Phase Noise and AVC Loop Studies

Quartullo Danilo

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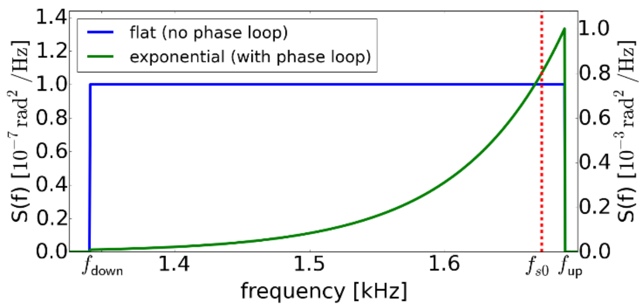
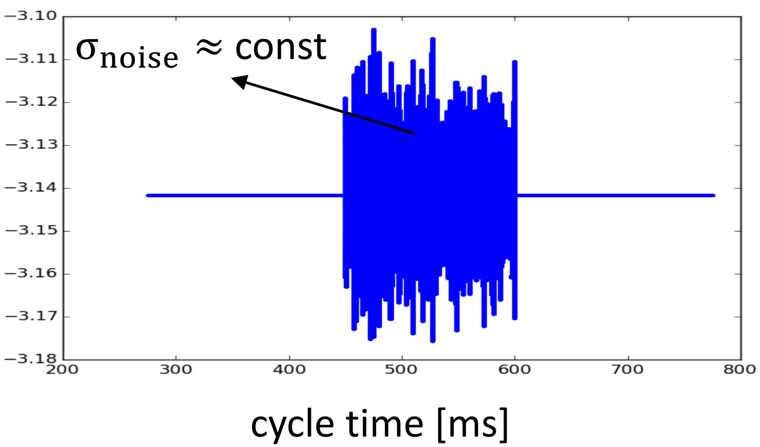
    - Introduction
    - Scanned parameters
    - Results
    - Summary and future plans

RF phase noise: introduction (1/3)

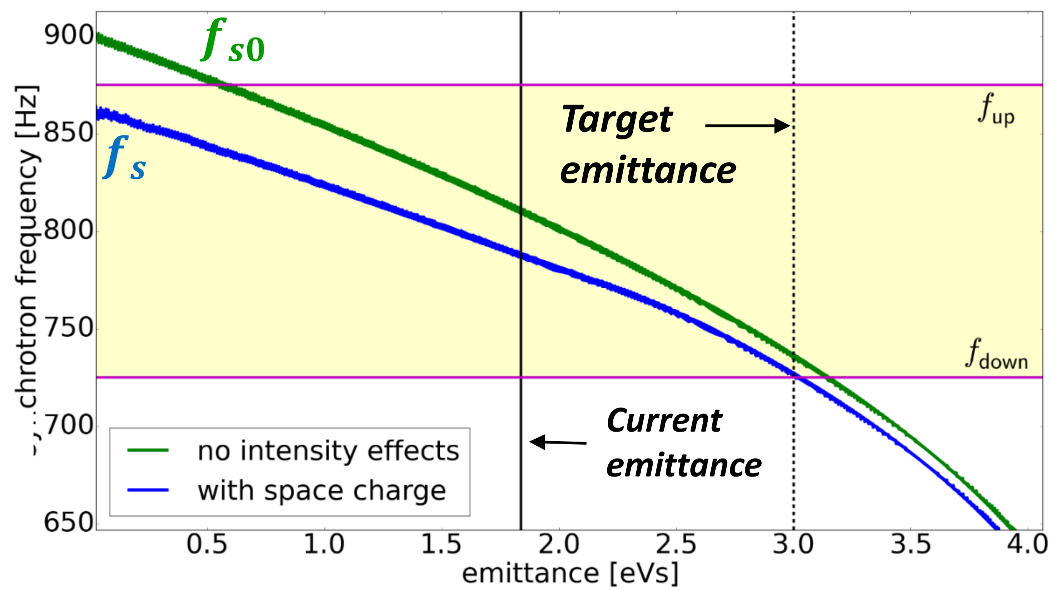
- Current blow-up: high harmonic phase modulation from dedicated RF system (C16) => difficult to set, control in operation and reproduce in simulations.
- Band-limited RF phase noise in h=1 can replace this method saving also RF voltage.



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



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

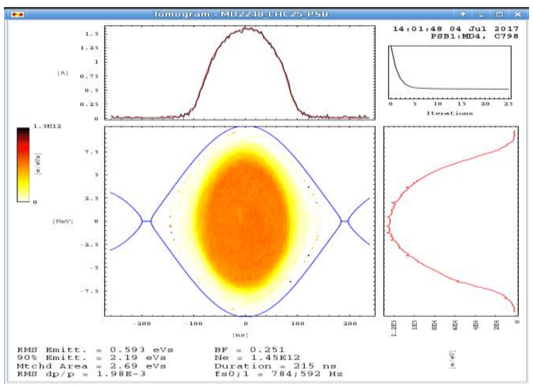


- Synchrotron frequency distribution in single PSB RF.
- The bunch emittance increases from 1.8 to 3 eVs applying phase noise in the band [725 – 875] Hz.
- Space charge lowers the synchrotron frequency (PSB below transition) and the noise band should follow it.

RF phase noise: introduction (2/3)

- Last July it was proved during an MD that it is possible to blow up the longitudinal emittance of LHC25ns beams from 1 eVs to 2.8 eVs injecting RF phase noise in h=1
- This blow-up was also obtained with the C16 but with more constraints (sequential plateaus in bucket area during ramp) and more spent time for setting => noise very promising

RING 1

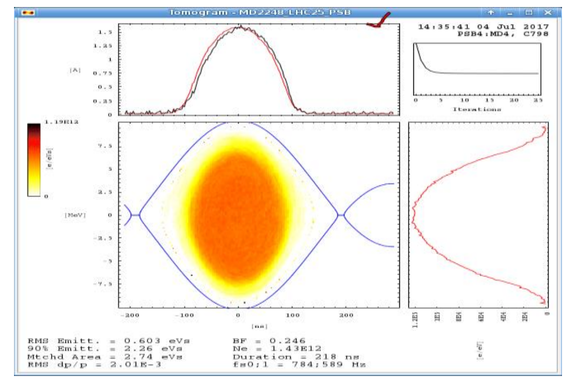


$\varepsilon_l = 2.69$ eVs

(2.80, 2.78, 2.73, 2.68)

$\tau = 215$ ns

RING 2

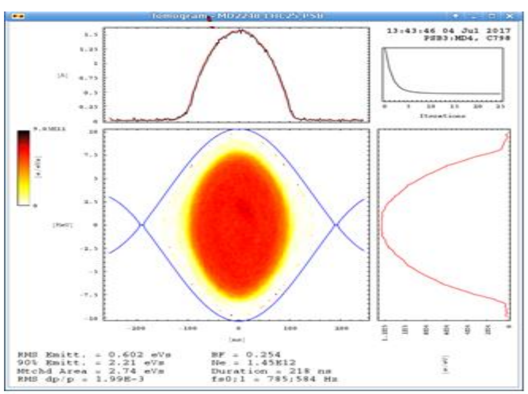


$\varepsilon_l = 2.74$ eVs

(2.73, 2.73, 2.71, 2.74)

$\tau = 218$ ns

RING 3

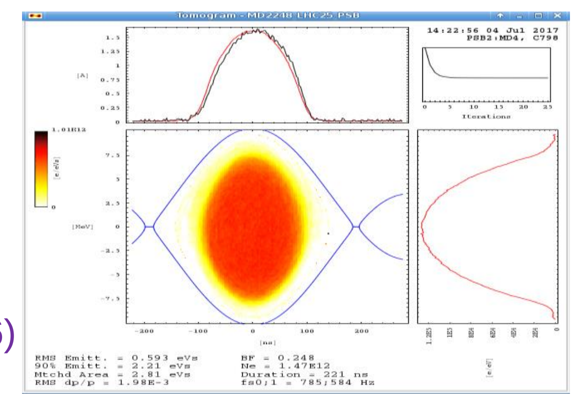


$\varepsilon_l = 2.74$ eVs

(2.69, 2.69, 2.72, 2.73)

$\tau = 218$ ns

RING 4



$\varepsilon_l = 2.81$ eVs

(2.80, 2.67, 2.76, 2.66)

$\tau = 221$ ns

RF phase noise: introduction (3/3)

- However more tests were needed for better understanding and to cover more cases
- Several MDs have been carried out in the past weeks to ascertain if **RF phase noise injection in h=1 can substitute C16 for different machine and beam parameters**
- **5 different types of beam** have been considered
  - LHC INDIV
  - BCMS
  - LHC25ns
  - ISOLDE
  - SFTPRO
- Noise calculated with Python and pasted into spare GFAS through Inspector
  - This speedups the setting but some additional improvements will help even more
- 100 ms of blow-up possible using 10 μs point spacing (LLRF trigger time)
  - Enough for now but in the future it could be necessary more
- Possibility to inject noise through phase loop and directly into the C02 drive
  - Useful to set the loops to zero without cancelling the noise.
- In the following results when blow-up with noise was not possible **it does not mean** that all possible configurations have been studied
  - However a lot of effort has been spent and maybe that is a hint that it does not work or at least it can be very difficult to set in operation with good reproducibility

