Physics Motivation

Light by Light scattering, with ZDC tag

Reaction plane
Capabilities of the ZDCs

- Measure energy & orientation of forward photons and neutrons
- Characterize different kinds of events
- Measure the distance between the nuclei and their orientation.
Other possible measurements

Search for invisible particles in pp
Both tungsten/quartz Cerenkov calorimeters
- ATLAS: EM + 3 Had modules
- CMS: EM + Reaction Plane Detector (RPD) + 4 Had

Beam at center of RPD
<table>
<thead>
<tr>
<th>Run</th>
<th>Energy</th>
<th>pp</th>
<th>Pb+Pb</th>
<th>Max Dosage in TAN</th>
<th>Total Int. Lumi</th>
<th>Max Dosage in TAN</th>
<th>Max Dosage in TAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>13 TeV</td>
<td>156 fb⁻¹ (3 years)</td>
<td>8 Grad/2017</td>
<td>8 Mrad/2018</td>
<td>5.02 TeV/n</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>14 TeV</td>
<td>270 fb⁻¹ (3 years)</td>
<td>15 Grad/year</td>
<td>53 Mrad/year</td>
<td>5.5 TeV/n</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>14 TeV</td>
<td>750 fb⁻¹ (3 years)</td>
<td>30 Grad/year</td>
<td>62 Mrad/year</td>
<td>5.5 TeV/n</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Radiation quartz rods (ATLAS)

Need to develop a rad hard medium for high luminosity running
New TAXN absorber for HL-LHC

132 m from IP

Slot
Cross section of TAXN

Slot is 5cm wide (ZDCs will be much lighter)
Is 5cm wide enough?

Transverse profile of Cherenkov photons from 1 TeV neutron. No significant losses from reducing active width to 4.5 cm.
We have to change for Run 4

• Current ZDCs will be too wide, and not radiation hard enough to operate in Run 4
• To support the physics program of ATLAS and CMS we must develop new, fast, segmented and rad hard detectors.
• Take advantage of new materials, fused silica and new electronics with 30ps timing opens many possibilities.
• CMS and ATLAS groups are working together to realize new ZDCs.
Joint Zero degree Calorimeter Project

ATLAS + CMS joint R&D effort  New collaborators are welcome!  j.zdcrd@cern.ch

- Ben Gurion University
- BNL
- Columbia University
- University of Illinois

- University of Kansas
- University of Maryland
Irradiation of fused silica rods

- BRAN group inserted fused silica rods from Hereaus into TAN during 2017, 2018.
- Rods 1cm diameter, 40cm high
### H$_2$ and OH content of rods varied

<table>
<thead>
<tr>
<th>Bran Position</th>
<th>Irradiation period</th>
<th>Peak exposure (Grad)</th>
<th>Material</th>
<th>H$_2$ [mol/cm$^3$] (10$^{-17}$)</th>
<th>OH [ppm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>None</td>
<td>0</td>
<td>Spectrosil 2000</td>
<td>7.2</td>
<td>1120</td>
</tr>
<tr>
<td>1</td>
<td>04/2016 - 12/2018</td>
<td>3</td>
<td>Spectrosil 2000</td>
<td>7.2</td>
<td>1120</td>
</tr>
<tr>
<td>2</td>
<td>04/2016 - 12/2017</td>
<td>1.5</td>
<td>Spectrosil 2000</td>
<td>7.2</td>
<td>1120</td>
</tr>
<tr>
<td>3a</td>
<td>04/2016 - 12/2016</td>
<td>0.5</td>
<td>Spectrosil 2000</td>
<td>28.0</td>
<td>1000</td>
</tr>
<tr>
<td>3b</td>
<td>04/2017 - 12/2018</td>
<td>2</td>
<td>Spectrosil 2000</td>
<td>7.2</td>
<td>1120</td>
</tr>
<tr>
<td>4</td>
<td>04/2016 - 12/2017</td>
<td>1</td>
<td>Spectrosil 2000</td>
<td>0</td>
<td>1011</td>
</tr>
<tr>
<td>5</td>
<td>04/2016 - 12/2017</td>
<td>1</td>
<td>Suprasil 3301</td>
<td>30.0</td>
<td>15</td>
</tr>
<tr>
<td>6</td>
<td>04/2016 - 12/2018</td>
<td>2</td>
<td>Suprasil 3301</td>
<td>0</td>
<td>14</td>
</tr>
</tbody>
</table>
FLUKA simulation of radiation environment

