LHC Injectors Upgrade

SPS injection losses review, 30 November 2017

Lower Harmonic RF System in the SPS

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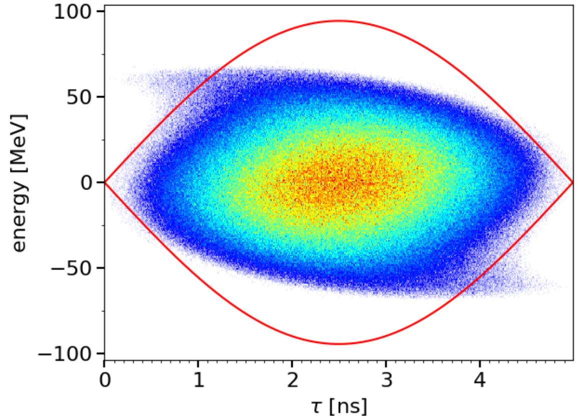
Acknowledgements: H. Damerau, A. Lasheen

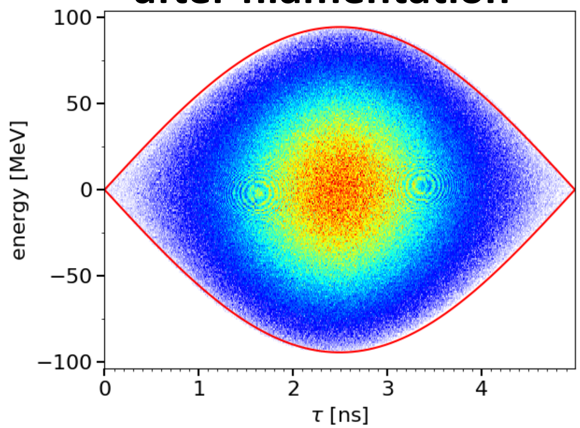
CERN

Present PS – SPS transfer of LHC beam

1st turn in SPS 200 MHz bucket



after filamentation



PS bunch:

- Created in 40 MHz RF system
- Rotated using 40 & 80 MHz RF (more in *A. Lasheen* talk)

SPS:

- No bunch-to bucket matching
- Particles injected close to separatrix

→ Full bucket, independent of capture RF voltage at 200 MHz

→ Could losses during beam transfer be minimised using a lower harmonic RF system in the SPS?

PS-SPS beam transfer – some history

- R. Garoby, Requirements to the PS RF system for filling the LHC with 25 ns spacing between bunches, CERN PS/RF/Note 93-04
- D. Boussard, RF scenarios at 26 GeV in the SPS as LHC injector, CERN SL/Note 93-12
- R. Garoby, A non-adiabatic procedure in the PS to supply the nominal proton bunches for LHC into 200 MHz RF buckets in SPS, CERN PS/RF/Note 93-17

The 80 MHz RF system in the SPS was proposed and eliminated after consideration of the coupled bunch instability and bunch rotation on the SPS flat bottom: “Scenario where the 9 ns long bunches are held all along 4.8 s flat bottom is unrealistic.” (D. Boussard, reduction of 200 MHz impedance by factor 10)

→ Bunch compression in the PS is much better and needs less hardware

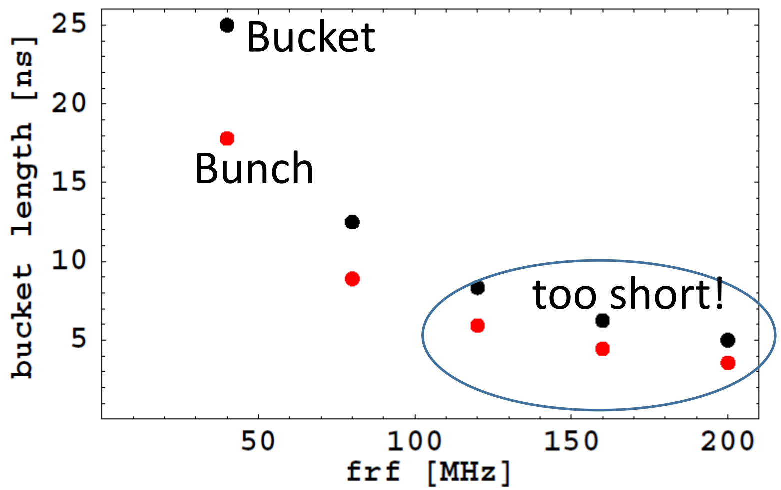
What is different now to consider a low frequency system again?

- High intensity required for HL-LHC and SPS capture losses increasing with intensity
- Experience with rotated bunches and issues related to the PS particle distribution (S-shape, halo)
- Larger longitudinal emittance needed in PS for beam stability
- LIU-SPS 200 MHz RF upgrade (power, LLRF)
- Experience in beam stabilisation using a higher harmonic RF system (800 MHz in BS mode)

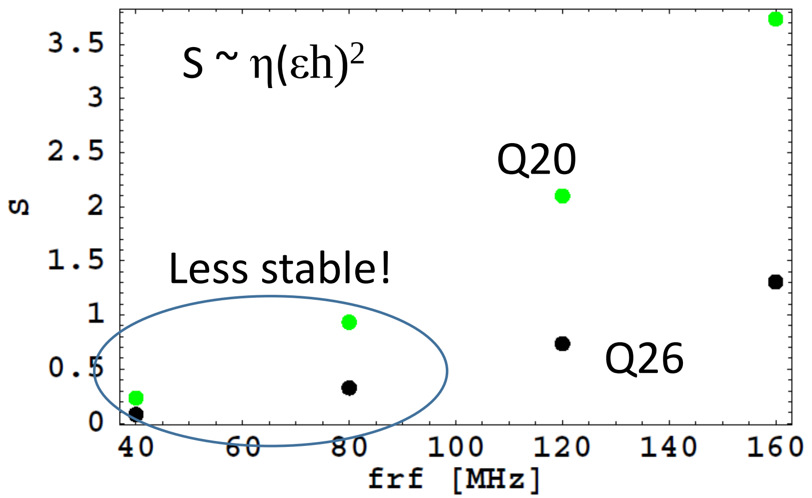
→ use 200 MHz as a Landau system

Choice of RF frequency

Bucket and bunch size



Beam stability for 0.5 eVs bunch relative to 0.35 eVs bunch in 200 MHz



- Bunch length for 0.5 eVs bunch with 0.9 momentum filling factor
- PS can produce adiabatically a 6 ns bunch
→ 40 MHz or 80 MHz

More unstable for 40-120 MHz
→ 80 MHz with lowest γ_t (Q20)

A need in the SPS 200 MHz RF system

- As Landau cavity: for given emittance and optics we lose in stability in all cases
- For acceleration: due to large bandwidth (TW) it works for ions and FT protons from 14 GeV/c
- For beam transfer to LHC: otherwise one needs the 200 MHz RF in LHC and even then the situation will be worse with transfer from the 40 & 80 MHz RF system in the SPS

→ Keep also the 800 MHz RF system, used for beam stabilisation in the 200 MHz RF system

