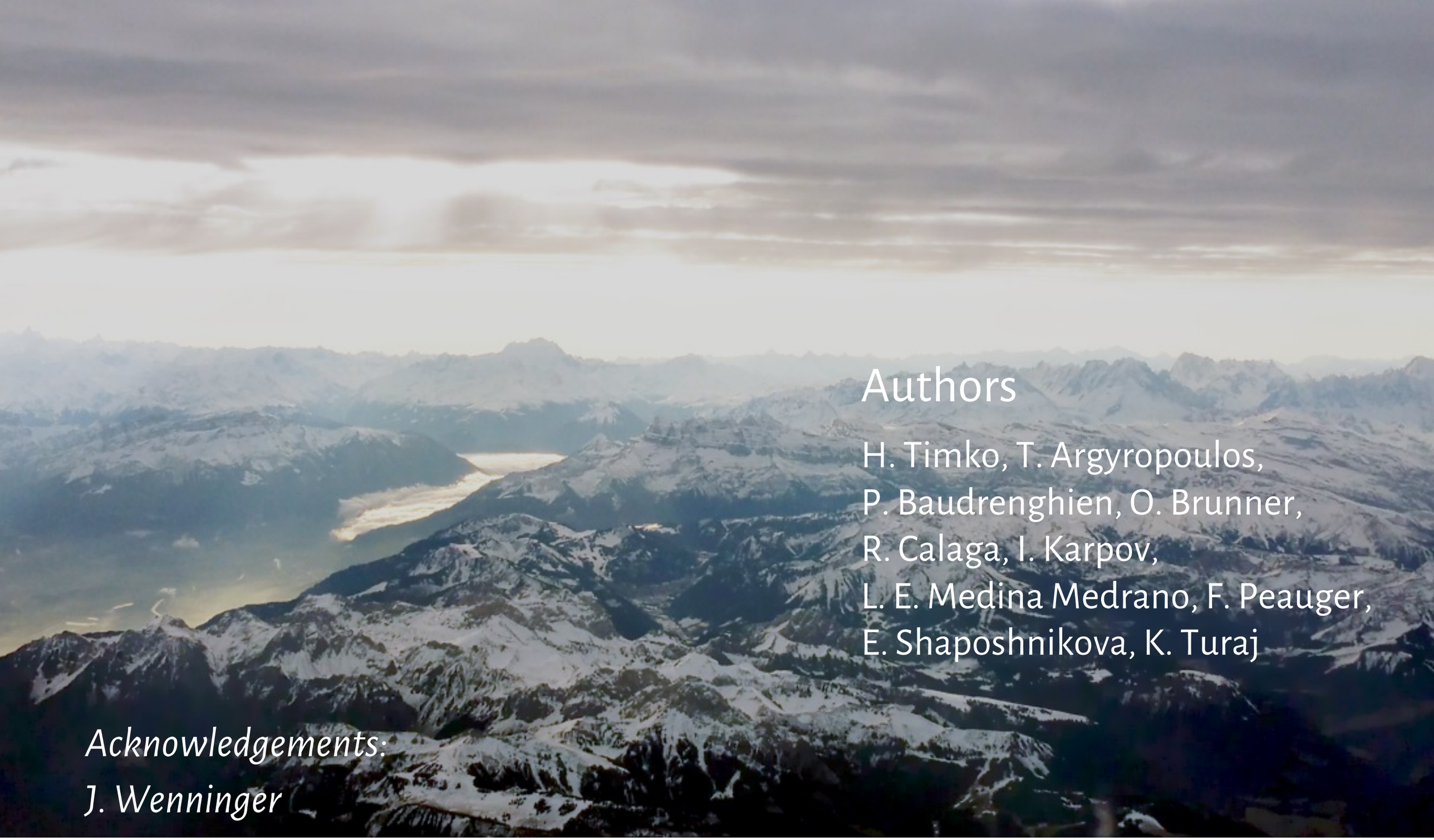

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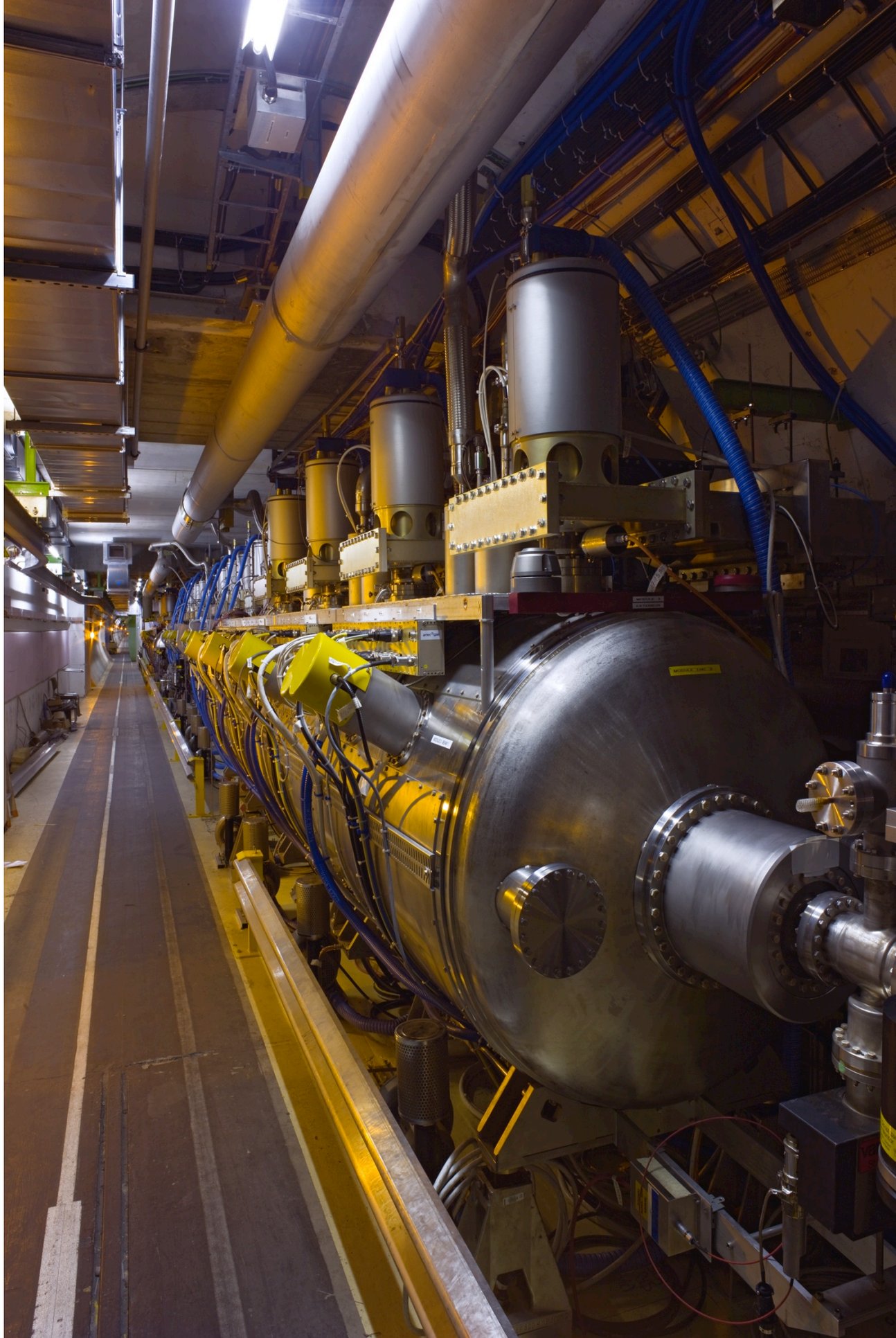
RF STUDIES FOR HL-LHC INTENSITIES