2016 pp 45 fb$^{-1}$

2017 pp 50 fb$^{-1}$

Dose [GRad]
Simulation of activation matches data

Distance along the fused silica rods (cm)

Activation of Na$^{22}$ (arb units)
Transmission measurement

- Two color centers observed:
  - C1 ~ 240 nm
  - C2 ~ 310 nm
- Further studies on the path length dependence require cutting the rods.
Transmission vs wavelength, dose

Rod 2: Spectrosil 2000, High OH, Low H₂, 2 years of irradiation

1.5 Grad
Transmission vs dose $\lambda=310\text{nm}$

![Graph showing transmission vs dose for different samples at $\lambda=310\text{nm}$]
Further irradiation tests

- n flux \( \sim 1.9 \times 10^{10} \text{ cm}^{-2} \text{ s}^{-1} \)
  - \( \sim 0.05 \) MRad/hour
- \( \gamma \sim 2 \) MRad/hour

- n flux \( \sim 2.5 \times 10^{13} \text{ cm}^{-2} \text{ s}^{-1} \)
  - \( \sim 0.1 \) GRad/hour
- \( \gamma \sim 12 \) GRad/hour

- 3 MeV Van de Graaff
  - e\(^-\) up to \( \sim 0.6 \) GRad/hour
  - \( \gamma \sim 12 \) GRad/hour

Increase irradiation a few Grad (3-4) to study transmission loss
- RPD placed at Cherenkov shower max;
- For Run4, the detector will be rebuilt (narrower space in TAN - 5cm).
Run3: Preliminary detector configuration

- **EM Module**
- **Hadronic Module**
- **Hadronic Module**
- **Hadronic Module**
- **IP**
- **RPD**

- **BRAN**

- **16 Quartz tiles**
- **64 Readout WLS fibers**

- **PMT**
- **Steel Case**
- **Lightguide**
- **Rod supports (steel)**

- **12 Cherenkov radiator gaps filled with fused silica rods**
- **11 tungsten layers**

Similar to Hadronic - but different sampling and segmented readout (4x2)

For Run 4 move to 4.7cm width
Future work

• Test fused silica up to several Grads in reactors
• Make a full Run 3 prototype for May 2020
• Refurbish ATLAS ZDC for Run 3 with fused silica, and add RPD
• CMZ ZDC is rad hard enough for Run 3
• For Run 4 develop rad hard identical ZDCs for CMS, ATLAS with fast electronics for timing.
• Segmented EM, RPD and hadronic sections should identify photons neutrons and their orientation in azimuth.
Summary

• New materials allow the possibility for the ZDCs to operate at the highest LHC luminosities.
• Increased segmentation and improved electronics will allow the ZDCs provide fast triggers for minimum bias A+A, p+A, γ+A, and γ+ γ events.
• ZDCs should also be able to operate for months of pp running.
• RPD and segmented EM section allow greatly increased separate of neutrons and photons and should allow us to measure orientation of collision.
Backup
Upgraded EM module

- Segmented design: 4 segments in x, 2 in z.
- Small Run4 prototypes tested @ Fermilab.

Will use rad hard fused silica rod and Winston cone light-guides
Reaction plane detector in CMS

- 4 x 4 array of quartz tiles, with wavelength shifting fibers.
- Background signal induced in the WLS fibers running behind other tiles.
- WLS fibers currently not radiation hard.
- Size 8.5 x 8.5 x 1.5 cm$^3$
- CMS 2018 HI data analysis.
- SPS Test beam.

- Different designs considered.
- Final implementation will be rad hard.
- Coupled reconstruction of the reaction plane.
Longitudinal Transmission measurement

Longitudinal transmission measurements allow to determine attenuation over similar scales relevant to ZDC and BRAN.

