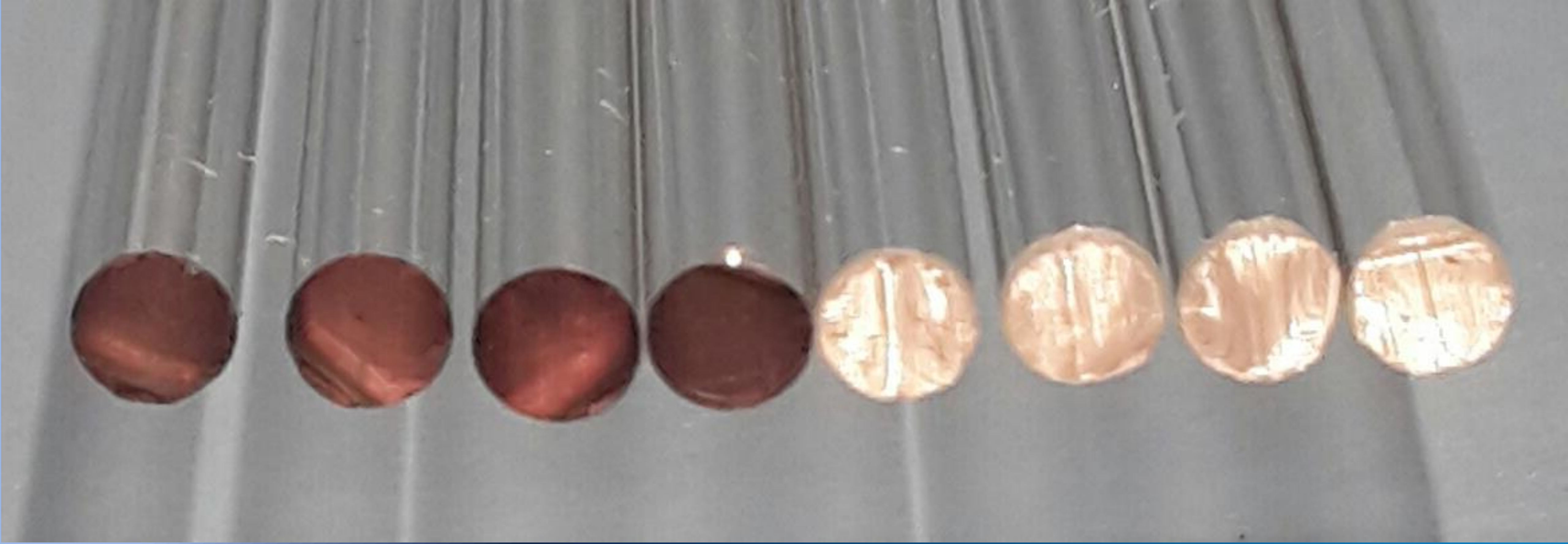


Photo courtesy of Giulio Avoni

A New ATLAS ZDC for the High Radiation Environment at the LHC

Michael Phipps (UIUC)
On behalf of the ATLAS ZDC
CALOR 2018
May 21, 2018

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

Photo courtesy of Peter Steinberg

The Current ATLAS Zero Degree Calorimeter (ZDC)

