# Collimation: experience and performance

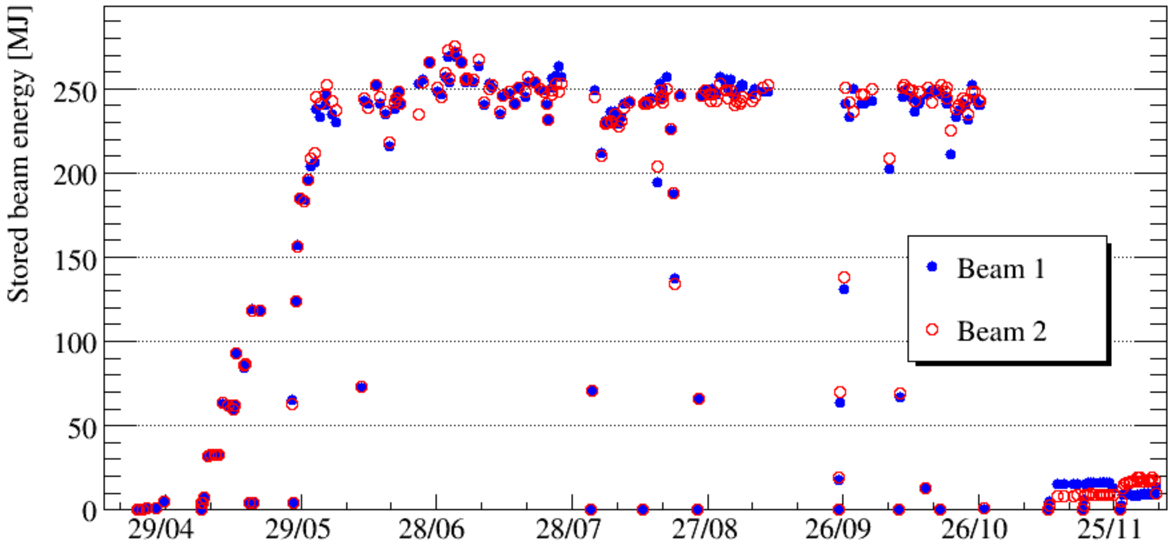
D. Mirarchi on behalf of the LHC Collimation team

Special thanks to BE-OP for the support during measurements, to BE-BI for being "our eyes", to BE-ABP for internal discussions.

*7th Evian Workshop, 13th December 2016*

# Introduction

- **No quench** from circulating beam losses with more than **250 MJ beams!**




- Very good **beam lifetime** and **stability**, **plus**:
  - ✓ **Alignment** of the entire system during **YETS commissioning** (43 movable ring collimators per beam)
  - ✓ Deployment of **settings along the entire cycle** based on outcomes of aperture measurements
    - → **Dedicated functions** for each collimator related to every beam process
  - ✓ System **validation** through betatron and off-momentum **loss maps**
    - → **YETS**, each **TS**, and **changes** of machine **parameters** (i.e. Xing ➔ TCTPs centre)

# Outline

I. LHC aperture and collimation settings
II. Collimation performance
III. Ion collimation
IV. Highlights from collimation MDs
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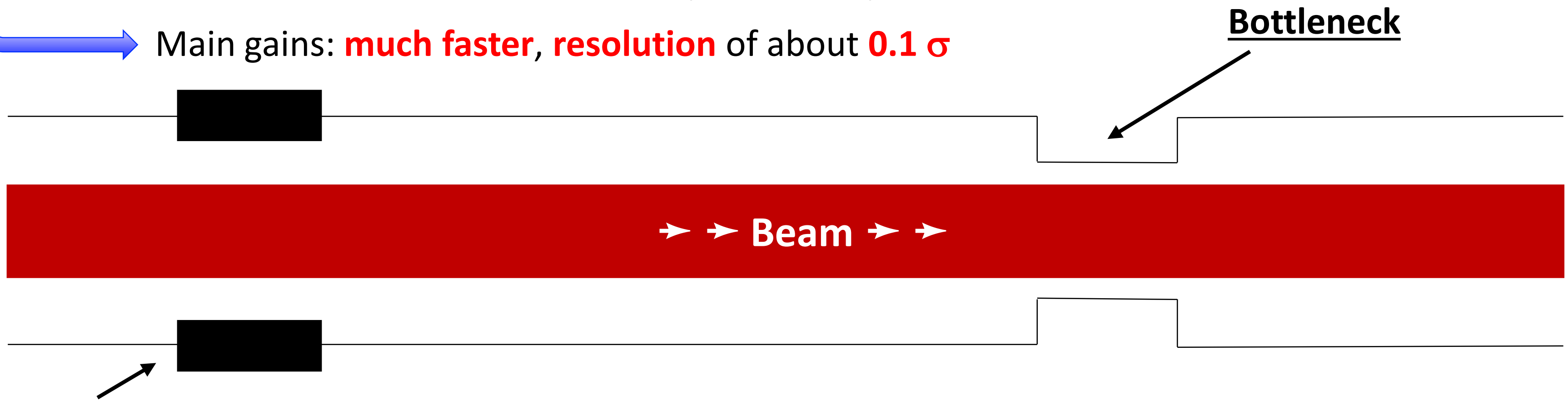
# LHC aperture

- Measurements performed at **injection** and with **squeezed beams** (both EoS and collisions)
- **New method** used and validated with respect to old procedure

  ⇒ Main gains: **much faster**, **resolution** of about **0.1 σ**




**Collimator** (**TCP** for global aperture at injection / **TCTP** for local aperture with squeezed beams)

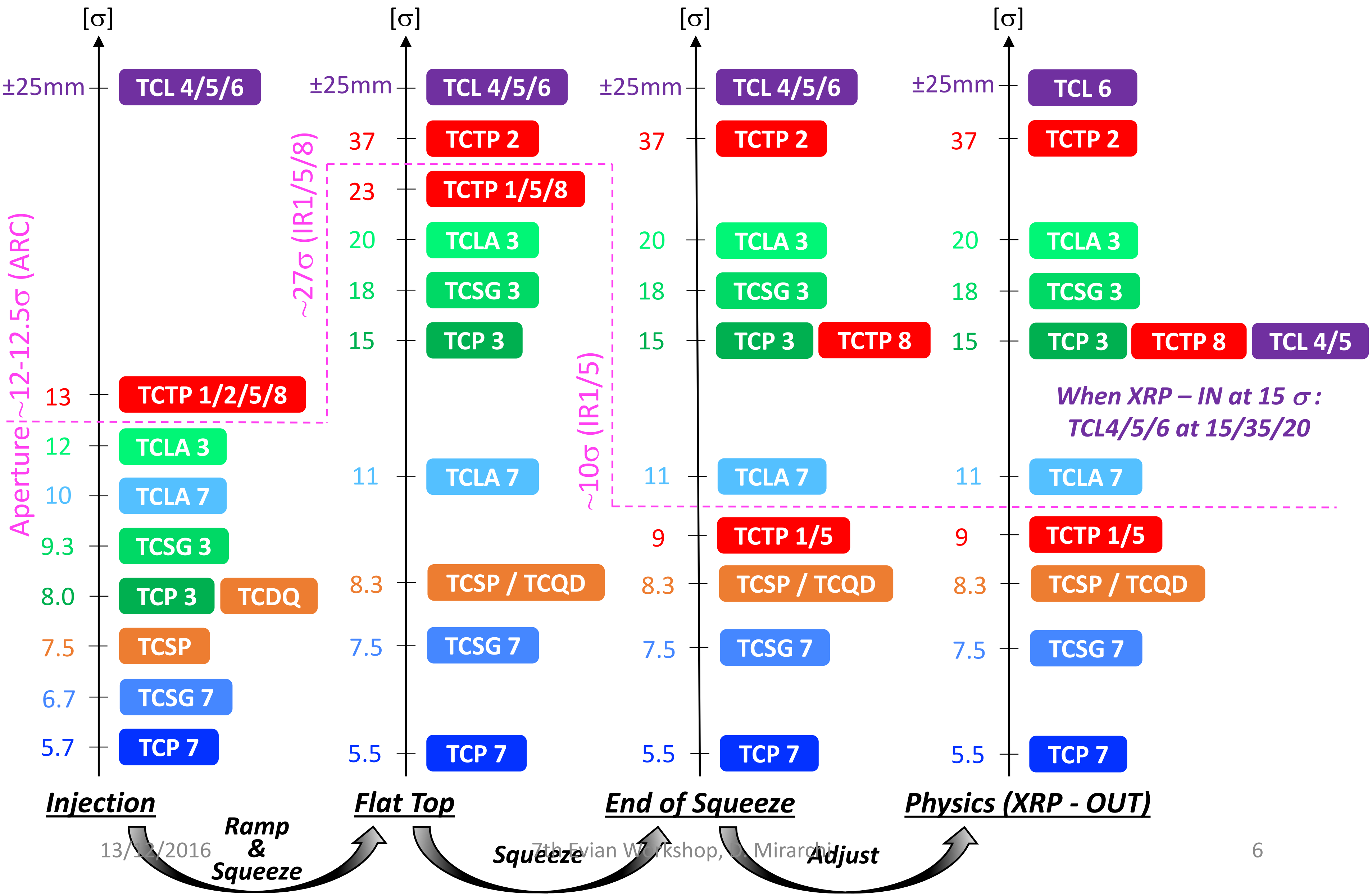
- ***Injection:*** confirmed **very good aperture**

| Date | B1H [σ] | B1V [σ] | B2H [σ] | B2V [σ] |
|---|---|---|---|---|
| 3/4 | 12.5 – 13.0 (MBCR. 4R8) | **12.0 -12.5** (Q6L4) | 12.5 – 13.0 (TCDQM.4L6) | 12.5 – 13.0 (Q4R6) |