Potential issues with the 80 MHz

- Lower beam stability due to lower harmonic number → 200 MHz as a Landau cavity, but
  - Residual 200 MHz voltage → limitation to min 80 MHz voltage → minimum bunch length from the PS
  - Some multi-batch instability was recently observed on flat bottom (LLRF?) and the 800 MHz RF was not very helpful
- Beam transfer to the 200 MHz RF system
  - Potential gain in losses only if they are related to the bunch shape due to the PS bunch rotation
  - Same losses (satellite bunches) if PS bunch has large tails
- Acceleration of larger emittance bunches in 200 MHz
- Impedance and beam loading in the new RF system
  - Effect on beam stability during the rest of the cycle

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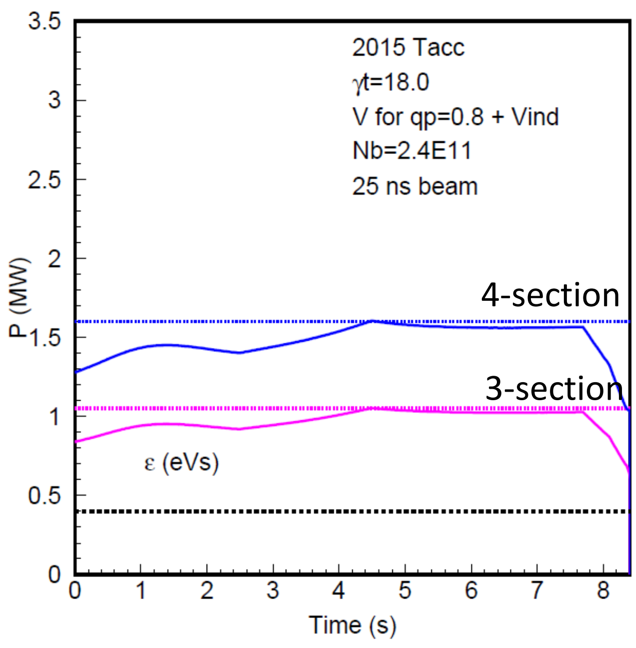
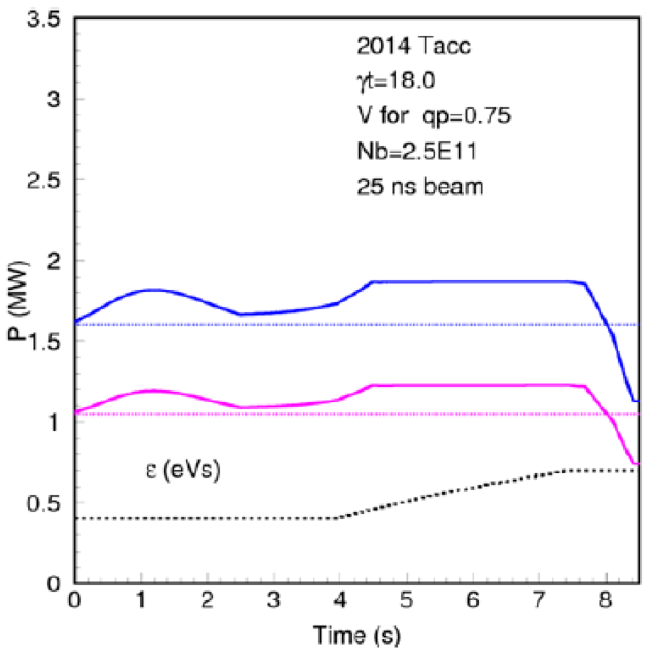
Acceleration in 200 MHz RF system: maximum possible emittance





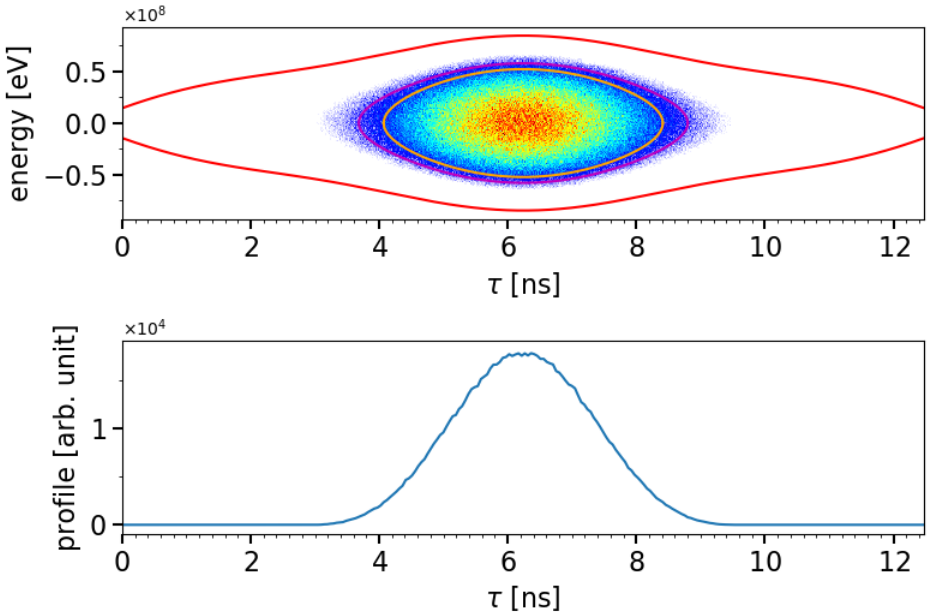
Bunches of 0.5 eVs can be accelerated with minimum qp = 0.8 (too high for present situation)
→ Simulations with realistic bunches to find precise limitations

