ESLS-RF & HARMONLIP WORKSHOPS 2025

Double- and Triple-RF systems for MAX4^{U}

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Outline

1. MAX4^U and MAX IV RF system
2. Double-RF
3. Triple-RF

Toolbox used

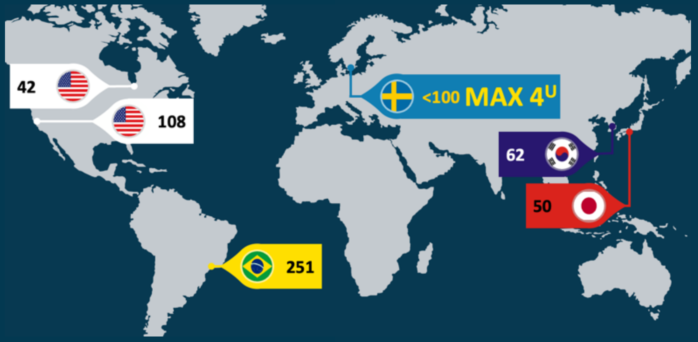
Pycolleff (GitHub)

ALBuMS, Mbtrack2 (GitLab)

Mbtrack (tracking)

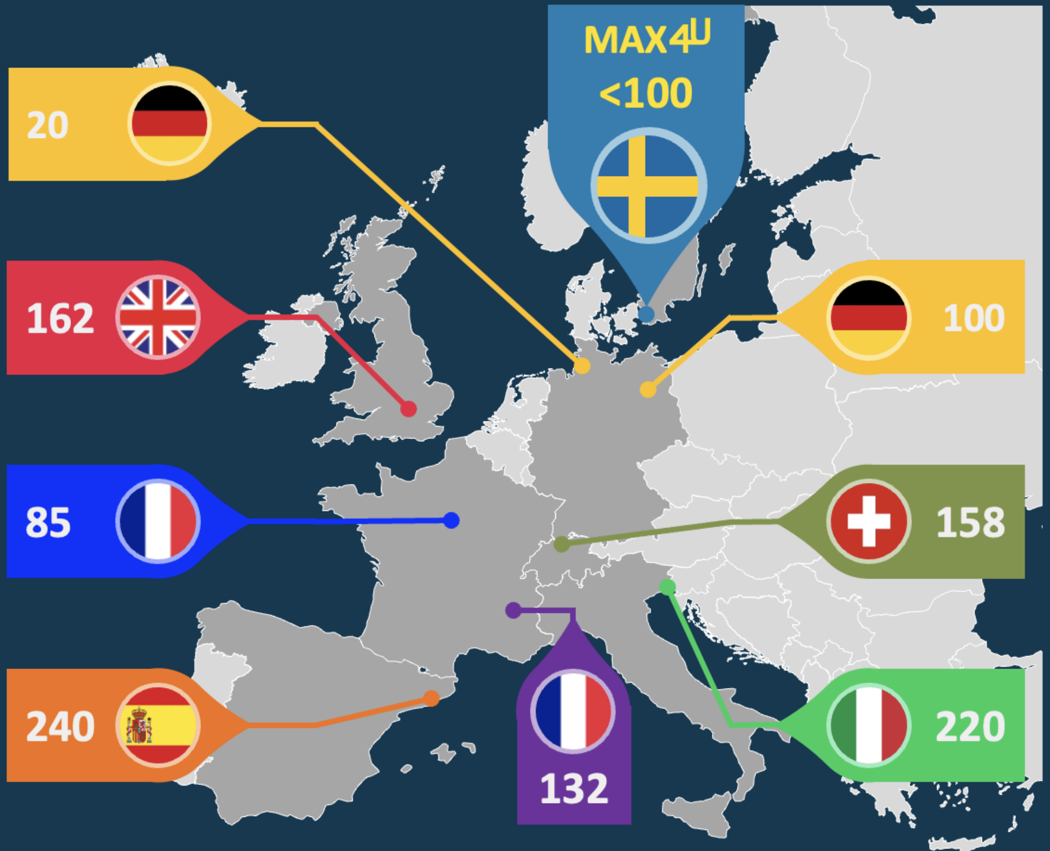
MAX 4U

Securing leadership, excellence, resilience, and relevance of Swedish research with X-rays for the next decades



A *"surgical"* upgrade of our 3GeV ring
from 328 to below 100 pm·rad

Horizontal Emittance [pm·rad]



c/o A.ROBERT

V5.0925

Relevant parameters for MAX4^U lattice candidates (CDR)

R3: MAX IV 3GeV Ring AR: Absolute Requirement SG: Stretched Goal

	R3 (as designed)	AR (i01-04-01-01)	SG (n01-01-01-01)	Units
Natural emittance	328	95	65	pm rad
Natural energy spread	7.69	7.55	8.46	10^{-4}
RF voltage	1.8	1.0	1.0	MV
Momentum compaction factor	3.06	0.944	0.540	10^{-4}
Energy loss per turn	364	414	474	keV
Natural bunch length	29	22	19	ps
Damping times (H/ V/ L)	15.73 / 29.05 /25.19	14.75 / 25.51 / 20.08	11.44 / 22.29 / 21.18	ms

Design current: 500 mA uniform filling

Requirements for bunch lengthening

R3 delivery conditions

- Beam current: 400 mA
- RF voltage: 1.13 MV
- Natural bunch length: 38 ps
- Double-RF system (2 passive HC3s): **180 ps (x 4.7 lengthening)**
- Beam lifetime with HC3s: 15 h
- Essential for HOMs rejection, alleviating IBS

MAX4^U lattices

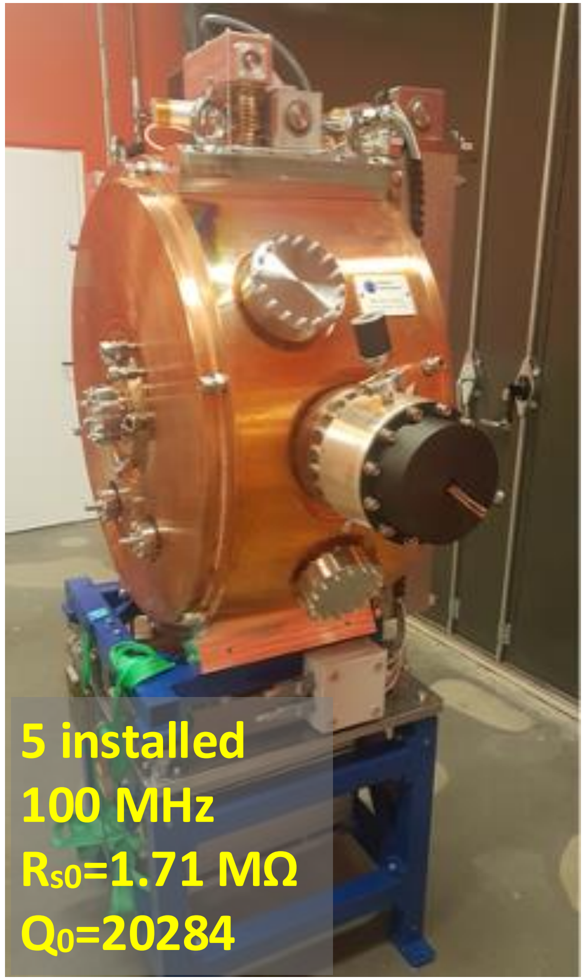
- Beam current: 500 mA
- RF voltage: 1.00 MV
- Natural bunch length: ~ 20 ps
- Ideal double-RF performance: **~120 ps (x 6 lengthening)**
- Higher lengthening factors required → Triple-RF system

