction*** *during cycle, but the SC effect is in fact increased due to bunch length shrinking!*

Loss of Landau damping in a single RF for HL-LHC beams

V(h=1) = 8 kV, ε_l = 1 eVs



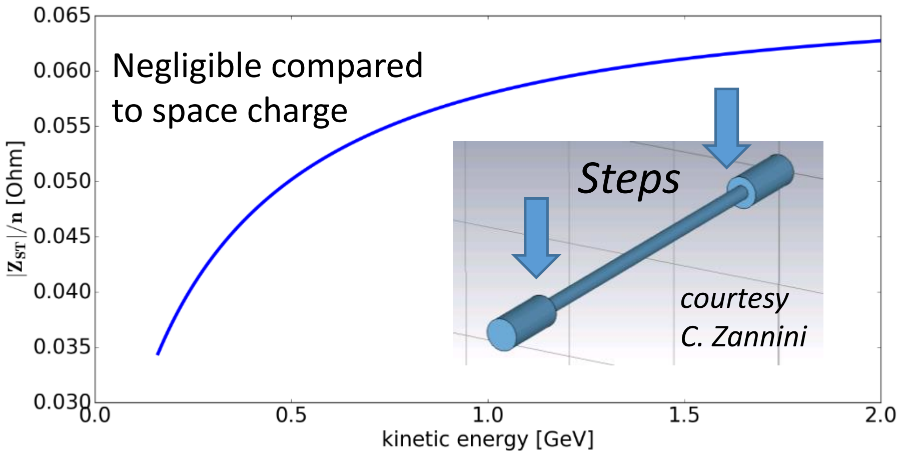
V(h=1) = 15 kV, ε_l = 1 eVs

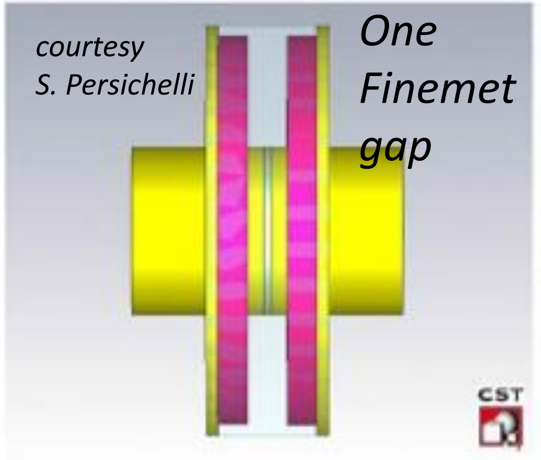


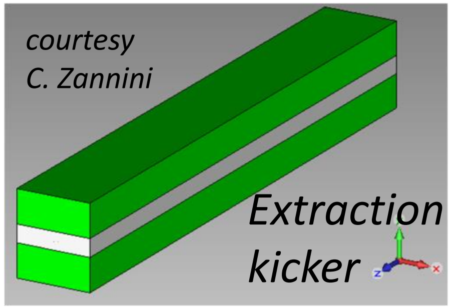
- ***Landau damping in a single RF is lost*** *for the whole cycle above ~3e12*
- *Dipole oscillations will be probably damped by phase loop*

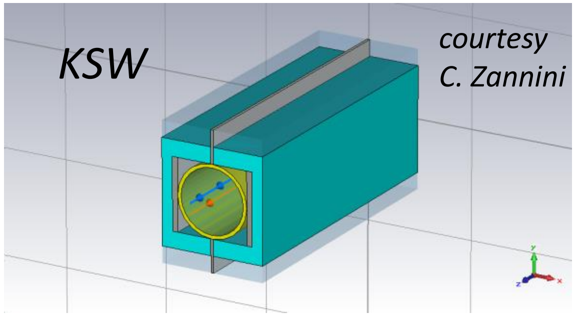
PSB impedance model

- Includes space charge and
  - Finemet cavities
  - Extraction kickers
  - Extraction kicker cables
  - KSW magnets
  - Resistive wall
  - Steps (beam pipe discontinuities)
- Impedances in red depend on the beam energy.





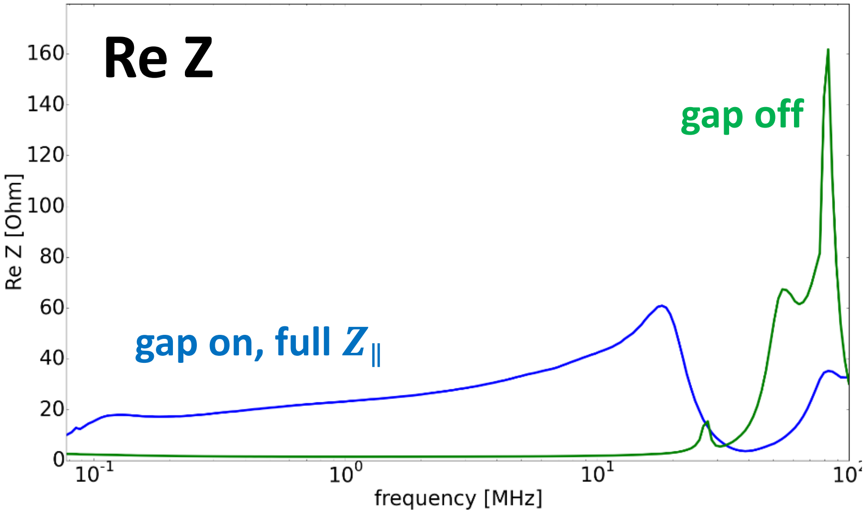


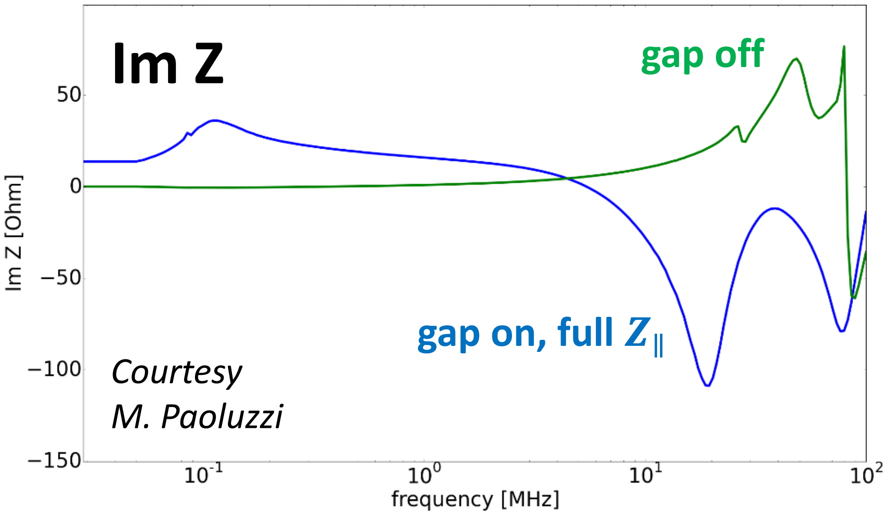


Space charge and Finemet cavities are the main impedance sources.

Finemet cavity impedance

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

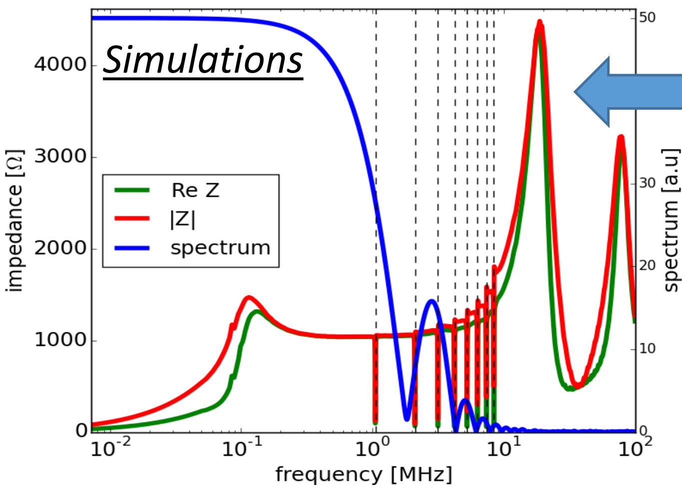




- f_{rev} varies from 0.99 MHz to 1.81 MHz → short-circuited impedance is very small in beam-spectrum range of frequencies

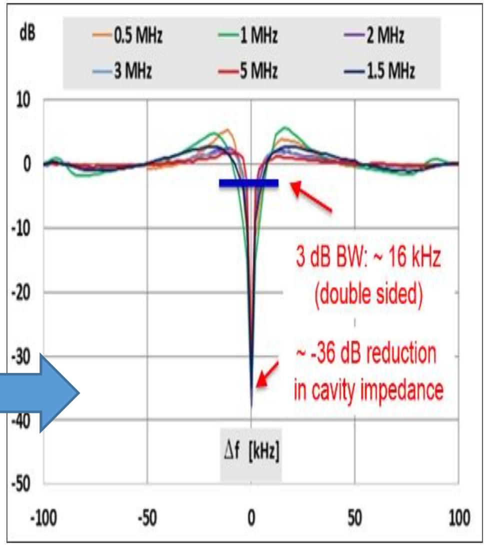
Effect of the PSB impedance model with Finemet cavities (closed-loop)

Impedance at 300 ms



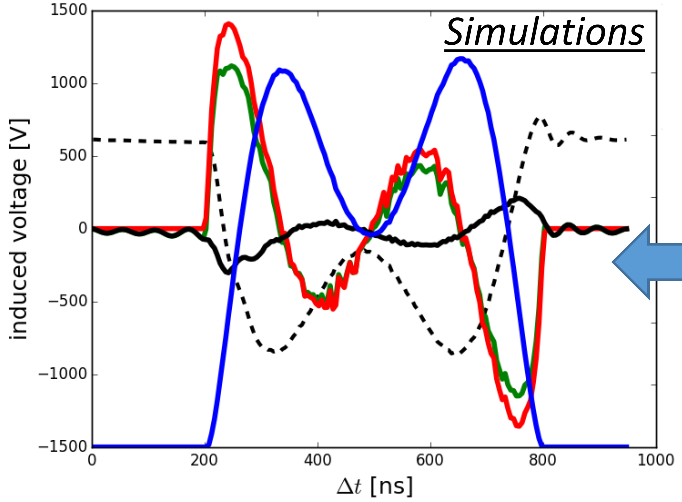
- Finemet impedance is reduced at first 8 (16) f_{rev} by LLRF feedback (notches).
- In simulations notches are reproduced using the measured feedback transfer functions.

