Review of Harmonic Cavities in Fourth-Generation Storage Rings

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67th ICFA Advanced Beam Dynamics Workshop on Future Light Sources,
Lucerne, Switzerland, August 2023.

MAX IV

Outline

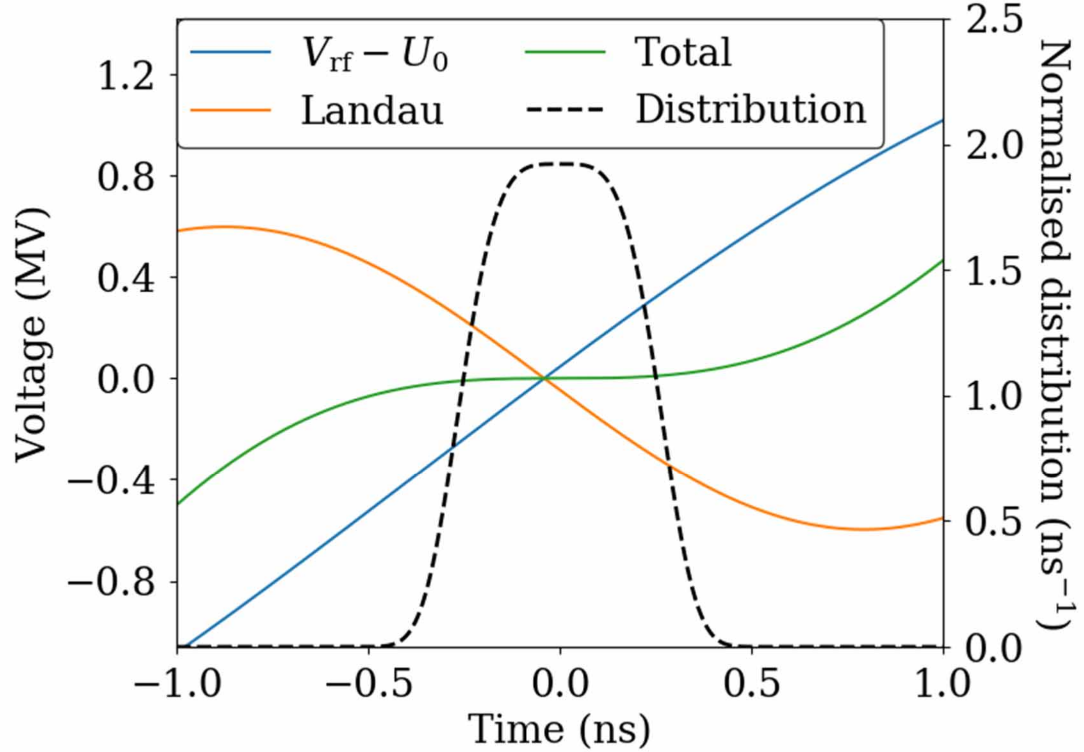
- Introduction to harmonic cavities
- Survey of solutions at 4th generation storage-ring light-sources
- Collective effects
- Cavities at multiple harmonics

HarmonLIP

- LEAPS internal project supported by LEAPS Working Group 2
- 1.5 day workshop in October 2022 at MAX IV in Lund, Sweden
- Next workshop to be hosted by ESRF in March 2024

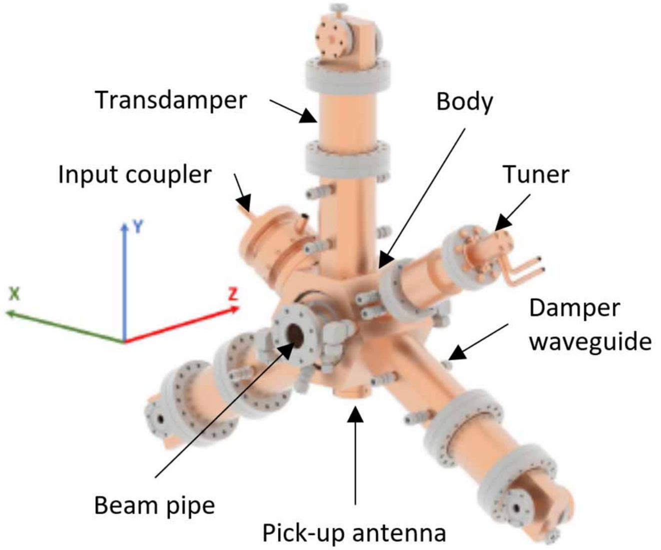
Harmonic Cavities (HCs)

- Harmonic cavities used to flatten the RF potential to lengthen the bunches
  - Longer Touschek lifetime
  - Less intrabeam scattering
  - Reduced heating of vacuum components



J. M. Byrd & M. Georgsson, PRSTAB 4 030701 (2001)
M. Georgsson, Å. Andersson & M. Eriksson, NIM A 416 2-3 pp 465-474 (1998)

Types of Harmonic Cavity

	Passive	Active
Normal conducting (MAX IV 300 MHz)	 Å Andersson et al., "The 100 MHz RF System for the MAX IV Storage Rings", IPAC 2011, San Sebastián, Spain.	 F. Perez et al., "3HC - Third Harmonic Normal Conducting Active Cavity Collaboration between HZB, DESY and ALBA", IPAC 2022, Bangkok, Thailand.
Superconducting	 P. Bosland et al., "Third Harmonic Superconducting Passive Cavities in ELETTRA and SLS", SRF XI, Trävemunde, Germany.	 P. Zhang et al. Radio-frequency system of the high energy photon source. Radiat Detect Technol Methods 7, 159–170 (2023).

