LHC Injectors Upgrade

Simulations of Longitudinal Beam Stabilisation in the CERN SPS with BLonD

J. Repond, K. Iliakis, M. Schwarz, E. Shaposhnikova

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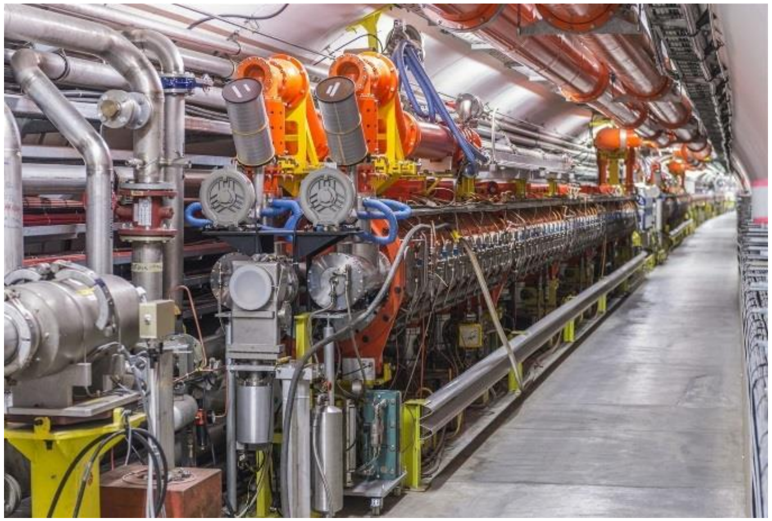
The Super Proton Synchrotron (SPS)
A machine with 40 years of history

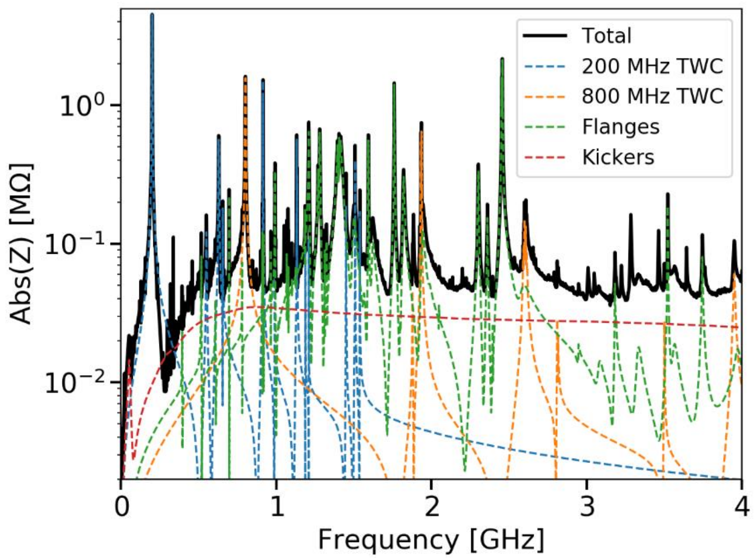
- **Since 2008 the SPS is the injector of the Large Hadron Collider (LHC)**
  - Synchronous momentum (proton) between 25.92 and 451.15 GeV/c

SPS 200 MHz Travelling Wave Cavities (TWC)



- **The SPS has two RF systems**
  - 4 cavities at 200 MHz (acceleration)
  - 2 cavities at 800 MHz (stabilisation)

- **Present longitudinal impedance model**
  - Hundreds of various machine elements included



The High-Luminosity LHC project (HL-LHC)
Target and limitations in the SPS

- **Major upgrades of the SPS are necessary to reach the intensity target of HL-LHC**

	Nominal LHC	HL-LHC
Beam pattern	4 batches of 72 bunches	
Bunch intensity [particles per bunch (ppb)]	1.15×10^{11} →	2.4×10^{11}
Bunch lenght at extraction (average)	1.65 ns	
Maximum V_{200} (beam-loading at flat top)	7 MV →	10 MV

