Simulations of RF beam manipulations including intensity effects for CERN PSB and SPS upgrades

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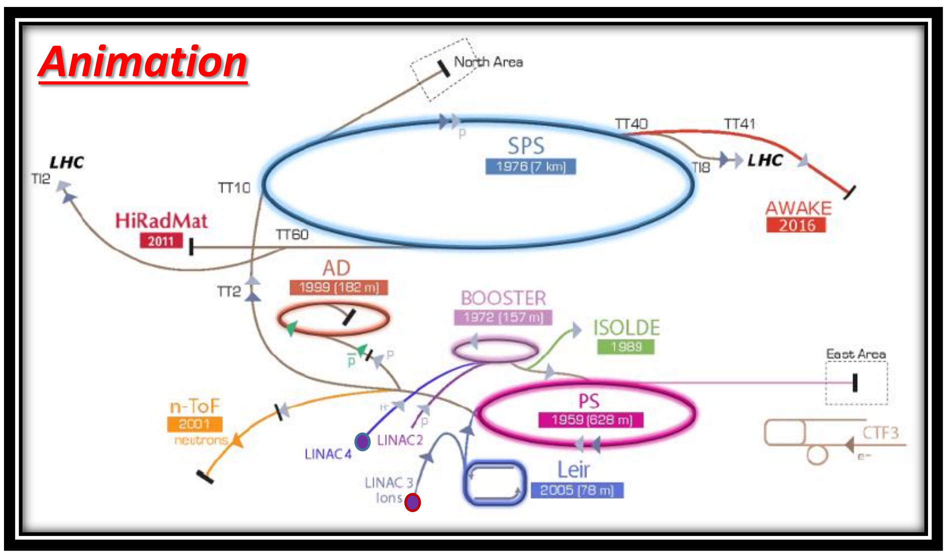
Introduction and motivations (1/3)

- After CERN upgrade (LS2) in 2021 the LHC injection chain will be upgraded and more demanding beam parameters will be required.
  - ➢Simulations in longitudinal plane needed to foresee beam stability issues.
  - ➢Need of a longitudinal beam dynamics code able to simulate acceleration ramps with machine-dependent features in a reasonable time -> **CERN BLonD code**.



- CERN machines studied during my PhD:
  - ➢ PSB (protons)
  - ➢ SPS (ions)

Introduction and motivations (2/3)

- Main changes in the PSB after LS2 interesting for the longitudinal plane:

  - Higher injection energy through Linac4 and different injection schemes.
  - Higher extraction energy through new magnet power supplies.
  - Higher acceleration rate.
  - Different momentum program.
  - Different RF systems.
  - Different space charge and impedances.
  - Higher intensities, higher controlled longitudinal emittance blow-up required at extraction for CERN PS.

Introduction and motivations (3/3)

- After LS2 the peak luminosity has to increase:
  - Number of bunches in the LHC has to increase or equivalently the bunch spacing has to decrease (from 100 ns to 50 ns).
  - Bunch-splitting or batch compression difficult to perform in the PS.
  - Proposed alternative: momentum slip-stacking in the SPS to interleave two batches in longitudinal plane and reduce bunch spacing
- SPS not presented here:
  - For brevity reasons
  - Work in progress…

Contents

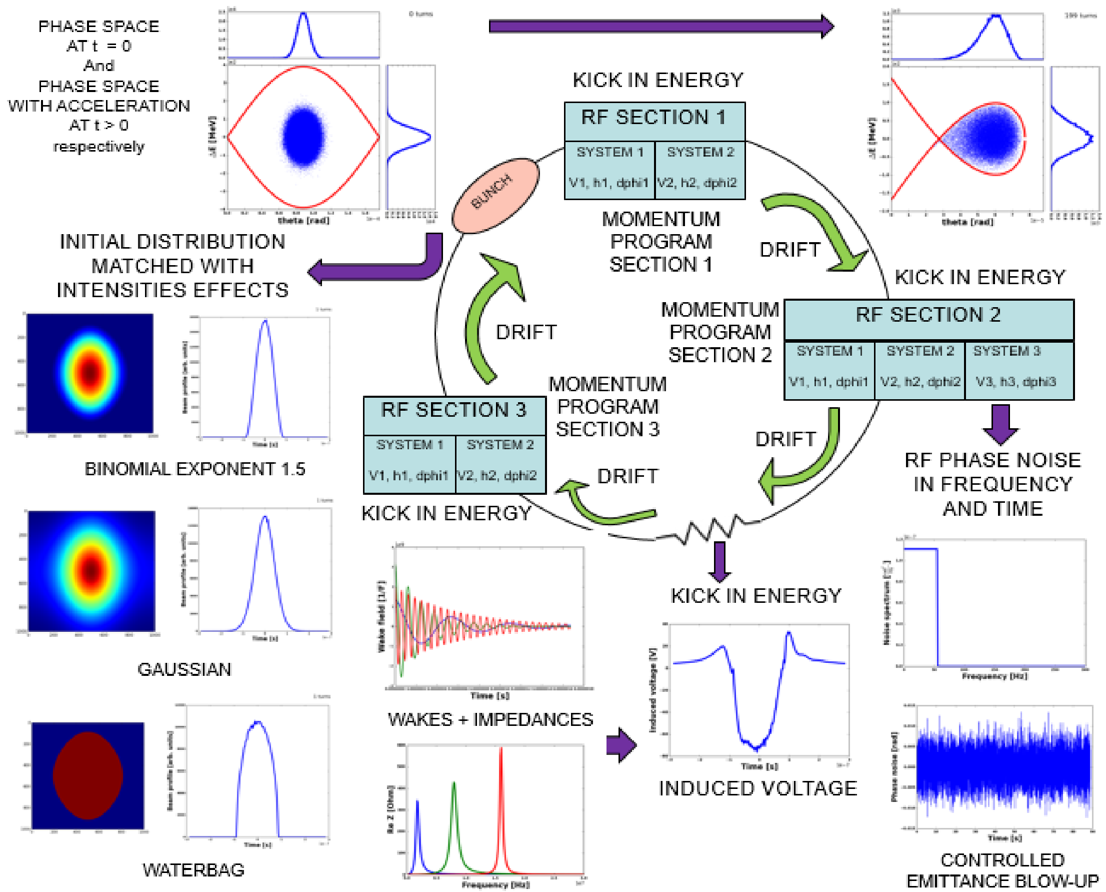
BLonD main features (1/2)

- BLonD is a Beam Longitudinal Dynamics simulation code for synchrotrons developed at CERN by me and other BE/RF colleagues.
- All LHC injector chain machines have been simulated with BLonD (SPS was the first Refs [1], [2])
- 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, beam and cavity-based feedbacks...)
  - Monitoring, plotting, data analysis
  - Documentation

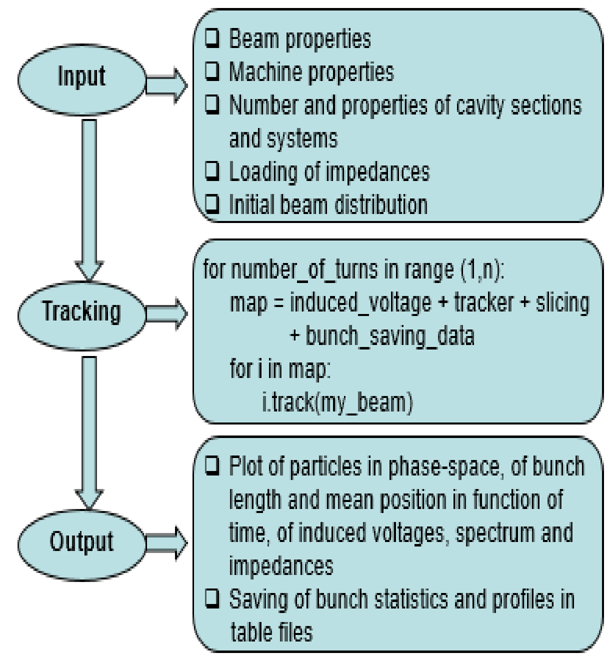
https://blond.web.cern.ch/

BLonD main features (2/2)

♦ Example of model adopted and code capabilities



♦ Code diagram



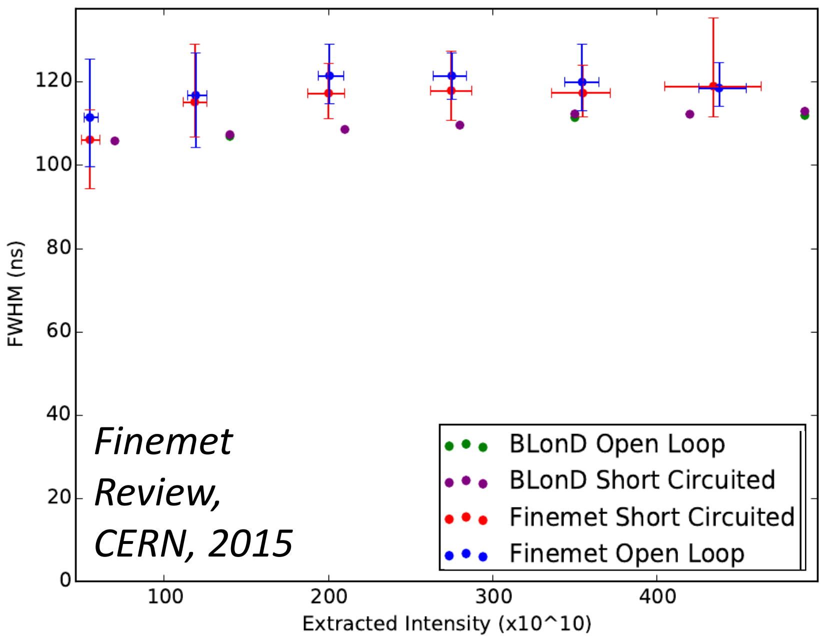
Longitudinal equations of motion

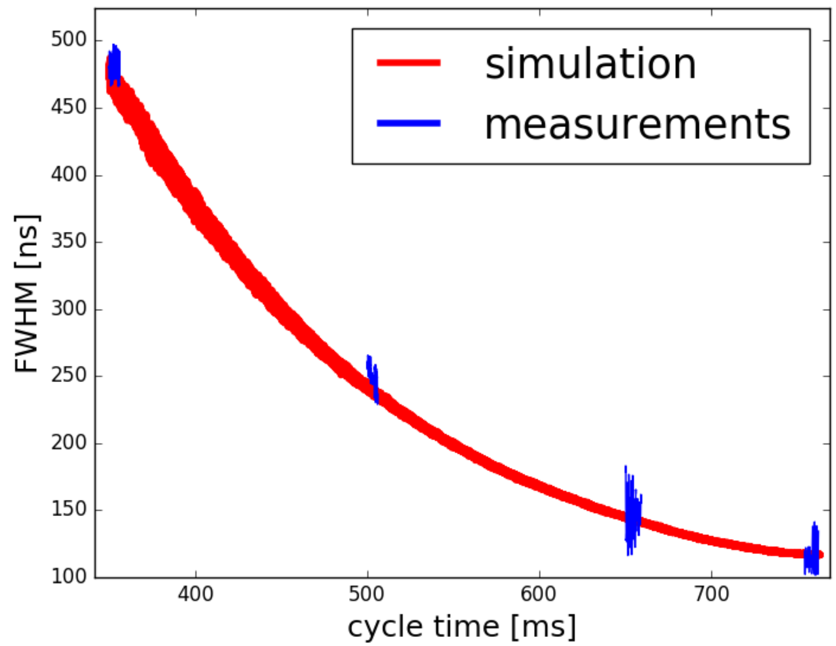
$$\Delta E^{(n+1)} = \Delta E^{(n)} + q\sum_i V_i \sin\left(\omega_{i,rf}^{(n)}\Delta t^{(n)} + \varphi_{i,rf}^{(n)}\right) - \beta_s^{(n+1)} c\left(p_s^{(n+1)} - p_s^{(n)}\right) + E_{ind}^{(n)}\left(\Delta t^{(n)}\right)$$

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

Examples of benchmarking: measurements

- Comparison with PSB measurements, **good agreement**

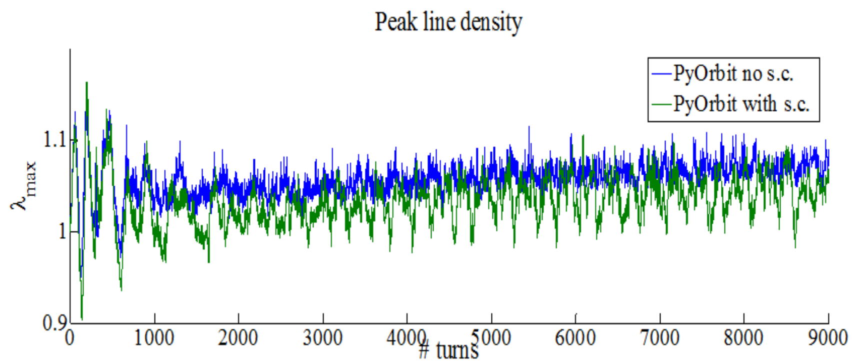


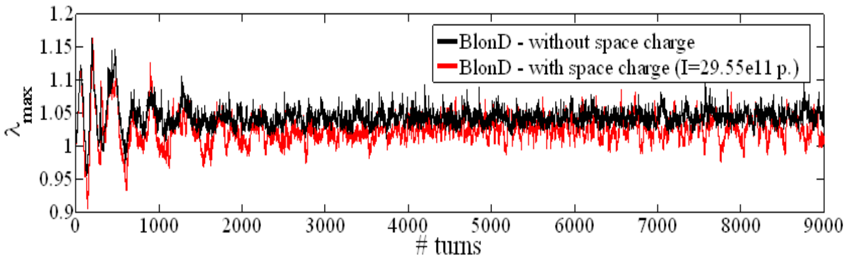


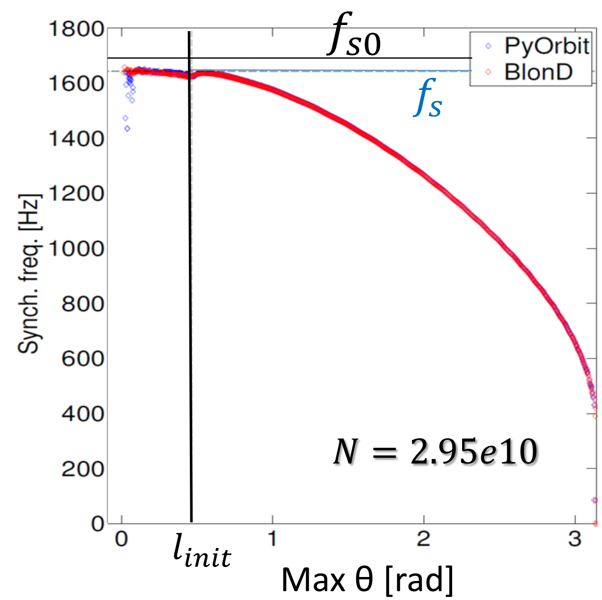
FWHM bunch length at PSB extraction for various intensities, full ramp simulation

Acceleration in single RF with full impedance model.
Bunch length during ramp, $N = 5 \times 10^{12}$.
Significant shot-to-shot variations in bunch length in measurements.