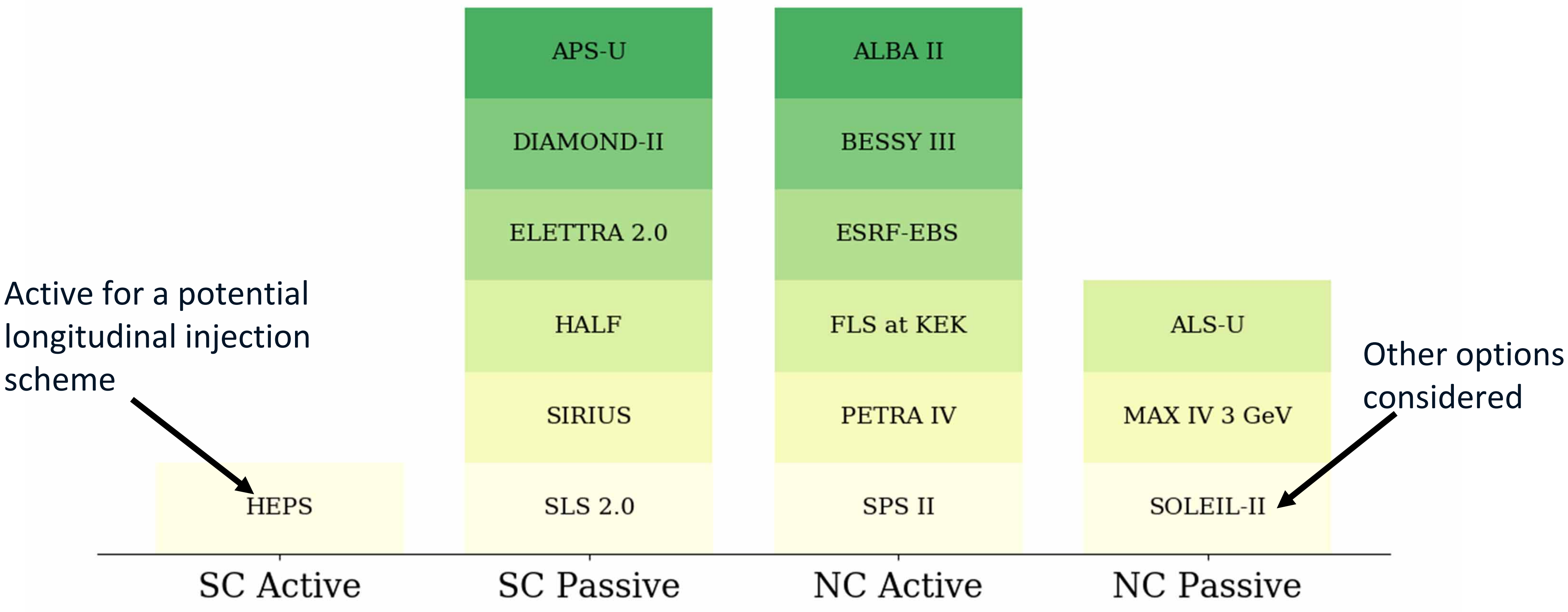
Survey

Harmonic Cavity Survey

- Survey of harmonic cavity systems carried out in preparation for HarmonLIP
- Extended outside Europe for this talk

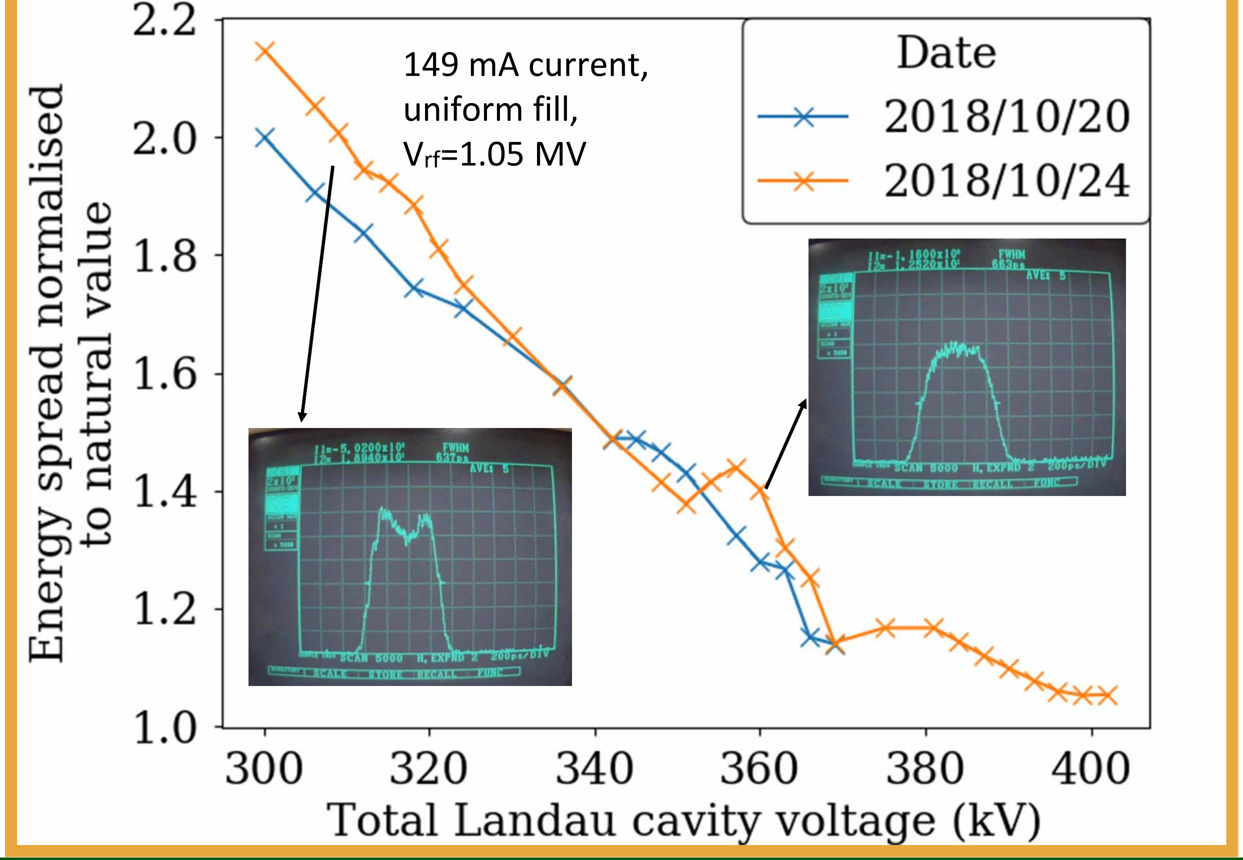
MAX IV 3 GeV
DIAMOND II
PETRA IV
FLS at KEK
SOLEIL-II
APS-U
BESSY III
HEPS
SLS 2.0
ESRF-EBS
ALS-U
HALF
ELETTRA 2.0
SIRIUS
ALBA II
SPS-II