HL-LHC WP2 meeting, 2nd April 2019

Outline

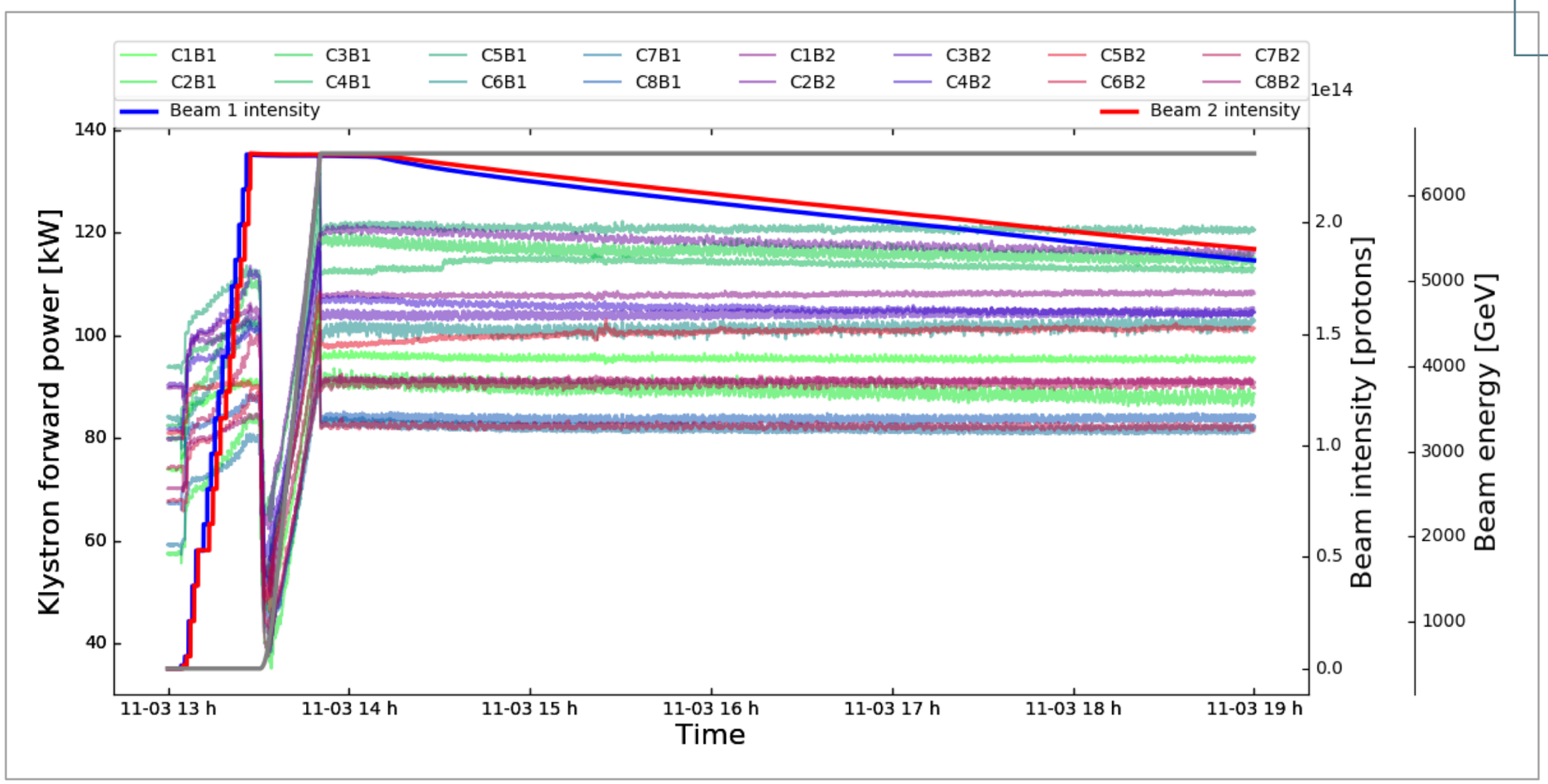
- Full detuning
- Required voltage and power consumption at injection
- SPS-LHC energy matching
- Controlled emittance blow-up
- Ongoing studies
- Conclusions



Full-Detuning Beam-Loading Compensation

- Operational since mid-2017, reduces the RF power consumption
  - Used during the ramp and at flat top, where higher voltage is needed
  - The power required becomes independent of the beam current

