Longitudinal Beam Dynamics in Ultra-low Emittance Rings

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Outline

- Choice of RF frequency
- Landau cavities
- Active Landau cavities
- Collective effects - Robinson mode coupling, mode 1 excitation
- Transient beam loading
- Changes in ID gaps
- Cavities at additional RF harmonics

Impact of RF Frequency

Parameter	$\propto$
Energy acceptance	$1/\sqrt{h}$

- Lower frequency means better energy acceptance for same RF voltage

M. Borland, R. Hettel, S. C. Leemann, D. S. Robin, NAPAC 2016, TUB21O01, Chicago, IL.

Impact of RF Frequency

Parameter	$\propto$
Energy acceptance	$1/\sqrt{h}$
Synchrotron tune	$\sqrt{h}$

- Resistance to HOM-driven coupled-bunch instabilities (neglecting effect of bunch length)

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Natural bunch duration (time) $\sigma_{0\tau}$	$1/\sqrt{h}$

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Flat-potential bunch duration (time) σ_{τ}	$1/h^{\frac{3}{4}}$
Lengthening factor	$1/h^{\frac{1}{4}}$

- Lower RF frequency allows for more lengthening and longer absolute bunch durations

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Lengthening factor	$1/h^{\frac{1}{4}}$
Impedance power dissipation/heating (same average current)	$1/(h\sigma_\tau^{0\dots3}) = h^{-1\dots+\frac{5}{4}}$

- Impedance dependent: favours lower RF frequency for resistive-wall and high-frequency resonators

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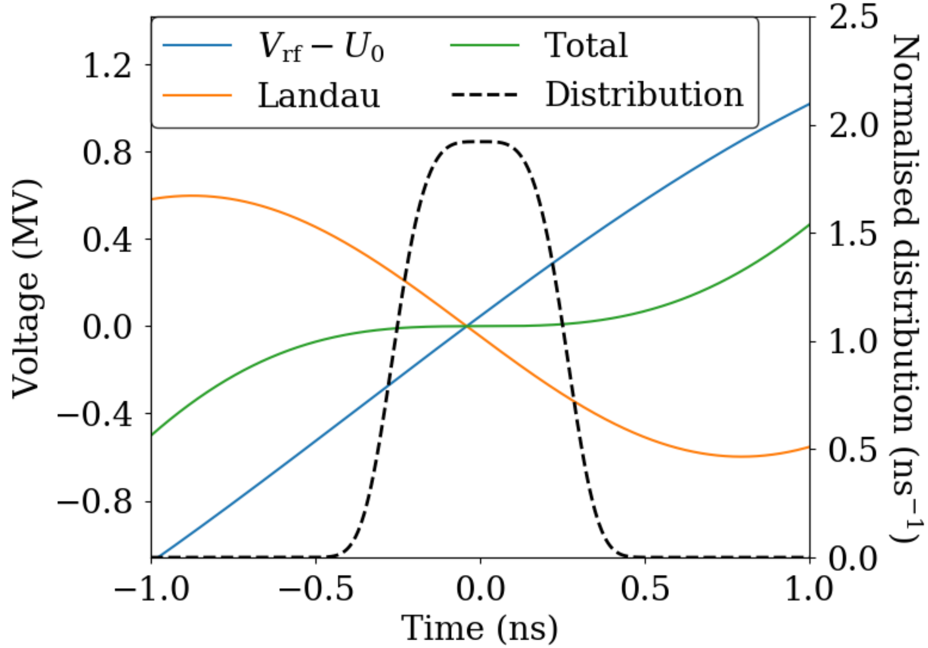
Touschek, IBS scattering	$1/(h\sigma_\tau) = 1/h^{\frac{1}{4}}$

Landau Cavities

- Landau cavities used to flatten the RF potential to lengthen the bunches
  - Longer Touschek lifetime, less intrabeam scattering
  - Landau damping, rejection of impedance at high frequency



