Review of Collective Effects in Harmonic Cavity Systems

Francis Cullinan
MAX IV laboratory, Lund, Sweden

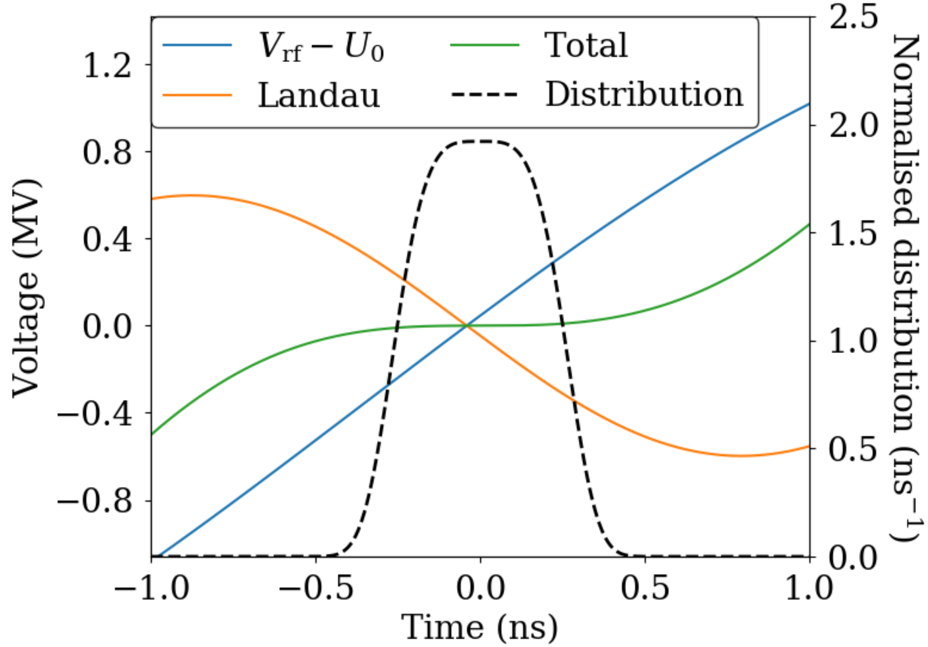
HarmonLIP, MAX IV, Lund, Sweden
October 2022

Outline

- Harmonic (Landau) cavities
- Active harmonic cavities
- Longitudinal plane:
  - Robinson instability (mode coupling)
  - Mode-1 excitation
  - Inhomogeneous beam loading
- Transverse plane:
  - Long-range resistive wall
  - Transverse mode-coupling instability
- Future directions - multiple higher harmonics

Harmonic Cavities (HCs)

- Harmonic 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)

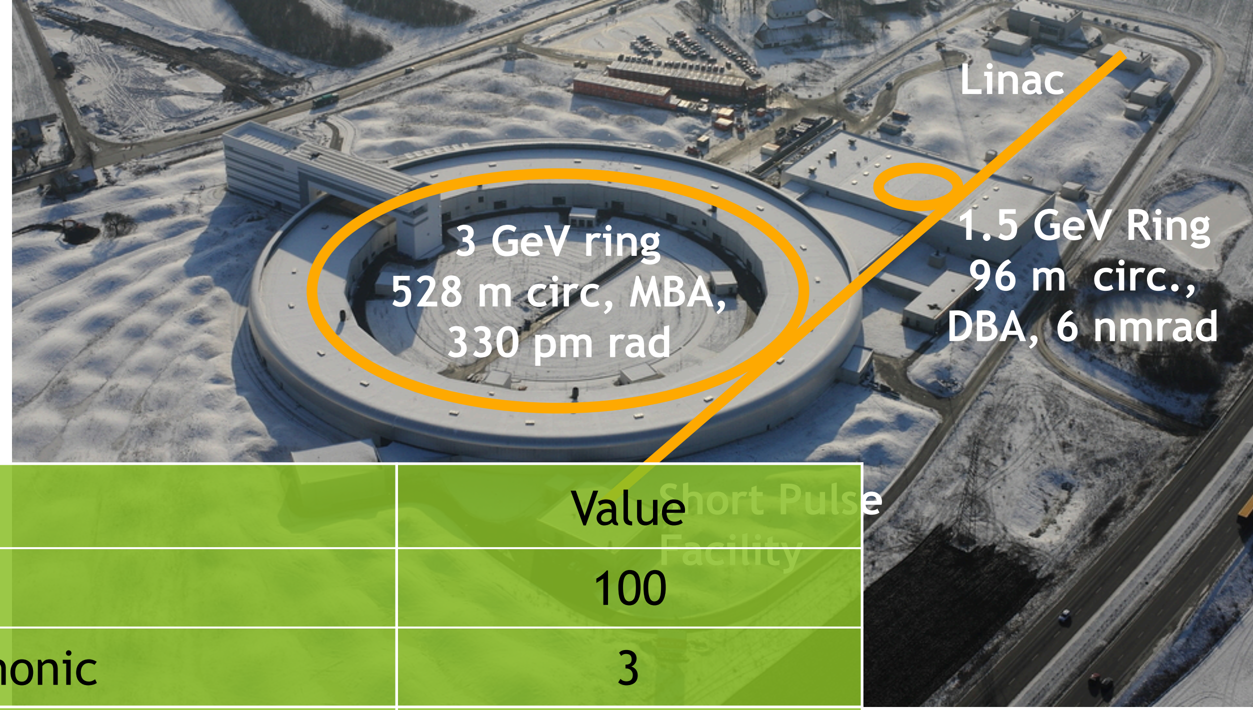
M. Georgsson, Å. Andersson & M. Eriksson, NIM A **416** 2-3 pp 465-474 (1998)

Flattened potential

- Optimal bunch lengthening (flat potential):
  - 1st and 2nd derivative of RF voltage = 0
  - In a passive system, requires control of at least two parameters for each beam current (HC detuning, Rs, Q-factor, main RF voltage)
- 0 first derivative possible for one HC detuning (semi-flat)
  - Asymmetric longitudinal bunch profile
  - Formula for voltage fraction $k = V_{\mathrm{HC}}/V_{\mathrm{rf}}$ at appropriate HC detuning:

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

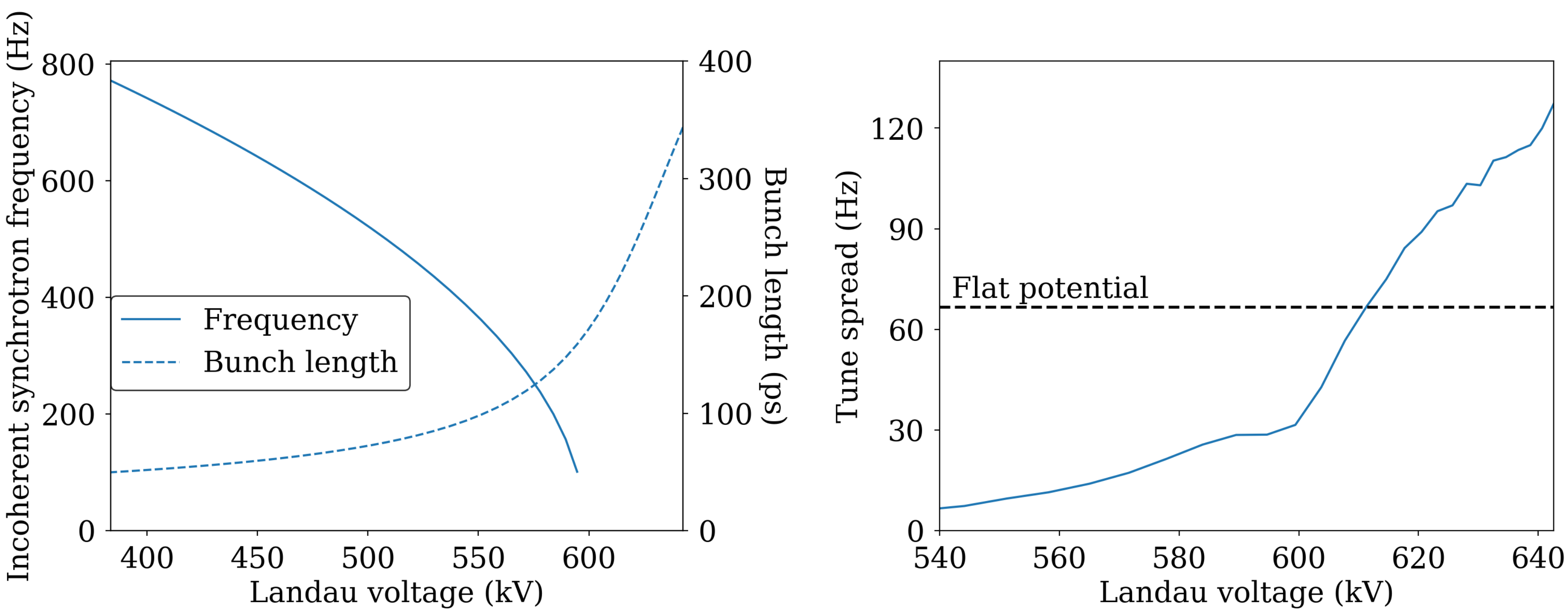
The MAX IV 3 GeV Ring



Parameter	Value
RF frequency (MHz)	100
Harmonic-cavity (HC) harmonic	3
Total HC shunt impedance (MΩ)	8.25
HC quality factor	20800
Beam current (mA)	500
RF voltage (MV)	1.8
Natural RMS bunch duration (ps)	30
RMS duration with ideal HC lengthening (ps)	167
Harmonic number	176
Number of main (harmonic) cavities	6 (3)

Synchrotron tune

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

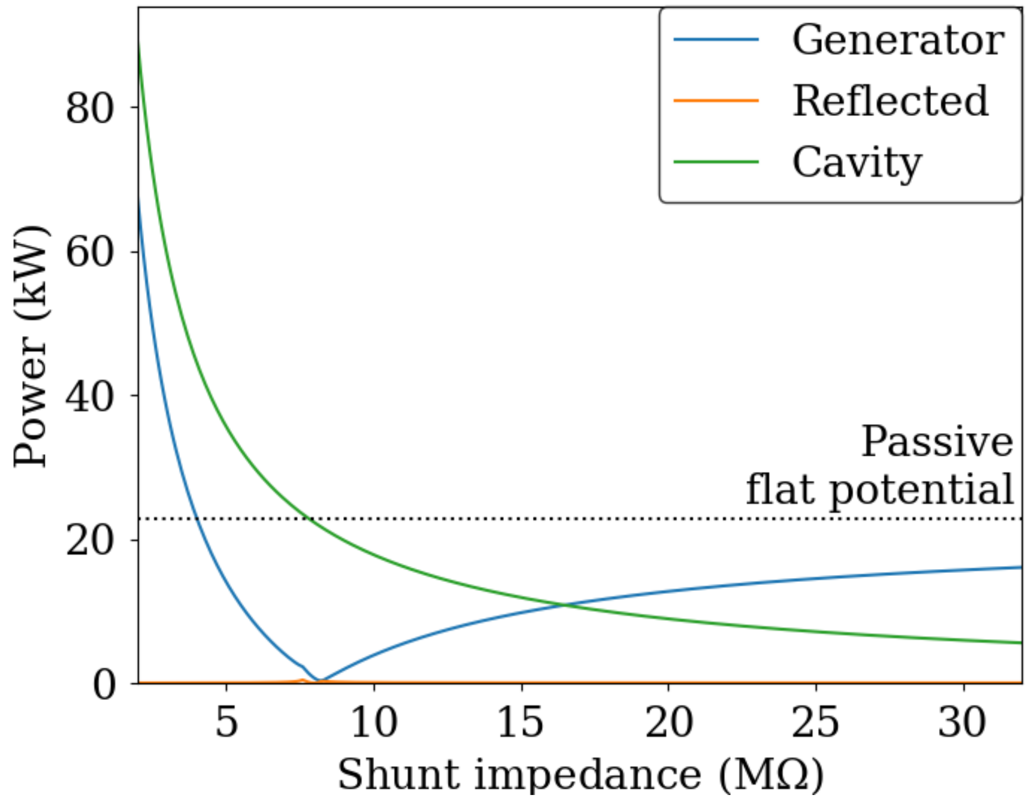


T. Olsson, F. Cullinan & Å. Andersson, PRAB **21** 120701 (2018)
P. F. Tavares, Å. Andersson, A. Hansson & J. Breunlin, PRSTAB **17** 064401 (2014)

Active cavities

- Same formulas as for main system apply
- Powers at matched condition
- Convenient relation for flat potential for passive HC at harmonic n:

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

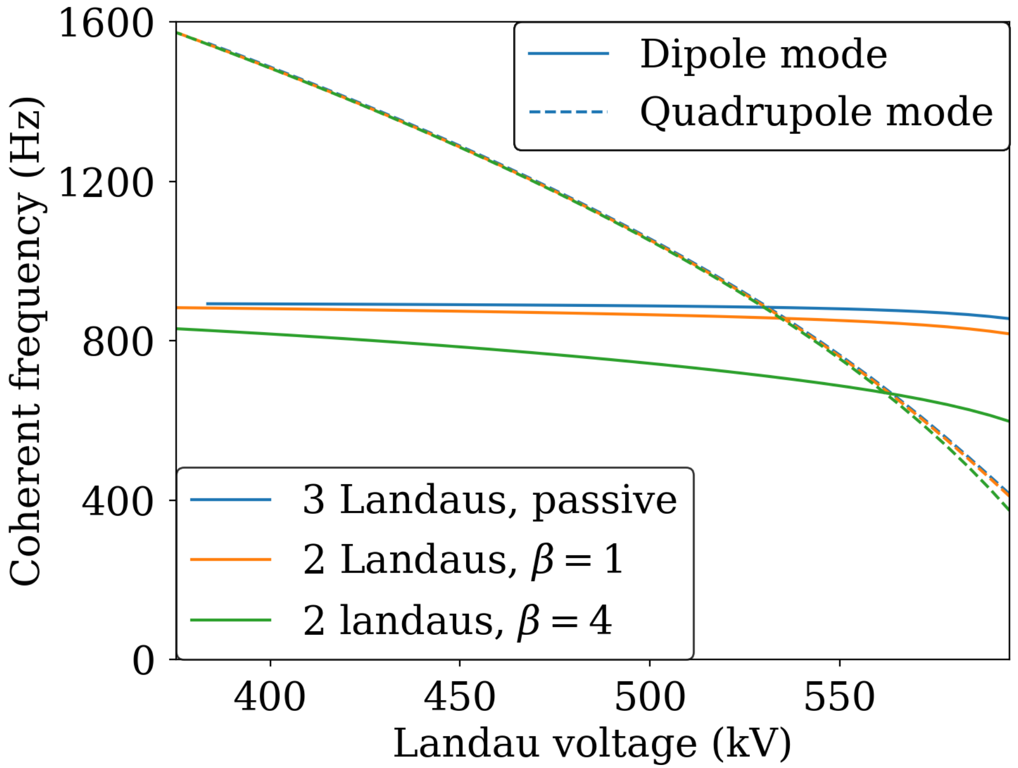


P. B. Wilson, SLAC-PUB-2884 (1991)

Longitudinal Plane

Robinson Mode Coupling

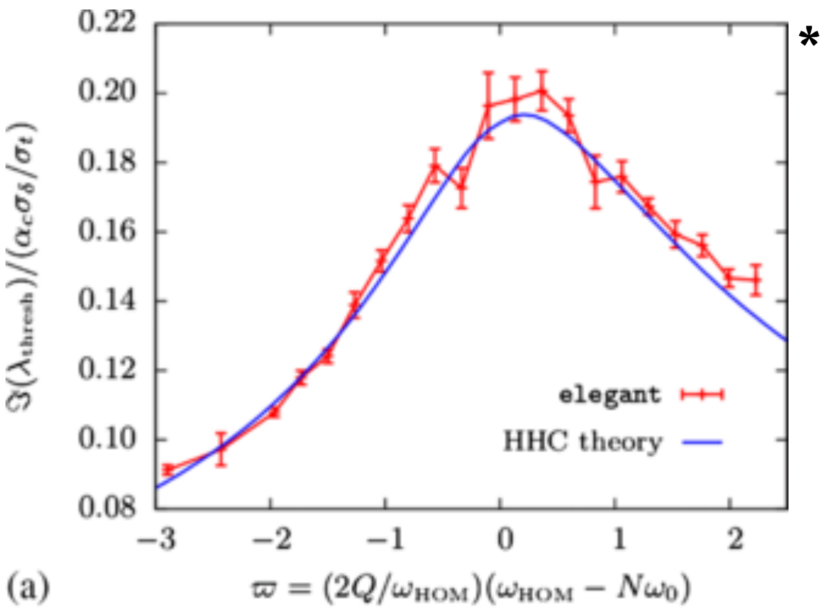
- Active HCs tuned for minimum generator power
- Can be damped in the main RF cavities using a mode-0 damper*



R. A. Bosch, K. J. Kleman & J. J. Bisognano, PRSTAB 4 074401 (2001)
P. B. Wilson, SLAC-PUB-2884 (1991)
*D. P. McGinnis, presented at the Low-Level Radio Frequency Workshop 2019, Chicago, IL (2019)

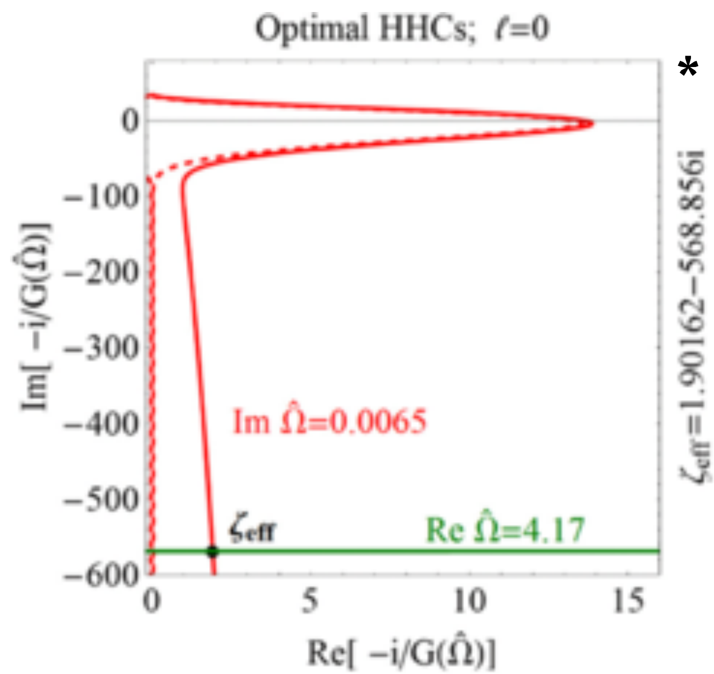
Arbitrary RF potentials

- Krinsky & Wang, then Lindberg - specific integral formula for full flat potential:



S. Krinsky & J. M. Wang, Part. Accel. **17**, 109 (1985)
*R. R. Lindberg, PRAB **21** 124402 (2018)

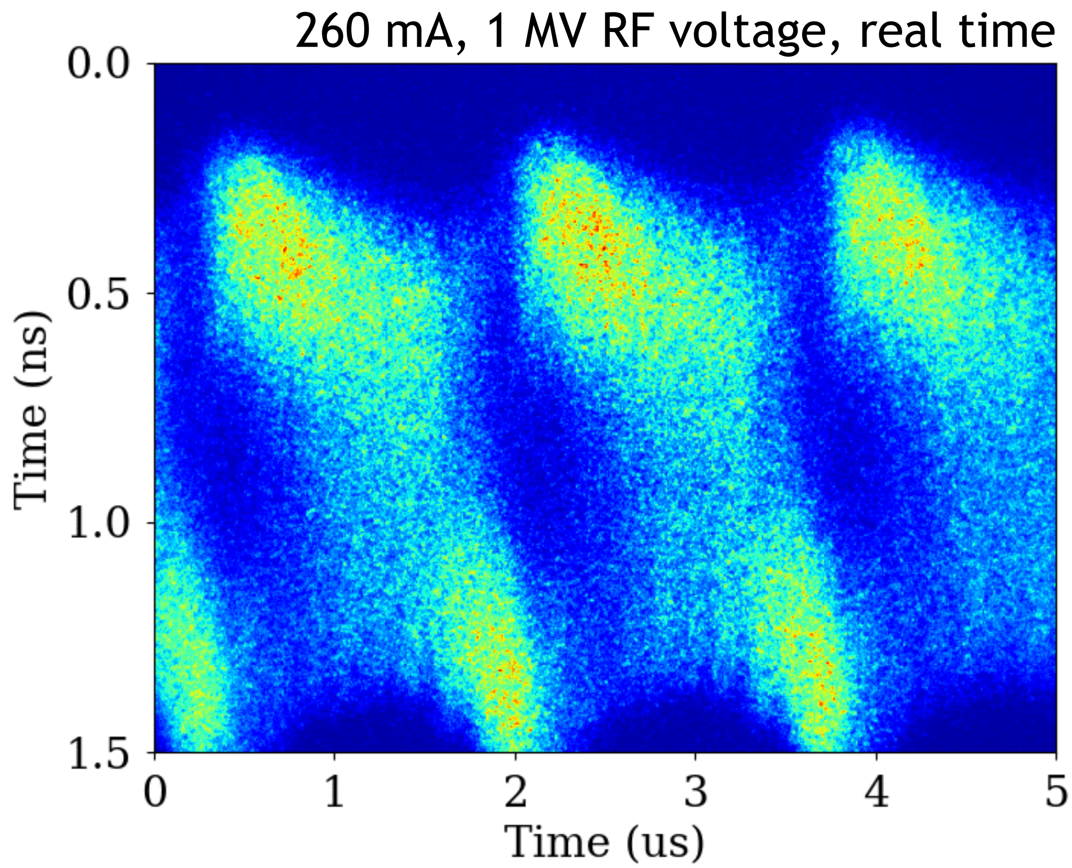
- Venturini - arbitrary potential, discretisation on a grid:



*M. Venturini, PRAB **21** 114404 (2018)

Mode 1 Instability

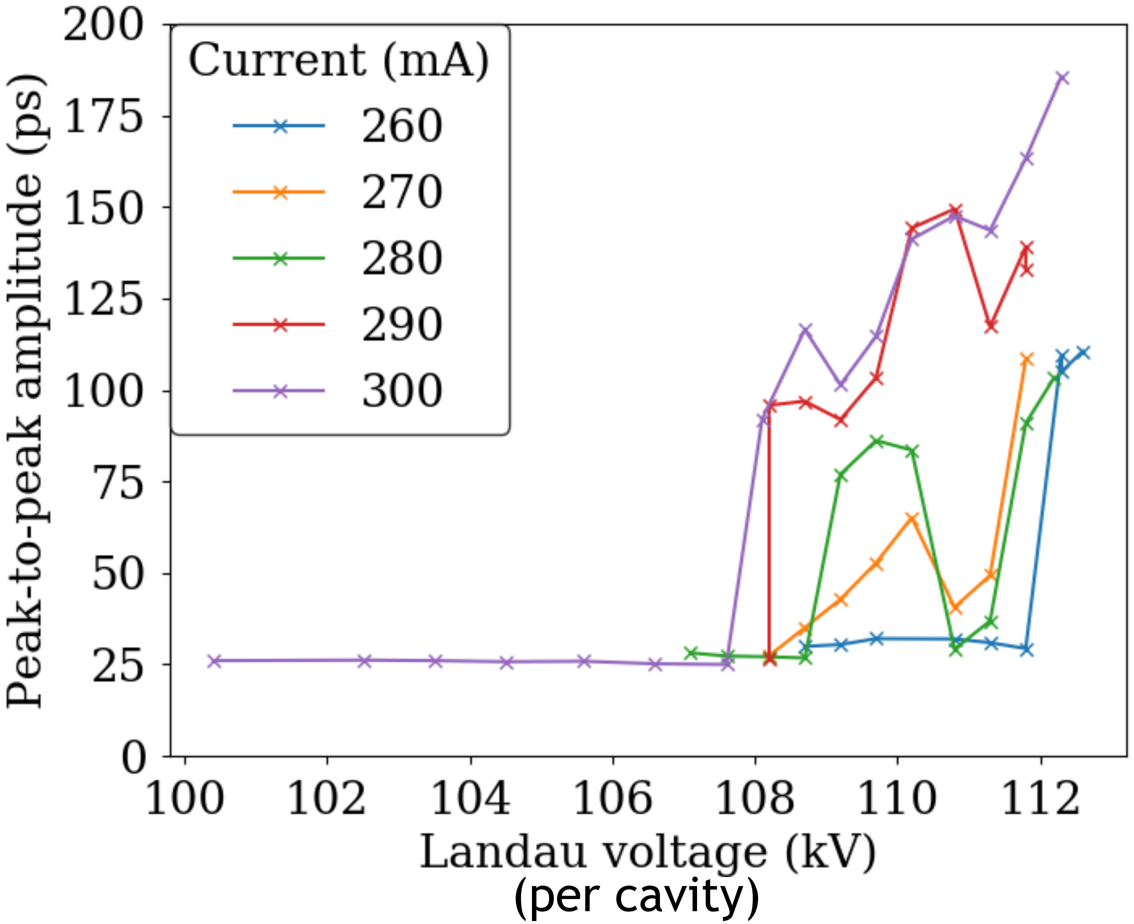
- Excess HC shunt impedance can lead to excitation of mode 1
- Seen experimentally at MAX IV - under investigation
- Avoided during operation by using a nonuniform fill



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

Experimental Observation of Mode 1

- Low frequency - typically ~10 Hz
- 1 MV RF voltage



Mode 1 - Remarks

- Flattening of the RF potential leads to a low incoherent synchrotron frequency
- Reactive impedance means that coherent oscillation frequency is even lower
- Growth rate becomes very large

Eigenvalue of coupled-bunch motion matrix

Complex coherent frequency

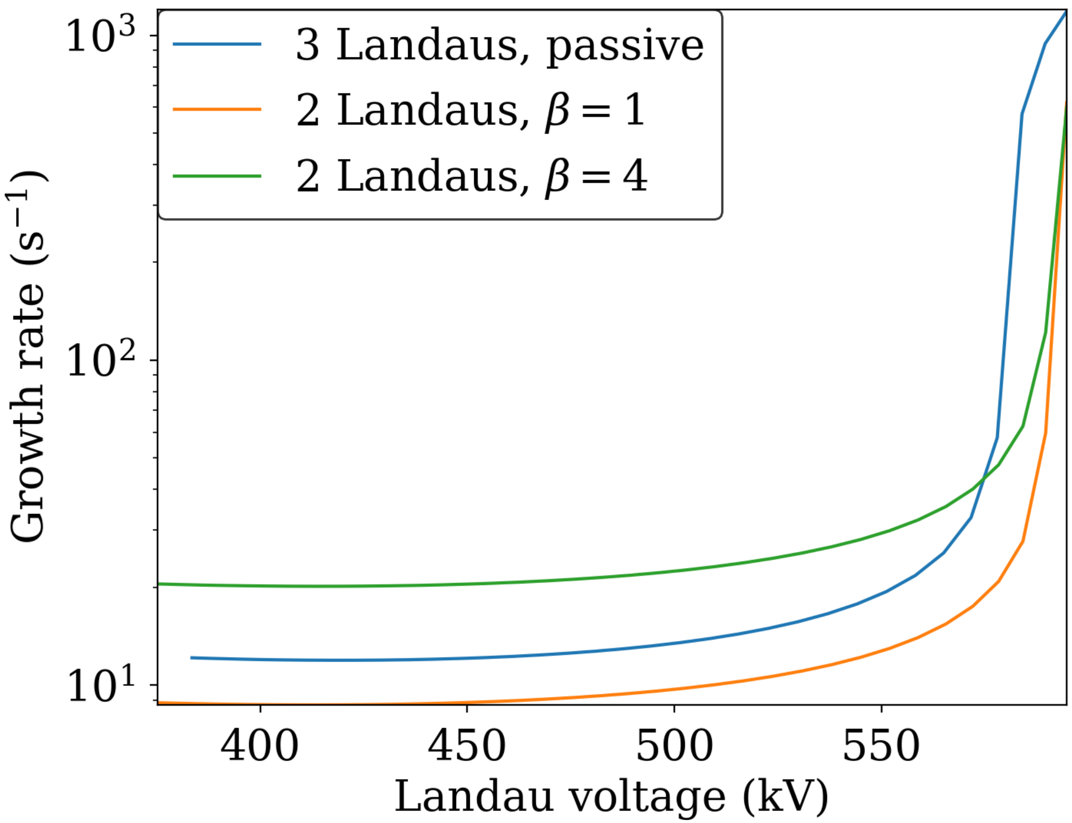
$$\mathrm{Im}(\Omega) = \frac{\mathrm{Im}(\lambda)}{2\mathrm{Re}(\Omega)} - \frac{1}{\tau}$$

Radiation damping

F. J. Cullinan, Å. Andersson & P. F. Tavares, PRAB **23** 074402 (2020)

Mode 1 Instability

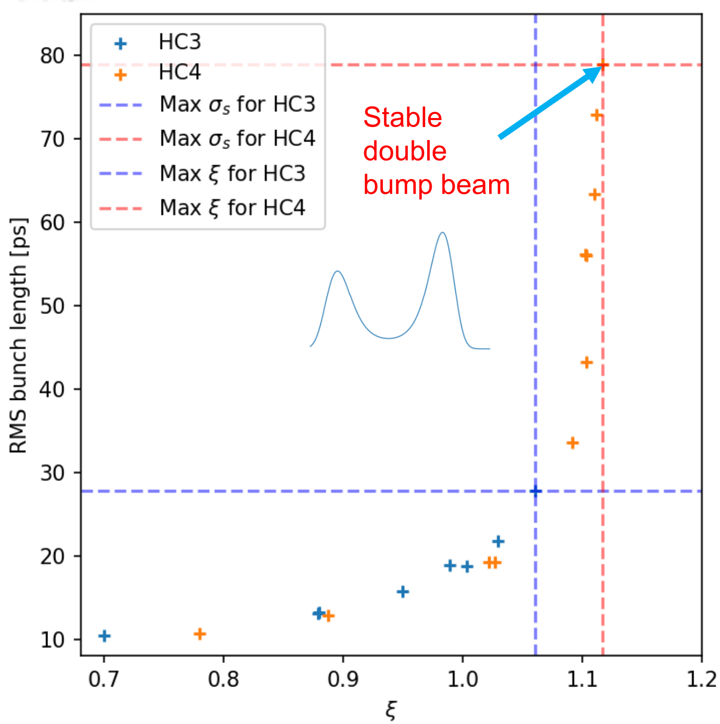
- Lower R/Q beneficial
- Lower Q for same R/Q is worse
- Theory assumes point bunches (with form factors) but no small-tune-shift approximation



Superconducting passive

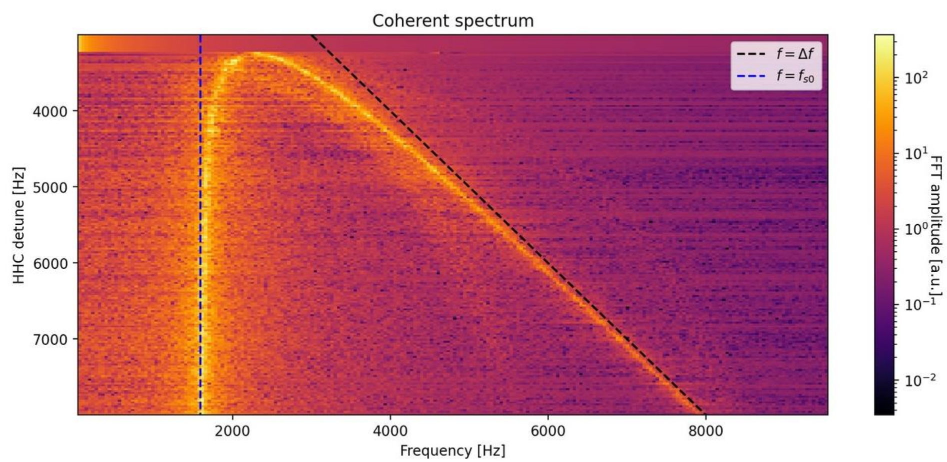
Bunch lengthening at low current (20 mA)

We also want to have the possibility to lengthen the bunches at low current, for example for the single bunch mode (at 20 mA) where the Touschek lifetime and IBS are very critical.



In that case, the picture is very different as the 4th HC allow to lengthen the bunches all the way to double bump bunches in a stable way.

The 3rd HC is very rapidly limited by another instability which could be the "fast mode coupling instability" [1] or some type of Robinson instability (?).



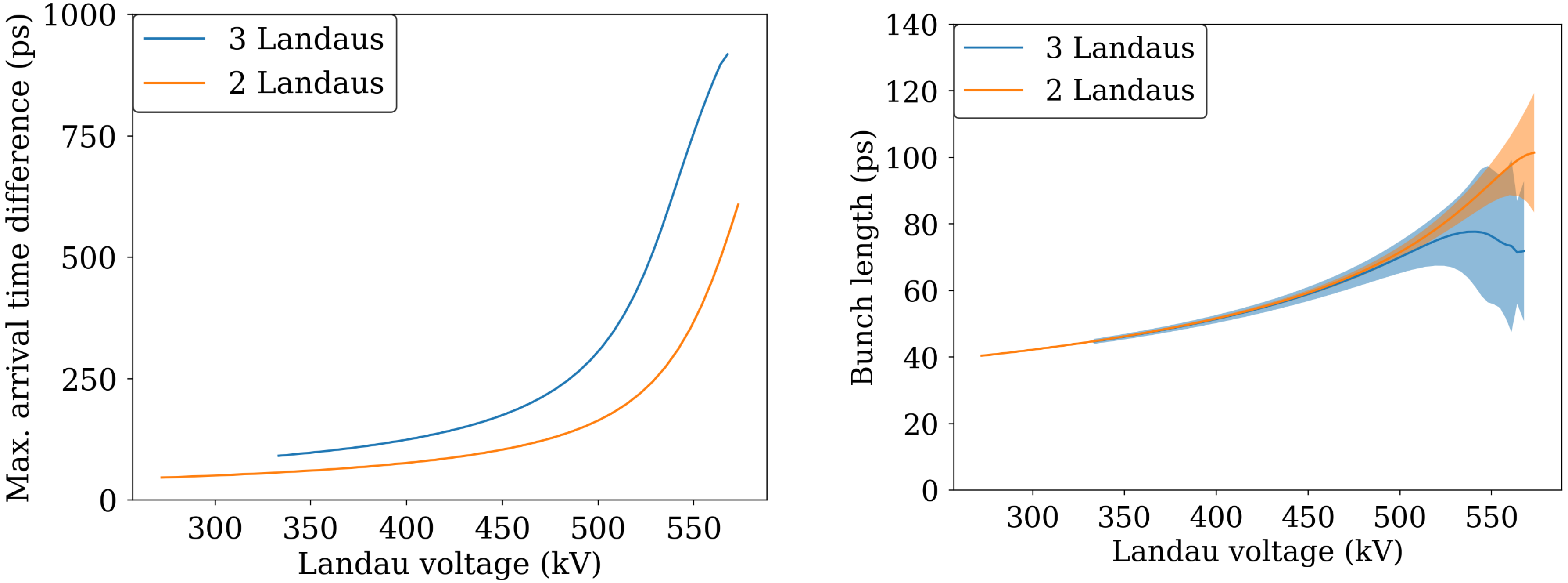
[1] R. A. Bosch, K. J. Kleman, and J. J. Bisognano, "Robinson instabilities with a higher-harmonic cavity", Physical Review Special Topics-Accelerators and Beams 4, Publisher: APS, 074401 (2001).

I.FAST Workshop 2022 16

A. Gamelin, presented at I.FAST Workshop 2022, Karlsruhe, Germany (virtual)

Inhomogeneous Beam Loading

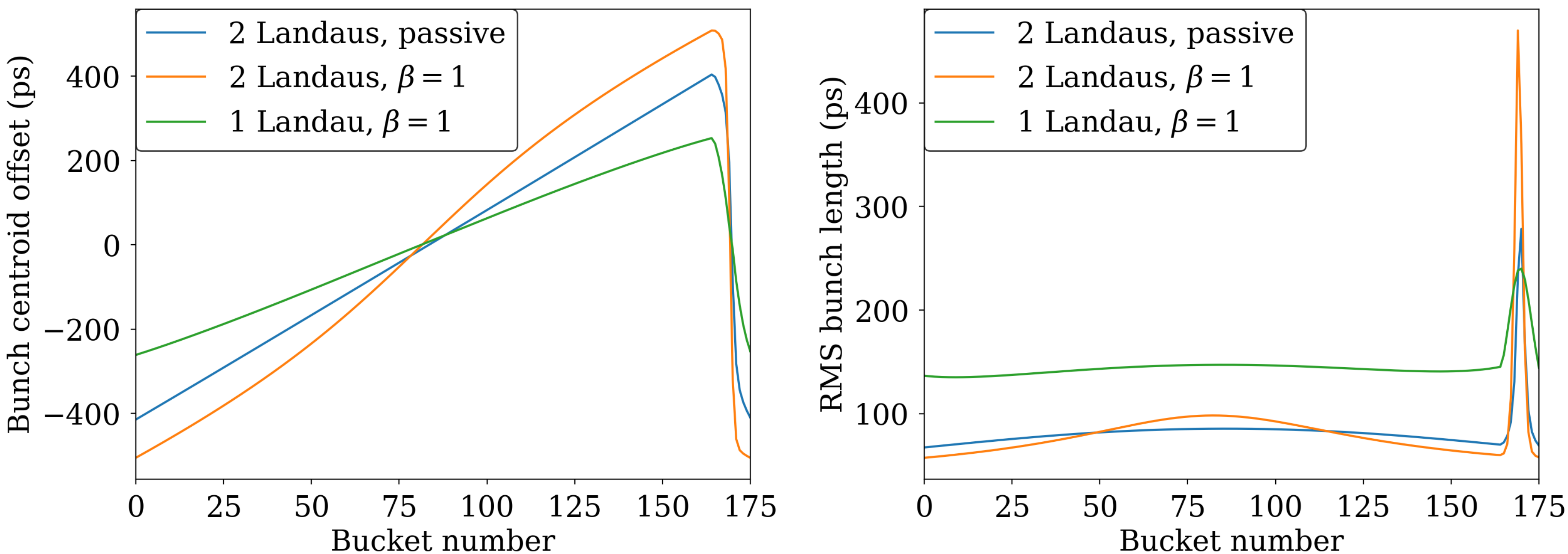
- 165/176 RF buckets filled
- Lower R/Q reduces effect without sacrificing lengthening



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

Inhomogeneous Beam Loading - Active cavities

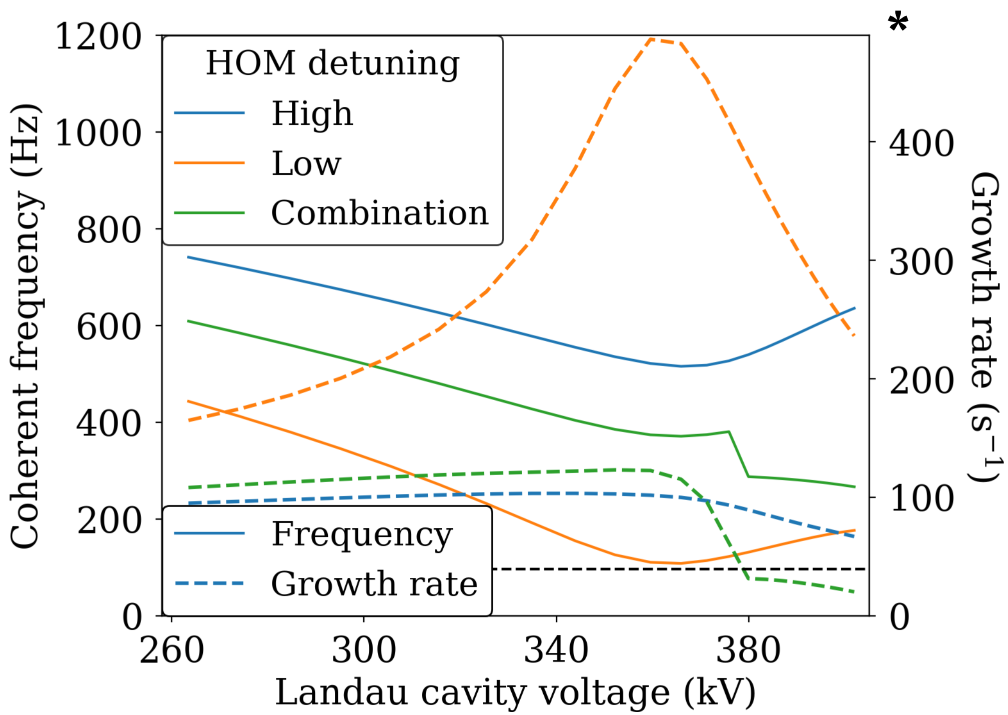
- With conditions close to flat potential for uniform fill (lower RF voltage of 1.5 MV)



MAX IV

Inhomogeneous Beam Loading - Longitudinal Stability

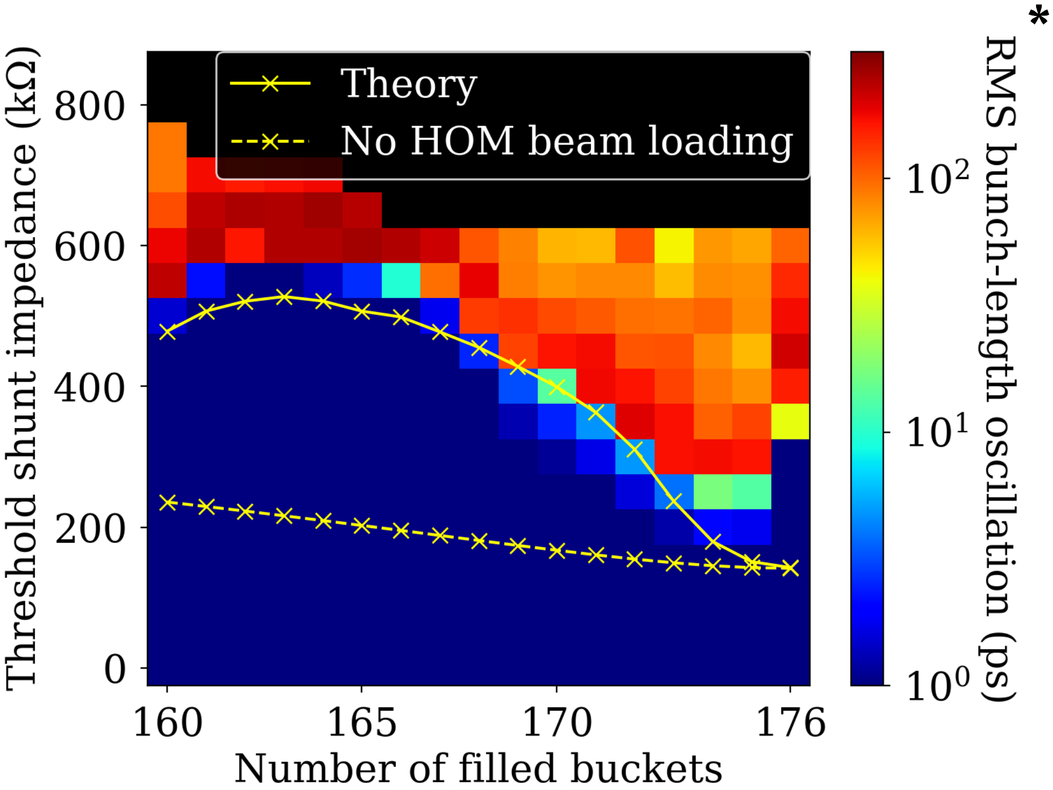
- Growth rates start to decrease as Landau fields start to generate tune spread
- Pair of identical HOMs - tune to cancel reactive impedance for maximum Landau damping



*F. J. Cullinan, Å. Andersson & P. F. Tavares, PRAB **23** 074402 (2020)

Quadrupole Stability

- Can be of concern because they evade most bunch-by-bunch feedbacks
- Threshold currents (shunt impedances) higher in nonuniform fills

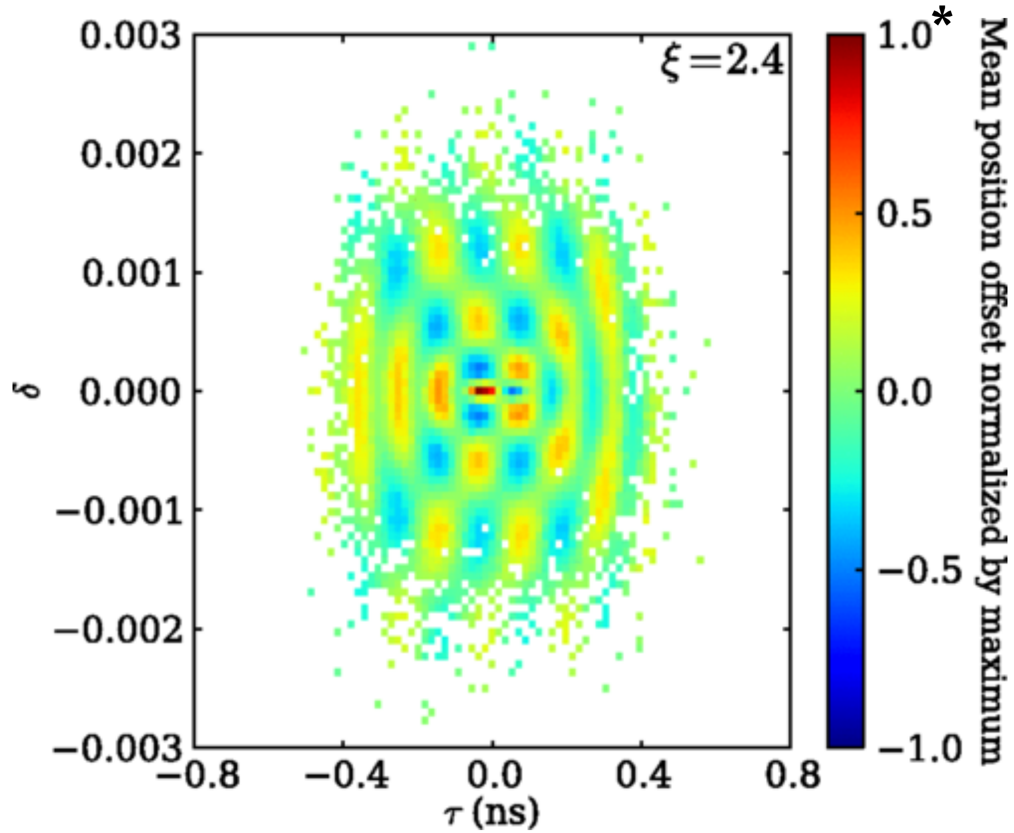


*F. J. Cullinan, Å. Andersson & P. F. Tavares, PRAB **25** 044401 (2022)

Transverse Plane

Long-range resistive wall

- Synchrotron tune spread
  - Azimuthal head-tail modes damped
  - Radial head-tail modes less affected
- Diffusion due to quantum excitation must be included

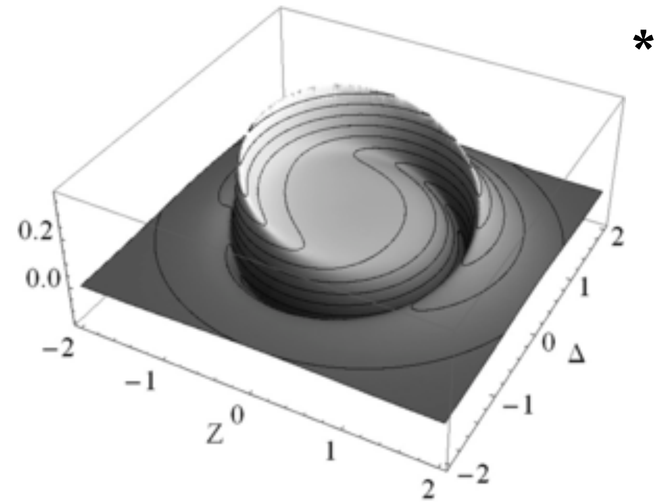


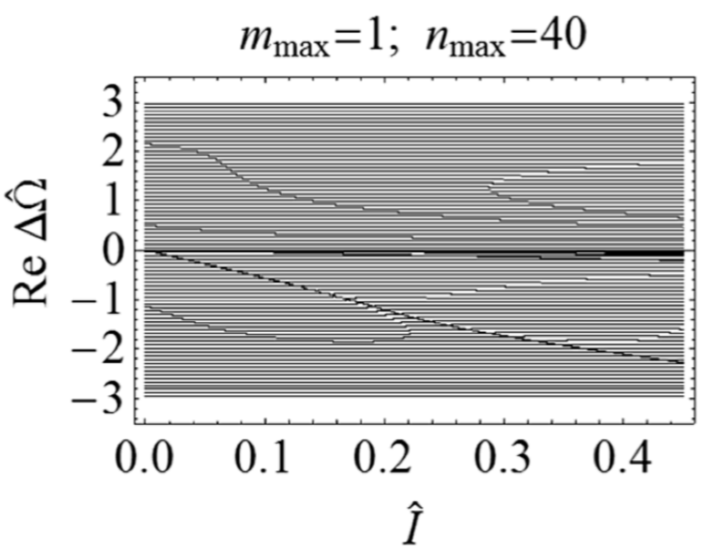
*F. J. Cullinan, R. Nagaoka, G. Skripka & P. F. Tavares, PRAB **19** 124401 (2016)
R. R. Lindberg, PRAB **19** 124402 (2016)
T. Suzuki, Part. Accel. **12** 237 (1982)
F. Cullinan, R. Nagaoka, G. Skripka & P. F. Tavares, presented at NOCE, Arcidosso, Italy (2017)

Transverse Mode-Coupling (TMCI)

Flat potential:

- Amplitude dependence of synchrotron tune means that head-tail modes are always coupled for one part of beam
  → Lower threshold current predicted





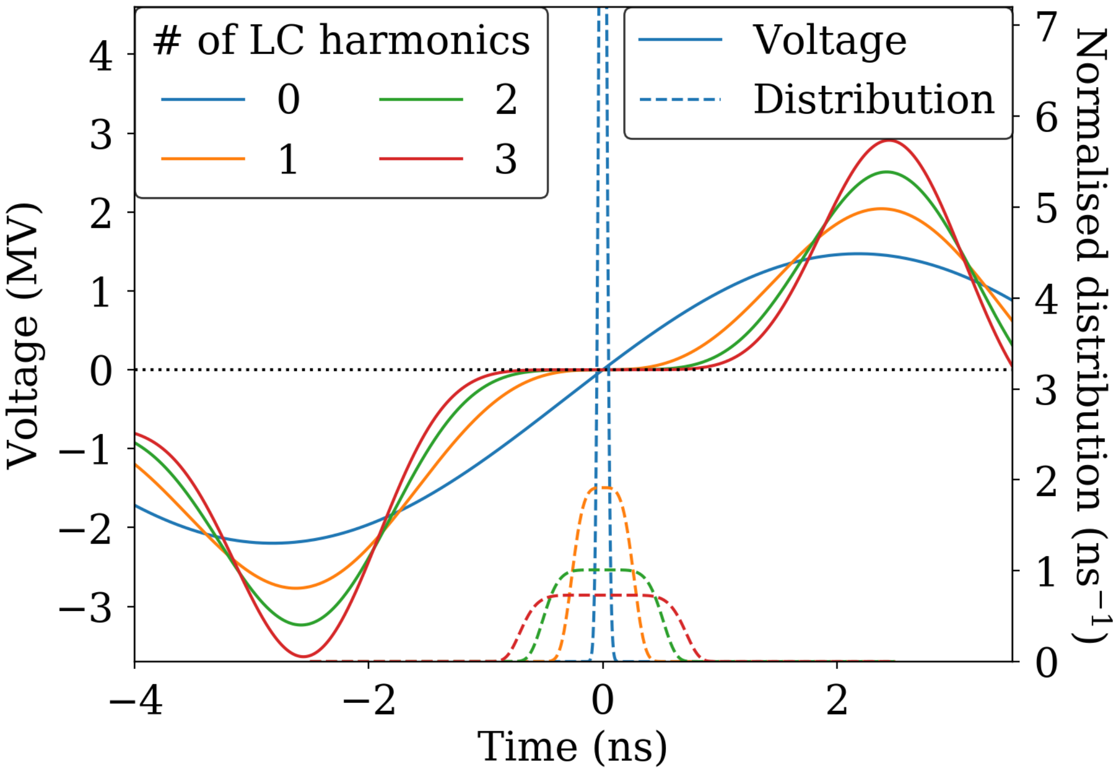
*M. Venturini, PRAB **21** 024402 (2018)

Future Directions

Multiple Higher Harmonics

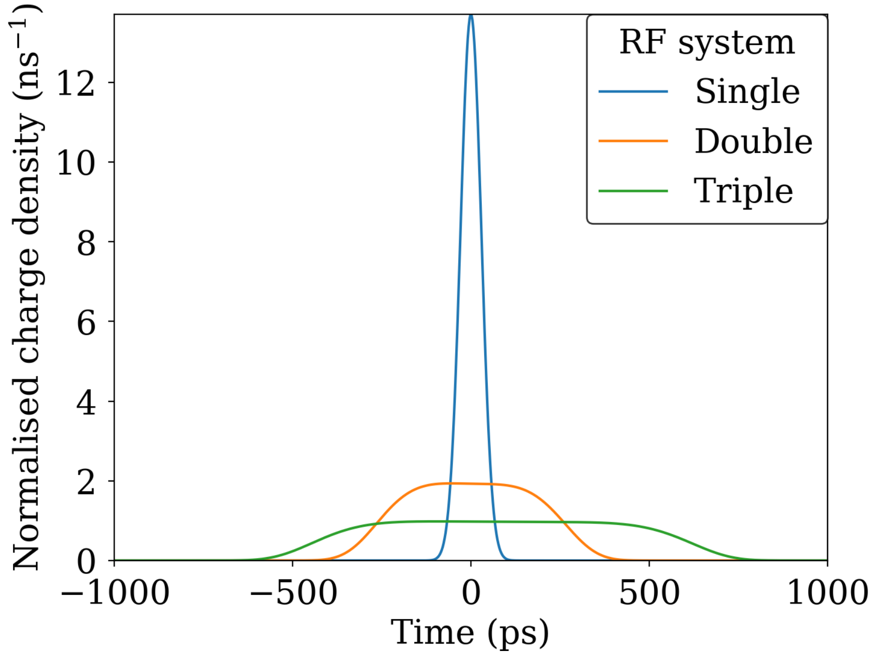
Developed by
Å. Andersson &
P. F. Tavares

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



Triple RF system

- 3rd-harmonic cavities can be passive

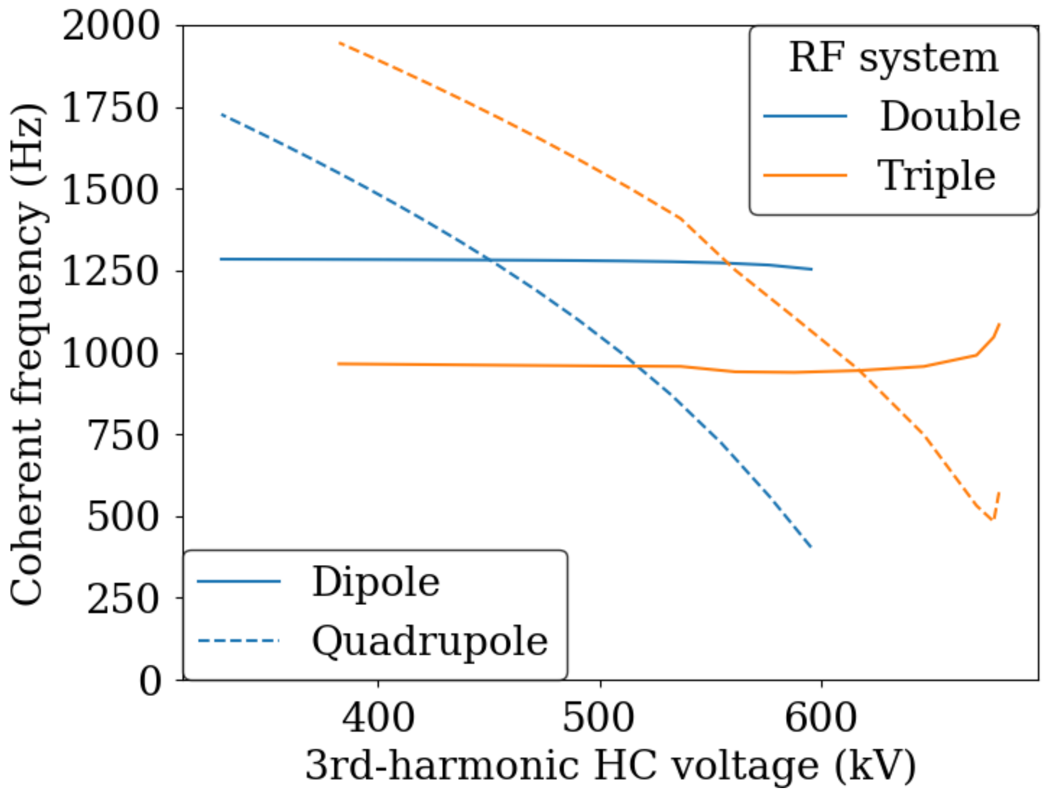


Parameter	Single	Double	Triple
RF voltage (MV)	1.8	1.8	1.5
RMS bunch duration (ps)	29.1	166	312
Detuning of 3rd-harmonic cavity (kHz)	-	94.4	70.4
Voltage in 3rd-harmonic cavity (kV)	-	598	703
Voltage in 5th-harmonic cavity (kV)	-	-	140
Phase of 3rd-harmonic cavity (degrees)	-	-174	-174
Phase of 5th-harmonic cavity (degrees)	-	-	3.5

Robinson coupling

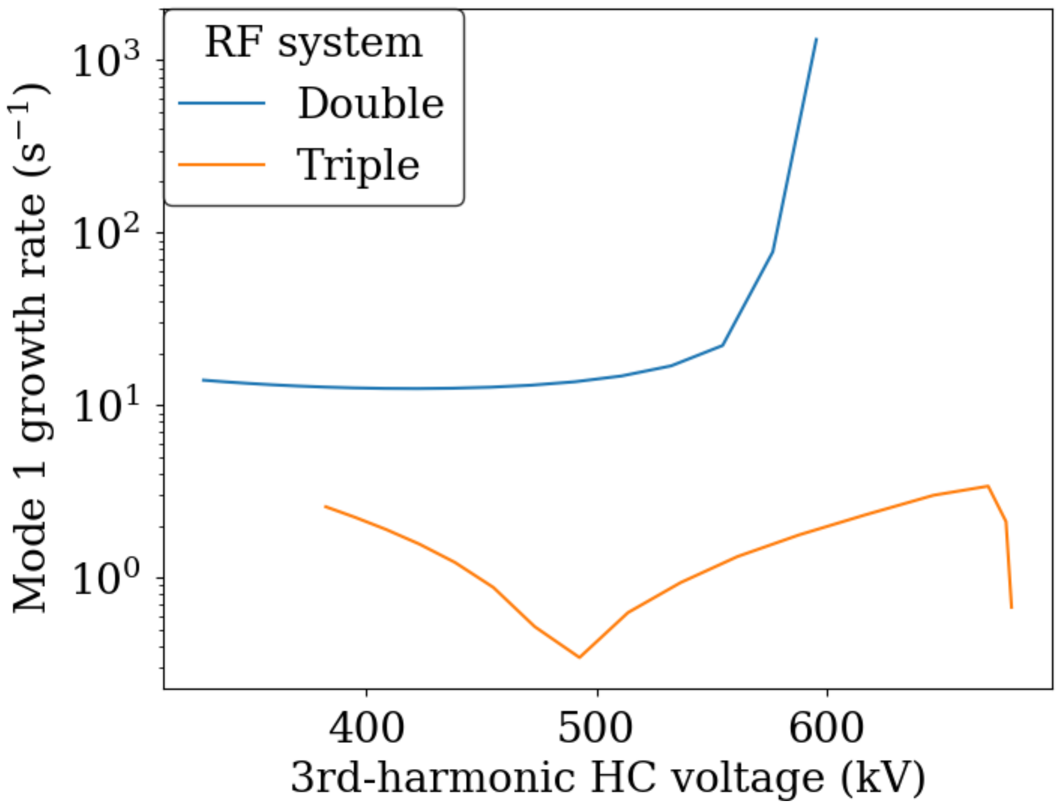
- 5th Harmonic cavity (EU type): R_s=3.1×10^6, Q_0=27000

- Robinson mode coupling still present, potentially worse
- Active damping still needed



Mode 1 stability

- Impedance of 5th-harmonic cavity damps mode 1



Conclusion

- Harmonic cavities have both stabilising and destabilising effects
  - + Longer bunches - rejection of (high-frequency) impedance
  - + Synchrotron tune spread - Landau damping
  - - Lower synchrotron frequency - longitudinal focussing, head-tail mode separation (TMCI)
  - - Large impedance - Robinson, mode-1
- Various implementations of harmonic cavities exist with different advantages (active/passive, super/normal conducting)
- Collective effects must be comprehensively studied with full effect of harmonic cavities included
- Even more bunch lengthening can be achieved with additional harmonic cavities at higher harmonics
  - 5th-harmonic cavity under construction for MAX IV 3 GeV ring

MAX IV