Impact of broad-band impedance on longitudinal coupled-bunch instability

Ivan Karpov, CERN

Acknowledgements:

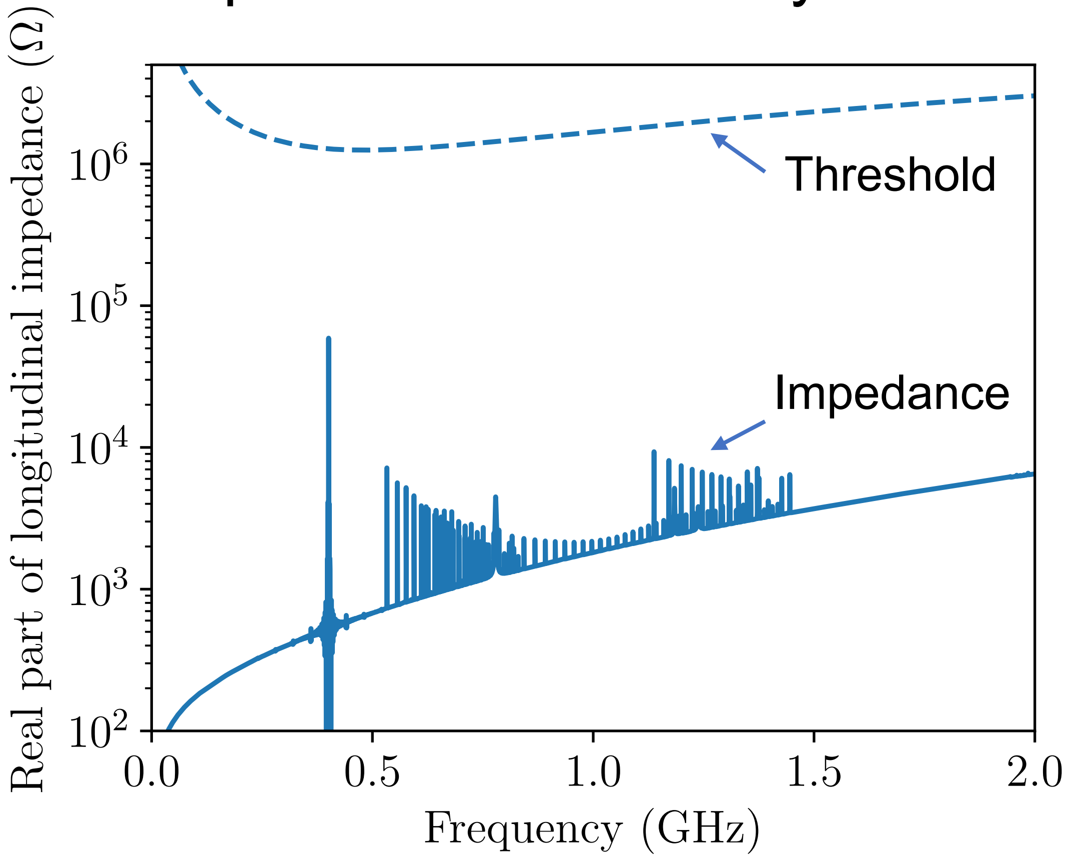
Theodoros Argyropoulos, Alexey Burov,
Rama Calaga, James A. Mitchell, Nicolas Mounet,
Sigurd Nese, Elena Shaposhnikova, and Helga Timko

the 11th HL-LHC Collaboration Meeting, CERN, 19-22 October 2021

Longitudinal stability of multi-bunch beam: LHC

- Evaluation of multi-bunch instability threshold using macro-particle simulations for ≈ 3000 bunches is computationally very expensive
- Instead, it can be analytically calculated for one narrow-band impedance (from stability diagrams of Balbekov and Ivanov using Lebedev equation)
- Coupled-bunch instabilities were not observed so far, as expected for nominal LHC beams, contrary to the loss of Landau damping (LLD) due to inductive impedance $\mathrm{Im}Z/k$ ($k = f/f_0$)

Coupled-bunch instability **LHC**



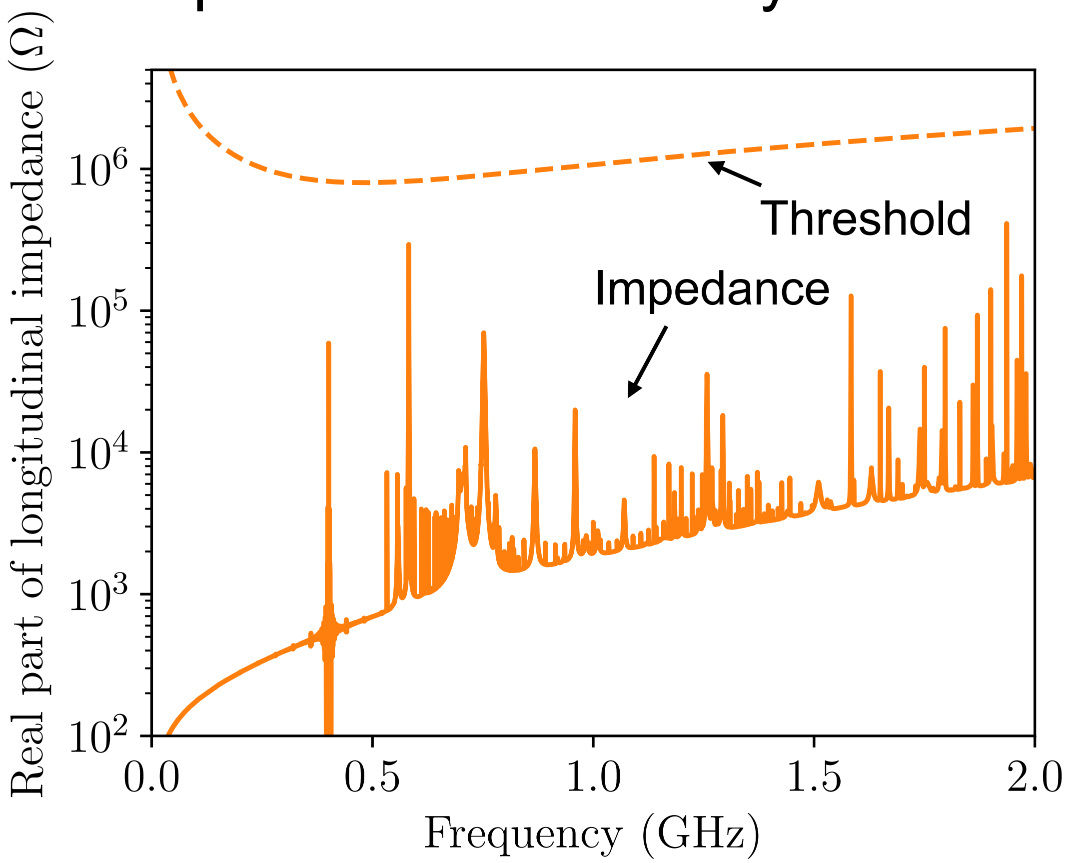
E = 450 GeV, V_{rf} = 6 MV, τ = 1.3 ns

Longitudinal stability of multi-bunch beam: HL-LHC

- For HL-LHC intensity, one higher order mode (HOM) of DQW crab cavities (CC) is only by factor of 2.7 below the CBI threshold.

→ The impact of loss of Landau damping ($\mathrm{Im}Z/k$) on the multi-bunch instability threshold can be critical

Coupled-bunch instability **HL-LHC**



E = 450 GeV, V_{rf} = 8 MV, τ = 1.3 ns

Loss of Landau damping in LHC
Single bunch

LLD threshold is *(IK, TA, ES, PRAB 2021)*

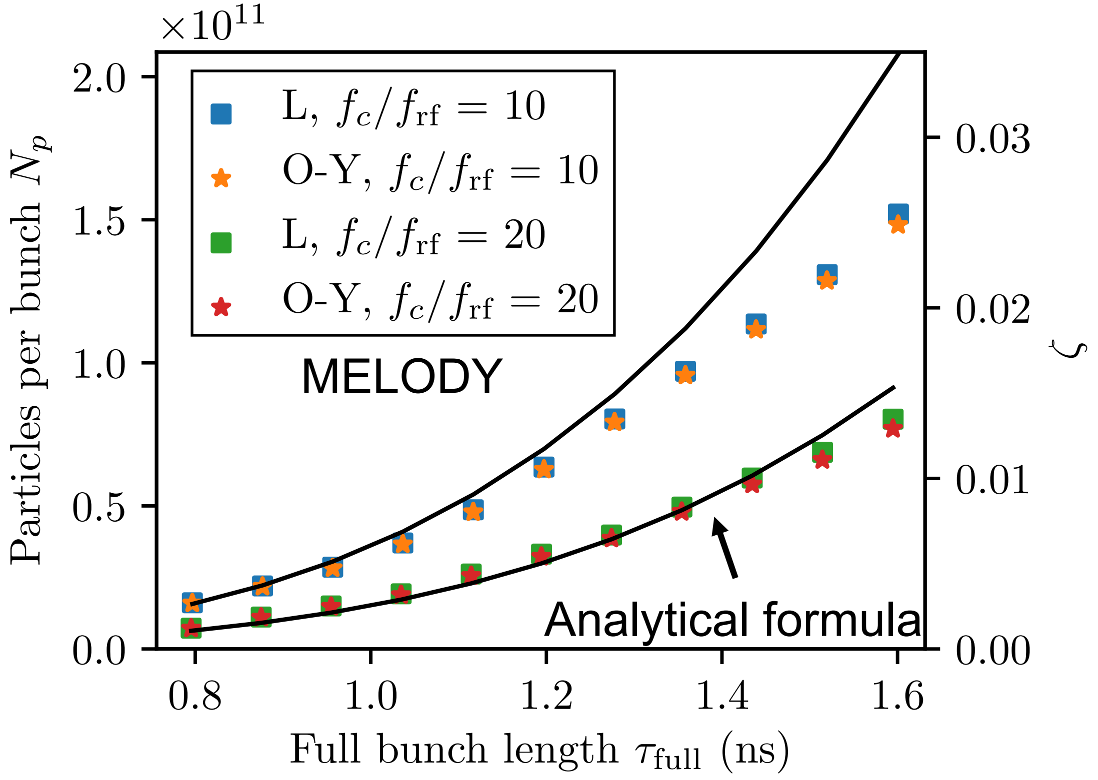
$$N_{\mathrm{th}} \propto \frac{V_{\mathrm{rf}}\tau^4}{f_c\,(\mathrm{Im}Z/k)_{\mathrm{eff}}}$$

