Longitudinal Modelling and Operational Optimization Across the Complex

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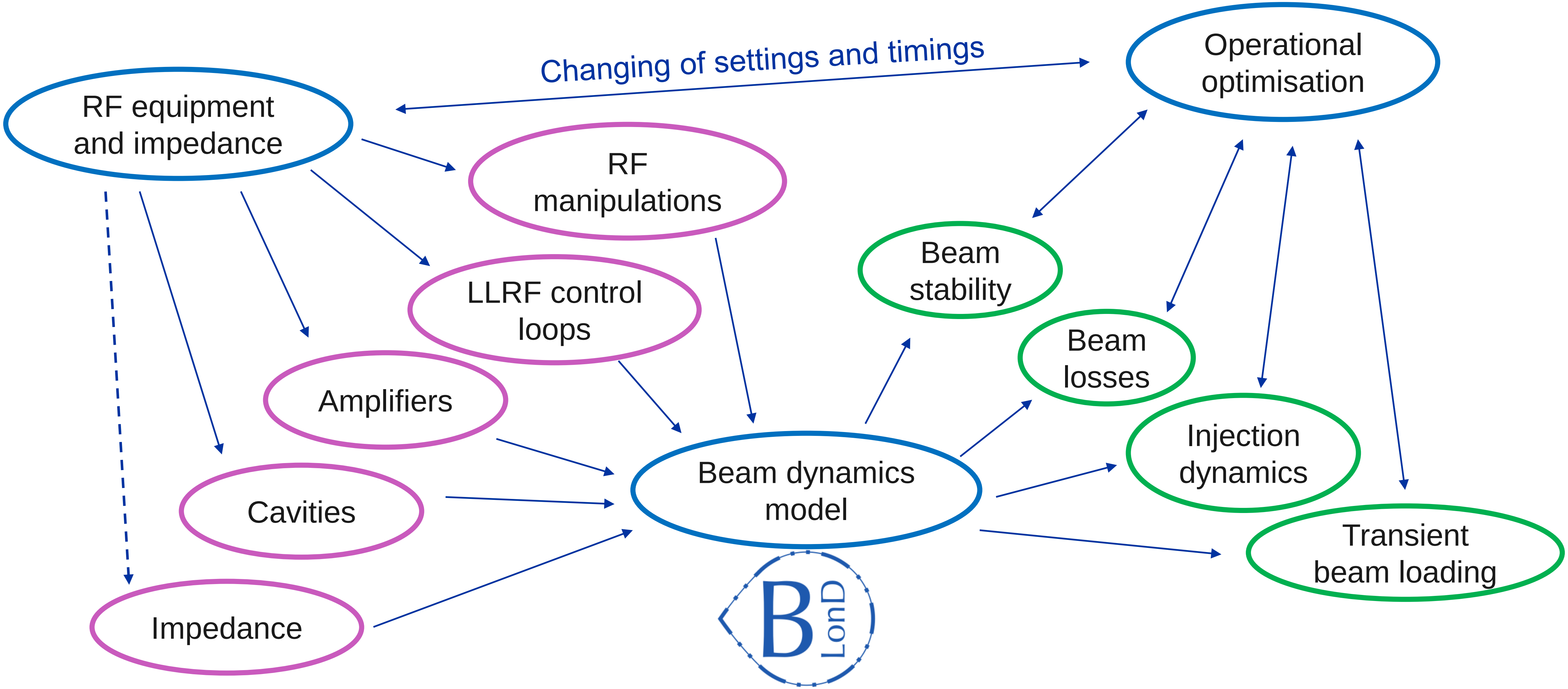
Joint Accelerators Performance Workshop, Montreux, Switzerland, 11th December 2024

Outline

- **Modelling longitudinal control loops and their applications**
  - Optimizations of equipment across the chain
- **LHC power limitations at injection**
  - Detuning and RF power transient optimization
- **Longitudinal aspects of BCMS and standard beams**
  - Evolution along the flat bottom in the LHC
- **Outlook**

Beam Dynamics Modelling and Equipment



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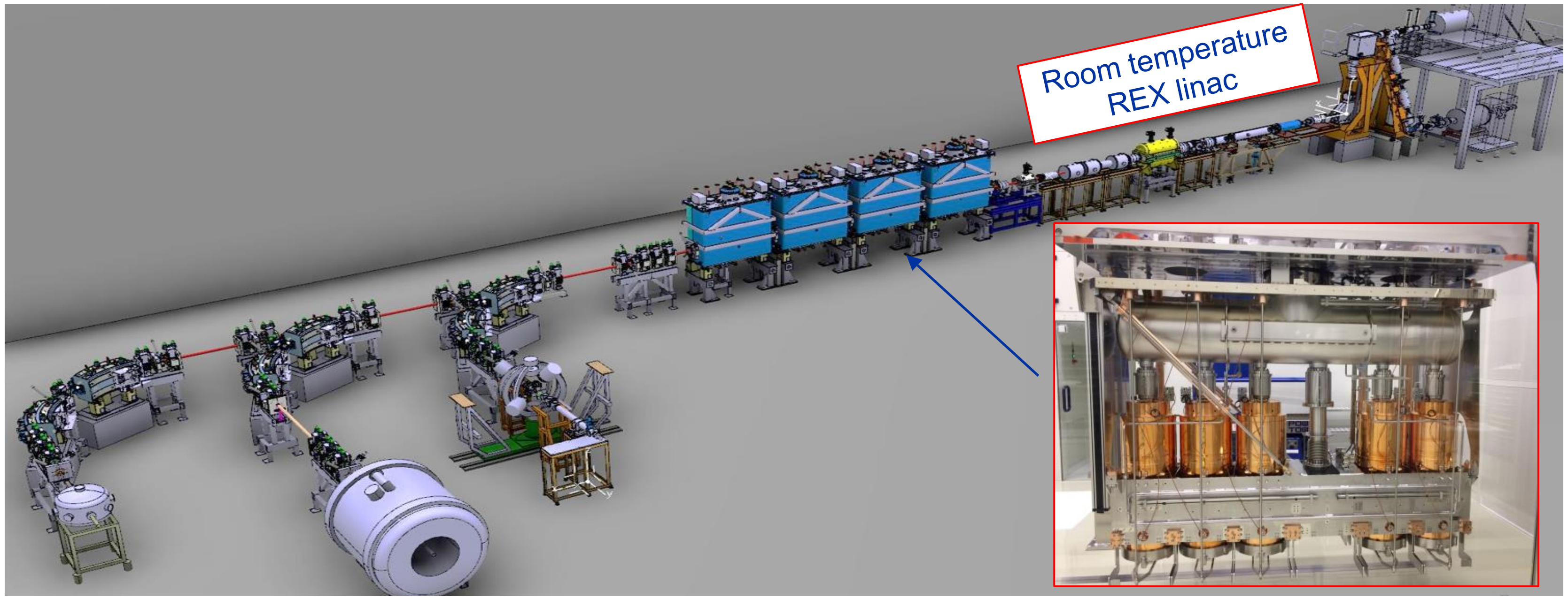
Applications of Modelling Across the Chain

Accelerator	Scenario	What was modelled	Achievement
REX/HIE-ISOLDE	Various ion beams	Energy gain and time of flight via transit time factor from simulation	Faster rephasing of the cavities when switching beam types
PSB	Most operational beams	Multi-harmonic cavity controller	Understanding origin of slow instability
PS	Fixed target beam	Phase jump and beam control loops	Reduction of EAST losses and increase of TOF intensity
SPS	LHC-type beam	Beam control and cavity control	Accurate prediction of losses and beam parameters at flat bottom
SPS	Ion slip stacking	Voltage and frequency manipulation	Optimization tool used for the cycle
LHC	Proton beams	bunch length feedback	Improvement of regulation and a flat bunch length target
LHC	Ion beams	Intra-beam scattering	Improved lifetime of the ion beam at capture

REX/HIE-ISOLDE – Cavity Rephasing for Different Beams

- **Motivation**
  - Linac accelerating around 25 different beam-types
  - Rephasing with beam was very time consuming
- **What is being modelled?**
  - Zero-order transit time factor behaviour
  - Time of fight between cavities

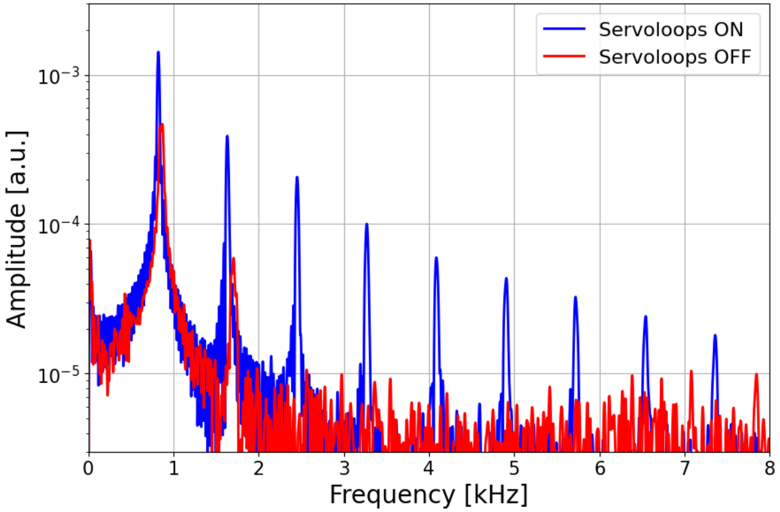
- **Operational outcome**
  - Model successfully applied and used systematically in 2024
    - Saving shifts dedicated to setup
    - Reduced downtime during physics campaign



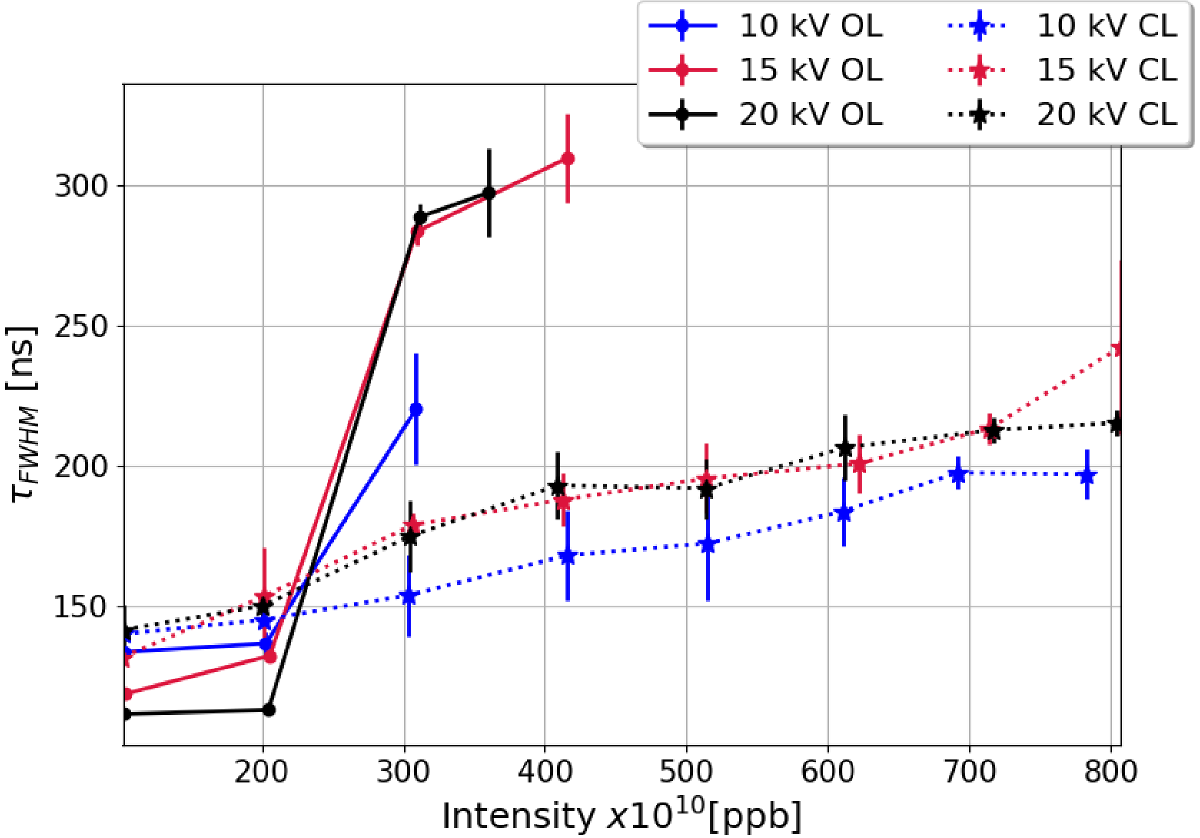
Courtesy of
J. A. Rodriguez

PSB – Most Operational Beams

- **Motivation**
  - Servo-loop-dependent slow instability
    - Could not be explained with current beam dynamics model
- **What is being modelled?**
  - Dynamic behaviour of the cavity controller
  - Intensity effects



