Loss of Landau damping for reactive impedance and a double RF system

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Outline

- ☐ Longitudinal reactive impedance
- ☐ Analytical calculations
- ☐ Simulations
- ☐ Application for the SPS ppbar parameters
- ☐ Results for
  - Bunch lengthening mode (BLM)
  - Single RF and bunch shortening mode (BSM)
- ☐ SPS today
- ☐ Conclusions

Longitudinal reactive impedance

- ☐ Reactive beam coupling impedance:

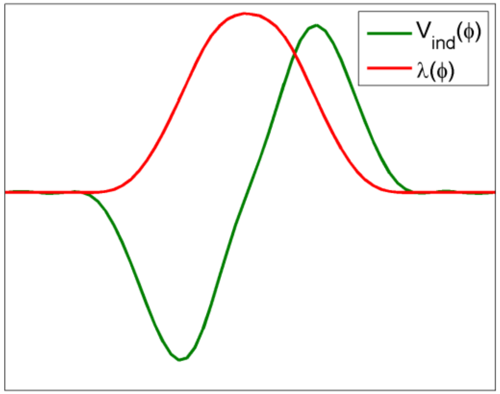
$$\frac{Z_{eff}(\omega)}{n} = i\left[\underbrace{\omega_0 L}_{\text{Inductive}} - \underbrace{\frac{g_0 Z_0}{2\beta\gamma^2}}_{\text{Space charge}}\right]$$

➡ Independent of frequency

n = ω/ω_0 , ω_0 the revolution angular frequency, g_0 = 1 + 2ln(b/α) for a circular beam of radius α in a circular beam pipe of radius b

- ☐ Total voltage: $V_t(\varphi,t) = V_{RF}(\varphi,t) + V_{ind}(\varphi,t)$

$$V_{ind} \sim \mathrm{Im}\left[\frac{Z_{eff}}{n}\right] \frac{\partial\lambda}{\partial\varphi}$$



⇒ **focusing** or **defocusing** depending on what part is dominant

Above transition:

Space charge → focusing

Inductive → defocusing

Analytical calculations

- Method: finding the **Van Kampen modes** for the perturbation *f* of particle distribution (**A.Burov, HB2010**)

- **Find the steady state** starting from a known particle distribution function F(I), I is the canonical action

- Solve the Vlasov equation:

$$\frac{\partial f}{\partial t} + \Omega(I)\frac{\partial f}{\partial \varphi} - \frac{\partial V}{\partial \varphi}F'(I) = 0$$

Following the Oide and Yokoya expansion:

$$f(I,\varphi,t) = e^{-i\omega t}\sum_{m=1}^{\infty}[f_m(I)\cos m\varphi + g_m(I)\sin m\varphi]$$

and **neglecting** azimuthal mode coupling leads to the equation:

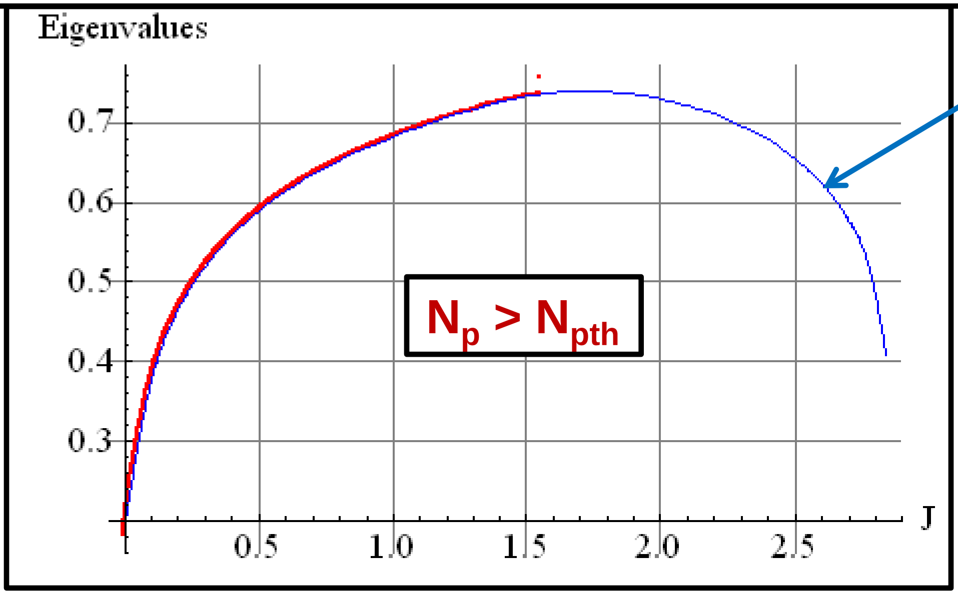
$$[\omega^2 - m^2\Omega^2(I)]f(I) = -m^2\Omega(I)F'(I)\int V_m(I,I')f(I')dI'$$

