LHC Injectors Upgrade

LHC Injectors Upgrade Workshop

Montreux, 13-15 February 2019

LHC Injectors Upgrade

Session IV: LIU beam performance ramping up phase
SPS ramp up (protons)

Outline

- Plan to ramp up to LIU beam parameters, milestones
- Reference measurements to validate post-LS2 impedance models (and reduction)
- **Losses at PS-SPS transfer, injection and flat-bottom**
- Longitudinal stability during the cycle
  - Impact of RF upgrade (power, LL) and longitudinal impedance reduction
  - Deployment of longitudinal emittance blow-up
  - 800 MHz voltage programme
- Horizontal instability
  - Origin and expected impact with LIU parameters
  - Do we have sufficient knobs to suppress it without post-LIU developments?
- Reconditioning for high intensity with respect to e-cloud
  - Experience from the past
  - Intensity ramp up
  - Operational issues that could limit scrubbing efficiency (kicker heating, outgassing, …)

SPS beam parameters before LS2

Beam performance achieved at the SPS flat top (double RF system)
for PS batches with different number of bunches

number of bunches per injection	bunch intensity at 450 GeV/c [10^{11}]	transverse emittance [µm]	bunch length [ns]	total number of bunches at SPS extraction	main limitation
1 ok	3.7	2.5	2.7	1	long. Instability space charge
12	2.0	2.??	1.8??	4 x 12	long. instability
48	1.4	2.2??	1.5	4 x 48	beam loading
72 ok	1.3	2.5	1.6	4 x 72	beam loading

The LIU intensity was achieved in the PS in 2018 (with ϵ_t ~ 5.0 µm)
→ HL-LHC intensity available for SPS studies after LS2

HL-LHC target: how far is the SPS?

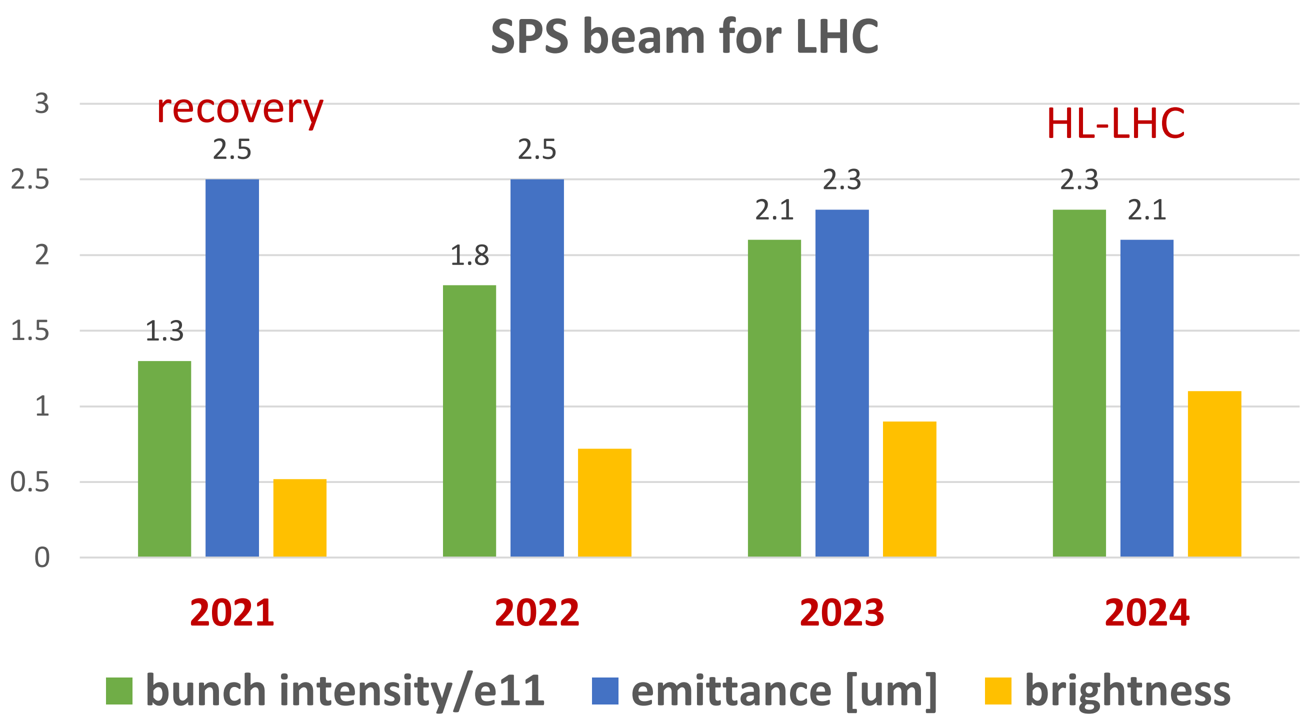
LIU target	intensity per bunch $[10^{11}]$	transverse emittance [µm]	bunch length [ns]	longitudinal emittance [eVs]	number of bunches
SPS injection	2.6	1.9	3.2	0.35	72
SPS extraction	2.3	2.1	1.65	0.57	4 x 72

13% reduction:
10% losses + 3% scraping

10% uncontrolled
emittance blow-up

60% controlled
emittance blow-up

LHC beam ramp-up in the SPS during Run 3



← Beam (4x72) at the end of year with
- losses < 10% (LIU budget)
- average bunch length < 1.65 ns

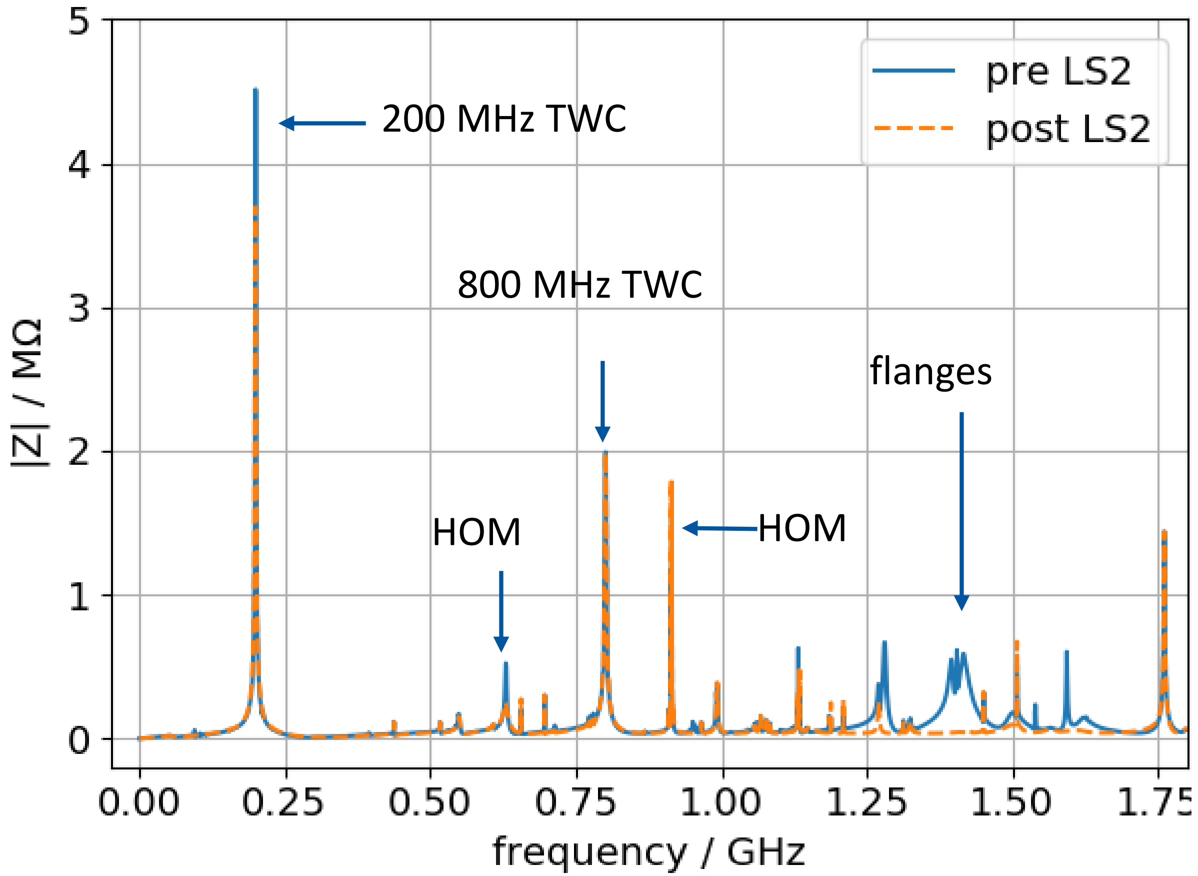
Intensity ramp-up concerns mainly the SPS,
while brightness - PSB & PS (*talk of A. Huschauer*).
LHC is interested in increase of intensity first (*talk of R. Tomas*)

Are the upgrades there?
Beam measurements during Run3

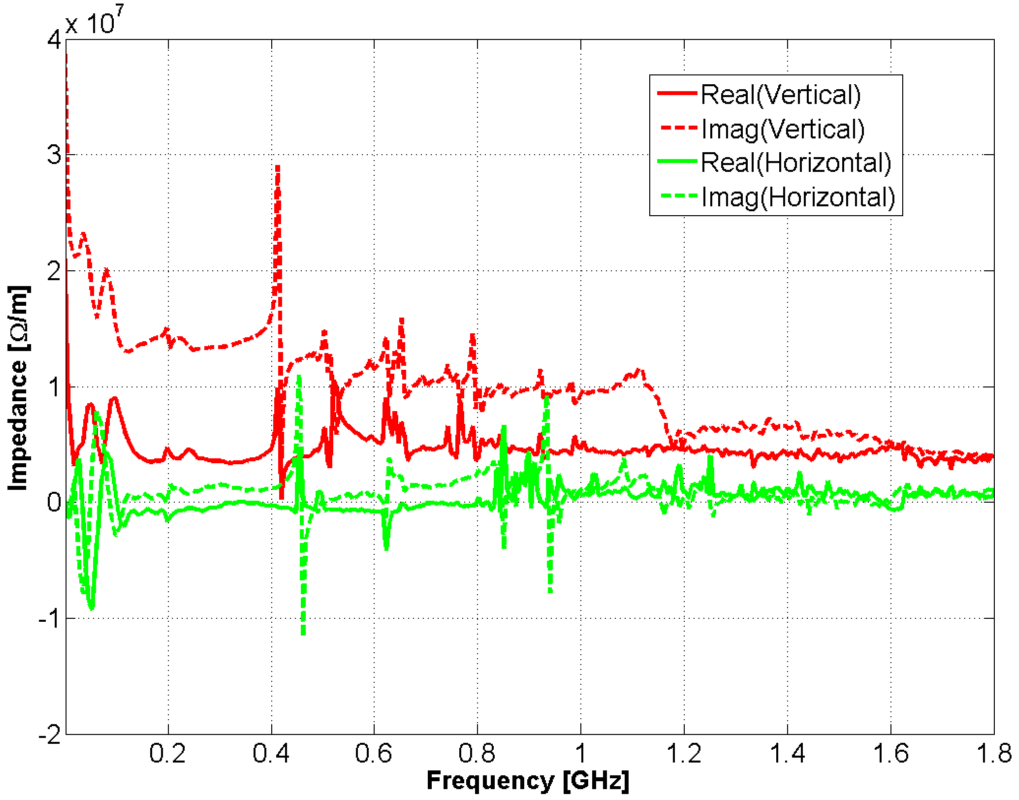
- 200 MHz RF (power and LLRF) upgrade
  - ✓RF voltage available for low intensity – 15 MV & HL-LHC intensity ~ 10 MV
  - Beam loss reduction in the SPS – difficult to compare (too many new things)
    - Simulations for 4 batches and more complete model of the FB system in 2020
  - ✓Beam instability at flat bottom (12 bunches)
- Impedance reduction (630 MHz HOM and vacuum flanges)
  - ✓Reference measurements
    - ✓Quadrupole frequency shift
    - ✓Spectrum of unstable long bunches with RF off
    - Synchronous phase shift – uncertainties in interpretation
    - ✓Single-bunch instability during ramp
  - ✓Multi-bunch instabilities during ramp

