HiLumi
HL-LHC PROJECT

Operational experience with ions

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On behalf of the LHC collimation team

Special thanks to: J.M. Jowett, M.Schaumann, A. Lechner.

CERN

LHC Collimation Project CERN

Outline

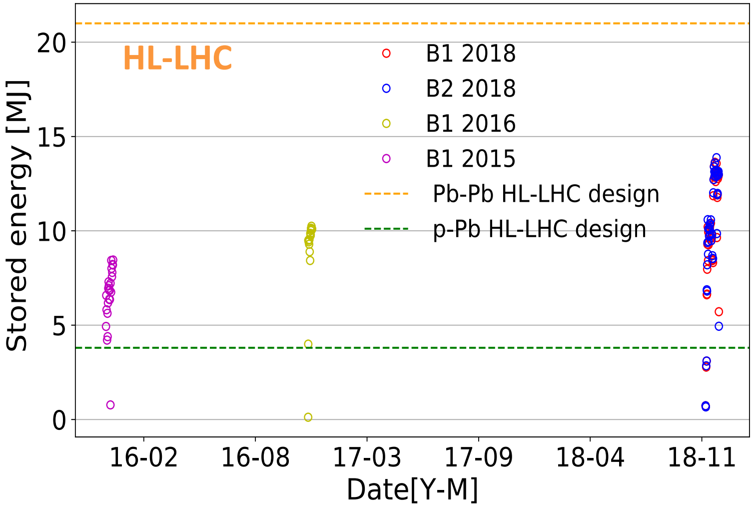
- Introduction
- Review of relevant aspects in Run II ion runs
  - Collimator settings overview
  - Heavy-ion simulations and implication during commissioning
  - Run II cleaning performance overview
  - 2018 dumps triggered in IR7
- Highlights from the crystal collimation tests with ion beams
- Run II Pb-Pb BFPP losses and mitigation
- Luminosity reach with present upgrade scenarios
- Conclusions

Introduction

- The **HL-LHC beam intensity** poses serious challenges on the collimation system performance specially for ions.
  - **Factor 100 worse halo cleaning efficiency** than for protons **due to fragmentation processes**.
    - ➡ Could be limiting if nothing is done (more details in A. Lechner's talk).
  - Risk of magnet quenches in the IR's DS due to **BFPP losses.**

Run II heavy-ion runs

	2015 Pb-Pb	2016 p-Pb	2018 Pb-Pb
β* IP1/2/5/8	0.8/0.8/0.8/3	0.6/2/0.6/1.5	0.5/0.5/0.5/1.5
E_{Pb} [Z TeV]	6.37	4-6.5	6.37
Pb/bunch [10^8]	2.0	2.1	2.2
N_b	518	540	733
Peak L_{AA} [10^{27} cm^{-2} s^{-1}]	3.6	850	6.1

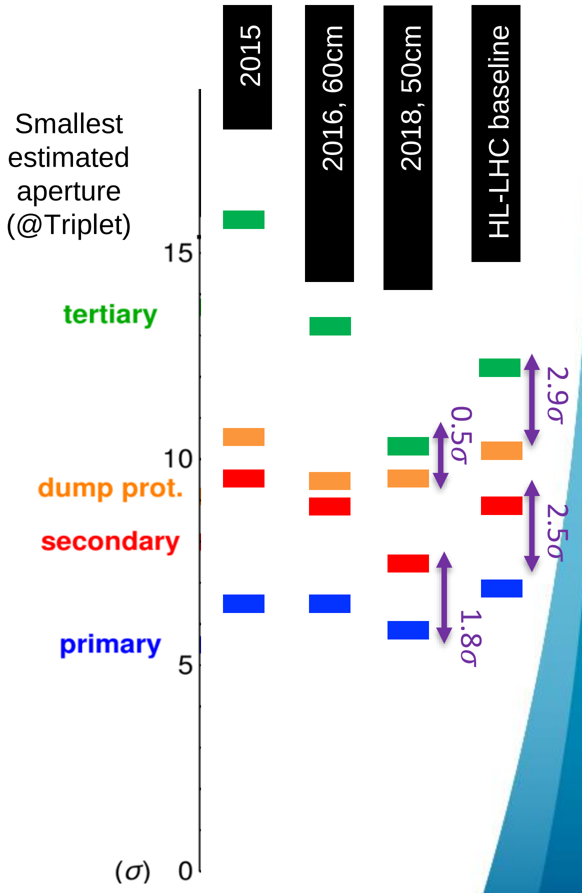


No magnet quenches from circulating ion beam losses but 7/48 fills dump on losses in IR7 in 2018.

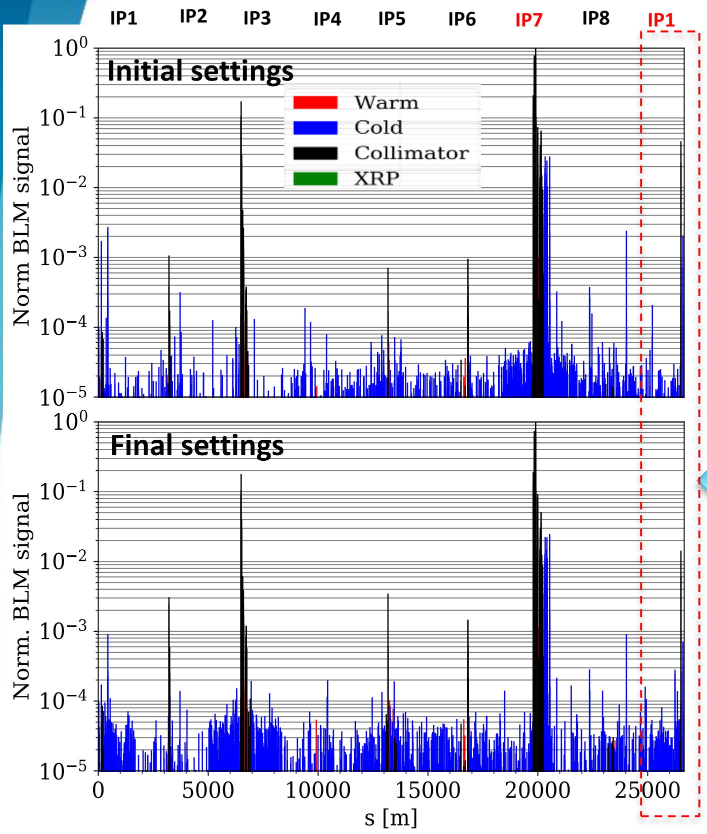
Collimator settings

- Collimator settings chosen close to the proton run ones (gain in set-up time).
- In 2018 we were operating significantly tighter than HL-LHC designed settings for the TCTs and IR7!
  - In 2018, some collimator settings were adjusted empirically and based on indications from simulations because too high losses were observed at them.

2018	Physics initial [σ, ε=2.5E-6]	Physics final [σ, ε=2.5E-6]
TCP/TCSG/TCLA IR7	**5.9/**7.7/11.8	**6.5(only left jaw B1)-5.9(B2) /**7.7/11.8
TCP/TCSG/TCLA IR3	17.7/21.3/23.7	17.7/21.3/23.7
TCTs IR5 **IR1**	10.6 **10.6**	13 **13(B1)-10.6(B2)**
TCT IR2	10.6	10.6
TCT IR8	17.7	17.7
TCDQ IP6 **TCSP IP6**	8.8 **8.8**	8.8 **8.8(B1)-13.2(only R B2)**
TCL4/5/6 IR1/5	17.7/17.7/out	17.7/17.7/out



