Recent Improvements to SPS spill quality

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Outline

- ➔ Introduction on spill quality in the SPS
- ➔ Work towards improved spill macro structure
- ➔ Investigation and analysis of spill frequency content
- ➔ Operational implementation
- ➔ Future studies and conclusions

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Introduction

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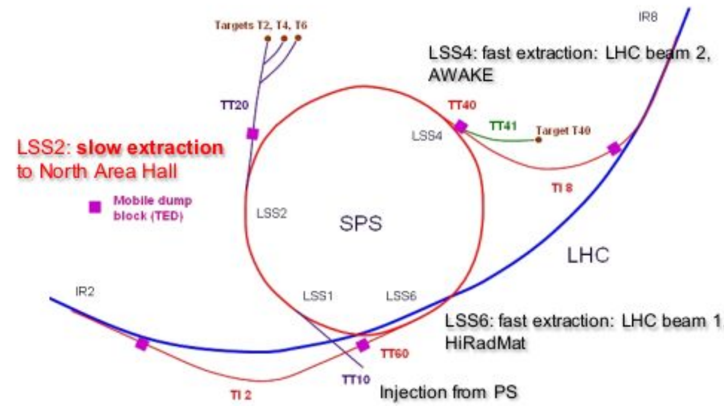
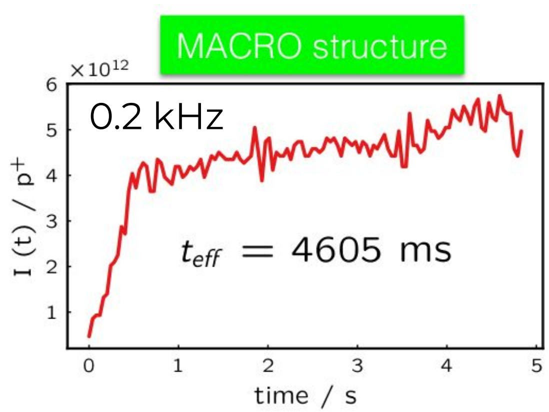
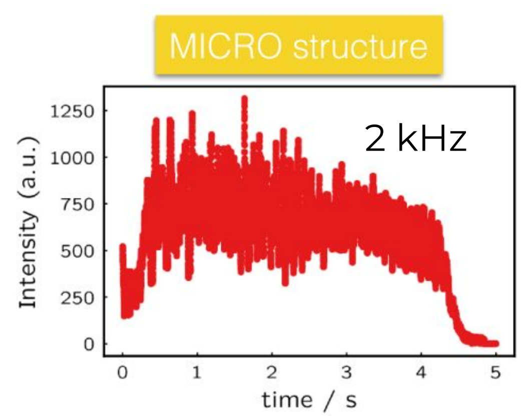
  - Spill macro structure variations (very low frequency)
  - Spill high frequency harmonic content







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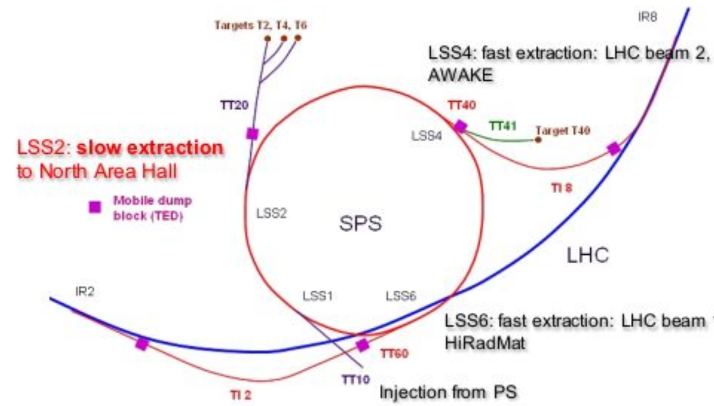
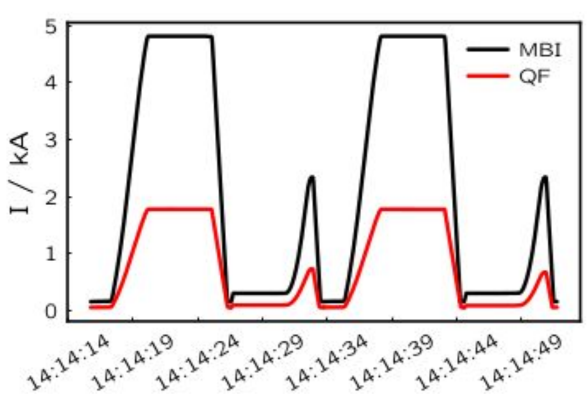
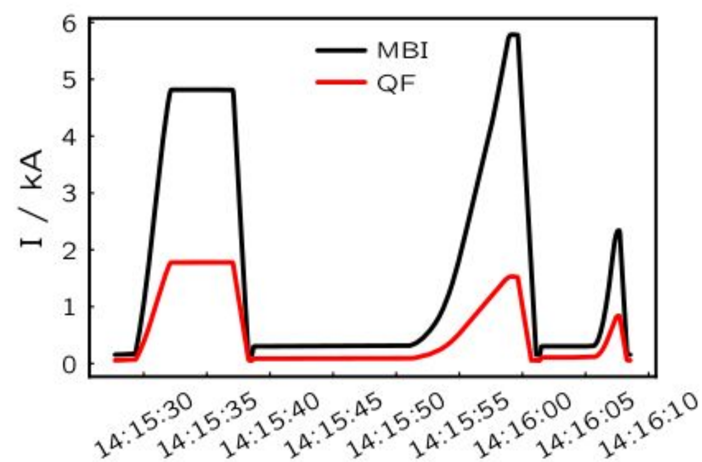
- ➔ The macro structure is dependent on the machine reproducibility and transverse and longitudinal beam parameters stability