- **The intensity increase in the SPS is limited by**
  - Beam-loading in the 200 MHz RF system (addressed by RF upgrade)
  - Longitudinal multi-bunch instabilities during cycle (addressed by impedance reduction)
  - Large particle loss at flat bottom, growing with intensity (partially from injected bunch)
- **Limitations should be lifted up by RF upgrades and impedance reduction**
  - Future achievable performance needs intensive studies

Studies are mainly performed using particle simulations

The BLonD code for longitudinal beam dynamics simulations in synchrotrons

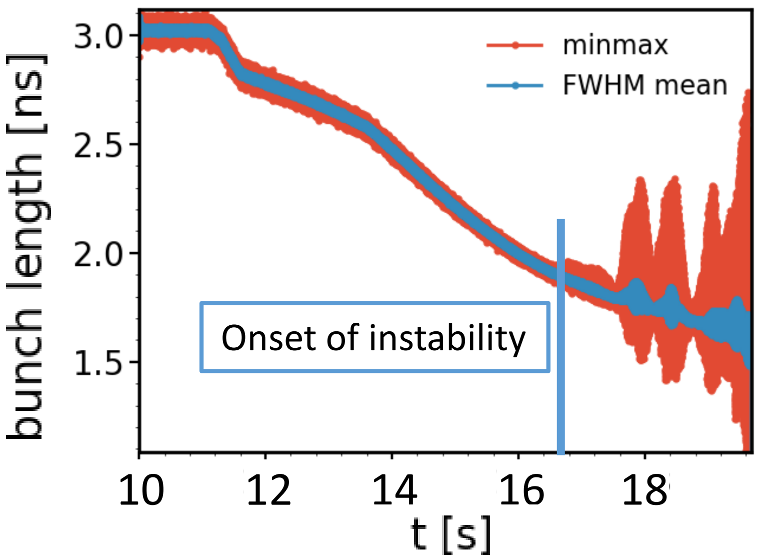
BLonD is a 2D particle tracking code modelling the longitudinal phase space motion with following features [1,2]

- **Multi-bunch and multi-batch beam**
- **Multi-harmonic RF system or Multi-RF systems**
- **Low-Level RF beam and cavity control loops (LLRF)**
  - One-turn delay feedback
  - Phase-loop, controlled emittance blow-up by phase noise
  - Radial-loop
  - Frequency-loop / synchro-loop, momentum slip-stacking
- **Full longitudinal beam-coupling impedance model**
  - Induced voltage in frequency or time domain by using a slicing of the beam
- **Initial distribution matched to the RF bucket with intensity effects,**

Example of BLonD simulation for SPS
Stability during cycle

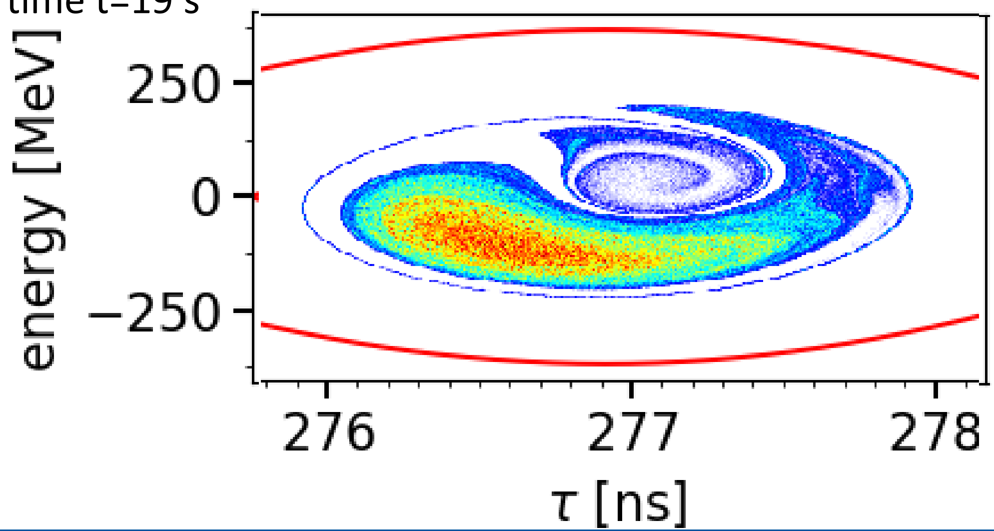
- **Simulation with intensity effects needs >= 1 million macroparticles per bunch**
  - All parameters were chosen after convergence studies
- **Simulation of instability threshold (nominal batch) needs 72 bunches**
  - Effect of the long range wakefields of the SPS impedance model
- **Before optimisation it took ~ 168h for a 10 s ramp (~440,000 turns)**

