CERN

LHC RF Studies

12th HL-LHC Collaboration Meeting - Uppsala, Sweden

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CERN, SY-RF Group

Outline

- Overview of ongoing RF studies
  - Update on FE-FRT demonstrator
- RF power limitations at injection
  - Where we are today and plans for Run 3
- Advances on the BLonD simulation model
  - Modelling cavity feedbacks and next steps
- Voltage calibration studies
  - Beam-based calibration results
- Conclusions

Ongoing RF Studies

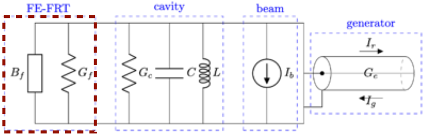
- Improved longitudinal impedance model
- Investigations of longitudinal stability
- Demonstrator of a ferro-electric fast reactive tuner (FE-FRT)
- Power limitations at injection

Ongoing RF Studies

- Improved longitudinal impedance model $\longrightarrow$ Fellow starting 1st October
- Investigations of longitudinal stability $\longrightarrow$ See talk by I. Karpov
- Demonstrator of a ferro-electric fast reactive tuner (FE-FRT)
- Power limitations at injection

Transient Detuning: Compensation of beam loading

- **Transient Detuning:**
  - Compensation of beam loading by means of non-mechanical tuning of cavity frequency
  - Fast frequency switching between bunch trains to minimize required RF power (P_g)
  - Potential power savings over present half-detuning scheme used at LHC injection settings



TDD: Use tunable B_f to minimise this bracket within LHC orbit

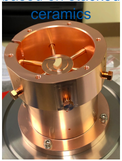
$$P_g = \frac{{}^{R}/_{Q}\, Q_e}{2}\left(\left[\frac{|\dot{V}_c|}{\omega_0\, {}^{R}/_{Q}} + \frac{|V_c|}{2\, {}^{R}/_{Q}\, Q_L} + \frac{|V_c| G_f}{2} + \frac{\Re(I_{b,RF})}{2}\right]^2 + \left[\frac{|V_c|}{\omega_0\, {}^{R}/_{Q}}(\dot{\varphi}_c - \Delta\omega_0) + \frac{B_f |V_c|}{2} + \frac{\Im(I_{b,RF})}{2}\right]^2\right)$$

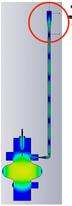
- **Transient Detuning Demonstrator (TDD)**
  - Based on a ferroelectric fast reactive tuner (FRT)
  - Applied to LHC cavity:
    - targets: tuning range of 18 kHz
    - target tuning speed : < 100 ns
  - TDD proof-of principle being tested in SM18 now
    - Demonstration of TD expected by mid 2023
    - Will confirm TDD inputs for BLonD simulations

TDD Prototype

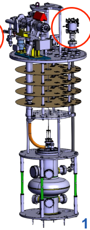
TDD Design

Coupled resonance FRT based on stacked ceramics





E-Field



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Courtesy I. Ben-Zvi, A Castilla, A. Macpherson, N. Shipman

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Recap of RF Power Limitation Studies

- RF power limitations are expected for HL-LHC beam intensities

Table: Optimized half-detuning parameters in *steady-state* at flat-bottom

Year	Intensity	Voltage	Bunch length	RF peak beam current	Optimum Q_L	Optimum detuning	Min. avg. klystron forward power
2022	1.4×10^{11} p/b	4 MV	1.22 ns	1.339 A	16600	-12.07 kHz	84 kW
HL-LHC	2.3×10^{11} p/b	7.8 MV	1.24 ns	2.178 A	19890	-10.07 kHz	265 kW

[1] H. Timko, Talk at Chamonix 2022, https://indico.cern.ch/event/1097716/contributions/4618900/

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Caveats:

- Design is 300 kW/klystron, but line-by-line differences in available power: 260-310 kW
- Need regulation margin for cavity feedback and to back off from klystron saturation
- Unmatched bunches at injection and need to get through injection transients without significant losses

Plan for Measurement Studies Run 3

Power limitations and dynamics at injection

- Minimum capture voltage w.r.t. losses
- Voltage and power calibration
- Optimization of injection
- Longitudinal damper
- Persistent injection oscillations at high intensity
- Tomography measurement of energy mismatch