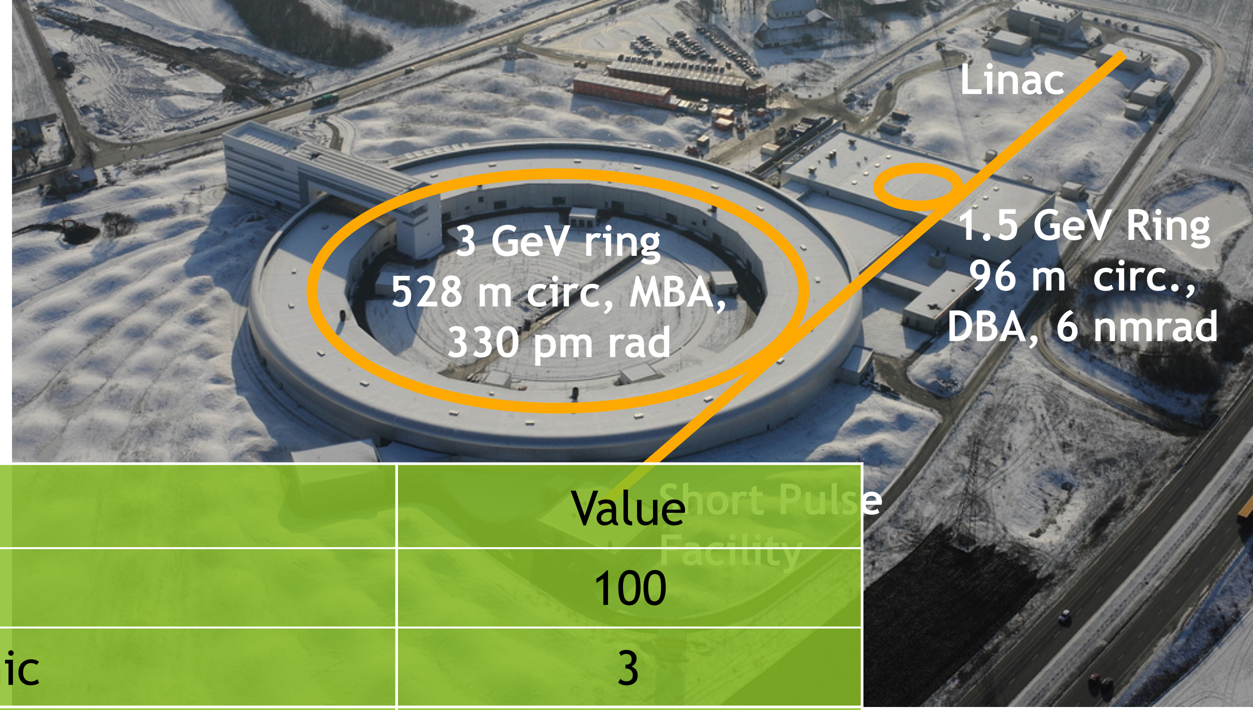
J. M. Byrd & M. Georgsson, PRSTAB **4** 030701 (2001)

Flattened potential

- Optimal bunch lengthening (flat potential):
  - 1st and 2nd derivative of RF voltage = 0
  - Requires control of two parameters (LC detuning, Rs, Q-factor, beam current, main RF voltage)
- 0 first derivative possible for one LC detuning (semi-flat)
  - Asymmetric longitudinal bunch profile
  - Formula for voltage fraction k at appropriate LC detuning:

$$\frac{(1-n^2)V_{\mathrm{rf}}^2}{(2I_0|F|R_s)^2}k^4 + \left(n^2 + \frac{U_0}{I|F|R_s}\right)k^2 + \frac{U_0^2}{V_{\mathrm{rf}}^2} - 1 = 0$$