Types of Harmonic Cavity - Survey



Damping of Longitudinal Coupled-Bunch Instabilities

F. Cullinan, Å. Andersson, and P. Tavares, IPAC2020, WEVIR05.

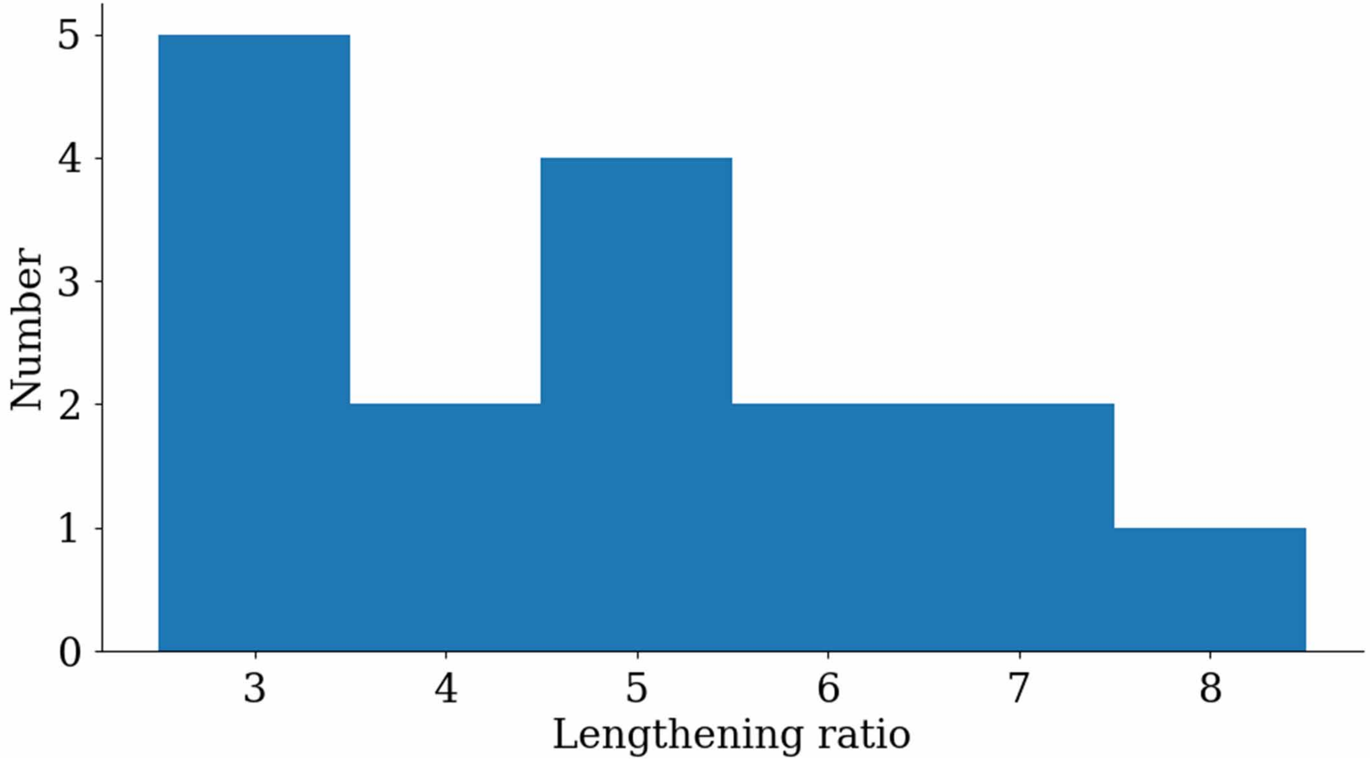


- +Longer bunches - rejection of (high-frequency) impedance
- +Synchrotron tune spread - Landau damping
- -Lower synchrotron frequency - longitudinal focussing

Not required for damping in (almost) any other 4th-generation synchrotrons

Lengthening Ratios

- As a multiple of the natural bunch length
- Not specified whether effect of short-range wakefield should be included
- Often a range given…



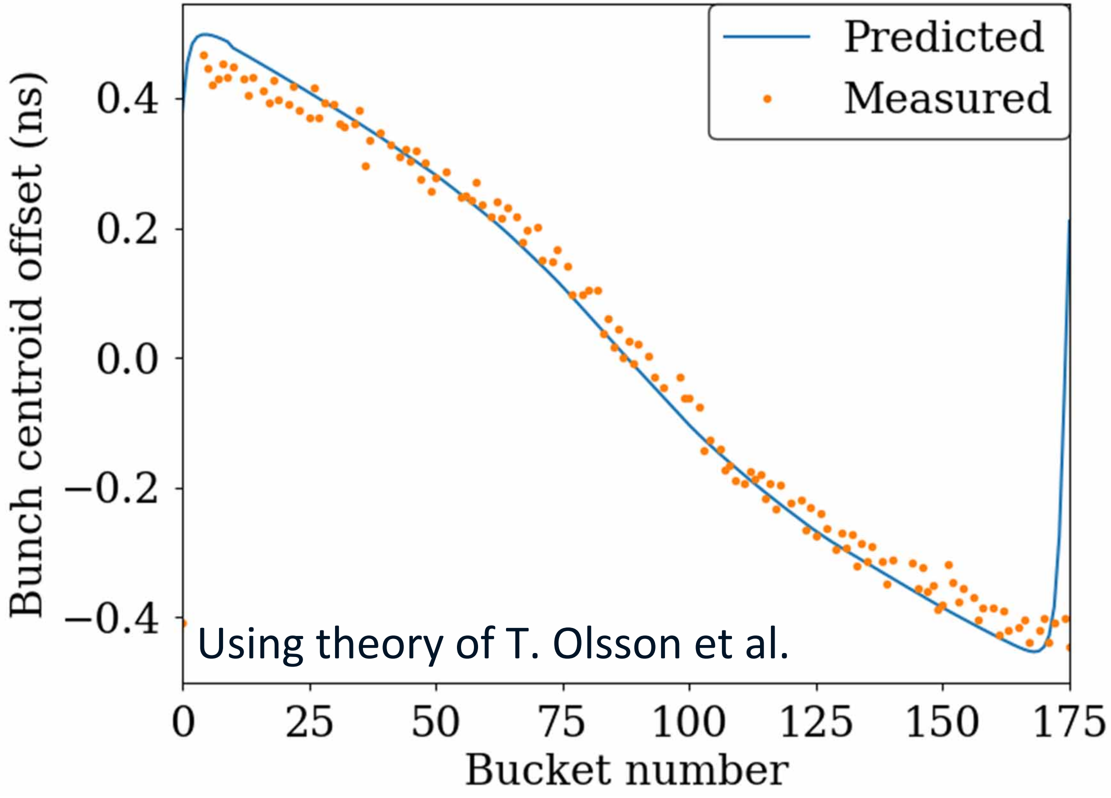
F. Cullinan, 67th ICFA Advanced Beam Dynamics Workshop on Future Light Sources: FLS 2023,
Lucerne, Switzerland, August 2023.

