LHC Longitudinal Studies

Helga Timko, Theodoros Argyropoulos, Andy Butterworth, Rama Calaga,
Nuria Catalan Lasheras, Konstantinos Iliakis, Birk Karlsen-Bæck,
Ivan Karpov, Katarzyna Turaj, Michail Zampetakis
CERN, SY-RF Group

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Longitudinal Studies for HL-LHC

Power limitations at injection

- Measurements, modelling & simulations
- Minimum voltage and losses in operation

Machine diagnostics

- Logging of injection power transients
- Longitudinal machine-learning tomography

Longitudinal beam stability

- Refining the threshold of single-bunch loss of Landau damping

Longitudinal impedance model

- Refining the LHC & HL-LHC impedance model

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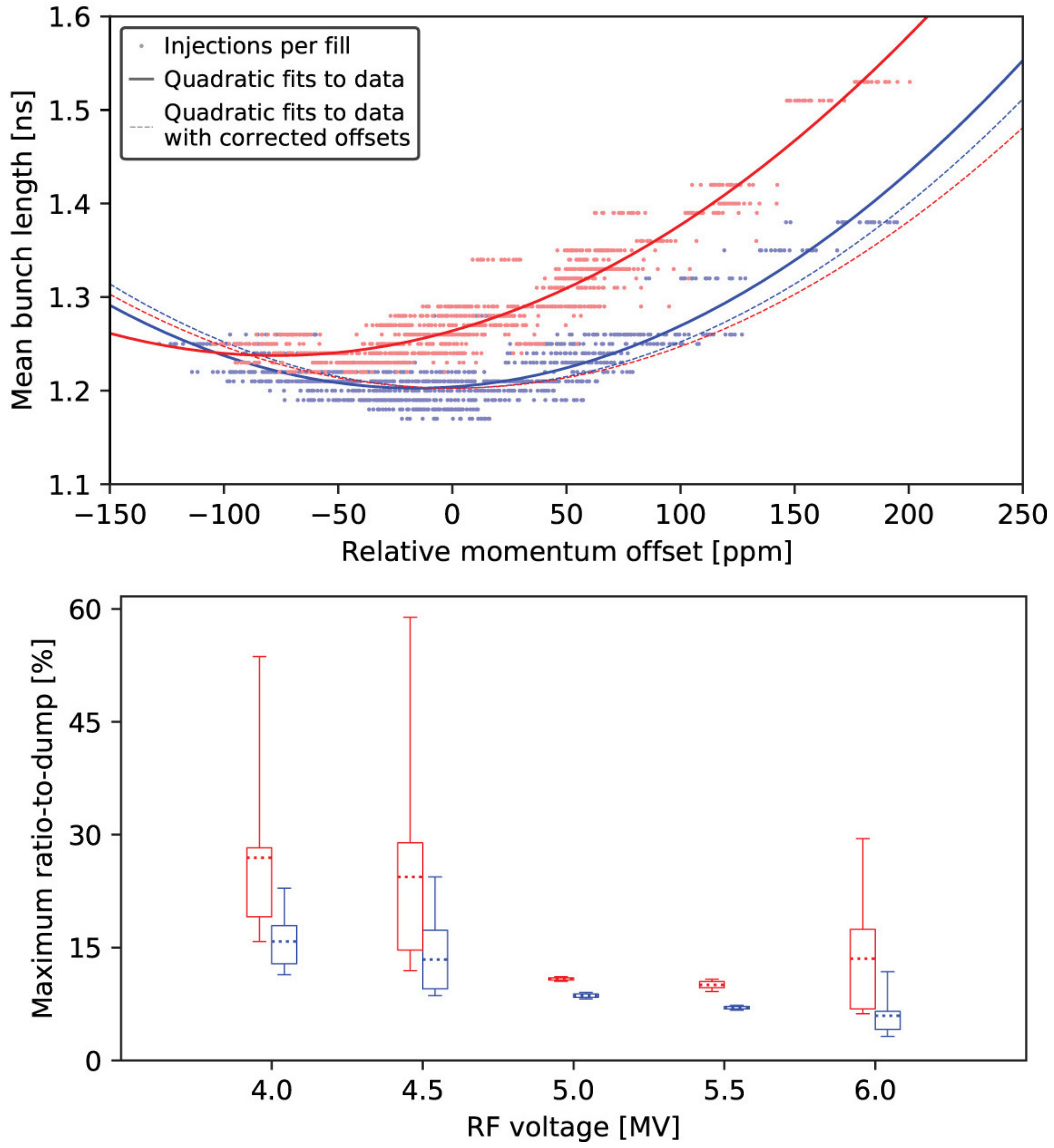
Predictions based on 2018

Estimates based on 2018 operation [1]

- Two scenarios for Run 3 with 'small' and 'large' longitudinal emittance
- The minimum voltage was scaled from 2018 experience with large SPS-LHC energy mismatch [2]

When	Bunch parameters		SPS	LHC parameters				
	Bunch intensity	Bunch emittance	Momentum spread	Main RF voltage	Bunch length	Optimum detuning	Optimum Q_L	Average power
2018	1.4×10^{11} p/b	0.40 eVs	3.74×10^{-4}	4 MV	1.22 ns	-12.1 kHz	16.6 k	84 kW
Run 3	1.8×10^{11} p/b	0.49 eVs	4.59×10^{-4}	6 MV	1.22 ns	-10.4 kHz	19.4 k	161 kW
Run 3	1.8×10^{11} p/b	0.57 eVs	4.95×10^{-4}	7 MV	1.28 ns	-8.6kHz	23.3 k	183 kW
HL-LHC	2.3×10^{11} p/b	0.57 eVs	5.32×10^{-4}	7.8 MV	1.24 ns	-10.1 kHz	19.9 k	265 kW

Estimated injection voltage and average power in the half-detuning scheme from [1]



Studies of optimum injection voltage [2]

Top: bunch length vs energy mismatch

Bottom: start of ramp losses

[1] H. Timko: 'LHC RF: possible limitations and planned Run 3 studies', LHC Performance Workshop 2022.

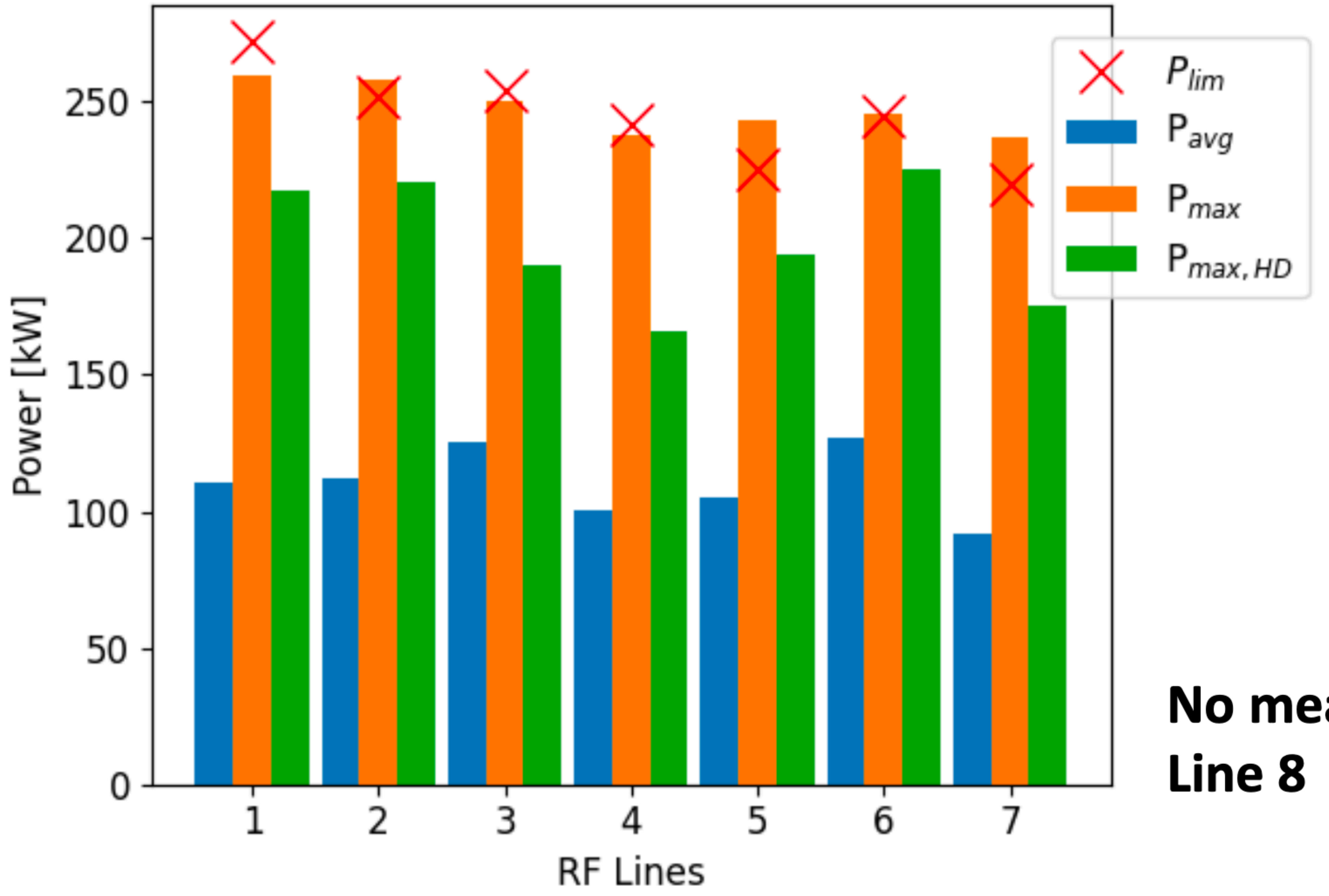
[2] L. Medina *et al.*, 'Optimal injection voltage in the LHC', NIMA, **1039**, 166994, 2022.

Predictions based on 2022

Estimates based on 2022 MDs

- MDs with 1.8x10^{11} p/b and 4 MV capture voltage showed that there is still margin in power
  - First-turn transients did not deteriorate the beam
  - This beam was not ramped and losses at start of the ramp are unknown
  - Relies mainly on eliminating the first-turn transients by pre-detuning the cavities
- Concluded that we can push the intensity to 2.0x10^{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

Power measurements at injection [3]

Although the first turn transients are close to saturation, there is some margin in peak power in the half-detuning scheme to increase the intensity

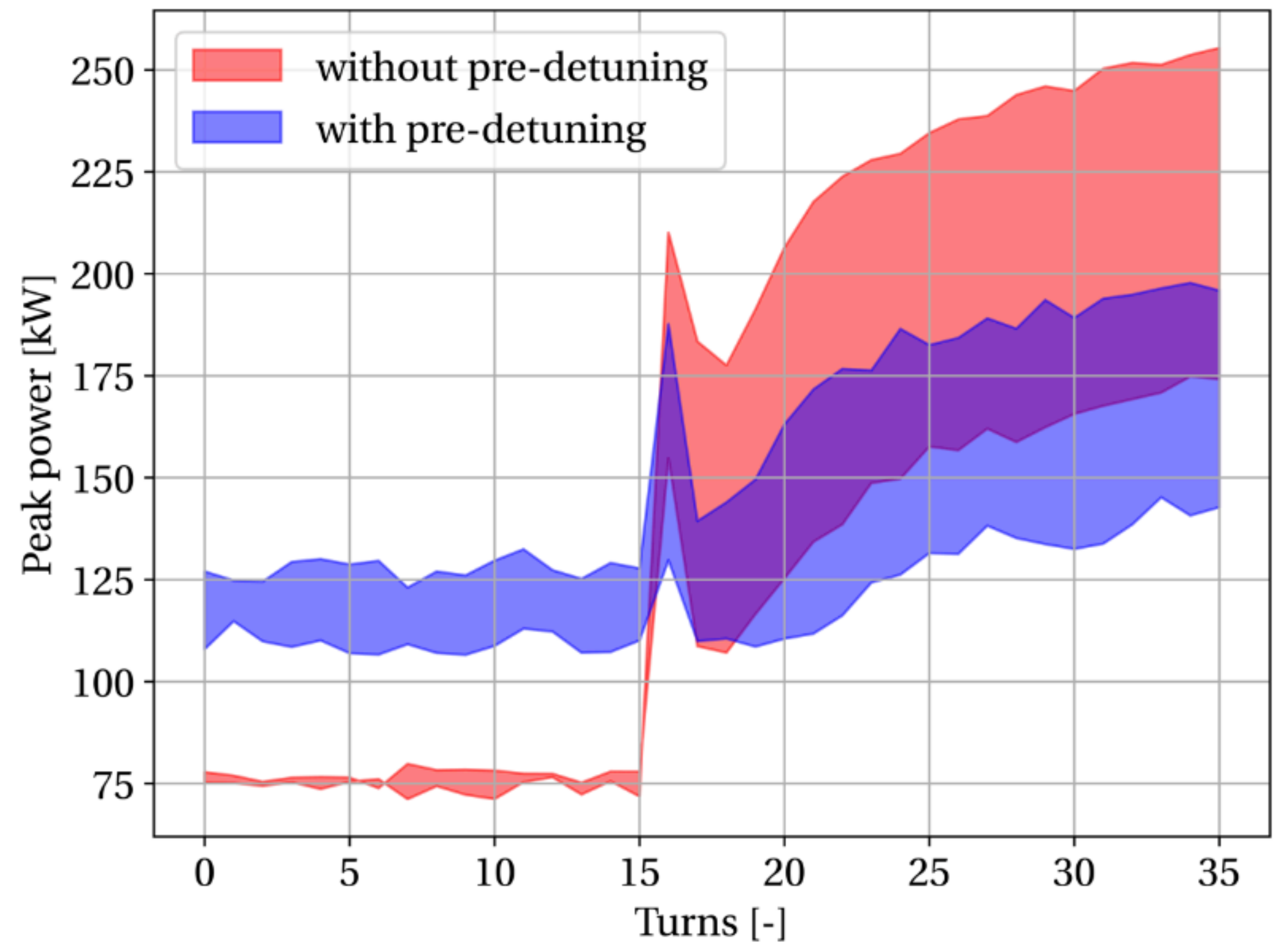
- ❑ **Almost all lines cross P_{lim}** for short time at first injection
- ❑ **~55% margin on P_{avg} /~ (10%-30%) on $P_{max,HD}$**