Matching SPS RF voltage to PS bunches for stability simulations

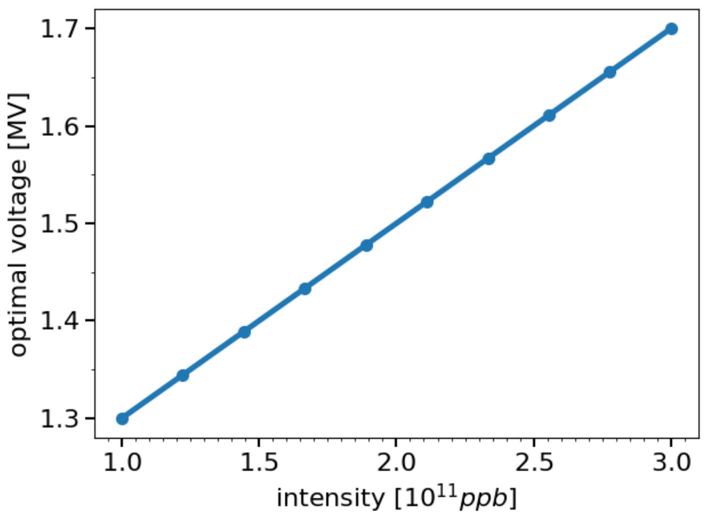
The bunch is matched to the RF

Voltage at $N = 0$ for a given emittance

80 MHz [MV]	200 MHz	Emit [eVs]	Tau [ns]
1.1	0	0.35	5.1
1.0	0	0.5	6.4



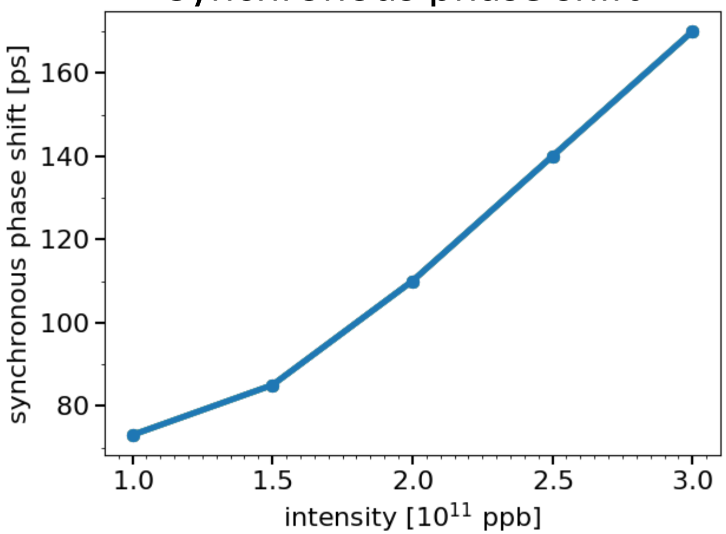
Matched 80 MHz voltage with intensity effects (to minimise emittance blow-up)



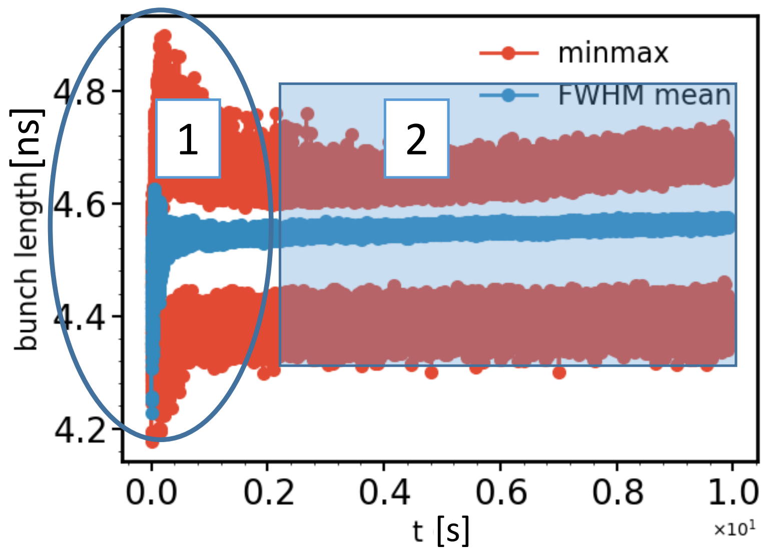
Effect of beam-loading in 200 MHz RF system

- **LLRF upgrade:** -26 dB reduction on 200 MHz main harmonic
  → Induced voltage saturates around 100 kV ($N = 1 \times 10^{11}$)
- **Synchronous phase shift** due to beam-loading in 200 MHz
  → Mismatch for main part of the batch

Synchronous phase shift



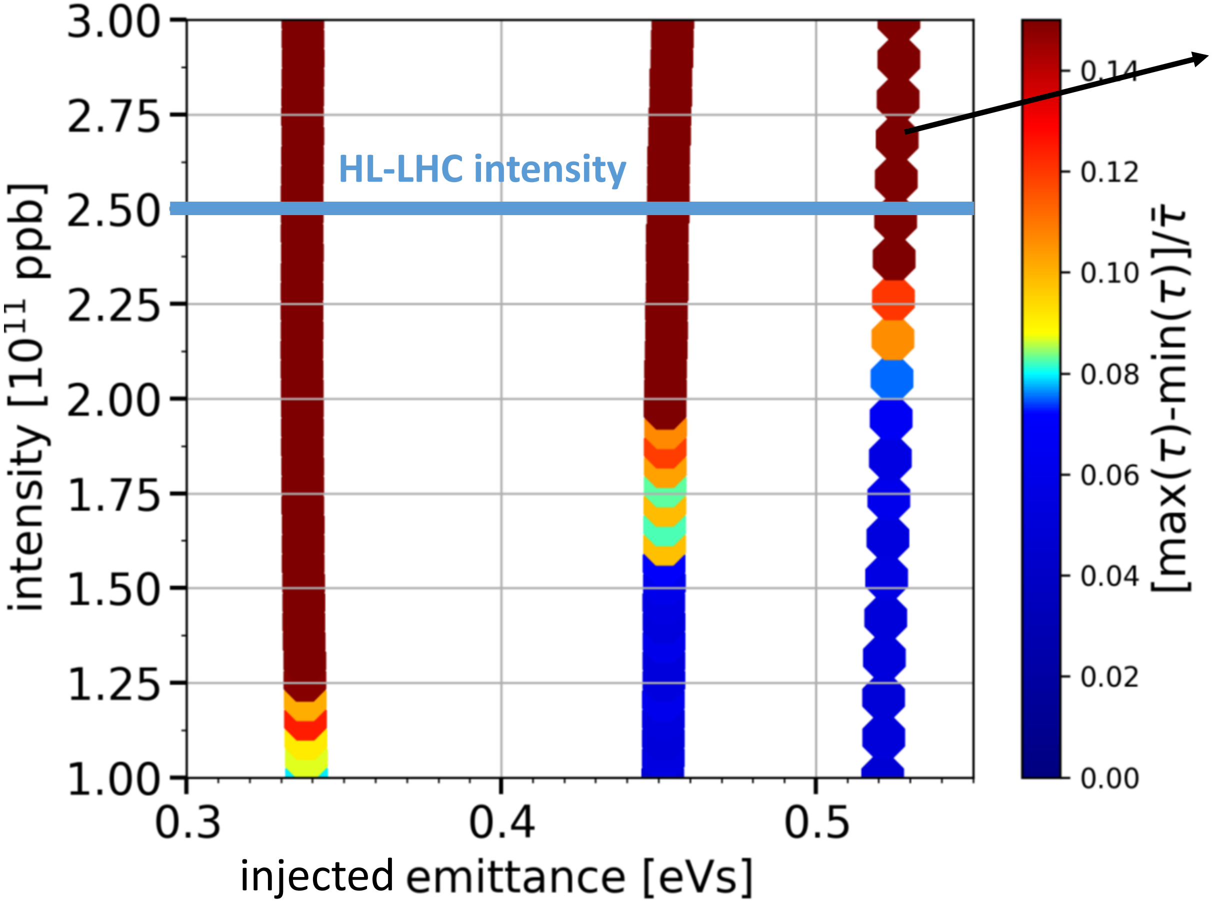
Evolution of average bunch length

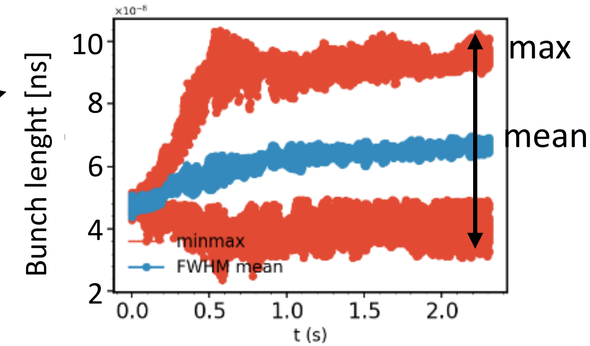


After filamentation:

1	→ 6-10% uncontrolled emittance blow-up
2	→ Peak-peak variation of bunch length gives criteria on beam stability/quality

Beam stability threshold in 80 MHz RF



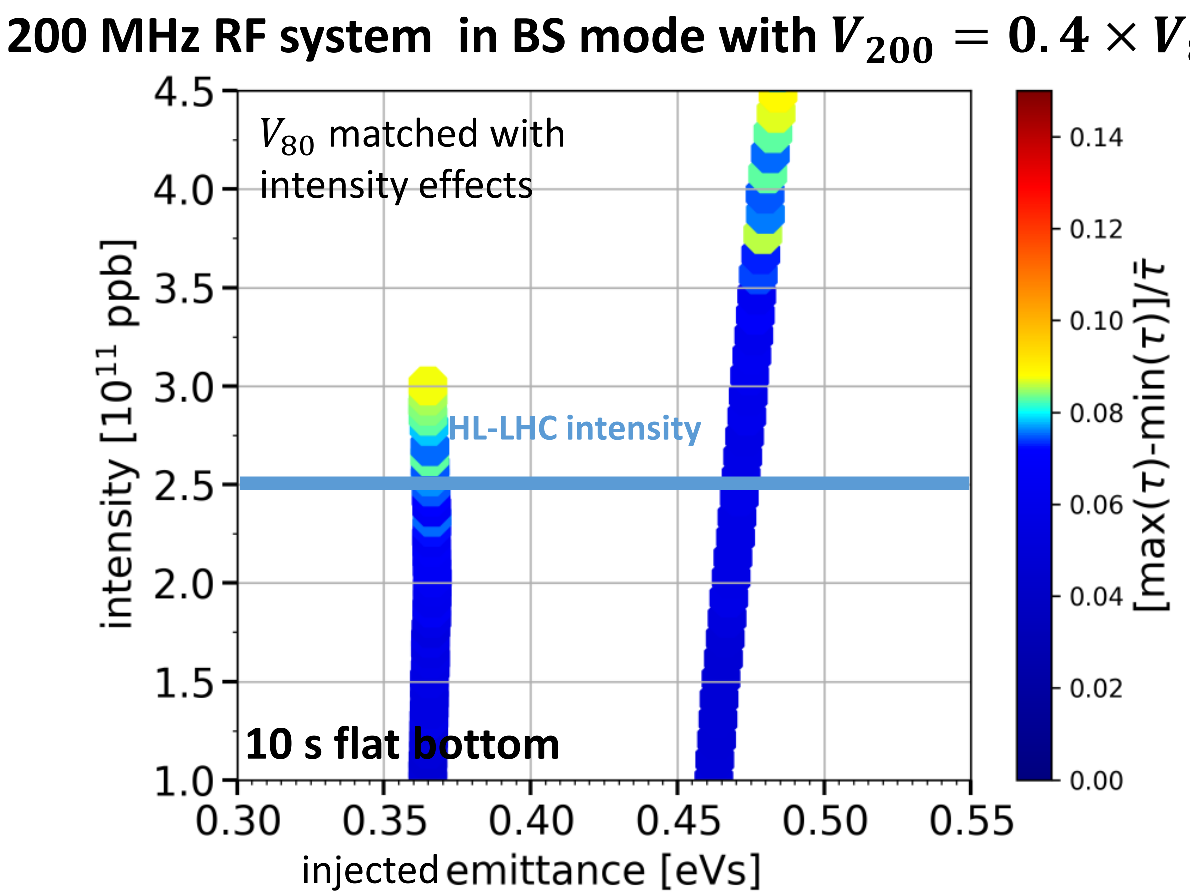


80 MHz RF system only, voltaged matched with intensity effects

→ Emittance needed for stability too large to be accelerated

→ Use 200 MHz as a Landau RF system

Stability threshold in 80+200 MHz RF



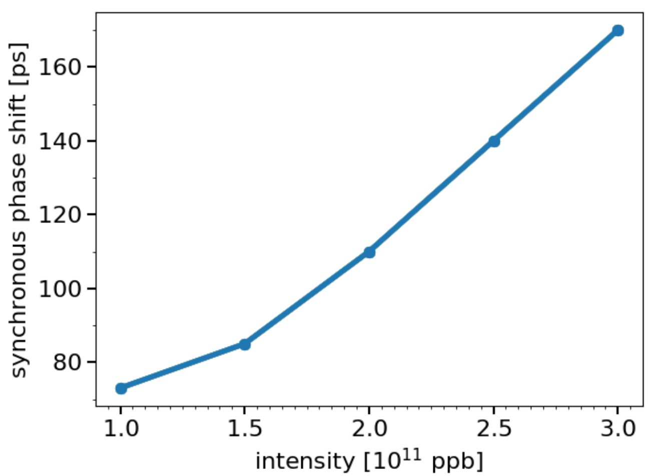
For HL-LHC intensity: Beam can be stabilised but

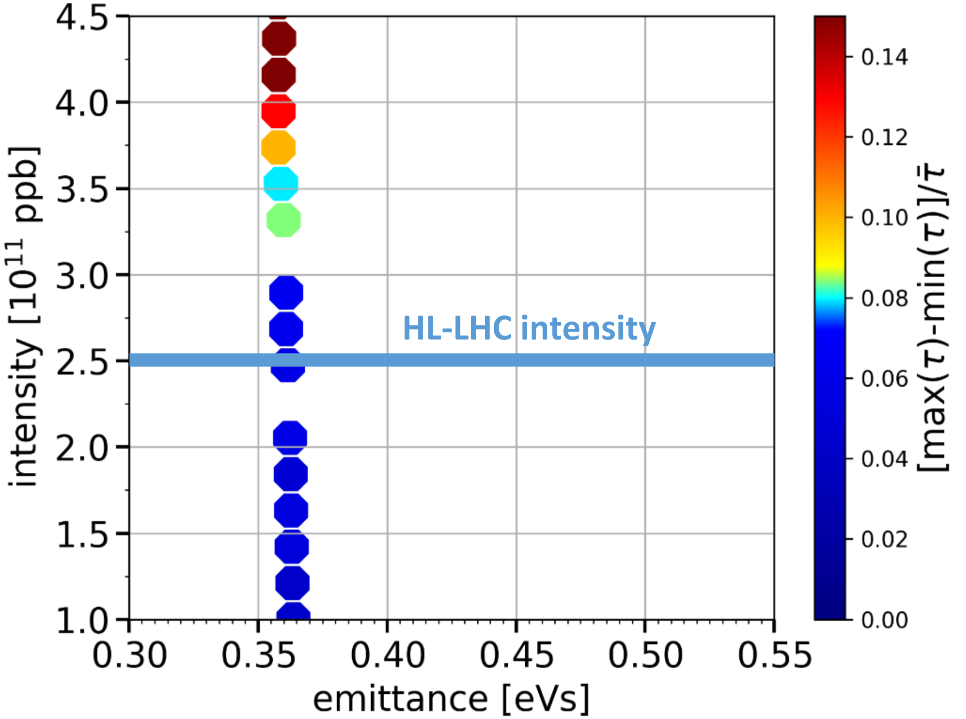
→ $V_{80} = 1.6\ MV$

→ >6% uncontrolled emittance blow-up, emittance variation along the batch

Beam stability threshold – mismatch compensation

Assuming the phase-loop corrects the mismatch at injection for main part of the batch





