LHC Beam Halo Working Group Report

F. Roncarolo

Many thanks (for input and material) to:
E. Bravin, S. Burger, D. Butti, R. De Maria, C. Hernalsteens, P. Hermes, T. Lefefre, S. Mazzoni, D. Mirarchi, C. Pasquino, J. Pucek, M. Rakic, S. Redaelli, G. Sterbini, J. Storey, G. Trad, R. Veness et al.

HL-LHC Collaboration Meeting, Genova, 09-Oct-2024

Contents

- Introduction to Beam Halo Working Group (BHWG) and short recap of Beam Halo Monitor (BHM) development history
- Revised functional specifications
- Review of monitor technologies suitable as BHM
- Conclusions / Outlook

Beam Halo @ HL-LHC

Controlling/minimizing the beam halo is crucial for:

- **Beam quality** and machine **stability**, preventing excessive losses and instabilities.
- Machine **protection**, safeguarding delicate components from damage.
- Maximizing **luminosity**
- **Reducing** detector **background**, enabling more accurate analysis of collision data

Beam Halo Monitoring included as BI deliverable @ HL-LHC

Beam Halo Monitoring history recap

- Scraping + BLM & BCT → ~'operational' beam halo measurements
  - **Destructive**, only possible in dedicated machine periods (e.g. Commissioning, MDs, End of Fill)
- **Baseline** proposal for **non destructive** measurements: detector based on **SR imaging**. High dynamic range sensors soon discarded in favor of **coronagraph (core blocking)** system, in collaboration with KEK)
- **Up to 2023**: Extensive R&D, lab setups, simulations, prototype installed on LHC B2
- **Prove of principle** soon **achieved** (IPAC). Ultimate performance more difficult to assess. Details in previous collaboration meetings
- **2024**: setup new **Beam Halo Working Group** to wrap up on specifications and technologies

The Beam Halo Working Group

Mandate

- Review beam halo measurements' **specifications**
- Evaluate **coronagraph** system performance
- Explore **alternative**/complementary **techniques**
- Inform decision on **second** synchrotron radiation **source**

Invitation List

Group	Required (and alternates)	Optional
SY-BI	F.Roncarolo (Chair), J.Pucek (Scientific Secretary), D. Butti, S. Mazzoni, B. Salvachua, S. Morales Vigo, J. Storey	T. Lefevre, R.Veness C.Pasquino
BE-ABP	S. Redaelli, M. Rakic, P. Hermes, R. de Maria, G. Sterbini	
BE-OP	G. Trad, D. Mirarchi	
SY-RF	H. Timko	R. Calaga
MPP	C. Hernalsteens	D. Wollmann

Beam Halo Working Group – Agendas

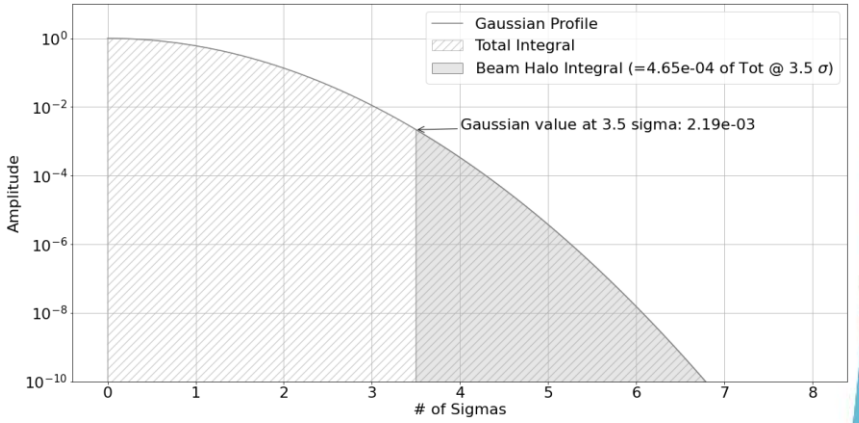
WG - LHC Beam Halo Monitoring · Indico (cern.ch)

