Controlling the temporal spill structure: burst mode slow extraction R&D at CERN-SPS

M. Pari, M.A. Fraser, B. Goddard, V. Kain, F.M. Velotti

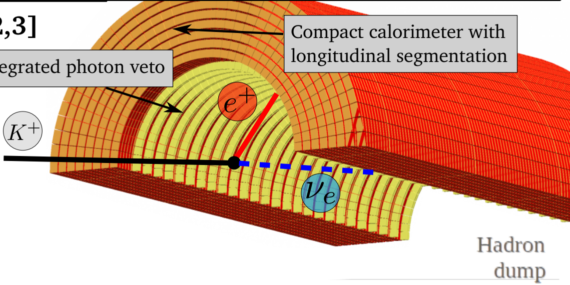
Michelangelo Pari,
Phys. Dep. G. Galilei and INFN Padova, Padova, IT
CERN, Geneva, CH

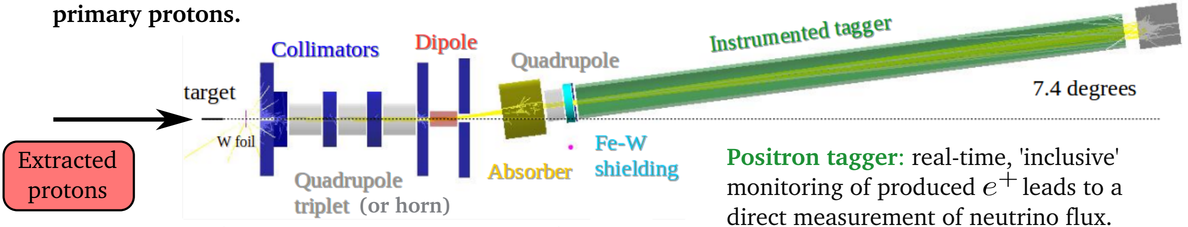
This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 681647).

Enhanced NeUtrino BEams from kaon Tagging [1,2,3]

CERN Neutrino Platform: ENUBET/NP06

- Concept of **monitored** neutrino beam: hadron beamline followed by an **instrumented** decay tunnel for high precision cross section measurement.
- Pile-up levels in instrumented decay tunnel pose hard constraints on maximum hadron flux: **slow extraction is the best option for the primary protons.**





Hadron beamline:
collects, focuses, transport K^+ to the tagger

Positron tagger: real-time, 'inclusive' monitoring of produced e^+ leads to a direct measurement of neutrino flux.

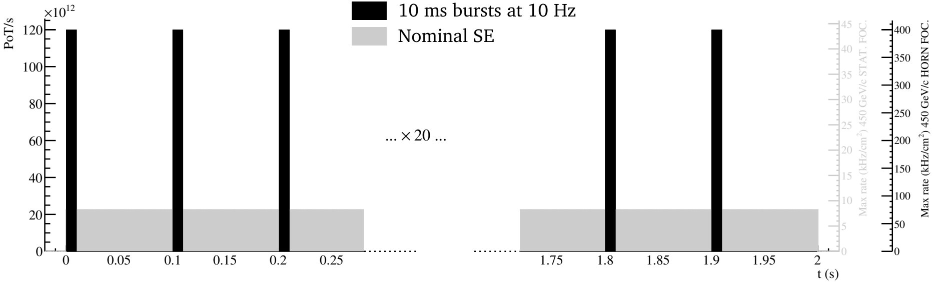
[1] Eur. Phys. J. C, vol. 75, no. 155, 2015
[2] CERN-SPSC-2016-036, Oct. 2016
[3] CERN-SPSC-2018-034, Oct. 2018

Concept of burst mode slow extraction

Given the constraints on maximum particle rate at detector and primary proton energy, CERN-SPS Slow Extraction (SE) would allow optimal operation of the facility.

Strong focusing after target (based on magnetic horns) would maximize the output neutrino flux ⟶ **pulsed operation only!**

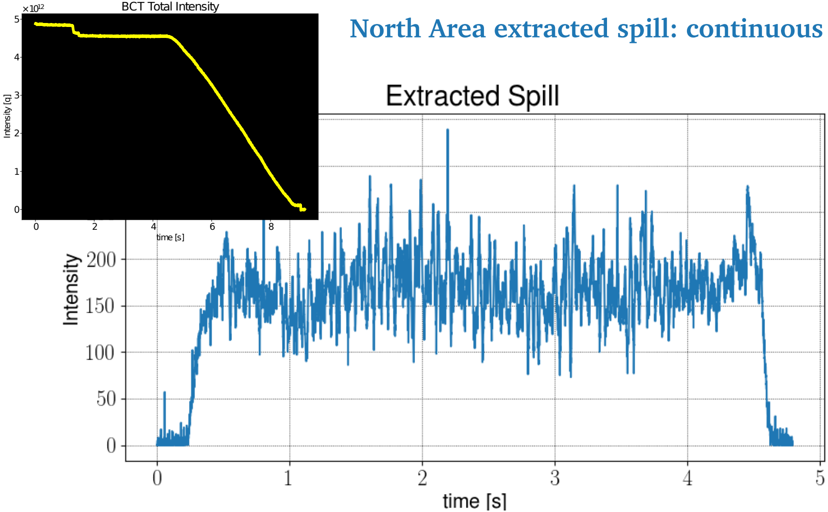
ENUBET operation: example (proposed in SPSC-EOI-014 [2])



From simulations [1]: $\sim\times$**10 neutrino flux increase in burst mode**

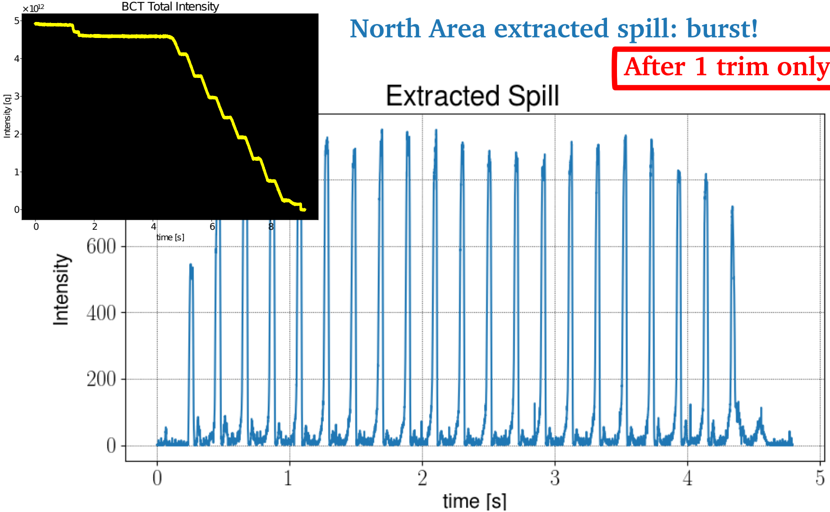
Following the ENUBET concept, a first method to implement a bursted version of the CERN-SPS North Area (NA) continuous spill has been developed and tested.

North Area extracted spill: continuous (nominal)



Measured spill in extraction TL with secondary emission foil.