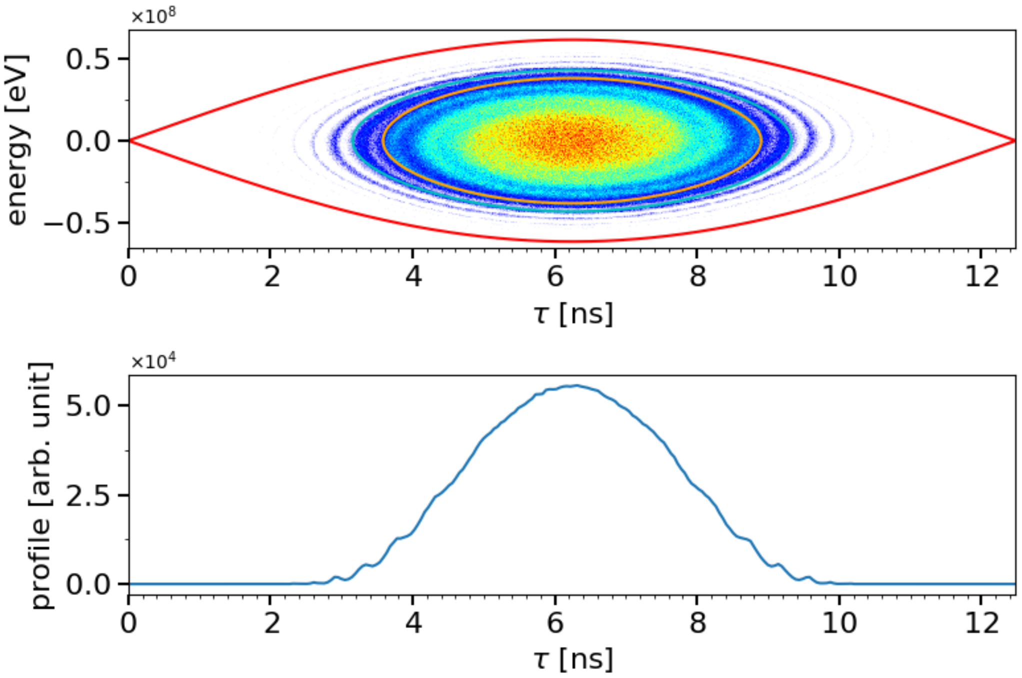
For HL-LHC intensity and nominal emittance:

→ Stable beam but emittance variations ~7% along the batch

→ Bunch oscillations undamped on a 10 s flat bottom

Matching SPS RF voltage to PS bunches for transfer 80 MHz → 200 MHz simulations

- **Production of PS bunch with tails** (simulated with $N = 0$)
  → Matched with RF and large tails before splitting
  → Splitting
  → Adiabatic reduction of bunch length to **6 ns** before extraction



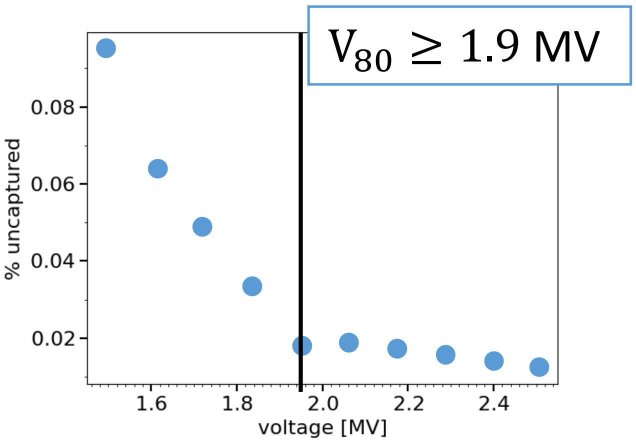
Nominal case

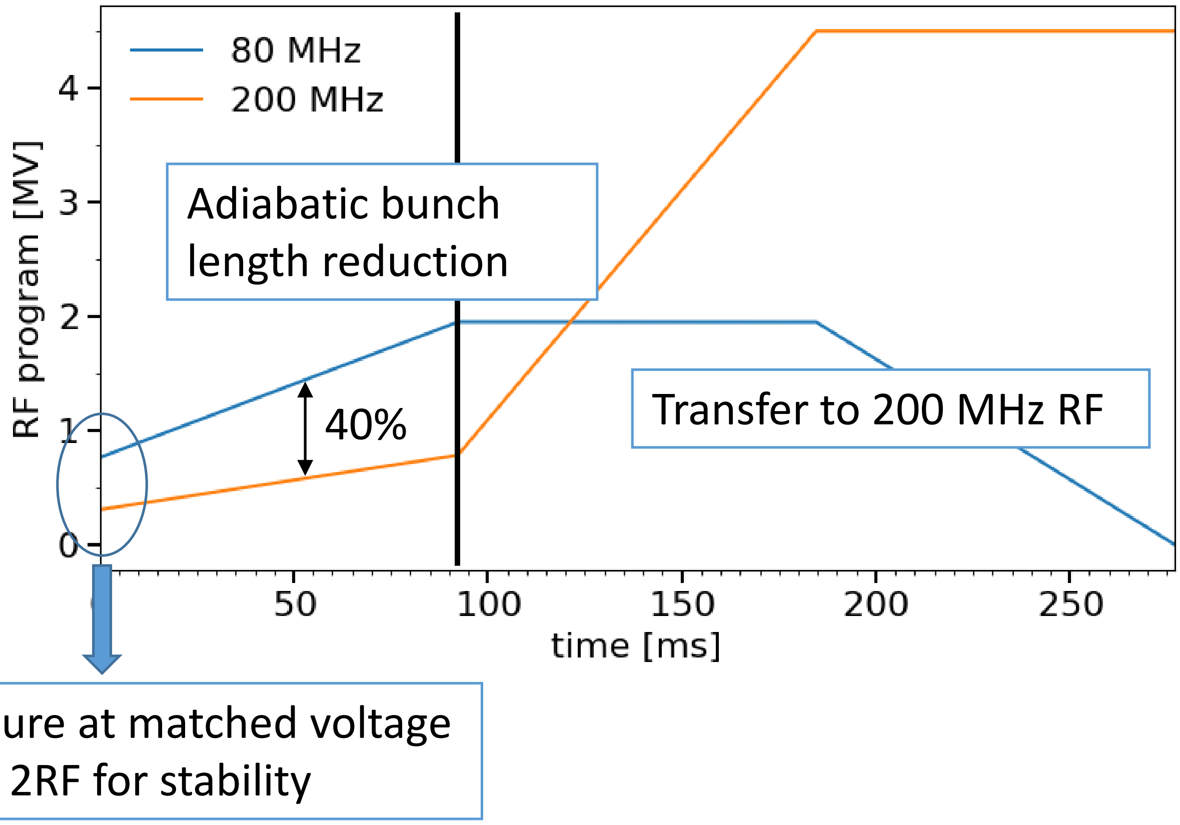
(PS simulations with measured bunch profile before splitting)