Three main color centers observed: \textbf{C1} \sim 240 \text{ nm}, \textbf{C2} \sim 310 \text{ nm}, \textbf{C3} \sim 640 \text{ nm}
\( \lambda = 240 \text{ nm} - \text{Different H}_2 \text{ level} \)

<table>
<thead>
<tr>
<th>Rod</th>
<th>Irr. Period</th>
<th>Peak exp.</th>
<th>Material</th>
<th>H(_2) [mol/cm(^3)]</th>
<th>OH [ppm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>04/2016 - 12/2017</td>
<td>1 Grad</td>
<td>Spectrosil 2000 (High OH, H(_2) free)</td>
<td>0</td>
<td>1011</td>
</tr>
<tr>
<td>2</td>
<td>04/2016 - 12/2017</td>
<td>1.5 Grad</td>
<td>Spectrosil 2000 (High OH, Low H(_2))</td>
<td>7.20e17</td>
<td>1120</td>
</tr>
<tr>
<td>3a</td>
<td>04/2016 - 12/2016</td>
<td>0.5 Grad</td>
<td>Spectrosil 2000 (High OH, High H(_2))</td>
<td>2.80e18</td>
<td>1000</td>
</tr>
</tbody>
</table>

- Similar trends to 310 nm, but higher level of damage
- Transmission cut-off for high H\(_2\) confirmed at 240 nm

Fig.19: Transmission for \( \lambda = 240 \text{ nm} \) for rods with different H\(_2\) level
Longitudinal Transmission measurement

Longitudinal transmission measurements allow to determine attenuation over similar scales relevant to ZDC and BRAN.

Three main color centers observed: \(C1\) ~ 240 nm, \(C2\) ~ 310 nm, \(C3\) ~ 640 nm

Primary sensitivity region of the PMT [300 ; 500] nm
\( \lambda = 310 \text{ nm} \) - \textbf{SAME MATERIAL}

- Self-repairing effect observed with increasing H\(_2\) concentration
- Hints for a cut-off of this effects (lack of H\(_2\)?)
- Measurement of remaining H\(_2\) quite difficult. Different possibilities being inspected
- H\(_2\) free rod shows initial loss but stable plateau above 100 MRad

<table>
<thead>
<tr>
<th>Rod</th>
<th>Irr. Period</th>
<th>Peak exp.</th>
<th>Material</th>
<th>( \text{H}_2 ) [mol/cm(^3)]</th>
<th>( \text{OH} ) [ppm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>04/2016 - 12/2018</td>
<td>3 GRad</td>
<td>Spectrosil 2000 (High OH, Mid H2)</td>
<td>7.20e17</td>
<td>1120</td>
</tr>
<tr>
<td>3b</td>
<td>04/2017 - 12/2018</td>
<td>2 GRad</td>
<td>Spectrosil 2000 (High OH, Mid H2)</td>
<td>7.20e17</td>
<td>1120</td>
</tr>
<tr>
<td>2</td>
<td>04/2016 - 12/2017</td>
<td>1.5 GRad</td>
<td>Spectrosil 2000 (High OH, Mid H2)</td>
<td>7.20e17</td>
<td>1120</td>
</tr>
</tbody>
</table>

Fig.18: Transmission for \( \lambda = 310 \text{ nm} \) for rods with different \( \text{H}_2 \) level.
Results: $\lambda = 310 \text{ nm}$

- Using FLUKA simulations we can transform from transmission vs position along the rod to transmission vs [dose, hadron fluence and neutron fluence].
λ = 310 nm - Different OH level

- Rod with lower level of OH shows better transparency up to 1 GRad
- Hints for crossing point around 1 GRad
- More irradiation needed to extend analysis to higher doses and confirm interesting features (e.g. plateau for

<table>
<thead>
<tr>
<th>Rod</th>
<th>Irr. Period</th>
<th>Peak exp.</th>
<th>Material</th>
<th>H₂ [mol/cm³]</th>
<th>OH [ppm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>04/2016 - 12/2018</td>
<td>2 GRad</td>
<td>Suprasil 3301 (Low OH, H₂ free)</td>
<td>0</td>
<td>14</td>
</tr>
<tr>
<td>4</td>
<td>04/2016 - 12/2017</td>
<td>1 GRad</td>
<td>Spectrosil 2000 (High OH, H₂ free)</td>
<td>0</td>
<td>1011</td>
</tr>
</tbody>
</table>

Fig. 20: Transmission for λ = 310 nm for rods with different OH level

- Rod with lower level of OH shows better transparency up to 1 GRad
- Hints for crossing point around 1 GRad
- More irradiation needed to extend analysis to higher doses and confirm interesting features (e.g. plateau for
Fused Silica

