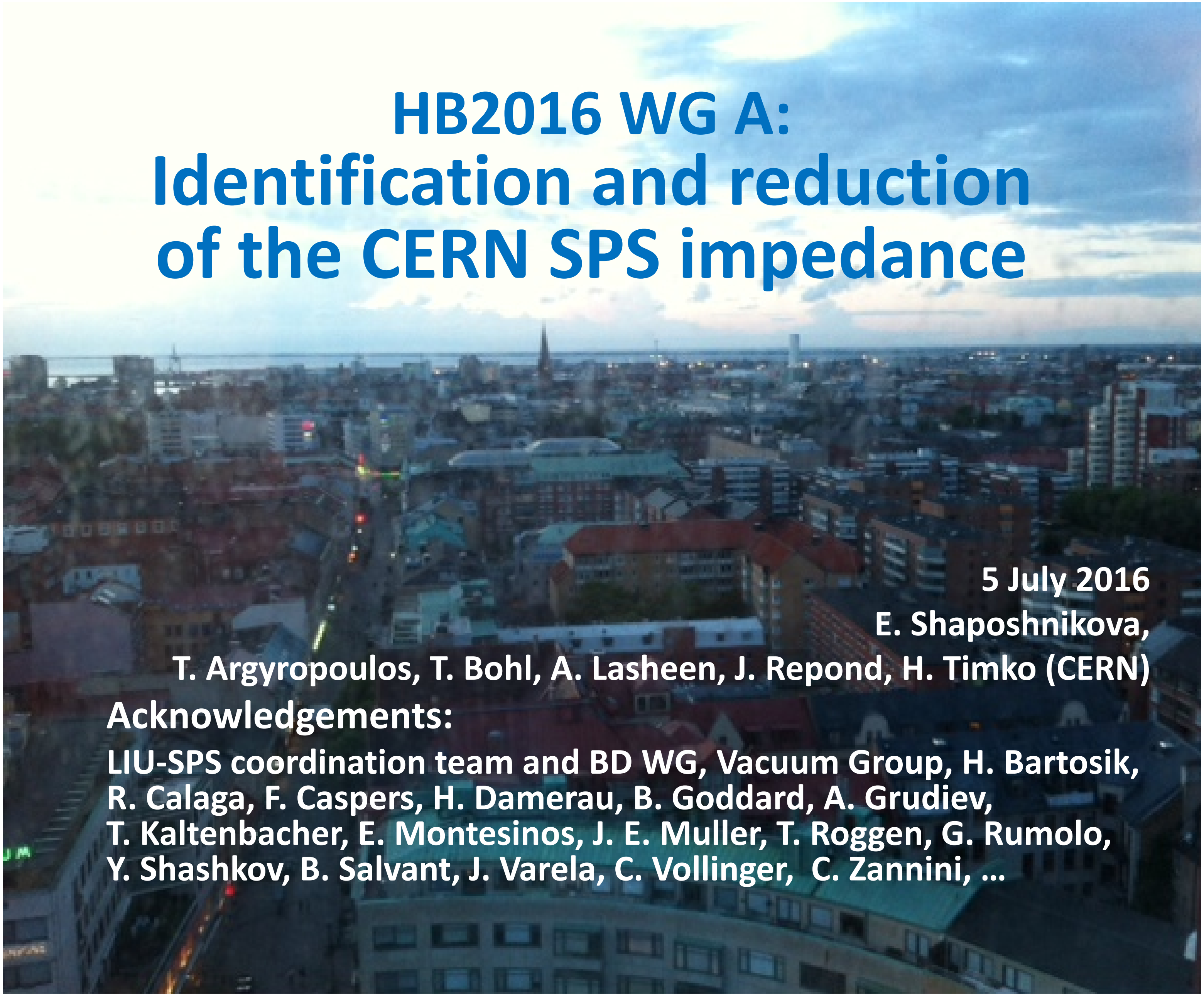

HB2016 WG A:
Identification and reduction of the CERN SPS impedance

5 July 2016

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Acknowledgements:

LIU-SPS coordination team and BD WG, Vacuum Group, H. Bartosik,
R. Calaga, F. Caspers, H. Damerau, B. Goddard, A. Grudiev,
T. Kaltenbacher, E. Montesinos, J. E. Muller, T. Roggen, G. Rumolo,
Y. Shashkov, B. Salvant, J. Varela, C. Vollinger, C. Zannini, …

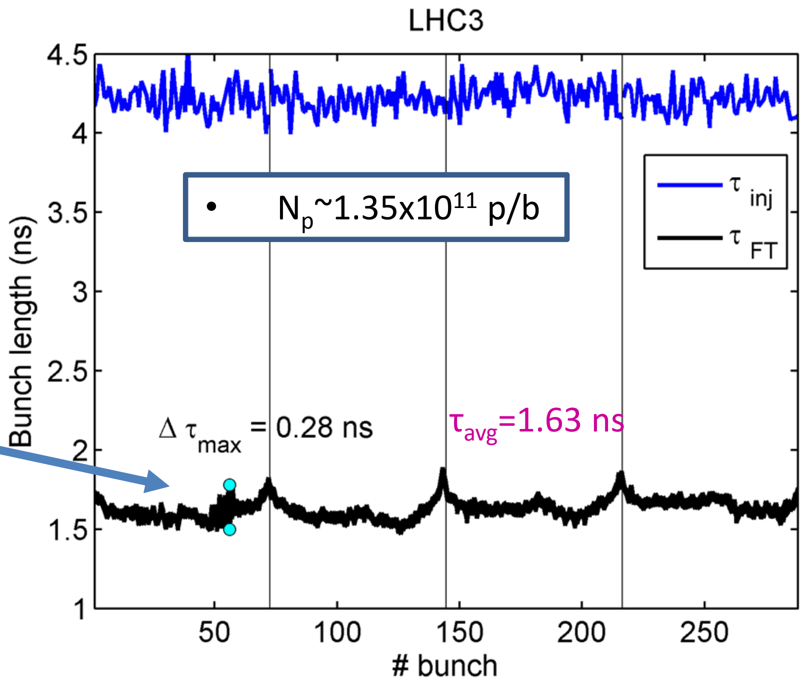
Outline

- Present limitations and need for SPS performance improvement
- Longitudinal single- and multi- bunch instabilities
- Longitudinal impedance identification
- Expected results of impedance reduction
- Transverse impedance

SPS: present achievements and future requirements

SPS (R=1100 m, 26 → 450 GeV/c) is the LHC injector

- **Delivered at 450 GeV/c:**
  4 x 72 bunches with 25 ns spacing, max intensity of $1.35\text{x}10^{11}$ p/b and bunch length of 1.65 ns (400 MHz RF system in LHC), transverse emit = 2.8 μrad



- **Required by HL-LHC:**

  4 x 72 bunches with intensity of $2.4\text{x}10^{11}$ p/b and the same other beam parameters (bunch length and transverse emittances) – LHC Injectors Upgrade **(LIU)** project

SPS: present limitations (longitudinal plane)

- Beam loading in the 200 MHz TW RF system (2x4 & 2x5 section cavities) limiting intensity of the 25 ns beam to ~1.4x10^{11} p/b

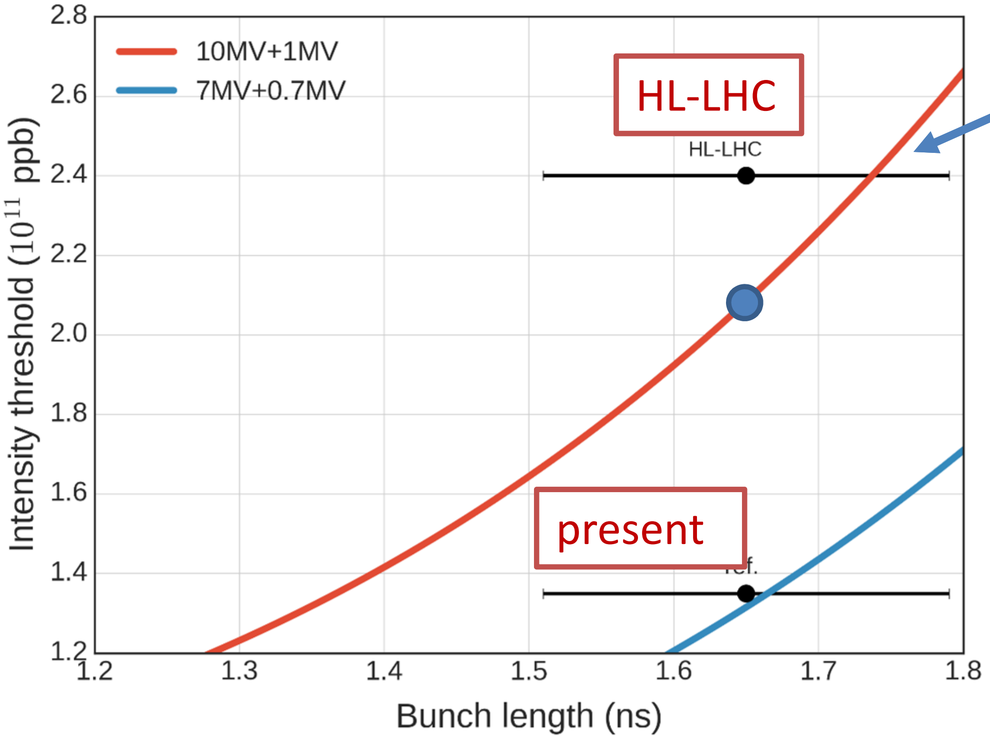
→ RF upgrade (6 shorter cavities & 2 new 1.6 MW power plants) – to be completed in 2021

- Longitudinal instabilities during ramp with a very low threshold (12 bunches with 0.4x10^{11} p/b!)

→ Present cures:
  - 800 MHz RF system in bunch shortening mode during ramp
  - Controlled emittance blow-up (limited to ~1.7 ns on flat top)

→ Additional measures for the HL-LHC beam (>2021):
  - Larger longitudinal emittance possible due to 200 MHz RF upgrade
  - Act on impedance sources!