Bunch length evolution during cycle



at time t=19 s

Bunch phase space at time t=19 s



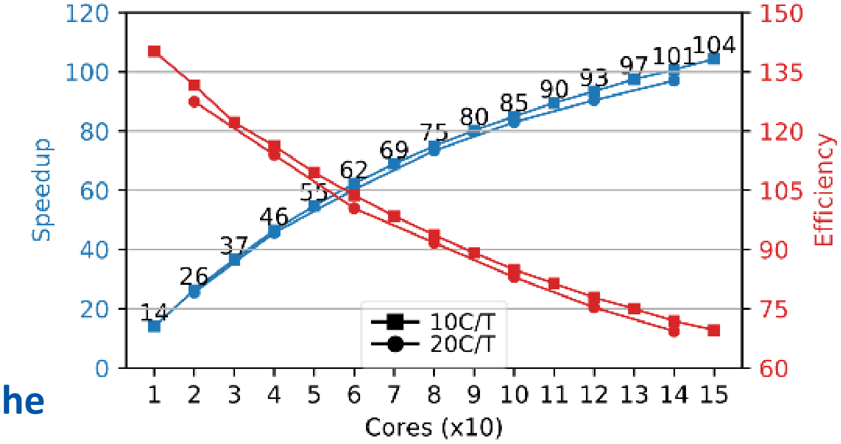
Runtime of BLonD simulations for SPS

> 2 years of optimisation allowed to reduce the runtime by two orders of magnitude! [3]

Optimisation type	Runtime (*)
Initial version (3 years ago)	168 h
Algorithm and multi-threading	30 h
MPI implementation (dev.)	1.5 h

(*) Runtime for 72 bunches through 10 s cycle time in the SPS

MPI Speedup-Efficiency graph



Performance improvement made more studies possible for the complicated SPS impedance model and multi-bunch beams

Instability threshold at flat top in SPS
Double RF system operation (DRF)

- **The intensity limit decreases like 1/Energy and is minimum at flat top (FT)**
  - Simulation carried out at highest energy (2 s)
- **Total voltage (DRF) at phase ϕ is**