SPS impedance model

Longitudinal impedance



Transverse impedance



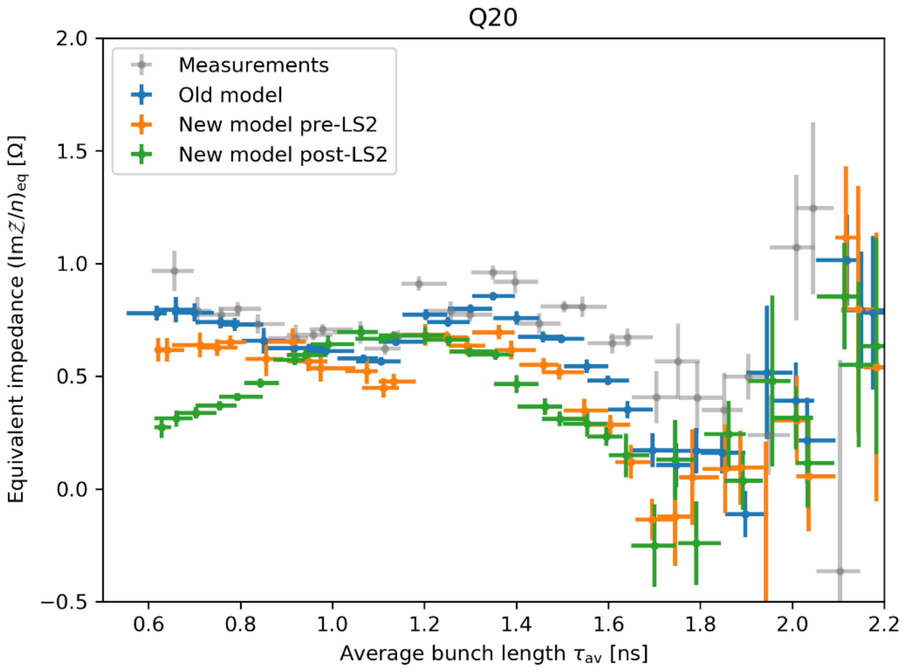
SPS impedance reduction during LS2: expected effect on the beam

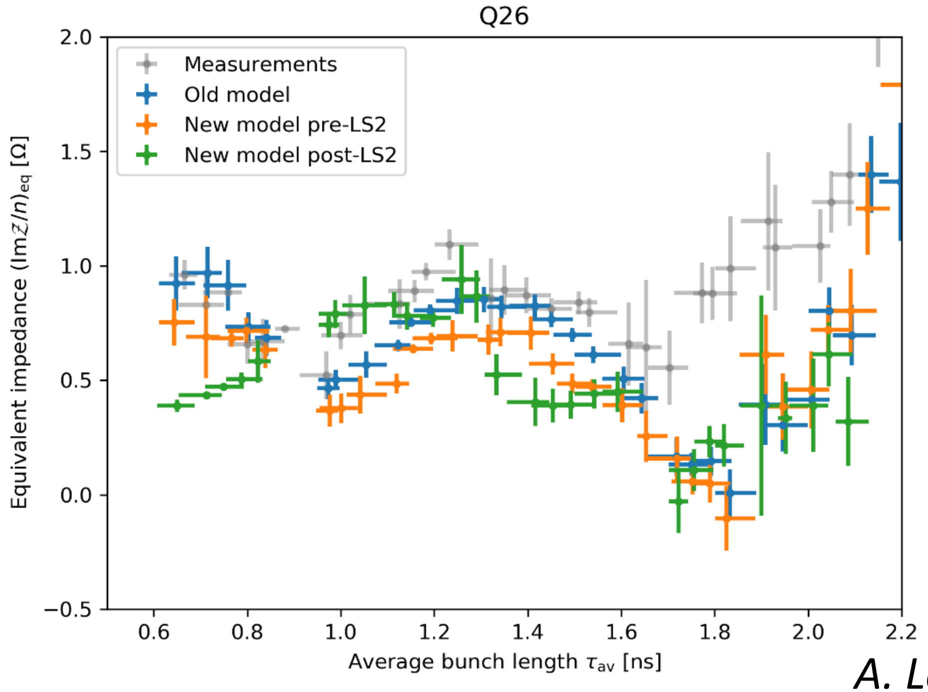
Impedance source	Resonant frequency [MHz]	Rsh [MOhm] / Q	Before LS2 instability on	Type of longitudinal instability	Impedance reduction
200 MHz TWC	200	4.5 / 130	flat-bottom	multi-bunch	by 18%
200 MHz TWC	630	0.53 / 330	ramp & flat-top	multi-bunch	244 kOhm/220
200 MHz TWC	915	3.0 / 5000	ramp & flat-top	multi-batch	?
QF vacuum flanges (110 + 31) & 15 PP	~1415	0.52 / 100	ramp & flat-top	multi & single-bunch	∞ (shielding)

Machine layout optimisation – not visible directly in beam measurements

Total reduction of low frequency $\mathrm{Im}Z/n = R_{sh}/(Q\, n_r)$ by 0.2 Ohm → less than measurement error?

SPS longitudinal reactive impedance from quadrupole frequency shift





A. Lasheen

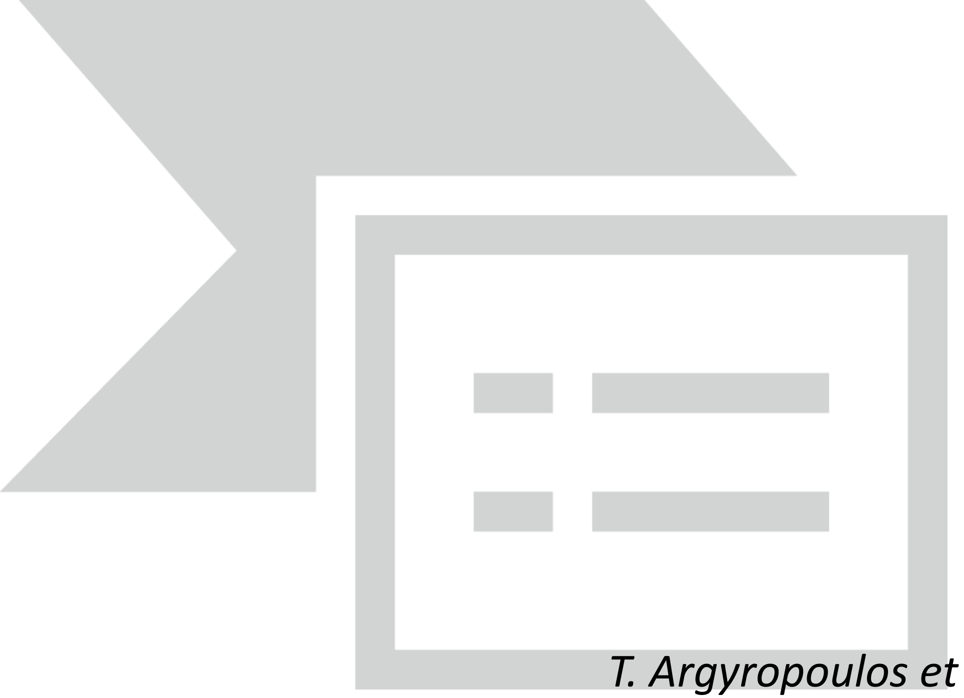
→ Overestimated space charge impedance of ~1 Ohm for Q20 (constant negative shift)?

→ **Measurements most indicative at small bunch lengths** (also most hard)

Reference impedance measurements:

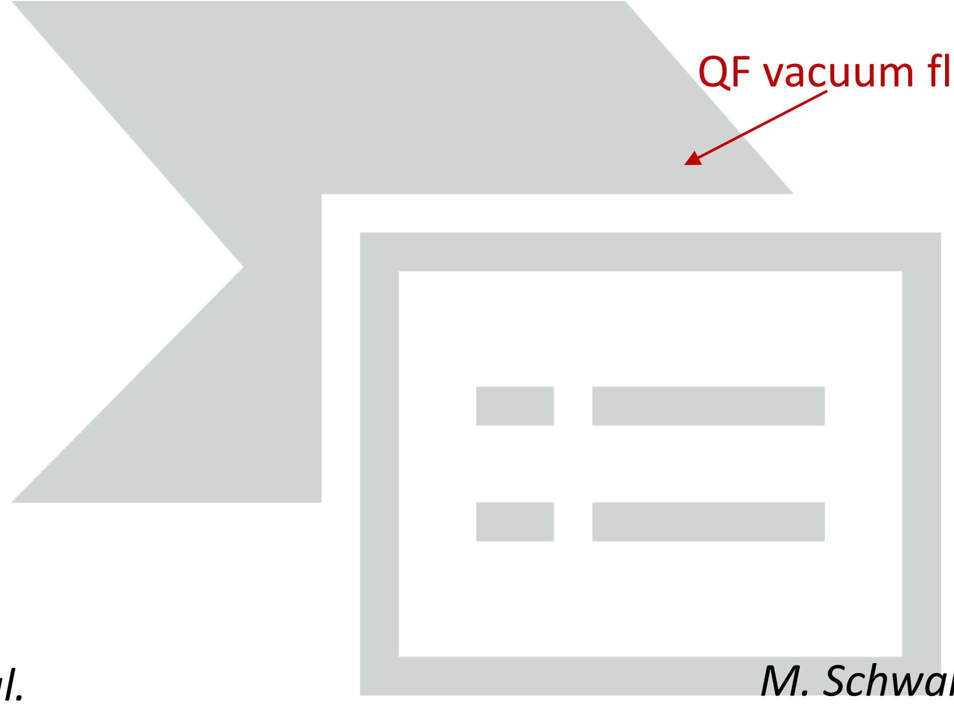
FFT of profiles of very long (~ 20 ns) bunches with RF off (Q20)