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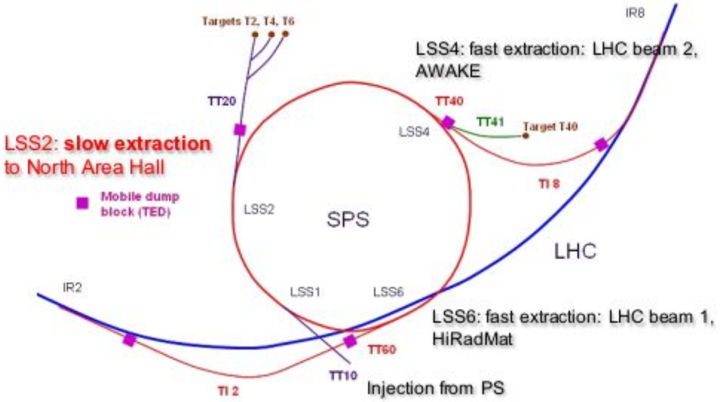
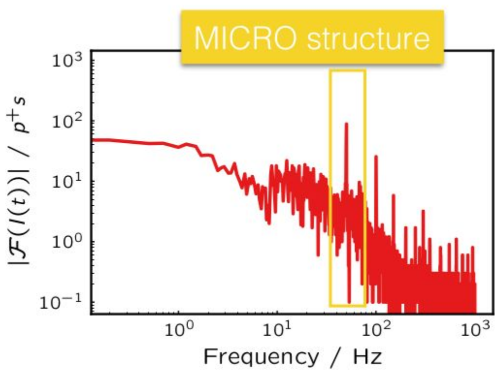
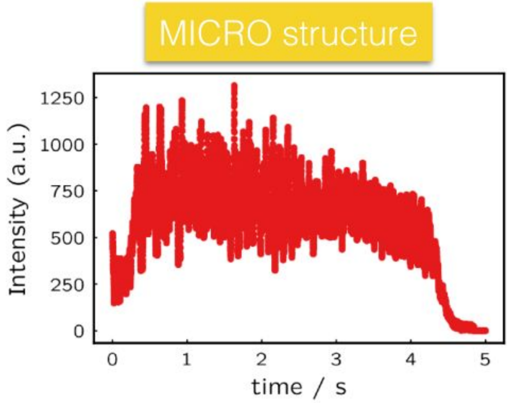
  - ◆ Spill macro structure variations (very low frequency)
  - ◆ Spill high frequency harmonic content
- ➔ The macro structure is dependent on the machine reproducibility and transverse and longitudinal beam parameters stability
- ➔ The HF harmonic content is a reflection of the noise from the main converters and any longitudinal modulation







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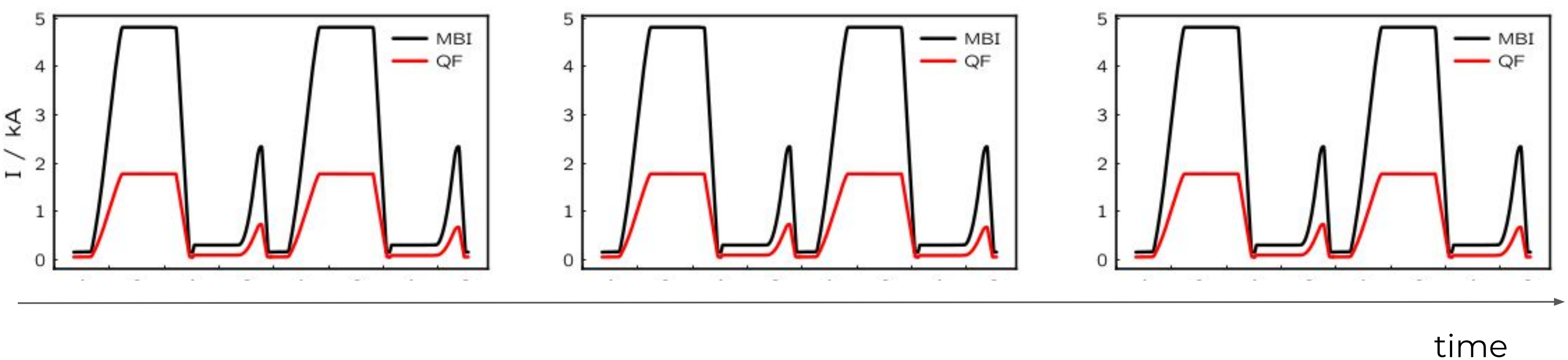
Work towards improved spill macro structure

➔ Main contributor to spill macro structure non-reproducibility was identified to be the change of super cycles

