Achromatic Telescopic Squeezing (ATS) scheme: principle, by-products and experience with beams

S. Fartoukh (BE/ABP) on behalf of HiLumi WP2

With contributions from the OP, OMC, Collimation, Lumi, Beam-beam & ADT teams
Recap: ATS motivations, principles, by-products and MD’s in Run I

ATS MD’s in 2016/2017 (round & flat optics)

2017 ATS LHC optics: Check-up after one operational year (2017 vs. 2016)

Expected ATS driven limitations for future LHC operation (7.0 TeV, lower $\beta^*$, flat optics, LIU beams ..)

Summary & Conclusions
ATS motivations, principles & by products (1/5)

- Lower $\beta^*$ need magnets of larger aperture, and new HW or sophistication (crab-cavity, flat optics) to “profit from the low $\beta^*$”

→ the HL-LHC Project

- But this does not tell how to produce the $\beta^*$

→ the ATS scheme ([PRSTAB 18-111002, 2013](#)) which solves many optics limitations coming from the overall ring:

1. **Optics matchability** to the arcs:
   - Some IR quads going to 0 T/m, others to max. field (200T/m)
   - Simply the matching section becomes too short at some point!

2. **Correctability of the chromatic aberrations induced**, not only $Q’$, but also $Q’’$, $Q’’’$, …, and off-momentum $b$-beating.

→ Arc sextupole strength (<600A)
How? a squeeze in two steps

1. **The Pre-squeeze:**
   - An “almost” standard squeeze,
     - Acting on the matching quads of IR1 and IR5 with new matching constraints on the left/right IR phase,
     - Till reaching some limits on matching quads (or sextupoles)

2. **The Tele-Squeeze:** A further reduction of $\beta^*$,
   - Acting only on IR2/8 for squeezing IR1 and IR4/6 for IR5,
   - Inducing $\beta$-beating bumps in s81/12/45/56 to boost the sextupole efficiency, but also the octupoles (see later).
A kind of generalized squeeze involving 50% of the ring!

Beam sizes [mm] @ 7 TeV from IR8 to IR2 for typical ATS "pre-squeezed" optics (left) and "telescopic" collision optics (right)

\[ \beta^* = 40 \text{ cm} \]

\[ \beta^* = 10 \text{ cm} \]

The new IR is sort of 8 km long!

\[ \text{Tele - Index} \equiv \frac{\beta^*_\text{Pre-Squeeze}}{\beta^*_\text{Squeeze}} = \frac{(\hat{\beta}_\text{Arc})_{\text{Mismatched}}}{(\hat{\beta}_\text{Arc})_{\text{FODO}}} \]
First demonstration with beam in 2011 (.. already with 30 cm $\beta^* !$) → Telescopic principle ($\times 4$) demonstrated in IR1

Thanks to G. Vanbavinckhove & OMC team
ATS motivations, principles & by-products (3/5)

Chromatic corrections (Q’): **No $\beta^*$ limits**

- Chromatic corrections (Q’): **No $\beta^*$ limits**

Typical sextupole settings [A] for the 32 families available per beam (from MD in 2011 @ 3.5 TeV)

$\beta^* > 40 \text{ cm}$

During the telescopic part, the chromatic correction is achieved by the $\beta$-beating!

$\rightarrow$ Only 25% of the RS circuits participate to the chromatic correction **during the pre-squeeze**

$\rightarrow$ All sextupole then kept ~ constant **during the tele-squeeze**
The magic lies in the choice of the betatron phases

.. Zoom in arc45: Pre-Squeeze to $\beta^*=40/40$ cm (round optics): Tele index $1H\times1V$

$\Delta \mu_x = \pi$ between strong SD's (every other FODO cells)

$\Delta \mu_y = \pi$ between strong SF's (every other FODO cells)

$\Delta \mu_x (Q11 \rightarrow IP) = 1.25 \times \pi + \varepsilon_y$
with $\varepsilon_y \sim 1/2 \tan^{-1}(b_{\min}/b_{\max})$

$\Delta \mu_y (Q10 \rightarrow IP) = 0.75 \times \pi + \varepsilon_x$
with $\varepsilon_x \sim 1/2 \tan^{-1}(b_{\min}/b_{\max})$

$\Rightarrow (\beta_{arc} \times \beta^*) \gamma \approx \text{cst}$

$\Rightarrow (\beta_{arc} \times \beta^*) \nu \approx \text{cst}$

$\rightarrow \pi/2$ phase in the arc cells
$\rightarrow \pi/2$ on the left/right side of the IR
$\rightarrow$ 2 sextupole families per plane but only one used for triplet correction
The magic lies in the choice of the betatron phases

.. Zoom in arc45: Squeeze to $\beta^* = 10/10$ cm (round optics) \): Tele index $4H \times 4V$

\[ \beta_{s sextupole} = \frac{1}{\beta^*} \]
The magic lies in the choice of the betatron phases.