Date	Subject
01 Mar 2024	KickOff meeting - LHC beam halo monitoring
22 Mar 2024	2nd BHWG - Coronagraph MD prep - Collimation specs
26 Apr 2024	3rd BHWG - MPP use cases - BGI as BHM
24 May 2024	4th BHWG - Beam-Beam specs - Wire materials simulations
05 Jul 2024	5th BHWG - 1st specs review - BGC as BHM - BSRH MD preliminary results
30 Aug 2024	6th BHWG - Func Specs final draft - Updated BSRH MD results

FUNCTIONAL SPECIFICATIONS

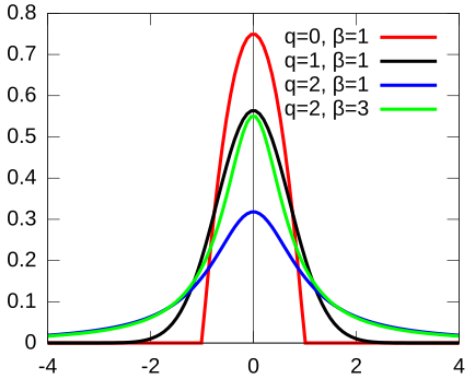
Functional Specs –revisited

- During meetings: revisited definitions and use cases
- Final draft document already circulated and commented by contributors (SY-BI, BE-ABP, TE-MPE, et al.)



Three ways to qualify / quantify halo:

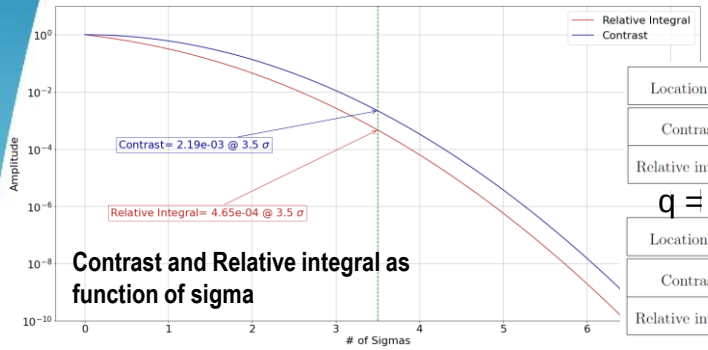
1. **Relative integral**, as the ratio between the beam profile (image) integral from xx σ to ∞ and the beam profile (image) integral from 0 to ∞
2. **Contrast**, defined as the ratio between the beam profile (image) intensity at xx σ and the beam profile (image) maximum
3. **Q-value** of the q-Gaussian model of the charge distribution



General reminders / hypotheses

- Relative integral comparable to scraping meas only in case of beam radial symmetry satisfied
- monitors with PSF, pixel size, required calibration factors etc… → raw profile(image) != beam profile(image)

Definitions, Simulations, Measurement



Contrast and Relative integral as function of sigma

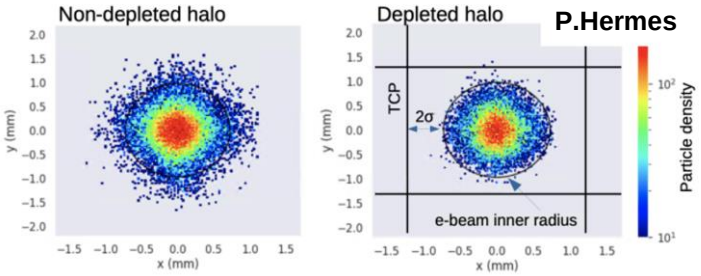
q = 1

Location [σ]	3	3.5	5
Contrast	1.1e-2	2.2e-3	3.7e-6
Relative integral	2.7e-3	4.7e-4	5.7e-7

q = 1.05

Location [σ]	3	3.5	5
Contrast	1.7e-2	4.8e-3	6.1e-5
Relative integral	5.2e-3	1.3e-3	1.5e-5

