LHC Injection Dynamics for the HL-LHC Era

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XXXVIII Ph.D. School in Accelerator Physics – 3rd Year Entrance Presentation 24/10/2024

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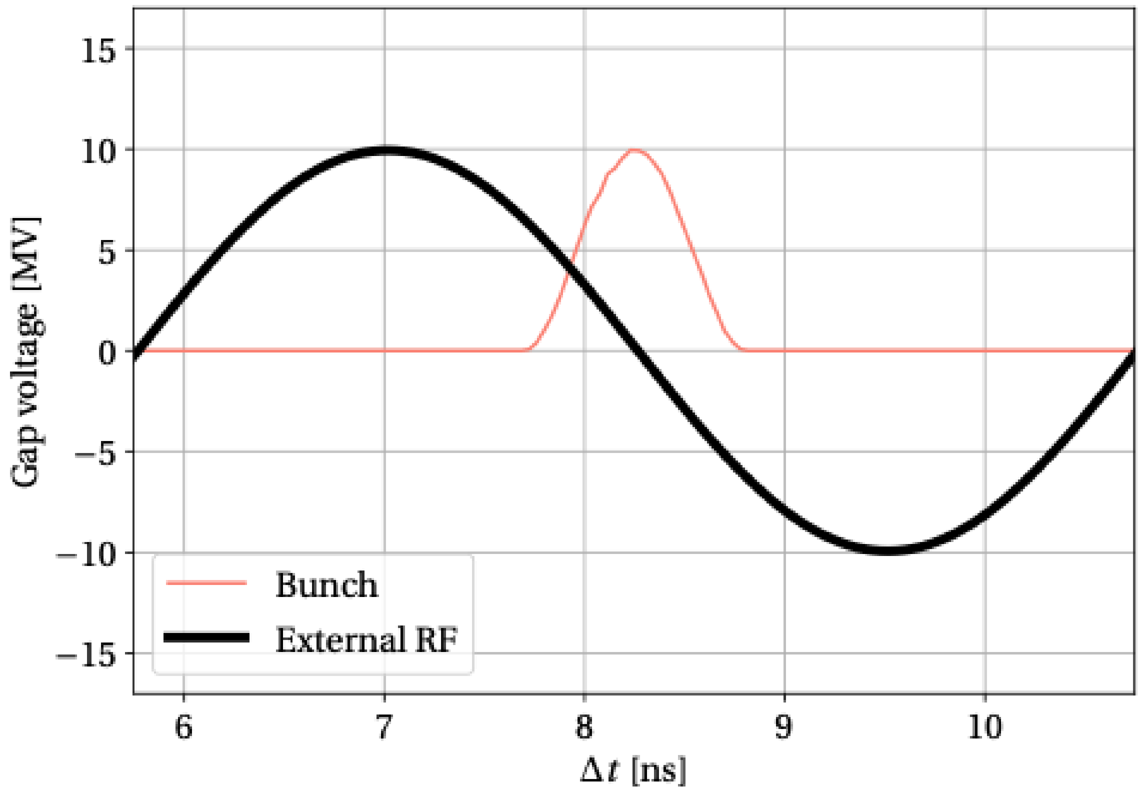
Beam Loading and Cavity Controllers

Superconducting cavities

- Oscillating voltage from an RF cavity



- Half-detuning beam-loading compensation scheme [1]

Without beam

$$P = \frac{1}{8}\frac{V_a^2}{(R/Q)Q_L}\left(1 + \frac{4}{Q_L^2}\left(\frac{\Delta f}{f_{rf}}\right)^2\right)$$

With beam

$$P = \frac{1}{8}\frac{V_a^2}{(R/Q)Q_L} + \frac{1}{8}(R/Q)Q_L\left(-2\frac{V_a}{(R/Q)}\frac{\Delta f}{f_{rf}} + \Im(I_{RF,beam})\right)^2$$

Total gap voltage, V_a → Total field in the cavity

Loaded quality factor, Q_L → Field for a given power

Cavity detuning, Δf → Difference between the resonant frequency and the rf frequency

R upon Q, (R/Q) → Accelerating field for a given energy stored in the cavity

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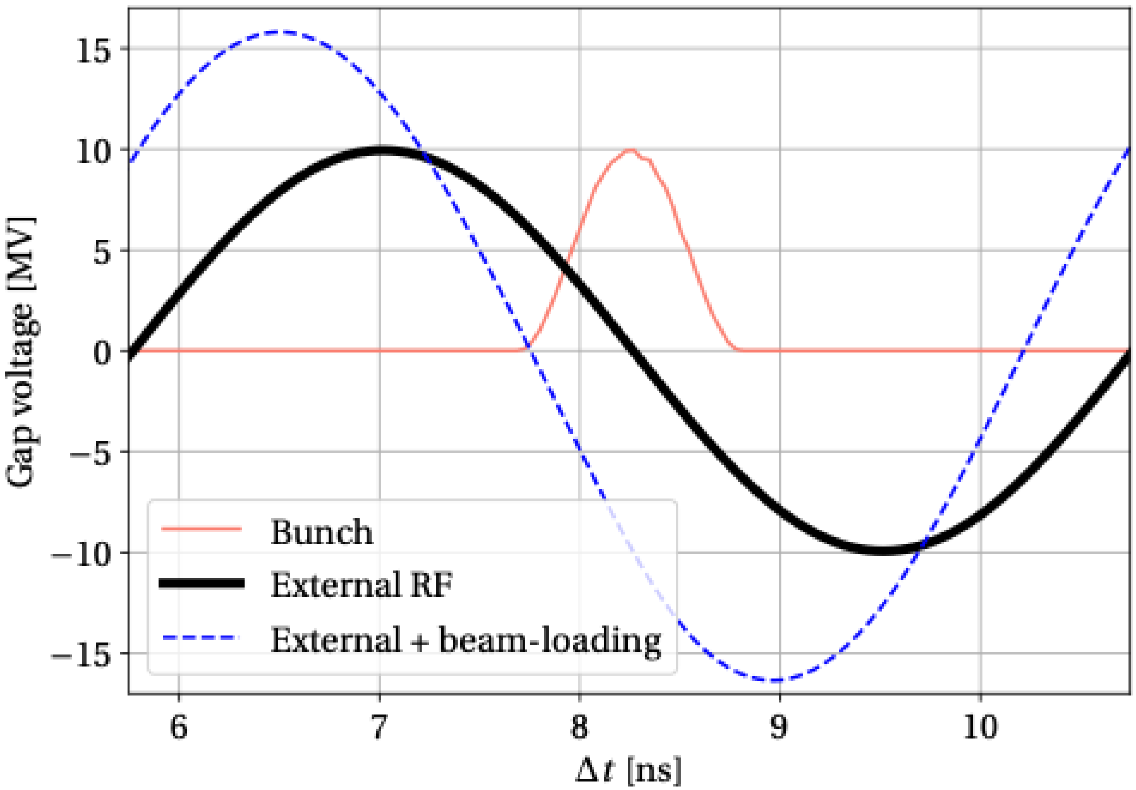

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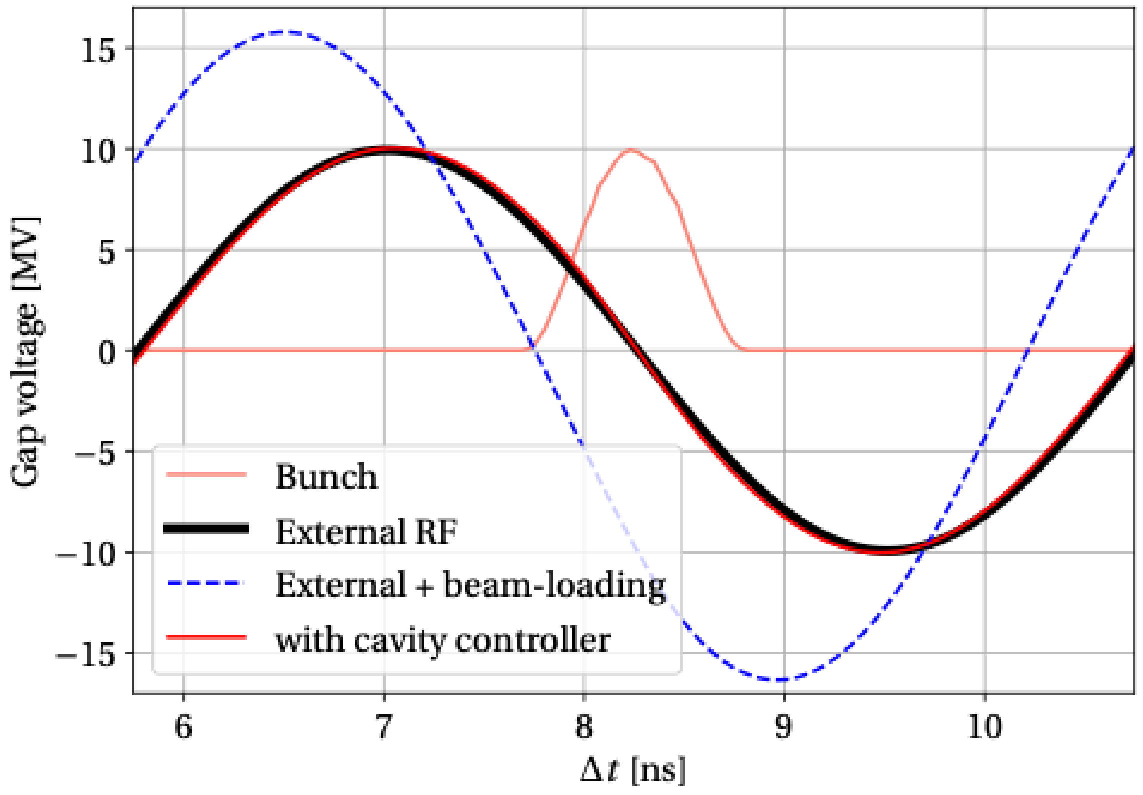