Beam stability @450 GeV/c in a double RF now and after RF upgrade



Bunch length variation due to controlled emittance blow-up in presence of beam loading

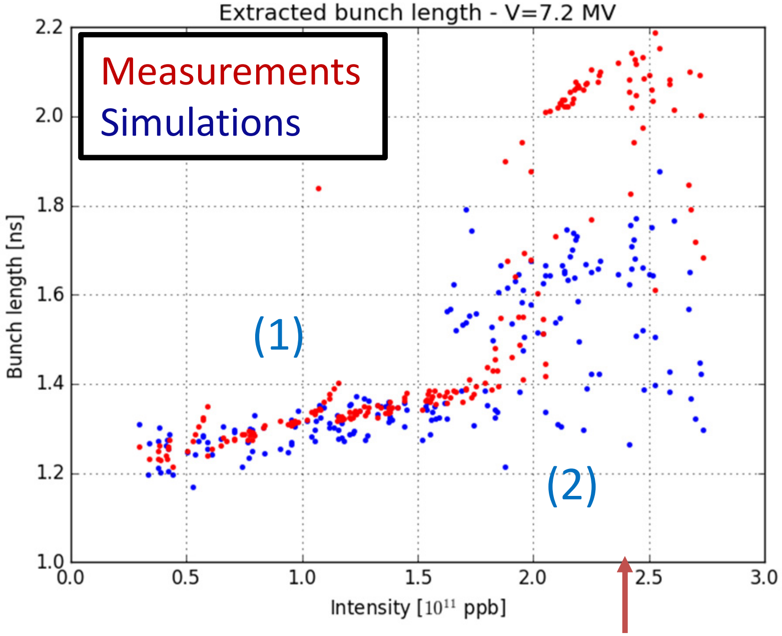
Simulations with 72 bunches and full SPS impedance model using code BLonD

More 800 MHz voltage is available but it is kept at 10% level of 200 MHz voltage to avoid region with ω'(J)=0 during ramp

→ Planned 200 MHz RF upgrade alone (larger emittance) is not sufficient for HL-LHC → Impedance reduction

Bunch length at 450 GeV/c: single bunch instability

Bunch length at 450 GeV



Intensity/10^{11}

HL-LHC intensity

Single 200 MHz RF system, 7.2 MV

→ Strong dependence of bunch length on intensity (ε ~ 0.3 eVs):

(1) Potential well distortion & slow instability (threshold ~ 1.1x10^{11})

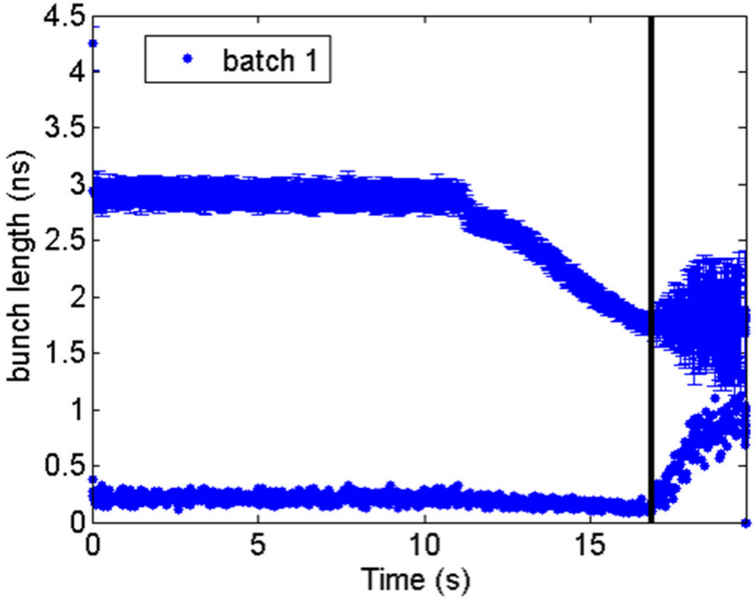
(2) Fast instability

Source of this instability was not known (see talk at HB'2012)

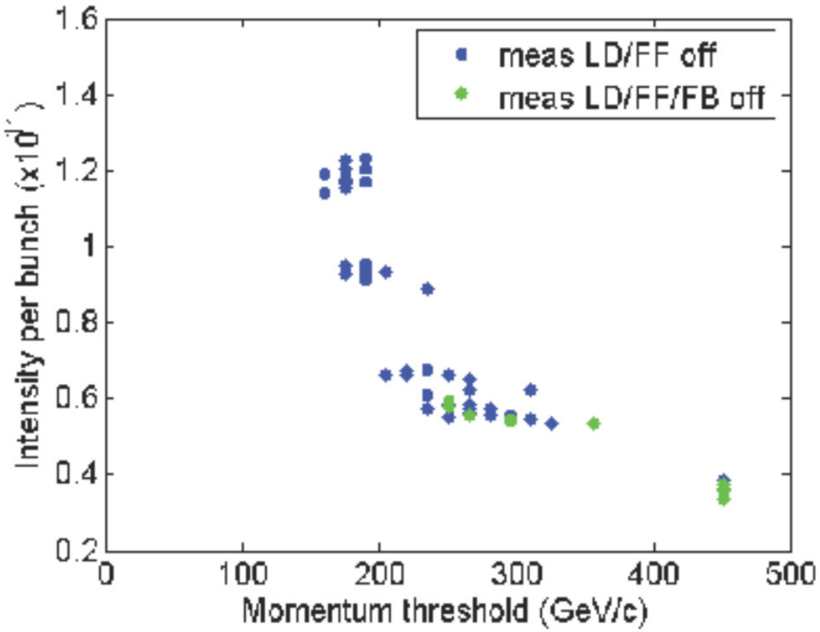
Simulations of the whole acceleration cycle using full SPS impedance model

Multi-bunch instability: measurements for 12 bunches at 25 ns

Bunch length during ramp



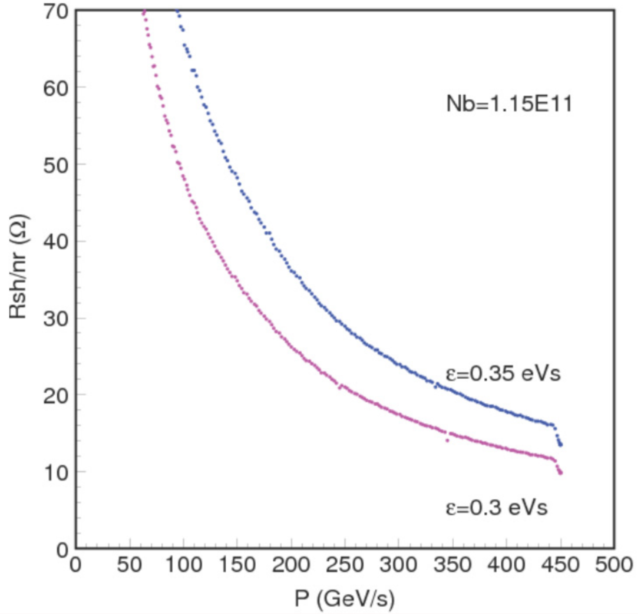
Intensity threshold as a function of beam energy



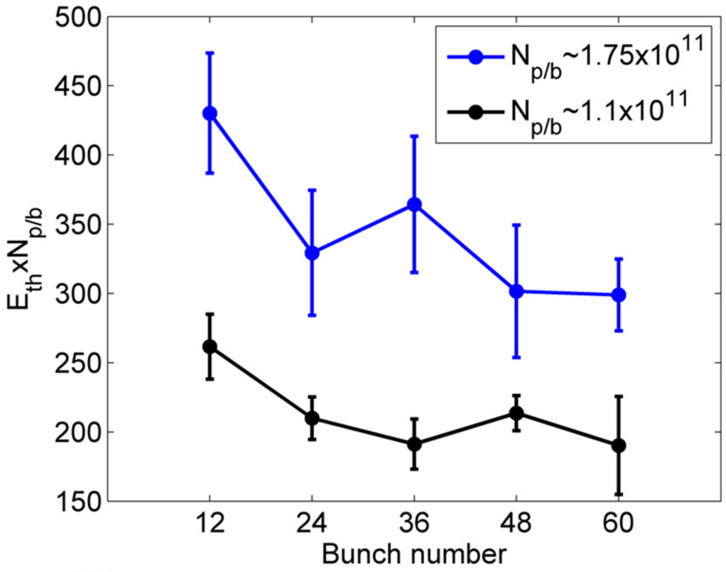
→ Use dependence of intensity threshold on energy to study impedance driving this instability?

