RF Power Reach

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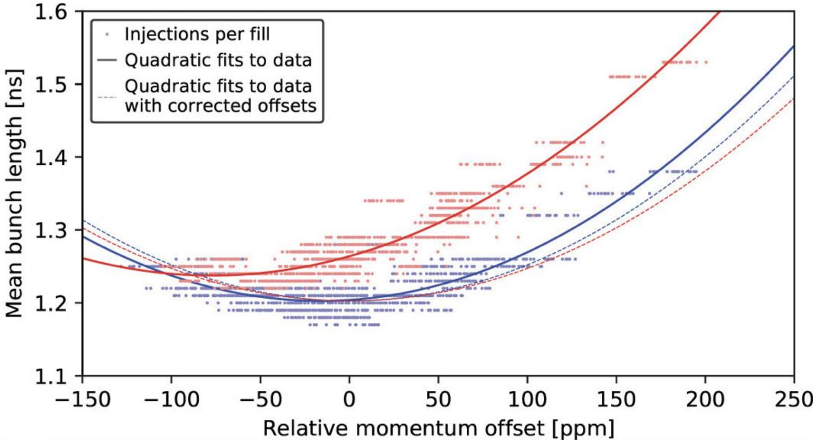
Outline

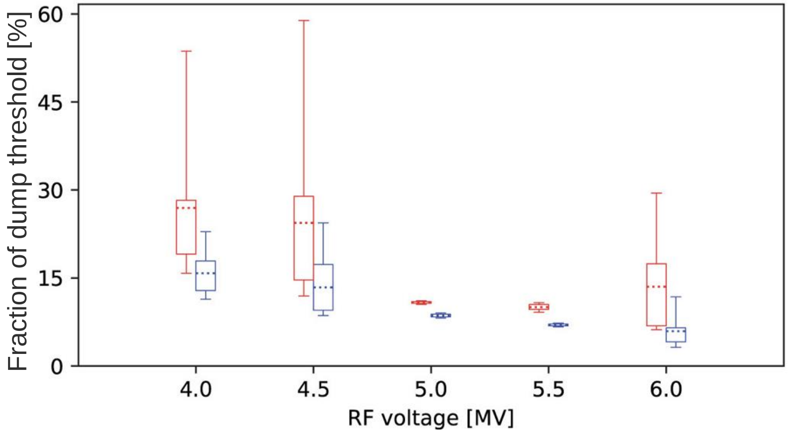
- **Predictions from 2018**
- **Progress in 2023**
  - Calibration Campaign for EYETS 2023/24
  - SPS-LHC Energy Matching
  - RF Power Transients and Pre-detuning
  - Results from High-intensity LHC RF MD 2023
- **Predictions and plan for 2024**
  - Simulating and Measuring Longitudinal Beam Losses
  - Updated estimates of RF power
- **Conclusions and outlook**

Power Limitations at Injection

- **Estimates based on 2018 operation [1]**
  - Voltage reduction campaign with the given SPS-LHC energy mismatch gave an optimal capture voltage of 4 MV [2]
  - Limitation from start-of-ramp losses (capture and flat-bottom)
  - Start-of-ramp losses depend on injection errors and RF voltage
  - 300 kW available power in currently installed klystrons

When	Bunch parameters	SPS	LHC parameters		
	Bunch intensity	Momentum spread	Main RF voltage	Bunch length	Average power
2018	1.4×10^{11} p/b	3.74×10^{-4}	4 MV	1.22 ns	84 kW
Run 3	1.8×10^{11} p/b	4.95×10^{-4}	7 MV	1.28 ns	183 kW
HL-LHC	2.3×10^{11} p/b	5.32×10^{-4}	7.8 MV	1.24 ns	265 kW



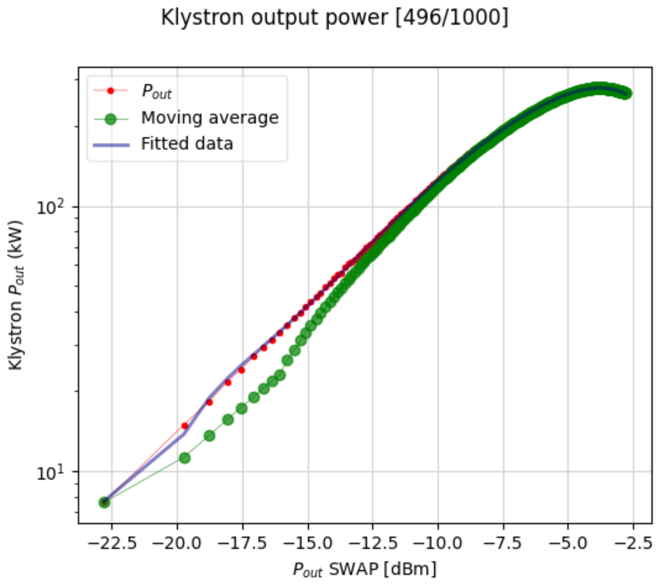


Results from the 2018 voltage reduction

[1] H. Timko: “LHC RF: possible limitations and planned Run 3 studies”, LHC Performance Workshop 2022
[2] L. Medina *et al*., “Optimal injection voltage in the LHC”, NIMA, **1039**, 166994, 2022

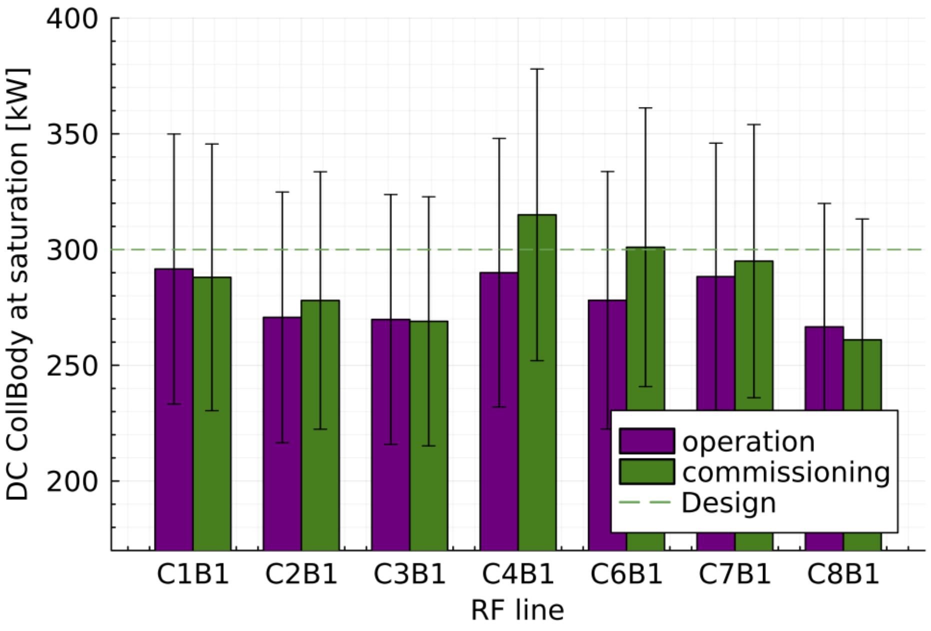
Klystron Saturation Power

- **With cavity detuned**
  - Saturation curve of each klystron is measured during commissioning
- **With cavity on resonance**
  - Most RF lines are below the design power