LHC impedance model

- Broad-band impedance cut-off frequency
- Beam-based impedance measurements

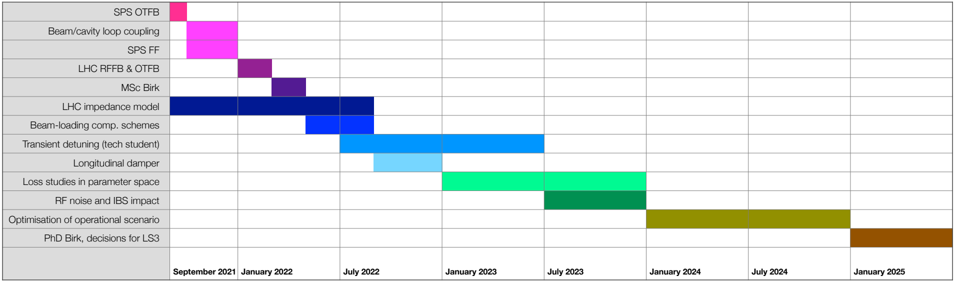
Beam dynamics studies throughout the cycle

- Controlled emittance blow-up during the ramp
- Accurate threshold of loss of Landau damping
- Coupled-bunch stability threshold
- Longitudinal Schottky measurements

Other measurements

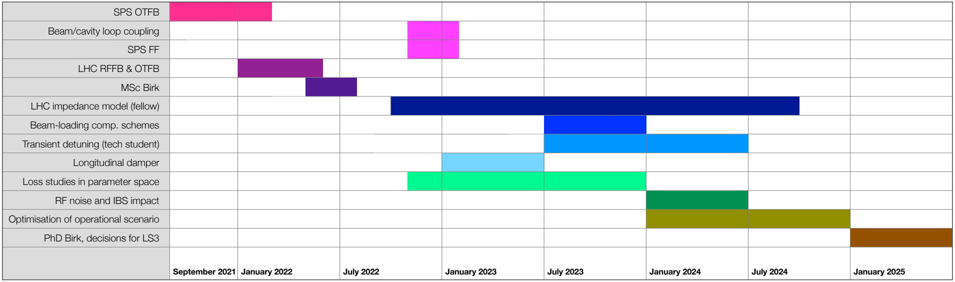
- Longest bunch length at flattop for physics
- Continuous emittance blow-up at flattop
- Voltage calibration with beam
- Longitudinal BTF

Plan for Simulation Studies



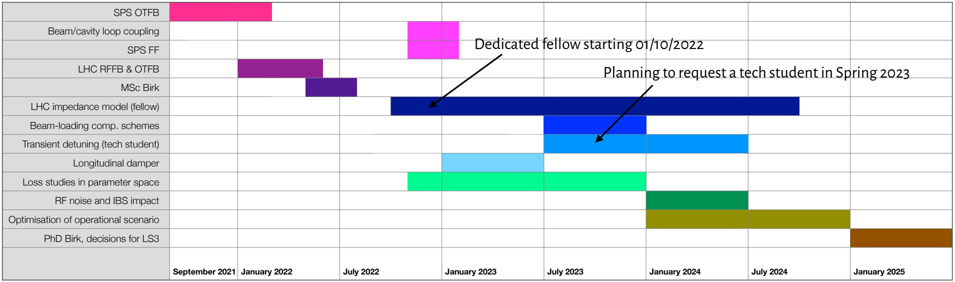
Original timeline (September 2021)

Plan for Simulation Studies



Updated timeline (September 2022)

Plan for Simulation Studies



Updated timeline (September 2022)

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Motivation for Simulations

LHC Simulations

- Dynamic power requirements
  - Unmatched beam giving turn-by-turn dynamics
  - Beam- and cavity loops giving bucket-by-bucket dynamics
- Impedance model to be improved

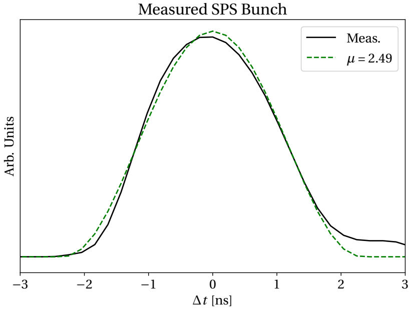
SPS Simulations

- Cannot measure halo particles
- Want to accurately reproduce flat-top beam distributions
- Strong intensity effects and a good impedance model available
- SPS cavity controller is needed
  - Reduces RF cavity impedance
  - Redistributes the bunches across the batch

SPS Halo Population

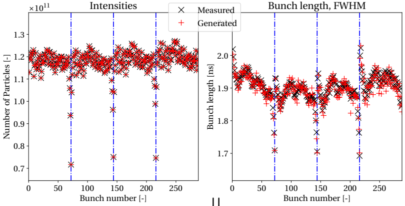
- There is no direct (non-destructive) measurement of the halo available
- Model the profile with a binomial distribution in simulations, where μ must be fine-tuned for our studies

$$\lambda(t) = \lambda_0 \left(1 - \frac{t}{\tau_{\mathrm{full}}/2}\right)^{\mu+\frac{1}{2}}$$