Examples of challenges and parameters' space to be covered



Bunch-by-Bunch q-factor

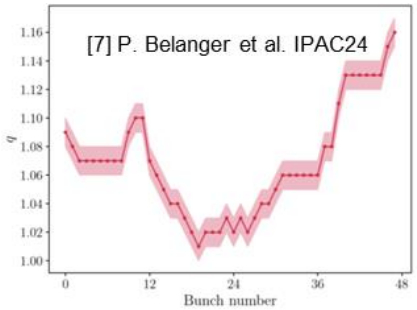
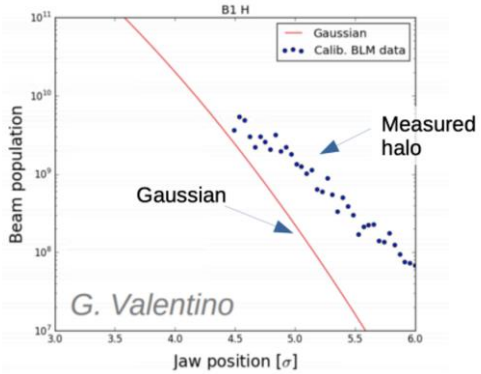
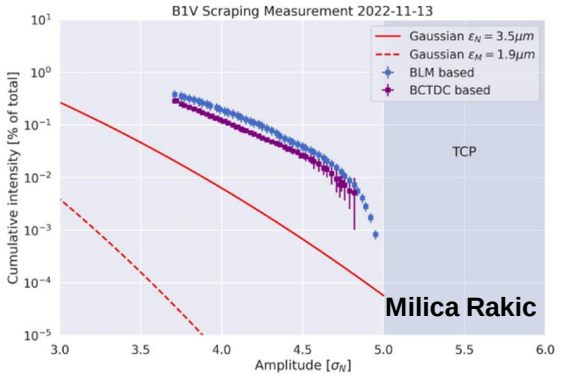


Figure 3.2 – Indirect q value computation for all bunches in one train, [7]





Use cases - requirements

- Collimation
- Machine Protection
- Measurements of beam-beam effects
- ‘Others’

Minimum requirements: the lower performance range in terms of sensitivity, resolution and/or accuracy for the monitor to be considered useful

Ultimate requirements or **desiderata**: more demanding performance levels that would enhance halo monitoring effectiveness in optimising the LHC’s overall protection and/or physics reach

Warning or Interlocking functionalities implying high availability and reliability to avoid spurious beam dumps.

Functional Specs

Parameter	Remarks	Unit	Collimation	MP	Beam-Beam
ROI	e.g. 3.5 to $+\infty$	Sigmas $\epsilon_n = 2.5\mu m$	4.7 to 6.7, 6.5 to 8.5	4.7 to 6.7, 6.5 to 8.5	3.5 to 8.5
Contrast Required	Resolve halo at xx sigma / core-peak=1e-4	-	10^{-4} at upper bound	10^{-6} at 6.7σ	5×10^{-5} at 7σ
Relative Integral	(Halo/total) measurement range for ROI	# of p	5% to 0.5%	1.4% to 0.2%	
Absolute Integral	# of p in ROI	# of p	1.5×10^{12}	$(1-4) \times 10^{10}$	
Charge Required	Yes / No	-	Yes	Yes	No
Profile Required	Yes / No	-	No	No	Yes (complementary to BWS)
Profile Desirable	Yes / No	-	Yes	Maybe	-
2D Image Required	Yes / No	-	No	No	Yes
2D Image Desirable	Yes / No	-	Yes	No	-
Acq. Rate	for full machine	Seconds	≈ 60	≈ 10	≈ 60
Gating and Integration	Bunch per Bunch / Trains / other	-	Beam	Train of 48b	bunch per bunch
Integration over Multi Turns Acceptable	Yes/No	Yes	Yes	Yes	Yes
Interlocking Desired	Yes / No (=monitoring only)	-	No	Yes	No