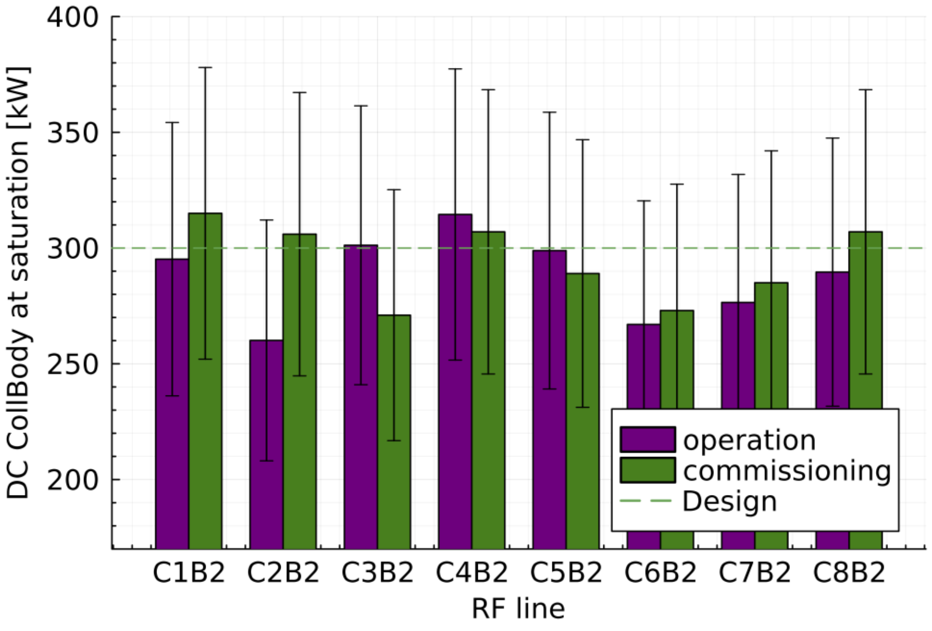


Measured saturation curve during commissioning

Beam 1



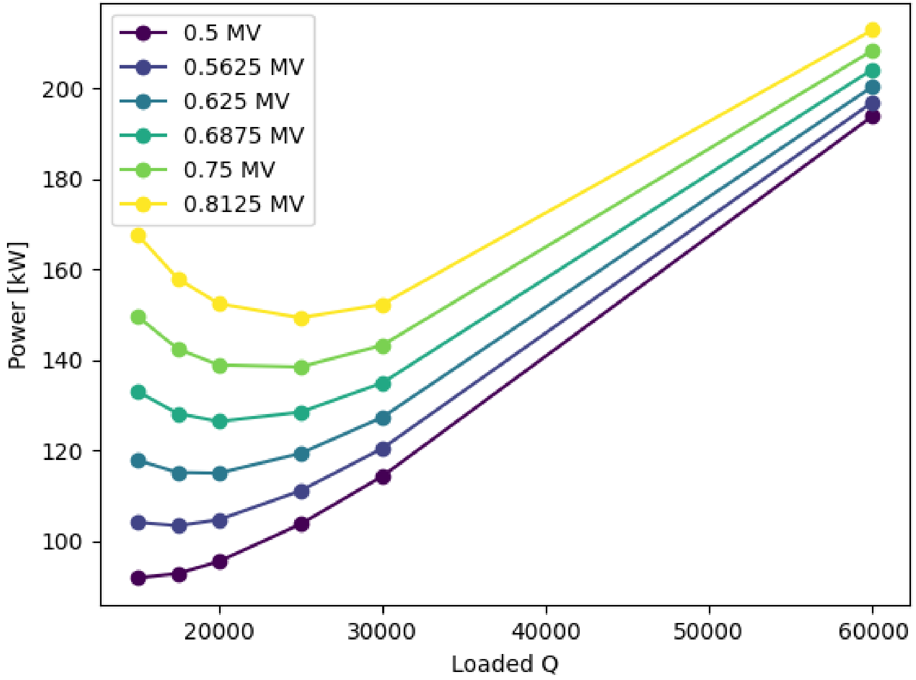
Beam 2



RF power measured in operation (purple) and during commissioning (green)

Calibration Program

- **Motivation**
  - Three parameters to understand: RF voltage, Q_L and RF power
  - Long standing issue with accurately measuring at least two of the parameters
- **The Program**
  - Cavity Q_L calibration
    - Measurement through voltage decay in the cavity
    - Measurement with beam in half-detuning
  - Beam-based voltage calibration

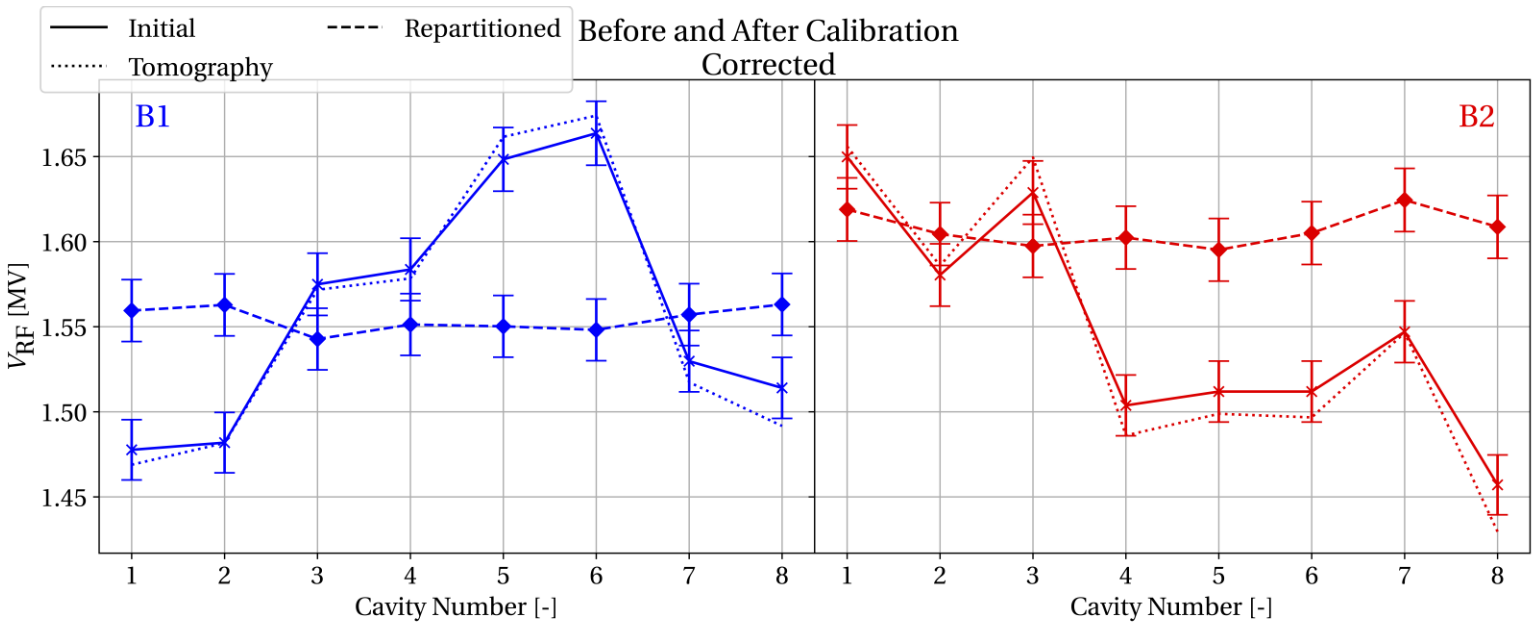


Power as a function of loaded *Q* with beam from theory

$$P_{opt} = \frac{1}{8}\frac{V_a^2}{(R/Q)Q_L} + \frac{1}{32}(R/Q)Q_L I_{RF,beam}^2 = \frac{V_a I_{RF,beam}}{8}$$

Beam-based Voltage Calibration

- **Beam-based voltage calibration**
  - Tomography and synchrotron frequency analysis in good agreement
  - We now have a good idea of the voltage in the cavities (< 3% precision)
  - Correction factors will be implemented in the LLRF

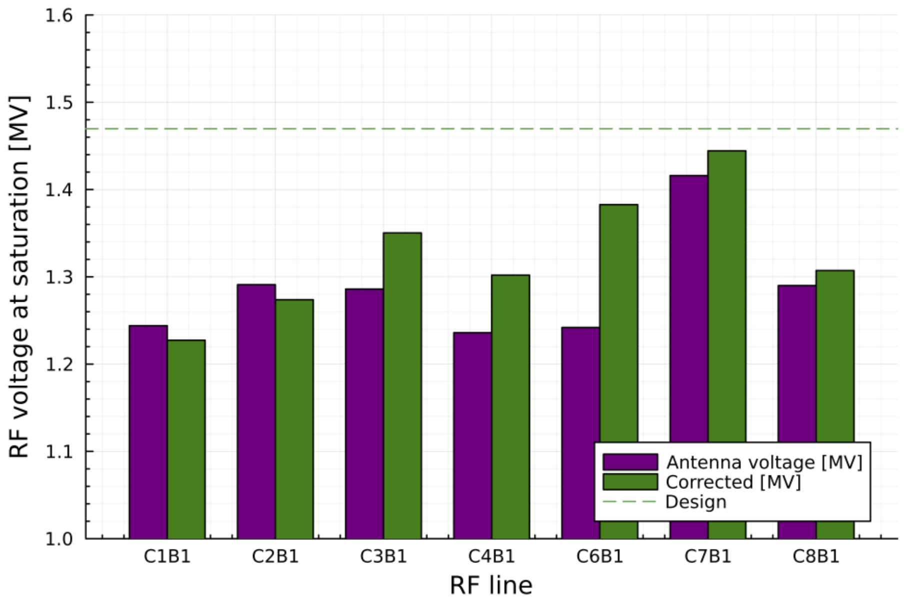


RF voltage experienced by the beam when considering intensity effects and non-linearity of the RF bucket at a set point of 1.5 MV

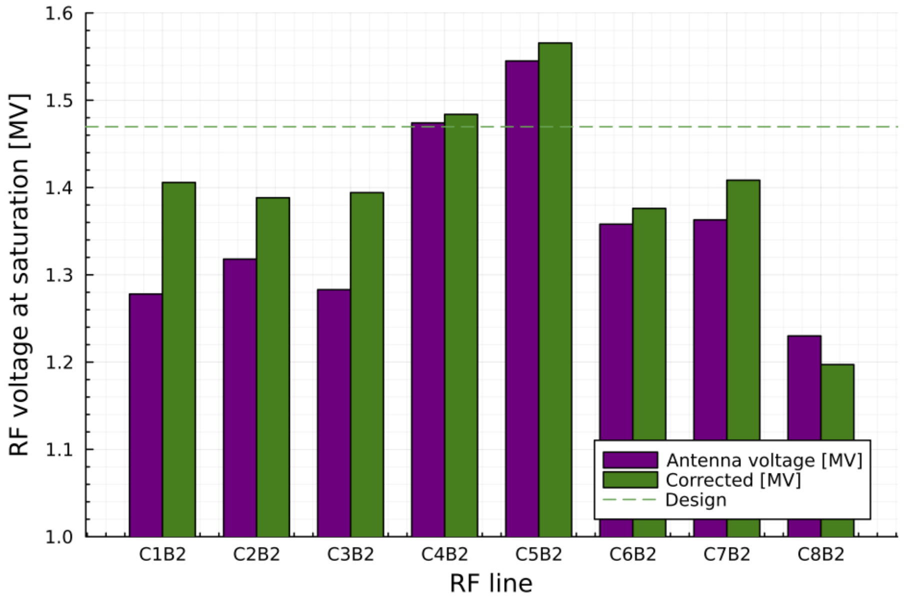
Calibration Without Beam

- **Klystrons should provide around 300 kW**
  - We do not get the expected voltage from all lines
  - Is the power correct and Q_L wrong?
  - Is the Q_L correct and the power wrong?
  - Mixture of both
- **Loaded *Q* factor measurements**
  - Measurements performed without beam
  - Plan to measure Q_L with batched beam in 2024