- ***Squeezed beams:*** **very good agreement** with respect to expectation from **2015 scaling**

| Date | Config. | B1H [σ] | B1V [σ] | B2H [σ] | B2V [σ] |
|---|---|---|---|---|---|
| 10/4 | Coll. | 11.3 (Q3R5) | **10.0** (Q3L1) | 11.6 (Q3R1) | 10.7 (Q3R1) |
| 17/4 | Coll. | 11.0 (Q3R5) | **9.9** (Q3L1) | 12.1 (Q3R1) | 10.4 (Q3R1) |

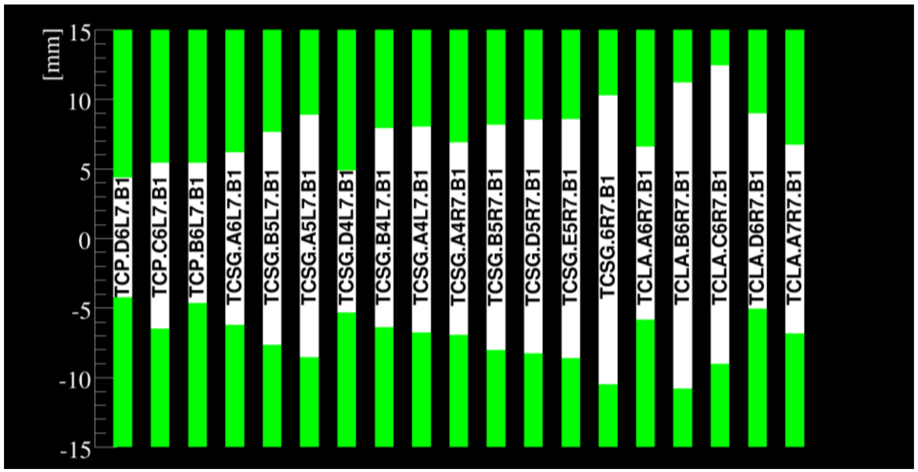
# Settings along cycle



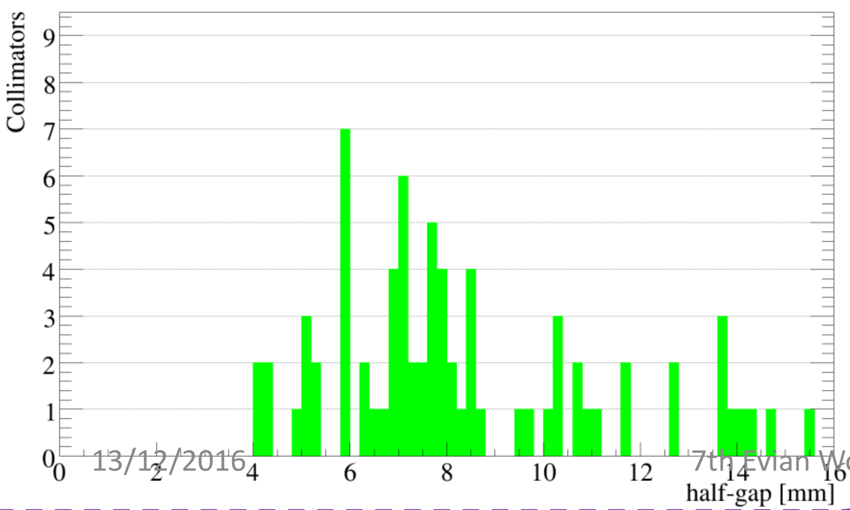
# … in mm

## Injection

- Collimators **gap in IR7**

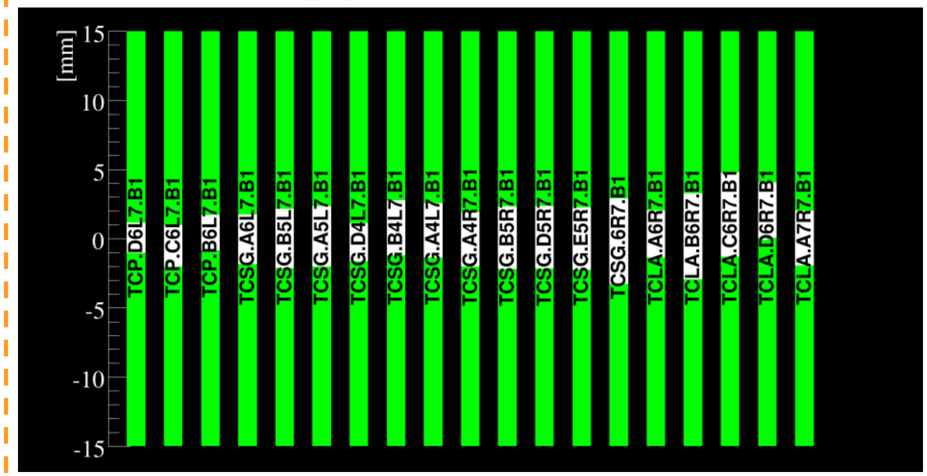



- Distribution of **half-gaps for the entire system**

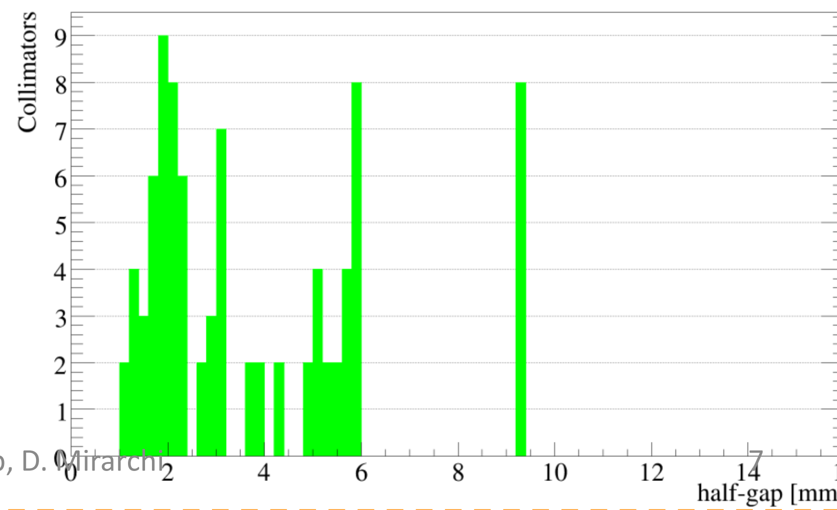



## Physics

- Collimators **gap in IR7**

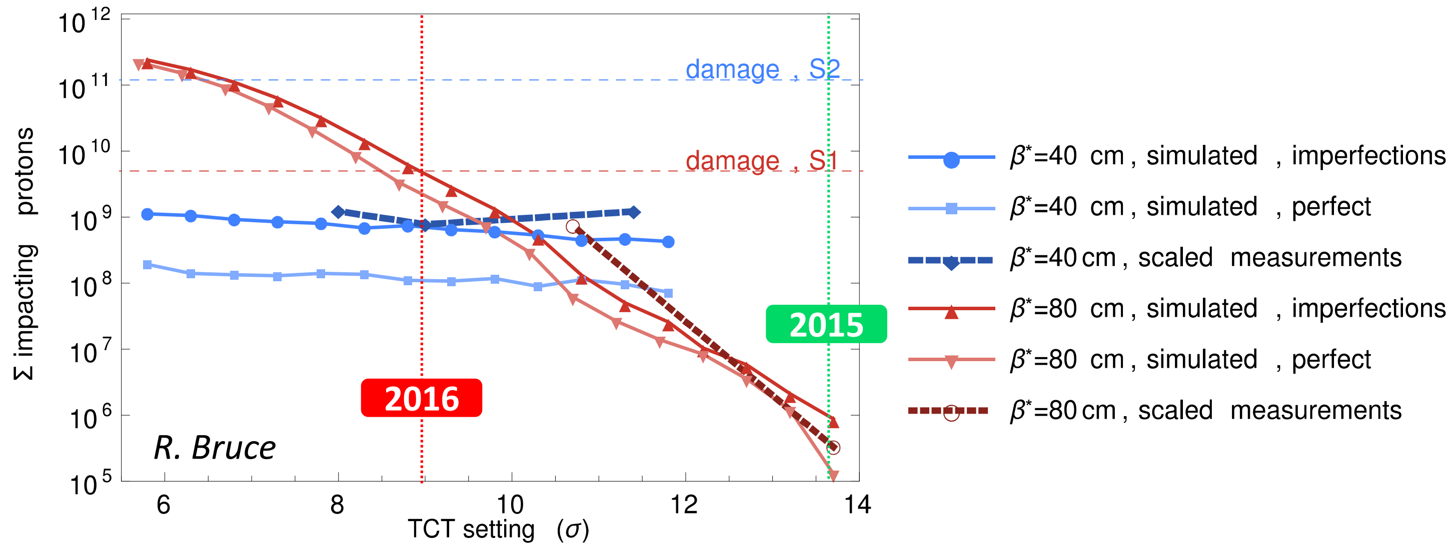



- Distribution of **half-gaps for the entire system**



# From 2015 to 2016

- **Main changes** with respect to 2015 to allow safe operations with **β*= 40cm**:
  - ✓ **TCTPs** functions during **Ramp&Squeeze**, all TCTPs at 37 σ at flat top during 2015
  - ✓ **Optimised phase advance** MKD-TCTs allowed **TCTs 1/5** from 13.7 σ in 2015 (β*=80cm), to **9 σ** in 2016