Table 3.1 – Summary of minimal specifications

Synthetic Summary Table

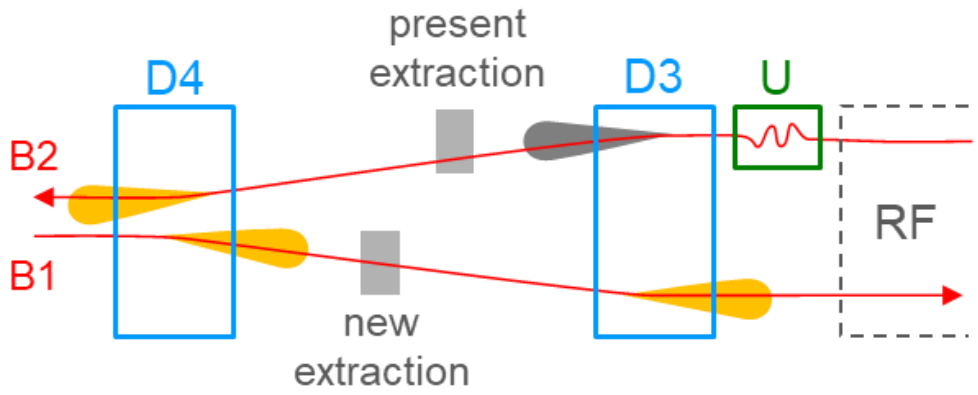
- Ranges and Requirements: Assessing minimum reach and desired capabilities
- Key Highlights:
  - Beam-beam Interactions: Need for profiles, images, and **bunch-by-bunch** analysis
  - Machine Protection (MP): **10-second integration time**, capability to gate on 48 bunches
  - Collimation System: Integral measurements sufficient, profiles preferred, ability to resolve halo **up to 8.5 sigma**

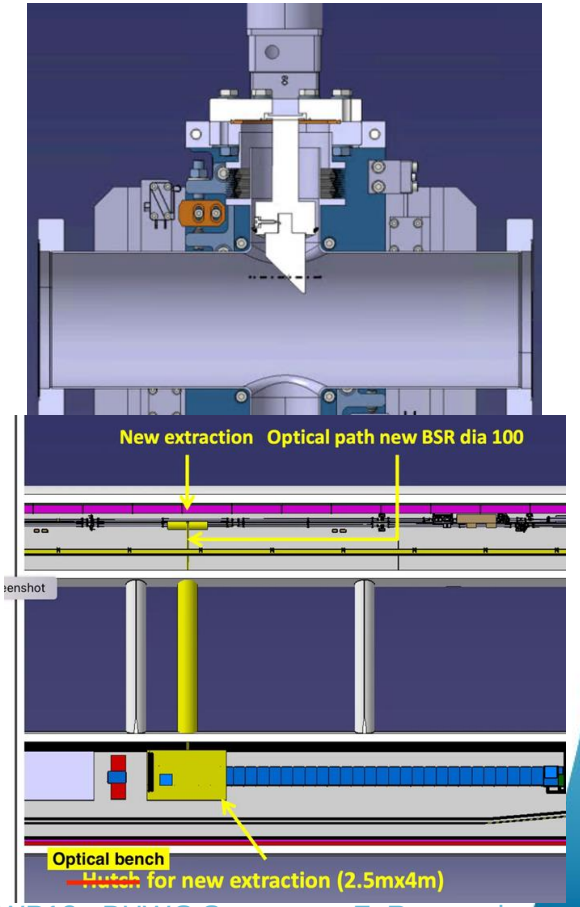
Detector Technologies

SR imaging

- **Coronograph** extensively discussed in **next talk by J.Pucek**.
  - Ultimate reach (expected to be limited by SR source diffraction) being assessed via MDs with prototype on one LHC beam
- **Alternatives- using SR**:
  - More **standard ‘occulting’ imaging telescope**. No need for Lyot stops and related re-imaging present in coronagraph
  - **HDR camera**: can re-iterate on ultimate performances reach (update survey made many years ago)
  - **Slit Scanner** (not presented at BHWG yet):
    - Sample and count SR slices with a fast moving slit. Fast gated intensified PMT allows probing all LHC bunches faster than imaging.
    - Beam halo spatial resolution and accuracy also affected by SR diffraction and optical line quality. No 2D image. Being tested at SPS and LHC.