standard eigen-system problem of linear algebra

Analytical calculations

Continuous and discrete spectrum

Example of 2 RF systems in Bunch Lengthening mode for azimuthal mode m =1



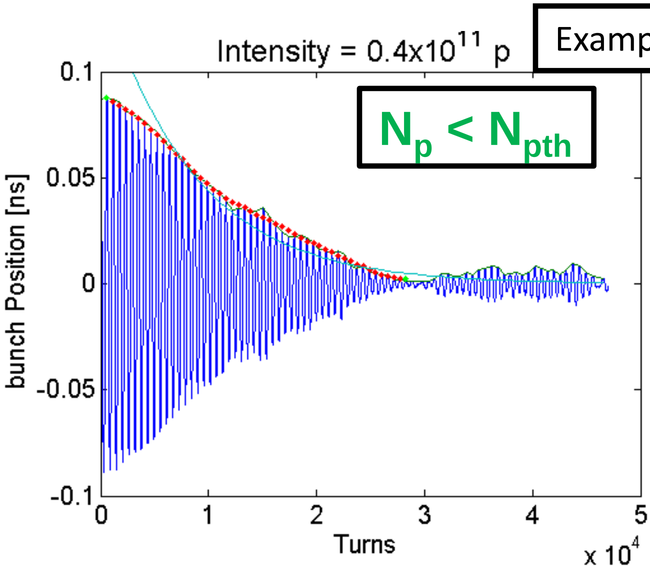
$\Omega_s(J)$

- **Continuous**: singular modes → coincide with the incoherent frequency spectrum of the particles → **Landau damped**
- **Discrete**: smooth functions → **unstable** ($Im(\omega_\mu) \neq 0$) or **without Landau damping** (mode above the incoherent particle spectrum)

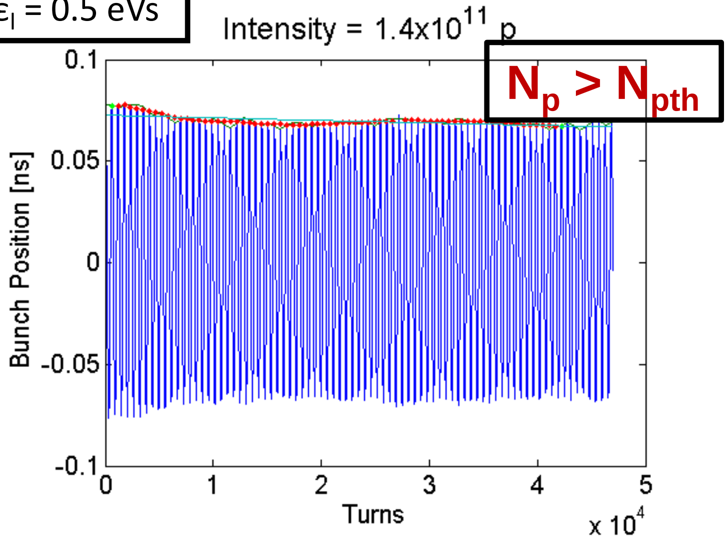
Simulations

- Simulations were done using a Matlab code for single bunch only for comparison with the analytical calculations for **dipole mode** (m = 1)
- $5\text{x}10^5$ macro-particles, enough to see the effect of Landau damping
- **Matched distribution** created and injected with a **phase error** of 3°
- Track for t ~ 300 T_s
- Average the amplitude of the dipole oscillations $<\phi_{max}>$ after the transients (>100 T_s)