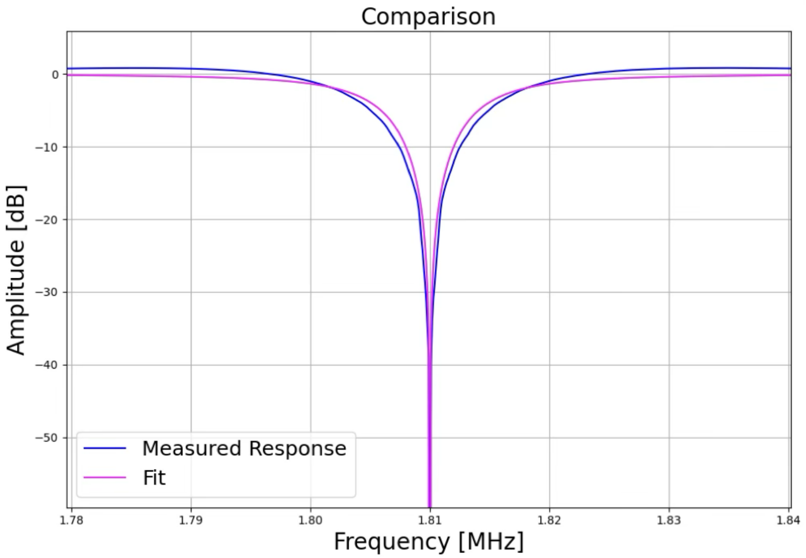
Loops amplifying the spectrum of bunch length oscillations at flat top
Courtesy of M. Marchi



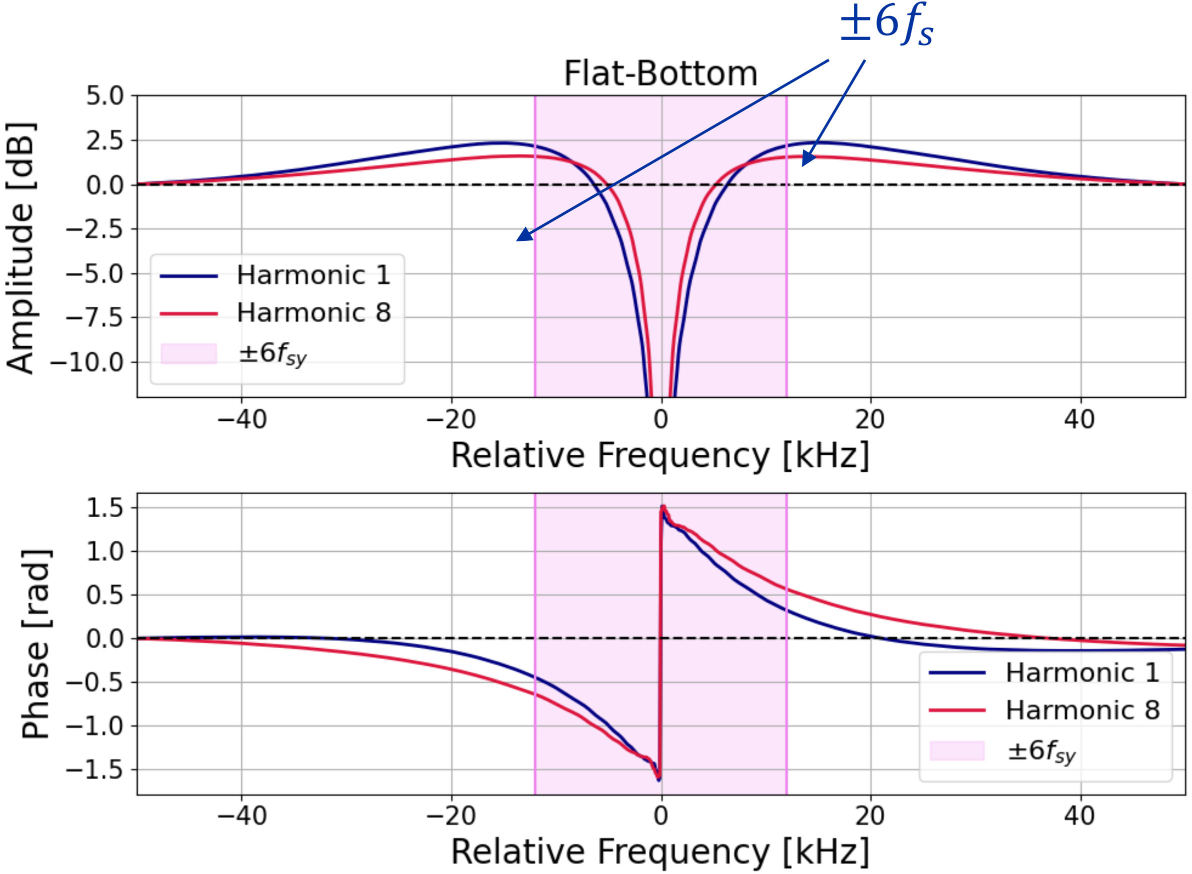
Strong impact from configuration of servoloops on longitudinal stability
Courtesy of M. Marchi

PSB – Most Operational Beams

- **Outcome**
  - Imperfect loop regulation at some of the synchrotron side bands
- **Next steps**
  - Explore different implementation of the loops in tracking simulations
  - Optimize settings of notch filters



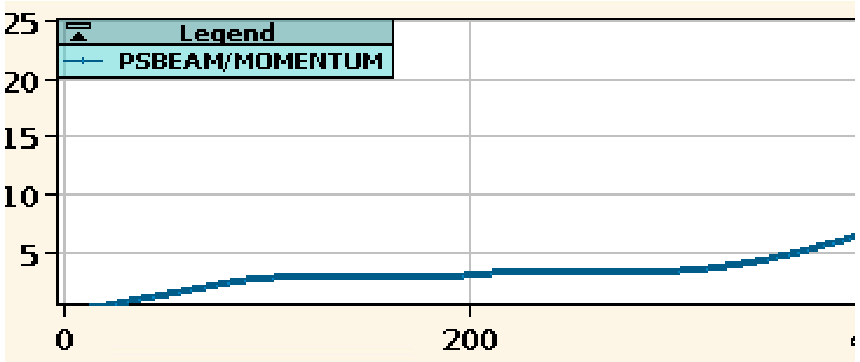
Courtesy of M. Marchi

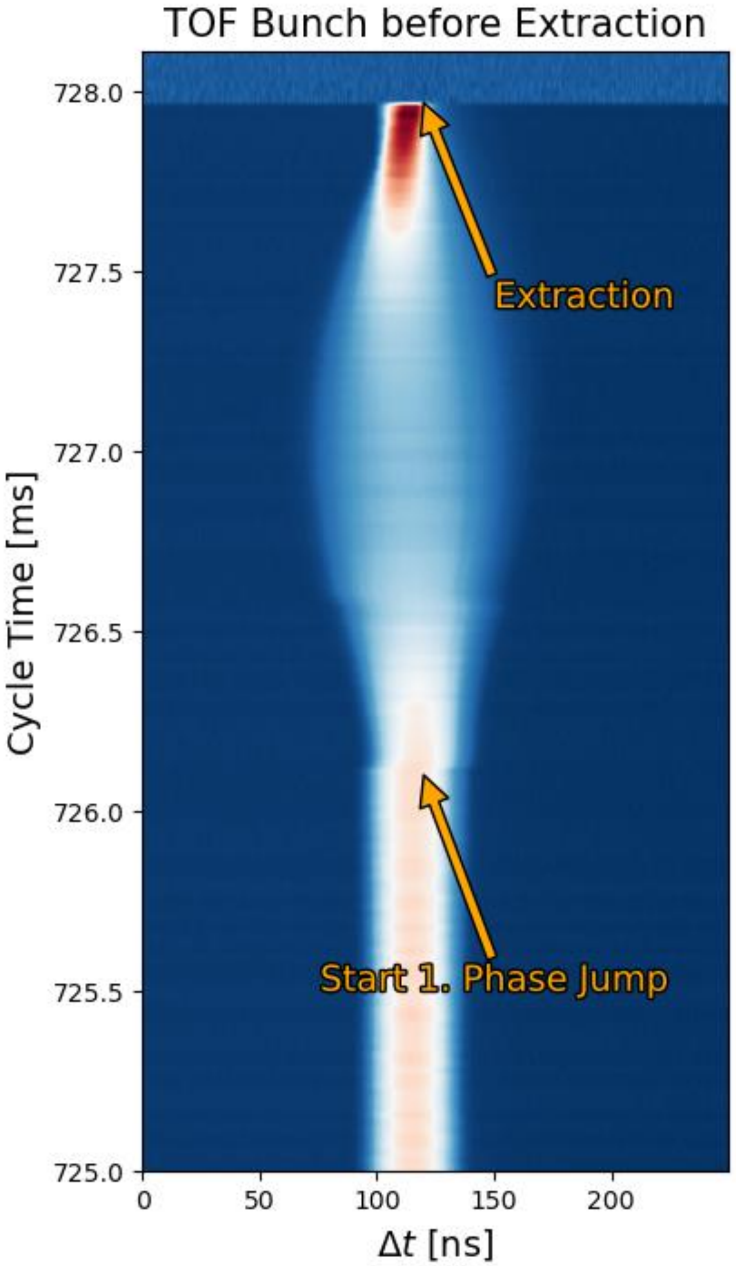


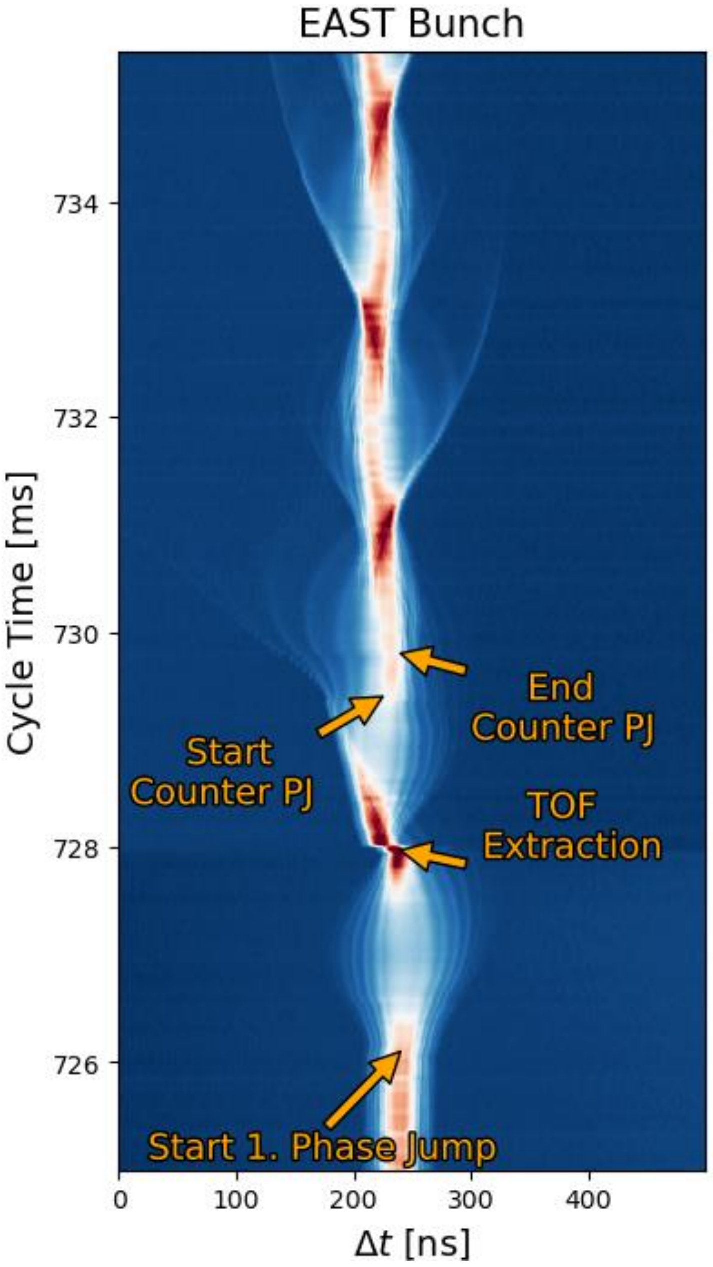
Over-shoot in a frequency span including synchrotron side-bands
Courtesy of M. Marchi

PS – Parasitic TOF with EAST

- **Motivation**
  - Deliver beam to two destinations with one cycle
  - Manipulation of TOF induces losses in EAST beam