- Effective impedance $(\mathrm{Im}Z/k)_{\mathrm{eff}}$ can be computed for arbitrary impedance model
- Knowledge of effective cutoff frequency f_c is crucial
- Dependence on bunch length τ in 4$^{\mathrm{th}}$ power

Results agree with semi analytical calculations using code MELODY*

**Matrix Equations for LOngitudinal beam DYnamics*

LLD threshold for in **LHC**



$E = 450$ GeV, V_{rf} = 6 MV, $\mu = 2$, $(\mathrm{Im}Z/k)_{\mathrm{eff}}$ = 0.07 Ω

Loss of Landau damping in LHC
Single bunch

LLD threshold is *(IK, TA, ES, PRAB 2021)*

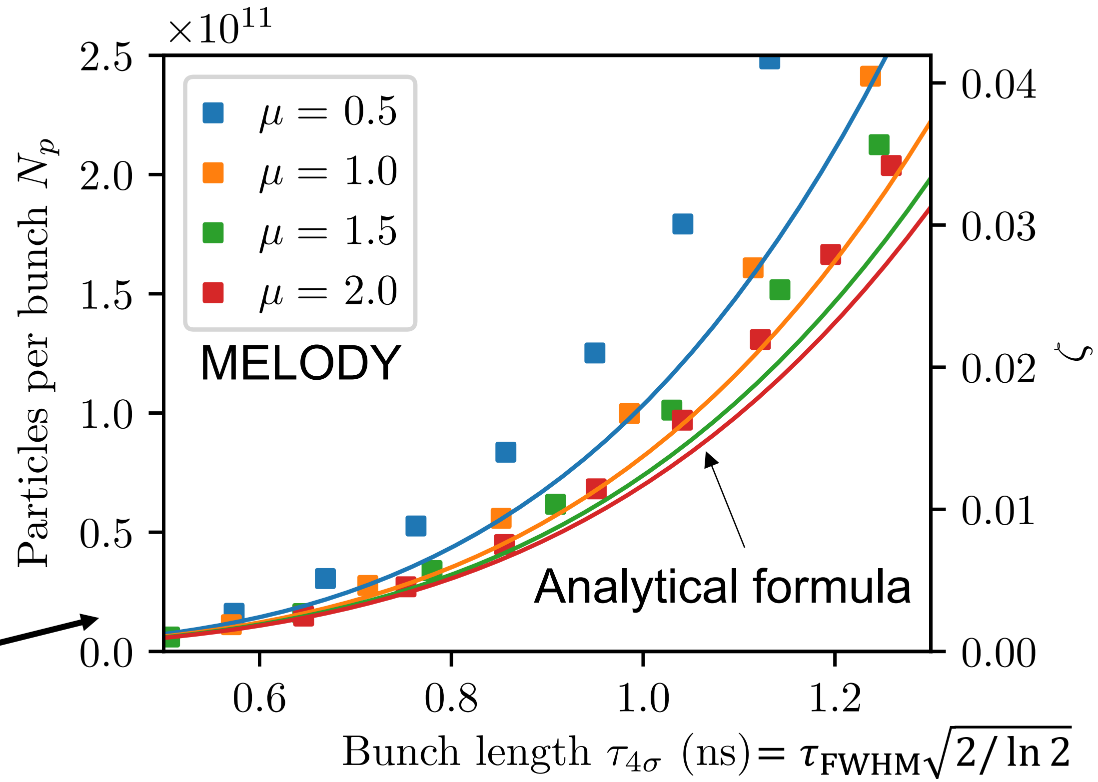
$$N_{\text{th}} \propto \frac{V_{\text{rf}}\tau^4}{f_c\,(\text{Im}Z/k)_{\text{eff}}}$$

- Effective impedance $(\text{Im}Z/k)_{\text{eff}}$ can be computed for arbitrary impedance model
- Knowledge of effective cutoff frequency f_c is crucial
- Dependence on bunch length τ in 4th power

Results agree with semi analytical calculations using code MELODY*

**Matrix Equations for LOngitudinal beam DYnamics*

LLD threshold in **LHC** for different distributions (μ)



E = 450 GeV, V_{rf} = 6 MV,
$(\text{Im}Z/k)_{\text{eff}}$ = 0.07 Ω, f_c = 4 GHz

HL-LHC impedance model and $(\mathrm{Im}Z/k)_{\mathrm{eff}}$

Model from May 2020 (*N. Mounet)* with broad-band (BB) resonator impedance at $f_r = 5$ GHz

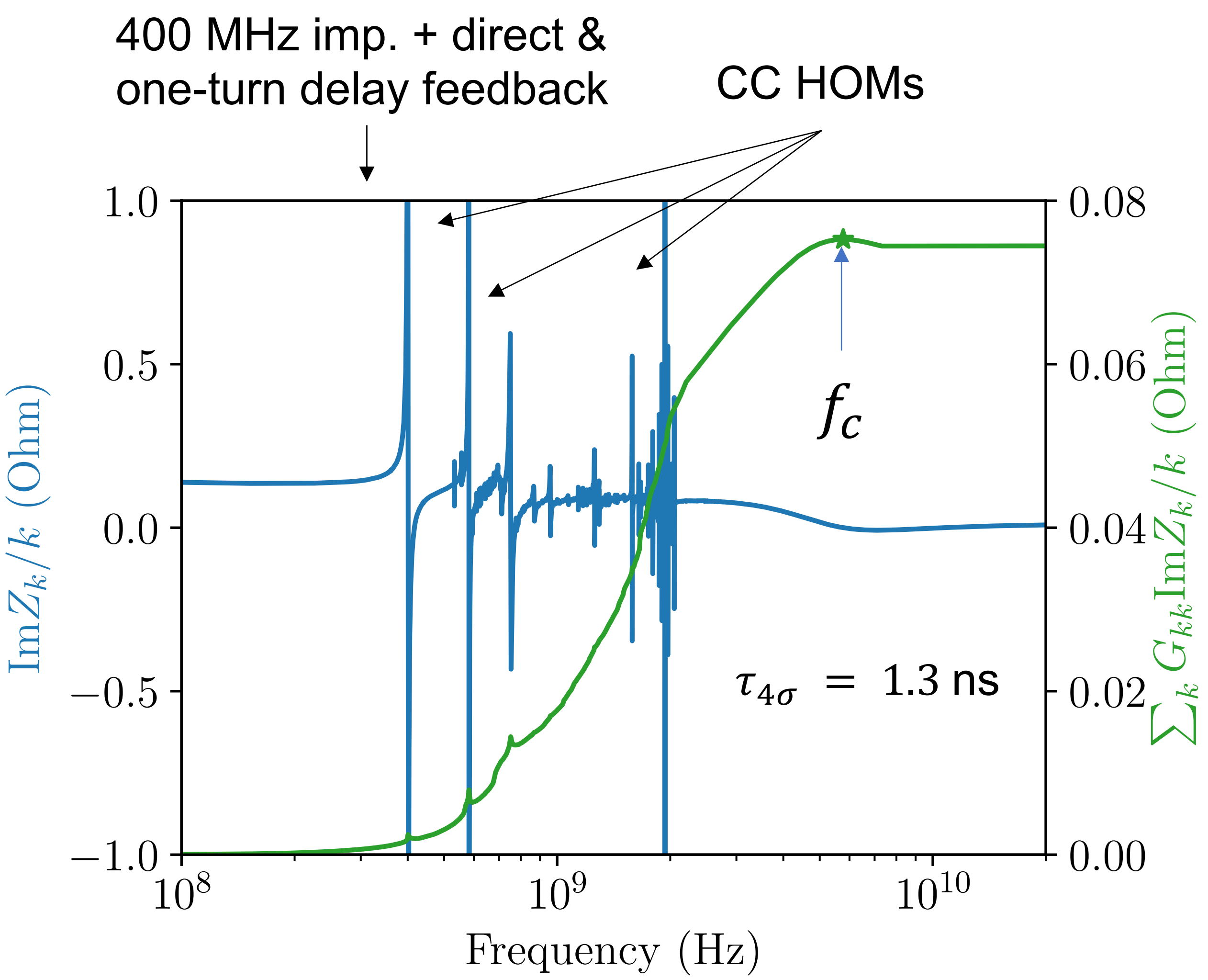
Effective impedance

$$(\mathrm{Im}Z/k)_{\mathrm{eff}} = \frac{\sum_{k=1}^{k_c} G_{kk}\mathrm{Im}(Z_k/k)}{\sum_{k=1}^{k_c} G_{kk}}$$

$$G_{kk} = \frac{1}{2} - J_0^2(y) - J_1^2(y) + \frac{J_0(y)J_1(y)}{y},\ y = \pi k f_0 \tau$$

The maximum of nominator is reached at $k_c = f_c/f_0$ *(S. Nese, 2021)*

→ For 4σ bunch length of about 1.3 ns $(\mathrm{Im}Z/k)_{\mathrm{eff}} \approx 0.075$ Ohm, $f_c \approx$ 5.8 GHz