Measurements



Courtesy M. Paoluzzi

Induced voltage at 300 ms

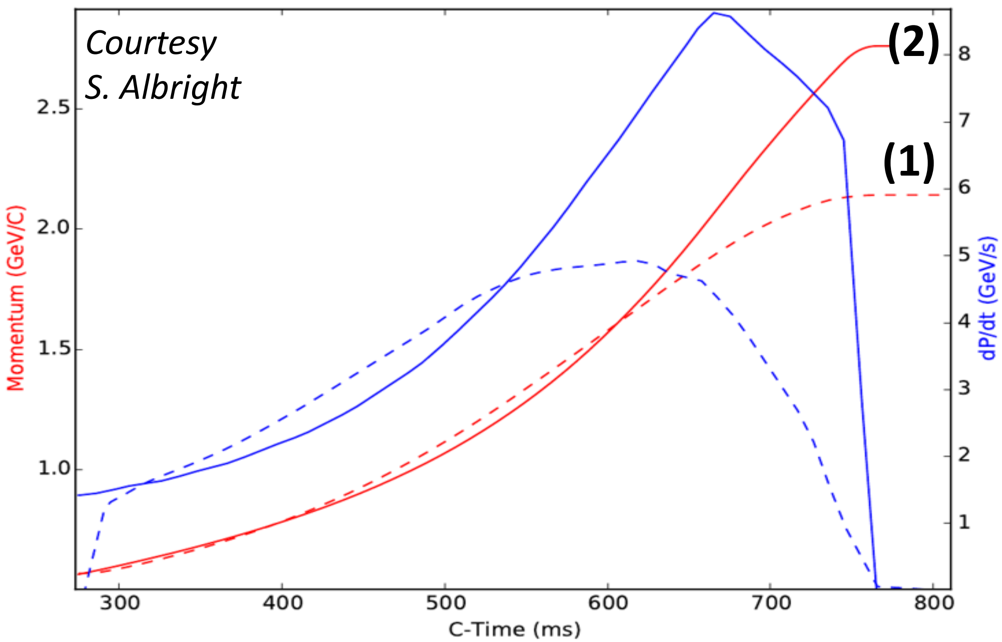


- **Bunch profile** (1 eVs) in a double RF (bunch lengthening mode).
- **Multi-turn induced voltage** as the sum of **space-charge** and **Finemet voltage** with reduction by feedback (FB).

--- Finemet voltage without reduction by FB

Acceleration cycles

Two different momentum programs and derivatives



1. 160 MeV -> 1.4 GeV
   - N = 1.6e13 (ISOLDE)

2. **160 MeV -> 2 GeV**
   - **N = 3.6e12 (HL-LHC)**
   - **N = 1.6e13 (high-intensity)**

   => Most critical cases (studied in simulations)

Cycle

- *Cycle length = 1.2s (the same as now): C275 -> C775*
- *Faster acceleration than now for HL-LHC beams (and faster deceleration at the end)*

Injection

- *Injection at $\dot{B} > 0$*
- *No longitudinal painting*
- *Bunch emittance = 1 eVs after filamentation*

Beam-based feedbacks in simulations

- ➢ The main goal of the phase loop is to damp the rigid-bunch dipole oscillations reducing the difference between the beam and designed synchronous phases.
- ➢ The aim of the radial loop is to maintain the beam orbit at the design one.
- ➢ Realistic and phase and radial loops in simulations starting from PSB RF synoptic

Additional contributions, e.g. noise

$$\sin\Delta\varphi = \sin(\Delta\varphi_{b,rf} + \varphi_{add})$$

Beam phase measured at the h=1 RF frequency and phase

(1)

$$\Delta f_{pl}^{n+1} = A_1^{pl}\Delta f_{pl}^{n} + Gain_{pl}(B_0^{pl}\sin\Delta\varphi^{n} + B_1^{pl}\sin\Delta\varphi^{n-1})$$

(3)

$$\frac{\Delta R^n}{R_d} = \frac{\Delta f_{rf}^{n}}{f_{rf,d}^{n}}\frac{\gamma_n^2}{\gamma_t^2 - \gamma_n^2}$$

$\gamma_t = 4.077$

$R_d = 25e3$ mm

$$\Delta f_{rl}^{n+1} = A_1^{rl}\Delta f_{rl}^{n} + Gain_{rl}(B_0^{rl}\Delta R^{n} + B_1^{rl}\Delta R^{n-1})$$

(2)

$$f_{rf}^{n+1} = f_{rf,d}^{n+1} + \Delta f_{rf}^{n+1} = f_{rf,d}^{n+1} - FGPL_{gain}\,\Delta f_{pl}^{n+1} - FGRL_{gain}\,\Delta f_{rl}^{n+1}$$

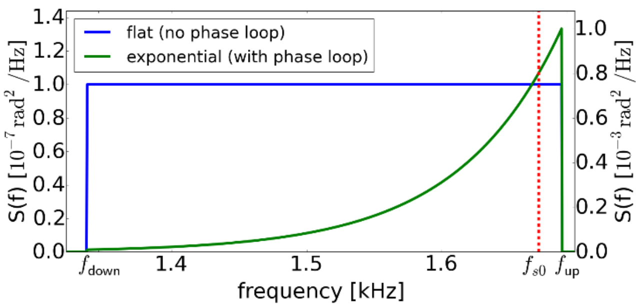
$$V_{rf}^{n+1} = V_1^{n+1}\sin\omega_{rf}^{n+1}$$

Remarks:

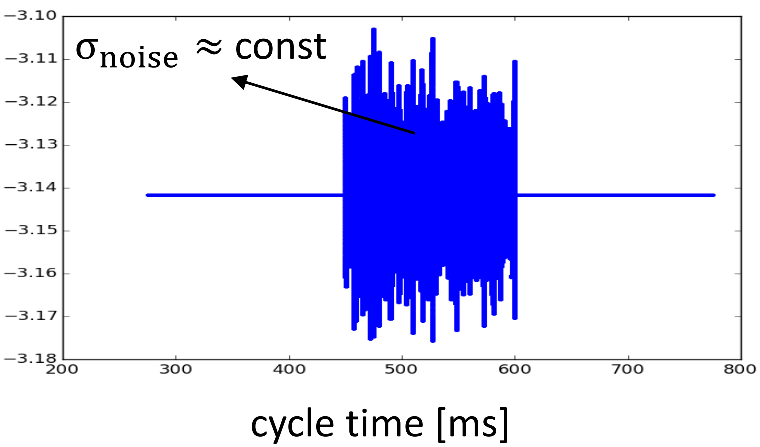
- In simulations $\Delta\varphi_{b,rf}$ is obtained convolving the beam profile with the window-function of the band-pass filter of the machine.
- In simulations estimate of ΔR using (3) instead of radial position pick-up measurements
- Two gains for phase loop and two gains for radial loop (one ‘global’ and one ‘local’)
- The ‘global gain’ is not seen inside (1) and (2)

New emittance blow-up with band-limited RF phase noise

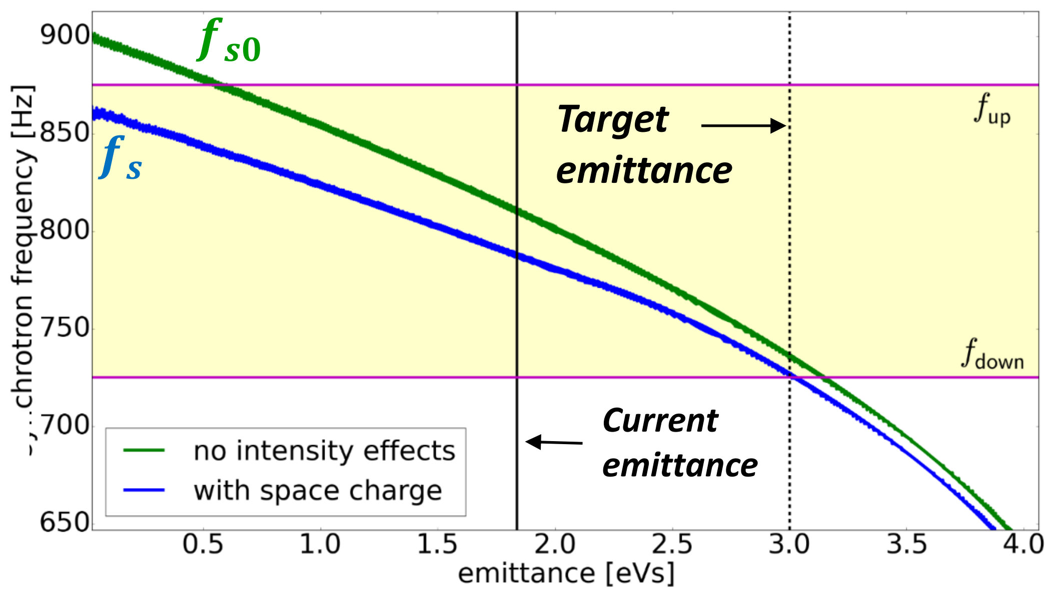
- Current blow-up: high harmonic phase modulation from dedicated RF system (C16) => difficult to set, control in operation and reproduce in simulations.
- Band-limited RF phase noise in h=1 can replace this method saving also RF voltage.



$$\boldsymbol{\varphi}_{\mathbf{noise}} = \mathrm{IDFT}\left(\mathrm{DFT}\,(\mathbf{N(t)}) \cdot \sqrt{\mathrm{f}_{\mathrm{rev}}\,\mathbf{S(f)}}\right)$$



$$\boldsymbol{V}_{\mathbf{rf}} = \boldsymbol{V}_{\mathbf{1}}\,\mathbf{sin}(\boldsymbol{\omega}_{\mathbf{rf,d}}\boldsymbol{t} + \boldsymbol{\varphi}_{\mathbf{noise}})$$

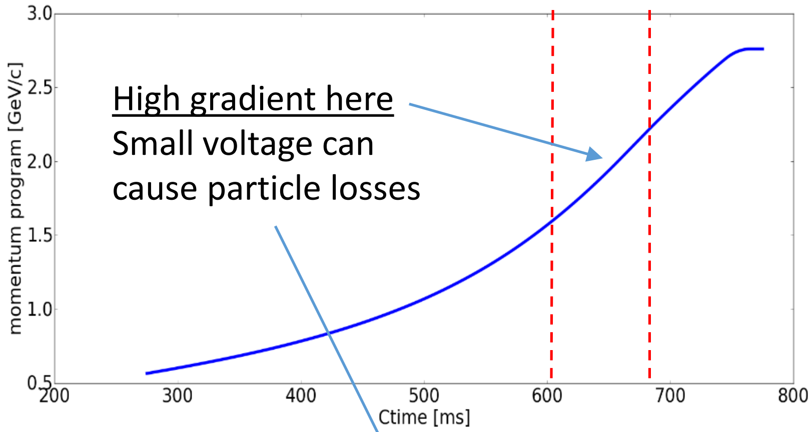


- Synchrotron frequency distribution in single PSB RF.
- The bunch emittance increases from 1.8 to 3 eVs applying phase noise in the band [725 – 875] Hz.
- Space charge lowers the synchrotron frequency (PSB below transition) and the noise band should follow it.