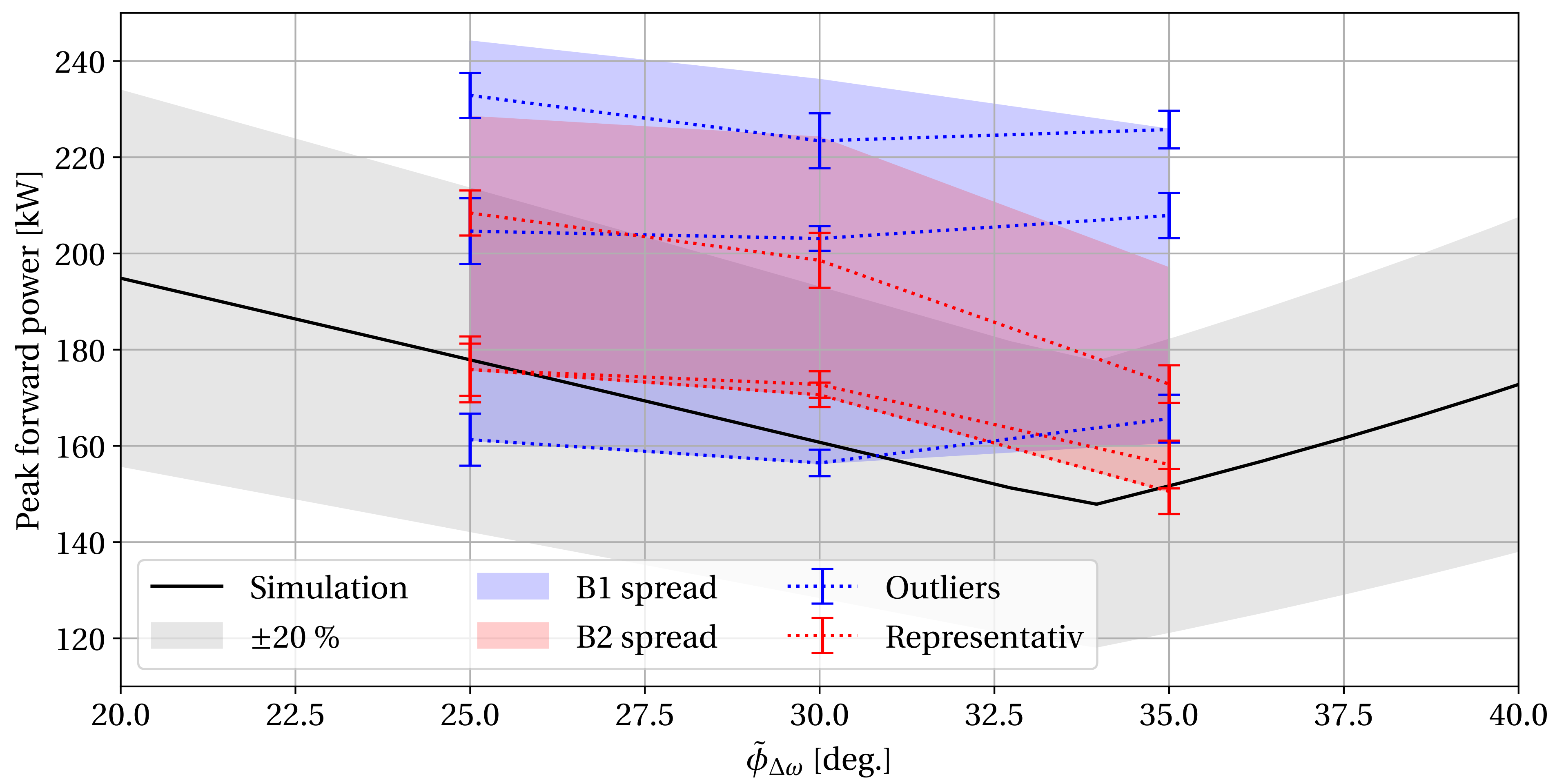
[3] T. Argyropoulos *et al.*: 'RF power at injection & longitudinal tomography', LHC Chamonix Workshop 2023.

Pre-detuning

Reducing first-turn transients

- Pre-detuning the cavities close to the optimum half-detuning value
- Equalises the maximum power between first turn and steady state
- Put into operation in May 2023 [4]
  - Fine-tuning to be finished in 2024





Top: turn-by-turn peak power with and without pre-detuning

Bottom: optimum detuning phase in simulations and measurement

Courtesy of B. E. Karlsen-Bæck

[4] B. E. Karlsen-Baeck *et al.*, 'Effects of cavity pre-detuning on RF power transients at injection into the LHC', to be published, Proc. HB2023, 2023.

MD results from 2023

Can indeed capture 2.0x10^{11} p/b

- Injection voltage of 4-7 MV
  - Standard beam of 72b trains
- With 7 MV, close to the saturation limit for most klystrons
  - Required fine-adjustment of cavity frequency and Q_L
  - Little operational margin remaining
- Losses still have to analysed
  - Correlating abort gap population with start-of-ramp losses
  - To determine the minimum capture voltage

When	Bunch parameters		SPS	LHC parameters				
	Bunch intensity	Bunch emittance	Momentum spread	Main RF voltage	Bunch length	Optimum detuning	Optimum Q_L	Average power
2023	2.0x10^{11} p/b	0.55 eVs	5.09x10^{-4}	7 MV	1.25 ns	-9.7 kHz	20.6 k	206 kW

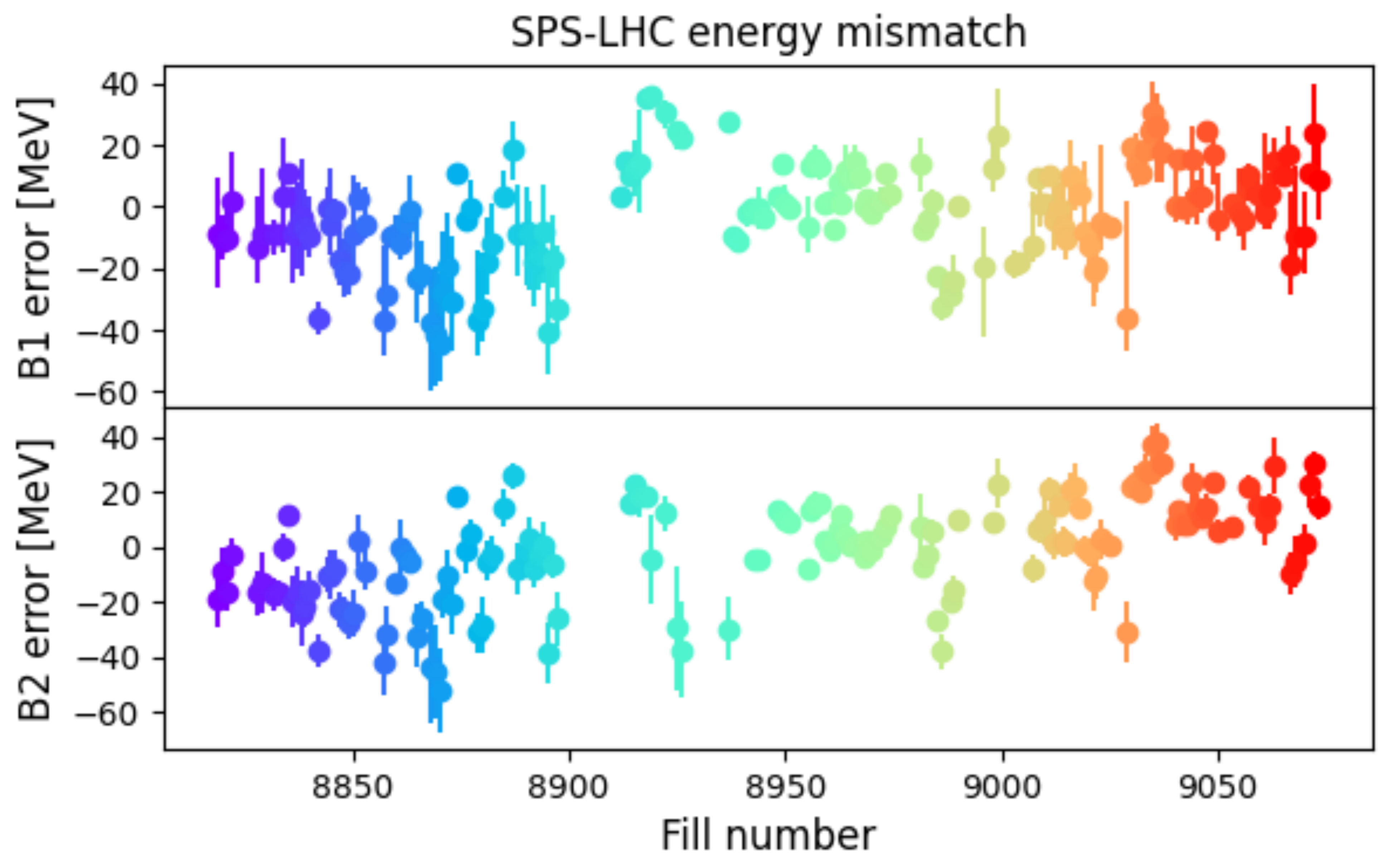
Maximum voltage and power maintainable with 2.0x10^{11} p/b

In the theoretical best case, power transients reach 230-310 kW for 206 kW average power

Operational experience in 2023

Physics fills with 1.6x10^{11} p/b

- **Hybrid beam: 56b 8b4e + 3-5 trains of 36b BCMS**
- **Improved SPS-LHC energy matching**
  - Small blow-up due to filamentation (±50 ps)
- No significant losses at the start of ramp
- **Bunch length**
  - At injection: 1.08 ns (ML tomography)
  - At the end of filling: 1.23 ns (beam quality monitor)
  - Small emittance bunches arriving from SPS
- Capture voltage of 5 MV was sufficient
  - Probably still margin to reduce the capture voltage further (test next year)



SPS-LHC energy matching based on longitudinal machine-learning tomography

2023 range from -60…40 MeV

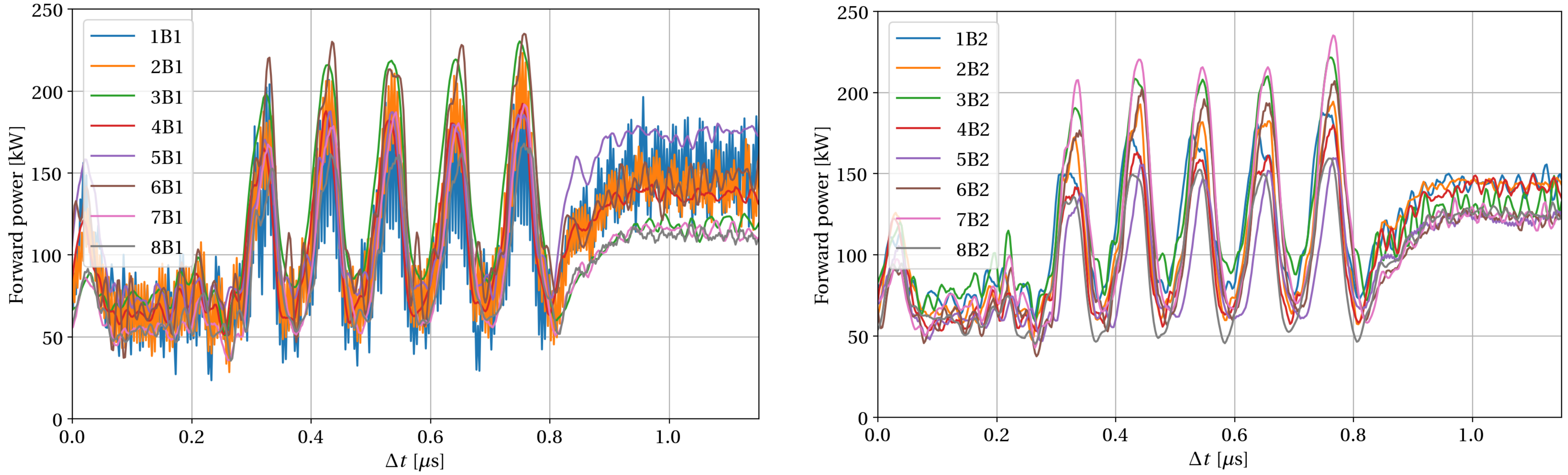
2018 ranged from -60…90 MeV

Beam-loading transients

Power transients in steady state, hybrid beam

- Analysed 13 physics fills with 1.6×10^{11} p/b
- Transients could be optimised (theoretical peak power: 150 kW)

Peak power [kW]	C1	C2	C3	C4	C5	C6	C7	C8
Beam 1	223.3±4.9	221.9±2.8	229.1±4.2	192.5±3.8	207.5±3.9	237.9±6.8	186.9±3.5	173.6±3.3
Beam 2	189.0±5.4	198.0±5.3	220.1±4.8	182.6±4.1	160.8±3.4	209.3±5.2	228.1±5.2	164.8±3.6