.. Zoom in arc45: \textbf{Squeeze to }$\beta^*=20/5 \text{ cm (flat optics)}$: Tele index 2H$\times$8V
ATS motivations, principles & by products (4/5)

**Chromatic aberrations: a zoo to manage carefully at low $\beta^*$**

1. Off-momentum $\beta$-beating: $\frac{\delta}{\beta} \approx \frac{1}{\beta^*}$. Up to $+/- 50-100\%$ in the bucket
   → Collimation hierarchy (limits the retraction $n2/n1$), off-momentum aperture, etc..

2. Non-linear chromaticities: $Q'' \approx \frac{1}{\beta^*^2}$ up to 100 K-units, $Q''' \approx \frac{1}{\beta^*^3}$
   → Dynamic aperture, life time, ..

3. Spurious dispersion from $X$-angle: $D_{x,y} \approx \theta_x/\beta^* \approx \frac{1}{\beta^*^{3/2}}$, up to 10 m in the IT
   → Aperture, background, $Q'$ variations from bunch to bunch due to BBLR pacman effect (up to $+/- 10$ units from bunch to bunch in HL-LHC !)

While these was NOT limiting the LHC in 2016 ($40 \text{ cm } \beta^*$ and “large” TCP/TCS retraction of 2 $\sigma$), a clean chromatic correction is an in-built feature of ATS optics:
→ **Optically speaking, the ATS “puts the lattice sextupole inside the triplet” thanks to its phasing configuration**
Illustration with a “non-feasible” non-ATS 15 cm $\beta^*$ LHC optics (Q7 beyond limits and Q6 @ 0 T/m)

→ With **No specific IP1-IP5 phase**: chromatic $\beta$-beat, Q”', Q''',.., spurious dispersion

→ **Phasing IP1 and IP5 by $p/2$ would only partly solves the problem**: chromatic $\beta$-beat in half of the ring, huge Q””, still spurious dispersion.
With the ATS, the non-linear chromaticity vanishes, the W’s become “triangular”, the spurious dispersion can be corrected.

**Tunes vs. $\delta_p$**

**Chromatic Montague functions**
(amplitude of the off-momentum b-beating)

Dispersion reduced to ~50 cm in the IT (not accounting IR2/8 contribution) with ±2.5 mm bumps in s81/s12/s45/s56 (proved in MD, not implemented yet in OP)

**Closed orbit with X-scheme**

**H and V dispersion**
ATS motivations, principles & by-products (5/5)

Landau damping and beyond (BBLR mitigation)

- Two categories of octupoles in s81/12/45/56: the “strong” (with increased $\beta \propto 1/\beta^*$) and the “weak” (with decreased $\beta \propto \beta^*$)

Beam 1/2 | “Strong“ OF.b1/OD.b2 | Weak OF.b1/OD.b2 | Strong OD.b1/OF.b2 | Weak OD.b1/OF.b2
---|---|---|---|---
Total | 7+4 = 11 | 6+4 = 10 | 4+7 = 11 | 4+6 = 10
MO tune spread amplification at constant strength during the Tele-Squeeze

\[ \Delta Q_{\text{spread}} \propto \beta_{MO}^2 \propto 1/\beta^*^2 \]

- \( \sim 60\% \) for a tele-index of 2 (very reasonable for LHC)
- > 400\% for a tele-index of 4 (typical HL-LHC)

At large tele-index (>3), the MO’s are so efficient that they can mitigate the long-range Beam-Beam effect

Tele-index \( r_{tele} \) (i.e. \( \beta^*_{\text{collision}}/\beta^*_{\text{pre-squeeze}} \))

Simulated MO scan with 150 \( \mu \)rad X-angle
\( N_b=1.2E11, \gamma_c=2.5 \mu m, \) and \( r_{tele} \sim 3 \) (from 1 m to 35 cm)

As for the “strong sextupoles” (used for the IT chromatic correction), the “strong octupoles” are located at \( \sim \pi \) w.r.t. the IT and hence the BBLR encounters.

