Outline

• The current ATLAS ZDC
• Radiation damage to the current ZDC
• Design considerations and physics goals for an upgraded ZDC
• Irradiation studies for an upgraded ZDC
• Design conclusions
The Current
ATLAS
Zero Degree
Calorimeter (ZDC)

Photo courtesy of Peter Steinberg
The ZDC and the BRAN Luminosity Monitor sit in the TAN region 141 m from the ATLAS interaction point. Sensitive to neutral particles unaffected by forward magnets.

***Collaboration between ZDC and BRAN for radiation-based upgrade R&D (results shown later)***

ATLAS ZDC and BRAN Luminosity Monitor Location
• Tungsten absorbing, fused quartz sampling calorimeter
• Four independently read out modules along each ATLAS arm
• 1.1 $\lambda_{\text{int}}$/module
• Only used during heavy ion running
  • Measures event-by-event impact parameter for Pb+Pb collisions
  • Provides triggers for ultra peripheral collisions
• Resolution for single spectator neutrons: ~14-17%
• Sits in extremely high radiation area
  • Shower max: ~18 Grad/year (pp running)
Measuring Radiation Damage to the Current ZDC
Two batches of irradiated fused quartz rods from ZDC shipped to the University of Illinois for spectrometry analysis.

- First batch (rod 1) saw a full year of LHC running in 2011 (which included $pp$ and $Pb+Pb$) and another $p+Pb$ run in 2012.
  - SIGNIFICANT signal loss in these rods (see visible damage in photo).
- Second batch (rod 2) was irradiated during recent heavy ion running (removed during $pp$ runs).

<table>
<thead>
<tr>
<th>Rod</th>
<th>Material</th>
<th>Radiation Exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>GE214 Fused Quartz</td>
<td>None (control rod)</td>
</tr>
</tbody>
</table>

Photo courtesy of Giulio Avoni
Nomenclature and Mechanism for Radiation Damage

- **Nomenclature for SiO$_2$**
  - **Natural (α) quartz**: least pure option. Crystalline structure
  - **Fused quartz**: natural quartz but glass-like. Impurities (e.g., Al) at the 10s of ppm level. Used in ATLAS ZDC
  - **Fused silica**: synthetic and glass-like. Pure at the 10s of ppb level. Most expensive option.

- **Schematic** shows known defects to characteristic SiO$_4$ tetrahedral
  - Intrinsic and radiation-based defects cause absorption sites that excite and luminesce at longer wavelengths
  - Purity crucial for high transmission and radiation insensitivity

*Courtesy of Heraeus*

*Schematic of known absorption sites in fused silica*
Optical Spectrometry of Irradiated Fused Quartz

What we can say so far:

- Fused quartz has very wide absorption sites whose size increase with increased dosage
- Rod 1: pp running turned rods almost completely opaque across full UV-visible region -- even now, 7 years after irradiation
- Rod 2: heavy ion running turned rods opaque in Cherenkov-transmission region ZDC is sensitive to
- Fused quartz unsuitable for long term operation during pp or heavy ion running in the ZDC

![Radiation Induced Transmission Loss](chart.png)
Matching Absorption Sites to Molecular Defects

- Study underway at Ben Gurion University to systematically study damage seen in LHC cocktails.
- Using Soreq nuclear reactor we’re able to irradiate quartz samples to different dosages:
  - First sample rods irradiated with $8 \times 10^{17}$ neutrons/cm$^2$.
- Spectrafluorometry scans photoluminescence for different excitation wavelengths (see figure).
- Correlating luminescence with particular absorption sites can help identify the molecular defect.
  - Knowing this allows us to understand creation and annealation criteria.

Example of Spectrafluorometry Analysis of Irradiated Quartz Rods: Appearance of new absorption line at $\lambda \approx 530$ nm.