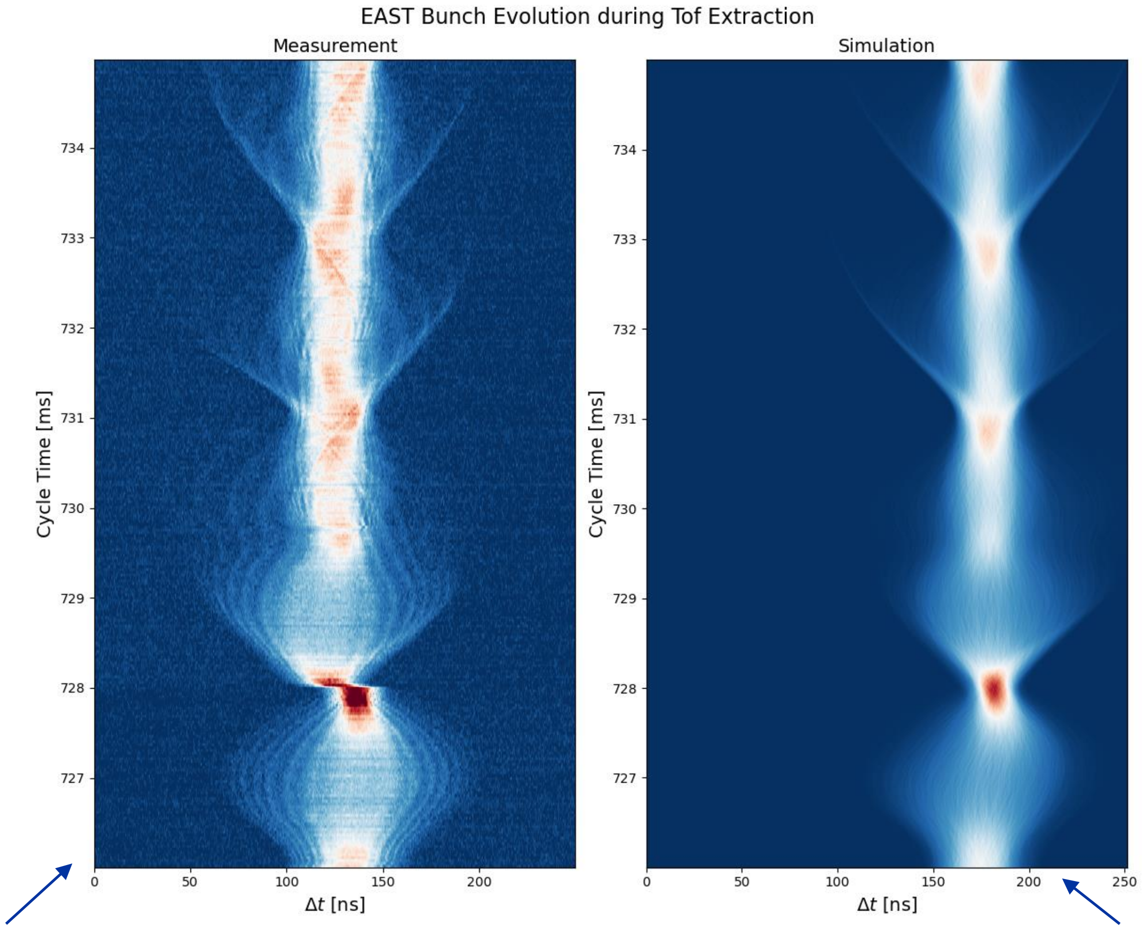




Courtesy of O. Naumenko

PS – Parasitic TOF with EAST

- **What is being modelled?**
  - New implementation of PS beam control
  - PS impedance model
- **Operational outcome**
  - Optimization in simulation
    - EAST losses decreased from 7% to 1.5%
  - Contributed to doubling of TOF intensity
    - 3.5 x 10^{12} p/b to 8.0 x 10^{12} p/b



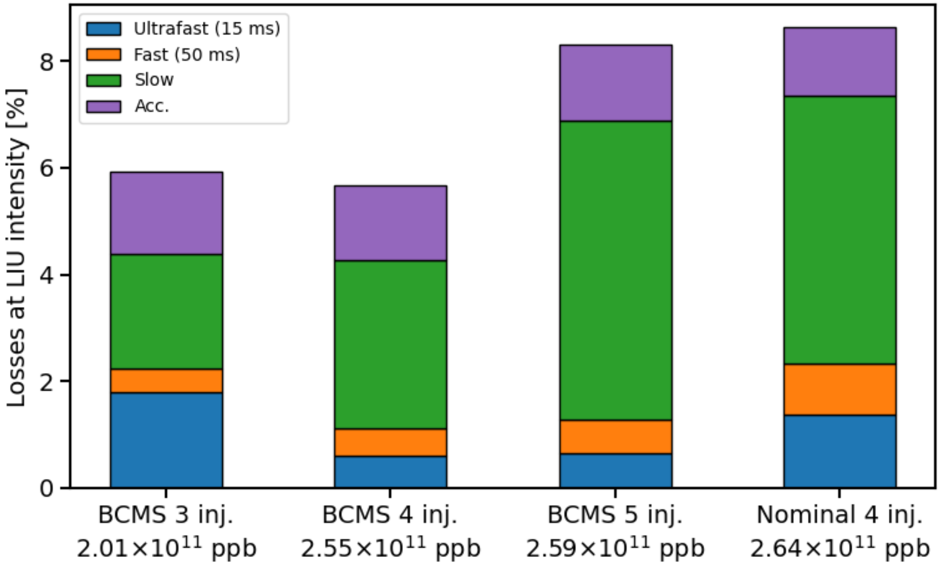
Measurement

Courtesy of O. Naumenko

Simulation

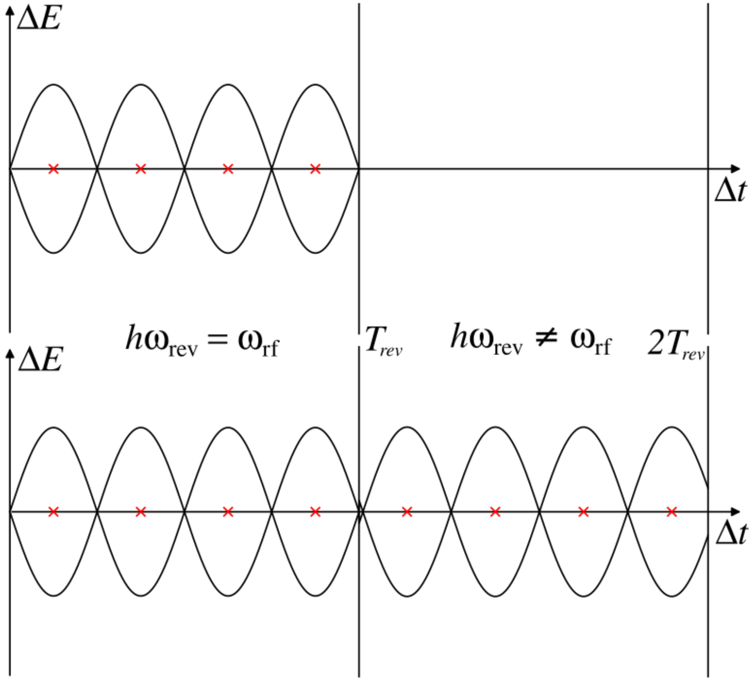
SPS – Capture of LHC-type LIU Beams

- **Motivation**
  - Help analyse and disentangle sources of beam losses at transfer
  - Coupling of beam and cavity control models in simulation
- **What is being modelled?**
  - Strong transient beam loading with LIU intensity
  - Complex dynamics during beam transfer
  - SPS impedance model



Measured losses with LIU intensities

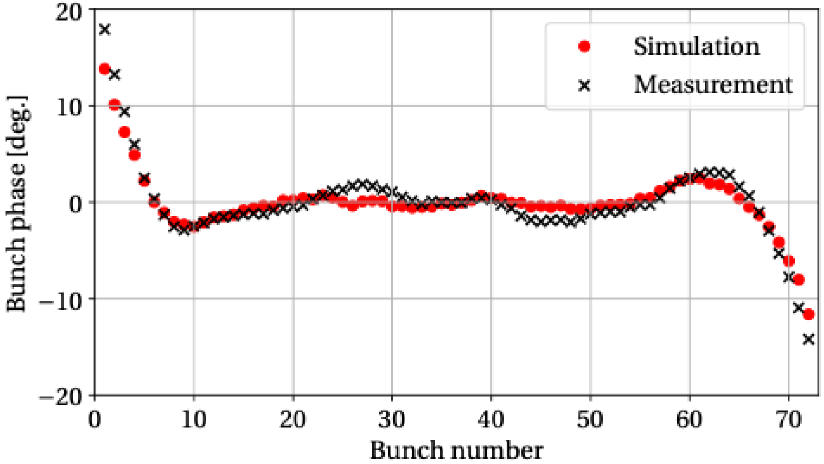
Courtesy of J. Flowerdew



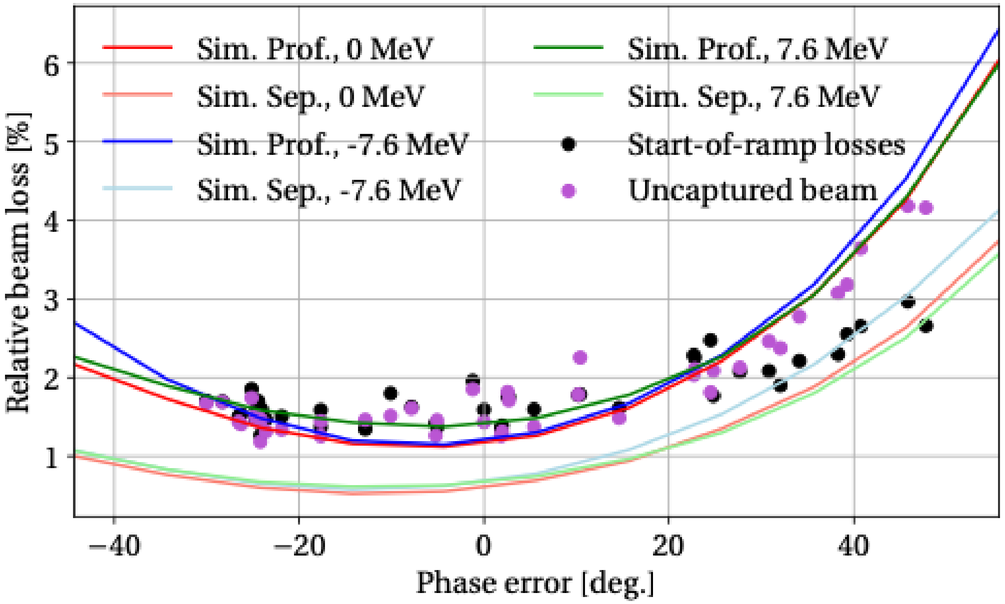
Coupling of beam and cavity models

SPS – Capture of LHC-type LIU Beams

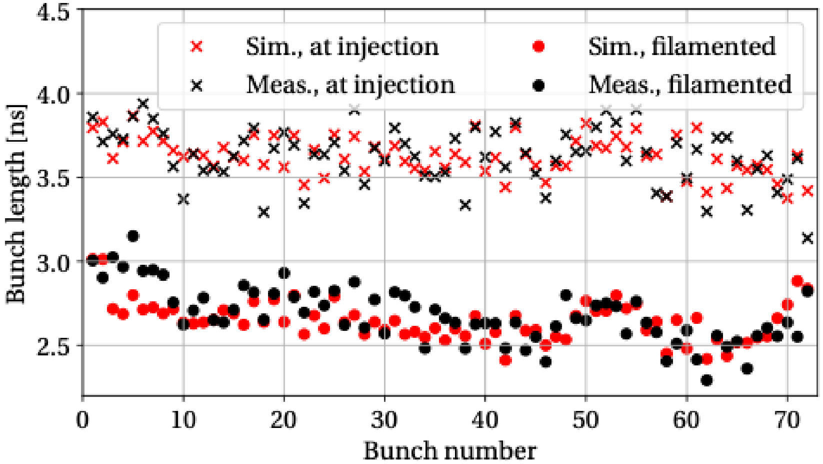
- **Outcome**
  - Benchmarked simulation model against measured beam parameters and beam losses
- **Next steps**
  - Apply the full model for PS-SPS transfer studies