Fill Patterns - Semi-analytical Methods

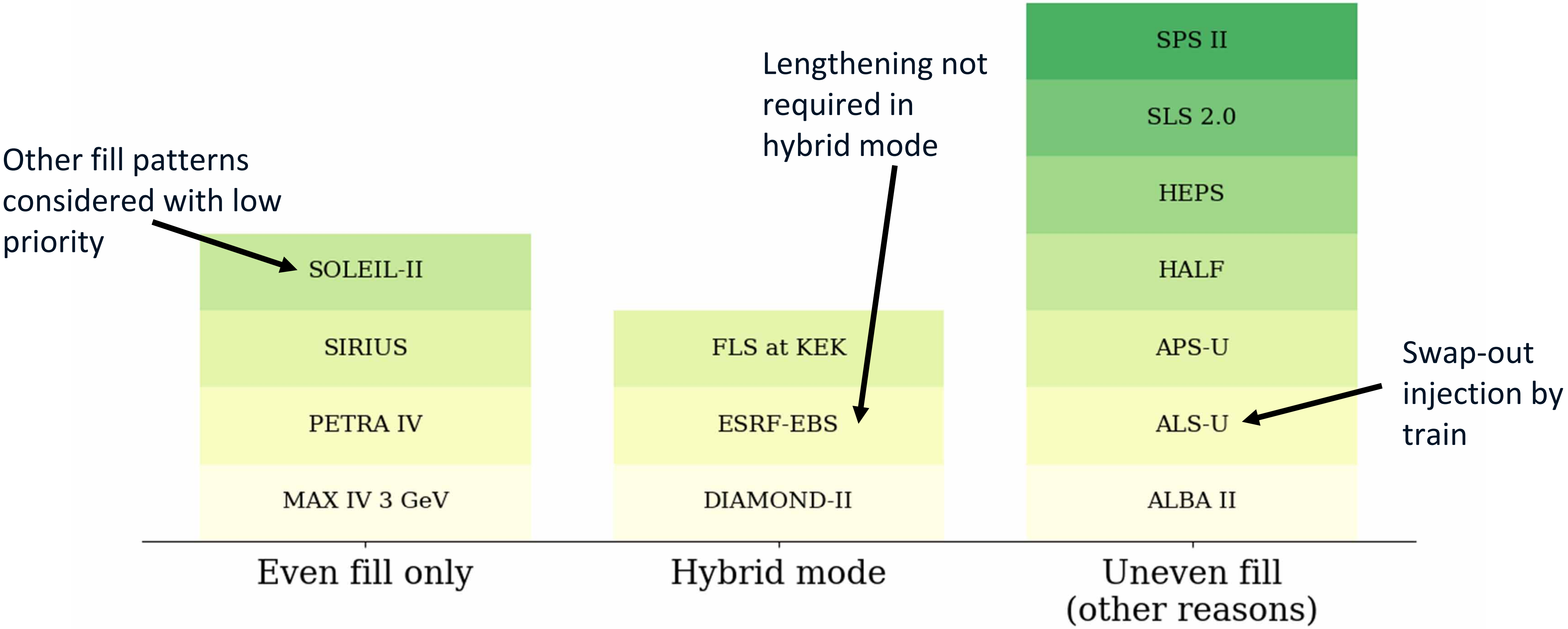
Semi-analytical methods developed:

- N. Yamamoto, T. Takahashi & S. Sakanaka, PRAB **21**, 012001, (2018).
- T. Olsson, F. J. Cullinan & Å. Andersson, PRAB **21**, 120701 (2018).
- R. Warnock & M. Venturini, PRAB **23**, 064403 (2020).
- R. Warnock, PRAB **24**, 024401 (2021) and PRAB **24**, 104402 (2021).
- T. He et al., PRAB **24**, 044401 (2021).

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



Fill Patterns - Survey



F. Cullinan, 67th ICFA Advanced Beam Dynamics Workshop on Future Light Sources: FLS 2023, Lucerne, Switzerland, August 2023.

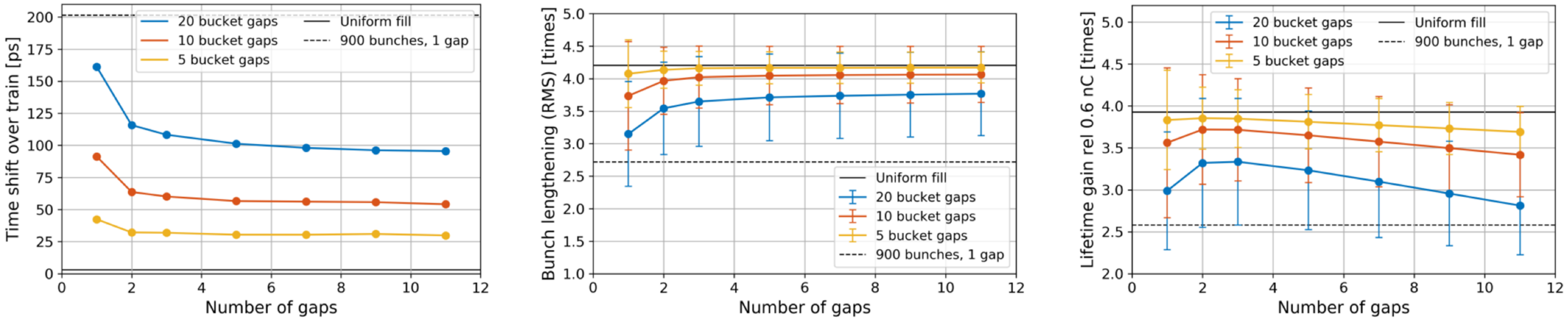
Fill Patterns - Multiple Trains

T. Olsson and H.-C. Chao, TUPOMS031, IPAC 2022, Bangkok, Thailand.

Transient Beam Loading

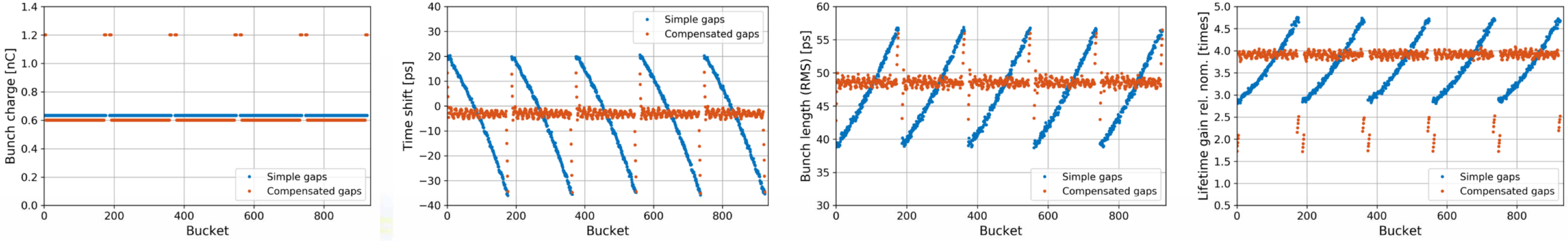
- Additional gaps helps up to the point where the bunch length no longer increases → lifetime gain decreases due to higher bunch charge.

Simulations for all IDs closed including 8 NC MCs with RF feedback, SC HC and longitudinal impedance.



- Future option to add guard bunches/compensated gaps but not included so far in favour of less complex fill pattern.