$$V(\phi) = V_{200}\,[\sin\phi + r\sin(n\phi + \phi_{800})],$$

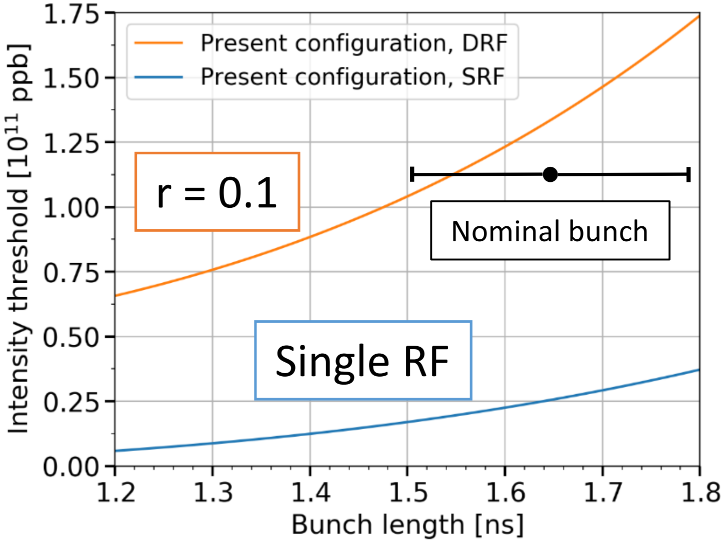
with

V_x the x MHz voltage, $\mathrm{r} = \frac{\mathrm{V}_{800}}{\mathrm{V}_{200}}, \mathrm{n} = \frac{h_{800}}{h_{200}} = 4,$

$\phi_{800} = \pi$ (bunch shortening mode)

- **Nominal DRF operation (r=0.1) is not sufficient to ensure beam stability with spread in bunch length**
  - Controlled emittance blow-up during ramp but the average bunch length at extraction to the LHC is fixed to 1.65 ns to fit in the 2.5 ns RF bucket of the LHC

Instability threshold (FT) for 72 bunches, before LIU upgrades

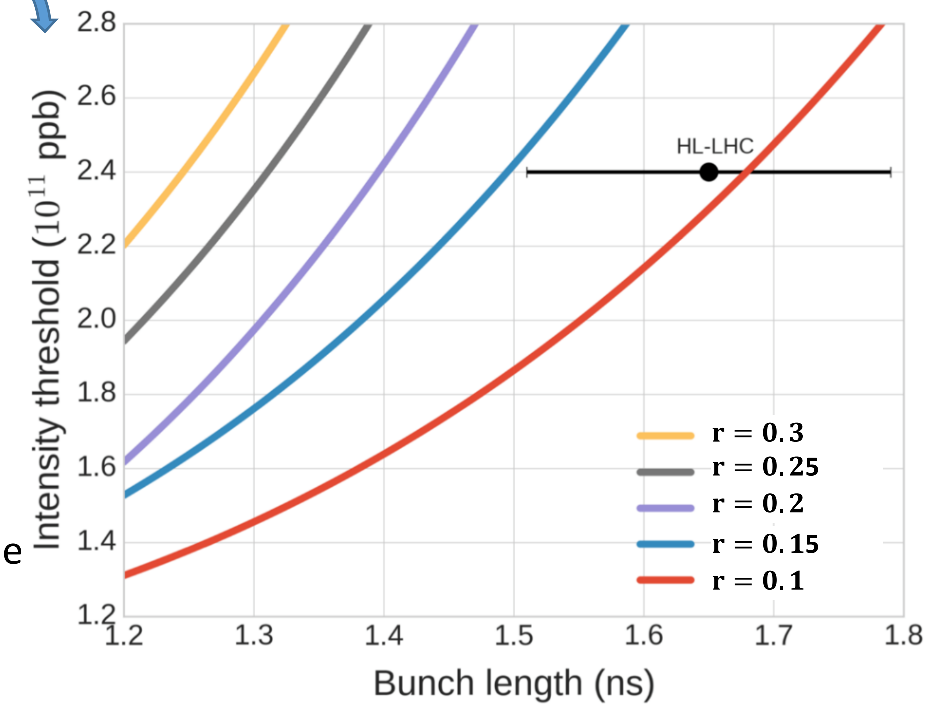


The beam stability at flat top can be significantly improved by using double RF system

Future instability threshold in double RF
Effect of voltage ratio increase

- **Instability thresholds of 72 bunches after LIU upgrades for higher voltage ratios at flat top**
  - Impedance model after upgrades
  - $V_{200} = 10$ MV