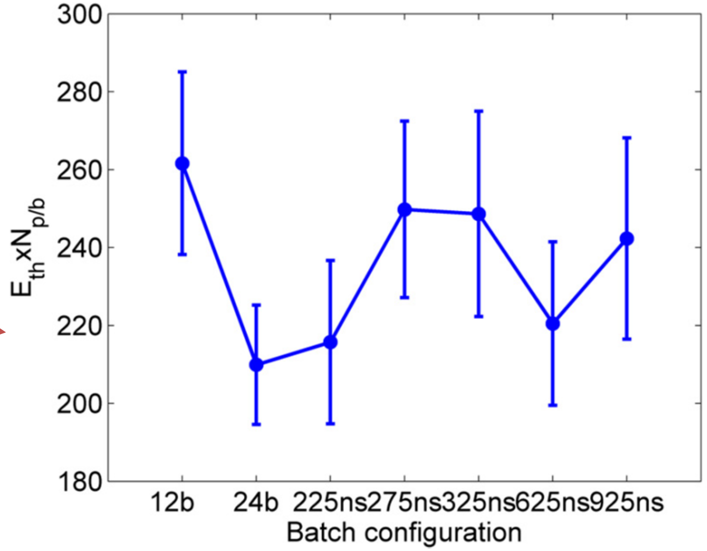
Multi-bunch instability:
12 bunches at 25 ns in a single RF

Stability threshold during ramp

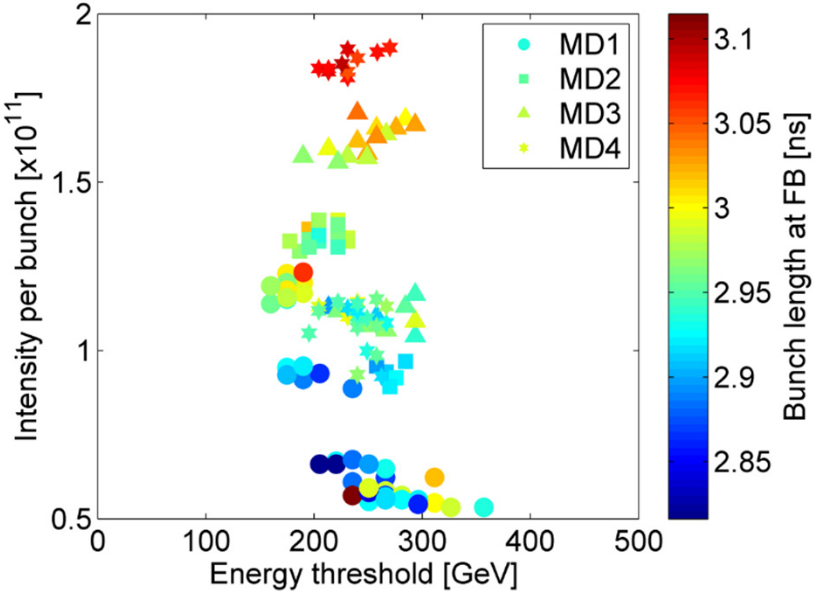


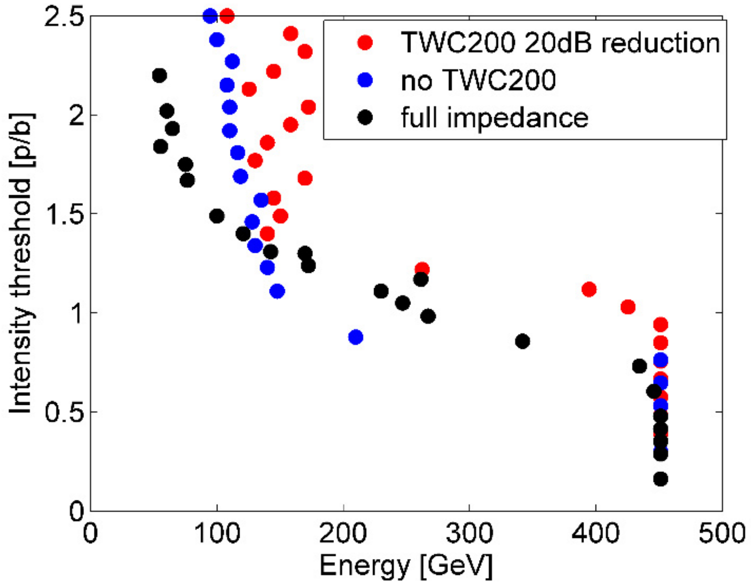
Energy threshold for coupled-bunch instability scales as E_{th}~1/N
→ plot E_{th} x N
→ weak dependence on number of bunches in batch and gap length between batches





Multi-bunch instability:
12 bunches at 25 ns



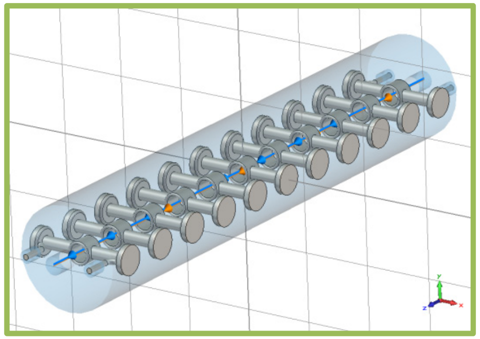


→ Sharp dependence of intensity threshold on energy → difficult to use energy threshold for comparison

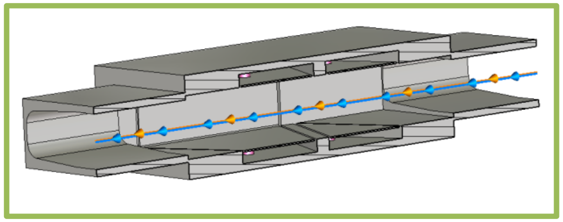
Measurements compatible with low Q impedance
(200 MHz: Q=150, 630 MHz HOM: Q=500)

Present SPS impedance model: main contributors

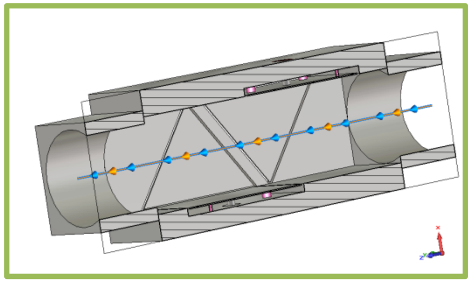
TW RF cavities:
200 MHz and 800 MHz



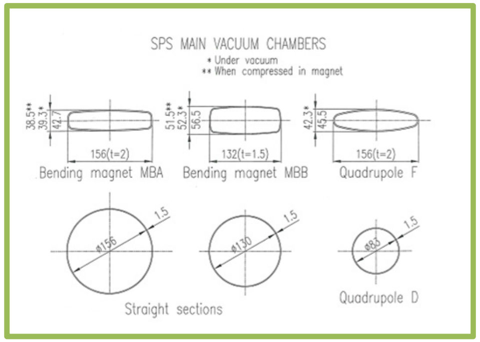
Beam position monitor H



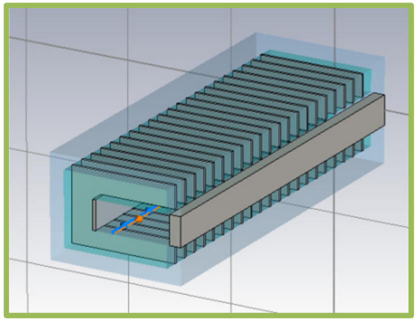
Beam position monitor V



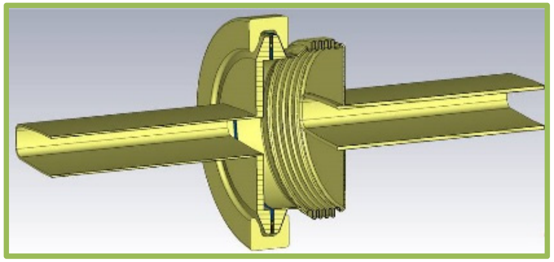
Vacuum chambers



Kickers



Vacuum flanges

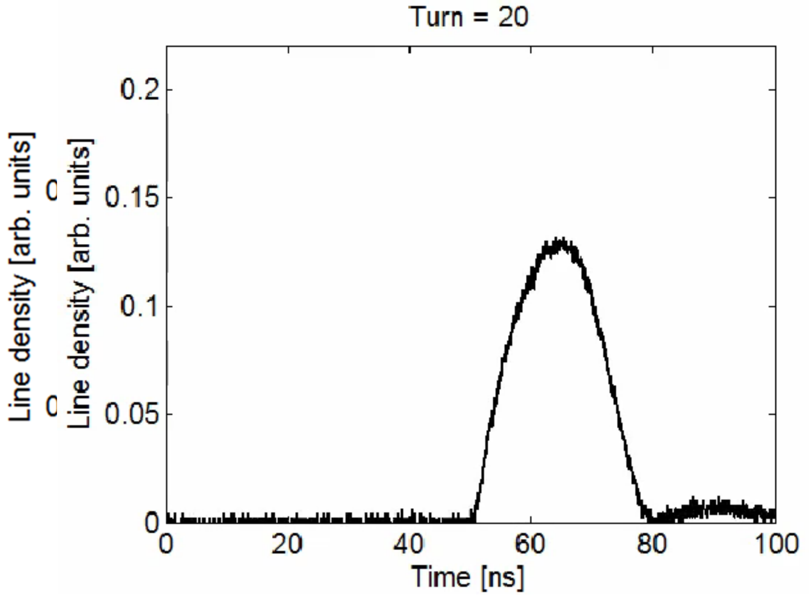


Spectrum of unstable single bunches (1/3)

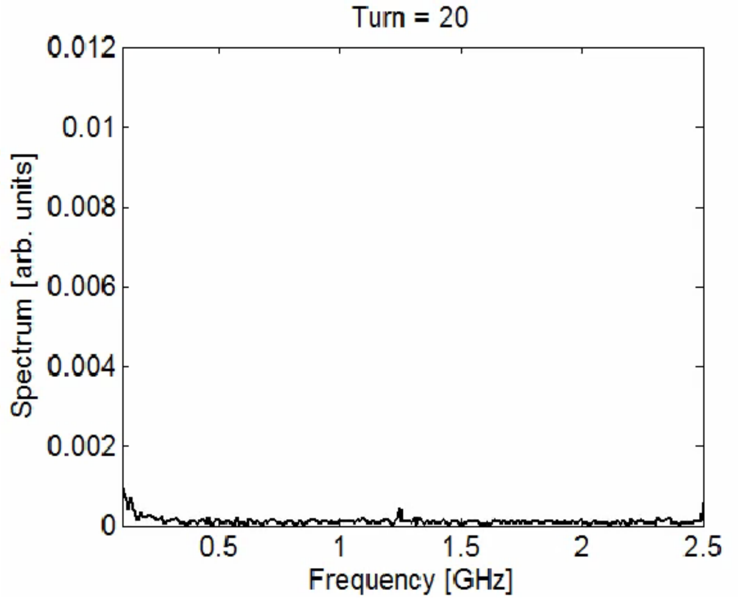
Method of measurement:

- Inject long single bunches into ring with RF off
- Bunches with low momentum spread: slow debunching and fast instability
- Measure bunch profiles or spectrum amplitude at given frequency
- Use projection of spectra to see longitudinal impedances with high R/Q