Beam 1

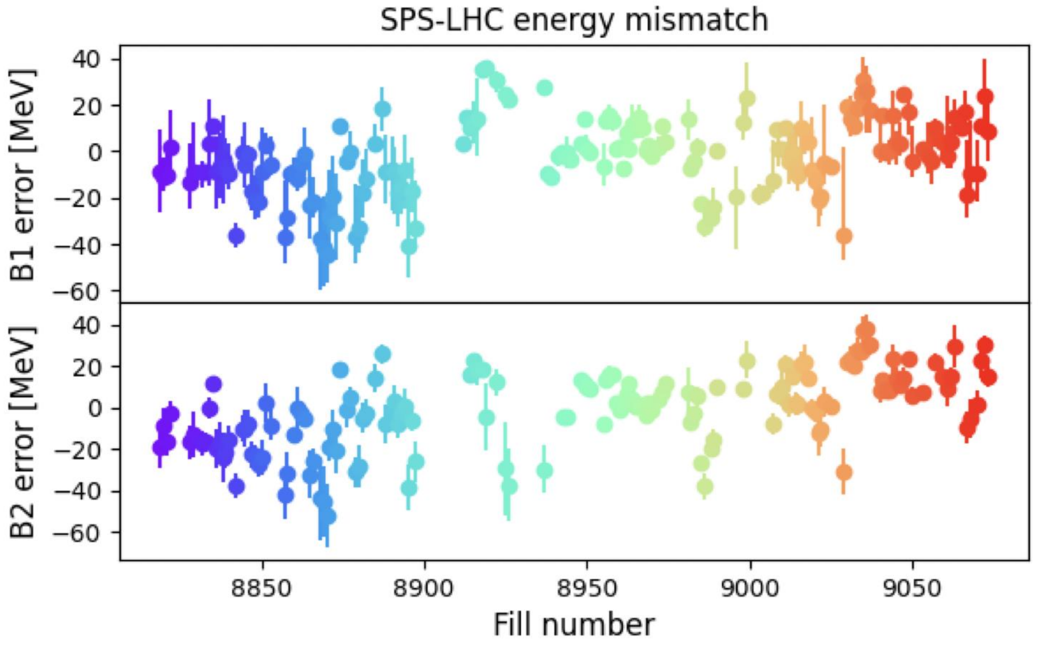


Beam 2



SPS-LHC Energy Matching and Tomography

- **New diagnostics**
  - Logging of RF power transients at injection
  - Machine Learning Tomography to extract beam parameters, e.g. injection errors batch-by-batch
- **Improved energy matching**
  - In 2018 (orbit based): -60 MeV to 90 MeV
  - In 2023 (ML based): -60 MeV to 40 MeV
  - More frequent energy matching
- **To do: Compare with data based on orbit**

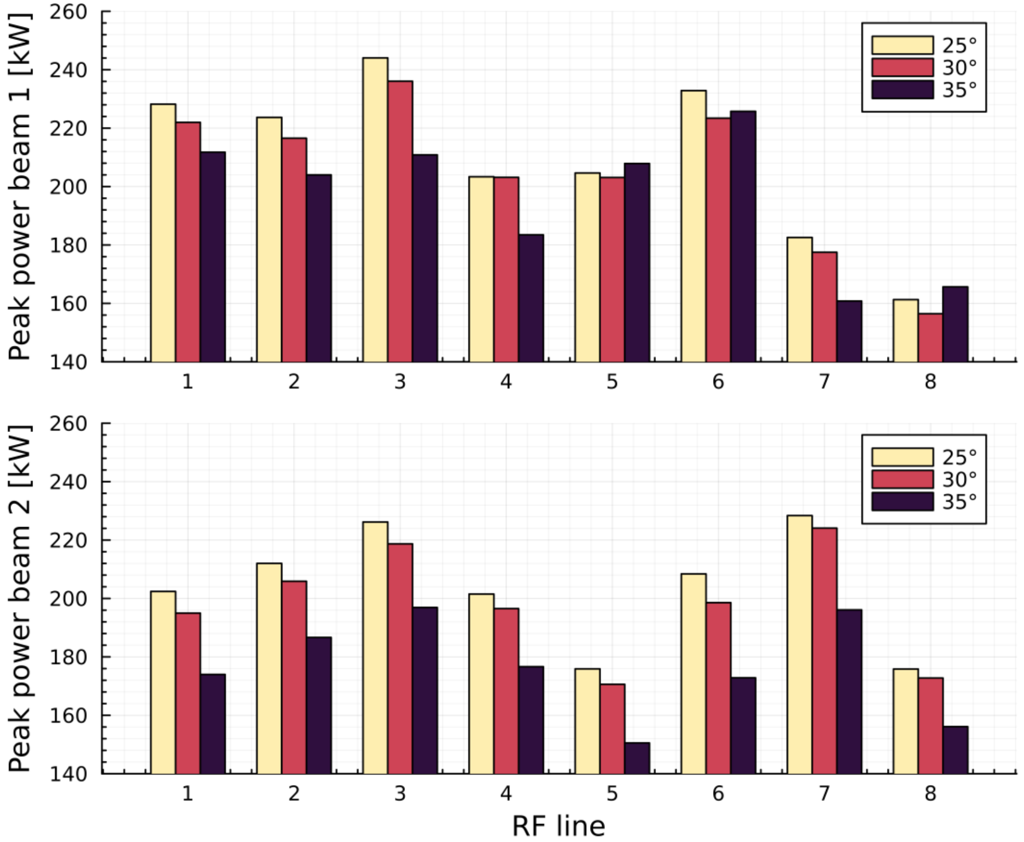


Fill-by-fill energy matching from end of May to July 2023 [3]

[3] H. Timko *et al.*, “Advances on LHC RF power limitations studies at injection”, In proc. HB2023, Geneva, Switzerland

RF Cavity Pre-detuning in Operation

- **The pre-detuning scheme**
  - Detuning the cavity to the beam before it is injected
- **In operation**
  - Put into operation starting April 2023
  - Initial optimization performed mid of July 2023
    - Further fine-tuning is planned for 2024
- **Results**
  - Reduction in RF power injection transients
  - Now the limitation comes from steady-state transients (due to feedback regulation)



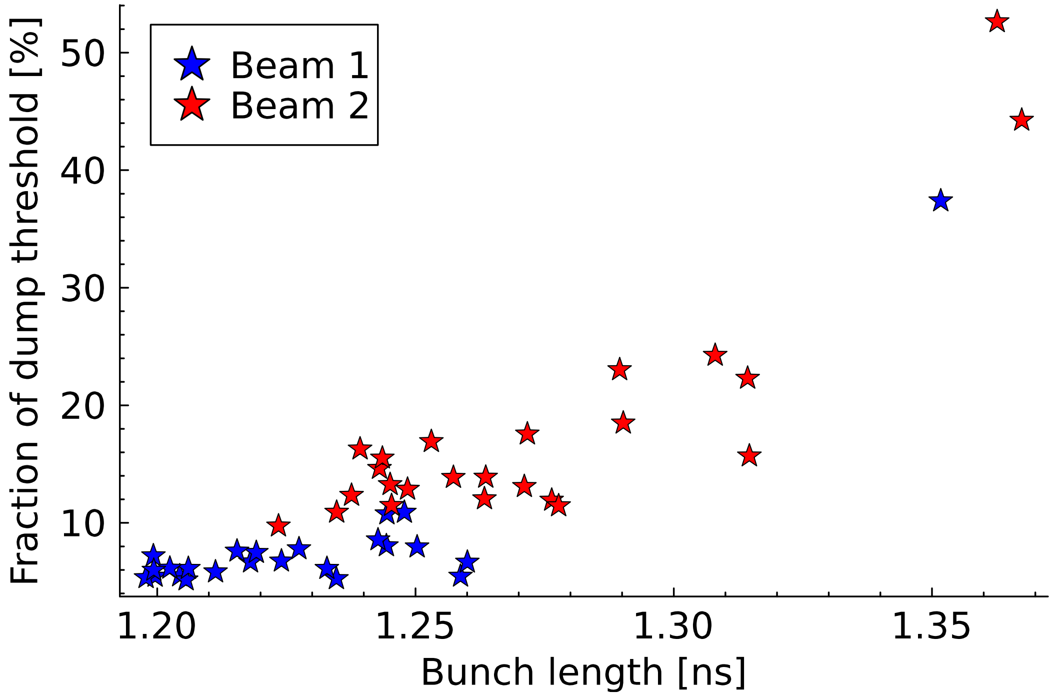
Reduction of peak power as pre-detuning angle approaches optimum

Results from High-intensity RF MD this Year

- **First-turn beam parameters in the LHC**
  - 72 bunches with average length of 1.6 ns and bunch intensity of $1.91{\times}10^{11}$ p/b
  - Longest bunch was 1.88 ns, shortest was 1.42 ns
- **Injections with 4 MV, 5 MV and 7 MV**
  - Beam captured with both 4 MV and 7 MV without saturating thanks to pre-detuning
  - We do not know what the uncaptured losses would have been
- **Correlate start-of-ramp losses to abort gap population**
- **Possible paths to take for MDs in 2024**
  - Leave the beam to blow up on flat-bottom
  - Do a small ramp