Measurements before LS2 at various bunch intensities



T. Argyropoulos et al.

Measurements & simulations



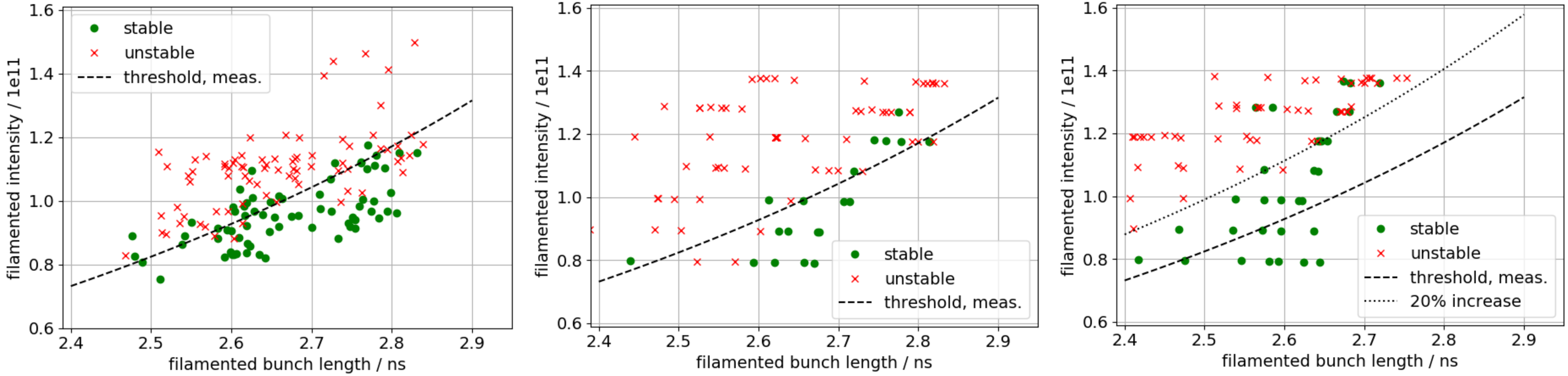
M. Schwarz

→ Shielding of vacuum flanges is visible in simulations (1.4 GHz peak)

Beam instabilities on the SPS flat bottom:

12 bunches, Q20, 1RF, V_{200} = 4.5 MV, FB off

Measurements before LS2 | **Simulations: before LS2** | **Simulations: after LS2**

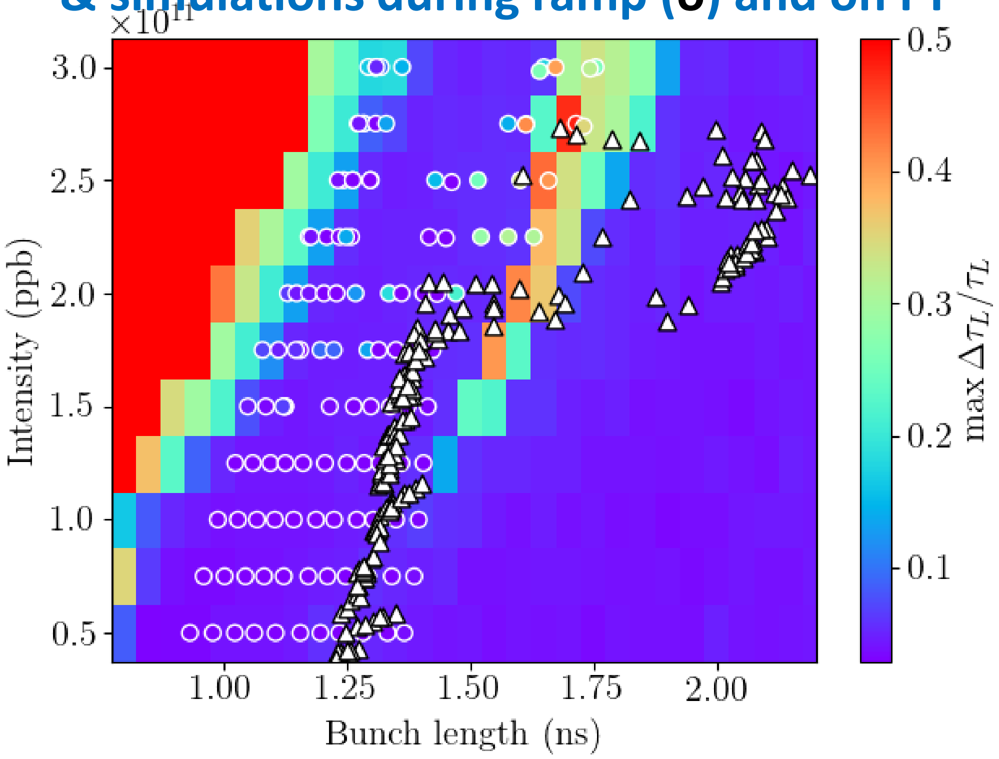


M. Schwarz

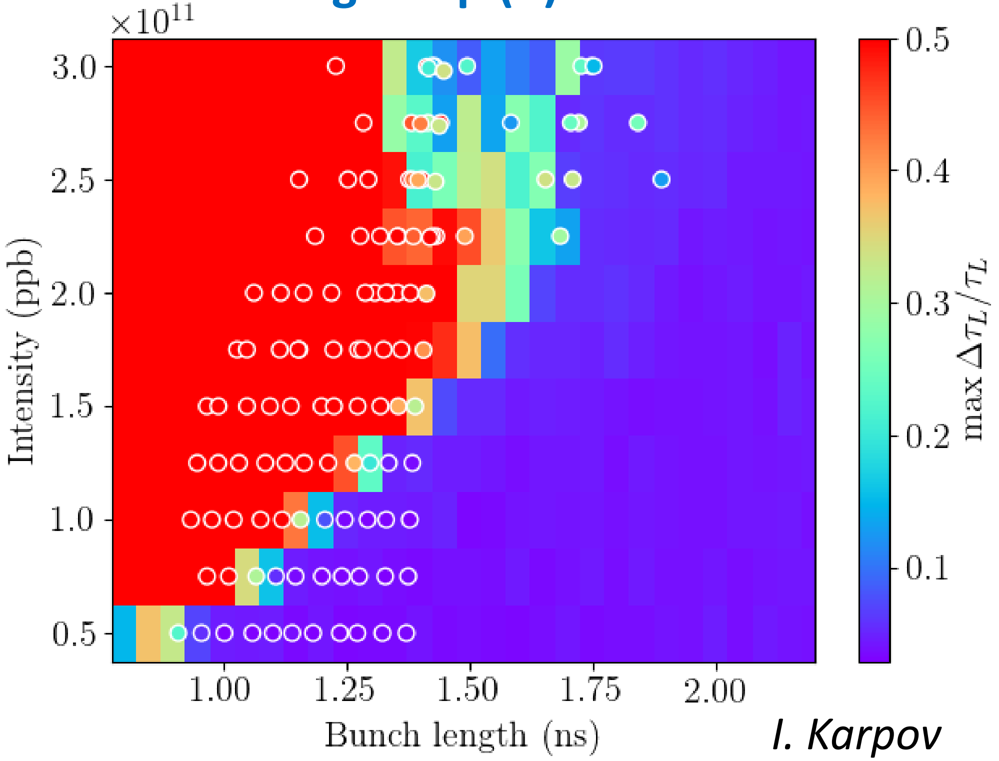
→ 20% reduction of the 200 MHz impedance is visible in simulations

Single bunch instabilities: ramp and flat top (FT)

Stability < LS2: Measurements (Δ) on FT & simulations during ramp (o) and on FT



Stability > LS2: simulations during ramp (o) and on FT

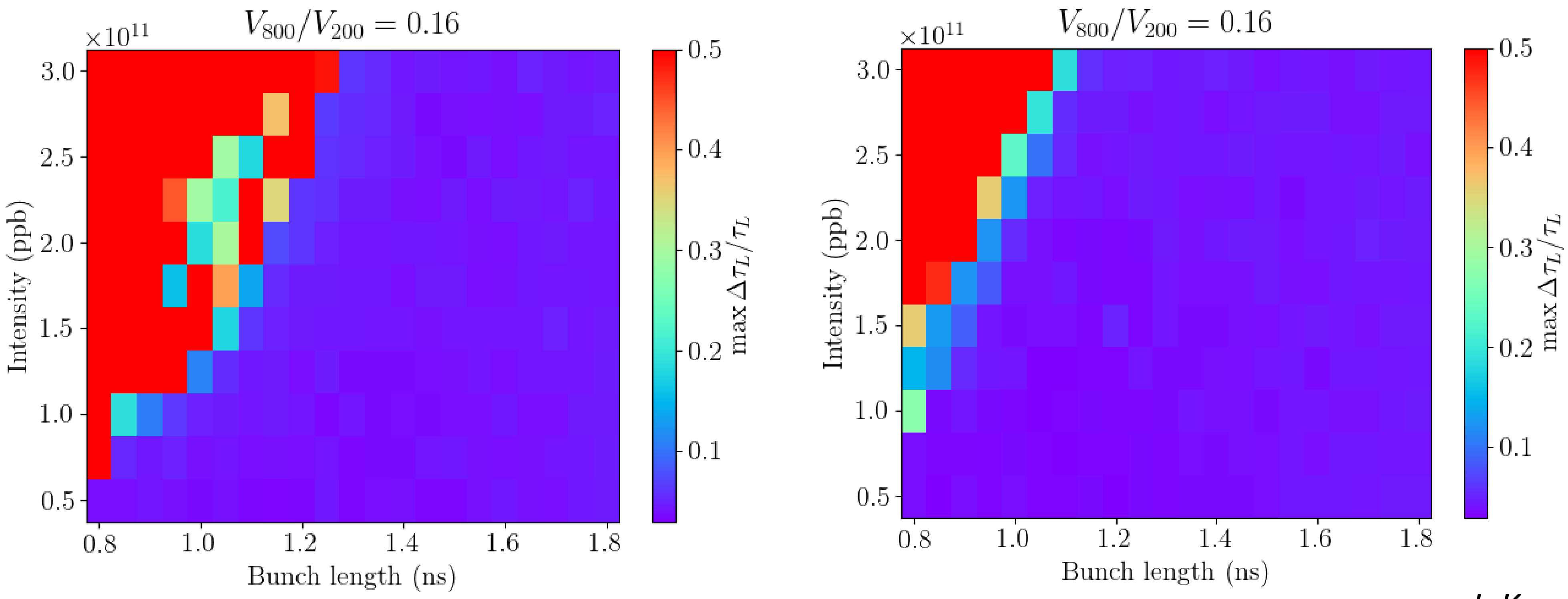


I. Karpov

→ The flat top thresholds are not necessary minimum

→The threshold increase will not be visible in single RF (measurements)