Examples of benchmarking: PTC-PyOrbit







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

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

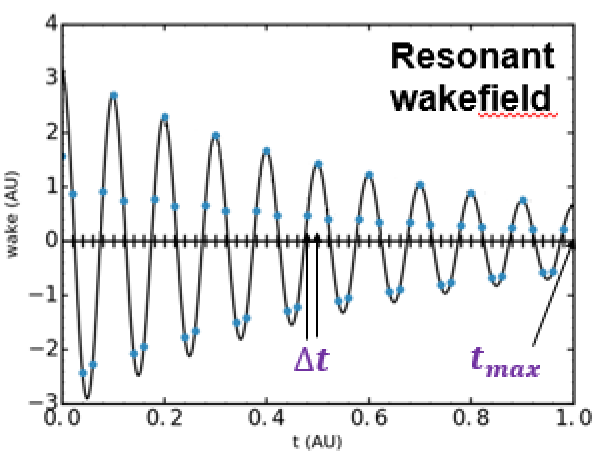
*Syncrotron frequency distribution for a matched parabolic bunch with space charge below transition => **perfect agreement***

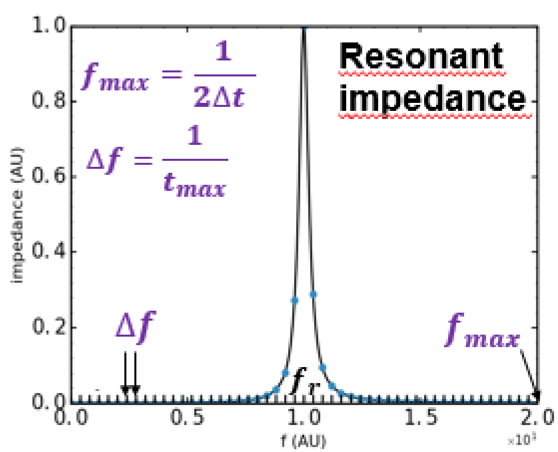
Refs [3], [4]

Examples of benchmarking: Music (1/3)

- BLonD and MuSiC 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}).





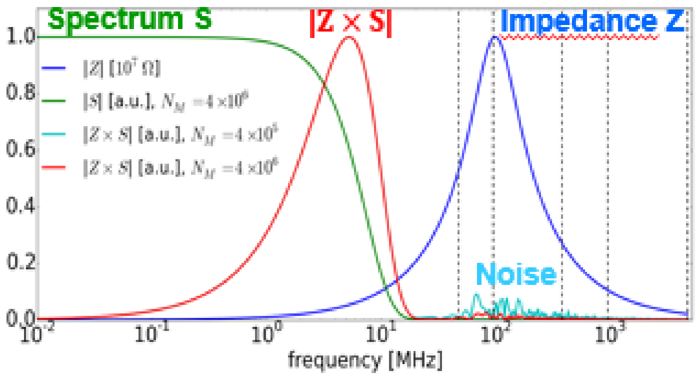
$$V_{ind}(\phi_i) = \frac{Q_{tot}}{N_M} \sum_{j=1}^{N_M} w_{\parallel}(\phi_i - \phi_j)$$

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

Refs [5], [6]

Examples of benchmarking: Music (2/3)

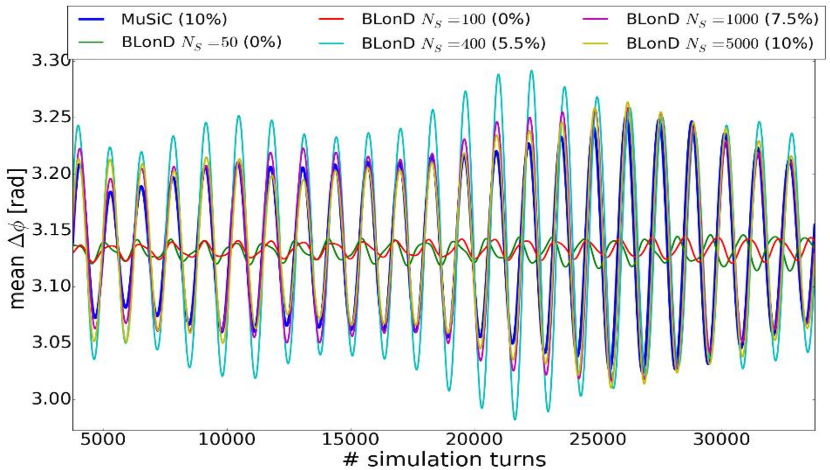
- **Short-range wake field example:**
  - Broad-band resonator impedance with f_r higher than the bunch spectrum cut-off frequency is difficult to simulate in BLonD: fixed N_M, physical contributions are lost if f_{max} is too low and noise is included if f_{max} is too high.

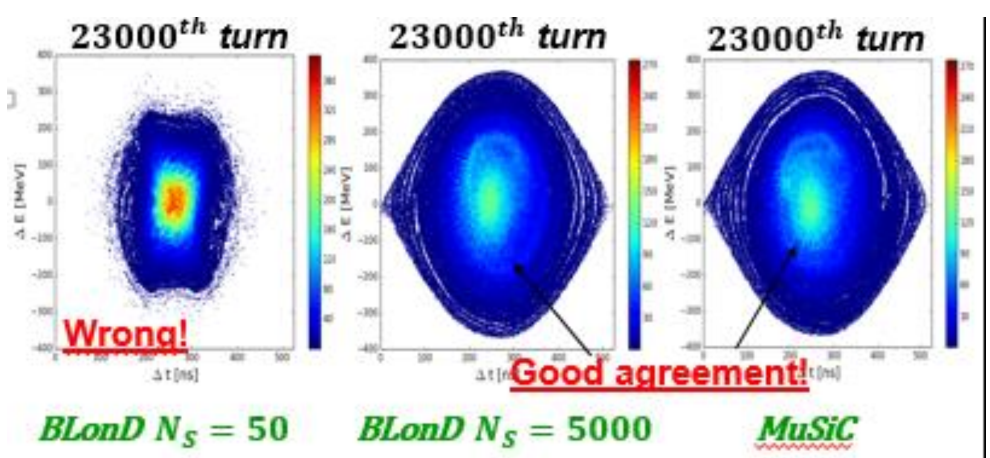


- High intensity effects, simulations should show filamentation, possible losses and later equilibrium in phase space.

- **Computational time:**
  - The largest possible Δf in BLonD can be choosen, that is $\Delta f = f_0/N_S$.
  - BLonD <u>**faster**</u> than MuSiC (factor 27).

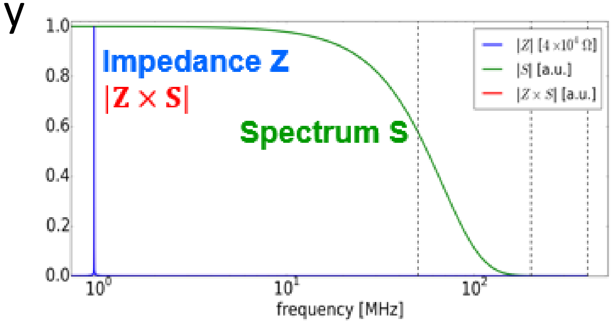
- **Results (BLonD in freq. domain):**





Examples of benchmarking: Music (3/3)

- **Long-range wake field example:**
  - ➢ 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



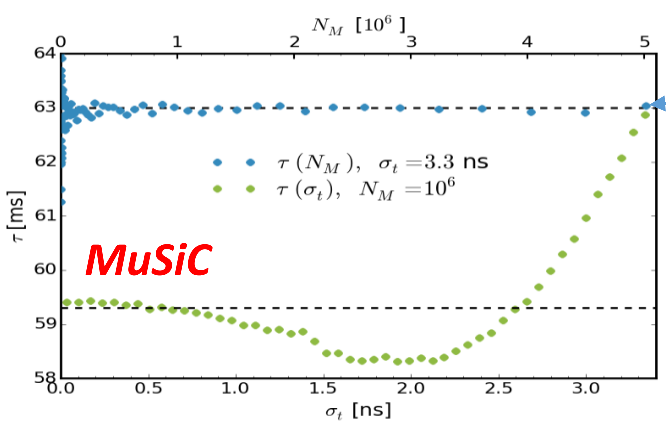
- **If $f_r = pf_0 + mf_s$, $p \in \mathbb{N}$, $m \in \mathbb{Z}$, then Robinson instability can be observed.**

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

Form factor — *Modified Bessel function of first kind*

$$\frac{1}{\tau_a} = \frac{-\pi\eta e^2 N_P}{E_0 T_0^2 \omega_s} \sum_{m=\pm 1} m\, x\, \mathrm{ReZ}(x) G_m(x\sigma_t) \qquad G_m(s) = \frac{2e^{-s^2}}{s^2} I_m(s^2) \qquad x = pf_0 + mf_s$$

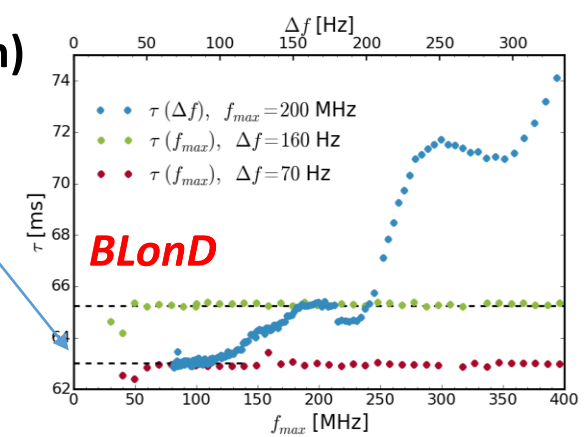
- **$\tau_a \approx 59.3$ ms and the instability growth time τ from MuSiC and BLonD should converge to τ_a for short bunches (no Landau damping effect).**



- **Results (BLonD time domain)**
  - ➢ Good agreement

Computational time:

- ➢ BLonD acts unnecessarly also on empty buckets.
- ➢ MuSiC faster than BLonD (factor 5).



Code optimization

- Example of speed-up:
  - LHC ramp with feedbacks, no collective effects, single bunch
  - Histogram and tracking with 50000 particles and 100 bins on a PC, 1000 turns.

numpy.histogram, python tracker

Function/Module	Total Time	Local Time
track	4.510	0.008
slice_constant_space_histo...	3.477	0.006
histogram	3.476	0.048
beam_coordinates	0.001	0.001
gaussian_fit	1.024	0.014
convert_coordinates	0.001	0.001
plot_long_phase_space	3.064	0.001
track	1.877	0.008
kick	1.456	1.455
drift	0.385	0.216
kick_acceleration	0.027	0.027

C++ histogram, C++ tracker

Function/Module	Total Time	Local Time
track	1.191	0.008
gaussian_fit	0.993	0.014
slice_constant_space_histo...	0.188	0.167
data_as	0.048	0.016
__init__	0.026	0.026
beam_coordinates	0.001	0.001
__getattr__	0.000	0.000
convert_coordinates	0.002	0.002
loadtxt	1.113	0.335
track	0.747	0.611
drift	0.082	0.067
data_as	0.048	0.016
__init__	0.026	0.026
ascontiguousarray	0.016	0.006
__getattr__	0.000	0.000

- **RESULTS:**

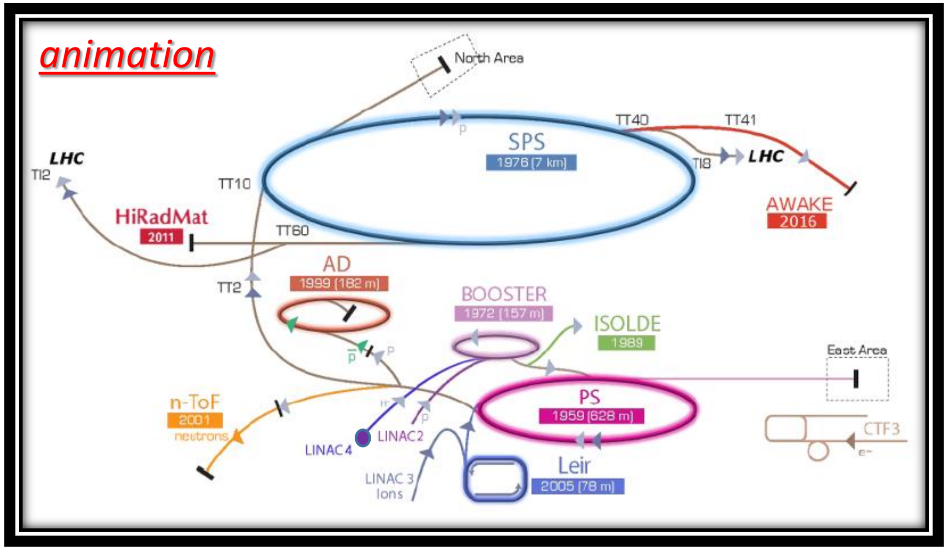
  histogram: from 3.477 to 0.188

  tracker: from 1.877 to 0.747

Contents

Motivation remainder

- 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), now 1.4 GeV
  - Higher acceleration rate, more demanding beam parameters
  - RF systems: narrow-band ferrite => broad-band Finemet
    (Finemet review, CERN, 2105, Refs [7], [8], [9], not discussed here for brevity)
- 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



<u>After LS2 relevant PSB parameters:</u>

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

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

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!

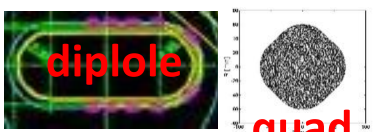
Ref [14]

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

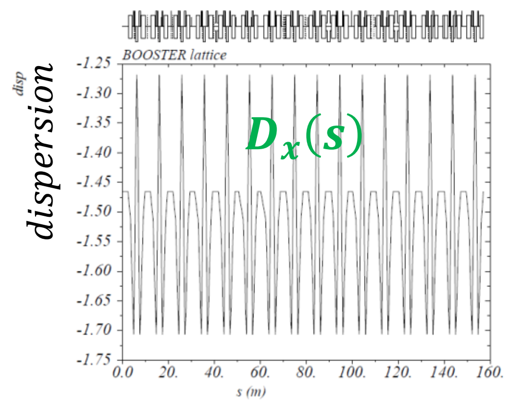
$$\nabla^2 \boldsymbol{E} - \frac{1}{c^2}\frac{\partial \boldsymbol{E}}{\partial t} = \frac{\nabla \rho}{\varepsilon_0} + \mu_0 \frac{\partial \boldsymbol{J}}{\partial t}$$

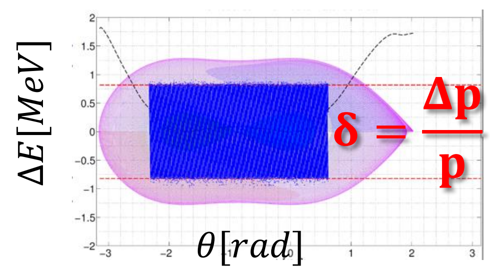
LSC

OUTPUT:

- Z/L averaged over 1 σ

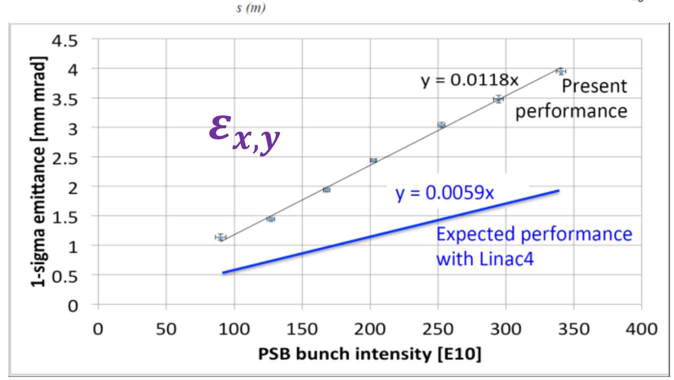
$$\frac{Z}{n} = \sum_{i=1}^{211} L_i \left(\frac{Z}{n\,L}\right)_i = \mathbf{633.14\ \Omega}$$