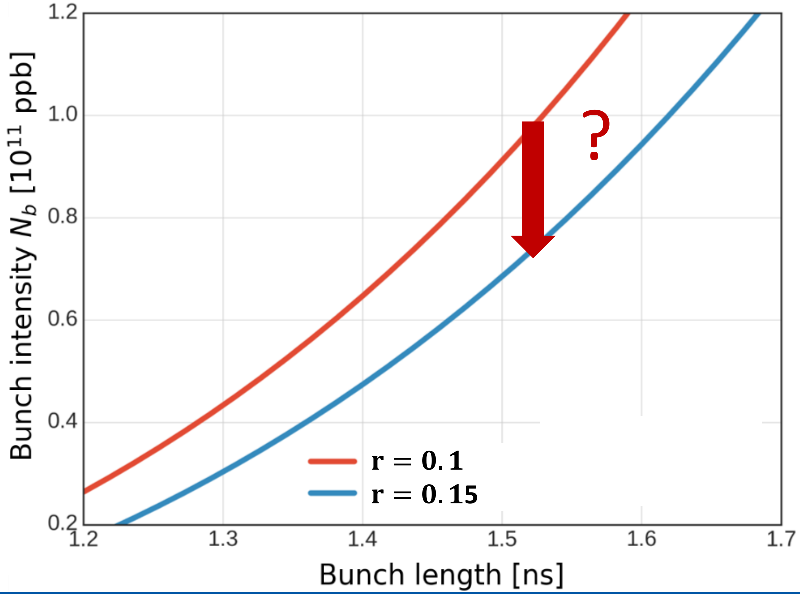
- **The increase of the voltage ratio r gives sufficient margins but**
  - V_{200} drops quickly above an intensity of 2.4×10^{11} ppb due to beam loading in the 200 MHz cavities
  - Only $r = 0.2$ is realistic due to hardware limitations



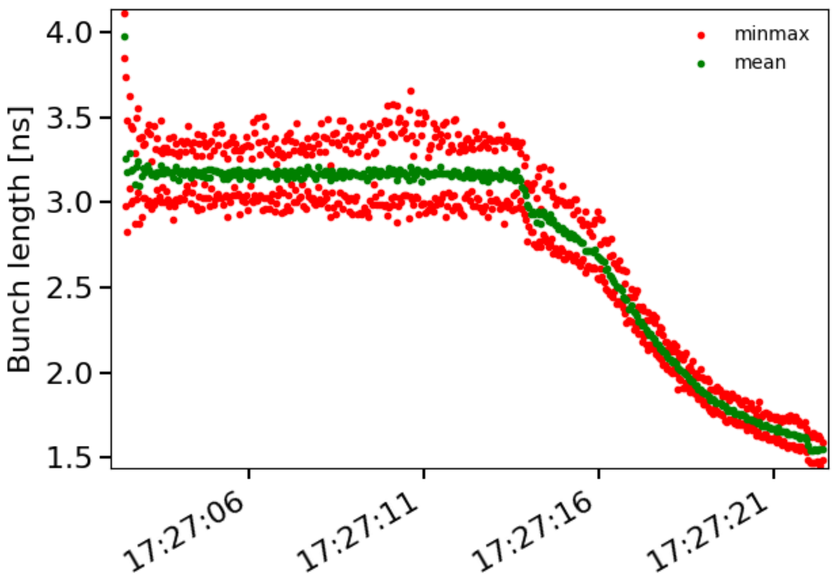
The beam stability at flat top can be significantly improved by increasing the voltage ratio, but what about ramp?

Larger voltage ratio during cycle?