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

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

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

(1)

$$\Delta \boldsymbol{f}_{pl}^{n+1} = \boldsymbol{A}_1^{pl}\Delta\boldsymbol{f}_{pl}^{n} + \boldsymbol{Gain}_{pl}(\boldsymbol{B}_0^{pl}\sin\Delta\boldsymbol{\varphi}^{n} + \boldsymbol{B}_1^{pl}\sin\Delta\boldsymbol{\varphi}^{n-1})$$

(3)

$$\frac{\Delta\boldsymbol{R}^n}{\boldsymbol{R}_d} = \frac{\Delta\boldsymbol{f}_{rf}^n}{\boldsymbol{f}_{rf,d}^n}\frac{\boldsymbol{\gamma}_n^2}{\boldsymbol{\gamma}_t^2 - \boldsymbol{\gamma}_n^2}$$

$\boldsymbol{\gamma}_t = 4.077$

$\mathbf{R_d} = \mathbf{25e3\ mm}$

(2)

$$\Delta \boldsymbol{f}_{rl}^{n+1} = \boldsymbol{A}_1^{rl}\Delta\boldsymbol{f}_{rl}^{n} + \boldsymbol{Gain}_{rl}(\boldsymbol{B}_0^{rl}\Delta\boldsymbol{R}^{n} + \boldsymbol{B}_1^{rl}\Delta\boldsymbol{R}^{n-1})$$

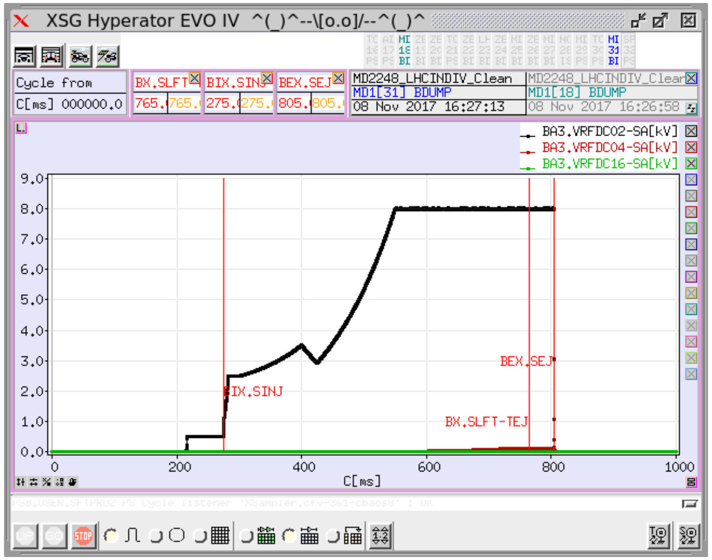
$$\boldsymbol{f}_{rf}^{n+1} = \boldsymbol{f}_{rf,d}^{n+1} + \Delta\boldsymbol{f}_{rf}^{n+1} = \boldsymbol{f}_{rf,d}^{n+1} - \boldsymbol{FGPL}_{gain}\,\Delta\boldsymbol{f}_{pl}^{n+1} - \boldsymbol{FGRL}_{gain}\,\Delta\boldsymbol{f}_{rl}^{n+1}$$

$$\boldsymbol{V}_{rf}^{n+1} = \boldsymbol{V}_1^{n+1}\sin\boldsymbol{\omega}_{rf}^{n+1}$$

Remarks:

- In simulations $\Delta\boldsymbol{\varphi}_{b,rf}$ 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)

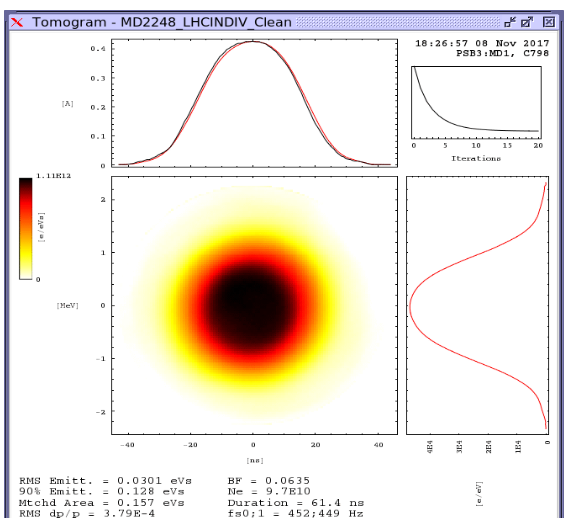
LHCINDIV



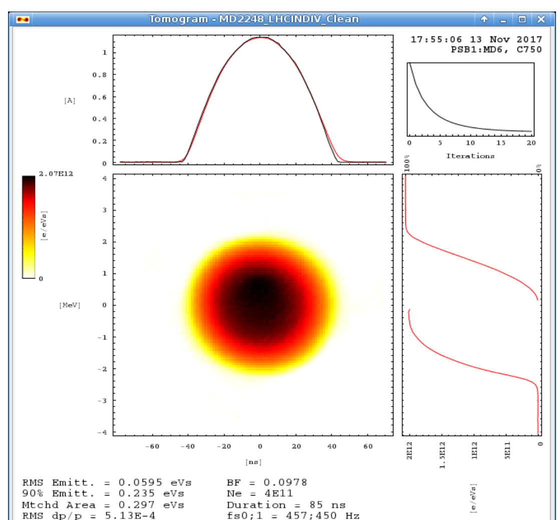
- No C04
- C02 voltage such to have fs0 constant during longitudinal shaving
- Noise in the band [0, fs] in C300-C400 to excite losses (one piece of noise)
- Noise injected through PL and into C02
- PL gain, different noise bands, rms amplitude and spectrum shapes scanned

C16 better than noise

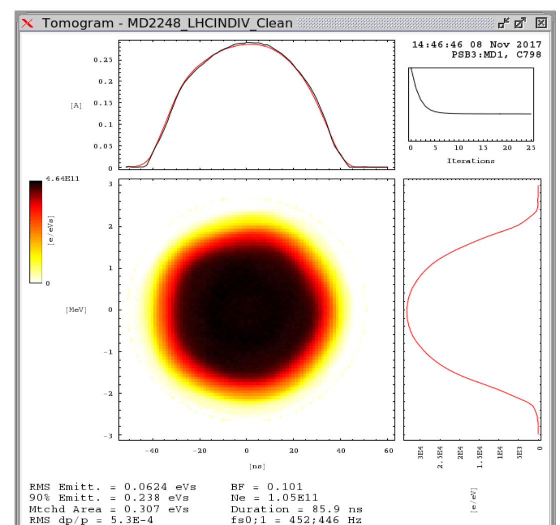
With noise: correct intensity, too small emittance



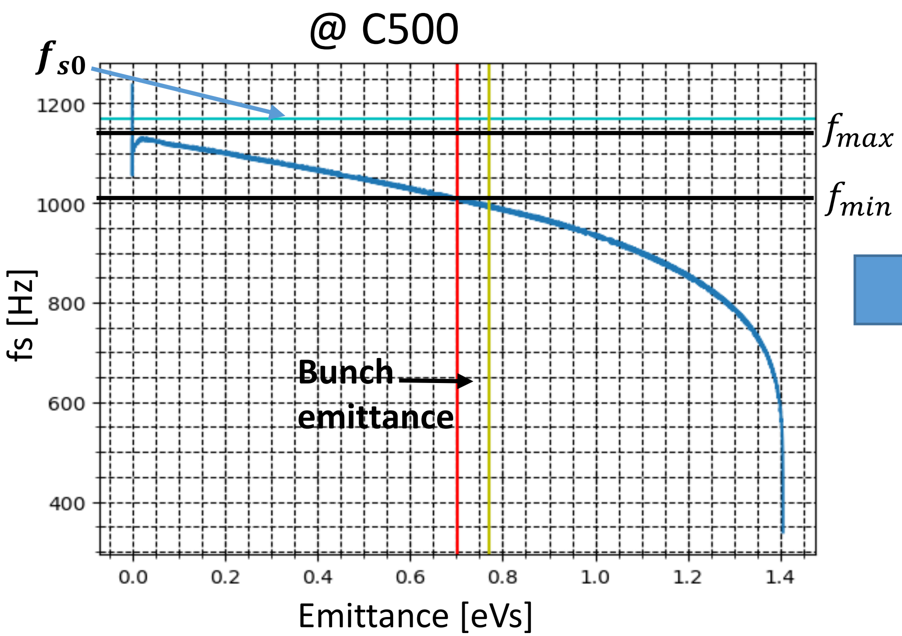
With noise: correct emittance, too high intensity