  - ✓ Possible to **tighten the hierarchy in IR7**, from 5.5/8.0/14 σ to **5.5/7.5/11 σ** in 2016 (TCP/TCSG/TCLA)
  - ✓ **Tighter TCSP/TCQD,** from 9.1 σ in 2015 to **8.3 σ** in 2016

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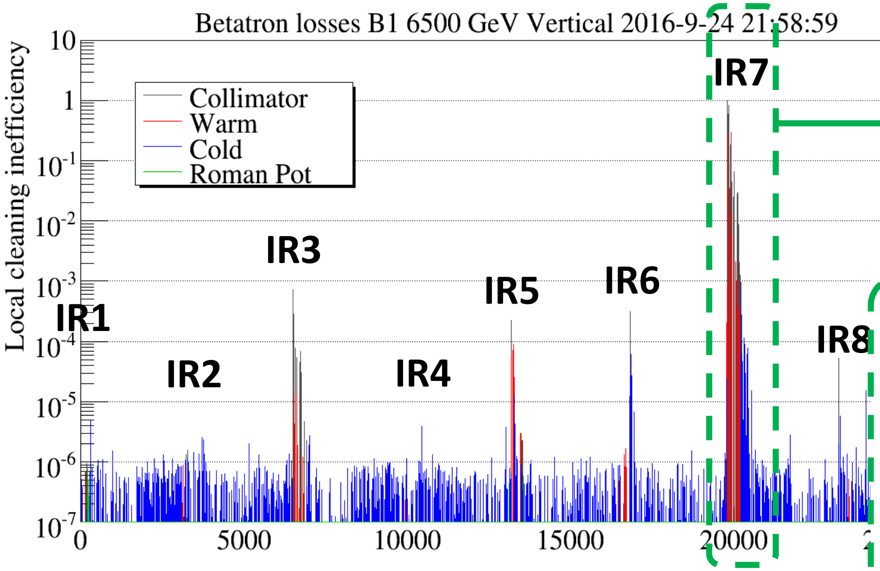
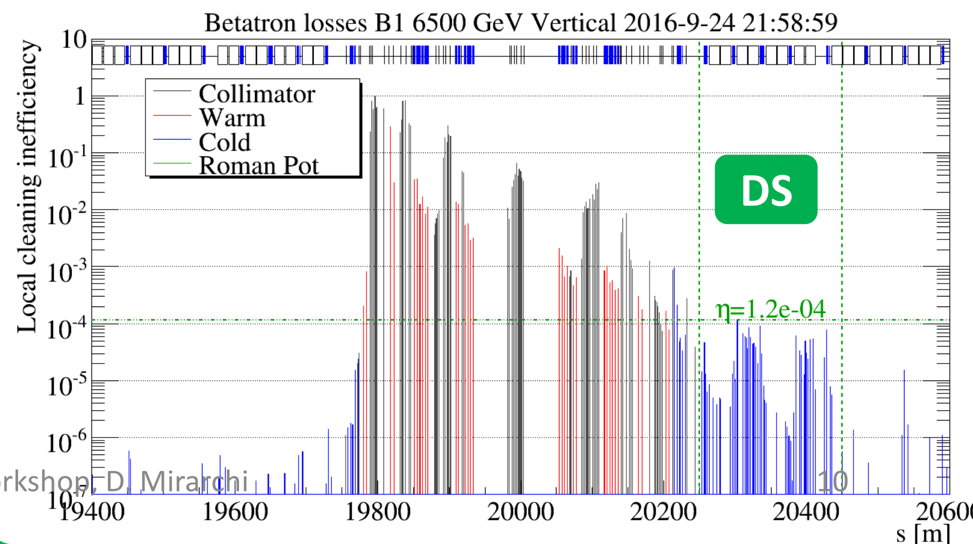
# Cleaning (I)

- **Significant** activity of performances **qualification**:
  - ✓ **112** loss maps after **YETS** (100 β + 12 δp/p) → **4 fills** top energy, 2 fills injection
  - ✓ **23** loss maps after **TS1** (20 β + 3 δp/p) → **1 fill** top energy, 2 fills injection
  - ✓ **29** loss maps after **TS2** (24 β + 5 δp/p) → **2 fills** top energy, 2 fills injection
- **ADT** used of **β** loss maps, new **"gentle"** procedure used for **δp/p** loss maps

→ **Significant reduction of fills needed** (see Alessio's and Daniel's talks)




Example of qualification beam loss map in physics configuration (TS2)

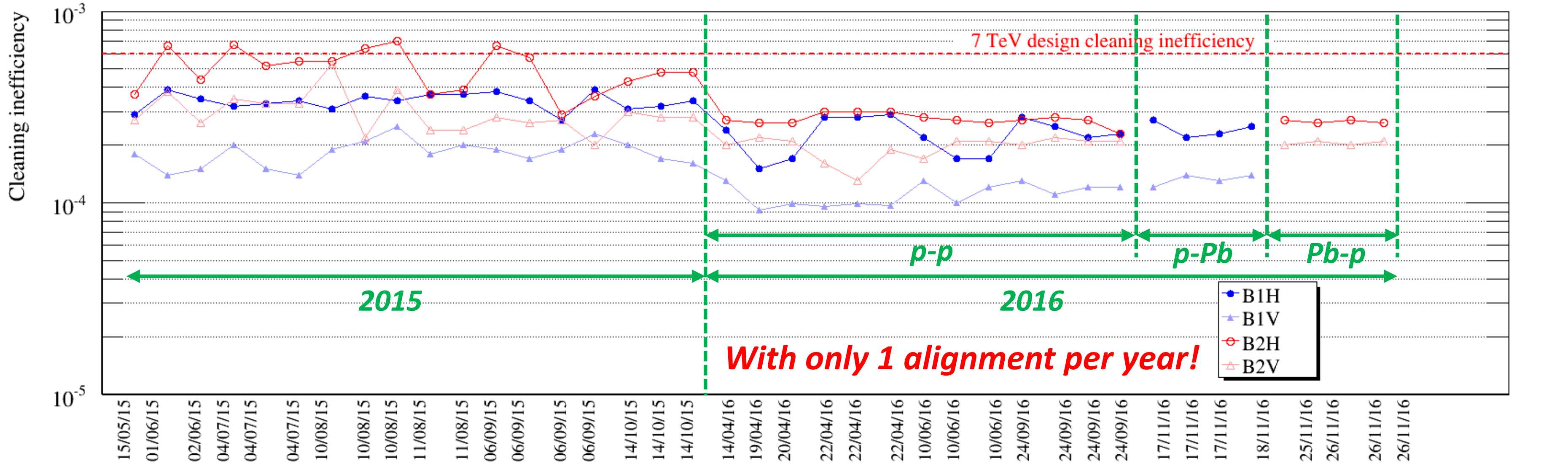



- ➢ **Only IC** used and **bkg subtracted**
- ➢ Local **cleaning inefficiency** given by:

$$\eta_i = \frac{BLM_i}{BLM_{TCP}}$$

# Cleaning (II)

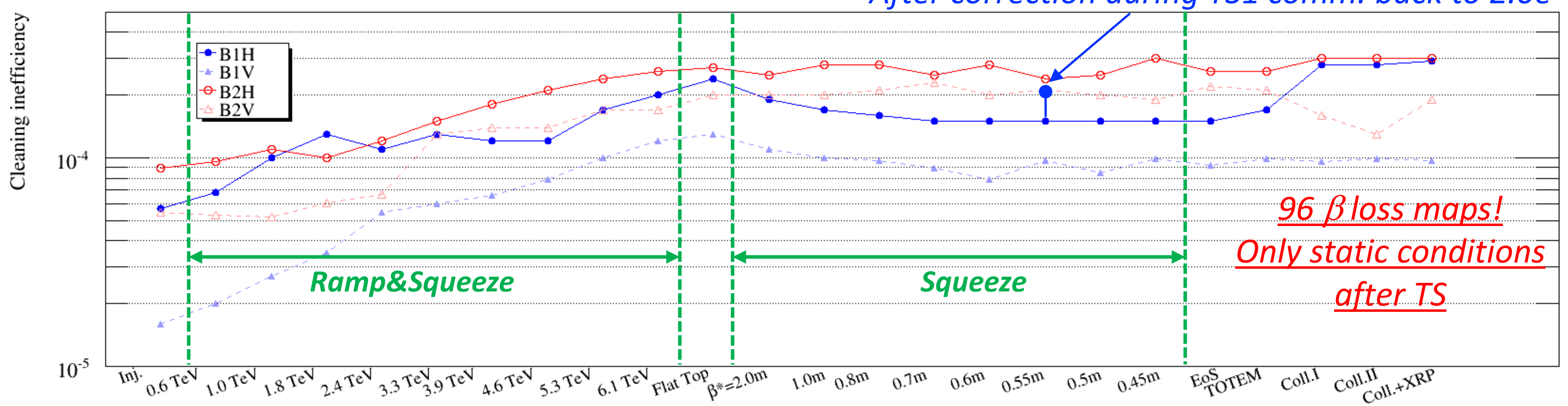
- **Clear improvement** with **tighter hierarchy** and **stable performances** along the year:




- **β loss maps along the entire cycle** after YEST to prove **safe operations with R&S and down to β* = 40cm**:

**ADT** used **"on the fly"** during **dynamic phases**

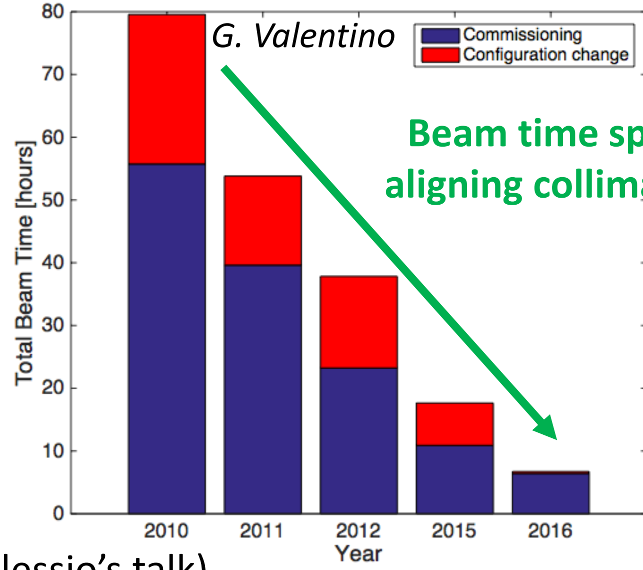
*After correction during TS1 comm. back to 2.0e-4*



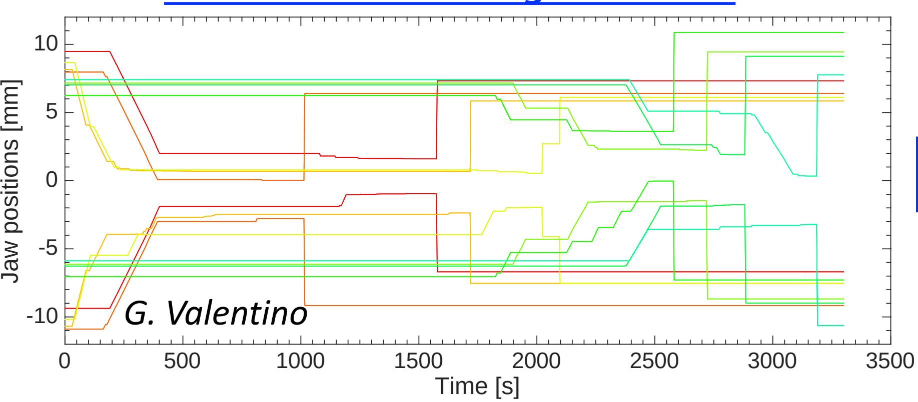

*Decrease of **ineff. for B1H** during squeeze due to a small (~100 um) **bump building up toward IR7-TCLAs***

# Alignment

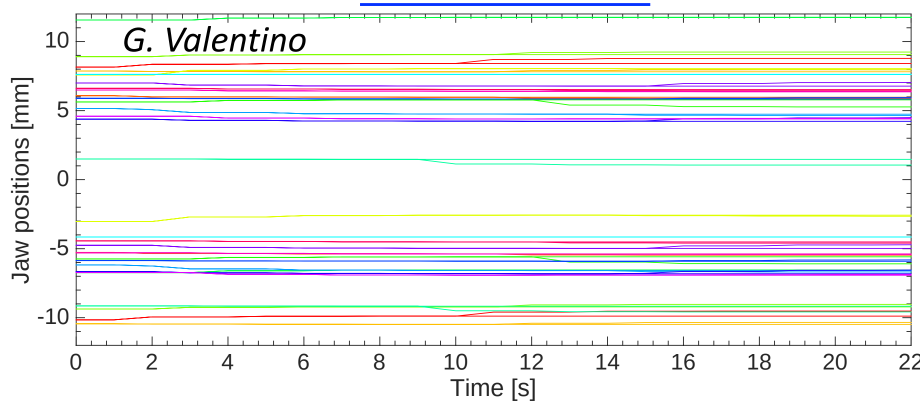
- **Key improvements** in 2016:
  - ✓ **BLM** feedback loop
    - ➢ Beam based alignment based on **100Hz** data
  - ✓ **BPM** collimators
    - ➢ Automated **parallel alignment**
    - ➢ Continuous **orbit monitoring** (β* reach!) (see Alessio's talk)




From about 1h to align all TCTPs




To less than 30s!




Joint collaboration ABP/BI/OP

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# Ions setup

- Main activities carried out during **ion beams commissioning**:

  - **4 Z TeV:**
    - ✓ **Generation of new ramp functions** for all collimators involved: cut of functions for p-p at 4 TeV
    - ✓ **Function generation** and **alignment of TCTPs** at:
      - Flat Top
      - Collisions

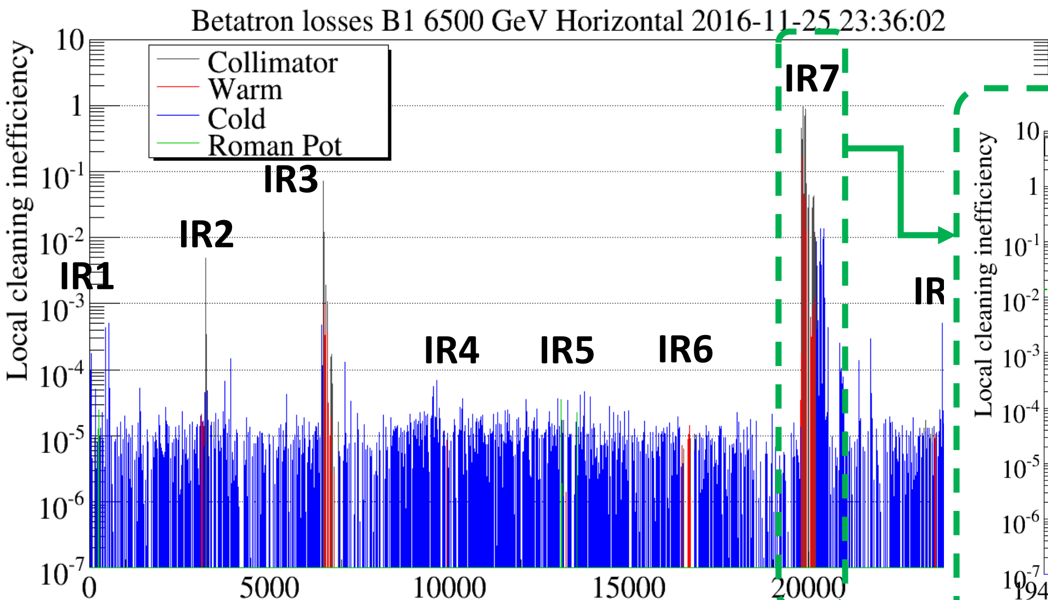
  - **6.5 Z TeV:**
    - ✓ **Same ramp functions** used for **p-p** physics
    - ✓ **Function generation** and **alignment of TCTPs** at:
      - Flat Top (with new β* after combined Ramp&Squeeze)
      - End of Squeeze
      - Collisions