Simulated and measured 200 MHz bunch phases after filamentation



Simulated (lines) and measured (dots) beam losses

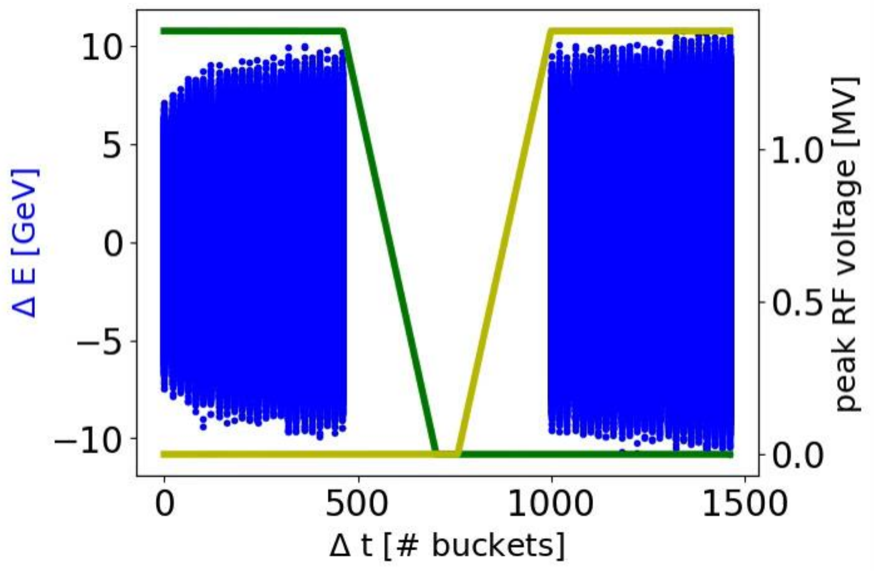


Simulated and measured bunch lengths at injection and after filamentation

SPS – Slip Stacking with Ions

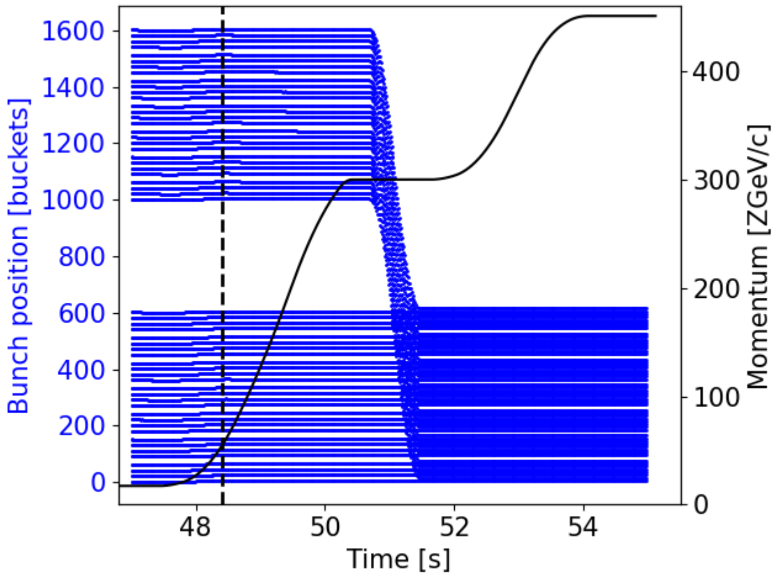
- **Motivation**
  - Complex RF manipulation to merge ion batches
  - Complicated orchestration of timings and functions

- **What was modelled?**
  - Two groups of cavities with different voltage and frequency programs
  - Beam phase and radial loop
  - SPS impedance model



Simulation of slip stacking of two ion bunch trains in the SPS

Courtesy of D. Quartullo

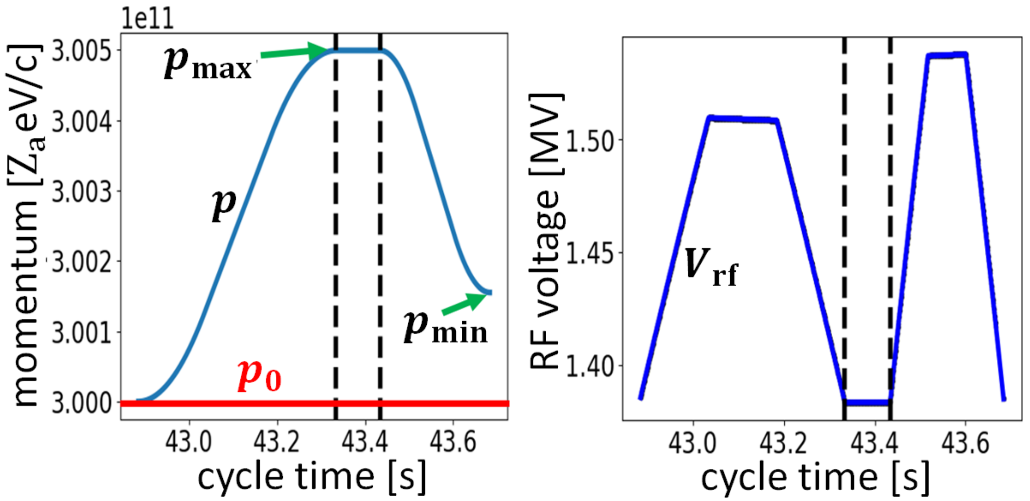


Position of the bunches through the cycle

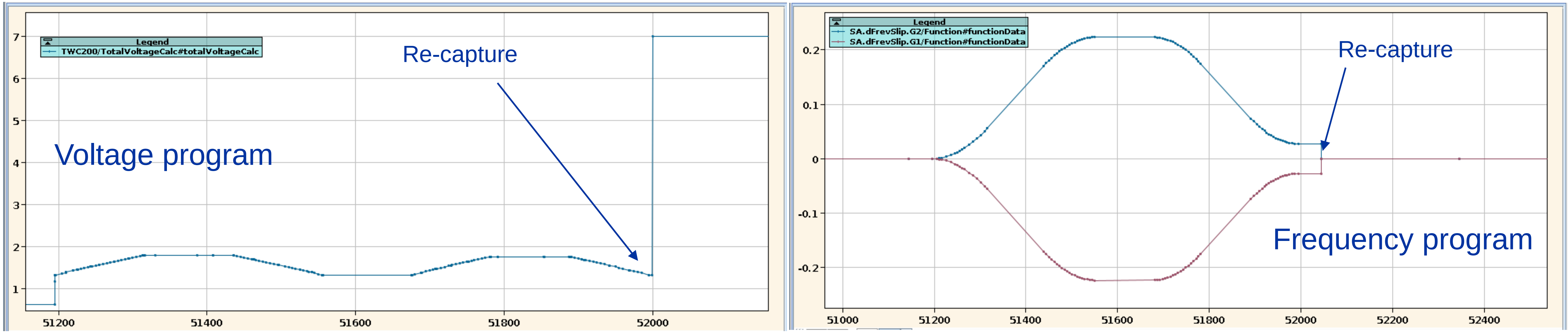
Courtesy of T. Argyropoulos

SPS – Slip Stacking with Ions

- **Operational outcome**
  - Voltage and frequency programs worked as predicted in simulation
  - Simulations/calculations integrated in operational expert application for use in the CCC
  - Importance of 800 MHz system for beam stability
  - Usual optimization required for the rest of the cycle



Simulated voltage and frequency programs
Courtesy of D. Quartullo



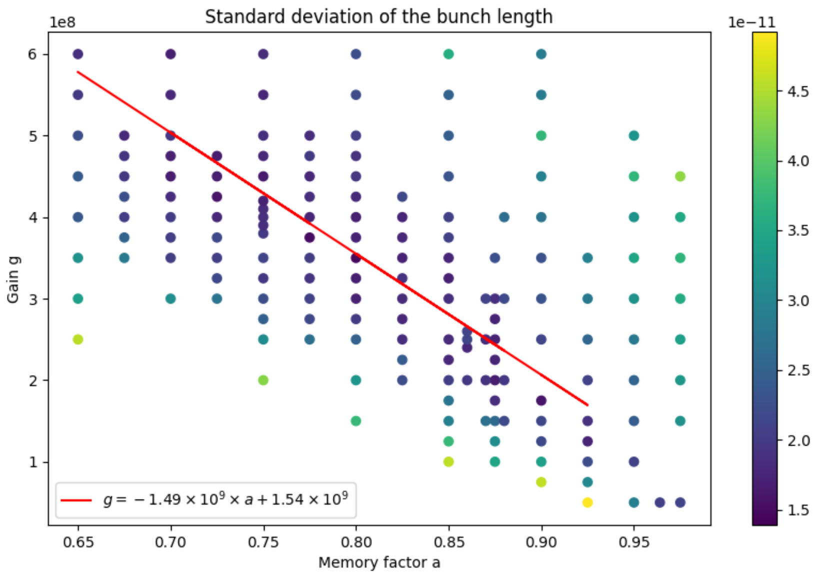
Operational voltage and frequency programs

LHC - Blow-up Optimization in the Ramp

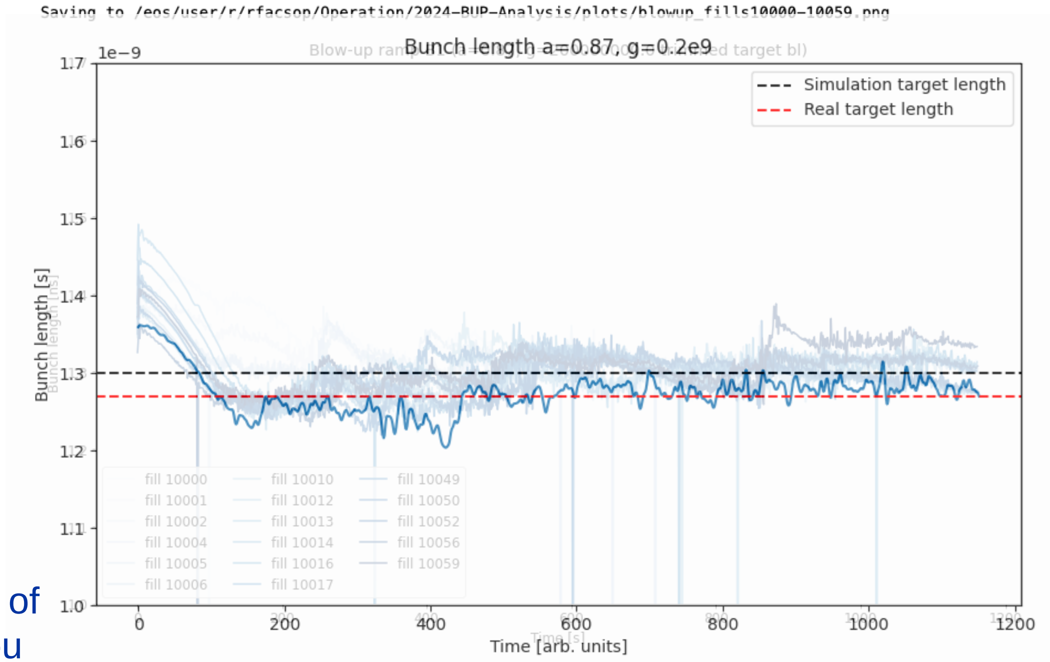
- **Motivation**
  - Heating issue due to short bunches
    - Avoid over and under shoots of the bunch length with better regulation
- **What was modelled?**
  - Bunch length feedback used to regulate the noise amplitude during the ramp

$$x_{n+1} = ax_n + g(\tau_{targ} - \tau_{meas})$$

  - LHC impedance model
- **Operational outcome (see talk by A. Calia)**
  - Significantly improved regulation of the bunch length
    - Better set of feedback parameters
    - Flat bunch length target is now being used during the ramp