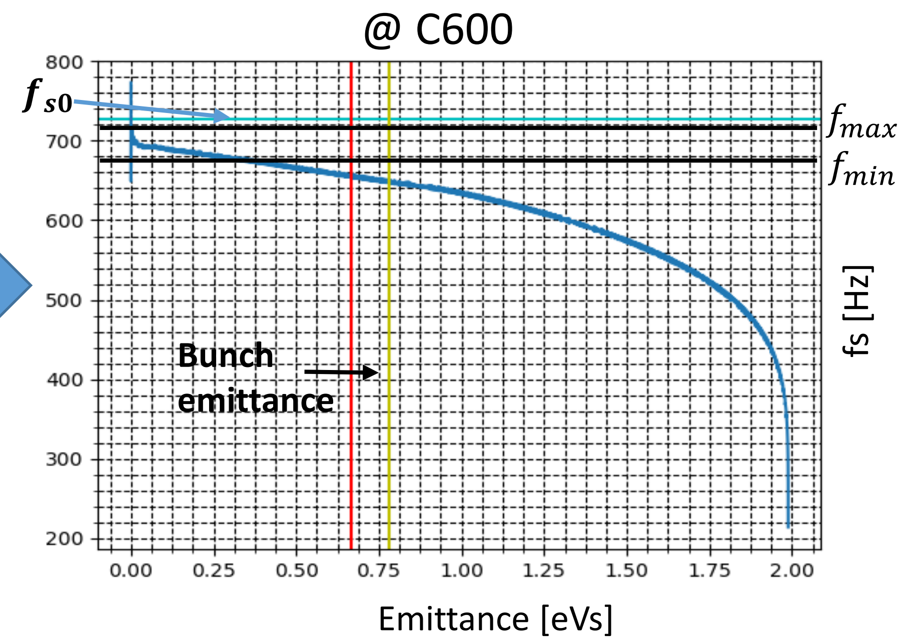


With C16

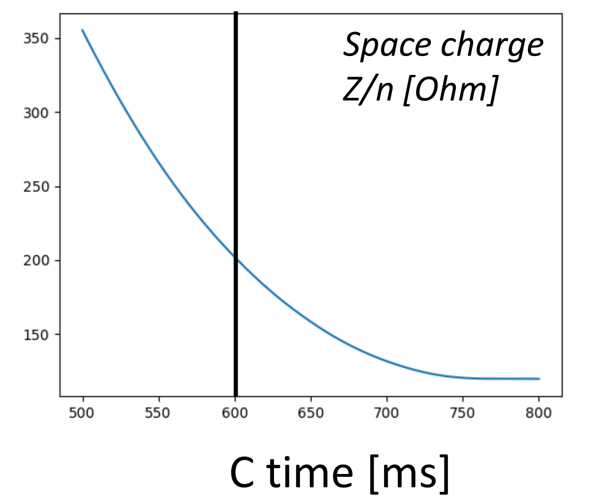


BCMS (1/2)

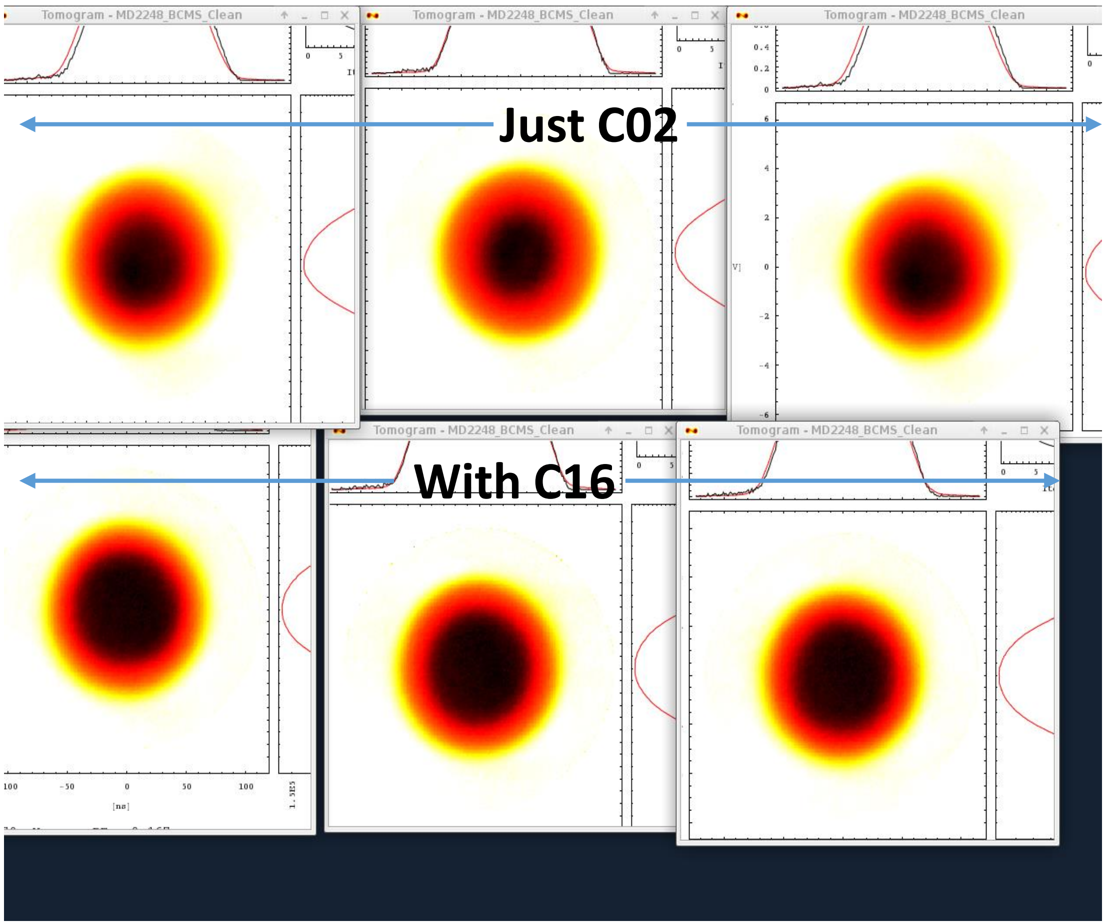




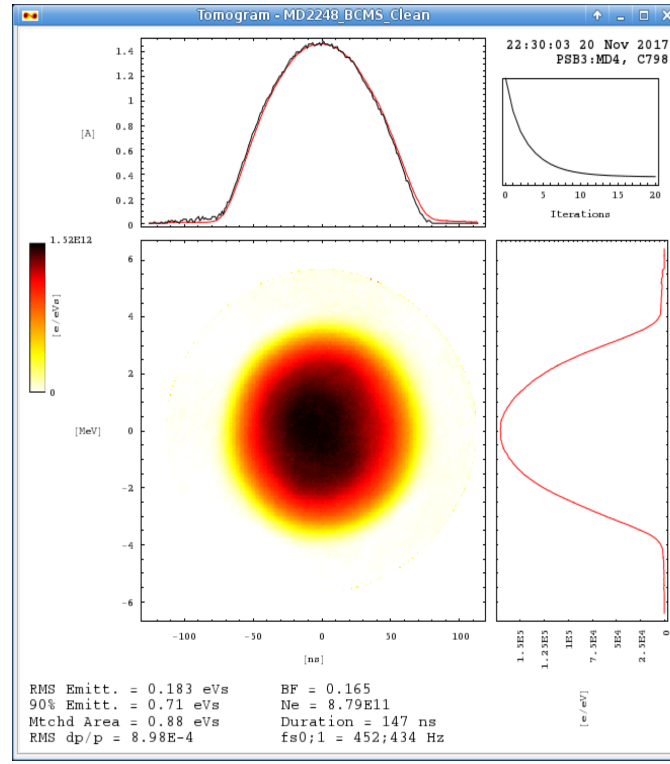
- No C04
- No matched area emittance blow-up but RMS emittance blow-up
- Noise during C500-C600.
- Just the bunch core has to be targeted
- Large fs change in C500-C600 (noise regeneration every 5 ms)
- Space charge lower the synchrotron frequency and that was taken into account to estimate fs
- Different noise bands tried, different Ctime frames and gains for PL, noise through PL and C02…



BCMS (2/2)



With noise

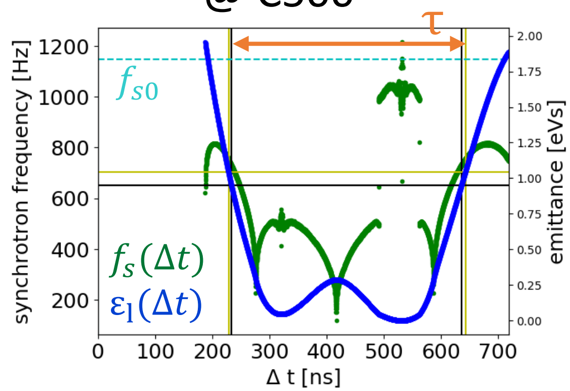


C16 better than noise

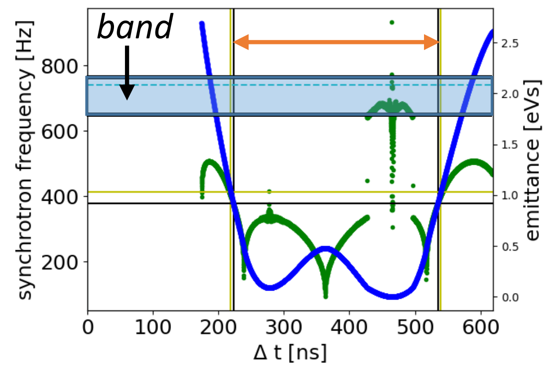
LHC25ns (1/3)