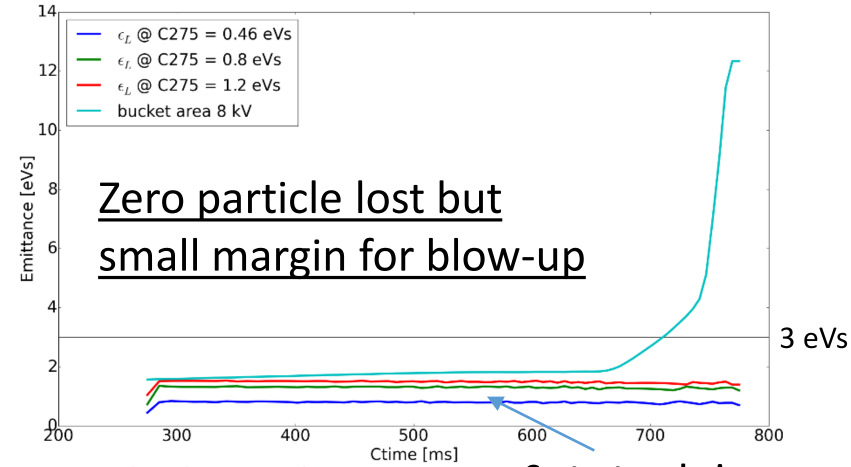
Refs [15], [16]

Simulations LHC beams: constant 8 kV

Smooth momentum program

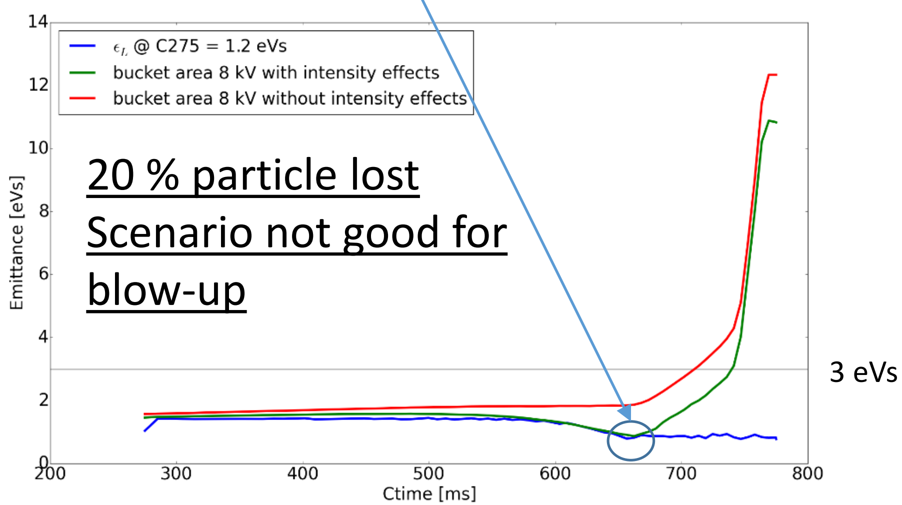


1) No blow-up, no intensity effects

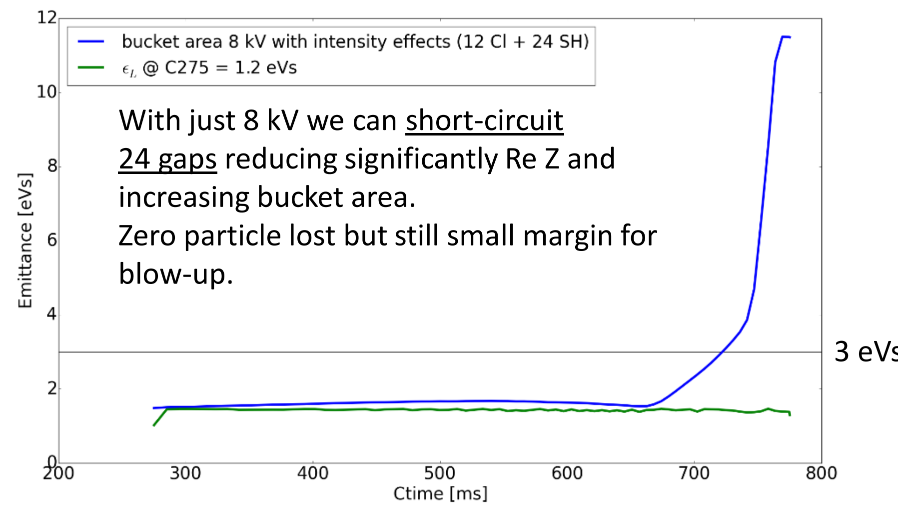


Costant ε_L during ramp (Liouville theorem)

Here ε_L according to vc1 definition to check critical points during the ramp



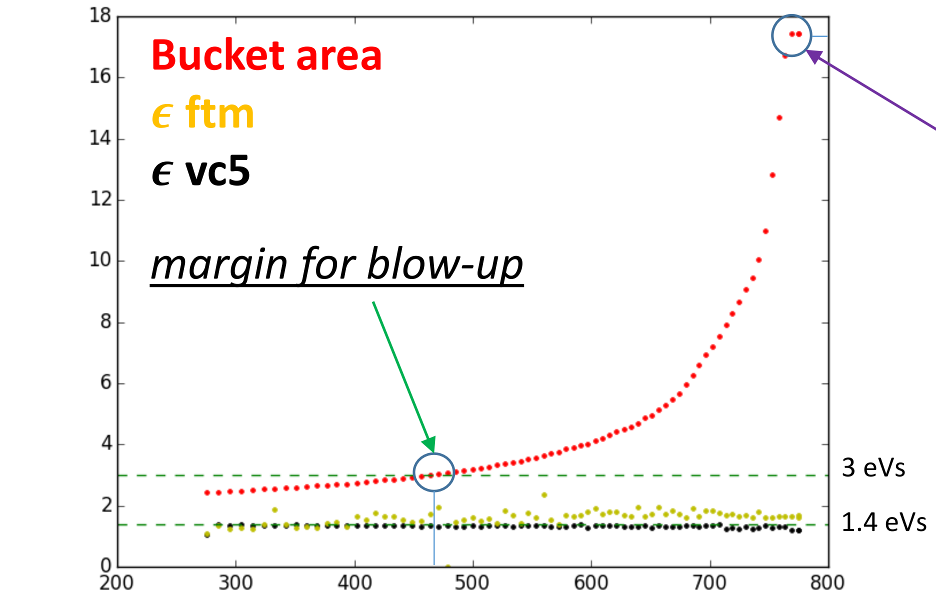
2) No blow-up, with intensity effects (open-loop for Finemet gaps)



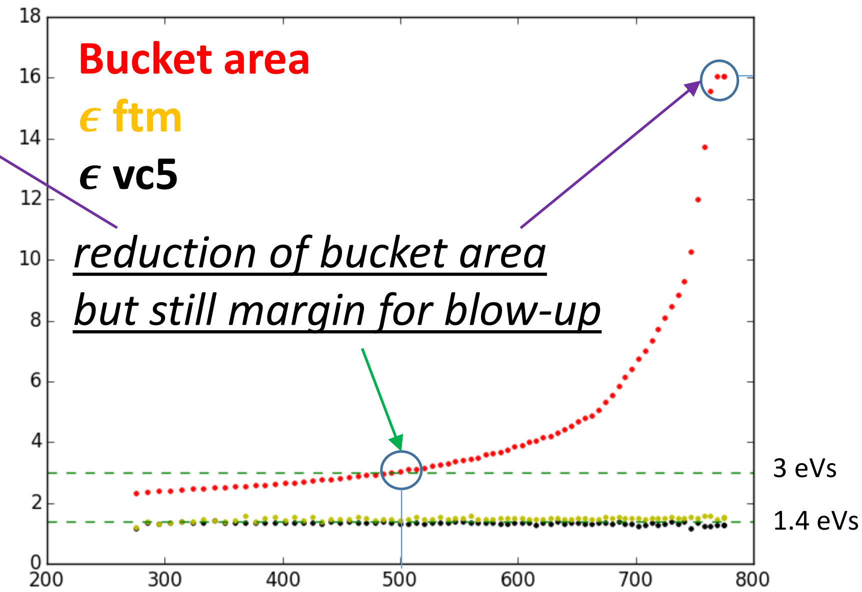
3) No blow-up, with intensity effects and short-circuiting some Finemet gaps