\( \rightarrow 4^{\text{th}} \) order BBLR resonance driving terms are also mitigated
ATS MD’s in 2016/2017 (round & flat optics)

→ ATS MD’s in Run I (2011-12) demonstrated the basics, down to 10 cm $\beta^*$ (in non-operational machine conditions, e.g. w/o X-angle) with
(i) low intensity beams and
(ii) not always with state of the art optics correction

→ ATS MD’s in Run II (2016-17-..18) studied on 3 fronts a new version of the ATS optics (optimized for machine protection aspects)

1. Round telescopic optics with pushed pre-squeezed $\beta^*$ (40 cm), limiting the high intensity tests to “small” tele-index
   → for LHC ($r_{tele} \sim 1.3$ @ $\beta^* \sim 30$ cm)

2. Round telescopic optics with larger pre-squeezed $\beta^*$ (1 m), enabling high intensity tests @ large tele-index
   → for (HL-)LHC ($r_{tele} \sim 3$ @ $\beta^* \sim 30$ cm)

3. Flat optics (just started) → for (HL-)LHC
1. 1\textsuperscript{st} Front (2016): round optics with pushed pre-squeeze

(i) Validate the 2017 LHC optics with a few nominals

(ii) Demonstrate optics correct-ability with probes at lowest possible $\beta^*$ (pushed pre-squeezed optics and pushed tele index)

$\rightarrow$ Pre-squeeze to 40 cm (limited by sextupoles)

$\rightarrow$ “Mini-telescope” down to 33 cm with few INDIV’s

$\rightarrow$ “HL-LHC telescope” ($\times$ 4) down to $\beta^*=10$ cm with probes
• Tele index of \( \sim 1 \) @ \( \beta^* = 40/33 \) cm

\( \rightarrow \) Changing to the ATS is transparent for collimation (at least for small telescope)

### 2016 OP

![Graph showing cleaning inefficiency](image)

### 2016 ATS MDs

<table>
<thead>
<tr>
<th>Optic Name</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>R2016ats_A40C40A10mL300</td>
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</tr>
<tr>
<td>R2016ats_A37C37A10mL300</td>
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<tr>
<td>R2016ats_A33C33A10mL300</td>
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</tr>
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</tr>
<tr>
<td>R2016ats_A17C17A10mL300</td>
<td>452</td>
</tr>
<tr>
<td>R2016ats_A14C14A10mL300</td>
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<tr>
<td>R2016ats_A12C12A10mL300</td>
<td>676</td>
</tr>
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<td>R2016ats_A10C10A10mL300</td>
<td>804</td>
</tr>
</tbody>
</table>

*Courtesy of D. Mirarchi and Collimation team*
• Tele index of $2 @ \beta^* = 21\,\text{cm}$ (from $40\,\text{cm}$) → $\sim 5\%-10\% \beta$-beat after correction!

Remember these locations for B1H

**Beam 1**

**Beam 2**

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**Courtesy of J Coello de Portugal and OMC teams.**
• Tele index of $2 @ \beta^*=21$ cm (from 40 cm)

→ As expected, the W’s are “triangular”!

(one sector of sextupoles compensate for the chromatic effect of one triplet)

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Courtesy of J Coello de Portugal and OMC teams

Beam 1

Beam 2
• Tele index of 4 @ $\beta^* = 10$ cm (from 40 cm) → 20% level but w/o further correction!

Worst case for B1H with 26% peak $\beta$-beating (same location)
2. 2\textsuperscript{nd} Front (2017): round optics with “down-graded” pre-squeezed $\beta^*$ to enable large telescope

(i) Validate HL-LHC telescope with trains (OP mechanics, interlocks, collimation, life time,..)