- **Qualifications** performed:

  - ✓ **26** loss maps for **4 Z TeV** commissioning (20 β + 6 δp/p) ⇒ **2 fills** top energy, 2 fills injection
  - ✓ **20** loss maps for **6.5 TeV p-Pb** commissioning (16 β + 4 δp/p) ⇒ **2 fills** top energy
  - ✓ **32** loss maps for **6.5 TeV Pb-p** commissioning (24 β + 8 δp/p) ⇒ **2 fills** top energy, 2 fills injection

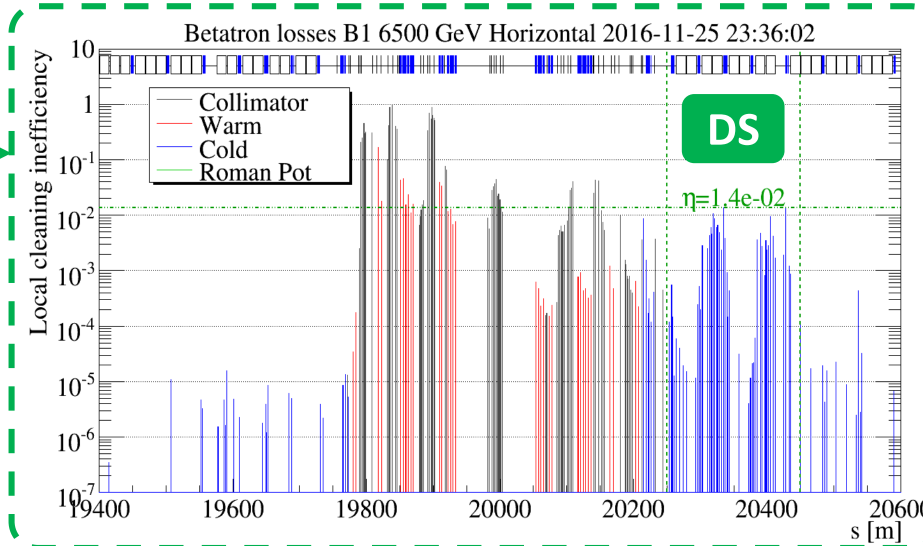
# Performances with ion beams

- **Significant worsening** of performances due to **ions fragmentation**:

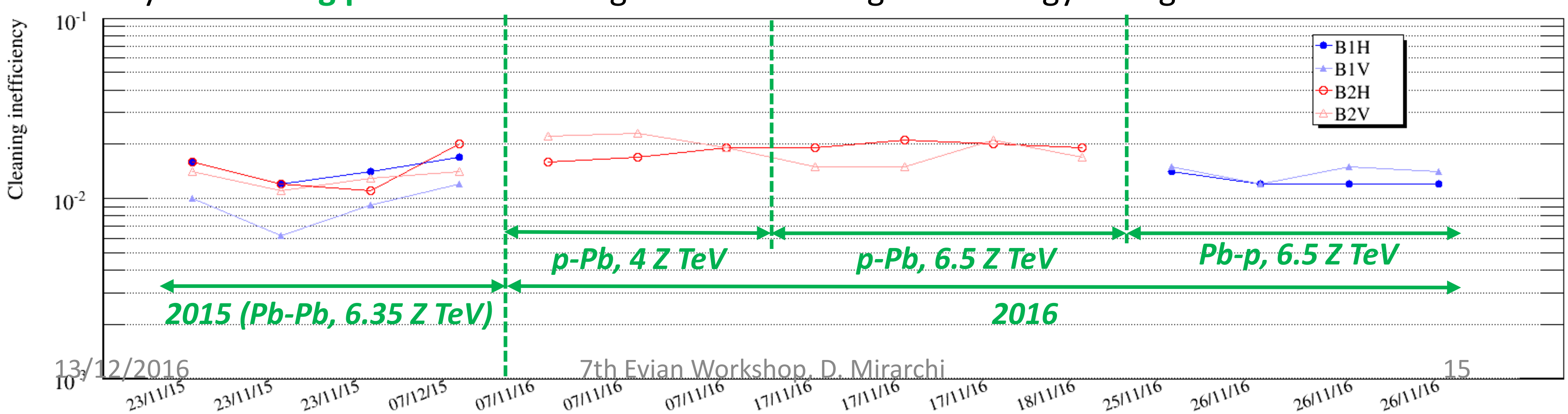



*Cleaning factor of about 100 worse than with p*

*Example of Pb-Pb loss maps in physics*




- Summary of **cleaning performances**: regardless of settings and energy change…



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# Collimation MDs

Several MDs performed/supported during 2016, with topics of different time scale in the future:

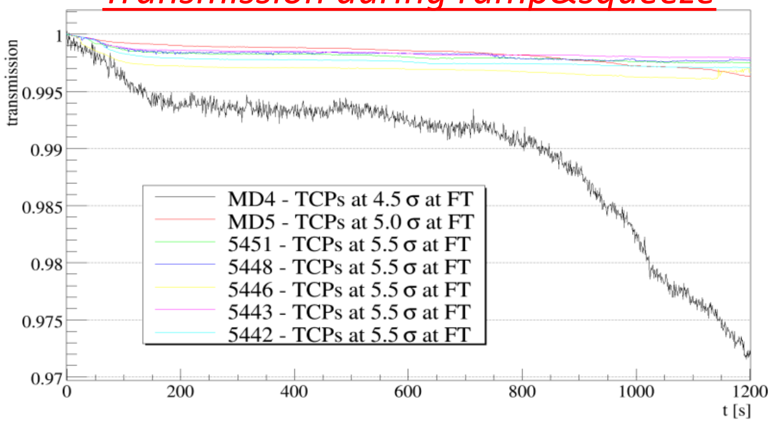
- Profited also in **2016 operations**:
  - ✓ Control of losses during **δp/p loss maps** → Collaboration with OP for tests of **new FESA class** for "gentle" δp/p loss maps
- Operations in **2017**:
  - ✓ **Hierarchy limits**
  - ✓ Single collimators **impedance**
  - ✓ Operation with **TCPs at Tighter Settings**
  - ✓ Detailed **IR aperture** measurements
  - ✓ **TCTPs** induced **background**

  → Proposal of collimators **settings for 2017** (see Roderik's talk)
- Operations in **2017/HL-LHC**:
  - ✓ Collimation aspects of **ATS optics** → Both **cleaning** and **aperture** consistent with **standard optics** (see Stephane's talk)
- **HL-LHC**:
  - ✓ **Crystal** collimation → Measured **cleaning at top energy**, stable **channeling during energy ramp**
  - ✓ **Halo scraping** → Measurements of **diffusion speed** and **tail population**
  - ✓ Active **halo control** → Both **narrow band excitation** and **tune ripple tested**
  - ✓ **Coronagraph** → Support to BI for non-destructive **halo population** measurements

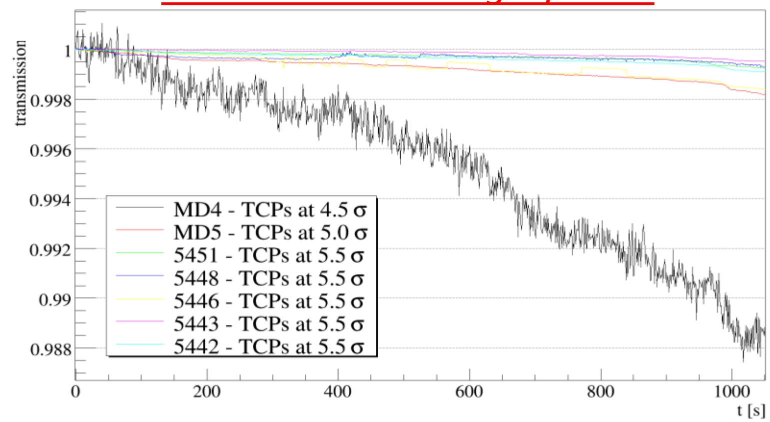
# Tighten collimators?

- How much can we **tight TCPs**?