Examples of ε_l = 0.5 eVs



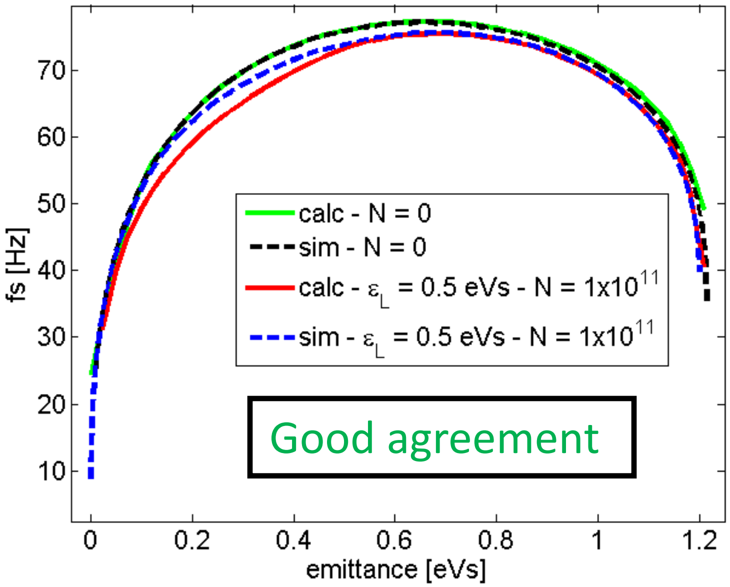
$N_p < N_{pth}$



$N_p > N_{pth}$

Calculations vs simulations

- Comparison of steady-state



Good agreement

In simulations f_s is found by tracking a few particles in the steady-state RF bucket

- Benchmarking with **another tracking code** (M. Migliorati) for single RF and different particle distributions is in **very good agreement**

Applications

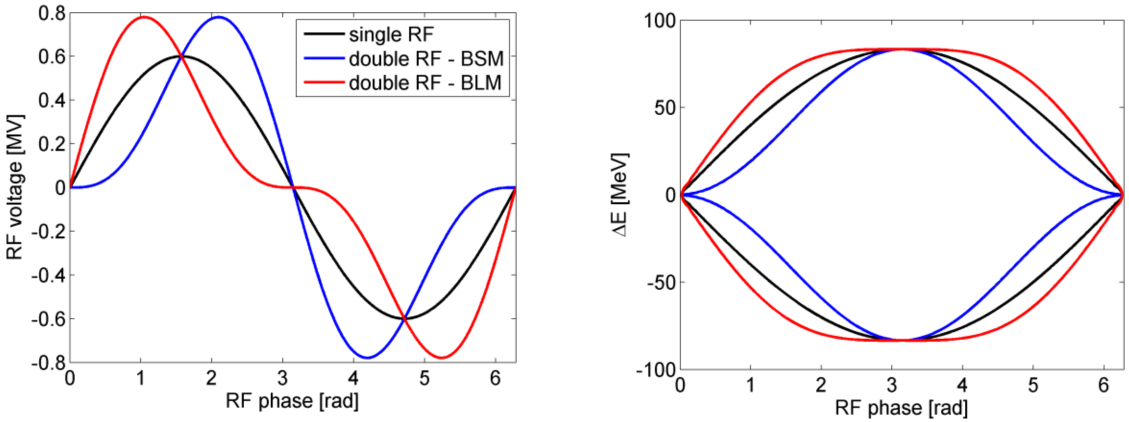
- Based on the parameters of the SPS ppbar operation

