Longitudinal Microwave Instability in a Multi-RF System

T. Argyropoulos

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Outline

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  - Impedance identification

☐ Longitudinal instability due to a high frequency resonator
  - Single RF system
  - Double RF system

☐ Longitudinal instability in the SPS

☐ Summary

Introduction

- ❑ Microwave instability observed in the proton machines as a fast increase of the bunch length (longitudinal emittance)

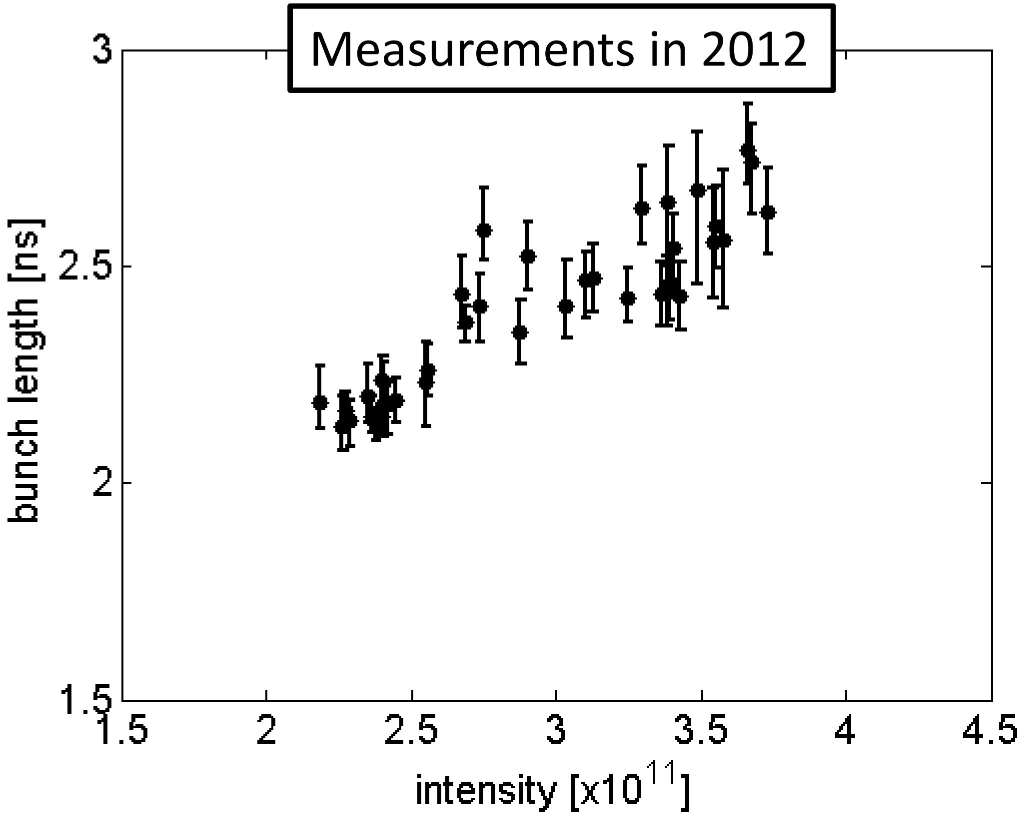
- ❑ Microwave (μw) instability observed in the CERN SPS in the past → main source the resonant (Q~50) impedance of the pumping ports (~1000) → **shielding them improved the beam stability**

- ❑ Today:
  - SPS injector of the LHC
  - Operation with double RF in bunch shortening mode (BSM): 200 MHz + 800 MHz

- ❑ Recently **uncontrolled emittance blow-up observed in the SPS at high intensities**→ one of the **main limitations** for the intensity increase required by the **HL-LHC project (~2.5×10^{11} p/b)**

Uncontrolled emittance blow-up (1/2)

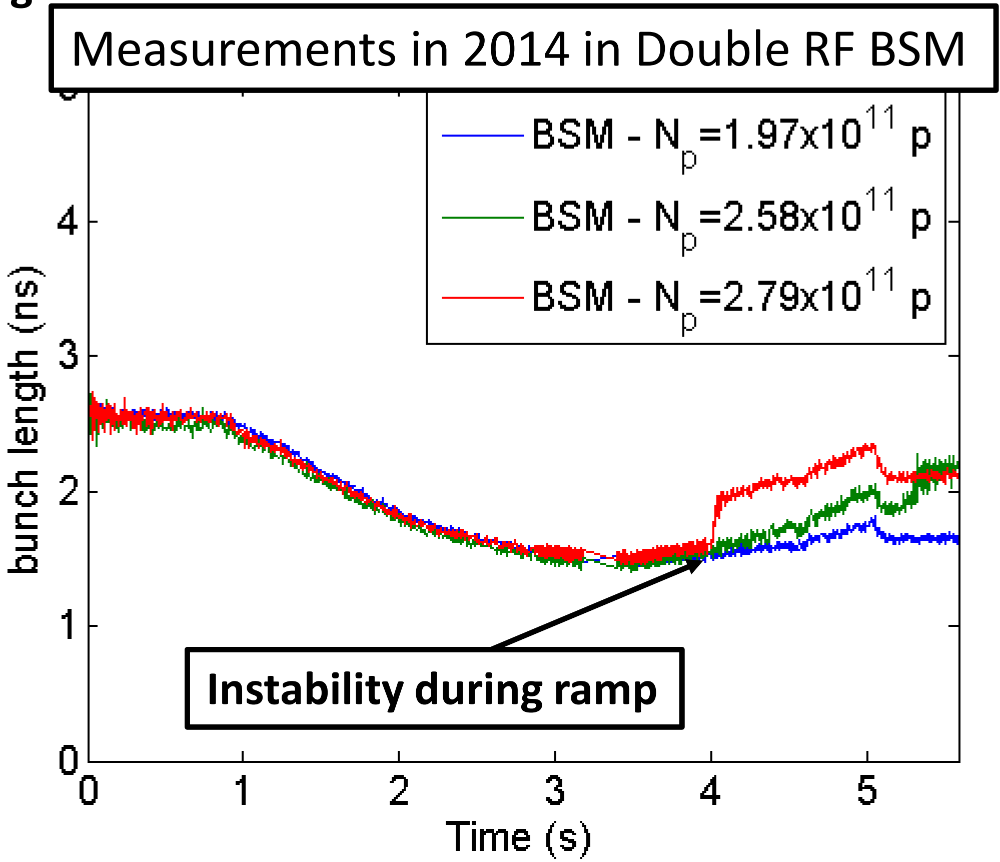
- Measurements of high intensity **single bunch at the SPS flat top (450 GeV/c)**
- **Double RF** systems (200 MHz + 800 MHz) in **BSM** with **$V_{800} = V_{200}/10$**