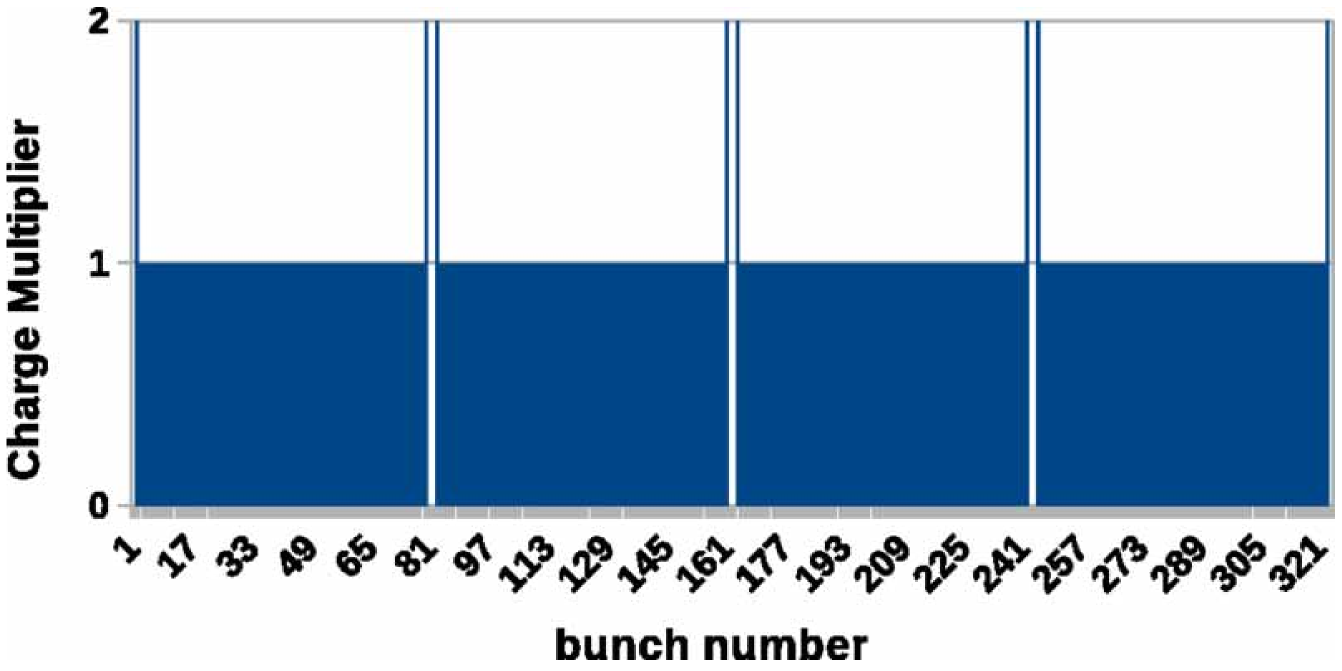
Example with 5 gaps of 10 buckets



Fill Patterns - Guard Bunches

- Reduce arrival time and bunch length variation along centre of train
- Help with ion clearing*

J. Calvey & M. Borland, PRAB **22**, 114403 (2019).



N. Milas and L. Stingelin, THPE084, IPAC 2010, Kyoto, Japan.
*J. Calvey & M. Borland, PRAB **22** 114403 (2019).

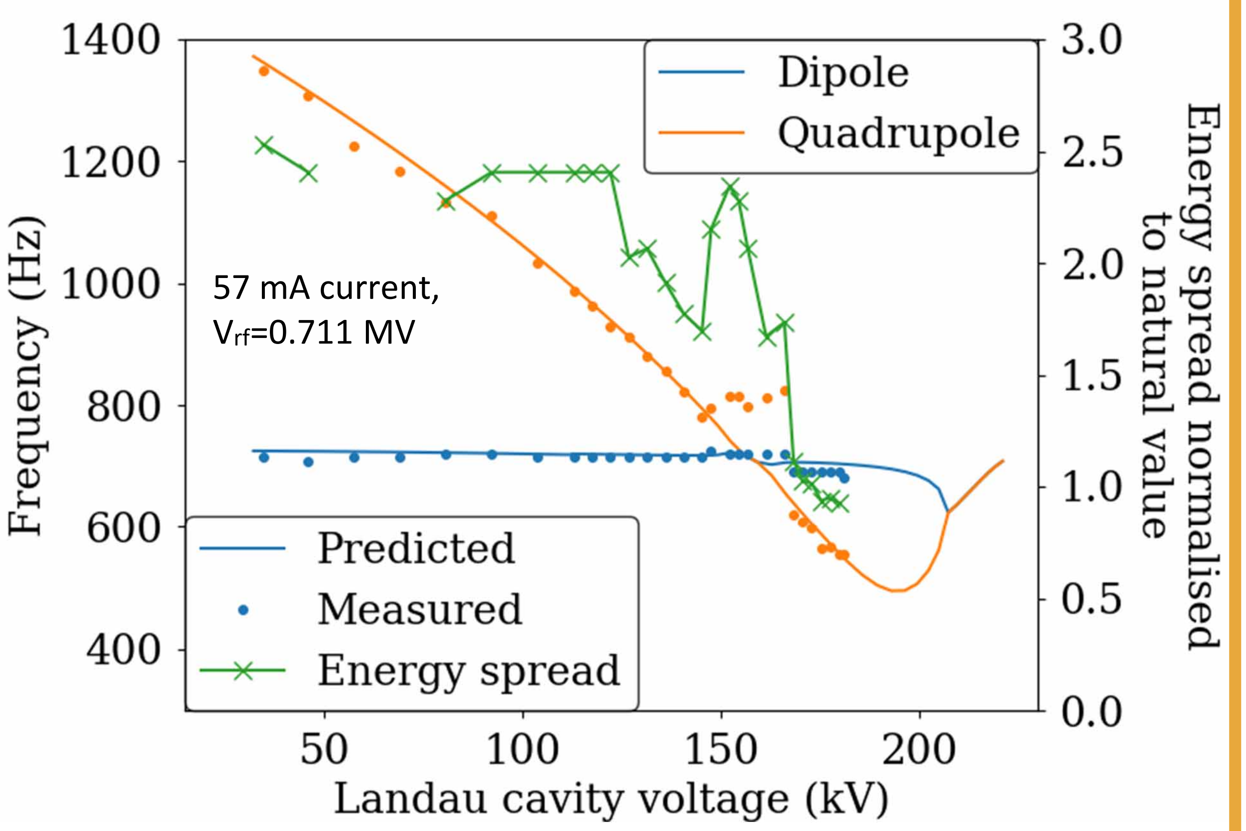
MAX IV

Collective Effects

Robinson Mode Coupling

- Can prevent reaching flat potential conditions
- Can be cured with a Mode-0 damper acting through main RF cavities*