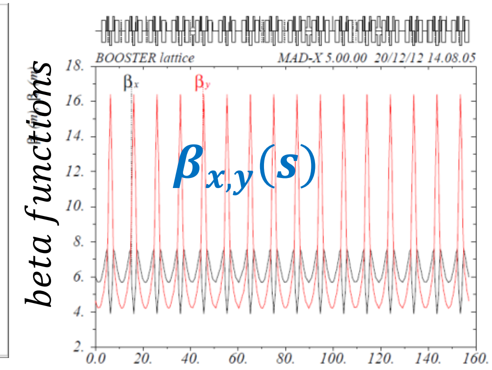




$$\sigma_x(s) = \sqrt{\varepsilon_x\,\beta_x(s) + D_x^2(s)\,\delta^2}$$

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

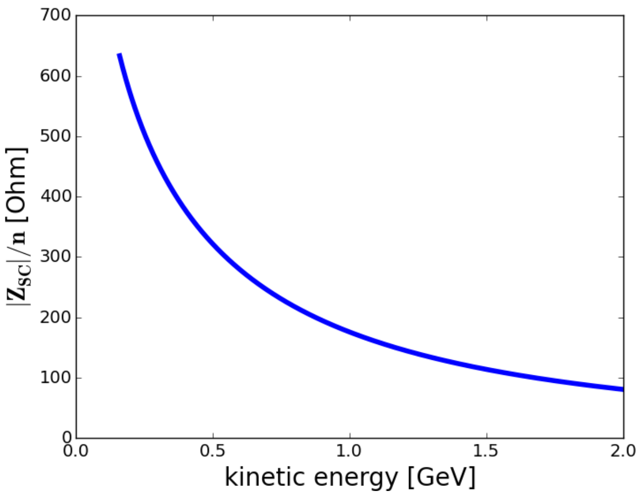




Space charge impedance during cycle

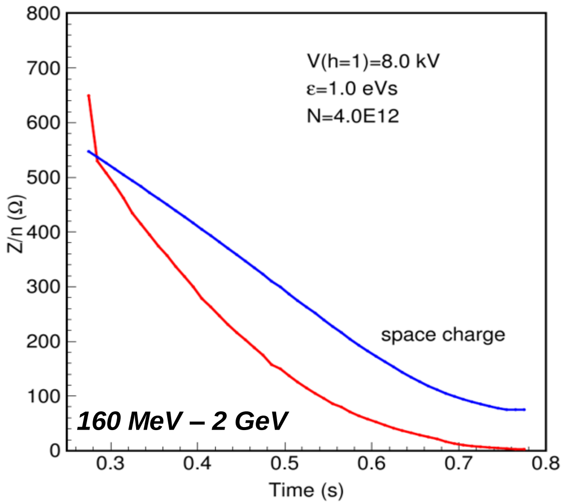
- Scaling based on value at 160 MeV of 633.14 Ohm => used in all simulations

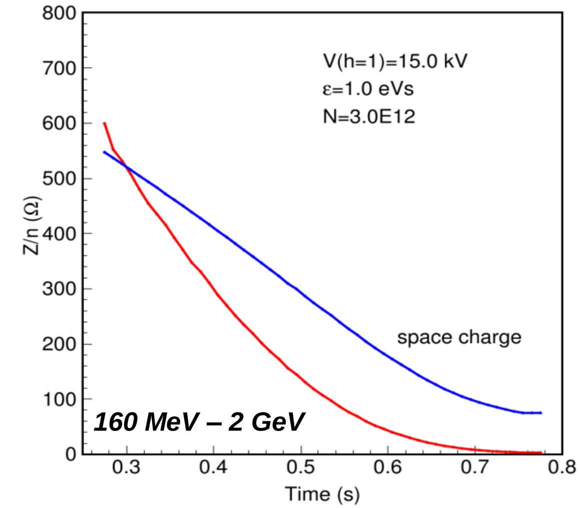
$$\frac{|Z_{SC}|}{n}(E_k) = \frac{Z_0}{\beta(E_k)\gamma(E_k)^2}\left(1.2 + \frac{1}{2}\ln\frac{\beta(E_k)\gamma(E_k)}{\beta(160\,MeV)\gamma(160\,MeV)}\right)$$



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

- **<u>Loss of Landau damping in single RF for both HL-LHC and ISOLDE beams</u>**
- ***Landau damping in a single RF is lost for the whole cycle above ~3e12***
- ***Oscillations will be damped by phase loop***



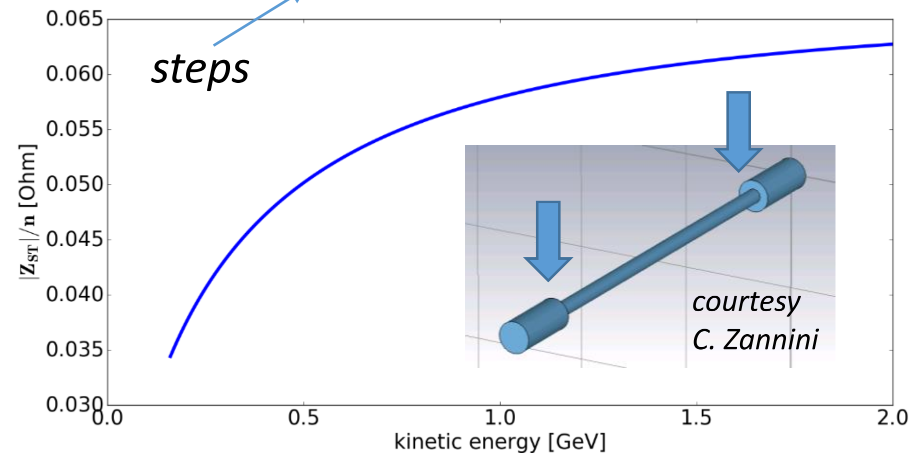


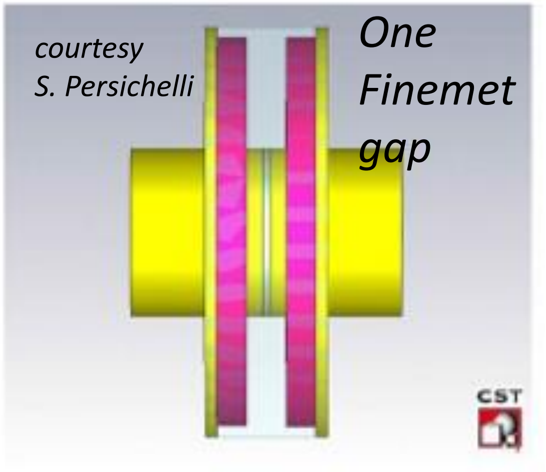
PSB impedance model

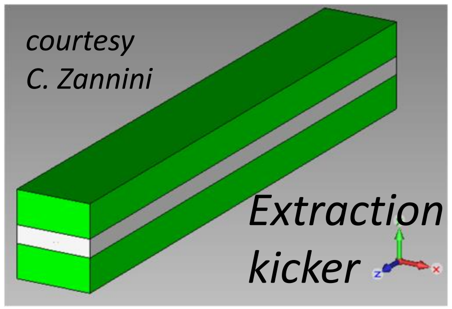
- Space charge +
  - Finemet cavities
  - Extraction kickers
  - Extraction kicker cables
  - KSW magnets
  - Resistive wall
  - Steps (beam pipe discontinuities)

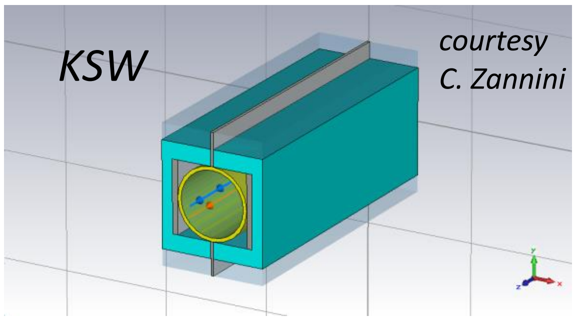
Impedances in red depend on the beam energy

Negligible compared to SC!







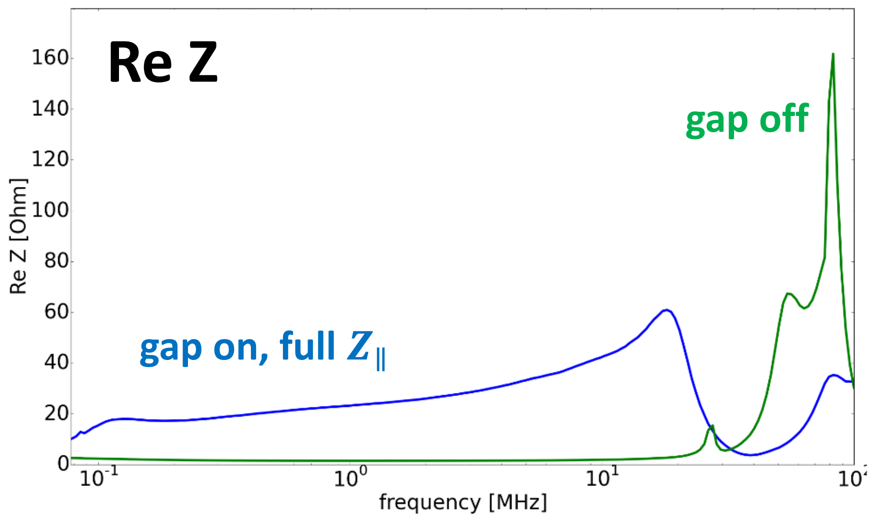


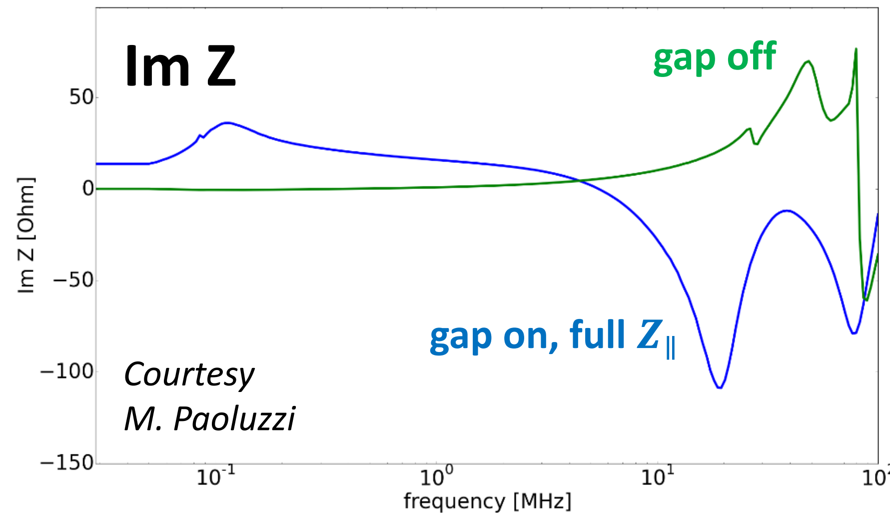
Space charge and Finemet are the main sources.

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*

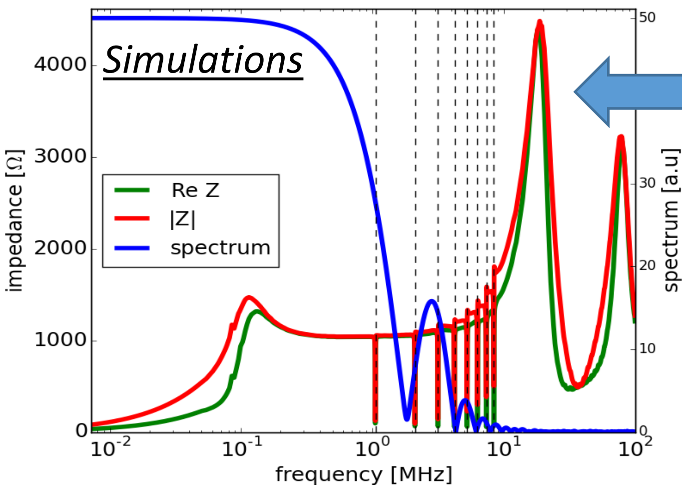




- f_{rev} varies from 0.99 MHz to 1.81 MHz → **short circuited impedance is very small for beam!**
- No dependence on the beam energy

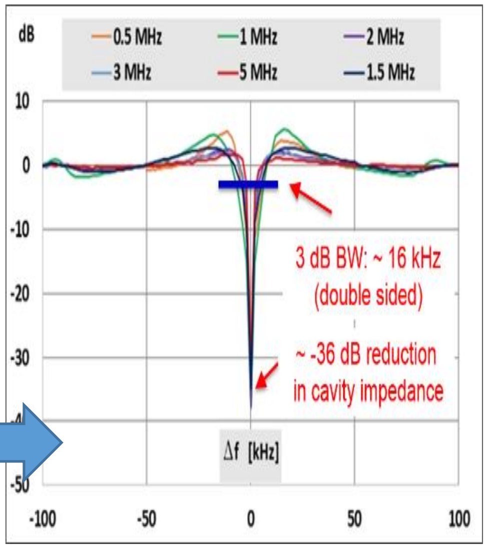
Full PSB impedance model with Finemet closed-loop

At 300 ms (frequenct domain)



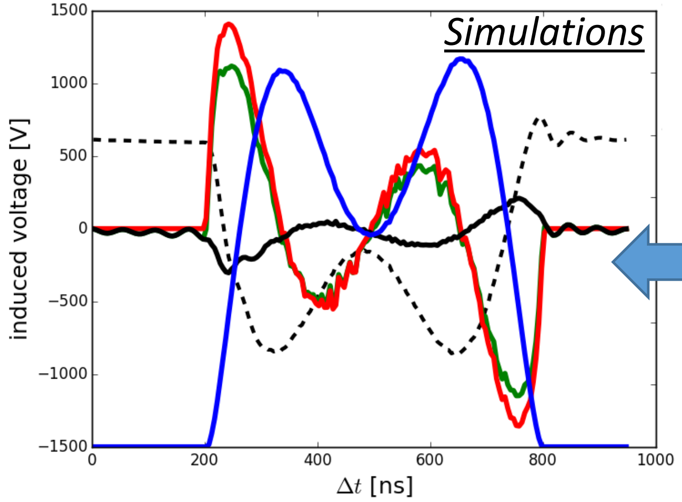
- Finemet impedance is reduced at first 8 (16) revolution harmonics through LLRF feedback (notches).
- In simulations notches are reproduced taking into account the measured feedback transfer function.

Measurements



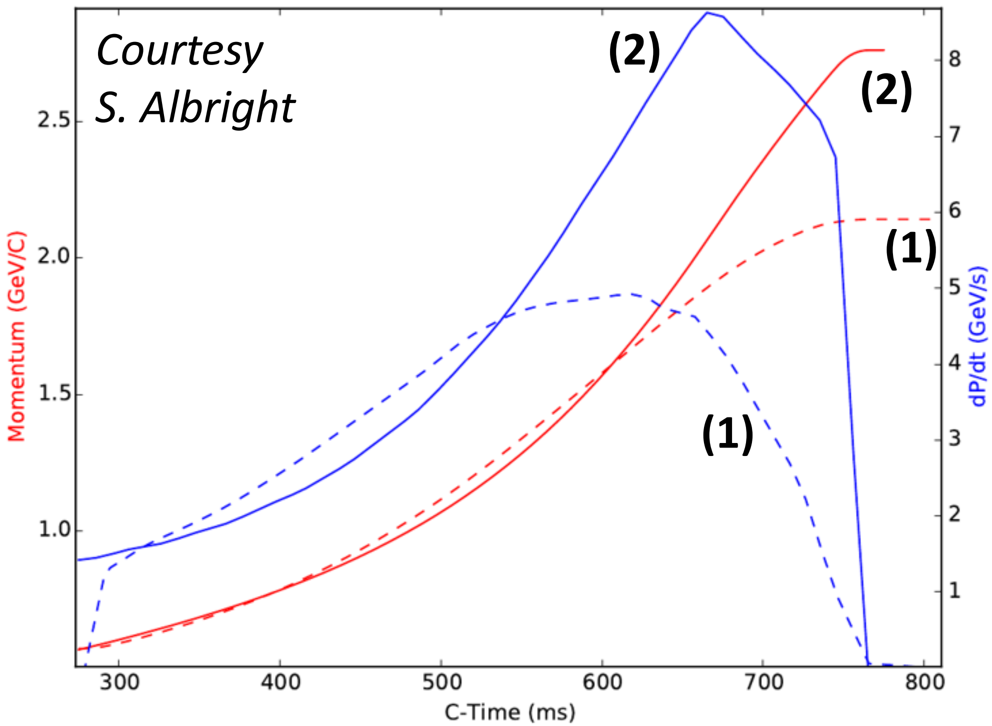
Courtesy M. Paoluzzi

At 300 ms (time domain)



- **Bunch profile** (1 eVs) in double RF (bunch lengthening mode).
- **Multi-turn induced voltage** as the sum of **space-charge** and **Finemet voltage with reduction by feedback.**
- Finemet voltage without reduction is in dashed line

Cycles



Two different momentum programs

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 interesting and critical cases!