Pb-Pb 2018 commissioning

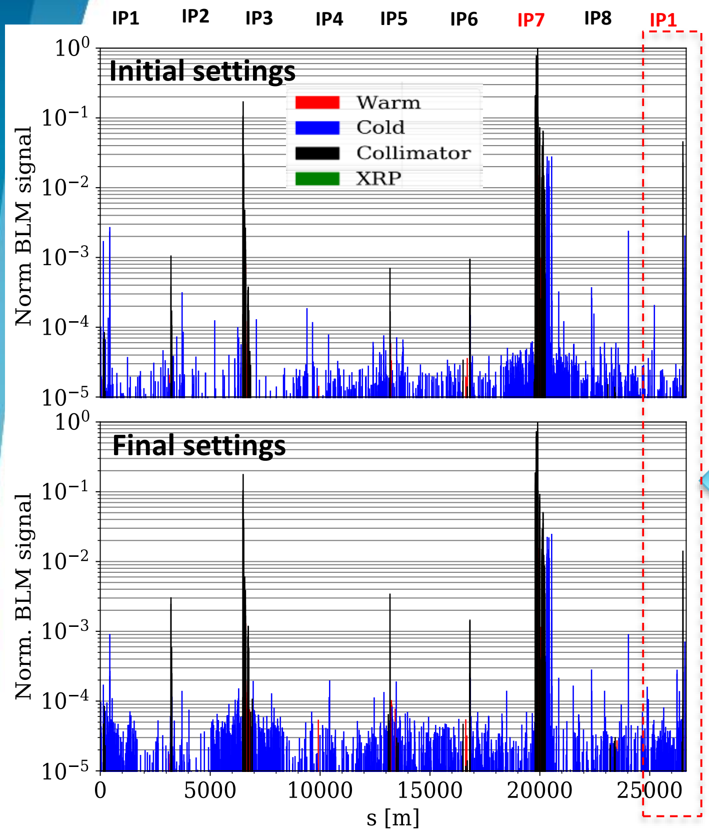


B1H-TCTPH in IP1

High losses observed on the **TCTPH in IP1** (even higher at End of Squeeze ~10% level of losses in the TCP).

Solution adopted: open the TCTPH by 2σ and TCP left by 0.5 σ. The losses were reduced to 1% level of losses in the TCP.

Pb-Pb 2018 commissioning



B1H-TCTPH in IP1

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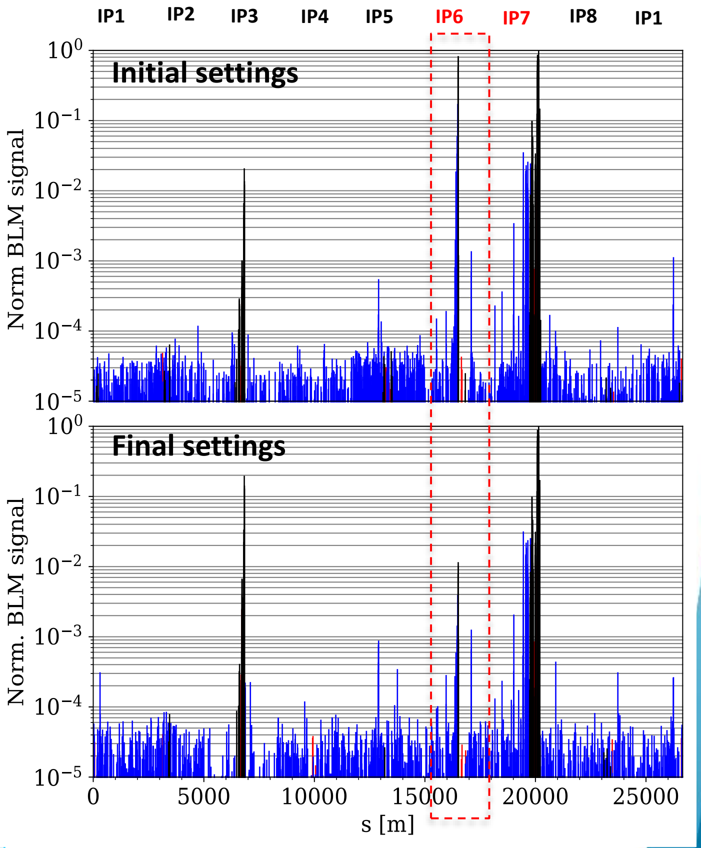
B2H-TCSP in IP6

High losses at the level of the TCP observed on the **TCSP jaw**.

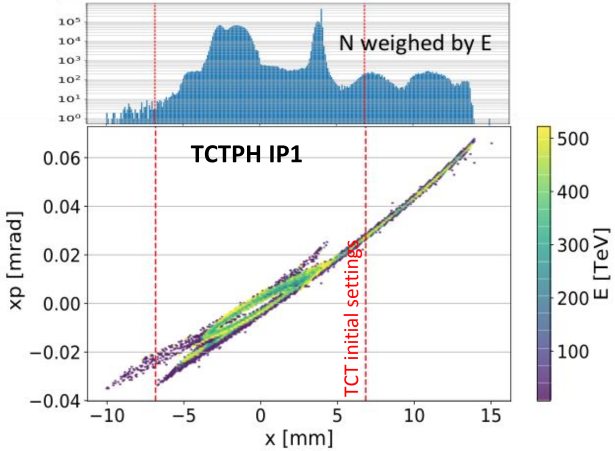
Solution adopted: opening the right jaw by 2 mm. The losses were reduced by 99%.

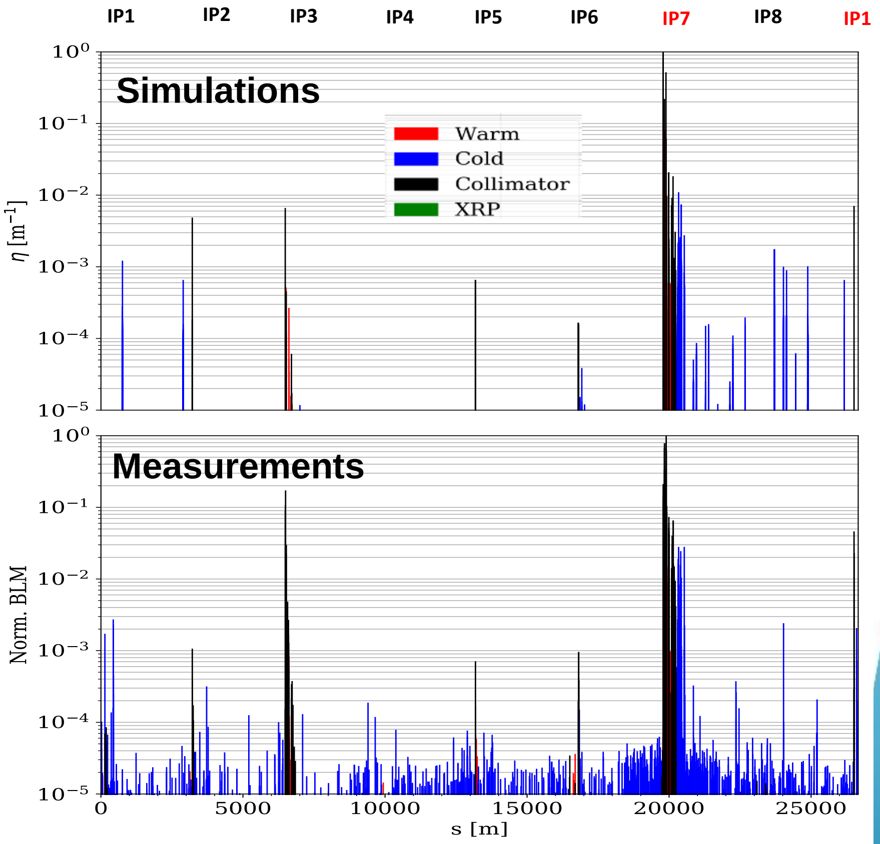


B1H IP1 TCTPH losses measurements and simulations

- **Collimator settings validation using hiSixtrack-FLUKA coupling** (Thanks to FLUKA team and P. Hermes)
  - Good modelling of heavy-ions loss mechanisms.
  - Collimator's debris tracked all along the ring.
  - No transport from loss location to BLM detectors.
- Losses were identified to be caused by **ion fragments scattered out of the left TCP (about 87%).**