- Are small emittance blow-ups also possible (to 1.4 eVs instead of 2.8 eVs)?
- 8+6 kV in bunch lengthening mode
- Noise in C500-C600 regenerated every 10 ms to follow fs change
- All four rings tested
- Attention to losses in C500-C600 (small margin in bucket area there)
- Noise through phase loop

@ C500

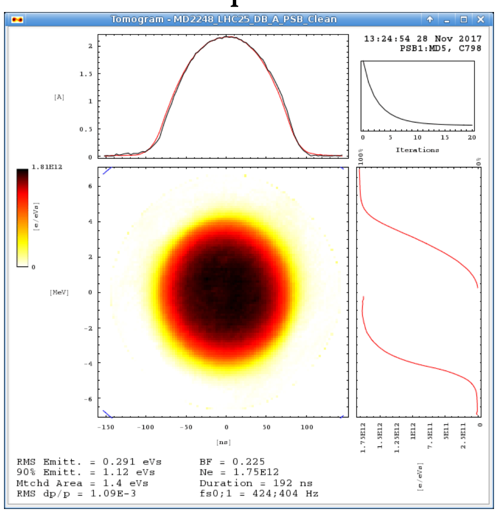


@ C600

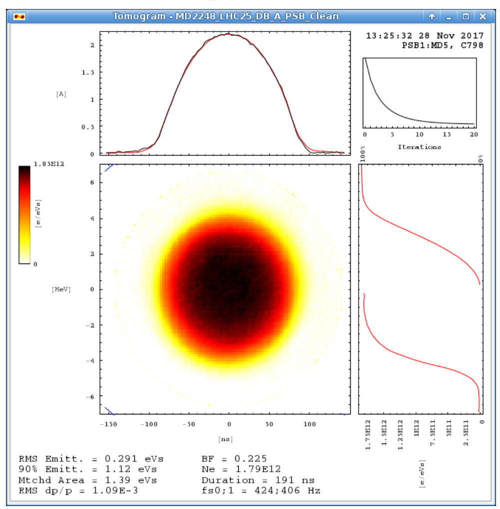


Ring 1

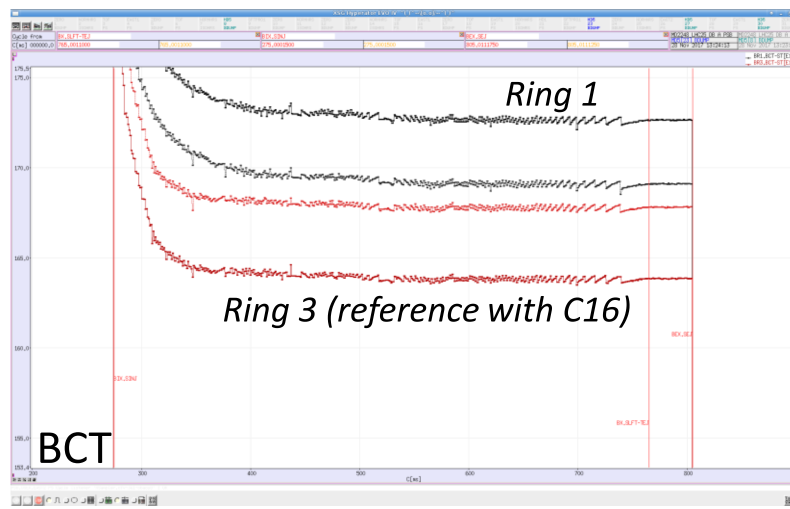
Shot 1 $\varepsilon_l = 1.4$ eVs



Shot 2 $\varepsilon_l = 1.39$ eVs



Comparison of losses with C16 and noise

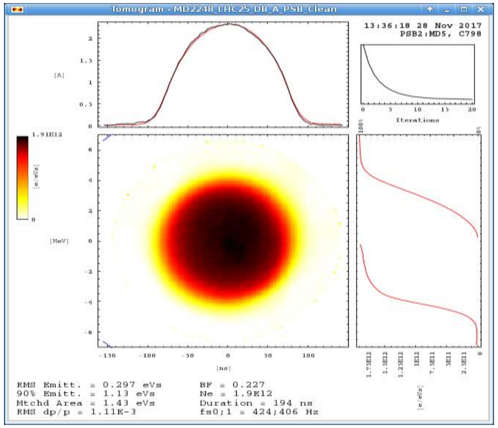


- $\sigma_{noise} = 0.068$ rad, flat spectrum

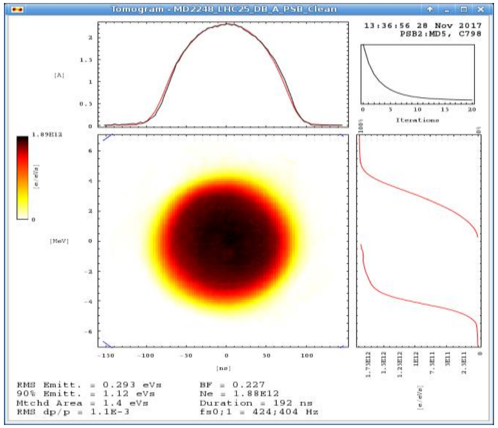
LHC25ns (2/3)

Ring 2

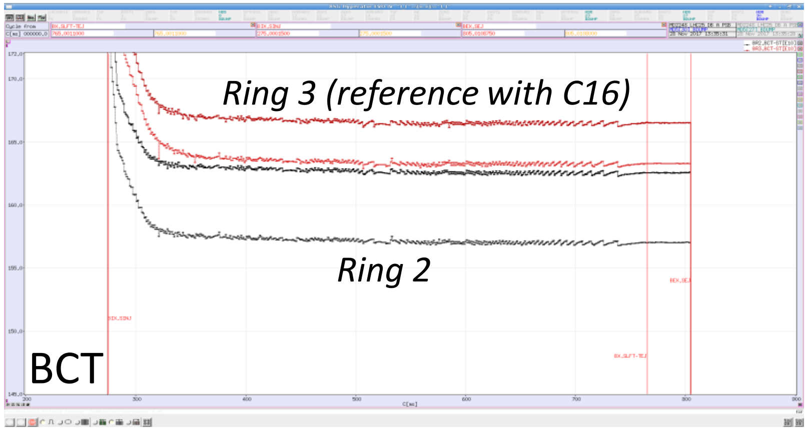
Shot 1 $\varepsilon_l = 1.43$ eVs



Shot 2 $\varepsilon_l = 1.4$ eVs



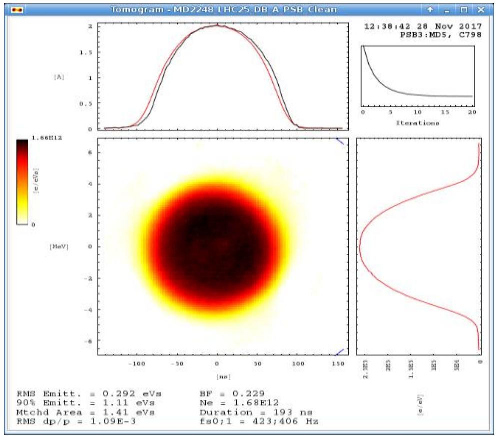
Comparison of losses with C16 and noise



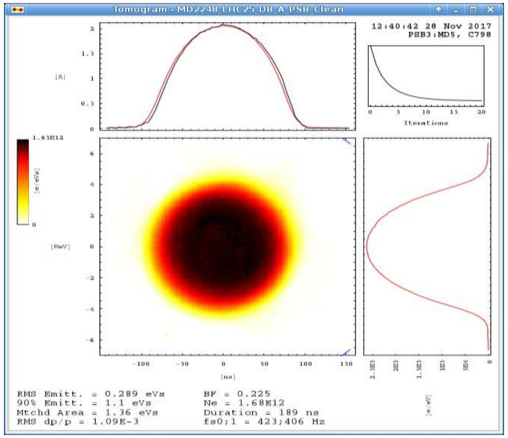
- Same frequency bands used for Ring 1 but $\sigma_{noise} = 0.085$ rad and linear spectrum

