BBLR compensation in Run 3:
Bunch-by-bunch losses and wire operation

P. Bélanger, G. Sterbini, D. Kaltchev, R. Baartman
On behalf of the BBCW team

Special thanks to:
K. Paraschou, H. Bartosik and M. Rufolo for their invaluable inputs,
G. Iadarola for xsuite and the help with simulations,
M. Hostettler for the implementation of the wire in operation and LHC operation during MD with G. Trad,
The collimation team for the help with crossing angle reduction (C.E. Montanari, B. Lindstrom, M. D'Andrea, S. Redaelli, M. Giovannozzi)

13th HL-LHC Collaboration Meeting : https://indico.cern.ch/event/1293138/contributions/5469244/

Introduction

Experimental Framework

Machine Development

2023 Operation

Historical collaboration

1997
V. Shilsev et al.
e⁻ Q-compression

1999
Y. Papaphilippou, F. Zimmermann
PRST-AB 2, 104001

2000
J.-P. Koutchouk
DC wires for LHC

J.-P. Koutchouk et al.
Wires in the SPS
Since 2004

2004
B. Erdeley, T. Sen
FERMILAB-TM-2268-AD

W. Fischer et al.
Wires in RHIC
2006

C. Milardi et al,
Wires in DAΦNE
Since 2006

2007
H. J. Kim, T. Sen
PAC07-THPAN114

2008
U. Dorda
PhD Thesis

2012
T. Rijoff
M.Sc.Thesis

F. Zimmermann et al.
Specification of the
LHC wires, 2013

2015
S. Fartoukh et al.
PRST-AB 18, 121001

1st Workshop on (HL-)LHC
Wire Compensation
December 2015

2016
A.S. Patapenka et al.
NAPAC2016-TUPOB17

March 2017
2nd Workshop on (HL-)LHC
Wire Compensation

Experiment in the LHC
2017-2018

Run 3, BBCW operation
2022-2023

September 2022
HL-LHC Satellite Meeting,
BBCW

2023
P. Belanger et al., IPAC
paper on Wire MD

September 2023
HL-LHC Collaboration
Meeting

Beam-Beam Long-Range compensation

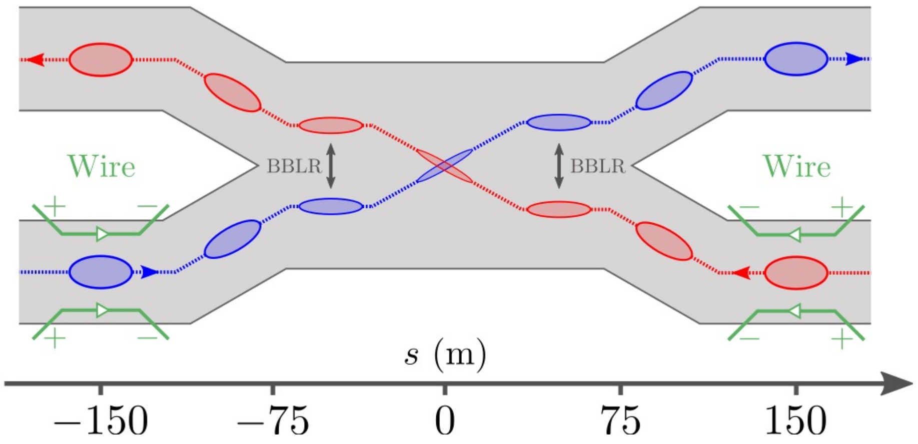
- **Beam-beam** interactions:
  - **Head-on**: necessary for luminosity production
  - **Long-range**: lead to undesirable tune-spread

- BBLR is akin to **multipolar error**:
  - Leads to beam losses
  - Reduction of dynamic aperture
  - **Reduction of integrated luminosity**
  - **Strongest source of non-linearities!**

- Can be **compensated** with DC wires (BBCW)

- Run 3, embedded in the **collimators of IP1 + IP5**

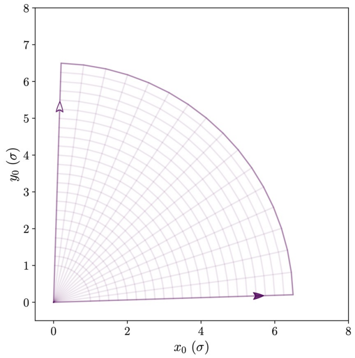
- Double-wire configuration to **target octupolar terms**



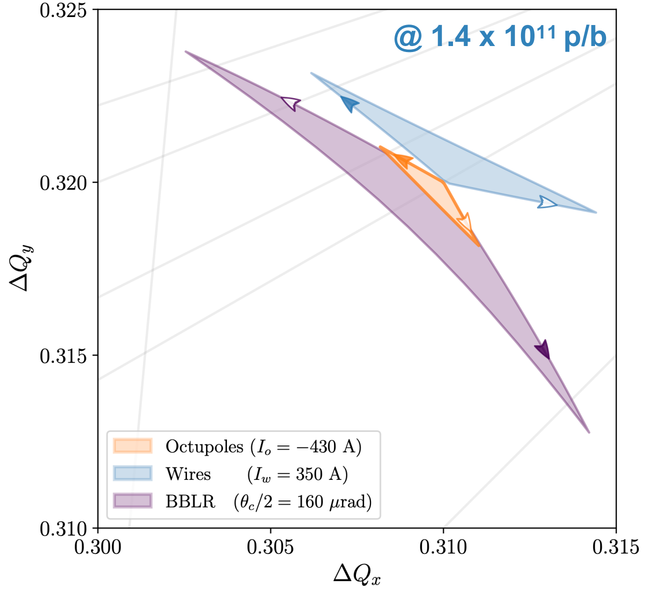
"If the optics and layout conditions (β-aspect ratios, wire distance, etc.) **cannot be met**, wire currents and distances should be used for **cancelling the LR leading order effect**, i.e. **octupole-like tune-spread**."

Y. Papaphilippou - BBLR 2015 workshop (https://indico.cern.ch/event/456856/contributions/1968793)

Footprint compression

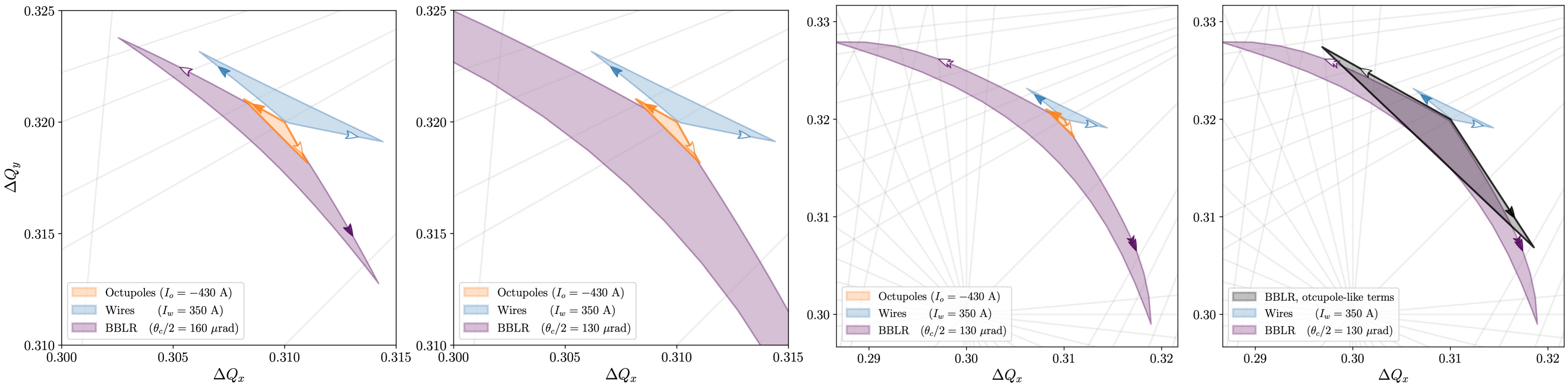


- **Deviation from a linear machine** measured with Resonance Driving Terms (**RDTs**)
  - Chaos, diffusion, and ultimately **beam losses**
- **Detuning** (subset of RDTs) can be visualized in the tune diagram as a **footprint**
- **Lateral "wings" of BBLR** need to be compressed to avoid **resonances**
- **Wires naturally compensate** laterally
  - Note: non-optimal β_x/β_y yields tilt
- **Octupoles powered negatively** compensate laterally, but enhance along the diagonal (not dramatic)



Beam-Beam Limit?