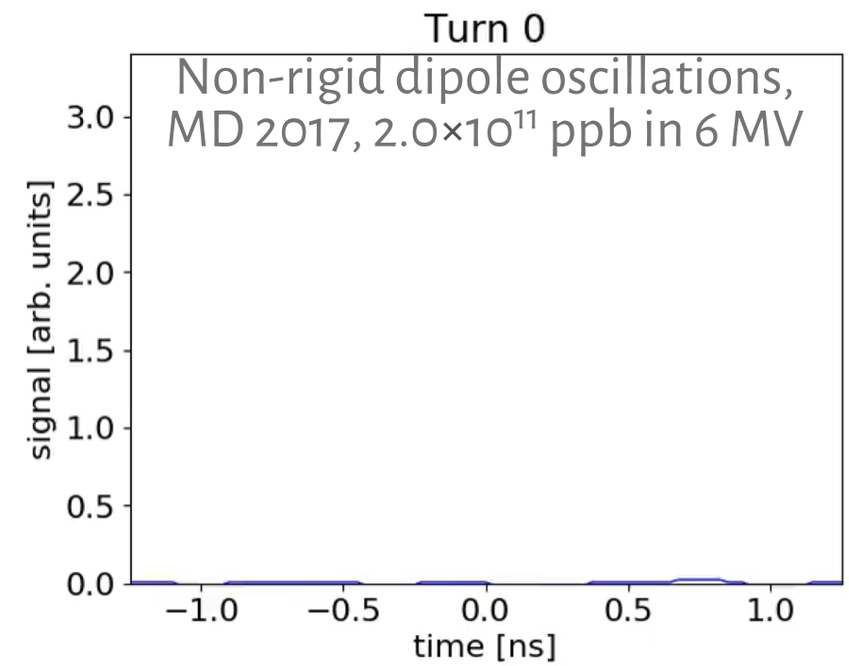
$$P = \frac{V_0^2}{8\frac{R}{Q}Q_L}$$

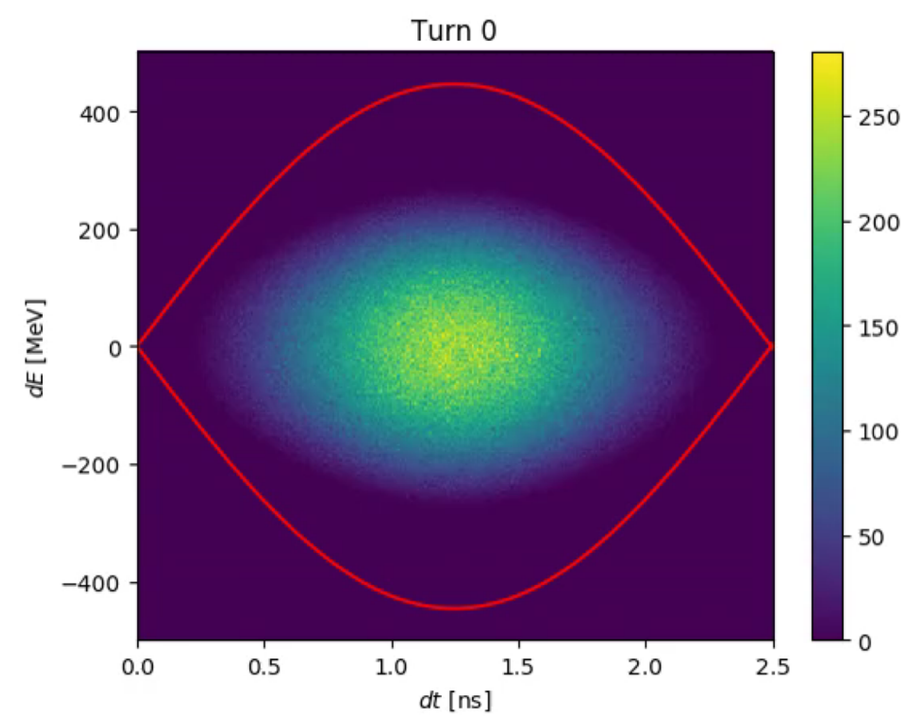


With 2017 beam parameters, the power consumption at top energy (N.B. ±20 % spread) is reduced from 190 kW in half-detuning mode to 100 kW in full-detuning mode

Beam Stability at Injection

- Persistent injection oscillations
  - Observed since first start-up with beam
  - Damping time ~1 h, can survive the ramp and potentially impact stability
  - Peak-to-peak oscillation amplitude up to 50°
  - Flat bottom losses with 1.9×10^{11} ppb
- Is due to a large mismatch between the LHC bucket height and the momentum spread of the arriving bunch [7]
  - Intensity effects and injection errors have an impact, too





Simulations, 2.3×10^{11} ppb in 8.5 MV

Optimum Injection Voltage

- ‘Matched’ voltage w.r.t. dp/p of arriving SPS bunch: ~2 MV
  - Not possible to use, too much injection losses (3 MV were tried at LHC start-up)

- Higher voltage preferable to reduce capture losses

- Lower voltage preferable for beam stability & reduced RF power consumption

- Optimum LHC capture voltage depends on the SPS beam arriving
  - For SPS Q26 optics, $V_{SPS} = 7$ MV, 1.65 ns at transfer: $V_{LHC} = 6$ MV
  - For SPS Q20 optics, $V_{SPS} = 7$ MV, 1.40 ns at transfer: $V_{LHC} = 4$ MV

Voltage Limitations at Injection

- Half-detuning scheme at injection is limiting for Run III $P = \frac{V_0 I_{b,pk}}{8}$

- Two MDs were preformed with beam
  - First MD (as operational): all lines set to the same voltage, cavities are pre-detuned with 12b only → strong transient when 144b are injected

    Maximum voltage maintainable: 9 MV for 50 kV klystron HV & 1.15×10^{11} ppb.
  - Second MD (as operational): asking for less voltage in "weak" lines, cavities are pre-detuned for 144b → no transient when 144b are injected

    Maximum voltage maintainable: 10 MV for 58 kV klystron HV & 1.3×10^{11} ppb.

Klystron HV	Cathode current	DC power	RF power	Measured saturation
50 kV	7.8 A	390 kW	230 kW	190-220 kW
58 kV	8.6 A	500 kW	300 kW	250-280 kW

Operational settings of present LHC klystrons: 30 % more power available with 58 kV w.r.t. 50 kV

Power Limitations at Injection

- Klystron saturation in CW measurements: 250-280 kW/line
  - In theory, ~8 MV/beam should be doable with HL-LHC beam current
  - In operation with beam, the lines seem to saturate at lower levels, thus providing less voltage

- Source of this discrepancy currently under investigation
  - Is it due to the pulsed behaviour of the system?
  - Can we still gain in voltage by optimising the system or are we fundamentally limited?

E.g. circulator adjustment, and clamping mechanism currently under investigation

Detailed analysis of MD results concerning transient behaviour is currently ongoing

Can we do 1.8×10^{11} ppb in Run III?