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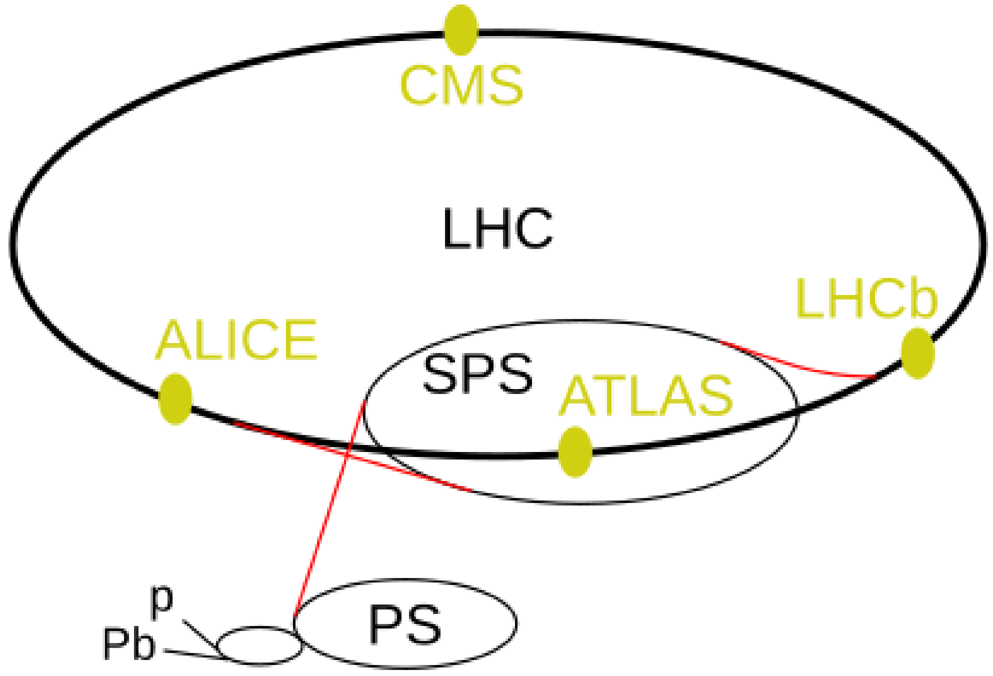
The Large Hadron Collider and the HL-LHC Era

- The Large Hadron Collider [2]
  - 27-km long, two counter-rotating beams
  - More than 2000 bunches per ring
  - Collisions in four interaction regions (IR)
  - Beam energy: 450 GeV/c to 6.8 TeV/c
  - Nominal 1.15×10^{11} p/b
  - Ultimate 1.8×10^{11} p/b

- The High Luminosity Upgrade [3]
  - Upgrade and addition for a lot of equipment, e.g. crab cavities, magnets, collimators etc.
  - Bunch intensity doubling
    - 1.15×10^{11} p/b -> 2.3×10^{11} p/b
  - Luminosity increase



https://en.wikipedia.org/wiki/Large_Hadron_Collider

[2] O. Bruning *et al.*, Rep. CERN-2004-003-V-1, 2024
[3] O. Aberle *et al.*, Rep. CERN-2020-010, 2020

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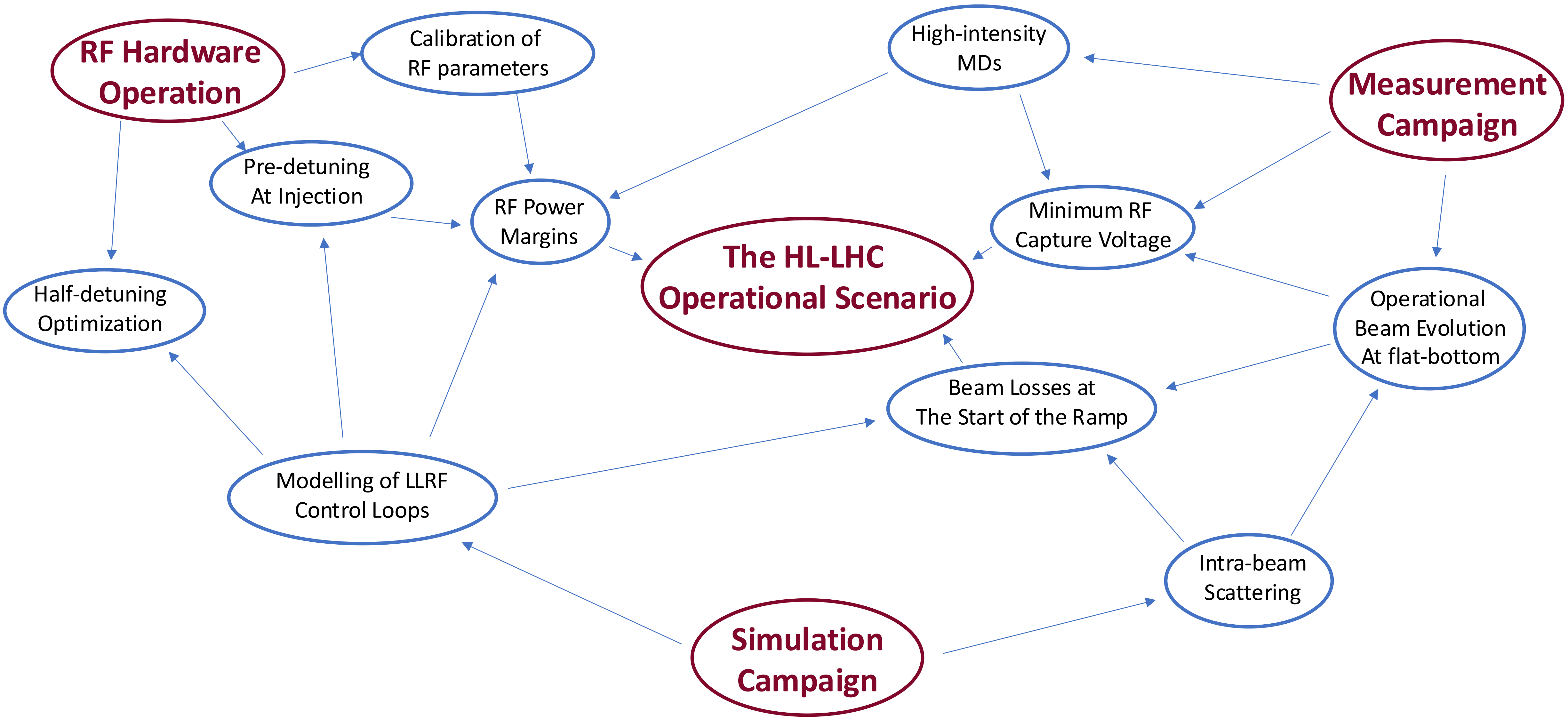
  - Luminosity increase

- 400 MHz superconducting RF cavities (8 per beam)
  - Each powered by a klystron (max. 300 kW [4])
- High enough voltage to
  - Capture injected momentum spread
  - Counteract debunching at flat bottom
- Low enough voltage to
  - Not saturate the klystrons
  - Have stable bunches

[2] O. Bruning *et al.*, Rep. CERN-2004-003-V-1, 2024
[3] O. Aberle *et al.*, Rep. CERN-2020-010, 2020
[4] O. Brunner et al., in Proc. PAC’03, 2003