- Footprint becomes **significantly larger** with reduction of crossing angle
- **Technologically still within reach** with standalone wires (proposed for HL)
  - 450 Am of current instead of 350 Am **(factor 1.3)**
  - Compensation of all RDTs **(not only octupolar)**
  - Possibility of a closer approach to the beam **(scales as 1/d^4)**



Introduction

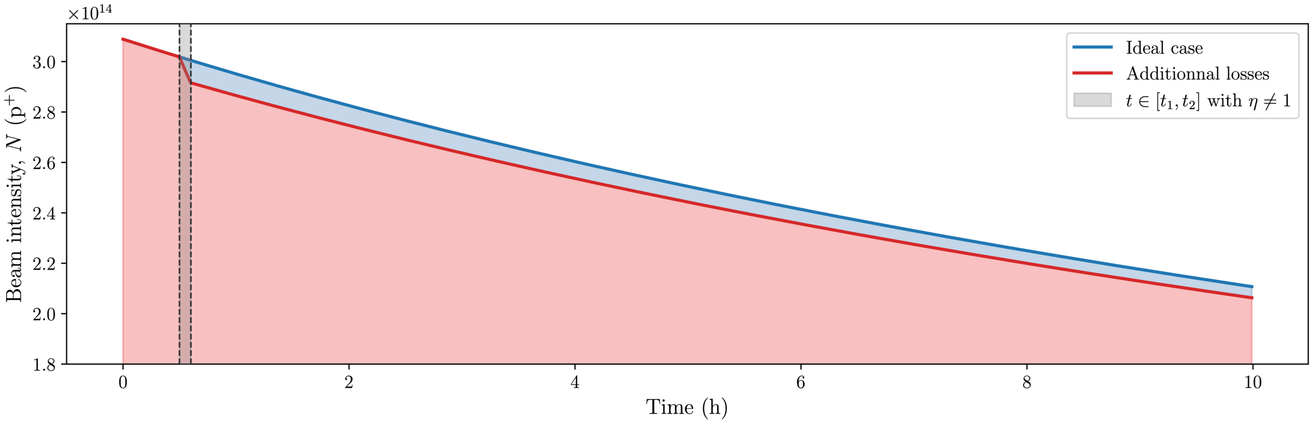
Experimental Framework

Machine Development

2023 Operation

Figure of Merit for collider: burn-off efficiency

- In a luminosity-leveled collider, the number **of injected protons is critical, provided that they burn-off**
- **Hence, protons lost early** heavily impact the **integrated luminosity** of a fill



- **Burn-off Efficiency**: ratio of burn-off losses to total losses
  - Directly quantifies the **efficiency** of the collider
  - Single parameter which also contains **luminosity-normalised losses**:
  - More interesting than beam lifetime

$$\eta \equiv \left[\frac{dN}{dt}\right]_{\text{bo}} \Big/ \left[\frac{dN}{dt}\right]_{\text{total}} = \frac{\sigma_{\text{pp}}\mathcal{L}}{\sigma_{\text{pp}}\mathcal{L} + R_\ell N}$$

$$\left(\frac{1}{\eta} - 1\right) = \frac{R_\ell N}{\sigma_{\text{pp}}\mathcal{L}}$$

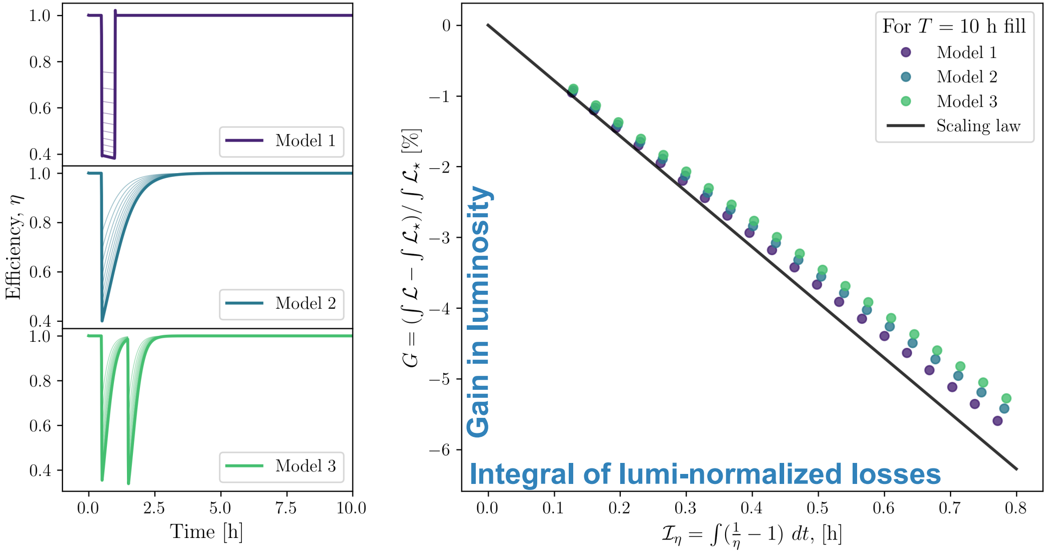
Figure of Merit for collider: burn-off efficiency

- **Integral** of efficiency linked to **Relative Gain** in integrated luminosity: (for short losses at the start of a fill)
- **If η = 0.5 for 30 minutes**, reduction of **integrated luminosity of −3 %** for 10 h of proton-proton collisions

*** Simple scaling law**

$$G \sim -r_0 \left[\frac{r_0 T + 2}{r_0 T + 1}\right] \cdot \int_0^T \left(\frac{1}{\eta} - 1\right)$$

lumi-normalized losses

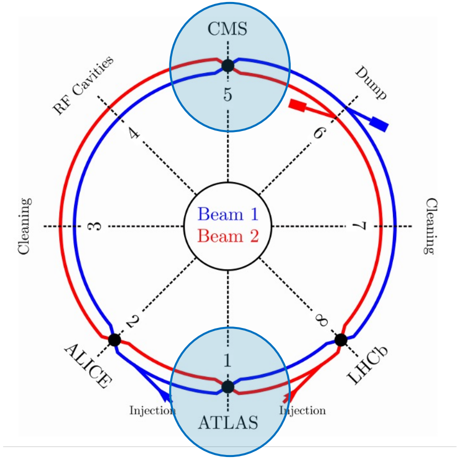


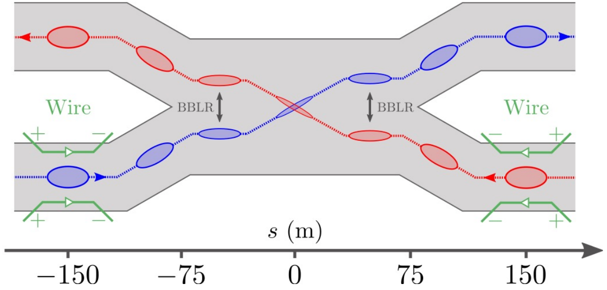
*** General concept, applicable to any losses, not only BB.**

Run 3 BBCW hardware

- BBCW embedded in **IP1/IP5 TCT collimators**
- **Demonstration hardware**, used during MD and operation
- Used in **two-jaws configuration** (octupolar corrector)
- Only used at **end of fill** (β^* = 30 cm)

Parameter		MD	Operational Fill	
Wire current	I_w	350	350	(A)
Wire pos. IP1|IP5	d_w	9.2 | 12.4	9.2 | 12.4	(mm)
Beam Energy	E	6.8	6.8	(TeV)
Bunch intensity	N_b	1.4×10^{11}	1.0×10^{11}	(p^+/b)
Beta at the IP	β^*	30	30	(cm)
Half-crossing	$\theta_c/2$	130 – 160	160	(μrad)
Num. of bunches	n_b	158	2413	
Bunches per train		48	48	