Measurements in 2012

Bunch lengthening **can not be explained by potential well distortion** with the SPS impedance model (**ImZ/n ~ 3.5 Ω** but **ImZ/n >15 Ω is needed**) → **blow-up during ramp**

Uncontrolled emittance blow-up (2/2)

- Single bunch with high intensity in double RF system ($V_{800} = V_{200}/10$)
- 200 MHz RF voltage calculated for constant bucket area 0.5 eVs (~0.6 eVs in normal operation) → larger filling factor during cycle → **more Landau damping**

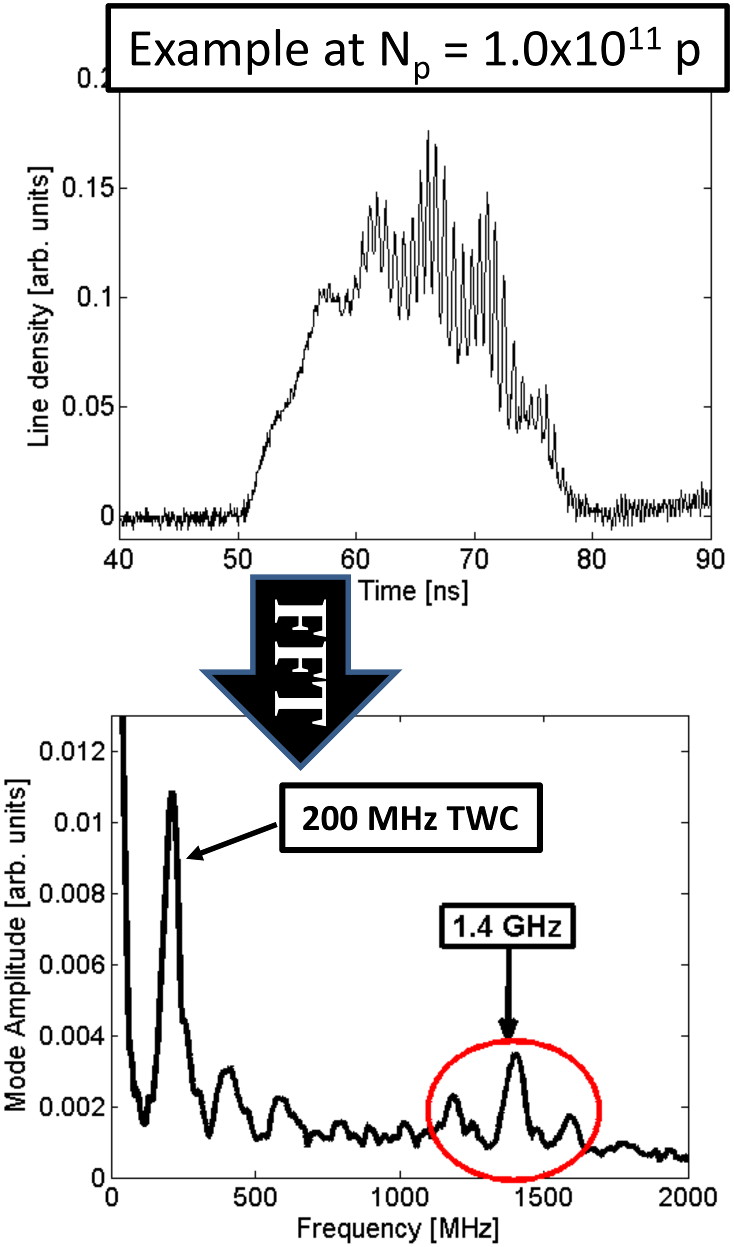

Measurements in 2014 in Double RF BSM

Instability during ramp

For $\varepsilon_l \approx 0.26$ eVs ⇒ $N_{th} \approx 2.5\text{x}10^{11}$ p

- **Lower threshold in a single RF system :** $N_{th} \approx 1.7\text{x}10^{11}$ p

Impedance identification

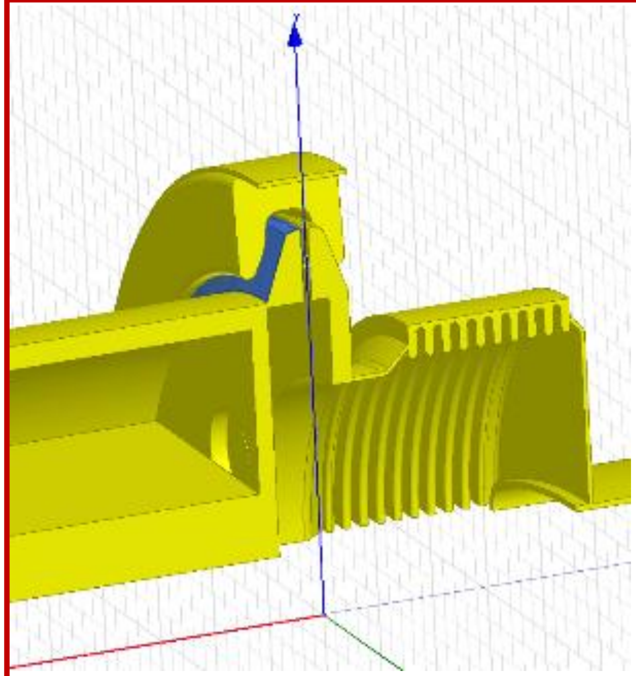


Example at N_p = 1.0x10^{11} p

200 MHz TWC

1.4 GHz

- **Beam measurements** at injection energy (26 GeV/c) with long bunches ($\tau\sim25$ ns) and RF off
- Small momentum spread → more unstable and slow debunching
- Line density modulated at 200 MHz and a higher frequency (1.4 GHz)



SPS Vacuum flanges are the best candidate with strong peak at **f_r = 1.4 GHz** with **R/Q = 9 kΩ (different types,~ 550)**

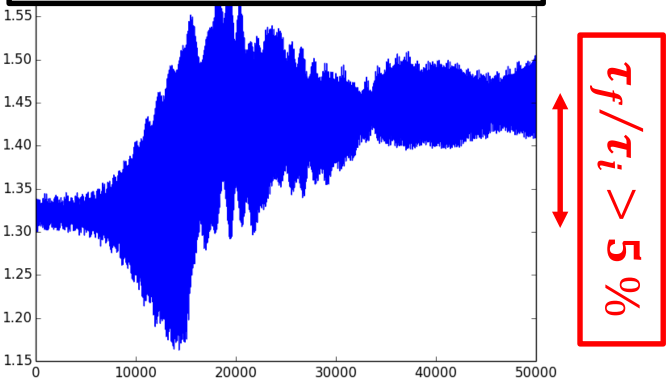
μw instability due to a resonator

- **Microwave instability threshold in a single RF system:**
  - broad-band impedance: $f_r\tau \gg Q \rightarrow N_{th}\left(\frac{R_{sh}}{n_r}\right)$
  - narrow–band impedance: $f_r\tau \ll Q \rightarrow N_{th}\left(\frac{R_{sh}}{Q}\right)$