Following the ENUBET concept, a first method to implement a bursted version of the CERN-SPS North Area (NA) continuous spill has been developed and tested.



North Area extracted spill: burst!

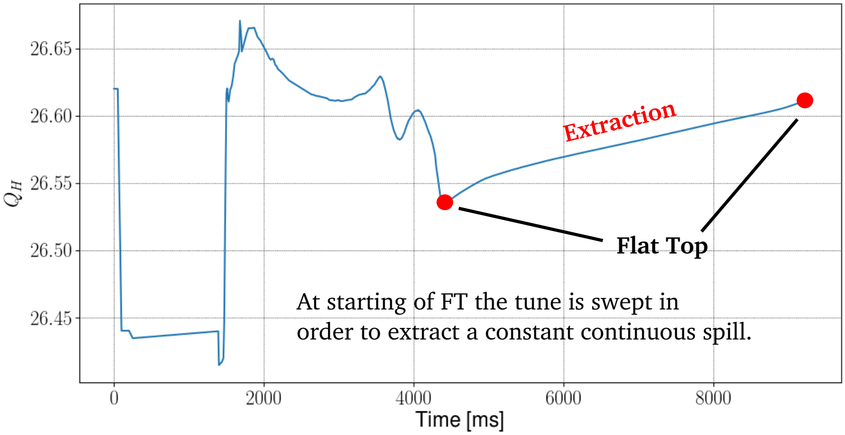
After 1 trim only!

Measured spill in extraction TL with secondary emission foil.

Implementation at CERN-SPS

The idea is to obtain the burst extraction with a tune change, exploiting the chromatic quadrupole driven slow resonant extraction of SPS.

SPS SFTPRO whole cycle - Q_H

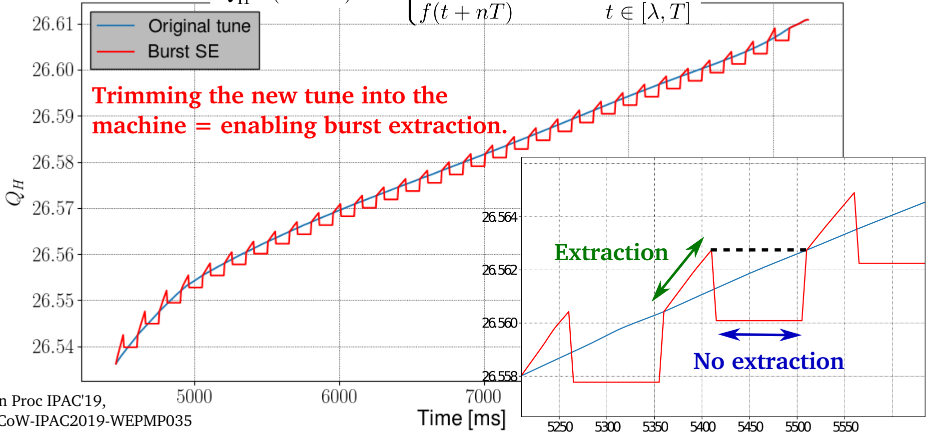


Implementation at CERN-SPS

Idea: the new tune to be set is a time-shrunk version of the original tune. Every burst period of the original tune is shrunk into a single burst length [4].

The same amount of particles are extracted in a fraction of the time.

$$Q_{\mathrm{H}}^{\mathrm{nom}}(t+nT) \longrightarrow \begin{cases} Q_{\mathrm{H}}^{\mathrm{nom}}\left(\frac{T}{\lambda}t+nT\right) & t\in[0,\lambda] \\ f(t+nT) & t\in[\lambda,T] \end{cases}$$



[4] M.Pari et al. in Proc IPAC'19, doi:10.18429/JACoW-IPAC2019-WEPMP035

Characterization of extracted spill

Experimental quantities correspondent to the demanded ones can be reconstructed from the spill *s(t)*:

- Effective burst length λ_{eff}
- Effective DF $= \frac{\text{eff. burst length}}{\text{T}}$

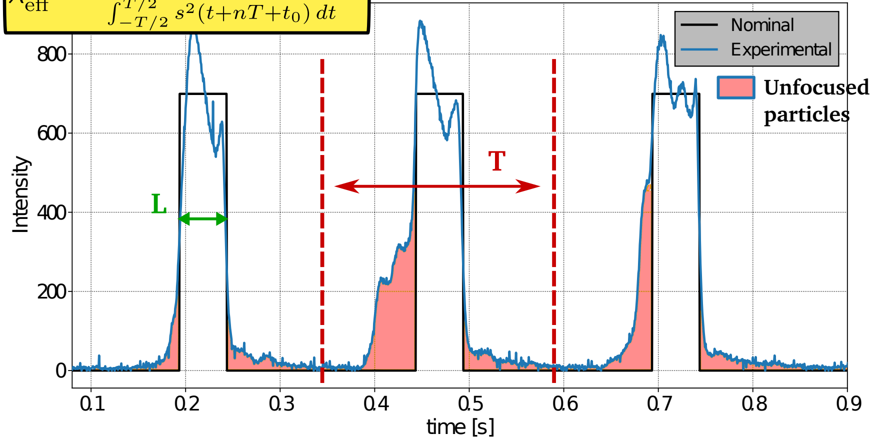
$$\lambda^n_{\text{eff}} = \frac{\left(\int_{-T/2}^{T/2} s(t+nT+t_0)\,dt\right)^2}{\int_{-T/2}^{T/2} s^2(t+nT+t_0)\,dt}$$

Demanded quantities:

L: burst length

T: burst period

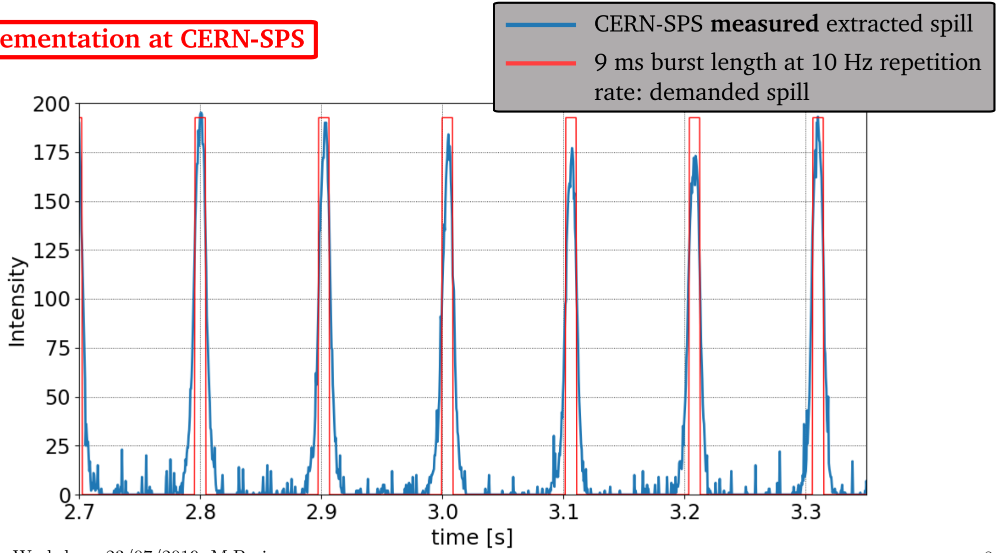
Duty factor: L/T



Effective burst length and duty factor

Typical spill obtained with burstControl application:

Implementation at CERN-SPS



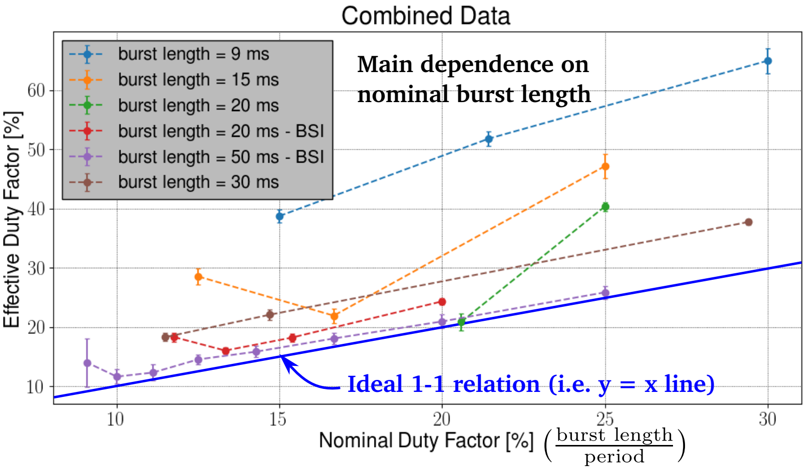
Effective burst length and duty factor

CONCLUSION

↓

Demanded burst length is not correctly reproduced, especially for small burst lengths (∼<10 ms, ENUBET ROI)

The closer to the 1-1 reference line the better



Iterative approach

In operation optimization approach, with the following goals:

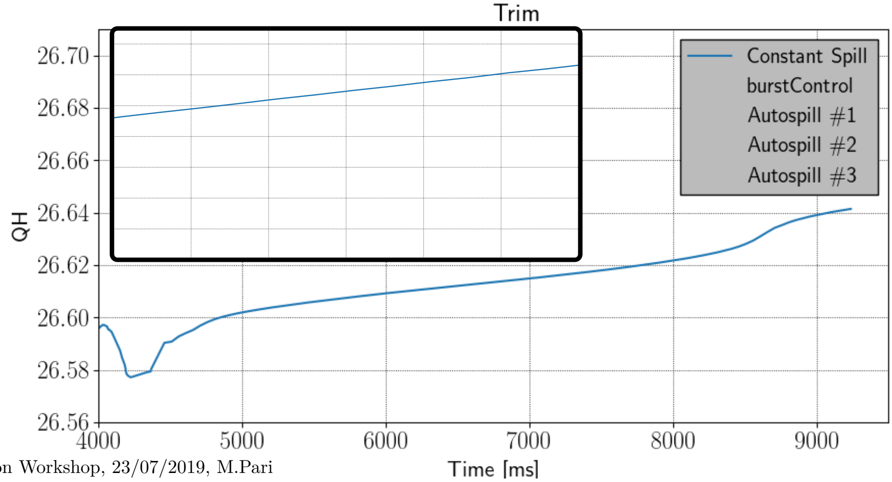
- Use an iterative algorithm in order to automatically converge to the correct value of effective burst length during operation. The Autospill application [5] (based on a feed-forward algorithm and successfully working for nominal spill optimization) has been upgraded for the task. The algorithm takes the measured and reference spills as input and acts on the tune slope in order to minimize the differences between them.
- Prove the possibility to reach the proposed ENUBET value of 10 ms of burst length.

[5] V.Kain et al. in Proc IPAC'16,
doi:10.18429/JACoW-IPAC2016-TUPMR051

Example of successful iteration

First burstControl tune setting (deterministic algorithm) followed by Autospill-Burst:

1. Optimize the tune for nominal Q-sweep slow extraction.

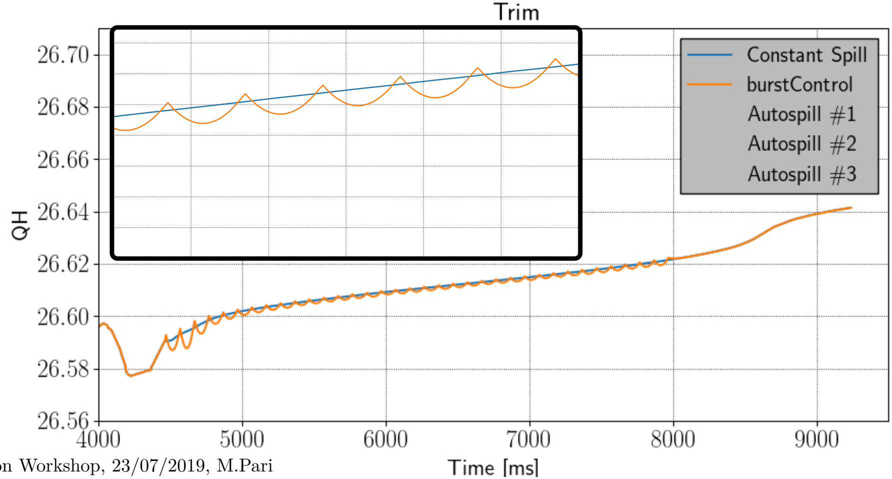


Example of successful iteration

First burstControl tune setting (deterministic algorithm) followed by Autospill-Burst:

1. Optimize the tune for nominal Q-sweep slow extraction.

2. Switch-on 10 / 100 ms burst-SE with burstControl.



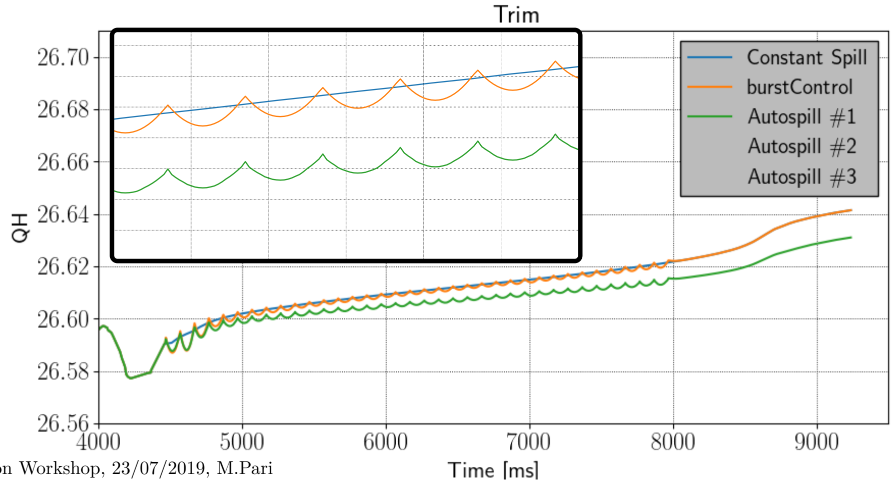
Example of successful iteration

First burstControl tune setting (deterministic algorithm) followed by Autospill-Burst:

1. Optimize the tune for nominal Q-sweep slow extraction.

2. Switch-on 10 / 100 ms burst-SE with burstControl.

3. Optimize the previous result with Autospill.



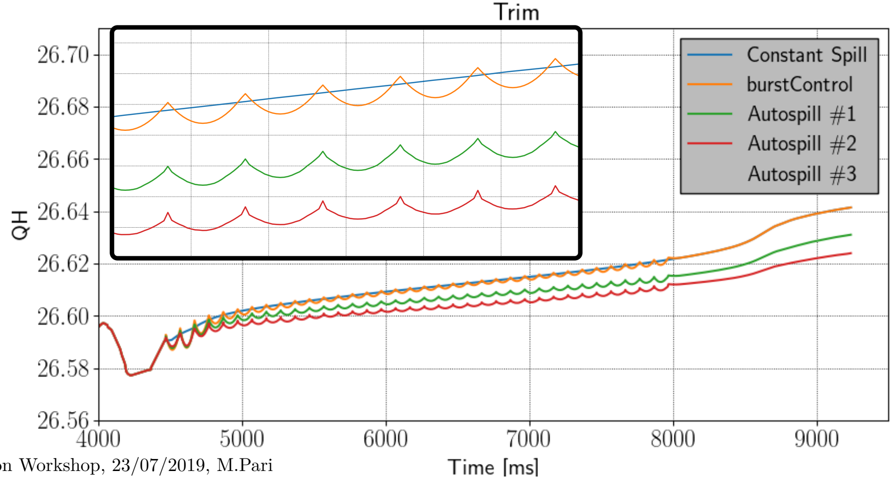
Example of successful iteration

First burstControl tune setting (deterministic algorithm) followed by Autospill-Burst:

1. Optimize the tune for nominal Q-sweep slow extraction.

2. Switch-on 10 / 100 ms burst-SE with burstControl.

3. Optimize the previous result with Autospill.



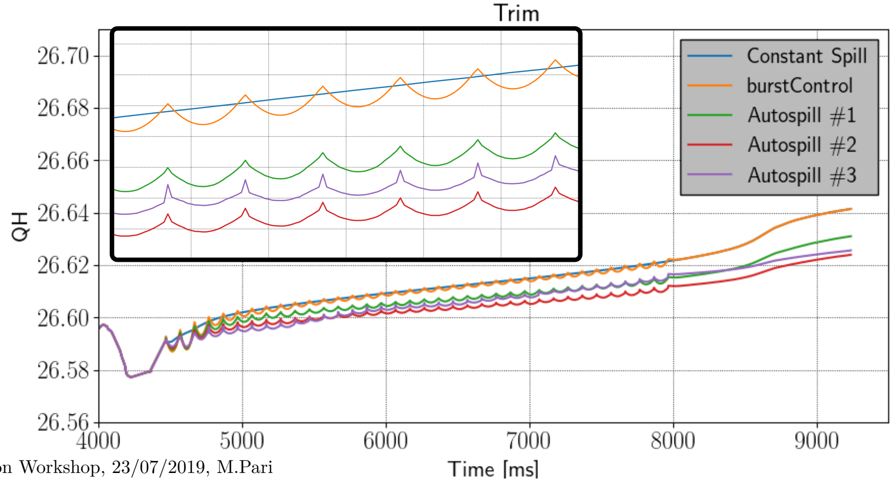
Example of successful iteration

First burstControl tune setting (deterministic algorithm) followed by Autospill-Burst:

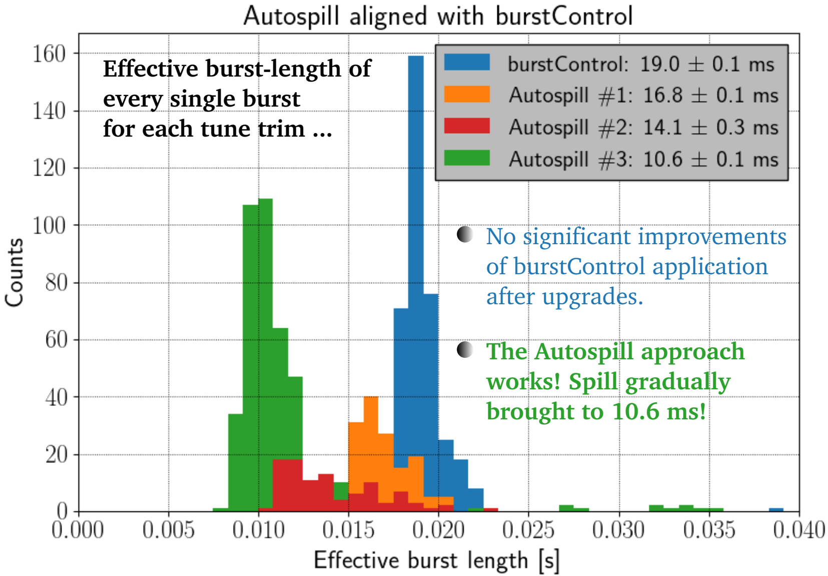
1. Optimize the tune for nominal Q-sweep slow extraction.