*Transmission during ramp&squeeze*



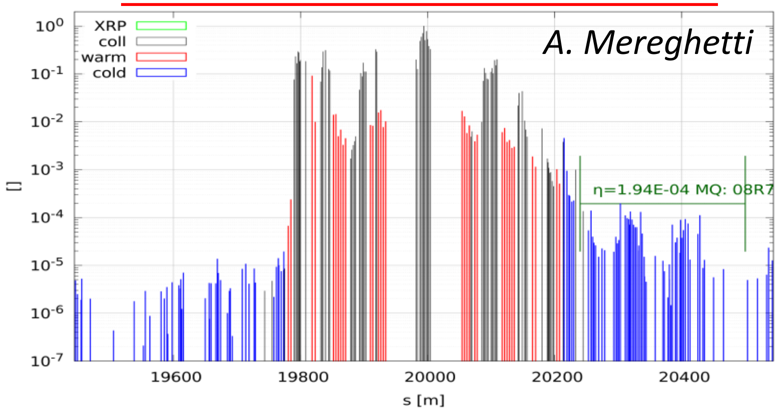

*Transmission during squeeze*



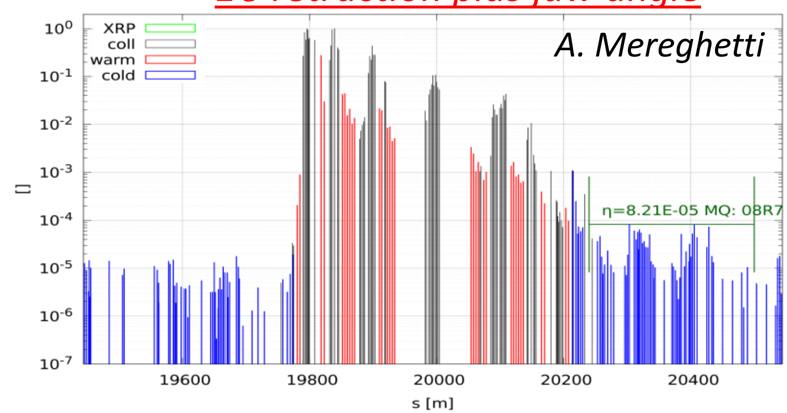

Transmission with **TCPs at 4.5/5σ** at **few %/‰ level**

- How much can we **squeeze the hierarchy**?

*1σ retraction between TCPs-TCSGs*




*1σ retraction plus jaw angle*

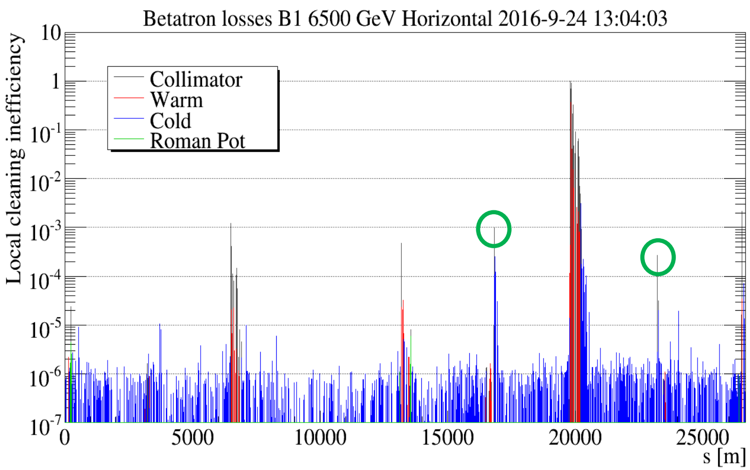



**Jaw angle** required to deploy **1σ retraction** to compensate hierarchy breakage due to tank tilt, **no problems with 1.5σ** retraction

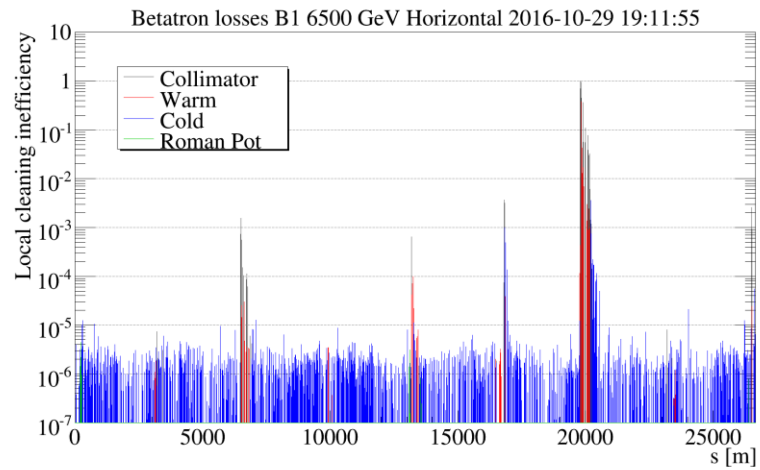
# ATS in 2017?

**Nothing dangerous observed** in $\beta$ loss maps: **squeezed beam** to **40cm** and **33cm**, **colliding beams** ($\beta^*$=33cm)

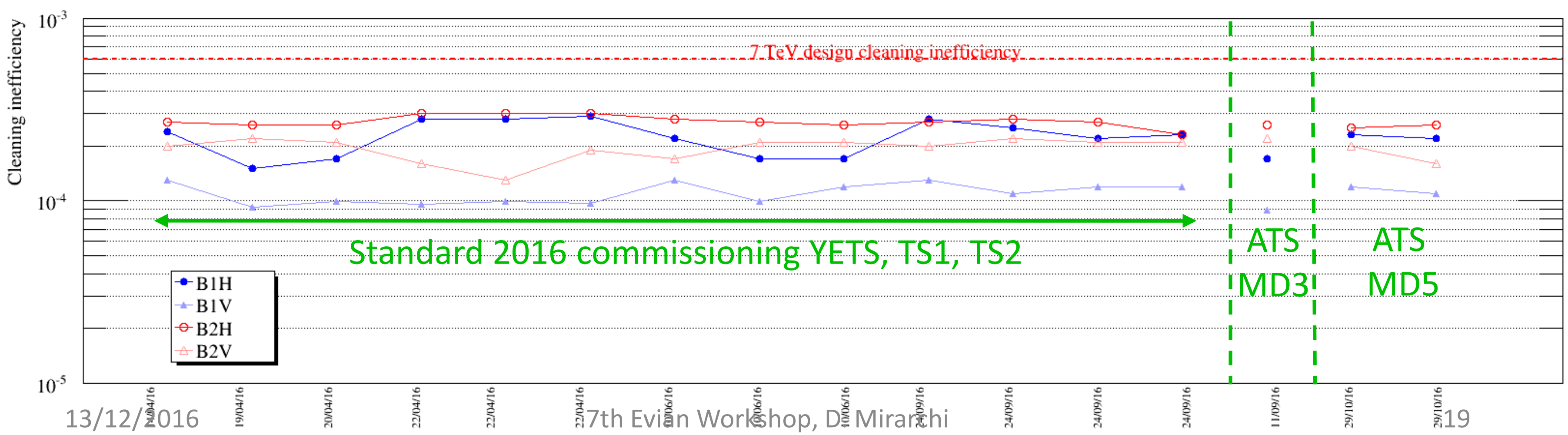
*TS2 validation, $\beta^*$=40cm, colliding*