Damage of Fused Silica – Collection of Absorbing Defects

General defects
- Oxygen rich material
- Oxygen deficient material

Oxygen deficiency
- 243 nm
- 265 nm

Twofold coordinated silicon
- 247 nm

Peroxy linkage
- 330 nm

OH - group
- 2.73 μm
- 1.39 μm

Peroxy radical
- 163 nm

Frank Nuernberg, Heraeus
λ = 310 nm - Different H₂ level

- Self-repairing effect observed with increasing H₂ concentration
- Hints for a cut-off of this effects (lack of H₂?)
- H₂ free rod shows initial loss but stable plateau above 100 MRad
- More irradiation needed to extend analysis to higher doses and confirm observed features

<table>
<thead>
<tr>
<th>Rod</th>
<th>Irr. Period</th>
<th>Peak exp.</th>
<th>Material</th>
<th>H₂ [mol/cm³]</th>
<th>OH [ppm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>04/2016-12/2017</td>
<td>1 Grad</td>
<td>Spectrosil 2000 (High OH, H₂ free)</td>
<td>0</td>
<td>1011</td>
</tr>
<tr>
<td>2</td>
<td>04/2016-12/2017</td>
<td>1.5 Grad</td>
<td>Spectrosil 2000 (High OH, Mid H₂)</td>
<td>7.20e17</td>
<td>1120</td>
</tr>
<tr>
<td>3a</td>
<td>04/2016-12/2016</td>
<td>0.5 Grad</td>
<td>Spectrosil 2000 (High OH, High H₂)</td>
<td>2.80e18</td>
<td>1000</td>
</tr>
</tbody>
</table>
Costs per module

Prices include 10% contingency

- EM
  - Tungsten Plates: $3K
  - Steel case: $2k
  - Winston Cones: $5K
  - Fused Silica Rods: $2k
  - PMTs: $3.5k
  - Total: $25.6k

- RPD
  - Tungsten Plates: $3k
  - Steel case: $5k
  - Winston Cones: $2k
  - Fused Silica Rods: $3k
  - PMTs: $3k
  - Total: $14.5k

- Hadronic
  - Tungsten Plates: $10K
  - Steel case: $1k
  - Winston Cones: $12k
  - Fused Silica Rods: $1k
  - PMTs: $11.2k
  - Total: $36

36
<table>
<thead>
<tr>
<th>Module</th>
<th>Cost</th>
<th>#</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hadronic</td>
<td>$29.1K</td>
<td>6</td>
<td>$175k</td>
</tr>
<tr>
<td>EM</td>
<td>$42.2K</td>
<td>2</td>
<td>$83k</td>
</tr>
<tr>
<td>RPD</td>
<td>$35.2</td>
<td>2</td>
<td>$70k</td>
</tr>
<tr>
<td>Final cost</td>
<td></td>
<td></td>
<td>$328k</td>
</tr>
</tbody>
</table>

For Run 3 there are no additional electronic costs for CMS.
Optical Spectrometry of Bran Rods

Rod 3 exposed for 1 year in BRAN, Rods 2, 4 and 5 for two years.

Rods irradiated for 2 years show same loss as rod irradiated for 1 year. Suggests saturation of absorption site.
Simulation vs data for activation

Simulation: Activity of Na-22 in rods vs length in FLUKA simulation
(Marta Sabate Gilarte, Francesco Cerutti)

Experiment: Count rate of 511 keV photon peak with GE-detector

Rod order in BRAN module

Dimension along the fused silica rods
Dose estimate for installation

- LS4 Ultimate scenario
- 10 minutes next to each element end (only part of the work)
- 2 worker: 1 in the aisle, 1 next to the element

<table>
<thead>
<tr>
<th>distance from IP</th>
<th>dose rate (µSv/h)</th>
<th>10 minute dose (µSv)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 week 1 month 4 month 1 year</td>
<td>1 week 1 month 4 month 1 year</td>
</tr>
<tr>
<td>TAXN</td>
<td></td>
<td></td>
</tr>
<tr>
<td>126m</td>
<td>900 450 150 55</td>
<td>150 75 25 9</td>
</tr>
<tr>
<td>130m</td>
<td>400 220 90 30</td>
<td>67 37 15 5</td>
</tr>
<tr>
<td>Aisle</td>
<td></td>
<td>2 hour dose (µSv)</td>
</tr>
<tr>
<td></td>
<td>- 50 25 10 5</td>
<td>100 50 20 10</td>
</tr>
</tbody>
</table>
Light-guide studies

Waveform generator → LED → Optical Fiber → X-Y stepped motors → Light Guide → PMT → Dark Box

Recorded PMT pulse height

DAQ → DRS4

HV Power Supply