The MAX IV RF system

Double-RF system

Triple-RF system

Main Cavity



HC3 (Passive)

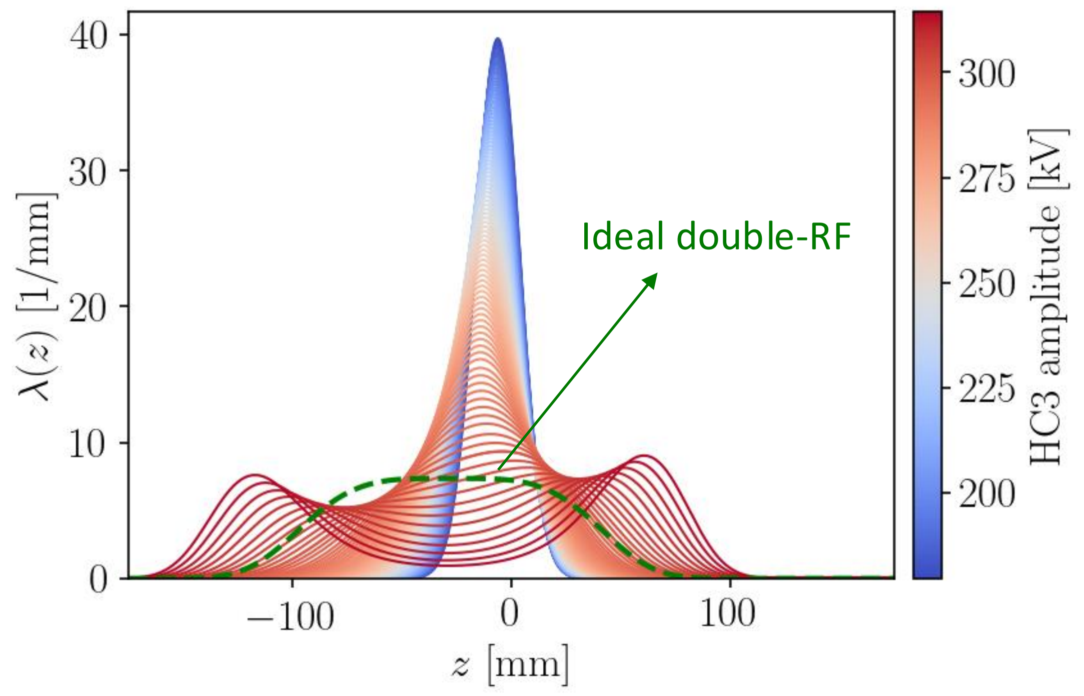
Images by Åke Andersson

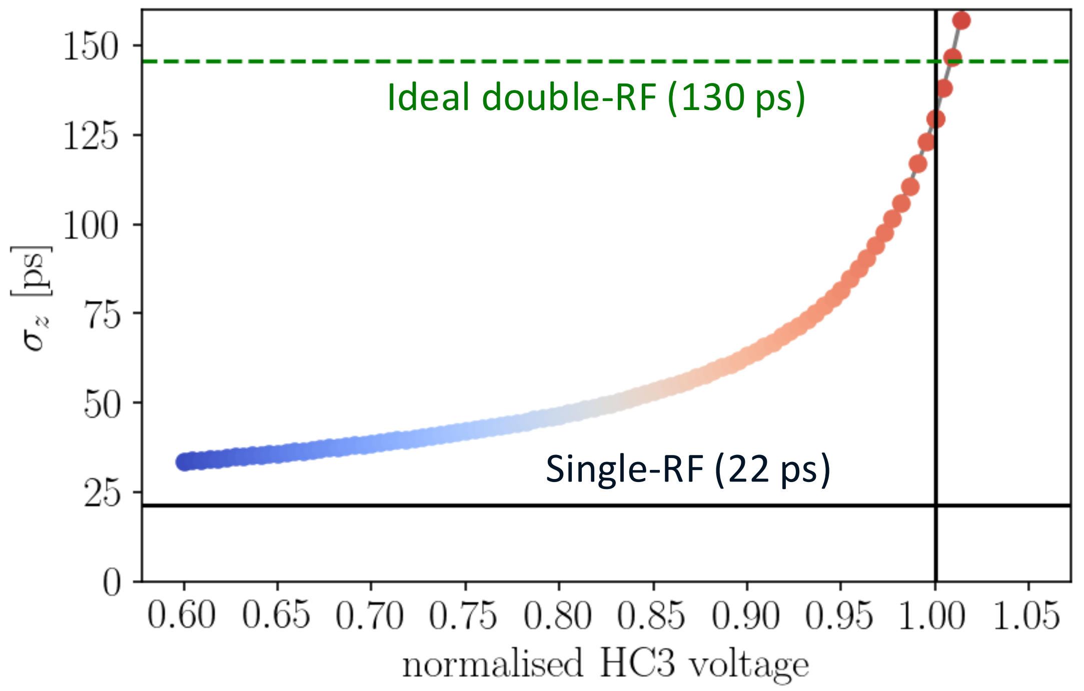
HC5 (Active)

Double-RF

Double-RF with passive HC3

- With V_{RF} = 1.0 MV, U_0 = 450 keV, ideal HC3 amp around 300 kV
- Example for AR lattice. Factor 6 of lengthening