Courtesy ATLAS group at Ben Gurion University (Z. Citron, Y. Bashan, D. Zamalin)
Future Machine Running and Physics Goals for HL-LHC
Design Considerations for Runs 3 and 4

- \( pp \) luminosity \((10^{34} \text{ cm}^{-2} \text{ s}^{-1})\)
  - Run 3: Increases by 2 x
  - Run 4: Increases by 5-7 x

- Heavy ion luminosity increases similarly:
  - Nominal \( p+Pb \): \(10^{31} \text{ cm}^{-2} \text{ s}^{-1}\)
  - Nominal \( Pb+Pb \): \(10^{28} \text{ cm}^{-2} \text{ s}^{-1}\)

- Crossing angle change during Run 4 (HL-LHC) causes:
  - ZDC to move closer to the IP (141 m to 126 m)
  - ZDC transverse width to shrink from 100 mm to 60 mm
• HI Physics Goals
  • Characterize collisional geometry event-by-event

• pp Physics Goals
  • BSM searches
  • Low-x physics
Irradiation Studies for an Upgraded ZDC

Photo courtesy of Marcus Palm
Is there a solution that can withstand \( pp \) radiation environment in HL-LHC? ➔ BRAN R&D on Fused Silica!

<table>
<thead>
<tr>
<th>Rod #</th>
<th>Material</th>
<th>Irradiation Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Spectrosil 2000 Fused Silica (High OH)</td>
<td>Control</td>
</tr>
<tr>
<td>2</td>
<td>Spectrosil 2000 Fused Silica (High OH)</td>
<td>2 LHC year: 04/16 - 12/17</td>
</tr>
<tr>
<td>3</td>
<td>Spectrosil 2000 Fused Silica (High OH, high H(_2))</td>
<td>1 LHC year: 04/16 - 12/16</td>
</tr>
<tr>
<td>4</td>
<td>Spectrosil 2000 Fused Silica (High OH, H(_2) free)</td>
<td>2 LHC years: 04/16 - 12/17</td>
</tr>
<tr>
<td>5</td>
<td>Suprasil 3301 Fused Silica (Low OH, high H(_2))</td>
<td>2 LHC years: 04/16 - 12/17</td>
</tr>
</tbody>
</table>

- BRAN luminosity monitor group carries out R&D on fused silica and has taken 2 years of live data with various Heraeus rods irradiated in the LHC tunnel.
- Different levels of OH and \( H_2 \) dopants tested

Transmission in undamaged fused silica
Heraeus Spectrosil 2000: Initial losses then stable signal amplitude for two years of irradiation in LHC tunnel

- After initial transmission loss BRAN sees flat signal size over two years of LHC running!
- Transmission loss occurs early in radiation history of fused silica rods
- Rods sent to University of Illinois for spectrometry analysis
- For more details see: https://indico.cern.ch/event/647714/contributions/2651509/attachments/1557659/2450420/Palm_HL-LHC_2017_BRAN.pdf

BRAN Luminosity Monitor: Performance of Spectrosil 2000 for 2 years of Irradiation

Result provided courtesy of Marcus Palm and BRAN Luminosity Monitor
BRAN Fused Silica Rods: Optical spectrometry results

- **230 nm absorption center:**
  - Possibly an E’ center
  - \( \equiv \text{Si}\bullet \) (oxygen deficiency)
  - Rods irradiated for 2 years show same loss as rod irradiated for 1 year
    - Suggests saturation of the absorption site!?  
    - Saturation of transmission loss might explain the observed early light losses followed by stable light yields at even higher doses.

- **325 nm absorption center:**
  - Specific defect unknown
  - Rod 3 appears to have annealed
  - Unclear if saturation occurs

- **629 nm absorption center:**
  - Non-bridging oxygen hole center (NBOHC)
    - \( \equiv \text{Si-O}\bullet \) (silicon deficiency)
  - Only shows up in OH-rich rods
  - Low OH rods show little visible radiation damage!