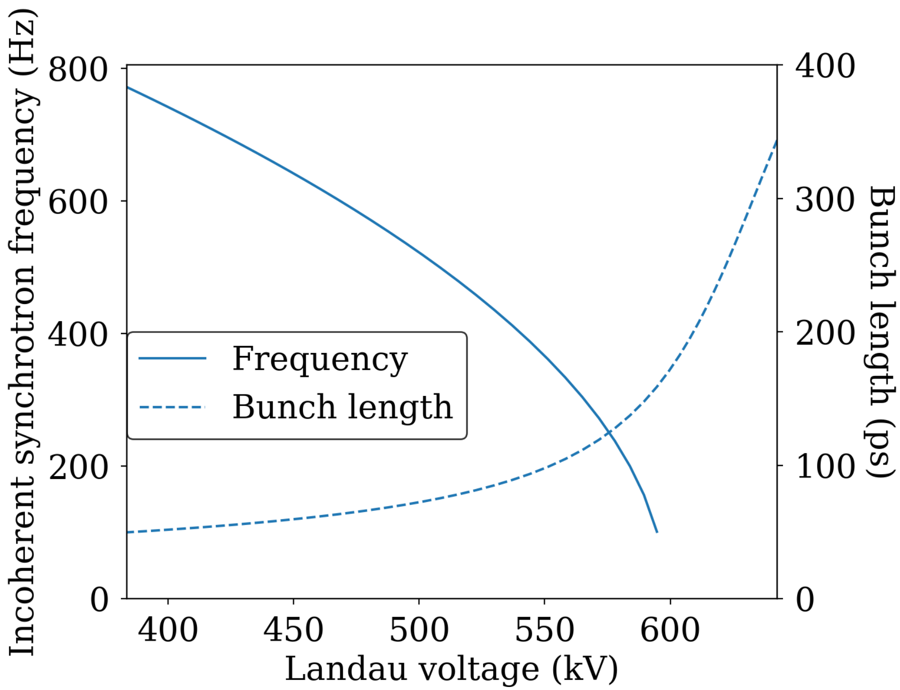
The MAX IV 3 GeV Ring

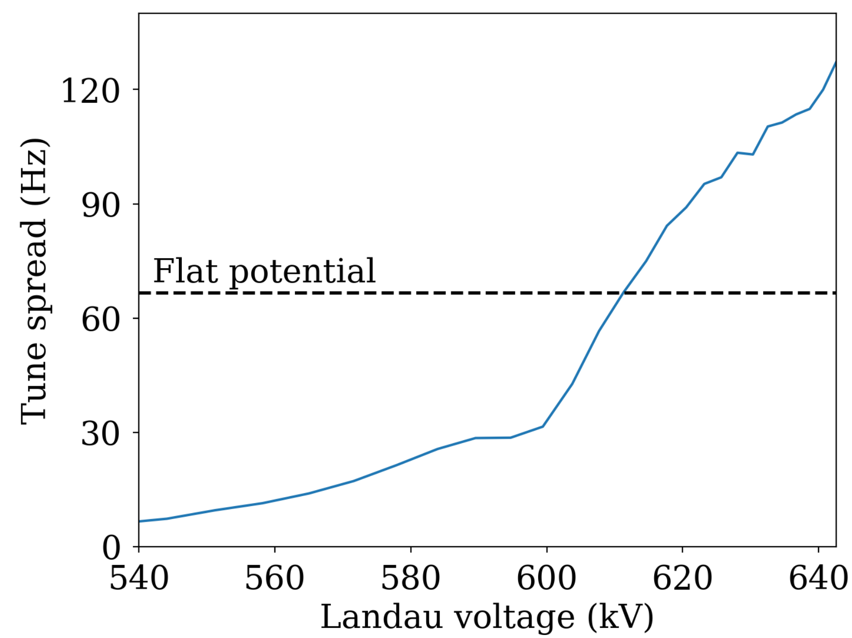


Parameter	Value
RF frequency (MHz)	100
Landau-cavity (LC) harmonic	3
Total LC shunt impedance (MΩ)	8.25
LC quality factor	20800
Beam current (mA)	500
RF voltage (MV)	1.8
Natural RMS bunch duration (ps)	30
RMS duration with ideal LC lengthening (ps)	167
Harmonic number	176
Number of main (Landau) cavities	5(3)

Synchrotron tune

- MAX IV parameters, 500 mA current
- Main RF voltage, 1.8 MV (flat potential with 3 LCs)