Bunch profile (SPS 26 GeV/c)



Spectrum of unstable bunch



Spectrum of unstable single bunches (2/3)

The linearised Vlasov equation for the line density perturbation $\rho(\theta,t) = e^{-i\Omega t}\sum_n \rho_n e^{in\theta}$

$$\rho_n = -i\frac{\eta n\omega_0}{2\pi E_0}(\frac{e\omega_0}{\Omega})^2\sum_{n'} G_{n-n'}Z_{n'}\rho_{n'}$$

describes a fast microwave instability, assuming particle distribution $F(\theta,\dot{\theta}) = G(\theta)\delta(\dot{\theta})$
For a costing beam $G_{n-n'} = N\delta_{n,n'}/(2\pi)$ and $\Omega_n^2 = -i\frac{(en\omega_0)^2 N\omega_0}{2\pi E_0}\eta\frac{Z_n}{n}$
→ the negative mass instability.
For a resonant impedance with bandwidth $\Delta\omega_r = \omega_r/2Q$ two regimes exist:

(1) Narrow-band impedance: $\Delta\omega_r << 1/\tau$
→We can assume for n' > 0: $G_{n-n'} \simeq G_{n-n_r}$

Then growth rate $\frac{\mathrm{Im}\Omega}{\omega_r} \simeq \left(\frac{Ne^2\omega_0|\eta|}{16\pi E_0}\frac{R_{sh}}{Q}\right)^{\frac{1}{2}}$

Instability spectrum: $\rho_n \sim nG_{n-n_r}$

→ centered at n ~ n_r with width ~ 1/τ

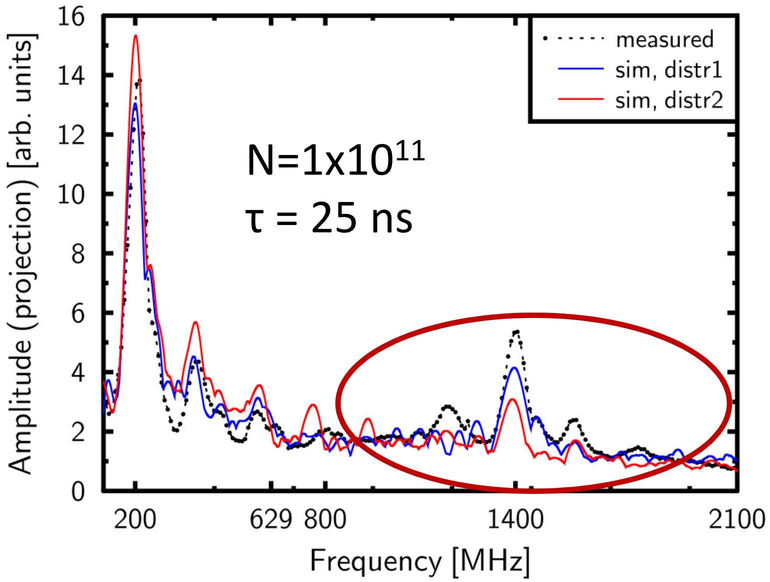
(2) Broad-band impedance: $\Delta\omega_r > 1/\tau$
→For a long Gaussian bunch assume

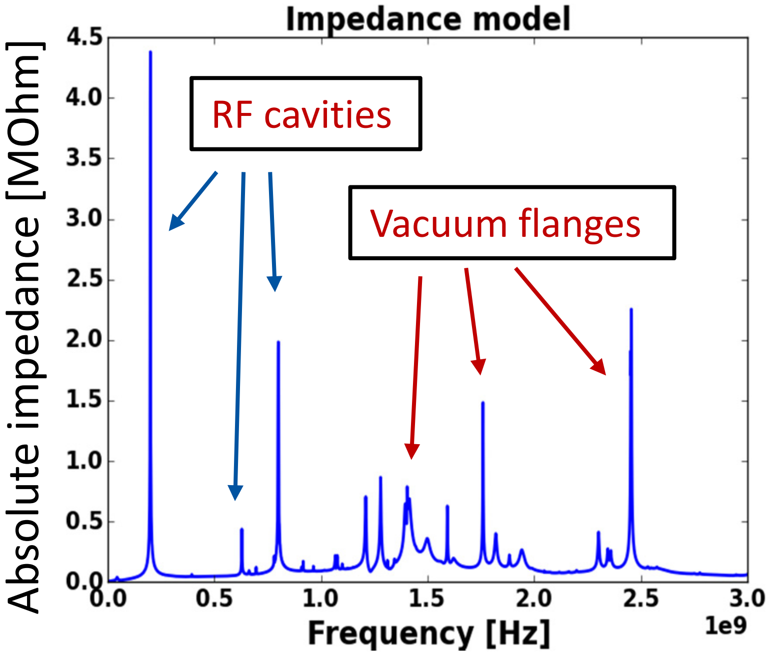
$$G_{n-n'} = \frac{N}{2\pi}\exp(-\frac{(n-n')^2\sigma^2}{2}) \approx \frac{N}{\sqrt{2\pi}\sigma}\delta_{n,n'}.$$

Growth rate $\Omega_n^2 \simeq -i\frac{(en\omega_0)^2 N}{(2\pi)^{3/2}E_0\sigma_t}\eta\frac{Z_n}{n}$

similar to a coasting beam where average current is replaced by peak.
→ Spectrum width ~ impedance $\Delta\omega_r$

Spectrum of unstable single bunches: narrow-band impedances (3/3)

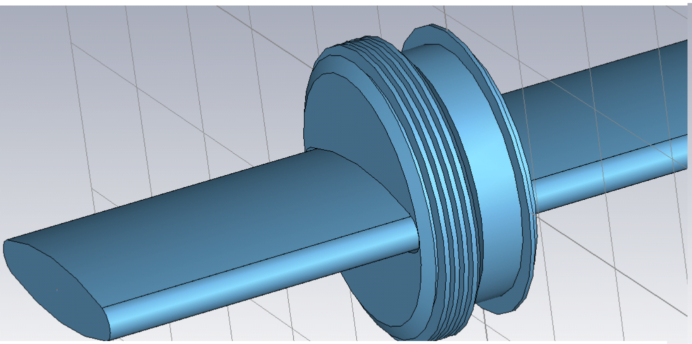




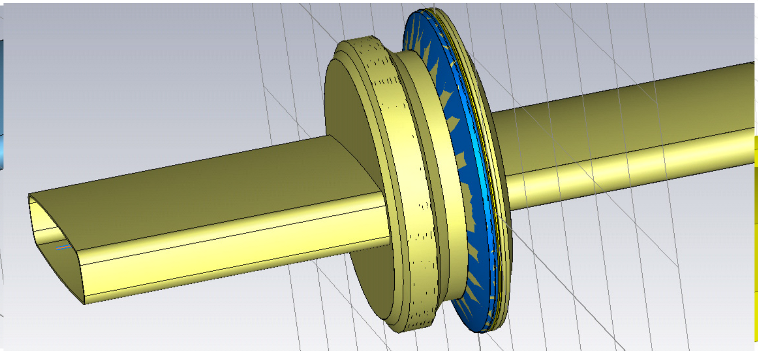
The main sources of longitudinal instability have been identified
→ shielding of ~ 200 vacuum flanges is planned in LS2 (2019 – 2020), issues with insulating flanges *(poster of T. Kaltenbacher et al.)*
→ Factor 3 reduction needed for the 630 MHz HOM (in 200 MHz TW RF cavity), but this impedance is already well damped *(poster of T. Roggen et al.)*

The SPS vacuum flanges

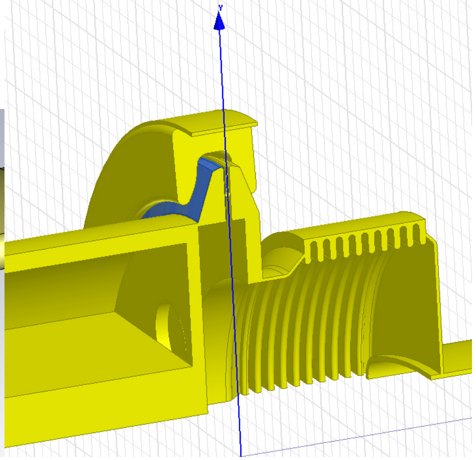
Group I – 1.4 GHz



Non-enamelled QF - QF **≈26**



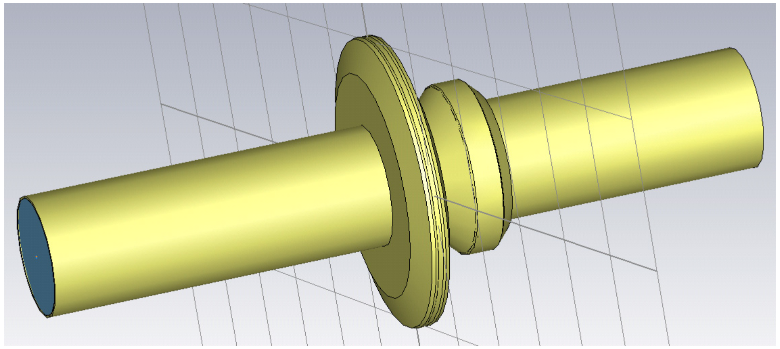
Enamelled QF - MBA ≈ **97**



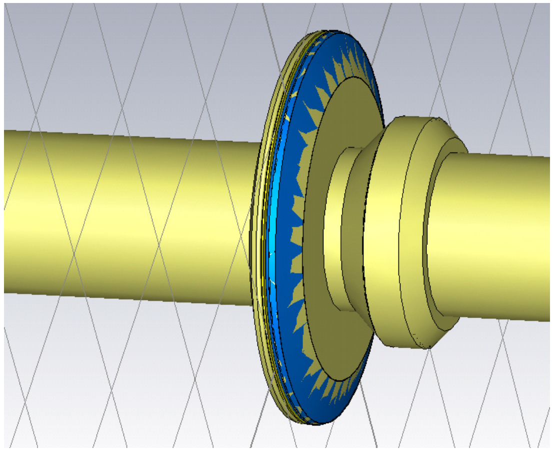
Non-shielded, enamelled BPH - QF ≈ **39**