- Conservative estimate based on first MD with operational margin
  - Available voltage: 6.6 MV for 1.8×10^{11} ppb
  - Available voltage: 5.2 MV for 2.3×10^{11} ppb

Bunch intensity	Extraction voltage		Rel. momentum spread		Emittance	
	Q20	Q22	Q20	Q22	Q20	Q22
1.8×10^{11} ppb	10 MV *	10 MV *	4.95×10^{-4}	5.50×10^{-4}	0.570 eVs	0.633 eVs
2.3×10^{11} ppb	10 MV	10 MV	4.95×10^{-4}	5.50×10^{-4}	0.570 eVs	0.633 eVs

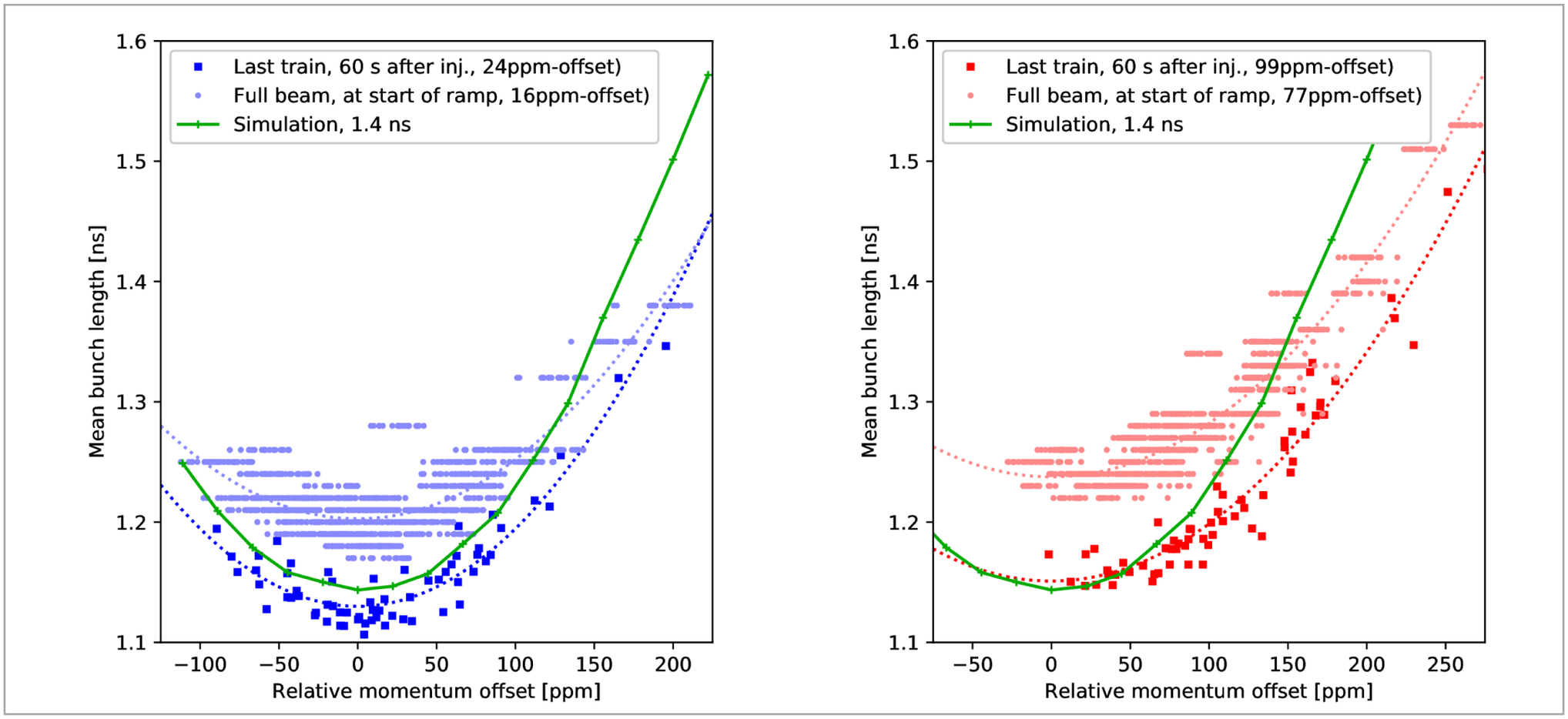
SPS extraction parameters depending on intensity and optics

** Will likely use the maximum voltage, even if not strictly needed from stability point of view*

- LHC capture voltage required, depending on SPS optics:
  - Min. 6.4 MV with Q20 (+26.6 % dp/p), i.e. *at the limit*
  - Min. 7.9 MV with Q22 (+40.7 % dp/p), i.e. *potentially out of reach*

Energy Errors at Injection

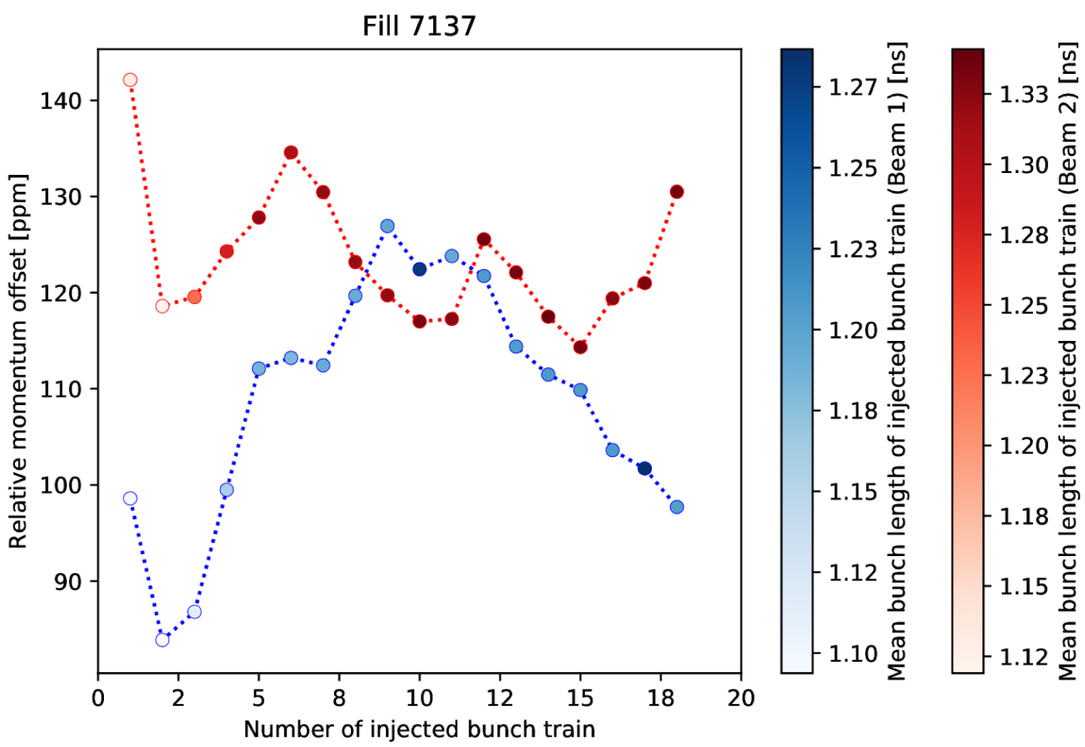
- Energy matching between SPS and LHC varies over time
  - In some fills, a large blow-up due to filamentation is observed
  - B2 slightly longer; measurement error or blow-up on flat bottom?