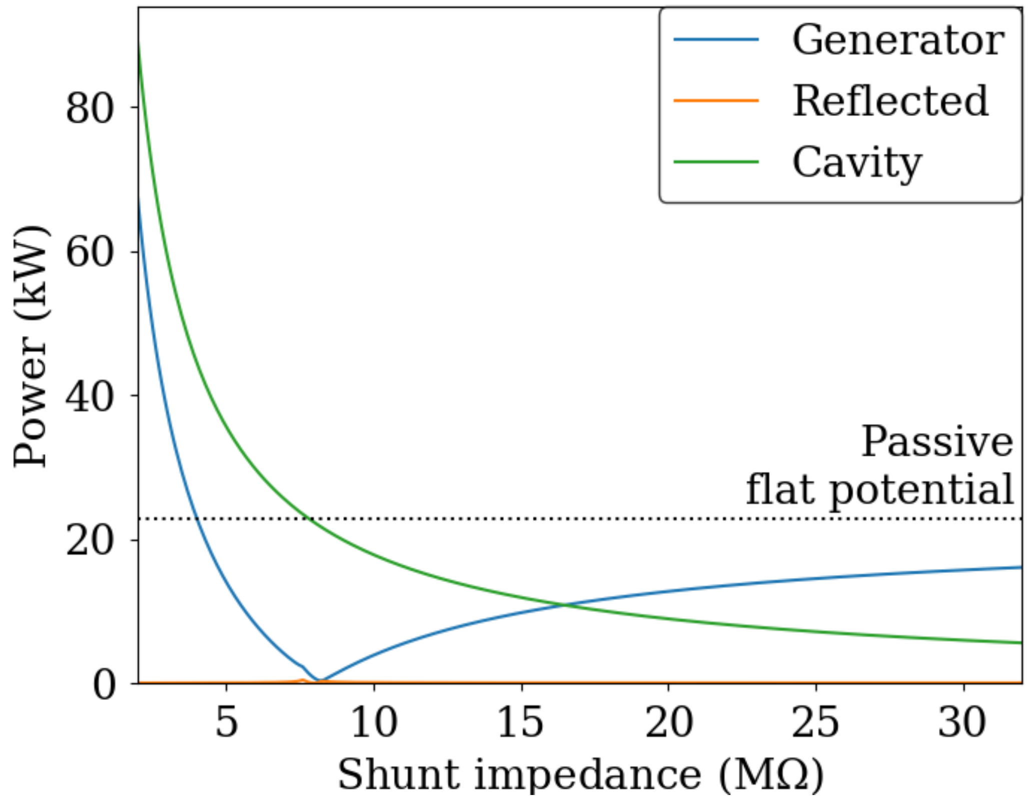


T. Olsson, F. Cullinan & Å. Andersson, PRAB **21** 120701 (2018)
P. F. Tavares, Å. Andersson, A. Hansson & J. Breunlin, PRSTAB **17** 064401 (2014)

Active cavities

- Same formulas as for main system apply
- Powers at matched condition
- Rule of thumb at flat potential for passive LC at harmonic n:

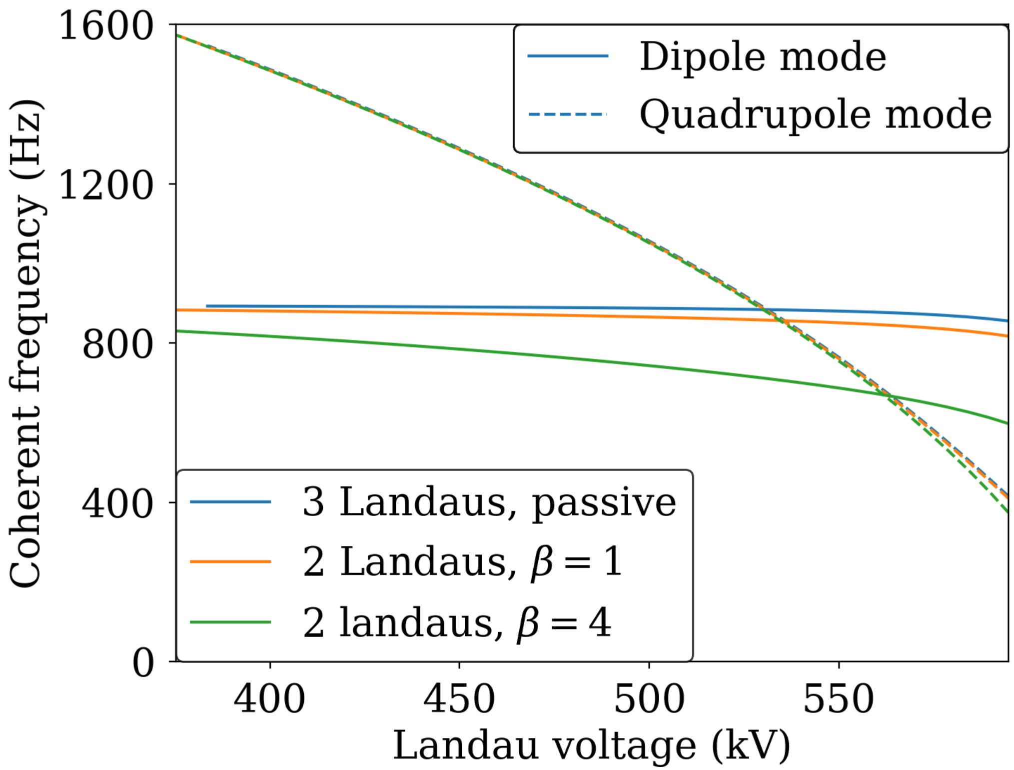
$$P_{\mathrm{hc}} = \frac{P_b}{n^2 - 1}$$