- 2 RF systems

  100 MHz – V_{100} = 0.6 MV
  200 MHz – V_{200} = 0.3 MV

  Operated in bunch lengthening mode above transition

$$V_{rf}(\varphi) = V_{100}\sin\varphi + V_{200}\sin(2\varphi + \Delta\varphi), \qquad \Delta\varphi = 0$$



- Injection at 26 GeV/c

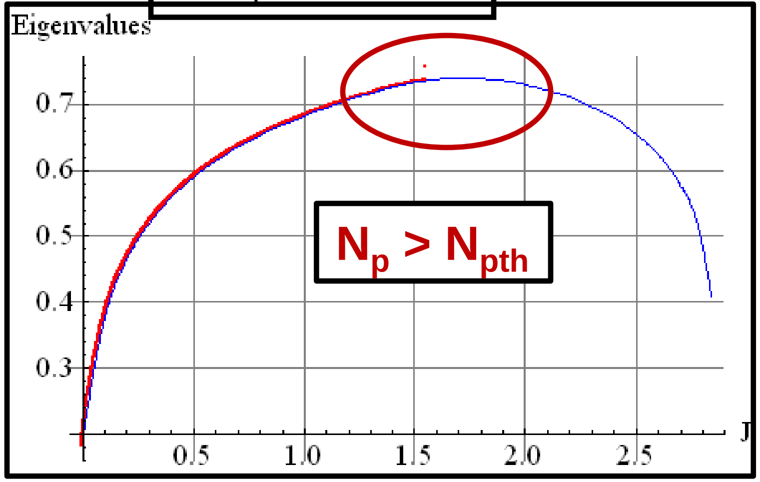
- Particle distribution $F(I) \sim (I_{lim} - I)^2$

SPS ppbar observations

Results for BLM

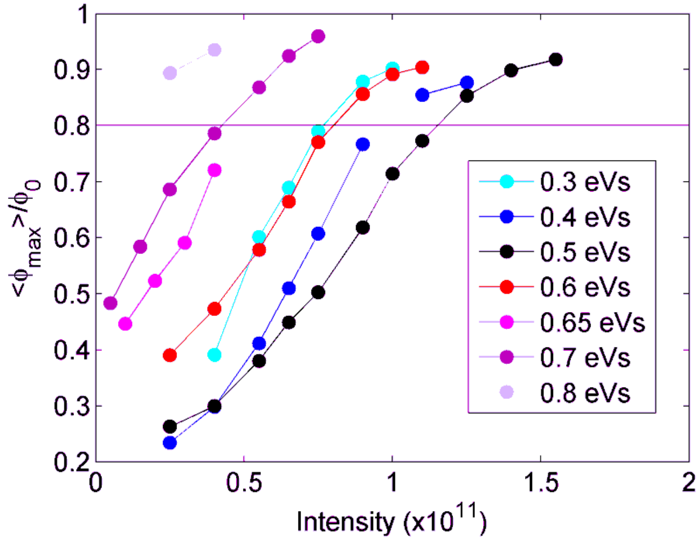
- ☐ All calculations and simulations for inductive impedance Z/n = 5 Ohms