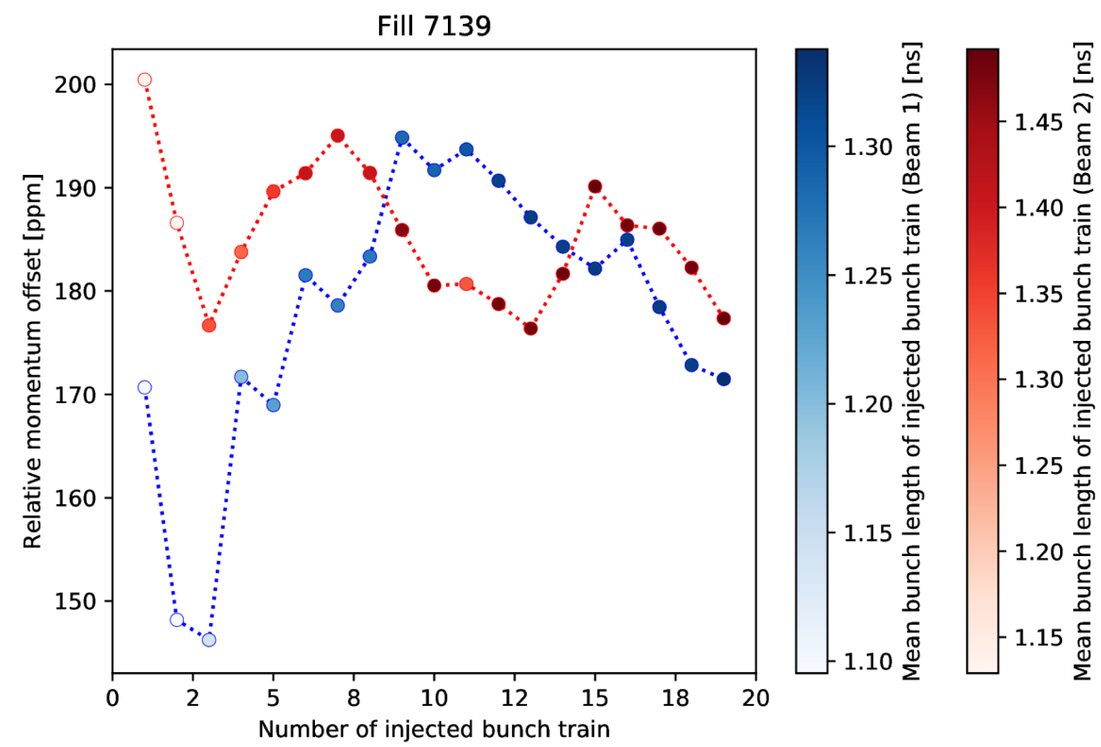


Correlation of energy errors and bunch length

Energy Errors at Injection

- Energy matching between SPS and LHC varies over time
  - In some fills, a large blow-up due to filamentation is observed
  - The beam phase loop only damps the injection errors of the first batches

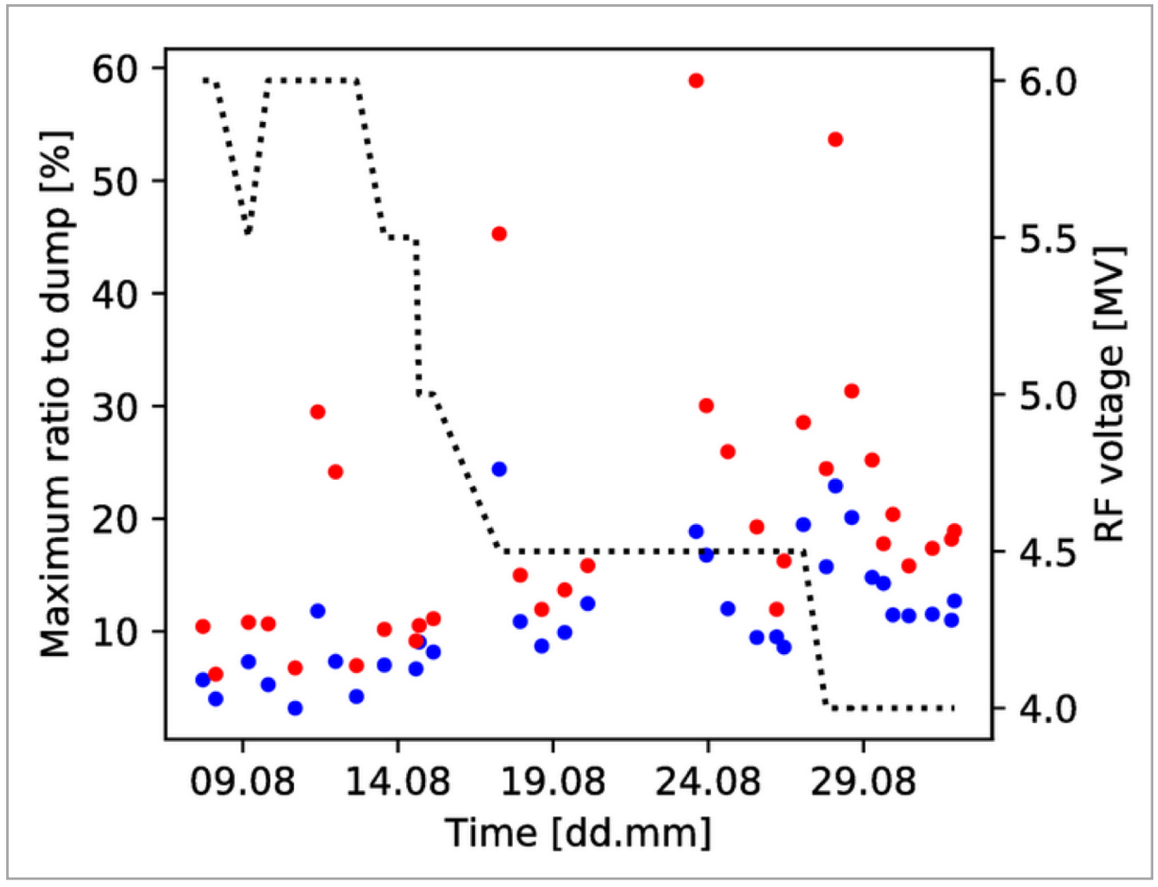




Fills with large energy errors: first batches remain short, while subsequent batches blow up