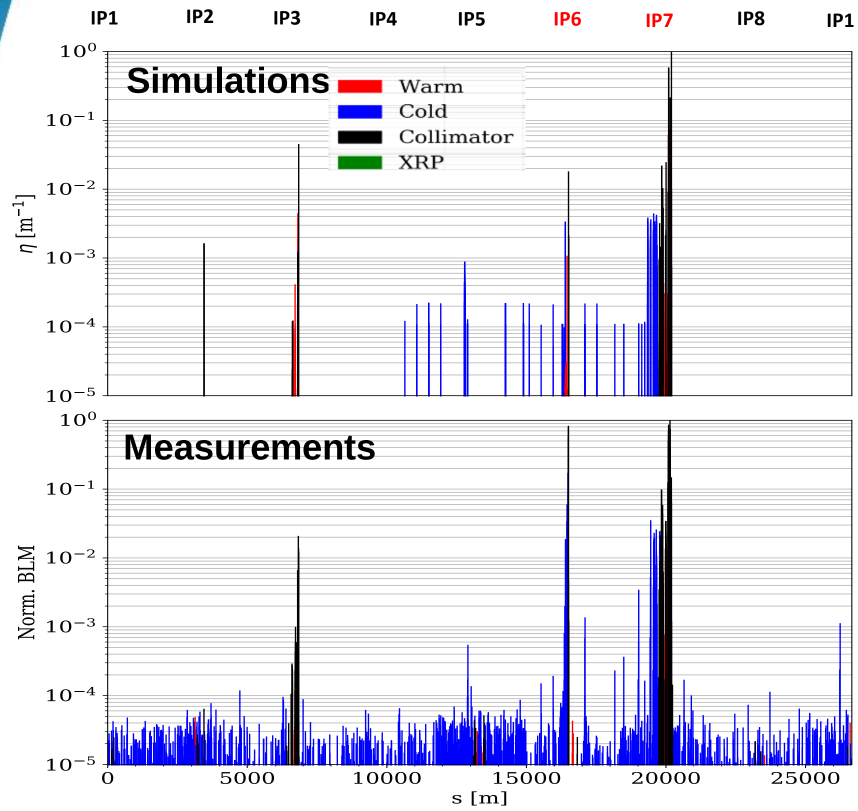
Solution: TCP left opened by 0.5 σ but not enough reduction, then open the TCTPH by 2σ because of less revalidation time needed.

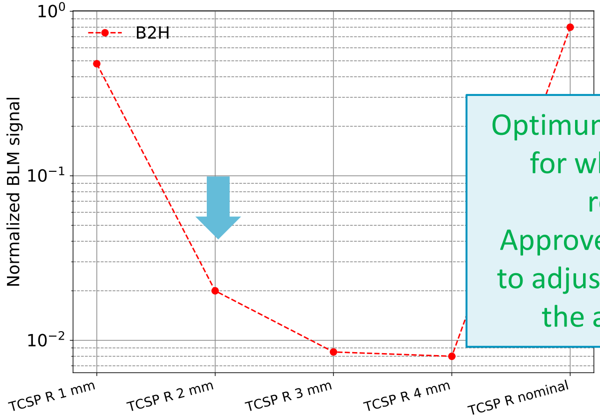




Quite good understanding of where the secondary beam is deposited in the ring but not in absolute values.

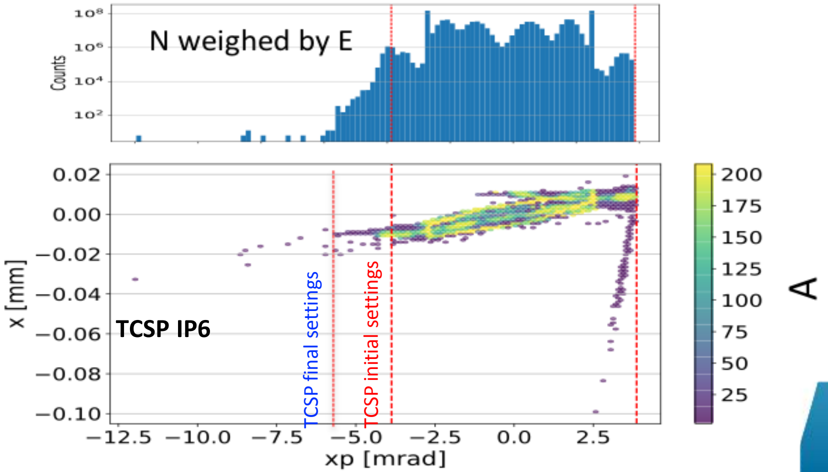
B2H IP6 TCSP losses measurements and simulations





Measurements

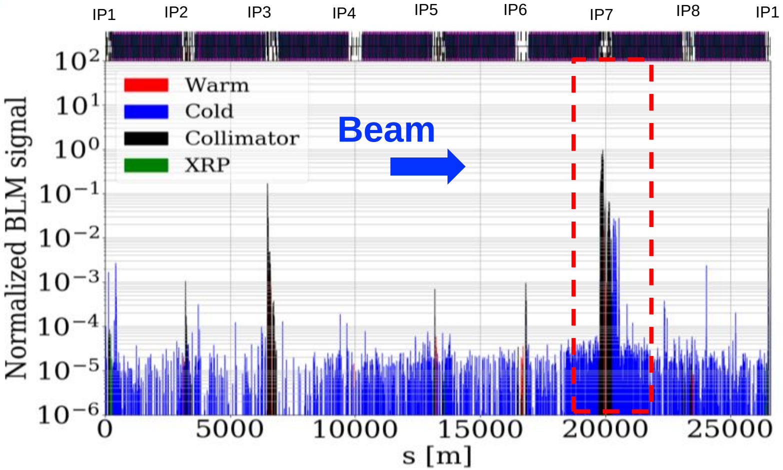
Optimum value accepted 2 mm for which the losses were reduced by 99%.
Approved by MP and required to adjust orbit interlock due to the asymmetric setting.

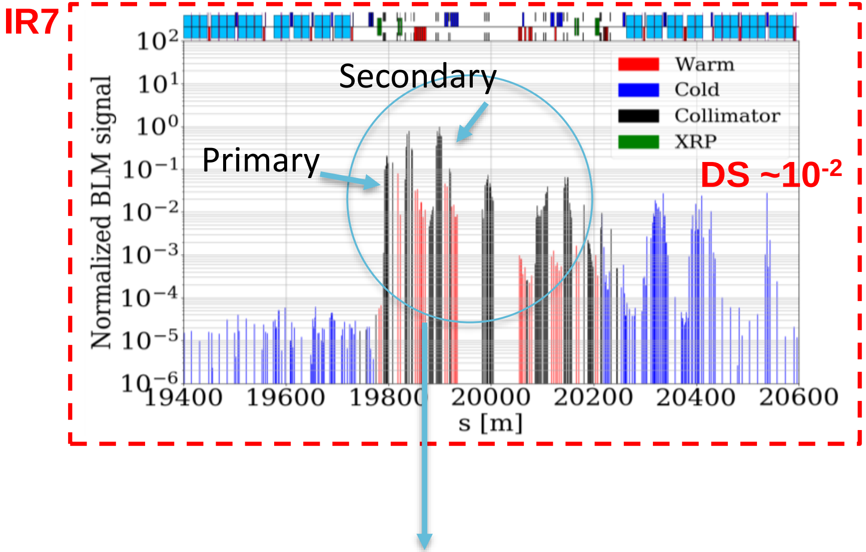


- Some discrepancies are present (detailed analysis on going).

Run II cleaning performance overview

Worse cleaning than for protons due to fragmentation, more cold spikes along the ring.





Apparent breakage of hierarchy:

- In 2018 the IR7 collimators were realigned but no change was observed in the distribution of losses.
- In addition, tests were performed by opening the TCSGs but again no change was observed in the distribution of losses.

➡ No broken hierarchy, TCSGs catch the leakage from the TCPs.