→ LIU baseline: shielding of Group I

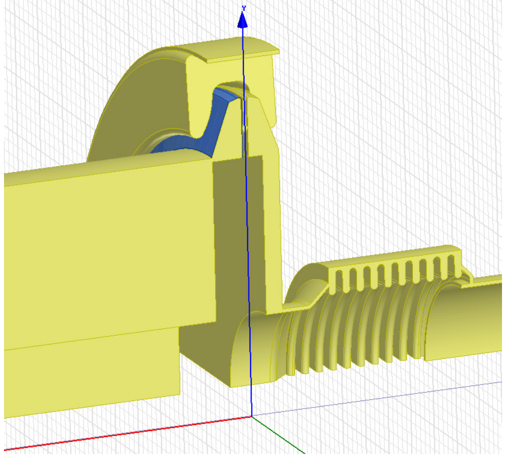
Group II



Non-enamelled QD - QD **≈75**

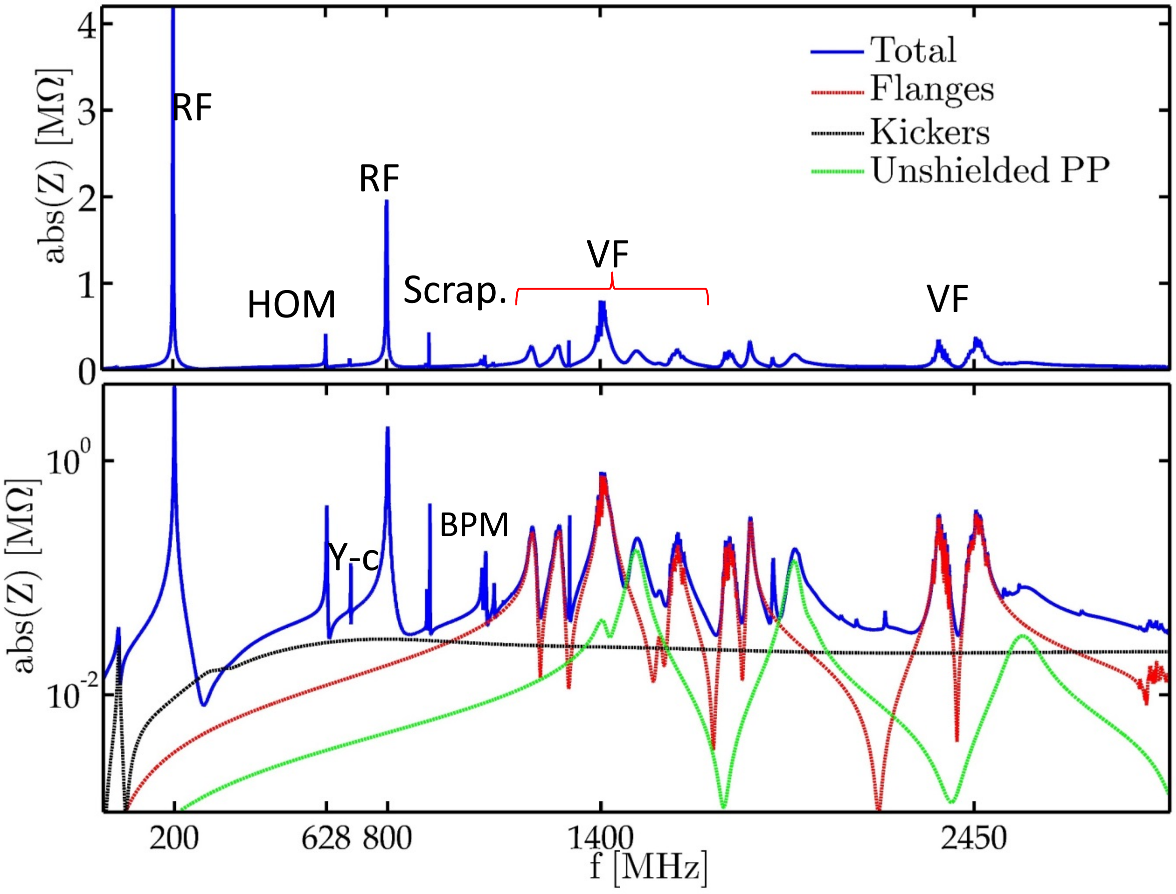


Enamelled QD - QD ≈ **99**



Enamelled BPV - Q≈ **90**

Present SPS impedance model

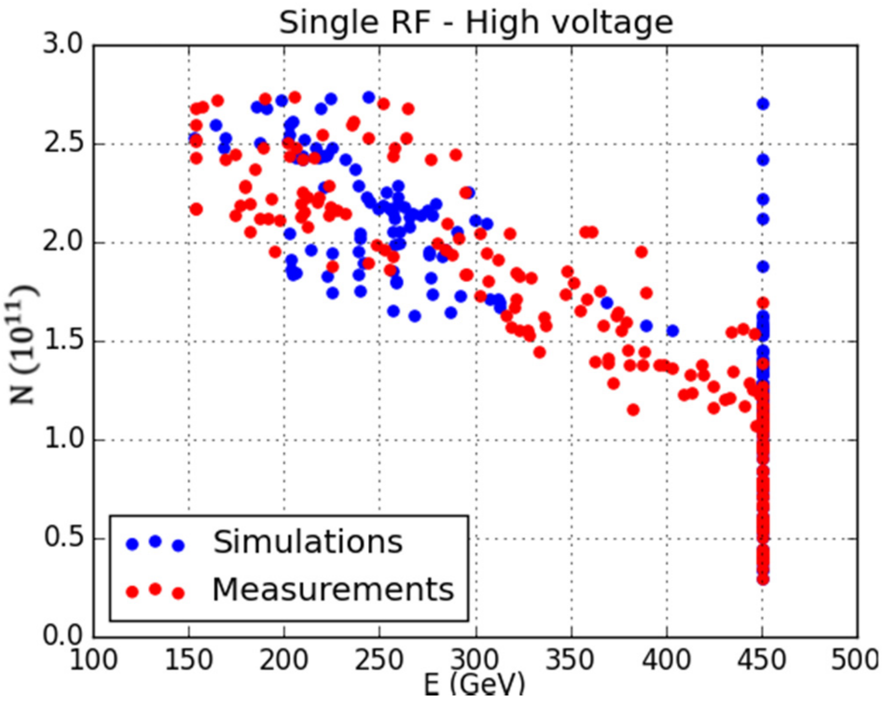


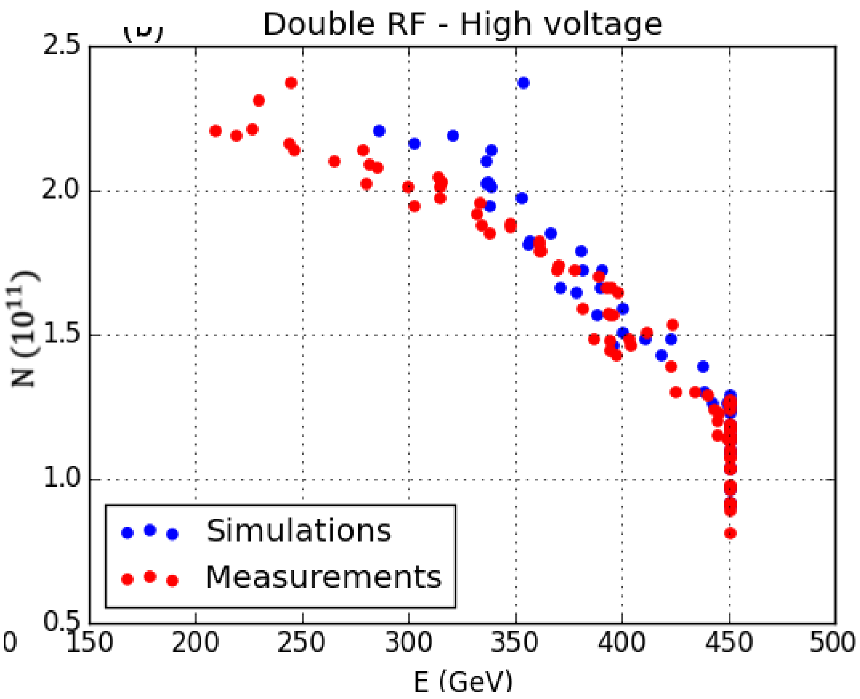
J. Varela, C. Zannini et al., 2015

Model includes:

- 200 MHz cavities (2+2) + HOMs
- 800 MHz cavities (2)
- Kicker magnets (8 MKEs, 4 MKPs, 5 MKDs, 2 MKQs)
- Vacuum flanges (~500) + DR
- BPMs: BPH&BPV (~200)
- Unshielded pumping ports (~ 16 similar + 24 various)
  - non-conformal assumed 0
- Y–chambers (2 COLDEX + 1)
- Beam scrappers (3 S + 4 UA9)
- Resistive wall
- AEPs (RF phase PUs, 2) ~ 0
- 6 ZSs + PMs
- 25 MSE/MST + PMs