Voltage Reduction Campaign 2018

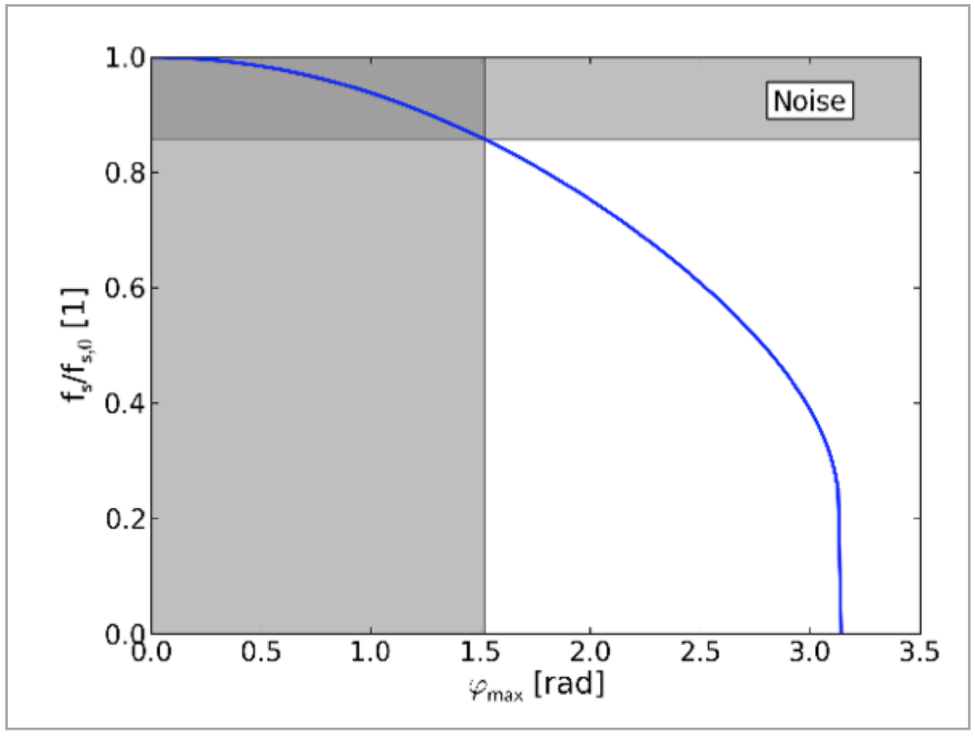
- Reduction from 6 MV to 4 MV improves beam stability
  - With large energy errors, start-of-ramp losses are close to dump threshold
  - With better energy matching, could we further decrease the voltage and thus save power?



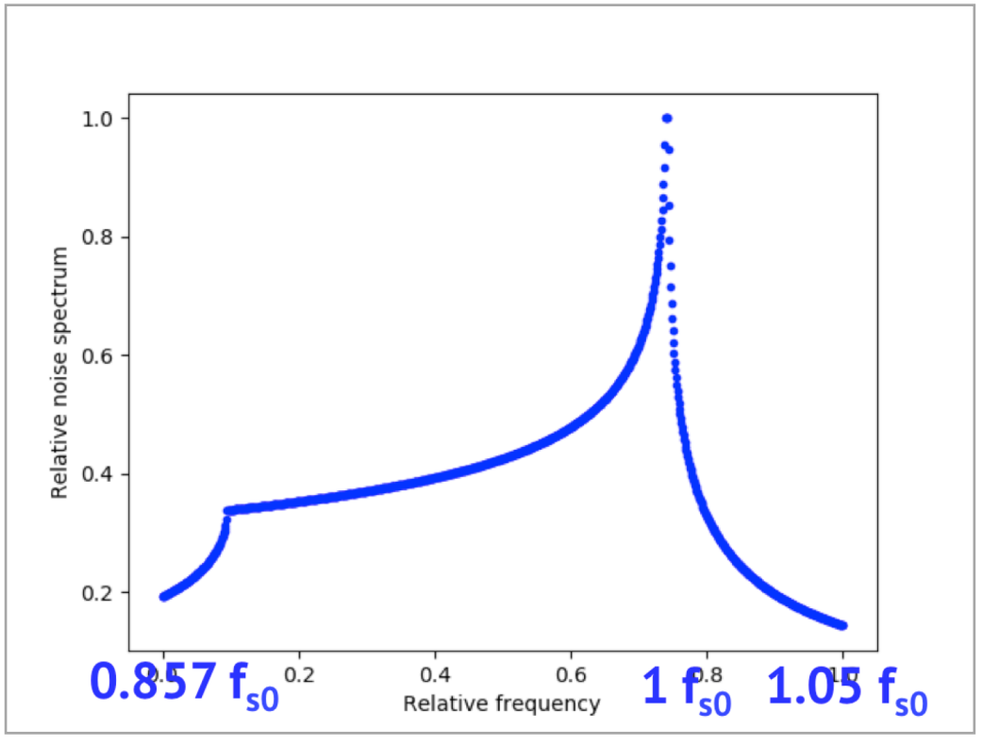
Increasing start-of-ramp losses with decreasing capture voltage

Controlled Emittance Blow-up

- Indispensable for the acceleration ramp to counteract single-bunch loss of Landau damping
  - The operational method generates a band-limited noise spectrum that targets the core of the bunch up to the target bunch length
  - Compensating also for the action of the beam phase loop



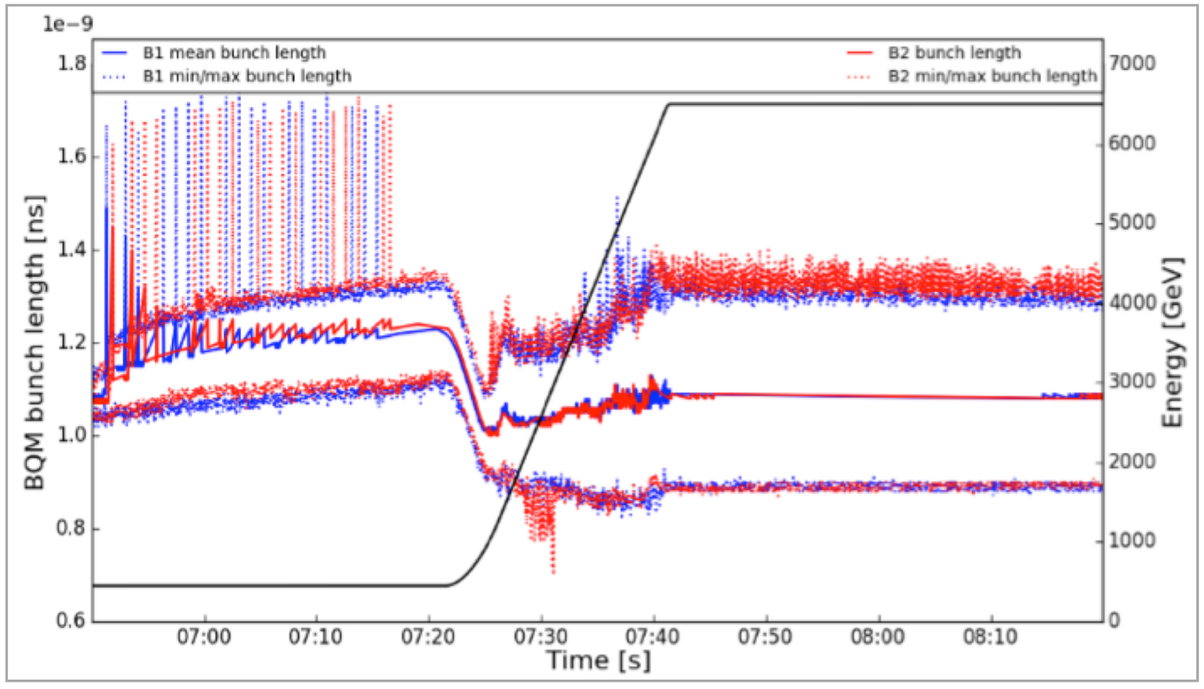
Blow-up spectrum w.r.t. to the synchrotron frequency distribution