Ring 3

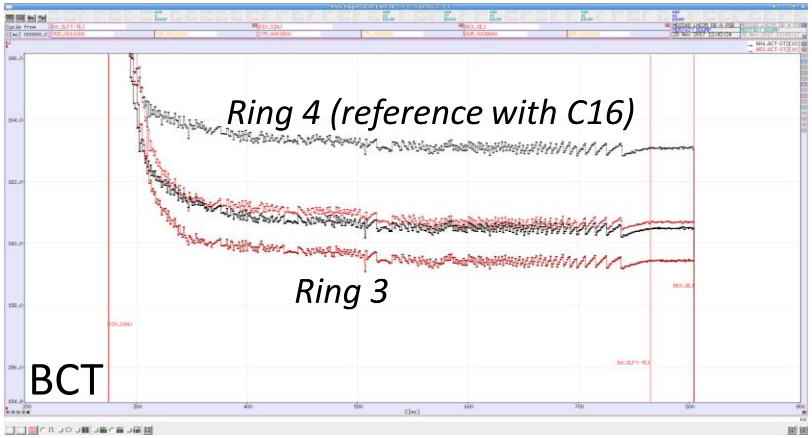
Shot 1 $\varepsilon_l = 1.41$ eVs



Shot 2 $\varepsilon_l = 1.36$ eVs



Comparison of losses with C16 and noise

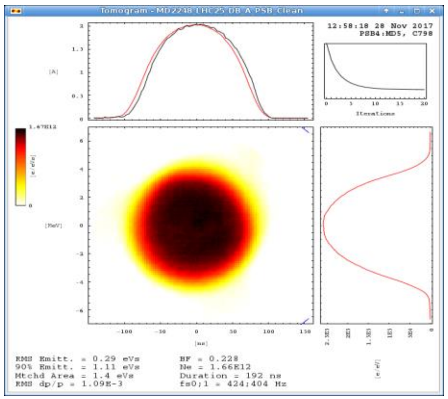


- Same frequency bands used for Ring 1 but $\sigma_{noise} = 0.08$ rad

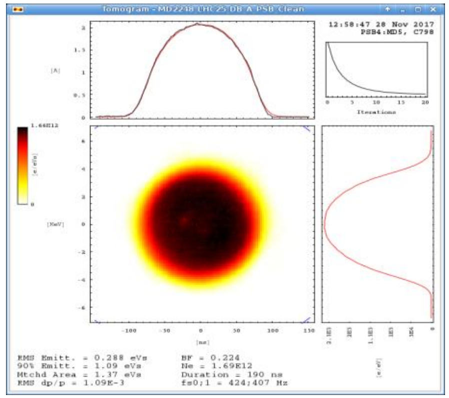
LHC25ns (3/3)

Ring 4

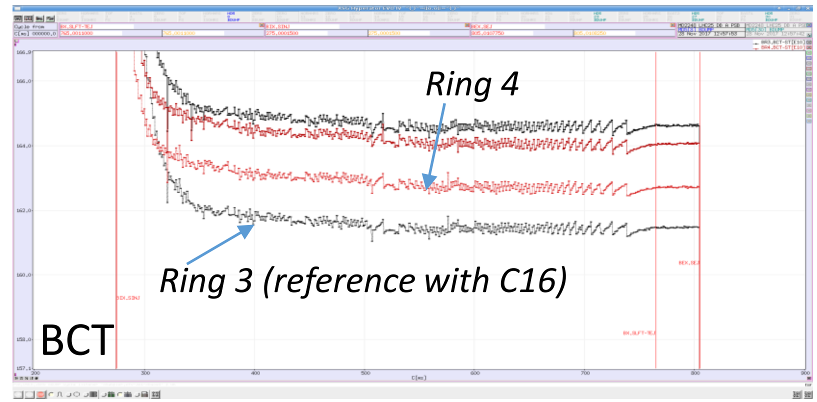
Shot 1 $\varepsilon_l = 1.4$ eVs



Shot 2 $\varepsilon_l = 1.37$ eVs



Comparison of losses with C16 and noise

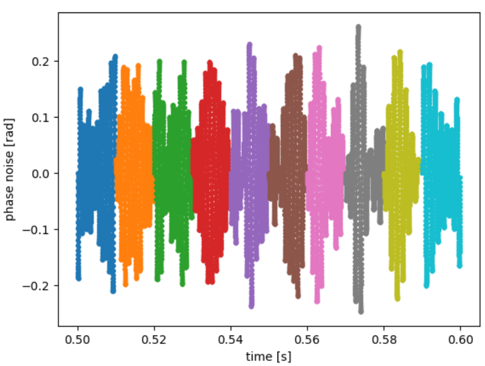


- Same frequency bands used for Ring 1 but $\sigma_{noise} = 0.09$ rad and linear spectrum

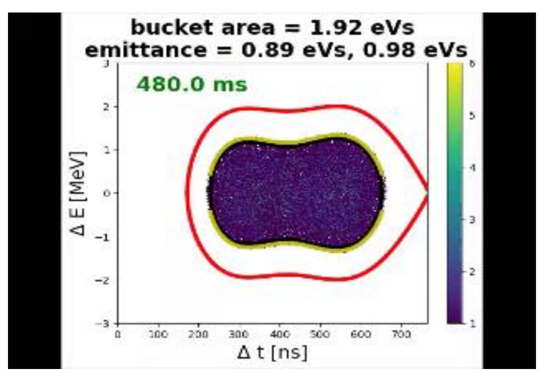
C16 and noise are equivalent

Simulation in BLonD code: with intensity effects, phase and radial loops (same gains used in MD)

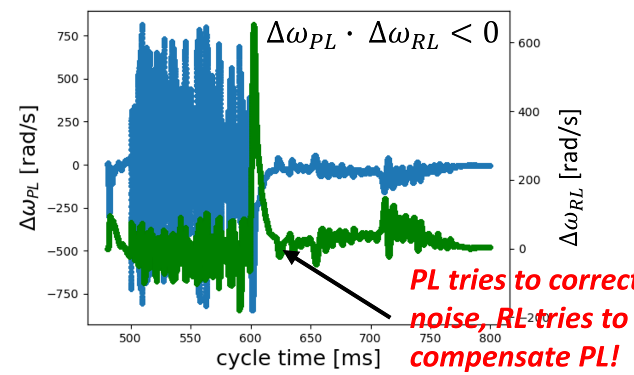
Noise used MD and simulation



Phase space in simulation



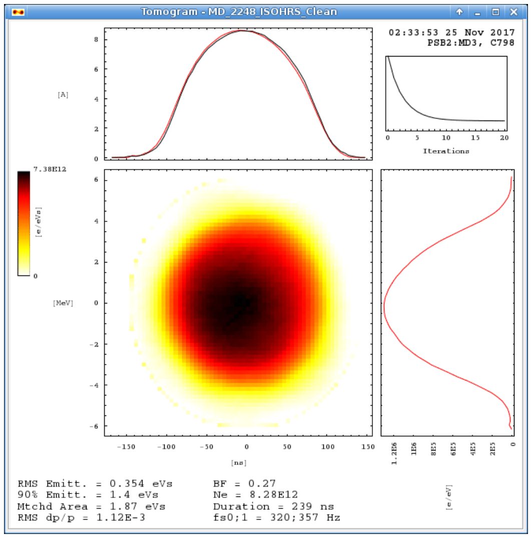
Loop corrections during cycle



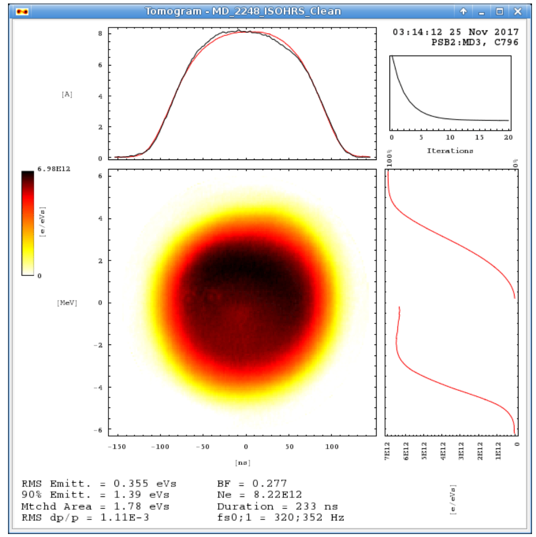
ISOLDE

- N = 800e10, target emittance at extraction $\varepsilon_l = 1.8$ eVs
- RF 8+8 bunch lengthening, quality of the beam less important here

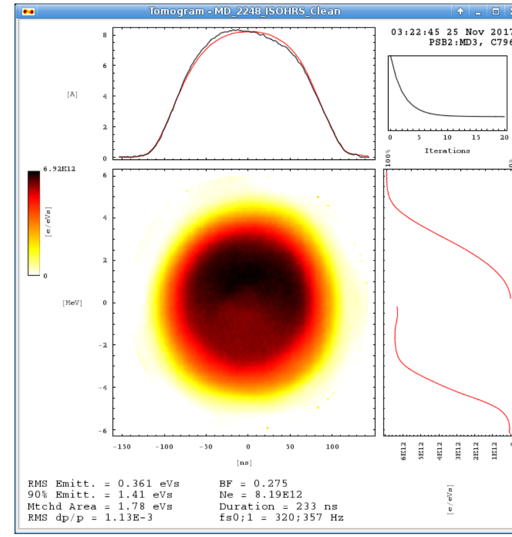
C16 $\varepsilon_l = 1.87$ eVs



Noise shot 1 $\varepsilon_l = 1.78$ eVs



Noise shot 2 $\varepsilon_l = 1.78$ eVs



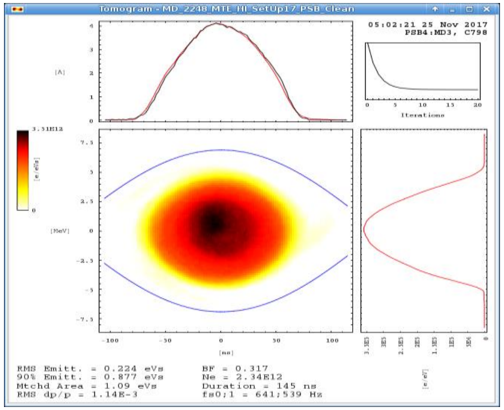
- Same noise program used for LHC25ns beam with just a different amplitude (0.15 rad)!
  - Synchrotron frequency distribution ‘not so different’ from the case 8+6
- The parameter setting for the C16 for the LHC25ns and ISOLDE beams is very different.
  - More time for setting up