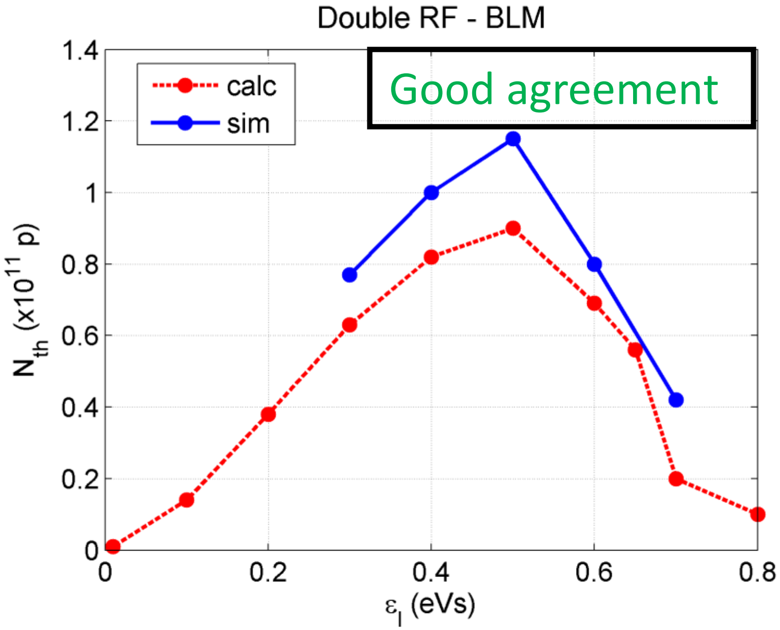
Example calculation



$N_p > N_{pth}$

Results from simulations





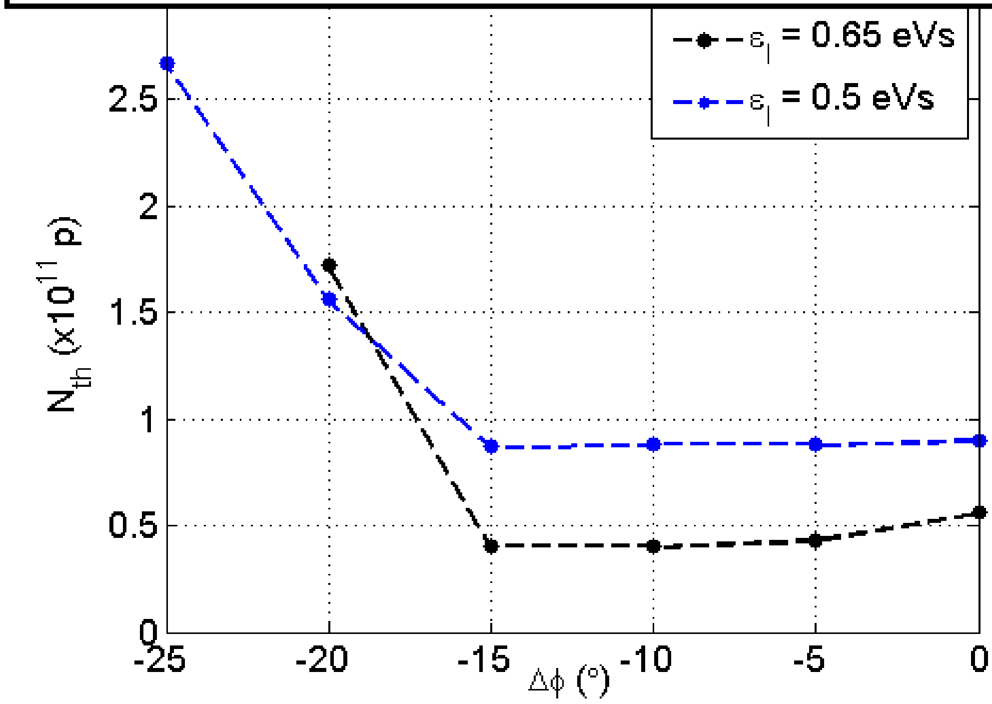
Good agreement

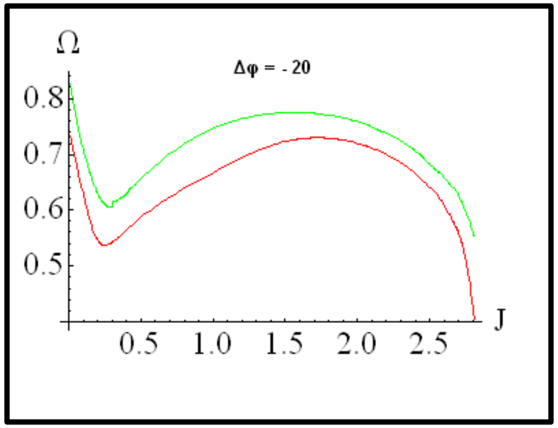
- N_{th} increases until a critical value of ε_l (>0.5 eVs)
- After that the threshold is decreasing
- This critical value is very close to the region where $\omega_s'(J) = 0$