Second SR extraction systems





- More compact extraction system
- More light collected (Roman Pot-like object, move closer to beam at flat top)

Second SR source systems

Not presented at BHWG yet

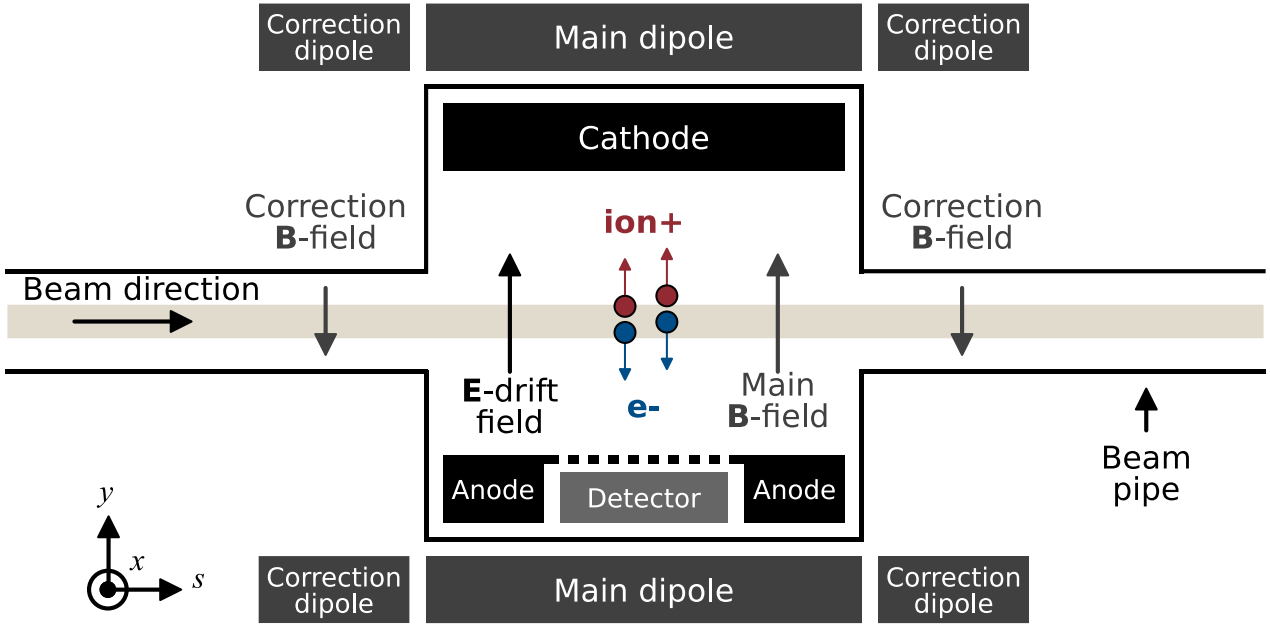
The **HL-LHC baseline** includes **new light extraction systems (BSRTMB):** for Beam Halo Monitor (BHM) and ~~streak camera~~ implementation. Progress has been made:

- Completed comprehensive design, integration, and RF impedance studies through simulations and laboratory measurements
- Produced and installed Beam 1 system with a remotely movable (dummy) mirror
  - Fully tested in LHC environment, with integration into operational sequences and interlocks as collimator-like equipment
  - Validated RF simulations using temperature probes, confirming no heating issues during LHC operation
- Requested necessary cables and fibers for both beams

Next:

- Go ahead with integration studies and installation plans, including option for optics in UA – PRO and CONS being assessed
- **BHM review end of 2024 to clarify next steps/decisions**