Single bunch in 1 & 2 RF systems: instability during ramp

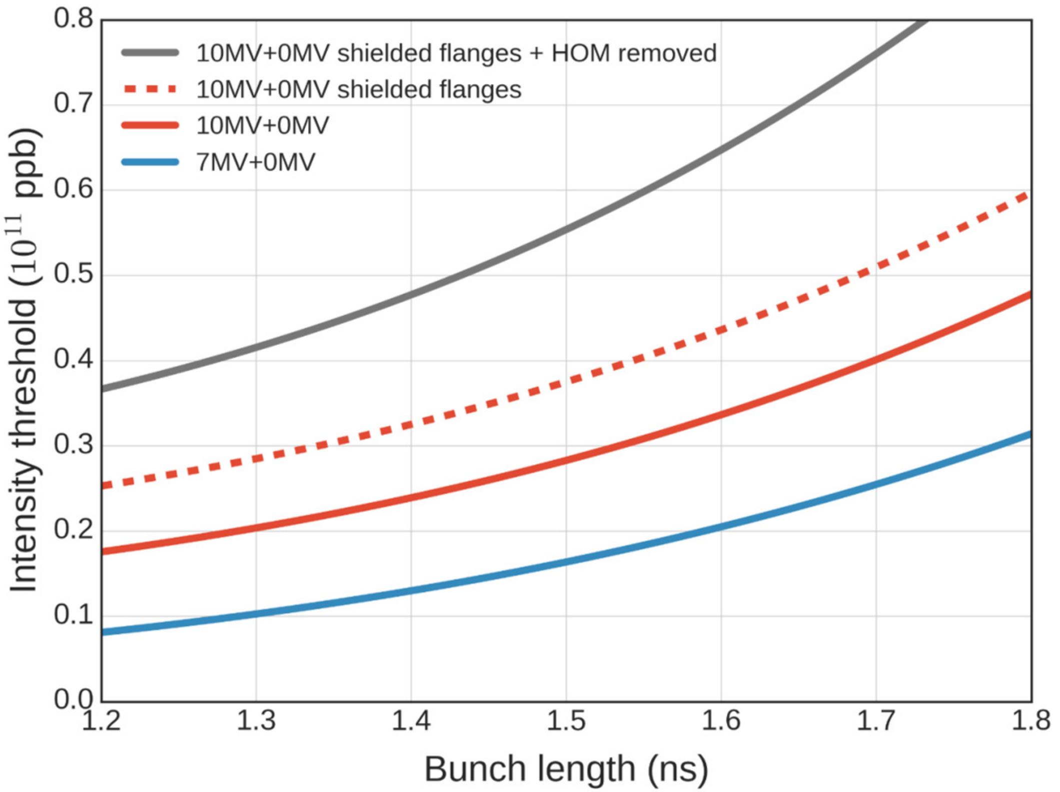




→ Good agreement between measurements and simulations (BLonD)

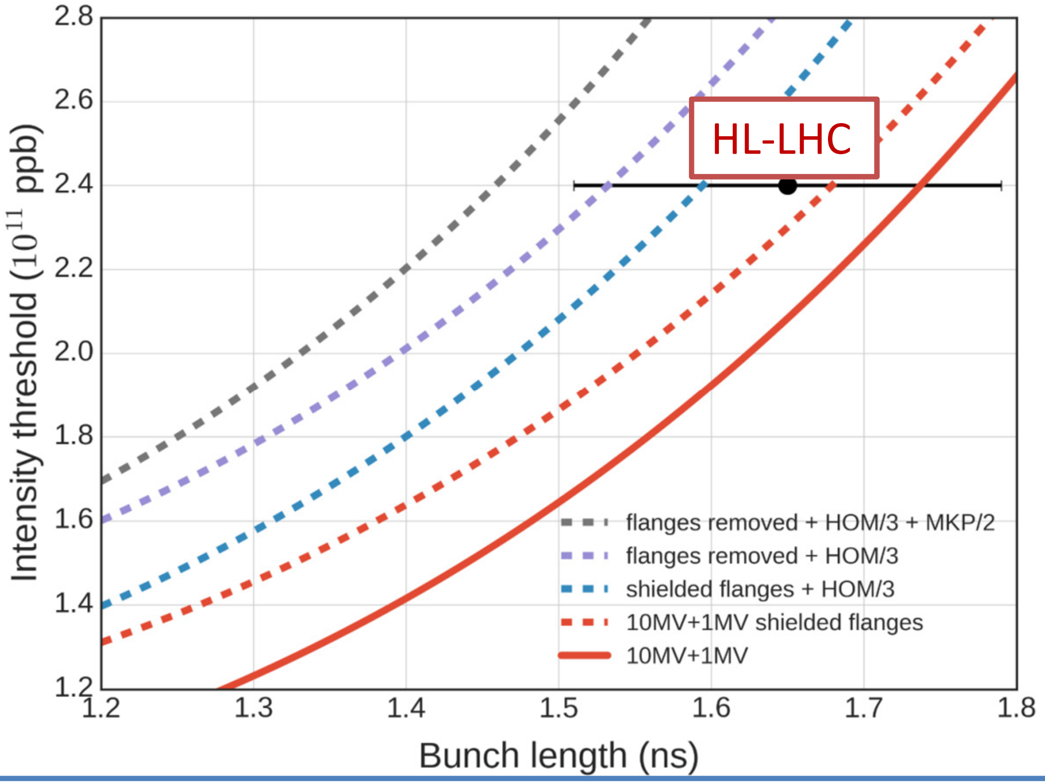
→ For a single bunch the difference in the threshold in 1 & 2 RF is very small (~ 1.0x10^{11} and 1.2x10^{11}), but not true anymore for 72 bunches!

Effect of impedance reduction at 450 GeV/c in a single RF system



→ RF upgrade and Impedance reduction are not sufficient in a single RF system
→ Double RF operation and controlled emittance blow-up during ramp needed

Effect of impedance reduction at 450 GeV/c in a double RF system



→ In a double RF operation the RF upgrade and baseline impedance reduction should be sufficient to reach HL-LHC parameters, but without margin

→ Other options: higher 800 MHz and bunch rotation on the SPS flat top, reduction of the MKP impedance (M. Barnes et al.), 200 MHz RF system in LHC

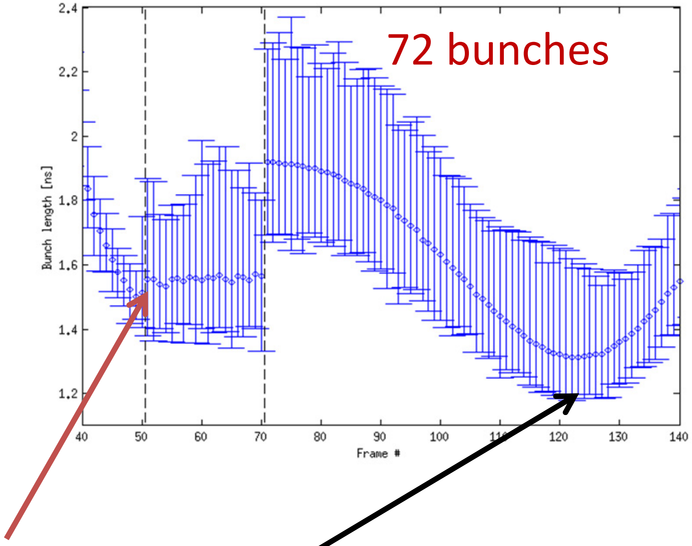
Bunch rotation tests in the SPS

- Good results were achieved for a single bunch (AWAKE experiment)

Test with 1&2 batches of 72 bunches (1.1x10^{11}/b): 7 MV ↘ 2-3 MV ↗ 7 MV

- With adiabatic voltage increase bunches are 20% longer
- In both cases – uncontrolled longitudinal emittance blow-up, especially at low voltage (before rotation) due to instability

→ Impedance reduction of vacuum flanges should help



7 MV adiabatic: 1.55ns & step: 1.3 ns

Synchrotron frequency shift: reference impedance measurements

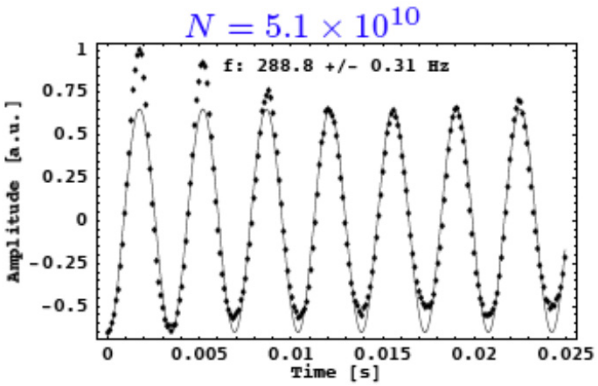
Measurements of **quadrupole oscillation frequency** of bunches injected with variable intensity and constant length (26 GeV/c)

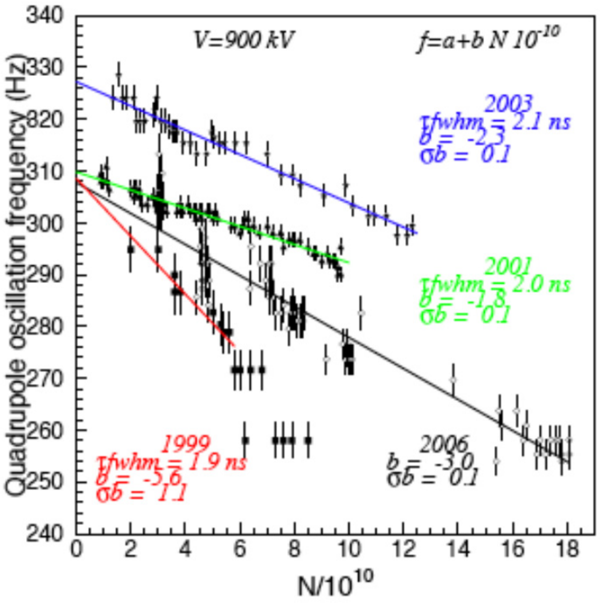
$$\boxed{f_{2s}(N) = a + b \times N/10^{10}}$$

1999: before impedance reduction: **b = -5.6**
2001: 1st impedance reduction: **b = -1.8**
2003: installation of 4 extraction kickers: **b = -2.3**
2006: 5 more kickers installed: **b = -3.0**
→ Successful reference measurements

2007: a few kickers serigrafed (shielded) – but effect was not measurable anymore (increase of b)