- Particle simulations carried out to confirm this analytical predictions using the code ***BLonD*** (longitudinal beam dynamics code developed at CERN) resonator impedance: **f_r = 1.4 GHz, R/Q=10 kΩ**

Criterion for Instability threshold: $\tau_f/\tau_i > 5\,\%$ or $\Delta\tau_f > 100$ ps

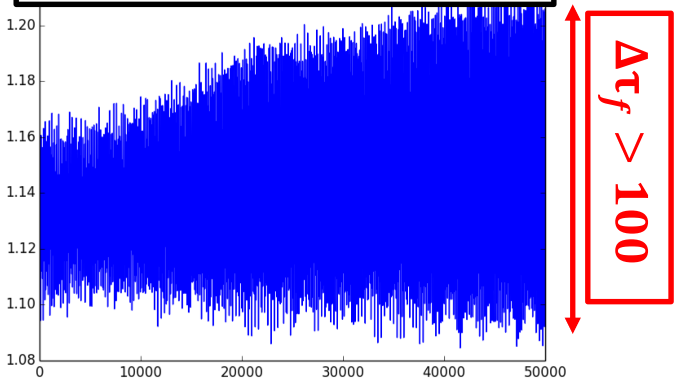
ε_l = 0.5 eVs – N_{th} =3.4E11



$\tau_f/\tau_i > 5\,\%$

Q20 - Double RF - V_{200} = 7 MV

ε_l = 0.3 eVs – N_{th} =3.5E11

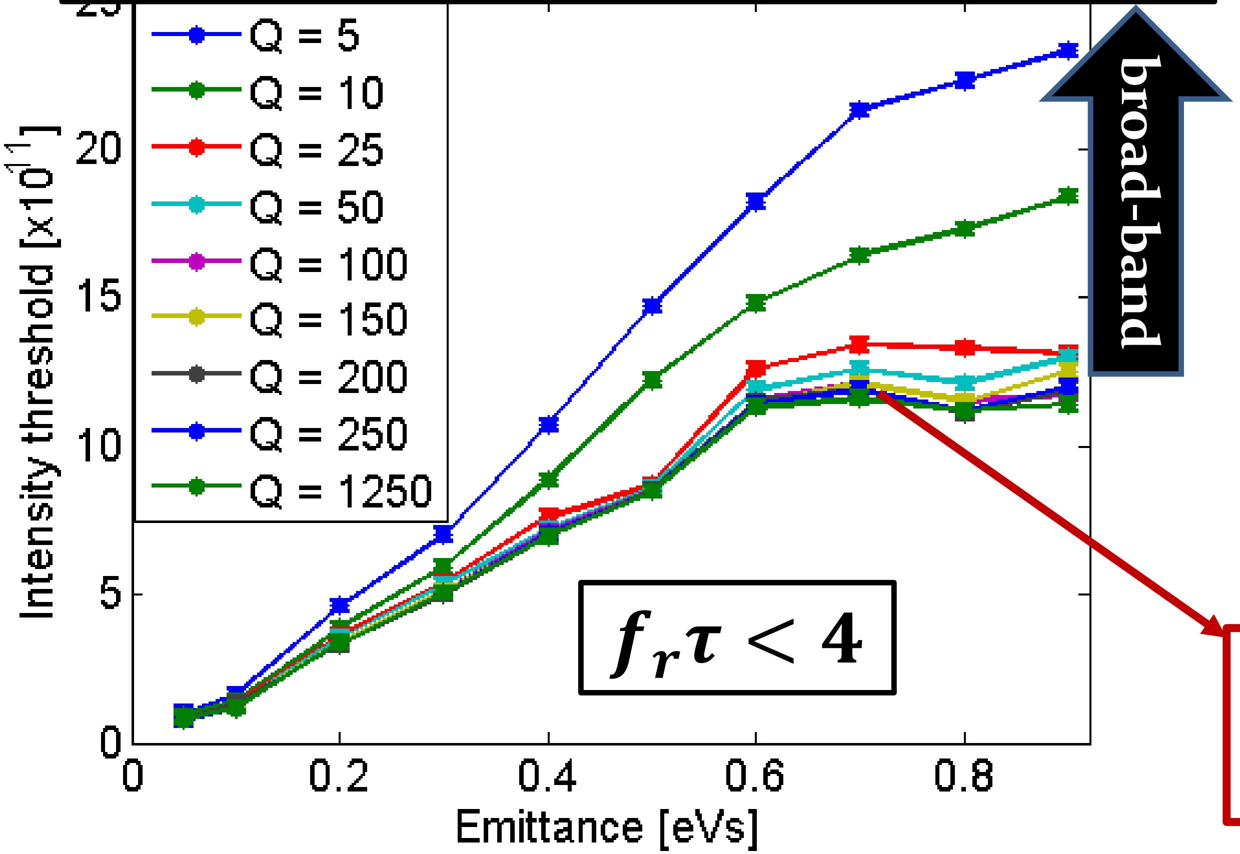


$\Delta\tau_f > 100$

Simulations – single RF

- ☐ Simulations at SPS flat top (450 GeV/c) with $V_{200} = 2$ MV
- ☐ Scanning **Q** but keeping **R/Q constant**

Instability threshold from simulations in a single RF



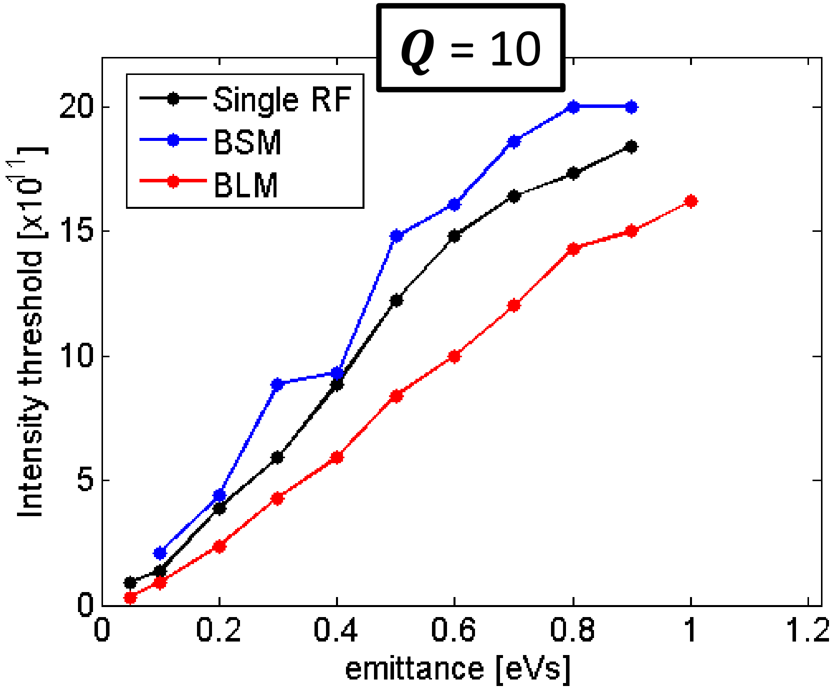
- ☐ **Same threshold for Q ≥50 →** narrow-band regime → **R/Q** is important