Overview of the Project



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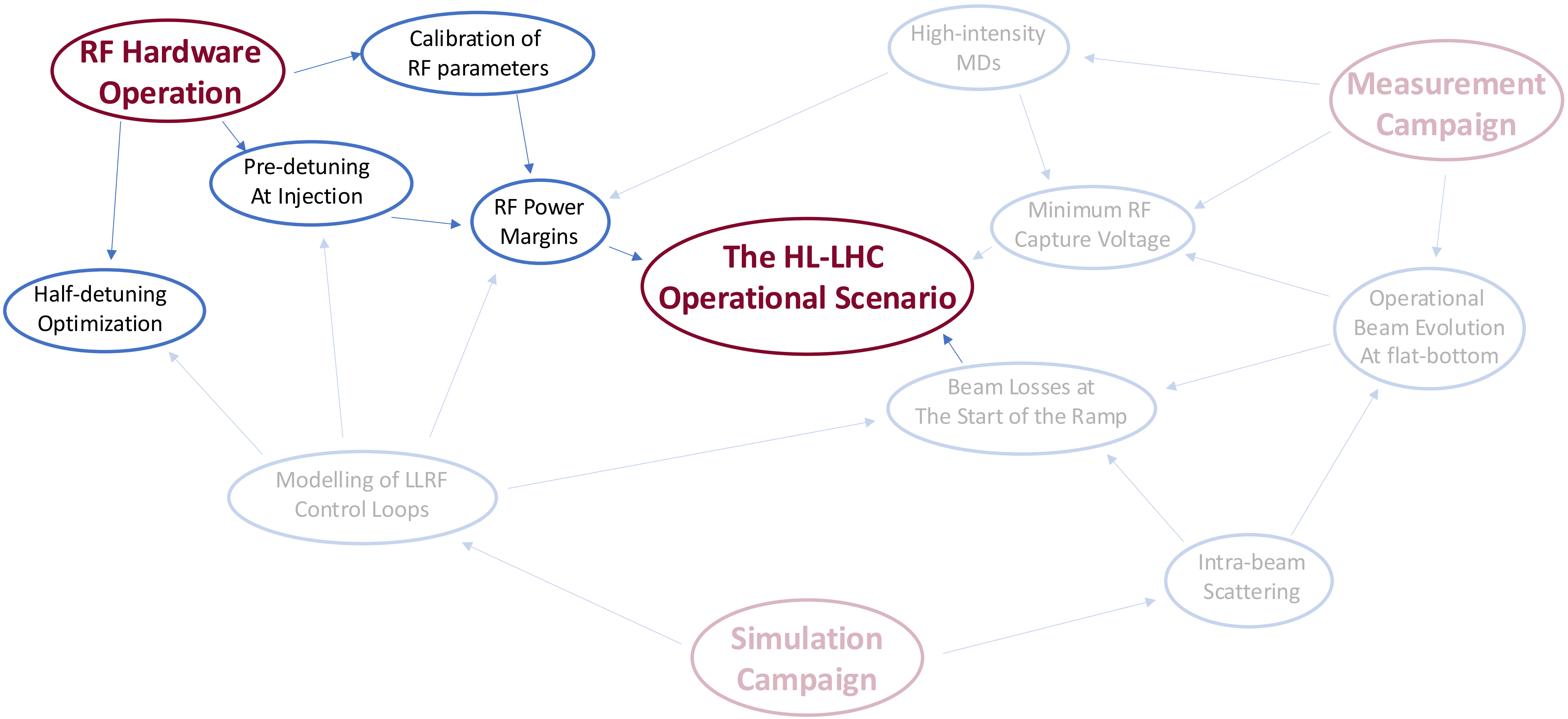

Optimization of the RF Hardware RF Voltage [5]

- Beam-based calibration of the RF voltage
  - Inject low-intensity bunches with small longitudinal emittances
  - Measure line-density profiles of the beam
- Reconstruct synchrotron frequency
  - Potential-well distortion and non-linear part of the RF bucket
- Corrections implemented in the hardware
  - Estimated precision of RF voltage improved from 10% to 3%

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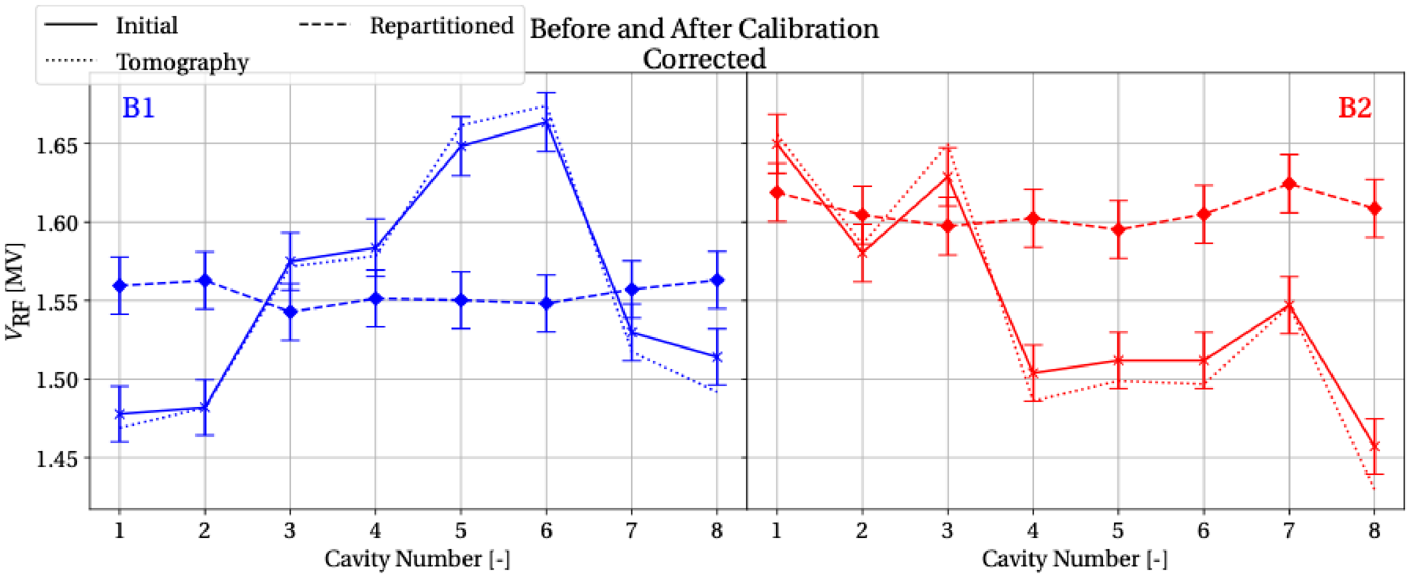

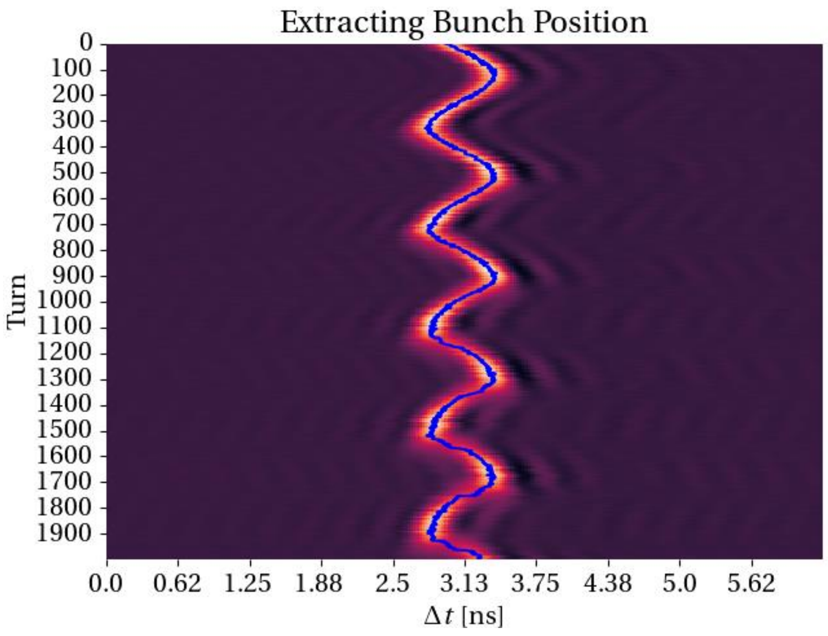

[5] B. E. Karlsen-Baeck et al., CERN-ACC-NOTE-2024-0008, 2024

Optimization of the RF Hardware
Loaded Quality Factor

Participated during month-long LHC hardware commissioning in 2024

- Loaded quality factor in the LHC RF cavities
  - Controlled by coupler
    - Flat bottom: 2.0×10^4 -> flat top: 6.0×10^4
- Measured during hardware commissioning each year
  - Before: calibrate from transfer function measurements (from open-loop response of the cavity controller)
- New calibration method to be used in 2025
  - Measure voltage decay in the cavity