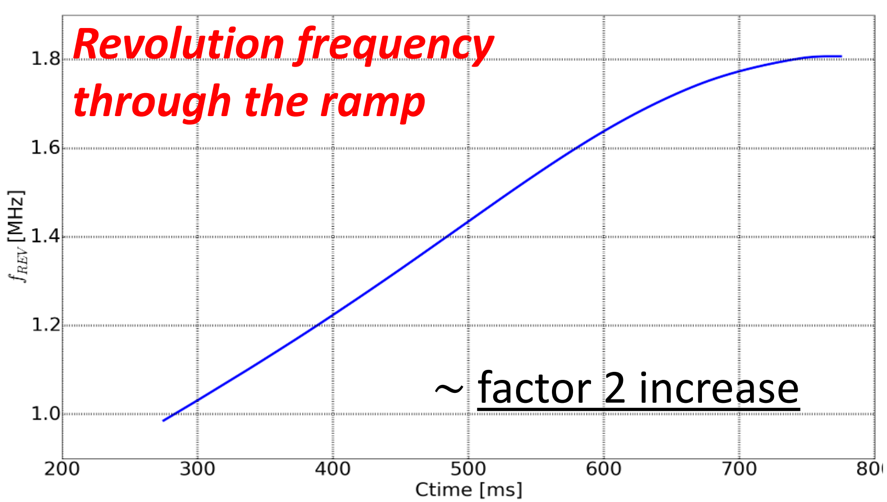
Simulation LHC beams: constant 16 kV

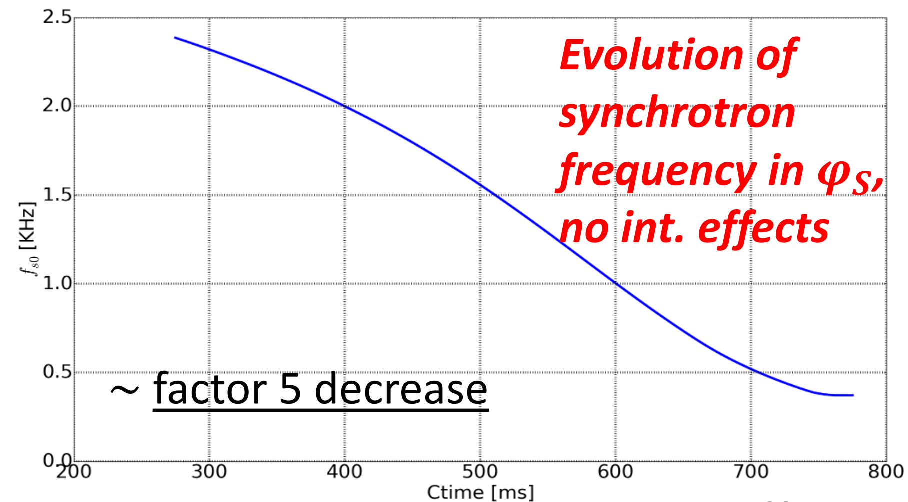
1) No blow-up, no intensity effects



2) No blow-up, with intensity effects



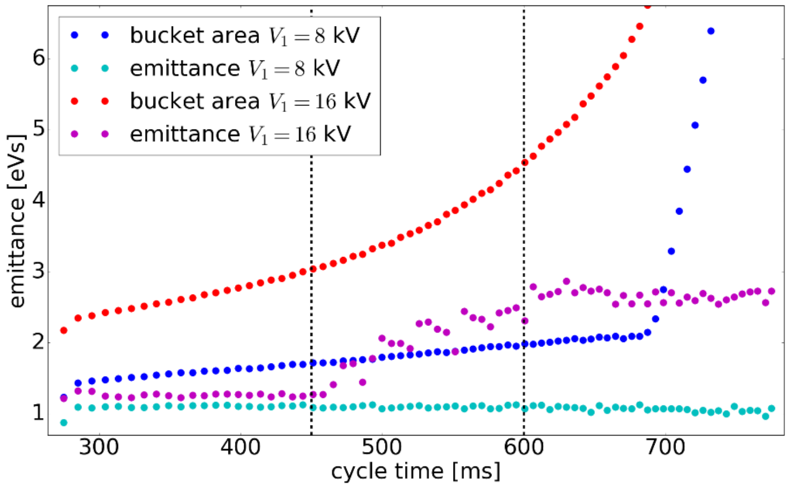




The RF noise must be regenerated to follow f_{REV} and f_{s0}!

Simulation LHC beams: constant 16 kV

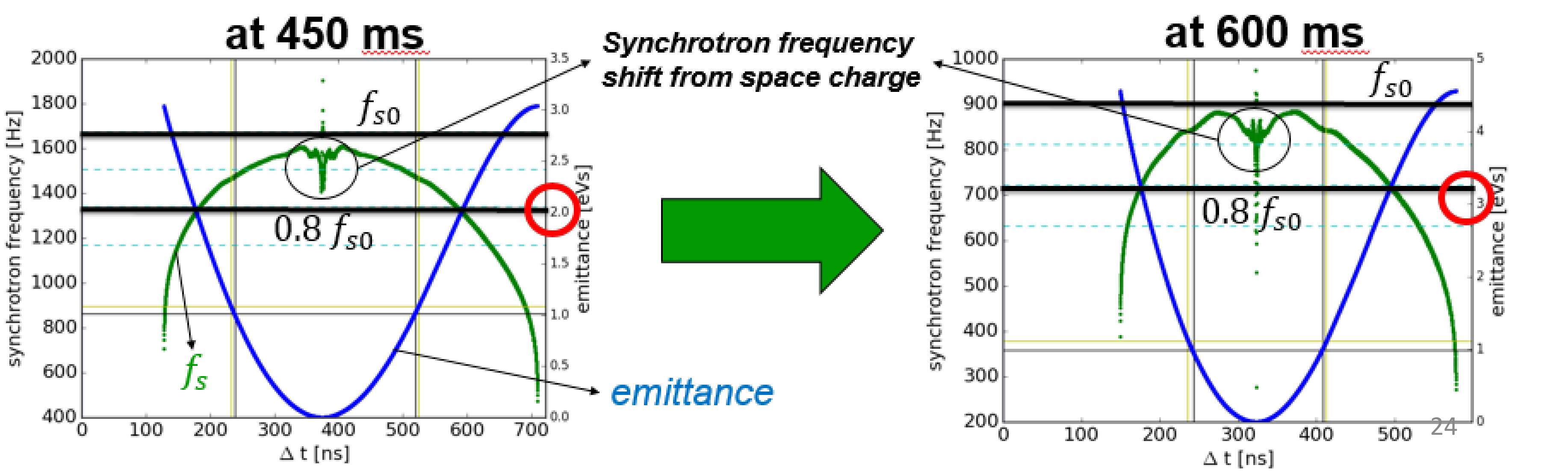
3) With blow-up, with intensity effects, no feedbacks



Few time margin for blow-up with 8 kV

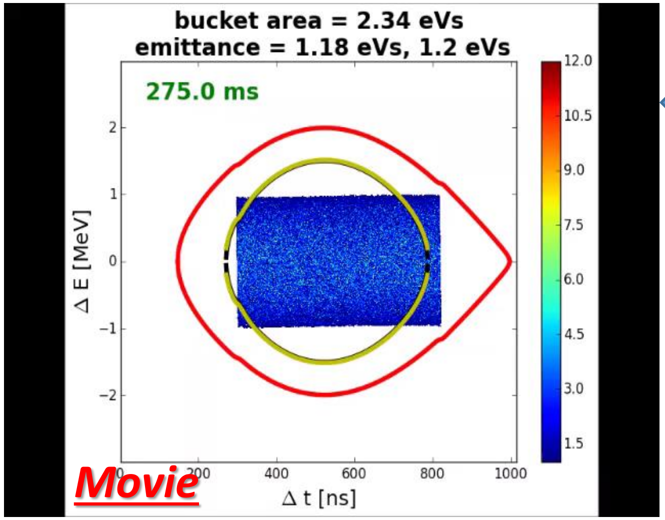
1 eVs -> 3 eVs with 16 kV, no losses

- TARGET INTERVAL : C450-C600
- SPECTRUM BAND = [0.8 f_{s0}, f_{s0}]
- choosing 0.8 f_{s0} the targeted matched area increases from 2 eVs to 3 eVs in [C450, C600], see Figures
- every 5000 turns we generate a new sample of noise to follow f_{REV} and f_{s0}
- S(0) is increased until the desired blow-up is obtained
- S(t) = S(0) $\frac{f_{s0}(0)}{f_{s0}(t)}$, spectrum amplitude rescaled with f_{s0} to have the same rms σ_{φ_noise} during the ramp



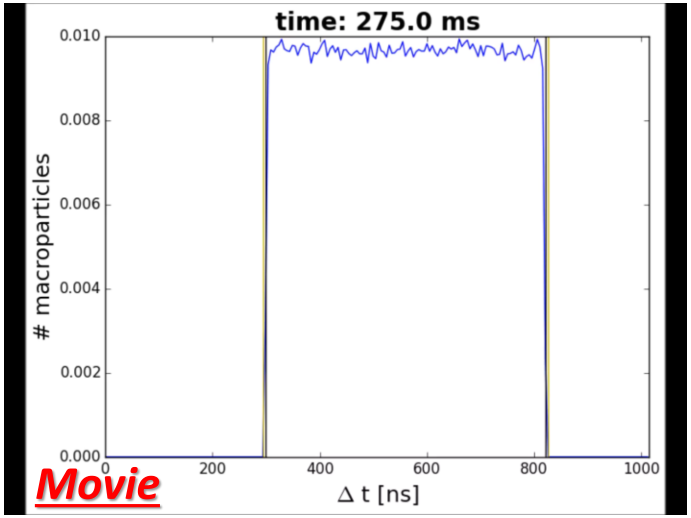
Simulation LHC beams: constant 16 kV

3) With blow-up, with intensity effects, no feedbacks



Separatrix
Hamiltonian

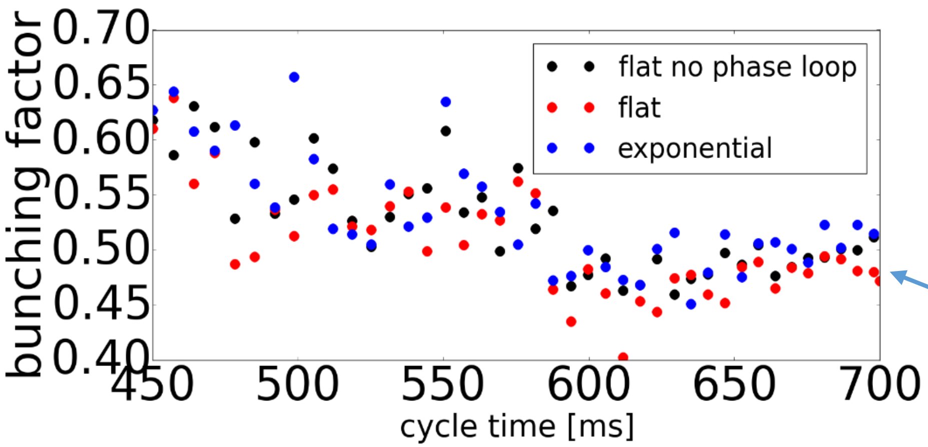
Bunch length marked using PSB conventions