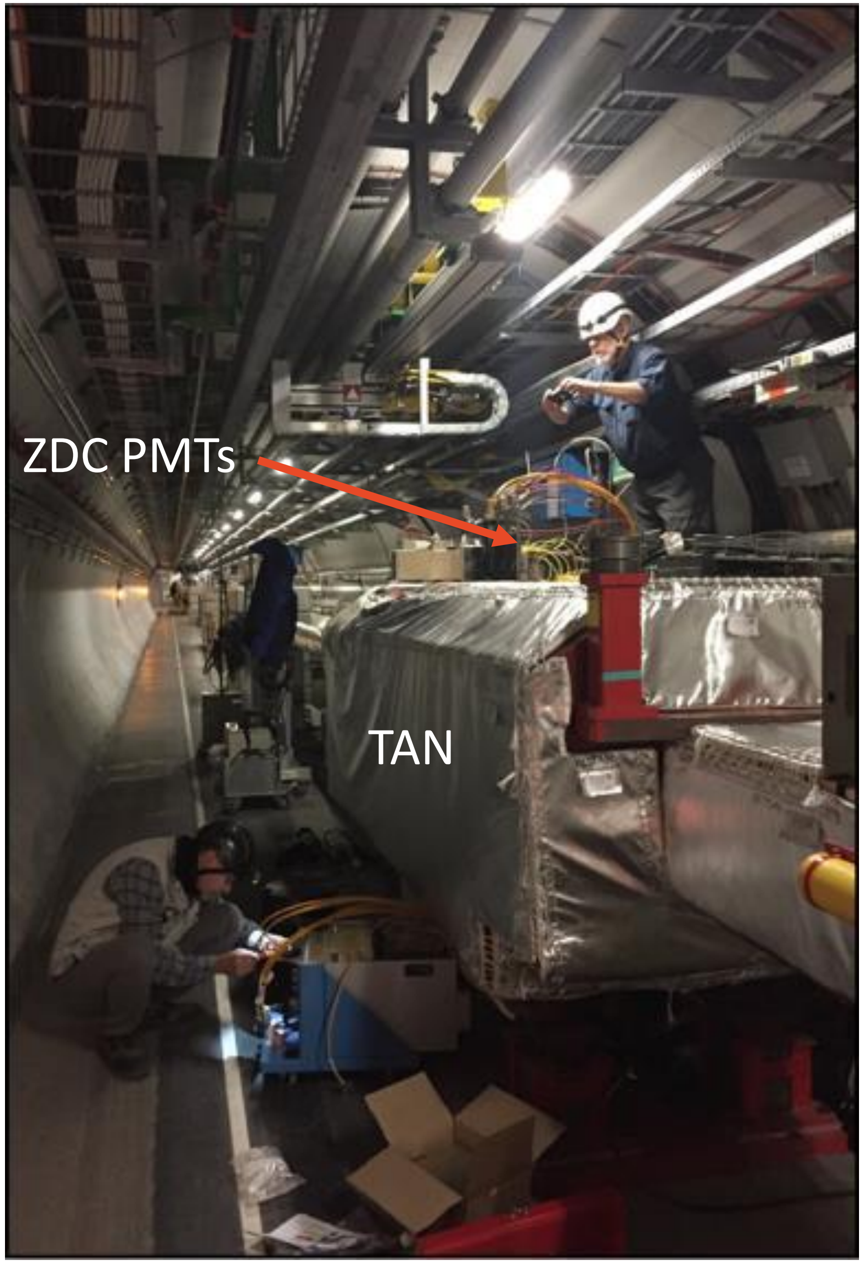
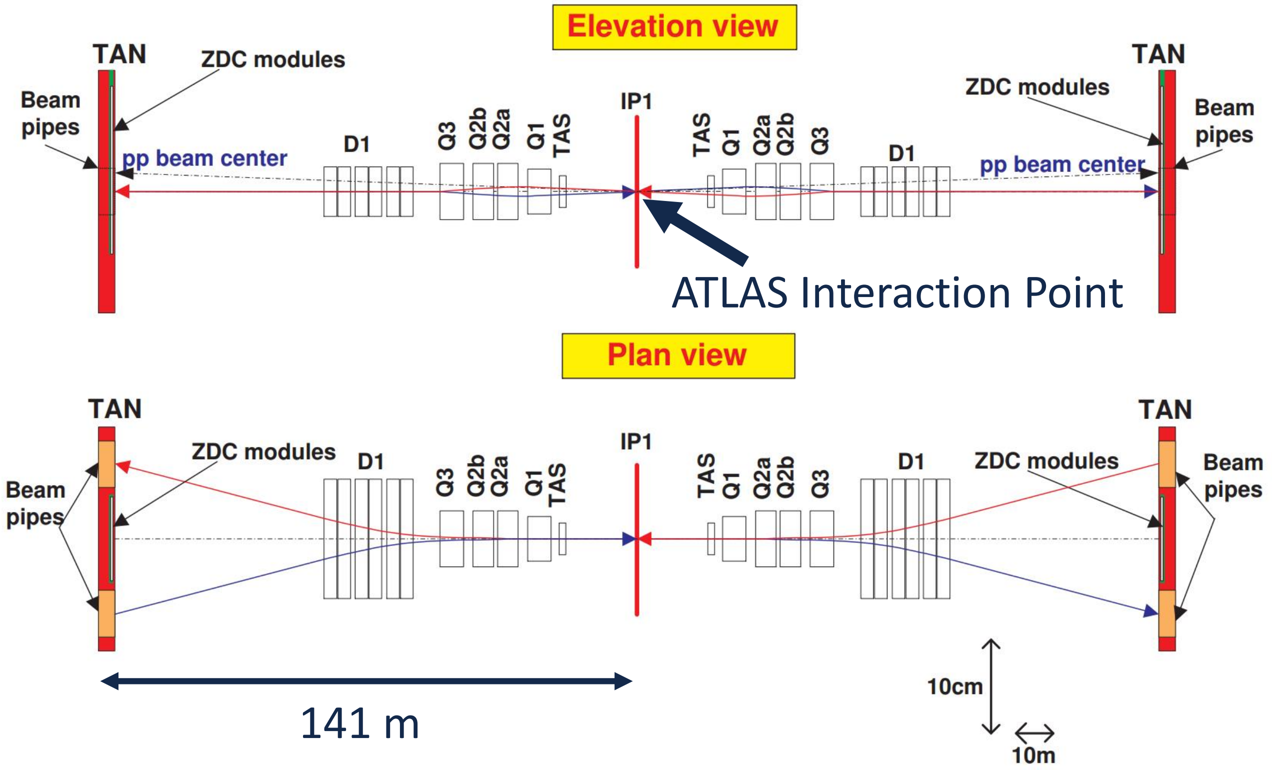
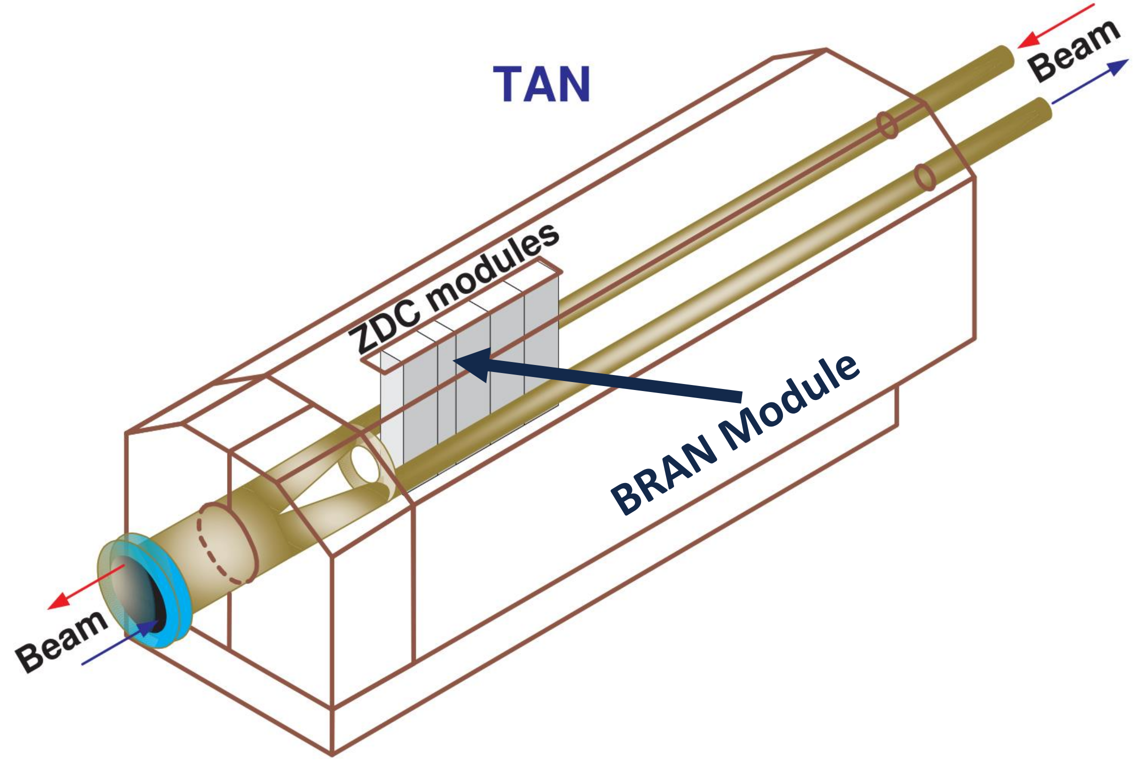