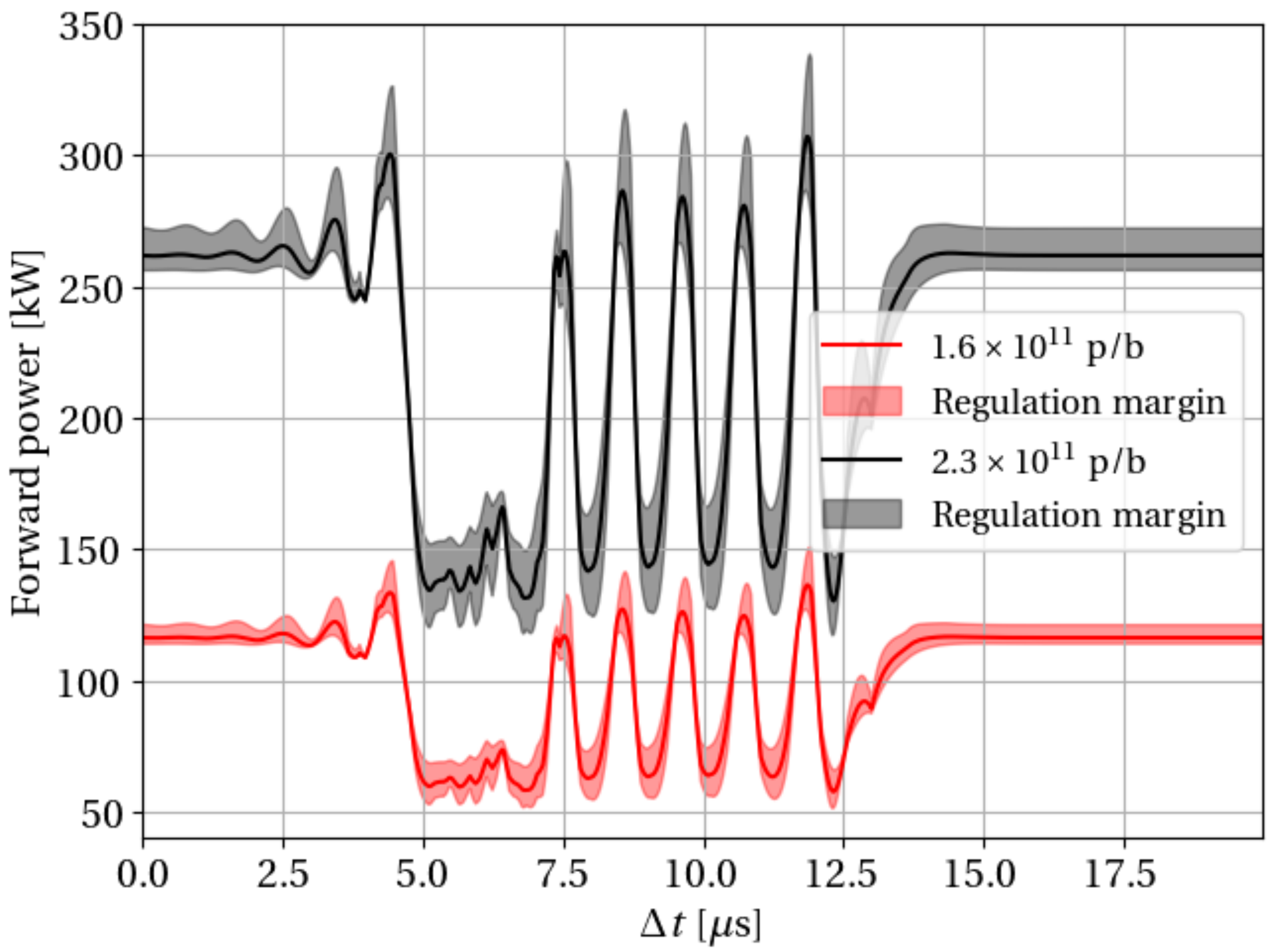


Measured forward power in beam- and no-beam segments
Left: B1 lines, right: B2 lines

Courtesy of B. E. Karlsen-Bæck

Simulated transients, hybrid beam

- Extrapolation to HL-LHC intensities
  - Theoretical peak power: ~330 kW



Simulated power for 2023 and HL-LHC intensities

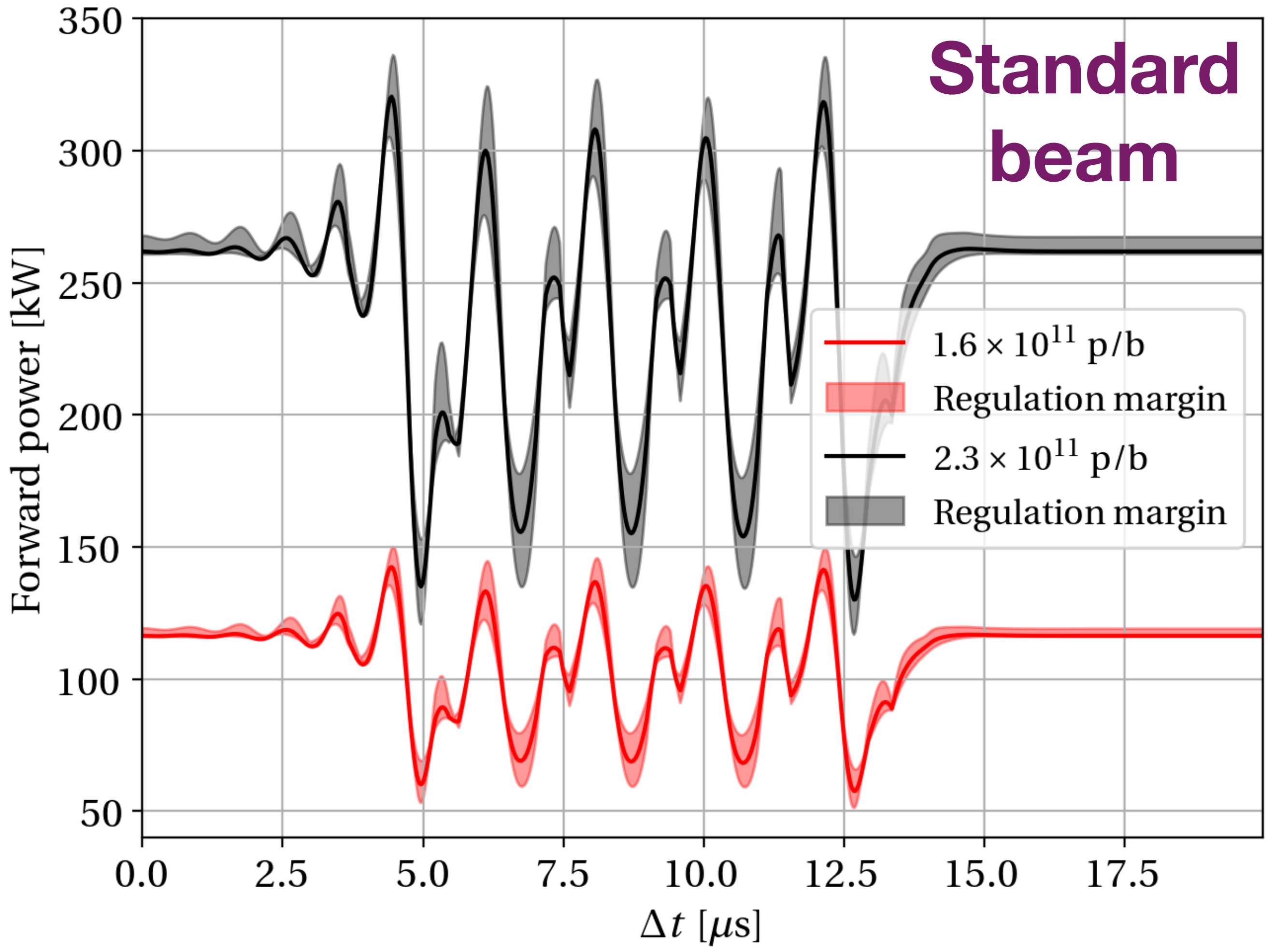
The regulation margin assumes ±2.5 k in QL, ±3 dB in RFFB gain and ±5 % in OTFB gain

Courtesy of B. E. Karlsen-Bæck

Updated estimates for HL-LHC

Scaling based on operational experience with 1.6x10^{11} p/b

- Hybrid beam, captured with 5 MV
  - Bunch length 1.08 ns at injection, 1.23 ns at end of flat bottom
  - No issues with beam losses at start of ramp
- What is the present system, as is, capable of?
  - MD experience with 2.0x10^{11} p/b: 206 kW average, ~230-310 kW peak power
- Scaling to HL-LHC
  - Capture voltage: 7.9 MV (confirms 2018 estimates)
  - Power at capture: 267 kW average, with 330-340 kW optimised peak power



Simulated power for 2023 and HL-LHC intensities with regulation margin

Courtesy of B. E. Karlsen-Bæck

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)	1.6x10^{11} p/b	0.36..0.45 eVs	9.4 MV	1.7 MV	(4.24..4.68)x10^{-4}	5 MV	1.08..1.23 ns	-11.8..-11.0 kHz	17.0..18.3 k	119..127 kW	**160-230 kW**
2023 (max)	2.0x10^{11} p/b	0.55 eVs	9.4 MV	1.7 MV	5.09x10^{-4}	7 MV	1.25 ns	-9.7 kHz	20.6k	**206 kW**	**230-310 kW**
HL-LHC	2.3x10^{11} p/b	0.58 eVs	10 MV	2 MV	5.32x10^{-4}	6.5..7.9 MV	1.25..1.32 ns	-11.6..-9.9 kHz	17.3..20.3 k	**212..267 kW**	**320±15 kW**

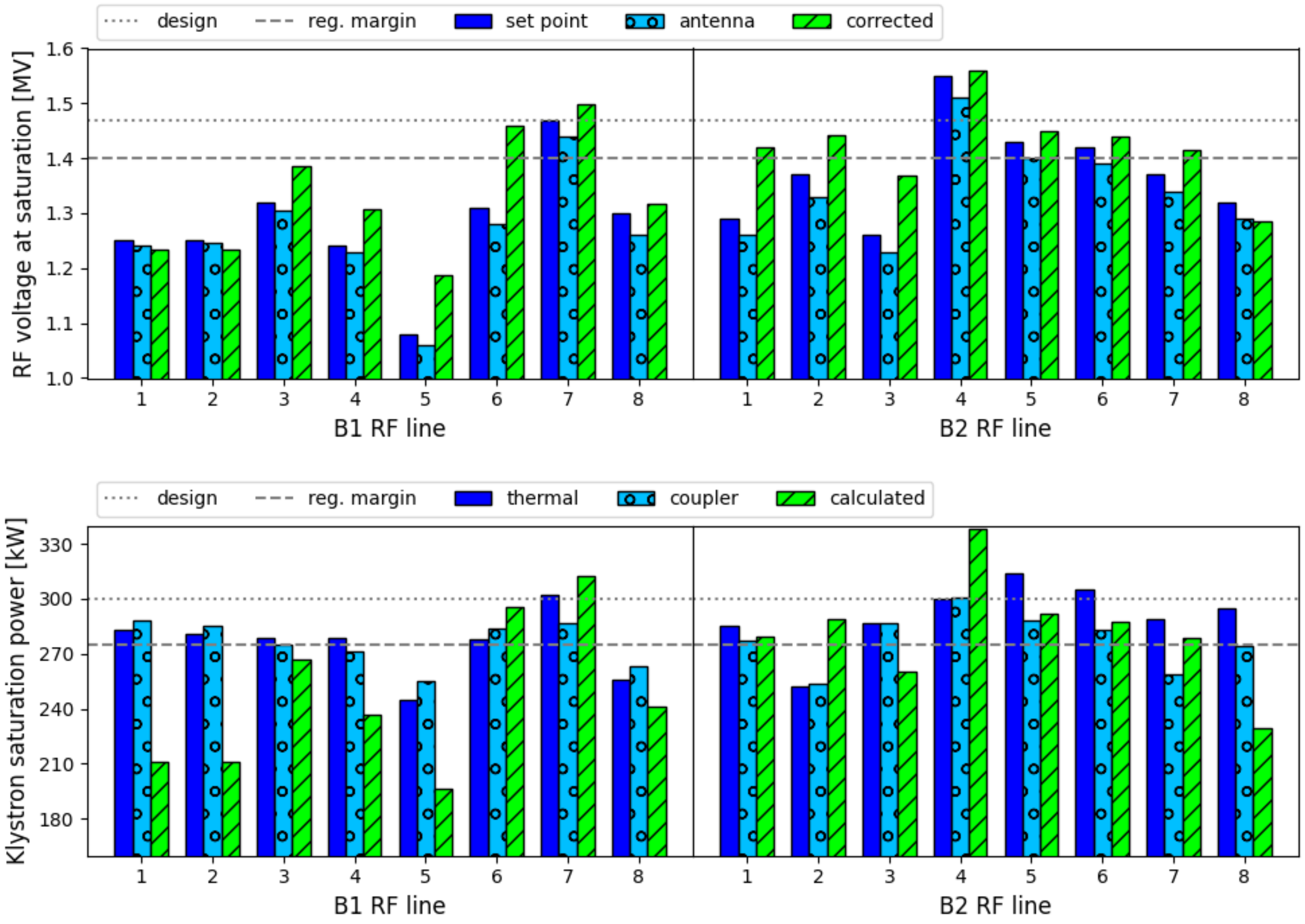
Maximum power and voltage available (1)

Maximum voltage obtained w/o beam

- Just without saturating yet
- Q_L = 20 k in all cases
- Folding in the beam-based voltage calibration results from a 2022
- If we trust the voltage more:

$$P = \frac{V^2}{8R/QQ_L}$$

  - Expect to have 1.4 MV for 275 kW
  - B1: 2/8 cavities, B2: 6/8 cavities OK
  - 4B2 unphysical high power



Top: RF voltage at saturation

Bottom: RF power at saturation

Maximum power and voltage available (2)