→ More measurements were done recently

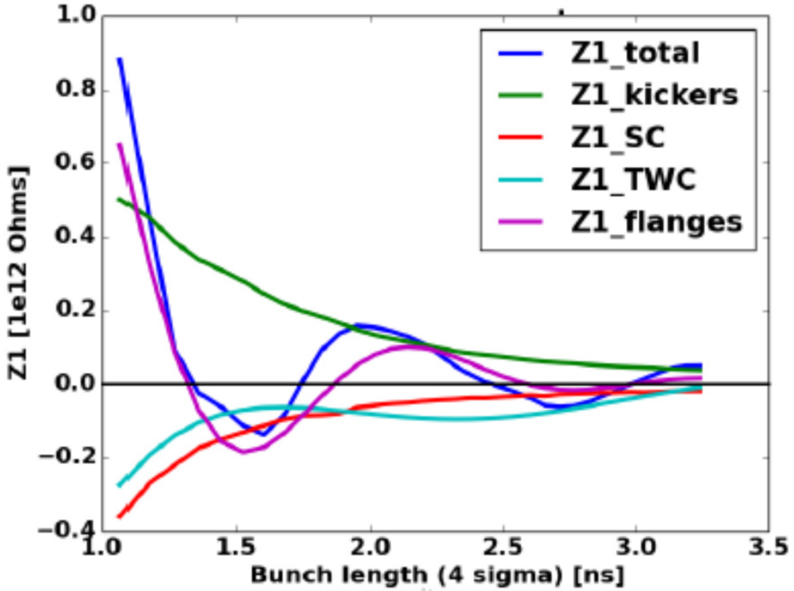


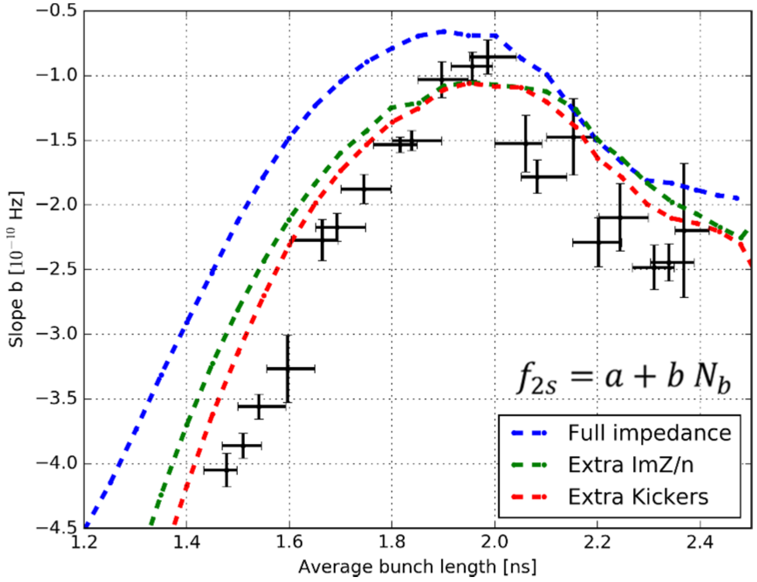


Synchrotron frequency shift: effective impedance $(\mathrm{Im}Z/n)_{\mathrm{eff}}$

Reactive impedance of the SPS has a complicated frequency structure

Effective impedance Z1 of SPS





→ For constant ImZ/n one expects **Δ**f ~ImZ/n /$\boldsymbol{\tau}^3$

→ Are we still missing ImZ/n impedance > 1 Ohm?

Transverse (reactive) impedance: betatron tune shift measurements (1/2)

Measurements of coherent betatron tune shift due to effective impedance:

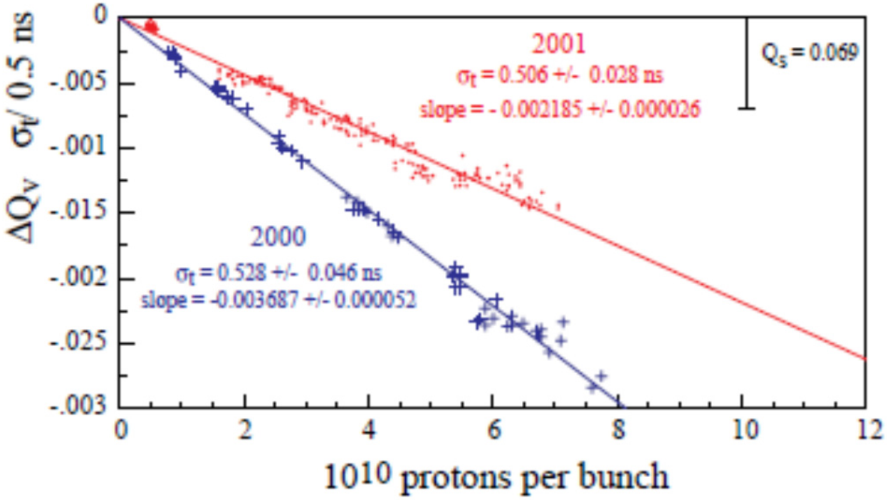
$$\Delta\omega_\beta = \frac{N\,e\,c}{4\sqrt{\pi}\,\omega_\beta\,(E/e)\,T_0\,\sigma_t}\,i(Z_\perp)_{\text{eff}}$$

$$(Z_\perp)_{\text{eff}}(\omega_\xi) = \int_{-\infty}^{\infty} Z_1^\perp(\omega)\,h_m(\omega-\omega_\xi)\,dw$$

where $\omega_\xi = \xi\,\dfrac{\omega_\beta}{\eta}$

For Gaussian bunch and m=0

$$h_0(\omega) = \frac{\sigma_t}{\sqrt{\pi}}\,e^{-(\omega\sigma_t)^2}$$

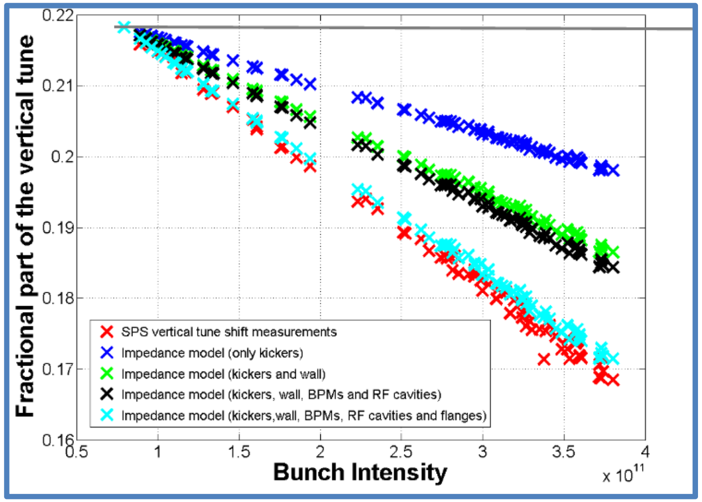


→ Results of the 1st SPS impedance reduction are visible in the reference measurements (H. Burkhardt, G. Rumolo, F. Zimmermann, PAC'01)

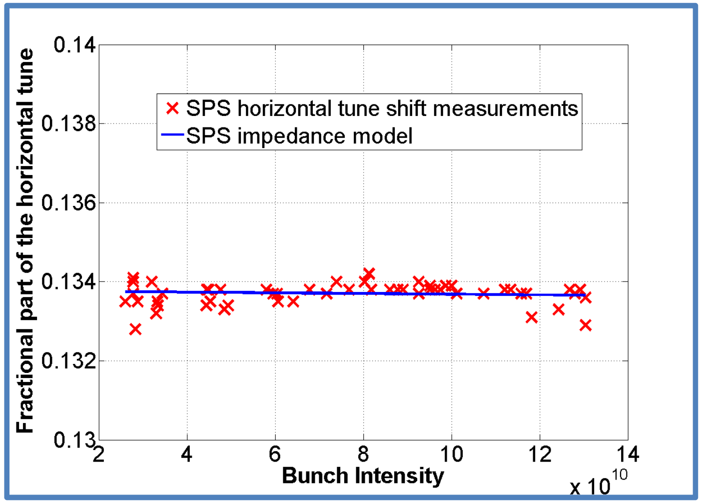
year	$\mathrm{Im}\,Z_x$ MΩ/m	$\mathrm{Im}\,Z_y$ MΩ/m
2000	-0.9 ± 1.8	26 ± 3
2001	-0.35 ± 0.53	18.4 ± 0.5

Transverse (reactive) impedance: betatron tune shift measurements (2/2)