Results for BLM

☐ Programme the phase between the 2 RF system

calculated threshold versus the phase shift between the 2 RFs



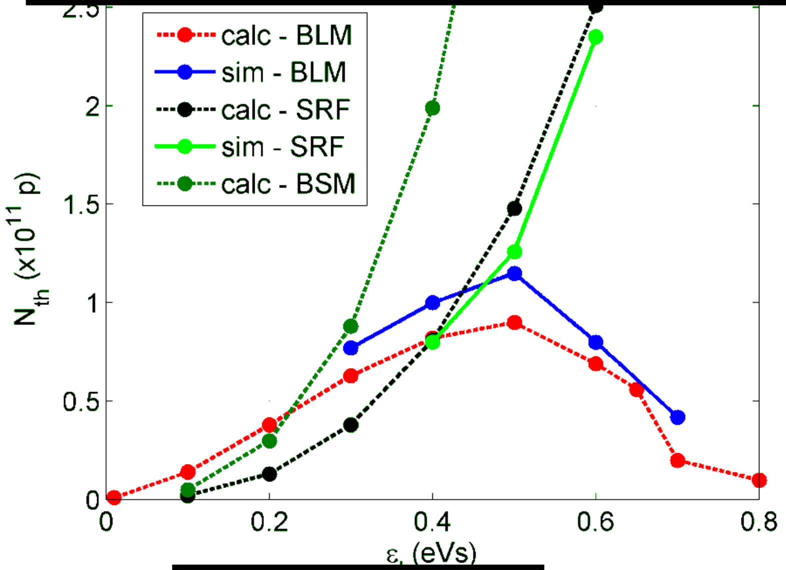


Simulations and calculations confirm observations in the SPS during ppbar

- **Unstable** bunches with emittance > 0.65 eVs
- Can be stabilized in BL-mode by some phase shift

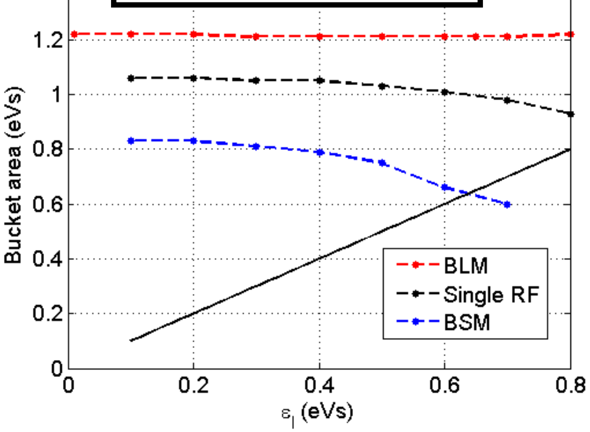
Results for Single and Double RF

Loss of Landau damping thresholds versus ε_l

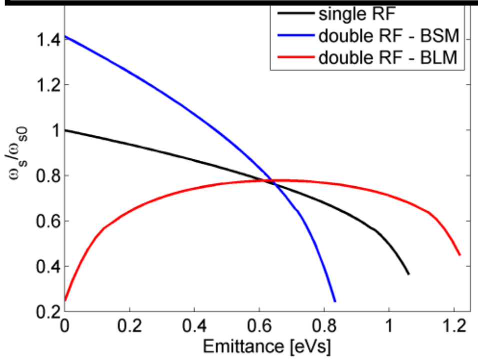


- Single RF and Double RF in BSM: monotonic behavior of f_s → threshold increases with the emittance (more $\Delta f_s/f$)
- Very high thresholds are applicable only for low emittances due to limited bucket area