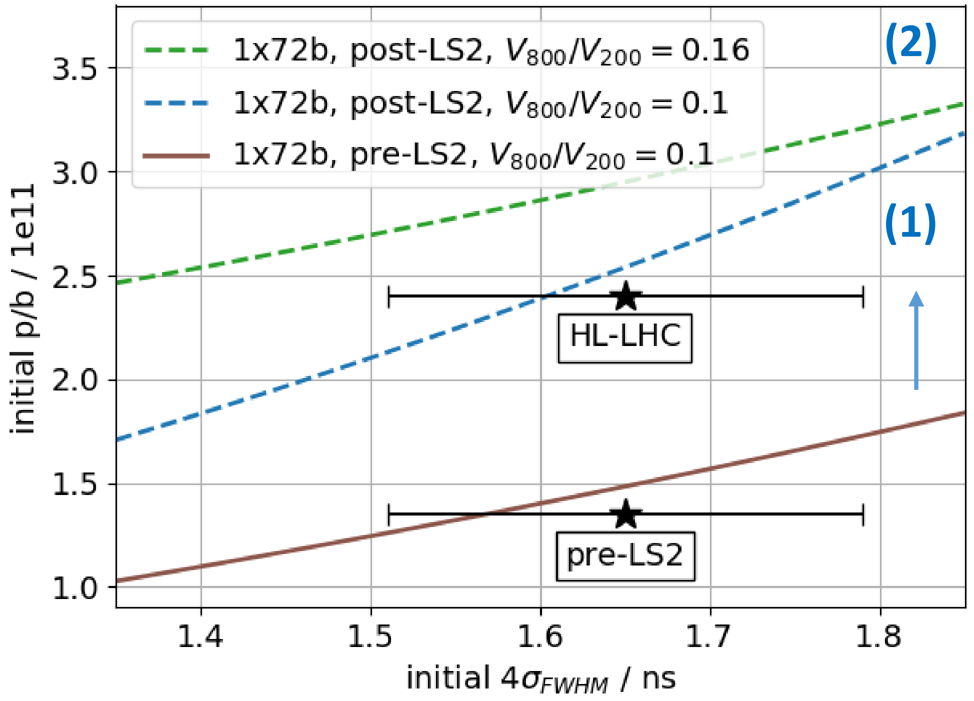
Single bunch instabilities: 2RF, flat top



I. Karpov

→ **The threshold increase is visible in double RF** (but possible problem with 800 MHz phase calibration in measurements – A. Lasheen, PhD thesis)

Multi-bunch stability thresholds



Simulations with 72 bunches on SPS flat top (minimum threshold)

← Double RF system: 200 & 800 MHz in BS mode
← Beam loading limitation included

(1)

Increase of 200 MHz RF voltage 7 MV → 10 MV

630 MHz HOM damping (factor ~2.5)

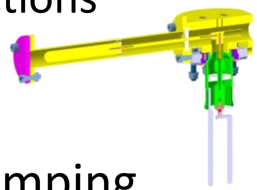
QF vacuum flanges shielding

(2)

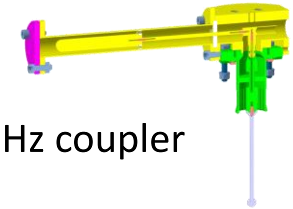
Increase of 800 to 200 MHz voltage ratio 0.1 → 0.16

HOM at 630 MHz

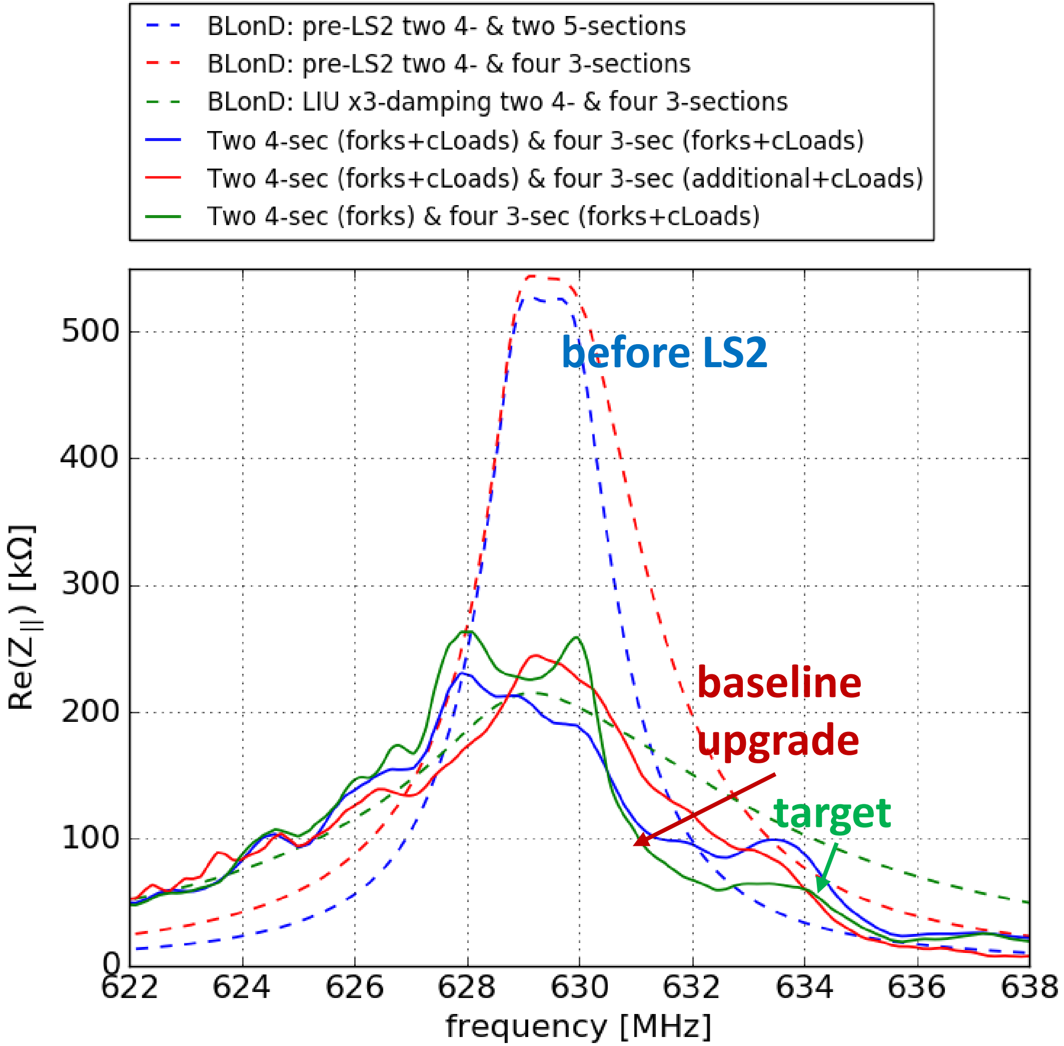
- **Optimum HOM damping in 200 MHz TWC** determined **for all cavity types**:
  - additional fork-couplers in 4 sections
  - complex loads everywhere



- **Backup solutions** can increase damping further if needed:
  - 5 mm longer fork-couplers
  - fork-couplers & resonant posts in 3 sections

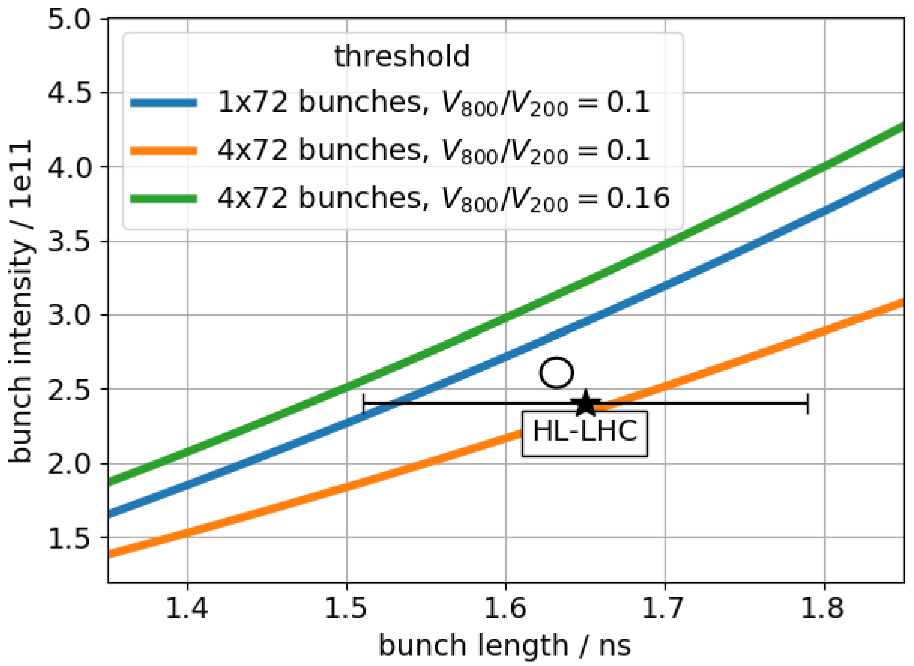


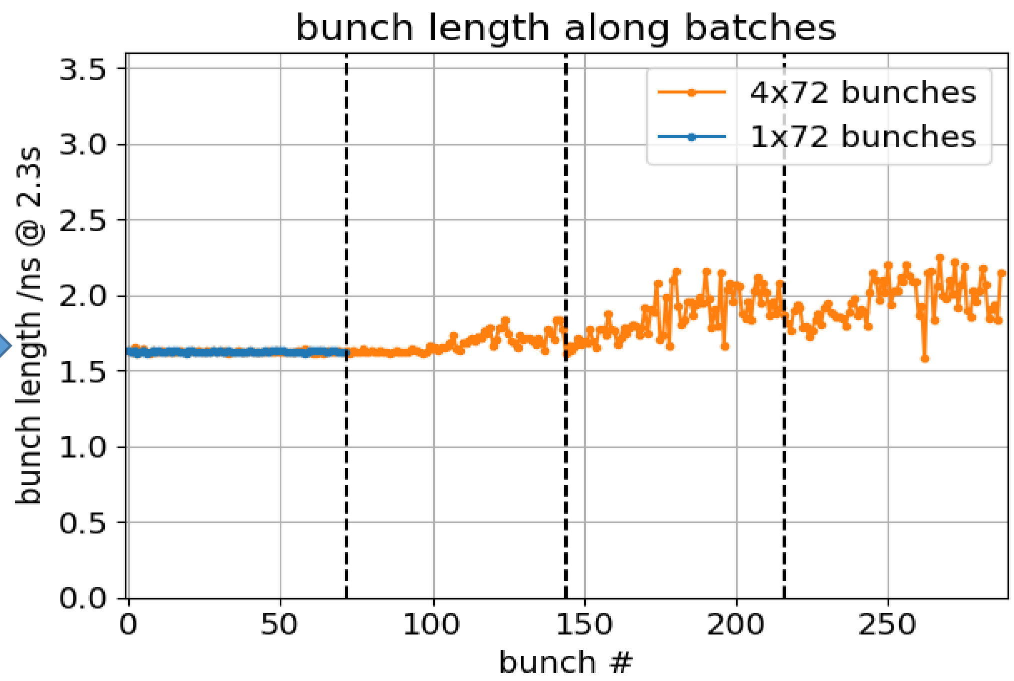
existing 630 MHz coupler



SPS flat top simulations with 4 batches: effect of 915 MHz HOM

Stability thresholds on the SPS flat top simulated with BLonD (in double RF system)



