Update on Luminosity monitoring for HL-LHC

M. Palm (BE-BI-PM)
Outline

- BRAN: HL-LHC luminosity monitor
- Results & observations
  - Fused silica
  - Aluminum mirrors
- Design considerations
- Summary & Outlook
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Overview

- **BRAN**: Beam RAte of Neutrals
- **What**: Machine luminosity monitors
- **Where**: IP1/5, IP2, IP8
- **Use cases**: Finding collisions, backup instrument for OP (if no data from experiments), cross-check experiments, sanity check, …
- **Precision**: ~1% @ 1 Hz (absolute luminosity not necessary)
- **Challenges**: Large dynamic range, radiation (IP1/5: 180 MGy/year), limited space
- **HL-LHC**: Cherenkov radiation based monitors
BRAN prototype

**Luminosity monitoring**
Forward Neutral debris from IP → Absorption in TAN → Charged secondaries → Cherenkov radiation

- 2 different Cherenkov media tested in LHC (TAN, Left of IP1)

**Fused silica rods**
- 400x10 mm
- \( e^\pm, \mu, p, \ldots \)

**Air + Mirror**
- Aluminum mirror (coating) \( \phi 10 \text{ mm, } 45^\circ \)
- \( e^\pm, \mu, p, \ldots \)
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Radiation effects - Transmission

- Main concern: reduced optical transmission
- 4 rods recuperated from TAN after 1-2 years of LHC operation
  - No visible discoloration or opacity (by eye)
- Shipped to ZDC group at University of Illinois for measurements

ZDC Quartz rods

Unirradiated

Irradiated
(p-p: 2011, Ions: 2010-2012)

[Courtesy: M. Phipps & G. Avoni]

BRAN Fused silica rods (irradiated)

2016

2016-2017

2016-2017

2016-2017

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Measured rod transmission

- Sharp absorption centers in UV range (214 nm, 325 nm)
  - Most of the Cherenkov light is in this region
- Broad absorption around 630 nm

Note:
- Rod #3 (red) only exposed during 2016, 1.5 years of annealing.
- Other rods: 2016-2017, 0.5 years of annealing

Conclusion
- Quartz type matters...
- Visible range will still provide a signal even if UV transmission should drop to 0. “Signal floor”.

Transmission along entire rod, coaxial

Estimated signal loss

[Courtesy: M. Phipps - “ZDC Upgrade: Spectroscopic Results”]
General performance

- Good agreement between prototype signal and ATLAS luminosity

- Signal “gain”:
  - \( G_{\text{slot}} = \frac{\langle U_{\text{slot}} \rangle}{L_{\text{tot}}/N_b} \)

- Fairly stable gain from mid-2016 until today
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Mirror with largest signal (#12) has also degraded the most
  - Currently: -20%/10 fb^{-1}
  - No sign of flattening out…
  - Reflectivity will be re-measured during LS2 to verify if signal loss is due to mirror degradation.
    - Other possibility: diffuse reflections?
  - \textbf{Fused silica rods seems to be the best option.}

<table>
<thead>
<tr>
<th></th>
<th>Mirror #10</th>
<th>Mirror #11</th>
<th>Mirror #12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial gain</td>
<td>0.6%</td>
<td>2.8%</td>
<td>8.3%</td>
</tr>
<tr>
<td>Gain loss</td>
<td>-32%</td>
<td>-43%</td>
<td>-83%</td>
</tr>
</tbody>
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Outline

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- Design considerations
  - Available space
  - X-ing angle
  - Dynamic range
- Summary & Outlook
Available space

- **50 mm** available between beam pipes
- **100 mm** available above copper block
**X-ing angle**

### Vertical X-ing, IP5(?)
- Shower is centered
- Robust against X-ing angle changes

### Horizontal X-ing, IP1(?)
- Off-centered: BRAN intercepts “tail”
- Fluence gradient: ~0.5%/μrad

#### Simulations: Courtesy A. Tsinganis & F. Cerutti

- Cannot only intercept fraction of shower → X-ing angle dependence
- Luminosity-levelling by X-ing angle
- X-ing angle drift/shift during beam separation scans?
  - HL-LHC: no precise estimate (LHC: <1 μrad [preliminary est.])