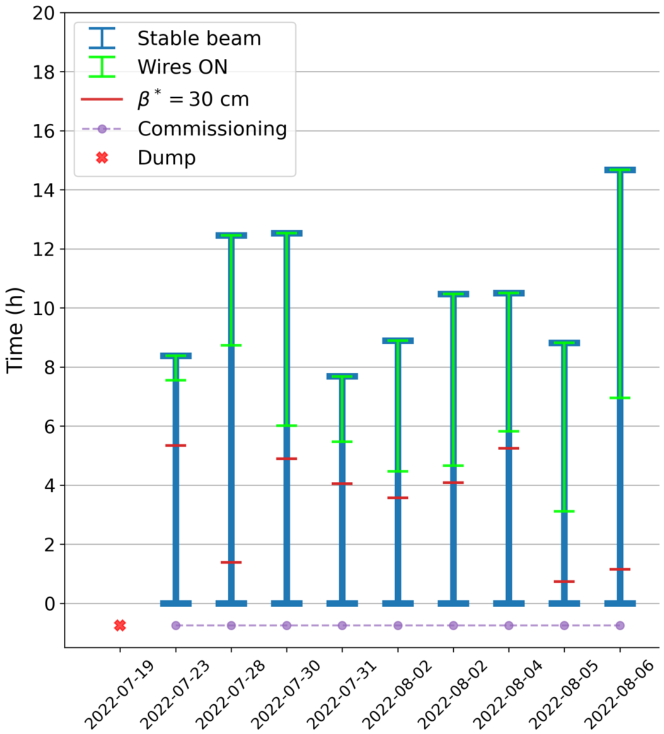


Commissioning and operation

- **Parasitic (end-of-fill) commissioning during intensity ramp-up**
  - 5th axis alignment using the collimator alignment system
  - Tune feed-forward system to compensate quadrupole effect
  - Implementation of wire powering in LHC cycle

- **In 2022**, used in 60+ fills, caused **6 beam dumps**:
  - **No beam dumps from instabilities**
  - 2 dumps from orchestration (IDLE power supply)
  - 4 dumps from excessive leakage current (earth fault)
  - Beam 2 wires repaired and used for the rest of Run 3
  - Beam 1 wires no longer operational

- **In 2023**, used in 36 fills, caused **0 beam dumps:**
  - Discussions to repair B1 wires for 2024



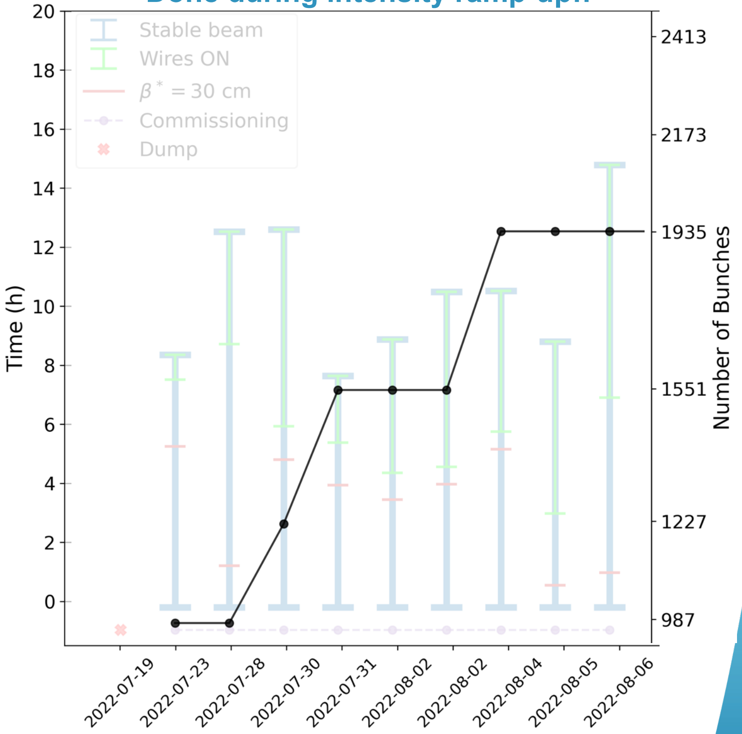
Commissioning and operation

- **Parasitic (end-of-fill) commissioning during intensity ramp-up**
  - 5th axis alignment using the collimator alignment system
  - Tune feed-forward system to compensate quadrupole effect
  - Implementation of wire powering in LHC cycle

- **In 2022**, used in 60+ fills, caused **6 beam dumps**:
  - **No beam dumps from instabilities**
  - 2 dumps from orchestration (IDLE power supply)
  - 4 dumps from excessive leakage current (earth fault)
  - Beam 2 wires repaired and used for the rest of Run 3
  - Beam 1 wires no longer operational

- **In 2023**, used in 36 fills, caused **0 beam dumps:**
  - Discussions to repair B1 wires for 2024

***Done during intensity ramp-up!!**



Introduction

Experimental Framework

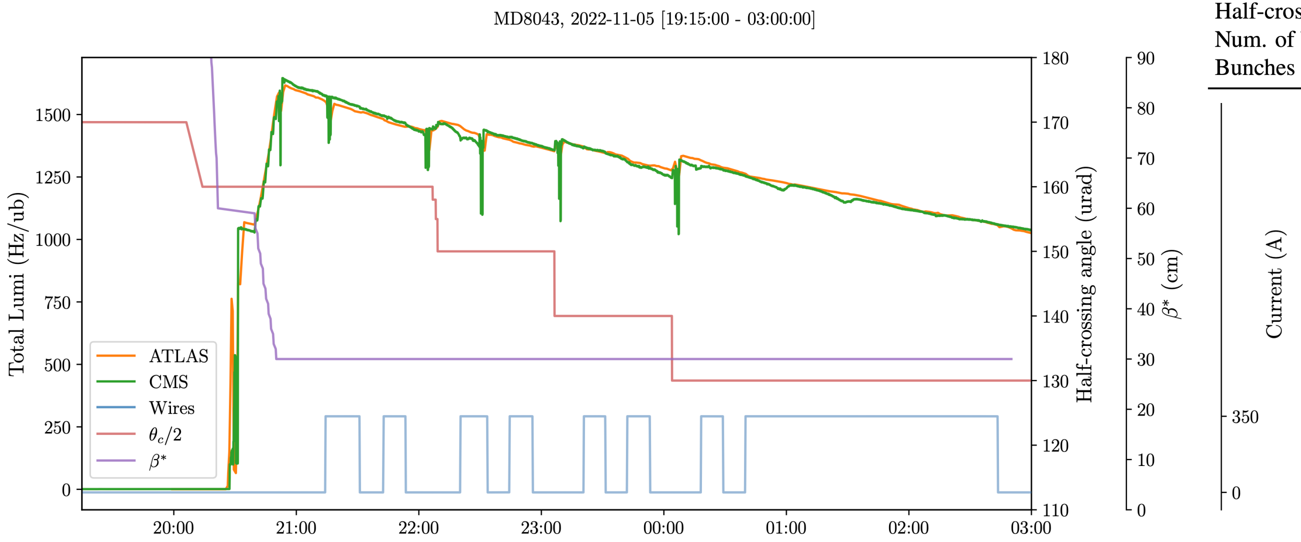
Machine Development

2023 Operation

Machine Development (Nov. 2022)

- Pushing for a **high BB regime**:
  - Small crossing angle
  - High bunch intensity
- Cycling of **BBCW ON/OFF**, measuring bunch-by-bunch losses

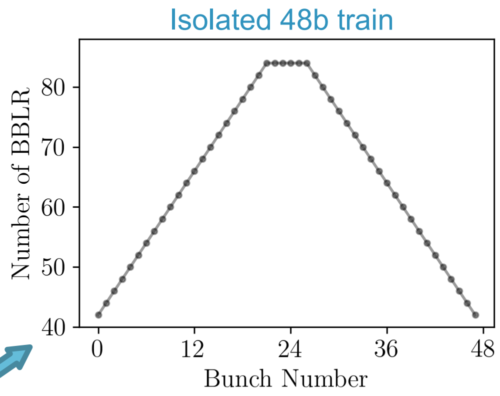
Parameter		MD
Wire current	I_w	350
Wire pos. IP1|IP5	d_w	9.2 | 12.4
Beam Energy	E	6.8
Bunch intensity	N_b	1.4×10^{11}
Beta at the IP	β^*	30
Half-crossing	$\theta_c/2$	130 – 160
Num. of bunches	n_b	158
Bunches per train		48