Photo courtesy of Peter Steinberg

ATLAS ZDC and BRAN Luminosity Monitor Location

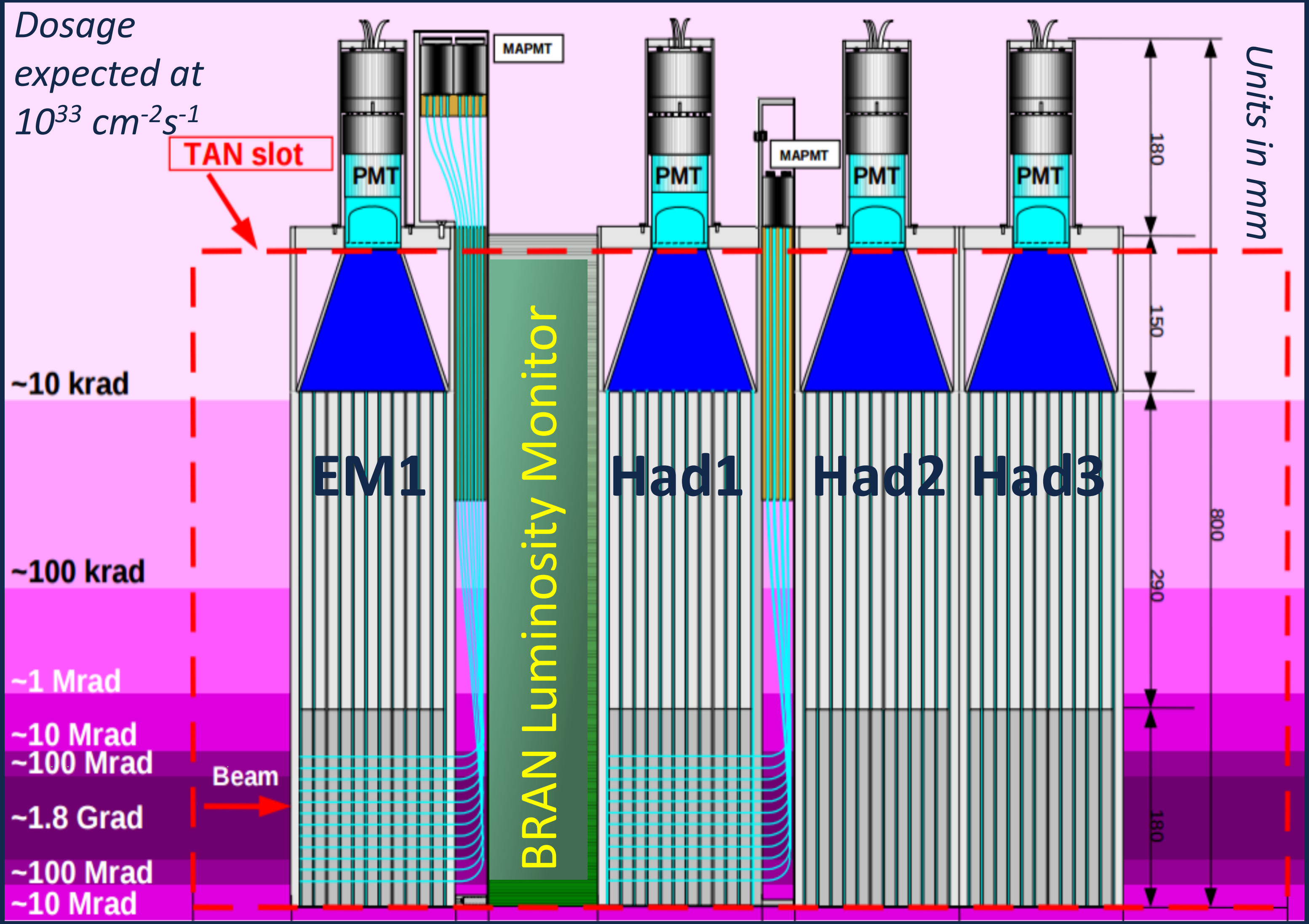




The ZDC and the BRAN Luminosity Monitor sit in the TAN region 141 m from the ATLAS interaction point