#### Conclusion: for horizontal X-ing, the measured BRAN luminosity will have a X-ing angle dependence

- Infer X-ing angle from rods between pipes?
  - Need very precise calibration…
  - Dose rate in left/right rods is different → rod transmissions will change at different rates
- Shorter rods above beam pipes?
  - Wider profile → Less precision
  - Dose rate ~2-3 orders of magnitude lower → Transmission slowly degrading over several years (~1000 fb⁻¹)
Dynamic range

- Luminosity range (p-p & Pb-Pb)
  - Total luminosity: 12 orders of magnitude
  - Signal range:
    - ~20,000 times more signal for Pb-Pb than p-p for a given luminosity
    - Light yield per bunch crossing “only” spans 4-5 orders of magnitude.

- Total light yield: 8 orders of magnitude

Light yield per bunch: ~4-5 orders of magnitude
Design considerations: summary

- Fused silica rods/Aluminum mirrors?
- X-ing angle dependence (horizontal)
  - We have to live with it.
- Physical space constraints
  - Difficult to fit more than two parallel quartz rods + PMT + “cross-talk shielding” in 50 mm
- Dynamic range
  - 4-5 orders of magnitude in terms of photons/collision should be covered
- Available light
  - If we extract a sufficient fraction of light from the fused silica rod to the PMT, we can cover a very large dynamic range
- Transmission loss
  - Almost all observed transmission loss of fused silica occurs within first ~10 fb^{-1}, but then remains stable.
  - Foresee (manual) adjustment of light yield e.g. at first technical stop after installation.
  - Design constraint: this should be quick and simple!
- Also: If we can’t handle X-ing angles very well, then we should at least make sure that the BRAN has an “impressive” dynamic range.

- Warning: the TAN/TAXN is a beast against which many detectors have failed...
  - “Simple but reliable” better than “Perfect but complex”
Channel sensitivity range

[Diagram showing sensitivity range for high and low sensitivity modes.]

- **High sensitivity**
  - ~0.01 p-e/coll
  - 100 cps

- **Low sensitivity**
  - ~0.01 p-e/coll
  - 110 cps

- **Counting mode**
  - ~1 p-e/coll
  - 11 kcps

- **Integral mode**
  - ~1 p-e/coll
  - 11 kcps

- **Coincidence counting** between equal-dose rods (left/right)

- **Shower direction**

- **Light yield** in a.u.

- **Single pilot pair (1E10)**
- **Single beam scan pair (0.1% of head-on lumi)**
- **Single nominal pair (1.5E8)**
- **Max lumi 1000 bunches**

- **Max lumi 2748 bunches**

- **p-e = photoelectron**
- **cps = counts per second**
Low sensitivity channel

- Current prototype serves as baseline for precise light yield estimates and dimensions

- Movable: re-adjust light yield after first ~10-20 fb^{-1}

- Clamp/locking ring: blocks light + quick adjustment

- Flat top: only “fast” rays (large \( \theta \)) will exit → Better bunch-to-bunch resolution

- Studs, keeping rod in place

- Light-absorption at bottom

- Reduce thickness of tube “floor” (shower partially missed in 2016, when X-ing angle was negative)
High sensitivity channels

- HV off and cathode shielded at normal operation
  - Add pull-solenoid shutter

- Light yield tuning:
  - PMT-Rod distance
  - Graduated iris diaphragm

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Summary & Outlook

- Fused silica is a feasible Cherenkov medium for the TAXN environment

- Aluminum mirrors still degrading

- Horizontal X-ing angle dependence

- HL-LHC BRAN will measure luminosity over 12 orders of magnitude

- LS2: Replace 2 BRAN-A monitors (ionization chambers) with 2 fused silica BRANs
Thank you for your attention!