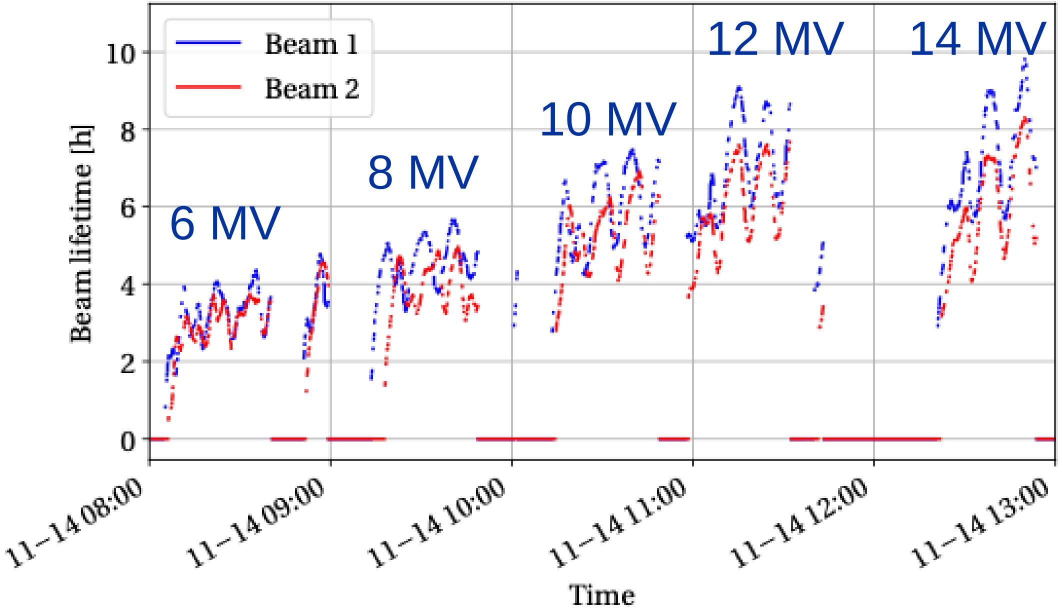
Courtesy of
N. Gallou



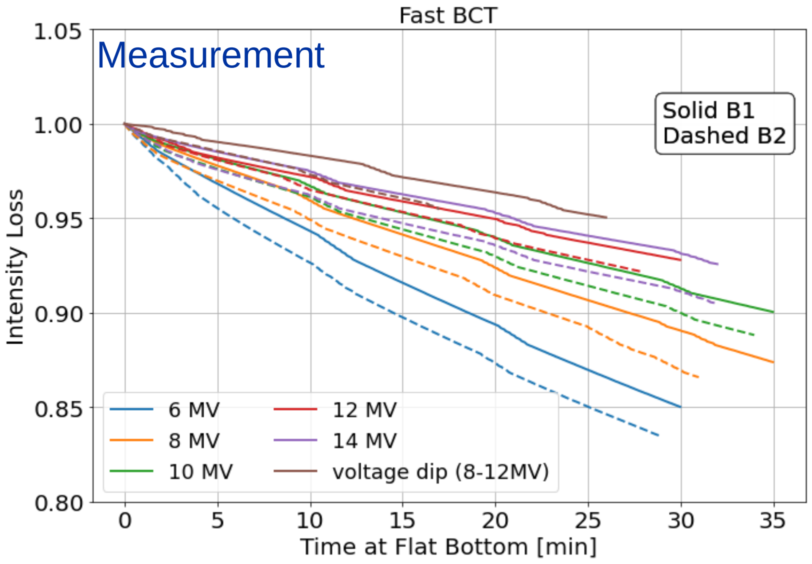
Courtesy of
N. Gallou

LHC – RF Optimization of Lifetime with Ions

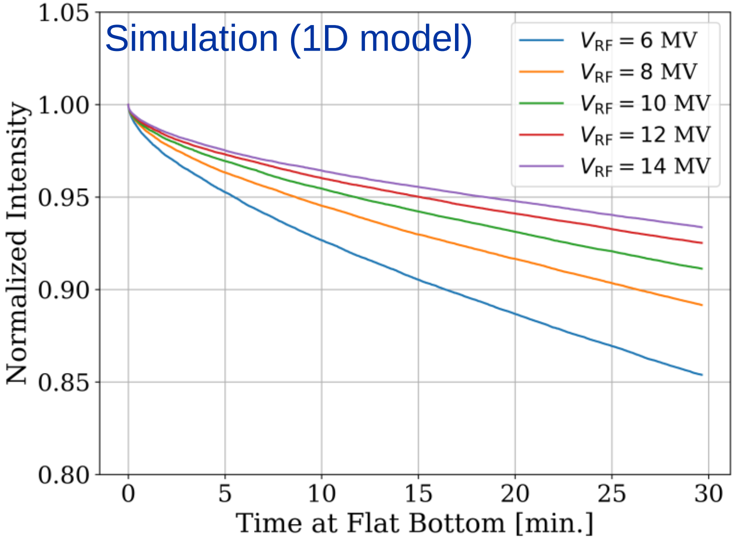
- **Motivation**
  - Significant beam losses at the start of the ramp with 8 MV
- **What is being simulated?**
  - Predicted using 3D intra-beam scattering (IBS) tracking model with non-Gaussian bunches
  - Confirmed also with 1D IBS model assuming Gaussian bunches
- **Operational outcome**
  - Reduction of start-of-ramp losses with ions
  - Improvement of beam lifetime with higher RF voltage



Lifetime improvement as a function of voltage from the Ion MD



Courtesy of N. Triantafyllou



Courtesy of M. Zampetakis

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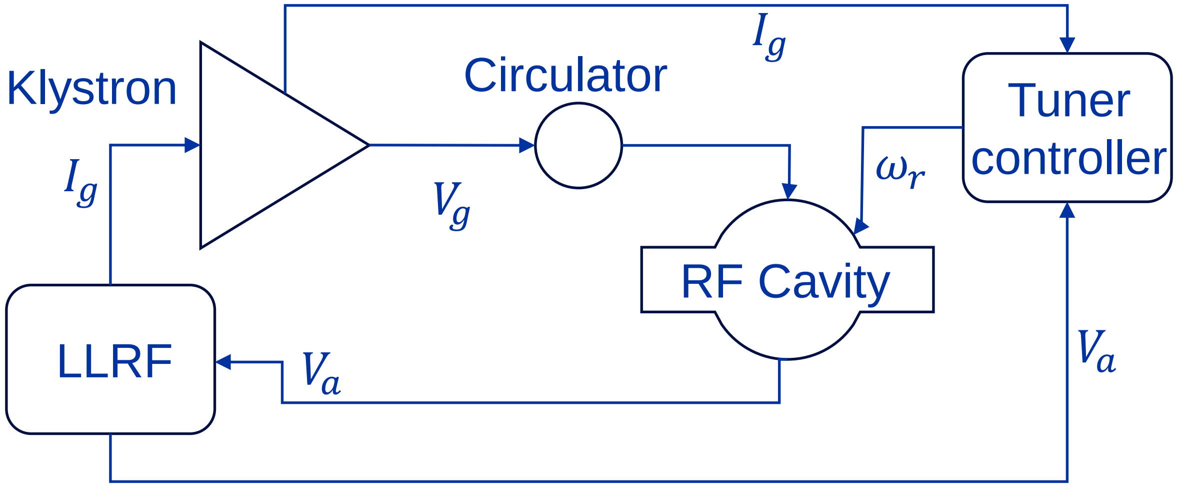
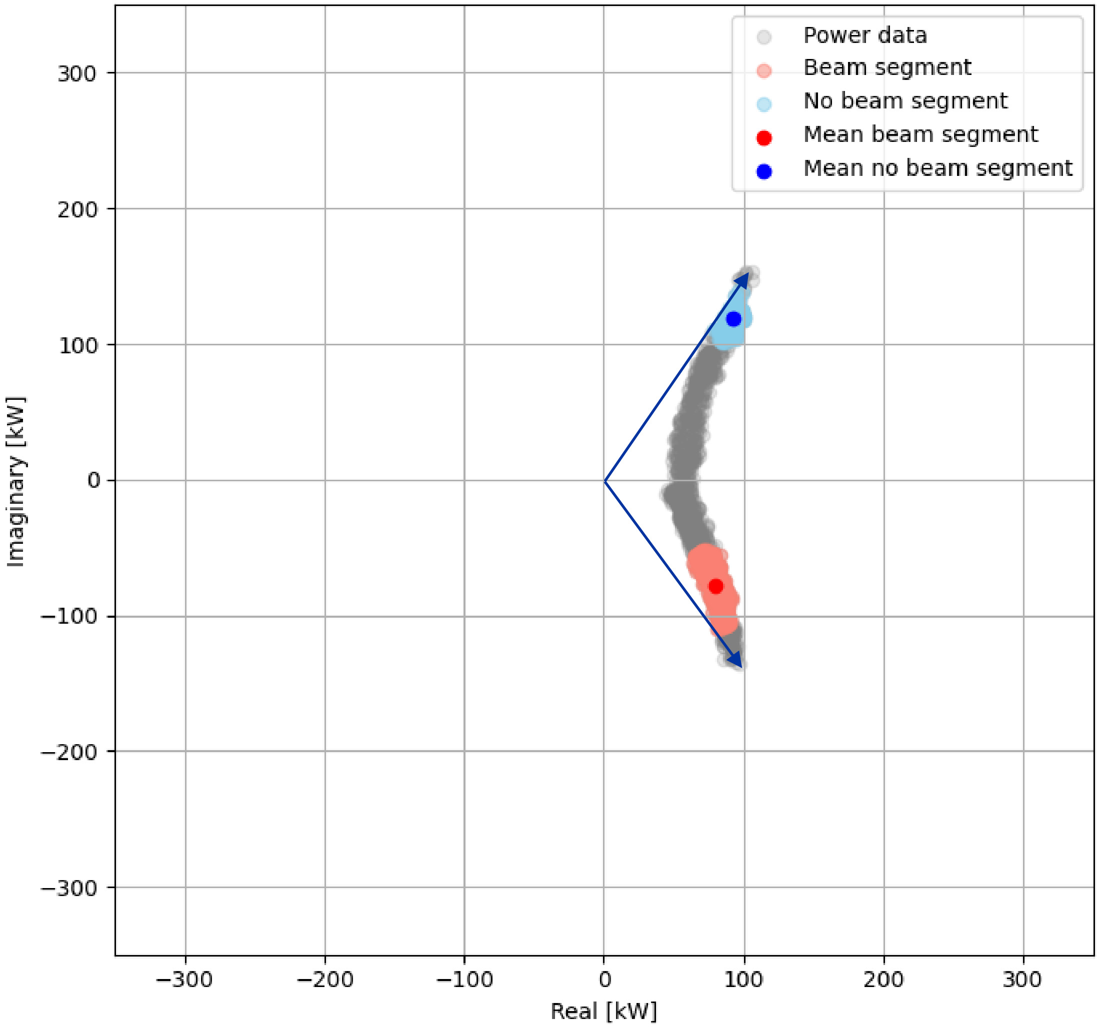
Model of half-detuning and cavity tuning in BLonD

- **Motivation**
  - Minimize RF power at injection and during flat-bottom
- **What is being modelled?**
  - Beam dynamics at injection including intensity effects
  - Regulation of beam and cavity control loops
  - Detuning of the RF cavities and the tuner controller

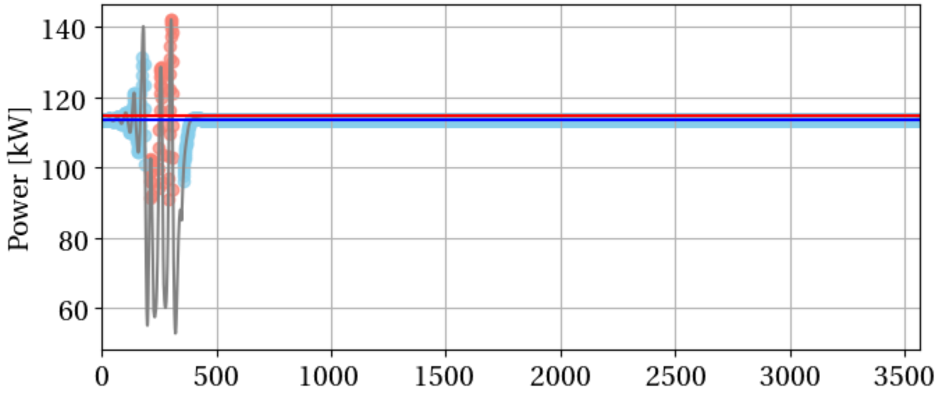




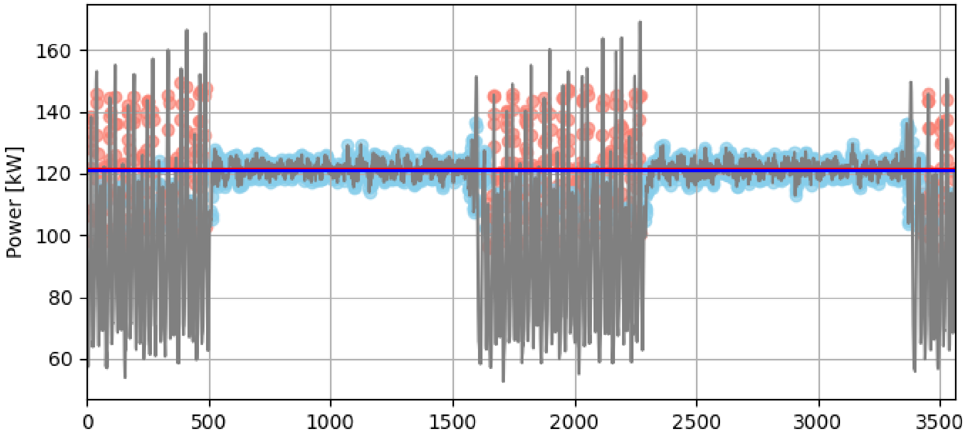
I- and Q-part of the RF power in half-detuning

Optimization of Half-detuning in the LHC

- **Half-detuning scheme**
  - Set up during commissioning with beam
  - Set up during high-intensity MDs
- **In the past**
  - Manually line-by-line
- **Algorithm to optimize half-detuning scheme**
  - Based on simulation model using of LHC cavity controller
  - Faster and more precise setting up of the scheme



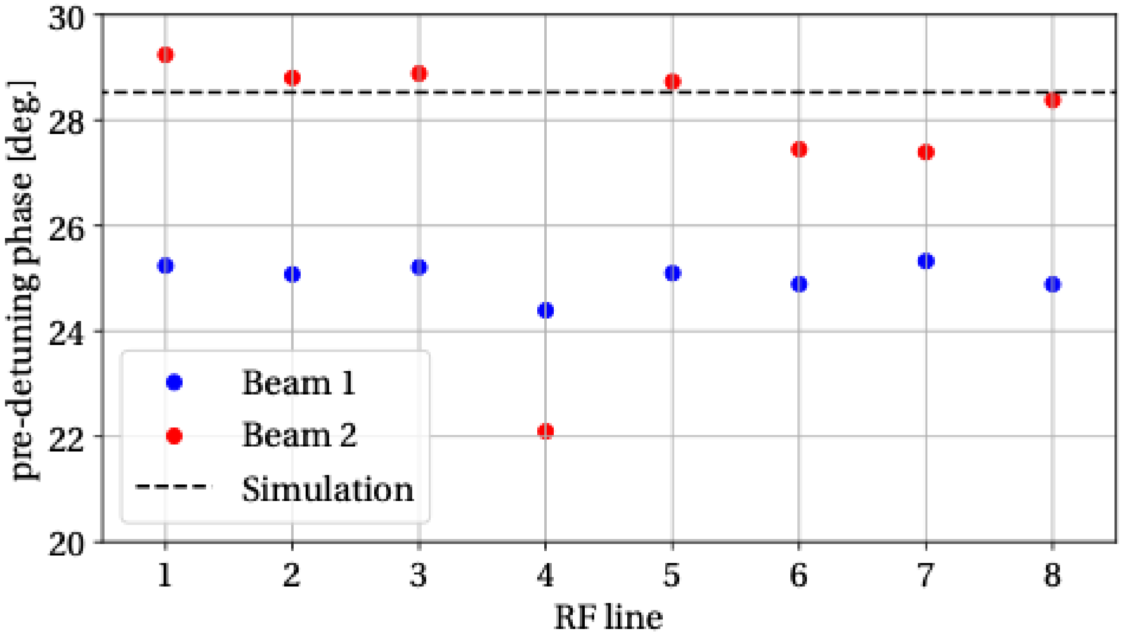
Algorithm applied on simulated data. Detected beam segment in red and no-beam segment in blue.