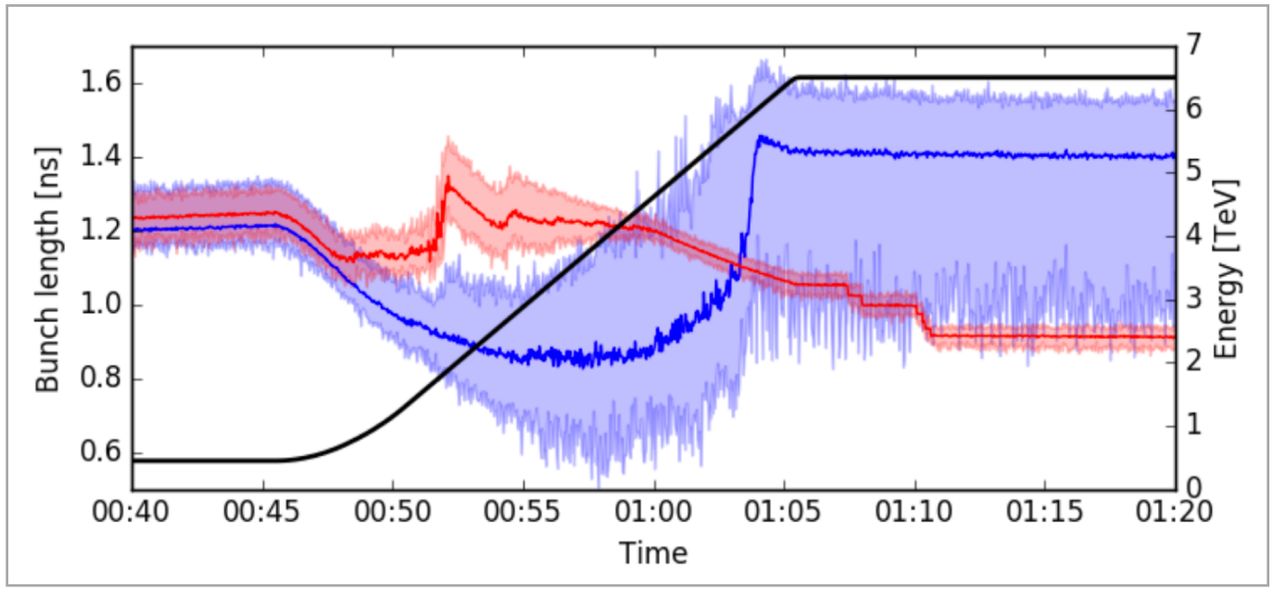
Pre-distorted noise spectrum used since 2015

Divergence of Bunch Lengths

- Observed for reduced target length
  - If due to intensity effects, the effect will be amplified in Run III & Run IV
  - In 2016, when the target bunch length was decreased from 1.25 ns to 1.1 ns
  - In MDs, when the target bunch length was 0.9-1.0 ns



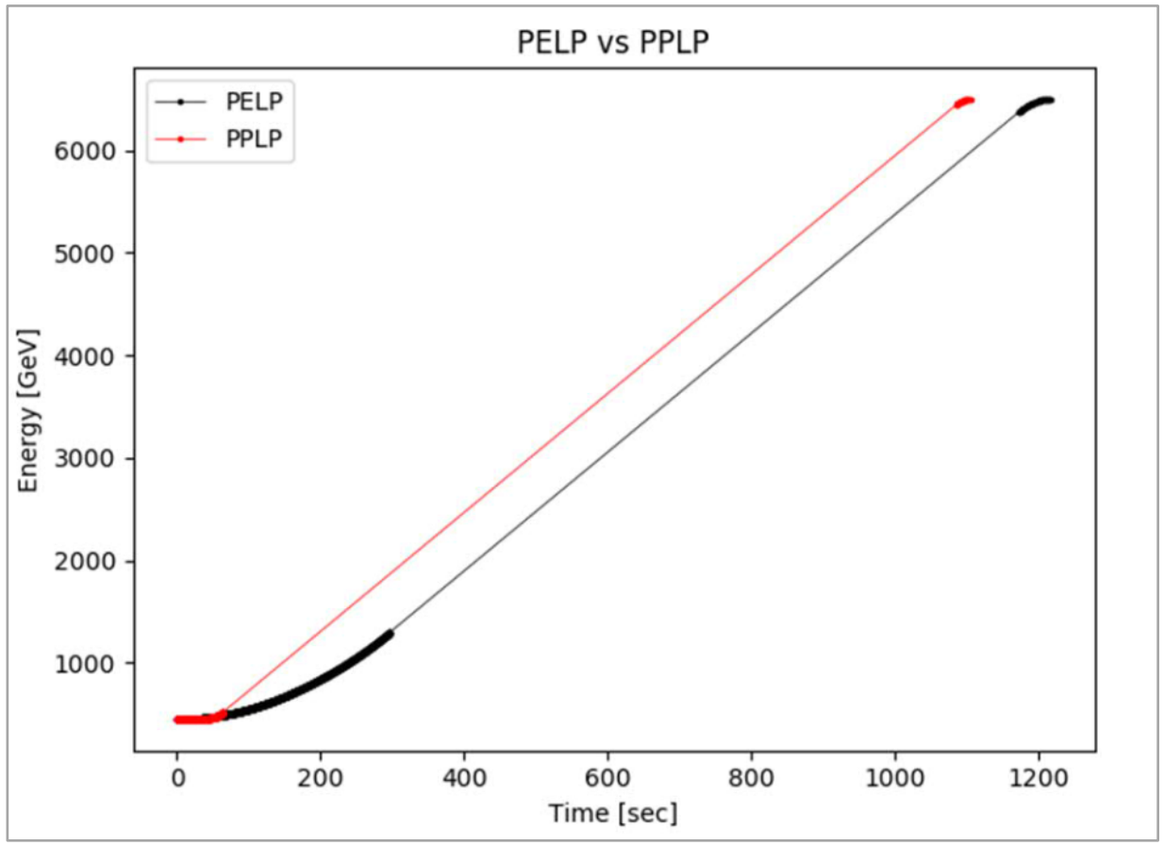
Increasing bunch length spread in operation