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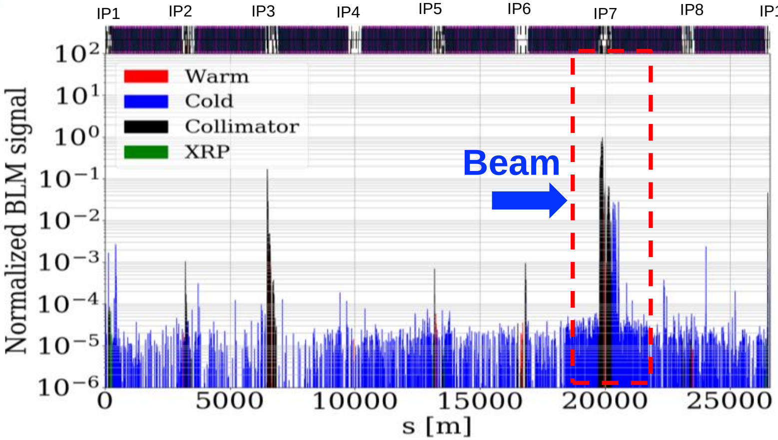
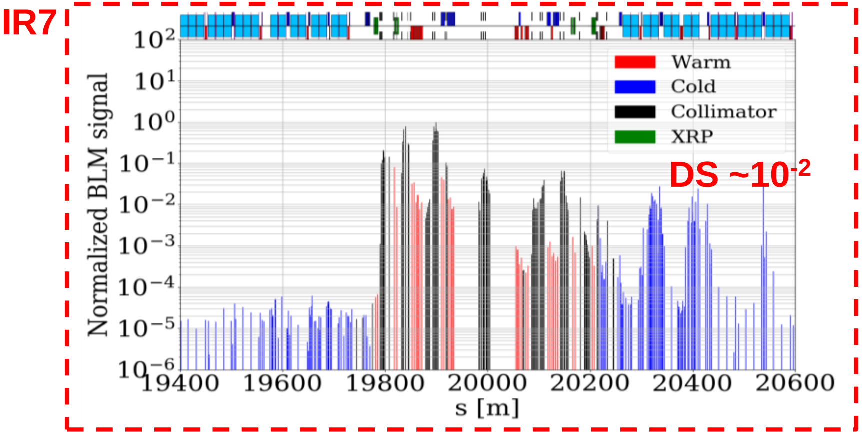
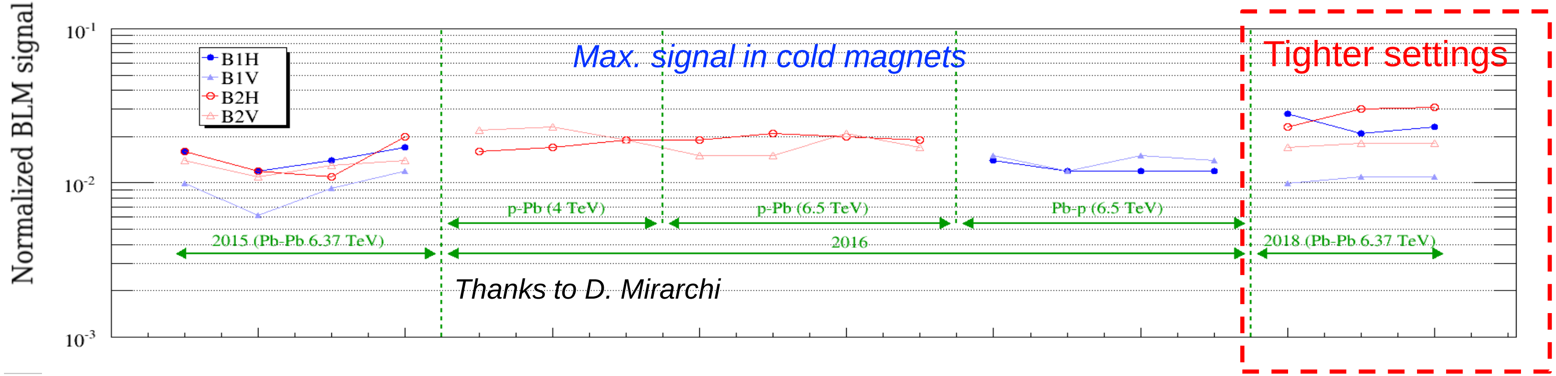
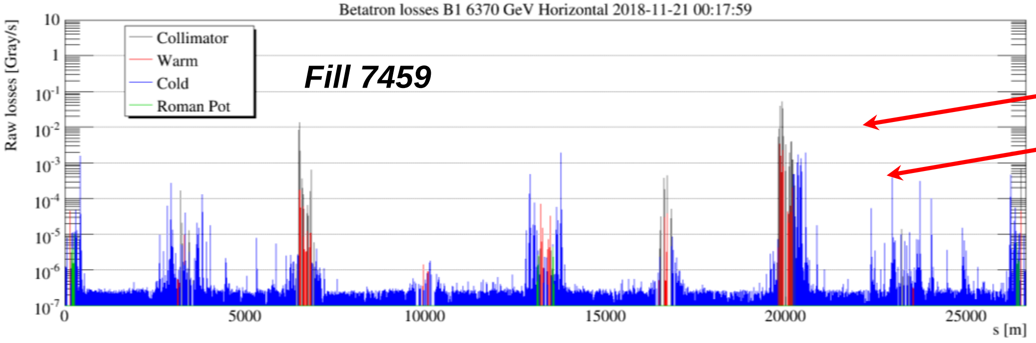






2018 dumps triggered in IR7



Limiting locations:

TCSG.A5L7.B1

MQ.13R7.B1

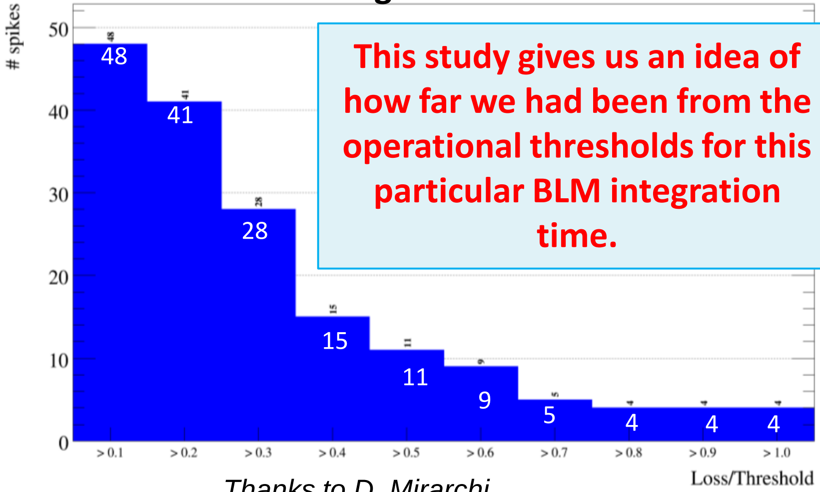
TCTPH.4L1.B1

Losses above BLM threshold (set at quench level)

- **7 dumps** with a similar signature out of 48 fills.
- Attributed to **horizontal trajectory oscillations** at 8-12 Hz and found to be **compatible with horizontal movement of Q5R2.**
- ADT and 100Hz BLMs at TCPs show that they were always present but **only observed in 2018** due to an enhancement of the effect because the **beam is squeezed to 50 cm β* in IP2.**

A better cleaning could contribute to mitigate this dumps.

1.3 s BLM integration time window



This study gives us an idea of how far we had been from the operational thresholds for this particular BLM integration time.

Thanks to D. Mirarchi

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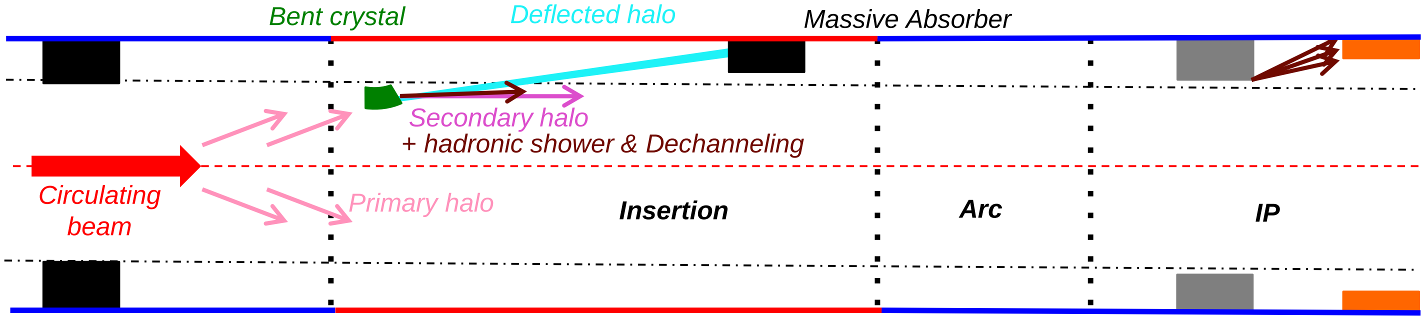
Highlights from the crystal collimation tests with ion beams

Crystal collimation (2013/2018).