Sensitive to neutral particles unaffected by forward magnets

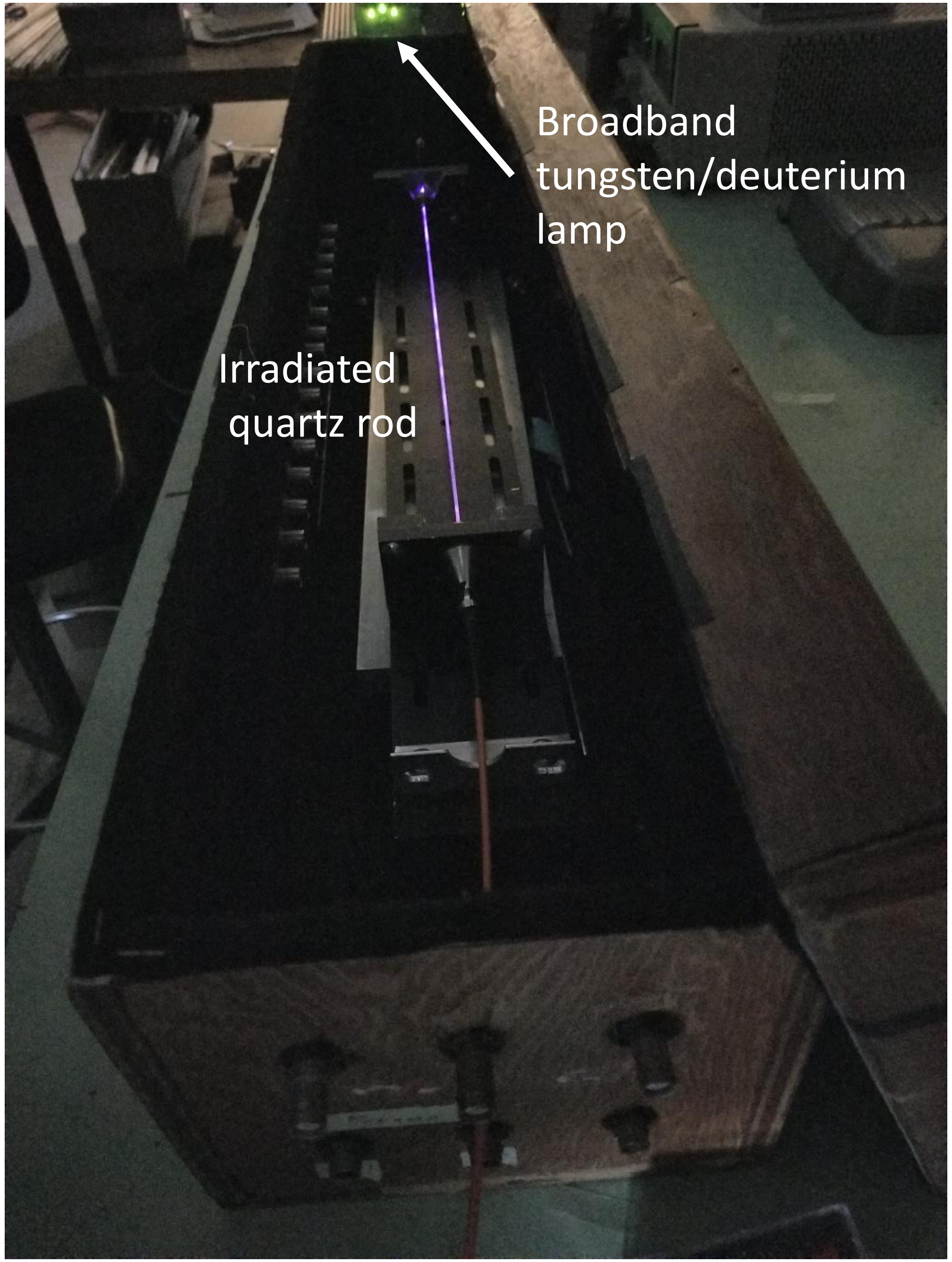
****Collaboration between ZDC and BRAN for radiation-based upgrade R&D (results shown later)****



- Tungsten absorbing, fused quartz sampling calorimeter
- Four independently read out modules along each ATLAS arm
- 1.1 λ_{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)

ATLAS ZDC
Module Description

Measuring Radiation Damage to the Current ZDC



Sample Selection for Optical Spectrometry

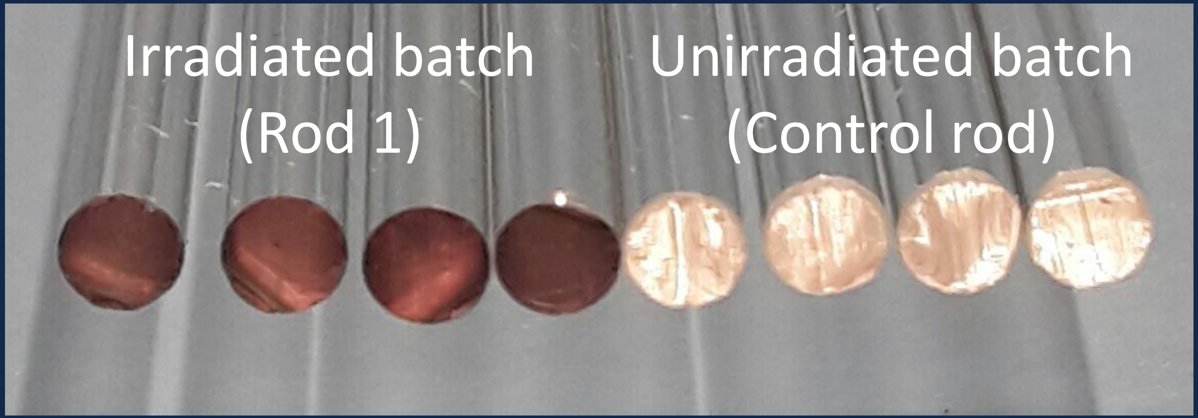
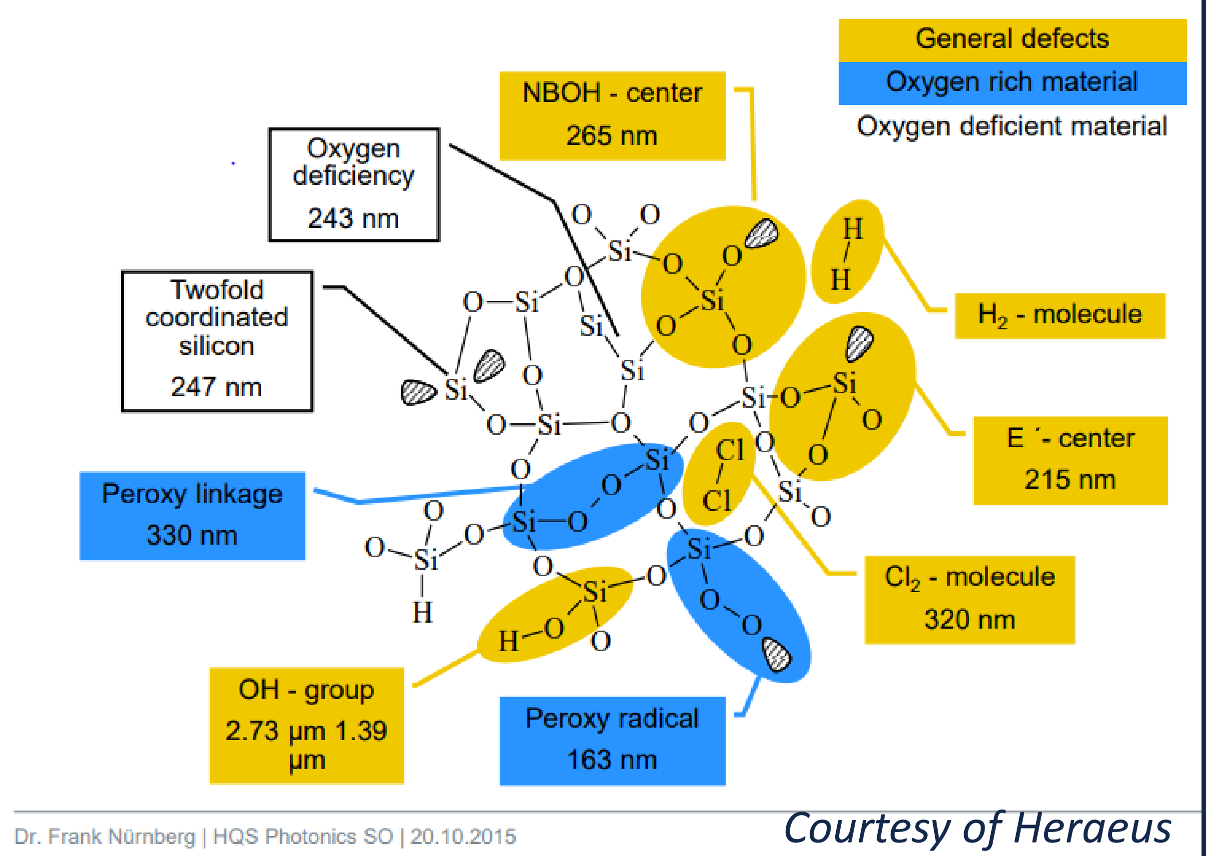