- **Instability threshold decreases for larger voltage ratio during cycle**
  - V_{200} follows the operational program, r is constant during whole cycle ($V_{800} = r \times V_{200}$)



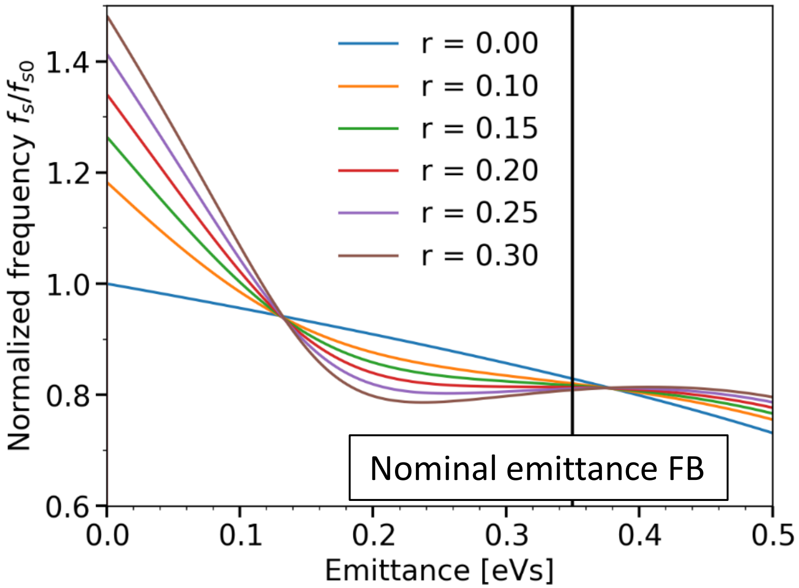
- **Ratio r=0.25 is not good at flat bottom**
  - Large bunch length oscillations measured ($N_b >$ nominal)

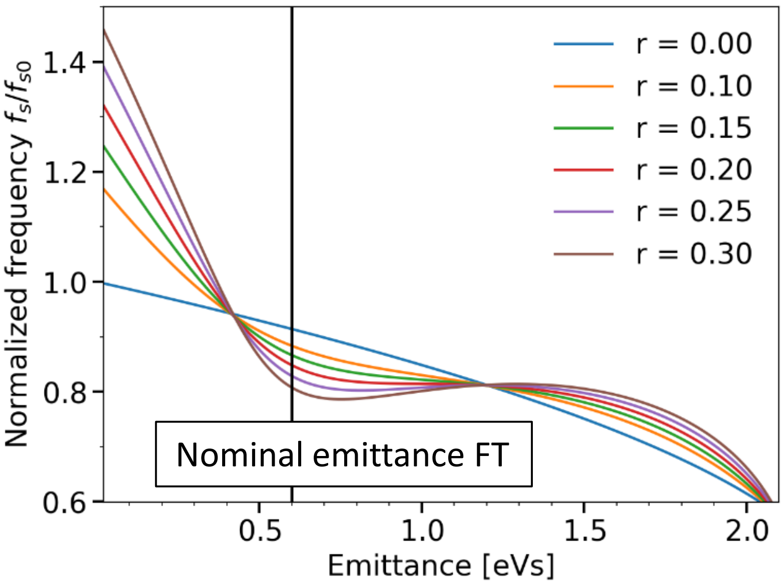


Value r > 0.1 doesn't increase stability. Why it is so different from high energy?

Synchrotron frequency distributions in the SPS (n=4, bunch shortening mode)

- **At flat bottom (FB): The distribution has a plateau inside the bunch**
- **At flat top (FT): Nominal bunch has no flat portion inside its emittance**