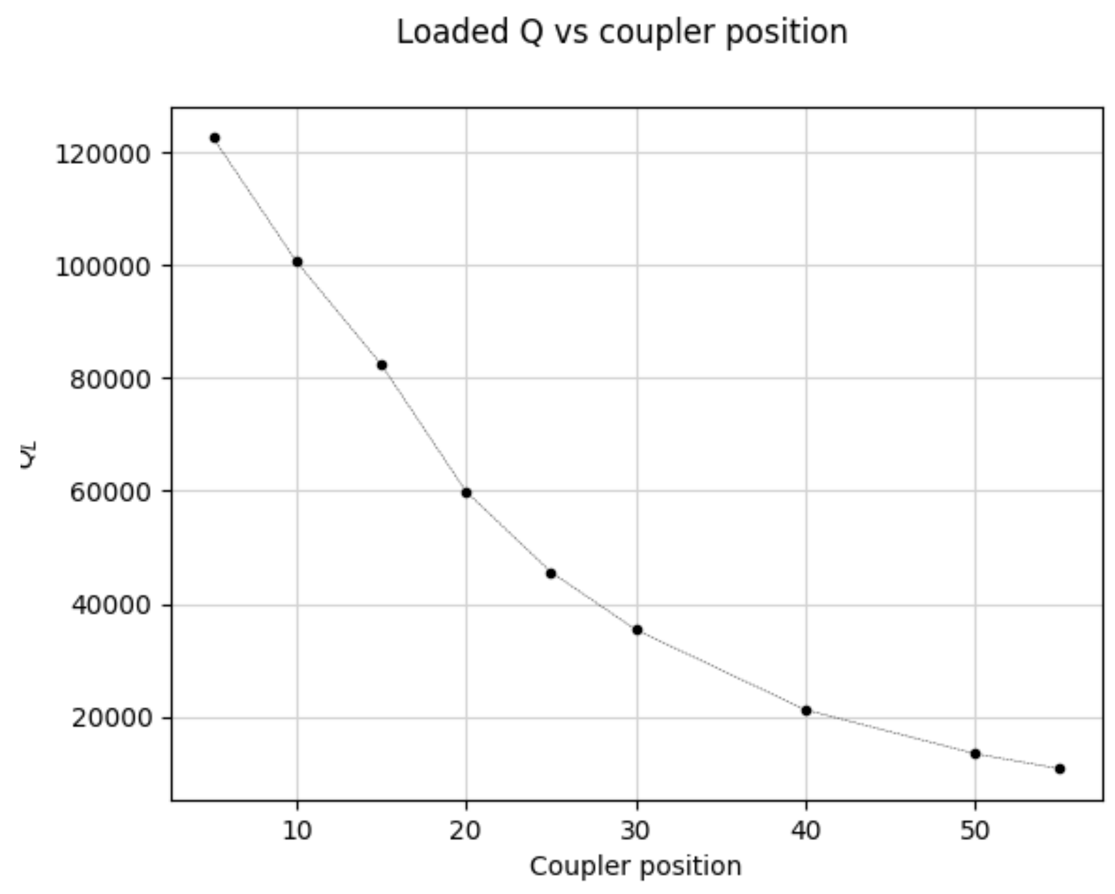
Analysis

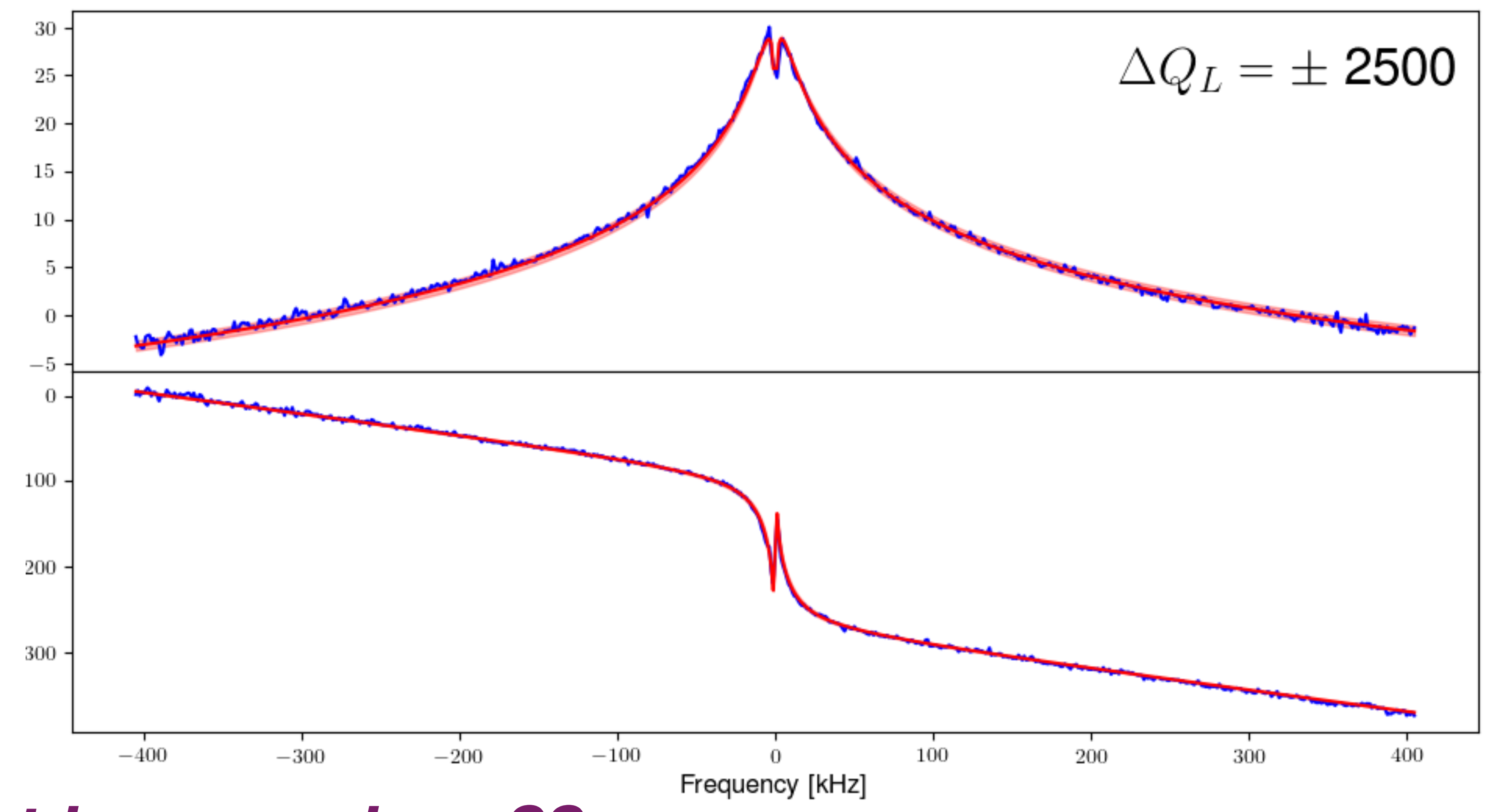
- The calculated power underperforms, especially on B1
  - What is the sensitivity to Q_L?
- Q_L is calibrated yearly with an open-loop response measurement
  - What is the error at injection values?
  - **Sensitivity study to be performed**
- Assuming an error of ±2.5 k
  - B1: 4/8 cavities, B2: 7/8 cavities OK
  - Could explain the excess on 4B2

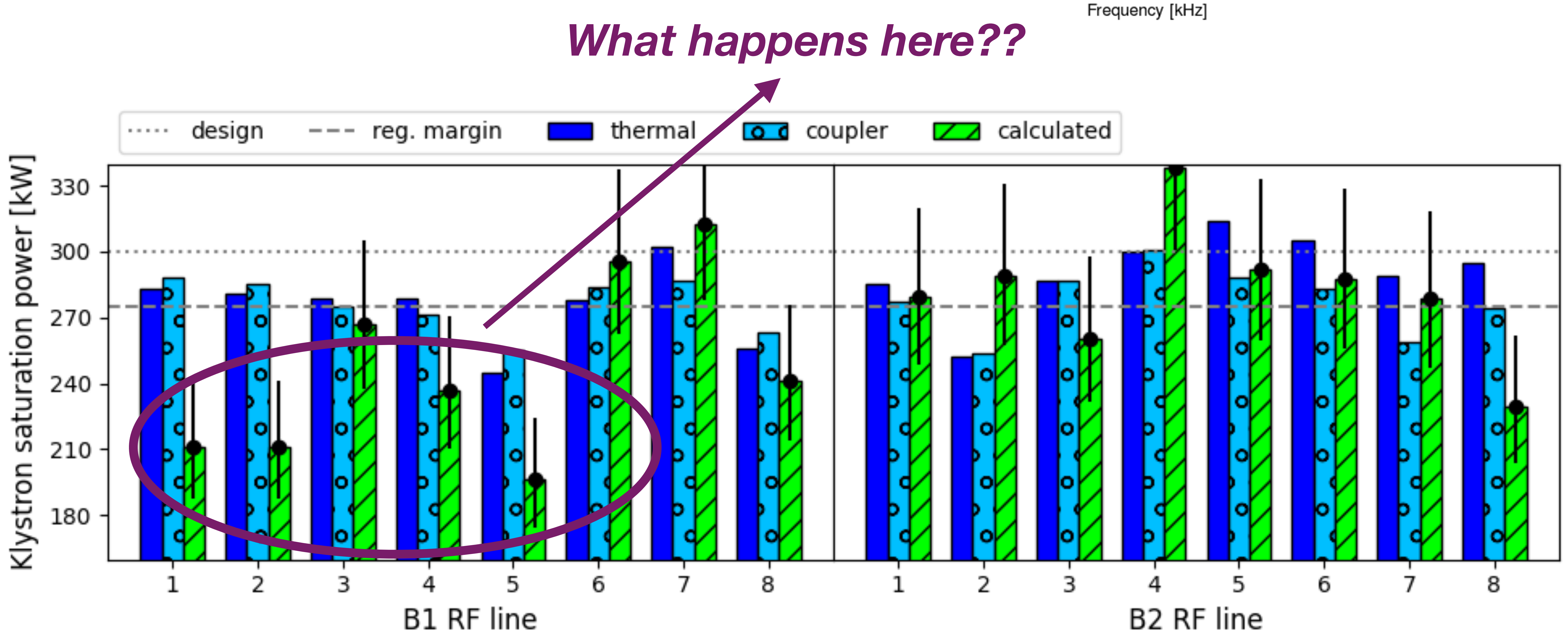
Top left: Q_L vs coupler position, 2B2 2022 data

Top right: open loop transfer function fit

Bottom: RF power at saturation with Q_L errors







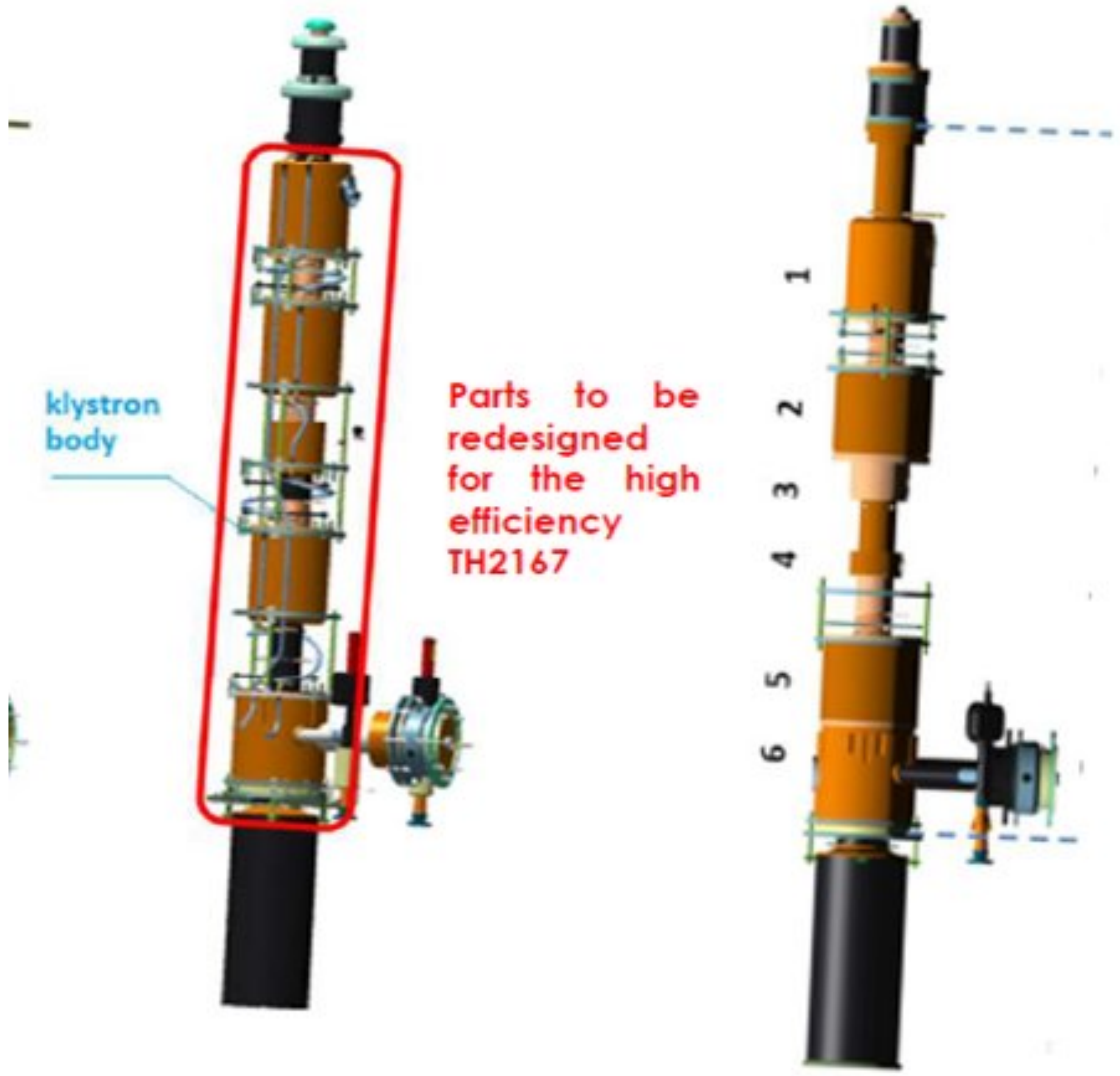
High-efficiency klystrons

Increasing the power reach of LHC klystrons

- Embedded into the LHC HV circuitry providing 500 kW DC
- The improved design allows to increase the efficiency from 60 % → 70 % [5]
  - RF power: 300 kW → 350 kW
- Plug & play replacement of the current LHC klystrons
  - Compatible with high voltage, driver, water, and waveguide network