F. Cullinan, Å. Andersson, and P. Tavares, IPAC2020, WEVIR05.



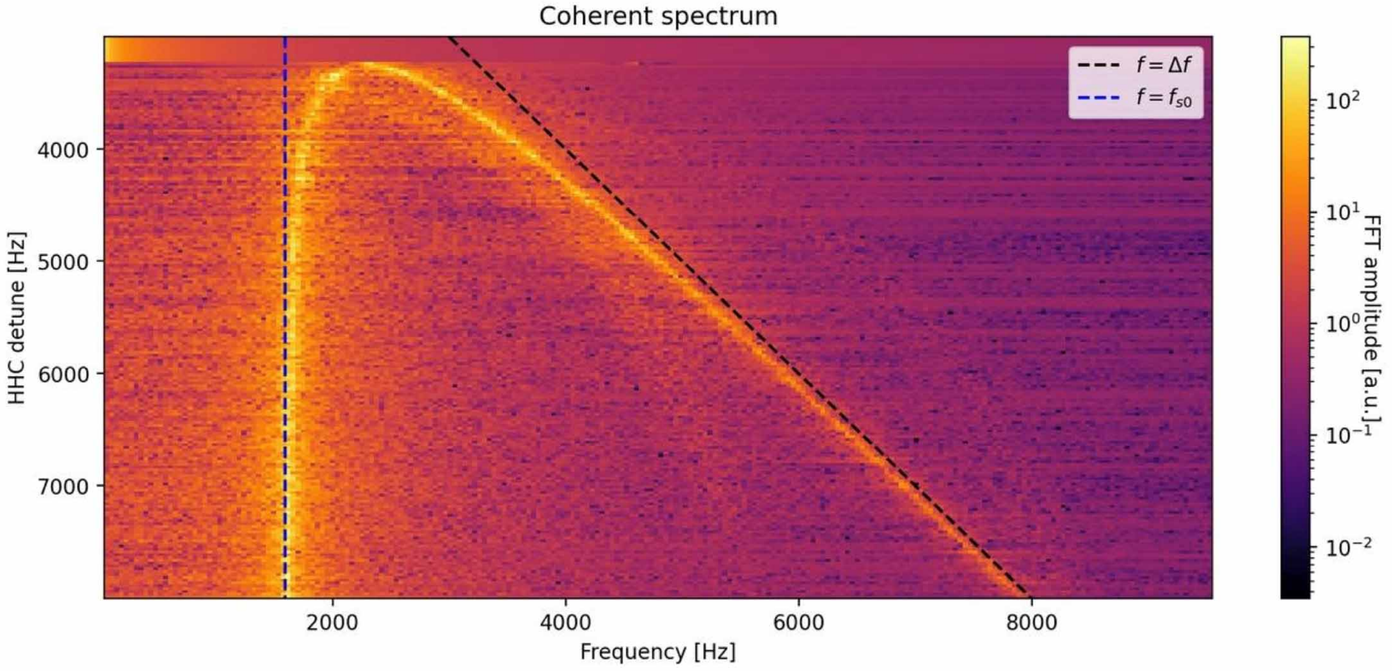
R. A. Bosch, K. J. Kleman & J. J. Bisognano, PRSTAB **4** 074401 (2001)

*D. P. McGinnis, LLRF 2019, Chicago, IL (2019)

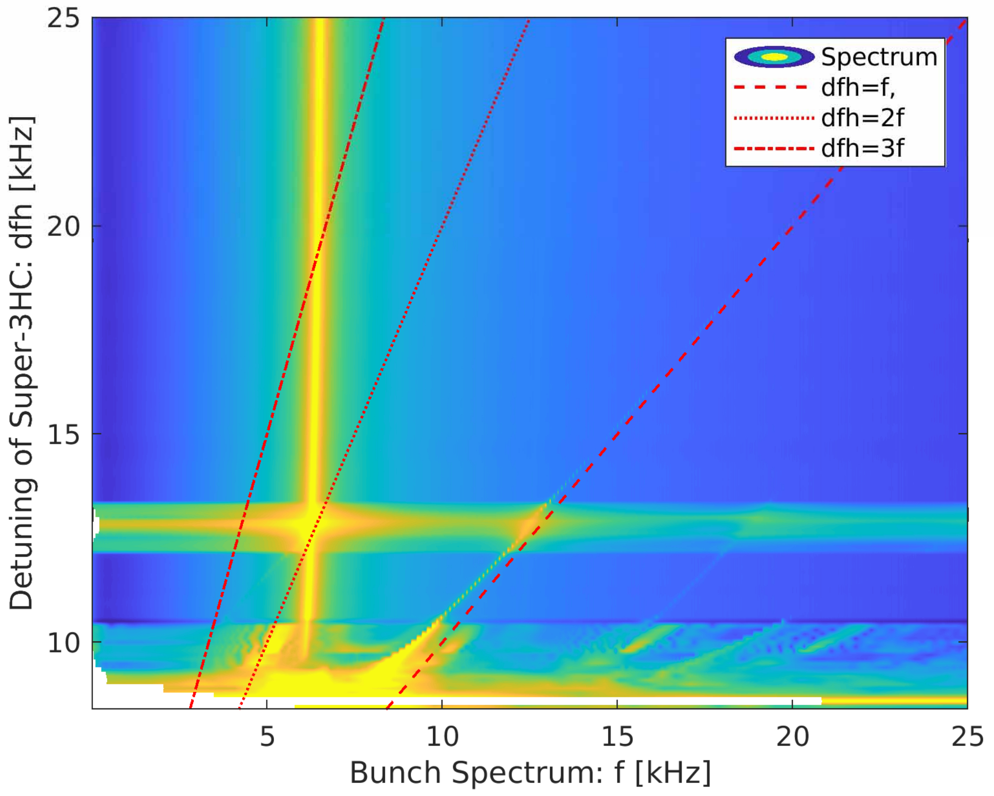
Robinson Modes - S and D Modes

- Two Robinson modes seen in simulation

A. Gamelin, I.FAST workshop 2022, Karlsruhe, Germany (2022)



See also A. Gamelin talk later (MO382)



L. Stingelin, HarmonLIP 2022, Lund, Sweden (2022)

F. Cullinan, 67th ICFA Advanced Beam Dynamics Workshop on Future Light Sources: FLS 2023, Lucerne, Switzerland, August 2023.