P. B. Wilson, SLAC-PUB-2884 (1991)

Robinson Mode Coupling

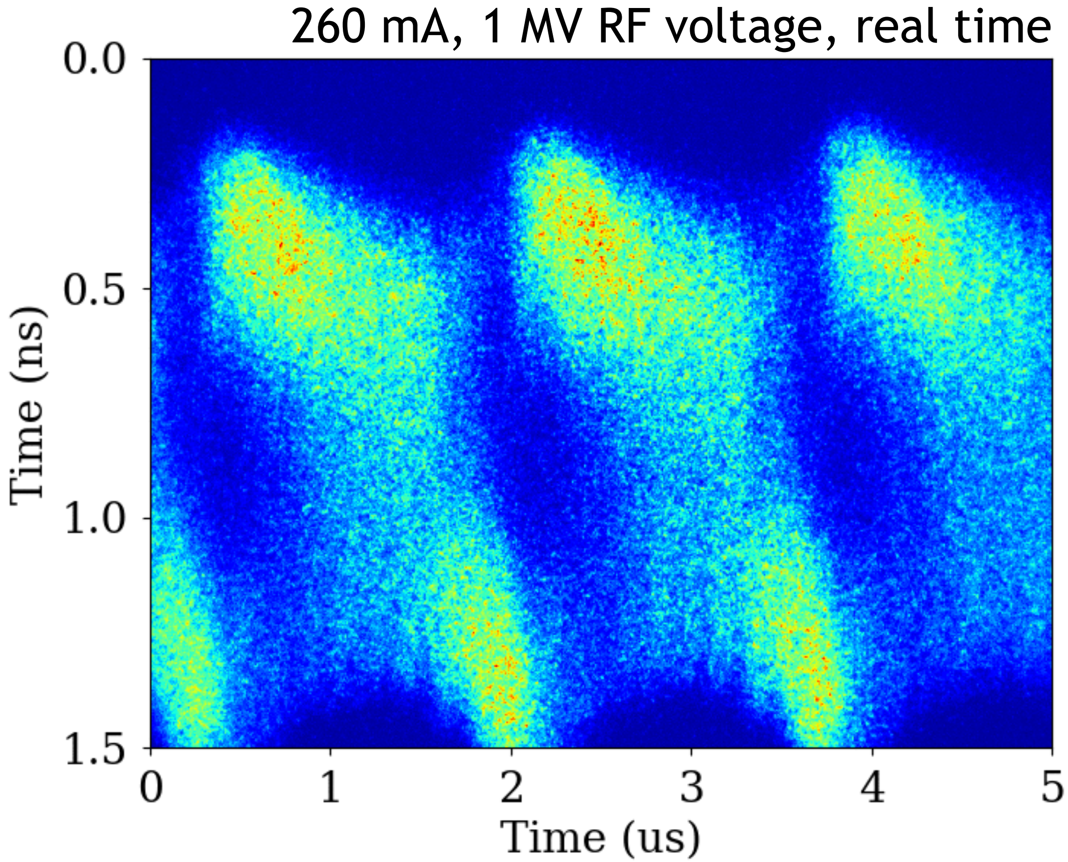
- Active LCs tuned for minimum generator power