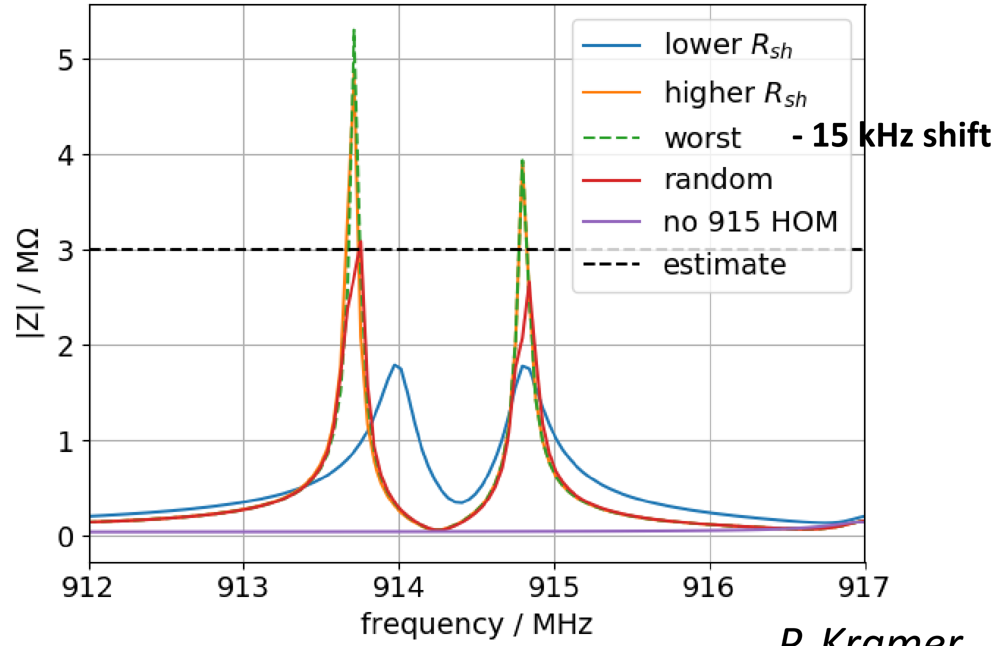


M. Schwarz

4-batch simulations possible thanks to significant speeding up of BLonD parallel computing (*K. I.*)

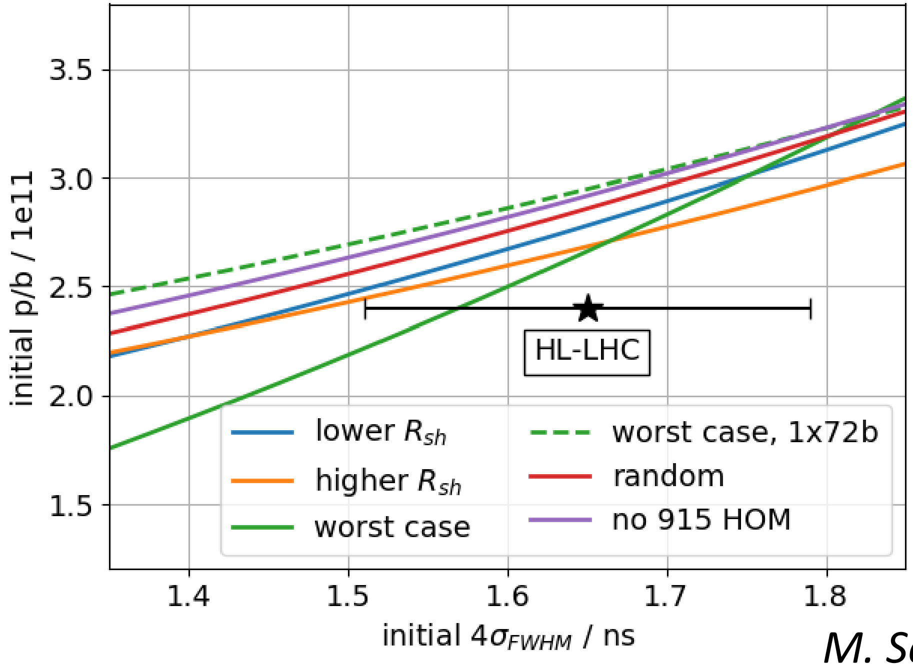
Effect of 915 MHz HOM on beam stability

Models of 915 MHz HOM



P. Kramer

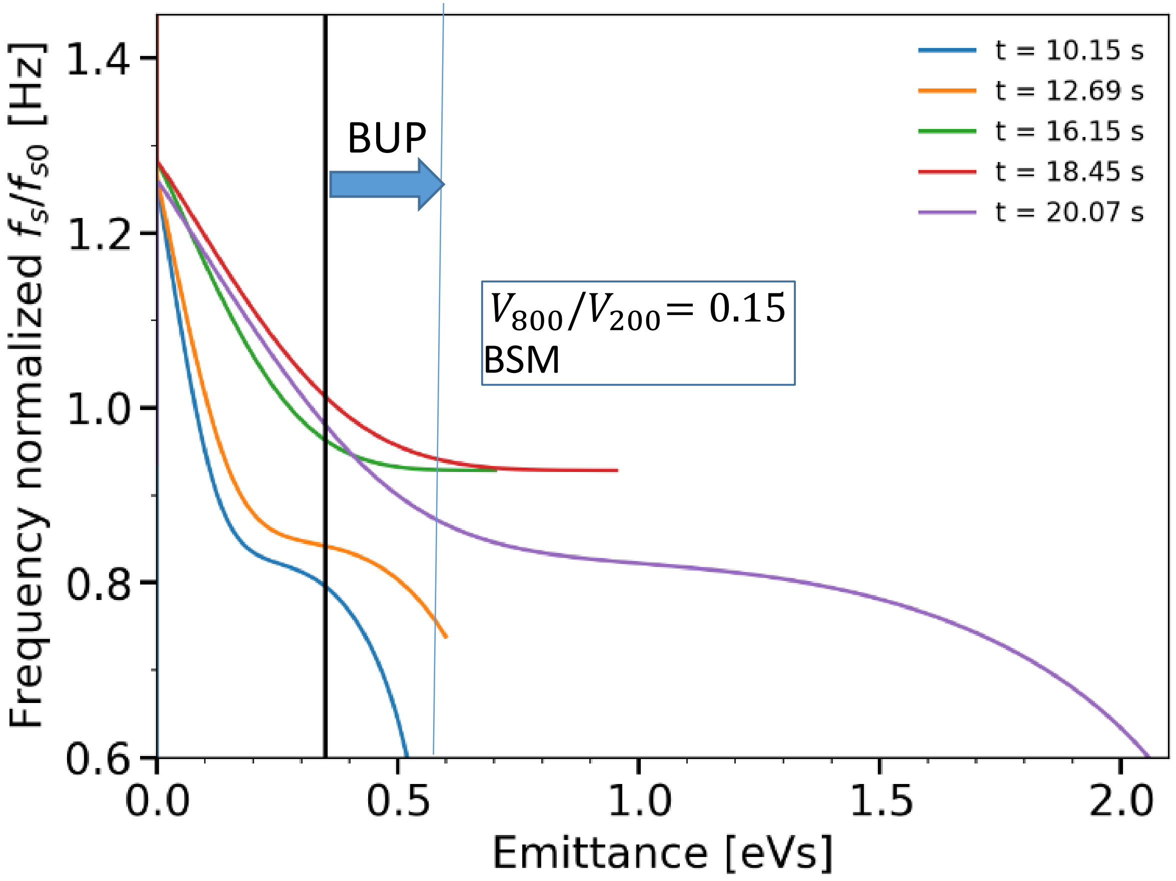
Stability thresholds on the SPS flat top simulated with BLonD for 4x72 bunches.
V_{800}/V_{200} = 0.16 with RF power limitation



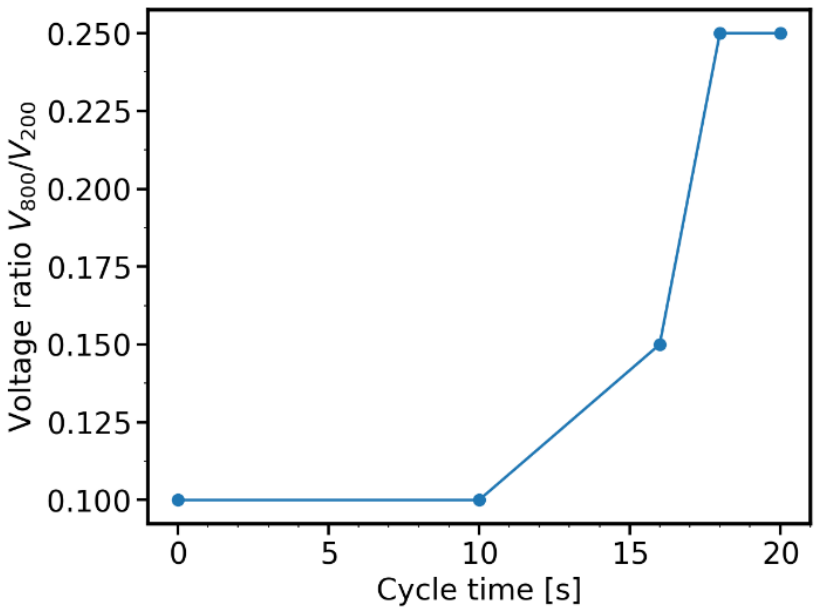
M. Schwarz

Model is not well defined due to unknown boundary conditions
The Fixed Target beam is unstable at intensity 10 times below operational 4×10^{13}