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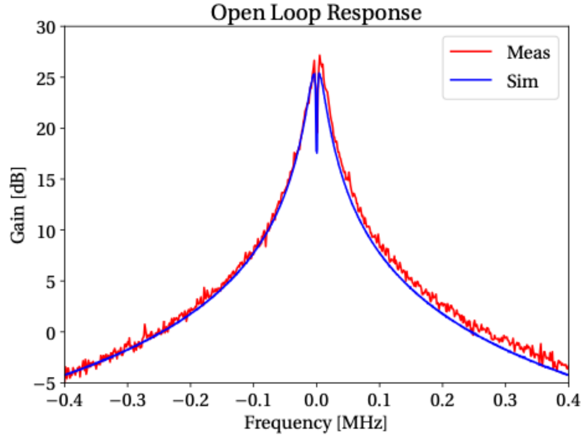
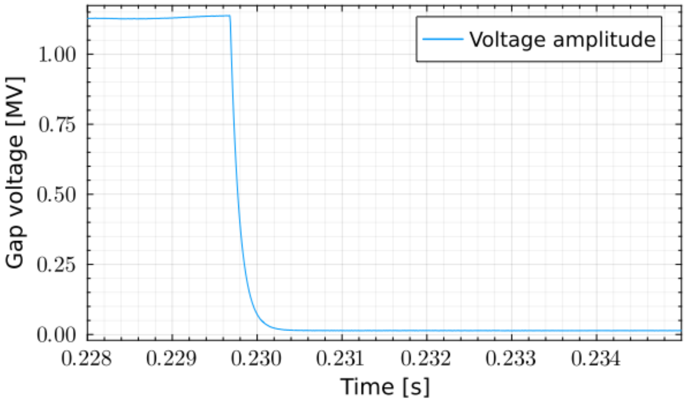
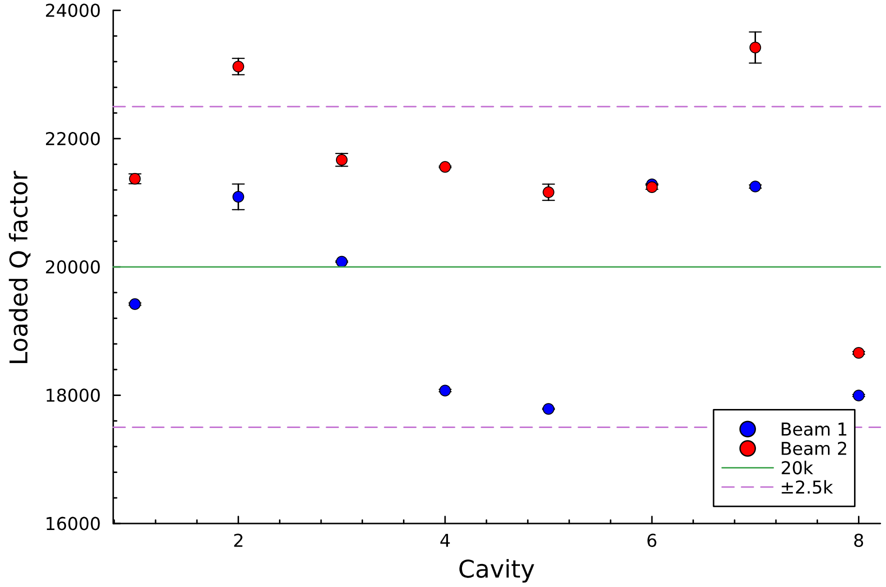


Measured and simulated open-loop response of an LHC RF cavity

vs.



Measured voltage decay in one of the LHC RF cavities

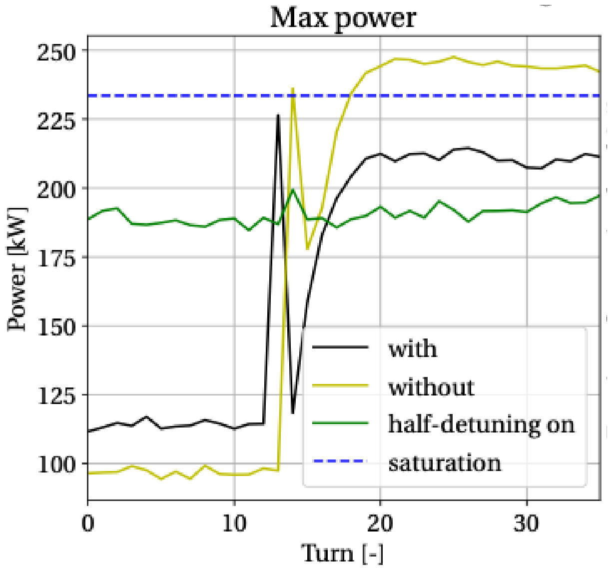


Measured Q_L via voltage decay when setting the setpoint Q_L to 20k

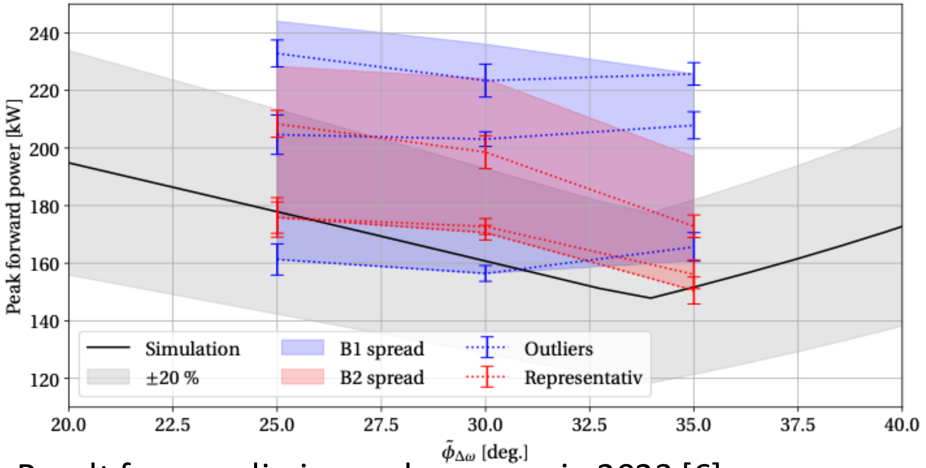
Pre-detuning the RF Cavities Before Injection

- Aim: Avoid high peak power at beam injection
  - Detune the RF cavity to anticipate the beam-loading due to the incoming beam [6]
- Pre-detuning phase
  - Phase associated with the frequency offset in tuner control
  - Scan performed in operation
  - Effect simulated using BLonD [7]

$$P = \frac{1}{8}\frac{V_a^2}{(R/Q)Q_L} + \frac{1}{8}(R/Q)Q_L\left(-2\frac{V_a}{(R/Q)}\frac{\Delta f}{f_{rf}} + \Im(I_{RF,beam})\right)^2$$