Super cycle 1 | Super cycle 2 | Super cycle 3



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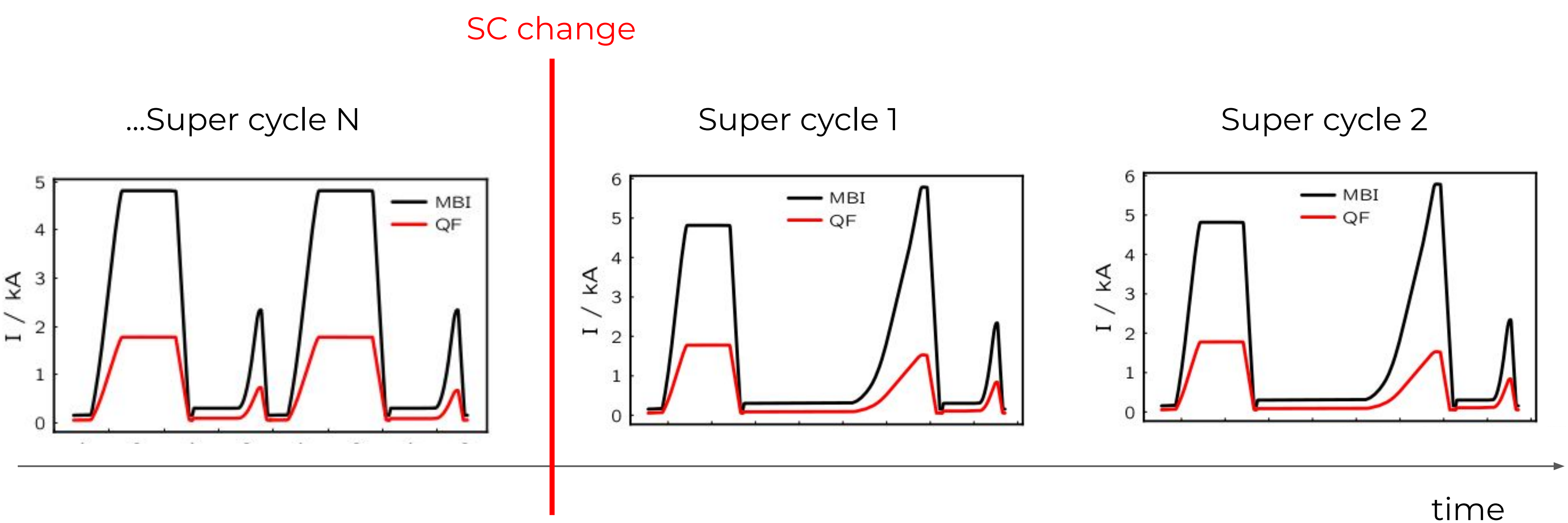
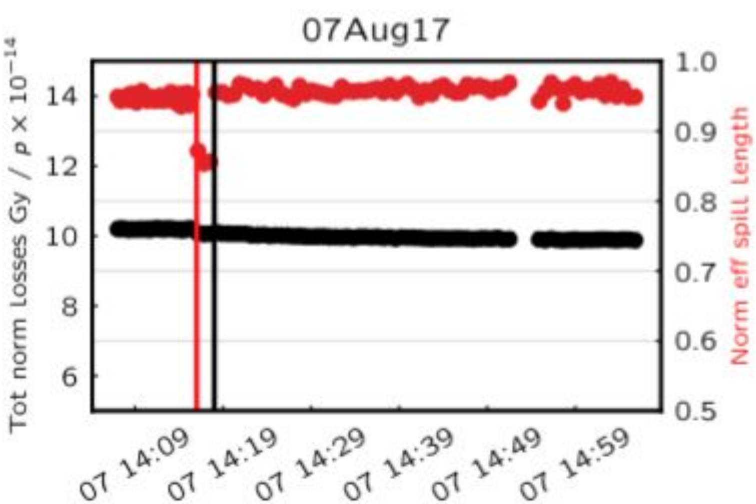
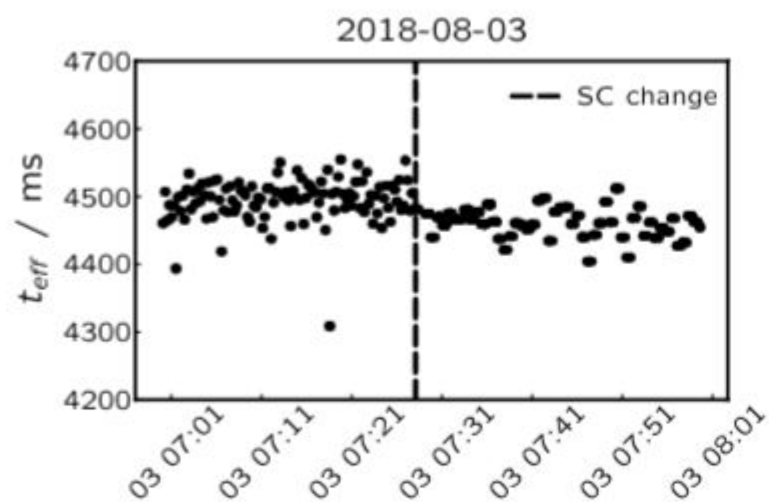


Work towards improved spill macro structure

- ➔ Main contributor to spill macro structure non-reproducibility was identified to be the change of super cycles
- ➔ We lose about 5 to 10% spill duty factor (DF) if nothing is done
- ➔ From beam-based measurements (see next slides), a systematic behaviour was observed - we can apply a systematic correction
- ➔ $\nu_x(t_{after}) = \nu_x(t_{before}) - 0.005$
- ➔ DF comes back to what was before the change!
- ➔ This has show to be very effective in 2017/8





Work towards improved spill macro structure

➔ Dedicated measurements campaign before LS2

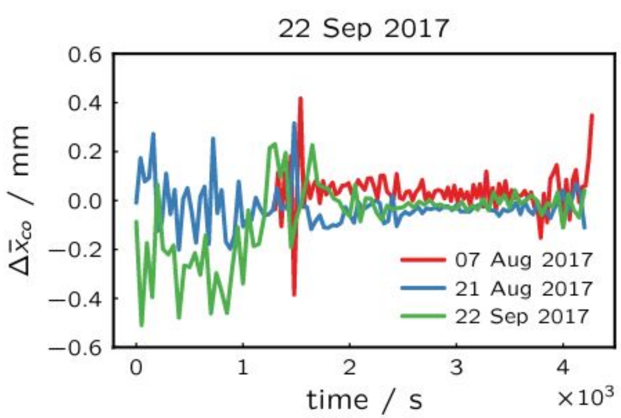
➔ Investigation looking at orbit and tune after SC change:

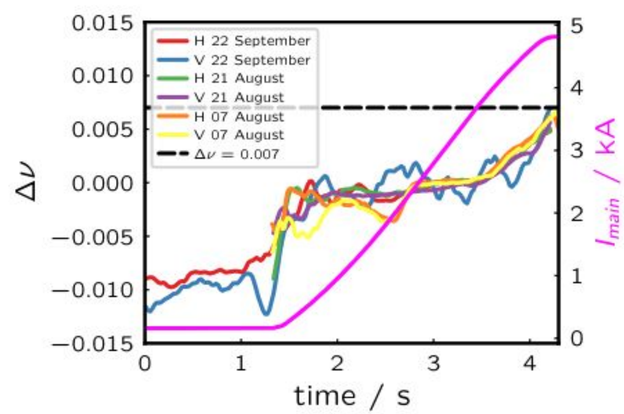
- Btrain not calibrated (no field marker), hence no info about remanent field at flat bottom
- Radial loop kicks in at start ramp

➔ Essentially no change in mean position (100 um = 2.3e-5 in Δp/p this is in the order of the SPS stability) after flat bottom

➔ Tune variation ($\Delta\nu = \nu_{productio} - \nu_{LHC\ fill}$), instead, were systematically observed in every measurement and with the same amplitude (in both planes!)