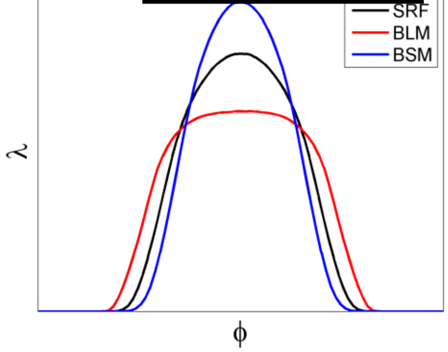
Bucket area for N_{th}



f_s distribution inside the bunch

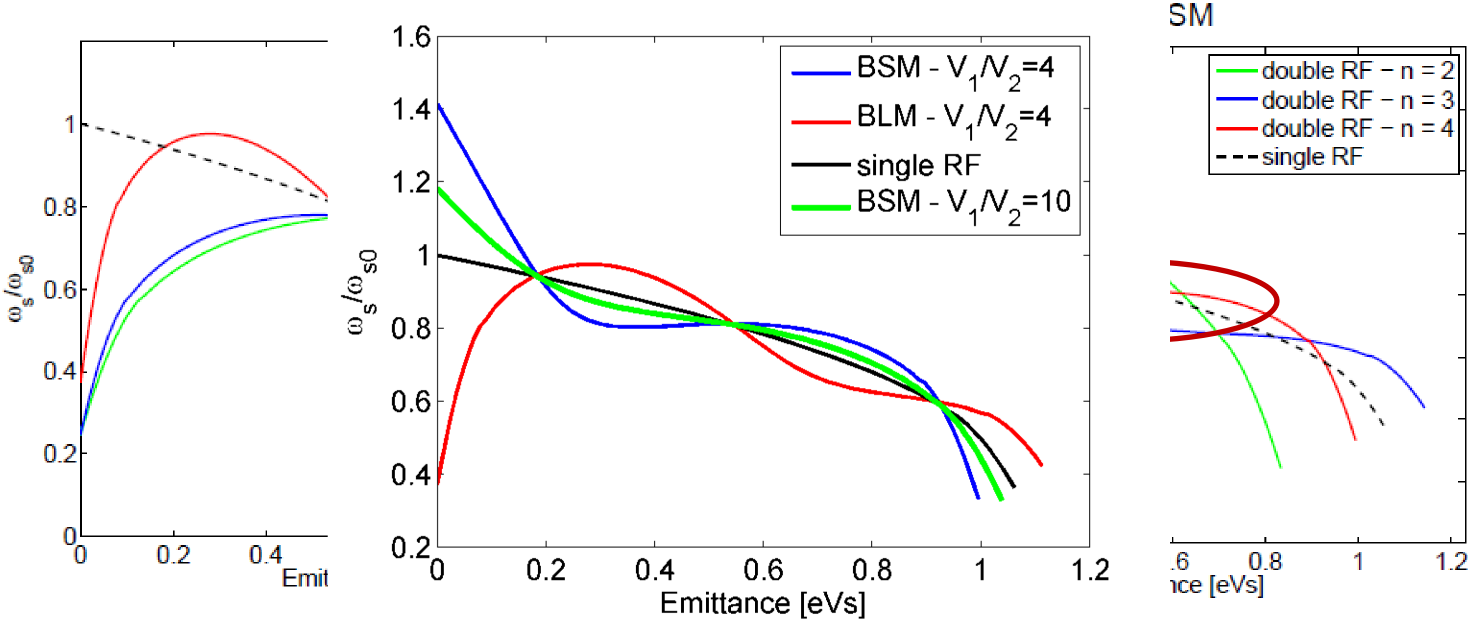


Line densities



Effects of the f_s

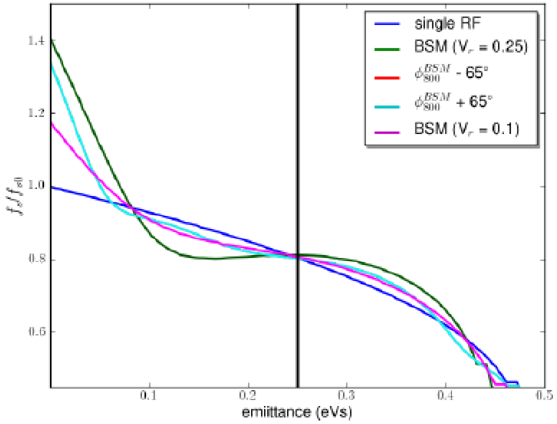
f_s distribution inside the bunch for different $n=h_2/h_1$ and $V_1/V_2 = n$