- *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

Beam-based feedbacks

- 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 $\Delta\varphi_{b,rf}$.
- The aim of the radial loop is to maintain the beam orbit at the design one.

RF frequency corrections by phase and radial loops

Total phase difference $\Delta\varphi = \Delta\varphi_{b,rf} + \varphi_{noise}$

Relative difference between beam orbit and design radii

$$\frac{\Delta R}{R_d} = \frac{\Delta\omega_{rf}}{\omega_{rf,d}} \frac{\gamma^2}{\gamma_t^2 - \gamma^2}$$

$$\Delta\omega_{pl}^{n+1} = a_1 \Delta\omega_{pl}^{n} + g_{pl}(b_0 \Delta\varphi^{n} - b_1 \Delta\varphi^{n-1})$$

$$\Delta\omega_{rl}^{n+1} = \Delta\omega_{rl}^{n} + (g_p + g_i)\left(\frac{\Delta R}{R_d}\right)^{n} - g_p \left(\frac{\Delta R}{R_d}\right)^{n-1}$$

$$\omega_{rf}^{n+1} = \omega_{rf,d}^{n+1} + \Delta\omega_{rf}^{n+1} = \omega_{rf,d}^{n+1} + \Delta\omega_{pl}^{n+1} + \Delta\omega_{rl}^{n+1}$$

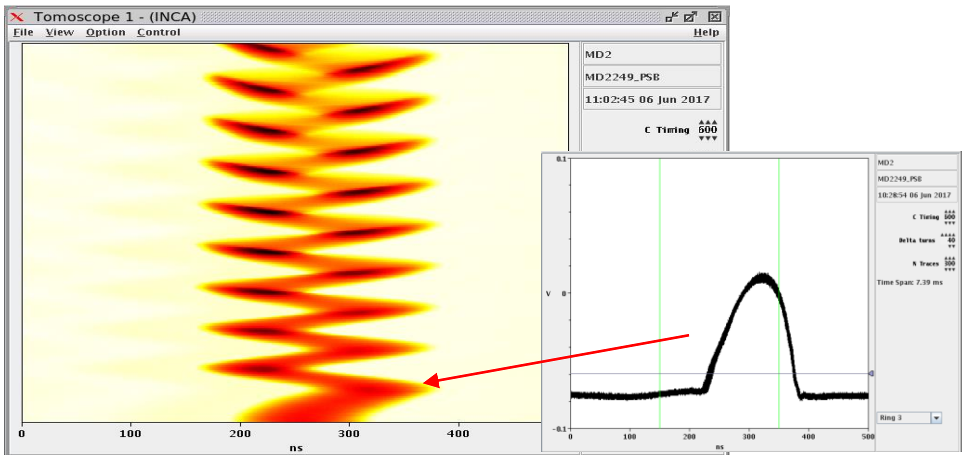
$$V_{rf} = V_1 \sin(\omega_{rf}\, t)$$

- **Model not perfect**: phase loop calibration between measurements and simulations necessary to have correct values for g_{pl} in simulations
- Correct values of g_{pl} are important for phase loop studies and also for noise injection (see later)

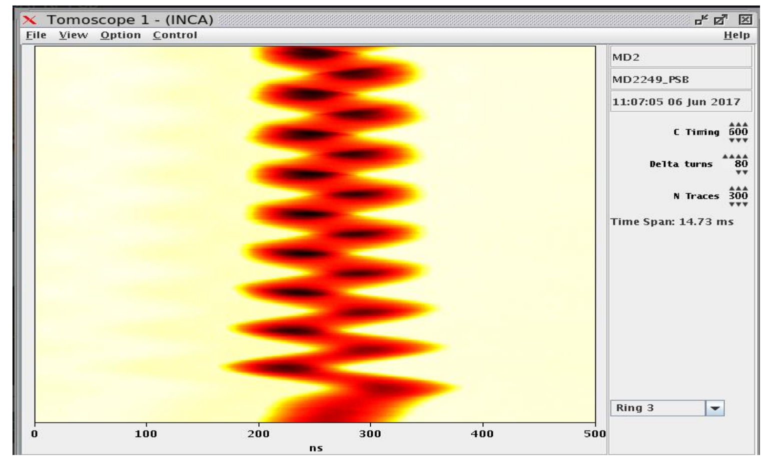
Phase-loop calibration: measurements

- Check dipole oscillations damping time with phase loop on after phase kick.
- Scan different gains, from 0 (off) to 0.5.

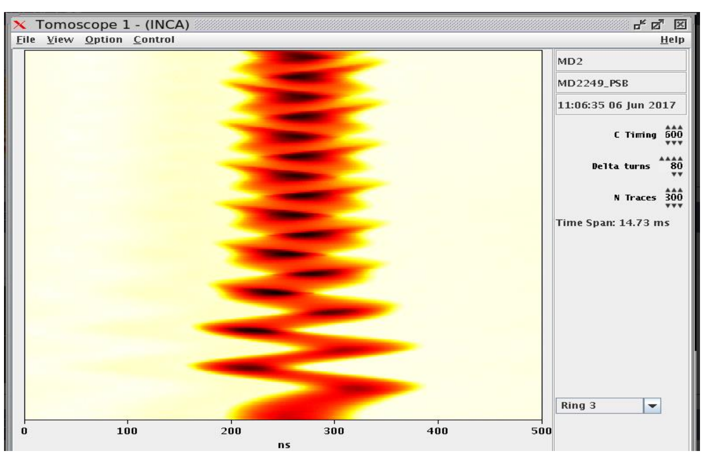
Gain 0



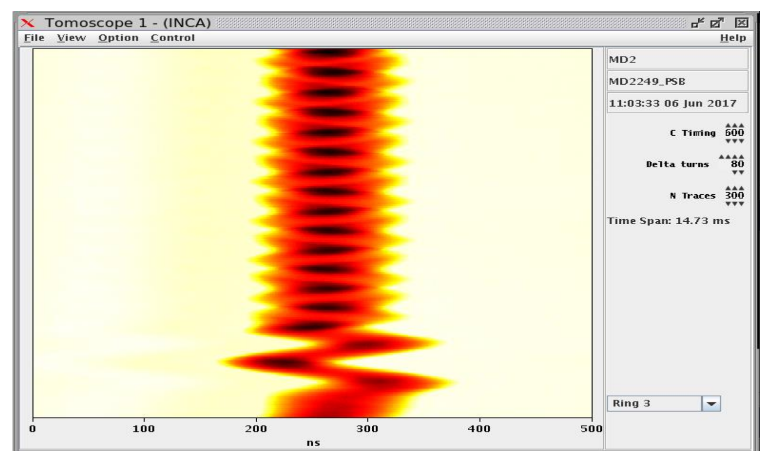
Gain 0.01



Gain 0.05



Gain 0. 5

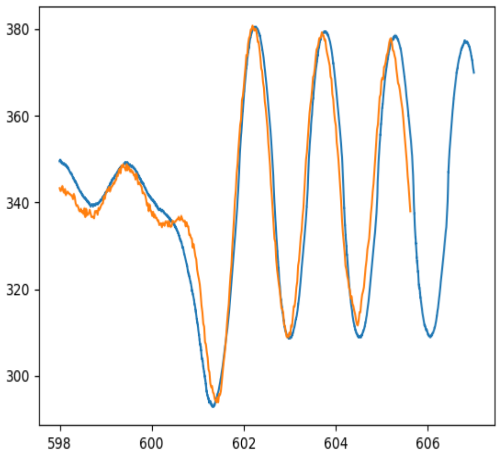


Phase-loop calibration: results

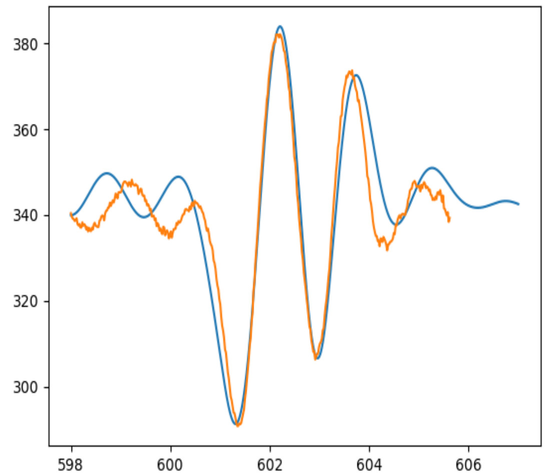
- Match bunch position evolution in measurements and BlonD to calibrate gains.

FWHM bunch position [ns]

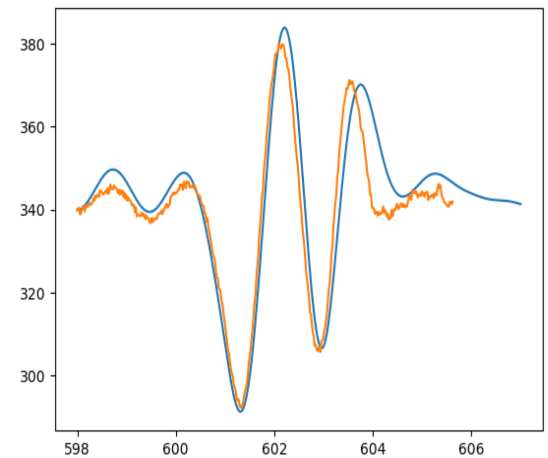
Meas: 0 phase shift, 0 gain
BLonD: 2 rad, 0 gain



Meas: 0 phase shift, 0.2 gain
BLonD: 2 rad, 1.84e3 gain

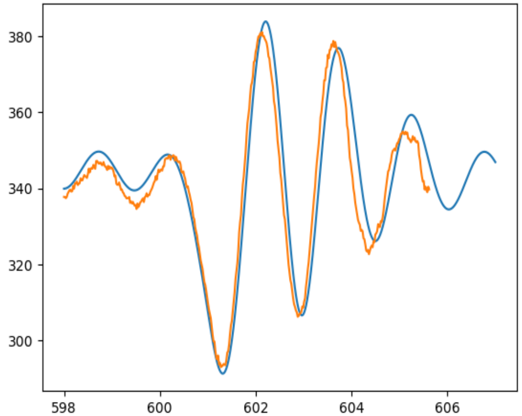


Meas: 0 phase shift, 0.4 gai
BLonD: 2 rad, 2.5e3 gain

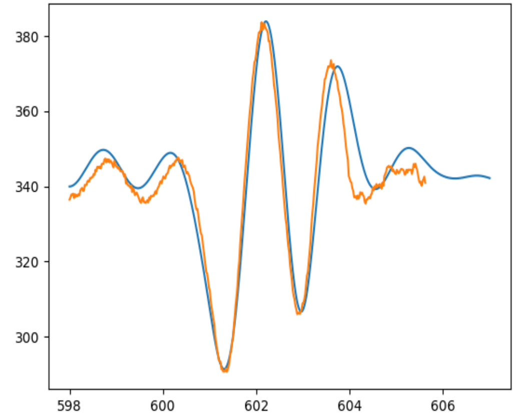


FWHM bunch position [ns]

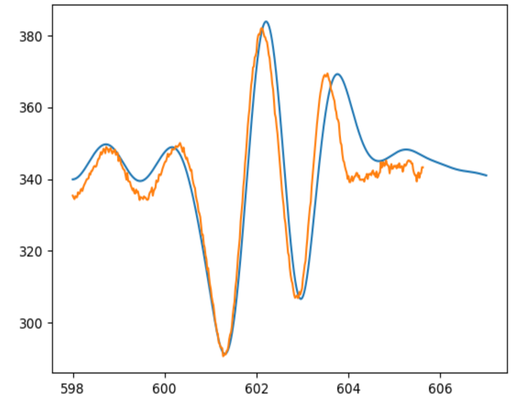
Meas: 0 phase shift, 0.1 gain
BLonD: 2 rad, 0.92e3 gain



Meas: 0 phase shift, 0.3 gain
BLonD: 2 rad, 2e3 gain

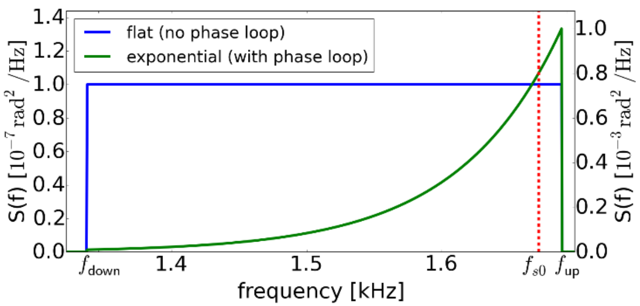


Meas: 0 phase shift, 0.5 gain
BLonD: 2 rad, 2.8e3 gain



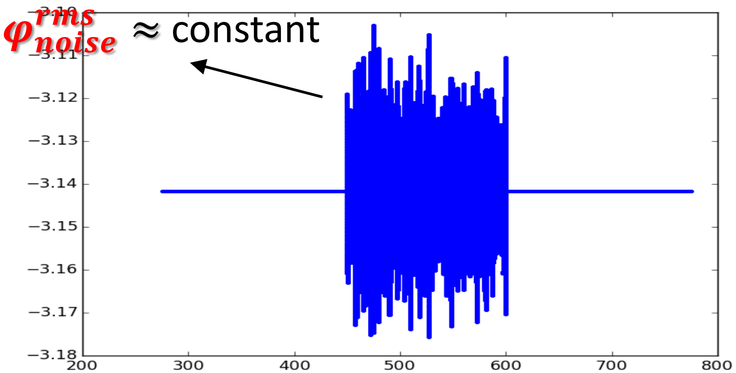
Band-limited RF phase noise

- Current blow-up with high harmonic phase modulation from dedicated RF system, difficult to set, control in operation and reproduce in simulations
- Can band-limited RF phase noise in h=1 substitute this method saving also some dedicated RF voltage?