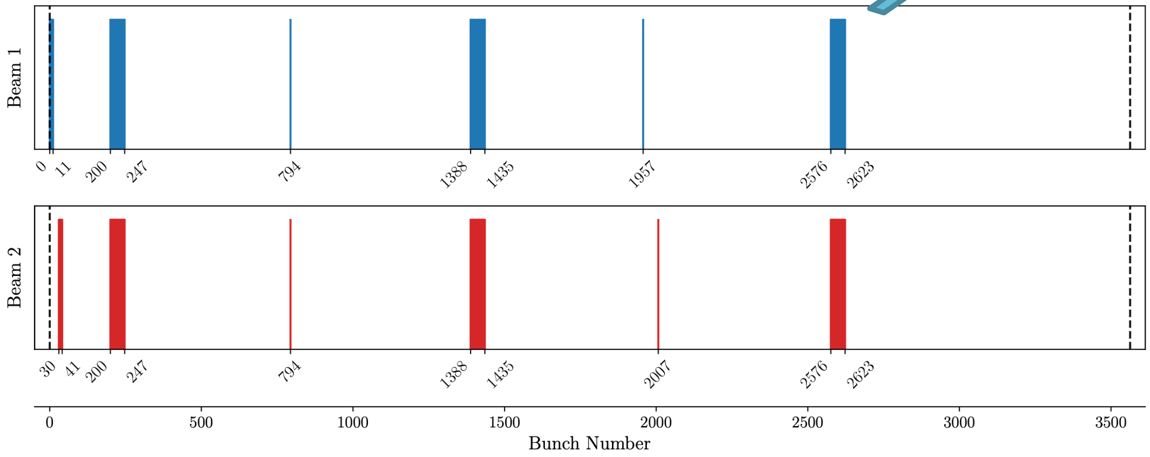


Machine Development (Nov. 2022)

- Filling pattern designed to
  - **Reduce e-cloud** effects
  - **Isolate beam-beam** effects, only IP1 and IP5 collisions/interactions

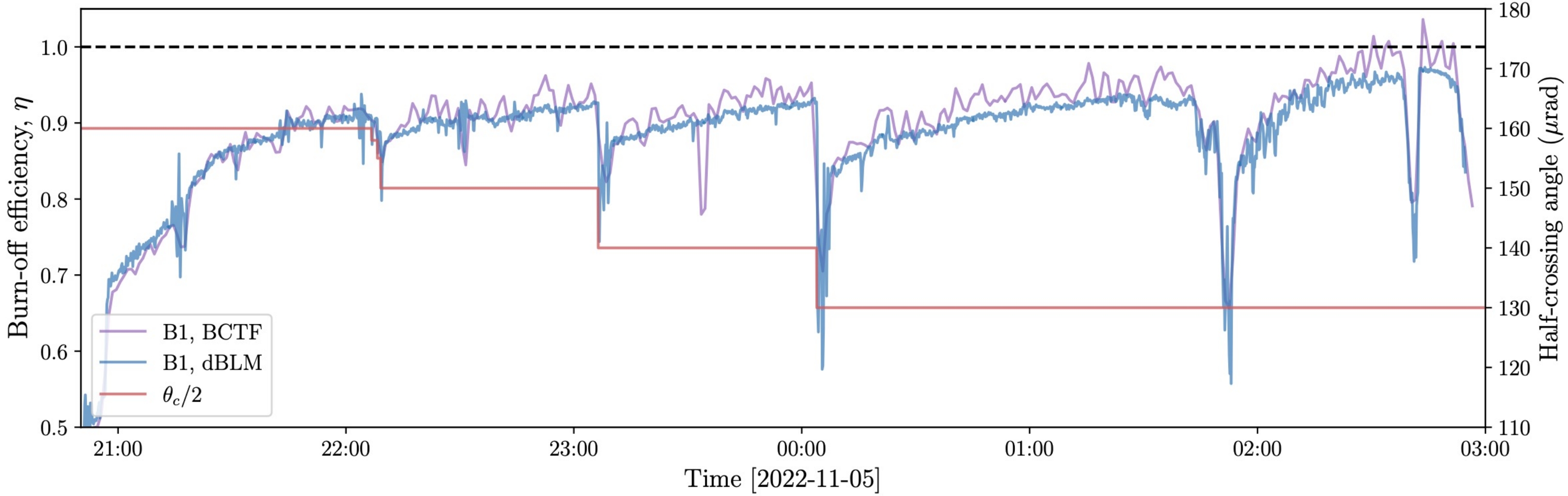
- **Rule of thumb:** BB effects scale according to the **number of BBLR**
  - Around 40 in IP1 and IP5 for the middle bunch of a train





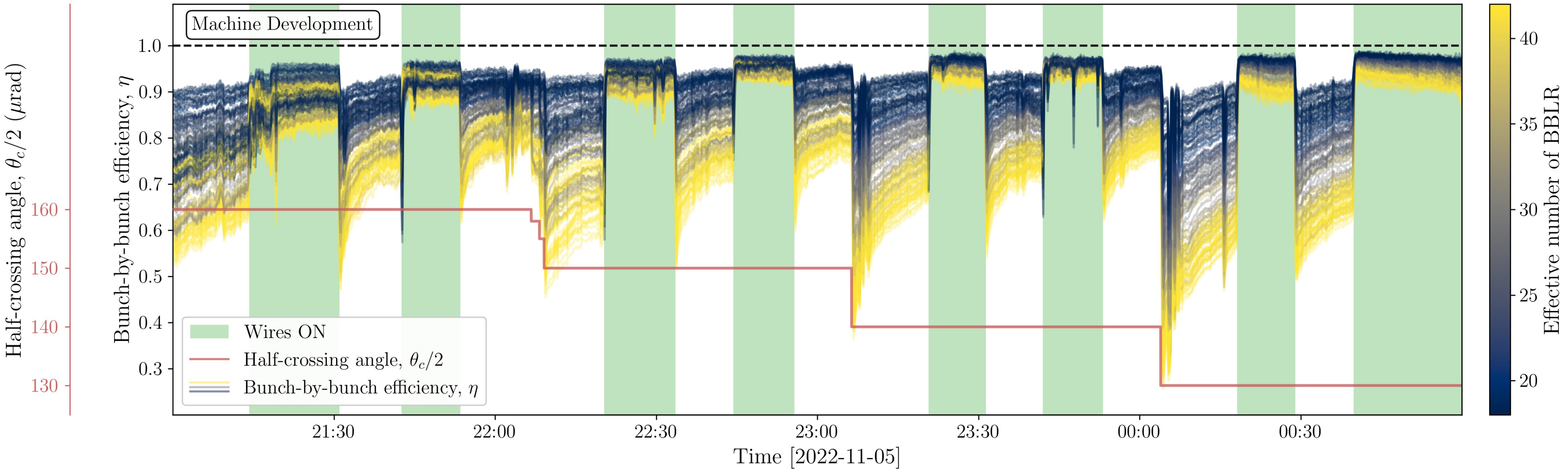
Measuring the efficiency

- Bunch-by-bunch efficiency can be measured combining:
  - Bunch-by-bunch luminosity
  - Bunch-by-bunch losses
    1. Derivative of BCTF (noisy)
    2. **Calibrated dBLM measurements**