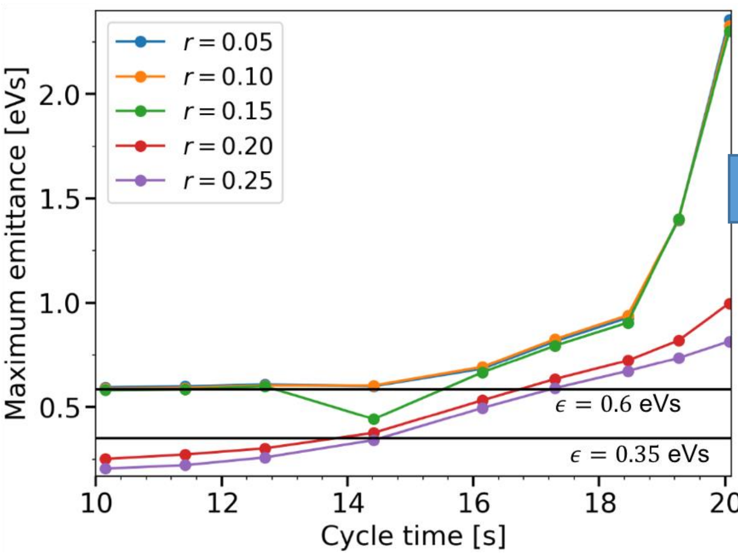




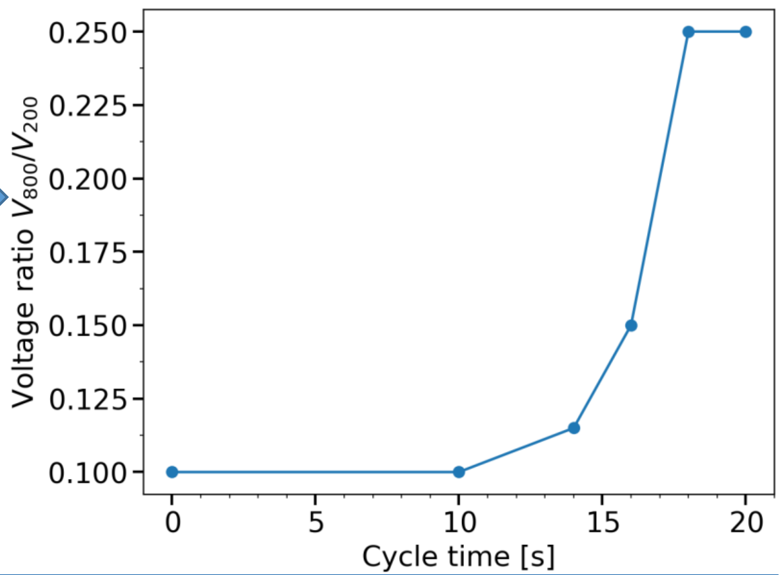
The Landau damping is lost in the region where $f_s'(\epsilon)$ goes to zero (plateau)

Optimised voltage ratio during ramp

- **For each voltage ratio, if $f_s(\epsilon)$ has a plateau, the bunch can have a max. emittance ϵ_m which avoids this region**
  - If no plateau, ϵ_m is the acceptance



- **The voltage ratio is kept low at FB (r=0.1) and can be increased during ramp to improve beam stability**



The beam stability has been improved in tests with 4 batches of 12 bunches ($N_b = 2 \times 10^{11}$ppb. . Setting now used for all high intensity LHC beams

Conclusions

- BLonD is a particle simulation code with many features to study the longitudinal beam dynamics in synchrotrons
  - Code optimisations have opened possibilities of new studies in multi-bunch with full impedance model

- Simulations allowed to have a better understanding of the beam dynamics in double RF system of the SPS

- Predictions are reliable and can be applied in operation
  - The optimised voltage program enhances beam stability during cycle and is now used in real machine conditions

References

- [1] The BLonD LONgitudinal Dynamics code, https://blond.web.cern.ch
- [2] H. Timko et al., «Benchmarking the Beam Longitudinal Beam Dynamics Code BLonD», in Proc. IPAC'16, Busan, Korea, May 206, WEPOY045.
- [3] K. Iliakis et al., «BLonD++: Performance Analysis and Optimizations for Enabling Complex, Accurate and Fast Beam Dynamics Studies», 18th Internatioal Conference on Embedded Computer Systems: Architectures, Modeling and Simulation (SAMOS), Greece, July 2018, to be published.