Noise better than C16

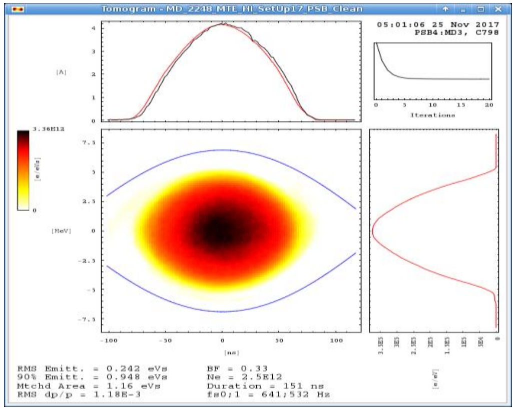
SFTPRO

- ➢ 2.6 eVs are needed before C700,
  - bunch splitting at extraction where the 2 bunches have 1.3 eVs emittance each
- ➢ RF 8+8 bunch lengthening

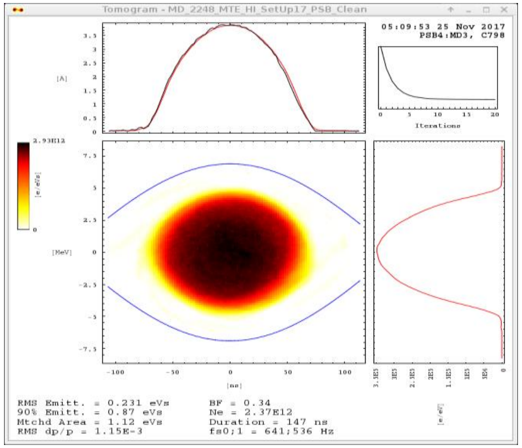
C16 left bunch $\varepsilon_l = 1.09$ eVs



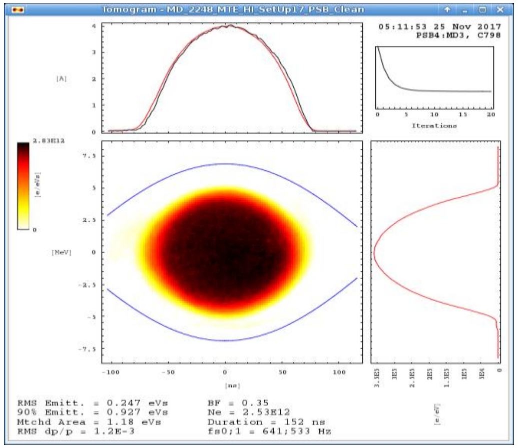
C16 right bunch $\varepsilon_l = 1.16$ eVs



Noise left bunch $\varepsilon_l = 1.12$ eVs



Noise right bunch $\varepsilon_l = 1.18$ eVs



- ➢ Noise during C550-C660, again following the LHC25ns case!
- ➢ Other different set of parameters for C16
- ➢ Much better bunch quality at extraction

Noise better than C16

Summary (1/2)

- Numerous MDs have been carried out recently to understand if RF phase noise can replace high frequency modulation for emittance blow-up after LS2.
- The following conclusions can be drawn:
  - Given a certain target emittance, high-frequency modulation requires usually less cycle time than noise to blow up the beam (see the examples shown here were C16 needs roughly half of the time for blow-up relative to noise).
  - When the theory behind high frequency modulation can be applied, the obtained blow-up is almost perfect.
  - However the application of theory can lead to constraints (see blow-up to 2.8 eVs of LHC beams) and to long spent time to set the various parameters (mostly for higher blow-up).
  - In addition the phase between the C16 and the C02 and C04 cavities is unknown and variable (problems of reproducibility and optimization).
  - On the contrary, some particular configurations for noise have been proven to be working numerous times under very different conditions (see ISOLDE and SFTPRO beams) with just very small changes froma case to case.
  - Simualtions can reproduce what is measured, but the reason why this particular configuration for blow-up works so well is still under investigation.
  - Finally some effort was spent to apply noise in single RF without success (the same applies to bunch shortening mode tested this year)

Summary (2/2)

- Injecting the noise directly into the C02 drive was not useful during MDs
  - Playing with the shape of the spectrum (flat, linear, exponential) allowed to inject the noise directly into the phase loop.
  - Tests have been done dropping the phase loop to minimal working value during blow-up but the results didn't improve.
- Possible improvements to facilitate operation:
  - More user-friendly way to set the parameters for noise (Simon already did a lot!)
  - Noise for more than 100 ms using 10 μs space.

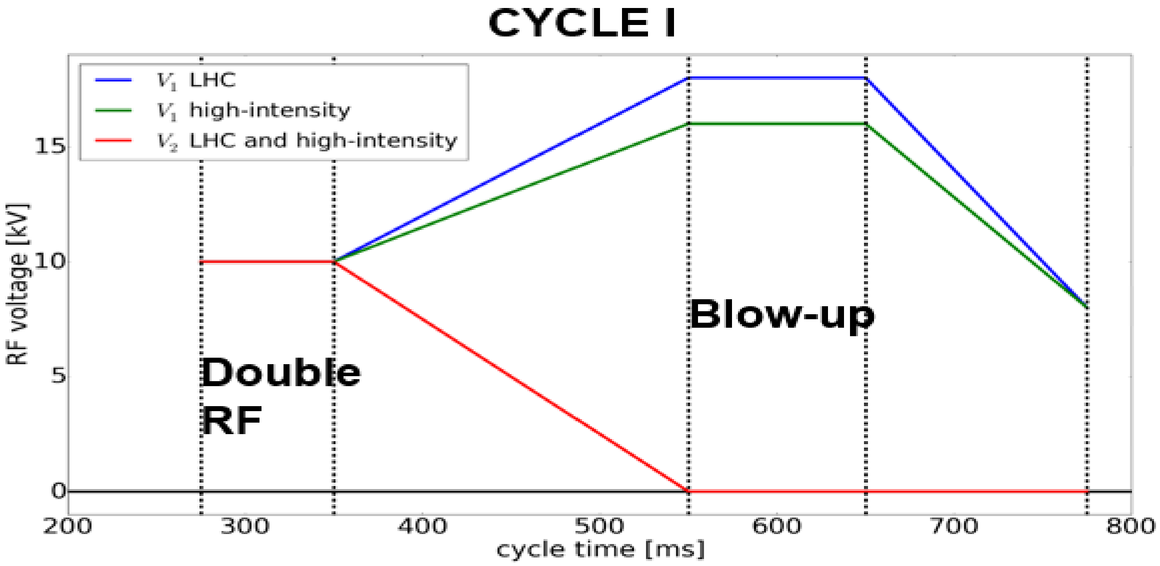
Future plans:

- Studies to understand better why noise in single RF is uneffective and why noise in bunch-lengthening gives brillian results.
- MDs to validate LLRF feedback model used in simulations.
- Additionan MDs for noise for a possible reliability run in 2018.
- MDs to measure synchrotron frequency shift due to space charge in single RF and double RF bunch shortening mode
  - Validation of Z/n estimation used in simulation
  - Very important for the choise of the noise band to apply.

Contents

Introduction (1/3)

- Several studies have been carried out this year to analyse the PSB longitudinal beam dynamics after LS2 in view of possibile instability issues.
- Two types of beam were considered, the HL-LHC (3.6e12) and an hypothetical high-intensity (1.6e13) one.
- Maximum available Finemet RF voltage 20 kV (4 kV left for spare).
- First part of the ramp in double RF (bunch lengthening) to reduce space charge.
- Controlled longitudinal emittance blow-up using phase noise in C550-C650.
- Noise injected in the phase loop of the main RF (h=1).
- V_1 is dropped after C650 to 8 kV to have the desired bunch length at extraction.
- Lower available voltage for high-intensity beams (higher beam loading to counteract).

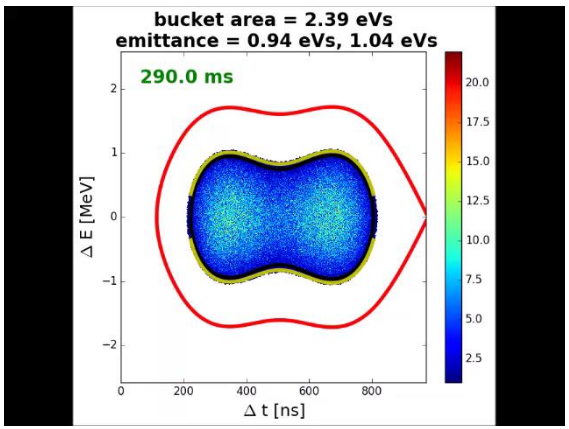


- Ramp entirely in single RF with V1 = 16 kV (cycle II) also tested in the past.