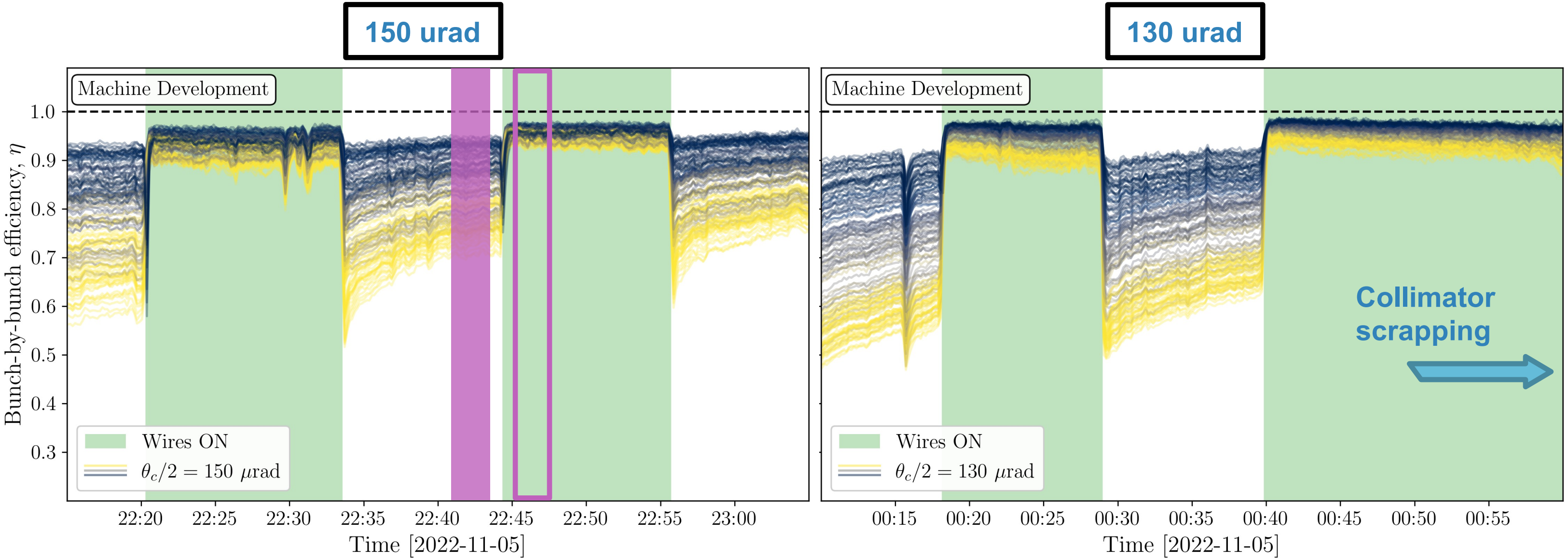


MD: successful BBCW compensation

- **Natural** efficiency improvement on a time scale of about **30 – 60 min**
  - Come at the cost of **significant and unrecoverable proton losses**
- **Immediate** efficiency improvement when powering the wires
  - Reduces the bunch-by-bunch variation
  - Other non-beam-beam losses remain in the machine



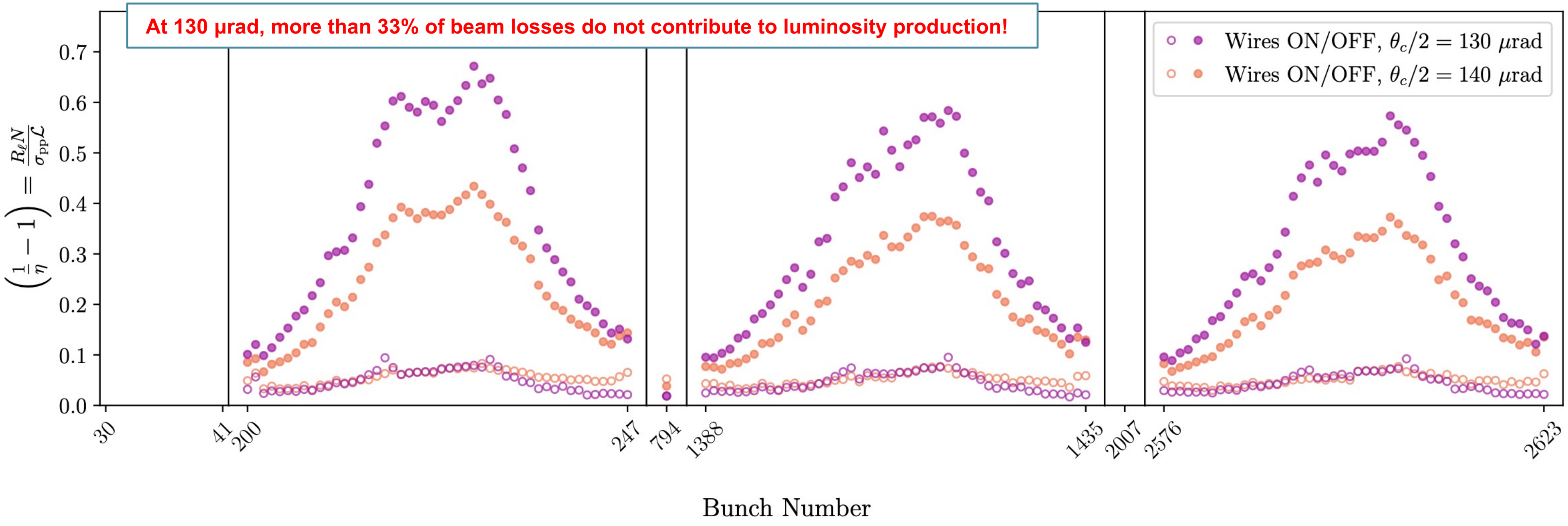
MD: successful BBCW compensation



At a given time, how do the losses from different bunches compare?

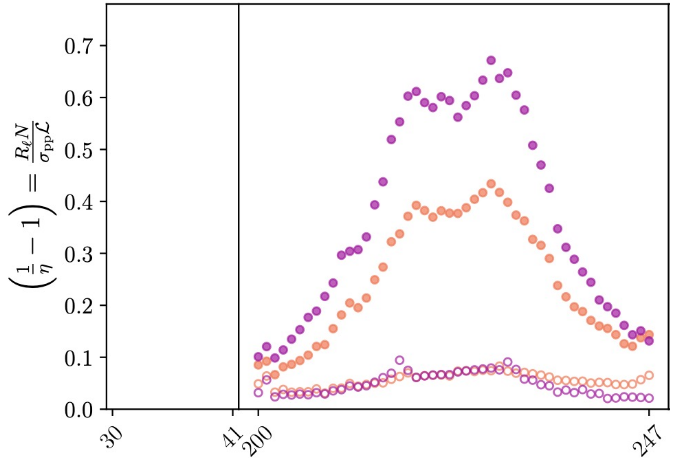
Bunch-by-bunch signature

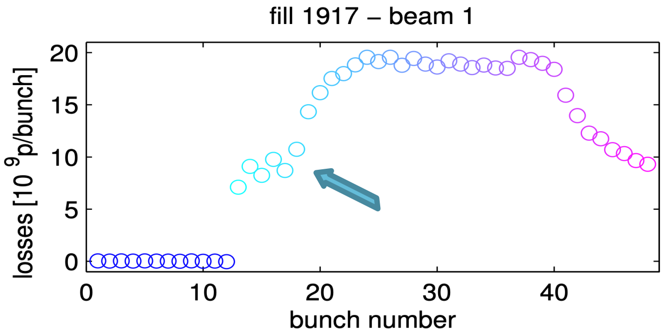
- **Luminosity-normalized losses**: implicitly includes variation of bunch intensity and emittance
- With **wires ON**: reduction of the crossing angle **does not affect** the normalized losses
- **Clear signature observed**: plateau at ¼ of the train and local maxima around the middle



Bunch-by-bunch signature

- **Luminosity-normalized losses**: implicitly includes variation of bunch intensity and emittance
- With **wires ON**: reduction of the crossing angle **does not affect** the normalized losses
- **Clear signature observed**: plateau at ¼ of the train and local maxima around the middle





A sight from the past, 6400 LHC fills ago!

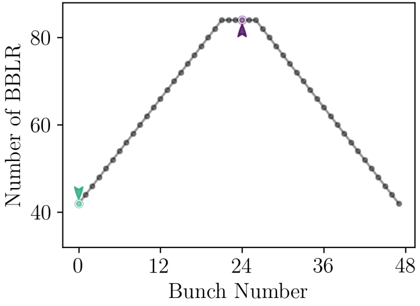
W. Herr et al. (2013): "Long-Range Beam-Beam Effects in the LHC"

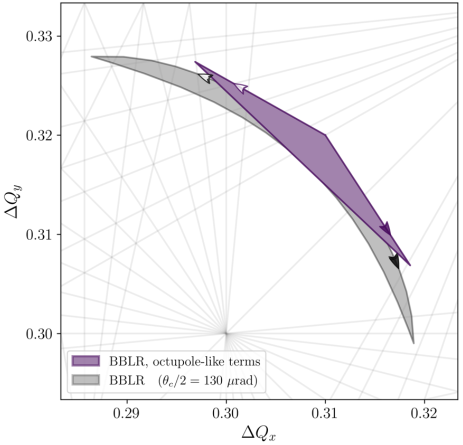
Evaluating BB Strength

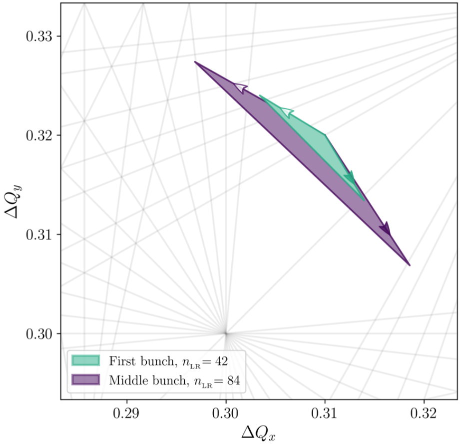
- Recall: BB effects scale according to the **number of BBLR,** rule of thumb
- **Not all BBLRs are equal** (beta functions, beam-beam separation, etc.)
- **Detuning** is a subset of RDTs, let's estimate the **BB strength via the area of the footprint** $\mathcal{A}$