Threshold reduction due to BBR impedance

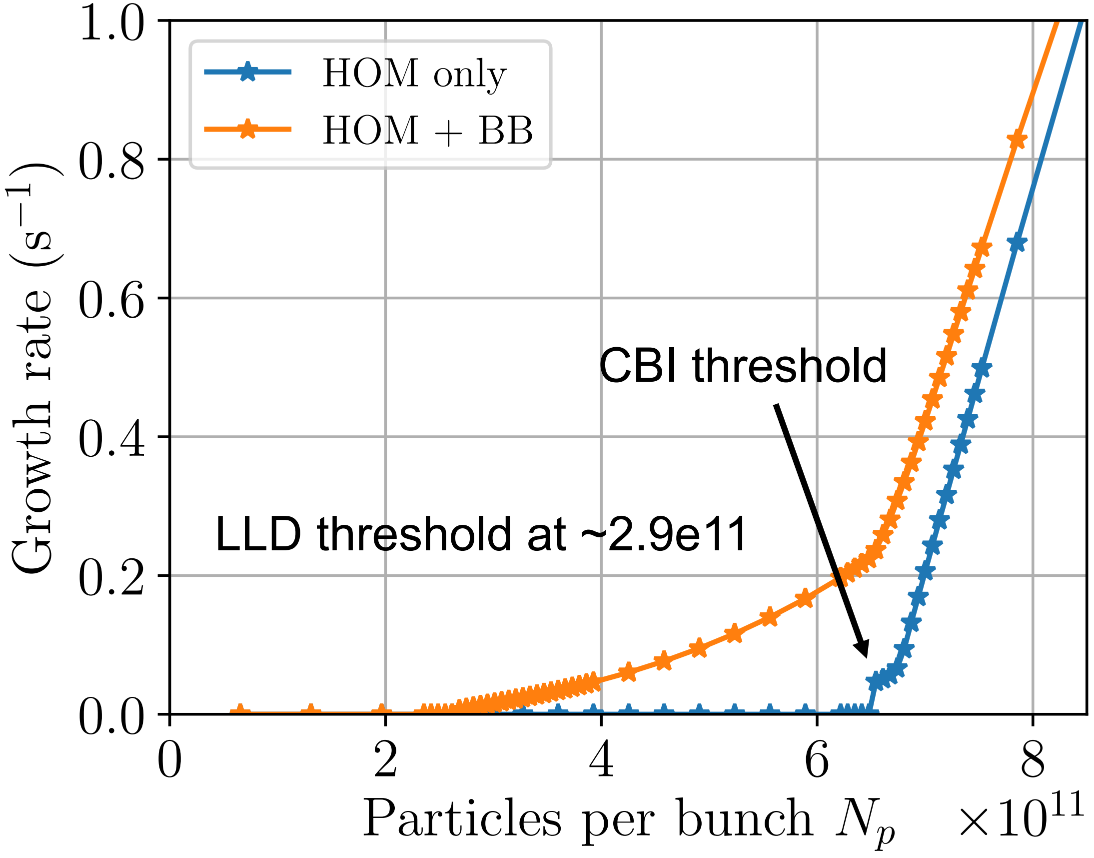
MELODY has been extended to multi-bunch case (using extended Oide-Yokoya method)

Results for broad-band $(\mathrm{Im}Z/k)_{\mathrm{eff}} \approx 0.075\ \Omega$ + narrow-band ($R_{\mathrm{sh}} = 4\times71\ \mathrm{k\Omega}$, f_r = 582 MHz) resonators

→ For this HOM, the CBI threshold is about ~3 higher than HL-LHC intensity

→ In the presence of BB impedance, the CBI threshold is reduced at ~ LLD threshold

Coupled-bunch instability in **HL-LHC**

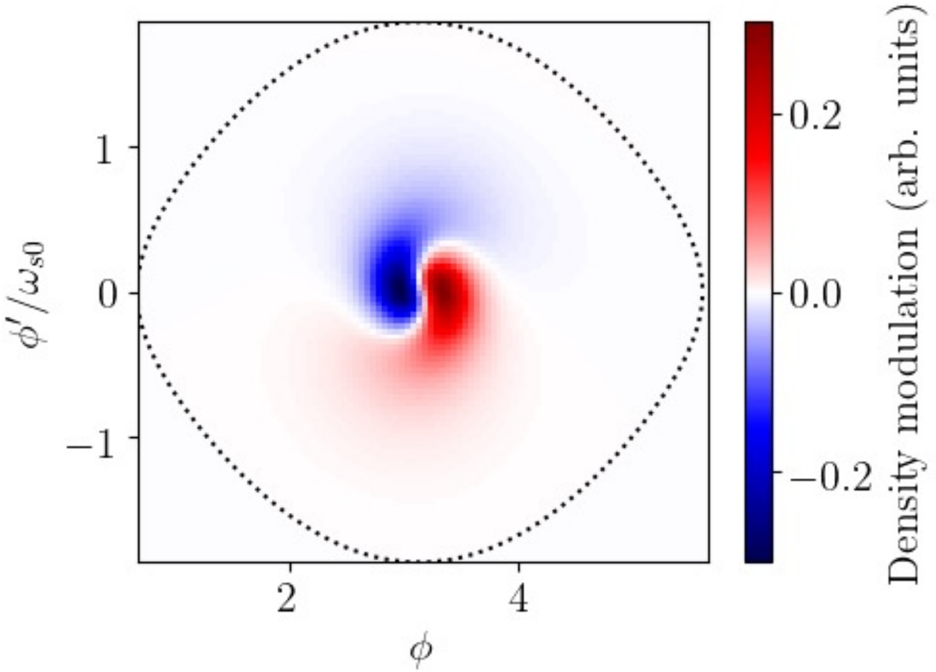


E = 450 GeV, V_{rf} = 8 MV, $\mu = 2, \tau_{4\sigma} \approx 1.3$ ns

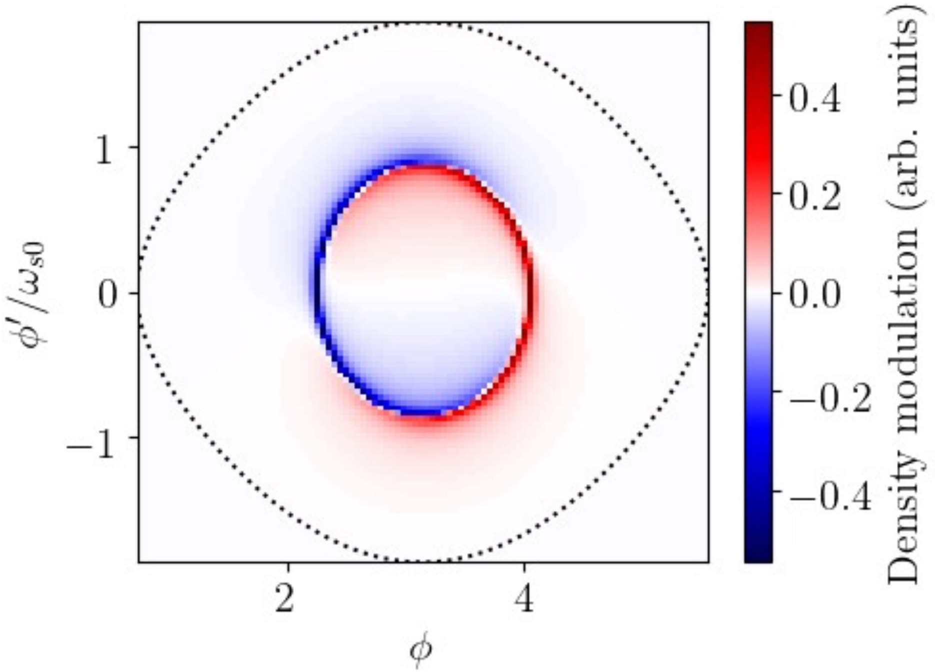
Types of coupled-bunch instability

It was expected that multi-turn or CB wake can make LLD mode unstable *(Y.H. Chin, et al, 1982)*

Mode structure BB + HOM, growth rate ~0.13 1/s



Mode structure HOM only, growth rate ~0.13 1/s

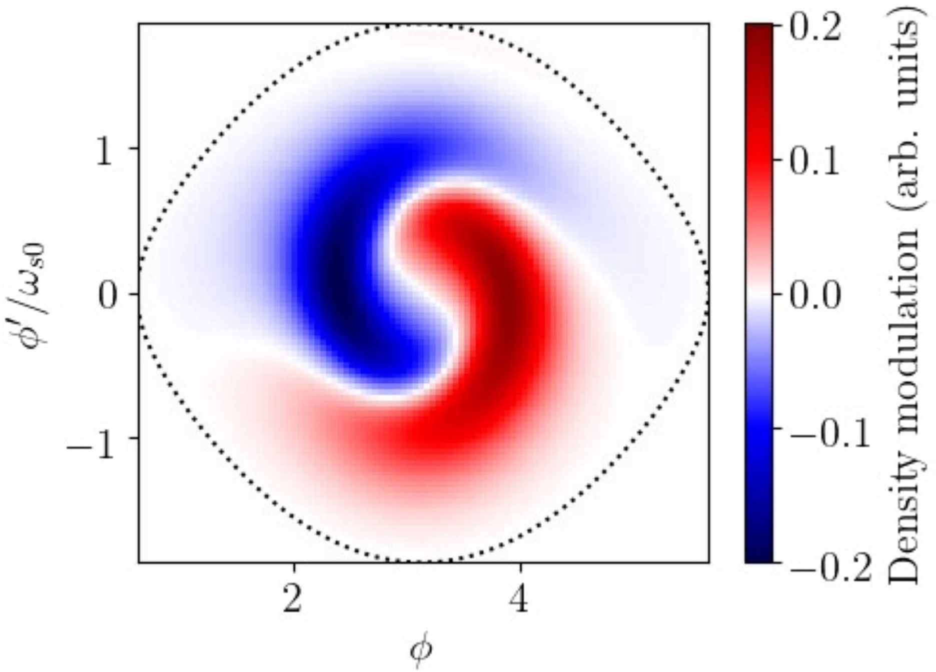


→ In presence of broad-band impedance and small growth rate, unstable mode is localized in bunch center (LLD type), which is different from the case of HOM alone