Complete layout for operational tests (one crystals per beam and plane).

Thanks to D. Mirarchi

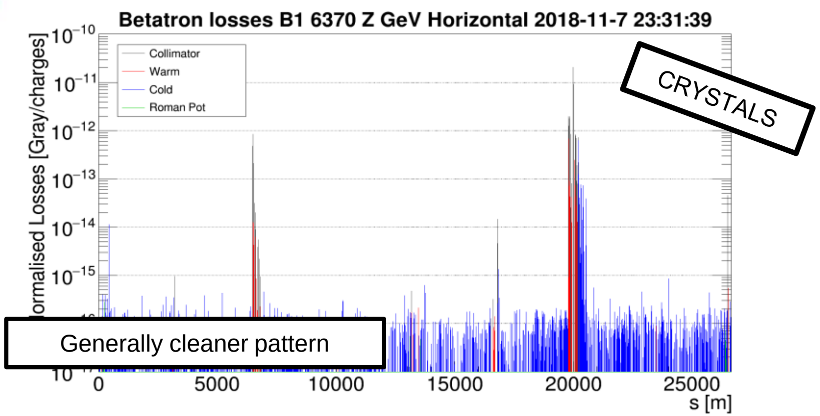


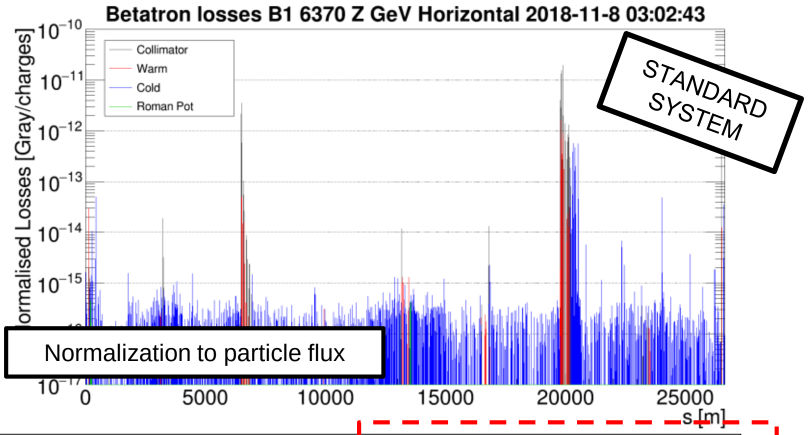
Full program of crystal collimation tests with Pb ions completed.

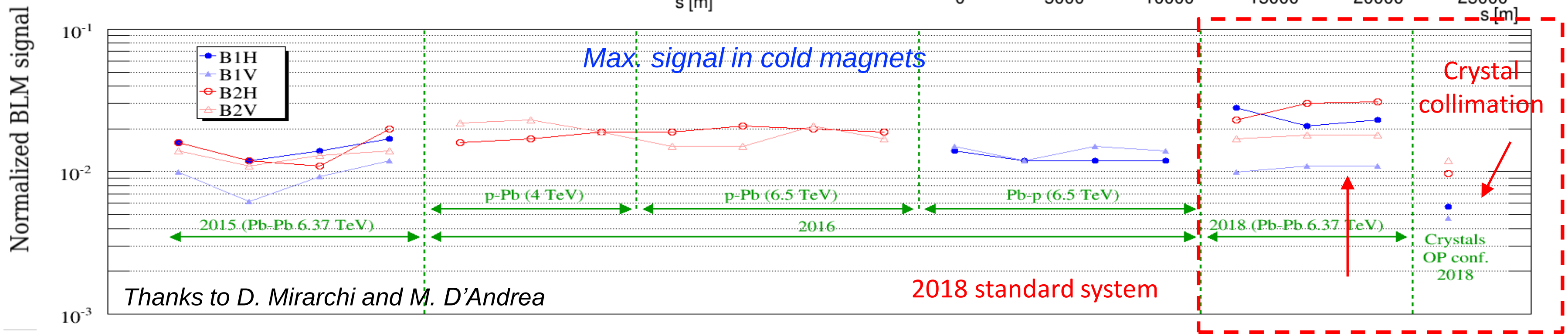
- Complete characterization of all crystal devices with Pb ion beam.
- Loss map campaign with different settings to be compared with standard collimation and previous measurements .
- Crystals channeling during dynamic processes.
- Test with sustained losses on all four planes at the same time.

(More details on D. Mirarchi's talk)

Highlights from the crystal collimation tests with ion beams







- ❑ **General improvement** in cleaning inefficiency.
- ❑ Crystals **successfully kept in channeling during squeeze and able to sustain high losses for several hours.**
- ❑ **Crystals were part of the intensity ramp up and they were injected with 600b.**

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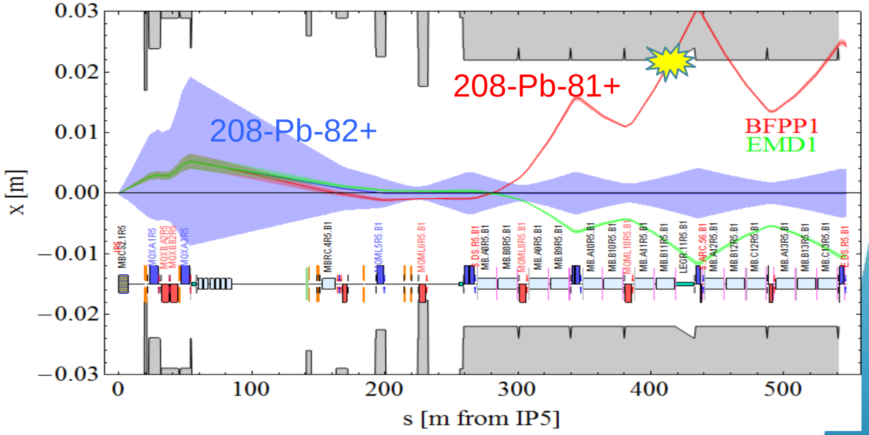
Run II Pb-Pb BFPP losses and mitigation

- **In Run II** the ALICE **luminosity was limited by the detector saturation not by Bound Free Pair Production (BFPP) losses because we could not go higher than 10^{27} cm^{-2} s^{-1} .**
  - The detector will be upgraded to accept ~50 kHz event rate in LS2.
  - In ALICE orbit bumps can not move BFPP losses into connection cryostat similarly to IP1/5 due to optics, TCLD is foreseen for HL-LHC.

- **For ATLAS and CMS in Run II due to the improvement in beam parameters and optics it was foreseen that the peak luminosity could be limited by BFPP losses** (A. Lechner's talk).

- In 2015 a **BFPP orbit bumps method was implemented** to move the secondary beam into the connection cryostat to reduce risk of quenches and **successfully removed ATLAS and CMS limitation.**



Later in the 2015 the first controlled LHC dipole quench using a BFPP beam confirmed a **luminosity limit at L≈2.5x10^{27} cm^{-2} s^{-1}** (≅50W into magnet).