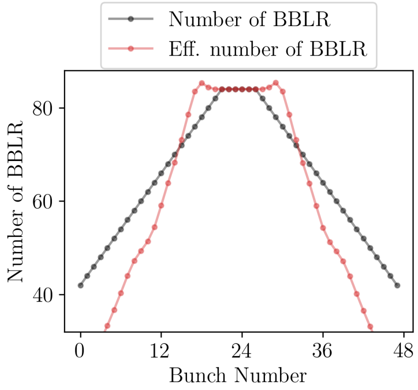
➡ **One recognizes the experimental b-by-b signature!**

$$n_{\mathrm{LR}}^{\mathrm{eff}} = \mathcal{A} \cdot \left[n_{\mathrm{LR}}^{\mathrm{mid}} \Big/ \mathcal{A}^{\mathrm{mid}} \right]$$



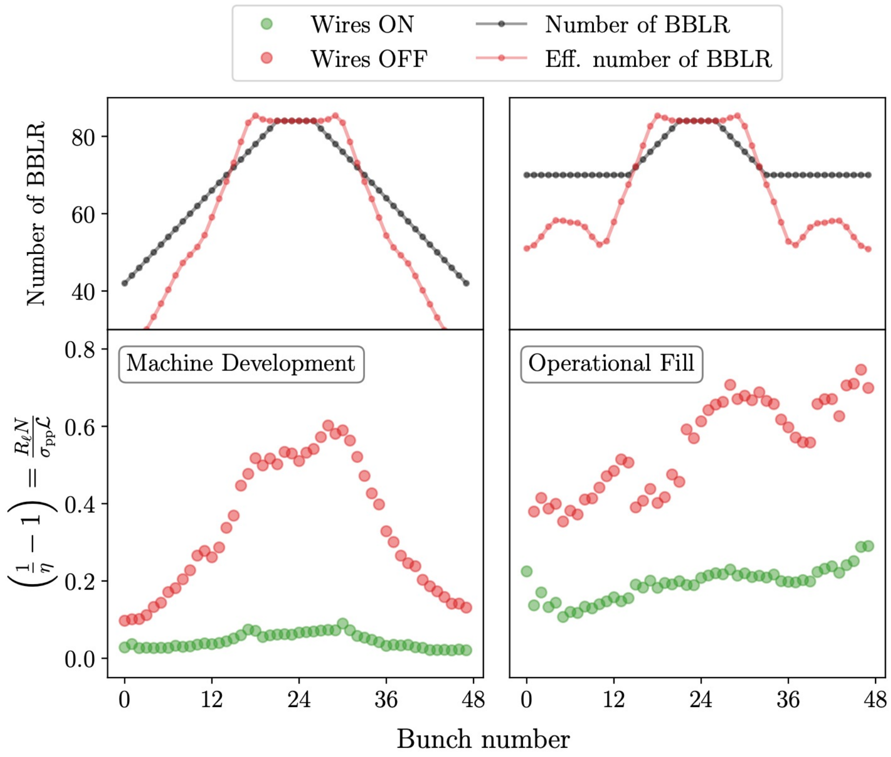






BB Strength and b-by-b signature

- Fundamental link between **RDTs, DA and beam losses** still to be understood
- Signature **depends on the filling pattern**
  - Future MDs should aim at studying various patterns
- Operational fills are less simple…
  - Interaction in **IP2 and IP8**
  - **E-cloud effects**



Introduction

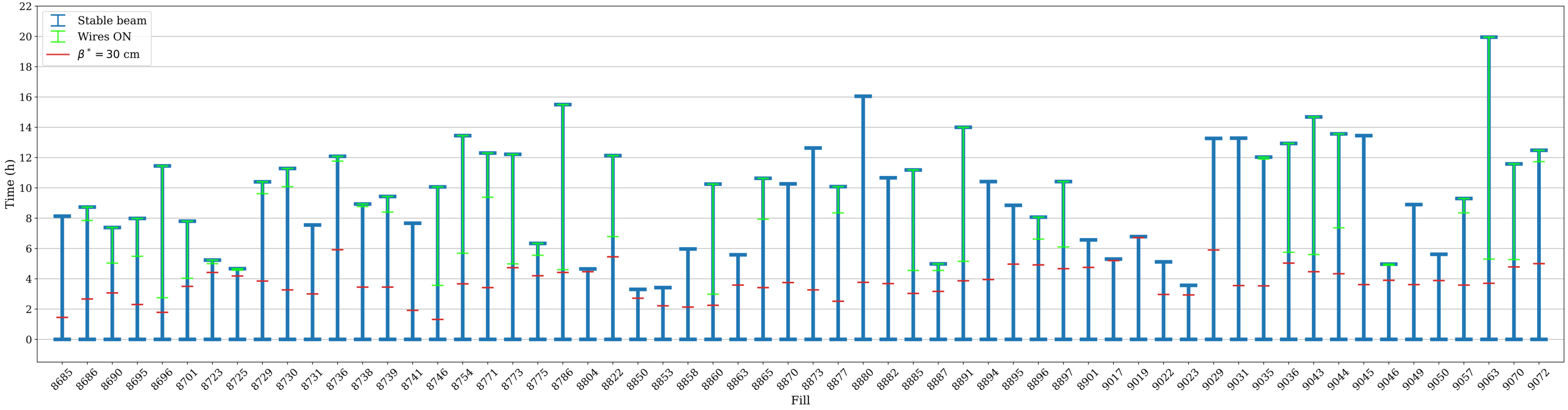
Experimental Framework

Machine Development

2023 Operation

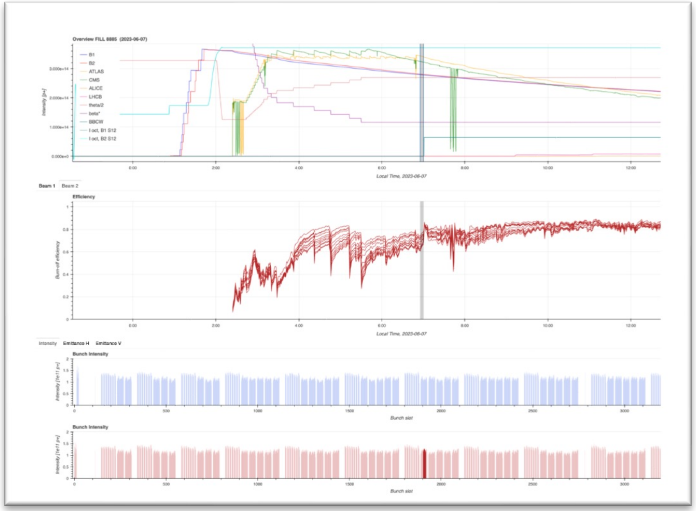
2023 Operational fills

- Fills from 2023, with β^* = 30 cm, >200 bunches and reaching stable beam:
  - **Wires ON : 36**
  - **Wires OFF: 24**
- **No beam dumps**
- Wires only turned on **relatively late in the fills**… significant number of protons already lost!
- **In general, not BB dominated regime**