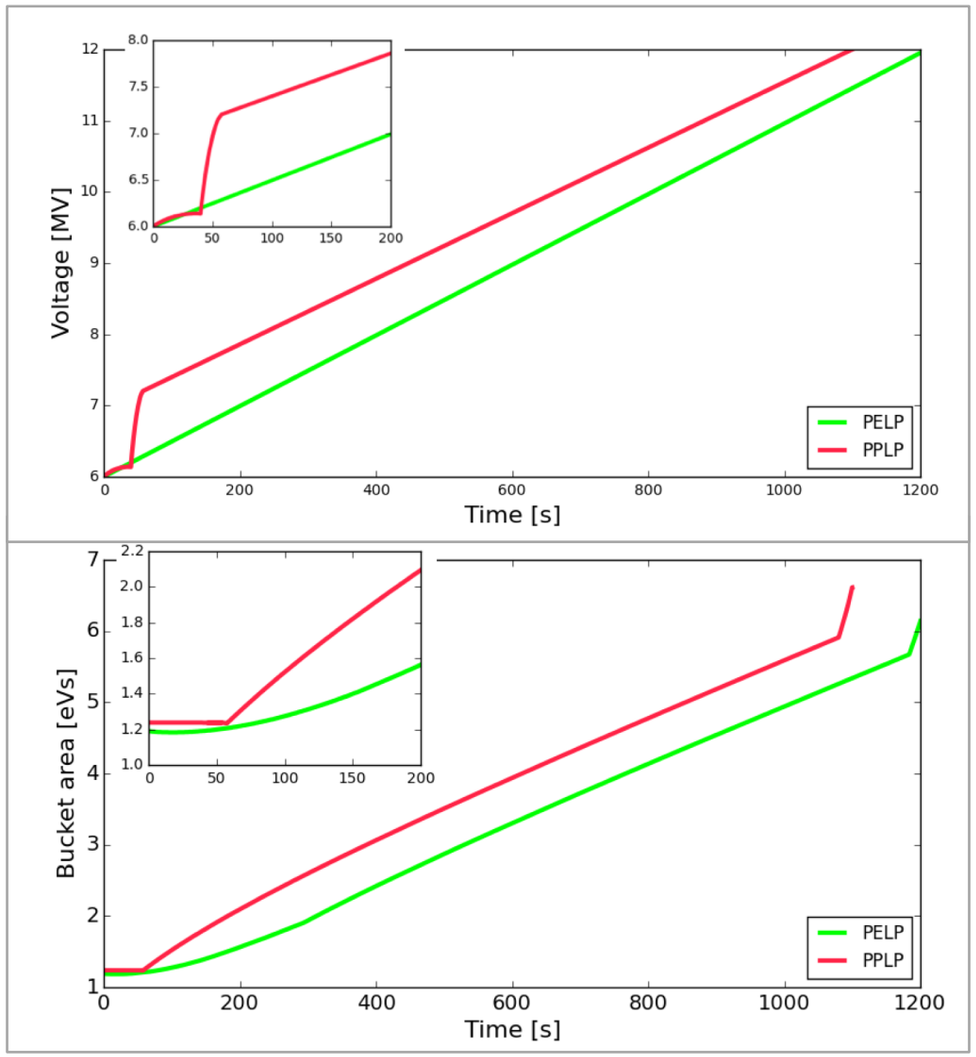
Divergence of bunch lengths in MD, 2016

Blow-up during PPLP Ramp

- The regulation of the blow-up is more challenging in the PPLP ramp (1100 s) than the operational PELP ramp (1210 s)
  - First 50 s: no bucket area for blow-up, next 150 s: need to blow up a factor 2



Momentum programmes of the PELP and PPLP ramps
PELP = parabolic-exponential-linear-parabolic
PPLP = parabolic-parabolic-linear-parabolic



Fast rise of RF voltage ramp to keep a constant bucket area

Studies in LS2

- RF power limitations at injection
  - Transient power limitations and system behaviour
  - Dynamic circulator adjustment, improved calibration schemes
  - Alternative beam-loading compensation schemes
  - Understand line-by-line differences and define appropriate operational margins

- SPS-LHC energy mismatch
  - Longitudinal damper using ACS
  - Correction on SPS and/or LHC side

- Controlled longitudinal emittance blow-up
  - Divergence
  - PPLP ramp
  - Alternative noise-generation methods

Conclusions

- Some challenges for the RF system at HL-LHC intensities have been identified
  - RF power consumption in the half-detuning scheme limits the capture voltage
  - Regulation of the controlled longitudinal emittance blow-up
- Studies ongoing to understand and overcome the limitations
  - Measurement and simulation studies to understand the source of the limitations and quantify the potential gain with different improvements (LHC/HL-LHC Beam Dynamics WG, *E. Shaposhnikova*)
  - Hardware options for improvements, such as high-efficiency or additional RF cavities (HL-LHC WP4, *R. Calaga*)

References

P. Baudrenghien, T. Mastoridis, '*Proposal for an RF roadmap towards ultimate intensity in the LHC*', Proc. IPAC'12, New Orleans, USA, 2012.

D. Boussard, '*RF power requirements for a high intensity proton collider - Part I*', Proc. PAC'91, San Francisco, USA, 1991.

I. Karpov, S. Albright, T. Argyropoulos P. Baudrenghien, E. Shaposhnikova, H. Timko, '*LHC MD 2042: Persistent Injection Oscillations*', CERN-ACC-NOTE-2018-0018, (2018).

H. Timko, E. Shaposhnikova, K. Turaj, '*Estimated LHC RF system performance reach at injection during Run III and beyond*', Rep. CERN-ACC-NOTE-2019-0005, CERN, Geneva, Switzerland, 2019.

H. Timko, T. Argyropoulos, I. Karpov, E. Shaposhinkova, '*Beam Instabilities after Injection to the LHC*', Proc. HB2018, TUP1WA03, Daejeon, Korea, (2018).

H. Timko , T. Argyropoulos, I. Karpov, L. Medina Medrano, M. Palm, B. Salvachua, J. Wenninger, '*Optimal Injection Voltage in the LHC*', to be submitted, (2019).

H. Timko, P. Baudrenghien, J. Esteban Müller, M. Jaussi, A. Lasheen, E. Shaposhnikova, '*LHC MD 1087: Controlled Longitudinal Emittance Blow-up with Short Bunches*', CERN-ACC-NOTE-2017-0018, (2017).