Beam Gas Ionization Monitor (BGI)- Concept



See J.Storey's presentation later today

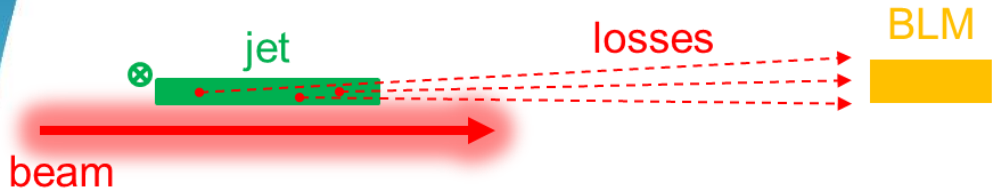
BGI as BHM

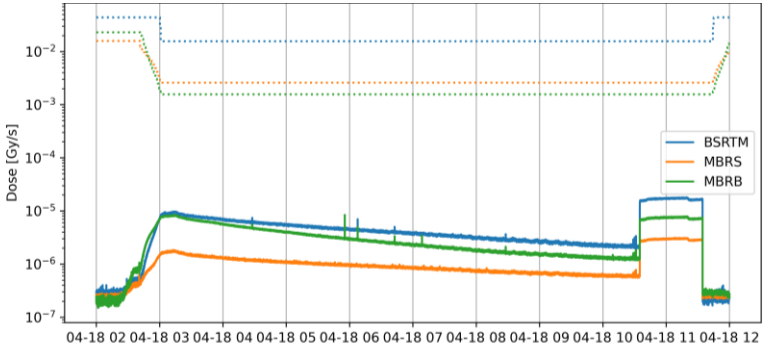
- **BGI** is a new **non-destructive transverse beam profile monitor** under development for HL-LHC (see J.Storey in few minutes)
- Timepix4 HPD with a spatial resolution $\sigma_{spatial}$=16µm & time resolution σ_{time}=200ps.

Parameter	Without Gas Injection	With Neon Gas Injection
Residual gas pressure	1x10-10 mbar	1x10-10 mbar
Injected gas pressure	N/A	1x10-8 mbar (Neon)
Integration time	1s	1s
HL-LHC beam	2.2x1011 ppb x 2760 bunches	2.2x1011 ppb x 2760 bunches
Total electron signal	15x10^6 electrons/s	8x10^9 electrons/s
Beam halo signal (>±5σ)	4 electrons/s	2200 electrons/s
Conclusion	Insufficient beam halo signal	"Useful" beam halo signal

Item	Comment/Mitigation
Signal strength	Sufficient with Neon gas injection
Timepix4 saturation	Mask pixels under beam core
Charged particle backgrounds	Use cluster finding & selection methods
Electron position preservation	Requires simulation studies
Budget	Neon gas injection system not currently included

Beam Gas Curtain (BGC) as beam profiler





- Continuous, ~non-invasive measurements
- Measures population integrated along jet
- If jet is moved, measures profile (emittance)

Possible limitation	Impact
Gas jet is not a step function	Reduced spatial resolution
High pressure background (Pmin)	Reduced sensitivity to halo population
Limited Pmax	++ integration time to have usable signals
Pressure fluctuations	Affect absolute measurements. Relative measurements still possible with constant pressure

General BGC status presented earlier today (D.Butti et al.)

Low Density Materials

SY-BI **studying** new nano-tube based materials for **fast wire scanners** (for **beam profile**, not focusing on beam halo)