Start-of-ramp Losses and the Beam Loss Monitors

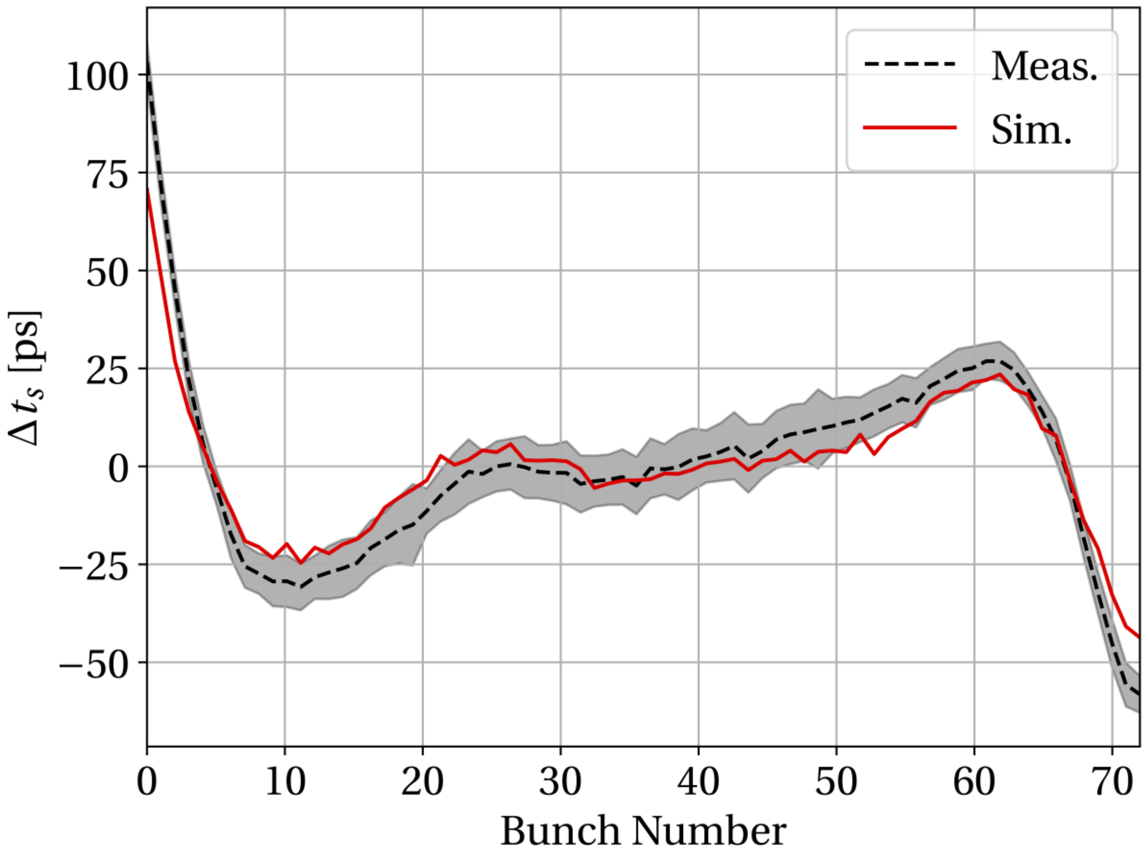
- **Correlation between fraction of dump threshold in IR3 at the start of the ramp**
  - **Beam 1: ~10%**
  - **Beam 2: ~20%**
- **The limitation for HL-LHC will be the Beam Loss Monitor (BLM) threshold to dump**
  - capture and flat-bottom losses
- **Review thresholds for start-of-ramp losses**



BLM threshold to dump in IR3 at 1.6×10^{11} p/b and 5 MV

Simulation Studies

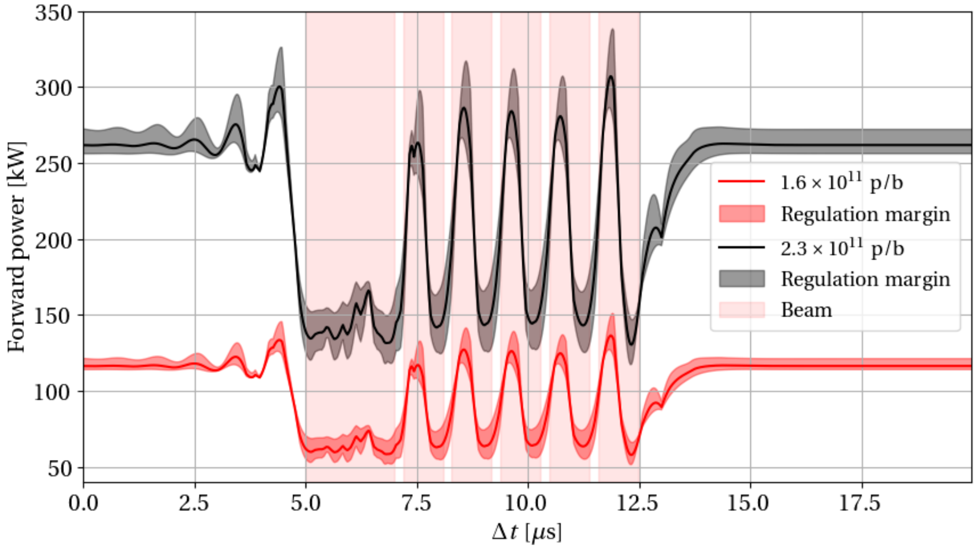
- **Detailed modelling of SPS and LHC LLRF controls in BLonD**
  - For the first time using both local and global LLRF control loop models
- **SPS simulations**
  - Modelling of flat top beam distributions
- **LHC simulations**
  - RF power demand
  - Effects due to transients in RF system
  - Capture losses
  - Pre-detuning



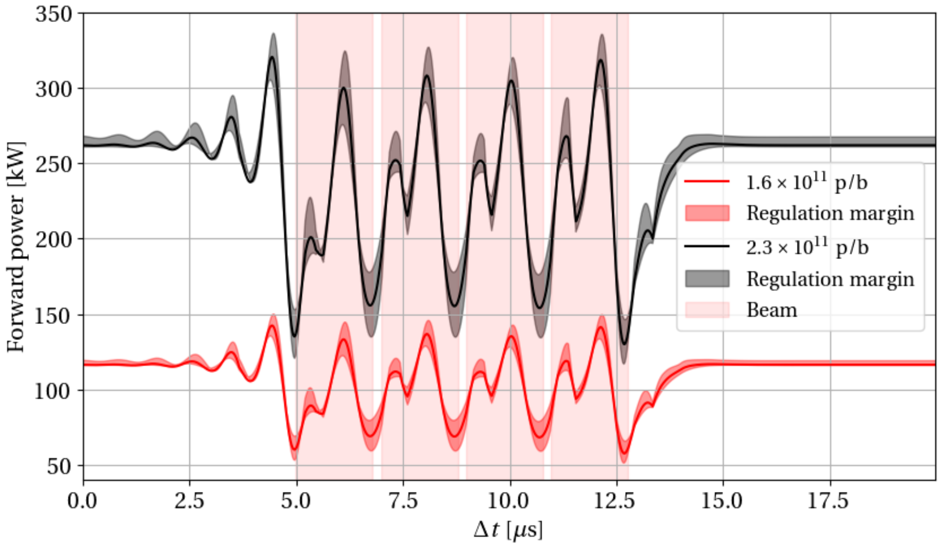
Example of the bunch-by-bunch phase offset in simulation and from measurement in the SPS

Steady-state Power in Simulation

- **Voltage scaled to HL-LHC from experience in 2023**
  - Design voltage for HL operation would be 7.9 MV
- **Using LHC LLRF model in BLonD**
  - Recreated steady-state power during operation with 2023
  - Best case scenario in steady-state gives at least 340 kW in peak power with 7.9 MV



Hybrid batch



4 x 72 bunches

Updated Estimates of RF Power

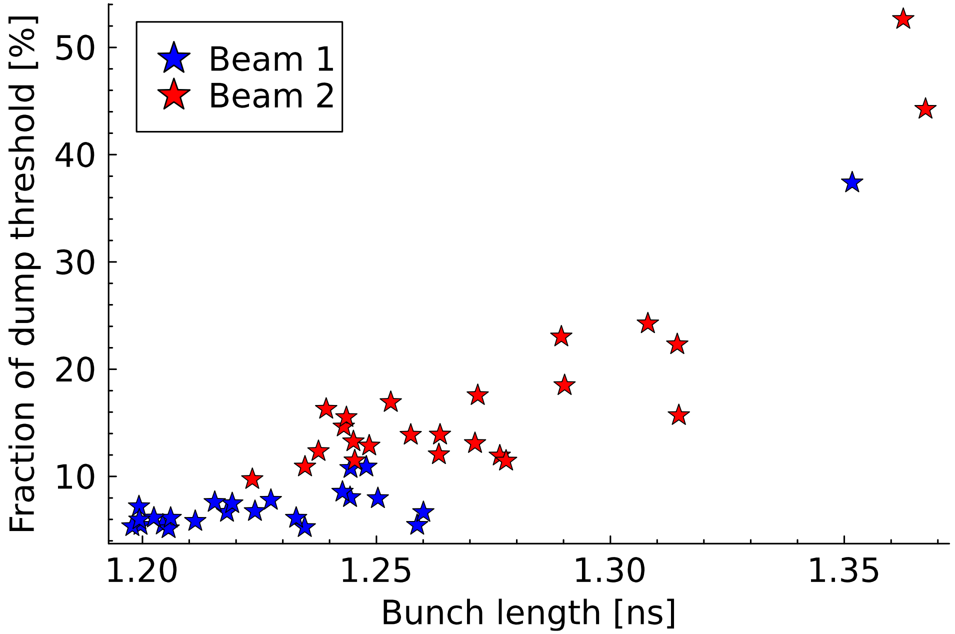
- **Pre-detuning mitigates RF power limitation at injection**
- **Analysis of operational experience with 1.6×10^{11} p/b**
  - For HL parameters at least 340 kW are required to keep regulation margin
- **High-efficiency klystrons (HEK) (from 300 kW to 350 kW) are a must**
  - Dump threshold correlated to bunch length which depends on voltage