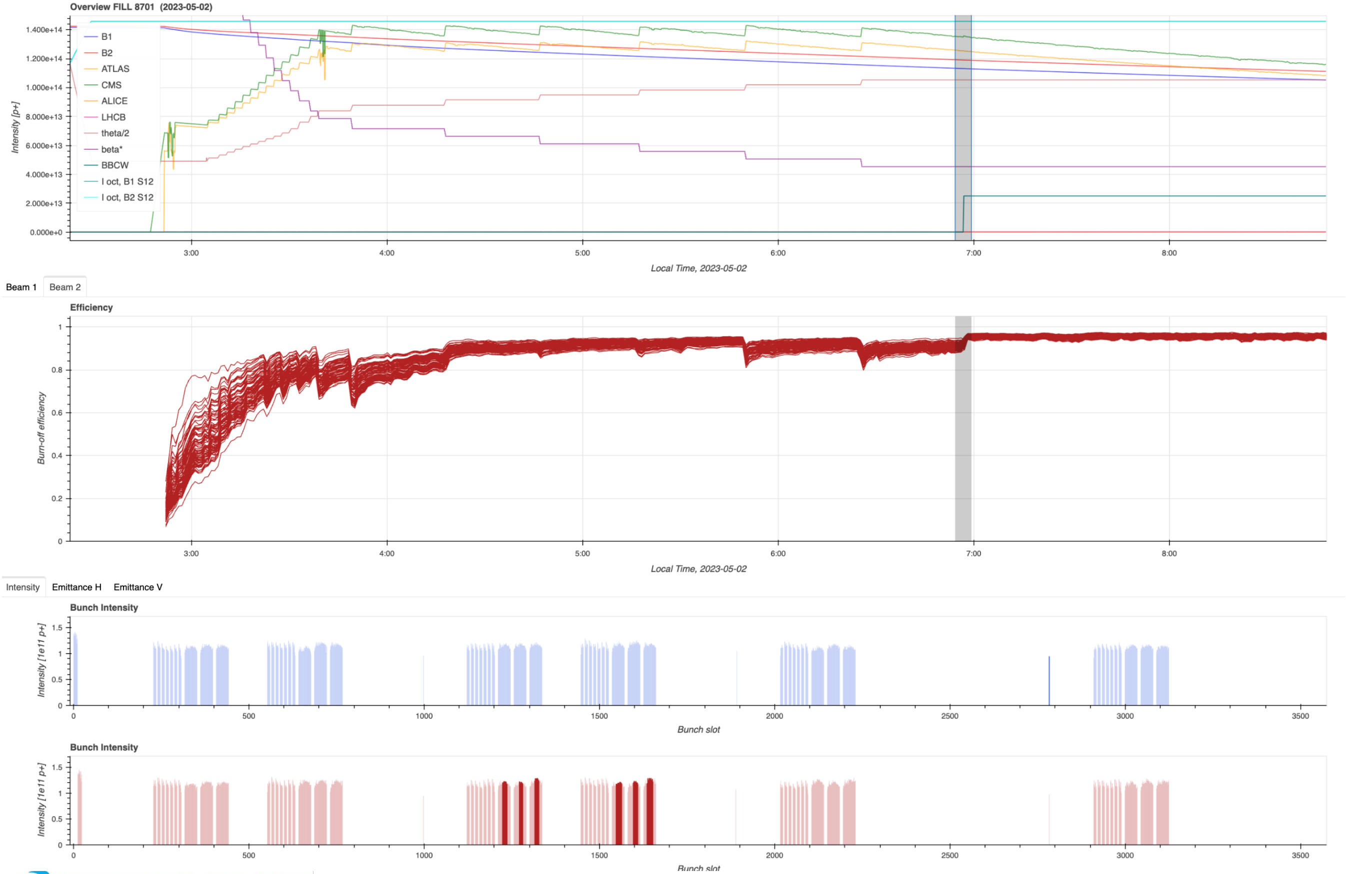


Monitoring effort

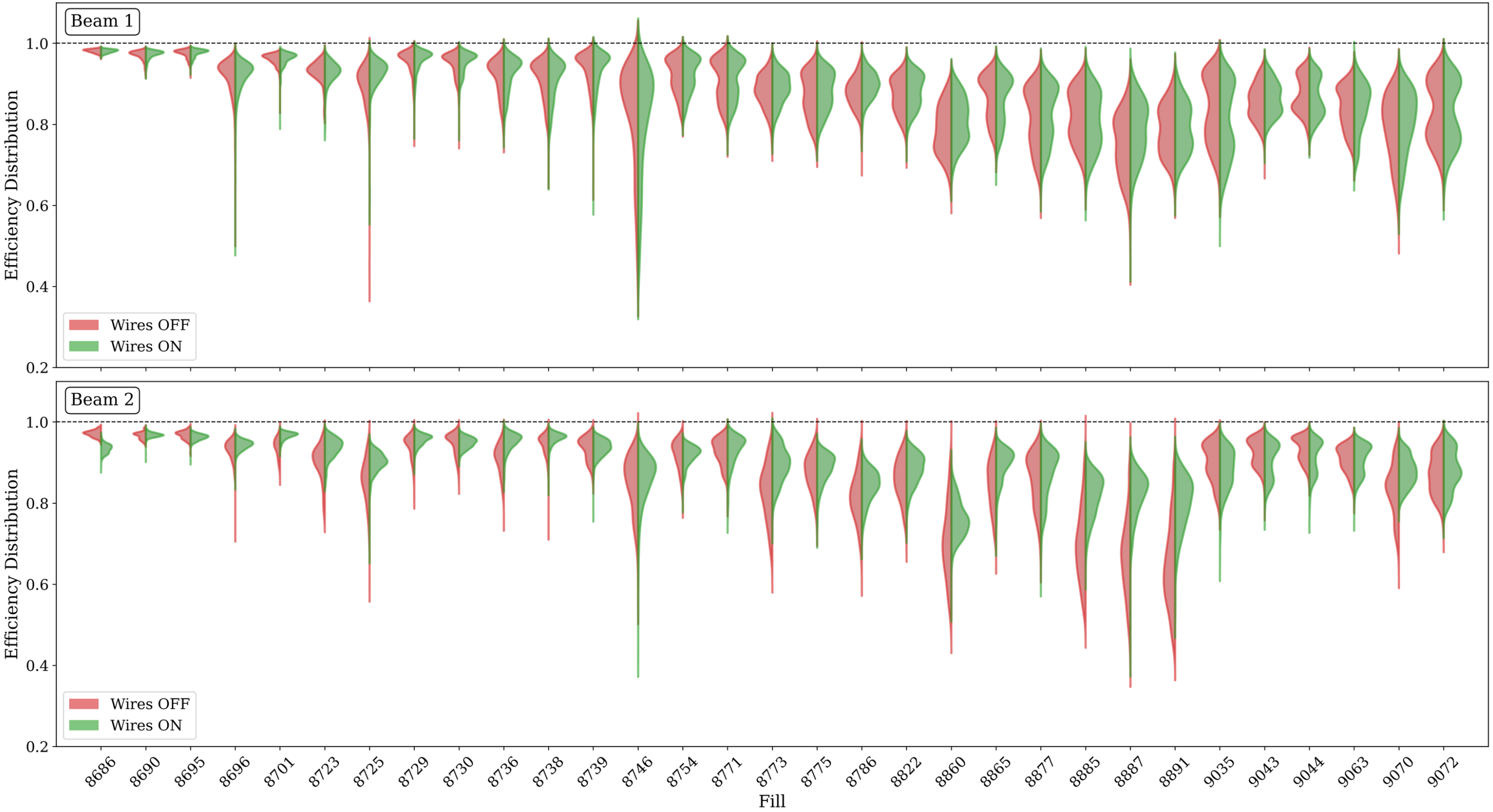
- Put together a website to access fill data rapidly:
  https://bblumi.web.cern.ch/Monitoring/
- Interactive interface with bunch-by-bunch data
- Should be pushed to a more centralized dashboard environment