Staged replacement of present LHC klystrons

- 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



Redesigning LHC klystrons for higher efficiency

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

Summary of expectations

Global analysis [6]

- Managed to capture 2.0×10^{11} p/b with up to 7 MV
- Several improvements have been implemented over 2022-2023
  - Pre-detuning removes the limitations from injection transients; focus now on peak power in steady state
  - Continuous operational optimisation of SPS-LHC energy matching lowers blow-up at injection
  - Operation with short bunches at 1.6×10^{11} p/b allows to capture with 5 MV
- Calibration measurements ongoing to verify margins in voltage and peak power
  - Voltage-based calibration shows a lack in voltage/power for 5/16 RF lines
- Projected HL-LHC peak power in the fully optimised (simulated) case is 320±15 kW
  - High-efficiency klystrons are a must, plus we will need to find a way to lower the figures

Next steps

- Year-end shutdown: implement the corrections from the beam-based voltage calibration
- 2024: repeat calibration measurements w/ and w/o beam
- Try reducing operational capture voltage to probe margins
- Prepare continuous adjustment of Q_L at injection

[6] H. Timko *et al.*: ‘Advances on LHC RF power limitation studies at injection’, Proc. HB’23 workshop, CERN, Geneva, Switzerland, 2023.

Longitudinal Studies for HL-LHC

Power limitations at injection

- Measurements, modelling & simulations
- Minimum voltage and losses in operation

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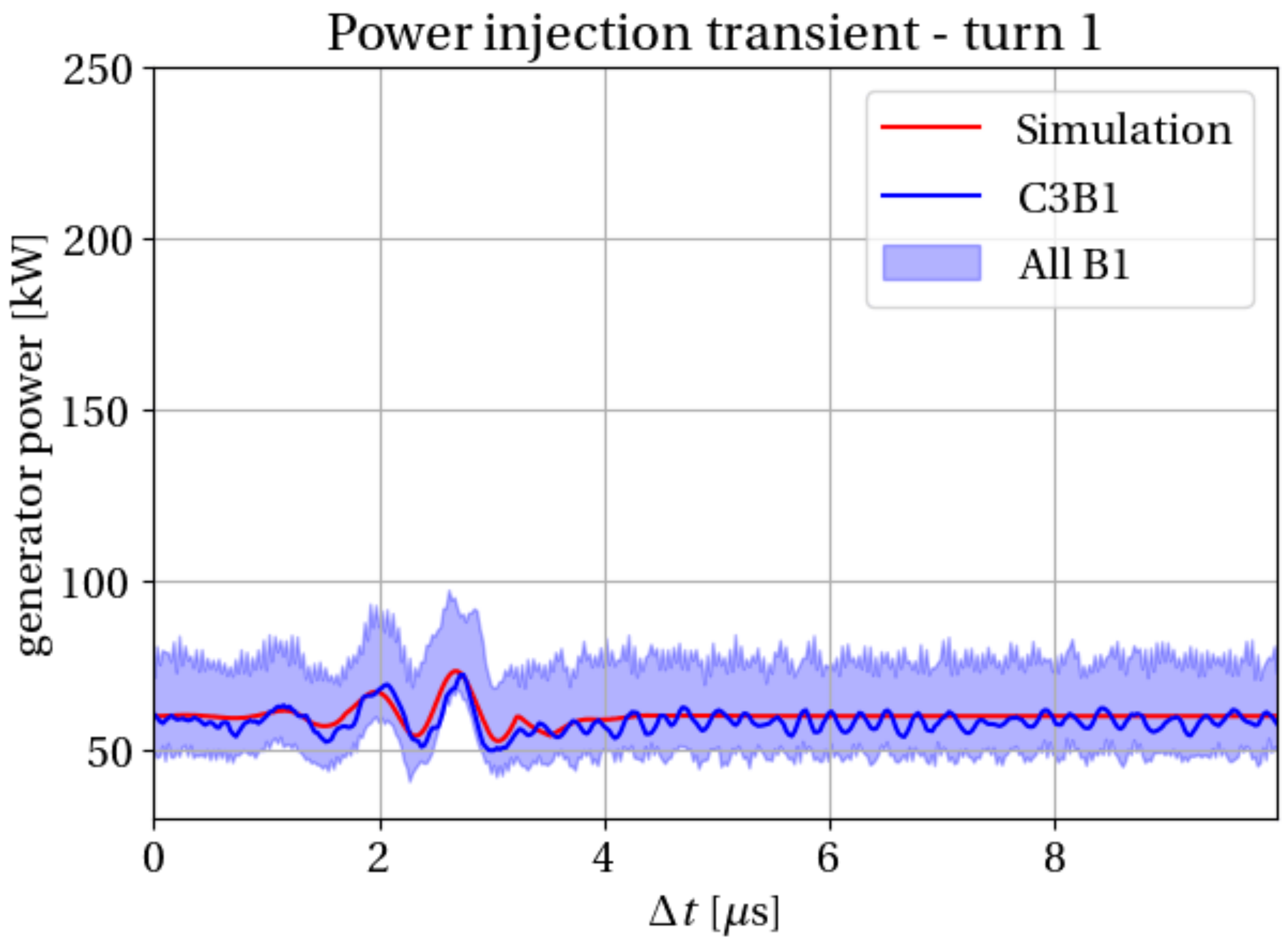
New logged signals

Adding operational observation tools to improve our knowledge about beam and RF parameters at injection

- Injection power transients
  - First 37 turns at injection
  - Limited by buffer size in VME cards
- Injection beam profiles
  - Batch-by-batch
  - Input for ML tomography

Injection transients with a 36-bunch batch of 1.8×10^{11} p/b

Courtesy of B. Karlsen-Bæck

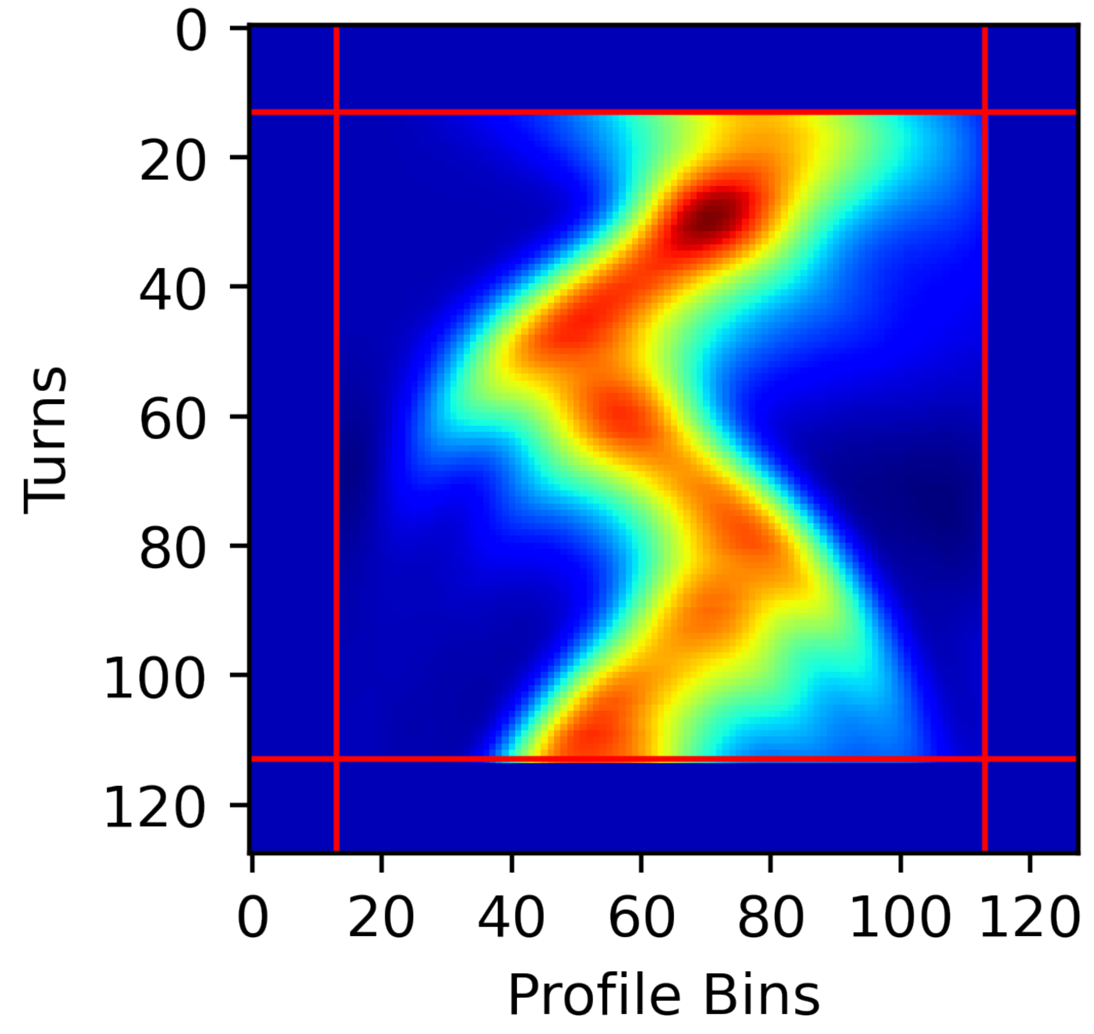


Machine-learning tomography: motivation

At injection: can now determine & log longitudinal beam parameters (e.g. injection errors, bunch length) and reconstruct the longitudinal phase space batch by batch, fill by fill [7,8]

- Tracking-based methods are too time consuming for online use, limited to single bunch
- Develop the ML model to:
  - Extract the desired beam parameters & 2D longitudinal beam distribution
  - Fast enough to allow for online use with multi-bunch beams

Encoder input



Encoder

- ➤ Extract beam parameters from beam profiles
- ➤ One model per parameter, seven in total
- ➤ First convolutional then fully connected layers
- ➤ ~22M parameters in total

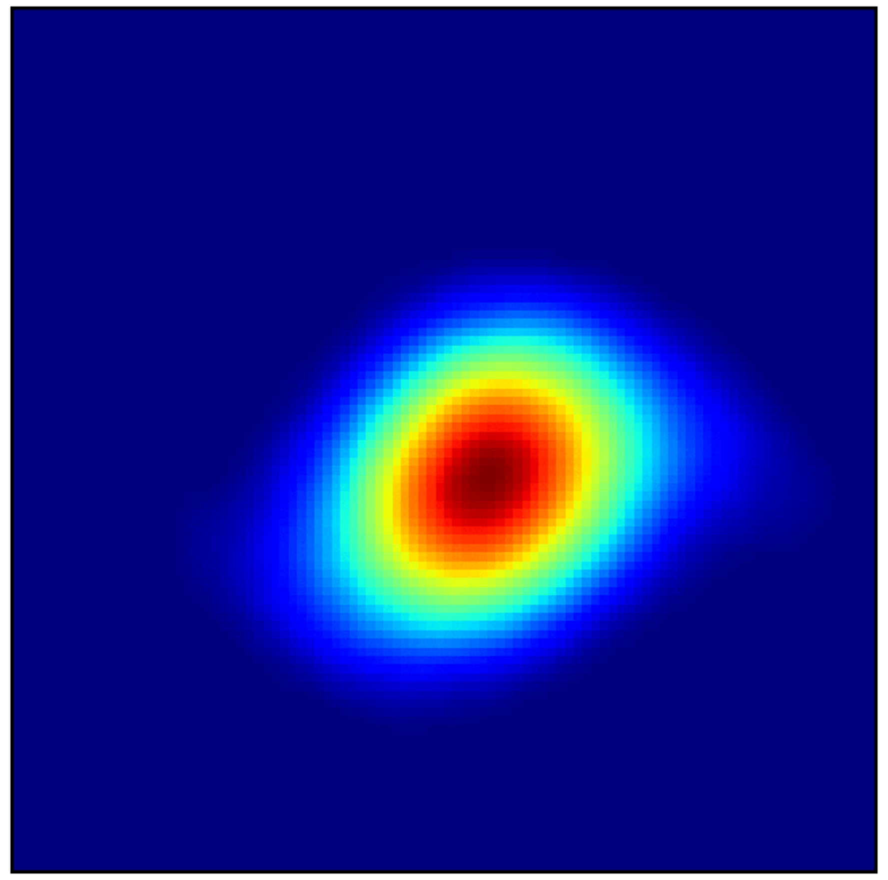
Encoder output/ Decoder input

Beam Parameters
Phase Error
Energy Error
Bunch Length
Intensity
LHC VRF
μ
SPS VRF

Decoder

- ➤ Re-construct phase-space from beam parameters
- ➤ Mirror encoder: first fully connected layers, then transpose convolutional
- ➤ ~8M parameters

Decoder output



[7] T. Argyropoulos and G. Trad, 'Machine-learning tomography and longitudinal beam parameters at LHC injection', Talk at CERN, Geneva, Switzerland, 2022.