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SPARE SLIDES

Acceleration of 4x12 bunches with 2e11 p/b

LHCMD4 | 30.08.2018 18:06:19

Transmission: 85.65 %

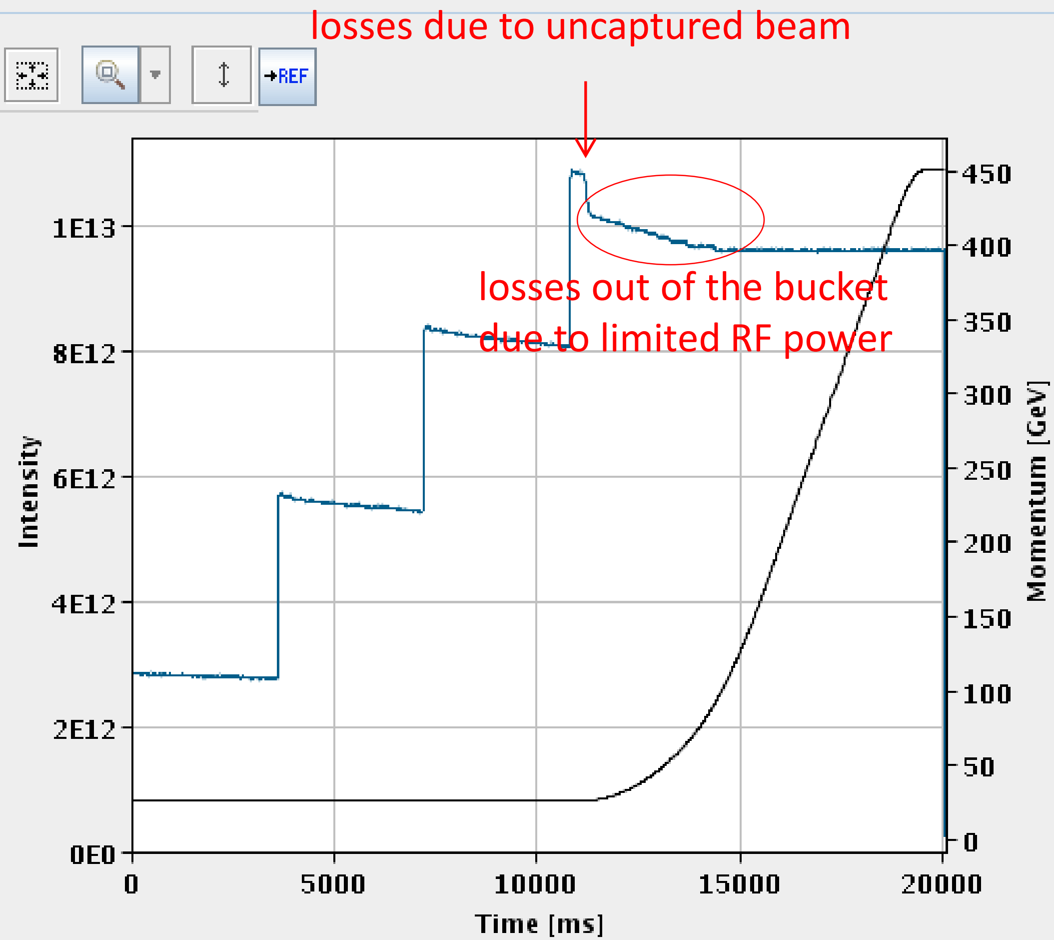
Total Intensity: 9.63E12

Bunch Intensity: 2.01E11

# of Bunches: 48 — 4x12 bunches, 25ns bunch spacing, 250ns batch spacing

Filling Schema: 1-12,22-33,43-54,64-75

Name	Time	Intensity
Injection 1	0	2.86E12
Injection 2	3600	2.85E12
Injection 3	7200	2.82E12
Injection 4	10800	2.70E12
Start Ramp	11100	1.09E13
Start FlatTop	19539	9.63E12
Extraction	19939	0.00E00
Std. Dump	20038	9.62E12



Courtesy: H. Bartosik