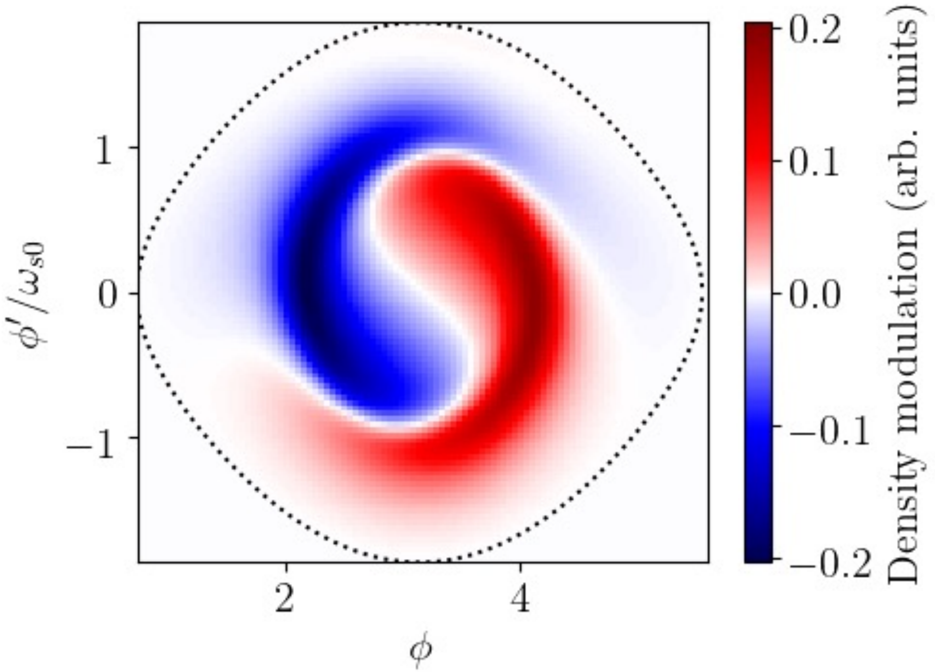
Types coupled-bunch instability

It was expected that multi-turn or CB wake can make LLD mode unstable *(Y.H. Chin, et al, 1982)*

Mode structure BB + HOM, growth rate ~0.4 1/s



Mode structure HOM only, growth rate ~0.4 1/s



→ At significantly higher intensity, the most unstable modes look similar with and w/o BB impedance, as they both pure CBI modes

Possible cures

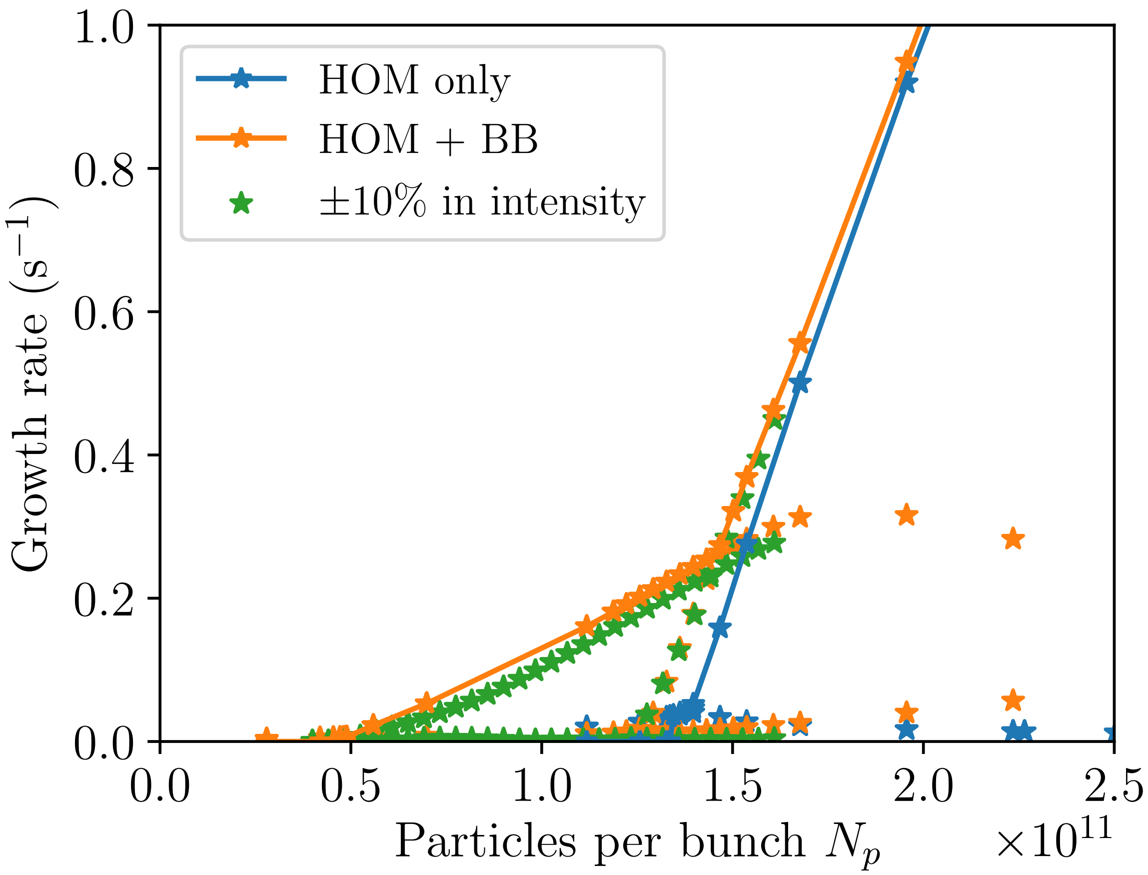
We are close to the threshold without margin

- Coupled-bunch feedback system?
- 2[nd] harmonic RF system → increase LLD threshold and CBI threshold
- Synchrotron frequency variation due to Bunch-by-bunch parameter variation (bad for luminosity, but unavoidable) and transient beam loading can help to suppress LLD type instability

MELODY was extended to treat individual bunches using a single matrix (dimensions depend on number of bunches)

→ Some reduction of growth rates is observed for a toy model (9 bunches)

Example for short bunches of ~0.8 ns



Possible cures

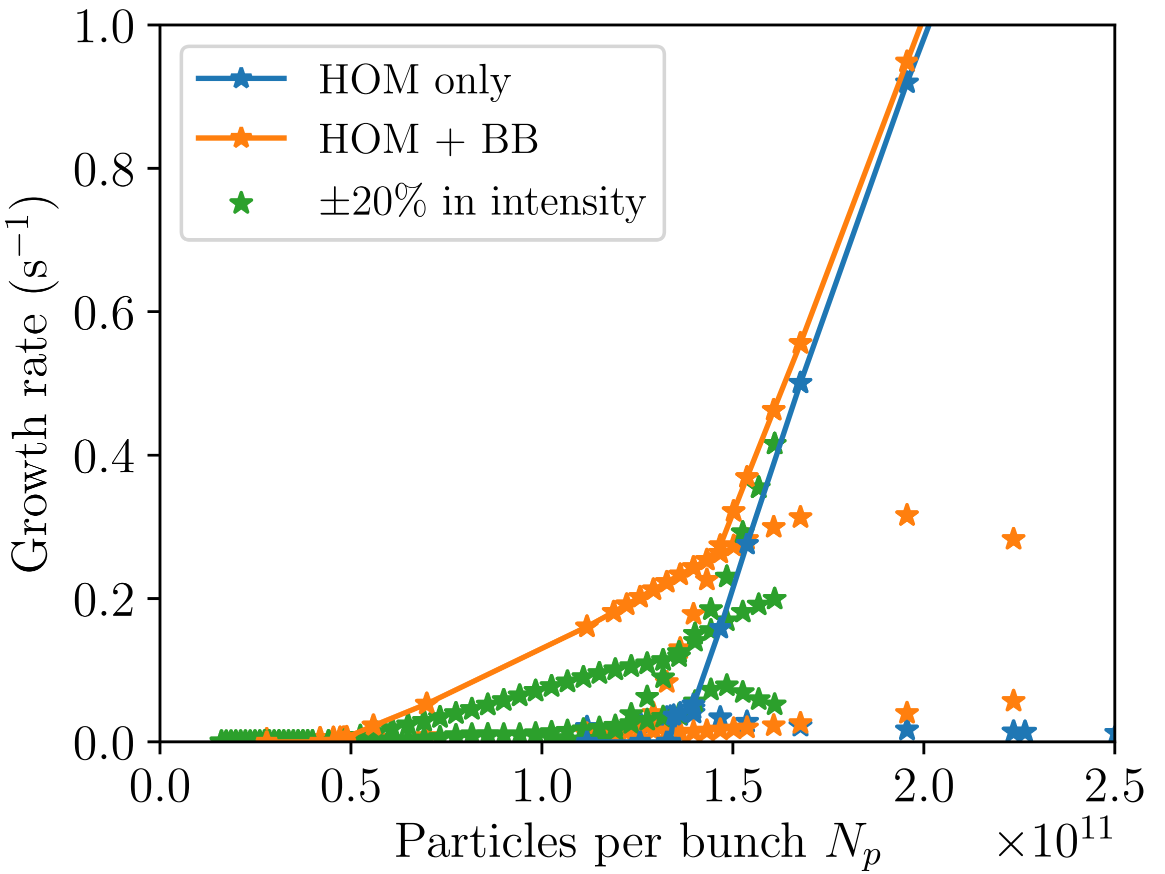
We are close to the threshold without margin

- Coupled-bunch feedback system?
- 2nd harmonic RF system → increase LLD threshold and CBI threshold
- Synchrotron frequency variation due to Bunch-by-bunch parameter variation (bad for luminosity, but unavoidable) and transient beam loading can help to suppress LLD type instability

MELODY was extended to treat individual bunches using a single matrix (dimensions depend on number of bunches)

→ Some reduction of growth rates is observed for a toy model (9 bunches)

Example for short bunches of ~0.8 ns



Summary

Loss of Landau damping was observed for short bunches injected into the LHC indicating that we are close to the threshold

Coupled-bunch instabilities due to HOMs were neither observed for nominal parameters, nor expected for HL-LHC (HOMs of CCs are at least ~3 below threshold)