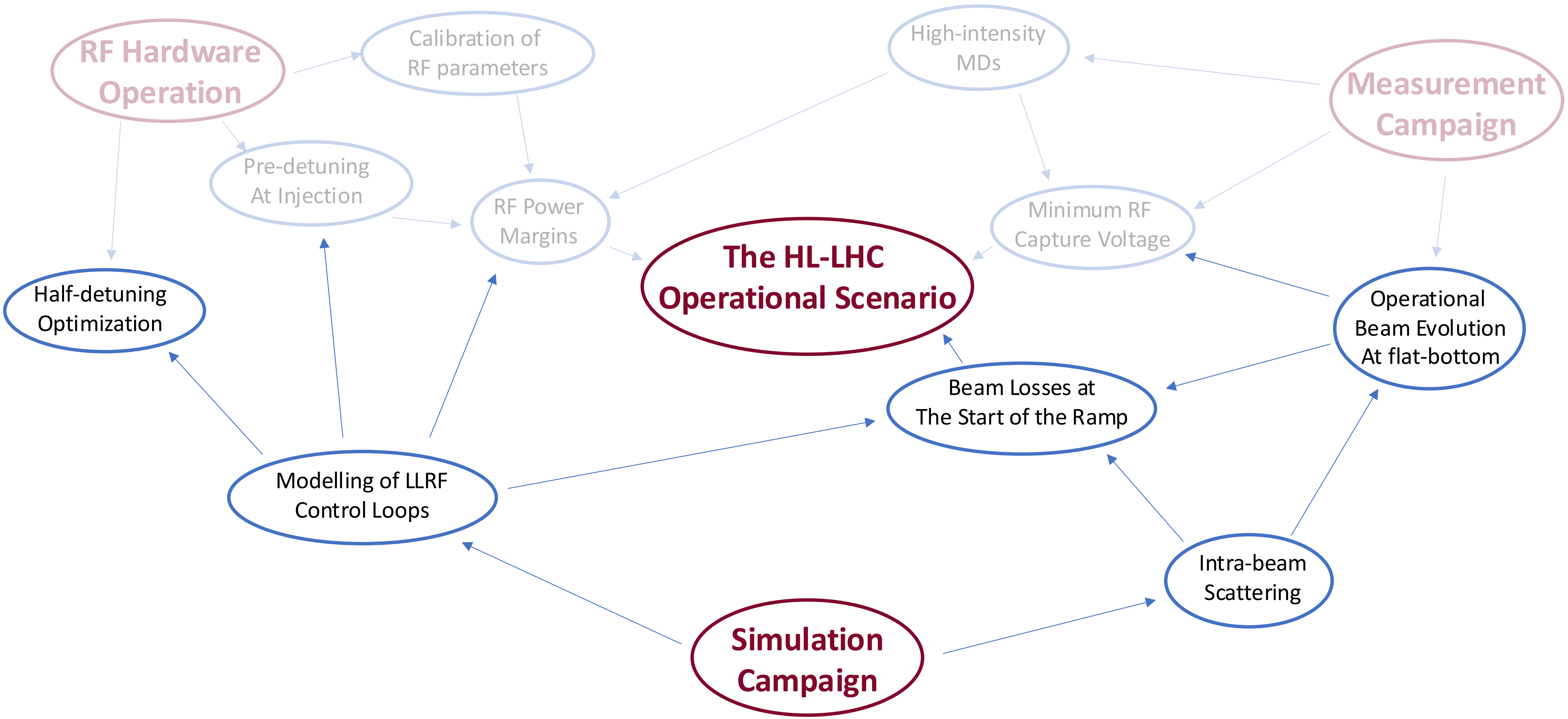
Result from initial test [8]



Result from preliminary phase scan in 2023 [6]

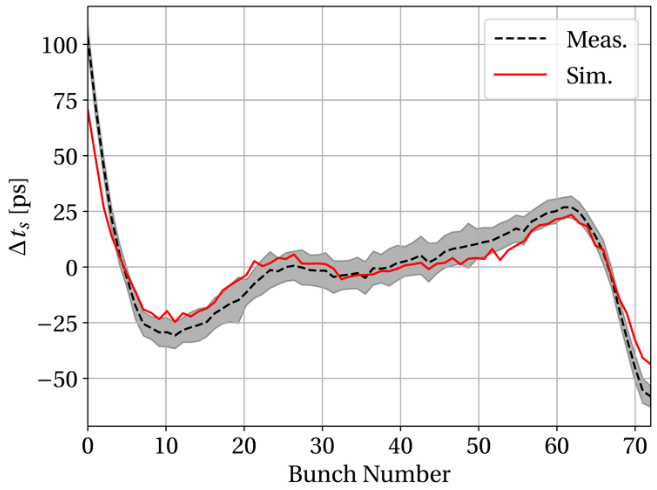
[6] B. E. Karlsen-Baeck et al., JINST **19** T04005, Contribution to HB'2023
[7] H. Timko et al., Phys. Rev. Accel. Beams, vol. 26, 2023
[8] B. E. Karlsen-Baeck et al., CERN-ACC-NOTE-2024-0002, 2024

Overview of the Project



Modelling of LLRF Control Loops

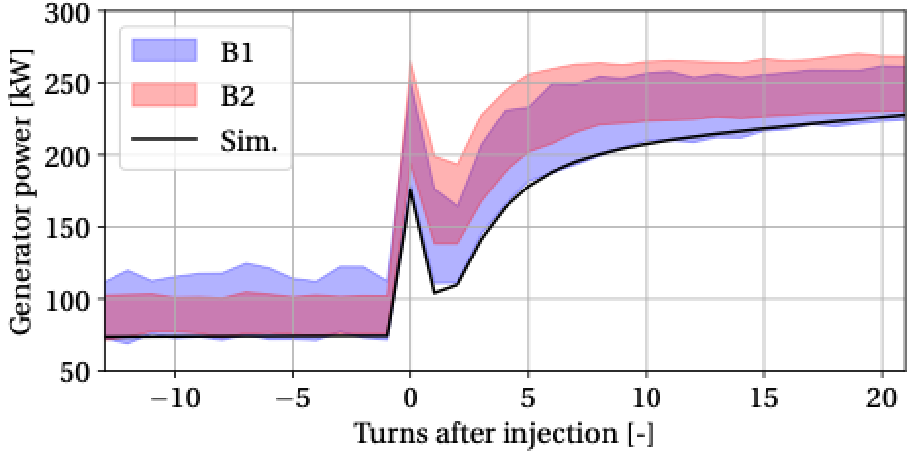
- SPS beam distributions [9,10,11]
  - Impedance model
  - Transient beam-loading
  - SPS cavity controller
    - One-turn delay feedback
    - Feedforward



Bunch-by-bunch phase offset in simulations and measurements [7]

- Modelling beam dynamics at LHC injection [11,12]
  - Intensity effects
  - Beam control loops →
  - LHC cavity controller →
    - Direct RF feedback
    - One-turn delay feedback

Requires coupling between local and global control loops

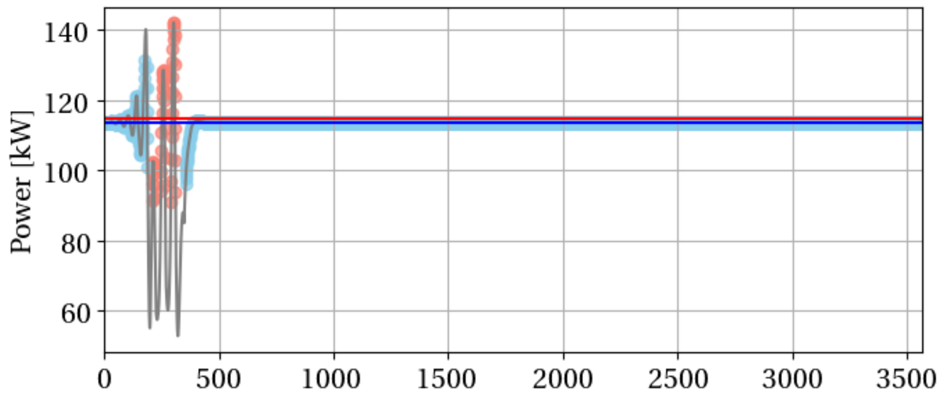


Measurement and simulation of an injection of a 36-bunch train in the LHC [11]

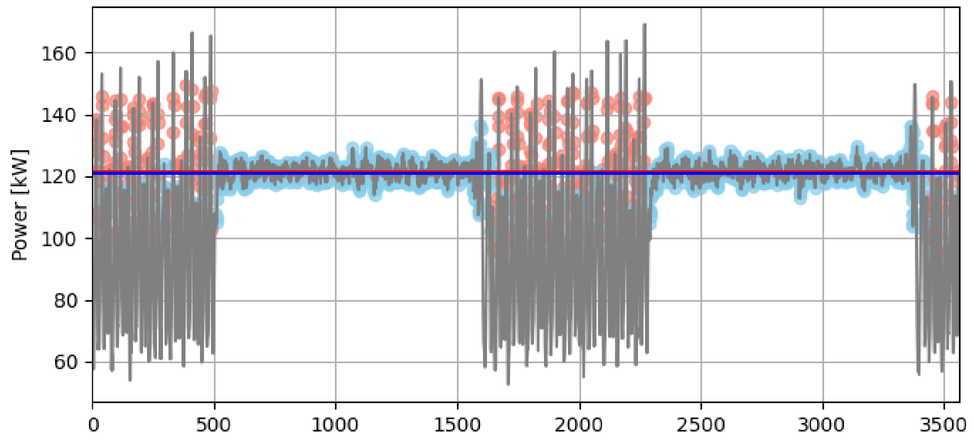
[9] P. Baudrenghien and T. Mastoridis, Rep. CERN-ACC-NOTE-2020-0032, 2020
[10] B. E. Karlsen-Baeck, Master thesis, Norwegian University of Science and Technology, 2022
[11] B. E. Karlsen-Baeck et al., in Proc. IPAC'23, 2023
[12] J. Holma, Rep. CERN-AB-Note-2007-012, 2007