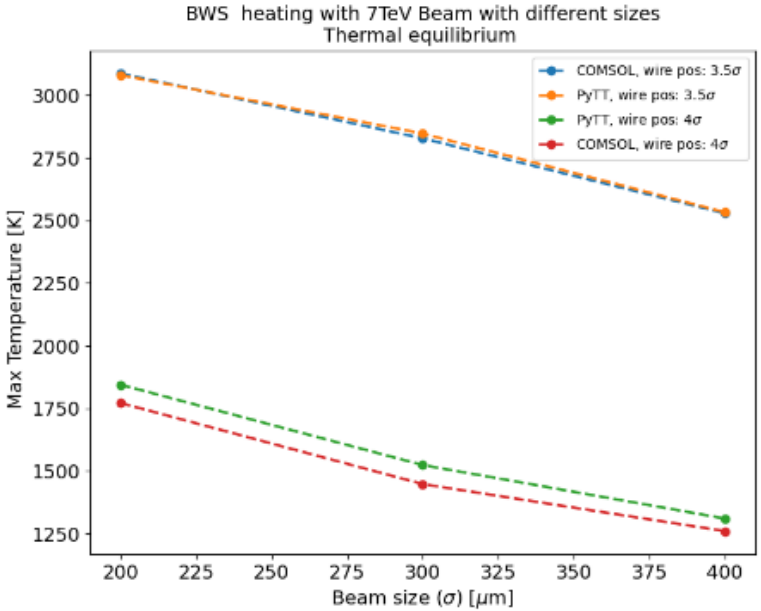
- Aim: use **same models to simulate beam halo 'probi**
- Challenges:
  - Current materials limited by high-Z impurities
  - Simulate/validate wire heating, losses, risks of quenches

Collaborations

- Bath University: Post-processing purification methods
- Global suppliers: Materials with suitable properties

Material requirements

- Specific densities and diameters
- Appropriate mechanical properties



Conclusions / Outlook

Beam Halo Working Group Progress

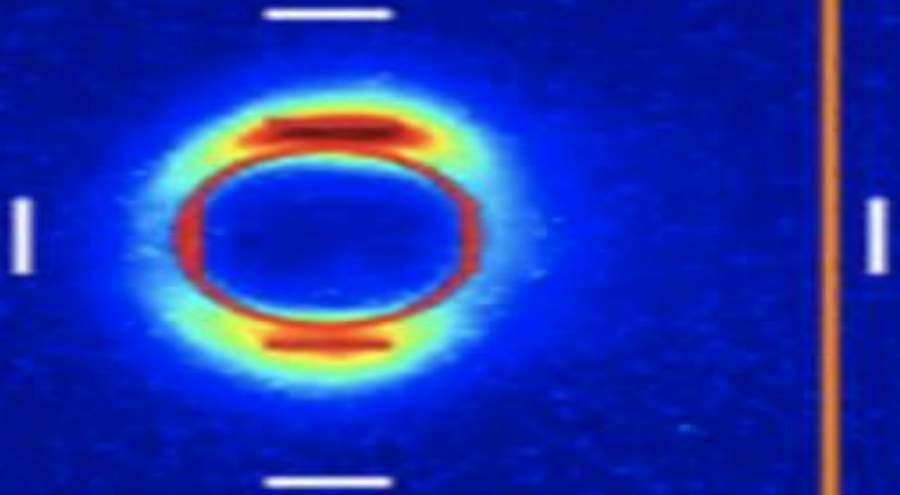
- Functional specifications document nearing completion
  - Assesses minimum requirements and desirable features
  - Relaxed specifications compared to previous 10^-5 contrast requirement
- Ongoing SR monitor tests and technology evaluations (J.Pucek in few min)
- BGI and BGC considered as potential BHM = extensions of beam profile monitors
- Challenge: no single monitor currently meets all specifications

Next steps (in BHWG meetings as needed):

- Slit scanner status and perspectives
- Evaluate second light source status and trade-offs
- Evaluate options with HL-LHC optics in IR4 (e.g. de-squeeze IR4 at flat top as extension of flat optics). Larger beam sizes beneficial for most(all?) monitors
- Review use cases in light of 'Update on collimation losses and halo limitations' and Integrated luminosity of the new HL-LHC baseline et al. Genoa presentations ?