Photo courtesy of Giulio Avoni

Rod	**Material**	**Radiation Exposure**
0	GE214 Fused Quartz	None (control rod)
1	GE214 Fused Quartz	2010 Pb+Pb, **2011 *pp***, 2011 Pb+Pb, 2012 *p*+Pb
2	GE214 Fused Quartz	2012 *p*+Pb, 2013 *p*+Pb, 2015 Pb+Pb, **2016 *p*+Pb**

- 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)

Nomenclature and Mechanism for Radiation Damage

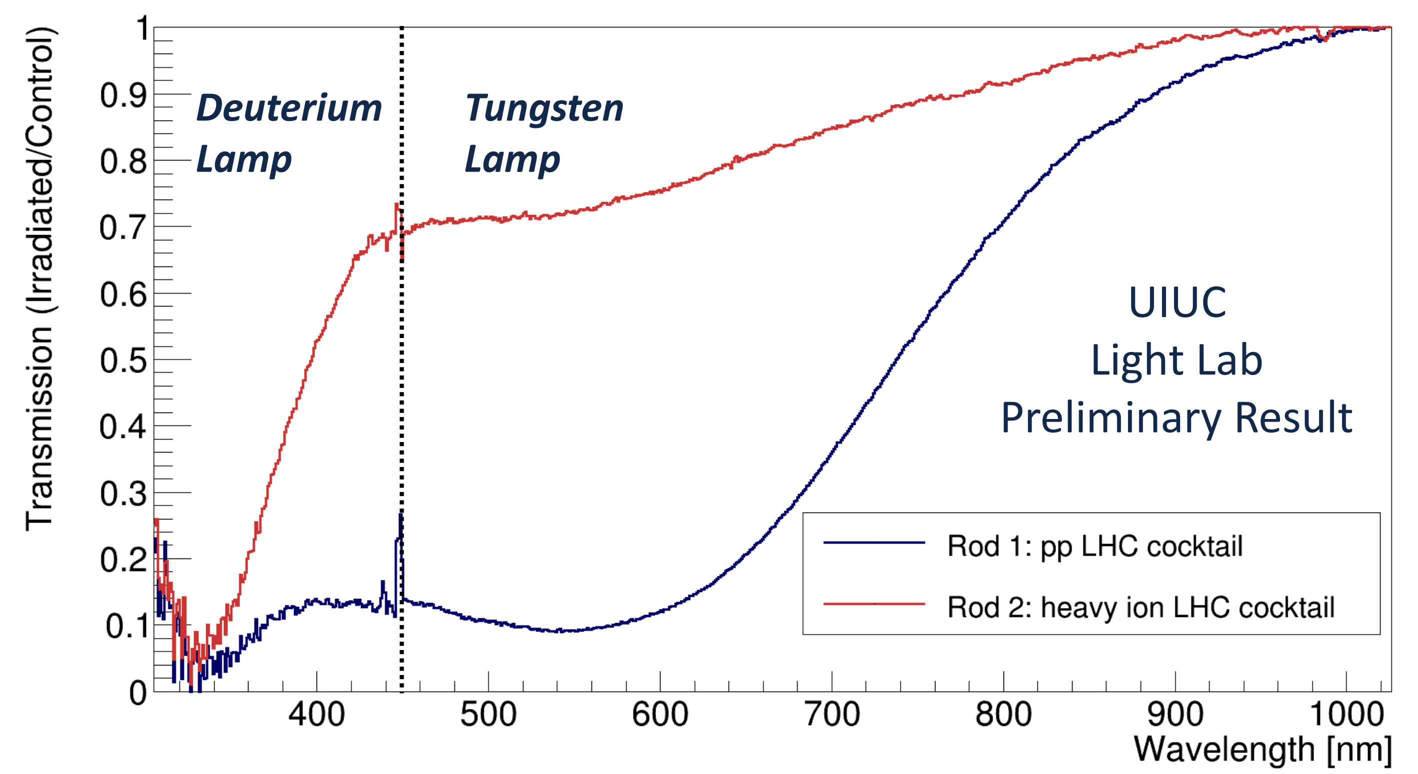


Courtesy of Heraeus

Schematic of known absorption sites in fused silica

- Nomenclature for SiO_2
  - ***Natural (α) quartz***: least pure option. Crystalline structure
  - ***Fused quartz***: natural quartz but glass-like. Impurities (eg. 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

Radiation Induced Transmission Loss (Irradiated / Control)