Measured SPS bunch profile (black) and a binomial fit (green)

Reconstructing SPS Bunch Parameters



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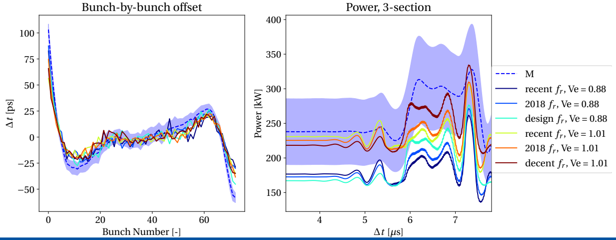
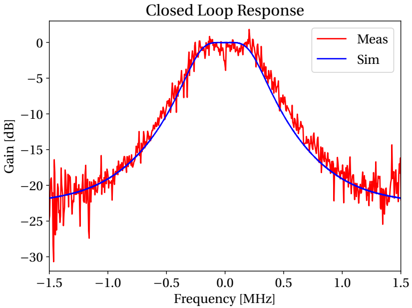


- Reconstruct bunch parameters with present intensities and extrapolate for HL-LHC intensities.

LHC Capture

- For now we have tested the LHC RFFB and OTFB model, which gives good results
- We will couple the cavity controller with the beam phase and synchronization loop (and longitudinal damper)
- We will investigate the dynamics of the mismatched bunches and bucket-by-bucket power consumption



Measurement of cavity 1B1 and simulated model

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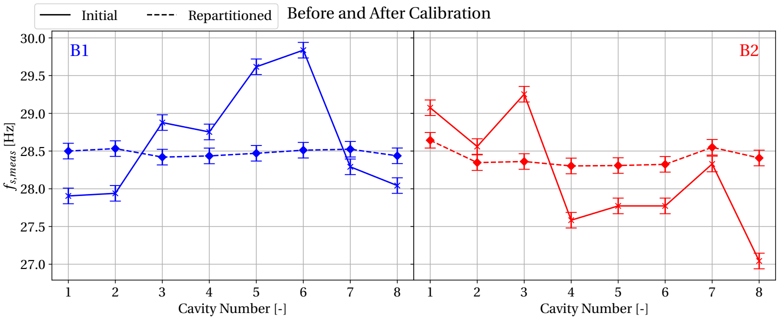
LHC RF Voltage Calibration - Why?

- To predict beam losses at HL-LHC intensities, we need to know how much power is available for each klystron/cavity.
  - Power is measured in steady-state from DC power - losses (thermal measurement with water flow)
  - In transient conditions it is hard to accurately measure RF power
- The other option is to calculate power from voltage and Q_L
  - Q_L is calibrated every year and we believe we know it quite accurately (to be exactly evaluated)
  - Voltage calibration - why now?
    - Voltage was carefully calibrated at LHC start-up
    - In Run 1 and Run 2, the synchrotron frequency was verified with the total voltage
    - We never did cavity-by-cavity voltage calibration with beam though

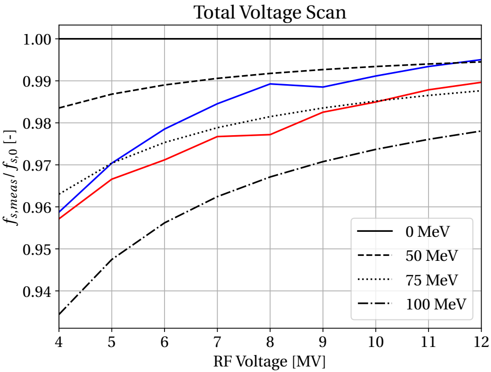
Cavity-by-cavity Calibration

- Voltage was calibrated from synchrotron frequency at capture of low-intensity pilot bunches, using one cavity at a time
  - The calibration error was found to be similar at different voltage levels
  - During the measurements, we showed that we can even out the voltage differences line-by-line



Total Voltage Scan

- Verified the correction of calibration error for the operational range of 4-12 MV/beam
- We had significant injection errors, which we need to take into account for our analysis
- Analysis ongoing



Measured synchrotron frequencies with expected result for different injection errors

Conclusions

- RF studies ongoing on many different aspects for HL-LHC
- Results from TDD proof-of principle expected by mid 2023
- Power limitations at injection
  - Significant progress to implement necessary models in BLonD
  - Measurement studies have started as well
- Still a long simulation and measurement program foreseen for Run 3

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