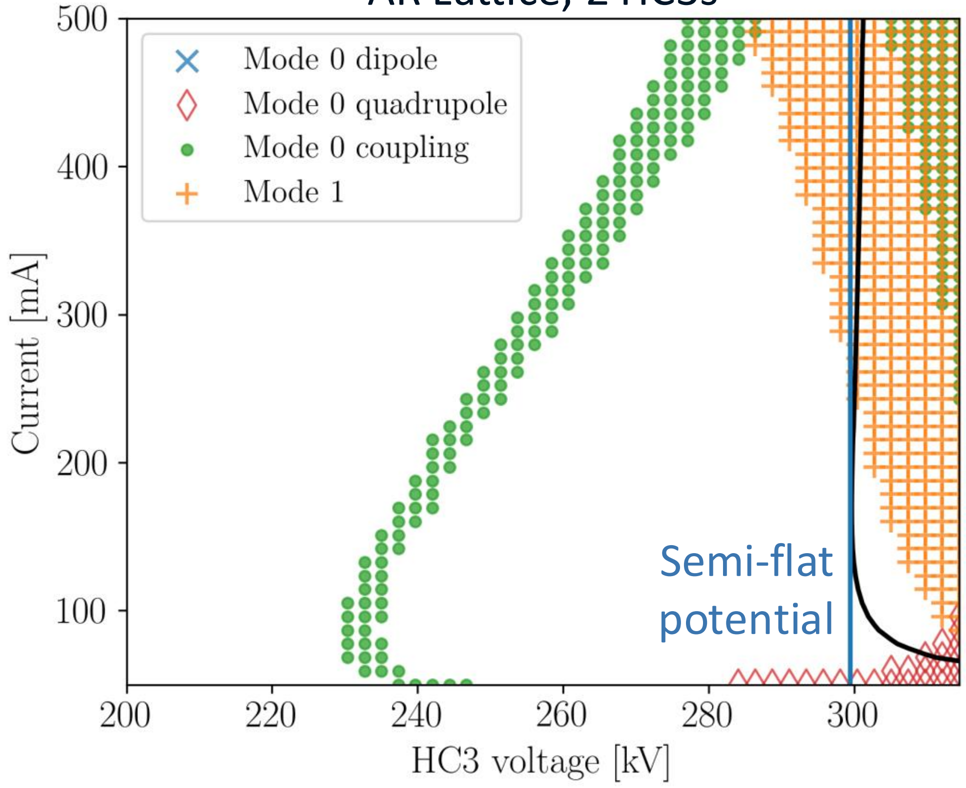




Longitudinal multibunch beam stability

- Stability estimates using Gaussian LMCI model[1]
- Bosch grids[2]: where in parameter-space the beam is predicted to be unstable and why
- Passive HC3 cavities
- Semi-flat potential = correct amplitude but not phase

AR Lattice, 2 HC3s

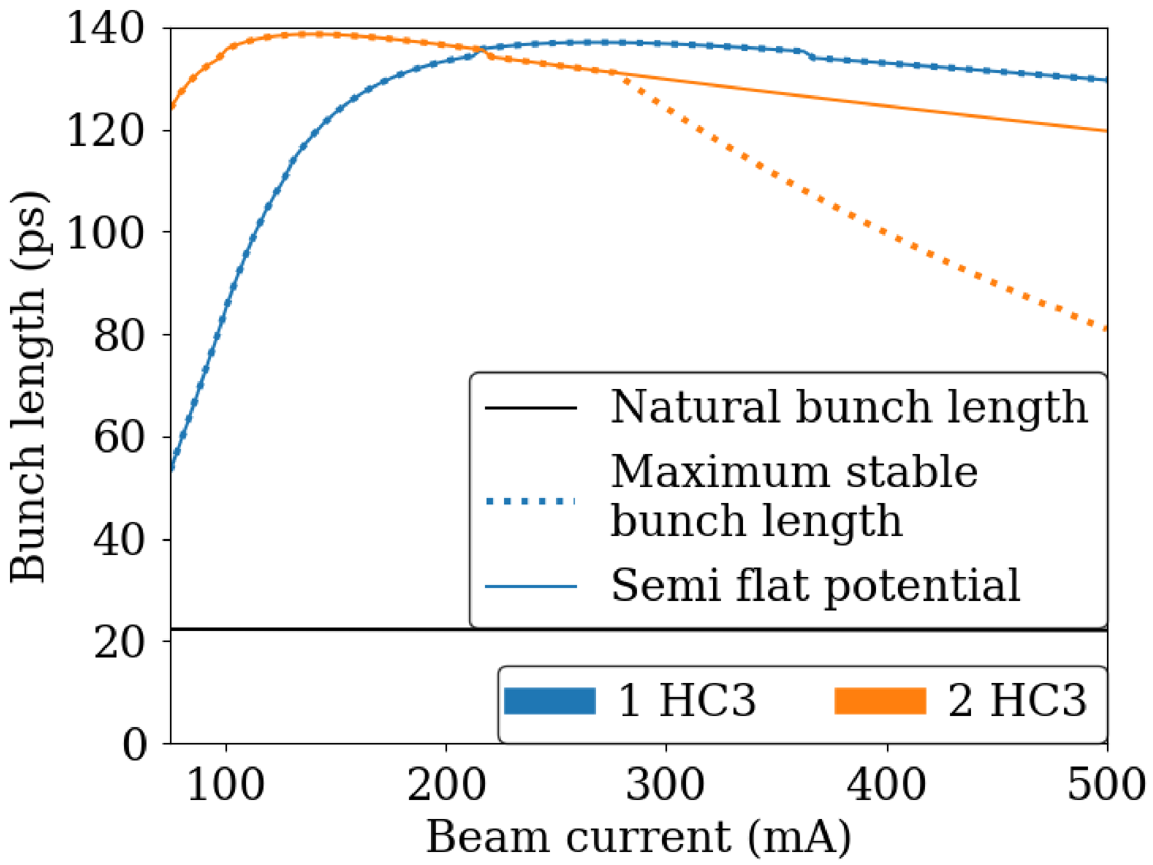


ξ=1 (HC3 voltage cancels main-RF slope)

[1] M. B. Alves, "Theoretical models for longitudinal coupled-bunch instabilities driven by harmonic cavities in electron storage rings", Phys. Rev. Accel. Beams **28** 03440 (2025)
[2] A. Gamelin, V. Gubaidulin, M. B. Alves, T. Olsson, "Semianalytical algorithms to study longitudinal beam instabilities in double rf systems" Phys. Rev. Accel. Beams **28** 054401 (2025)