*ATS MD, $\beta^*$=33cm, colliding*




**Cleaning performances comparable** with respect to standard optics:



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# Conclusions

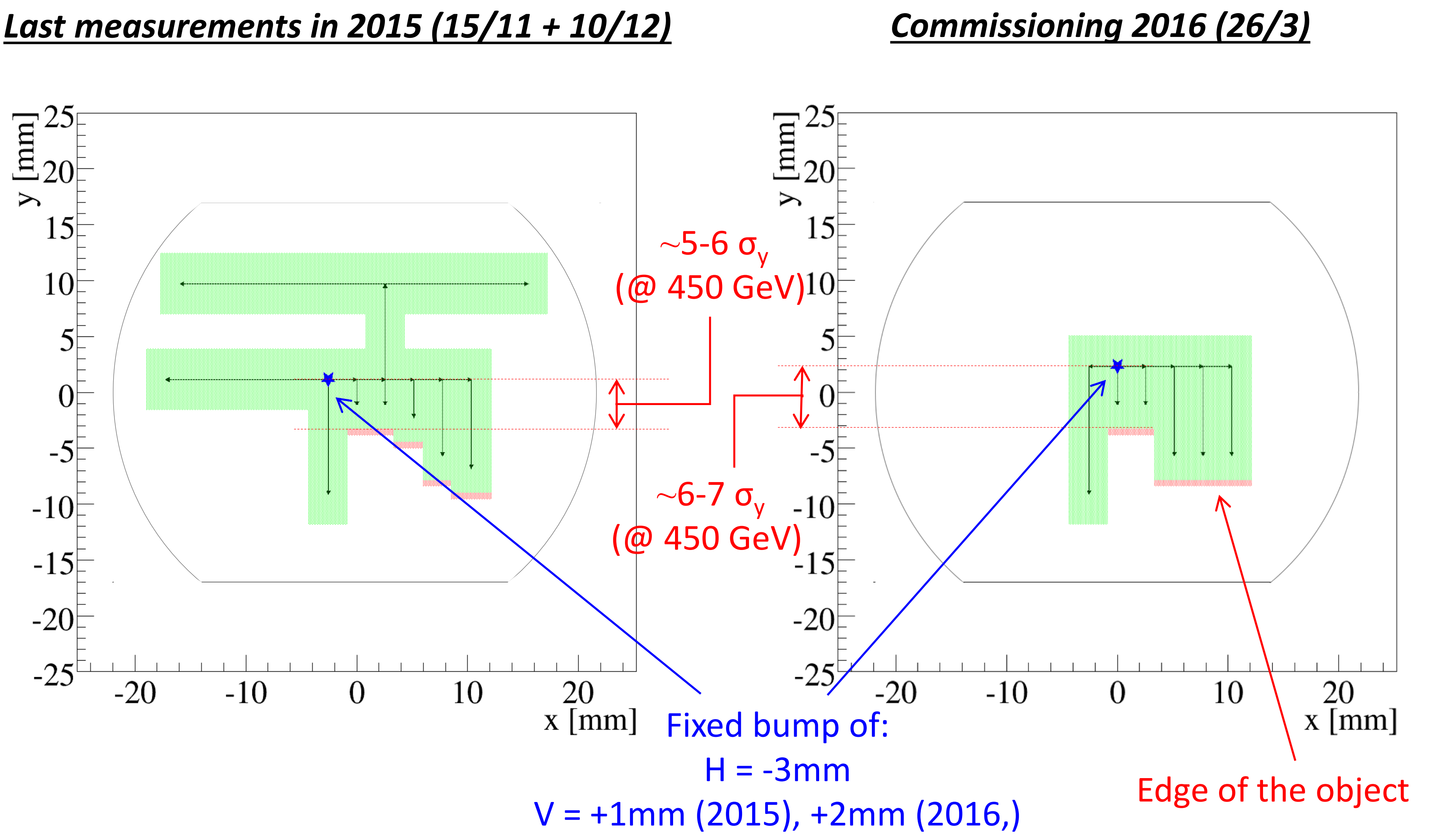
- **Aperture measurements** key ingredient for **settings** and **functions** deployment of **86 ring collimators**
  → **Reliable extrapolations from 2015** allowed **safe deployment of 40cm $\beta^*$**
- **Largest amount of loss maps** collected in the **lowest number of fills** required!
  → Mainly thanks to **new procedure for $\delta p/p$**. Plans to increment automation to do even better
- **Stable performances** along the year with a **single alignment**!
- Impressive improvements in **alignment speed**:
  - ✓ All system aligned in **about 5 hours** during YETS commissioning
  - ✓ **Main focus** will now be on making it as **automated** as possible for **further speed increase**
- **Stable performances** along the years with **ion beams**
- Large variety of **MDs** performed that span over **many topics** with **different time scale**

***No quench from circulating beam losses with more than 250 MJ beams!***
***Keep working for safe and "quench-free" runs***

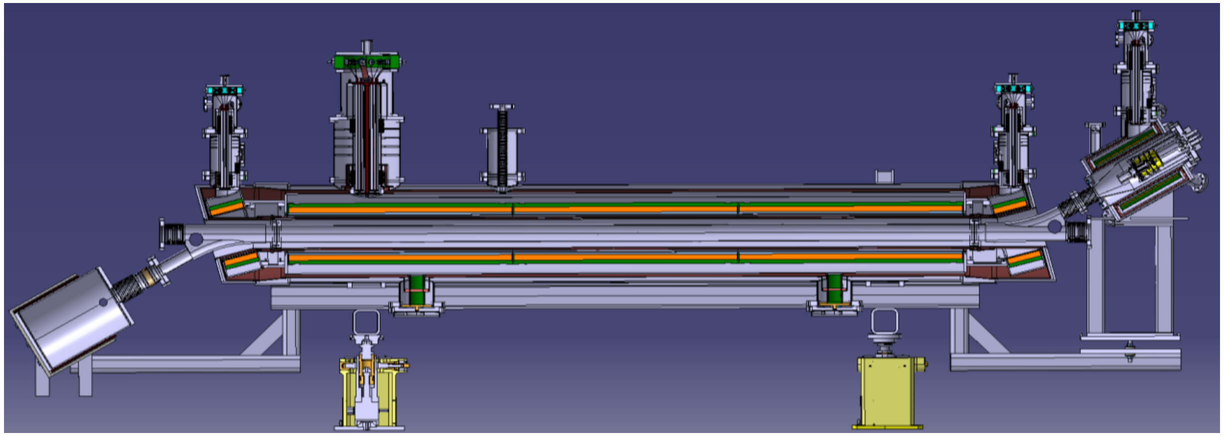
***Thank you for your attention!***

# ***BACKUP***

# Where is the ULO?

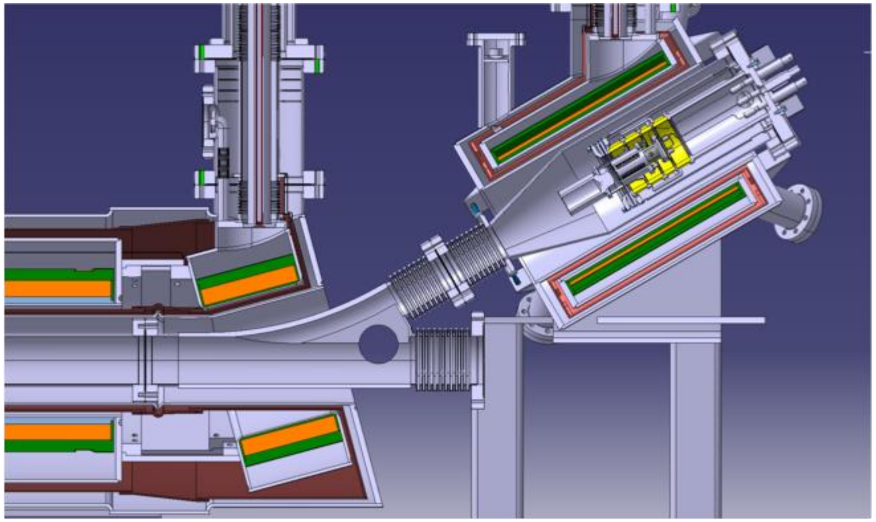


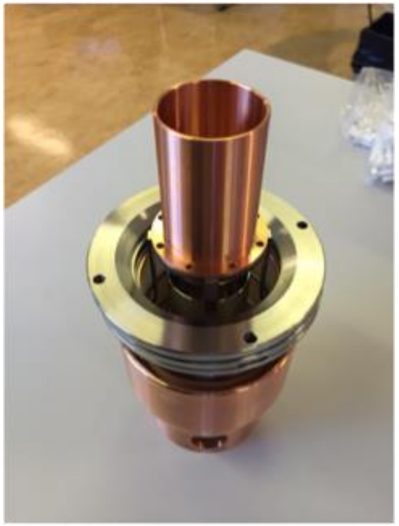
# E-lens



Recent **external review**: confirmed the need for <u>active halo controls</u> at the HL-LHC and fully <u>recommended to deploy HELs</u>.
We are in the process of assessing the addition of HELs to the <u>baseline</u>.

*Design: EN/MME*





First electron gun built at CERN under tests at Fermilab: produced current close to specs (4.2A vs 5A a first test)