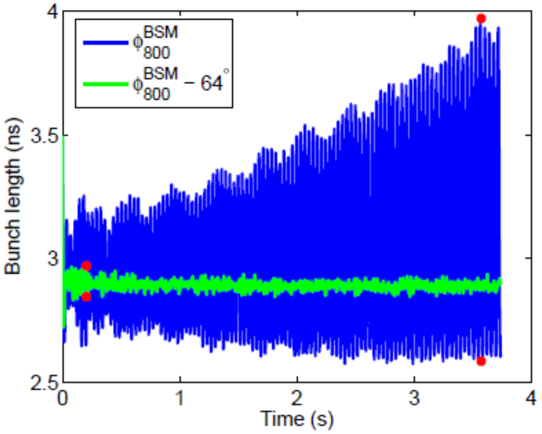
- Higher is n larger is spread for the same voltage ratio ($V_1/ V_2 = n$) but a region with zero derivative is closer to the bunch center
  - BLM: limitation to the bunch length (emittance)
  - BSM: limitation to the voltage ratio or bunch length

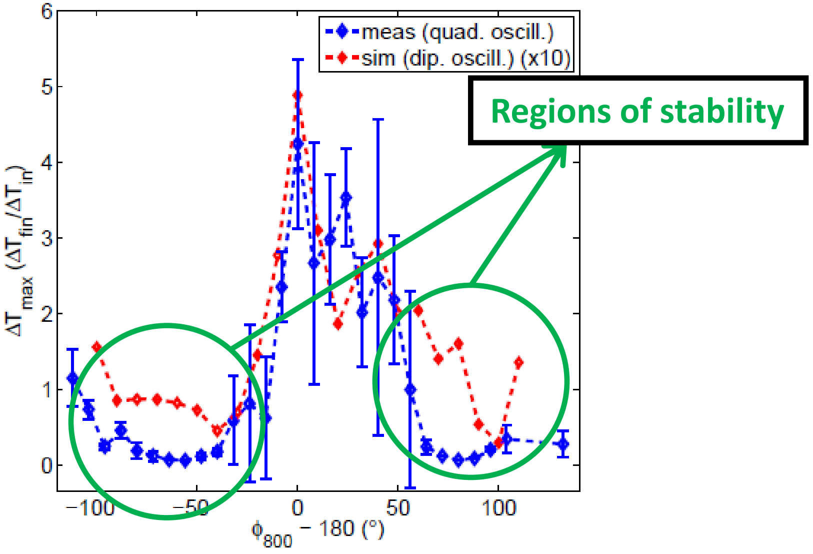
- **Now SPS has n=4** (red curves) with injected (LHC beam) emittances **> 0.35 eVs** → always unstable in BLM → operates in BSM with $V_1/ V_2 = 10$

SPS today – single bunch studies



- With V_1 / V_2 = 10 the f_s distribution is again monotonic
- Still much more Landau damping than in the single RF case





- Very good agreement between measurements and simulations (ESME) (**with the SPS impedance model**):
  - single bunches are unstable in BS-mode with V_1 / V_2 = 4
  - can be stabilised by significant phase shift of 800 MHz RF (IPAC12)

Conclusions

- ☐ The **synchrotron frequency distribution** inside the bunch is important for stability: provides the frequency spread necessary for Landau damping

- ☐ But regions with $\omega_s'(I) = 0$ can have the opposite effect

- ☐ This was proved for reactive impedance and BLM by both calculations and simulations, also in agreement with observations in SPS during ppbar

- ☐ Phase shift between the two RF systems helps to damp the dipole oscillations but the f_s distribution still has a non-monotonic behavior (studies are on-going)

- ☐ In the present SPS the single bunch instabilities in BSM (V2/V1=0.25) can be also damped by shifting the phase between the 2 RF systems as have been shown in measurements and simulations.

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