Algorithm applied to optimize a real LHC RF cavity. Detected beam segment in red and no-beam segment in blue.

LHC Pre-detuning Optimization

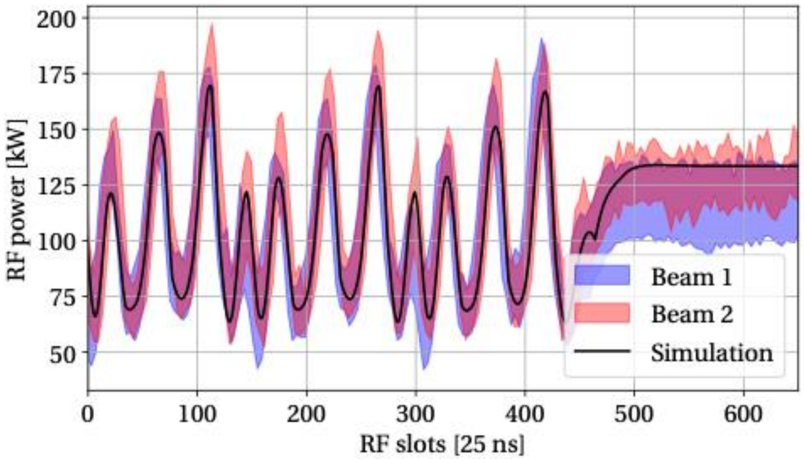
- **Last year**
  - Preliminary scan in pre-detuning scan was done
  - Simulations predicted a minimum in power
    - Greater understanding of the scheme
- **In 2024**
  - Operationally 25 deg. was used
  - Large operational scan in pre-detuning
  - Systematic difference between beams
    - Possibly due to difference in bunch length
  - Minimum found experimentally and validates the simulation model



Measured optimum pre-detuning setting from operational scan in 2024

Most recent projections for HL-LHC

- **Measured power has a large spread (±20%)**
  - Use cavity controller model to compute RF power
- **Results from high-intensity MDs in 2024**
  - With 2.0 x 10^{11} p/b with 2x48b batches
    - Confirmed required voltage found in 2023 (with 72b trains) for HL-LHC
    - Power at the limit of the present system
  - With 2.3 x 10^{11} p/b with 2x48b batches
    - Maximum voltage achieved during MD was 6.5 MV without one-turn delay feedback due to high beam loading as predicted in simulations
    - Unacceptable lifetime due to lack of RF power



Measured and simulated RF power with BCMS beams this year

Year	Intensity	SPS bunch length	SPS Voltage 200 MHz	SPS Voltage 800 MHz	LHC Voltage	LHC bunch length	Simulated peak power at optimum Q_L
2023	2.0 x 10^{11} p/b	1.55 ns	9.4 MV	1.69 MV	7 MV	1.20 ns	263 kW
2024	2.0 x 10^{11} p/b	1.50 ns	8.5 MV	1.45 MV	7 MV	1.11 ns	269 kW
2024	2.3 x 10^{11} p/b	1.60 ns	8.5 MV	1.53 MV	6.5 MV	1.19 ns	238 kW (with OTFB 283 kW)
HL-LHC	2.3 x 10^{11} p/b	1.65 ns	10 MV	2 MV	7.9 MV	1.25 ns	(320 ± 15) kW

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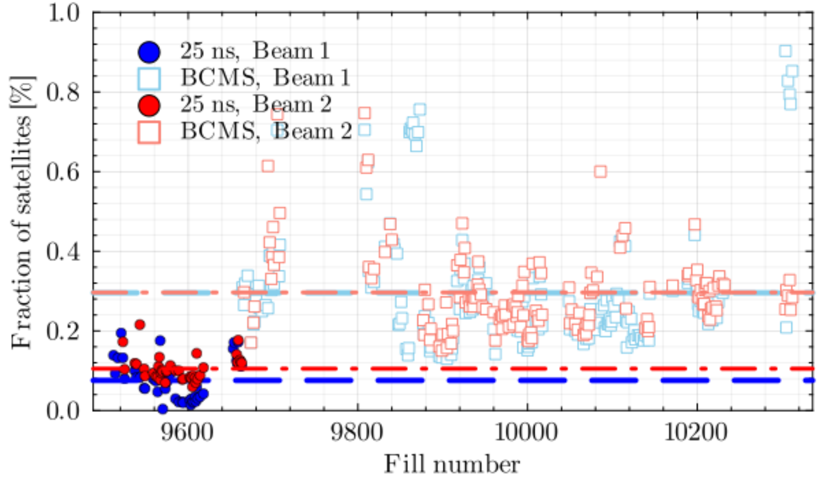
Bunch Length during Flat Bottom in the LHC

- **Batch Compression Merging Splitting (BCMS)**
  - More complex RF manipulation in the PS
    - Generation of more satellites at LHC flat top
  - Higher brightness than the standard beam
  - Identical longitudinally at injection in the LHC

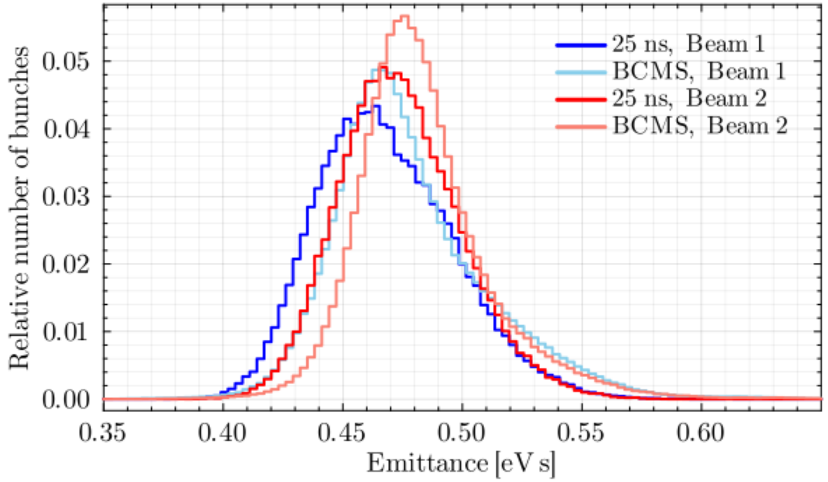
Relative difference in average bunch parameters with BCMS compared with standard 25ns beam after filamentation,
see talk by S. Kostoglou

Beam	Bunch length	Bunch intensity	Horizontal emittance	Vertical emittance
Beam 1	-4%	2%	-24%	-20%
Beam 2	-2%	2%	-25%	-23%

1%-limit for experiments



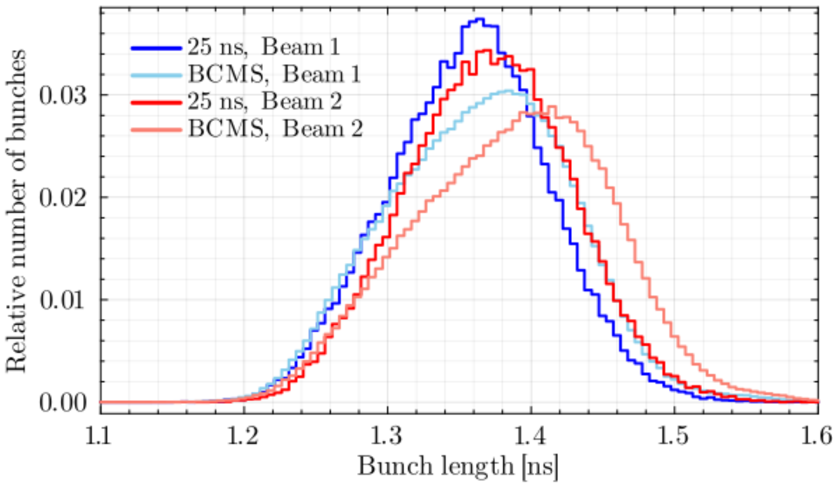
Increase in satellites at flat top with BCMS



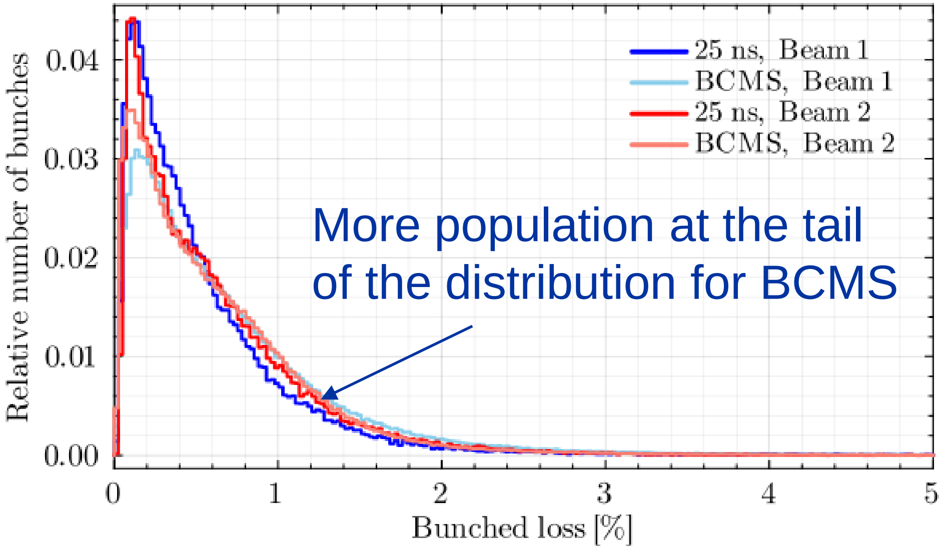
Longitudinal emittance from injectors is the same

BCMS and Standard Beam at the Start of the Ramp

- **Large increase in start-of-ramp losses when switching to BCMS**
  - Increase RF voltage from 5 MV to 5.5 MV
- **Yet at the start of the ramp**
  - The BCMS beam is longer, even with larger voltage
  - More protons lost out of the bucket



Bunch length at the start of the ramp

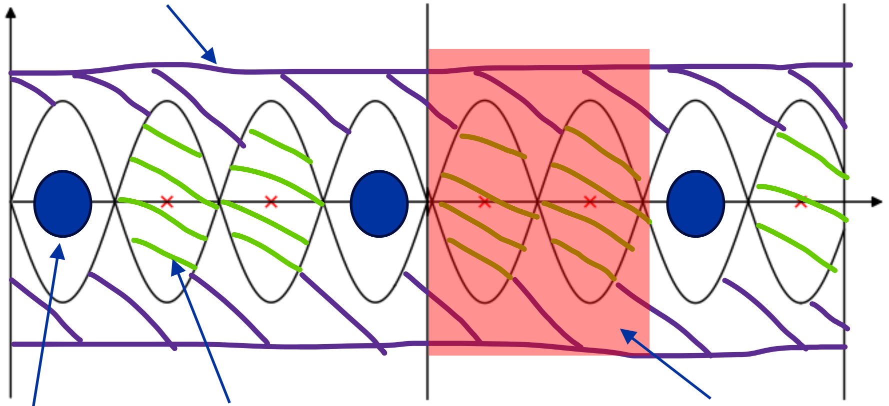


More population at the tail of the distribution for BCMS

Distribution of bunch intensity loss at the start of the ramp

Off-position Beam Analysis

- **Off-position beam**
  - Combination of DC BCT and FBCT measurements
- **Analysis for this year**
  - More off-position beam is off-momentum this year
    - Losses driven by uncaptured beam, IBS and RF background noise
- **Conclusion:**
  - More losses driven by IBS due to higher brightness with BCMS
    - supported by preliminary IBS simulations (20% increase in losses after 20 minutes)
  - Based on 2024 we need 10% more voltage with BCMS