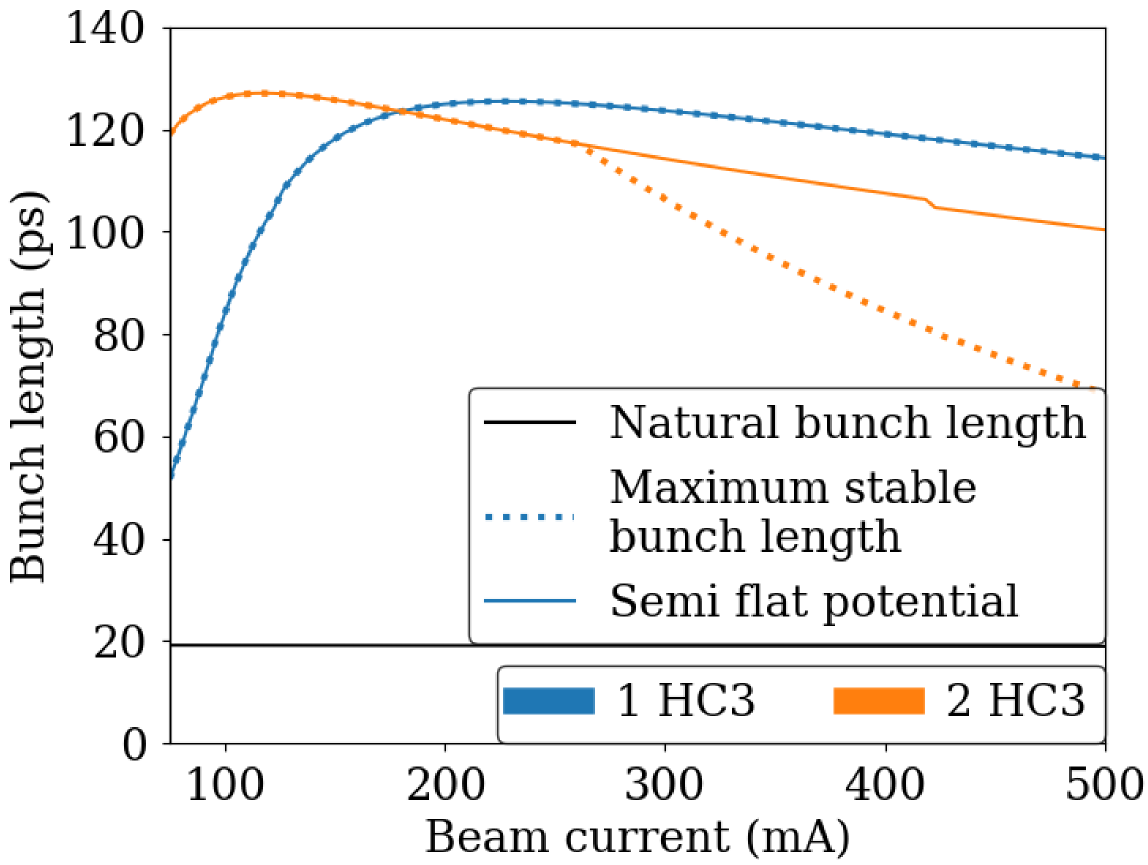
Mode 1: maximum stable bunch lengths – AR Lattice

- Assuming Mode 0 is controlled by mode-0 damper (TBC)
- Flat potential is where HC3 field level is same as for ideal lengthening
- Single HC3 cavity allows semi-flat potential to be reached at 500 mA



Mode 1: maximum stable bunch lengths – SG Lattice

- Assuming Mode 0 is controlled by mode-0 damper (TBC)
- Flat potential is where HC3 field level is same as for ideal lengthening
- Single HC3 cavity allows semi-flat potential to be reached at 500 mA



Analytical formula for Mode 1 (PTBL) threshold*

Valid for passive double-RF

$$\sigma_\tau = \lambda \frac{T_0 \sigma_\delta}{I_0 (R/Q) n^2} \sqrt{\frac{E_0 \alpha \hat{V}_{\mathrm{rf}}}{2\pi e F_n h^3}}$$

2 HC3s
n = 3
$F_n = 1$

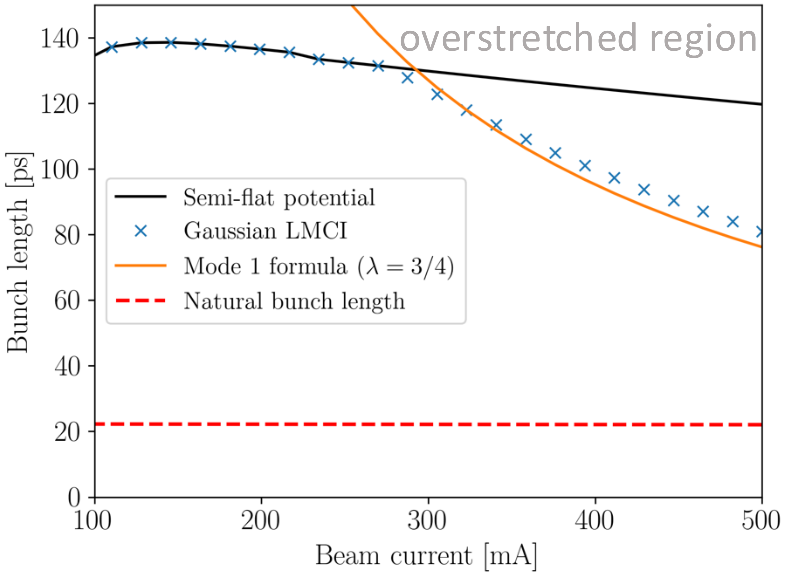
"Correction" factor

$$\omega_s \sigma_\tau = \lambda \alpha \sigma_\delta$$

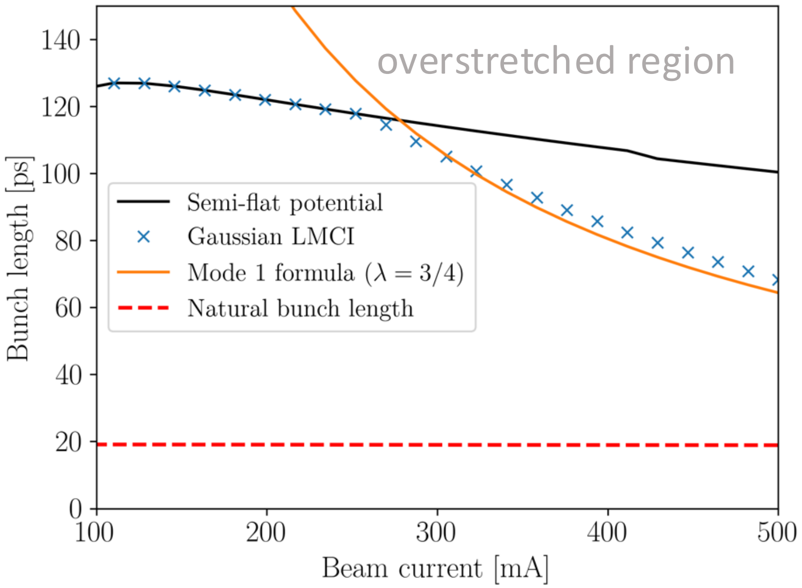
$\lambda = 1$ Linear dynamics Gaussian bunch