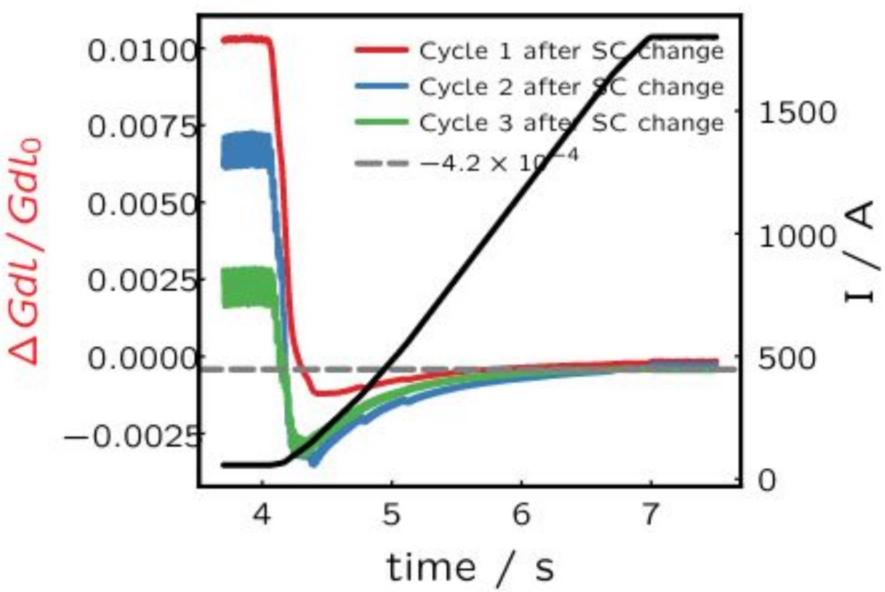
➔ Interestingly, the variation observed in both planes had the same amplitude and the same sign too

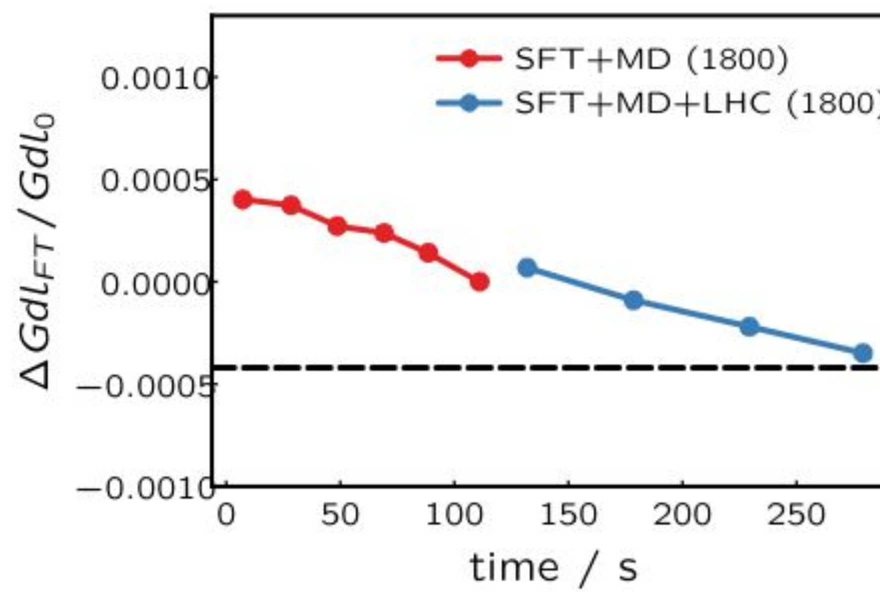




Work towards improved spill macro structure

- ➔ Magnetic measurements on SPS spare quadrupole showed significant hysteresis - at least in terms of what can cause the spill degradation
- ➔ We looked at the relative change of the integrated quadrupole strength: $$\frac{Gdl - Gdl_0}{Gdl_0} \equiv \frac{\Delta Gdl}{Gdl_0}$$
- ➔ Doing this, we measured a difference of $\frac{\Delta Gdl}{Gdl_0} = -4.2 \times 10^{-4}$ for a super cycle change





Work towards improved spill macro structure

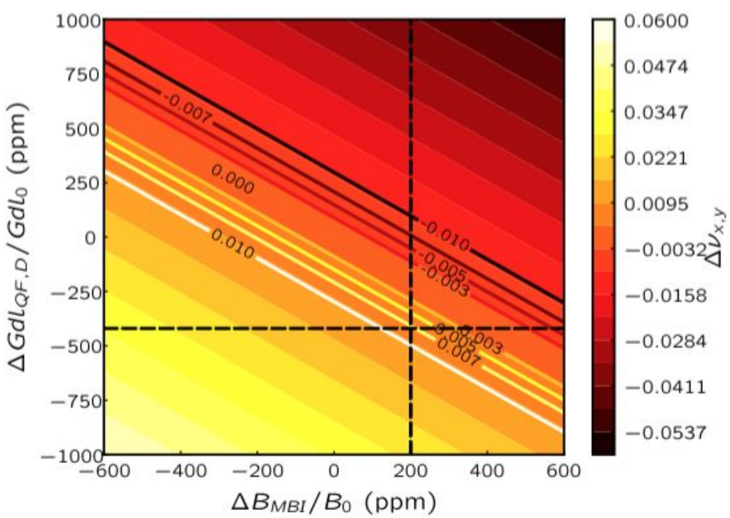
- ➔ From these measurements, we can now estimate how much we expect the tune to change as a consequence of a SC change
- ➔ Both contributions from QF/QD and MBI have to be considered:

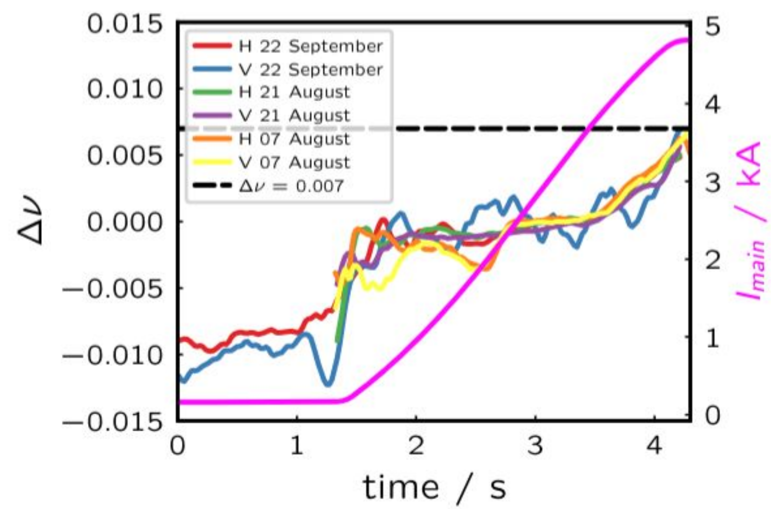
$$k_0(\Delta k/k + 1) = 0.3g_0(\Delta g/g + 1)/p_0(\Delta p/p + 1) = k_0(\Delta g/g + 1)/(\Delta p/p + 1)$$

- ➔ this can be simply done analytically or with MADX:

$$-\Delta\nu_x = \frac{N}{4\pi}[\beta_{x,max}\Delta k_F/k_F + \beta_{x,min}\Delta k_D/k_D] = -6.6 \times 10^{-3}$$
$$-\Delta\nu_y = -\frac{N}{4\pi}[\beta_{y,min}\Delta k_F/k_F + \beta_{y,max}\Delta k_D/k_D] = -6.6 \times 10^{-3}$$

- ➔ These numbers are very well in agreement! More details in [1]





Work towards improved spill macro structure

- ➔ As we know the source now, we are looking at how to use this
- ➔ Difficult to implement a direct feedback from main quads
  - For the dipoles we have a spare magnet => b-train data
- ➔ We are now investigating the possibility to build a synthetic q-train based on neural networks
- ➔ Significant effort to explore this possibility but still not concrete solutions
  - Looked into NARX, simple MLP but results not completely convincing
- ➔ The problem is highly non-linear and needs punctual accuracy in the order of 1e-4
  - Also needs to consider very long time sequences: super cycle in the order of 30-60 s for 1 ms sampling...

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Analysis of spill frequency content

- ➔ The other main contributor to spill quality are the high frequency harmonics
- ➔ These harmonics closely depend on the machine size, RF and main active elements
- ➔ For the SPS, the main frequencies of interest are:
  - 50 Hz and its harmonics (main source power supplies)
  - 43 kHz (SPS revolution)
  - 86 kHz (SPS batch structure)
  - 200 MHz (SPS RF system)

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} We cannot measure these frequencies...yet!

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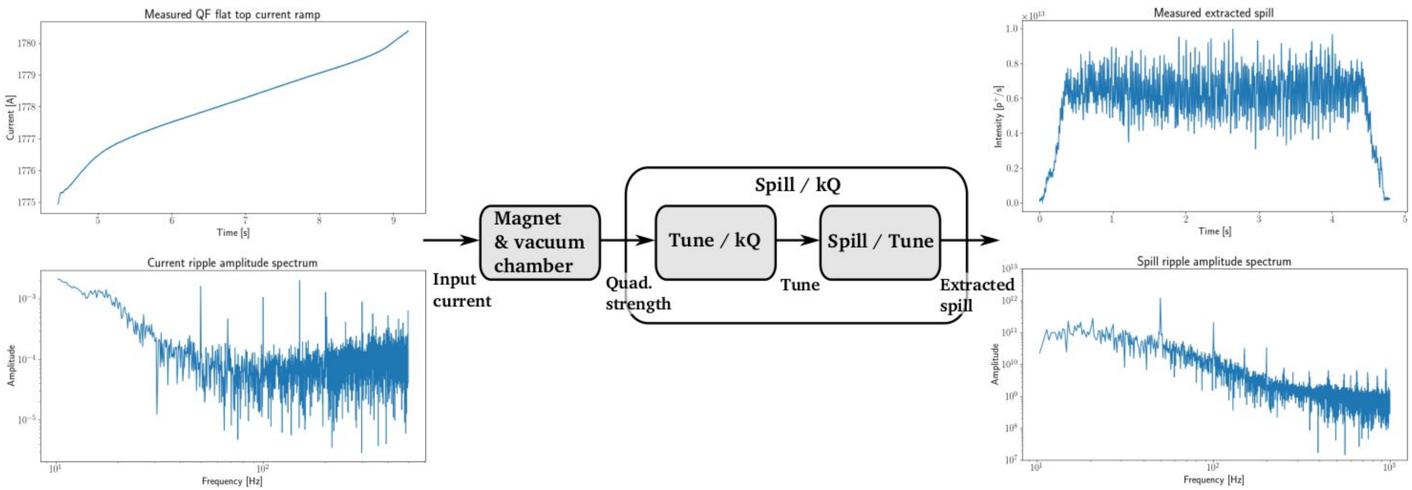
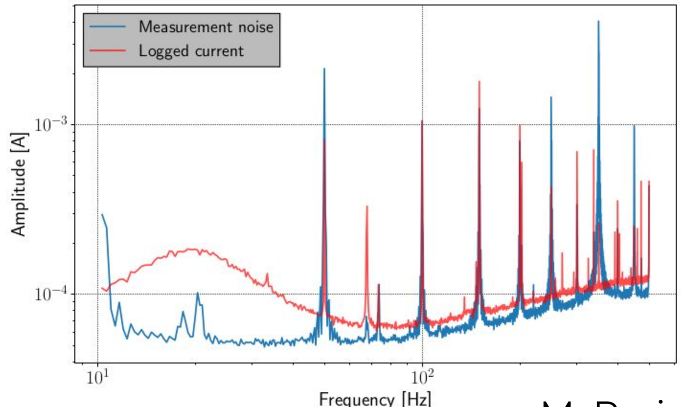
  - 200 MHz (SPS RF system)
- ➔ **Large part of M. Pari thesis focused on the spill frequency analysis**