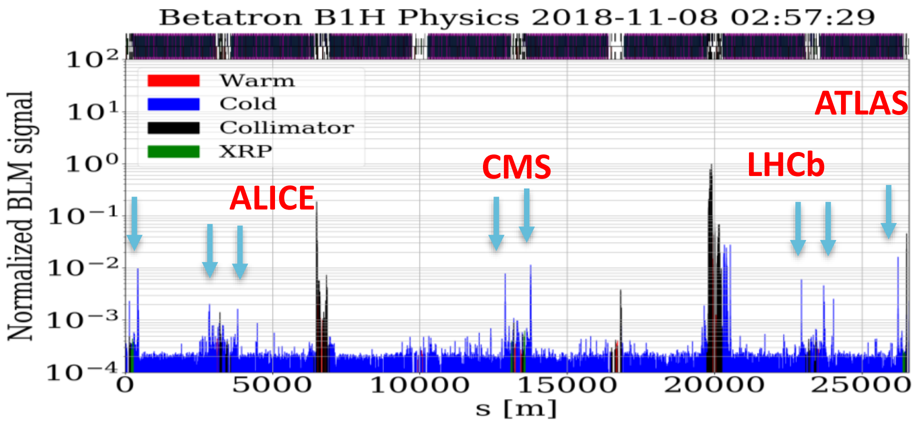
Thanks to J. Jowett and M. Schaumann

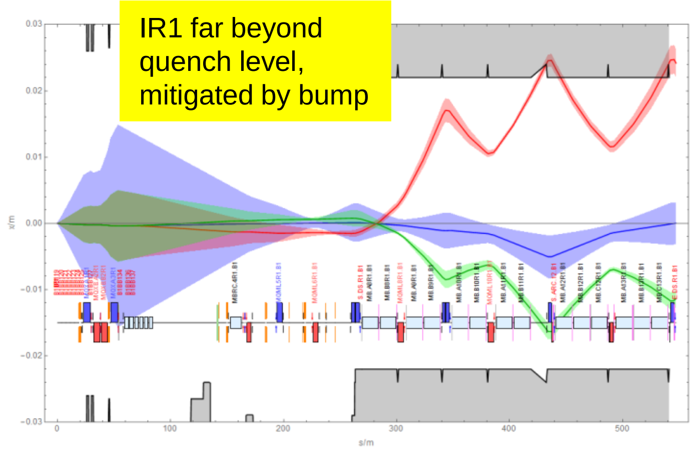
2018 BFPP bumps

- In the 2018 run, **bumps were adjusted empirically** in **ATLAS** and **CMS** a **good agreement with calculations** on the location of the losses have been observed.
  - With the exception of **left of IR5** (same as in 2015) but still the method worked well.

- In **ALICE** luminosity was still limited to 10^{27} by the **saturation of the detector** and BFPP losses were less critical however BFPP bumps were used to distribute the losses over two cells.

- Due to the **75 ns filling** scheme some collisions were provided for **LHCb** with a peak luminosity up to 10^{27} $cm^{-2}s^{-1}$ **with BFPP losses far from the quench limit**.



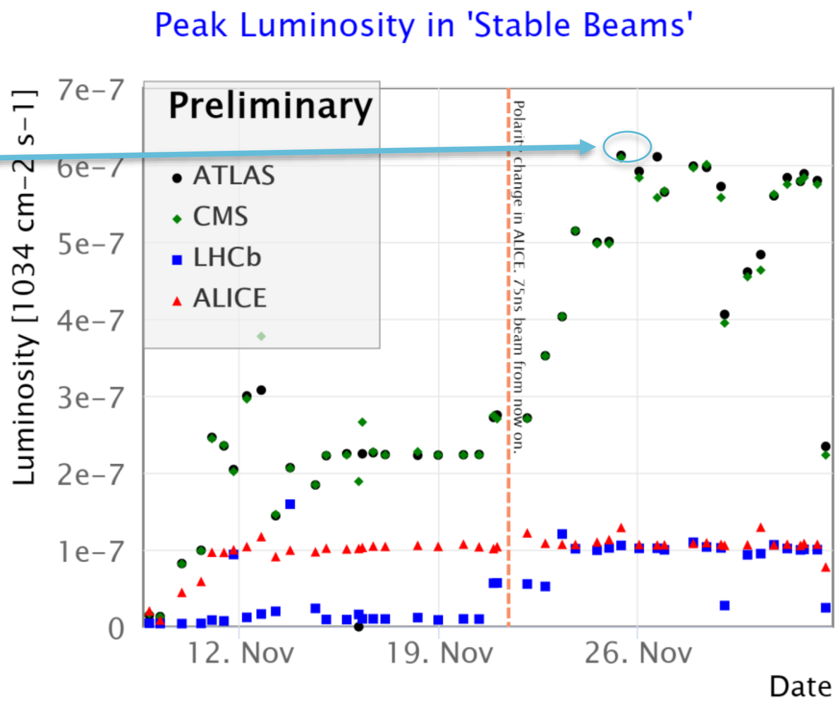


Thanks to J. Jowett

Are the BFPP bumps in IR1/5 a robust enough solution?

- Peak luminosity record achieved in 2018 in **ATLAS and CMS**.
- A margin between the BFPP level of losses and the thresholds used in operation still exists.
- Good control over the bumps.

$L=6\times10^{27}\ cm^{-2}\ s^{-1}$
$=6\times design$
Nominal HL-LHC levelling value is $7\times10^{27}\ cm^{-2}\ s^{-1}$



- Based on the 2018 results we are confident that we can go to $7\times10^{27}\ cm^{-2}\ s^{-1}$ in IP1/5.

Thanks to J. Jowett and C. Wiesner

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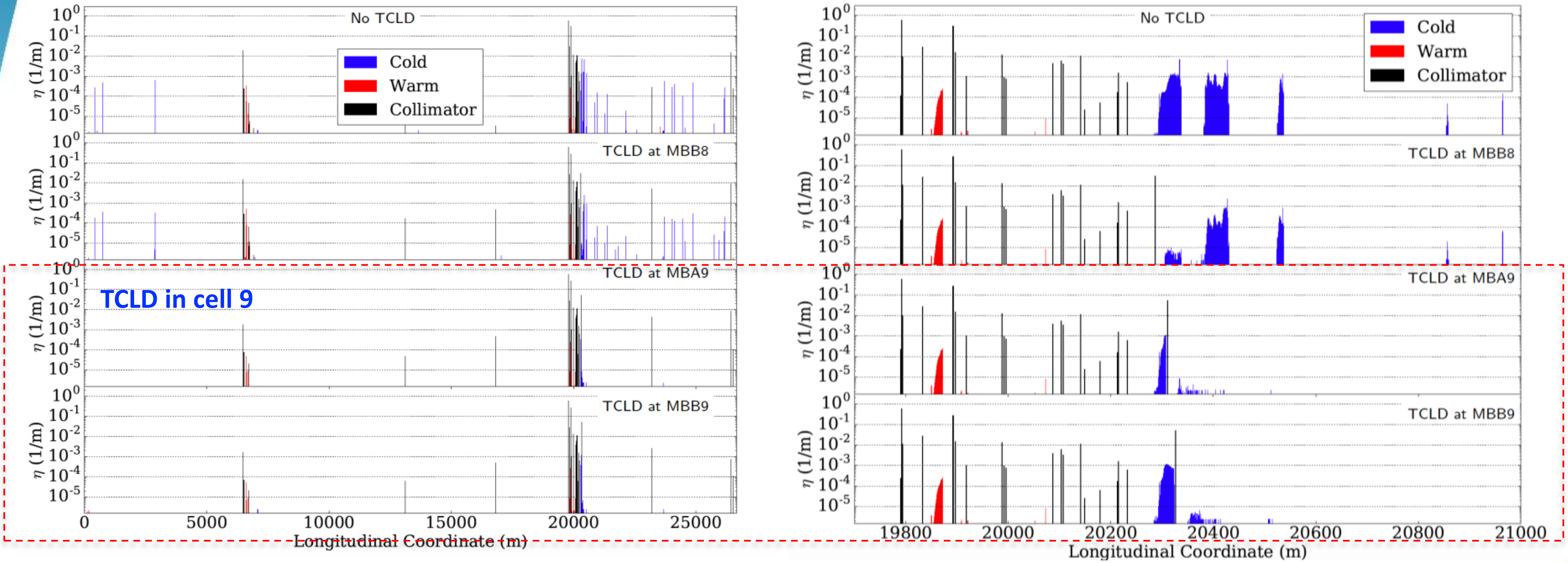
Luminosity reach with present upgrade scenarios

- **Halo and DS cleaning in IR7** improved by the installation of the **TCLD in IR7**.