$\lambda = 3/4$ Good match with Gaussian LMCI

AR lattice



SG lattice

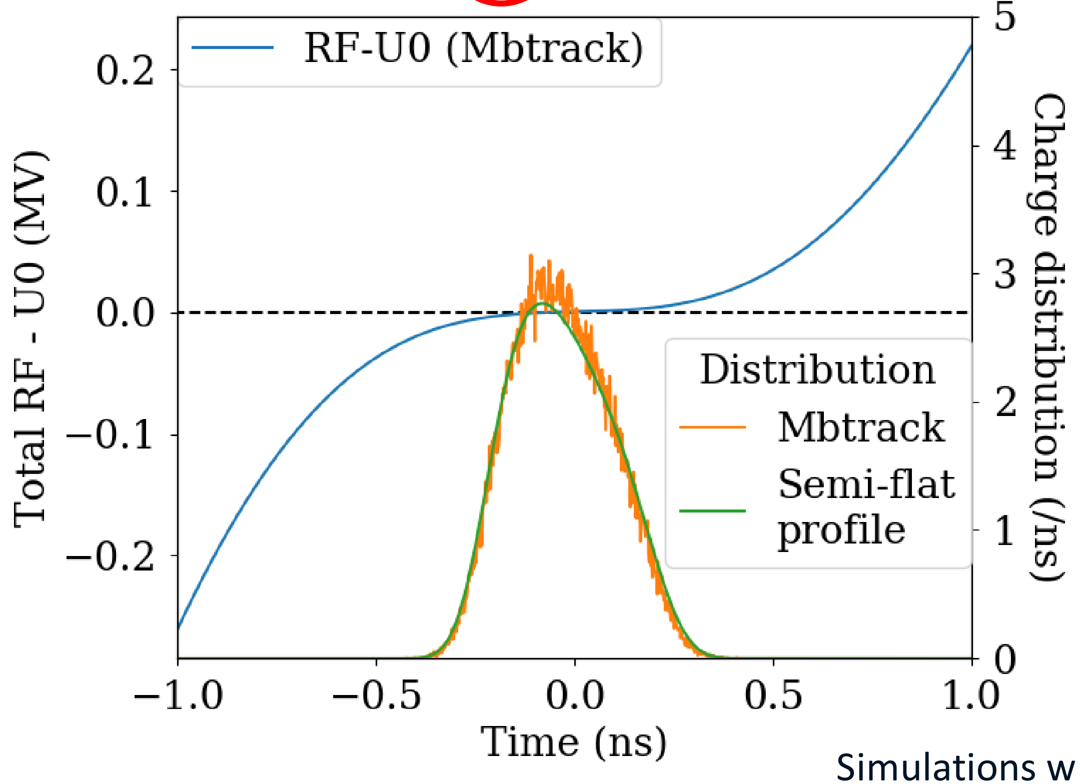


*Derivation in Appendix B of M. B. Alves, Phys. Rev. Accel. Beams **28** 03440 (2025)

Stable bunch profiles with single HC3

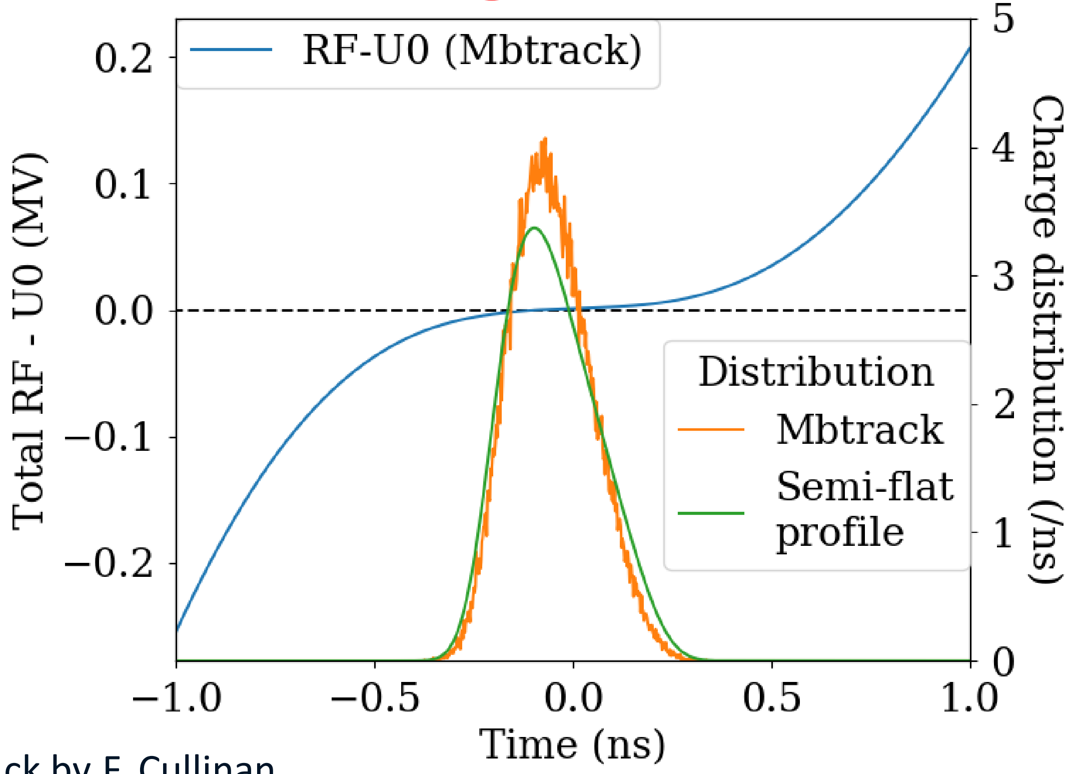
AR Lattice (natural bunch length=22 ps)

	Semi-flat	Mbtrack max. stable
Bunch length (ps)	130	126
HC3 voltage (kV)	299.5	298.4



SG Lattice (natural bunch length=19 ps)

	Semi-flat	Mbtrack max. stable
Bunch length (ps)	114	101
HC3 voltage (kV)	288.1	285.5



Simulations with Mbtrack by F. Cullinan

Triple-RF
(work in progress)

Triple-RF with 2 passive HC3s + 1 active HC5

- Given $V_{RF,}$ U_0 and harmonics → amplitudes and phases that cancel derivative of total voltage up to Nth order*
- Triple-RF: 4th order, Super-Flat Potential (SFP)