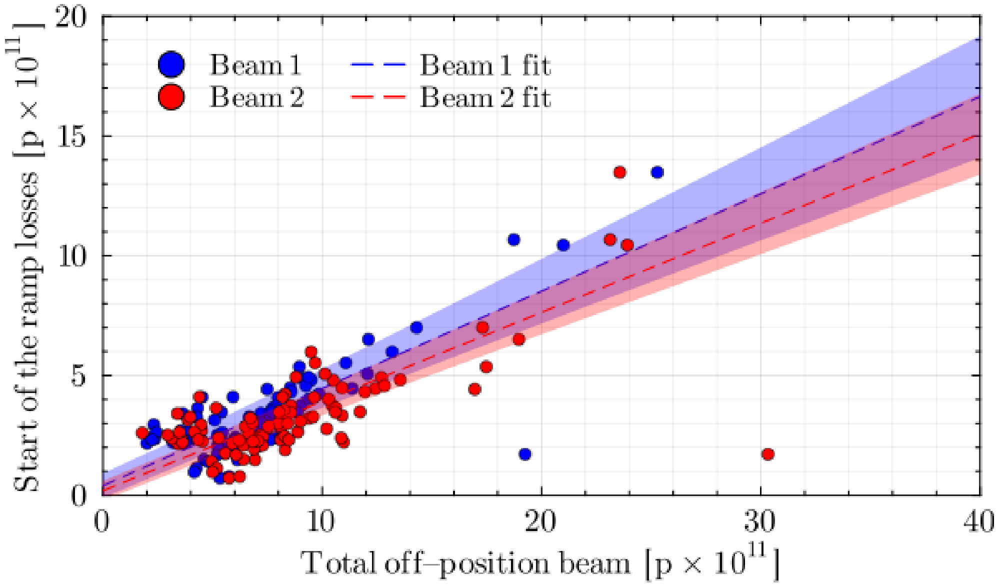


Off-momentum

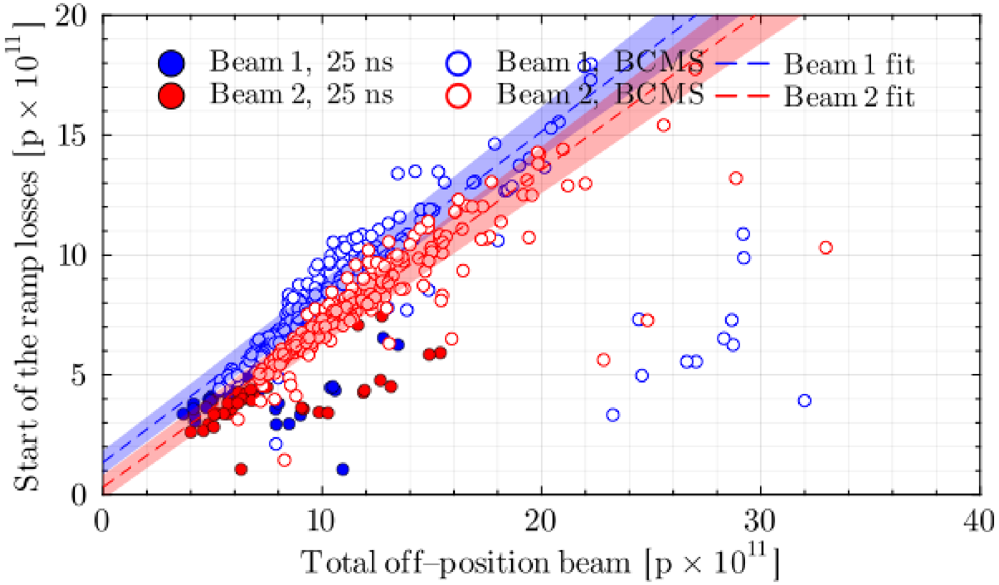
Satellites or ghosts

Off-position beam

Bunches



Fills in 2023



Fills in 2024

Summary of Key Points

- **Complex models of RF systems with high prediction accuracy**
  - Applied to large verity of scenarios across the complex
  - Simulations give experience which be applied in operation
  - Use beam dynamics models already at the design stage of control loops to give specifications for parameters?
- **LHC MD with 2.3 x 10^{11} p/b confirmed the projections for HL-LHC RF power demand**
  - Implement OP tools for pre-detuning and half-detuning
  - By how much will BLM thresholds be increased and how will this affect us? See talk by S. Morales
  - How does the bandwidth of the high-efficiency klystrons affect the projections?
- **Due to the higher brightness, the BCMS beam is harder to retain with the RF system at flat bottom**
  - Retain BCMS for HL-LHC? See also talk by S. Kostoglou
    - Will be addressed in discussion session

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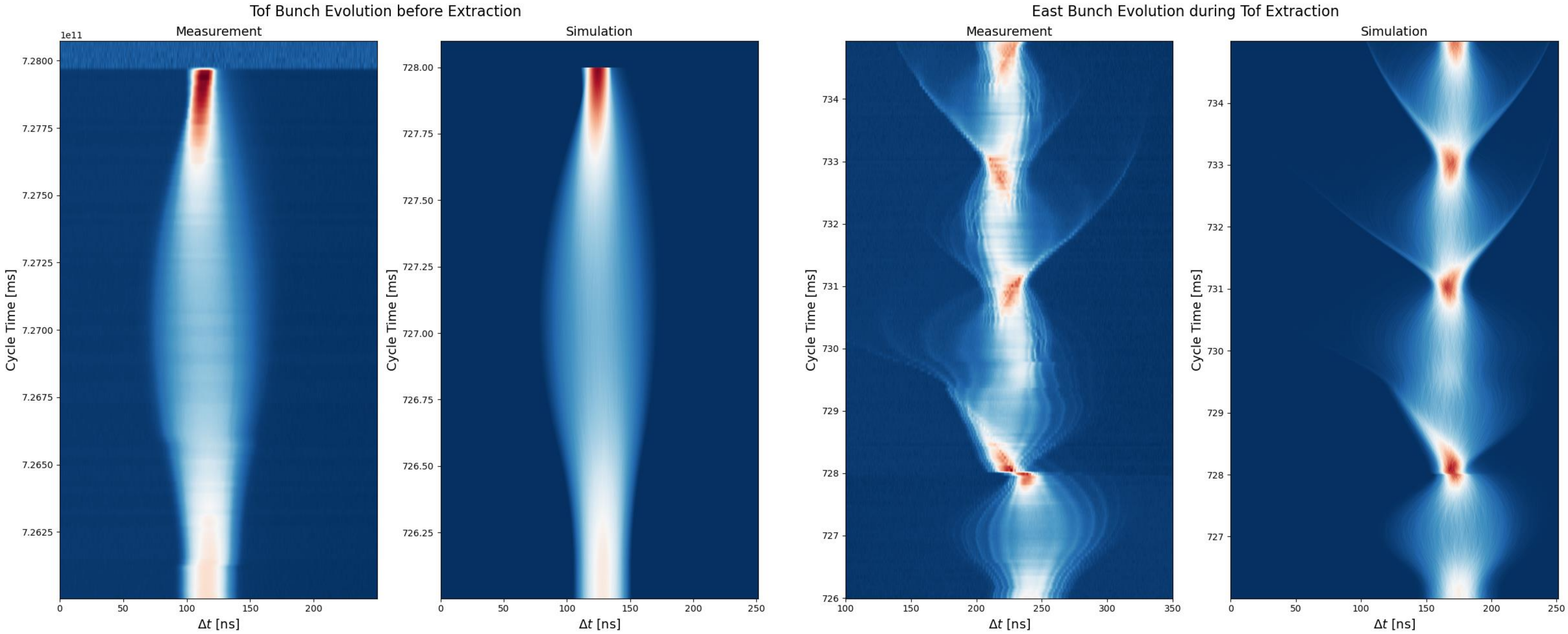
PS – Parasitic TOF with EAST

BLonD Simulations: Use new H8H16 beam feedback control model, PS Impedance Model



Model of half-detuning and cavity tuning in BLonD

Antenna voltage for a superconducting standing-wave RF cavity (slot-by-slot)

$$V_a^{(n)} = \left({}^{R}\!/_{Q}\right) \omega_{rf} T_s I_g^{(n-1)} + \left(1 - \frac{\omega_{rf} T_s}{2 Q_L} + i \Delta\omega T_s\right) V_a^{(n-1)} - \frac{1}{2} \left({}^{R}\!/_{Q}\right) \omega_{rf} T_s I_b^{(n-1)}$$

LLRF controls and amplifier

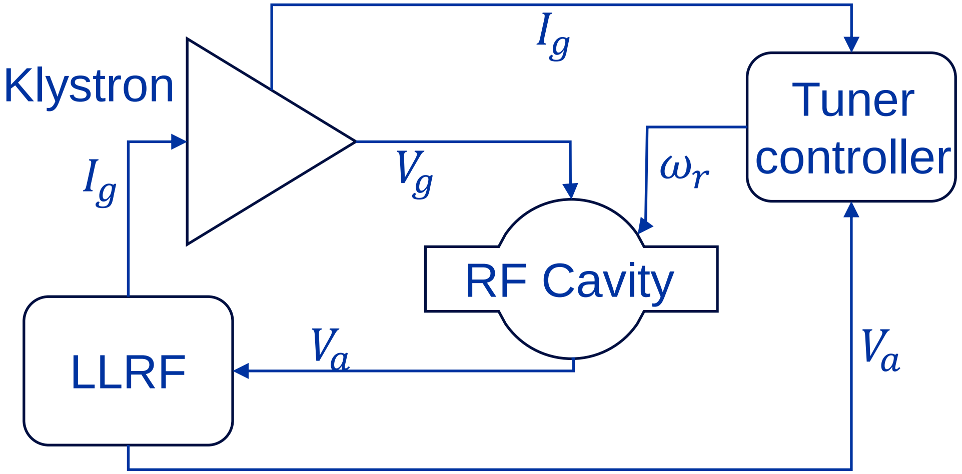
RF cavity

Beam

Cavity tuner feedback for half-detuning (turn-by-turn)

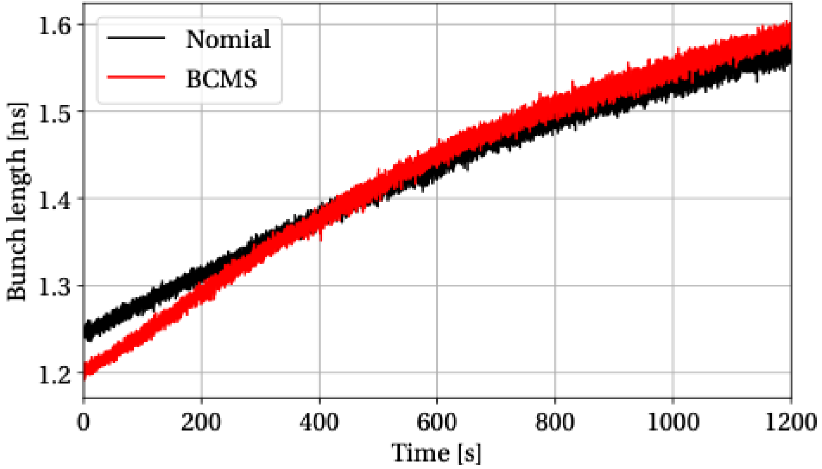
$$\left(\frac{\Delta\omega}{\omega_r}\right)_{n+1} = \left(\frac{\Delta\omega}{\omega_r}\right)_n - \frac{\mu}{2} \frac{\Im\{I_g V_a^*\}_{max} + \Im\{I_g V_a^*\}_{min}}{|V_a|^2}$$

I/Q-plot of detuning

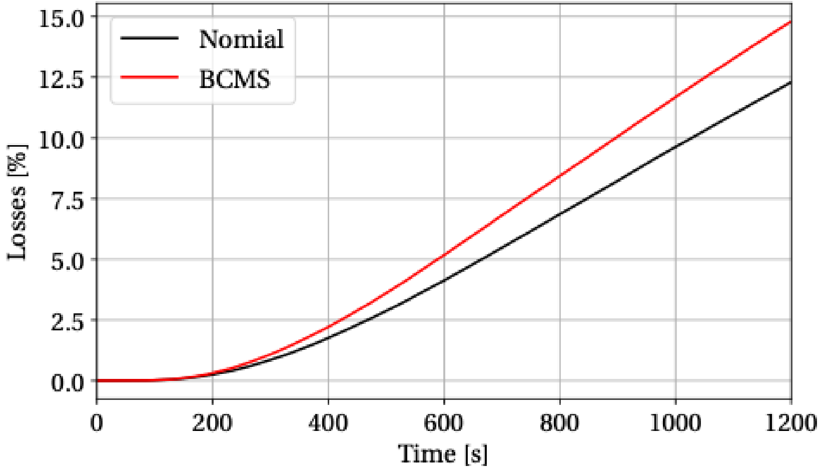


BCMS and Standard Beams in Simulations

- **From simulation**
  - After 20 minutes:
    - BCMS and STD have the same length
    - BCMS has 20% more losses than STD
  - Higher brightness give longer bunches and more debunched beam
- **NB! BLonD model assumes gaussian bunches**