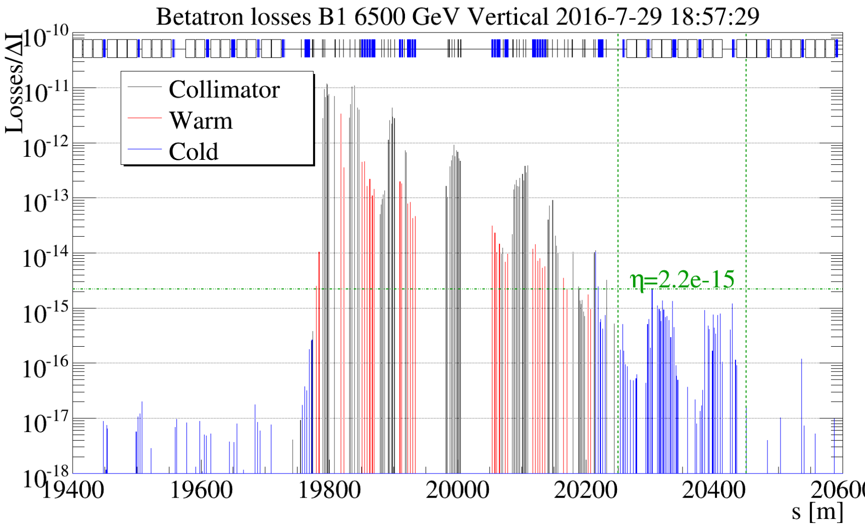
# Crystals

✓ Large level of **beam loss artificially generated** using transverse damper

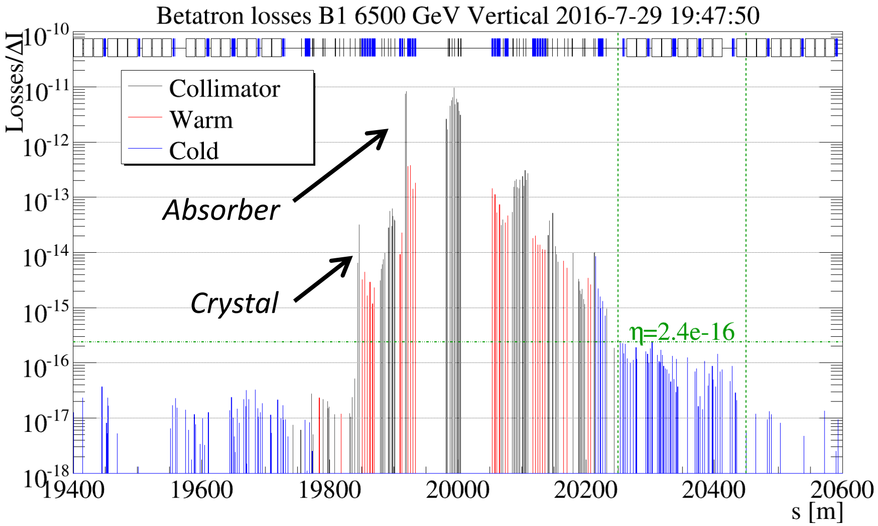
→ Losses recorded by BLM **normalised by number of protons lost**

→ *First Estimation of leakage from collimation insertion (i.e.* ***cleaning efficiency*** *of the system)*

## Standard collimation




## Crystal collimation




Observed about a **factor 10 better cleaning using crystal**, as expected from simulations!

# Loss map matrix – YETS

| LM | 450 GeV | | Ramp& Squ. | 6.5 TeV | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Inj. Prot. IN | Inj. Prot. OUT | | FT | Squ. | EoS | TOTEM | Coll. I | Coll. II | XRP |
| B1H | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| B1V | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| B2H | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| B2V | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| $+\delta p/p$ | ✓ | ✓ | — | ✓ | — | ✓ | ✓ | — | — | ✓ |
| $-\delta p/p$ | ✓ | ✓ | — | ✓ | — | ✓ | ✓ | — | — | ✓ |

✓ = done and OK

— = not requested

# Loss map matrix – TS1

| LM | 450 GeV | | Ramp& Squ. | 6.5 TeV | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Inj. Prot. IN | Inj. Prot. OUT | | FT | Squ. | EoS | TOTEM | Coll. I | Coll. II | XRP |
| B1H | ✓ | ✓ | – | ✓ | – | – | ✓ | – | – | ✓ |
| B1V | ✓ | ✓ | – | ✓ | – | – | ✓ | – | – | ✓ |
| B2H | ✓ | ✓ | – | ✓ | – | – | ✓ | – | – | ✓ |
| B2V | ✓ | ✓ | – | ✓ | – | – | ✓ | – | – | ✓ |
| $+\delta p/p$ | ✓ | – | – | – | – | – | – | – | – | – |
| $-\delta p/p$ | ✓ | – | – | – | – | – | – | – | – | ✓ |

✓ = done and OK

– = not requested

# Loss map matrix – TS2

| LM | 450 GeV | | Ramp& Squ. | 6.5 TeV | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Inj. Prot. IN | Inj. Prot. OUT | | FT | Squ. | EoS | TOTEM + Xing | Coll. I | Coll. II | XRP |
| B1H | ✓ | ✓ | — | ✓ | — | ✓ | ✓ | — | — | ✓ |
| B1V | ✓ | ✓ | — | ✓ | — | ✓ | ✓ | — | — | ✓ |
| B2H | ✓ | ✓ | — | ✓ | — | ✓ | ✓ | — | — | ✓ |
| B2V | ✓ | ✓ | — | ✓ | — | ✓ | ✓ | — | — | ✓ |
| +δp/p | ✓ | — | — | — | — | — | — | — | — | ✓ |
| -δp/p | ✓ | — | — | — | — | — | ✓ | — | — | ✓ |

✓ = done and OK

— = not requested

# Loss map matrix – 4 Z TeV (p-Pb)

| Loss Maps | 450 Z GeV | | Ramp& Squeeze | 4 Z TeV | | |
|---|---|---|---|---|---|---|
| | Inj. Prot. IN | Inj. Prot. OUT | | Flat Top | After cogging | Physics |
| B1H | ✓ | ✓ | – | ✓ | ✓ | ✓ |
| B1V | ✓ | ✓ | – | ✓ | ✓ | ✓ |
| B2H | ✓ | ✓ | – | ✓ | ✓ | ✓ |
| B2V | ✓ | ✓ | – | ✓ | ✓ | ✓ |
| +δp/p | ✓ | ✓ | – | – | – | ✓ |
| -δp/p | ✓ | ✓ | – | – | – | ✓ |

✓ = done and OK

– = not requested

# Loss map matrix – 6.5 Z TeV (p-Pb)

| Loss Maps | 450 Z GeV | | Ramp& Squeeze | 6.5 Z TeV | | | |
|---|---|---|---|---|---|---|---|
| | Inj. Prot. IN | Inj. Prot. OUT | | Flat Top | After cogging | End of Squeeze | Physics |
| B1H | — | — | — | ✓ | ✓ | ✓ | ✓ |
| B1V | — | — | — | ✓ | ✓ | ✓ | ✓ |
| B2H | — | — | — | ✓ | ✓ | ✓ | ✓ |
| B2V | — | — | — | ✓ | ✓ | ✓ | ✓ |
| +δp/p | — | — | — | — | ✓ | — | ✓ |
| -δp/p | — | — | — | — | — | ✓ | ✓ |

✓ = done and OK

— = not requested

# Loss map matrix – 6.5 Z TeV (Pb-p)

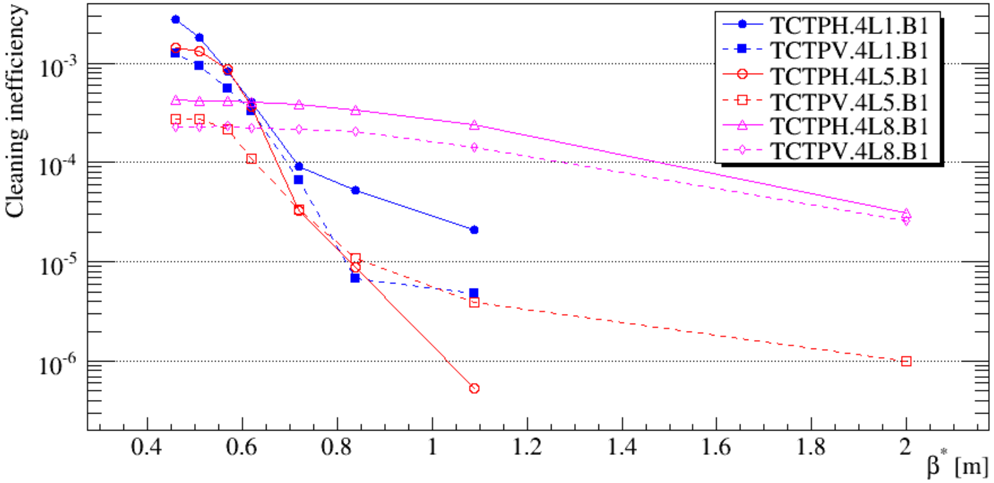
| Loss Maps | 450 Z GeV | | Ramp& Squeeze | 6.5 Z TeV | | | |
|---|---|---|---|---|---|---|---|
| | Inj. Prot. IN | Inj. Prot. OUT | | Flat Top | After cogging | End of Squeeze | Physics |
| B1H | ✓ | ✓ | — | ✓ | ✓ | ✓ | ✓ |
| B1V | ✓ | ✓ | — | ✓ | ✓ | ✓ | ✓ |
| B2H | ✓ | ✓ | — | ✓ | ✓ | ✓ | ✓ |
| B2V | ✓ | ✓ | — | ✓ | ✓ | ✓ | ✓ |
| +δp/p | ✓ | ✓ | — | — | ✓ | — | ✓ |
| -δp/p | ✓ | ✓ | — | — | — | ✓ | ✓ |

✓ = done and OK

— = not requested

# Performances

- Possible to monitor **losses on TCTPs along squeeze** (useful input for simulations)




*Example of losses on TCTPs during **B1H loss maps** along squeeze*

# Active halo control (R.Bruce, H.Garcia and J.Wagner)

- Two methods tested:
  - Narrowband excitation
  - Tune ripple.
- A total of 5 MDs were devoted to test these alternative methods.
- Procedure:
  - Octupoles generate tune spread.
  - With ADT we can excite frequencies wich correspond to certain amplitudes.
  - Goal; excite tails while keeping the core unaffected.
  - Observation: Intensity decrease with BCT and profile … g.