Scenario	Bunch parameters		SPS parameters			LHC parameters					
	Bunch intensity	Bunch emittance	Main RF voltage	4th harm. voltage	Momentum spread	Main RF voltage	Bunch length	Optimum detuning	Optimum Q_L	Average power	Peak power
2023 (hyb)	1.6×10^{11} p/b	0.36 eVs	9.4 MV	1.7 MV	4.24×10^{-4}	5 MV	1.08 ns	-11.8 kHz	17.0 k	127 kW	160-230 kW
2023 (max)	2.0×10^{11} p/b	0.55 eVs	9.4 MV	1.7 MV	5.09×10^{-4}	7 MV	1.25 ns	-9.7 kHz	20.6k	206 kW	230-310 kW
HL-LHC	2.3×10^{11} p/b	0.58 eVs	10 MV	2 MV	5.32×10^{-4}	7.9 MV	1.25 ns	-11.6 kHz	17.3 k	267 kW	320±15 kW

Very rough estimate of theoretical regulation margin

Discussion

- **Possibility for a shortened ramp for MDs**
- **Even with HEK we do not exactly know the operational margin we need**
- **A change in BLM thresholds could give an important additional power margin**
  - Allowing more losses is equivalent to allowing longer bunches
  - E.g. a bunch length increase from 1.25 ns to 1.29 ns would reduce the capture voltage (power) from 7.9 MV (267 kW) to 7 MV (237 kW)
- **There are other factors that also effect losses when going down in voltage**
  - Increase in capture losses
  - Effect from IBS will also change



BLM threshold to dump in IR3 at 1.6×10^{11} p/b and 5 MV

Summary

- **The RF system was able to capture 1.91×10^{11} p/b without saturating**
  - Losses to be determined
- **Power predictions for HL-LHC**
  - HE-klystrons will be a must
  - We do not know the margin needed
- **Power depends on voltage**
  - Voltage depends on losses
  - What losses can we accept?

Outlook

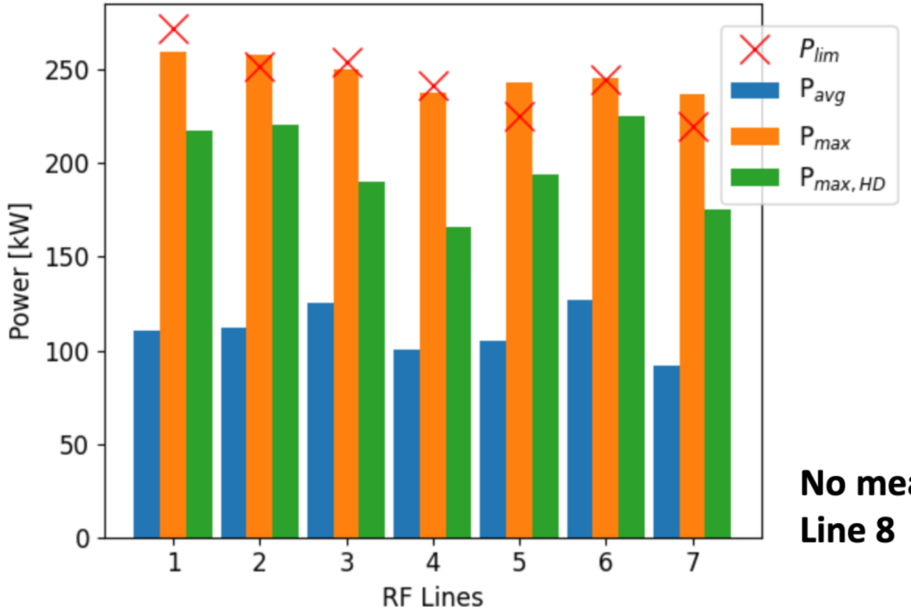
- **Tangible calibration strategy**
  - Calibration of Q_L will be performed
- **Simulation studies of losses**
  - Disentangling capture losses and flat-bottom losses
- **MD program for 2024**
  - Threshold of loss of Landau damping
  - Longitudinal beam loss at the start-of-ramp
- **Campaign to reduce RF voltage at injection**
- **Fine-tune pre-detuning scheme**

Backup Slides

Results Shown at JAP 2022

- **Captured 1.8×10^{11} p/b with 4 MV**
  - LHC pre-detuning will allow us to go to 2.0×10^{11} p/b without saturating
  - First-turn transients did not deteriorate the beam
  - Unknown start-of-ramp losses
- **Conclusion**
  - We can push the bunch intensity 2.0×10^{11} p/b

Summary of power for MD fill (BCMS 48b)
V_{RF} = 4 MV, N_p~1.8x10^{11} p/b, $\tau_{4\sigma}$~1.25ns



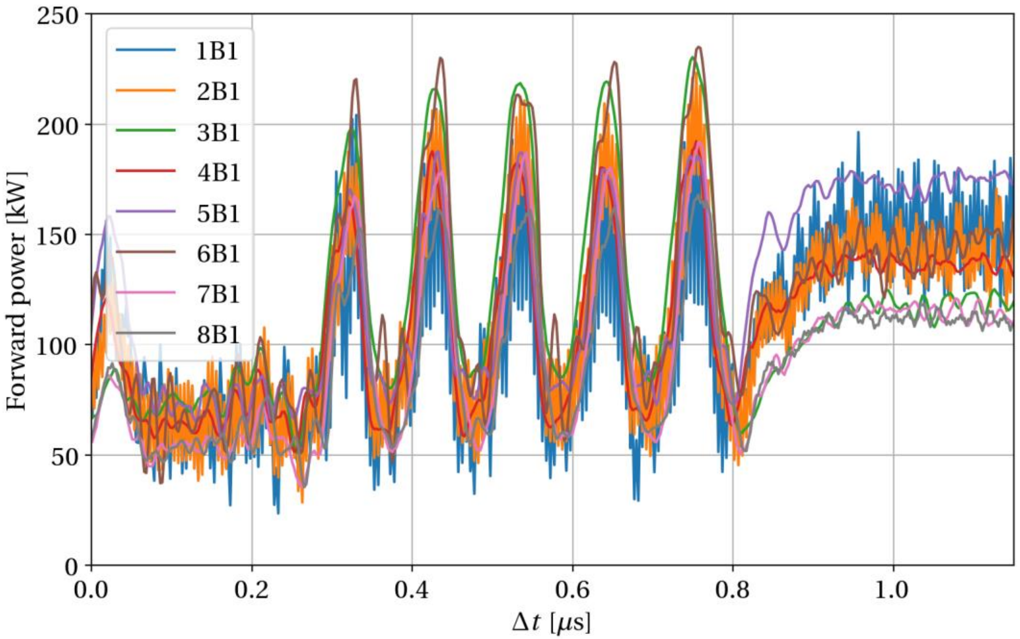
No meas. for Line 8

- ❑ **Almost all lines cross P_{lim} for short time at first injection**
- ❑ **~55% margin on P_{avg} /~ (10%-30%) on $P_{max,HD}$**

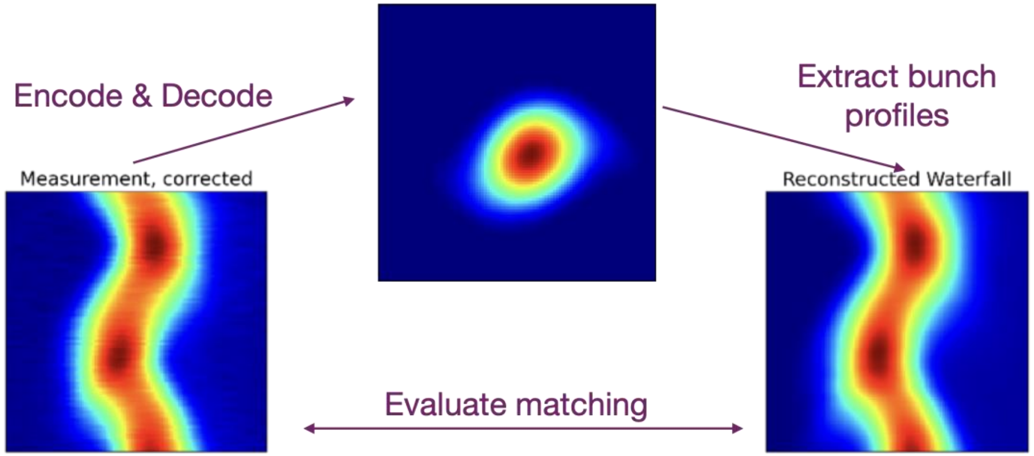
[4] T. Argyropoulos *et al.*, “RF power at injection & longitudinal tomography”, LHC Chamonix Workshop 2023

New Diagnostics Tools

- **Injection Power Transients**
  - Ig forward and antenna voltage acquired for every injection
  - First 20-26 turns of power transients
- **Tomography**
  - Only estimate of injection errors in phase and energy
  - Complementary to already existing measurements