[8] K. Iliakis, T. Argyropoulos, and G. Trad, 'Longitudinal tomography in the LHC', Talk at CERN, Geneva, Switzerland, 2023.

Machine-learning tomography: evaluation

Encoder evaluation (simulation data)

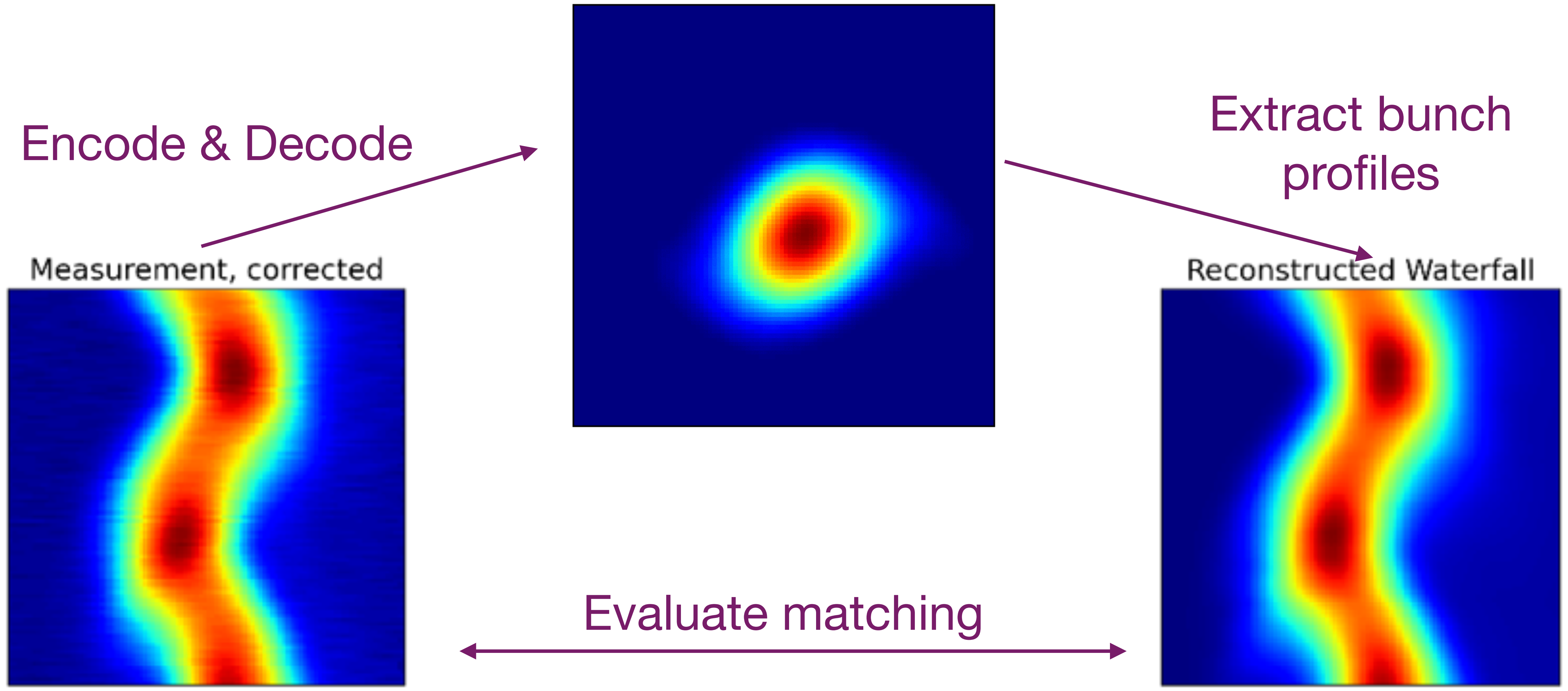
- Ground truth available only in simulations

	95 percentile
Phase Error	0.3 deg
Energy Error	1.56 MeV
Bunch Length	13.2 ps
Intensity	1.2e9 p
LHC VRF	0.05 MV
μ	0.2 a.u.
SPS VRF	0.16 MV

= max error of 95 % of the samples

Decoder evaluation (measurement data)

- Visually indistinguishable
- Takes ~50 sec for a full tomography reconstruction
  - For 48 bunches over 300 turns



Conclusion: excellent agreement in simulation data, good agreement in measurements

On-going

- Deploy operationally, apply model online at every injection, store beam parameters in NXCALS
- Refine based on observations from real measurements

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Theoretical model for multi-bunch stability

- Since broadband impedance defines the threshold of the loss of Landau Damping [9], its knowledge is crucial to predicting stability for HL-LHC intensities

$$\text{Instability threshold} \propto \frac{1}{\text{Contribution of BB impedance} + \text{Contribution of HOM impedance}}$$

Contribution of BB impedance $\propto (\mathrm{Im}Z/k)_{\mathrm{eff}}$ and f_c

Contribution of HOM impedance $\propto (R)_{\mathrm{sh}}/f_r$

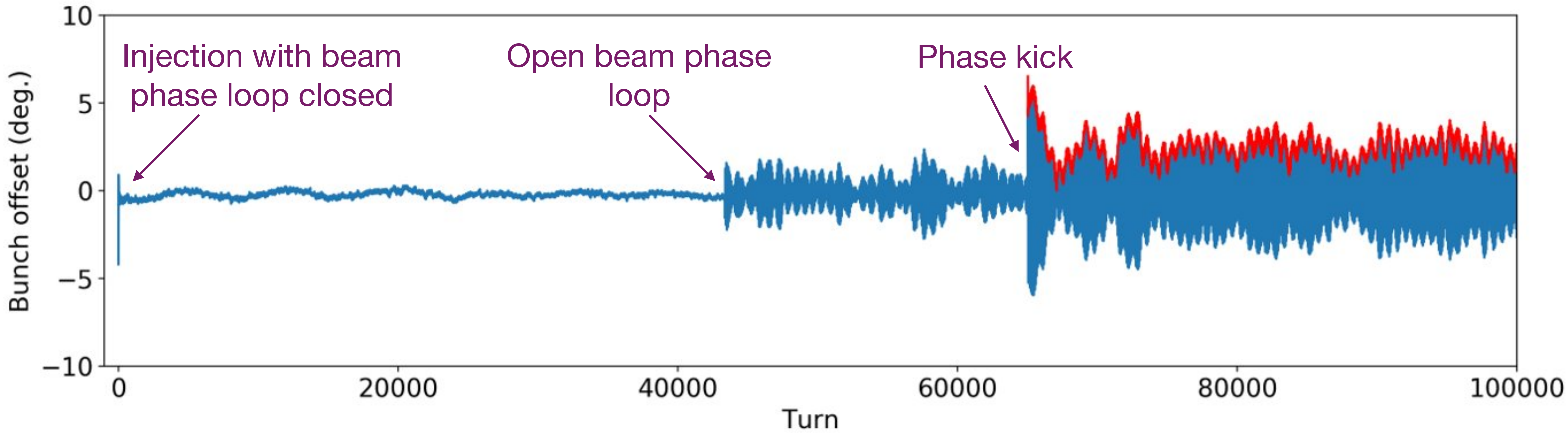
Possible scenarios	BB	HOM
Threshold is defined by BB imp., slow instability	Strong	Weak
Threshold is defined by HOM imp., fast instability	Weak	Strong
Threshold affected by both imp., fast instability	Strong	Strong

[9] I. Karpov and E. Shaposhnikova, ‘Impact of broadband impedance on longitudinal coupled-bunch instability threshold’, Proc. IPAC’22, Bangkok, Thailand, 2022.

Beam-based measurements of LLD threshold

Different measurements were performed before LS2 [10]

- New proposal: use a phase kick in steady state, with beam phase loop open
  - This technique is already used in the PS and SPS [11]
  - A precise knowledge of the RF voltage is important (pre-requisite: beam-based calibration)
  - Residual oscillation amplitude contains information about the effective impedance [12] for LLD



Example of SPS measurement on 29th April 2022

[10] J. Esteban Müller, ‘Longitudinal intensity effects in the CERN Large Hadron Collider’, PhD thesis, 2016.

[11] L. Intelisano, PhD project, ongoing.

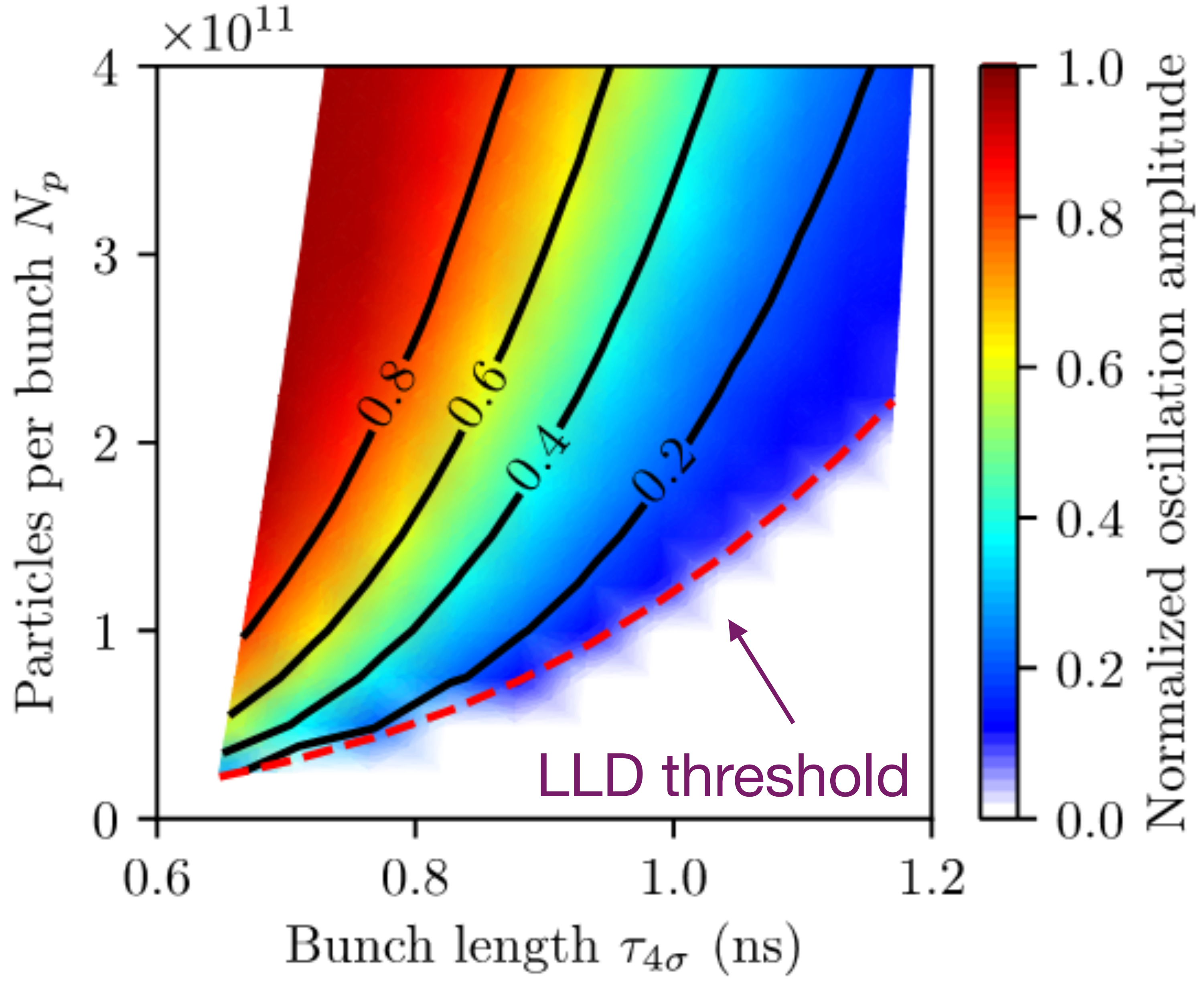
[12] I. Karpov, T. Argyropoulos, and E. Shaposhnikova, ‘Thresholds for loss of Landau damping in longitudinal plane’, Phys. Rev. Accel. Beams **24**, 011002, (2021).