Phase space evolution

Profile evolution

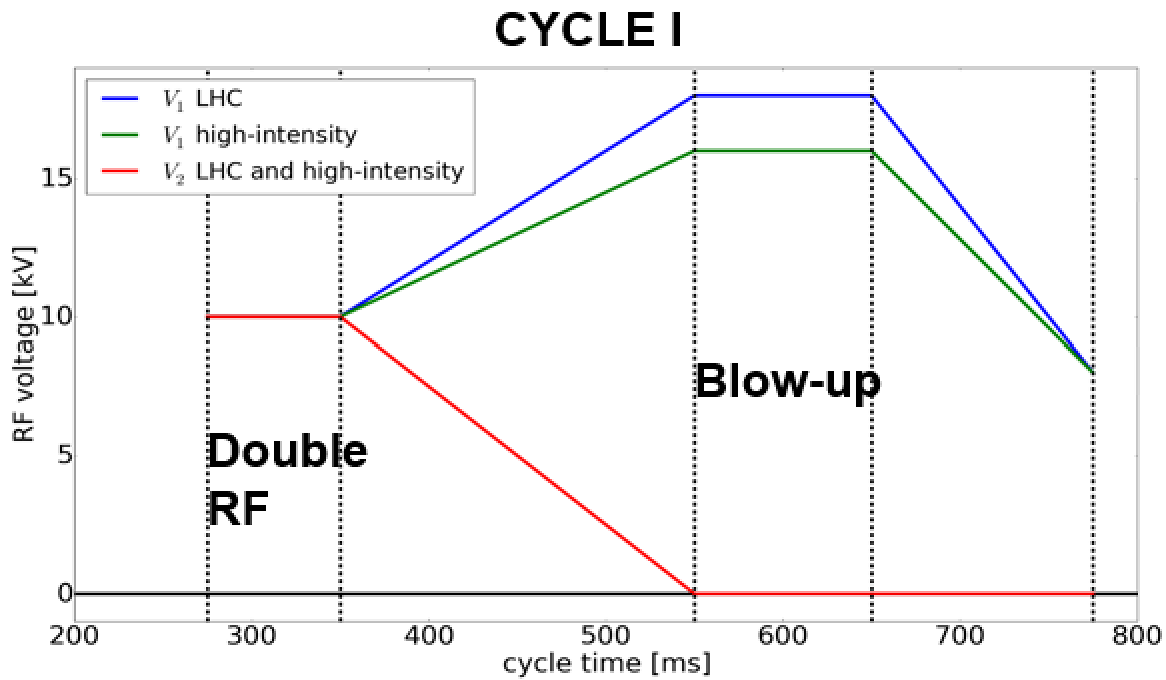
4) With blow-up, with intensity effects, with feedbacks



- Noise counteracted by phase loop which slows down the core diffusion.
  - spectrum changed from flat to exponential and $S(f_{s0})$ increased by factor 4.
  - Blow-up to 3 eVs still possible!
  - Exponential spectrum increases also bunching factor!

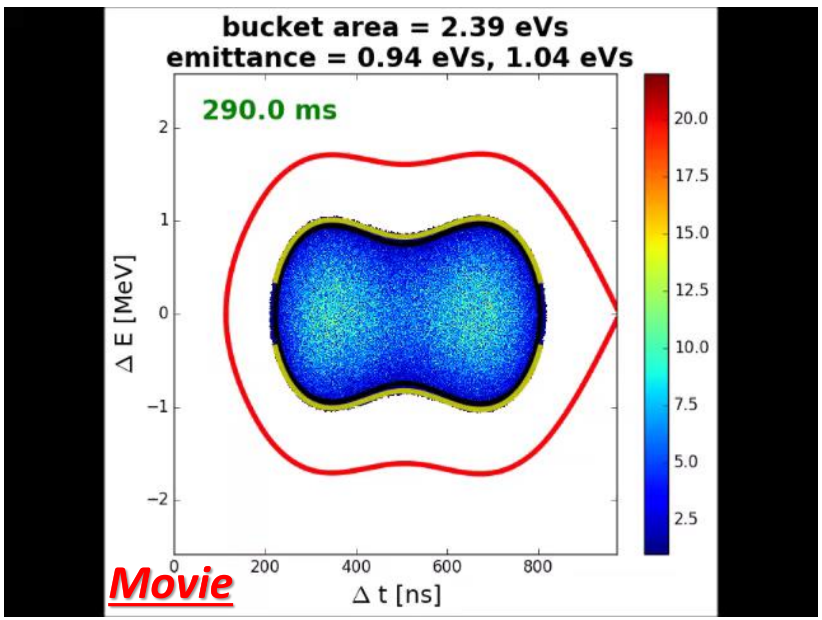
More realistic simulations: setting up

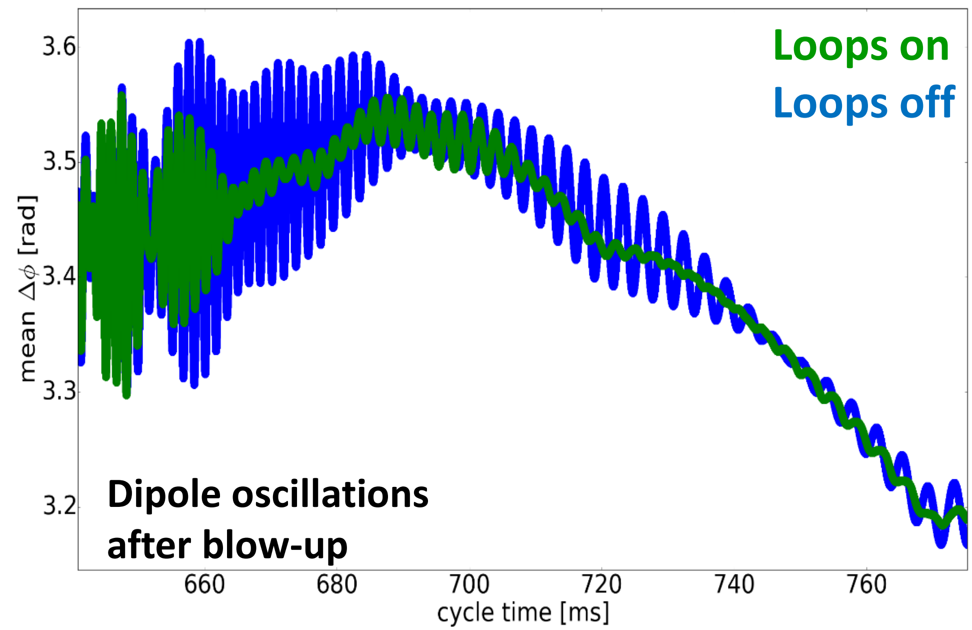
- LHC and high-intensity beams are studied. Maximum available RF voltage 20 kV.
- First part of the ramp in double RF (bunch lengthening) to reduce space charge.
- Controlled longitudinal emittance blow-up using phase noise in 550-650 ms.
- Noise injected in the phase loop of the main RF (h=1) at a limited sampling rate.
- V_1 is dropped after 650 ms to 8 kV to have the desired bunch length at extraction.
- Lower available voltage for high-intensity beams (higher beam loading to counteract).



More realistic simulations: LHC beams

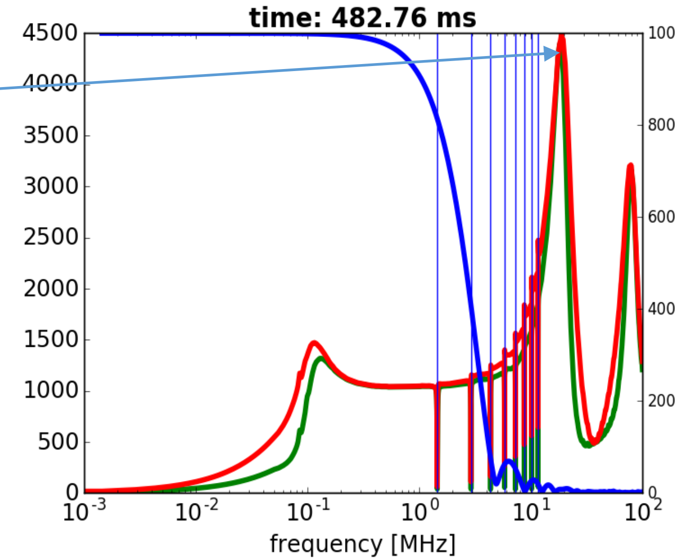
- For LHC beams ($N = 3.6 \times 10^{12}$) no instability observed using CYCLE I.
- Blow-up from 1 eVs to 3 eVs in just 100 ms without losses.
- The phase and radial loops are applied also after emittance blow-up.
- Dipole oscillations significantly damped.



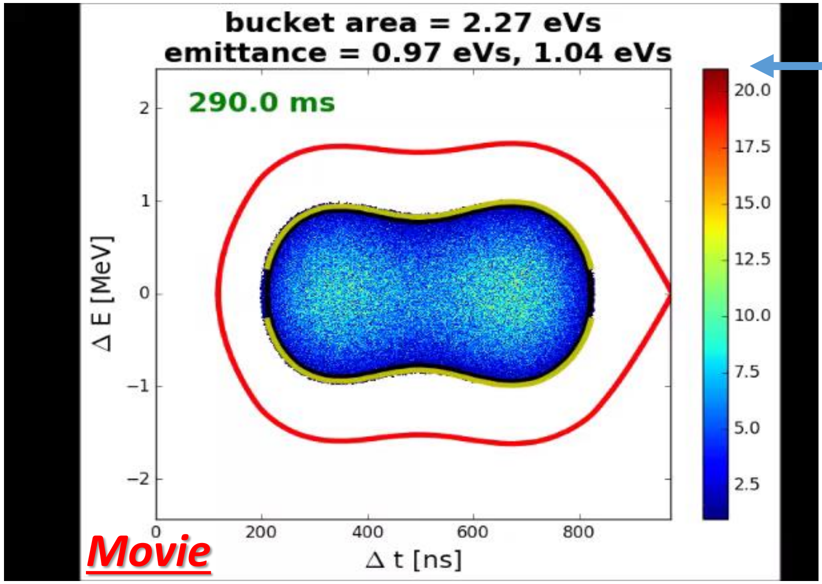


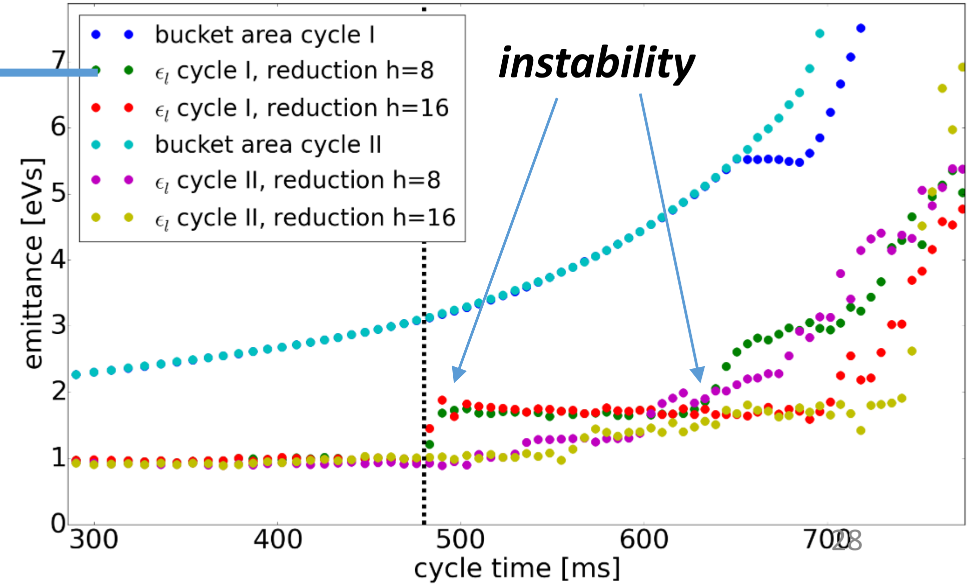
More realistic simulations: high-intensity