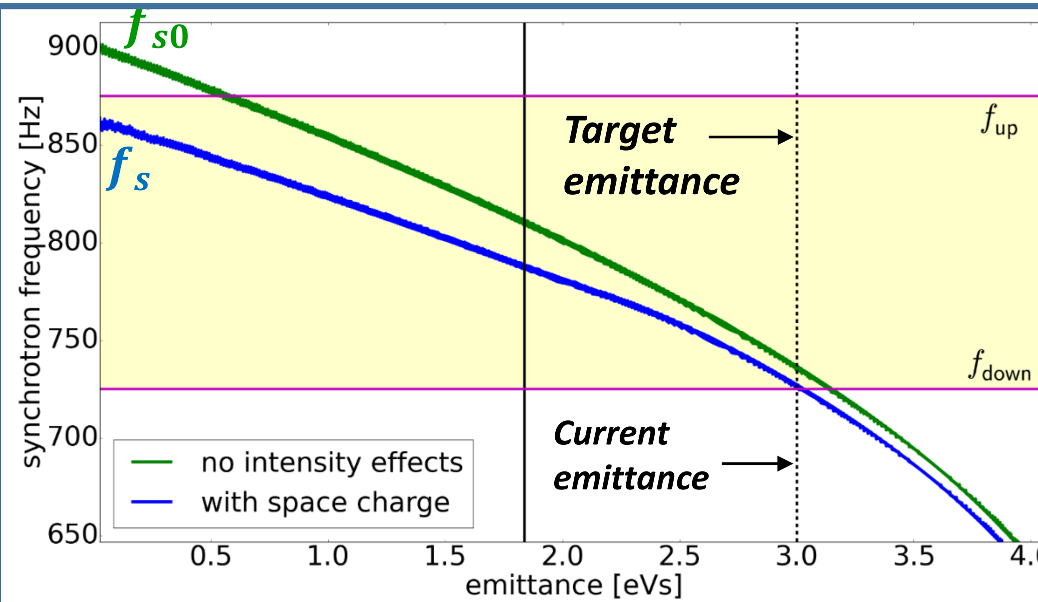


$$\varphi_{noise} = IDFT\left(DFT(N(t)) \cdot \sqrt{f_{rev}\, S(f)}\right)$$

$\varphi_{noise}^{rms} \approx$ constant



$$V_{rf} = V_1 \sin(\omega_{rf,d} t + \varphi_{noise})$$

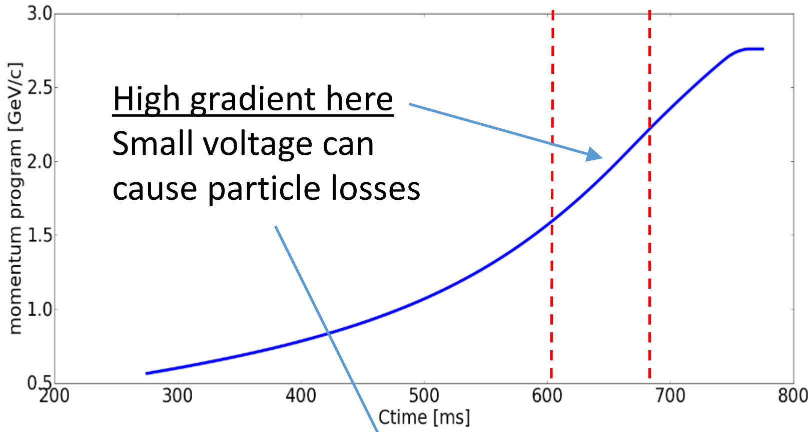


- Example of synchrotron frequency distribution in single RF in PSB.
- The bunch emittance increases from 1.8 eVs to 3 eVs applying phase noise in the band [725 Hz, 875 Hz].
- Space charge lowers the synchrotron frequency (PSB below transition) and the band should follow the decrease.

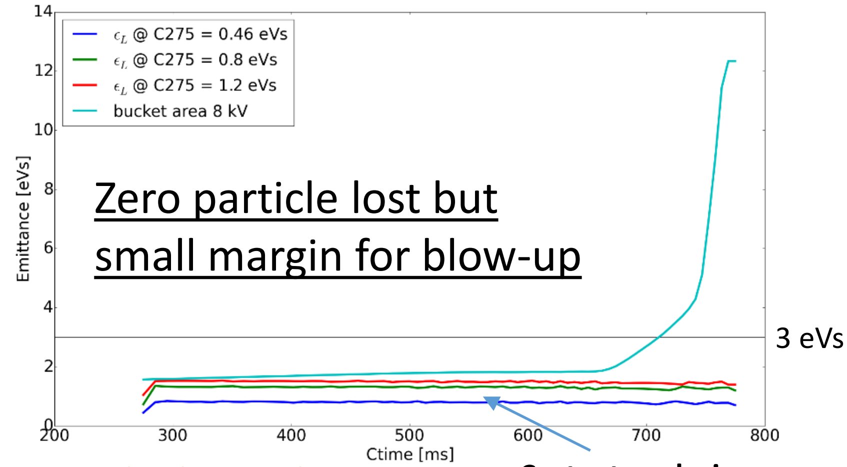
Refs [15], [16]

Simulations LHC beams: constant 8 kV

smooth momentum program

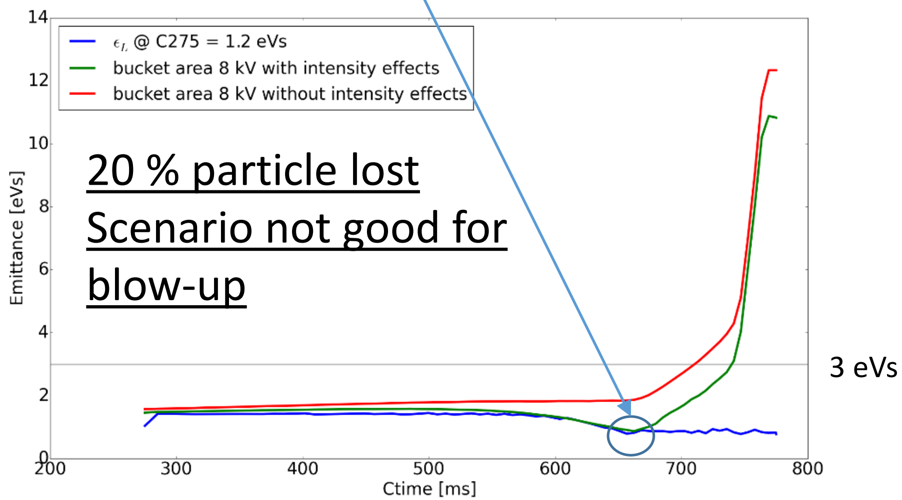


1) No blow-up, no intensity effects

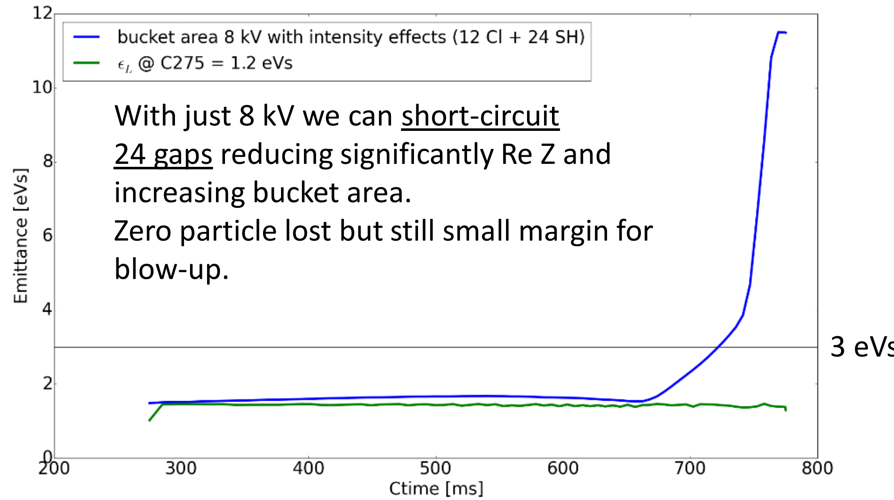


Here ε_L according to vc1 definition to check critical points during the ramp

Costant ε_L during ramp (Liouville theorem)



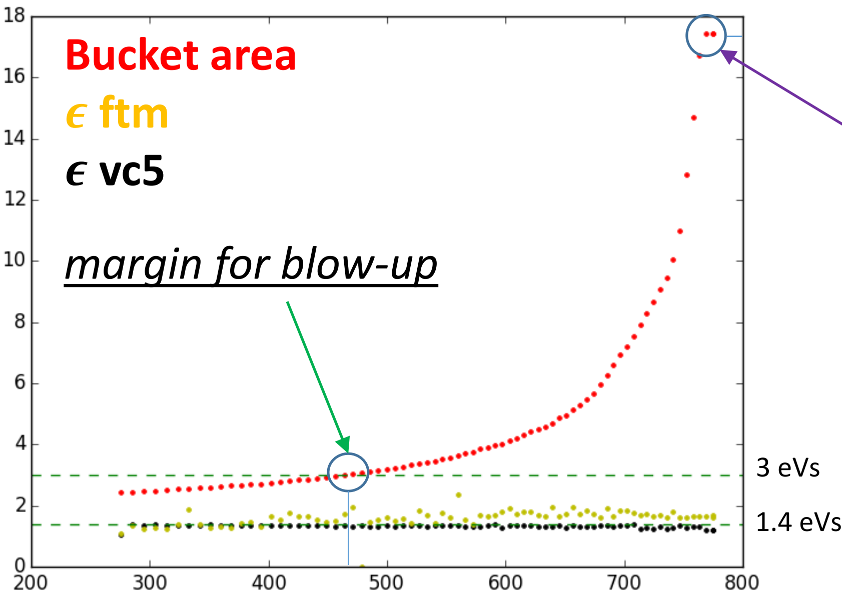
2) No blow-up, with intensity effects (open-loop for Finemet gaps)



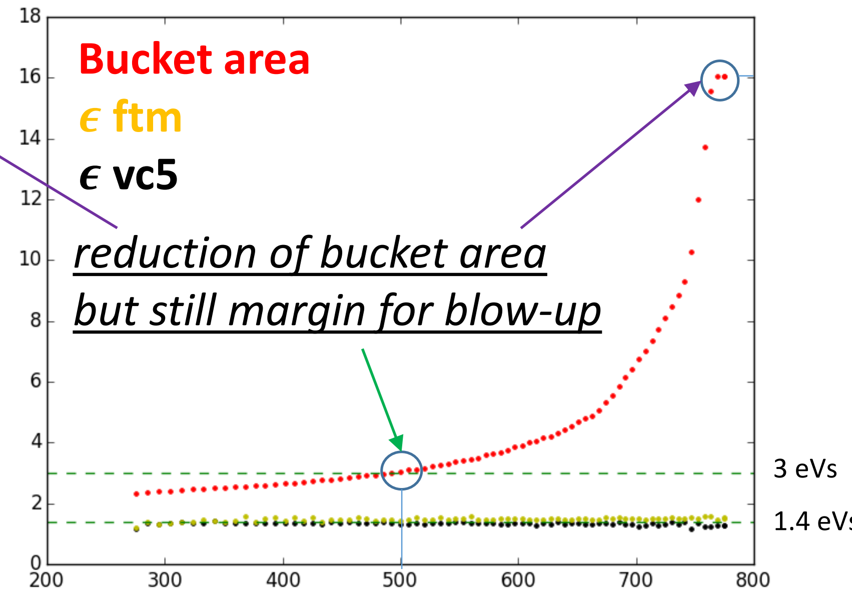
3) No blow-up, with intensity effects and short-circuiting some Finemet gaps

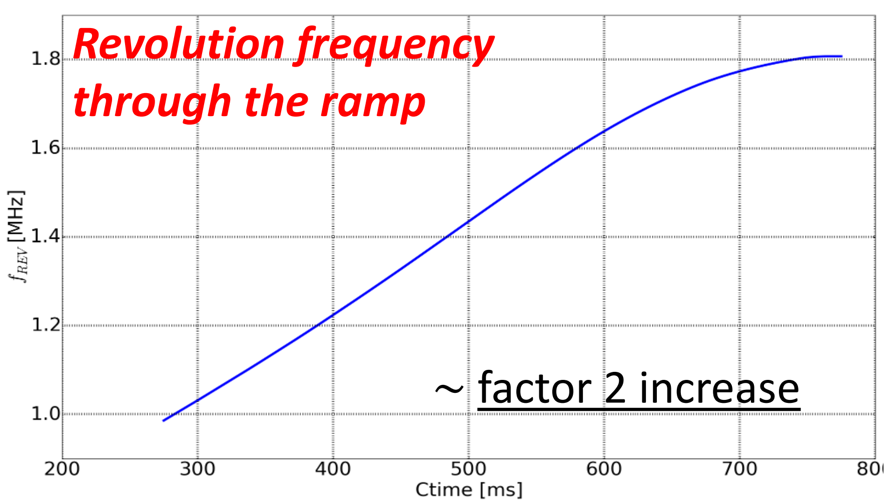
Simulation LHC beams: constant 16 kV

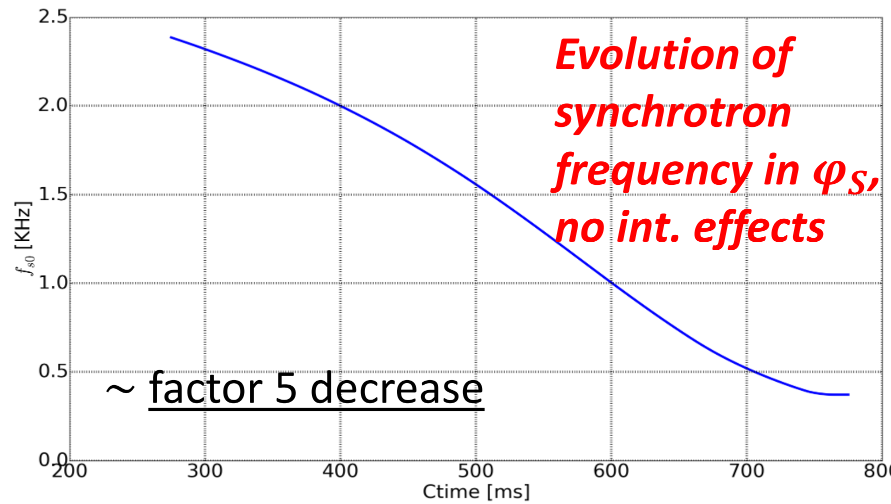
1) No blow-up, no intensity effects



2) No blow-up, with intensity effects



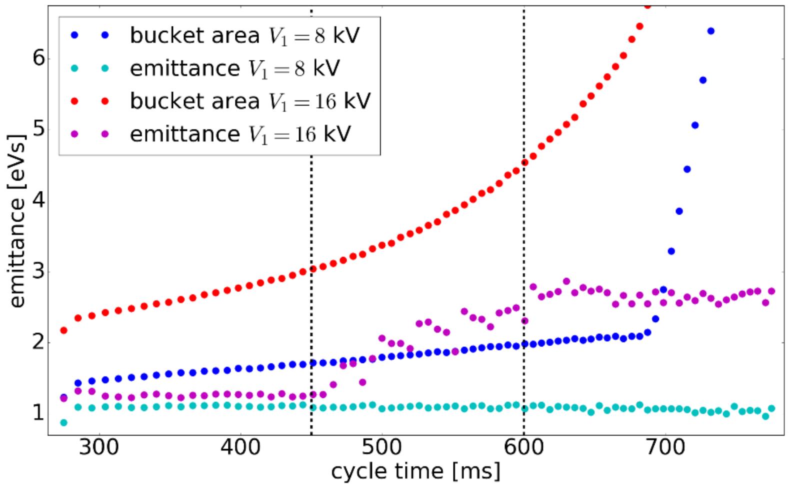




The RF noise must be regenerated to follow f_{REV} and f_{s0}!