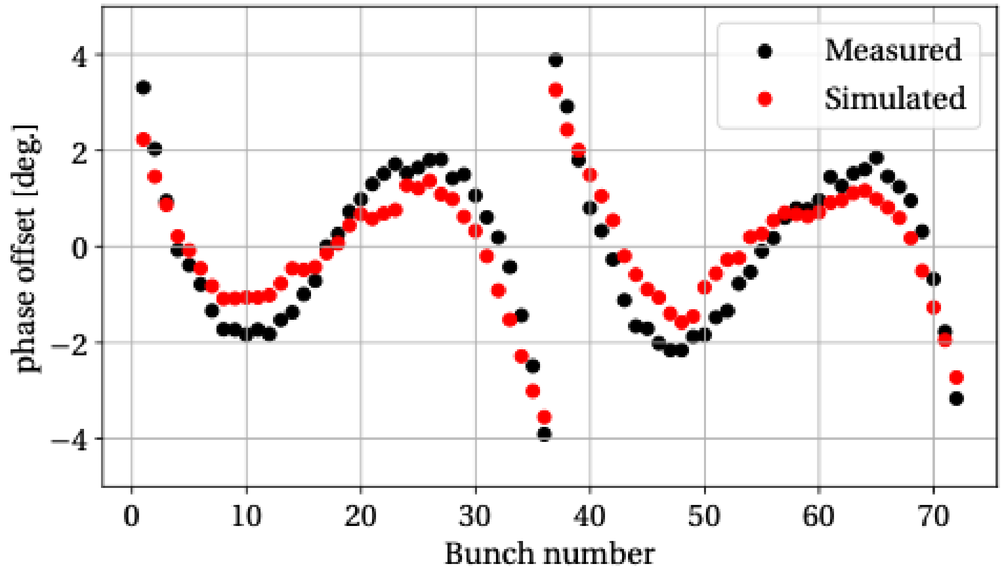
FWHM bunch length evolution



Relative losses out of the bucket

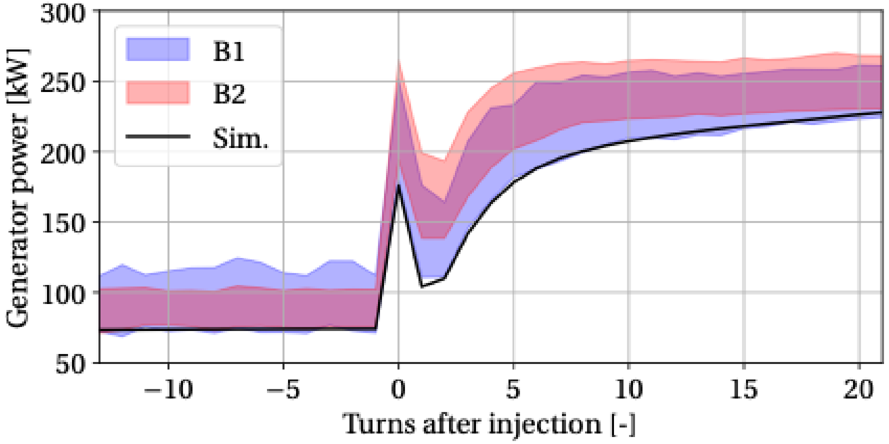
Power Limitations at Injection into the LHC

SPS beam distributions



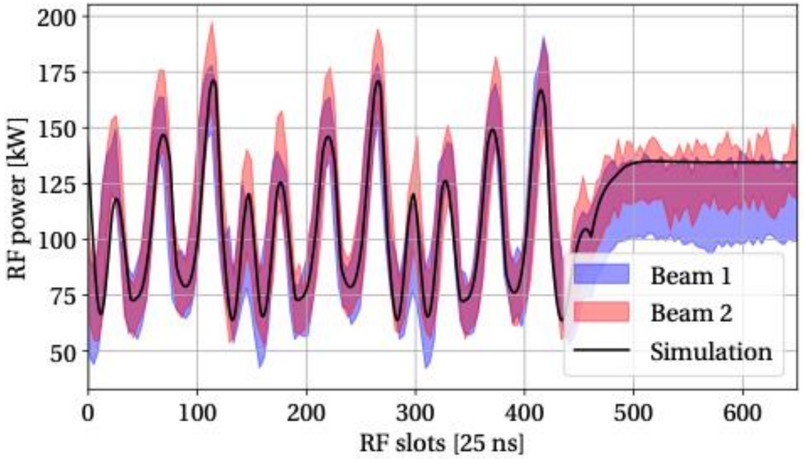
Measured and simulated bunch phase of the 72-bunch BCMS train in 2024

Injection transients



Example simulated injection transient in the LHC

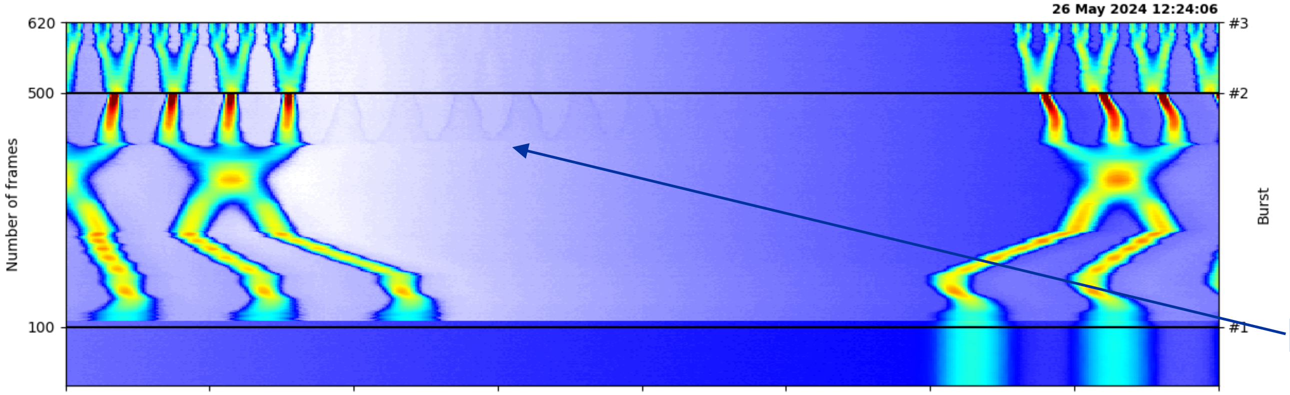
Steady-state power and cavity tuning



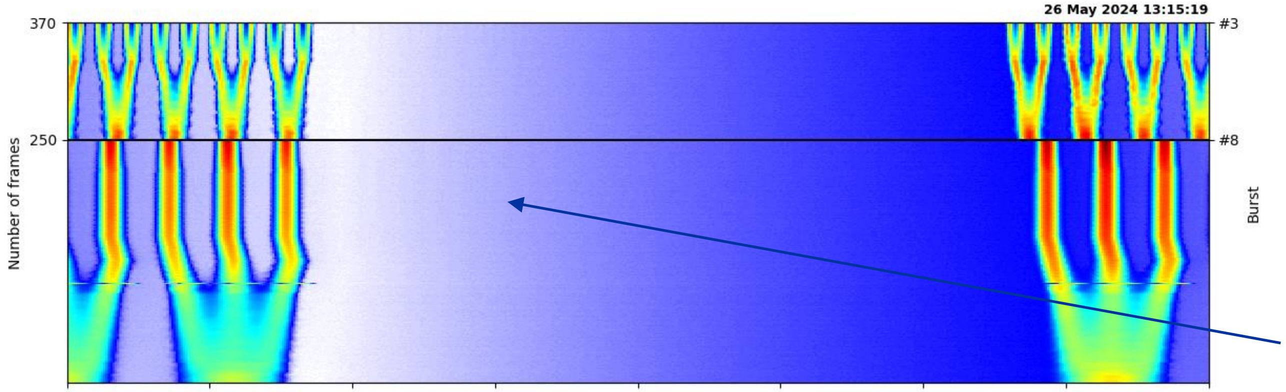
Example steady-state RF power slot-by-slot in the LHC

Ghosts and Satellites at the Flattop in the LHC

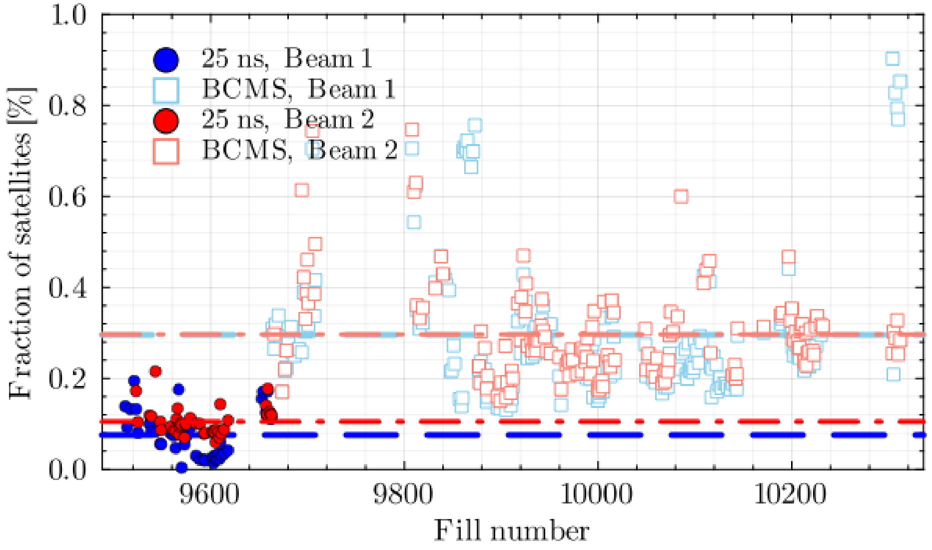
- **BSRL show a clear step when switching beam types**
- **In the PS the extra merging generate tails which one cannot get rid off**



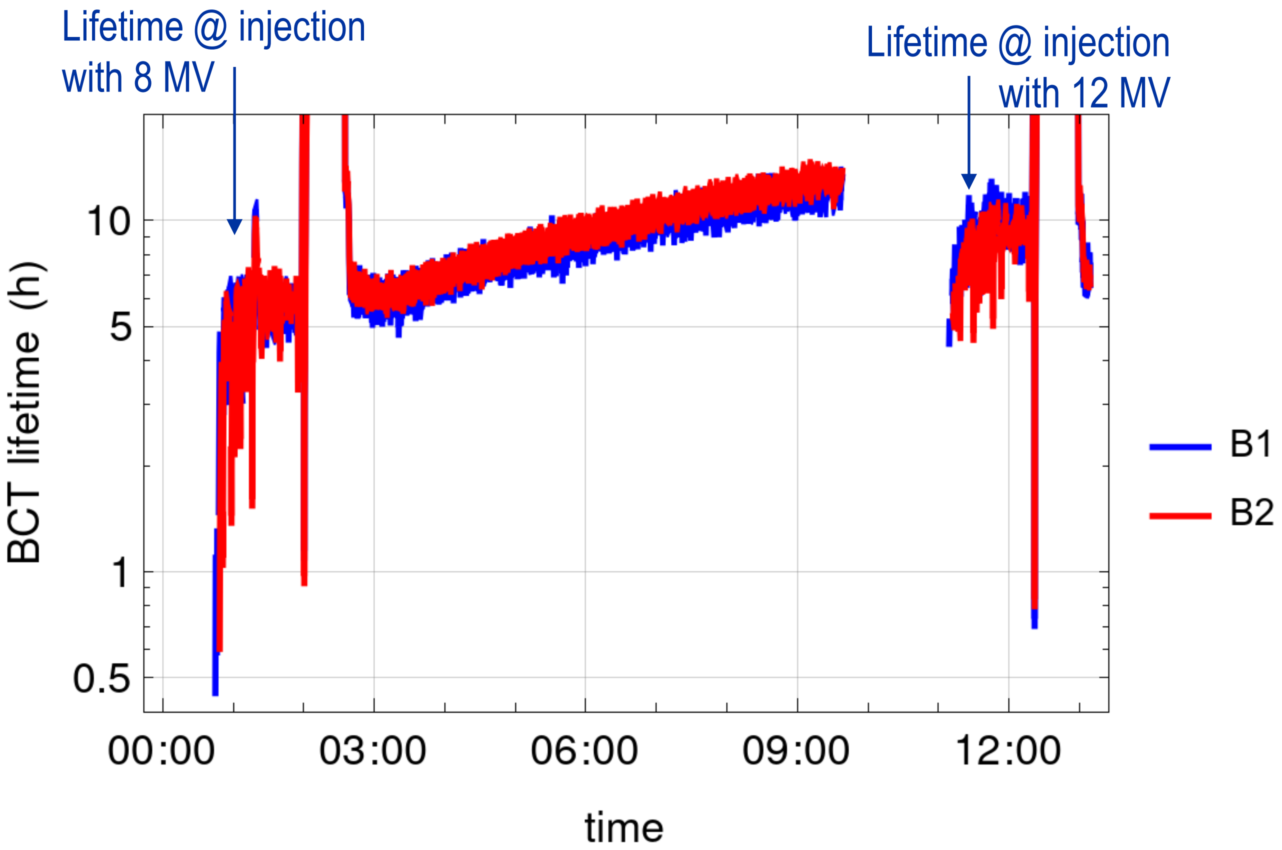
Before



After



Lifetime at injection for different RF voltages



Courtesy of R. Bruce