R. A. Bosch, K. J. Kleman & J. J. Bisognano, PRSTAB 4 074401 (2001)
P. B. Wilson, SLAC-PUB-2884 (1991)

Mode 1 Instability

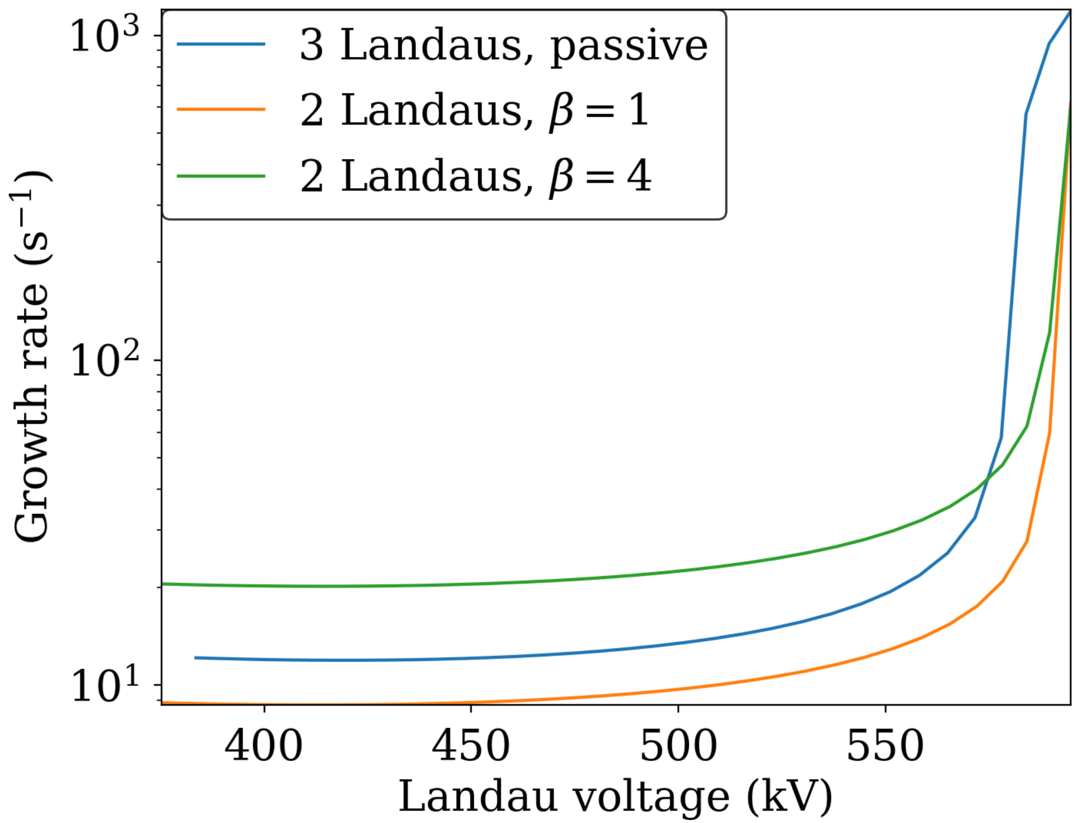
- Excess LC shunt impedance can lead to excitation of mode 1
- Seen experimentally at MAX IV - under investigation
- Avoided during operation by using a nonuniform fill



M. Venturini, PRAB **21** 114404 (2018)
T. He, W. Li, Z. Bai & L. Wang, PRAB **22** 024401 (2022)

Mode 1 Instability

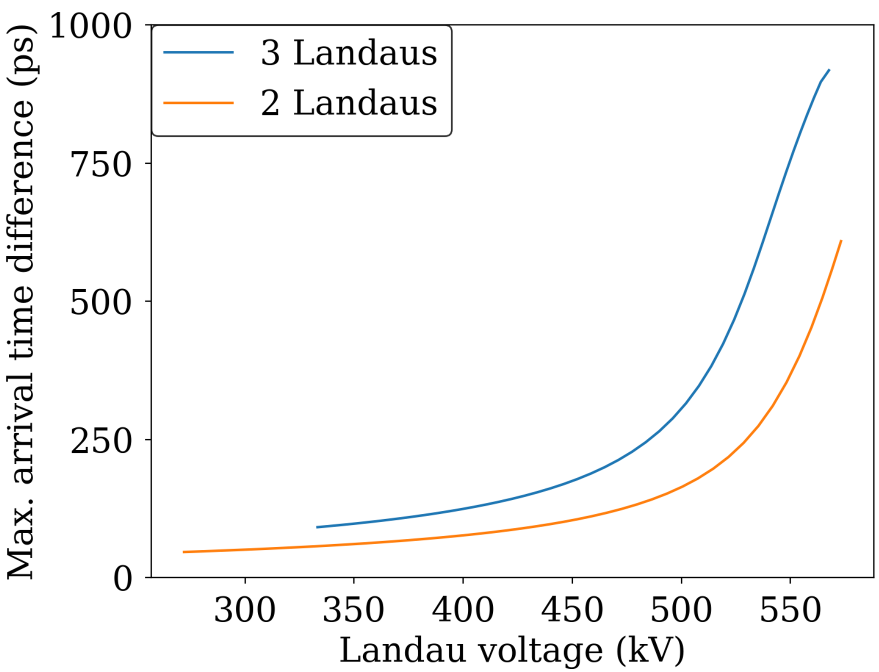
- Lower R/Q beneficial
- Lower Q for same R/Q is worse
- Results from point-bunch theory but no small-tune-shift approximation

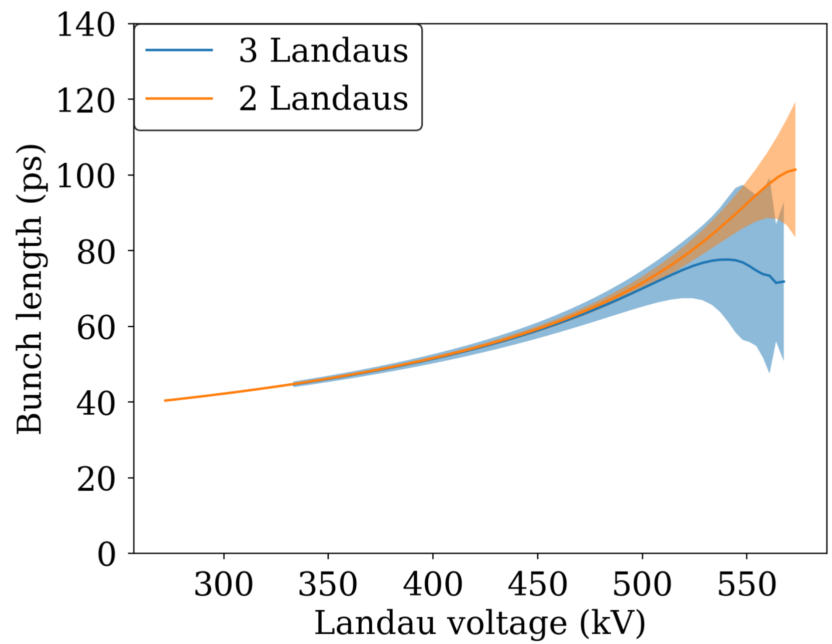


M. Venturini, PRAB **21** 114404 (2018)
T. He, W. Li, Z. Bai & L. Wang, PRAB **22** 024401 (2022)

Inhomogeneous Beam Loading

- 165/176 RF buckets filled
- Lower R/Q reduces effect without sacrificing lengthening

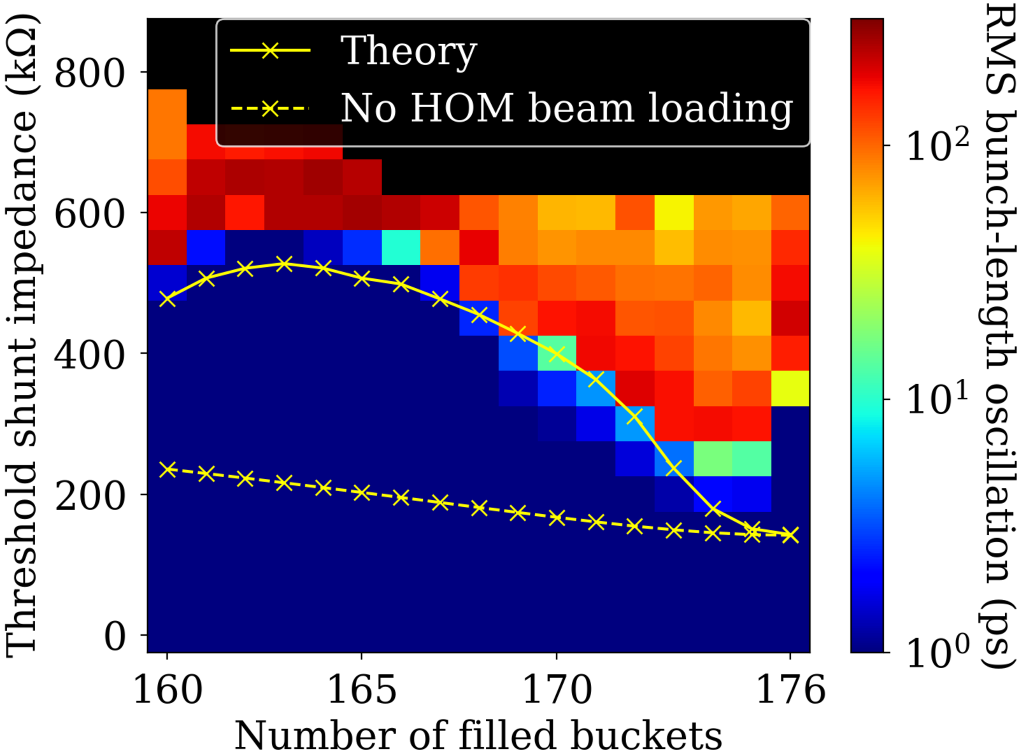




T. Olsson, F. Cullinan & Å. Andersson, PRAB **21** 120701 (2018)

Bunch-By-Bunch Feedback

- Combination with Landau cavities*
  - Synchrotron tune decreased - need lower cut-off DC rejection
  - Tune spread becomes comparable to mean value
- Quadrupole instabilities also a concern



*D. Teytelman, Joint AIRIES Workshop, Barcelona, 12-14th November, 2018.
F. Cullinan, Å. Andersson & P. F. Tavares, PRAB **25** 044401 (2022)

MAX IV

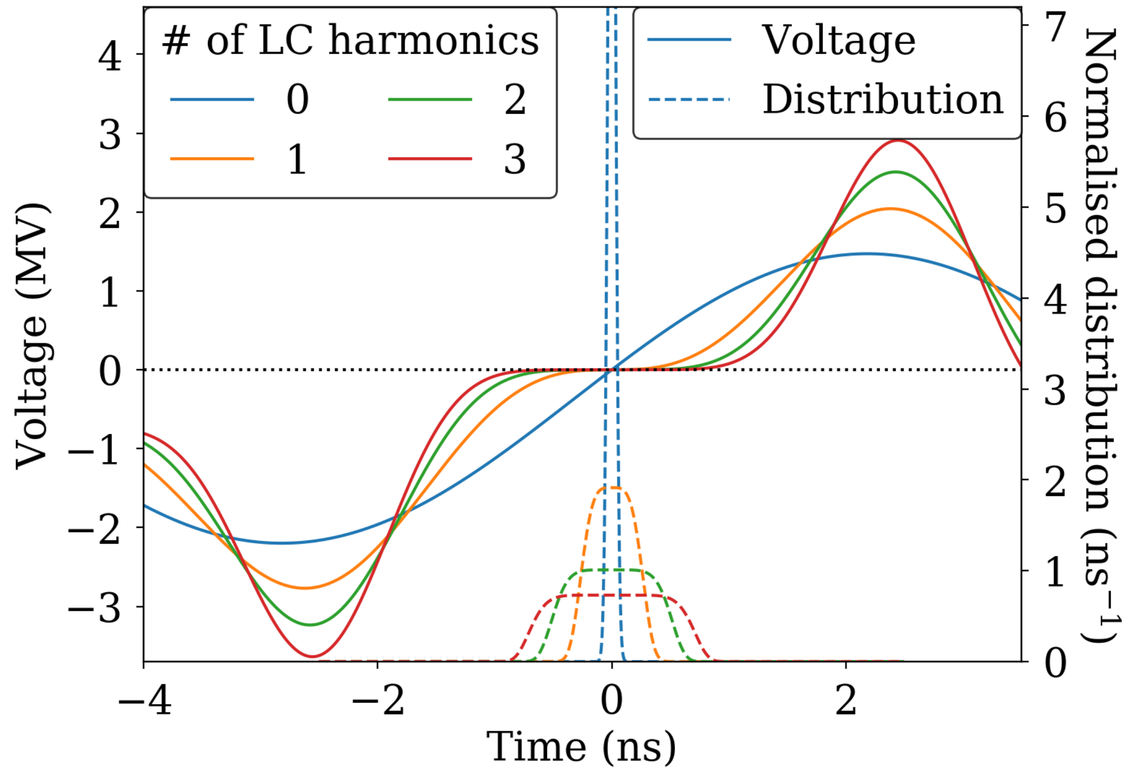
Changes in ID gap

- Feedforward device implemented on MAX IV 3 GeV ring
- Maintains flat potential by adjusting two parameters:
  - Main RF voltage (flat potential)
  - Landau cavity target field (flat or semi-flat potential)
- Stable beam during current ramp
- Flexibility in delivery current
- Attempt to maintain constant conditions

Multiple Higher Harmonics

Developed by
Å. Andersson &
P. F. Tavares

- Analytical method generalising flat potential to higher-order derivatives
- Arbitrary number of RF harmonics



Conclusion

- Longitudinal dynamics in ultra-low emittance storage rings present challenges
    - Lower synchrotron frequency
    - Need for bunch lengthening
- Beam dynamics arguments can be made for RF frequency choice
- Have to be aware of instabilities driven by cavity fundamental modes
- Nonuniform fills affect lengthening but offer alternative source of Landau damping
- Challenge to maintain dynamics during changing conditions (ID gaps, beam current)
- Cavities at more RF harmonics can be added for additional lengthening

Important topics not covered: negative momentum compaction, high-Q superconducting LCs, nonuniform fills with active LCs,…

MAX IV