Emit [eVs]	Tau [ns]
80 MHz capture	
0.37	5.9
In 200 MHz after rot.	
0.35	3.0

Transfer to the 200 MHz RF system – RF program

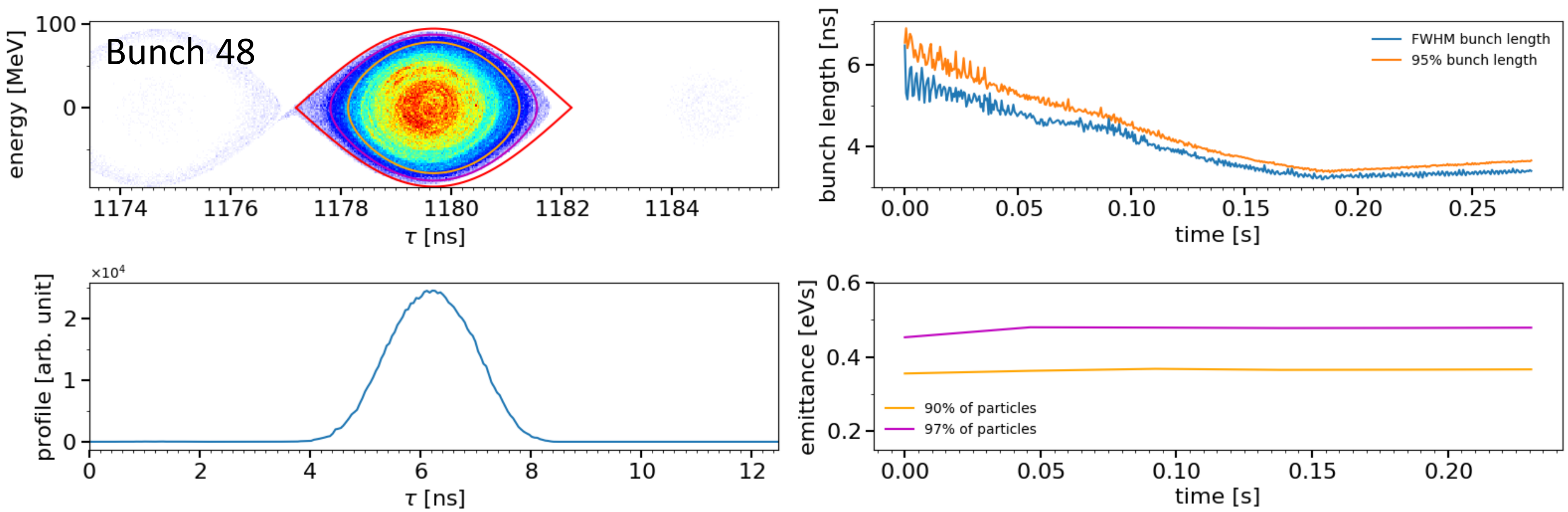
V_{80} is adjusted to minimise the satellites (w/o intensity effects)





Transfer to the 200 MHz RF system – including intensity effects

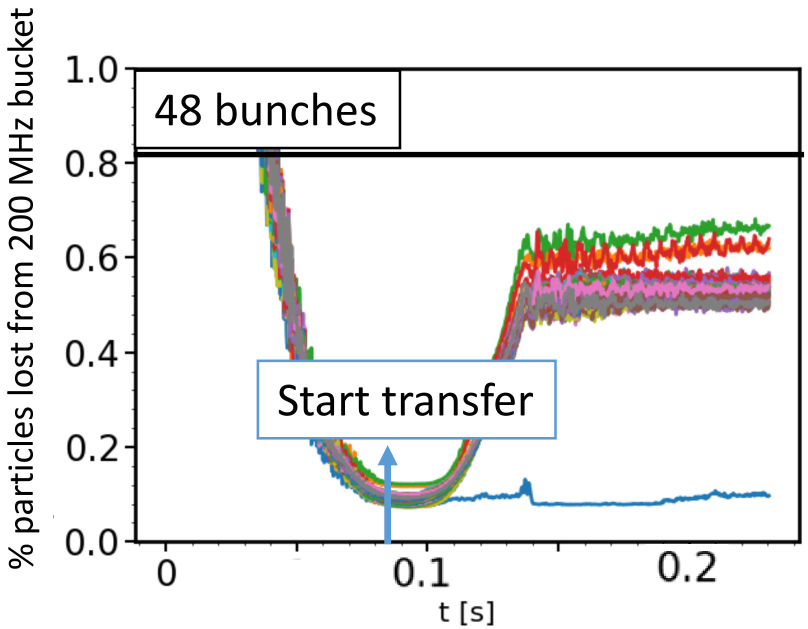
Phase-space, bunch length and emittance evolution



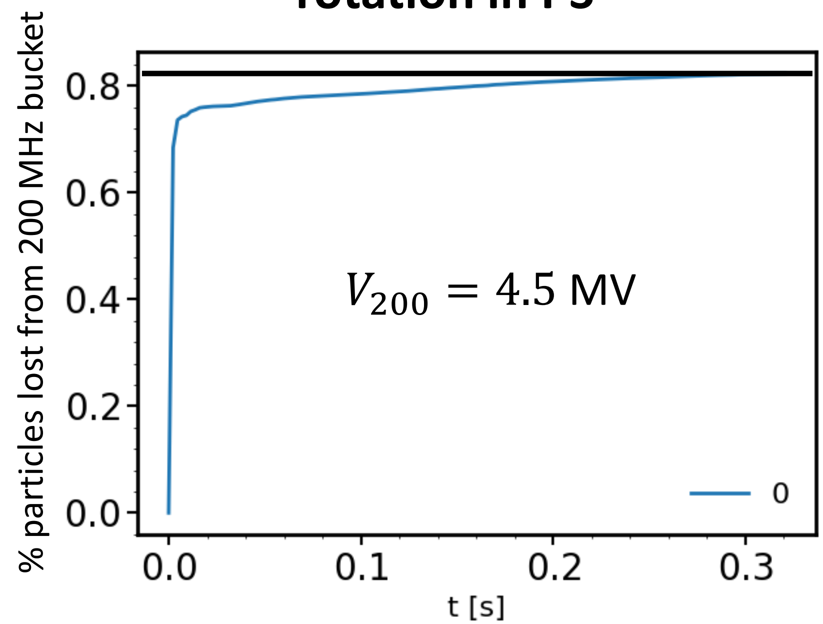
→ 97 % of particles contained in area with momentum filling factor of 0.85
→ Blow-up insignificant, final emittance: 0.4 eVs, average bunch length: 3.3 ns