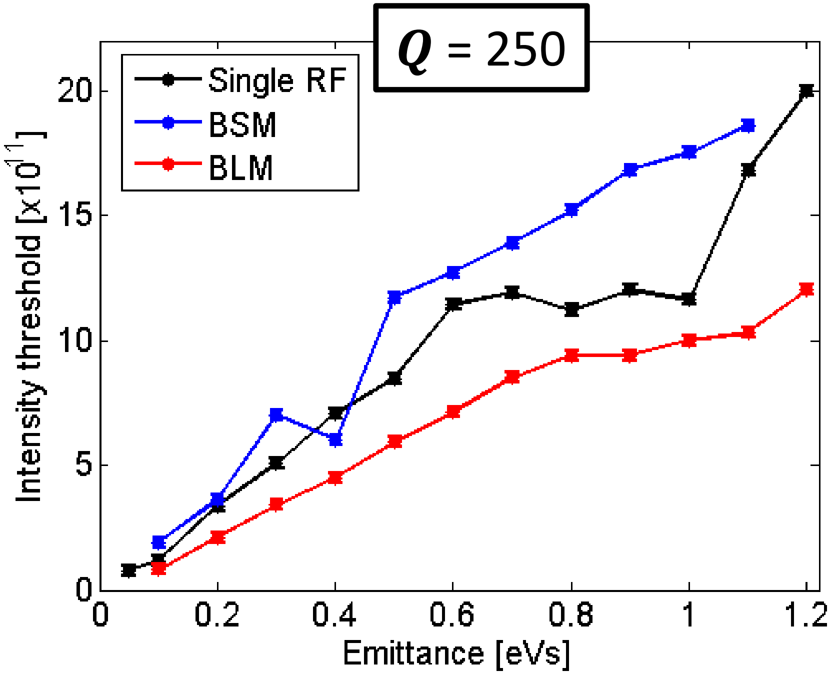
- ☐ For **Q< 50 →** approaching the broad-band regime → **R** is important

For the SPS vacuum flanges Q>70 → narrow-band regime

Simulations – double RF (1/2)

- Second harmonic RF system: **$h_2/h_1 = 2$** and **$V_1/V_2=2$**
- Simulations at SPS flat top (450 GeV/c) with V_{200} = 2 MV
- **Similar dependence with R/Q**

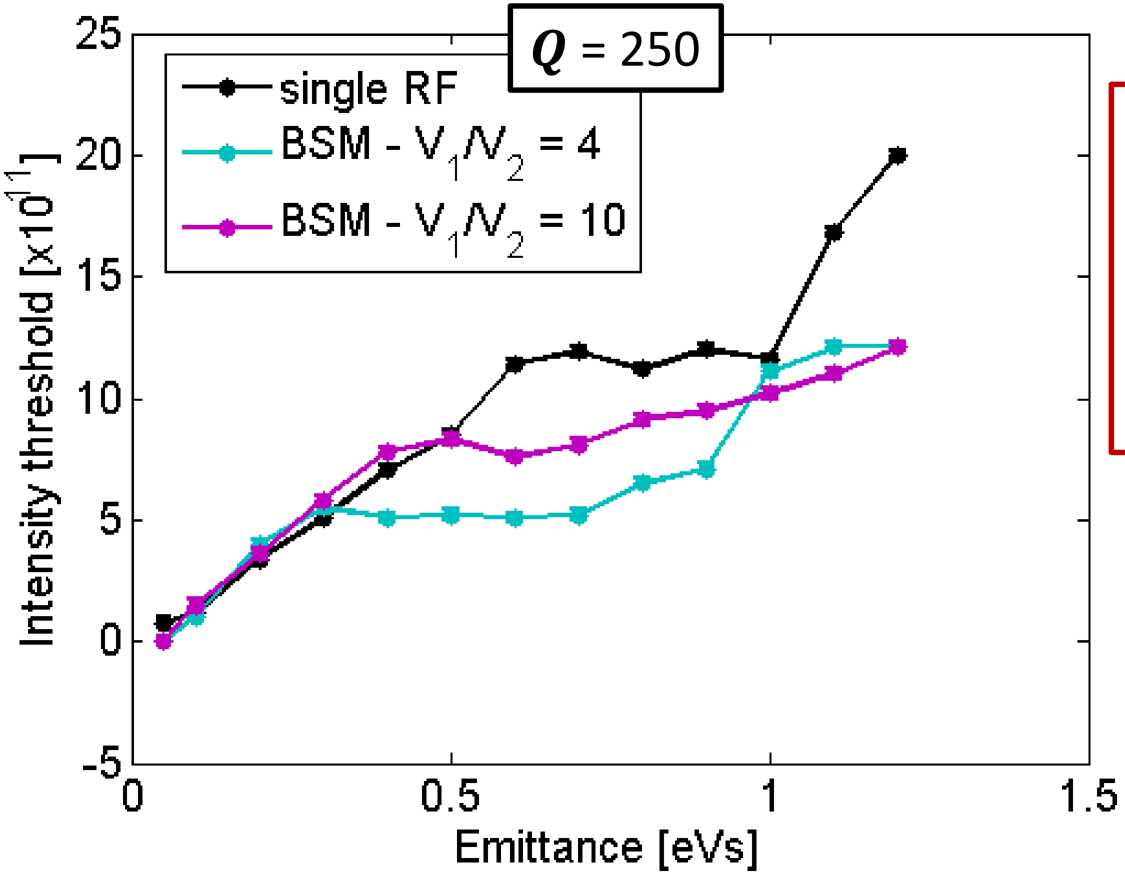




- Double RF in **BSM** has the **highest threshold** and double RF in **BLM** the **lowest** → **Dependence on the $\Delta p/p$**

Simulations – double RF (2/2)

- ☐ Fourth harmonic RF system: **h_2/h_1 = 4 (SPS today)**
- ☐ Simulations at SPS flat top (450 GeV/c) with V_{200} = 2 MV



- ☐ **After a certain ε_l single RF is better for stability**
- ☐ **Can be correlated with the synchrotron frequency distribution inside the bunch**