(ii) Demonstrate long-range beam-beam mitigation with octupole

$\rightarrow$ Pre-squeeze stopped @ 1 m (End of Ramp in 2017)

$\rightarrow$ Reach 35cm $\rightarrow$ 25cm with telescope only ($r_{tele}=3 \rightarrow 4$)
- Tele index of $3 @ \beta^* = 35 \text{ cm}$ (tele-squeeze from 1 m) → $\sim 10\%$ $\beta$-beat level reached after correction, but still with peak $@15$-20% in B1H (and 15% in B2V)

![Graphs showing tele-beat level before and after correction](image)

*Courtesy of A. Wegscheider and OMC teams*
• Tele index of $3 \@ \beta^* = 35$ cm (tele-squeeze from 1 m)

$\rightarrow$ Large tele index looks transparent for collimation

2017 OP

2017 ATS MDs

Cleaning inefficiency

10^{-3}

10^{-4}

10^{3}

10^{4}

Commissioning, Technical stop

MD 35 cm

7 TeV design cleaning inefficiency

B1H

B1V

B2H

B2V

Courtesy of D. Mirarchi, N. Fuster and Collimation team
• Tele index of $3 @ \beta^* = 35$ cm (tele-squeeze from 1 m)
  MD with a few trains (2 BCMS + 2 BCS trains) → 500h-1000h life time in the end of the squeeze
• Tele index of 3 @ $\beta^*=35$ cm (tele-squeeze from 1 m)

→ **Emittance growth in collision:** no anomaly vs. standard operation

![Graphs showing emittance evolution in collision](Image)

**What is the green region?**

The evolution of emittance if the initial value was the one measured, but the growth was $0.05 \mu\text{m}/\text{h}$

The band shows the ±1σ bunch-by-bunch standard deviation

**Legend**

- $\times$: non-colliding bunches
- $\bullet$: colliding bunches
- $\Xi$: evolution of colliding bunches (mean ± 1σ r.m.s)
- $\_\_\_\_\_$: evolution of non-colliding bunches (mean ± 1σ r.m.s)

**Courtesy of N. Karastathis and Lumi team**
• Tele index of 3 @ $\beta^*=35$ cm (tele-squeeze from 1 m)

→ First demonstration of BBLR mitigation with octupole (MO)

$$\sigma_{\text{eff}}_i \equiv \frac{|dN_i/dt|}{\mathcal{L}_i}$$

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Courtesy of A. Poyet, G. Sterbini, and Beam-Beam team
3. **3\textsuperscript{rd} Front (2017): Flat optics**

(i) Assess feasibility & optics correct-ability (probe beam)

(ii) … More to come in 2018 with in mind the LHC Run III & the “HL-LHC Plan B” (with wires and flat optics)

\[ \rightarrow \text{Crossing angle gymnastic @ 1 m:} \]

HV → VH crossing in ATLAS and CMS for “triplet aperture preparation”

\[ \rightarrow \text{Pre-squeeze down to 60 cm/60 cm at IP1 & IP5} \]

\[ \rightarrow \text{Tele-squeeze (tele index 1111} \rightarrow 1441 \rightarrow 2552): \]

- ATLAS: \((60/60) \rightarrow (60/15) \rightarrow (30/12)\)
- CMS : \((60/60) \rightarrow (15/60) \rightarrow (12/30)\)

The second segment was prepared but not played (MD time)
- IR1 & 5 : crossing plane rotation @ 1 m (no telescope)
  → LHC specific, not needed for HL-LHC with octagonal beam-screen

Round beam configuration
(V-crossing in ATLAS, H-crossing in CMS)

Flat beam configuration
(H-crossing in ATLAS, V-crossing in CMS)

New beam Process needed
X-angle gymnastic @ flat top (β* = 1m)

Effect of decreasing the beam aspect ratio at the IP (and increasing the vert. X-angle)

Effect of increasing the beam aspect ratio at the IP (and decreasing the vert. X-angle)
The Machine configuration page was lost 😊, but the process was successful!

H Xing in ATLAS (and LHCb)

V Xing in CMS (and Alice)
(60-15)-(15-60) was reached and corrected, although Page 1 needs some upgrade as well 😊

The worst case is B1H (25% peak $\beta$-beating at same location), with <10% for B1V 
→ Very encouraging after the very first try and only a few hours of OMC activities
• Flat optics 60/15 cm @ IP1 and 15/60 cm@ IP5
→ The W’s is amazingly good after a first try!!
2017 ATS LHC Optics: check-up after 1 year

- Implementation of ATS optics in the LHC for the 2017 Run, with additional (not necessarily ATS or HL-LHC specific) features
  - 40 cm (pre-squeeze) with option to go to 30 cm ("mini-telescope") or beyond (full telescope prepared down to 10 cm)
  - Combined ramp & squeeze pushed to 1 m (more in the future)
  - New IR6 optics with MKD/TCT phase optimization and $\beta^*$ reach
  - New, ..., new, IR4 optics fulfilling BI & ADT requests (next one to come for HEL integration)
  - New IR2 phase for squeeze-ability (2018 ion run)
  - New CMS IP shift bumps enabling to (easily) reach -1.5 mm
  - Concept of “CT-PPS” optics bump to maximize the normalized dispersion at the Roman Pots
  - ...