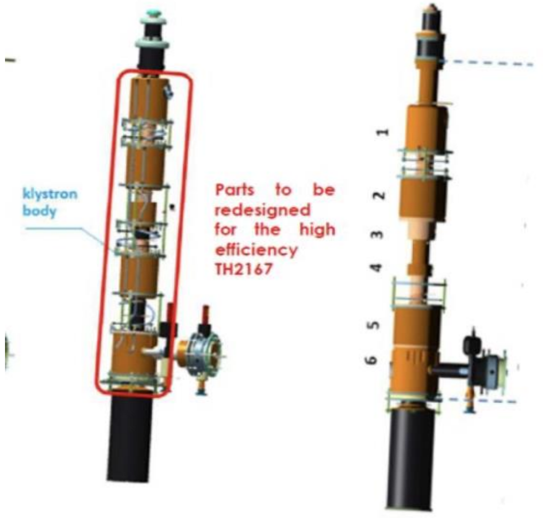


Transient taken from UCAP node



High-Efficiency Klystrons

- **Increasing the power reach of the LHC klystrons**
  - HL-LHC power estimates + operational margin = High Efficiency klystrons
  - Embedded into the LHC HV circuitry (modulator etc.) providing 500 kW DC
  - The improved design allows for an increase efficiency from 60% to 70% [5]
    - From 300 kW to 350 kW



Staged replacement of present LHC klystrons (best-case scenario)

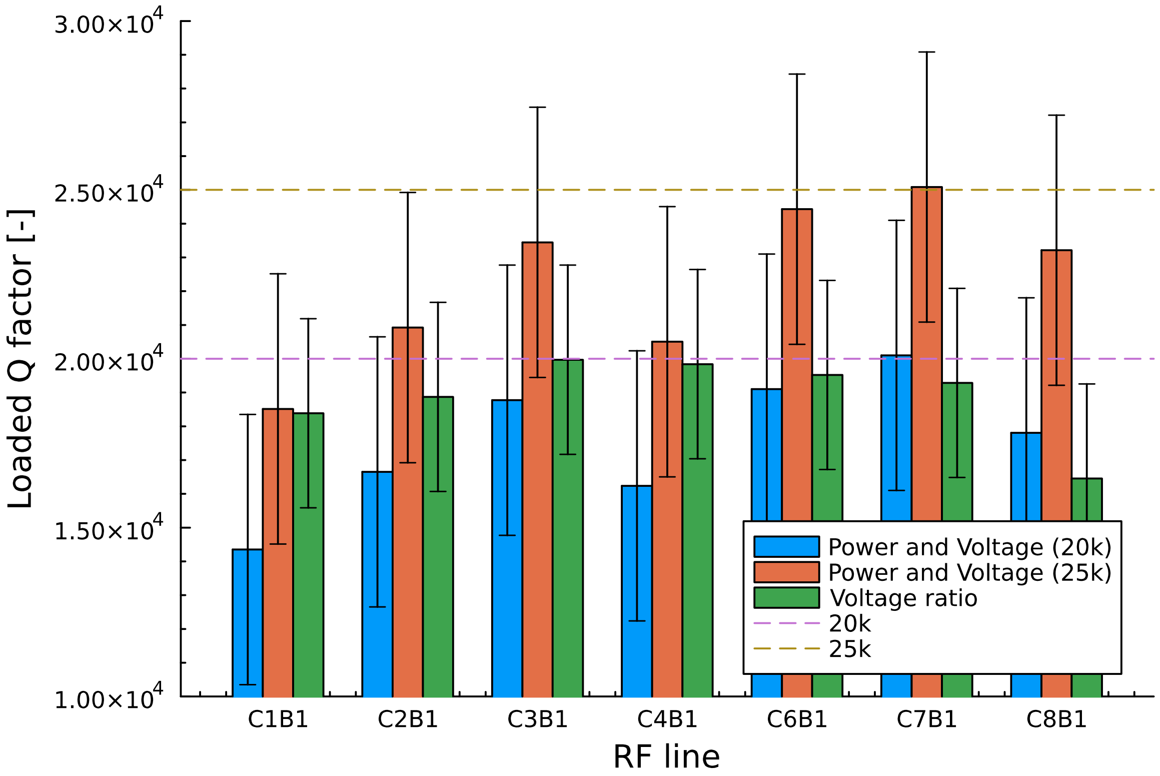
- 30 klystrons currently (16 operational + 14 spares)
- Prototype testing: 2024
- Production: 4 klystrons/year
  - 16 operational klystrons from 2026-2029
  - 14 spares from 2030-2033

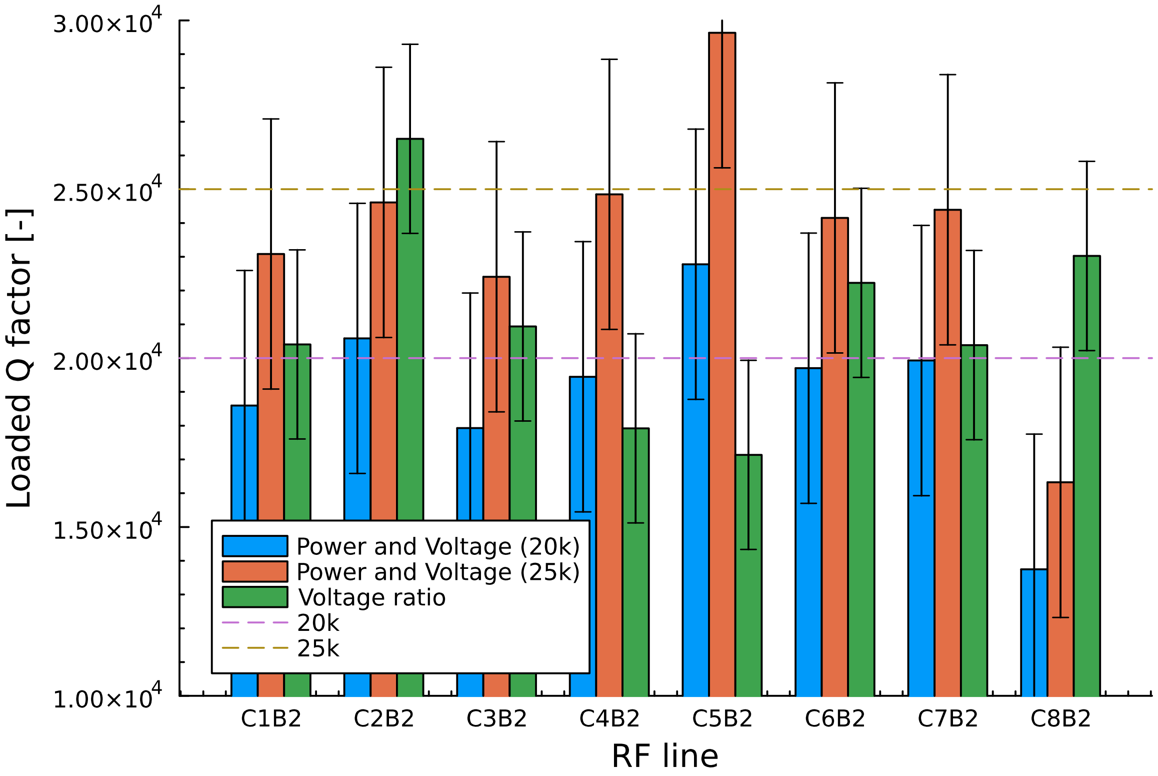
[5] A. Beunas *et al.*, "Towards high efficiency klystrons for LHC", Talk at FCC workshop, Brussels, Belgium, 2019

Program for 2024

- **Commissioning**
  - Measure Q_L without beam
  - Verify the voltage calibration with beam
  - Measure Q_L with beam
- **Pre-detuning**
  - Perform another parameter scan to optimize the detuning angle
- **LSA parameters**
  - Continuous Q_L management
- **Simulations**
- **Perform a ramp during a high intensity MD**

Calculating the Loaded Q Factor





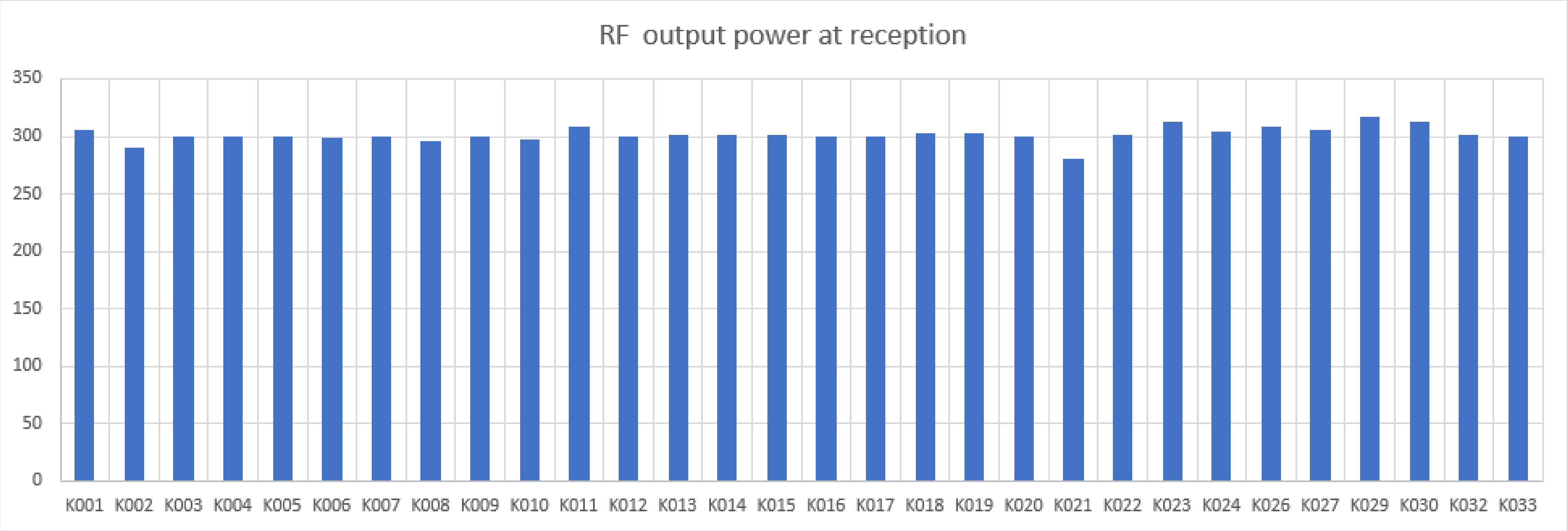
From voltage and power:

$$Q_L = \frac{V^2}{8\,{}^{R}/_{Q}\,P}$$

From voltage ratio:

$$Q_L = \frac{\Delta Q_L}{\left(\frac{V_{25k}}{V_{20k}}\right)^2 - 1}$$

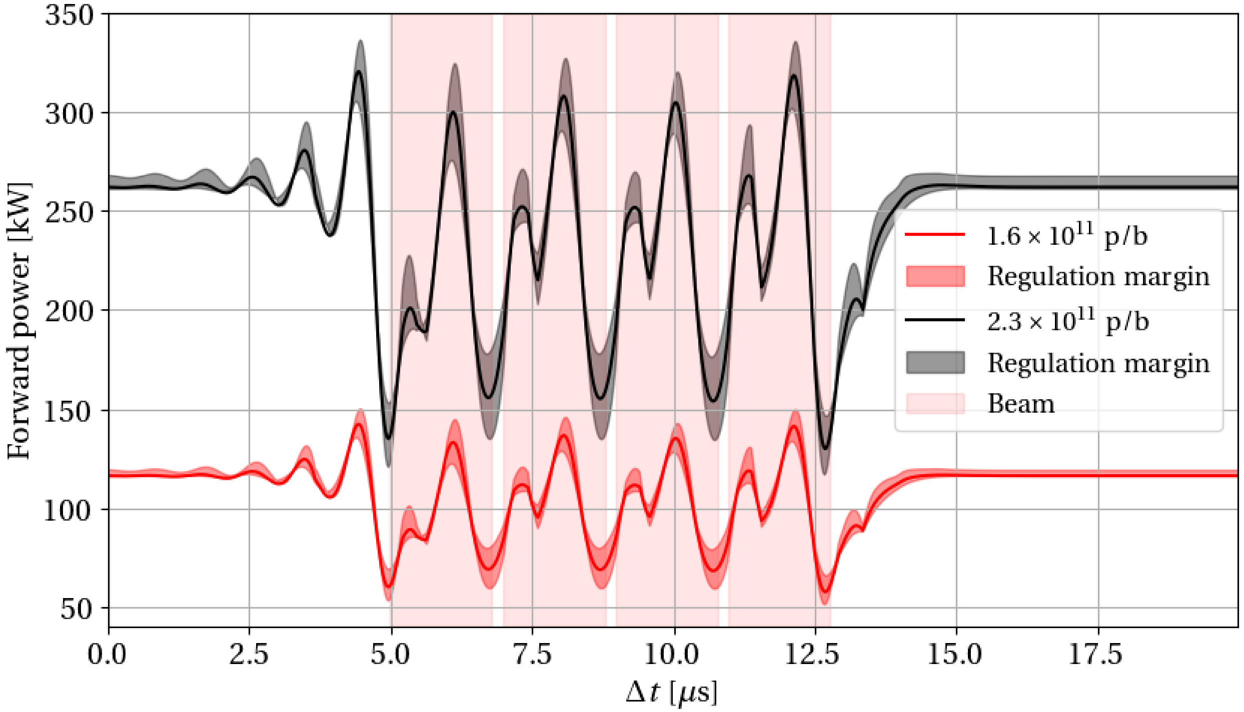
Klystrons at Reception



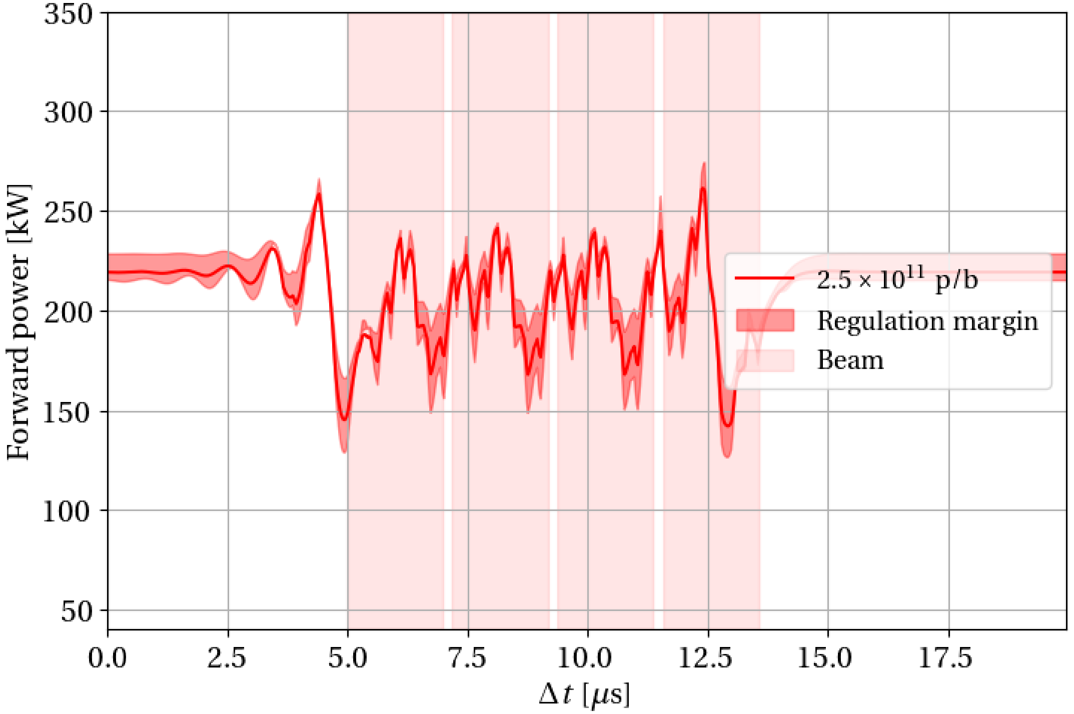
Steady-state Power with 8b4e

- **8b4e beam with 2.5×10^{11} p/b [6]**
- **4 PS batches with 56 bunches each**

4 x 72 bunches standard 25 ns



4 x 56 bunches 8b4e

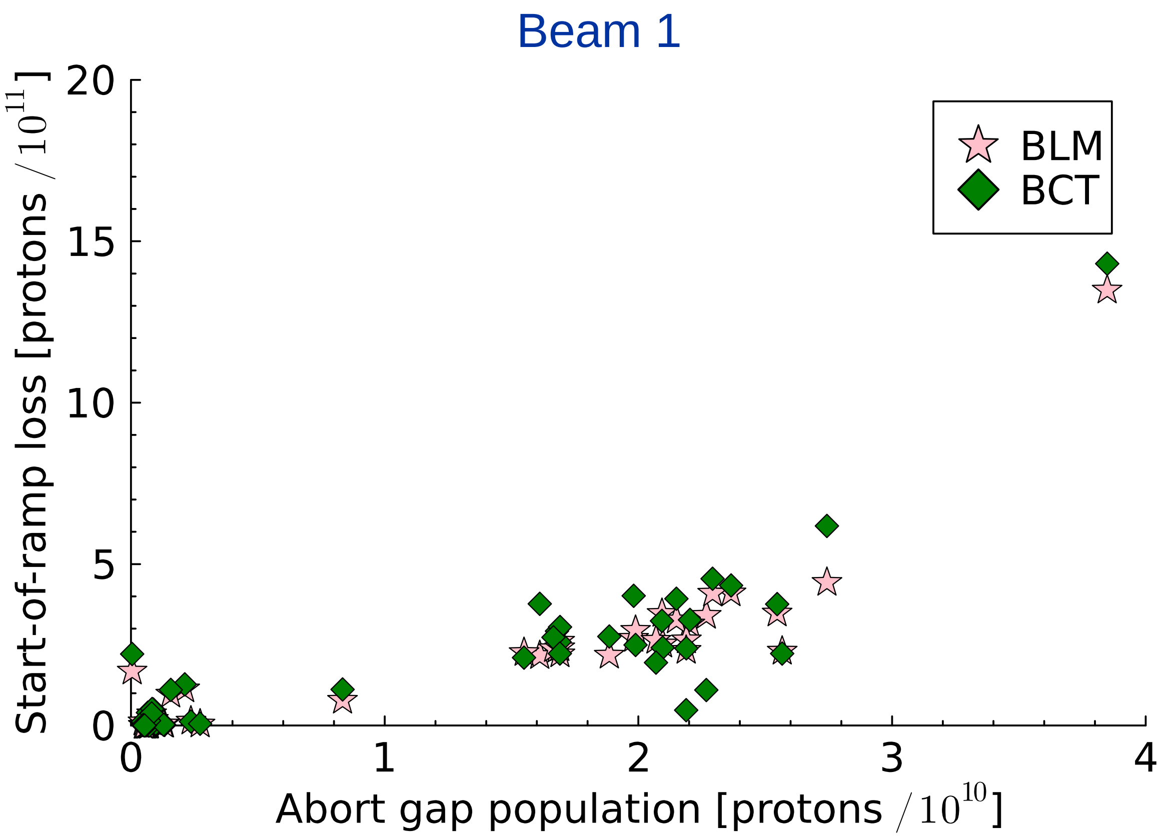


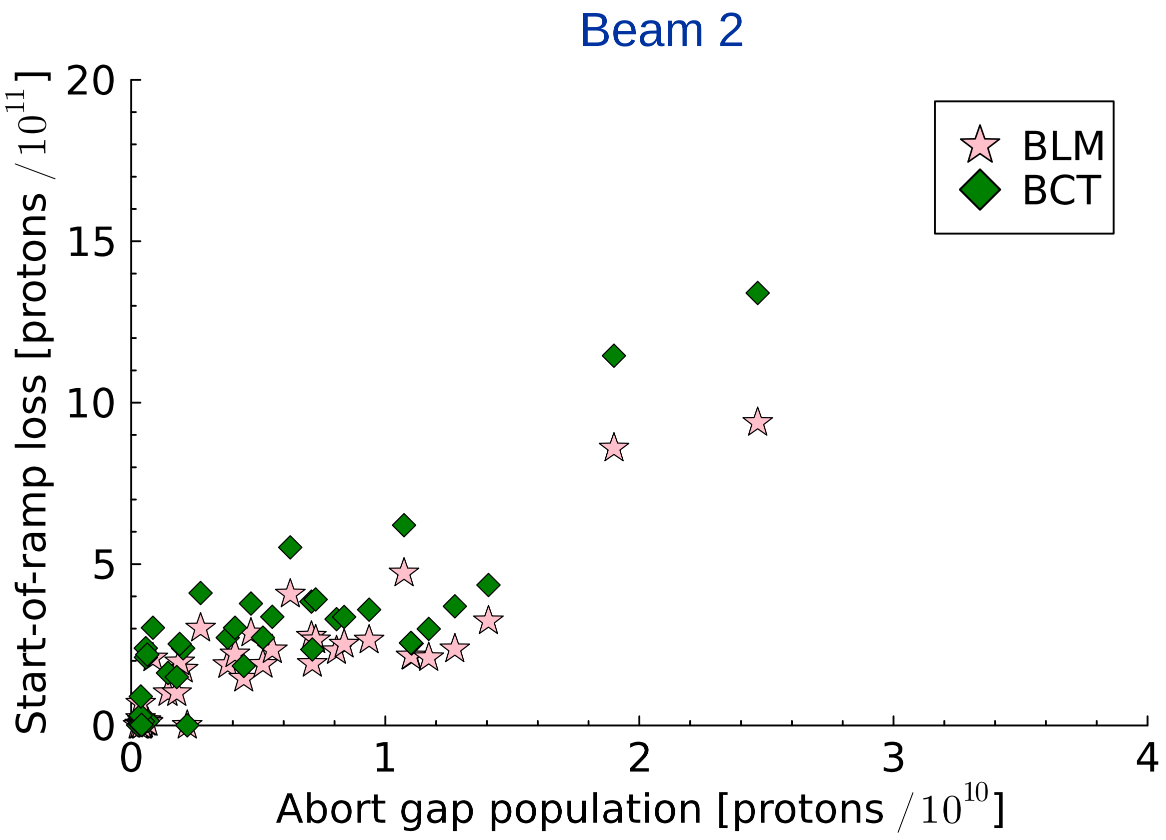
[6] R. De Maria *et al.*, "Status of HL-LHC Run 4 scenarios", LHC Chamonix Workshop 2023

Definition of Parameters

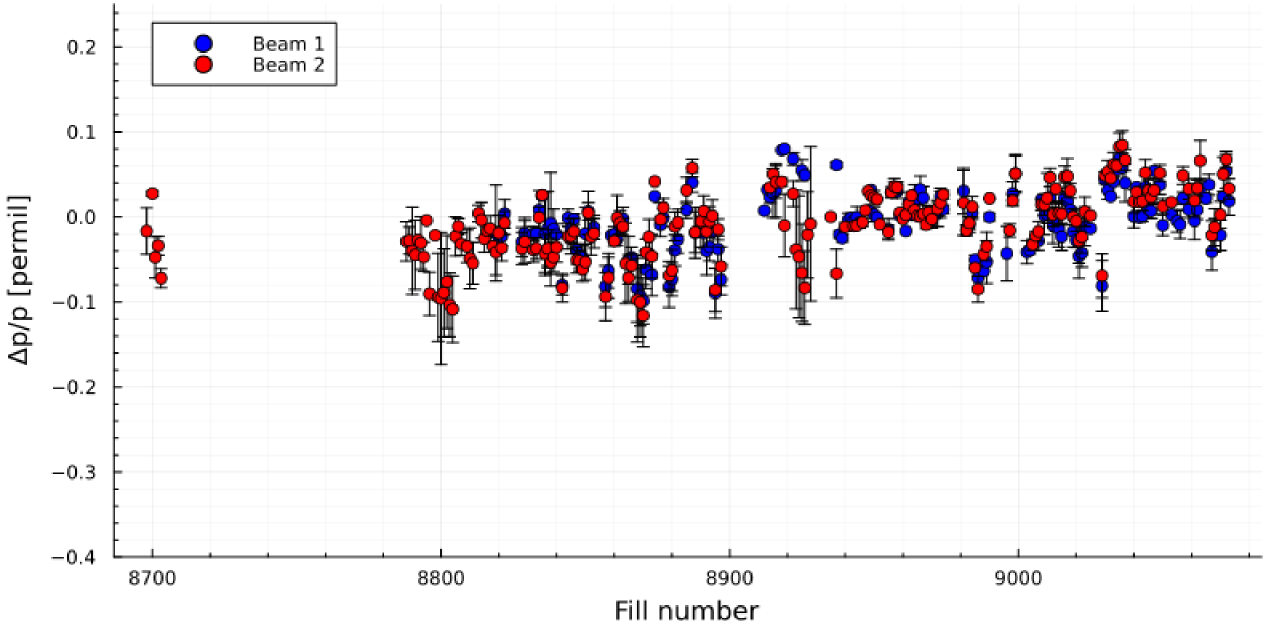
- **All parameters (bunch length, momentum spread etc.) is 4-sigma equivalent**