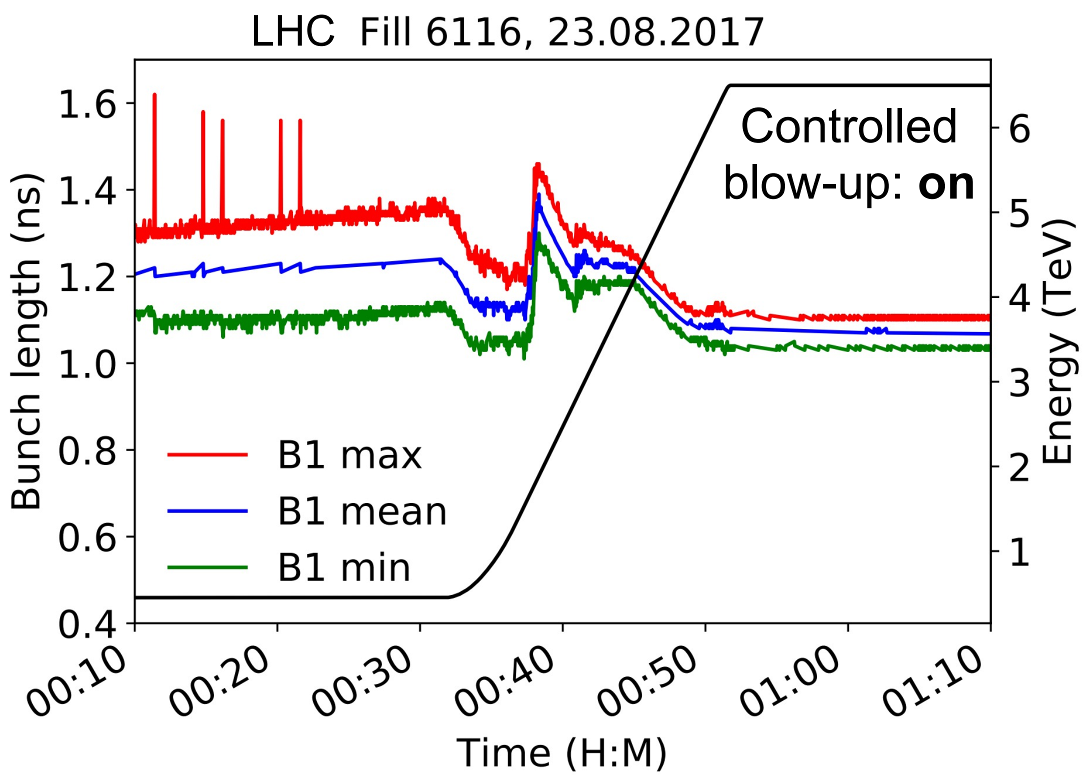
The coupled-bunch instability threshold is decreased in the presence of broad-band inductive impedance and another type of instability is observed

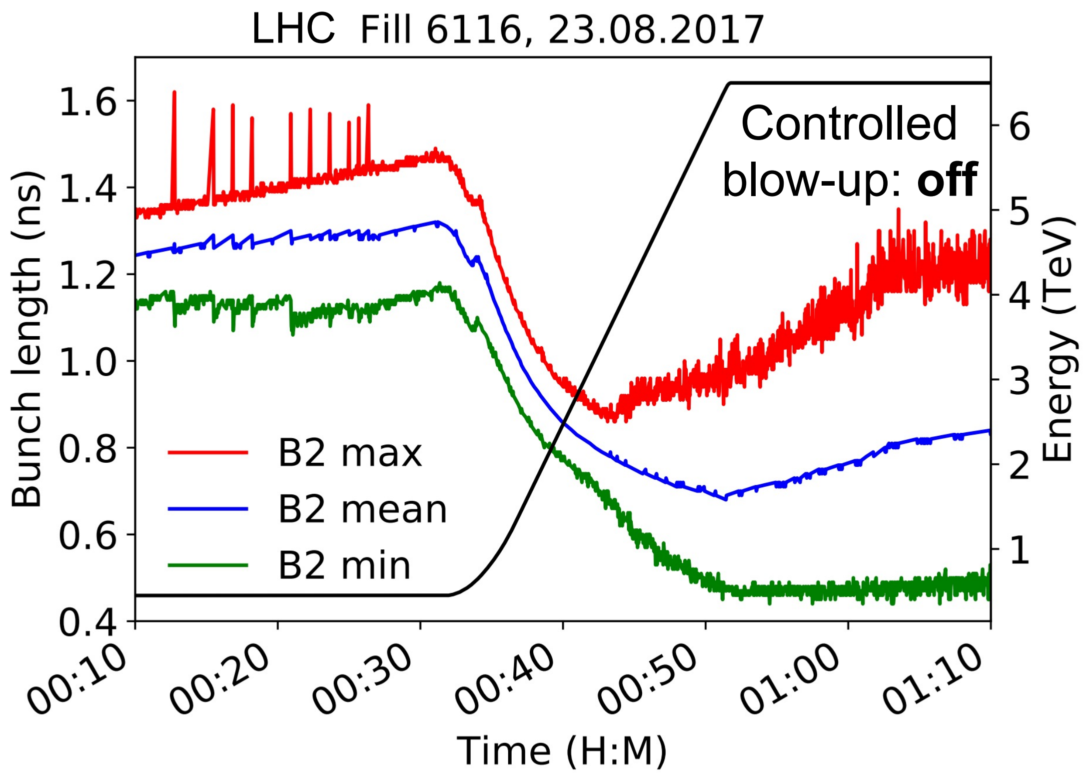
Possible cure of this instability is a natural spread of bunch-by-bunch parameters or increase of the LLD threshold by using 2^{nd} harmonic rf system

Thank you for your attention!

Spare slides

Longitudinal single-bunch stability

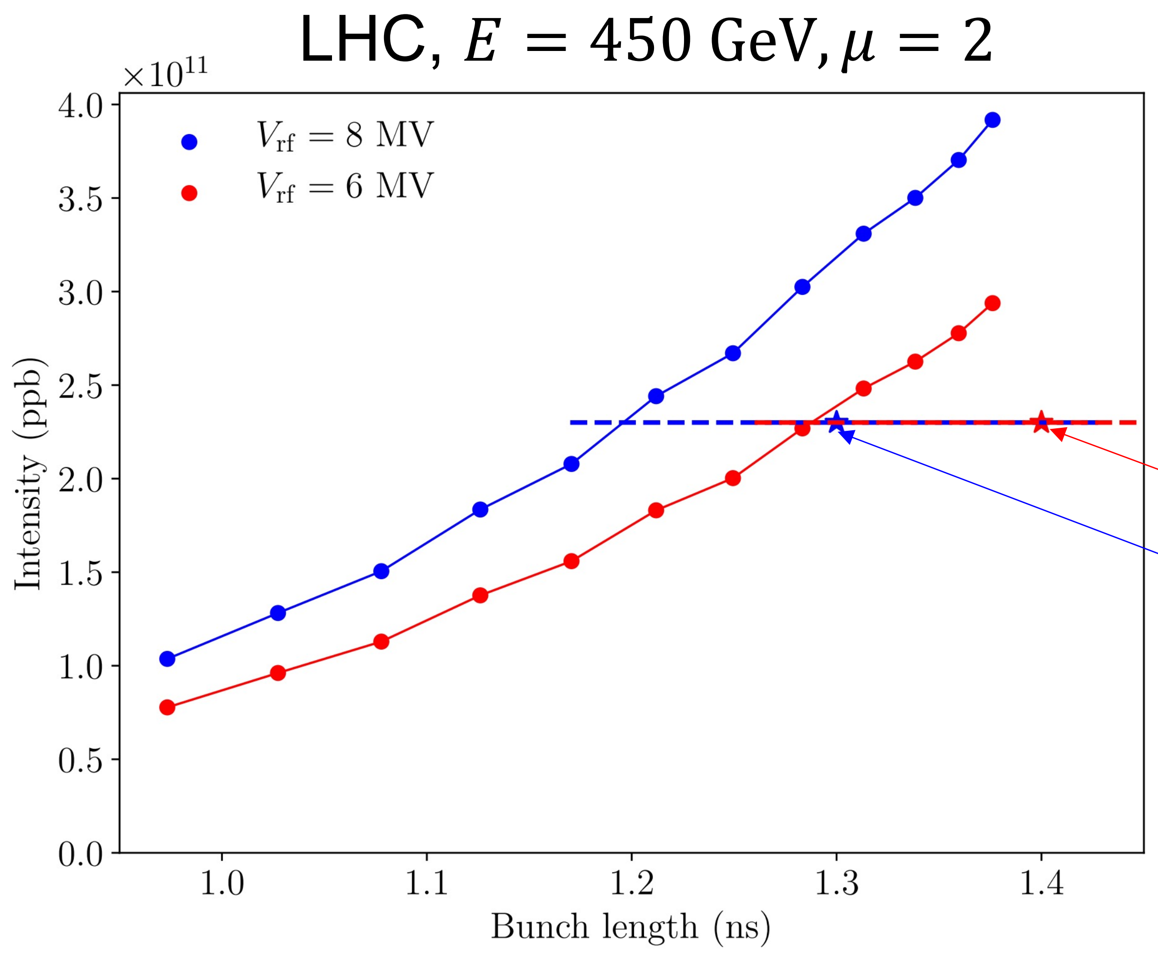




Bunch length shrinks during acceleration
→ Controlled blow-up must be applied to keep beam stable

*$\tau = \tau_{\mathrm{FWHM}}\sqrt{2/\ln 2}$ is scaled from full-width half-maximum (FWHM) bunch length

Single-bunch stability at 450 GeV



Results using MELODY for smoothed impedance (resistive wall + broad-band model at 5 GHz)