Simulation LHC beams: constant 16 kV

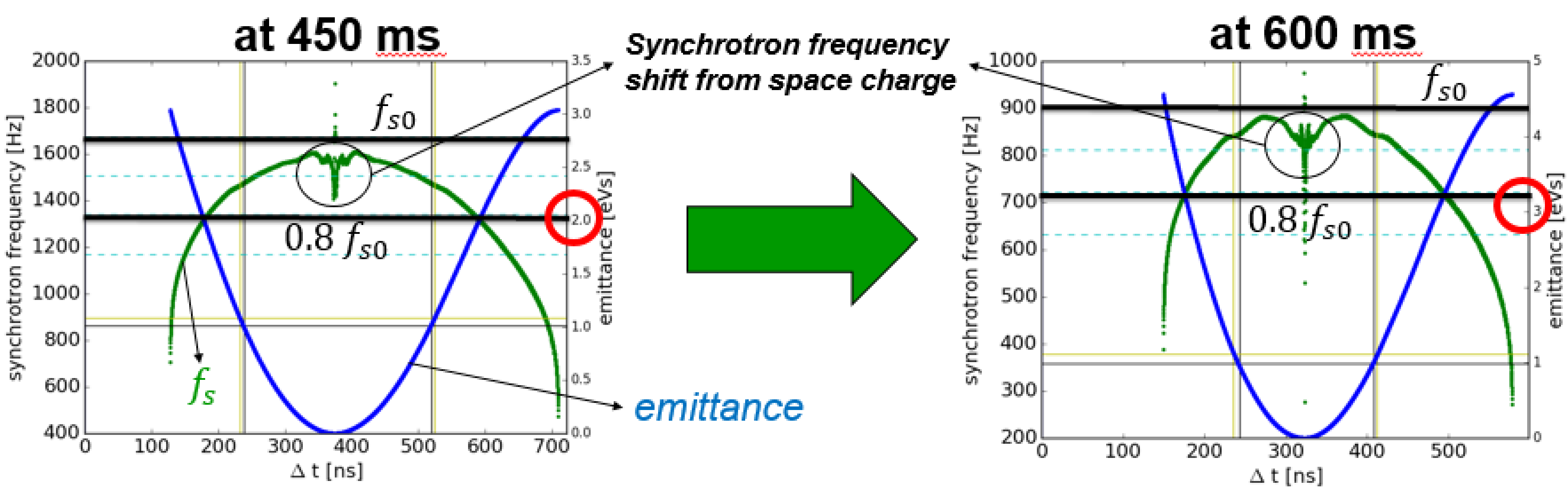
3) With blow-up, with intensity effects, no feedbacks



Few time margin for blow-up with 8 kV

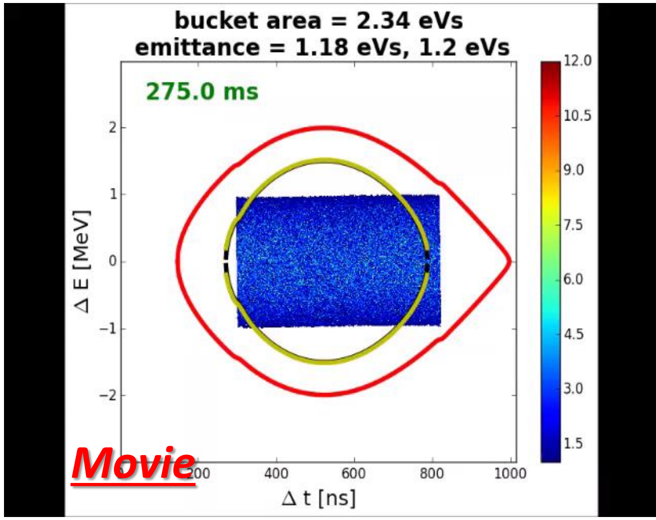
1 eVs -> 3 eVs with 16 kV, no losses

- 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

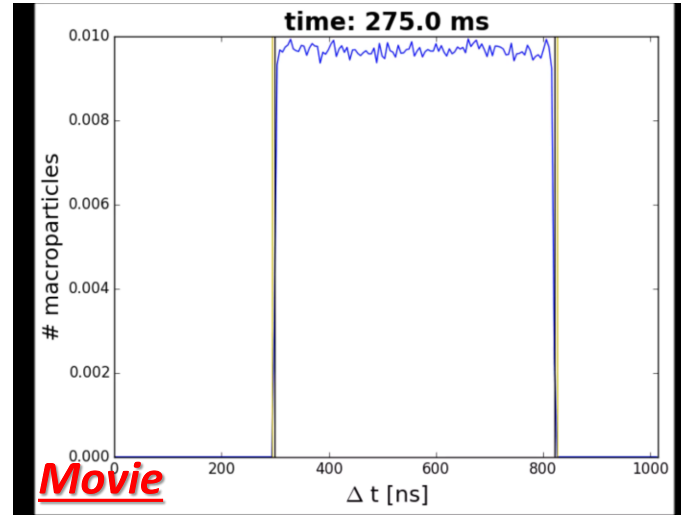


Phase space evolution

Separatrix

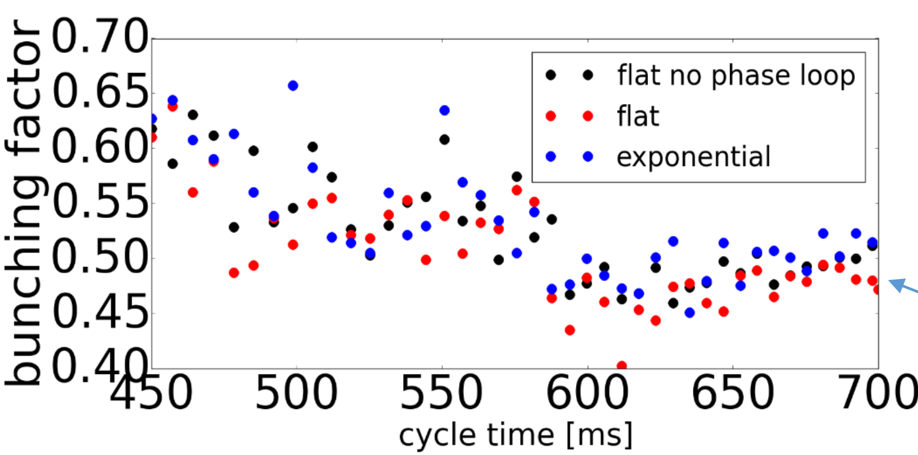
Hamiltonian

Bunch length marked using PSB conventions



Profile evolution

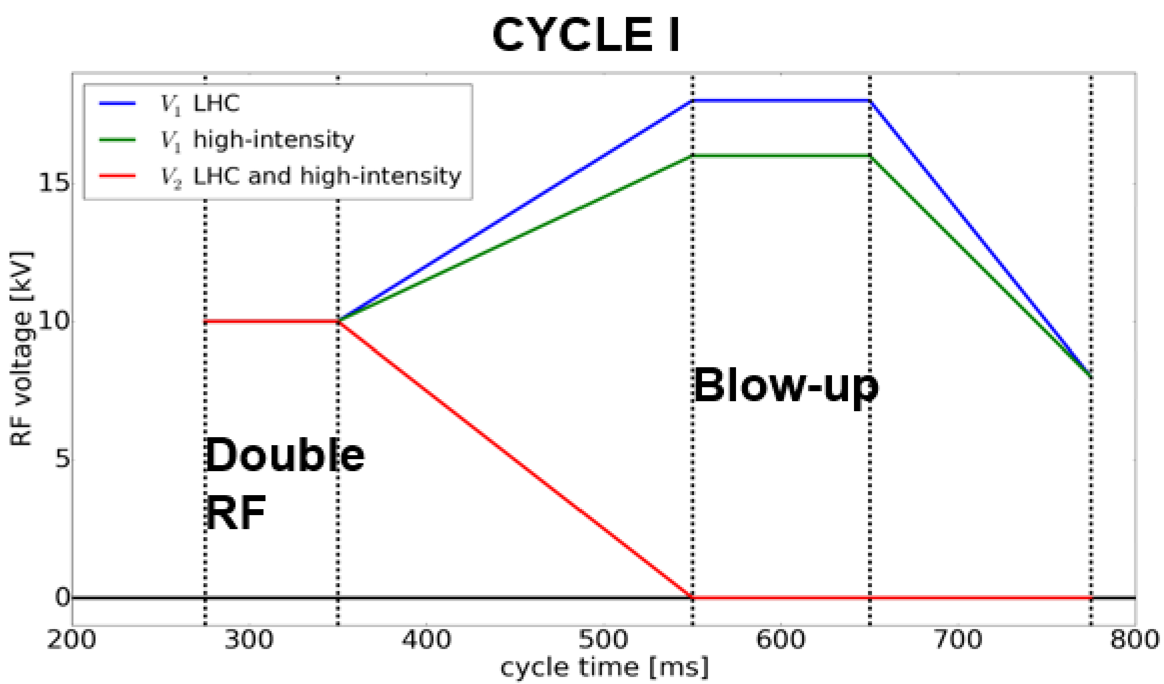
4) With blow-up, with intensity effects, with feedbacks



- 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!

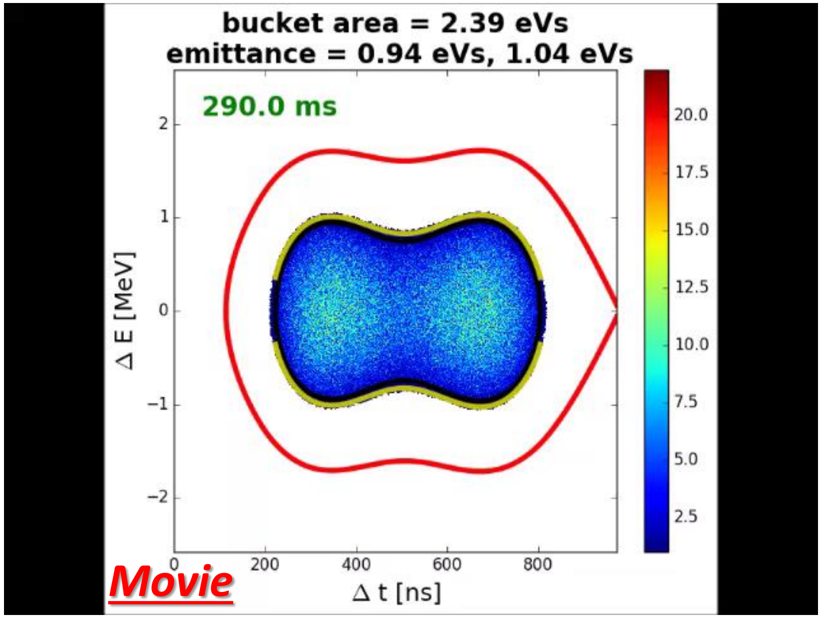
More realistic simulations: setting up

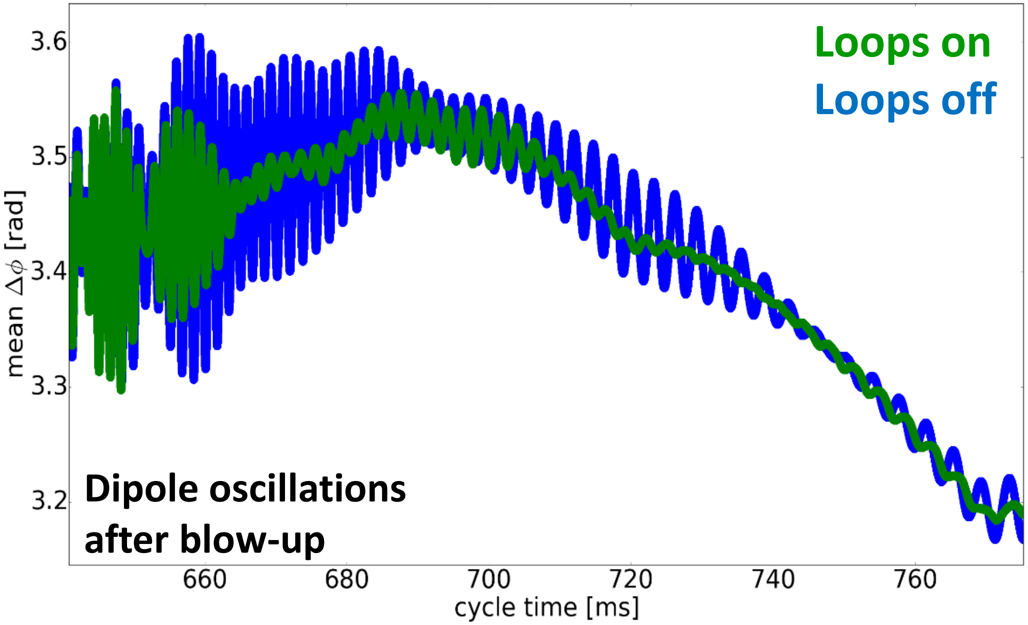
- LHC and high-intensity beams are studied. Maximum available RF voltage 20 kV.
- First part of the ramp in double RF (bunch lengthening) to reduce space charge.
- Controlled longitudinal emittance blow-up using phase noise in 550-650 ms.
- Noise injected in the phase loop of the main RF (h=1) at a limited 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

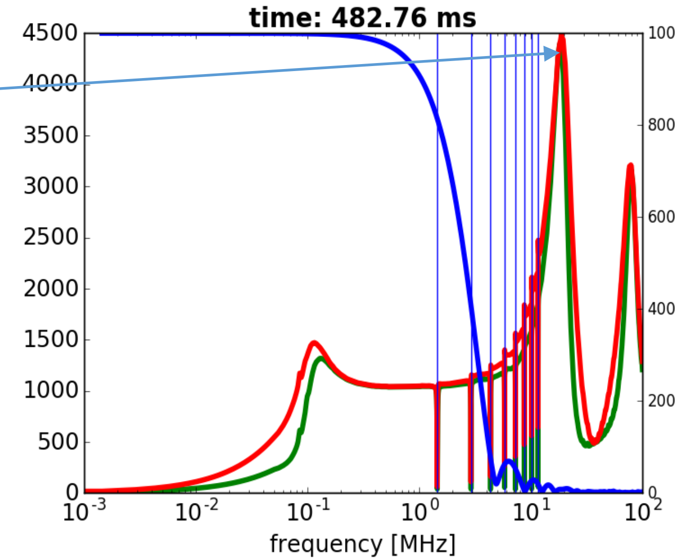
- For LHC beams ($N = 3.6 \times 10^{12}$) no instability observed using CYCLE I.
- Blow-up from 1 eVs to 3 eVs in just 100 ms without losses.
- The phase and radial loops are applied also after emittance blow-up.
- Dipole oscillations significantly damped.



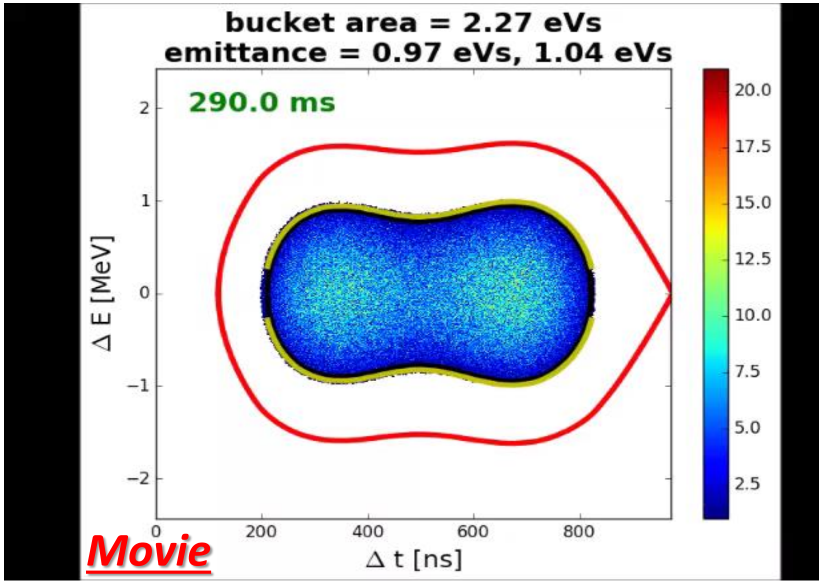


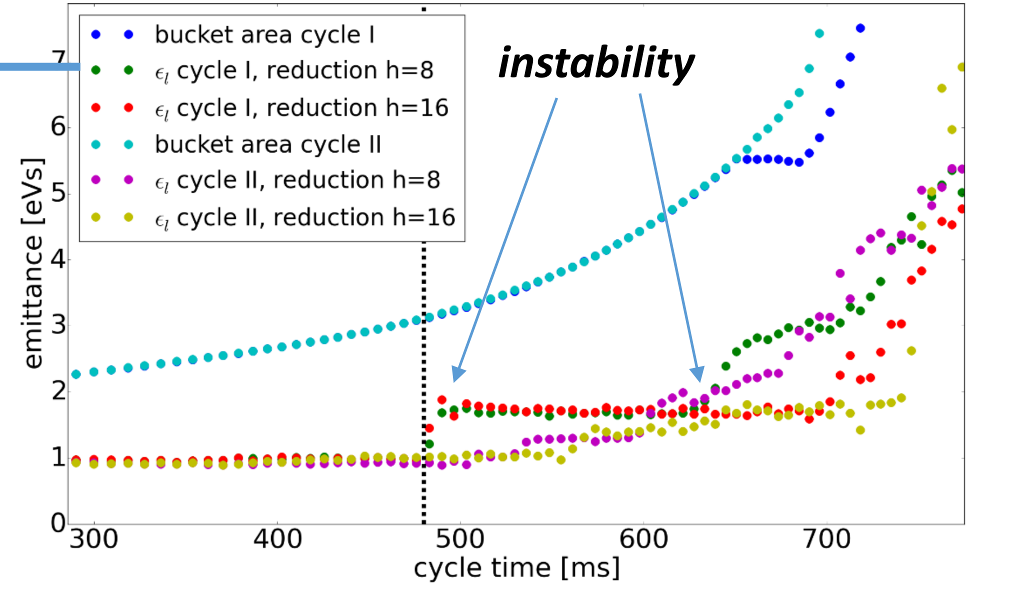
More realistic simulations: high-intensity

- 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!