Thanks to P. Hermes



- In addition, the **Run III** layout with the **MoGr TCPs and Mo coated MoGr shows to reduce the average inefficiency in the first cluster by a factor ~2 (simulations done for TCLD in C8, to be updated).**

(HL-LHC Annual meeting CERN, 15-18 Oct 2017,RunII layout and performance for lead ions)

Luminosity reach with present upgrade scenarios

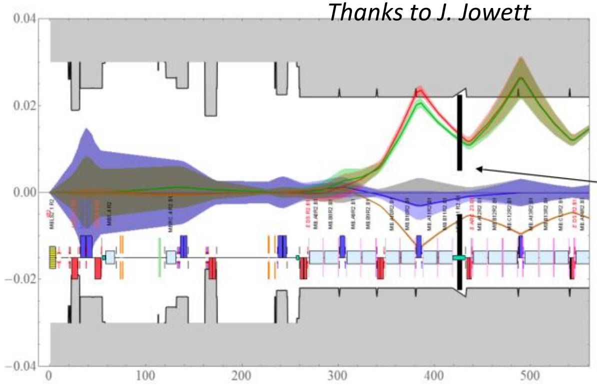
❑ BFPP losses in IP1/5 - BFPP bumps

- ❑ Good control of the losses by using the BFPP bumps demonstrated operationally.
- ❑ Based on the 2018 results **we are confident that we can go to $7x10^{27}$ cm^{-2} s^{-1}** ($6.1x10^{27}$ achieved in 2018!)

❑ BFPP losses in IP2 – TCLD in IR2

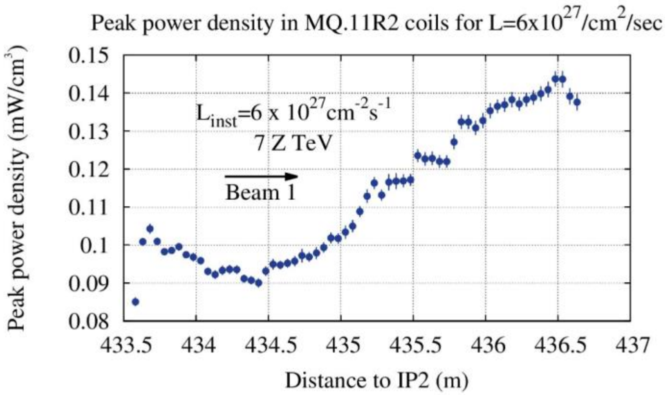
ALICE will be upgraded in LS2 allowing to go up to 6-$7x10^{27}$ cm^{-2} s^{-1}.

Thanks to J. Jowett



FLUKA energy depositions studies show that the losses estimated on the surrounding magnets and cryostat bus bars are below the quench limit (More in A. Lechner talk).

Thanks to C. Bahamonde, R. Garcia Alia, M. Brugger, F. Cerutti, A. Lechner



BFPP losses not expected to be limiting.

Conclusions (I)

- **Ion runs were closer to the limit than the proton runs during operation and in the set-up.**

  - The **worsening of the inefficiency** in halo cleaning in IR7 is a **limiting factor for higher intensities**. We have to take into account that for the short runs**, the availability is very important** and each single fill counts.

  - Control of heavy-ion beam losses, e.g. collimation and BFPP, is critical, complicated and may surprise. **Simulations are an increasingly reliable guide to understand the origin and locations of the losses.**

  - **Crystal collimation shows promising results** (more in Daniele's talk).

Conclusions(II)

- During Run II we have come **close** to the full **"HL-LHC" heavy-ion performance** but still about a factor **2 lower in intensity**. However with the **planned upgrades** and based on Run II operation we **expect to overcome the envisage intensity and luminosity limitations.**

	2015 Pb-Pb	2018 Pb-Pb	Pb-Pb HL-LHC	2016 p-Pb	p-Pb HL-LHC
β* IP1/2/5/8	0.8/0.8/0.8/3	0.5/0.5/0.5/1.5	0.5/0.5/0.5/1.5	0.6/2/0.6/1.5	0.5/0.5/0.5/0.5
E_{Pb} [Z TeV]	6.37	6.37	7	4-6.5	7
Pb/bunch[10^8]	2.0	2.2	1.8	2.1	1.8
N_b	518	733	1232	540	1232
E_b [MJ]	8.6	13.5	21	9.7	21
$L_{AA}[10^{27} cm^{-2} s^{-1}]$	3.6	6.1	7	850	1740

Thank you very much for your attention!

Luminosity reach with present upgrade scenarios

Quantity	design	achieved				upgrade
Year	(2004)	2010	2011	2015	2018	$\geq$2021
Weeks in physics	-	4	3.5	2.5	3.5	-
Fill no. (best)		1541	2351	4720	7473	-
Beam energy $E[Z\ \mathrm{TeV}]$	7	3.5		6.37	6.37	7
Pb beam energy $E[A\ \mathrm{TeV}]$	2.76	1.38		2.51	2.51	2.76
Collision energy $\sqrt{s_{\mathrm{NN}}}$ [TeV]	5.52	2.51		**5.02**	**5.02**	5.52
Bunch intensity N_b [10^8]	0.7	1.22	1.07	2.0	2.2	1.8
No. of bunches k_b	592	137	338	518	733	1232
Pb norm. emittance ϵ_N [μm]	1.5	2.	2.0	2.1	2.0	1.65
Pb bunch length σ_z m	0.08	0.07–0.1				0.08
β^* [m]	0.5	3.5	1.0	0.8	0.5	0.5
Pb stored energy MJ/beam	3.8	0.65	1.9	8.6	13.3	21
Luminosity L_{AA} [$10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	1	0.03	0.5	3.6	6.1	7
NN luminosity L_{NN} [$10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	43	1.3	22.	156	264	303
Integrated luminosity/experiment [$\mu\mathrm{b}^{-1}$]	1000	9	160	433,585	900,1800	10^4
Int. NN lumi./expt. [pb^{-1}]	43	0.38	6.7	19,25.3	39,80	4.3×10^5

Thanks to J. Jowett

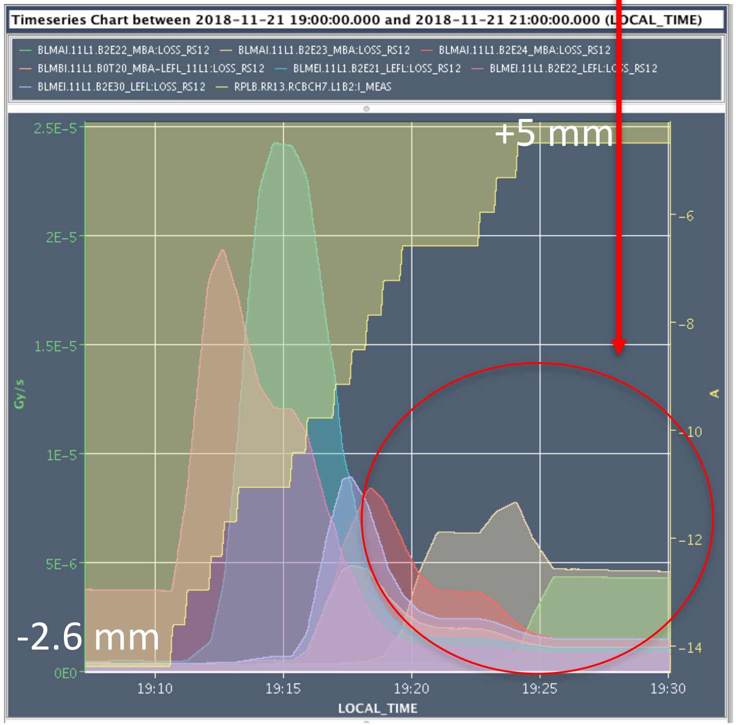
Aperture measurements 2018

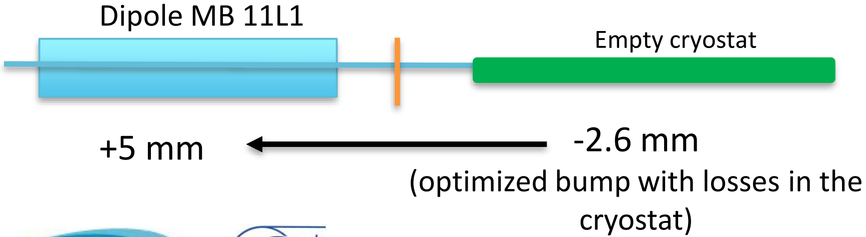
- Aperture measurements summary (Positive ALICE polarity)
  ****
  Wih octupoles ON
  ****
  B1H: at Q3L1 between 12.3-12.8 sigma
  B1V: at Q3L1 between 13.6-14.1 sigma
  B2H: at Q3R1 between 10.6-11.1 sigma
  B2V: at Q3R1 between 13.3-13.8 sigma
  With octupoles OFF
  ****
  B1H: at IP2 BLMEI.01L2.B1B10_BKGD_BCM between 13.4-13.9 sigma
  B1V: at IP2 BLMEI.01L2.B1B10_BKGD_BCM between 12.72-13.19 sigma
  B2H: at Q3R1 between 12.3-12.8 sigma
  B2V: at Q3R1 between 13.1-13.6 sigma
- aperture measurement summary (Negative ALICE polarity)
  ****
  B1H: Q3L1 between 13.24-13.73 sigma
  B1V: Q3L1 between 13.38-13.88 sigma
  B2H: Q3R1 between 14.15-14.65 sigma
  B2V: Q3R1 between 13.28-13.75 sigma

2018 BFPP losses control

- **Good control** to move the losses in a wide range of bumps amplitude and **large number of BLMs** available to monitor the changes.
- Example of BFPP bump scan in left of IP1 from operational settings (-2.6 mm) to +5 mm
  - Losses increase in MB.11L1 because the +5 mm bump moves the losses intentionally deep into the dipole.
  - Preparation of BFPP quench test.