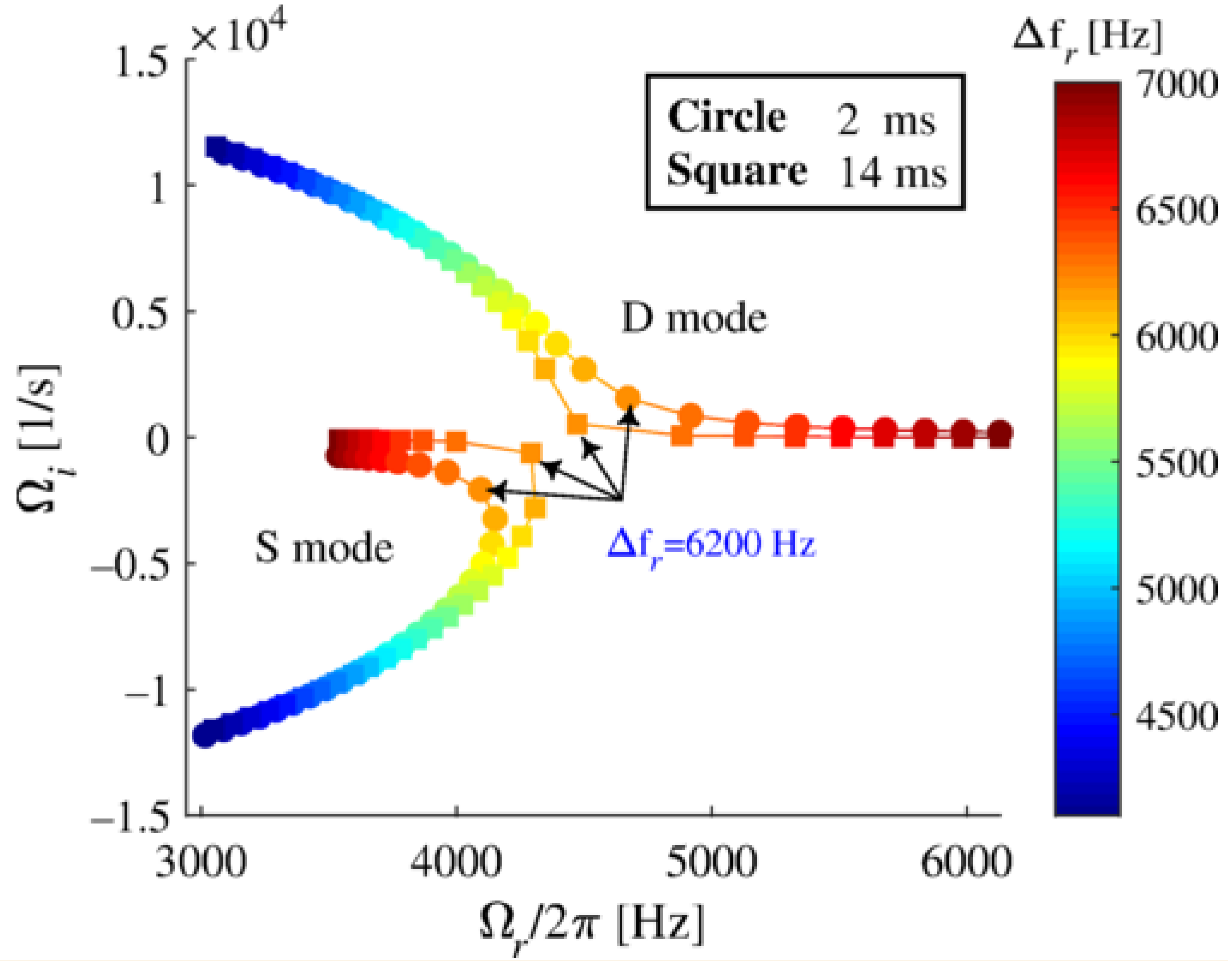
Robinson Modes - S and D Modes

- Second solution from single-particle Robinson instability equation + radiation damping

$$\Omega^2 - i\frac{2\Omega}{\tau_z} - \omega_s^2 = -i\frac{\omega_0 I_0 \alpha_c}{2\pi E/e}\sum_{p=-\infty}^{\infty}\left[p\omega_0 Z_{\parallel}(p\omega_0) - (p\omega_0+\Omega)Z_{\parallel}(p\omega_0+\Omega)\right]$$

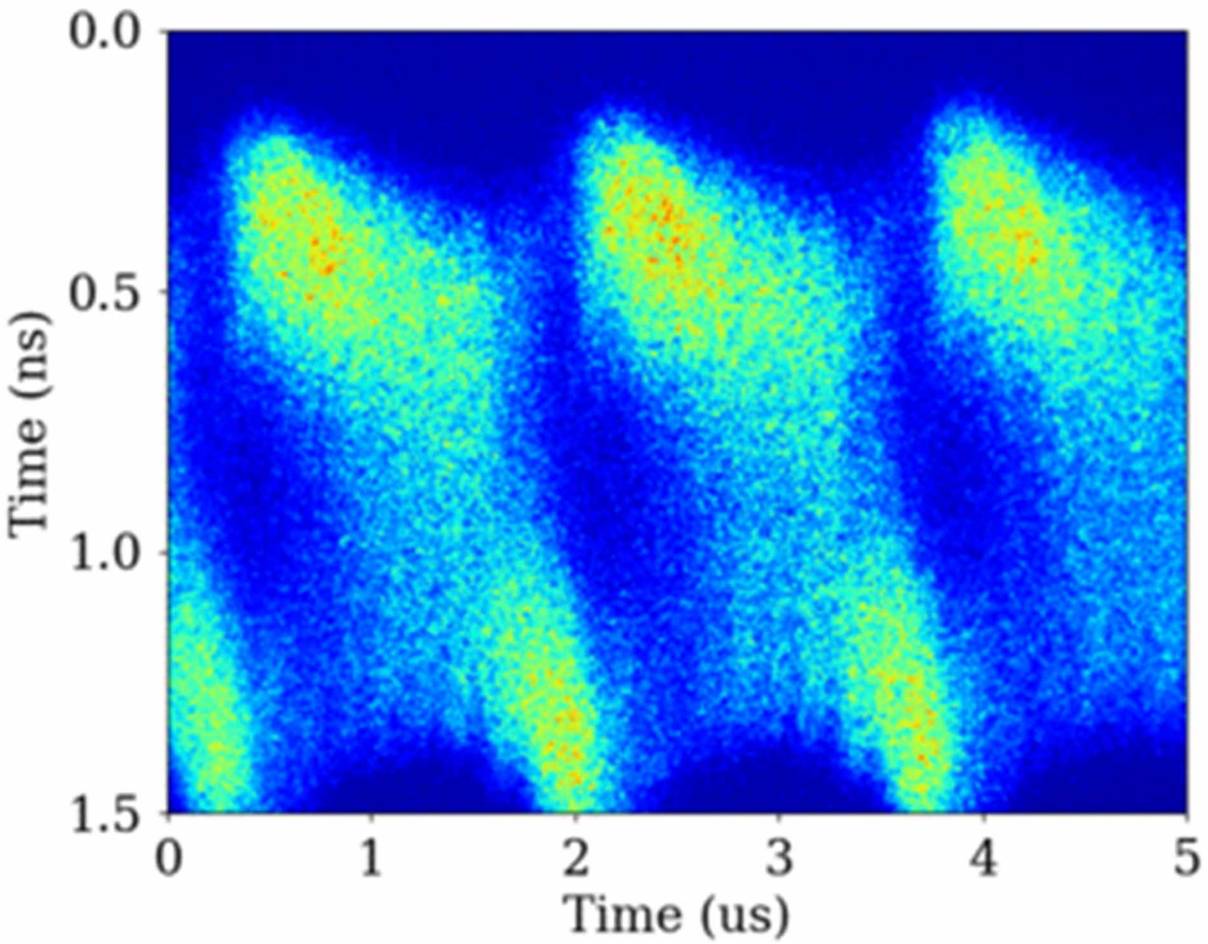
T. He et al., PRAB **26** 064403 (2023).

T. He et al., PRAB **26** 064403 (2023).



Mode 1 Excitation

- R. A. Bosch, K. J. Kleman & J. J. Bisognano, PRSTAB **4** 074401 (2001).
- M. Venturini, PRAB 21, 114404 (2018).
- T. He, PRAB **25** 024401 (2022).