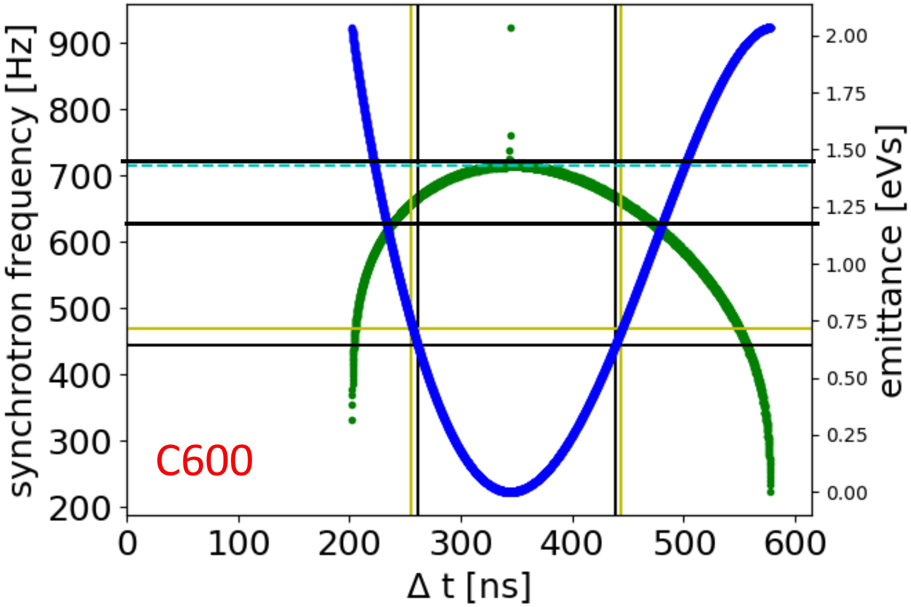


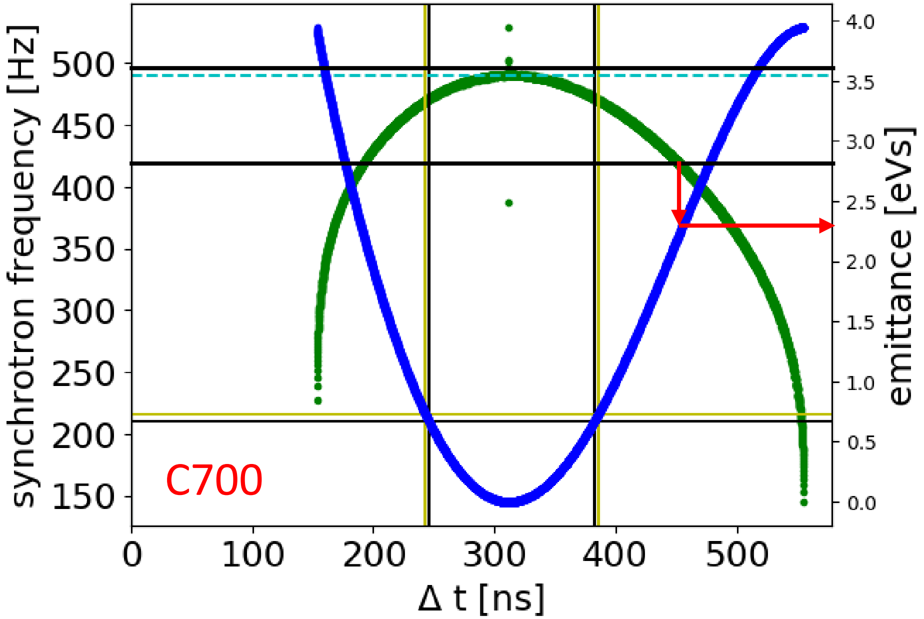
Phase noise in current machine (1/6)

- Phase noise injection tested in PSB for current situation:
  - Feasibility of the method applied to PSB
  - Reliability of simulations for future scenario

Single RF

- LHC_indiv beam with 0.8 eVs emittance at C600, N=3e11
- We want to blow up the beam to 2.8 eVs at C775
- Noise applied in C600-C700
- Single RF 8 kV
- As an example we take a band = [0.9 fs0, 1.01 fs0]
- The goal is to target 2.3 eVs

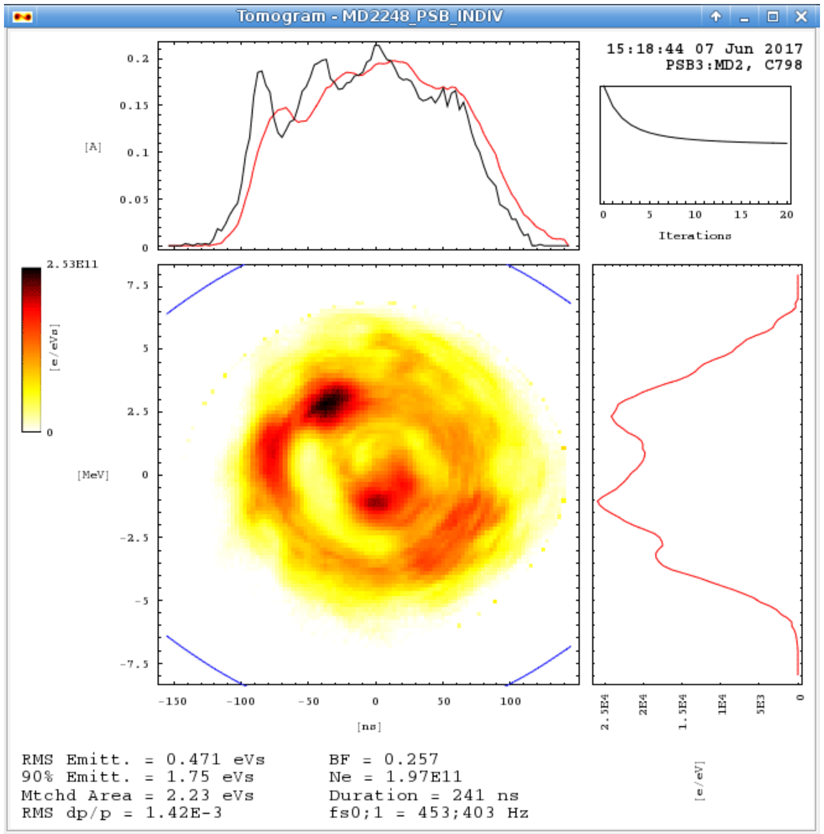




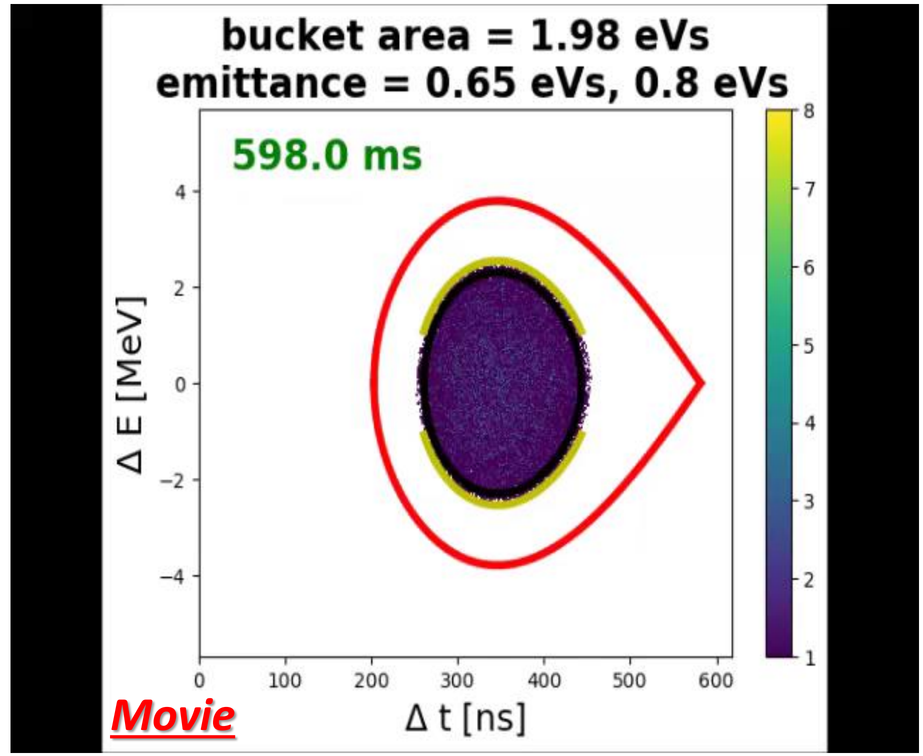
Phase noise in current machine (2/6)

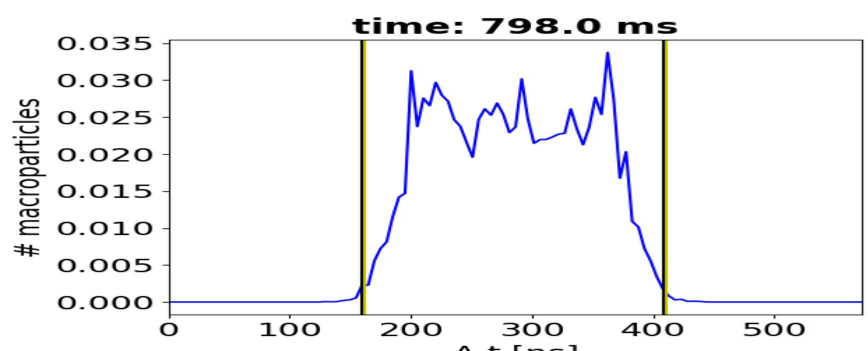
Single RF

MEASUREMENT



SIMULATION



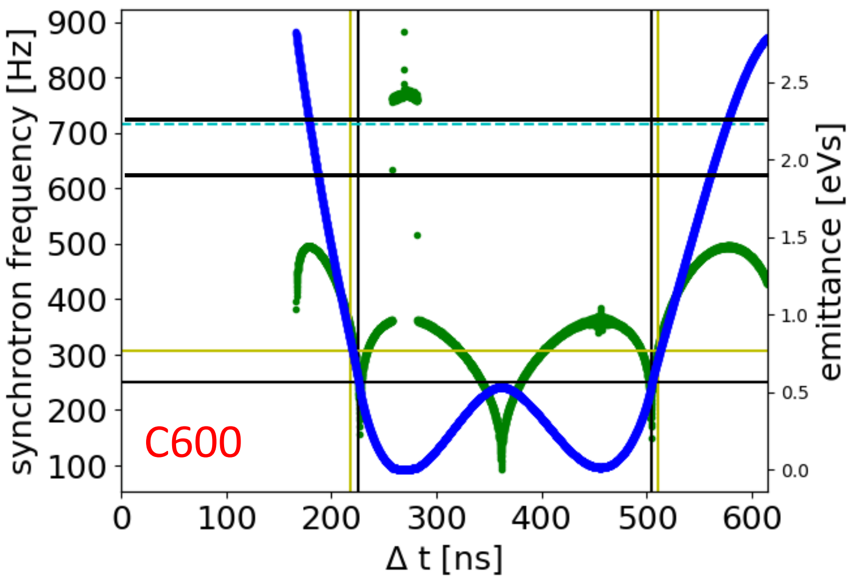


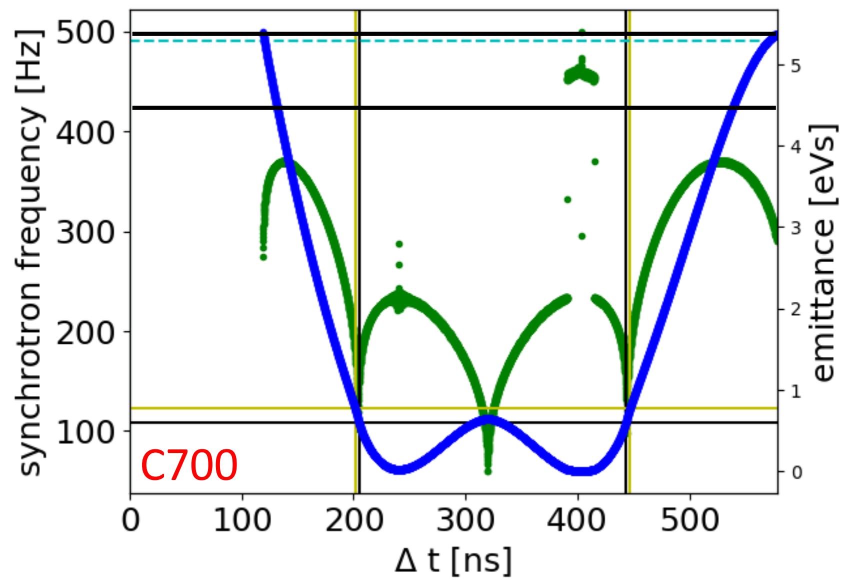
Not good bunch at C798:
Islands and no filamentation

Phase noise in current machine (3/6)

Double RF

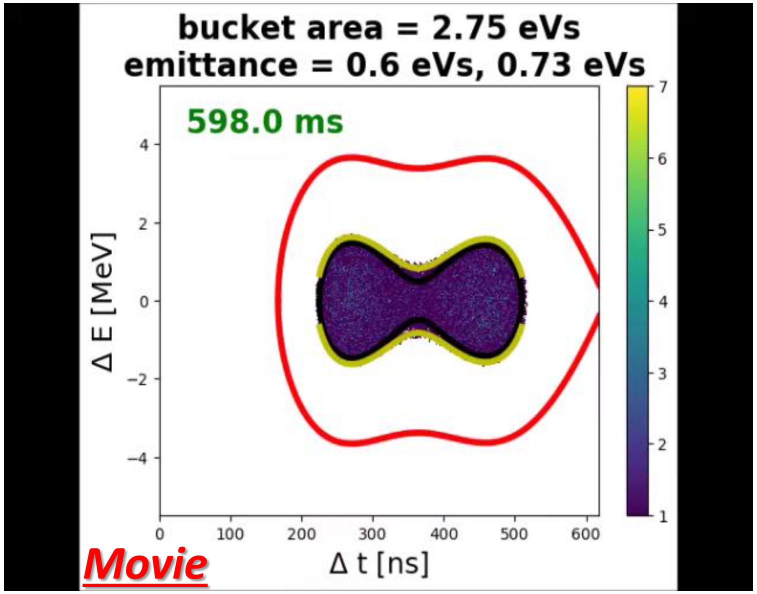
- LHC_indiv beam with 0.8 eVs emittance at C600, N=3e11
- We want to blow up the beam to 2.8 eVs at C775
- Noise applied in C600-C700
- Double RF 8+6 in bunch lenghtening in C600-C700, then linear decrease of V2 to 0 at C800
- The noise band follows fs0 in single RF 8 kV (exactly as for previous example)
- fs0 in single RF 8 kV ≈ 2 * fs0 lobes
- Quadrupole oscillations excited