Comparison of losses for intensity $N = 2.5 \times 10^{11}$ ppb

80 MHz → 4.5 MV at 200 MHz



200 MHz with -26 dB, single bunch, rotation in PS



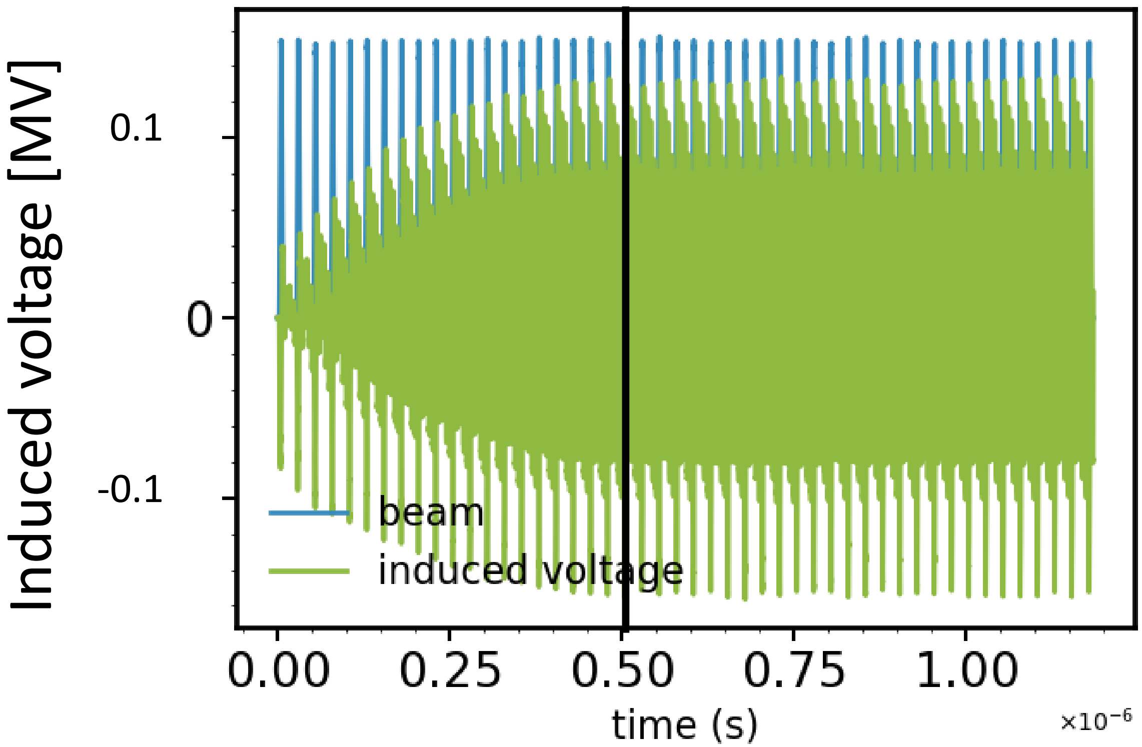
→ 0.1 % lost particles go to satellites
→ 0.5 % lost particles at transfer to 200 MHz buckets
Further losses are «flat bottom losses» from full 200 MHz bucket (4.5 MV)