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**Radiation Induced Transmission Loss (Irradiated / Control)**

**1 Year of LHC Running: Rod 3 (2015)**

**2 Years of LHC Running: Rods 2, 4, and 5 (2015 – 2016)**

![Graph showing radiation induced transmission loss](image)
• **Fused quartz** not acceptable in extreme radiation environments

• **Fused silica**
  - After initial transmission loss, PMT signal stable for **2 full years of LHC pp running** in extreme radiation area!
  - Damage occurs early in radiation history
    - Possibly caused by UV absorption site saturation
    - Design possibility: **detector pre-irradiation** before physics running to reach broad-band stable operation
  - Low OH fused silica sees little transmission loss in visible region
    - Design possibility: use **long pass filter, fused silica prisms, etc** to filter UV light completely

• Other applications for radiation hard fused silica:
  - Fused silica tiles
  - Optical fibers (narrow core + doped cladding)
  - PMT windows
Backups
PMT signal size for different BRAN rods during 2016 LHC run

- Calibration of data complicated by large bunch-to-bunch amplitude fluctuations (results have some uncertainty)
- Evidence for significant damage to PMT window. Likely responsible for large portion of the transmission loss
- Low OH rods performed significantly better than high OH rods
- Majority of transmission loss happened early during run
- For more details, see: https://indico.cern.ch/event/549979/contributions/2263224/attachments/1371475/2080303/BRANs_at_HL-LHC_version5.pptx
• PMT window used during runs suffered significant damage
• Significant portion of transmission loss seen in BRAN attributable to PMT window

• Signal from unirradiated rod divided by signal from irradiated rod with both using irradiated PMT windows
• At beginning of the run signal size was different by ~3 x ... after 5 fb⁻¹ they were the same
• Suggests:
  • fused silica damage happened early
  • fused silica transmission loss was only ~3 x
• Signature: 2 photons and no further activity with Pb ions escaping down beam pipe
• ZDC’s role
  • UPC trigger: no spectator neutrons observed on either arm (heavy ion)
  • Veto for forward neutral particle creation (pp and heavy ion)
• BSM search
  • If new physics present, additional loop corrections may be needed to match rate measured at LHC
In Pb nuclei gluon wave functions overlap with wavefunctions from many different nucleons.
• Means gluons saturation effects should be visible at higher x
• CMS, ATLAS, and ALICE have used ZDCs to tag ultra-peripheral PbPb collisions
• Photon hits nucleus and produces pair of jets or J/ψ
• ATLAS result (Bottom left): at high x and large pT, the dijet results consistent with no modification of nuclear matter
• CMS result (Bottom right): at x ~ 0.003 and low pT, there is a significant depletion of soft gluons in lead nuclei
• Future measurement: Match forward hadrons in ZDC with jets in forward calorimeter
• **E' center** (≡Si•)
  • Hole trapped in oxygen vacancy
  • 5.8 eV or 214 nm primary absorption center
  • No luminescence emission
  • See: L. Skuja “Optical properties of defects in silica” [link](https://link.springer.com/chapter/10.1007/978-94-010-0944-7_3)

• **Non-bridging oxygen hole centers (NBOHC)** (≡Si-O•)
  • Broken Si-O bond (2p bond splitting)
  • Reaction b/w paired Hydroxyl groups in OH rich fibers (“wet” silicas)
    • ≡Si-O-H H-O-Si≡ ≡Si-O• H-O-Si≡ +H•
  • Can also be created in low-OH silica through ruptured Si-O bond
    • Rupture can happen through neutron irradiation or the fiber drawing process (speed of the process)
    • ≡Si-O-Si≡ ≡Si-O• •Si≡
  • Absorption band at 4.8 eV (258 nm); another asymmetric absorption band at 1.97 eV (629 nm)
  • Photoluminescence band at 1.91 eV (649 nm)
  • See: S. Munekuni “Various types of nonbridging oxygen hole center in high-purity silica glass” [link](https://aip.scitation.org/doi/abs/10.1063/1.346719)