V_{RF} = 1.0 MV
U_0 = 450 keV

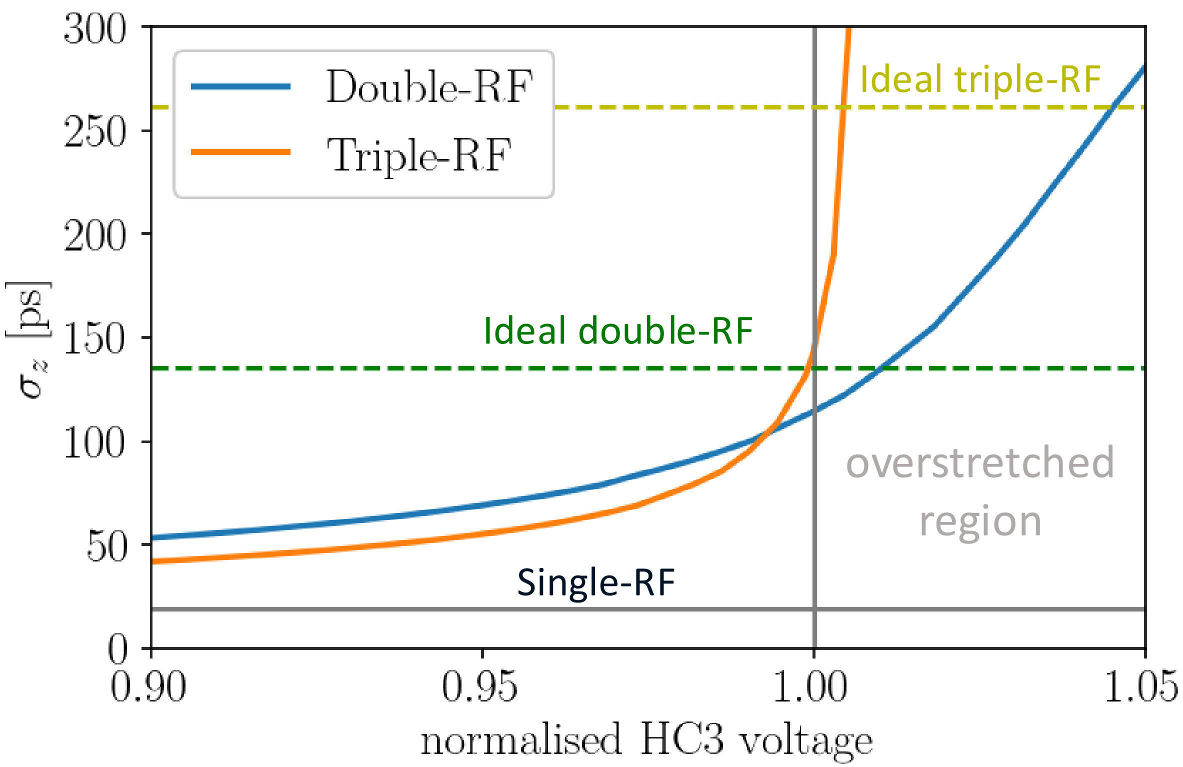
	Main Cavities		3rd harmonic (HC3)		5th harmonic (HC5)	
	Amp [kV]	Phase [deg]	Amp [kV]	Phase [deg]	Amp [kV]	Phase [deg]
Double-RF	1000	149.6	293	-11.1	--	--
Triple-RF	1000	148.2	434	-11.7	86	172.9

- Higher HC3 fields required in a triple-RF
- HC5 must be active

*F. Cullinan, P. Tavares, Å. Andersson, L. Malmgren,
"Harmonic Cavity Parameters for Flat Potential to Arbitrary Order" MAX IV Internal Note 20240410

Bunch lengthening sensitivity

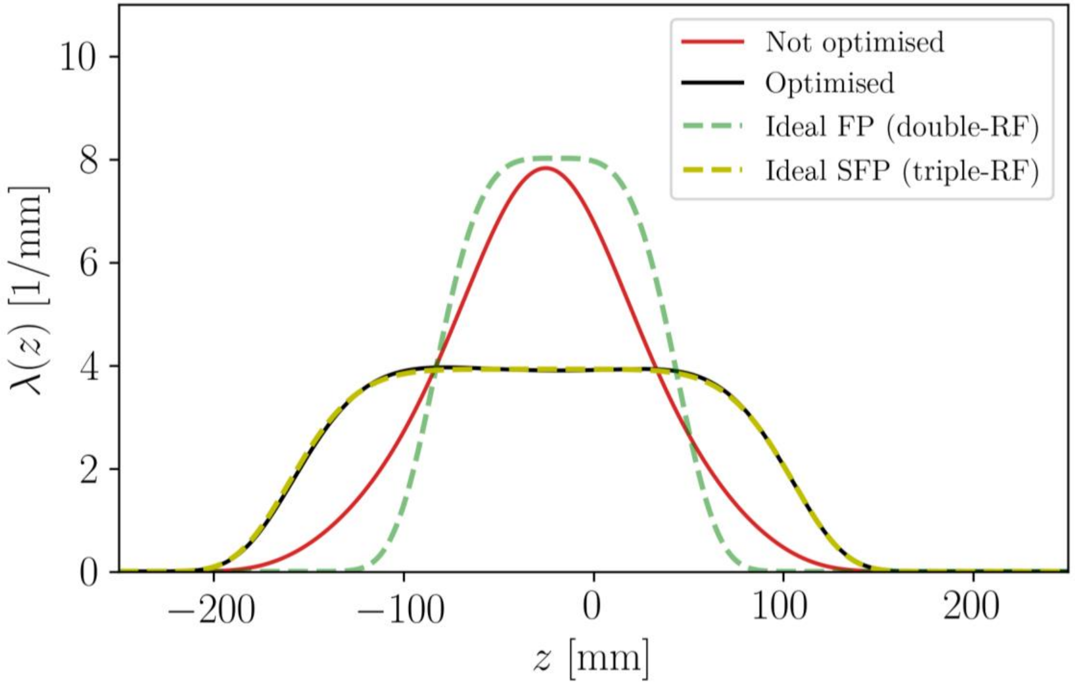
- Main and HC5 (active cavities) set to ideal amplitudes and phases
- Passive HC3 amp adjusted by detuning
- Bunch profiles much more sensitive to HC3 amp/phase variations
- Possible solutions to compensate for this limited control:
  - MC and HC5 adjustments
  - Active HC3s



Impact of finite Q factor of cavities - AR Lattice

	RF Voltage [MV]	HC3 Amp [kV]	HC5 Amp [kV]	σ_z ideal FP [ps]	σ_z ideal SFP [ps]	σ_z actual [ps]
Not Optimised	1.00	444.6	88.0	146	275	187 (-32%)
Optimised	1.33	626.5	123.1	133	259	258

- Main and HC5 amps used as optimisation knobs
- Benchmarking with Mbtrack in progress
- High HC3 voltage becomes challenging again