2. Switch-on 10 / 100 ms burst-SE with burstControl.

3. Optimize the previous result with Autospill.

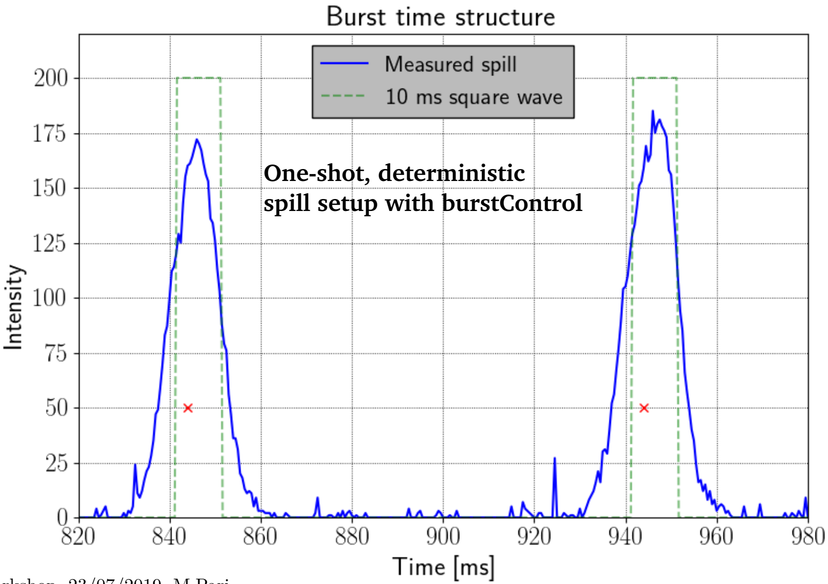


Example of successful iteration

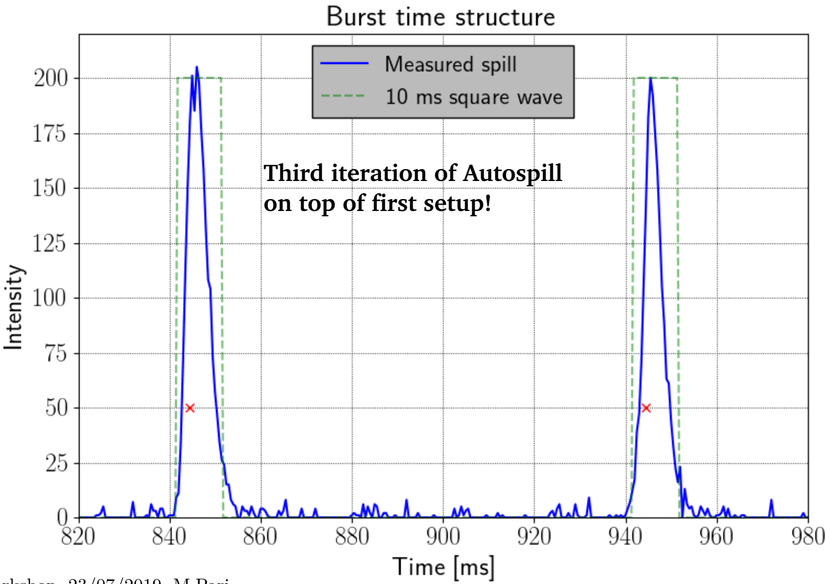


- No significant improvements of burstControl application after upgrades.
- **The Autospill approach works! Spill gradually brought to 10.6 ms!**

Example of successful iteration



Example of successful iteration



Modeling and simulation

Goals:

- Better understanding and characterization of the problem.
- Reproduce the obtained experimental results.
- Explore possible ways to improve the current limitations and produce a set of possible operational settings.

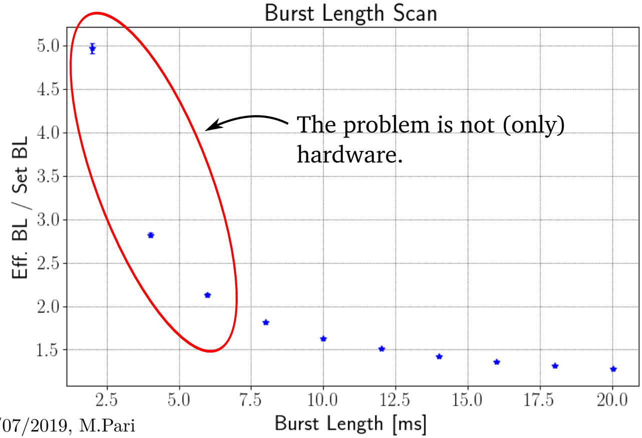
The burst mode slow extraction has been successfully implemented in a MADX simulation of the CERN-SPS, used for the study.

Modeling and simulation: results

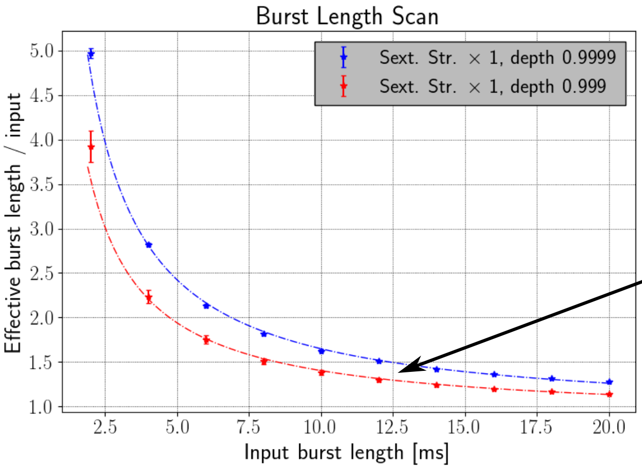
Important question:

The experimental results showed that we can't reproduce the input settings for short (< 10 ms) burst lengths, and we observed a significant contribution coming from the power converters chain.
Is this mainly an hardware problem?

NO: 1/x divergence can be observed!

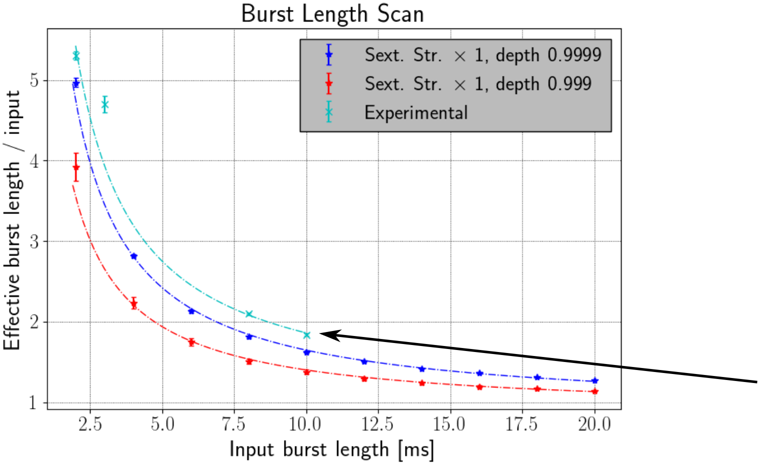


Modeling and simulation: results



For a fixed simulated demanded burst length, tune speed in non-extraction regions defines a range of achievable effective burst lengths (i.e. between red and blue)

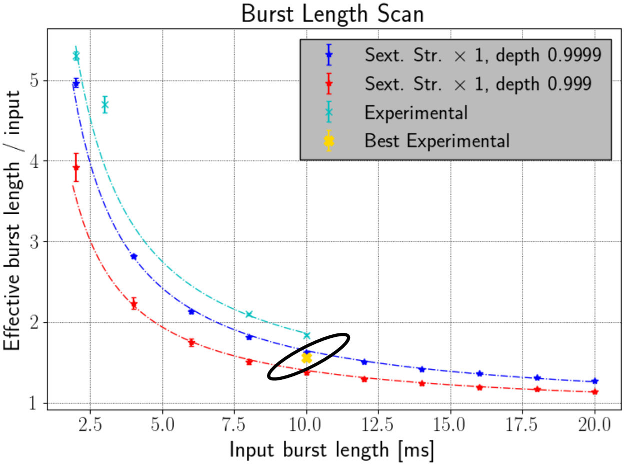
Modeling and simulation: results



For a fixed simulated demanded burst length, tune speed in non-extraction regions defines a range of achievable effective burst lengths (i.e. between red and blue)

In general, experimental data is worsened by power converters non-ideal effects, and lie out of the simulated range.

Modeling and simulation: results



With particular care in operation, experimental data can fit in the simulated range. In particular, the best experimental point has been obtained with Savitzky-Golay+Autospill.

For a fixed simulated demanded burst length, tune speed in non-extraction regions defines a range of achievable effective burst lengths (i.e. between red and blue)

In general, experimental data is worsened by power converters non-ideal effects, and lie out of the simulated range.