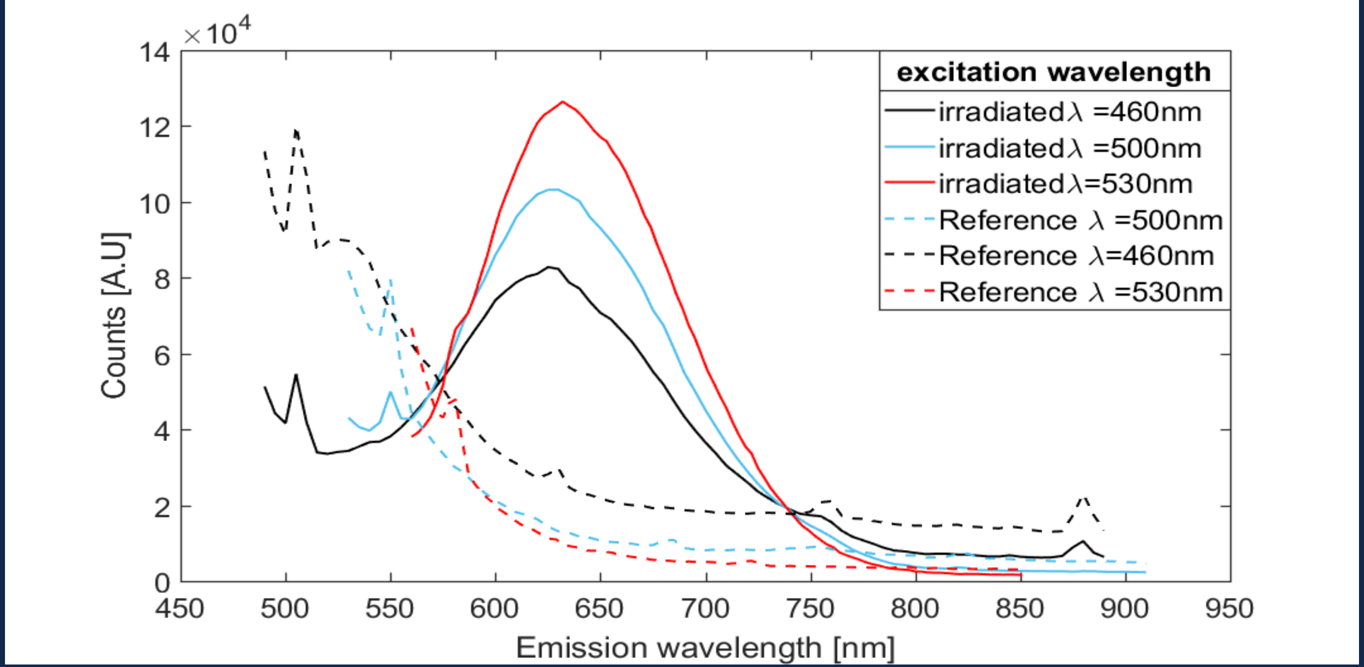


What we can say so far:

- 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
- Rod2: 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

Optical Spectrometry of Irradiated Fused Quartz

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

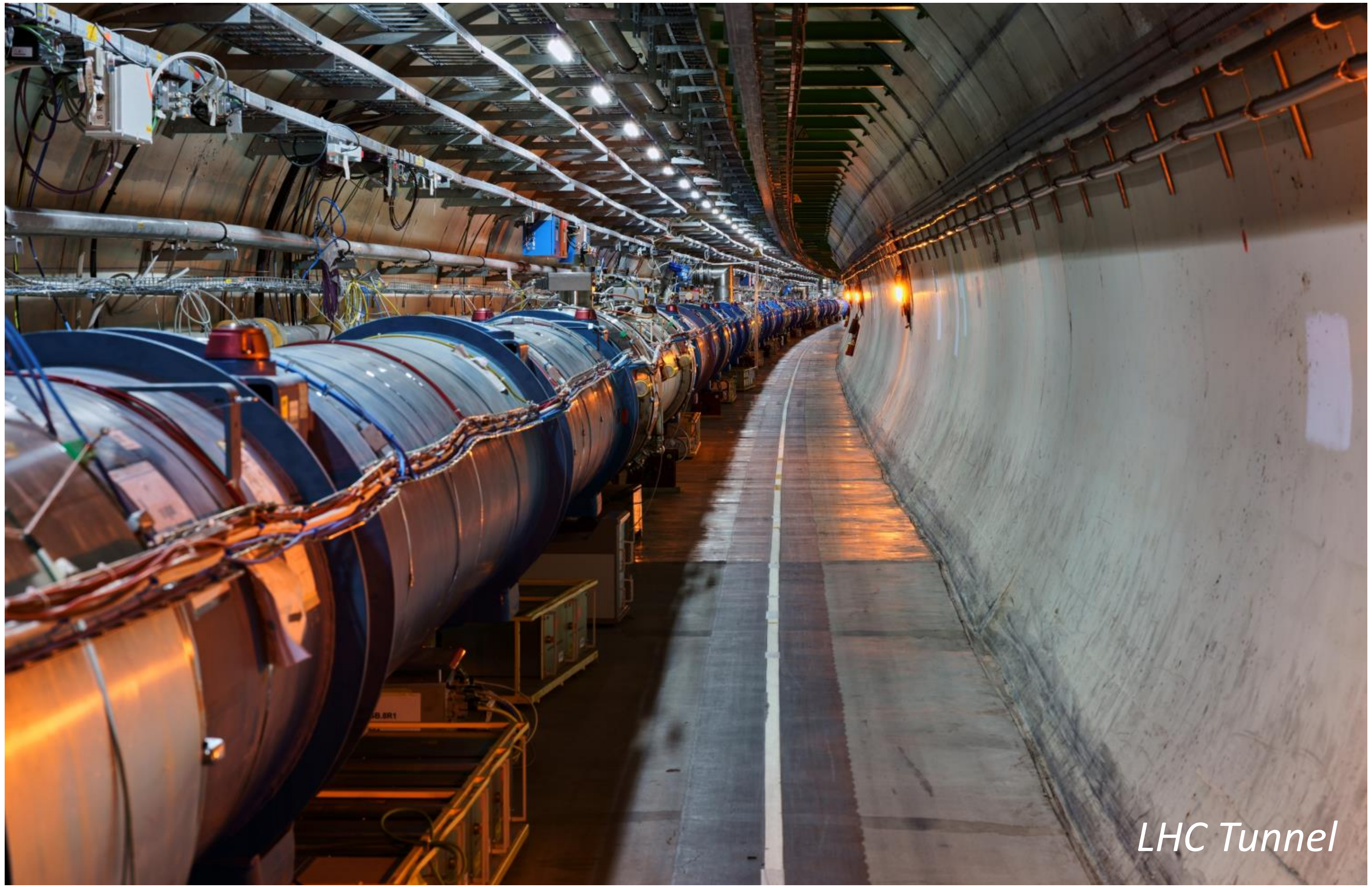


Courtesy ATLAS group at Ben Gurion University
(Z. Citron, Y. Bashan, D. Zamalin)