The 800 MHz RF voltage program



Voltage ratio program used for 12 high intensity bunches in 2018



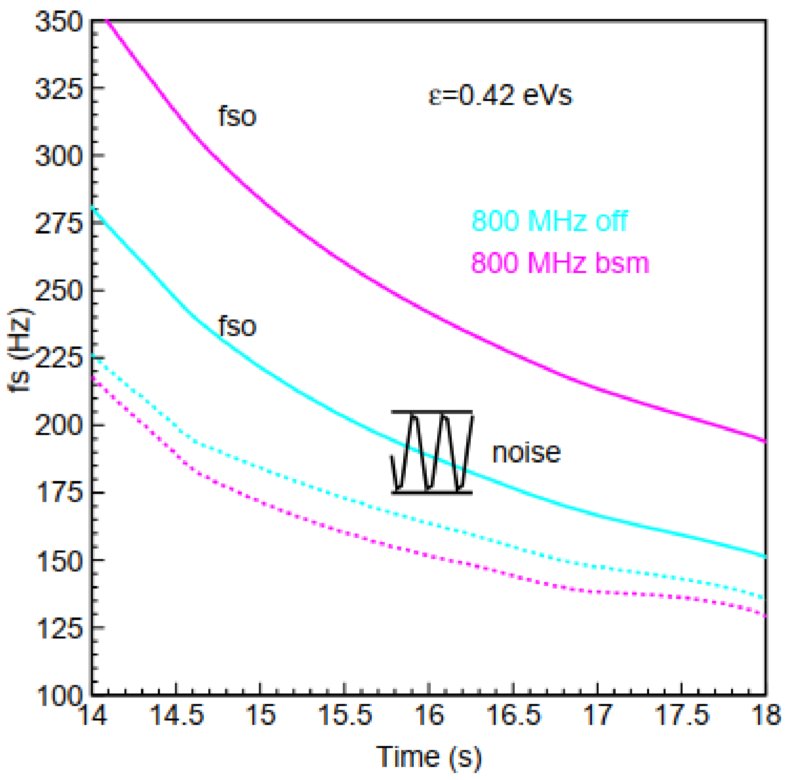
→ Better stabilisation was achieved with optimum 800/200 MHz voltage ratio

→ New operational tool needed in Run3

Controlled longitudinal emittance blow-up (BUP)

- The BUP is performed by adjusting f_{max}, f_{min} of the band-limited noise to overlap the required part of the synchrotron frequency spread.
- Was used in operation (during ramp) in the Q26 optics, but not in Q20.
- During the Q22 MD in 2018 the BUP setting-up was very long…
- The BUP is needed in Q20 for intensities above **1.6×10^{11}** ppb → in 2021?
- Method similar to LHC and now also to PSB

Why it is so complicated to set up?

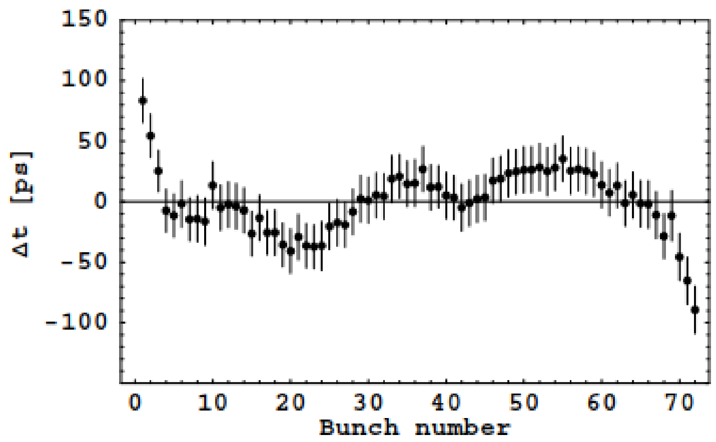


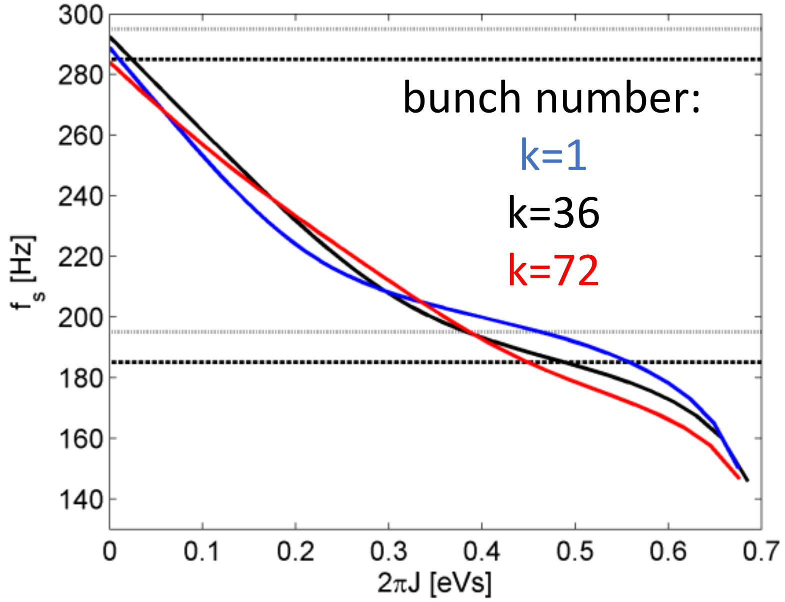
Controlled emittance blow-up: issues

- Synchrotron frequency distribution $f_s(J)$ depends on
  - Beam energy
  - RF voltage programs @ 200 & 800 MHz & phase ϕ_{800}
  - Intensity effects: intensity, bunch length (particle distribution) and beam loading (bunch position and therefore actual phase ϕ_{800})

→ $f_s(J)$ can be pre-calculated for average bunch

Main issue: bunch-by-bunch emittance & intensity variation



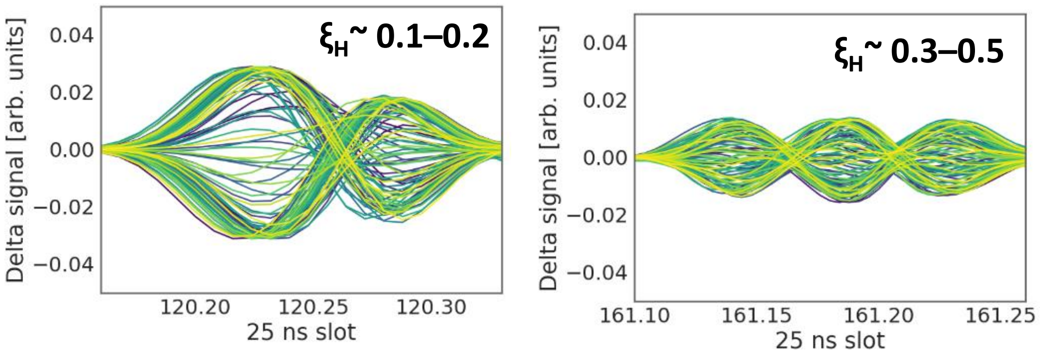


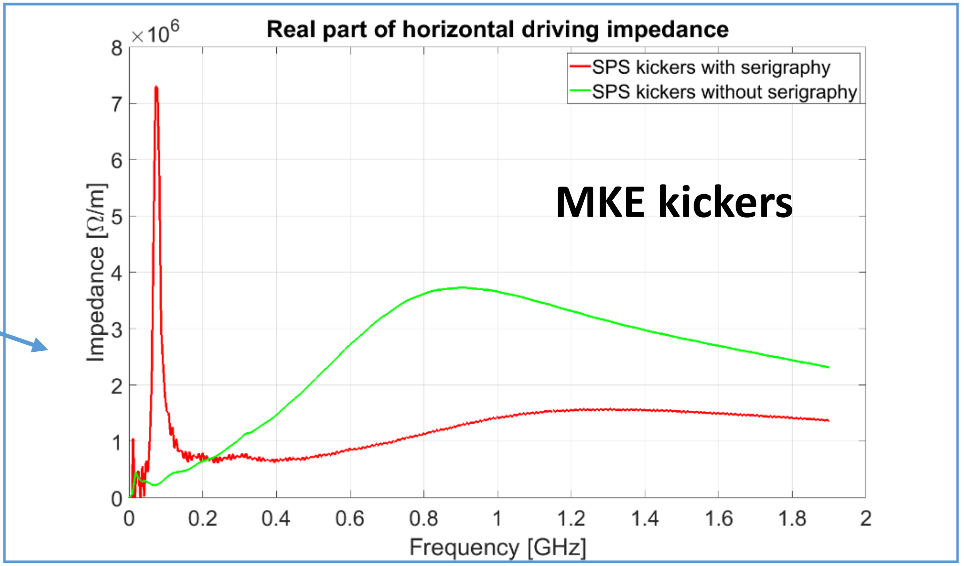
Controlled emittance blow-up: solutions

- Accurate 800 MHz phase calibration during the whole cycle
- Length of some bunches on flat top can be too large not because of insufficient emittance blow-up followed by instability
- Observables: bunch intensity, length and position => B(UP)QM
- Feedforward on bunch intensity and length
- Effect of phase loop → LHC experience.
- Feedback (amplitude) on bunch length - ?
- Machine learning
  - large number of iterations (cycles?)
  - machine protection (losses)

Horizontal instability: the origin

- Observed in 2017 with 4x48 bunches at the end of the 3rd & 4th batches
- The intensity threshold ~1.8x10^{11} ppb with chromaticity ξ = 0.2
  → losses and emittance blow-up
- The excited mode (1 or 2) depends on ξ_H
- Main features could be explained by Sacherer theory and existing MKE impedance model (plus what?)
- Reproduced in PyHEADTAIL simulations