Natural cleaning of the machine



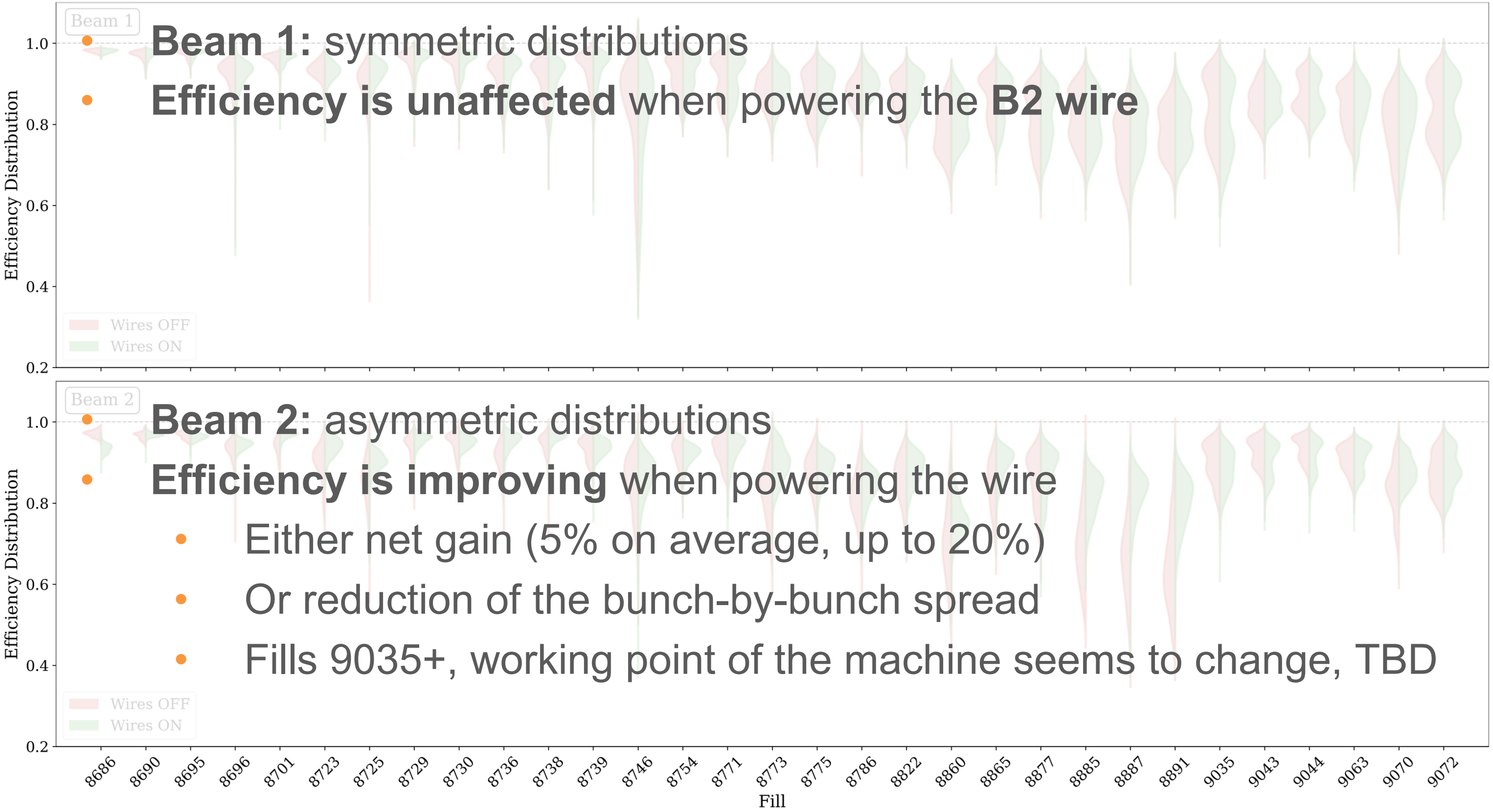
General trend: net positive impact



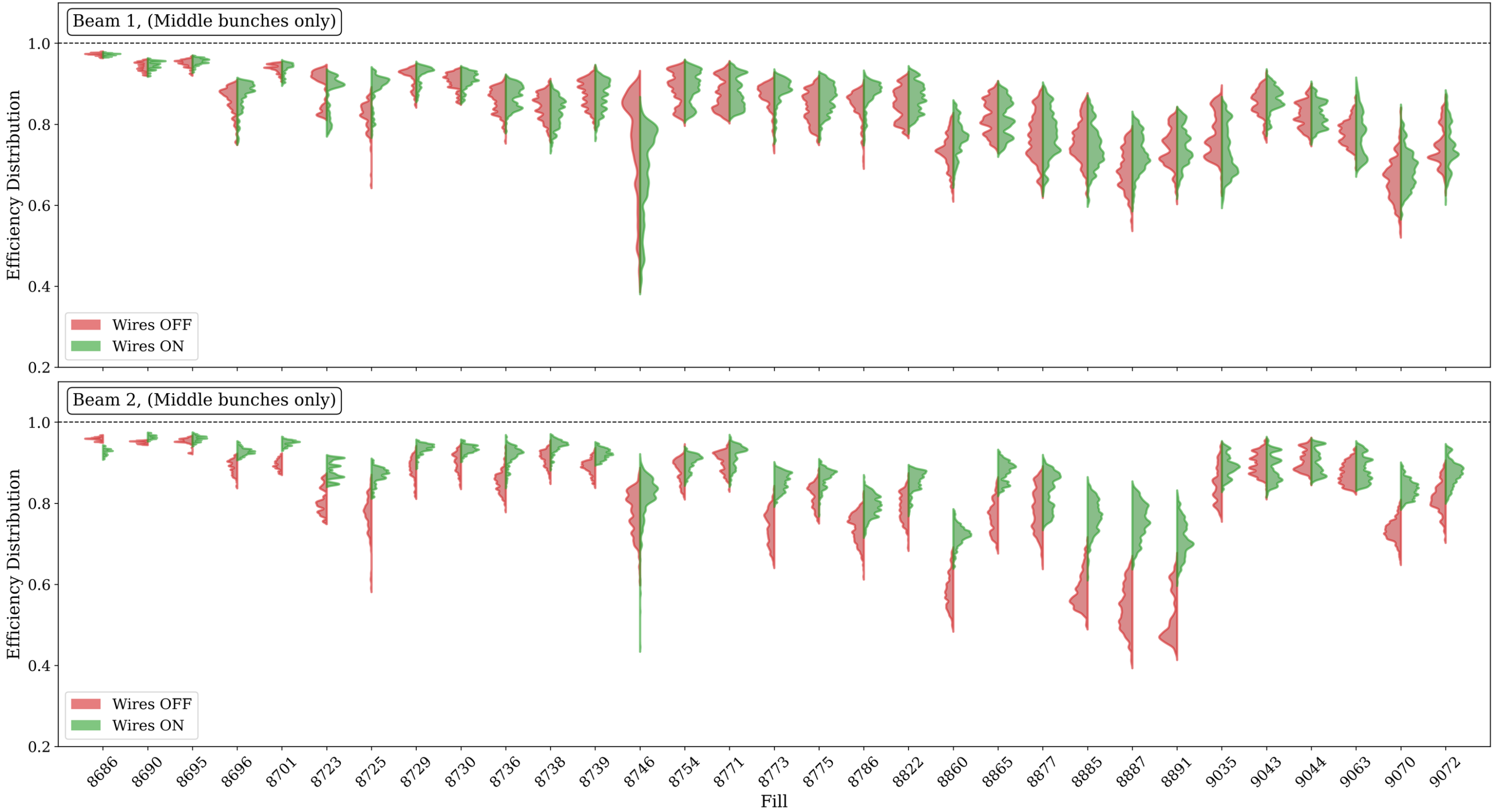
General trend: net positive impact

- **Beam 1:** symmetric distributions
- **Efficiency is unaffected** when powering the **B2 wire**

- **Beam 2:** asymmetric distributions
- **Efficiency is improving** when powering the wire
  - Either net gain (5% on average, up to 20%)
  - Or reduction of the bunch-by-bunch spread
  - Fills 9035+, working point of the machine seems to change, TBD



Trend for middles bunches (high beam-beam)



Summary

- Figure of merit: **Burn-off Efficiency**
  - Includes lumi-normalized losses
  - Linked to the **relative gain in integrated luminosity**
  - Measured from dBLM or BCTF

- BBCW **wires successfully compensate BB** effects in Run 3, up to 130 μrad and 1.4×10^{11} p/b
  - Fundamental **advantage over LHC octupoles**, especially with small crossing angle (non-octupolar footprint)
  - Can be enhanced further by **approaching closer** to the beam

- **Operation:**
  - **Net positive impact in 2023**, could be improved by powering earlier
  - Monitoring effort, **all data is readily available online**
  - **B1** should be repaired for 2024, to be used in combination with B2

- **Machine Development:**
  - Showed a **clear BB compensation** for IP1 and IP5
  - Highlighted a **distinct bunch-by-bunch signature**, in good agreement with effective signature from footprint studies
  - Fundamental link **between RDTs, DA and beam losses** still to be understood
  - Future MDs to study **various bunch-by-bunch signatures**?

Thank you!