Vertical tune shift @ 26 GeV/c



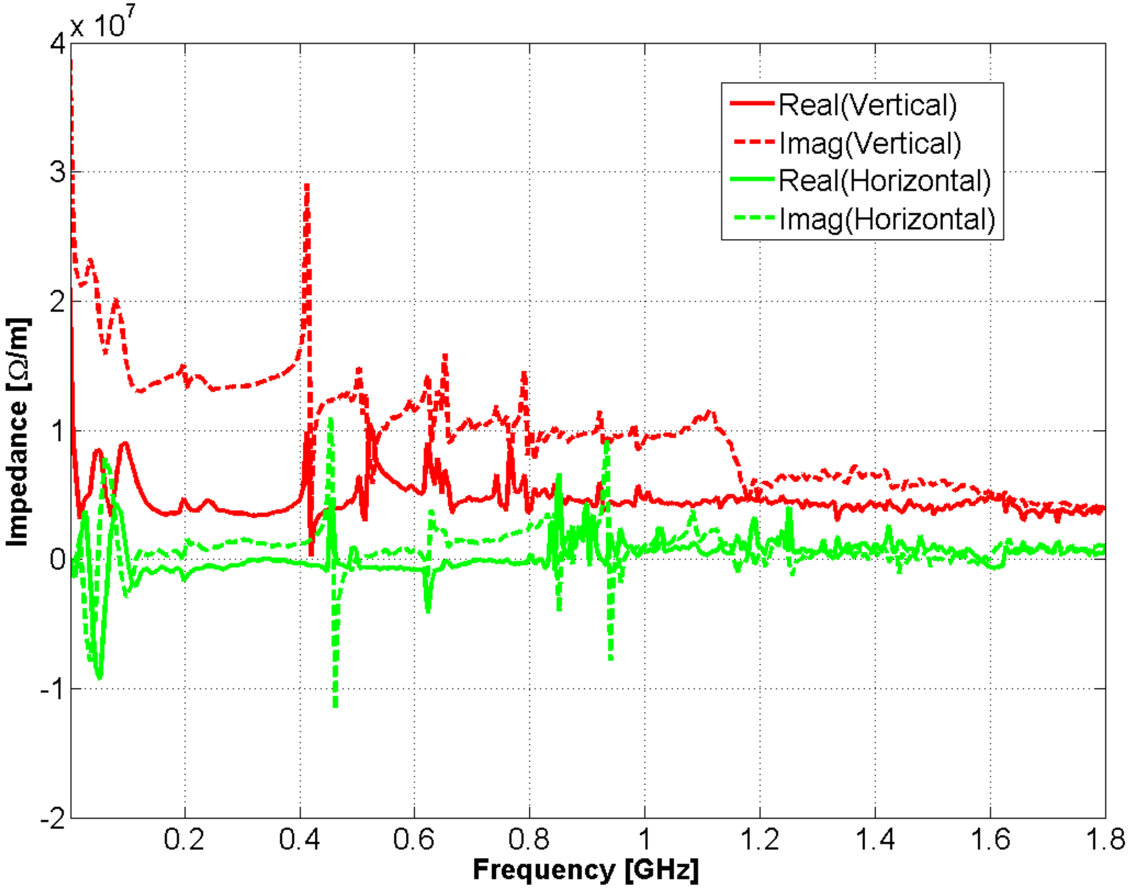
Horizontal tune shift



→ Present SPS impedance model reproduces > 90% of the vertical tune measured in the Q20 optics

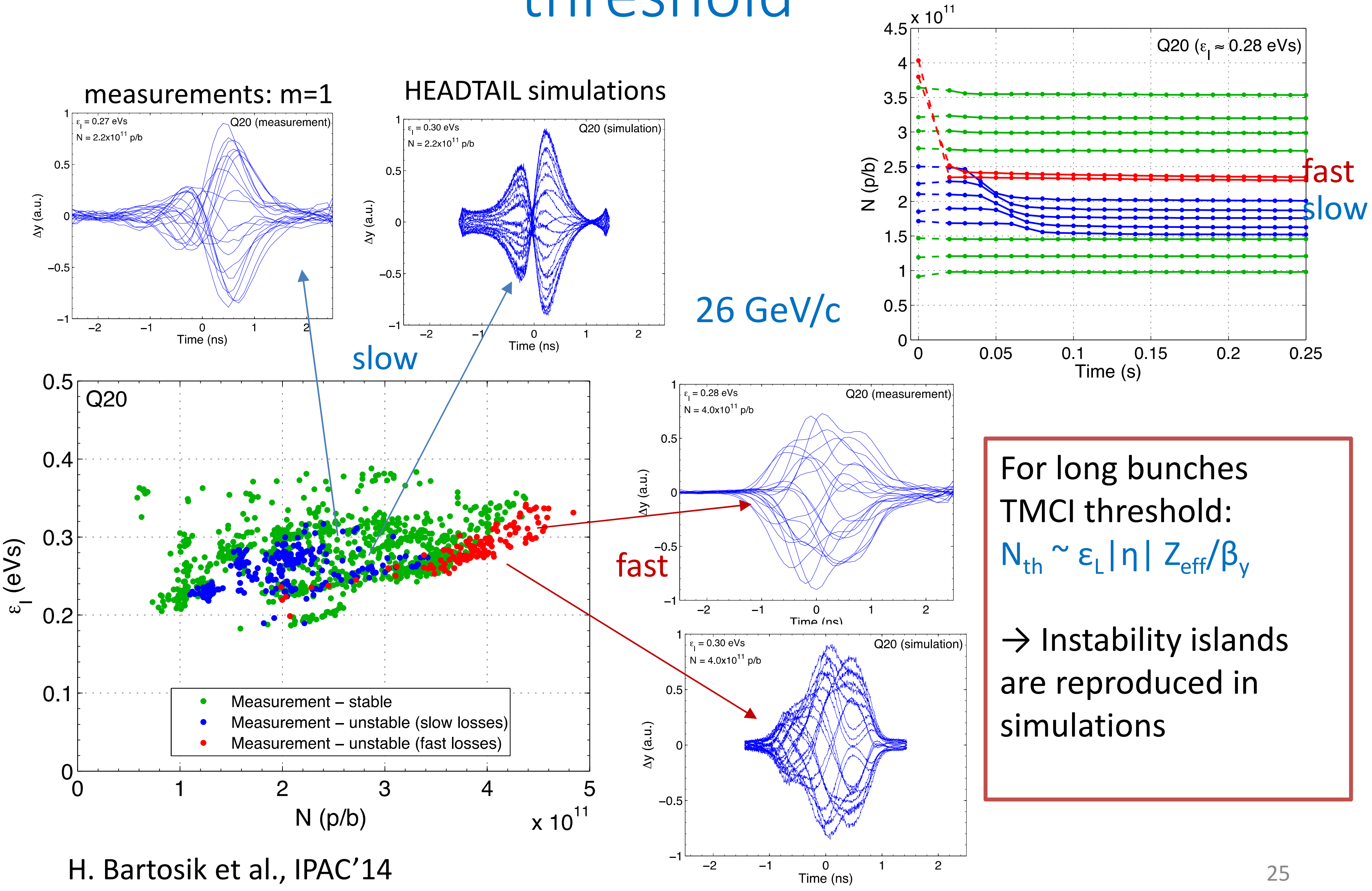
C. Zannini et al., PAC’15

SPS transverse impedance model



C. Zannini et al.

Transverse Mode Coupling Instability threshold



For long bunches TMCI threshold:

$N_{th} \sim \varepsilon_L |\eta|\, Z_{eff}/\beta_y$

→ Instability islands are reproduced in simulations

H. Bartosik et al., IPAC’14

Head-tail growth rate as a function of chromaticity

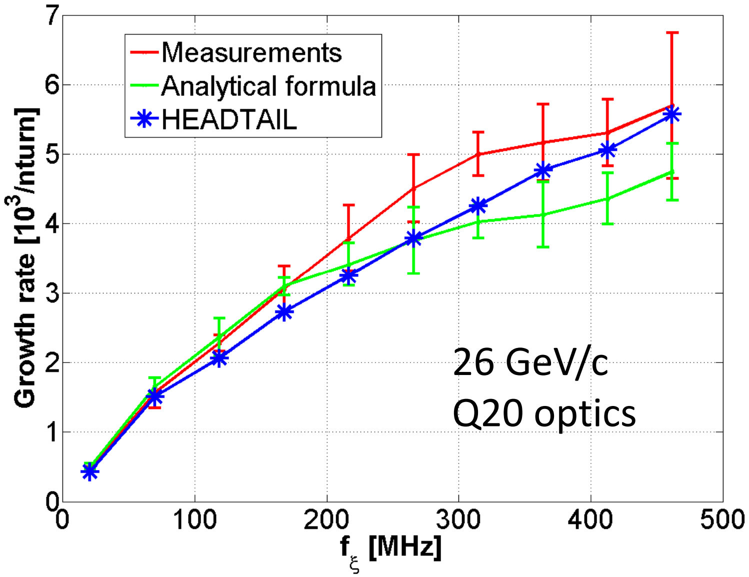
Effective impedance is a convolution of Z with longitudinal spectral density

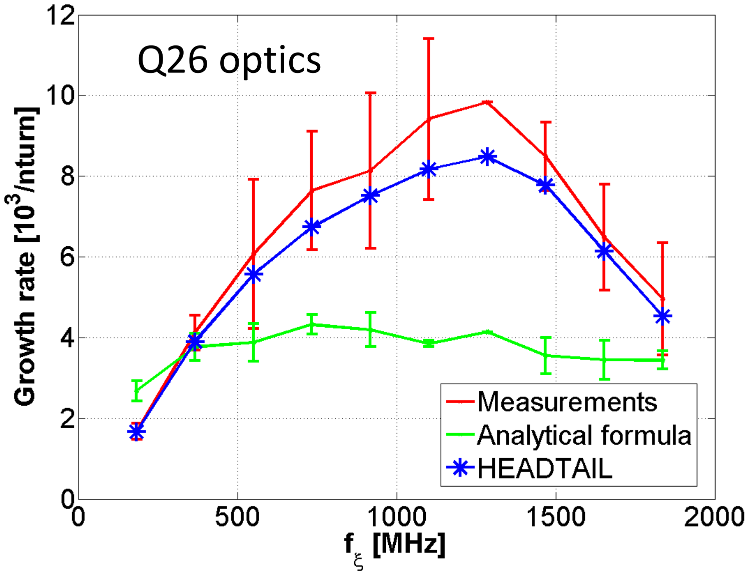
$$h_0(\omega) = \frac{\sigma_t}{\sqrt{\pi}} e^{-(\omega\sigma_t)^2}$$

where $\omega \rightarrow (\omega - \omega_\xi)$ and $\omega_\xi = 2\pi f_\xi = \omega_\beta \xi/\eta$, ξ is chromaticity, η - slip factor

→ By varying ξ frequency dependence of the impedance is sampled

→ Good agreement with simulations based on SPS impedance





C. Zannini et al., IPAC'15

Summary

- The SPS impedance was significantly reduced in the past in preparation of the SPS as an LHC injector. The HL-LHC project needs bunch intensities twice higher than nominal.
- One of the known intensity limitations is a longitudinal instability with a very low threshold which will be increased after upgrade of the 200 MHz RF system, but this is not sufficient to reach HL-LHC goals
- The impedance sources responsible for this instability were identified using beam-based measurements and new impedance reduction campaign is planned in synergy with partial aC-coating.
- Transverse impedance model is able to reproduce well beam measurements