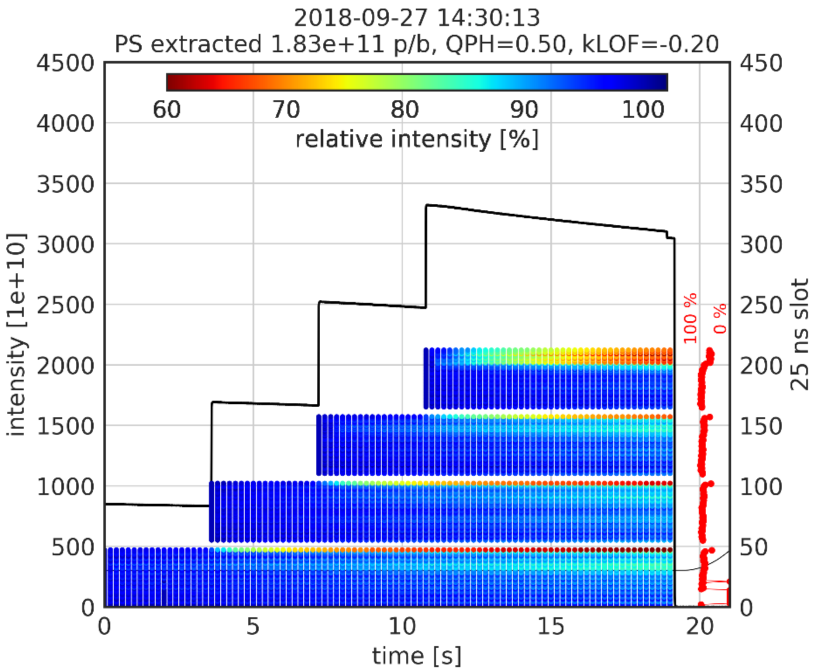




Horizontal instability: possible cures

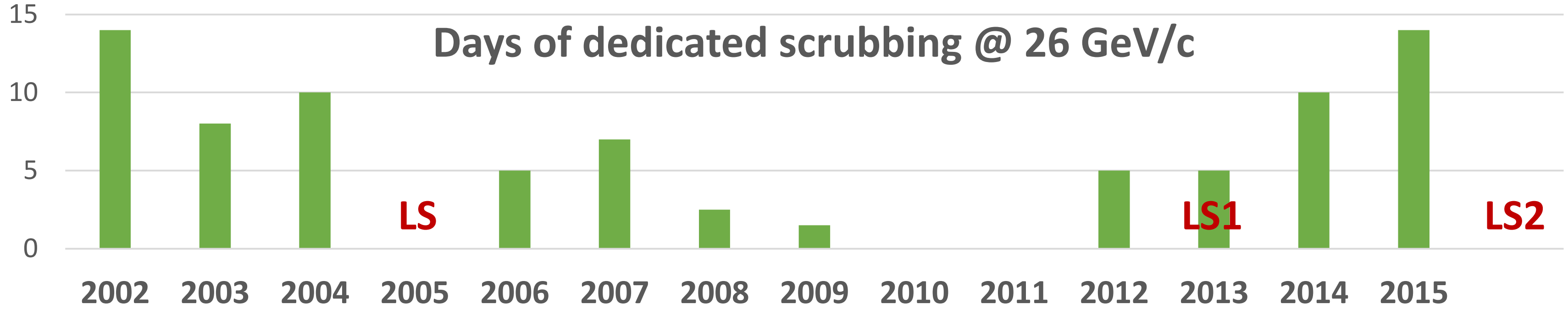
- In 2018 studies beam could be stabilised by
  - ξ > 0.6
  - batch spacing > 500 ns
  - partially with octupoles
- Difficulties for stabilisation above 2.1E11
- Possible knobs after LS2
  - chroma?
- Possible knobs after LS3
  WBFB in H-plane?

Do we have sufficient knobs to suppress it without post-LIU developments?



In 2017 all 7 MKE kickers had finally serigraphy significantly reducing the broad-band impedance

SPS e-cloud: experience from the past scrubbing runs

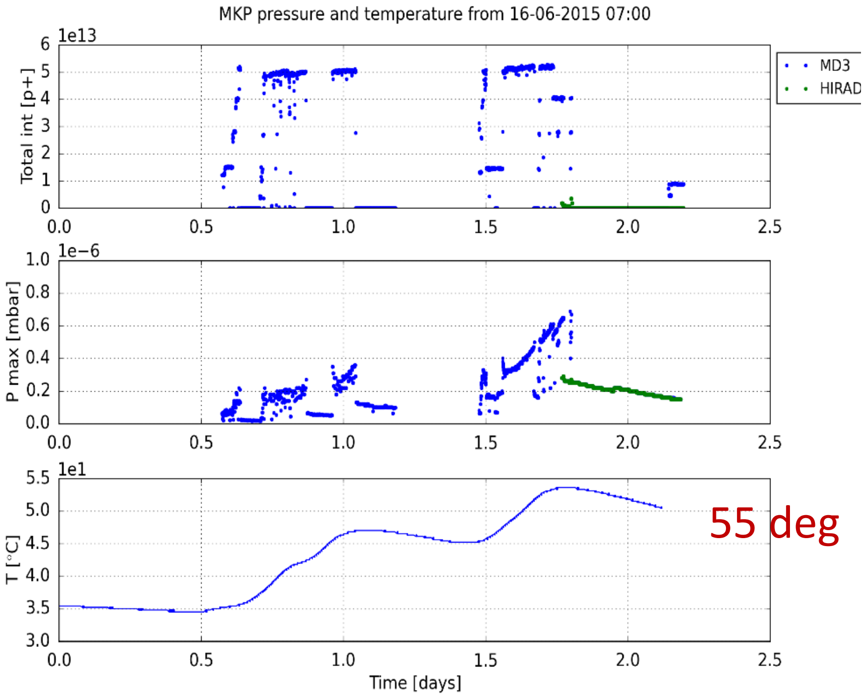


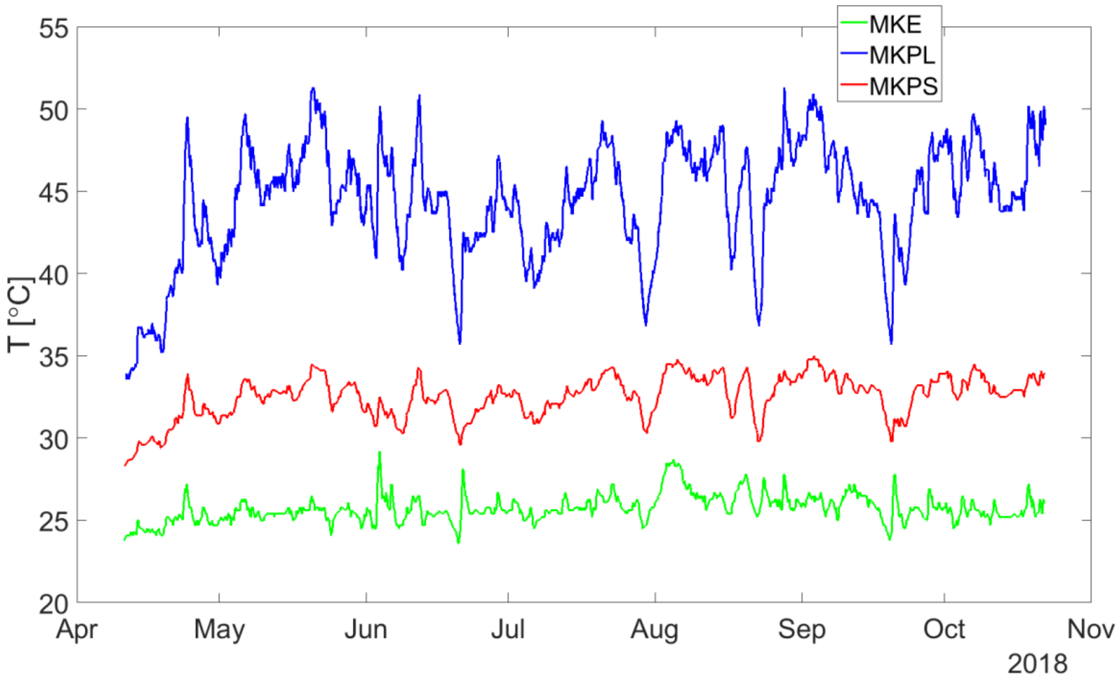
- **Improvements due to scrubbing** were clearly observed (for instabilities, emittance blow-up)
- Scrubbing is required for each intensity step (due to e-cloud strips moving outside)
- Limitations due to outgasing (pressure rise), heating (MKE, …) and sparking (FT beam – ZS)
- **One week was sufficient** to recover beam performance **after LS1** in 2014 (1.25×10^{11}, 2.6 µm)
- **High intensity** (up to 2×10^{11}) studies in 2016–2018: continuous emittance growth, b-b-b tune shift, but uncontrolled emittance blow-up **reduced** from 45% to 15% **after a few days** run

→ One week of scrubbing in 2021 and then a few days for each intensity step (each year) in Run3.

SPS e-cloud: operational limitations for scrubbing runs

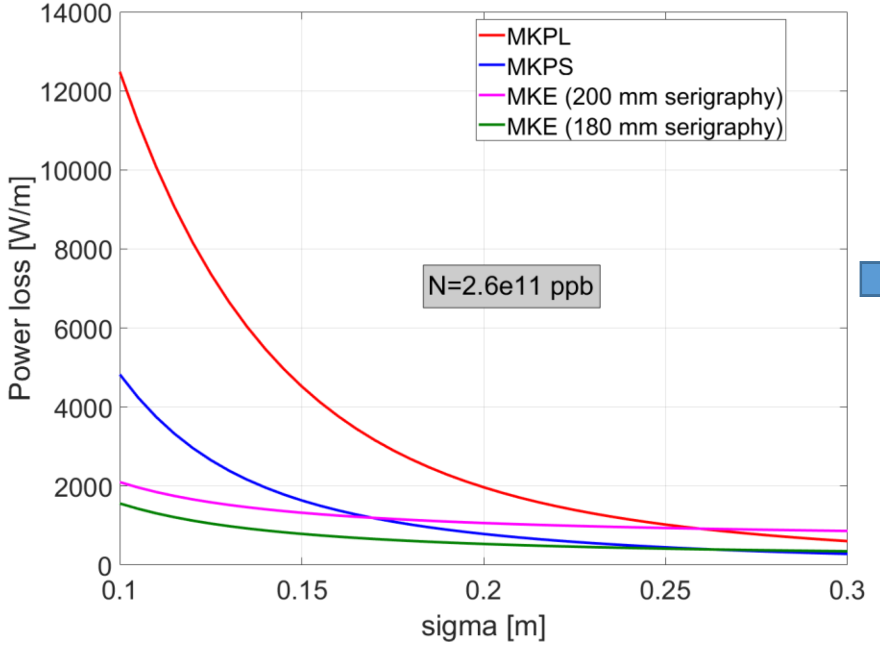
- ZS being upgraded -> less issues due to sparking is expected
- However MKPL heating could be a problem for long runs and even LHC filling