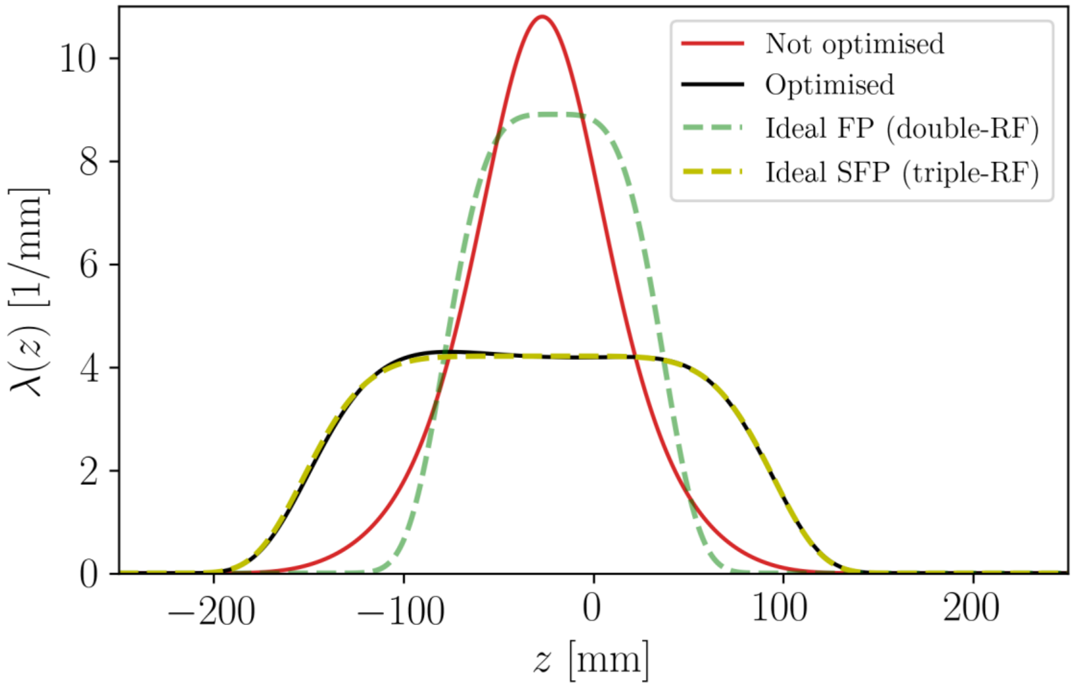


Also studied in He *et al.*, *NIM A* **1080**, 170672 (2025) *"Impact of short-range wakefields from radio-frequency cavity resonant modes on bunch lengthening"*

Impact of finite Q factor of cavities - SG Lattice

	RF Voltage [MV]	HC3 Amp [kV]	HC5 Amp [kV]	σ_z ideal FP [ps]	σ_z ideal SFP [ps]	σ_z actual [ps]
Not Optimised	1.00	425.9	83.9	135	262	143 (-45%)
Optimised	1.46	679.2	135.0	120	241	240

- Main and HC5 amps used as optimisation knobs
- Benchmarking with Mbtrack in progress
- High HC3 voltage becomes challenging again



Also studied in He *et al.*, *NIM A* **1080**, 170672 (2025) *"Impact of short-range wakefields from radio-frequency cavity resonant modes on bunch lengthening"*

Summary and next steps

- Low-α feature of MAX4^U brings challenges to bunch lengthening and stability
- **Double-RF**
  - Bunch lengthening: MAX4^U σ_z = 120ps (factor 6) vs. MAX IV R3 σ_z = 180ps (factor 5)
  - Mode-0 expected to be controlled with damper
  - Mode-1 stable only with single passive HC3
- **Triple-RF (work in progress)**
  - Much more sensitive to cavity parameters variations than double-RF
  - “Short-range wakes” from fundamental modes are relevant and can be compensated
- **Next steps**
  - Evaluation of collective beam instabilities with triple-RF system
  - Include full impedance model: Geometric, RW, HOMs, IDs
  - Experimental tests
    - Double-RF with 1 HC3
    - Triple-RF system

MAX4^{U} page

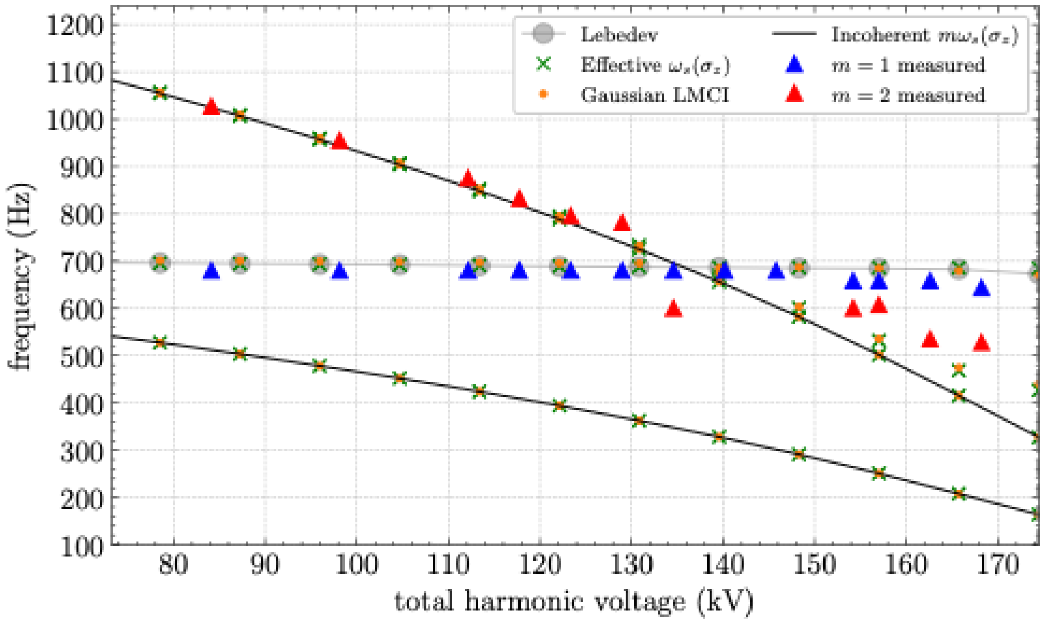
https://www.maxiv.lu.se/beamlines-accelerators/max-4u/