- Instability (high frequency modulation and uncontrolled longitudinal emittance blow-up) due to Finemet impedance peak at 20 MHz.
- Increasing the number of revolution harmonics at which the Finemet impedance is reduced delays the instability.
- Instability delayed also in single RF during all cycle ($V_1 =$ 16 kV, CYCLE II), however at extraction the emittance is larger than in CYCLE I.
- Absence of instability seen using CYCLE2 and widening notches bandwidth



20 MHz component also visible from the phase space!



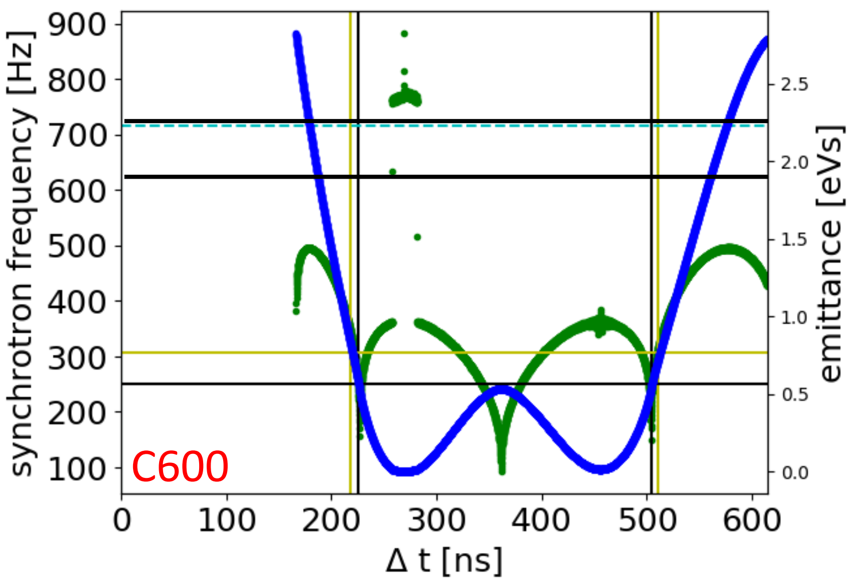


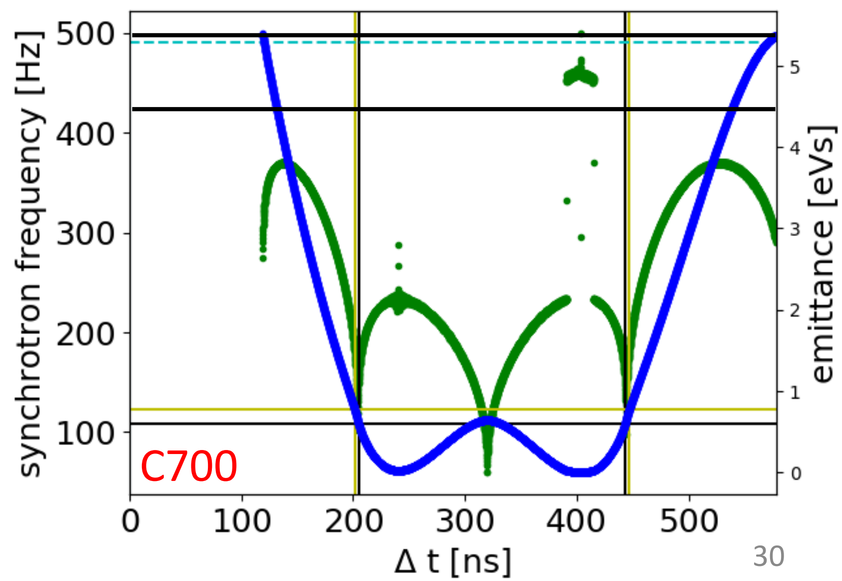
Contents

Phase noise in current machine (1/5)

First test (July 2017): LHC25ns beam, goal 2.8 eVs

- Noise applied in C600-C700
- Double RF 8+6 in bunch lenghtening
- Quadrupole oscillations excited (noise regenerated every 10000 turns to follow f_s change)



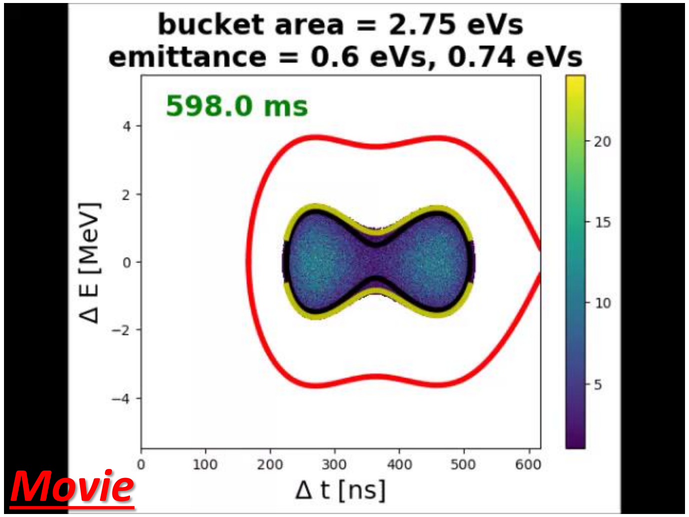


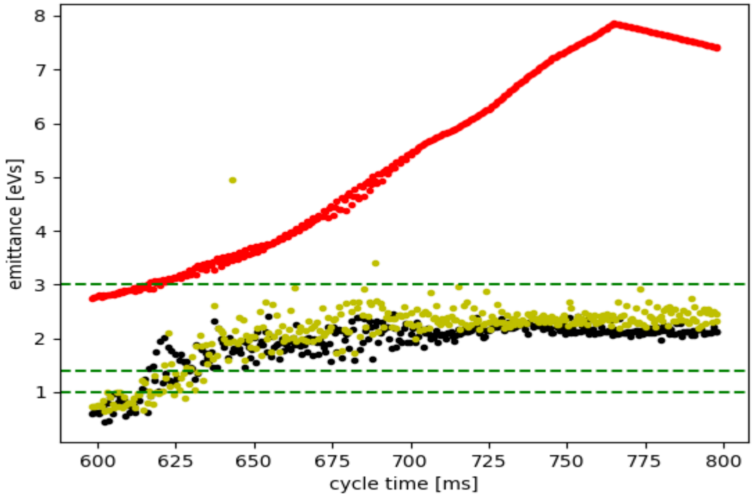
- Feedback loops included in simulations but no intensitity effects.
- First version of LLRF model in BLonD was **slightly different** from what is in the RF synoptics (e.g. no global gains, $\Delta\varphi$ instead of $\sin\Delta\varphi$ for phase loop, ΔR in meters and A_1^{rl}=1 for radial loop)
- This implied some calibration studies, including the choice of the rms amplitude of the noise to be injected (different from what used in simulations). **However…**

Phase noise in current machine (2/5)

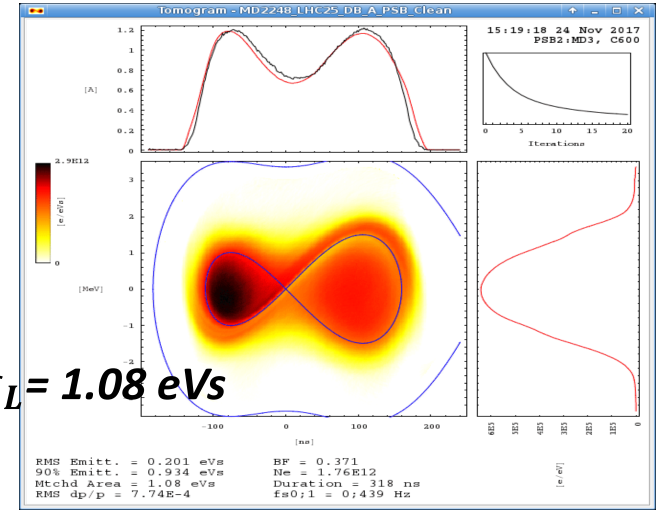
Results from 1st test

SIMULATIONS

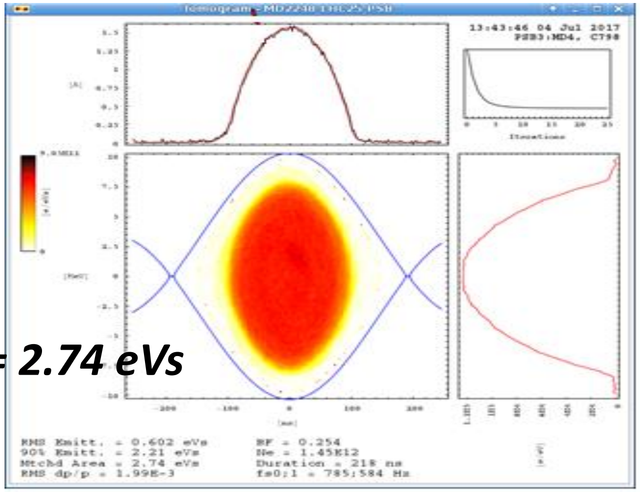




MEASUREMENTS



C600, ϵ_L = 1.08 eVs



C798, ϵ_L = 2.74 eVs

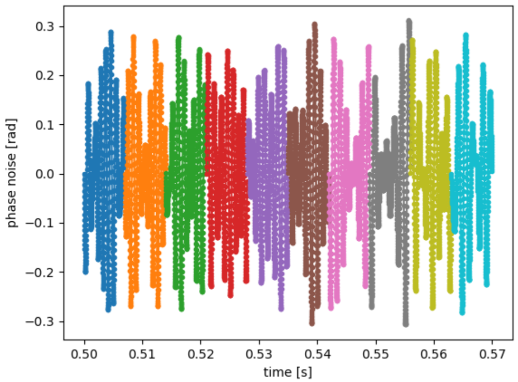
Phase noise in current machine (3/5)