Losses in the dipole magnet 11L1

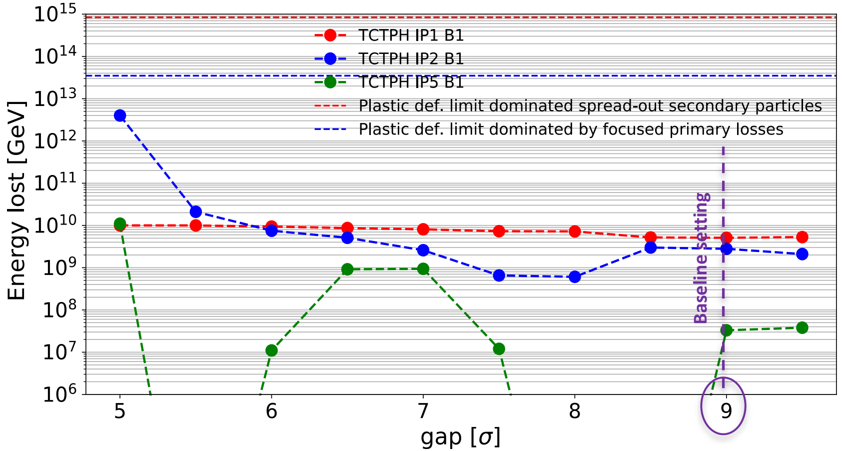




Thanks to M.Schaumann

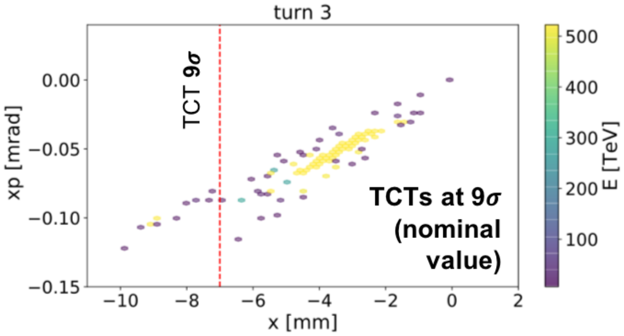
In the 2018 new ion optics the TCTPH in IP2 has an MKD-TCT phase advance that differ from ideal (0° and 180°) about ~43°/30° for B1/B2.

- Protons studies show a limit of 30° margin for safe operation.



	$\Delta\mu_x$ (B1)	$\Delta\mu_x$ (B2)
MKD-TCTPH IR1	176°	151°
MKD-TCTPH IR2	223°	212°
MKD-TCTPH IR5	162°	176°

TCTs impact distribution dominated by secondary spread-out beam



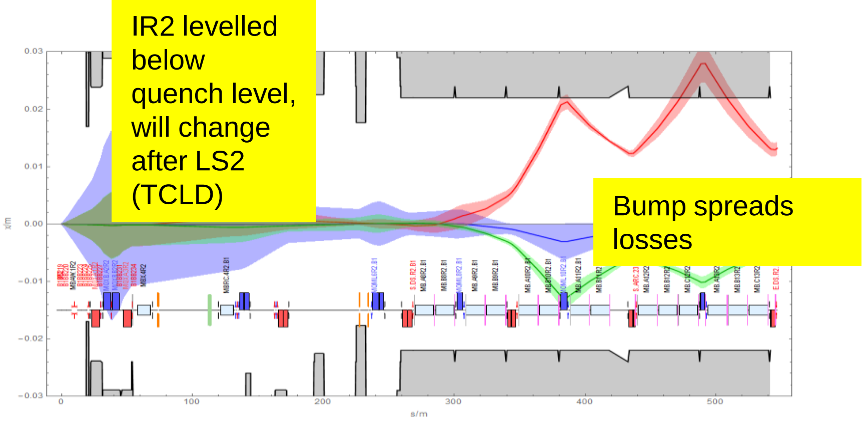
Dump failure simulations performed with hisixTrack-FLUKA coupling to ensure the protection of the TCTs for baseline settings. Sensitivity **study** performed for different **TCTs settings.**

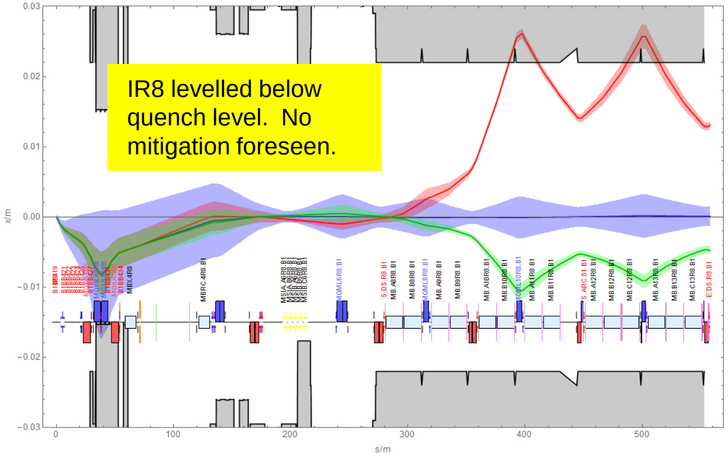
Conclusions:

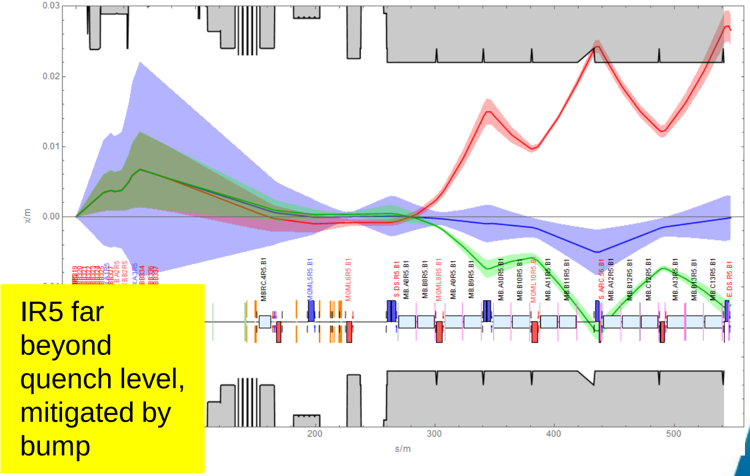
- Losses at the TCTs below the damage limit for **baseline settings (9 σ)** with 3.5σ operation margin for B1 and 4σ for B2.

For more details: https://indico.cern.ch/event/763571/

2018 BFPP bumps







Final values:

- ON_BFPP.R1=-2.6.;
- ON_BFPP.L1=-2.6;
- ON_BFPP.R2=-2;
- ON_BFPP.L2=-2.6.;
- ON_BFPP.R5=-2.5;
- ON_BFPP.L5=-1.6;

Initial values:

- ON_BFPP.R1=-5.;
- ON_BFPP.L1=-5.;
- ON_BFPP.R2=-3.;
- ON_BFPP.L2=-3.;
- ON_BFPP.R5=-5.;
- ON_BFPP.L5=-5.;