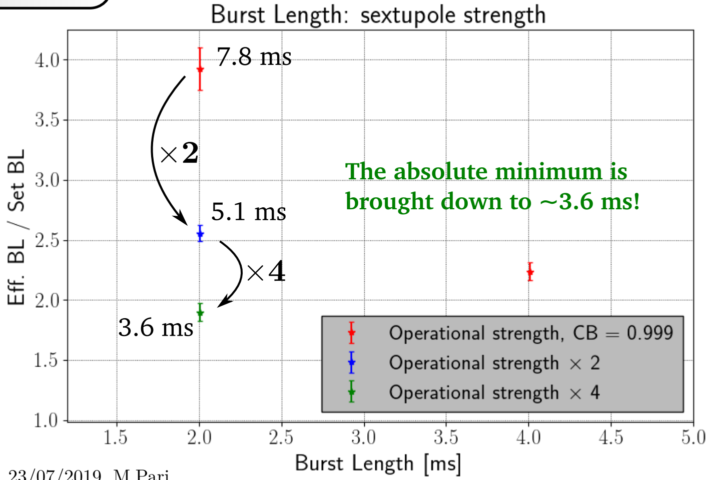
Possible improvements

How to reduce further the effective burst length to burst length ratio?

→ **Increase the particle velocity in phase space.**

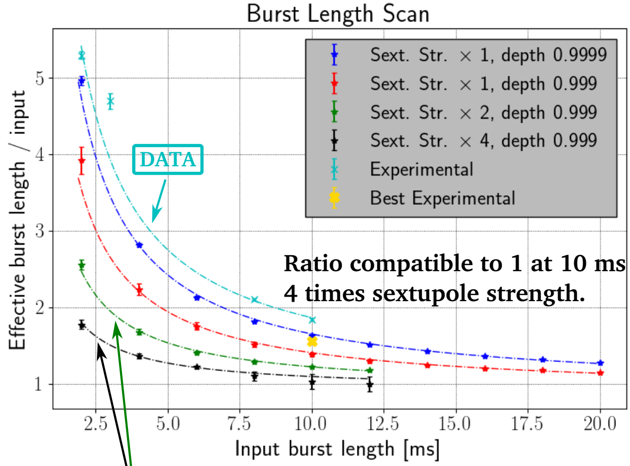
$$\Delta A = \frac{3}{4} S A^2$$

S → virtual sextupole strength



The absolute minimum is brought down to ∼3.6 ms!

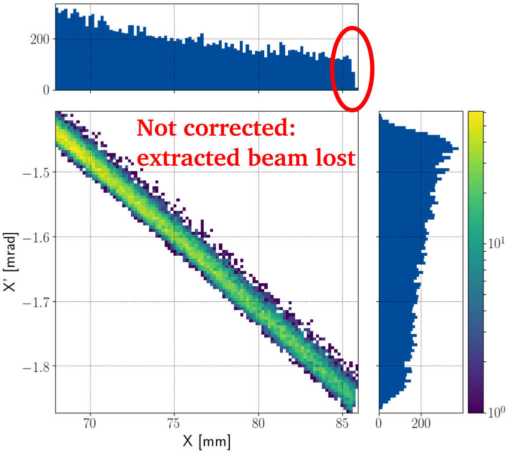
Possible improvements



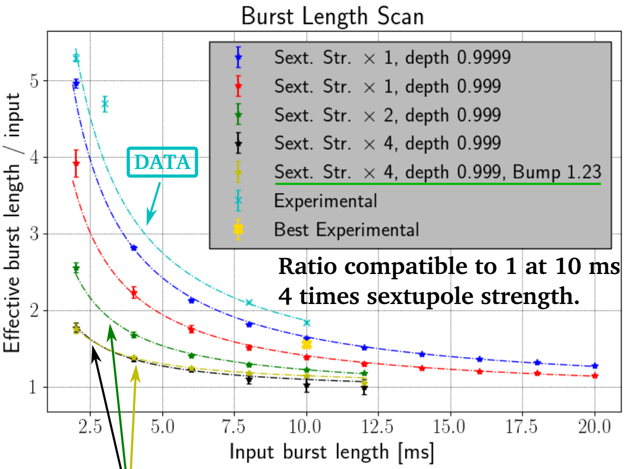
Ratio compatible to 1 at 10 ms for 4 times sextupole strength.

Sextupole strength $\times 2$ and $\times 4$ simulation results.

Such a significant increase in sext. strength requires adjustment of spiral step via the extraction bump: otherwise beam is lost.



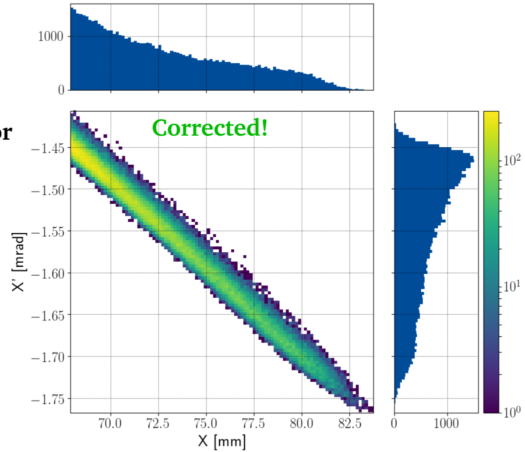
Possible improvements



Ratio compatible to 1 at 10 ms for 4 times sextupole strength.

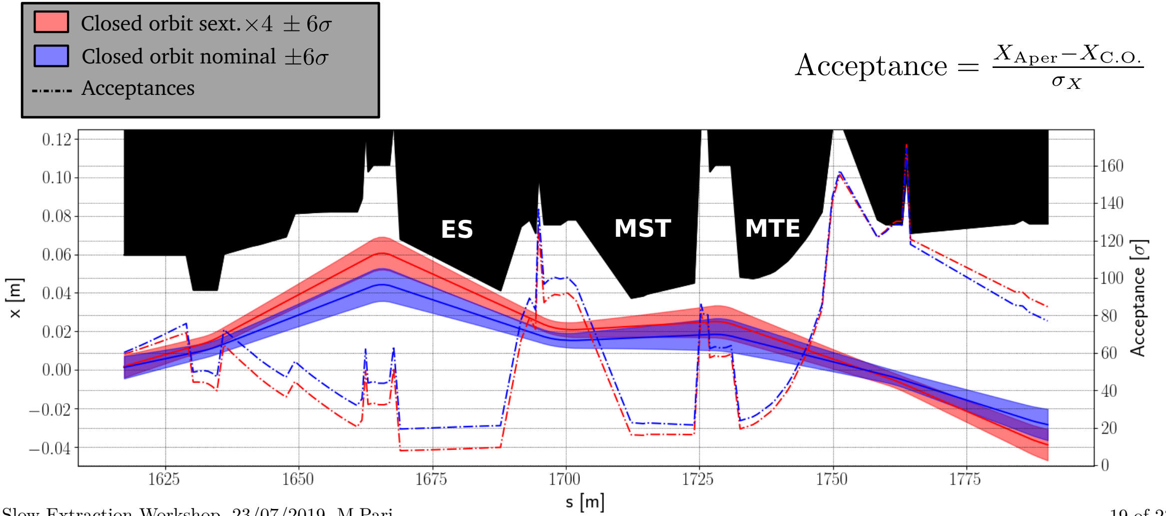
Sextupole strength $\times 2$ and $\times 4$ simulation results.

Adjusting the extraction bump does not reduce the improvement in burst length: the results are compatible.