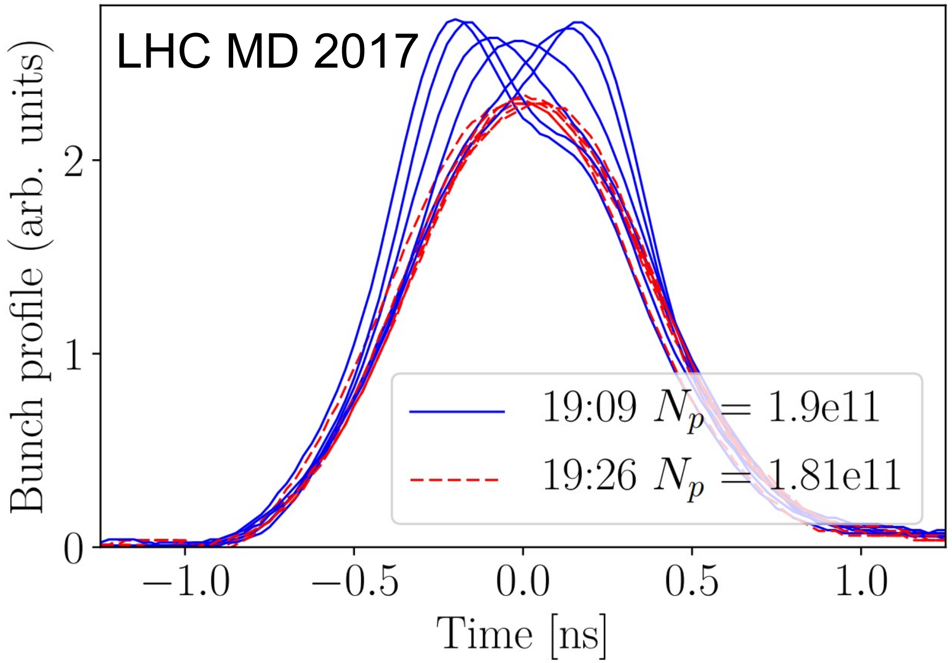
For LIU bunch from SPS (1.65 ns, 10MV@200MHz + 1.6 MV@800 MHz), bunch length in LHC (in absence of injection errors):

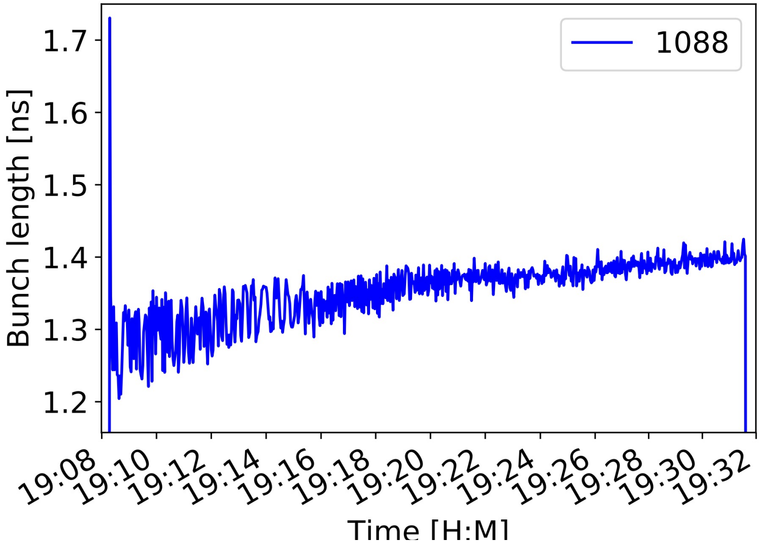
- 1.4 ns for 6 MV (LHC nominal 2017)
- 1.3 ns for 8 MV (HL-LHC design report)

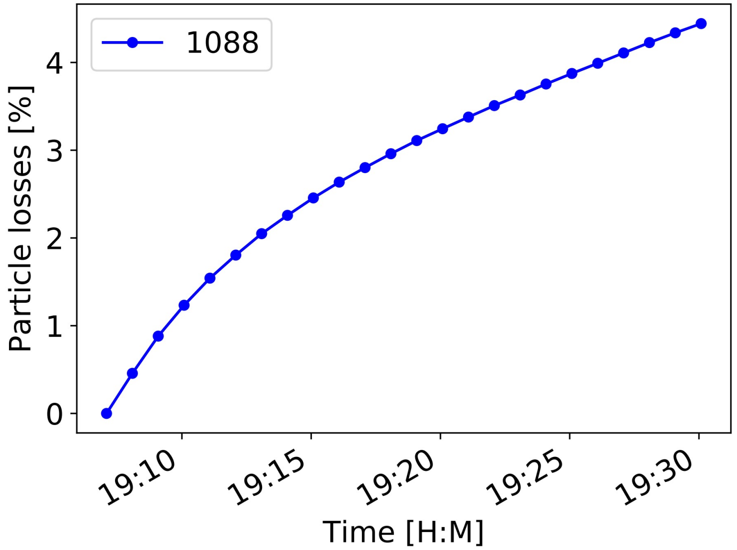
Two voltages $V_{\rm rf}$ provide similar single-bunch stability

There are constrains due to injection losses and rf power consumption *(see talk of H. Timko)*

Persistent oscillations after injection





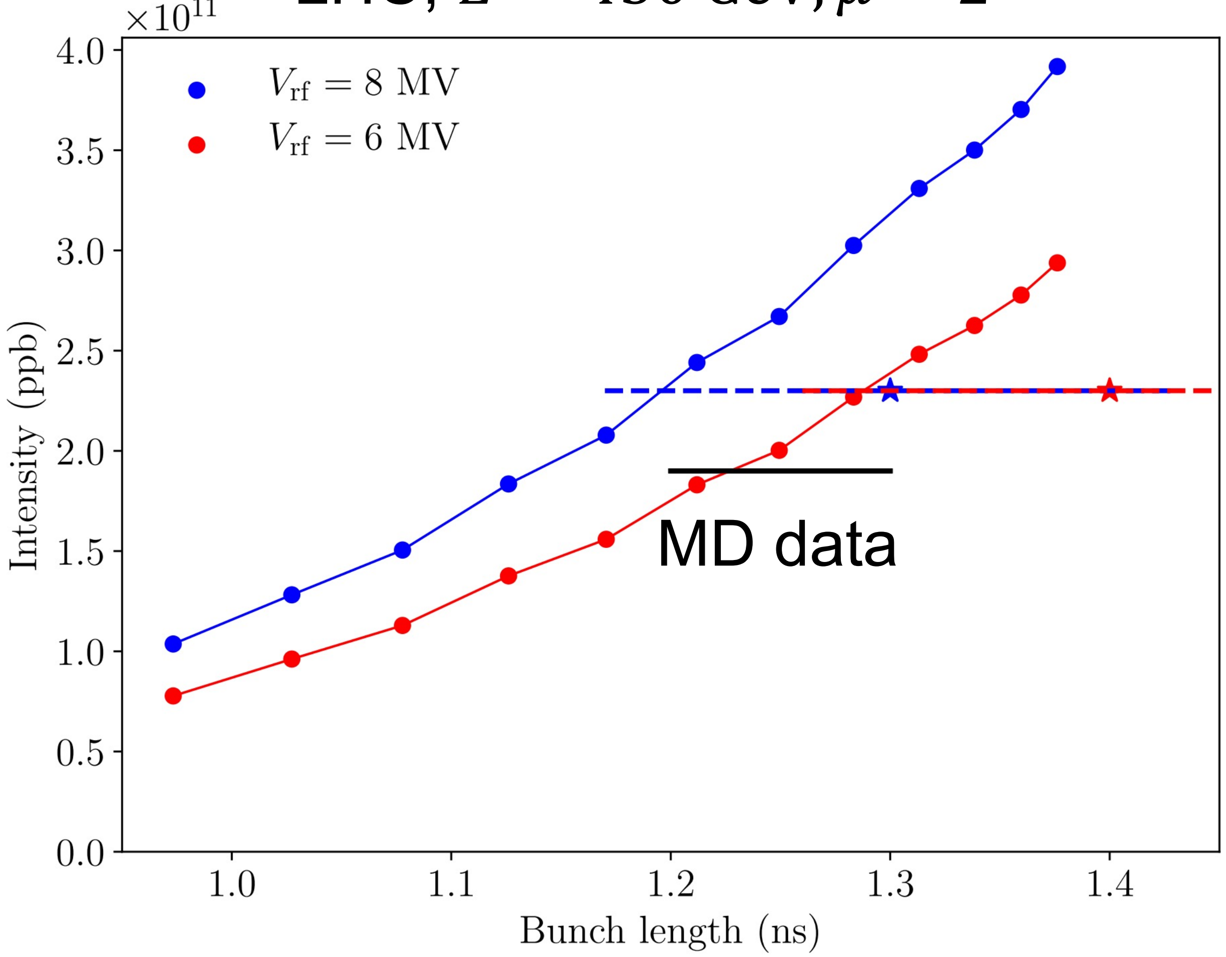


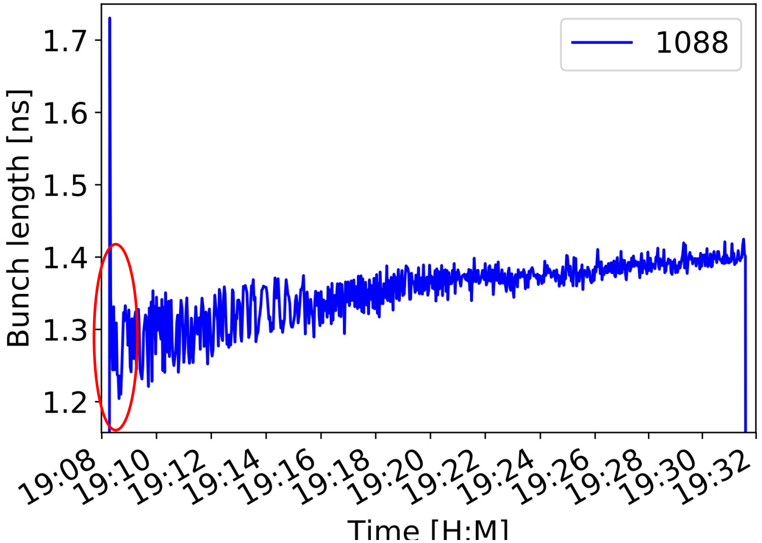
During 20 min oscillations lead to ~10 % bunch lengthening and ~5% particle loss *(H. Timko et al., HB2018)*