Half-detuning Optimization

- RF cavity tuner
  - The half-detuning beam-loading compensation scheme is implemented in the control board
  - Set point frequency adjusted each year with beam
- Before 2024
  - Each line adjusted by eye
    - Time consuming and not very accurate
- New algorithm developed in 2024
  - Optimization guided by simulation results
  - Scheme to quantify how well adjusted each line is
  - Set-up of half-detuning scheme is significantly more efficient



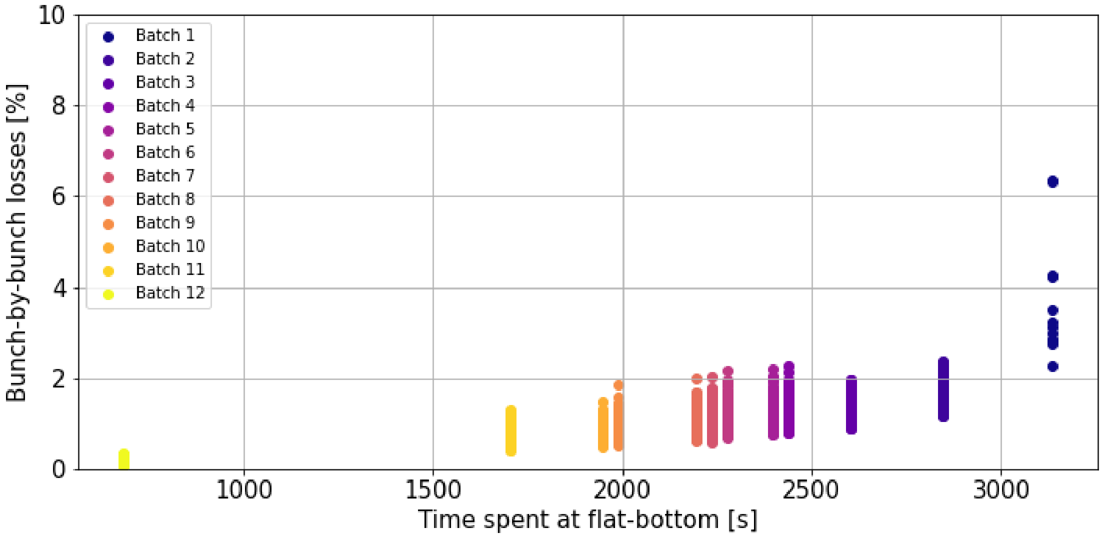
Automatic algorithm working simulated data



Automatic algorithm applied to optimize a real LHC RF cavity

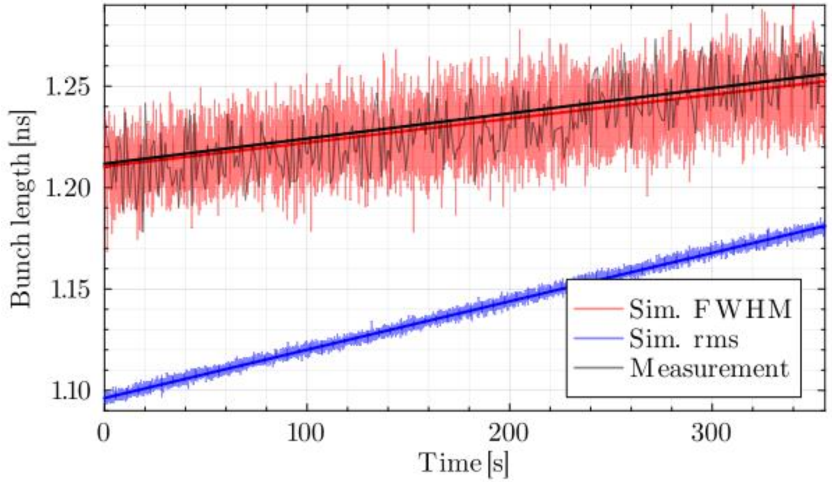
Debunching at due to Intra-beam Scattering

- Debunching during flat-bottom due to diffusion caused by
  - Intra-beam scattering
  - RF noise



Debunching losses as a function of time spent at flat bottom before injection for an LHC beam from 2023

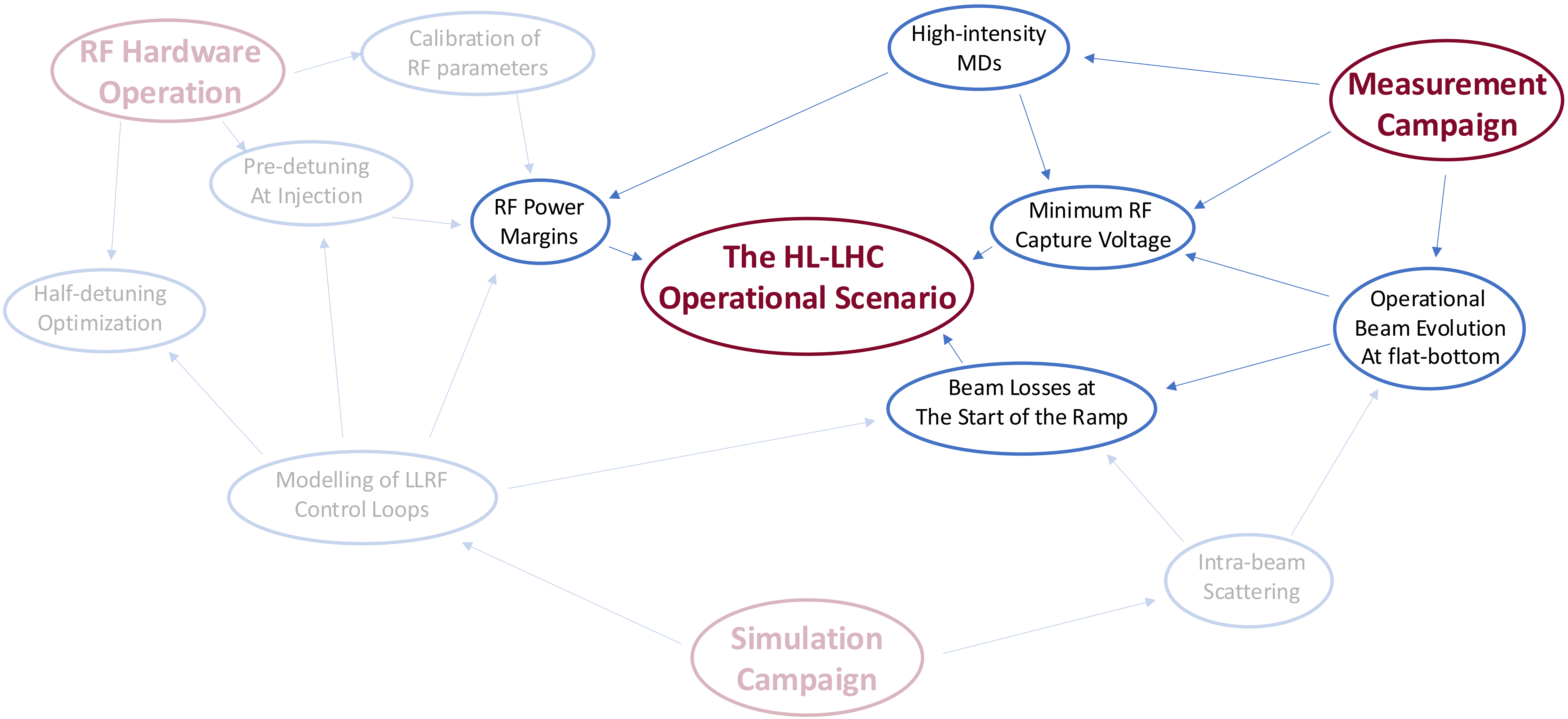
- Implementing the IBS model in BLonD [13]
  - Measurement of a single bunch at flat bottom
  - Comparison of the full width half maximum bunch length



Benchmarking with beam measurements [13]