Increasing the extraction sextupole strength by a factor 4 reduces the minimum acceptance at the ES from 19.4 beam sigmas to 7.8 beam sigmas.

$$\text{Acceptance} = \frac{X_{\text{Aper}} - X_{\text{C.O.}}}{\sigma_X}$$

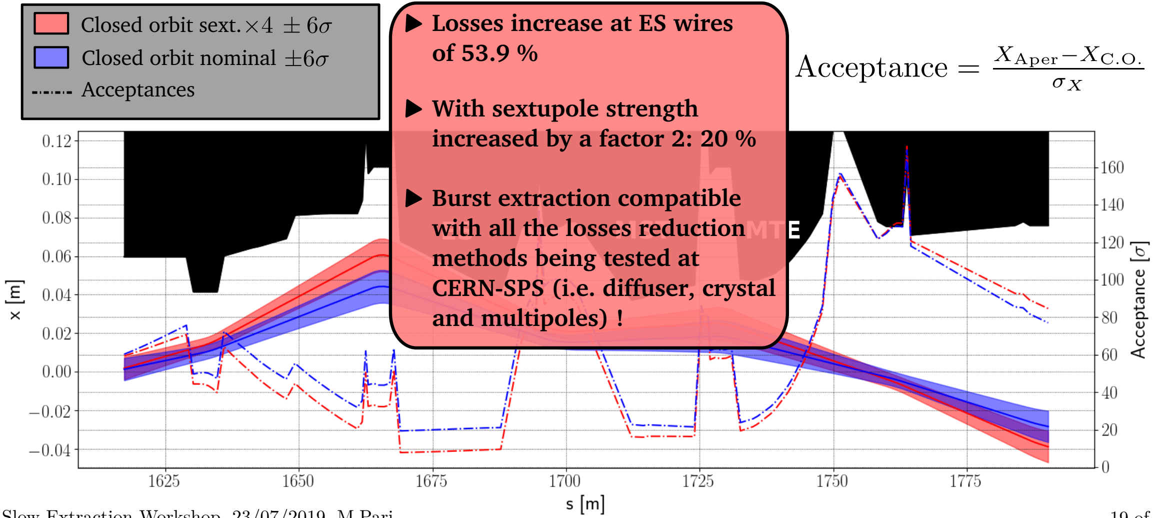


Possible improvements

Increasing the extraction sextupole strength by a factor 4 reduces the minimum acceptance at the ES from 19.4 beam sigmas to 7.8 beam sigmas.

- **Losses increase at ES wires of 53.9 %**
- **With sextupole strength increased by a factor 2: 20 %**
- **Burst extraction compatible with all the losses reduction methods being tested at CERN-SPS (i.e. diffuser, crystal and multipoles) !**

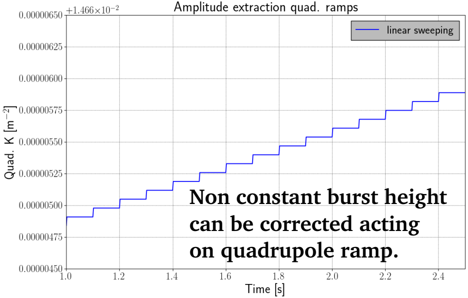
$$\text{Acceptance} = \frac{X_{\text{Aper}} - X_{\text{C.O.}}}{\sigma_X}$$



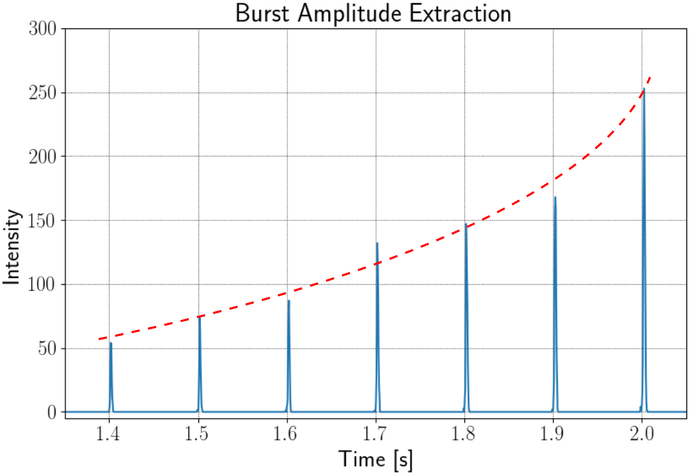
Possible improvements

Amplitude extraction is intrinsically faster than momentum extraction because only same amplitude particles get extracted at a time: another way to reach lower burst lengths.

Average burst length value (for input 2 ms) is: 3.16 ± 0.07 ms **against** 3.56 ± 0.11 ms **obtained with 4 times sextupole strength**



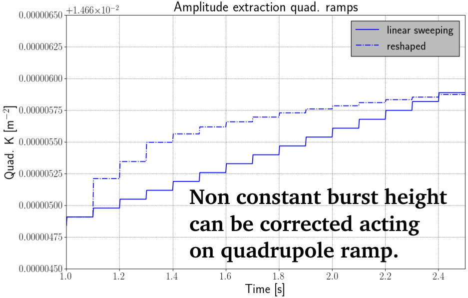
Non constant burst height can be corrected acting on quadrupole ramp.



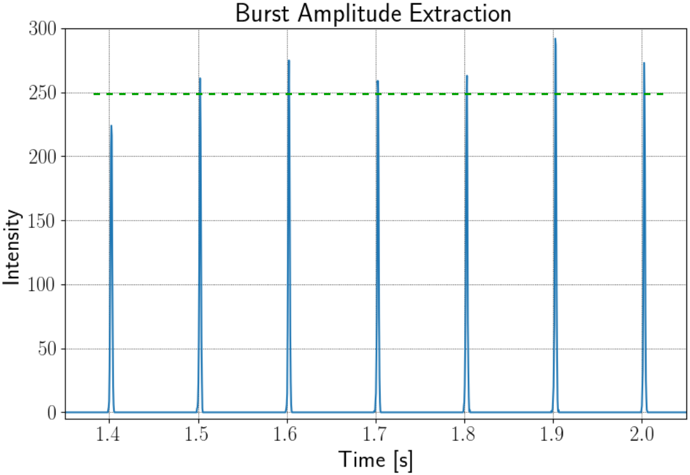
Possible improvements

Amplitude extraction is intrinsically faster than momentum extraction because only same amplitude particles get extracted at a time: another way to reach lower burst lengths.