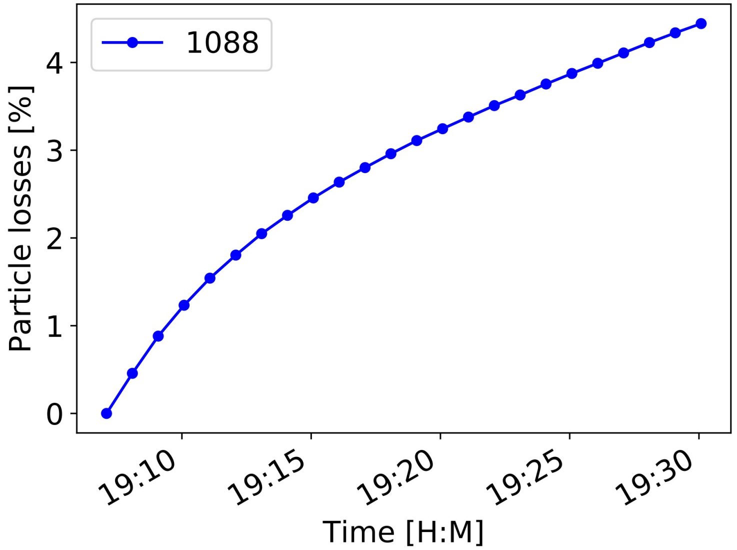
Similar oscillations were observed in Tevatron (*R. Moore, PAC2003*)

Persistent oscillations after injection

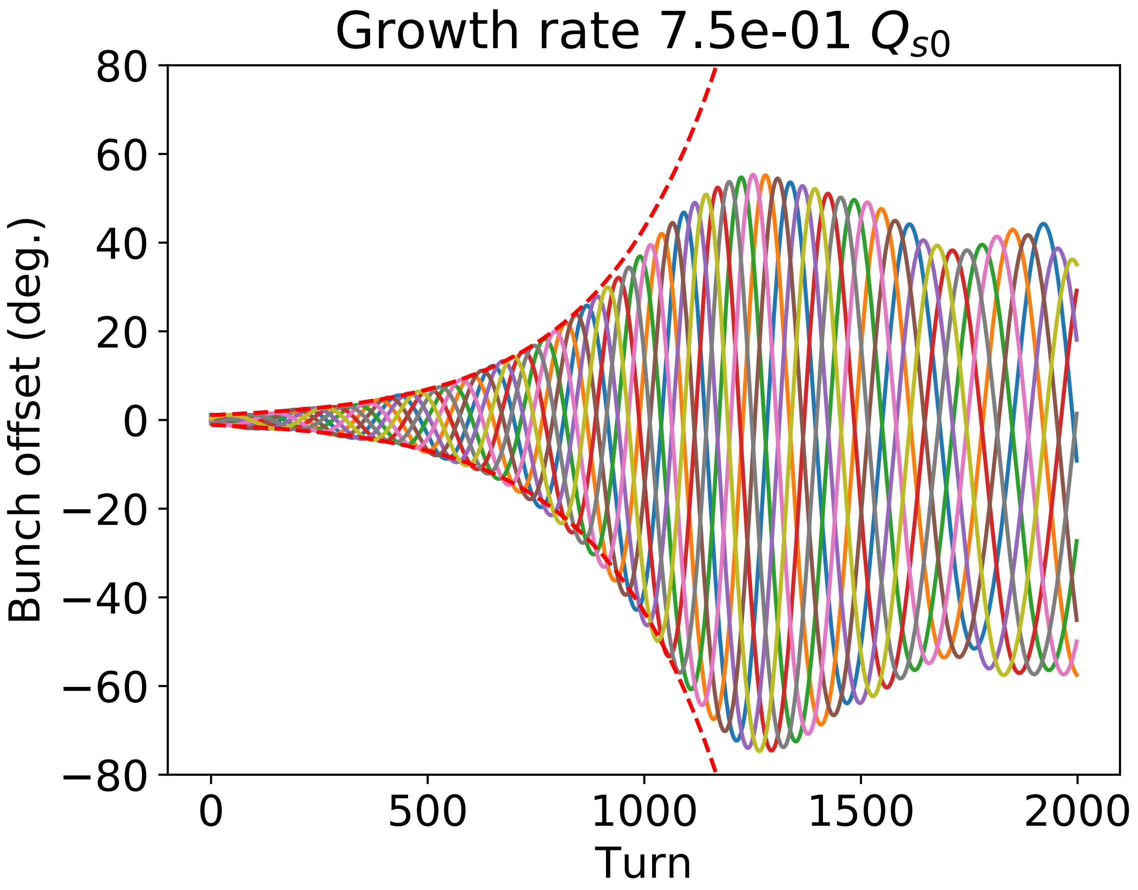
LHC, $E = 450\ \mathrm{GeV}, \mu = 2$





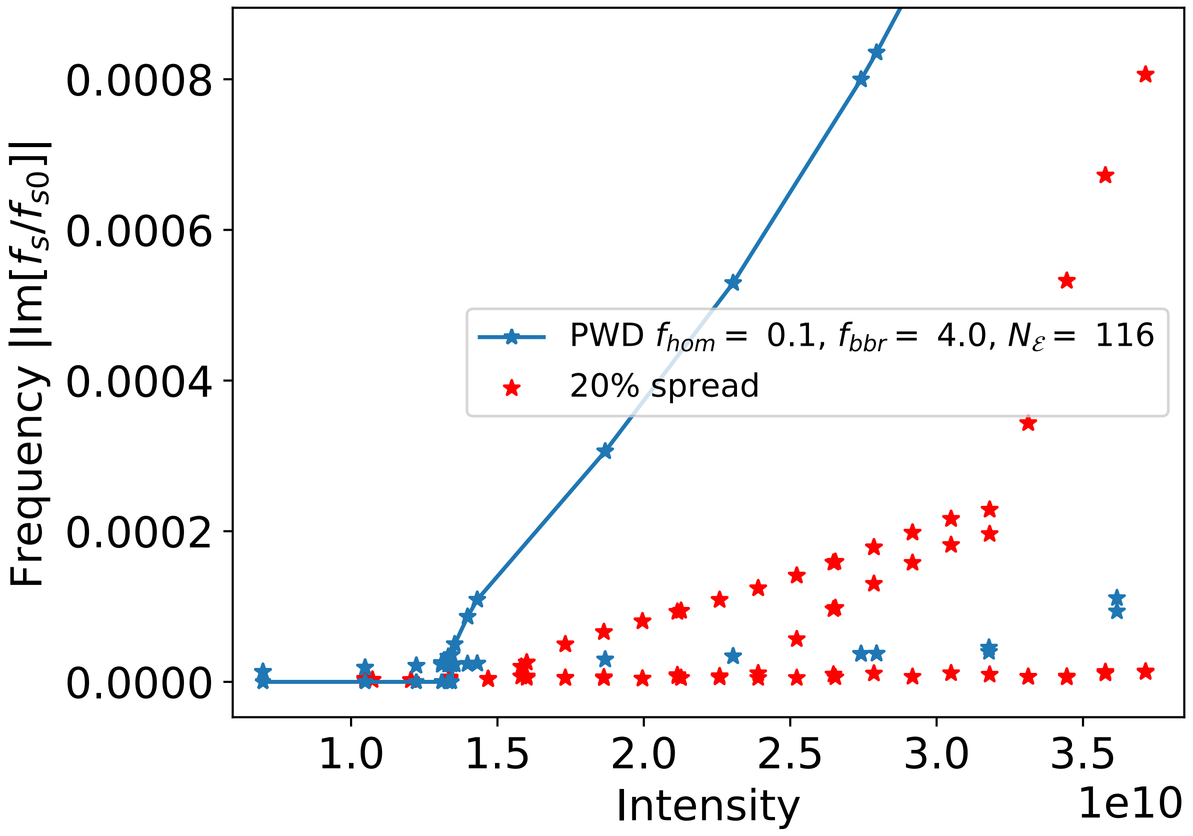


MELODY vs BLonD



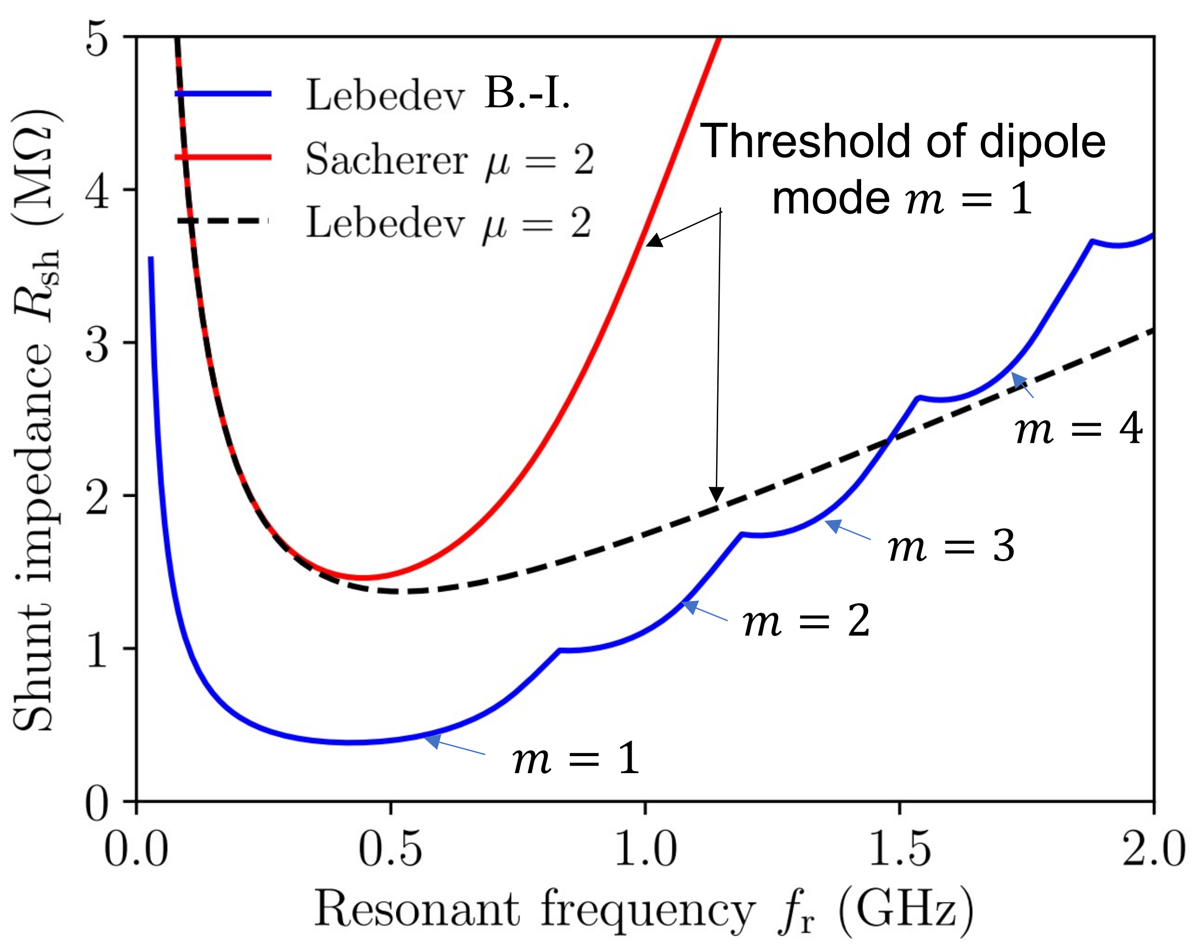
Impact of bunch-by-bunch spread

Fist results with +-20 % intensity variation



Lebedev vs Sacherer approach

$V_{\mathrm{rf}} = 16\ \mathrm{MV}, \tau = 1.2\ \mathrm{ns}, E = 7\ \mathrm{TeV}$



→ Factor of 4 difference is due to different distribution function.