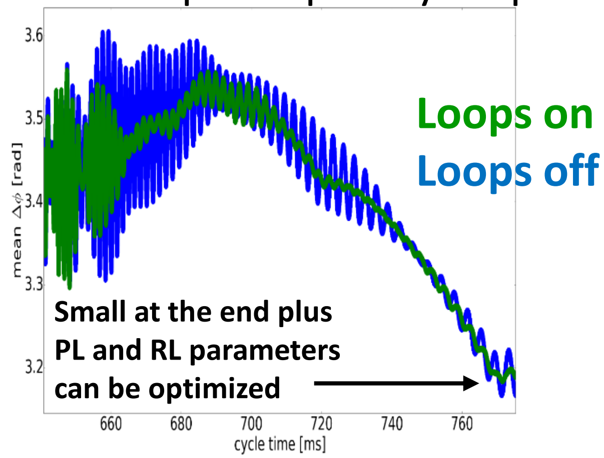
Introduction (2/3): HL-LHC

- In simulations it was possible to smoothly blow up a nominal HL-LHC beam (3.6e12) from 1.4 eVs to 3 eVs without any problem during C550-C650.
- The bunch length at extraction was 195-205 ns as required.

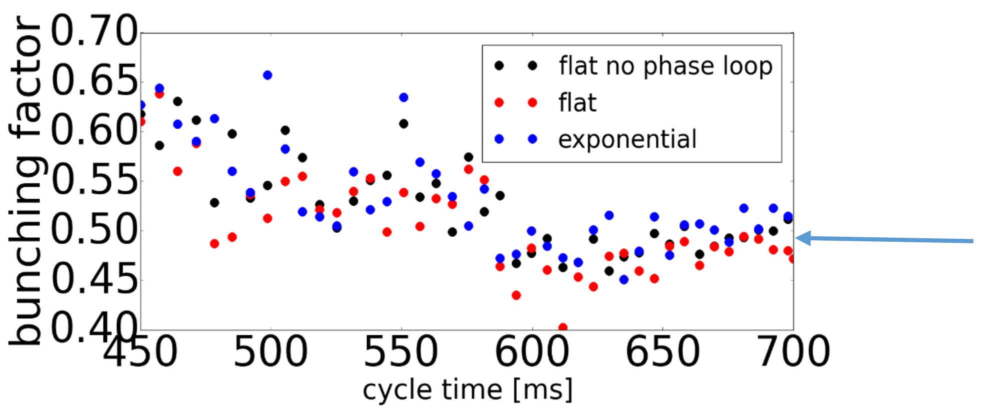
Phase space from C290 to C775



Dipole oscillations after blow-up damped by loops



- Blow-up in single RF using exponential spectrum to counteract phase loop action

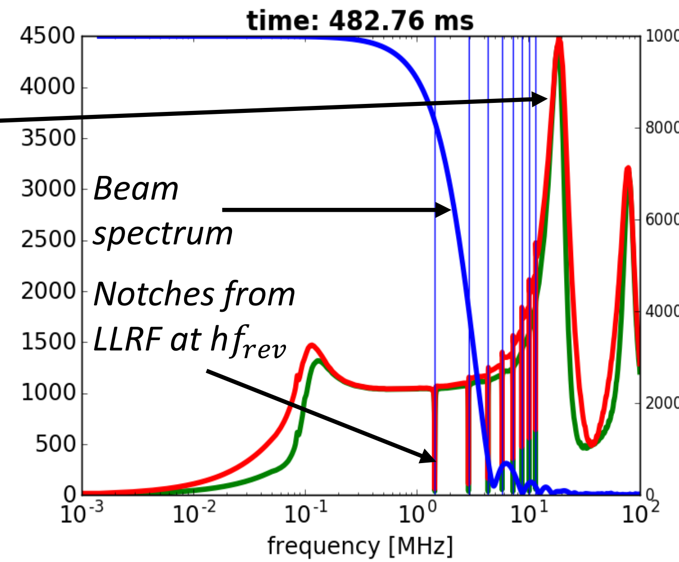


Exponential spectrum increases also bunching factor (good for transverse space charge)

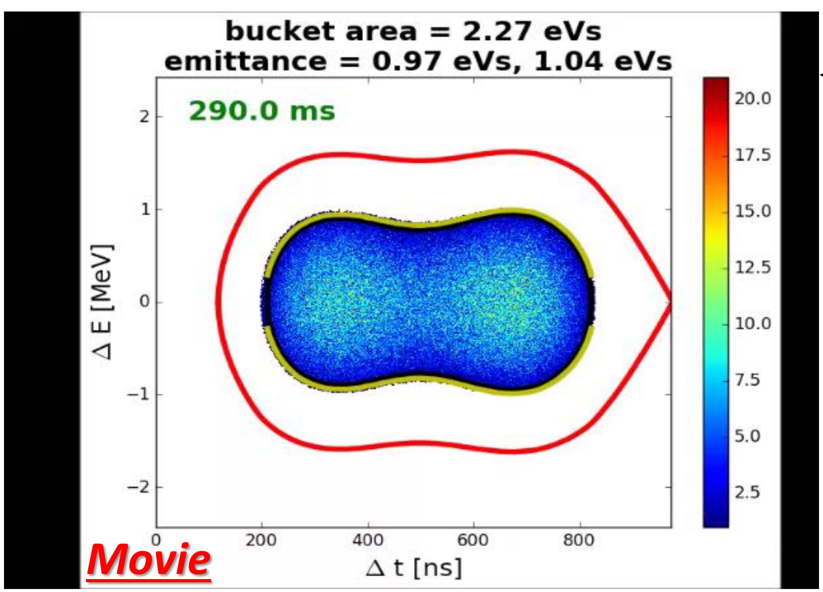
Introduction (3/3): high-intensity

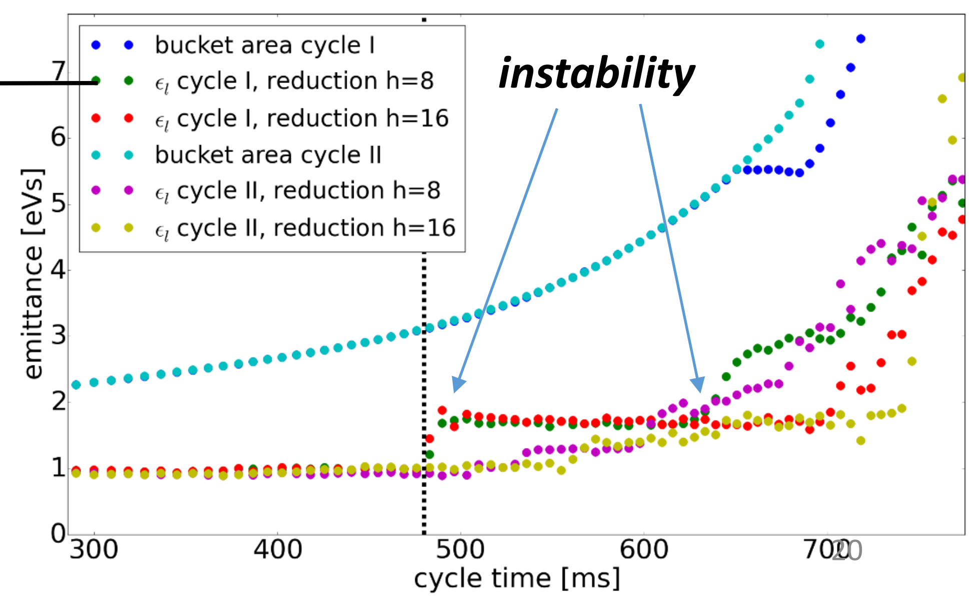
- Instability (high frequency modulation and uncontrolled longitudinal emittance blow-up) due to Finemet impedance peak at 20 MHz.
- Increasing the number of revolution harmonics at which the Finemet impedance is reduced delays the instability.
- Instability delayed also in single RF during all cycle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

PSB impedance model



20 MHz modulation visible in the phase space!

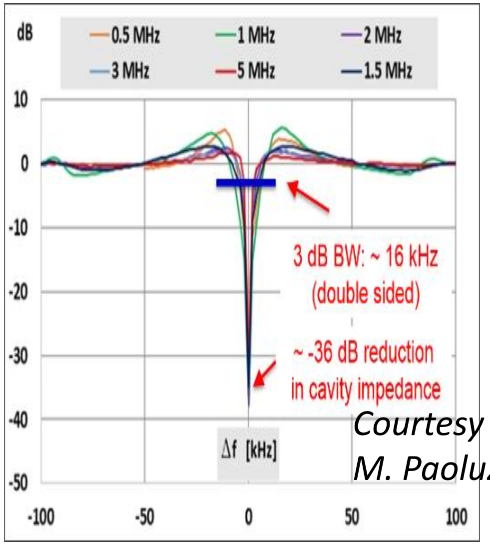




Scanned parameters

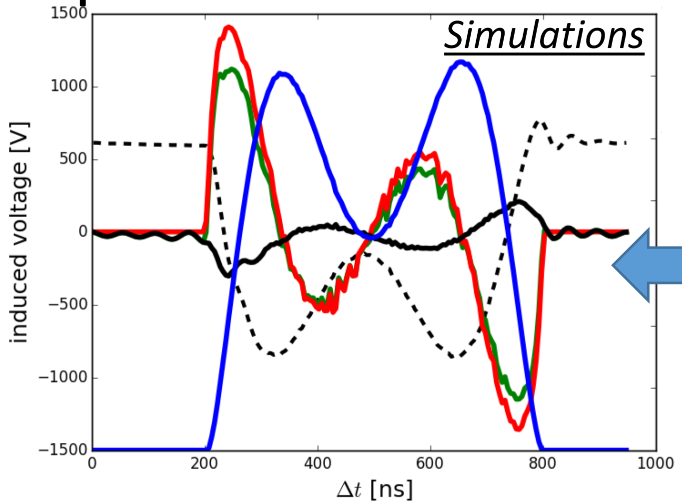
- Intensities: 1, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6 e13
- RF programs: constant 16; 8+8 and 10+10 kV bunch lengthening with drop of V1 to 8 kV and to V2 to 0 (similar to Cycle I)
- Longitudinal emittances at C300: 1, 1.2 and 1.4 eVs
- Number of notches: 8, 12, 16, 20
- Resonator model used here to represent notches
  - Same model used for previous results
  - Using directly the transfer function excites the instability even earlier and stronger (discrepancy between the two models has to be understood)
- No controlled blow-up and no loops were applied