0.8% lost particles in single bunch, may increase along the batch

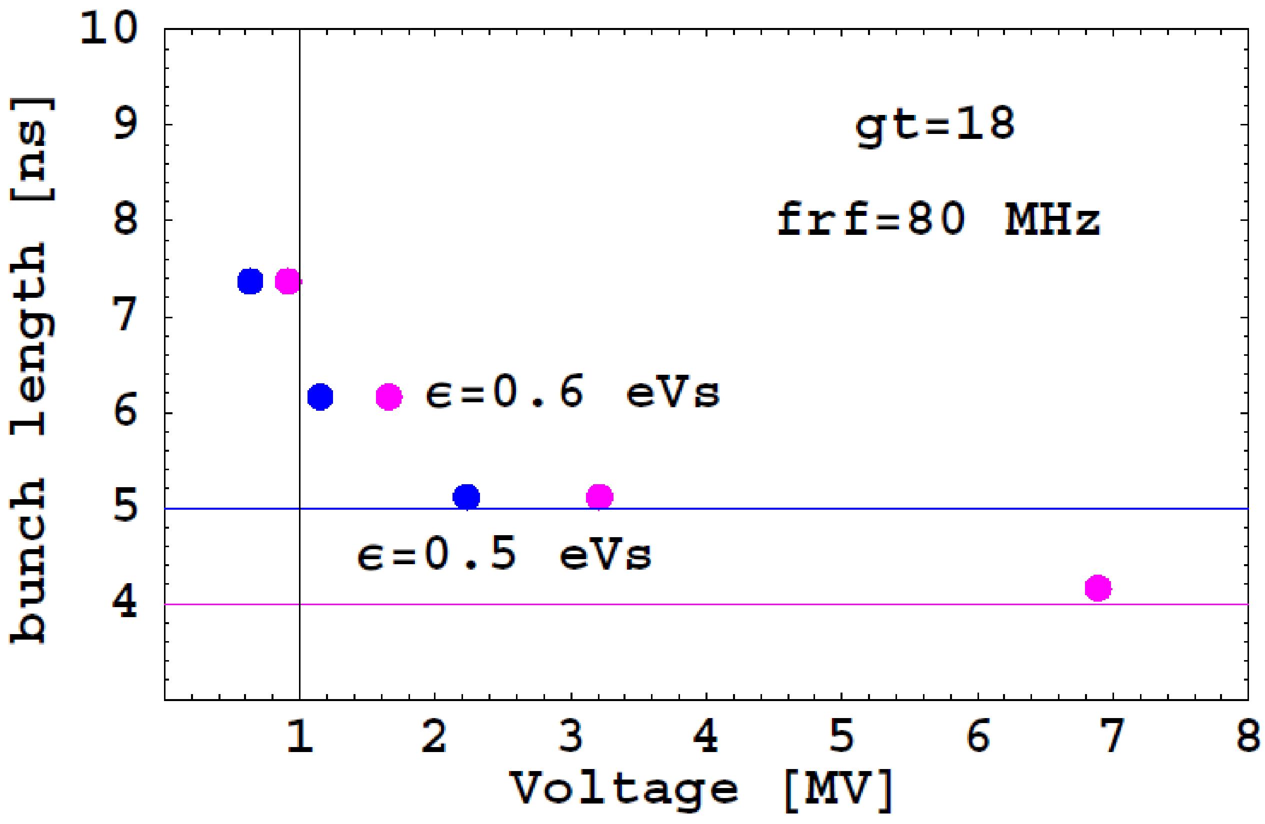
Summary

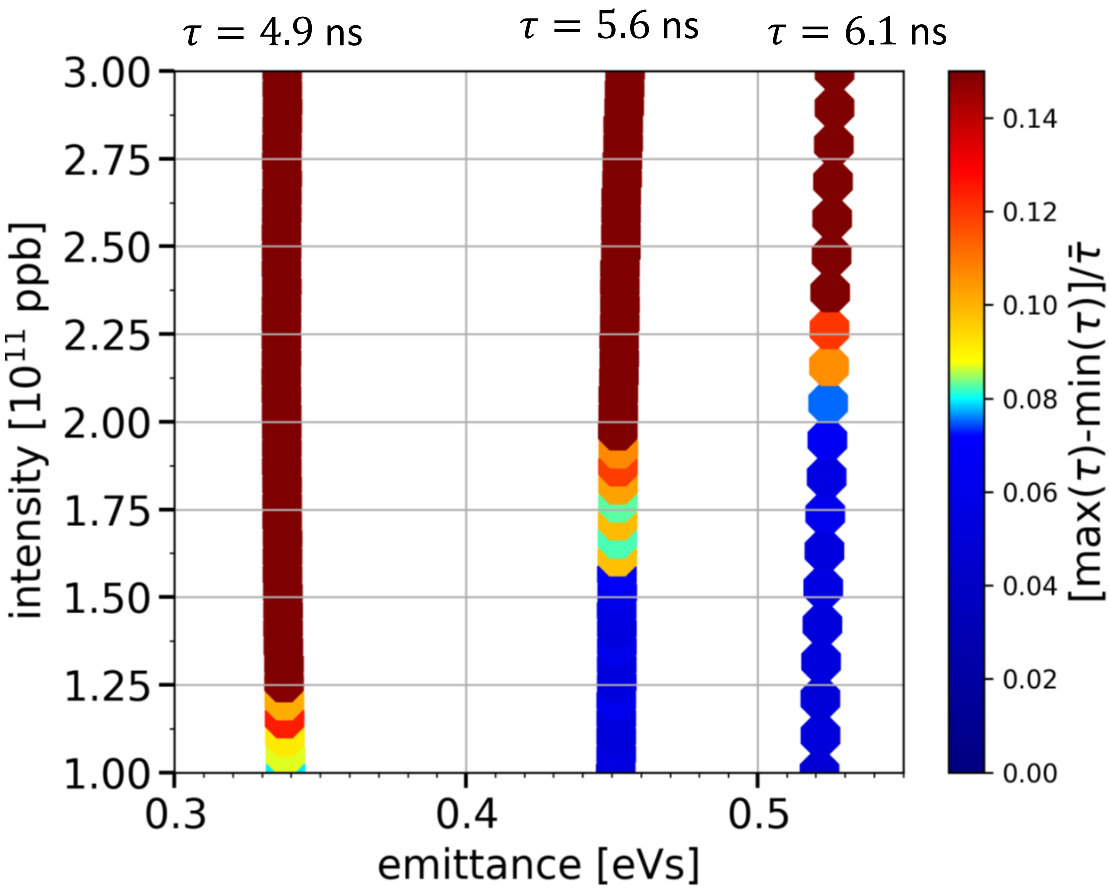
- The optimum frequency of a low harmonic RF system in the SPS is 80 MHz with ~1.6 MV required for capture
- High intensity beam of 0.35 eVs is unstable (Q20 optics) in a single 80 MHz RF even with upgraded - 26 dB 1-turn FB, but can be stabilised using in addition the 200 MHz RF system in bunch-shortening mode
- The 200 MHz RF system is still needed for beam acceleration and transfer to LHC
- Transfer to the 200 MHz RF requires the 80 MHz voltage of 1.9 MV and in simulations can be performed with < 1% losses
- Initial studies. Impedance and beam loading of 80 MHz RF not included yet, acceleration of larger emittances needs studies
- Drawbacks: cost, maintenance, reduced reliability

Backup slides

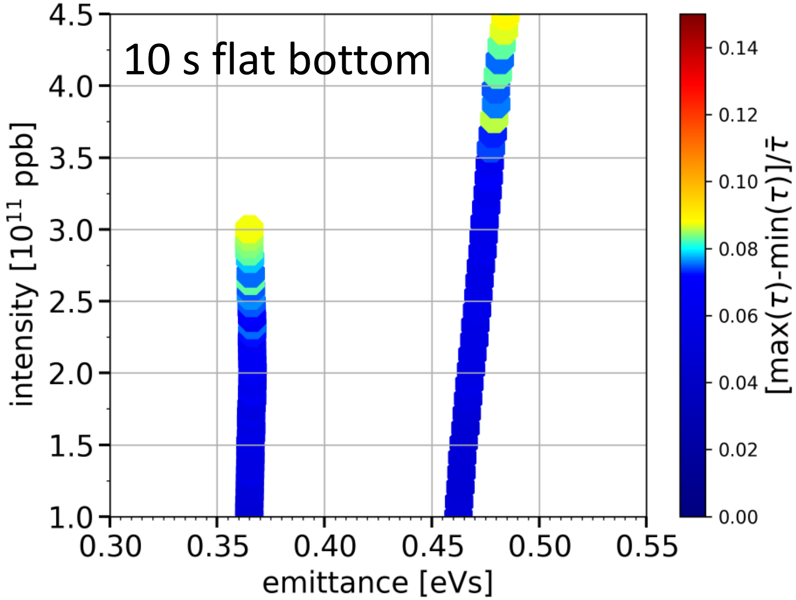

Induced voltage [MV]
0.1
0
-0.1
beam
induced voltage
0.00
0.25
0.50
0.75
1.00
time (s)
×10⁻⁶

The 80 MHz RF system



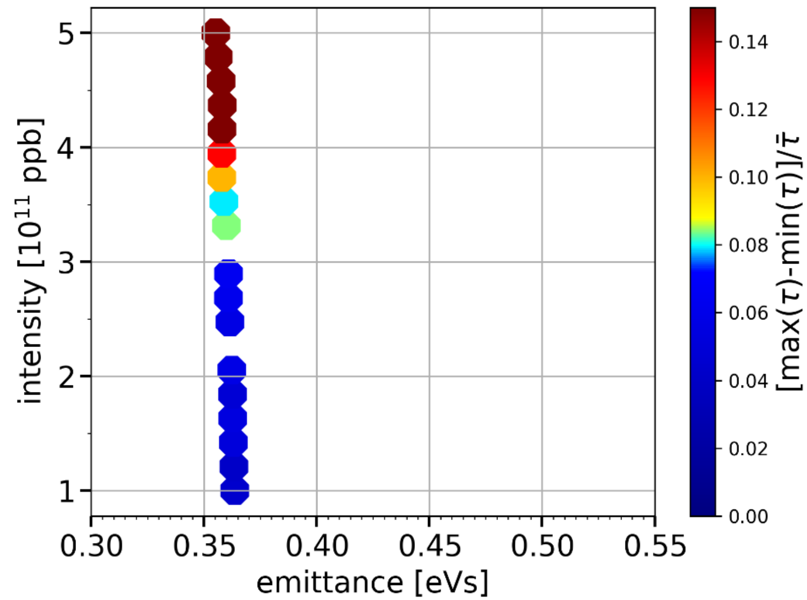

τ = 4.9 ns
τ = 5.6 ns
τ = 6.1 ns
intensity [10^{11} ppb]
3.00
2.75
2.50
2.25
2.00
1.75
1.50
1.25
1.00
0.3
0.4
0.5
emittance [eVs]
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
[max(τ)-min(τ)]/$\bar{\tau}$

$V_{200} = 0.4 V_{80}$



$\tau = 4.5$ ns $\quad \tau = 5.0$ ns

Assuming phase-loop recenter the second part of the batch at injection



PS bunches without rotation

PS	40 MHz	80 MHz	200 MHz	Emit [eVs]	Tau [ns]
V [MV]	0.6	0.9	0	0.35	5.3
				0.5	6.4
V [MV]	0.6	0.9	0.15	0.35	5.1
V [MV]	0.6	0.9	0.9	0.35	4.5
SPS		**80 MHz**	**200 MHz**		
		1.1	0	0.35	5.1
		1.0	0	0.5	6.4

PS - H. Damerau

- 150 kV at 200 MHz are available now, but serious problems expected for short bunch lengths (e-cloud, instabilities)