Check-up summary with beam: 2017 vs. 2016

- **Optics correct-ability**: as excellent as before

- **Collimation**: even improved (not due to the ATS but to the tighter collimator settings)

- **Luminosity Life time**: qualitatively very similar (even slightly improved)

- **Integrated Performance .. we know**: of course not only the 30 cm helped, but at least the ATS did not degrade!

Also take into account the **many other changes**:
- New beam types from injector in 2017 (8b4e, 8b4e BCS)
- X-angle change (150 mrad in 2017 vs. 185/140 mrad in 2016)
- X-angle anti-levelling in 2017 with ≥ 4 steps (150/140/130/120)
- Lumi Levelling with parallel separation
• **Optics correct-ability: excellent (5-7% peak, % level for $\beta^*$)**

- **2016 @ 40 cm** (before/after global correction)
- **2017 @ 40 cm** (with same local correction as 2016)
- **2017 @ 30 cm** (after 2nd global correction)

(Courtesy of E. Maclean and OMC team)
### Collimation

<table>
<thead>
<tr>
<th>Year</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCP/TCGG/TCLA</td>
<td>5.5/8.0/14</td>
<td>5.5/7.5/11</td>
<td>5.0/6.5/10</td>
</tr>
</tbody>
</table>

Big improvements over the years from the collimator setting management:

→ **the ATS did not play any role, neither positive nor negative** (as expected and confirmed in MD when comparing at constant settings)

![Collimation Diagram](image)

*Courtesy of D. Mirarchi and Collimation team*
• **Life time**: effective cross section in SB (all fills)

**2016**

Beam 1

Beam 2

**2017**

Beam 1

Further X-step tried out for a couple of fills only

Beam 2

X-angle steps

Beam 2 Stabilization @ ~2.3h

Beam 2 Stabilization @ ~1.6h

Courtesy of G. Iadarola, N. Karastathis and Lumi team
• **Luminosity**: extra lumi loss after 3 h in SB due to losses, emittance growth, or both beyond model → Quantitatively very similar

2016: ~3 – 6 % extra losses

2017: ~ 4 – 7 % extra losses

Courtesy of S. Papadopoulou and Lumi team
Limitations for future operation and mitigation (1/2)

- Operation at 7.0 TeV: magnet strengths
  - All settings 7.0 TeV compatible, even NC magnets (e.g. MQTL) but
    a) Some RSD circuits in s81/12/45/56 requesting 600A ++,
       - Preferably to be cured by pushing a bit these circuits
       - Otherwise can be mitigated by more telescope (higher pre-squeezed $\beta^*$)
    b) Q5.L6: MQY @3610 A nominal current (160 T/m @ 4.5 K)

<table>
<thead>
<tr>
<th>Target currents (w/o margin) for various cases</th>
<th>LHC: round optics (20 cm) Telescope (x2Hx2V)</th>
<th>HL-LHC: round optics with Telescope (x4Hx4V)</th>
<th>LHC: Flat optics (15/60 cm) Telescope (x3-4Hx1V)</th>
<th>HL-LHC Flat optics with Telescope (x5Hx2V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q5.L6b1</td>
<td>&lt; 3610 A</td>
<td>~ 3800 A</td>
<td>~3700-3800 A</td>
<td>~ 3900 A</td>
</tr>
<tr>
<td>Q5.L6b2</td>
<td>&lt; 3610 A</td>
<td>~ 3700 A</td>
<td>&lt;3610 A</td>
<td>~ 3700 A</td>
</tr>
</tbody>
</table>

- OK for the circuits but HW commissioning needed to probe the magnet limit
- Then decision: 1.9 K (HL-LHC baseline) or “patch” with warm quadrupole
Limitations for future operation and mitigation (2/2)

- **Large telescope with LIU beam: BETS & TCDQ**
  - The beam sizes are changing at the TCDQ during the tele-squeeze, increasing/decreasing for beam1/2, while the TCDQ gap in mm is presently fixed when the ramp is finished.
  - Including $\beta^*$ in the BETS would enable to move the TCDQ at FT.
  - Or embedding the full tele-squeeze in the ramp would allow to work at cst TCDQ settings at FT (constraining but possible).