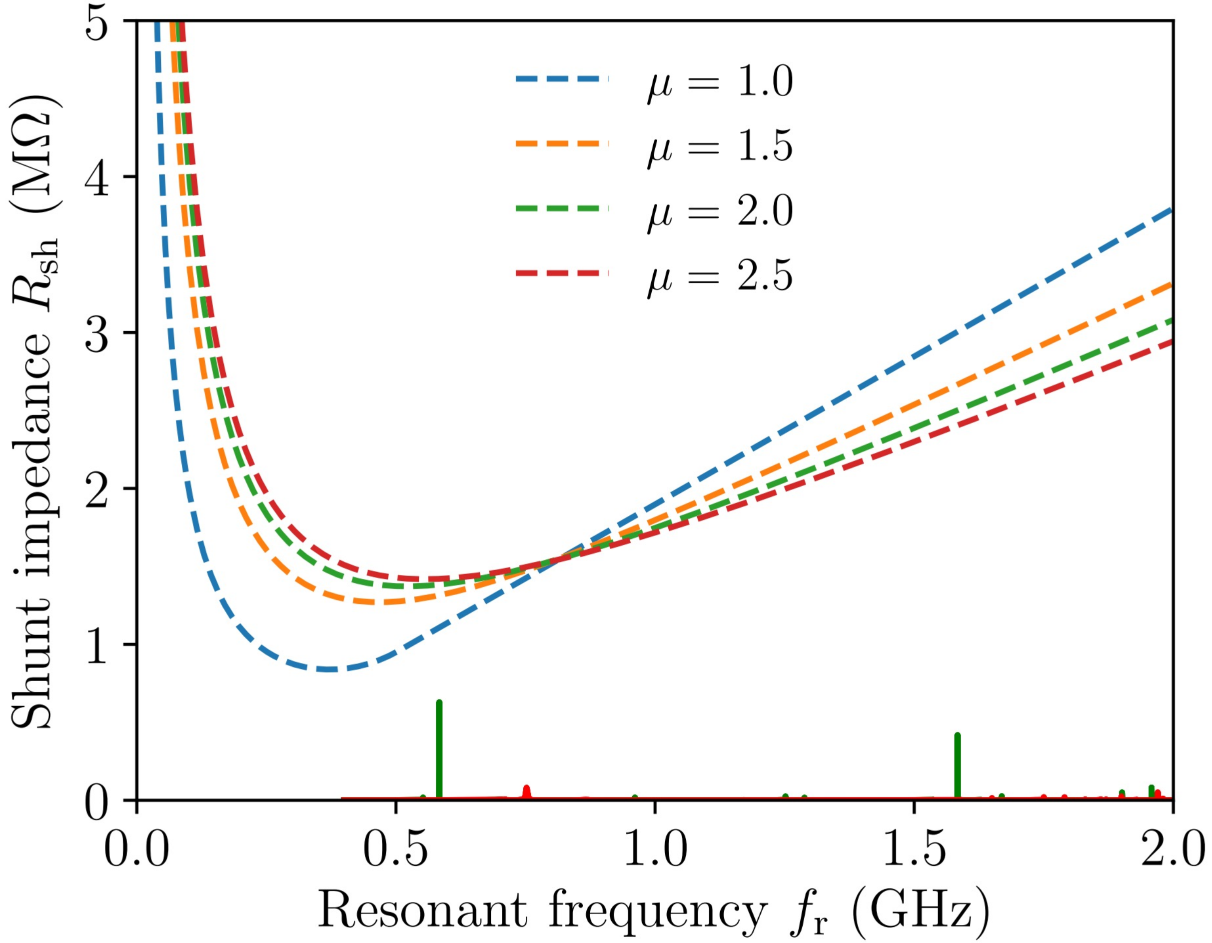
→ Stability diagram approach based on Lebedev equation was extended to binomial distribution.

→ For $\mu = 2$, the minimum thresholds are similar, but Sacherer approach underestimates threshold at higher frequencies

→ Sacherer approach can be obtained as a low frequency expansion of Lebedev equation (*E. Shaposhnikova et al., MCBI19*)

Results for HL-LHC flat top

$V_{\mathrm{rf}} = 16\ \mathrm{MV}, \tau = 1.2\ \mathrm{ns}, E = 7\ \mathrm{TeV}$

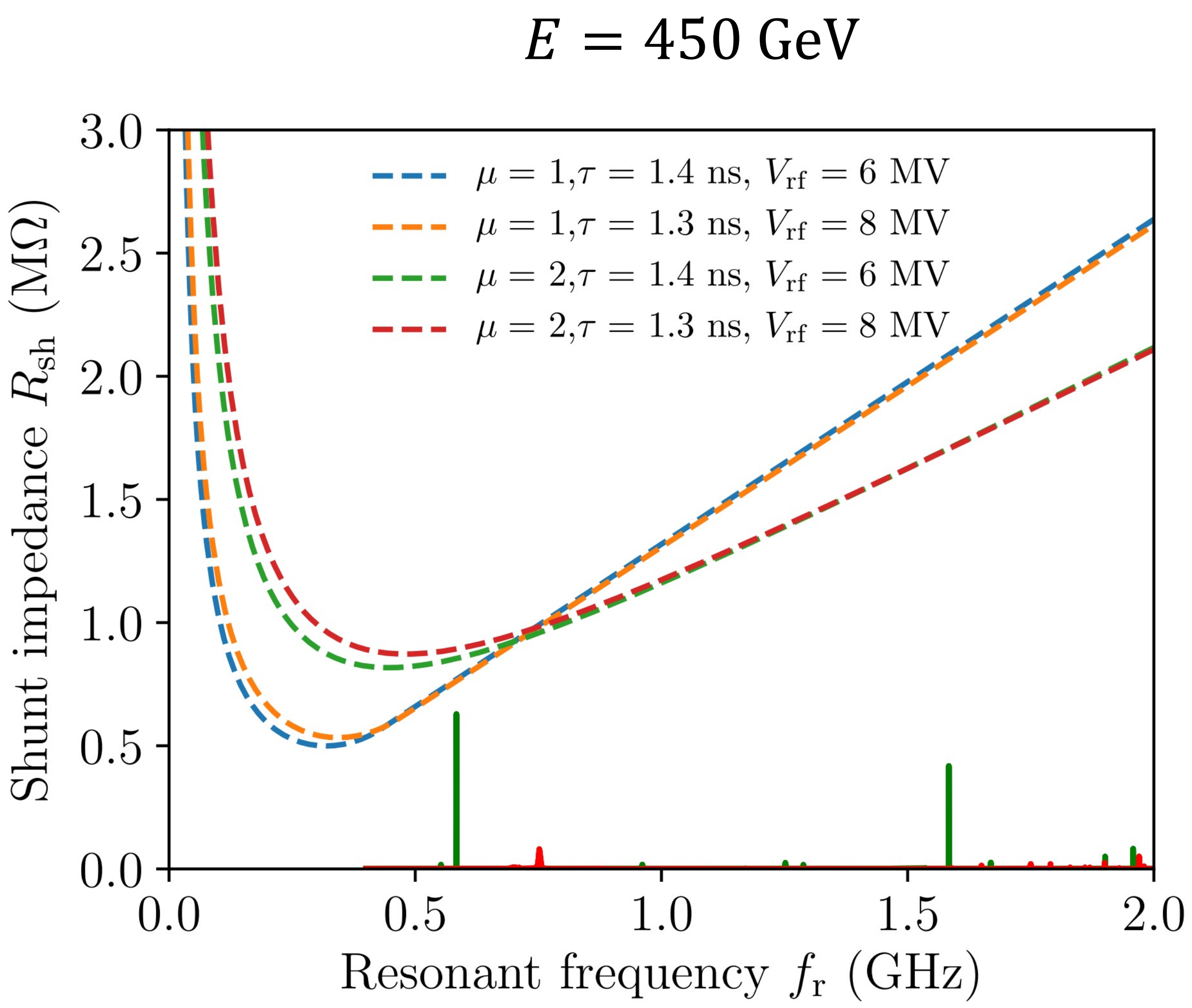


Crab cavity HOMs:
HL-LHC Double Quarter Wave (DQW) × 4
HL-LHC RF-Dipole (RFD) × 4

→ Thresholds for distributions with different μ and the same FWHM bunch length are similar (except $\mu = 1$)

→ Only one HOM is close to the stability limit for the worst-case scenario without frequency spread between CC.

Results for HL-LHC flat bottom



Crab cavity HOMs:
HL-LHC Double Quarter Wave (DQW) × 4
HL-LHC RF-Dipole (RFD) × 4

→ Thresholds are similar for 6 MV and 8 MV of rf voltage for the same bunch parameters at the SPS extraction.

→ Recommendation: further damping of the first high Q mode of DQW CC could be addressed for margin in machine operation.