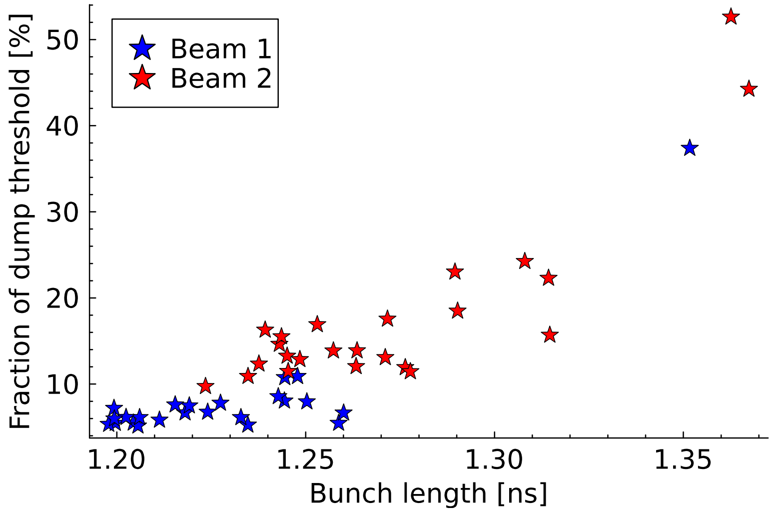
[13] M. Zampetakis et al., in Proc. IPAC’24, 2024

Overview of the Project



Off-momentum Losses at the Start of the Ramp

- Measured by Beam Loss Monitors (BLM)
  - Off-momentum losses measured in IR3
  - After a critical amount of losses, the beam is dumped
- Originate mainly from off-momentum particles
  - Combination of uncaptured beam and debunching beam
  - Partially cleaned by transverse bunch-by-bunch feedback



BLM threshold to dump in IR3 at 1.6×10^{11} p/b and 5 MV [14], from talk at JAP23, https://indico.cern.ch/event/1337597/timetable/?view=standard#25-rf-power-reach-1510

Longer bunches

↓

More beam losses

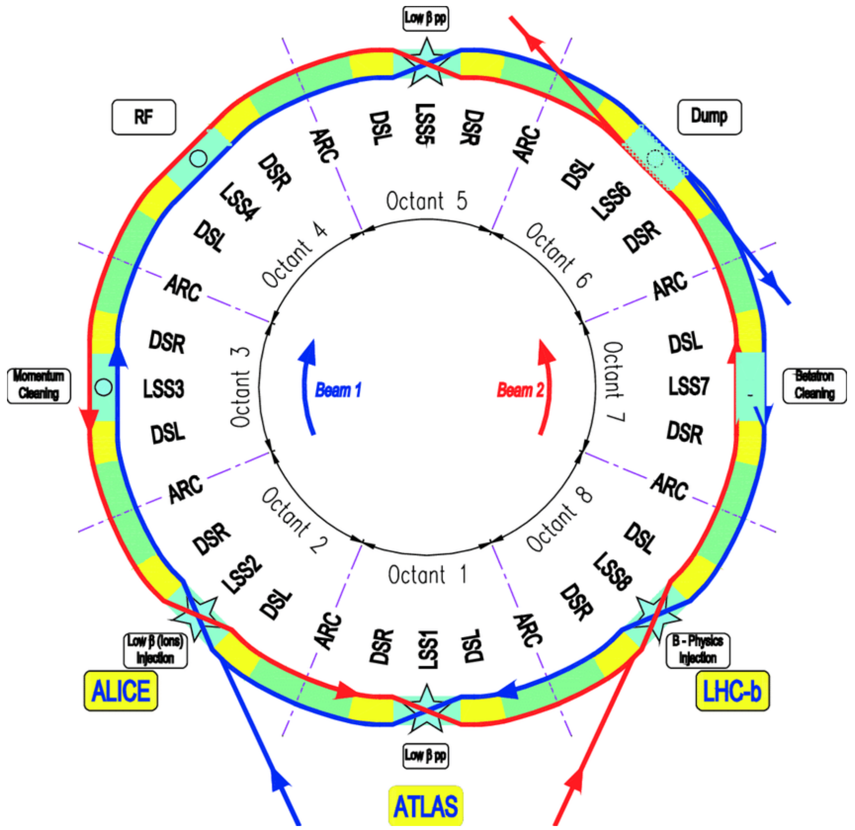
Higher voltage

↓

Shorter bunches

↓

Fewer losses

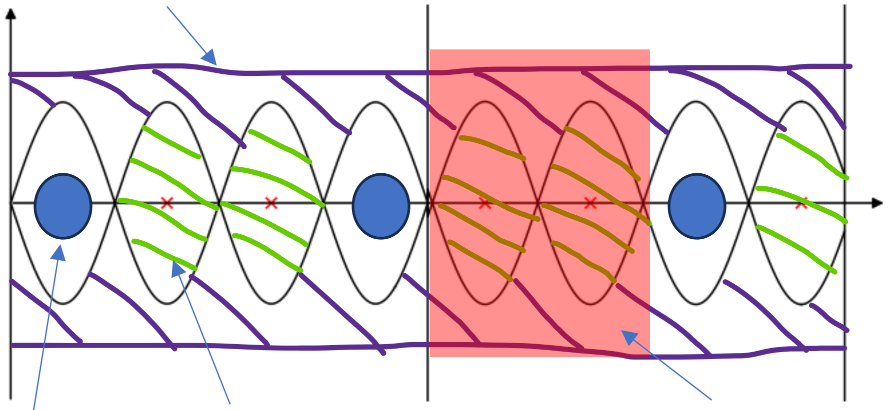


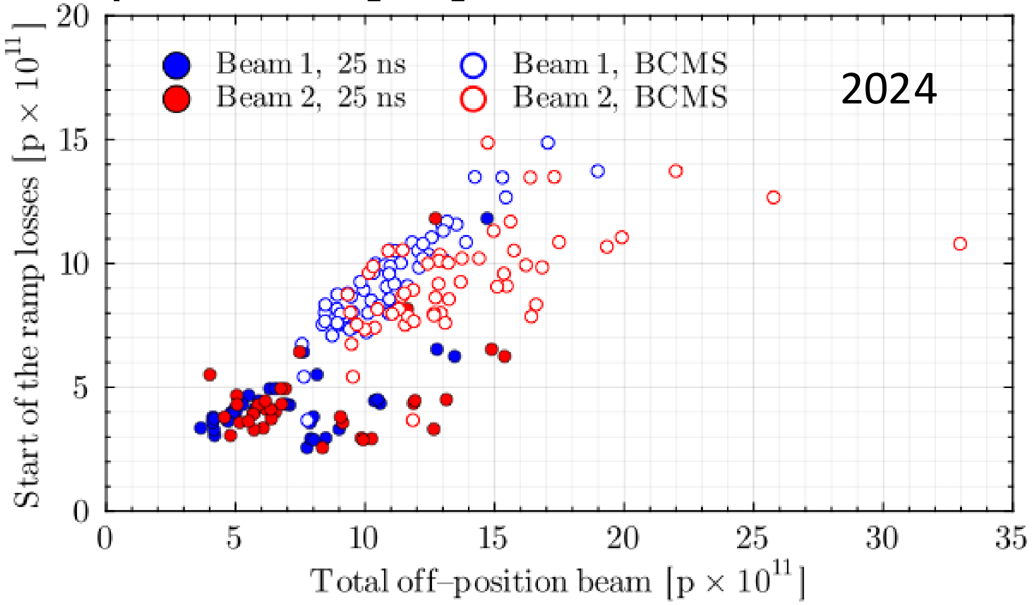
https://www.researchgate.net/figure/Layout-of-the-LHC-ring_fig1_344272046 [accessed 25 Jul 2024]

[14] B. E. Karlsen-Baeck et al., talk at JAP23, 2023

Correlation of Start-of-ramp Losses with Flat-bottom Observables

- Measurement devices
  - Bunch lengths -> Beam Quality Monitor (BQM)
  - Bunch intensities -> Fast Beam Current Transformer (FBCT)
  - Total beam intensity -> Direct Current BCT (DC BCT)
- Correlation of off-position beam with start-of-ramp losses [15]





[16] B. E. Karlsen-Baeck, presentation for LBOC, link: https://indico.cern.ch/event/1446081/#1-debunching-during-flat-botto

[15] B. E. Karlsen-Baeck et al., in Proc. IPAC'24, 2024
[16] B. E. Karlsen-Baeck and H. Timko, talk at LHC Beam Operations Committee, 2024

Machine Development Campaign

- MDs in the LHC
  - Dedicated beam time to perform measurements and test
- MD milestones
  - 2022: RF voltage calibration [5], capture of 1.8×10^{11} p/b and pre-detuning test [8]
  - 2023: Capture of 2.0×10^{11} p/b [17]
  - 2024: Capture of 2.3×10^{11} p/b and start-of-ramp losses with high-intensity beams

In total 6 x 8-hour MDs performed

Off-position beam analysis for Beam 2 during MDs [18]