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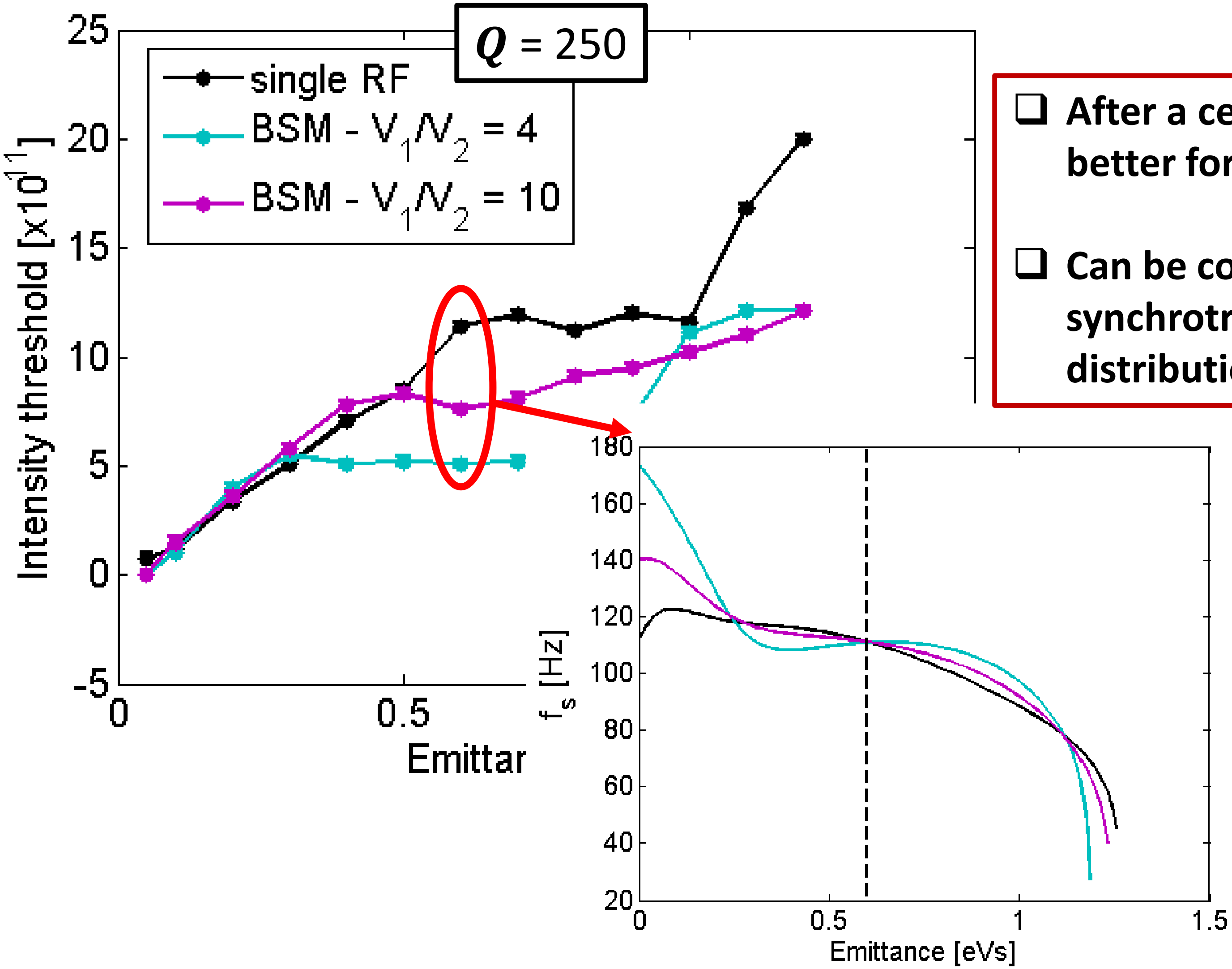

- **After a certain ε_l single RF is better for stability**
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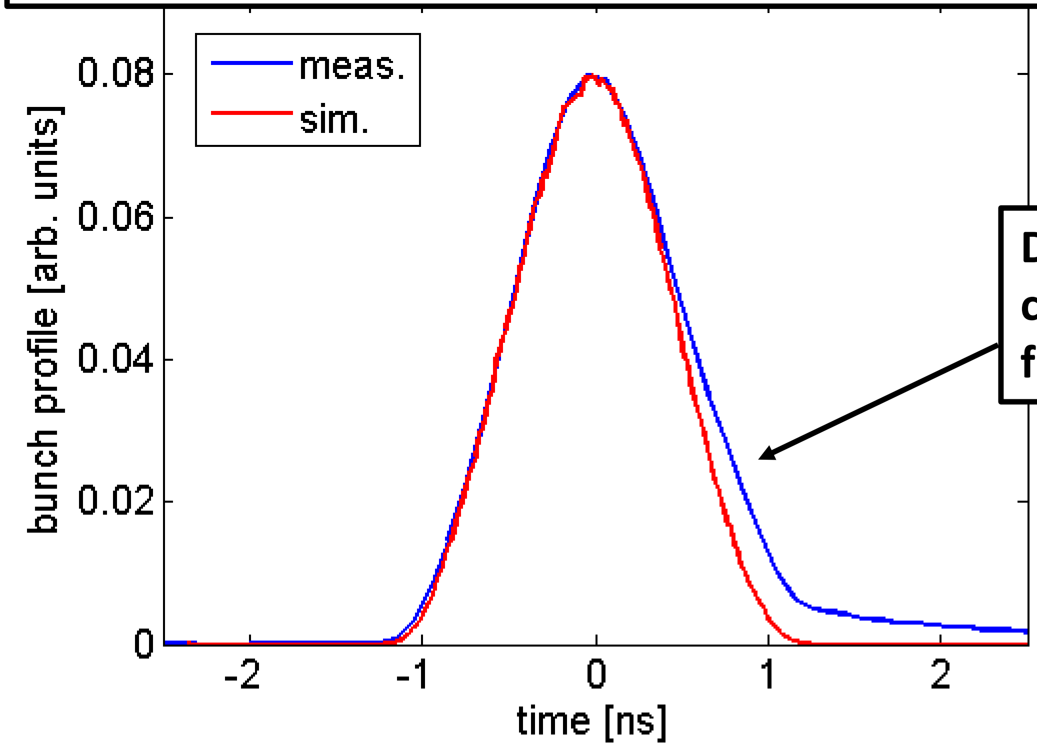
Longitudinal instability in the SPS

- Macroparticle simulations at the SPS flat top (450 GeV/c) using the full SPS impedance model: RF cavities, resistive wall, injection and extraction kickers, Beam Position Monitors (BPMs), vacuum flanges etc.