Backup Slides

HC3-related instabilities at MAX IV

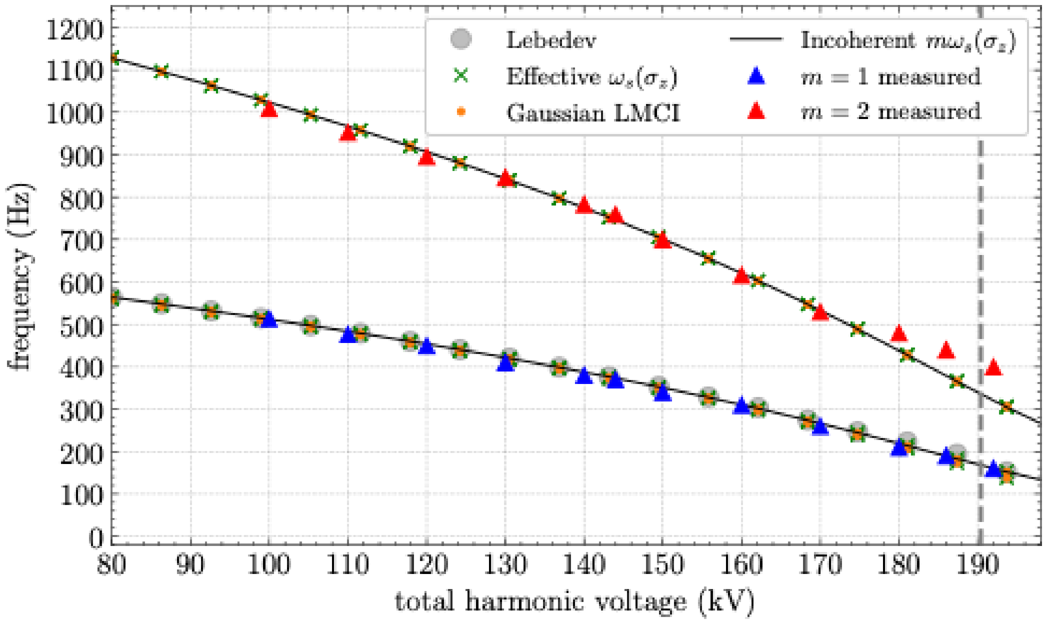
Measurements below threshold

Mode 0 Coupling



$V_{RF} = 650$ kV, $I_0 = 50$ mA

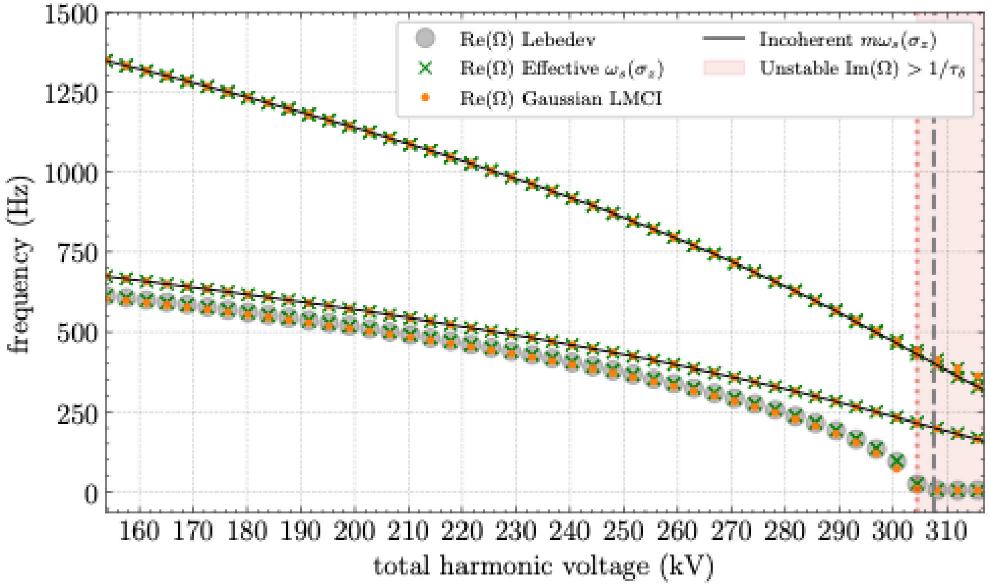
Mode 1



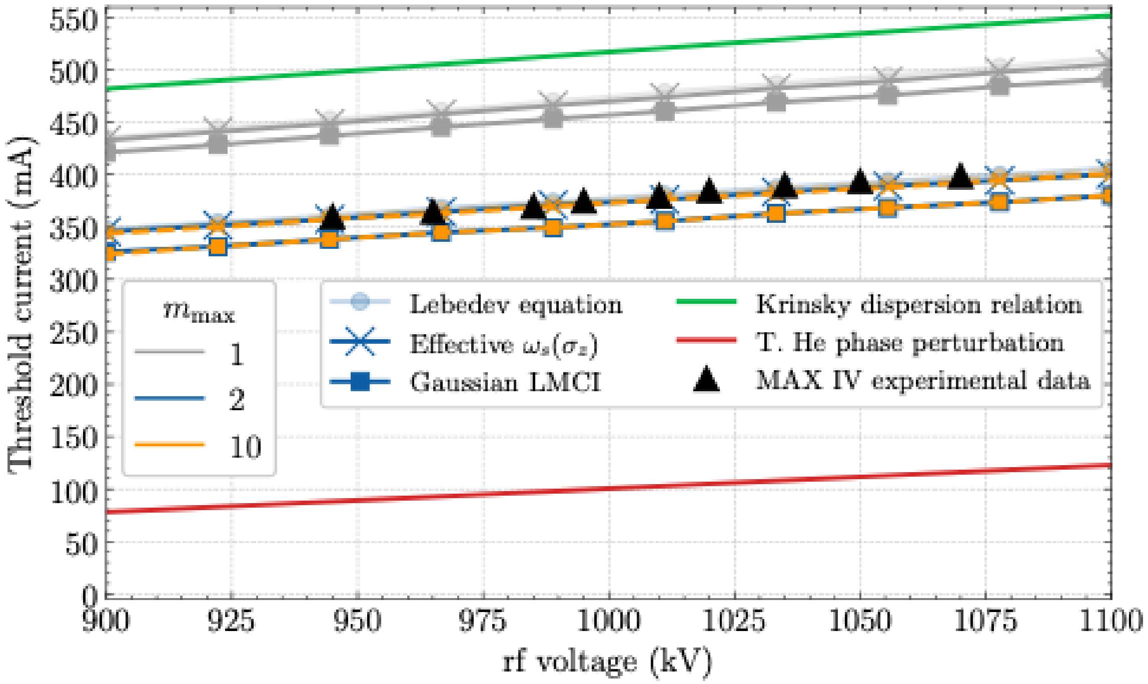
$V_{RF} = 689$ kV, $I_0 = 90$ mA

M. B. Alves, "Theoretical models for longitudinal coupled-bunch instabilities driven by harmonic cavities in electron storage rings", Phys. Rev. Accel. Beams **28** 03440 (2025)

Mode 1 thresholds at MAX IV



V_{RF} = 1.0 MV, I_0 = 300 mA, 3 HC3s



2 HC3s, V_{RF} = 1.0 MV: 400mA is achieved

M. B. Alves, "Theoretical models for longitudinal coupled-bunch instabilities driven by harmonic cavities in electron storage rings", Phys. Rev. Accel. Beams **28** 03440 (2025)