Notch measurement



Courtesy M. Paoluzzi

Typical induced voltage and bunch profile in simulation 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

Conventions:

when instability starts

emittance at C800

Results: 16 kV

Cases simulated in the past (Cycle II)

8 notches:

Intensity at C300 [1e13]

ε_l at C300	**1.0**	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**	**1.6**
1	C620, 5eVs	C610, 5eVs	C595, 5eVs	C595, 5eVs	C535, 5.5eVs	C520, 5.5eVs	C510, 5.5eVs
1.2	C630, 4.2eVs	C620 4.6eVs	C605 5eVs	C595 5eVs	C590 5eVs	C585 5eVs	C570 5.1eVs
1.4	C630 4.2eVs	C620 4.6eVs	C610 5eVs	C600 5eVs	C580 5.5eVs	C580 5.5eVs	C570 6eVs

16 notches:

Intensity at C300 [1e13]

ε_l at C300	**1.0**	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**	**1.6**
1	stable	C755, 1.2eVs	C740, 1.4eVs	C760, 5eVs	C650, 5eVs	C590, 5.5eVs	C570, 6eVs
1.2	stable	stable	stable	stable	C650 1.4eVs	C650 1.4eVs	C575 2eVs
1.4	stable	stable	stable	stable	stable	C675 1.6eVs	C670 1.6eVs

No losses where unstable, 16 resonators better than 8 as expected

Conventions:
when instability starts

Results: 8+8 kV

8 notches:

Intensity at C300 [1e13]

		1.0	1.1	1.2	1.3	1.4	1.5	1.6
ε_l at C300	1	C640	C620	C590	C550	C550	C500	C500
	1.2	C640	C630	C630	C600	C579	C570	C540
	1.4	C640	C640	C640	C640	C550	C580	C575

16 notches:

Intensity at C300 [1e13]

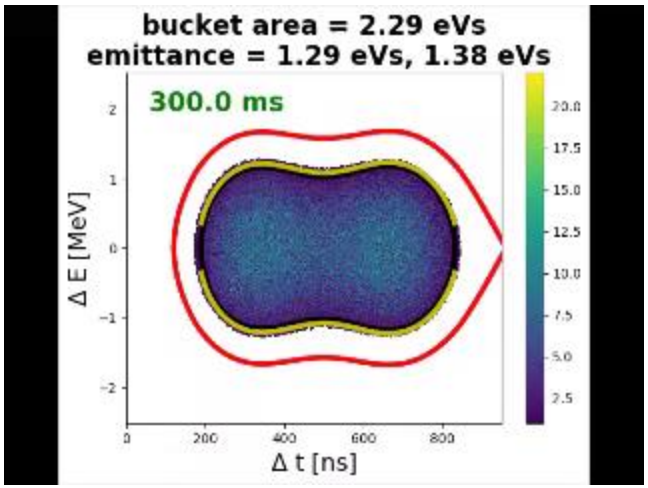
		1.0	1.1	1.2	1.3	1.4	1.5	1.6
ε_l at C300	1	C640	C640	C640	C640	C640	C640	C640
	1.2	C640	C640	C640	C640	C640	C640	C640
	1.4	C640	C640	C640	C640	C640	C640	C640

<u>Because of 8+8 voltage, bunch splitting at 640ns, then instability and losses (more than 50% for all the cases) start. Instability starts later with 16 resonators.</u>

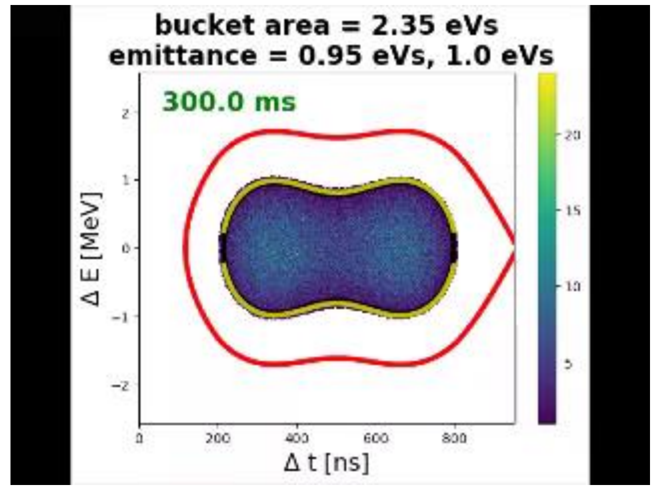
Results: 10+10 kV

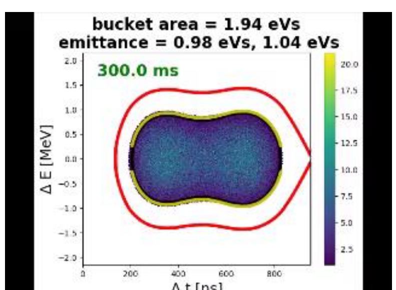
- Better results than 8+8 (using 16 notches).
  - Negligible losses (<1%)
  - However strong instability at the end of the ramp
  - Using eight notches gives even more instability

ε_l=1.4 eVs, N=1.6e13, C300-C741



ε_l=1 eVs, N=1e13, C300-C741





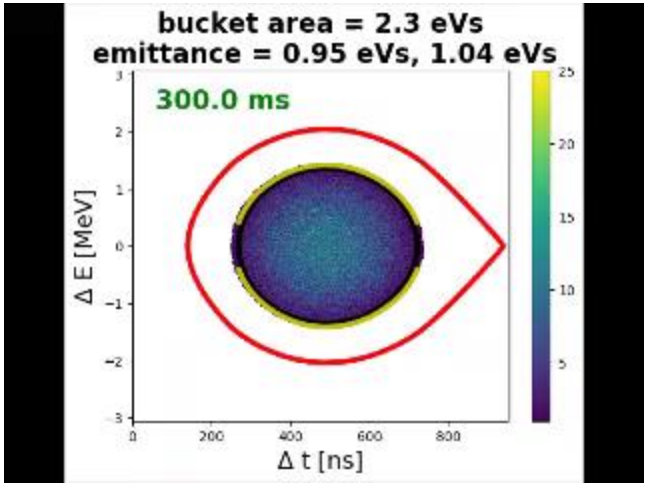
Typical case for 8+8 kV for comparison

ε_l=1 eVs, N=1.1e13, C300-C730

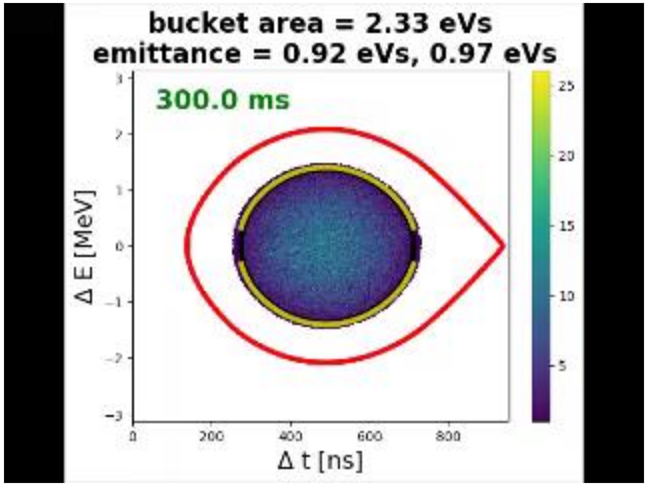
Using 20 notches

- Simulated also some cases with 20 notches in single RF 16 kV

ε_l=1 eVs, N=1.6e13, C300-C800



ε_l=1 eVs, N=1.2e13, C300-C741



- Results similar to the 16 notches case but further simulations are needed

Summary

- Simulations have shown that high-intensity beams can be unstable.
- Some parameters have been scanned
- Results show that 16 notches give better results that 8 notches, but still beams with intensity ~ 1.6e13 present instability
    - 16 kV case: more stable configurations, instability delayed
    - 8+8 kV case: high number of losses due to splitting and synchronous phase shift, with 16 notches instability delayed
    - 10+10 kV: no losses here (lower synchronous phase shift) and again 16 notches better than 8
- Few tests using 20 notches don't show particular improvements relative to the 16 notches case.

Future plans:

- Improve the model used in simulation
- Improve the number of simulations to have a better parameter range for scan
- Understand how this instability can be cured (attention to RF program design, noise injection in the first part of the ramp to keep bunch length constant,...)