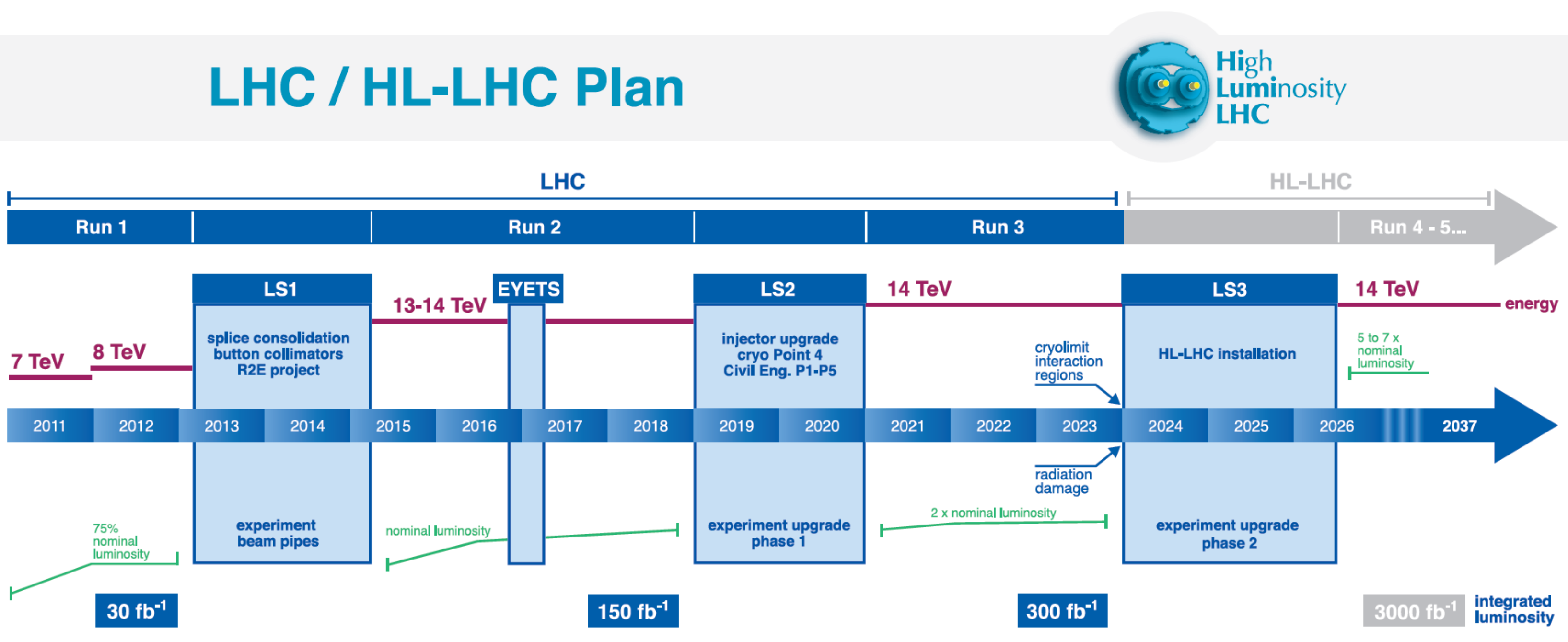
- Study underway at Ben Gurion University to systematically study damage seen in LHC cocktails
- Using Soreq nuclear reactor we're able to irradiate quartz samples to different dosages:
  - First sample rods irradiated with 8 * 10^{17} neutrons/cm^2
- Spectrafluorometry scans photoluminescence for different 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

Matching Absorption Sites to Molecular Defects

Future Machine Running and Physics Goals for HL-LHC


LHC Tunnel

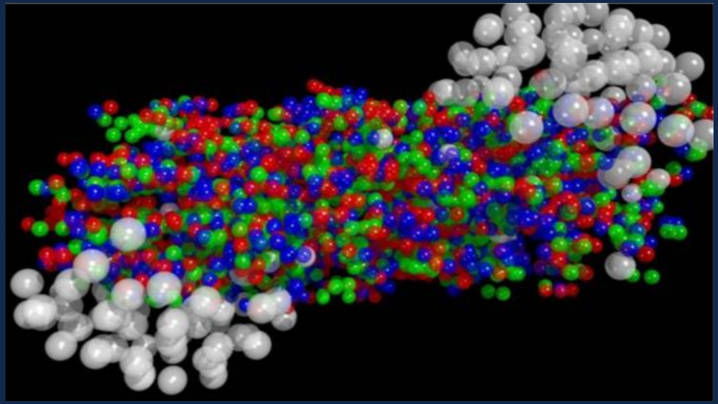
Design Considerations for Runs 3 and 4



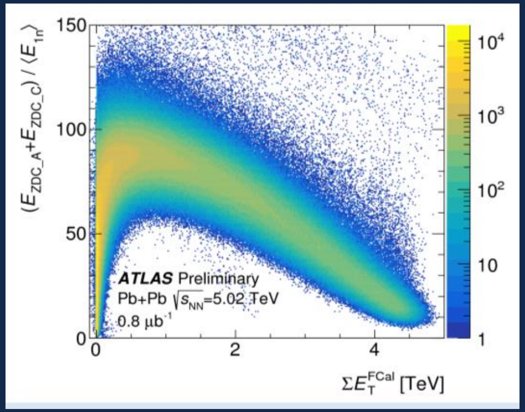
https://hilumilhcds.web.cern.ch/about/hl-lhc-project

- *pp* luminosity (10^{34} cm^{-2} 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} cm^{-2} s^{-1}
  - Nominal Pb+Pb: 10^{28} cm^{-2} 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