Sensitivity to the cut-off frequency

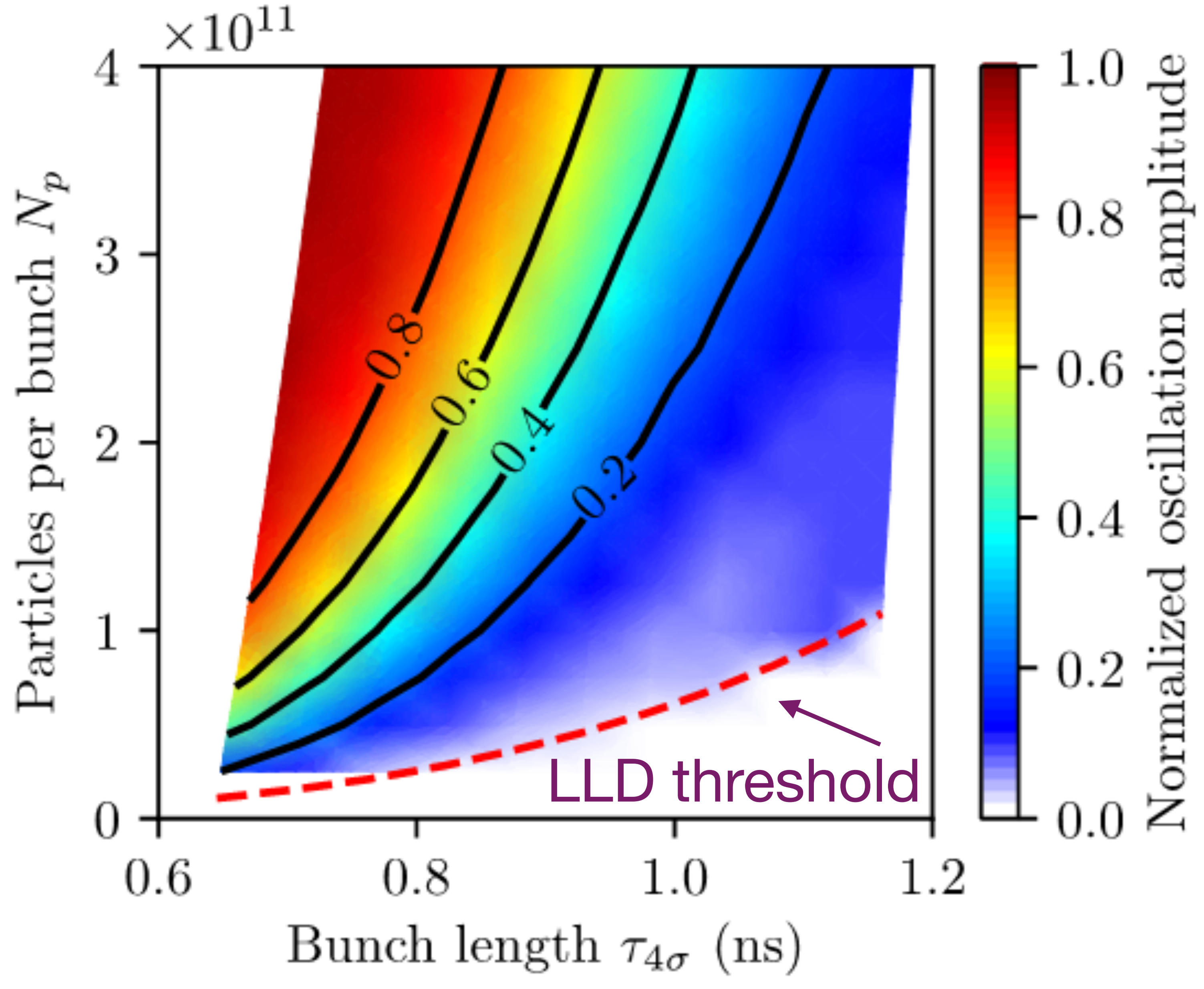
Connection to impedance studies

- Oscillation amplitude after the kick strongly depends on the effective cut-off frequency
- Scanning the parameter space allows to probe the longitudinal impedance

$f_r = 4$ GHz



$f_r = 8$ GHz



MELODY results for single broad-band impedance at LHC flat bottom

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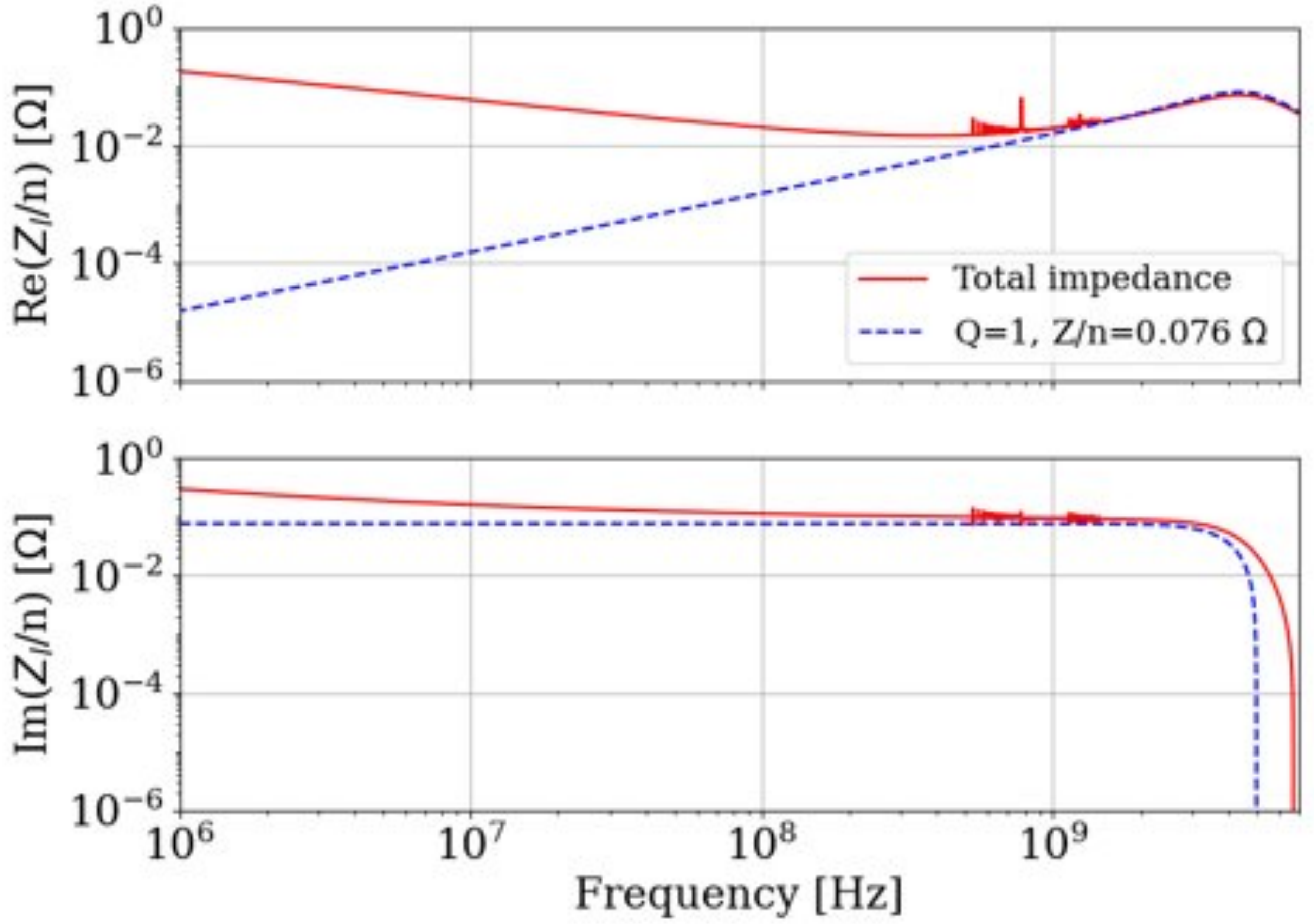
Present longitudinal impedance model

Full impedance: mostly interested in the imaginary part that drives instabilities

- Present model based on the model in the LHC Design Report and the refinement of it [13-15]
- Lower frequencies: resistive-wall behaviour $\sim \sqrt{\omega}$
- Higher frequencies: broad-band behaviour
- In the frequency range of the beam spectrum (~GHz), the impedance can be approximated as a broad-band resonator with

  $Z/n \approx 0.07\,\Omega$



Present longitudinal LHC impedance model at flat bottom (red) and its broad-band resonator approximation

Courtesy of M. Zampetakis

[13] O. S. Bruning, *et al.*, 'LHC Design Report Vol.1: The LHC Main Ring,' Tech. Rep. CERN-2004-003-V-16, CERN, Geneva, Switzerland, 2004.

[14] Python Wake and Impedance Toolbox, https://gitlab.cern.ch/IRIS/pywit.

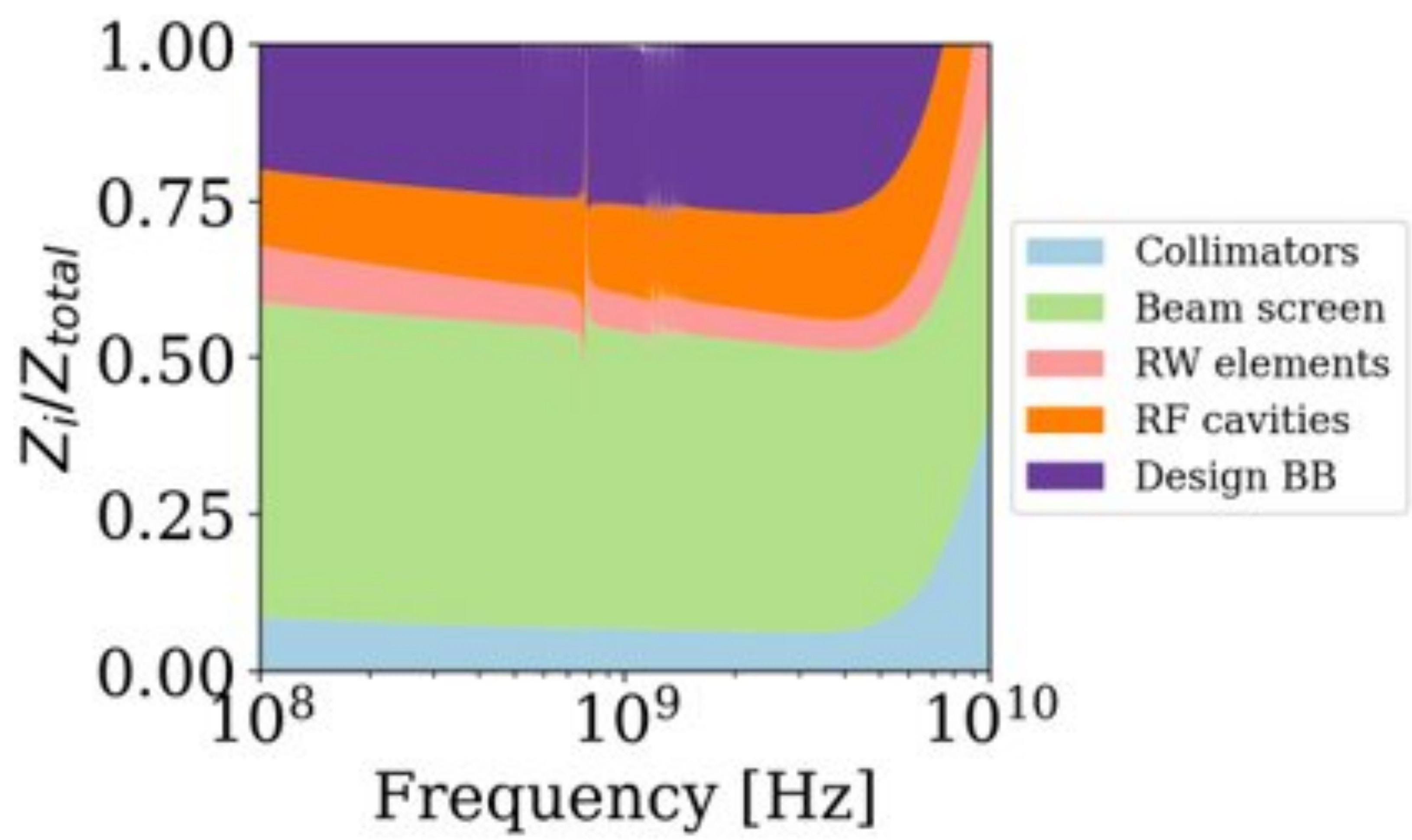
[15] Impedance Wake 2D code, https://gitlab.cern.ch/IRIS/IW2D.

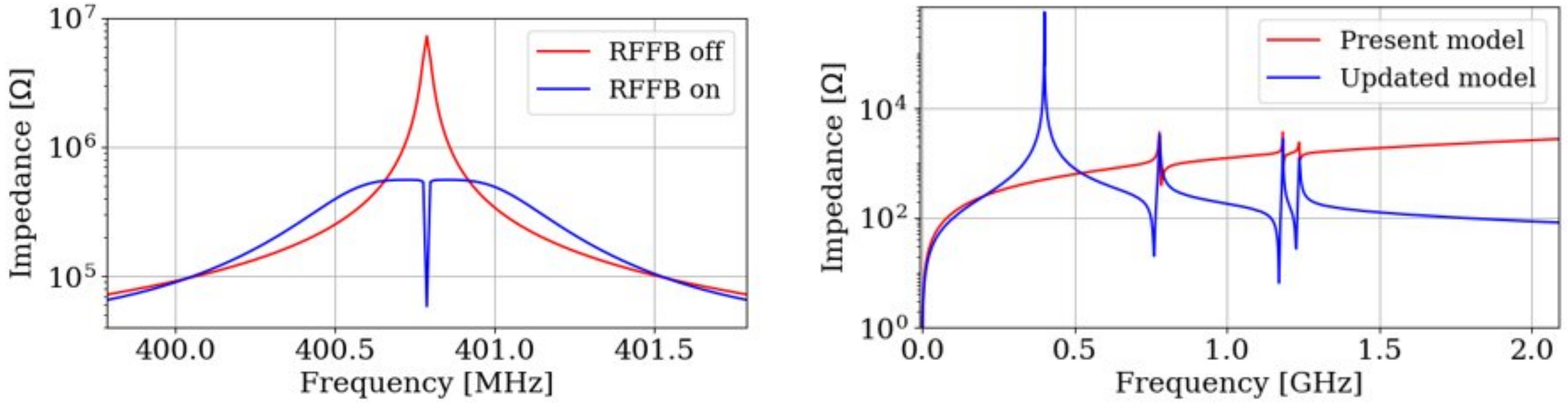
Refining the impedance model

Refining the main contributors around 1 GHz

The original model has been constructed with the highest transverse contributors in mind, which might not be the same in the longitudinal plane

- Beam screen
  - Wire measurements ongoing to verify the beam screen model and characterise the behaviour around the cut-off frequency
- Design broad-band impedance
  - Investigating whether any device models have been updated
- RF cavities
  - Included the fundamental mode with RF feedback





Top: relative impedance contributors of the present model, in the longitudinal frequency range of interest