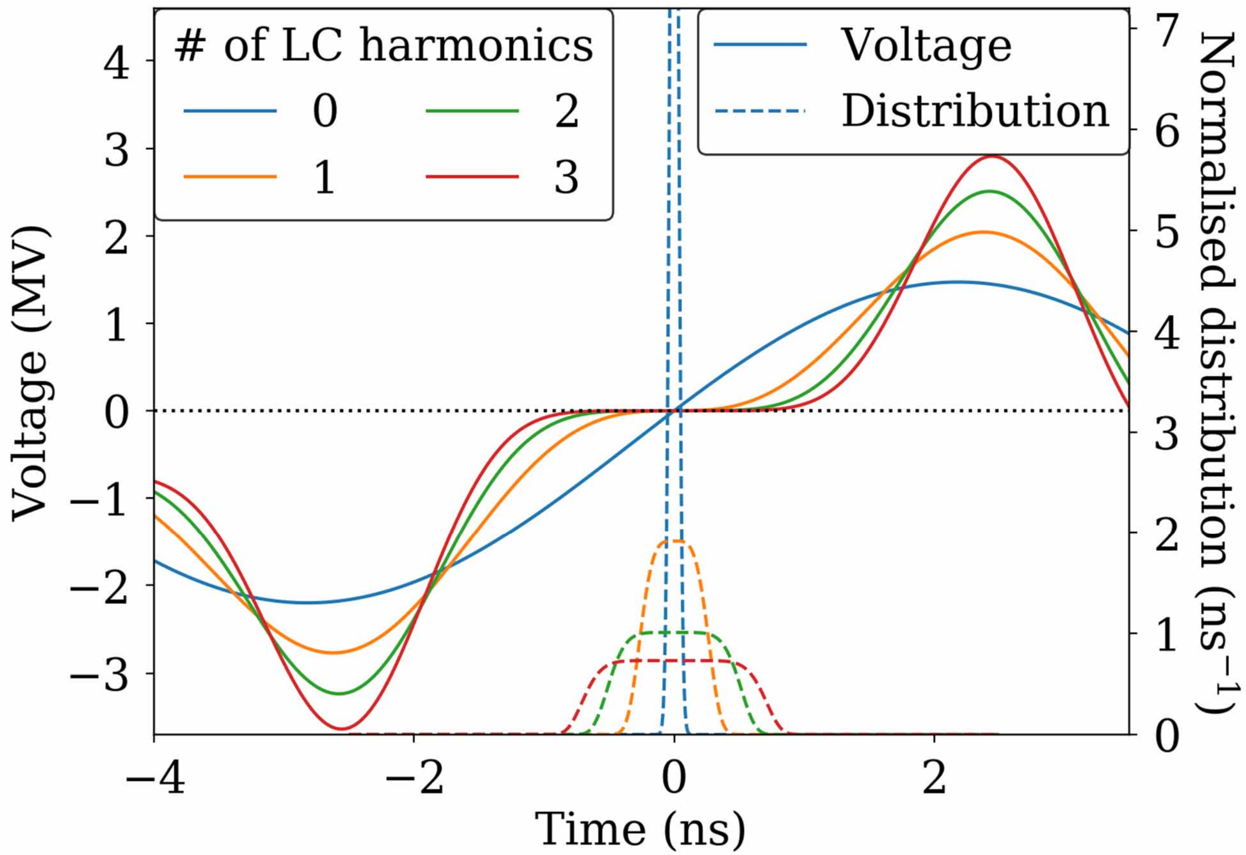


Cavities at Multiple Harmonics

Multiple Higher Harmonics

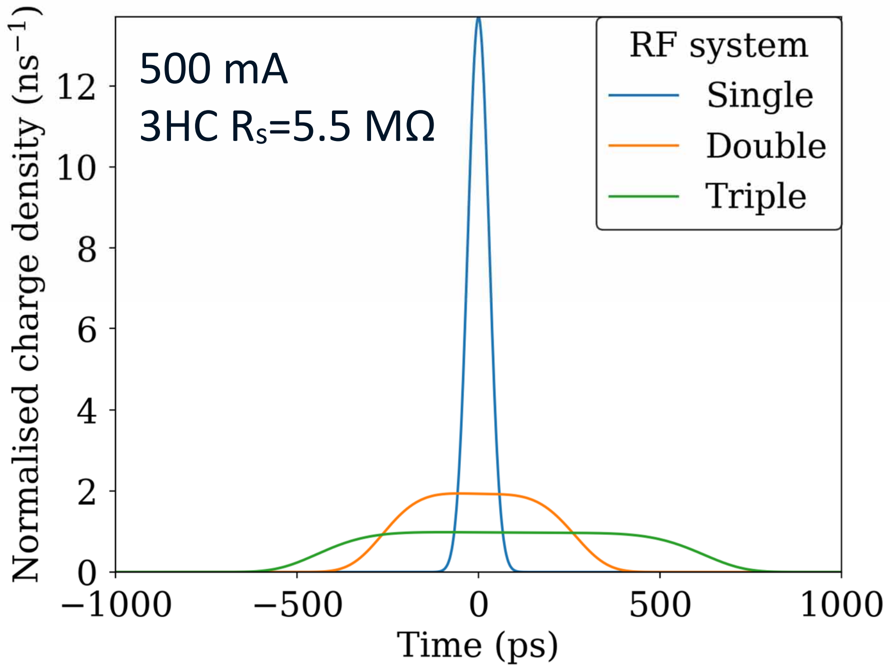
Developed by
Å. Andersson, L. Malmgren
& P. F. Tavares

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



Triple RF system

- 3rd-harmonic cavities can be passive
- 5th-harmonic cavity to be installed in the MAX IV 3 GeV ring



Parameter	Single	Double	Triple
RF voltage (MV)	1.5	1.5	1.2
RMS bunch duration (ps)	32.2	173	324
Detuning of 3rd-harmonic cavity (kHz)	-	76.8	57.1
Voltage in 3rd-harmonic cavity (kV)	-	486	568
Voltage in 5th-harmonic cavity (kV)	-	-	113

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Conclusion

- Harmonic cavities are essential in 4th-generation storage rings
- Survey reveals normal-conducting active or superconducting passive options preferred
- Not generally relied upon for damping of HOM-driven instabilities
- Harmonic cavity fundamental mode can drive several different instabilities
- Cavities at multiple RF harmonic can lengthen the bunches further

Acknowledgements

- Alexis Gamelin, SOLEIL
- Lukas Stingelin, PSI (SLS 2.0)
- Andreas Jankowiak, HZB (BESSY III)
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- Simone Dmitri, ELETTRA
- Ian Martin, DIAMOND
- Peter Hülsmann, DESY (PETRA IV)
- Francis Perez, ALBA
- Naoto Yamamoto, KEK
- Marco Venturini, ALS
- Ryan Lindberg, APS
- Fernando Henrique de Sá, SIRIUS
- Haisheng Xu, HEPS
- Tianlong He, HALF
- Nawin Juntong, SPS
- Takahiro Watanabe, SPring-8