  - **For the LIU beam @ full intensity, the TCDQ gap should be larger than 3.6 mm** (including 0.6 mm for the BPM interlock at P6), in order to preserve the TCDQ for the worst cases of failure scenarios (C. Bracco, A. Lechner et al.)

$$\rightarrow \beta_{TCDQ} [m] \geq 560 \times \left(\frac{7.0}{n_{TCDQ}[\sigma]}\right)^2 \times \left(\frac{7}{E[TeV]}\right)^2$$

  - To preserve the $\beta^*$ reach (i.e. working at $n_{TCDQ} \sim 7$), a scenario with a combined “$\beta$-TCDQ (&TCT) levelling” seems the only possibility, requesting de facto the upgrade of the BETS.
Summary & Conclusions

• The **ATS is NOT an option but a vital ingredient for HL-LHC**

• So far, regardless of the ATS, the beam follows precisely the MADX expectations (.. and the other way around!).

• Of course challenges are ahead, such as **preserving state of the art optics correction at large telescopic index** (very relevant for flat optics), but not a show-stopper (.. just more beam time).

• **Next steps for the 2018 ATS MD’s are**
  a) The **continuation of flat optics** development, including beam-beam studies with a few trains.
  b) The **completion of round optics** validation with **large telescopic index at full intensity** (or nearly full) for e-cloud studies with telescopic optics.
  c) In this exercise, to prepare with high priority the decision making process for the **Run III optics: flat vs. round optics**.
Beam size [mm] @ 7 teV ($\gamma\varepsilon=3$ $\mu$m) during Pre-squeeze and Tele-squeeze
First demonstration with beam in 2011 @ 1.2 m (pre-squeezed optics)

The off-momentum \( \beta \)-beating induced by the IT is confined in s81/12/45/56

Thanks to R. Miyamoto and OMC team
• Tele index of $4 \beta^*=10 \text{ cm (from 40 cm)}$

The spurious dispersion (w/o X-angle) is under control

(could be further corrected in H, hardly in V)

Max $1.5-2 \text{ m in the triplets}$

.. but for a $\beta_{\text{max}}$ of 24 km!
• Tele index of 3 @ $\beta^* = 35$ cm (tele-squeeze from 1 m)

→ Starting with MO<0 in another fill (BCMS with $\gamma \varepsilon \sim 3$ $\mu$m), the life time improved by reducing the X-angle!

→ Up to 20 $\mu$rad (10%) could be gained in X-angle

Courtesy of A. Poyet, G. Sterbini, and Beam-Beam team
X-angle steps in 2017

![Graph showing X-angle steps in 2017]

*Courtesy of N. Karastathis and Lumi team*
Summary of beam life time 1h in stable beam

Beam Lifetime at 1h in Stable Beams Along 2016

Beam Lifetime at 1h in Stable Beams Along 2017

Courtesy of N. Karastathis, S. Papadopoulou and Lumi team
Summary of effective cross-section after 1h in stable beam

2016

Effective Cross-Section at 1h in Stable Beams Along 2016

- Burn-off Limit
- LHC-25ns
- BCMS
- 140μrad Crossing Angle
- Beam 1
- Beam 2

Effective Cross-Section [mb]

- $\epsilon_n = 2.9\mu m$
- $\epsilon_n = 2.0\mu m$
- $\epsilon_n = 2.0\mu m$

LHCb Negative Polarity
LHCb Positive Polarity

2017

Effective Cross-Section at 1h in Stable Beams Along the Year

- Burn-off Limit
- TS2
- BCMS
- Beam 1
- Beam 2

Effective Cross-Section [mb]

- $\epsilon_n = 2.3\mu m$
- $\epsilon_n = 2.6\mu m$
- $\epsilon_n = 1.7\mu m$

LHCb Negative Polarity
LHCb Positive Polarity

Reduction to $\beta = 30cm$