Beam Halo monitoring review scheduled for December 2024

Thank you

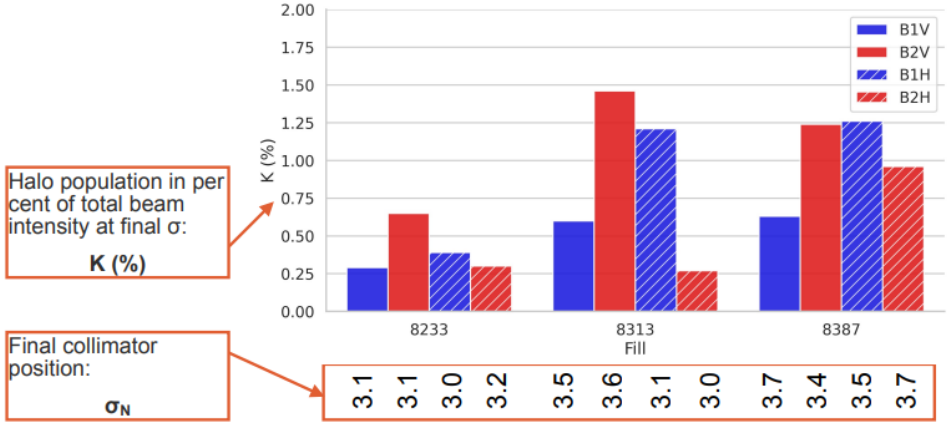


SPARES

Current transverse halo population

Conclusion on halo population:

- Halo overpopulated compared to Gaussian
  - In a range of a few percent
- Variance in halo population between measurements, beams and planes — need for versatility



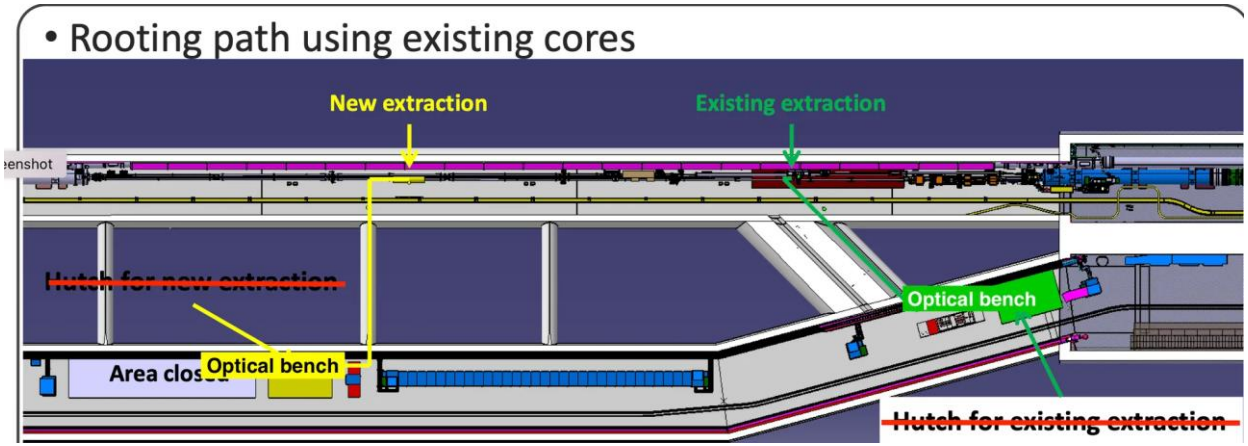
Fast failures

Depleted halos will delay the critical loss level but also the indirect failure detection time (from BLM or BCCM)

→ reduced margin for indirect detection

Classification	Failure	Detection	Elements
Beam effect of magnet protection equipment	QH	Direct	Triplets, D1, D2 (+ MB)
	CLIQ	Direct	Triplets IP1 & 5
Active device failure	ADT	Indirect	ADT H & V
	Crab cavities	Direct	IP1 & 5
Powering failure (resistive component)	BBCW	Direct	IP1 & 5
Powering failure (SC component)	Symmetric triplet quench	Direct / Indirect	Triplets IP1 & 5
Other	UFO	Indirect	Arcs
	Loss BB kick	N.A.	N.A.

Direct detection: external fault detection mechanism is interlocked
Indirect detection: protection must rely on interlocked beam-based measurements


• Rooting path using existing cores
New extraction
Existing extraction
Optical bench
Optical bench
Hutch for existing extraction

Fast Losses

Spurious CLIQ discharge failure case