Average burst length value (for input 2 ms) is: 3.16 ± 0.07 ms **against** 3.56 ± 0.11 ms **obtained with 4 times sextupole strength**

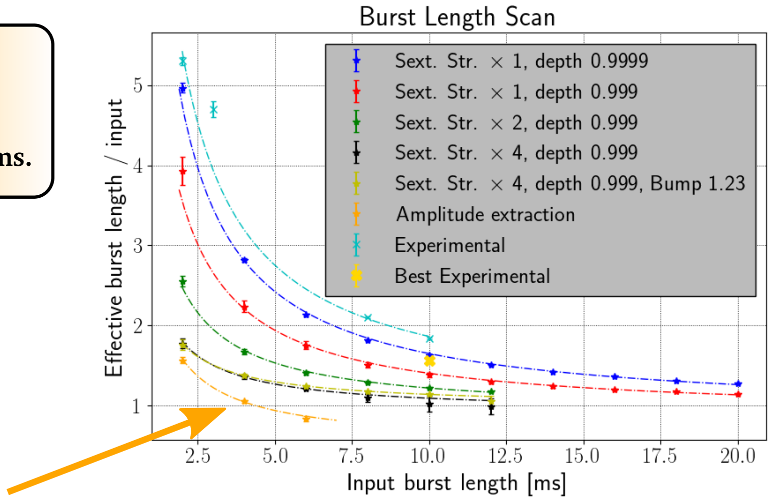


Non constant burst height can be corrected acting on quadrupole ramp.



Possible improvements

Drawback:
amplitude extraction can't reproduce burst lengths larger than 4 ms.

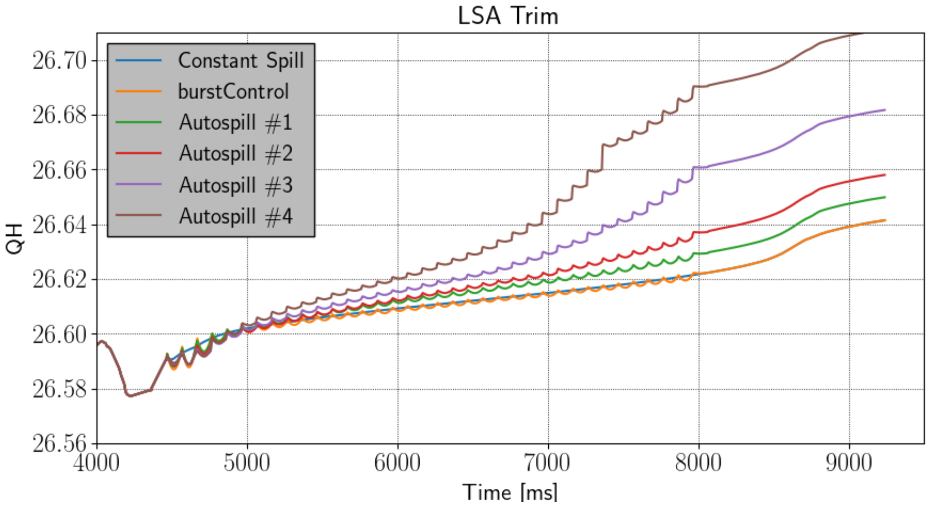


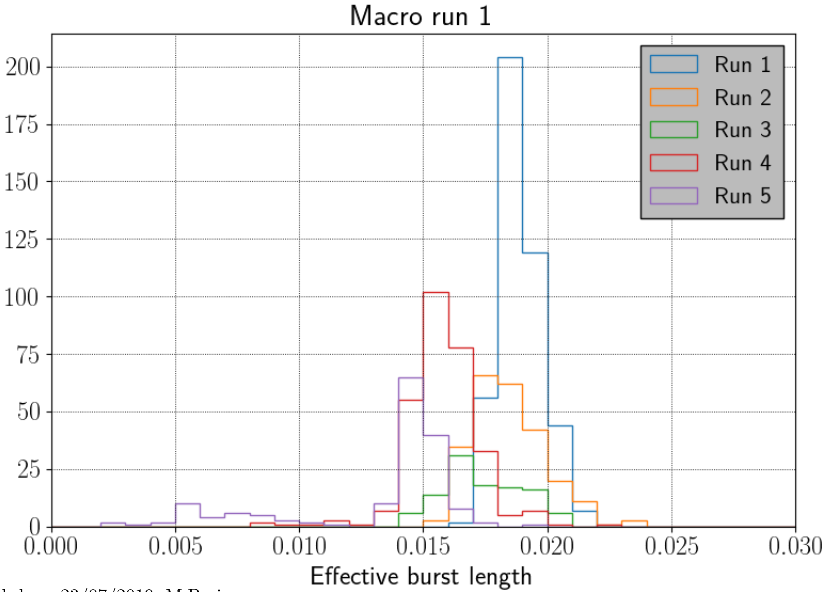
Conclusions

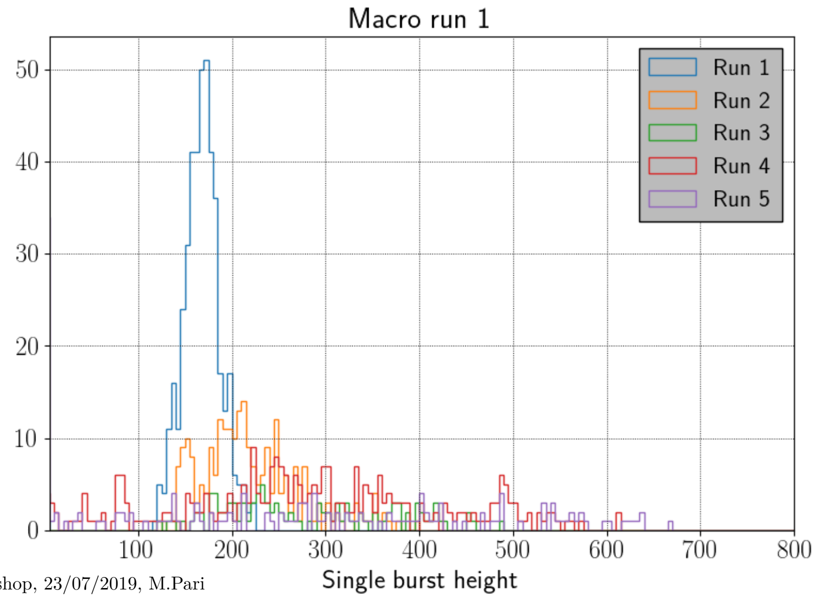
- Successfully implemented burst mode slow extraction in CERN-SPS.
- Showed no significant losses and dumped intensity increase during burst extraction in operation.
- The Autospill feed-forward algorithm has been upgraded to reduce the effective burst length to the demanded value: **achieved ENUBET first proposed burst length of 10 ms**.
- Successfully implemented burst-mode slow-extraction in MADX.
- The value of output/input burst length ratio higher than 1 is not only due to hardware. Proved to be also a beam dynamics effect with MADX simulations.
- Successfully improved output/input burst length ratio by acting on: tune speed, sextupole strength and machine chromaticity. There are margins for improvements!
  - E.g. explore amplitude extraction, losses optimization, etc.

Thank you

Backup


LSA Trim
Constant Spill
burstControl
Autospill #1
Autospill #2
Autospill #3
Autospill #4
QH
26.70
26.68
26.66
26.64
26.62
26.60
26.58
26.56
4000
5000
6000
7000
8000
9000
Time [ms]


Macro run 1
Run 1
Run 2
Run 3
Run 4
Run 5
200
175
150
125
100
75
50
25
0
0.000
0.005
0.010
0.015
0.020
0.025
0.030
Effective burst length


Macro run 1
Run 1
Run 2
Run 3
Run 4
Run 5
50
40
30
20
10
0
100
200
300
400
500
600
700
800
Single burst height