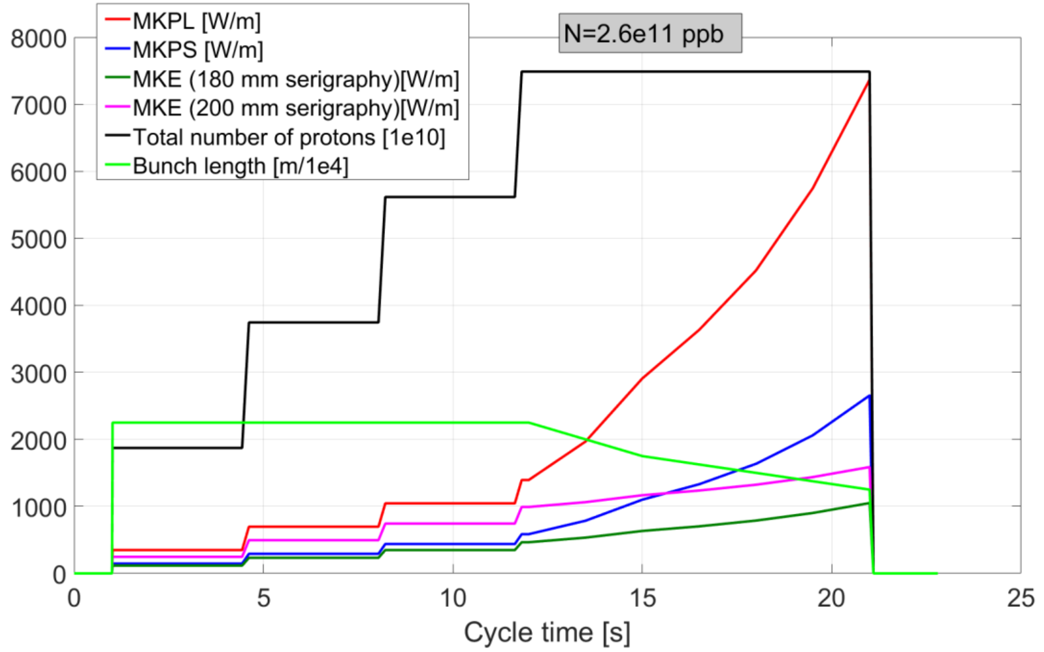


Potential limitations for intensity ramp up

Power loss in SPS kickers as a function of bunch length



Power loss in kickers during SPS ramp

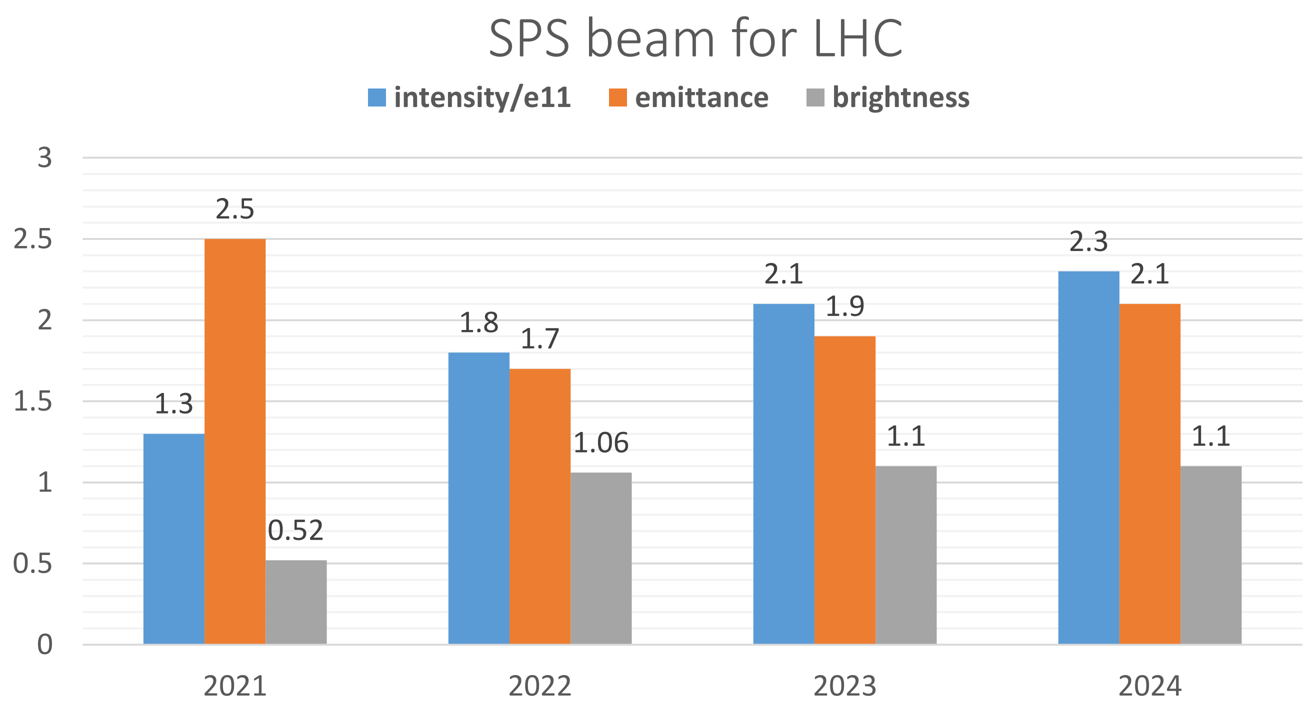


C. Zannini

Summary

- The SPS is responsible for LIU intensity ramp up during Run3
- Reference beam measurements available to confirm LIU-SPS upgrades
- Stability of 4 LHC batches and FT beam is affected by 915 MHz HOM
- Increased 800 MHz voltage becomes indispensable for beam stability during ramp, but will require sophisticated operational tool.
- Emittance blow-up will be needed in 2022, new tool should be implemented.
- Horizontal instability of 4 batches could be controlled?
- E-cloud scrubbing efficiency could be affected by MKPL heating

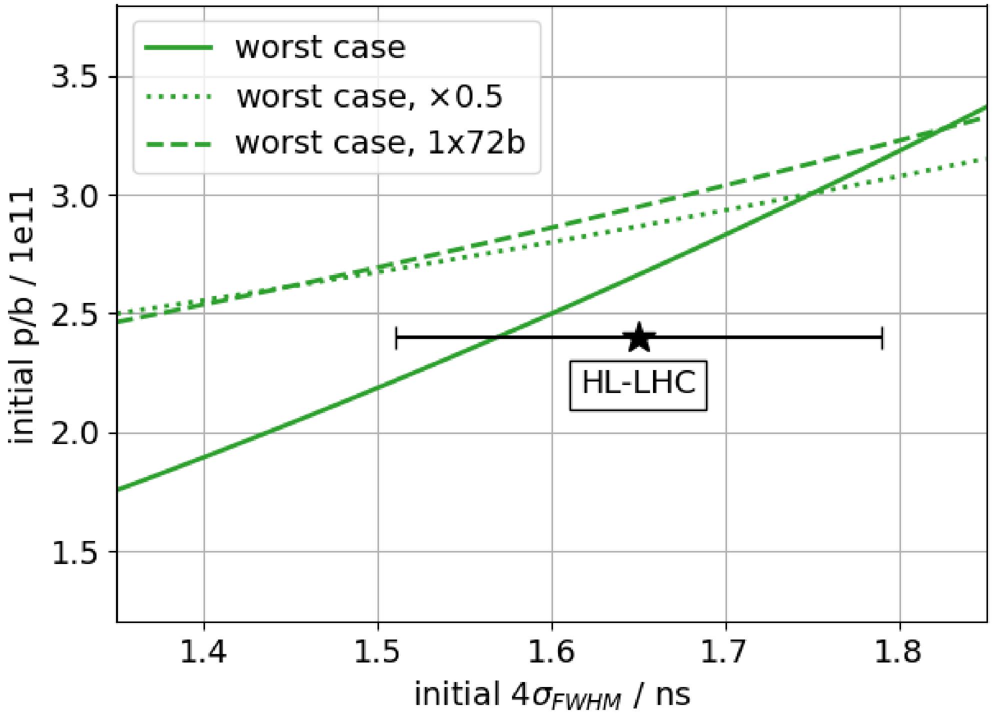
Ramp-up of the SPS beam parameters



LIU loss budget < 13%

→ Beam intensity ramp up concerns mainly the SPS, while brightness - PSB & PS

Effect of 915 MHz HOM on beam stability

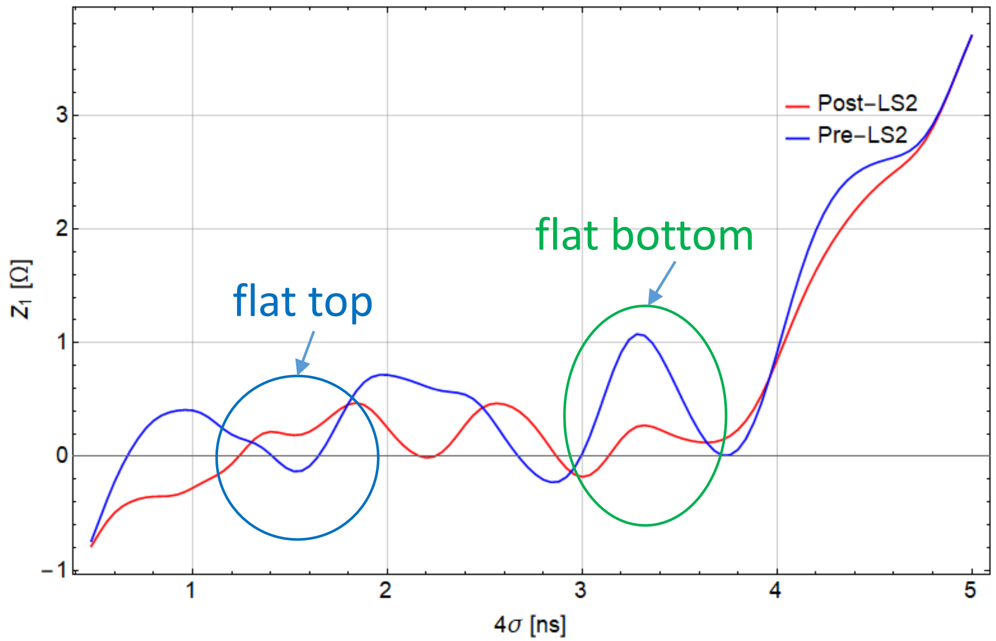


M. Schwarz

Damping of this HOM

Stability thresholds on the SPS flat top simulated with BLonD for 4x72 bunches.
V_{800}/V_{200} = 0.16 with RF power limitation

SPS impedance before and after LS2: longitudinal reactive impedance ???



The effective impedance Z_1 can be measured using the synchrotron frequency shift from quadrupole bunch length oscillations on the flat bottom

→ Some measurable reduction for bunch length in the "flat bottom" range of (3 – 4) ns?

→ No reduction at flat top for bunch lengths around 1.65 ns

E-cloud

Reconditioning for high intensity with respect to e-cloud

- Experience from the past
- Intensity ramp up
- Operational issues that could limit scrubbing efficiency (kicker heating, outgassing, …)