Acknowledgments:
E. Bravin, F. Roncarolo,
T. Schneider (Al-mirrors),
M. Phipps et.al (ZDC)
Backup slides
PMT saturation

- 2018 trend: Gain loss
- Prototype: light yield on PMT cannot be easily tuned → Change voltage instead (1250 V → 750 V)
- PMT recovered!
- Gain returned (slowly) to initial level
- Gain variation during fill stabilized: from ~10% to ~1% variation
PMT saturation

- 2018 trend: Gain loss
- Prototype: light yield on PMT cannot be easily tuned → Change voltage instead (1250 V → 750 V)
- PMT recovered!
- Gain returned (slowly) to initial level
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\[
G_{\text{bunch}} = \frac{\langle U_{\text{bunch}} \rangle}{L_{\text{bunch}}}
\]

Same signal as beginning of year

Note: 750 V signal rescaled

2016 2017 2018
Recap: data acquisition

- Voltage-integral histogram of single bunch pair logged
  - 25 ns window (=1 slot)
  - 2016-2017: No baseline correction

- Slot-integral has 3 components
  - \( \langle U_0 \rangle \): Background signal
  - \( \langle U_{tot} \rangle \): Baseline shift during collisions.
  - \( \langle U_{bunch} \rangle \): Mean signal from single bunch pair collision
  - \( \langle U_{slot} \rangle = \langle U_0 \rangle + \langle U_{tot} \rangle + \langle U_{bunch} \rangle \)

- Significant baseline shift with higher PMT current
  - \( \propto I_{mean} \)
  - \( \sim \text{Half(!)} \) the voltage integral comes from baseline (red) at high luminosity
  - Not logged 2016-2017
  - 2018: detailed logging
  - \( \rightarrow \) Restrict long-term evaluation to data points with similar luminosity

Recap: data acquisition

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Terminology

- **Quartz**
  - Natural or synthetic
  - *Crystalline* $\text{SiO}_2$
  - Purity: case-by-case

- **Fused quartz**
  - *Amorphous* $\text{SiO}_2$
  - Made from natural crushed quartz
  - Natural impurities may persist into finished product

- **Fused silica**
  - Synthetic amorphous $\text{SiO}_2$
  - Made from oxidized Si-gas
  - Potentially ultra-pure
Absorbed dose (Gamma spectroscopy)

- 2016: Negative X-ing angle
- 2017: Positive X-ing angle
- Current design: 30 mm gap: TAN-floor to end of quartz rod
- → BRAN “floor” should be made thinner.
Light yield

- Light from particles going exactly forward won’t reach PMT (total internal reflection at top)
  - Light extraction efficiency is pretty low
  - Angular divergence of charged secondaries ≠ 0
  - Each collision at \( \mu = 138 \) generates light equivalent to 2 million PMT “counts”
- \( \rightarrow \) We can have as much signal as we need
  - Light yield on PMT can be tuned by adjusting Rod-PMT gap

<table>
<thead>
<tr>
<th></th>
<th>Track length/event (charged particles) @ Dose peak</th>
<th>Photon yield, quartz</th>
<th>Equivalent PMT counts (incl. QE)</th>
<th>PMT counts/event</th>
<th>Nominal pile-up, HL-LHC</th>
<th>PMT counts/crossing (1 cm(^3) fused silica at dose peak)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>98 cm/cm(^3)</td>
<td>1003 photons/cm(^3)</td>
<td>145 counts/cm(^3)</td>
<td>14210</td>
<td>138</td>
<td>=&gt; 2,000,000</td>
</tr>
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Aluminum mirrors

- 3 mirrors installed
- Different heights

- Mirror with largest signal (#12) has also degraded the most
  - Currently: -20%/10 fb⁻¹
  - No sign of flattening out…
- Reflectivity will be re-measured during LS2 to verify if signal loss due to mirror degradation.
  - Other possibility: diffuse reflections?
- ⇒ We will go for fused silica rods.

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