M. Pari

Analysis of spill frequency content

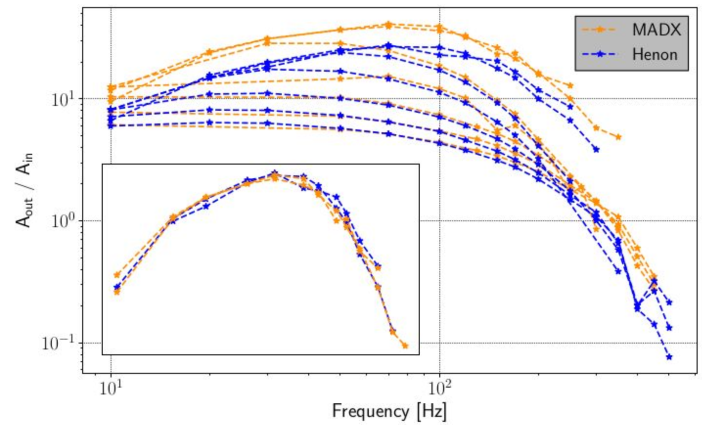
- The idea was to establish a model which could reproduce well the observed spill data - **all detailed in Michelangelo's thesis and in submitted PRAB paper**
- Our observables are:
  - Input current in the main quadrupoles (in fact only the focusing one...SE on H plane) measured with a DCCT
    - Sapling frequency 1 kHz
  - Secondary emission foil (BSI) to measure particles extracted in time
    - Sampling frequency 2 kHz
- Investigation on the effect of the shielding of vacuum chambers shown that in the bandwidth observable (500 Hz) we should not see any effect
  - Cut-off frequency more in the order of few kHz for the material of the SPS VC
- Transfer function between current tune basically linear
- Large 50 Hz noise on DCCT...difficult to benchmark model on these harmonics => need to look at the overall behaviour

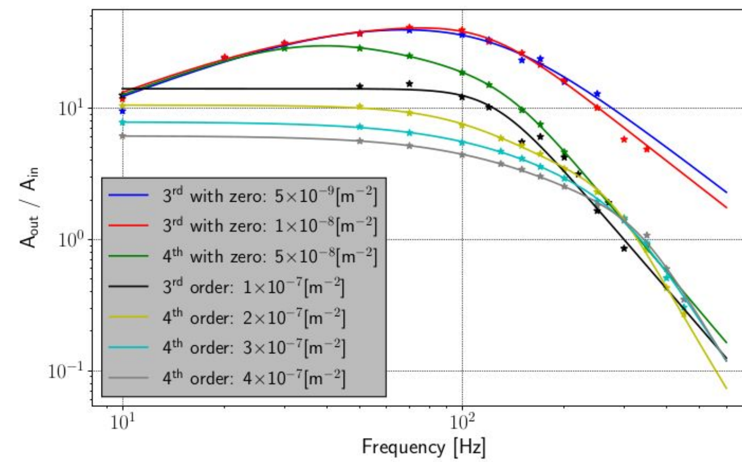


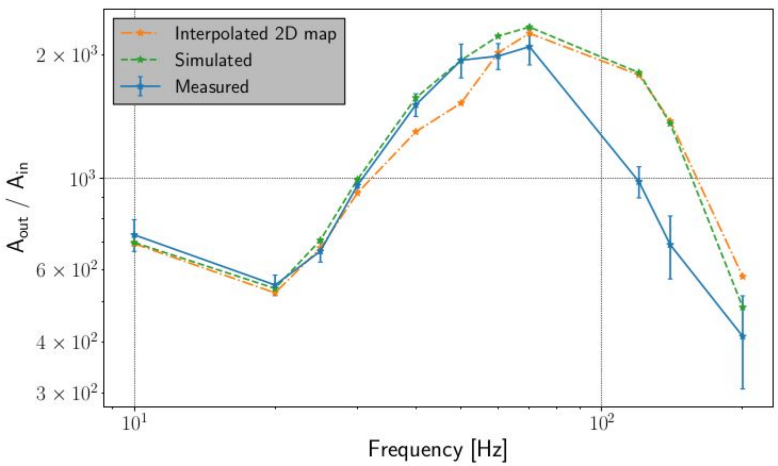
M. Pari

Analysis of spill frequency content

- MADX simulations used to develop simple Henon map based model
- Non-linear model of SPS SE frequency response developed
- <u>Great agreement</u> comparing with data for large ripple amplitude (above the DCCT noise)
  - Dedicated data taking, so very well controlled conditions