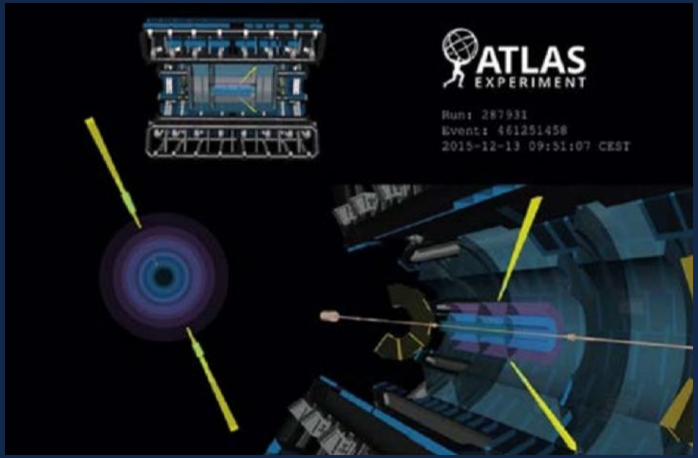
Physics Goals for an Upgraded ZDC



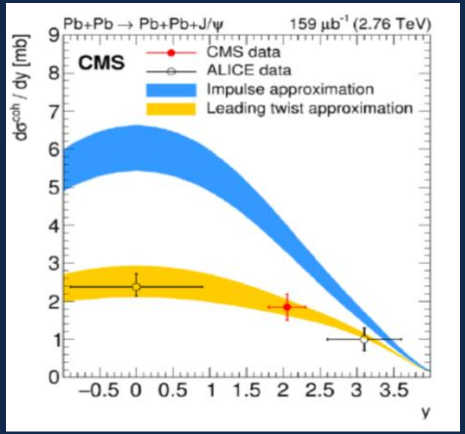
Heavy ion collision



Forward-backward ZDC energy correlation, reflecting nuclear geometry



Light-by-light collision



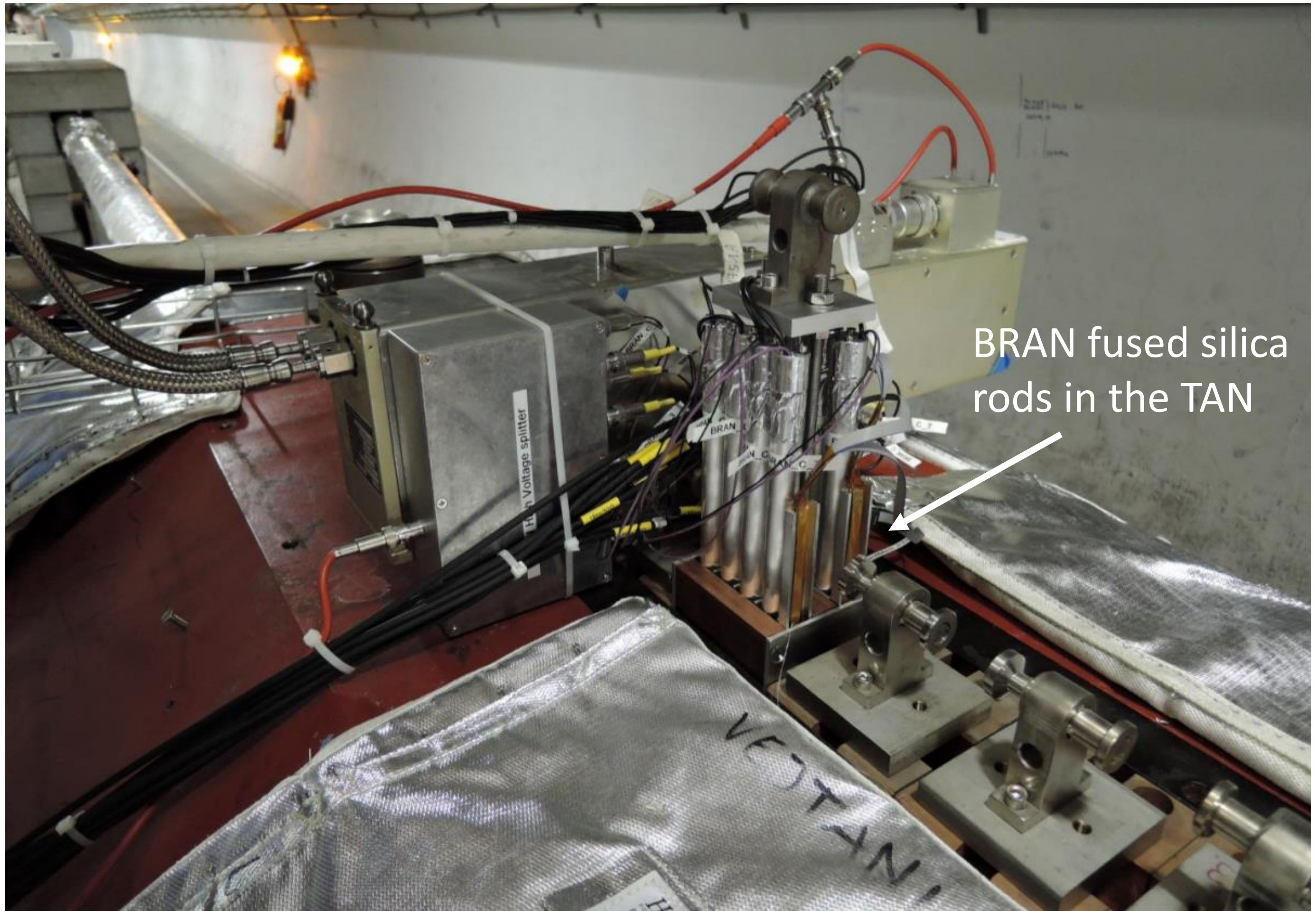
Identified UPC event leading to CMS J/Ψ low-x measurement

- **HI Physics Goals**
  - Characterize collisional geometry event-by-event
  - Light-by-light scattering:

    ATLAS Collaboration *in Nature Physics* **13**, 852-858 (2017)
  - Gluon saturation in Pb nuclei:

    CMS Collaboration in *Phys. Lett. B 772 (2017) 489.*
- ***pp* Physics Goals**
  - BSM searches
  - