# Collective Effects at MAX IV

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**8th Low-Emittance Rings Workshop, 2020, Frascati, Italy (virtual).**

# Outline

- Introduction to MAX IV, 3 GeV ring
- Landau cavities
- Bunch fill pattern used during delivery
- Determination of bunch distributions
- Evaluating stability of HOM-driven longitudinal coupled-bunch modes

For 1.5 GeV ring and more practical discussion, see IPAC talk (MC5 session)

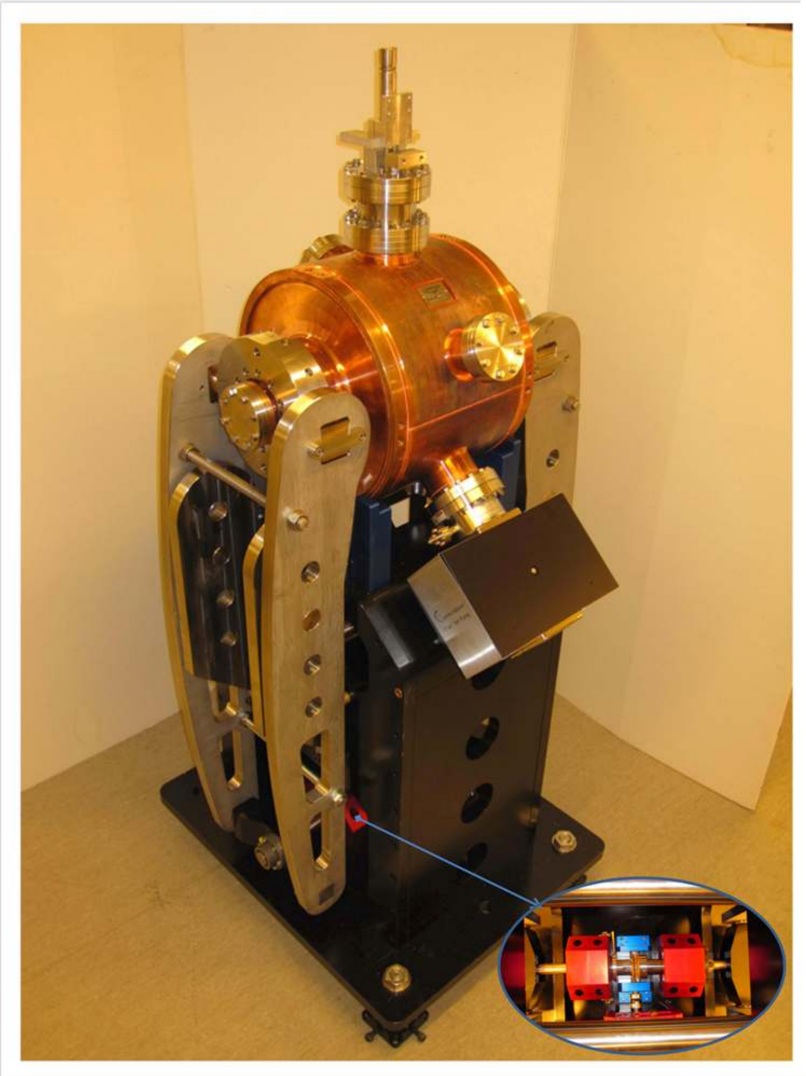
# The MAX IV Facility


## 3 GeV Ring

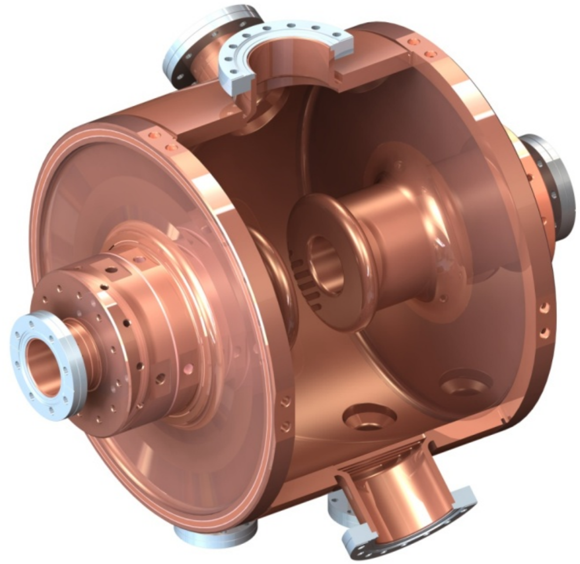
| Parameter | Value |
|---|---|
| RF frequency/MHz | 100 |
| Landau-cavity harmonic | 3 |
| Design current/mA | 500 |
| Natural bunch length/ps | 40 |
| Bunch length with ideal Landau-cavity lengthening/ps | 196 |
| Harmonic number | 176 |
| Number of main (Landau) cavities | 5(3) |

# Our 300 MHz 3rd Harmonic Cavities

Å. Andersson



Mechanical design, Elsayed Elafifi, MAX-lab

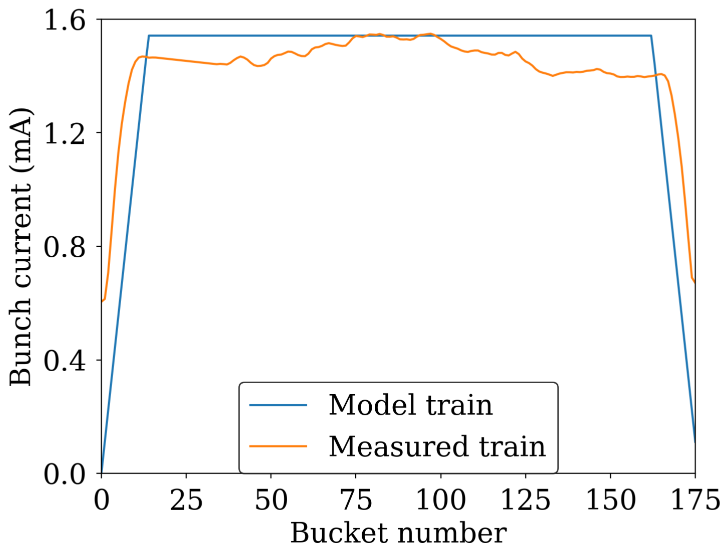


Inner length/diameter: 312mm/ 400mm

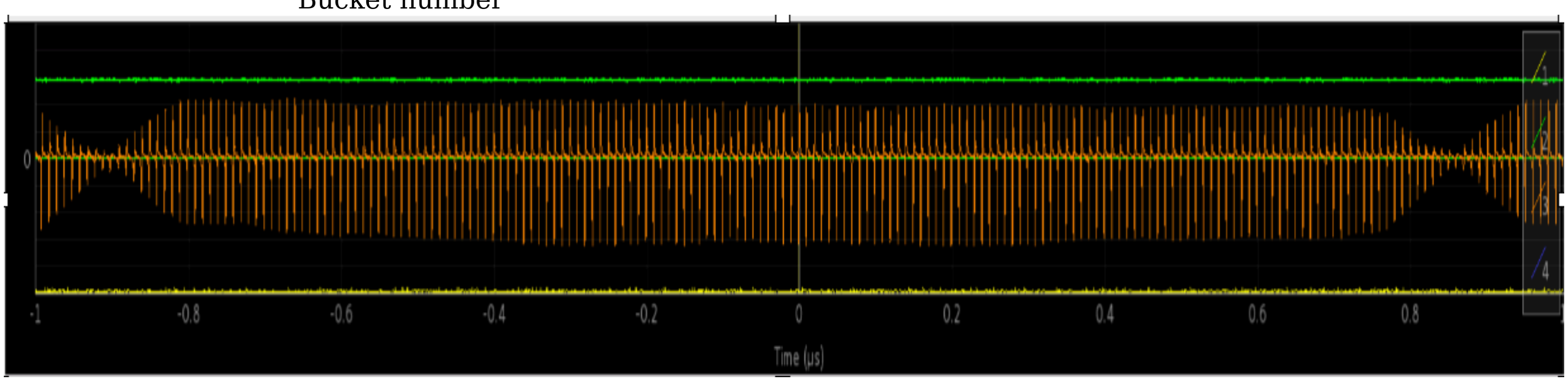
Theory $R_{sh}/Q$: 5.7MΩ/21600
(Definiton: $R_{sh} = V^2/P$)
Measured Q: Around 20900 ➔
$R_{sh}$ = 5.5 MΩ

# 3 GeV Ring Delivery

- 250 mA, nonuniform fill

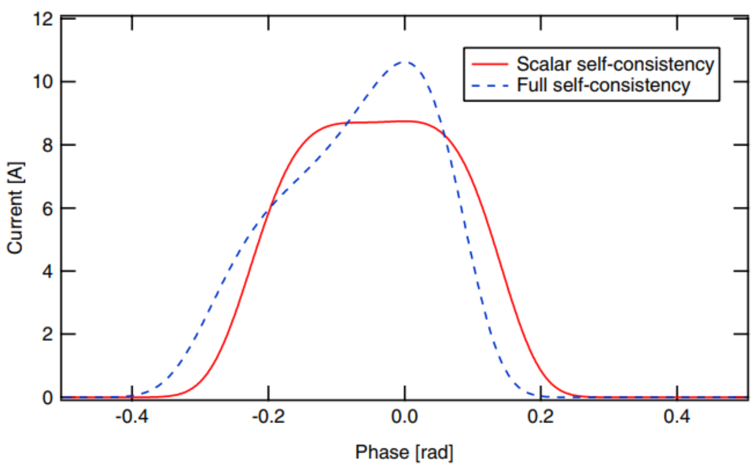


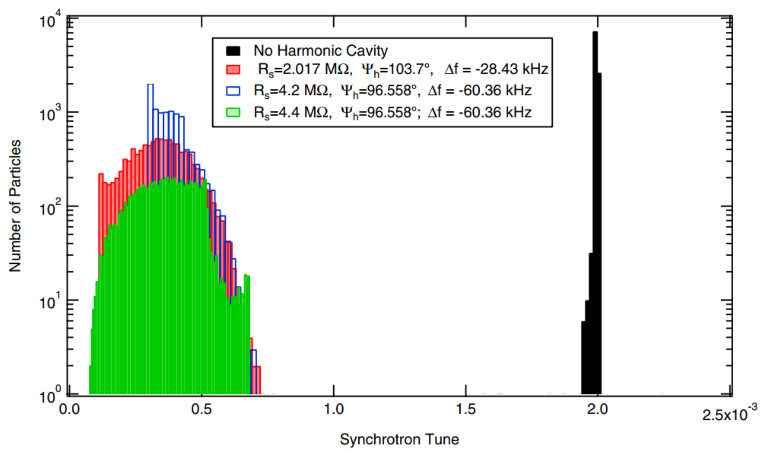




# Distributions with Landau cavities

- Bunch distribution calculation beyond flat potential in uniform fills
- Complex bunch form factor to account for asymmetries in longitudinal profile



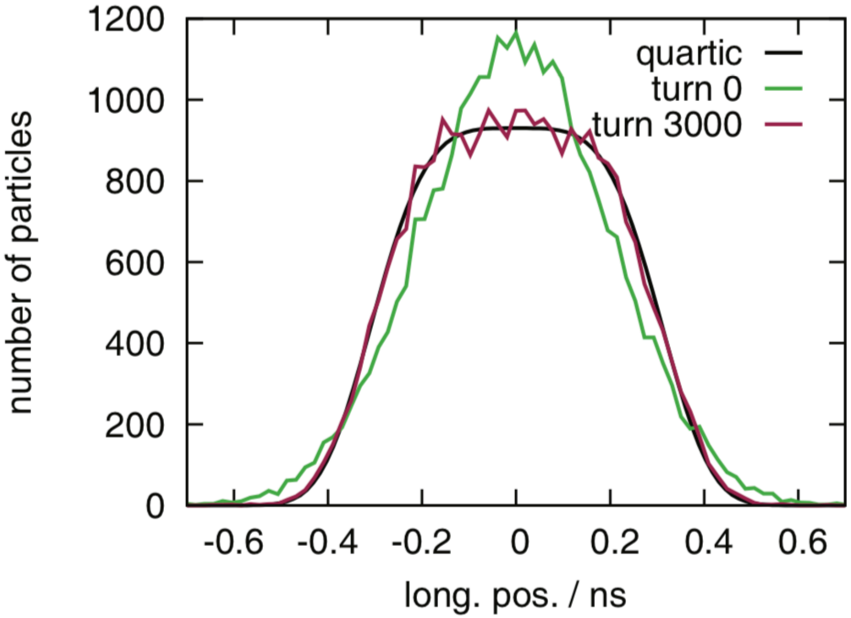

PRSTAB **17** 064401 (2014),
P. F. Tavares, Å Andersson, A Hansson & J. Breunlin,
**Equilibrium bunch density distribution with passive harmonic cavities in a storage ring**

P. F. Tavares

# Distributions with Landau cavities

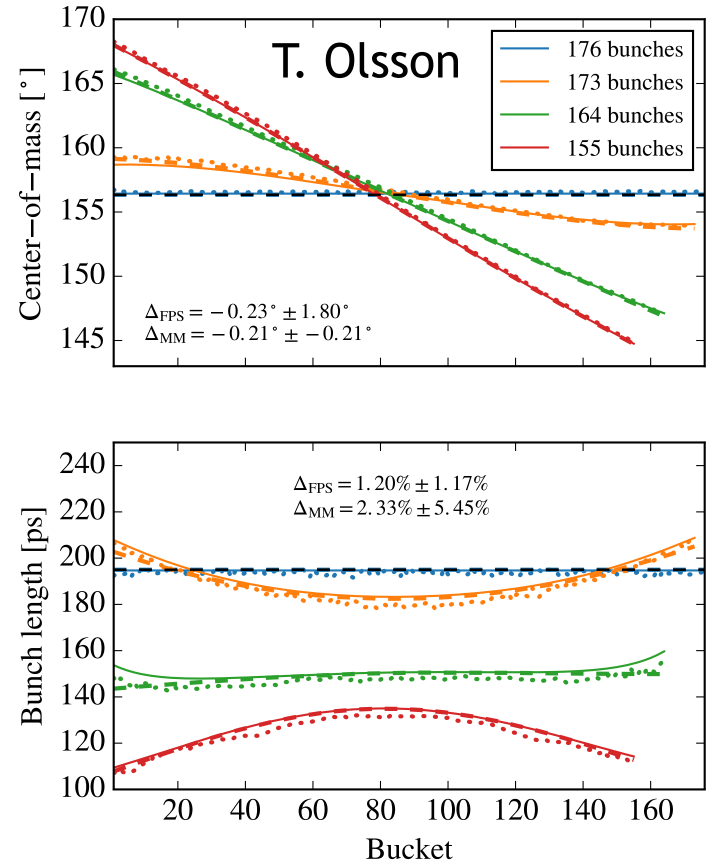
- Simultaneous development of macroparticle-tracking code *mbtrack* at SOLEIL

From M. Klein & R. Nagaoka, IPAC’13, MOPWO003 (2013)



# Nonuniform Fills

- Combine previous work with single-particle tracking to evaluate beam phase transients
- Excellent agreement with macroparticle tracking without a computing cluster




PRAB **21** 120700 (2018),
T. Olsson (now at DIAMOND), F. J. Cullinan & Å Andersson,
**Self-consistent calculation of transient beam loading in electron storage rings with passive harmonic cavities**

# Matrix Method

Determine equilibrium time offsets for each bunch:

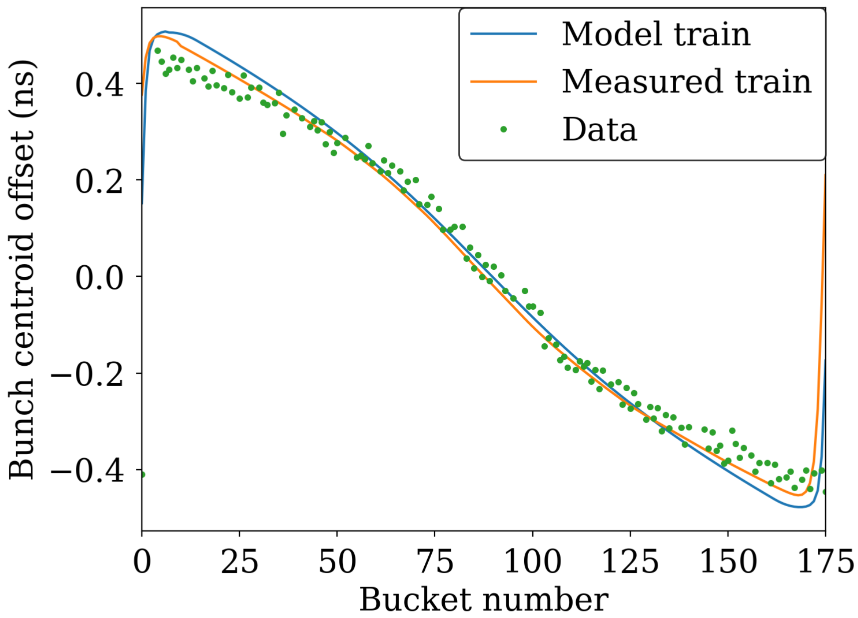
- Time domain method
- Each element is the beam-induced voltage from one bunch at the arrival time of another
- Determine roots (zero net energy gain) by Newton iteration
- Each iteration: bunch form factors and time offsets updated

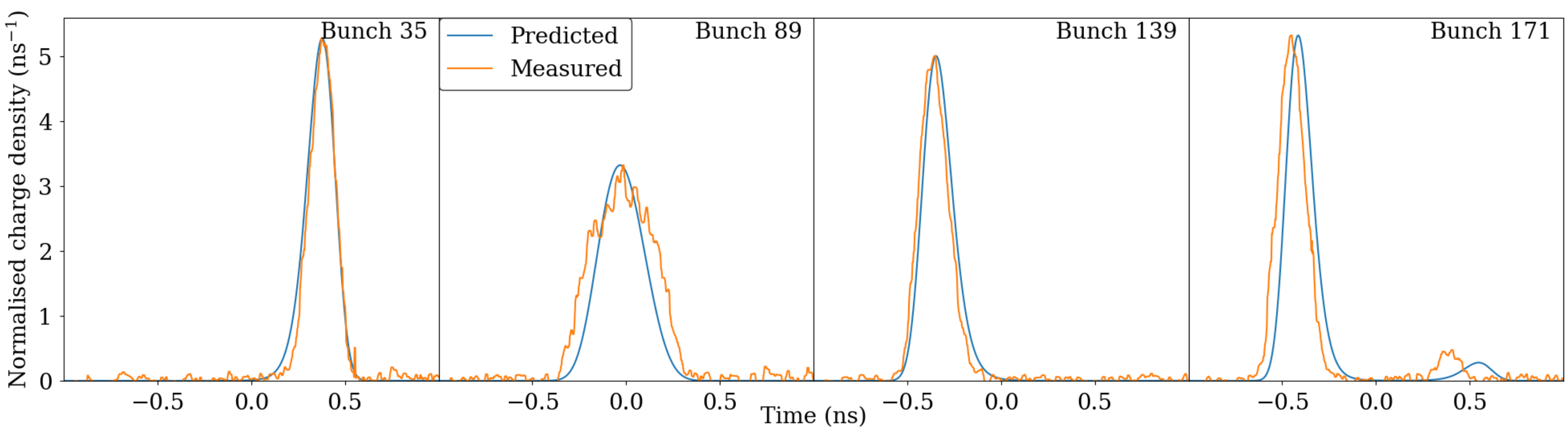
PRAB **21** 120700 (2018),
T. Olsson (now at DIAMOND), F. J. Cullinan & Å Andersson,
**Self-consistent calculation of transient beam loading in electron storage rings with passive harmonic cavities**

See also: R. Warnock & M. Venturini, PRAB **23** 064403 (2020)

# Matrix Method

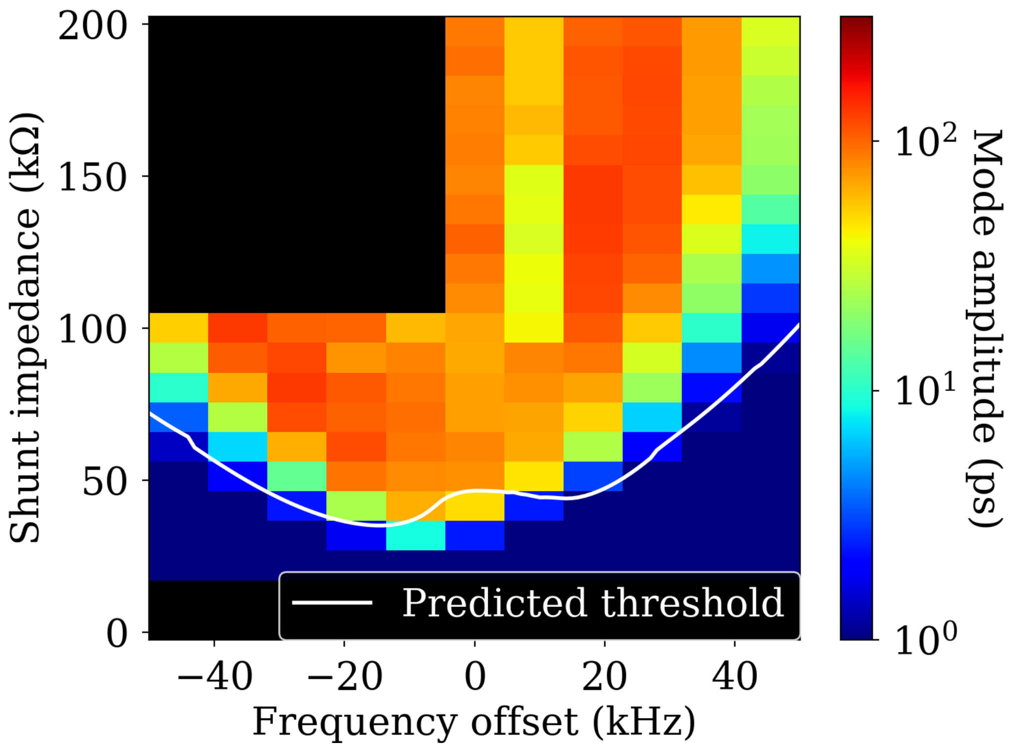
- Applied to delivery fill pattern



# Coupled-bunch Instabilities

- Use results from previous to determine stability against coupled-bunch instabilities
- Around 400 kV Landau-cavity voltage
- HOM Q=24000, frequency offset from (10h+167)$f_{rev}$




PRAB **23** 074402 (2020),
F. J. Cullinan, Å Andersson & P. F. Tavares,
**Harmonic-cavity stabilization of longitudinal coupled-bunch instabilities with a nonuniform fill**

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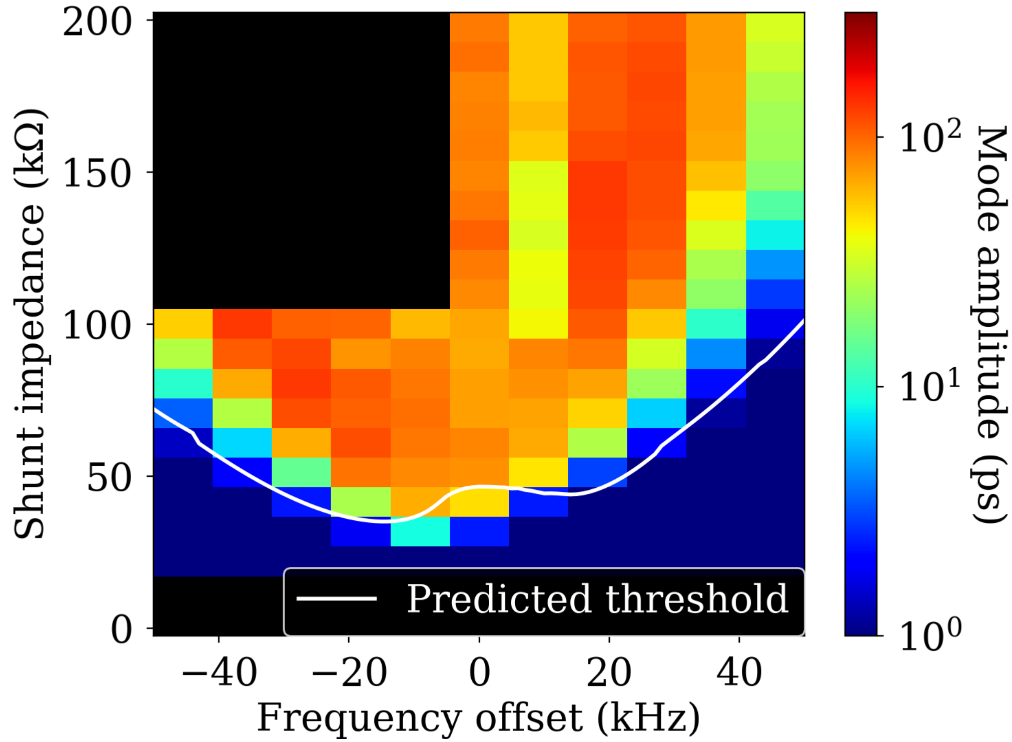
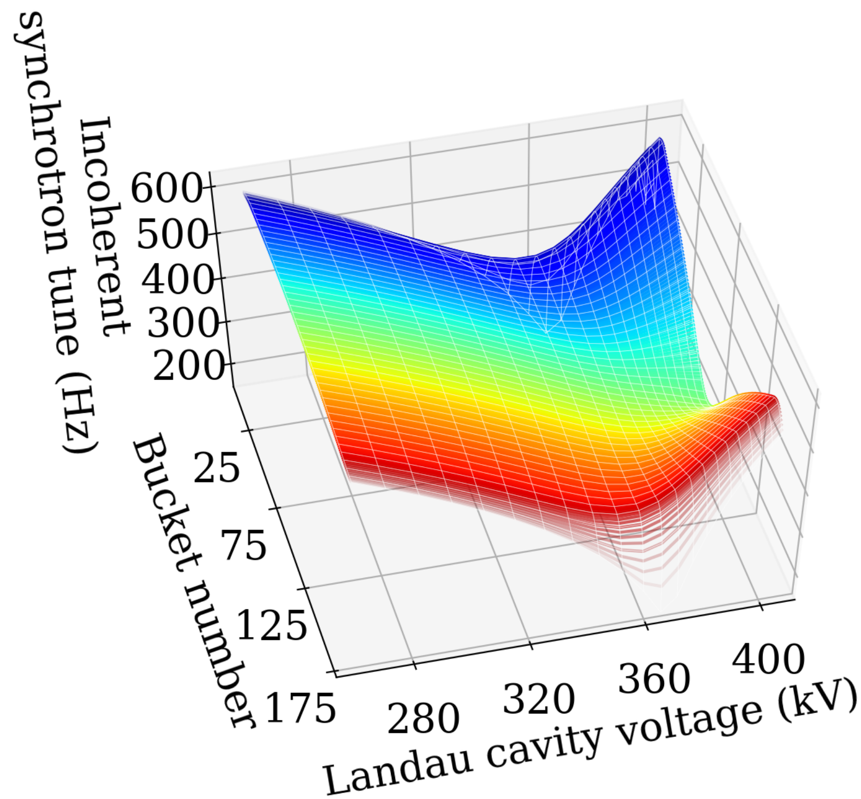



References on nonuniform fill:
G. Bassi, A. Blednych & V. Smaluk, PRAB **19** 024401 (2016)
G. Penco & M. Svandrik, PRSTAB **9** 044401 (2006) ← experimental
K. A. Thompson & R. D. Ruth, PAC'89 pp. 792-794 (1989)
K. A. Wang, P. J. Chou & A. W. Chao, PAC'01 pp 1981-1983 (2001)
O. Naumann & J. Jacob, PAC'87 pp. 1551-1553 (1987)

# Tune shift and spread

- Tune spread increases steeply when Landau-cavity voltage is increased above a certain value



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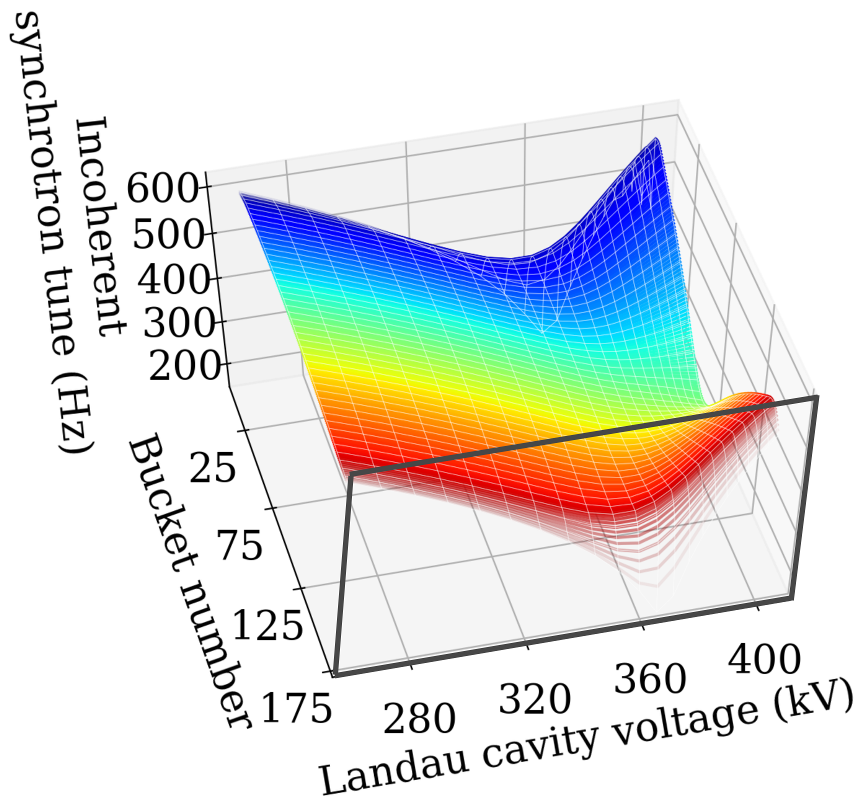

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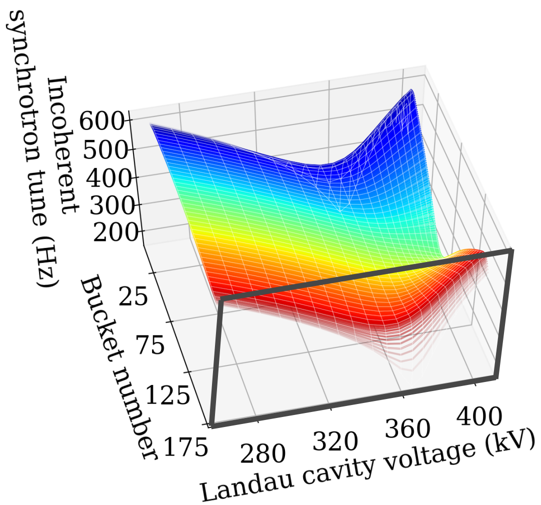
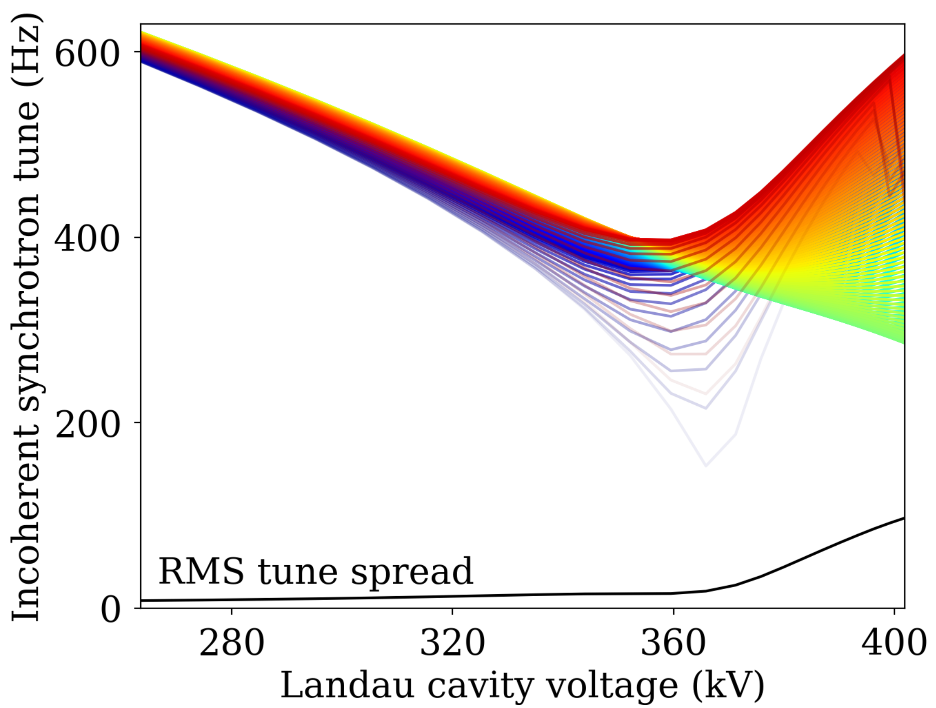
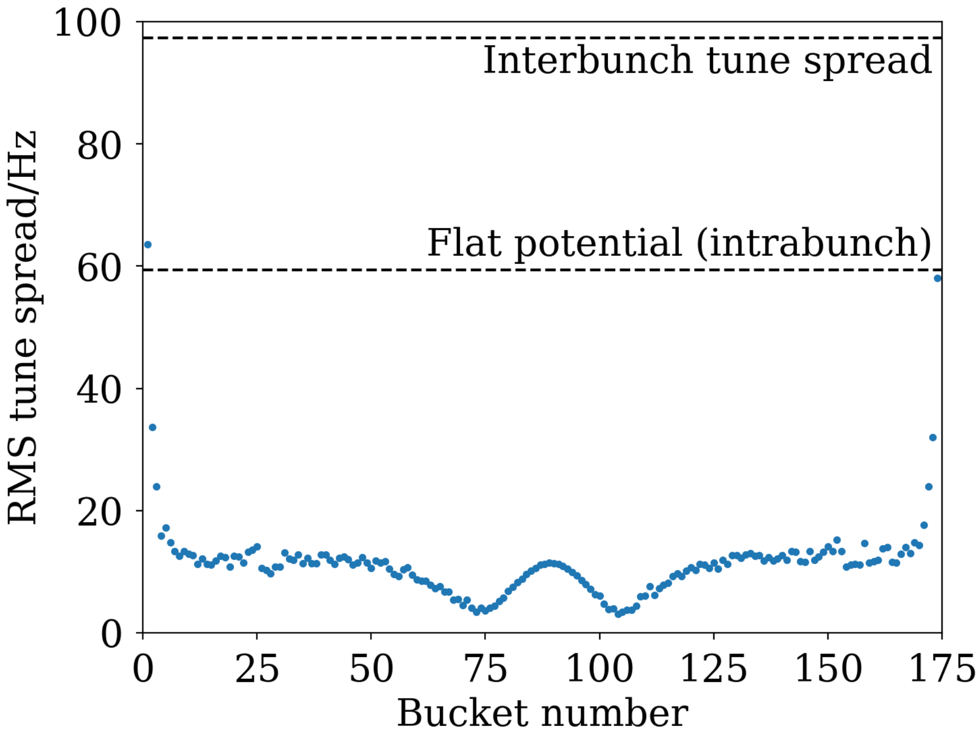


# Intrabunch vs Interbunch

- Tune spread within bunches much lower than between bunches



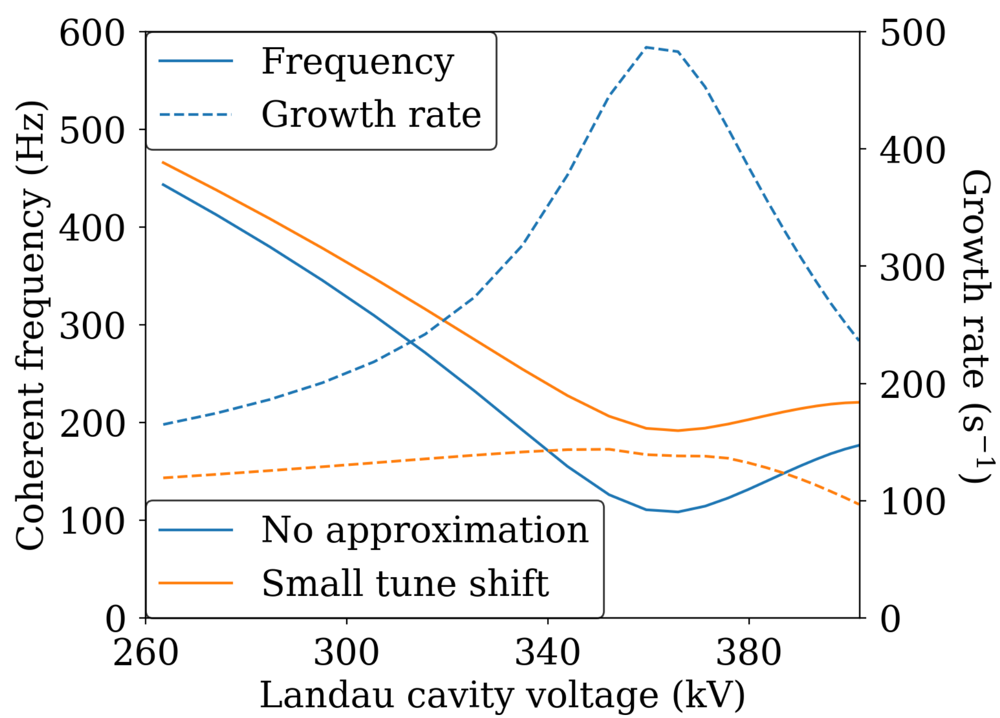

Uniform fill case:
S. Krinsky & J. M. Wang, Part. Accel. **17**:109-139 (1985)
M. Venturini, PRAB **21** 114404 (2018)
R. R. Lindberg, PRAB **21** 124402 (2018)

# Small tune-shift approximation

- Common to assume small tune-shift → eigenvalue λ is coherent complex frequency Ω
- Without assumption:

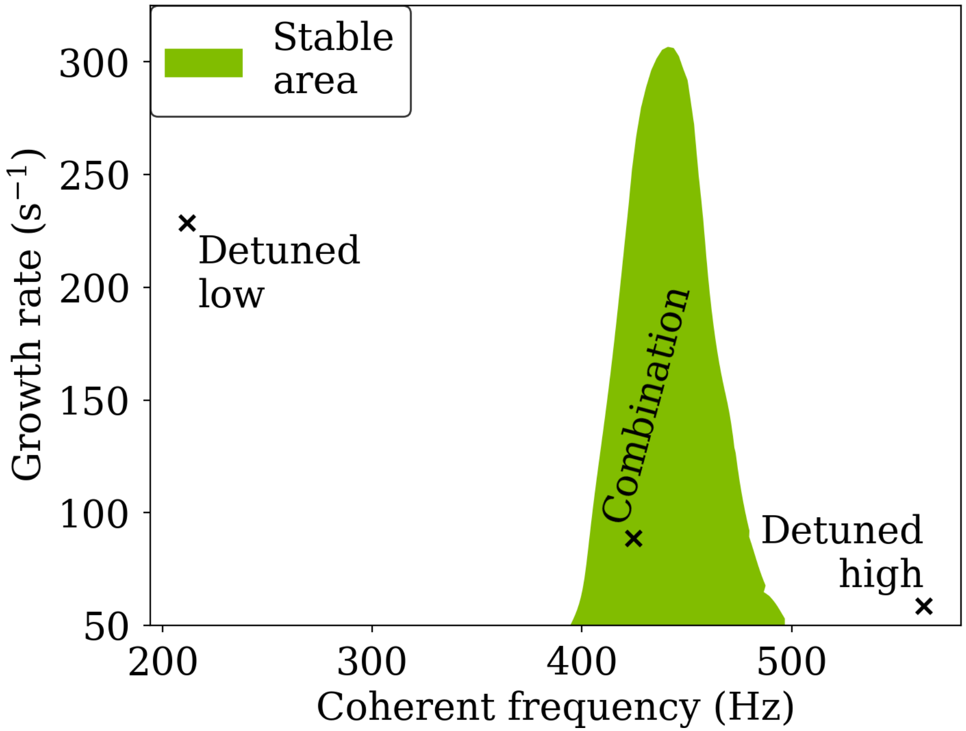
$$\mathrm{Re}(\Omega) = \sqrt{\frac{\mathrm{Re}(\lambda) + |\lambda|}{2}} \qquad \mathrm{Im}(\Omega) = \frac{\mathrm{Im}(\lambda)}{2\mathrm{Re}(\Omega)}$$

- HOM Rs=325 kΩ
- Frequency offset:
  -175 kHz



# Tuning of HOMs

- Coherent frequencies and growth rates in the absence of Landau damping
- Same HOM as before but two, each detuned by +/-175 kHz




Pointed out in: M. Venturini, PRAB **21** 114404 (2018)

# Conclusion

- Nonuniform fill pattern is used in MAX IV 3 GeV ring for reasons of stability
- Accurate numerical evaluation of bunch equilibrium time offsets and bunch profiles
- Evaluation of stability agrees well with macroparticle tracking
- Tune spread between bunches dominant
- Must allow for large coherent tune shifts
- HOM reactive impedance important for stability