Year	Beam type	Bunch Intensity	RF Voltage	Off-position beam	Off-position beam Scaled to 2748 bunches*	Ratio to dump
2023	Standard	1.93×10^{11} p/b	5 MV	12.15×10^{11} p	29.99×10^{11} p	(81.3 ± 9.3) %
2023	Standard	1.93×10^{11} p/b	7 MV	2.62×10^{11} p	10.54×10^{11} p	(29.4 ± 4.2) %
2024	BCMS**	1.97×10^{11} p/b	7 MV	0.26×10^{11} p	1.40×10^{11} p	(14.7 ± 6.6) %
2024***	BCMS**	2.31×10^{11} p/b	6.5 MV	13.57×10^{11} p	49.03×10^{11} p	(220 ± 24) %

*Also scaled for an average time at flat bottom of 30 minutes
**Low transverse emittance beam type
***With the OTFB open, note a few bunches saturated FBCT

[17] B. E. Karlsen-Baeck et al., technical report to be submitted about MD9525
[18] B. E. Karlsen-Baeck et al., talk at 14th HL-LHC Collaboration Meeting, 2024

From Operational Experience during Run 3

- Based on operational experience from Run 3
  - Beam parameters delivered from the SPS
  - RF capture voltage in the LHC
- Complimentary from the MDs
  - The RF voltages and consequently RF power needed to capture higher intensities

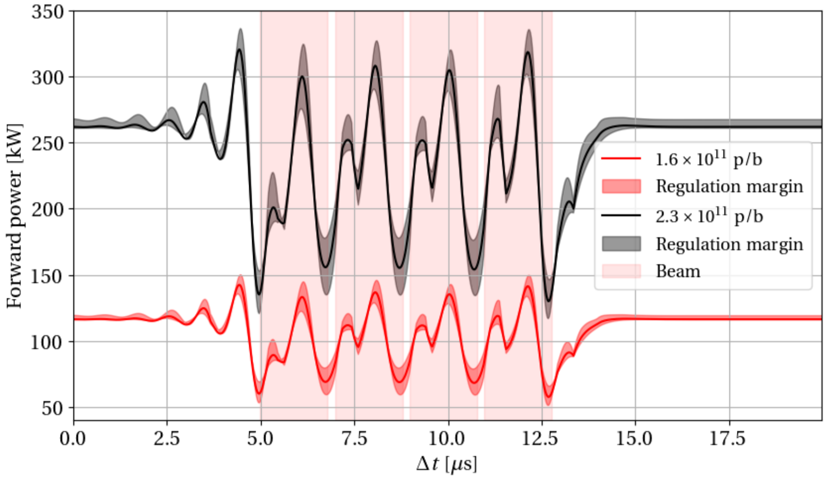
Predictions contributed to convincing the management to invest in High-Efficiency Klystrons, Talk at JAP workshop and HL-LHC workshop [14,19]

Lower voltage → Longer bunches → More beam losses

More margin in losses → More margin in RF power

Scenario	Bunch parameters			LHC parameters			
	Bunch intensity	Bunch emittance	Momentum spread	Main RF voltage	Bunch length	Average Power	Peak power
2023	1.6×10^{11} p/b	0.36 eVs	4.24×10^{-4}	5 MV	1.08 ns	127 kW	160-230 kW
2023 MD	2.0×10^{11} p/b	0.55 eVs	5.09×10^{-4}	7 MV	1.25 ns	206 kW	230-310 kW
HL-LHC	2.3×10^{11} p/b	0.58 eVs	5.32×10^{-4}	7.9 MV	1.25 ns	267 kW	320 ± 15 kW

Very rough estimate of theoretical regulation margin



Predicted RF power with the nominal HL-LHC beam

[19] H. Timko *et al.*, talk at 13th HL-LHC Collaboration Meeting, Vancouver, Canada, 25-28 September 2023

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  - Beam parameters delivered from the SPS
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Estimates triggered re-evaluation campaign of BLM thresholds, talk at JAP workshop [14]

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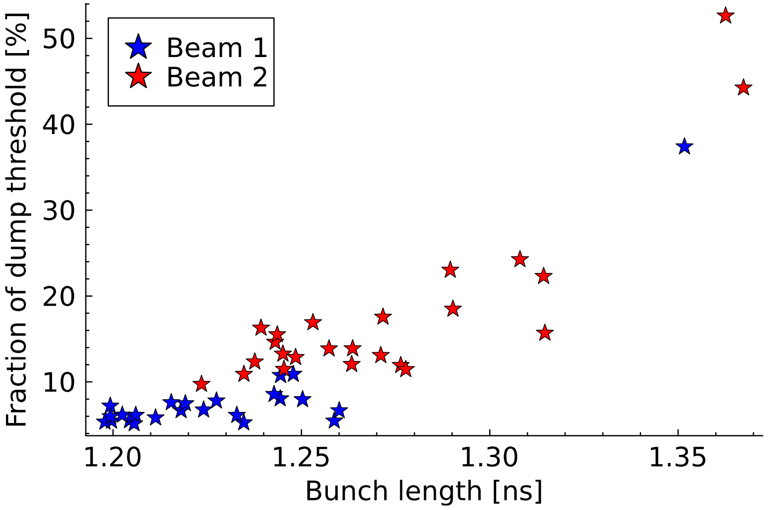

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Outlook for the Third Year

- Final verifications of hardware optimization
- Analysis of final measurements from 2024
  - Measure start-of-ramp losses with the HL-LHC bunch intensity
- Simulation campaign
  - Loss predictions for HL-LHC operation using beam dynamics model at injection
- Based on operational experience, hardware optimization, MDs and simulations
  - Formulate HL-LHC operational scenario and what the limitations will be

Summary

- Hardware
  - Maximally optimized performance of hardware to capture HL-LHC beam
- Simulations
  - Accurate model of injection dynamics has contributed to optimization of hardware and first capture of HL-LHC bunch intensity
- Measurements
  - Analysis of operational and MD data has given a significantly better understanding of beam losses at the start of the ramp and ultimately limitations for HL-LHC
- Third year
  - Apply simulation model to give accurate estimates of HL-LHC with input from hardware limitations and measurements

List of publications

1. H. Timko *et al.*, ''Beam longitudinal dynamics simulation studies'', Phys. Rev. Accel. Beams, vol. 26, 2023
2. B. E. Karlsen-Baeck *et al.*, "Validation of control loop modelling for power limitation studies with beams for HL-LHC", in Proc. IPAC'23, Venice, Italy, 2023
3. H. Timko *et al.*, "Advances on LHC RF Power Limitation Studies at Injection", in Proc. HB'2023, CERN, Geneva, Switzerland, 2023
4. M. Zampetakis *et al.*, "Refining the LHC Longitudinal Impedance Model", in Proc. HB'2023, CERN, Geneva, Switzerland, 2023
5. B. E. Karlsen-Baeck *et al.*, "Effects of cavity pre-detuning on RF power transients at injection into the LHC", JINST **19** T04005, Contribution to HB'2023
6. B. E. Karlsen-Baeck *et al.*, "Correlating start-of-ramp losses with beam observables at flat-bottom in the LHC", in Proc. IPAC'24, Nashville, TN, USA, 2024
7. K. Iliakis *et al.*, "Machine learning-based extraction of longitudinal beam parameters in the LHC", in Proc. IPAC'24, Nashville, TN, USA, 2024
8. M. Zampetakis *et al.*, "Modelling intra-beam scattering in the LHC for longitudinal beam loss studies", in Proc. IPAC'24, Nashville, TN, USA, 2024
9. B. E. Karlsen-Baeck *et al.*, "LHC MD 6944: RF Voltage Calibration", technical report CERN-ACC-NOTE-2023-0008, CERN, Geneva, Switzerland, 2024
10. B. E. Karlsen-Baeck *et al.*, "LHC MD 6945: Injection Power Transients", technical report CERN-ACC-NOTE-2024-0002, CERN, Geneva, Switzerland, 2024
11. B. E. Karlsen-Baeck *et al.*, "LHC MD 9525: Injection Power Transients with Different RF Settings", technical report to be submitted

❑ Conferences

I. 14th International Particle Accelerator Conference (IPAC'23), Venice, Italy, 7-12 May 2023

II. 68th ICFA Advanced Beam Dynamics Workshop on High-intensity and High-Brightness Hadron Beams (HB'23), CERN, Geneva, Switzerland, 9-13 October 2023

III. Joint Accelerators Performance Workshop 23, Montreux, Switzerland, 5-7 December 2023

IV. I.FAST Workshop 2024 on Bunch-by-bunch Feedback Systems and Related Beam Dynamics, KIT, Karlsruhe, Germany, 3-6 March 2024

V. 14th HL-LHC Collaboration Meeting, Genoa, Italy, 7-10 October 2024

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