- Distribution function: $F(H) = (1 - \frac{H}{H_0})^2$ → **from measurements**

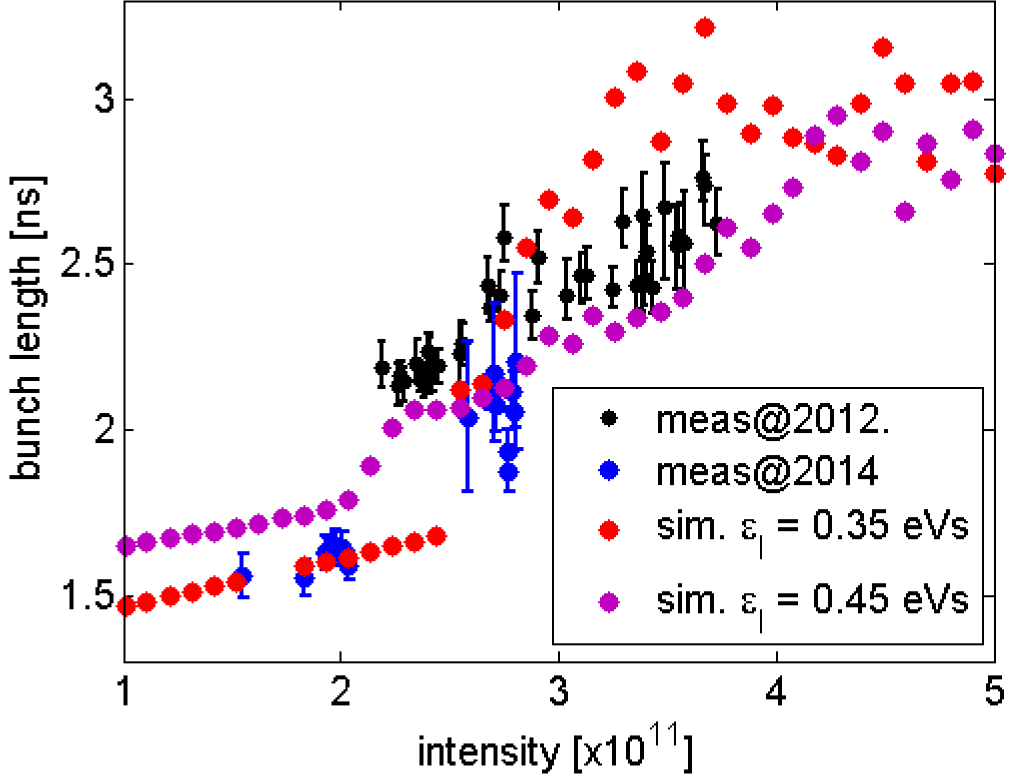
Double RF V_{200} = 2 MV – V_{800} = 0.2 MV – N=1.47x10^{11} p



Discrepancy due to cable transfer functions

Longitudinal instability in the SPS single bunch

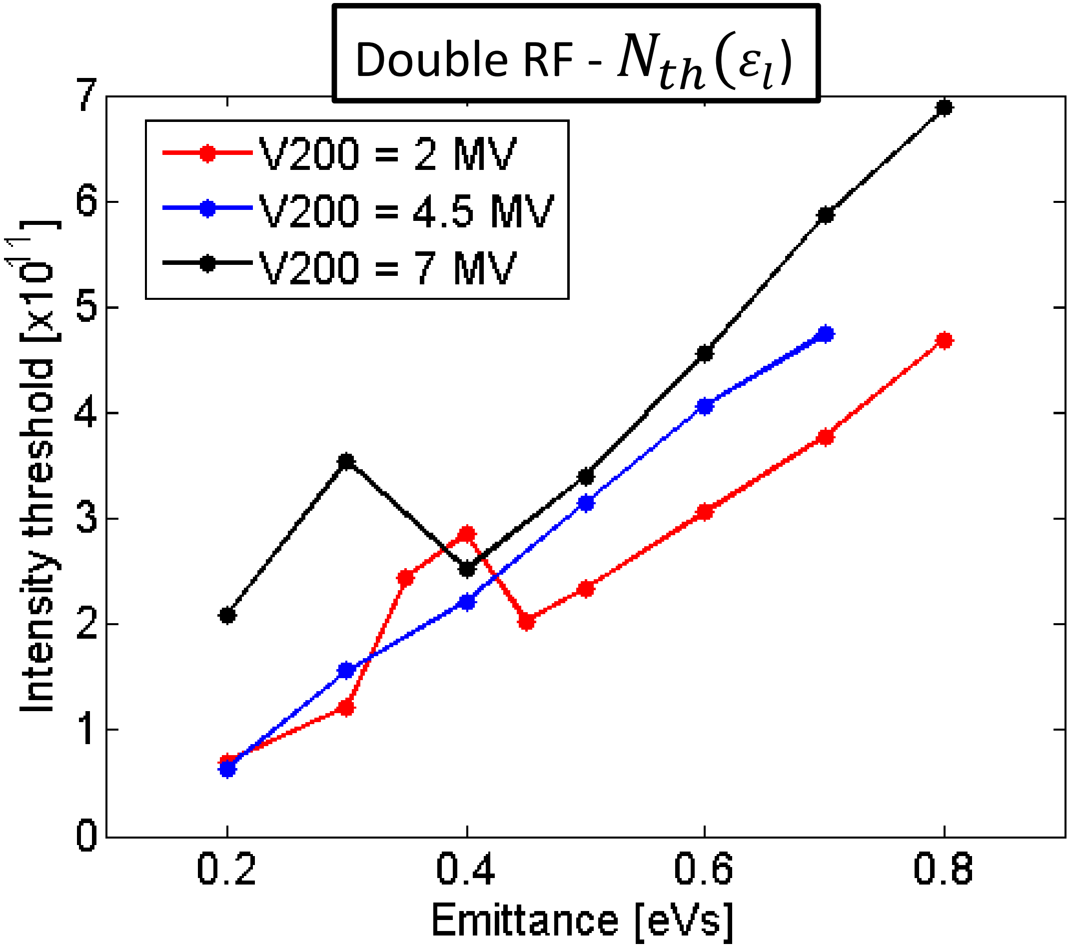
Double RF V_{200} = 2 MV – V_{800} = 0.2 MV



- ☐ Good agreement between measurements and simulations
- ☐ From measurements in 2014: $N_{th} \approx$ **2.5x10^{11} p** (more points are needed)
- ☐ From particle simulations with $\varepsilon_l \approx$ 0.35 eVs (maximum single particle trajectory): $N_{th} =$ **2.5x10^{11} p**
- ☐ Measurement in 2012 correspond to higher initial $\varepsilon_l \approx$ 0.45 eVs (from simulations) but points at lower intensity are missing
- ☐ In simulation: $N_{th} =$ **2.0x10^{11} p**