Second test (November 2017): LHC25ns beam, goal 1.4 eVs

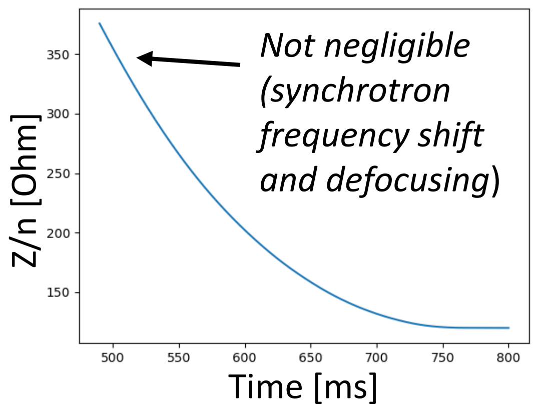
- Noise injected through phase loop at C500-C570, double RF 8+6 in bunch-lenghtening
- Quadrupole oscillations excited (noise regenerated every 7 ms to follow f_s change)
- Improved feedback loops model (in simulations exactly the same gains as in operation)
- Exactly the same noise program used in machine and simulations
- Space charge and impedances (C02, C04, resistive wall, ejection kickers and their cables, transition steps) included in simulations

Noise (σ_{rms}=0.138 rad)

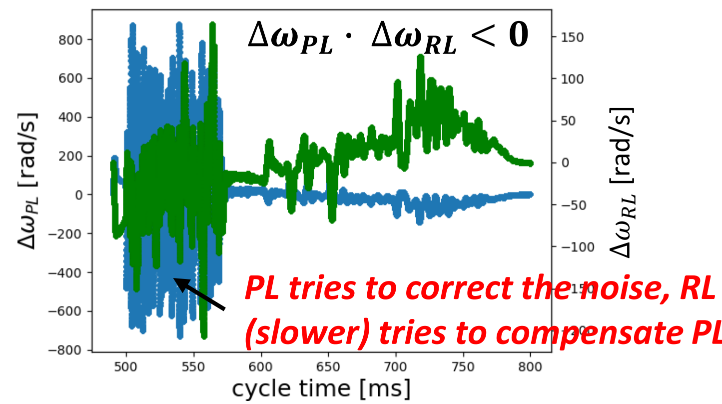
10 parts with different flat spectrums



Space charge in simulation



Phase and radial loop corrections in simulation

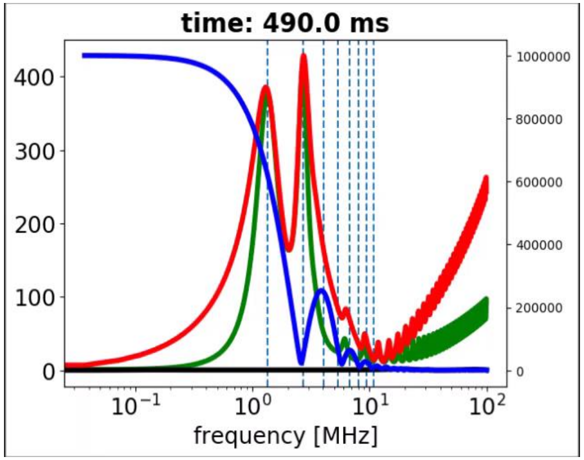


Phase loop ➡ $FGPL_{gain}$=0.2 $Gain_{pl}$=3000 A_1^{pl}=0.99803799 B_0^{pl}=0.99901903 B_1^{pl}= -0.99901003

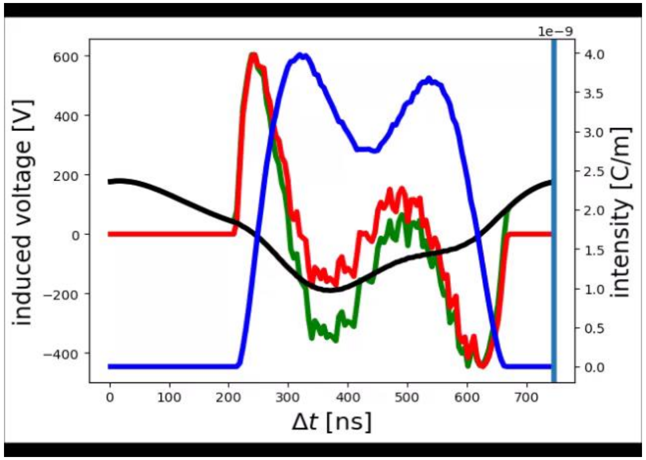
Radial loop ➡ $FGRL_{gain}$=3 $Gain_{rl}$=2.20000005 A_1^{rl}=0.99999988 B_0^{rl}=3.0000001 B_1^{rl}= 0

Phase noise in current machine (4/5)

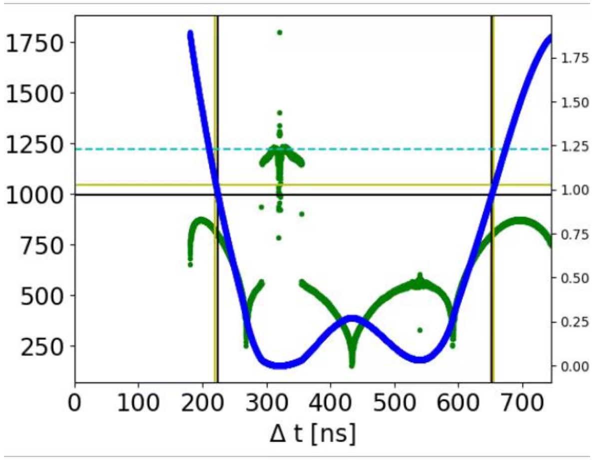
Bunch spectrum and |Z|, Re(Z)



Profile and total induced voltage (space charge plus impedance)



Synchrotron frequency distribution and emittance

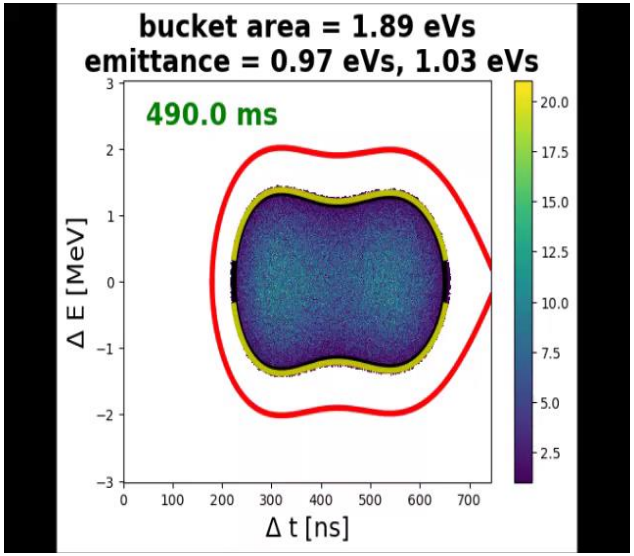


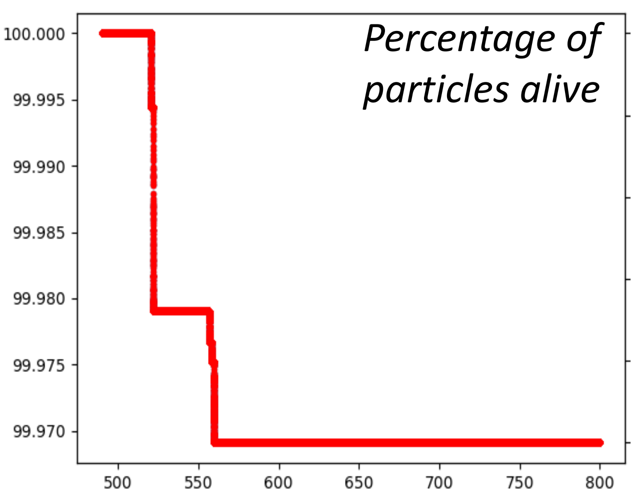
- The C02 and C04 impedances dominate at low f (beam spectrum) while other components dominate at higher frequencies (in simulation f_{max} = 100 MHz)
- Space-charge induced voltage is the highest at C490, while at C800 the opposite is true
- The C02 and C04 impedances generate multi-turn wakes (in simulation ~10 consecutive $\mathrm{T_{rev}}$)
- **To be studied further**: if the two peaks of the bunch profile have different heights (because of intensity effects, noise and imperfect calibration between C02 and C04), then the synchrotron frequency of the two internal lobes reaches f_s in single RF at 8 kV (f_{s0} dashed line)
- The previously called 'quadrupole band' would be in fact both quadrupole and dipole for the internal lobes, probably for that reason it worked so well for blow-up!