- **Scaling in the tables on slides 3 and 14**
  - First find emittance in LHC today from bunch length and voltage
  - Find bunch length in SPS given emittance in the LHC and the total SPS voltage
  - From bunch length and voltage, we get momentum spread
  - Use that $V \sim (\Delta p/p)^2$ and scale current LHC voltage to HL-LHC voltage with HL era SPS momentum spread (5.32×10^{-4})
  - Find HL-era bunch length from HL-LHC voltage and compute RF power from this

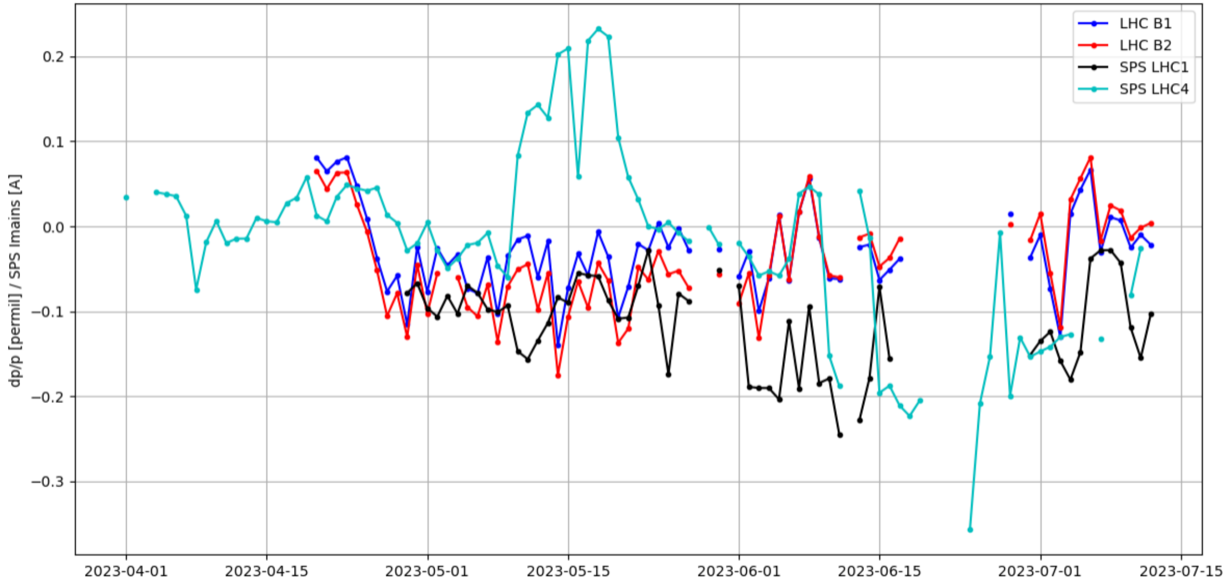
Start-of-ramp Losses and the Abort Gap Population





SPS-LHC Energy Matching





Plot by M. Hostettler

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