Longitudinal instability in the SPS single bunch

- Increasing the RF voltage in both RF systems → **larger $\Delta p/p$ → larger increase the instability threshold → µw type of instability**


Double RF - $N_{th}(\varepsilon_l)$

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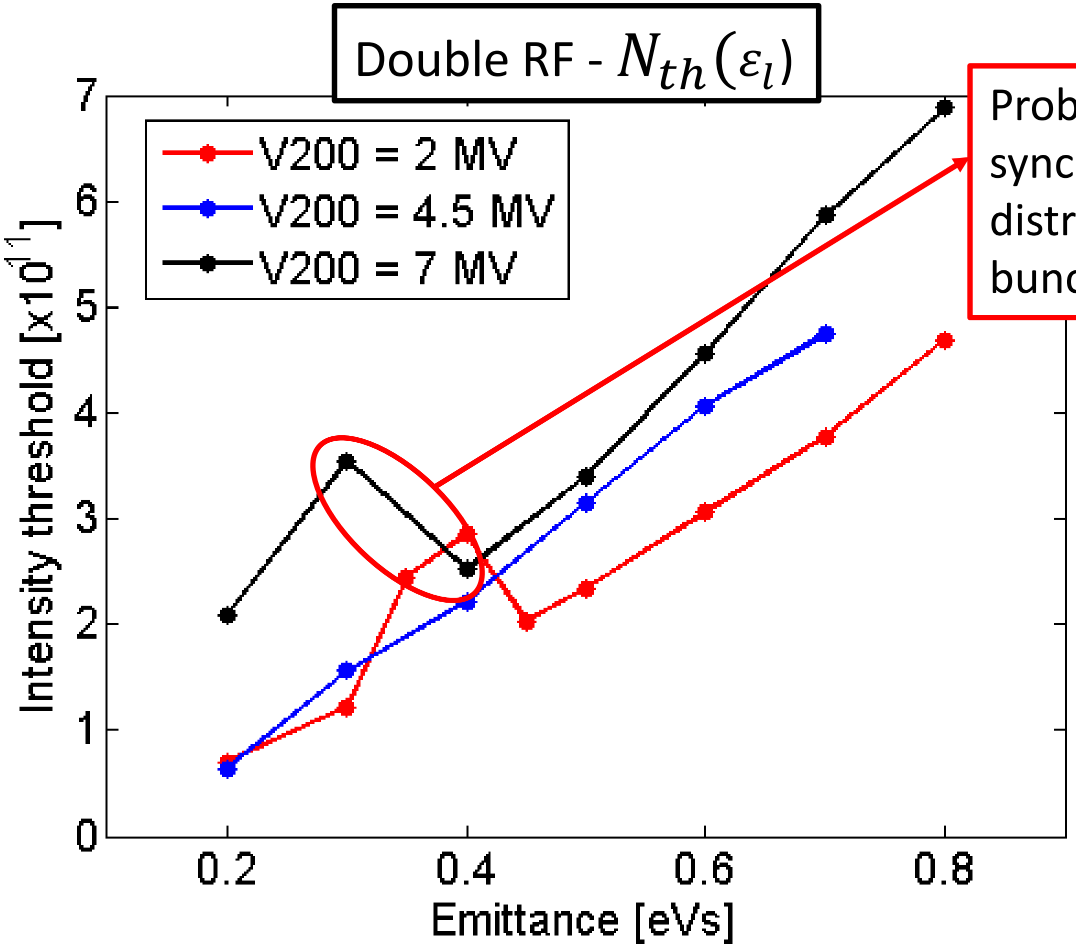

Double RF - $N_{th}(\varepsilon_l)$

Probably due to the synchrotron frequency distribution inside the bunch

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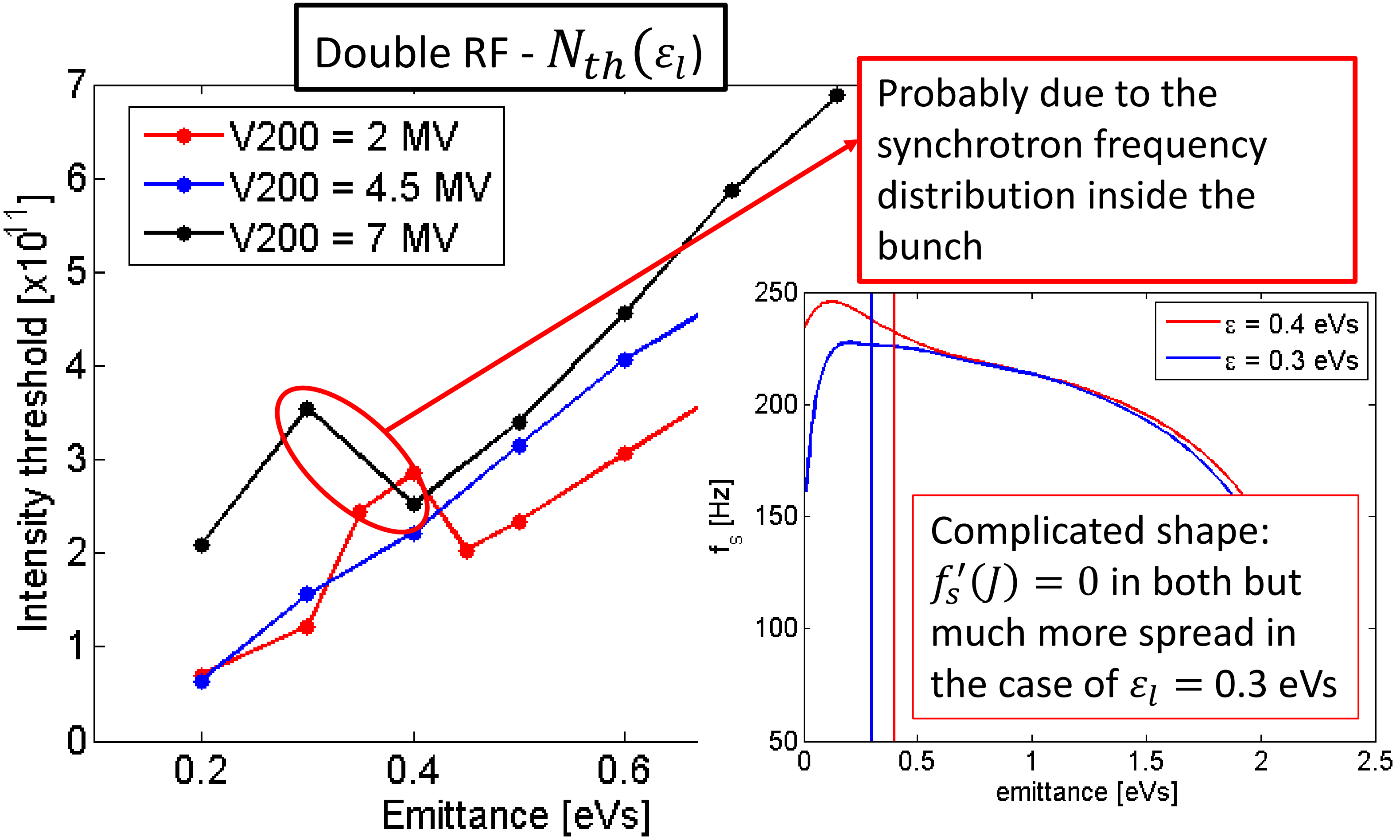