Phase noise in current machine (5/5)

Results from 2nd test

SIMULATIONS

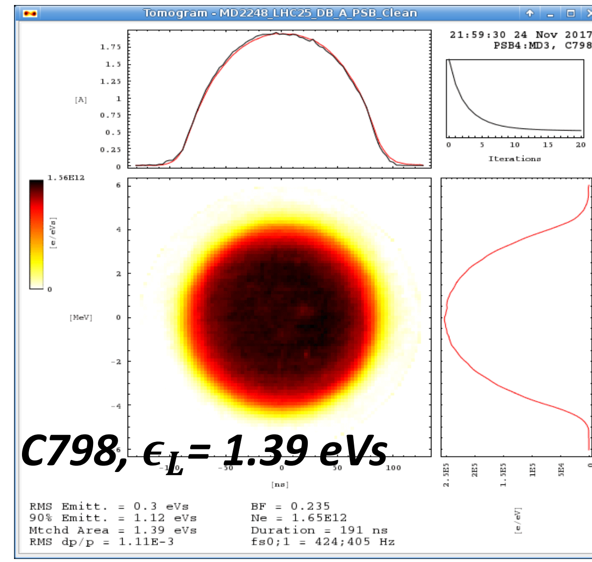


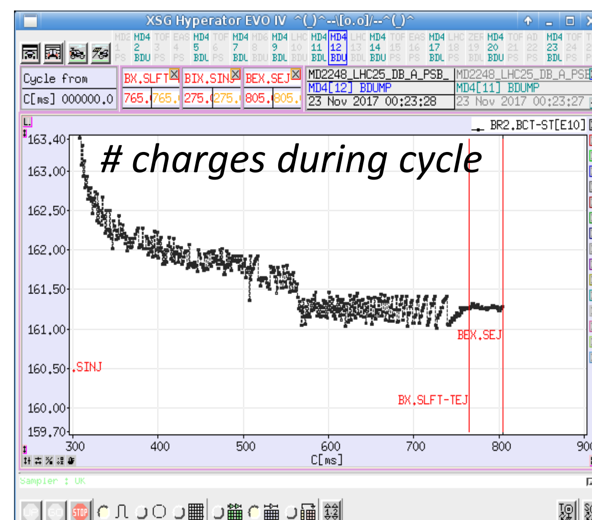


- Blow-up to 1.4 eVs in measurements!
- Noise in simulation slightly less effective, 1.3 eVs at C800.
- Probable reason: uncontrolled blow-up in machine from 1 eVs to 1.15 eVs in absence of C16 and noise.

- Very good reproducibility of losses during C500-C560!
- Also here some discrepancy in numbers likely due to the uncontrolled blow-up.

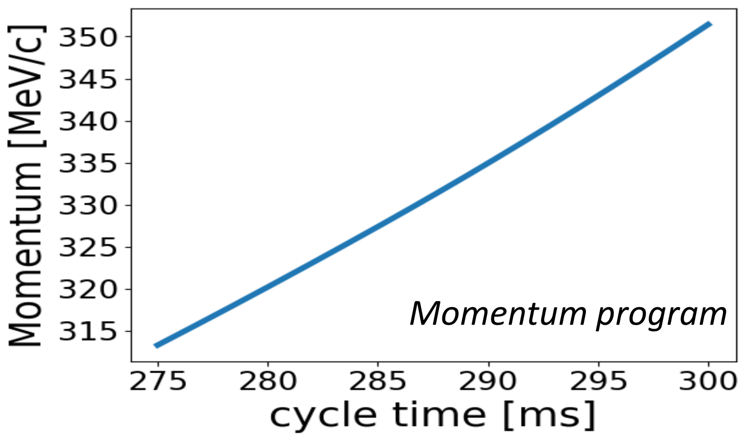
MEASUREMENTS

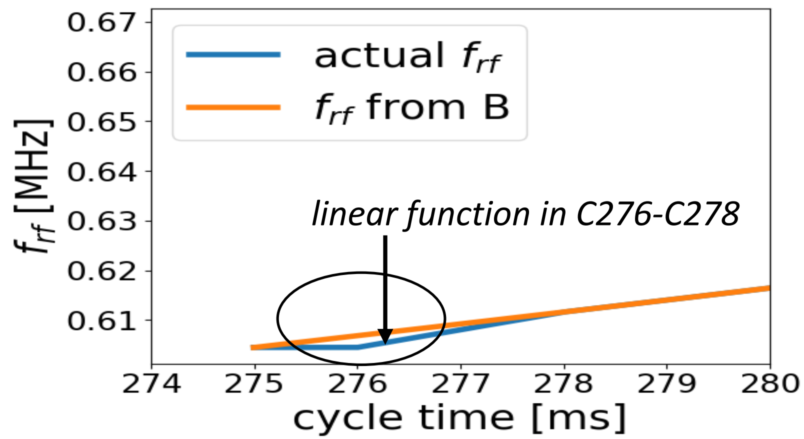




Fixed (RF) frequency injection (1/2)

- The PSB was conceived as an intensity booster for fixed-target physics (Ref [17]).
- No attempt was ever made to synchronize the turns injected into each ring as dozen of turns were supposed to be injected and superposed longitudinally.
- Injection at C275 with $\dot{B} > 0$, but f_{rf} is kept constant for 1 ms (C275-C276) and then re-joins the one synchronized with the magnetic field at C278.
- Simulations from C275 to C282 without intensity effects and feedback loops.
- Simulations for current machine, but the same principle will apply for the post-LS2 scenario.





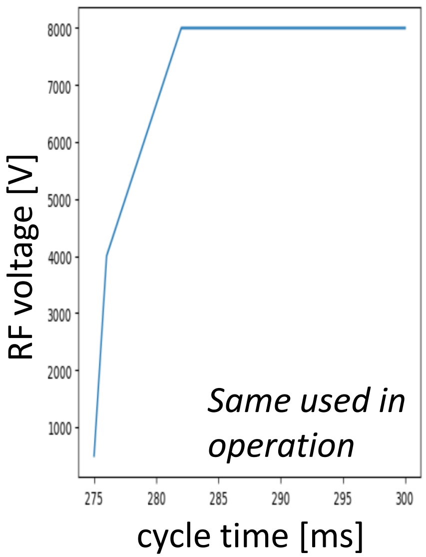
- If $\dot{B} > 0$ and f_{rf} = const, then the bunch experiences a deceleration with **negative synchronous phase** given by (Ref [17])

$$\sin\varphi_s = \underbrace{\frac{\gamma^2}{(\gamma^2-\gamma_t^2)}}_{<0} \underbrace{\frac{2\pi R\rho}{V}}_{>0} \underbrace{\frac{dB}{dt}}_{>0}$$

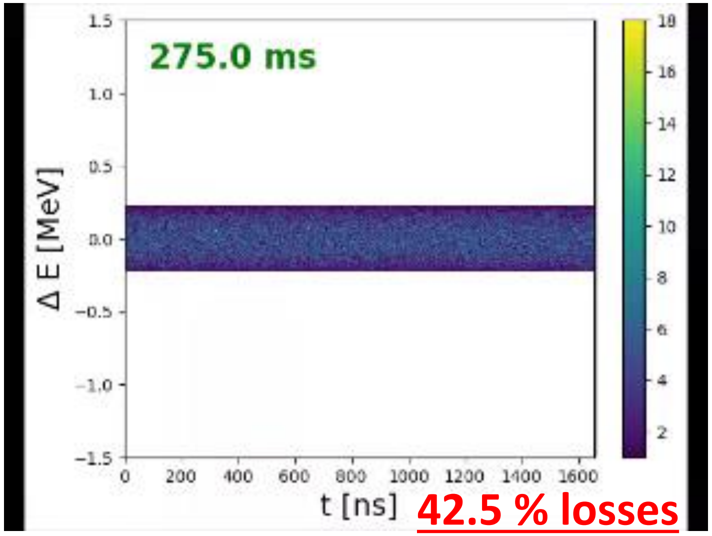
Fixed (RF) frequency injection (2/2)

First simulations: capture in single RF (C02)

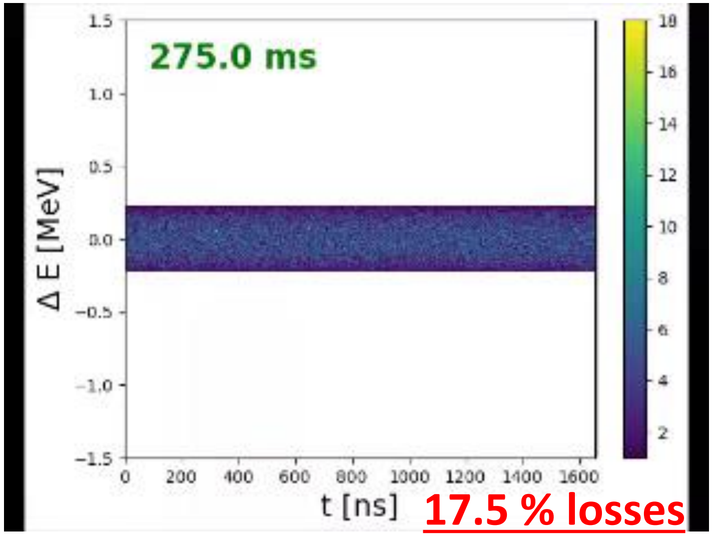
RF voltage program



Frequency following B



Fixed RF frequency



- In the fixed-frequency case the bunch loses energy and go down in phase space relative to the magnetic field reference $\Delta E = 0$; then it comes back to $\Delta E = 0$ when the actual frequency is equal to the design one.

- **Fixed-frequency injection helps to reduce particle losses** since deceleration implies more particles to be captured inside the expanding RF bucket.

- **Periodicity important here**: relative to the magnetic field reference frame, the bunch reaches an equilibrium where it is split in two parts.

Contents

- Introduction
- The CERN BLonD code
  - Main features and equations of motion
  - Examples of benchmarking with measurements, other code and analytical formulas
- PSB longitudinal dynamics studies for after LS2
  - Space charge and impedance model
  - Cycles and Landau damping
  - LLRF beam-based feedbacks
  - Phase noise injection for longitudinal emittance blow-up
  - Simulation results for LHC type beams
  - Simulation results for high intensity type beams
- PSB longitudinal dynamics studies for current machine
  - Phase noise for blow-up to 1.4 eVs and 2.8 eVs for LHC25 ns beams
  - Fixed-frequency injection (preliminary simulations)
- Conclusion
- References

Conclusion (1/2)

- The BLonD code is very useful for all PSB simulations.
- Several benchmarks with measurements, analytical formulae and other codes give BLonD sufficient reliability.
- Longitudinal beam dynamics of the PSB beams in the post-upgrade scenario after 2021, where there will be many important changes, was studied using BLonD simulations.
- The full present PSB longitudinal impedance model has been used with careful estimations of the dominant sources:
  - ➢ Space charge and Finemet impedance (with LLRF feedback)
- Phase and radial loops have also been carefully included in simulation.

Conclusion (2/2)

- RF phase noise injection for longitudinal emittance blow-up has been studied in simulations and ring.
- Simulations of HL-LHC beam don't show any instability.
  - It was possible to blow-up longitudinal emittance by factor 3 in just 100 ms, injecting noise through the phase loop.
- Simulations of high-intensity beams reveal micro-wave instability caused by Finemet impedance.
  - Possible cure: increase action of feedbacks (number of harmonics, bandwidth of transfer function).
- Comparison between measurements and simulations for current situation shows very good agreement:
  - Noise used to blow up the LHC25ns beam from 1 to 1.4 and 2.8 eVs.

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