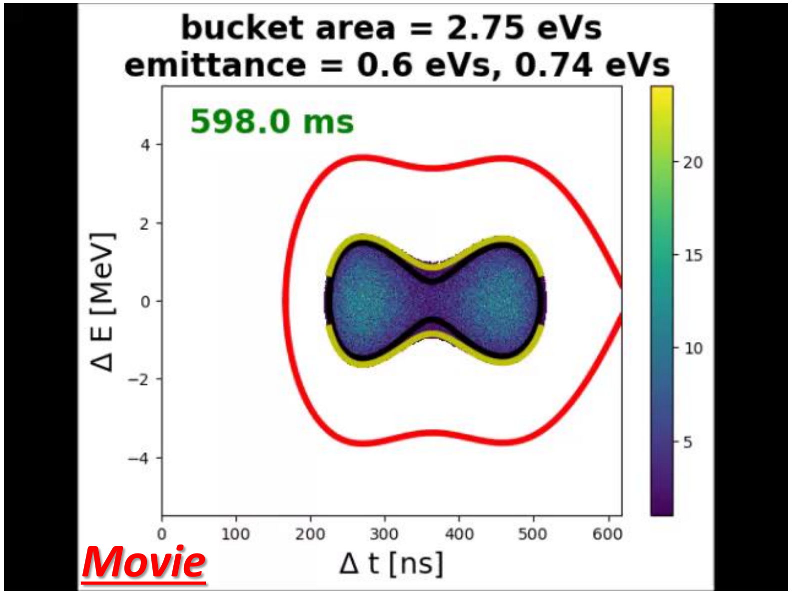




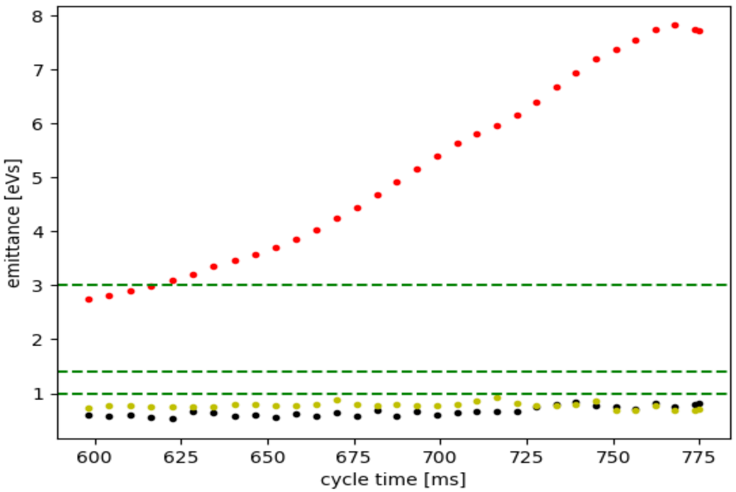
Phase noise in current machine (4/6)

Double RF (simulations)

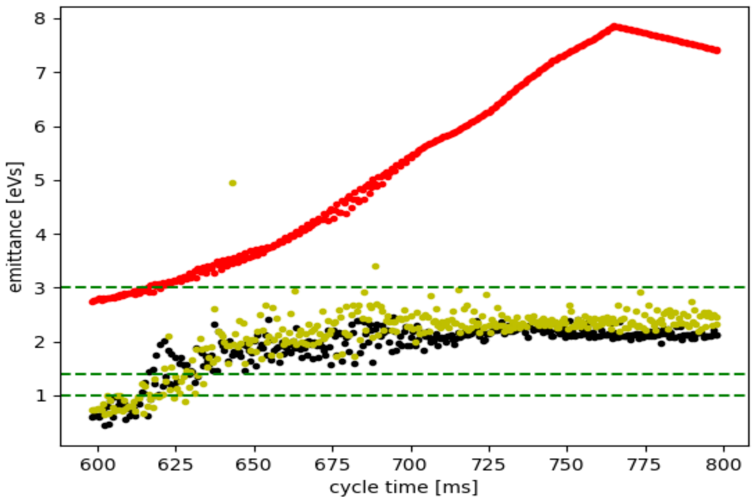




NO NOISE



WITH NOISE in C600-C700

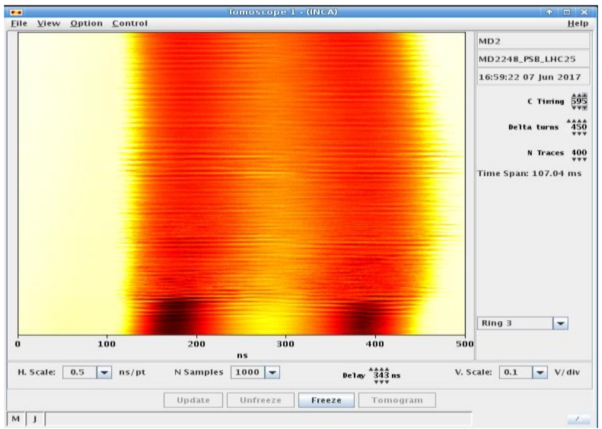


Phase noise in current machine (5/6)

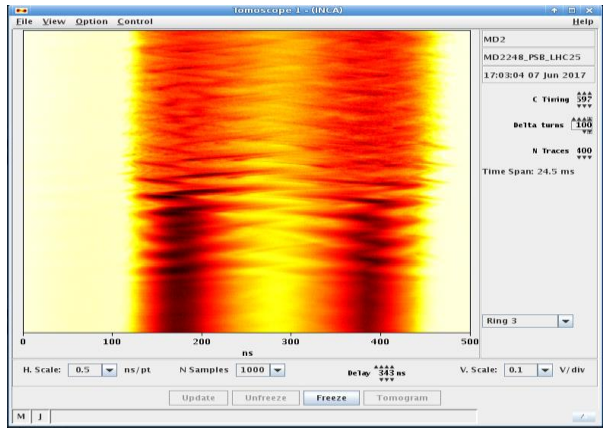
Double RF (measurements)

- Exactly same noise used in simulation, slightly different amplitudes for the 4 rings.

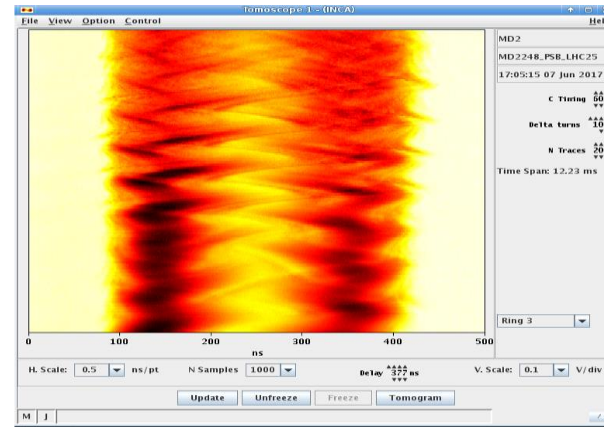
C595-C702



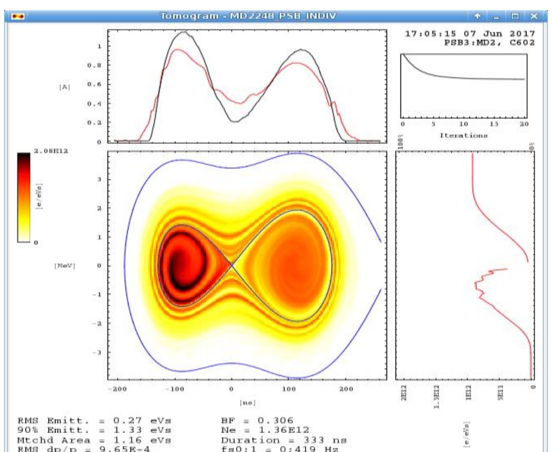
C597-C620



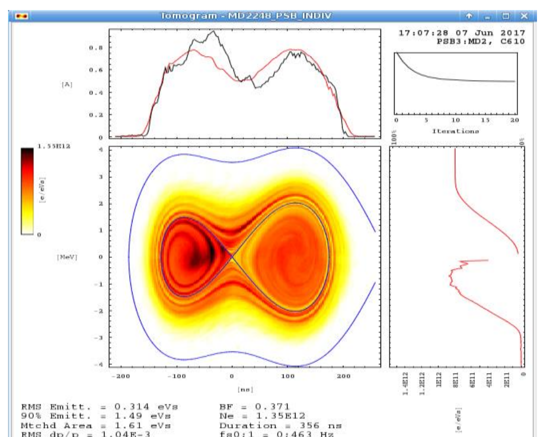
C602-C615



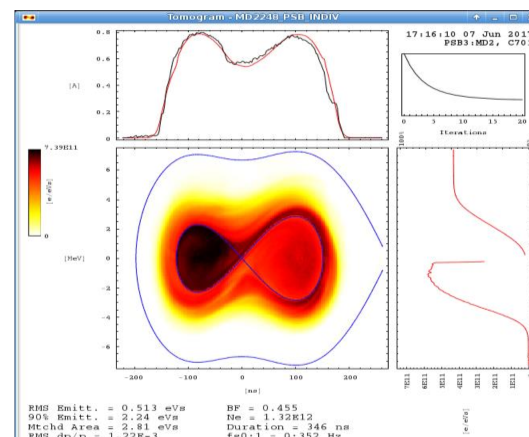
C602 $\varepsilon_L = 1.16$ eVs



C610 $\varepsilon_L = 1.61$ eVs



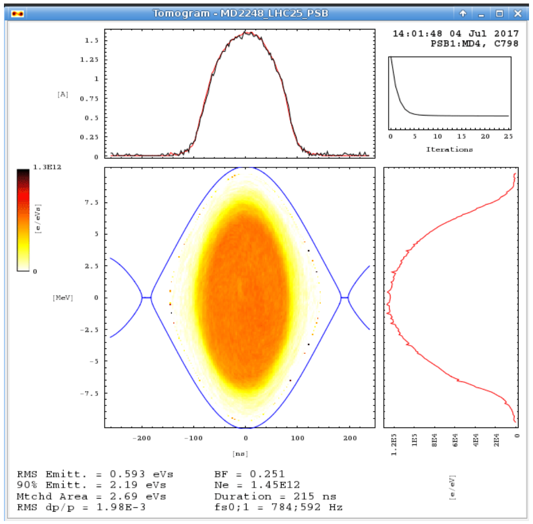
C701 $\varepsilon_L = 2.8$ eVs



Phase noise in current machine (6/6)

Double RF (measurements at extraction)

RING 1

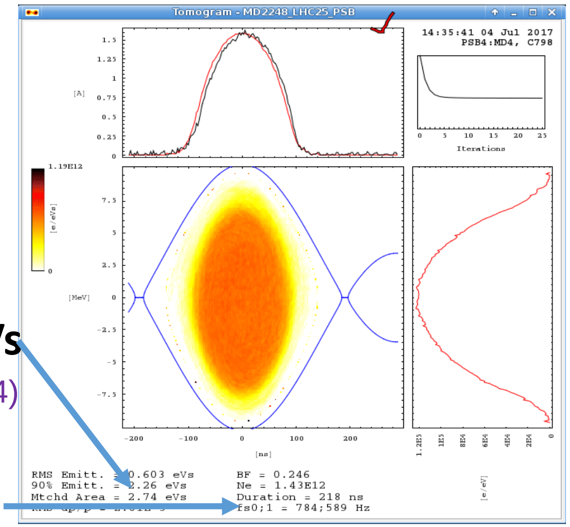


$\varepsilon_L = 2.69$ **eVs**

(2.80, 2.78, 2.73, 2.68)

b.l.= 215 ns

RING 2

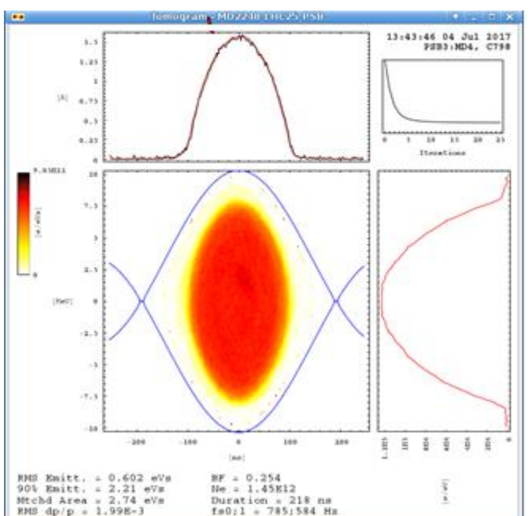


$\varepsilon_L = 2.74$ **eVs**

(2.73, 2.73, 2.71, 2.74)

b.l.= 218 ns

RING 3

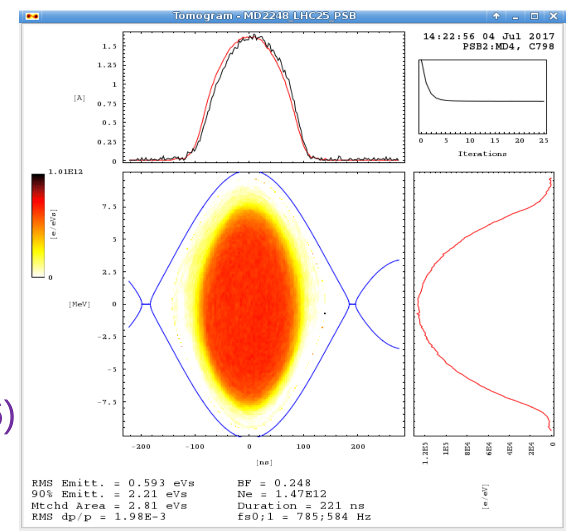


$\varepsilon_L = 2.74$ **eVs**

(2.69, 2.69, 2.72, 2.73)

b.l.= 218 ns

RING 4



$\varepsilon_L = 2.81$ **eVs**

(2.80, 2.67, 2.76, 2.66)

b.l.= 221 ns

Contents

Conclusion (1/2)

- *The BLonD code has been developed at CERN in the RF group more than three years ago and has been used in all CERN machines.*
  - *Particular care given by me firstly to general design and optimization, then to low energy rings features.*
- *Several benchmarks with measurements, analytical formulae and other codes give BLonD sufficient reliability.*
- *BLonD has been used to simulate longitudinal beam dynamics of the PSB beams in the post-upgrade scenario after 2021, where there will be many important changes.*
- *The complete PSB longitudinal impedance model has been used with careful estimations of the dominant sources:*
  - *space charge and Finemet impedance (with LLRF feedback)*
- *LLRF beam-based feedbacks have also been included (with measurements for gains calibration).*

Conclusion (2/2)

- *RF phase noise injection for longitudinal emittance blow-up has been studied and used in simulations*
  - *measurements of current situation reveal feasibility and robustness of the method.*
- *Simulations of HL-LHC don't show any instability.*
  - *It was possible to blow up the longitudinal emittance by factor 3 in just 100 ms, even combining noise with phase-loop*
- *Simulations of high-intensity beams reveal micro-wave instabilitiy caused by Finemet impedance.*
  - *Possible cure: increase action of feedbacks (number of harmonics, bandwidth of transfer function) and reduce RF-manipulations*
- ***Next steps:***
  - *BLonD: contribution in general design and optimization*
  - *PSB: conclude studies (more simulations and measurements related to LLRF feedbacks, RF phase noise and collective effects)*
  - *SPS: slip-stacking just started, it will require most of the time*

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