Double RF - $N_{th}(\varepsilon_l)$

Probably due to the synchrotron frequency distribution inside the bunch

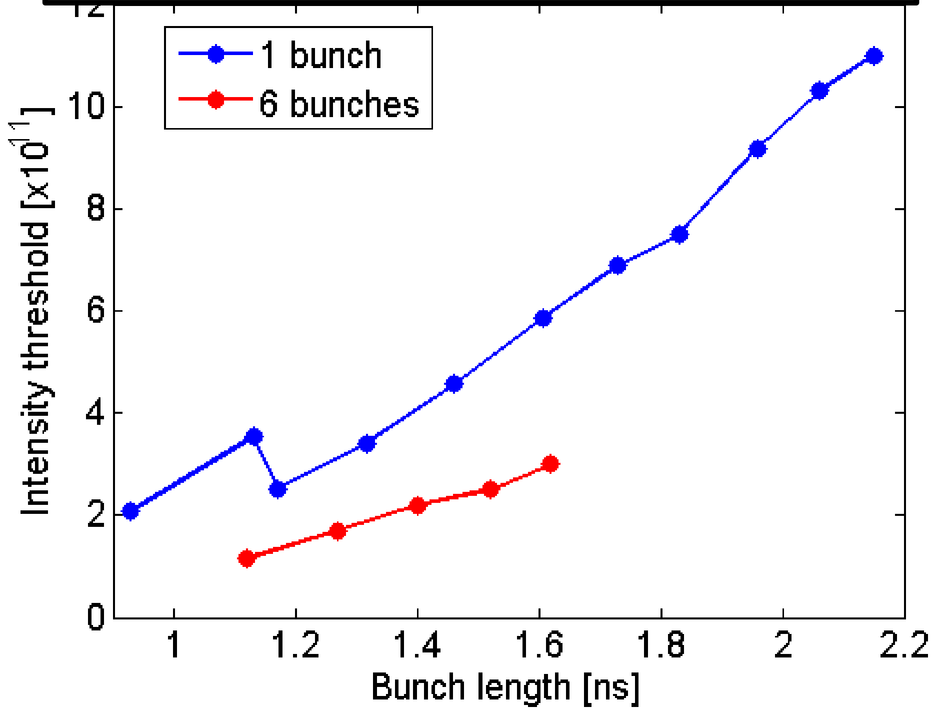
Complicated shape: $f_s'(J) = 0$ in both but much more spread in the case of $\varepsilon_l = 0.3$ eVs

Longitudinal instability in the SPS multi-bunch

Simulations for 6 bunches (25 ns spacing) at SPS flat top

Intensity threshold as a function of bunch length for 1 & 6 bunches

Double RF V_{200} = 7 MV – V_{800} = 0.7 MV



Qualitative agreement of simulations with measurements:

- N_{th} of 6 bunches is ~ twice lower than for single bunch (limitation for the HL-LHC parameters, ~ 2.5x10^{11} p/b needed)
- Only a few bunches are coupled, no coupled bunch modes → indeed **in measurements 25 ns and 50 ns spaced bunches are coupled, but batches spaced by 225 ns are decoupled**

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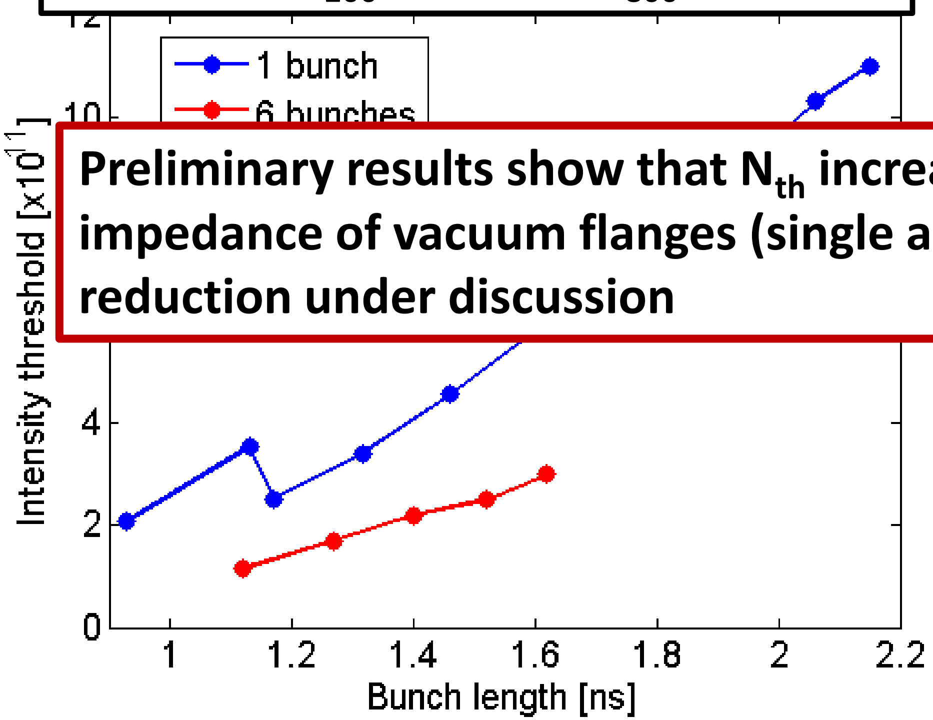

Preliminary results show that N_{th} increases by a factor of 2 without the impedance of vacuum flanges (single and multi bunch) → impedance reduction under discussion

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Summary

- Uncontrolled emittance blow-up is observed in the SPS → limitation for the HL-LHC intensity requirements

- Beam measurements identified a strong resonant peak at 1.4 GHz

- Macroparticle simulations for this type of resonators show that instability scales with R/Q (as expected from theory in single RF)

- Double RF vs single RF
  - **h_2/h_1 = 2: higher** N_{th} in BSM and **lower** in BLM (as expected from Δp/p)
  - **h_2/h_1 = 4: lower** N_{th} in BSM above a certain emittance

- Simulations with the current SPS longitudinal impedance model confirmed the uncontrolled blow-up → **SPS vacuum flanges the responsible impedance source**

- **Measures of reducing this impedance are under consideration**

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