Bottom: model with updated RF cavities

Courtesy of M. Zampetakis

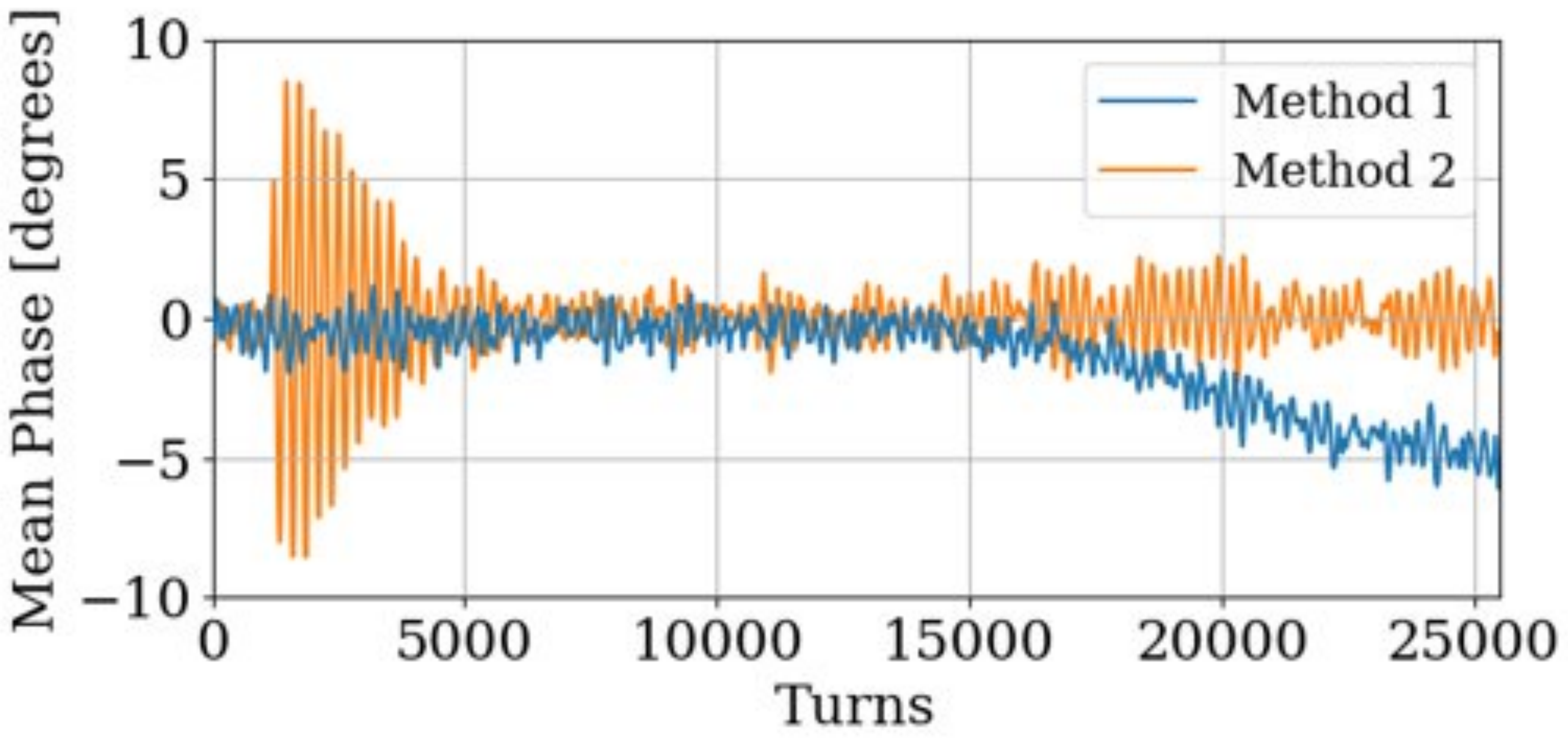
Estimating the cut-off frequency

In the present model: a cut-off frequency of 50 GHz is assumed for the broad-band contributions

- Was chosen for transverse applications to stay conservative for instability predictions at high chromaticity
- In the longitudinal plane, led to artificial losses for injection simulations [16]
- Finding a reasonable cut-off frequency by probing the LLD threshold in measurements [17]

Measurement method tested in the LHC

- Apply a phase kick to single bunches and observe the resulting oscillations
- Three phase kick methods were compared:
  - Method 1: phase offset in the RF cavities ⇒ adiabatic phase shift
  - Method 2: phase offset in the synchronisation loop ⇒ step-like
  - Method 3: injection phase offset ⇒ mix of dipole/quadrupole oscillations
- Systematic measurements still to be performed



Comparison of measurement methods 1 & 2

Courtesy of M. Zampetakis

[16] L. Medina Medrano *et al.*, '[Studies of longitudinal beam losses at LHC injection]', Proc. IPAC'21, online, 2021.
[17] I. Karpov: '[HL-LHC longitudinal stability]', Talk at the 12th HL-LHC Collaboration meeting, Uppsala, Sweden, 2022.

Summary

Power limitations at injection

- Several improvements in 2023 (energy matching, pre-detuning)
- Captured 2.0×10^{11} p/b bunch trains with 7 MV
- Will need high-efficiency klystrons and further improvements to achieve HL-LHC goals

Machine diagnostics

- New methods and signals available to measure beam and RF parameters at injection

Longitudinal beam stability

- A more accurate picture of Landau damping to predict longitudinal beam stability for HL-LHC

Longitudinal impedance model

- Improvements of the model are advancing on several fronts

Thank you for your attention!

Backup slides

Training

Simulation scenario:

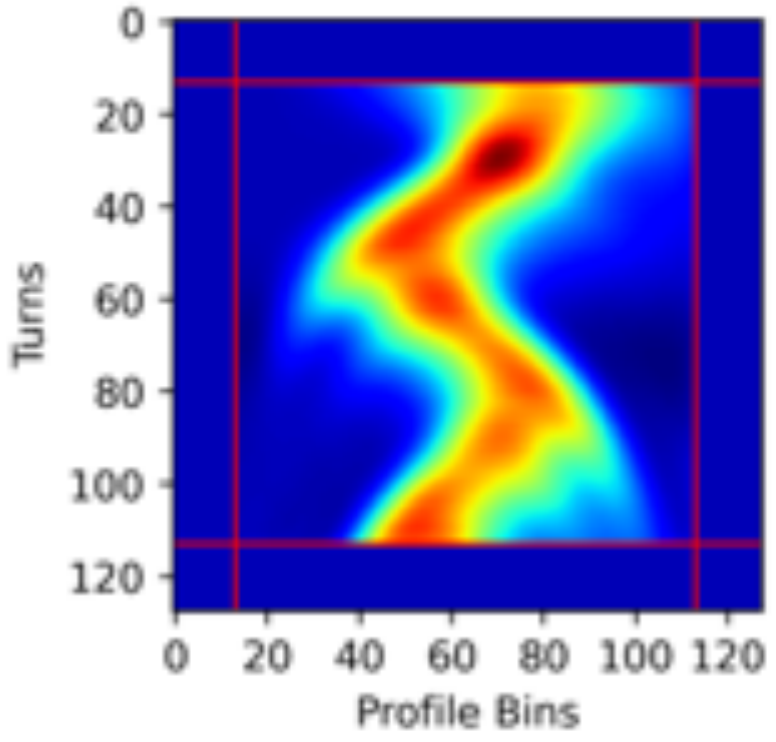
1. Generate single bunch in SPS with varying:
   a. Bunch length: 1.2 -- 1.8ns
   b. bunch intensity: 1e10 -- 3e11 protons
   c. LHC RF Voltage: 5 -- 12 MV
   d. binomial distribution factor μ: 1 -- 5 a.u.
2. Inject in LHC with varying:
   a. Phase error: -50 -- +50 degrees
   b. energy error: -100 -- +100MeV
   c. RF voltage: 3.0-9.2 MV
3. Track for 500 turns, 1M particles, 100 profile bins
4. Store bunch profiles, beam parameters, phase-space

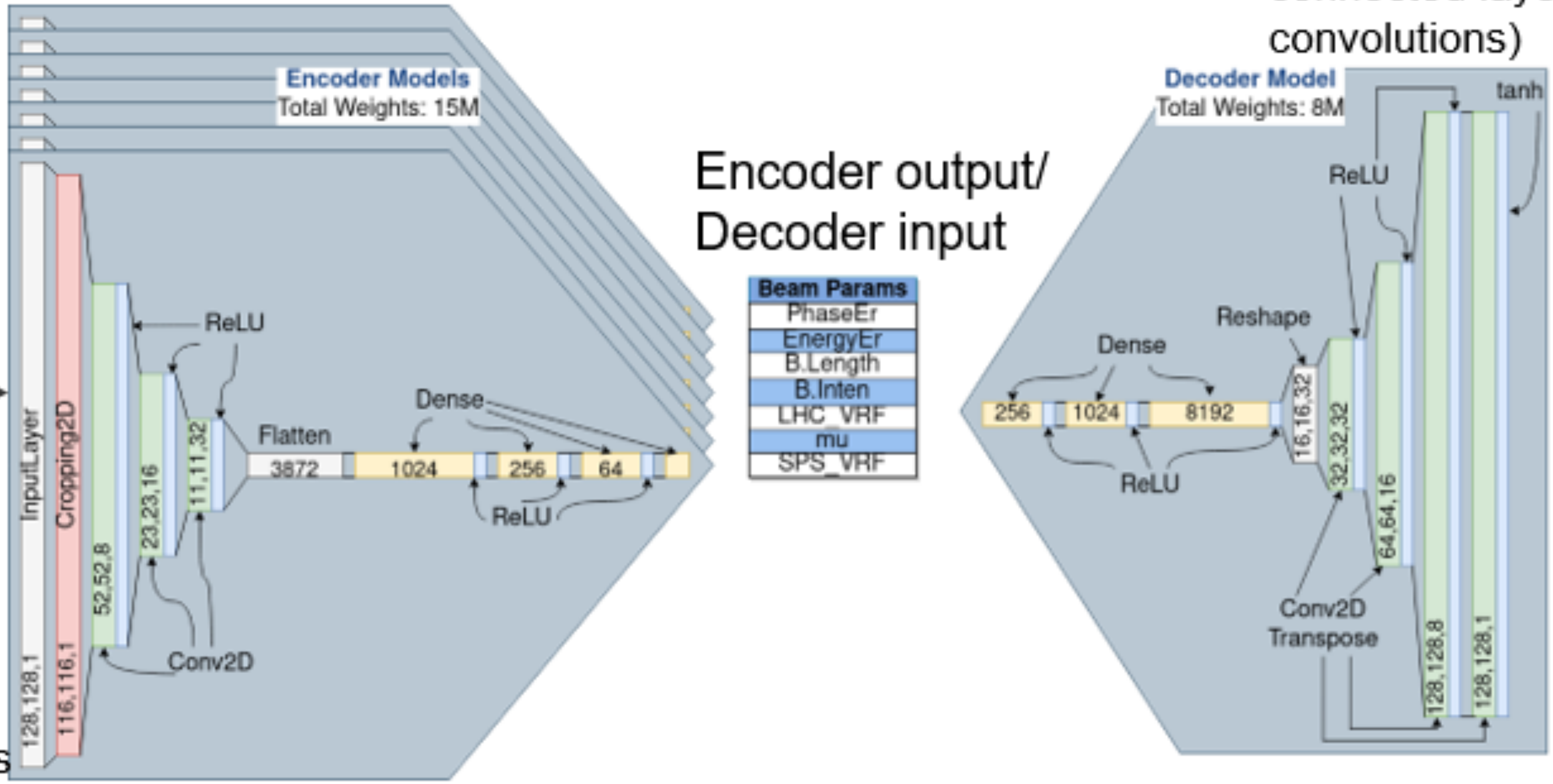
Training samples:

- 20K in total, 1B input points
- Training 85%, Validation 7.5%, Testing 7.5%

ML Tomography, Model Architecture

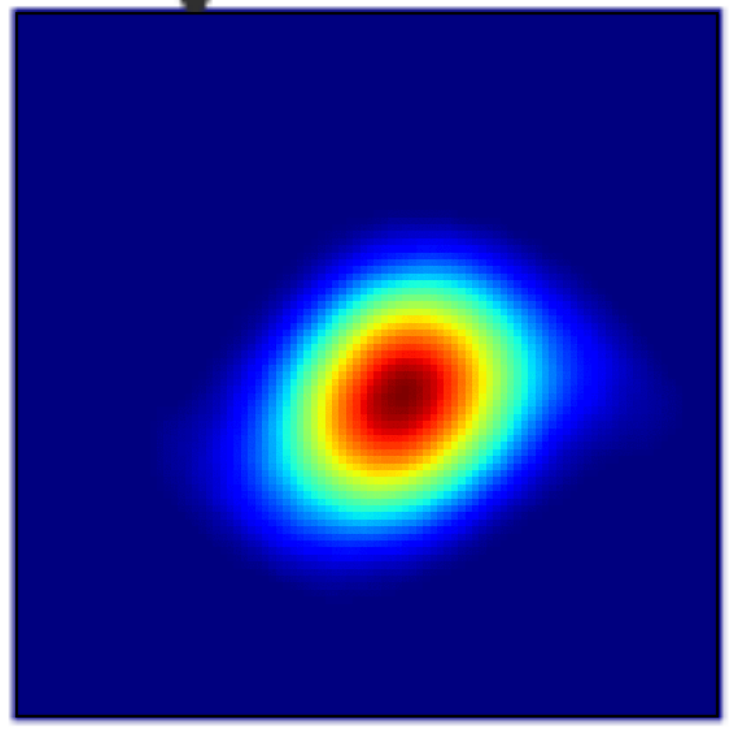
Encoder input





Encoder output/ Decoder input

Decoder output



Decoder

- ➤ Re-construct phase-space from beam parameters
- ➤ Mirrors encoder (first fully connected layers then transpose convolutions)

Encoder

- ➤ Extract the beam parameters from the recorded beam profiles.
- ➤ 1 Model per parameter
- ➤ Mostly convolutional and fully connected layers