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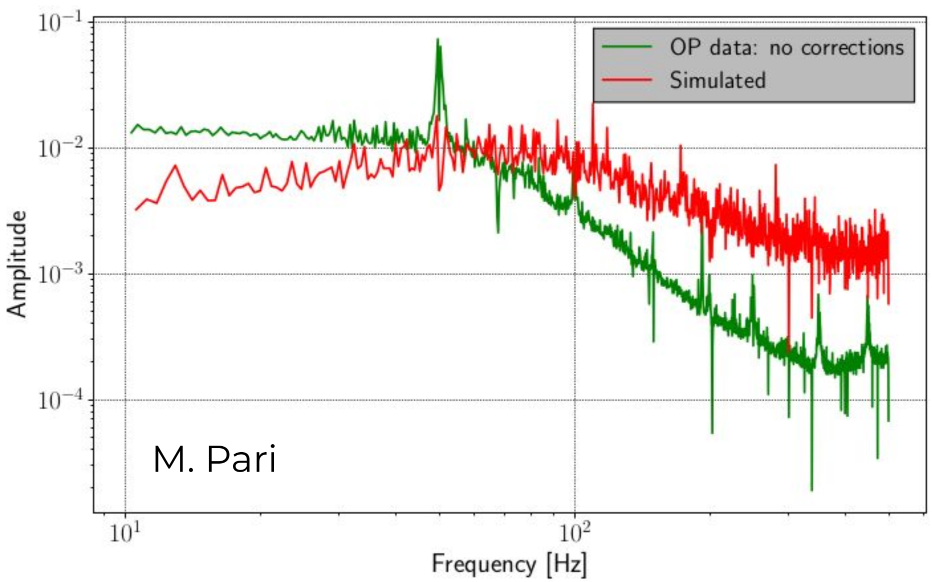
Analysis of spill frequency content

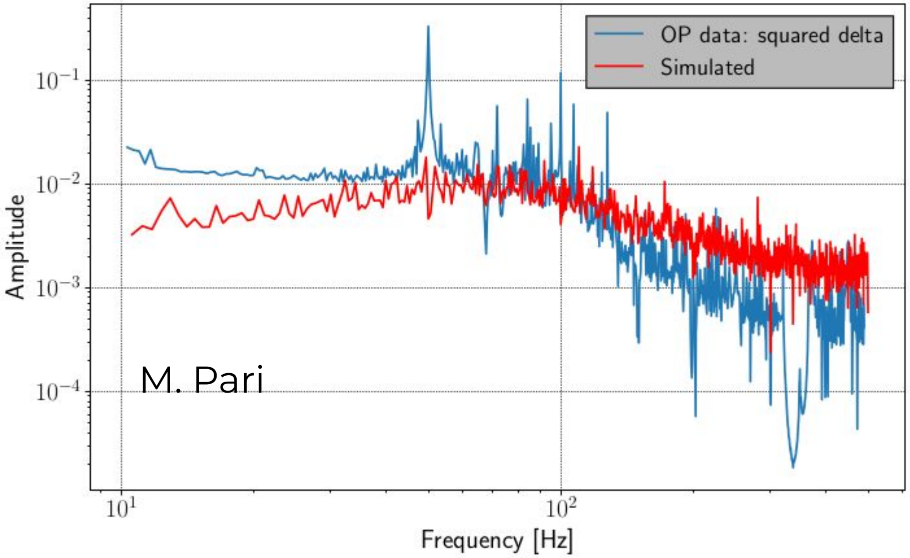
➔ Now the challenge was to reproduce also the “low” amplitude ripples and the dynamic environment of daily operation

➔ First comparison not so great



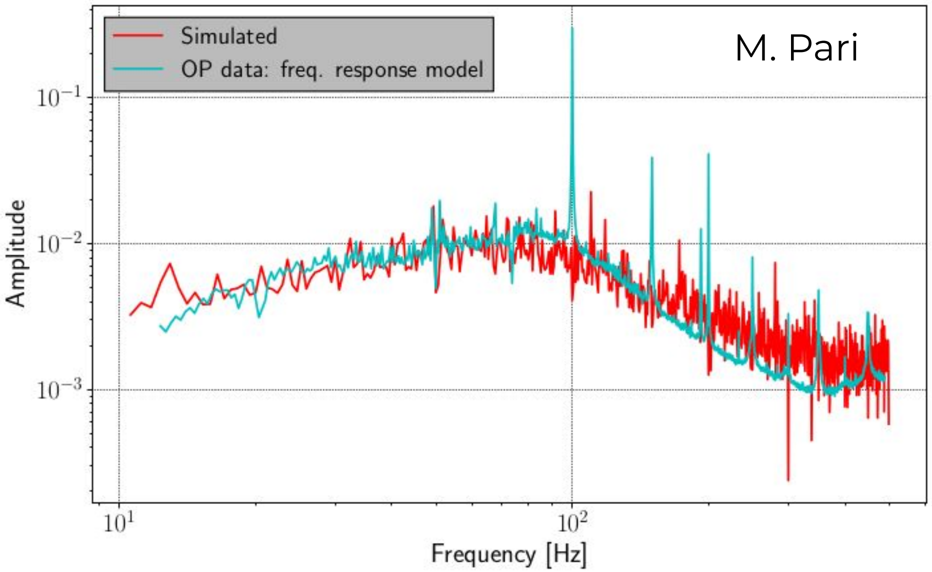
Analysis of spill frequency content

- Now the challenge was to reproduce also the “low” amplitude ripples and the dynamic environment of daily operation
- First comparison not so great
- Then removing the known noise of the DCCT for the main harmonics



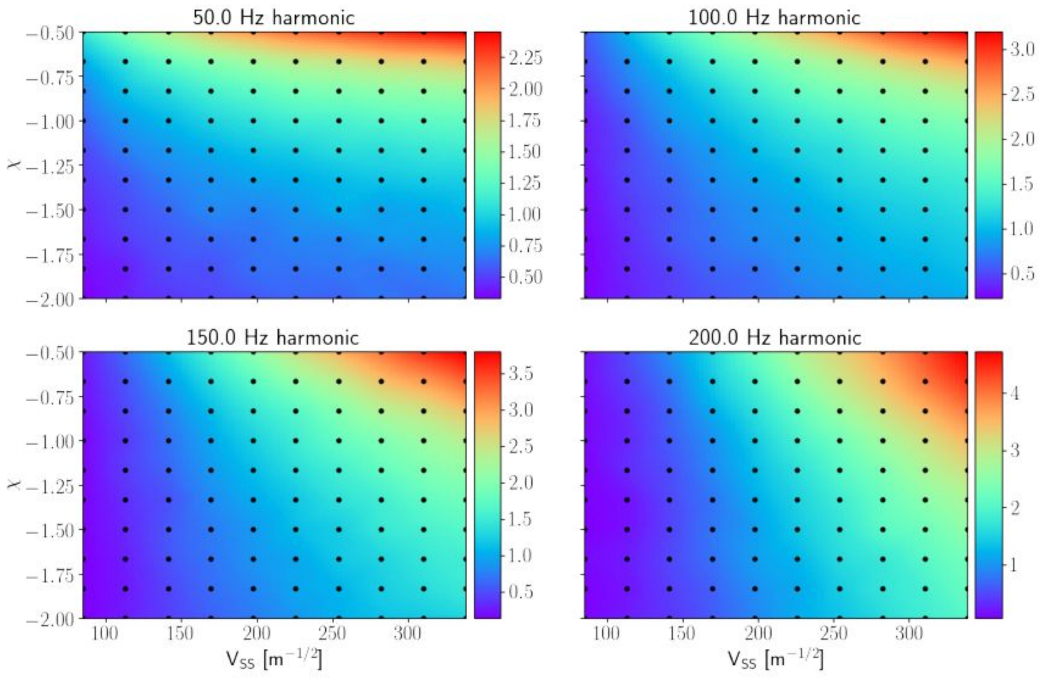
Analysis of spill frequency content

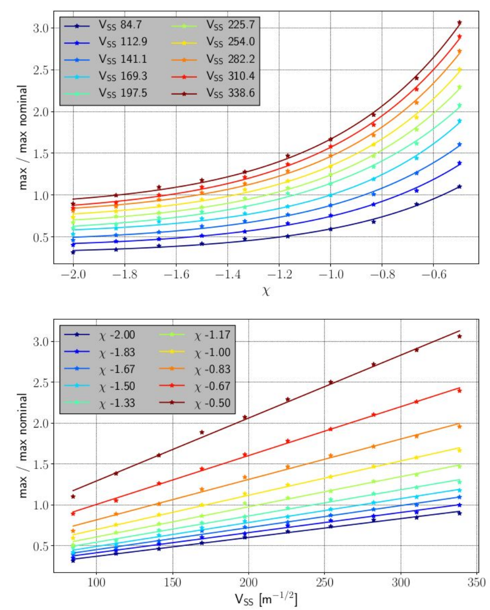
- ➔ Now the challenge was to reproduce also the “low” amplitude ripples and the dynamic environment of daily operation
- ➔ First comparison not so great
- ➔ Then removing the known noise of the DCCT for the main harmonics
- ➔ And finally removing the known transfer function between measurements and actual current on the mains



Analysis of spill frequency content

- Then, using this model, systematic scans of the SE parameter space can be done to try optimise the spill
- There are configurations that could be experimentally explored to reduce the 50 Hz and its harmonics
  - This of course has to be evaluated together with losses





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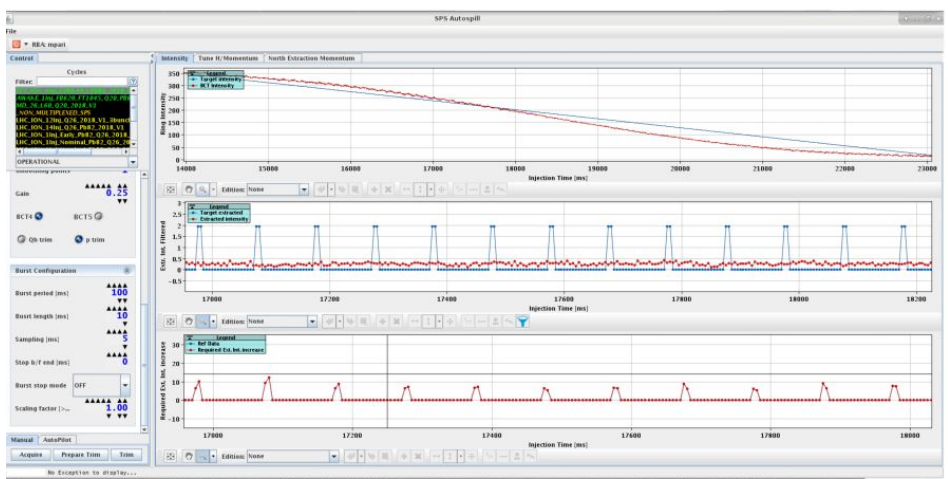
Operational implementation

- ➔ The SPS spill is optimised with a feed-forward based tool [2]
  - ◆ The reference momentum of the machine is adjusted to improve the spill
- ➔ In addition to this, we are now planning to inject all these new results in daily operation
- ➔ For the hysteresis control, we are looking at implementing in the control system a predictive model of magnetic field given previous history
  - ◆ Still need to show neural networks are up for this task…but loads of work ongoing
  - ◆ Infrastructure is almost there
- ➔ For the high frequency model, the idea is to exploit it to guide the evaluation of active regulation of the quadrupole currents
  - ◆ Also to guide in SE parameter optimisation during commissioning



Future work and conclusions

- ➔ Significant improvements in understanding of the SPS spill quality done in the recent years
- ➔ We have a model of the full slow extraction in MADX which we can use to benchmark simpler and faster models with
  - Henon map based model developed to study spill high frequency content
  - This will be used as starting point to investigate longitudinal improvements (P. Arutia PhD)
- ➔ Macro structure spill changes seem to be understood
  - Manual solution available
  - Work ongoing to develop NN driven synthetic q-train to act online
  - Exploration of deep NN to completely solve this problem
- ➔ Maps developed to model expected spill harmonics from input quadrupole current
  - ML can also be explored to build data driven spill quality model
  - Effect of many more machine parameters can be included
- ➔ Upcoming SPS commissioning will answer open points on many of these studies...
- ➔ ...can't wait for beam to be back!!

Thanks!!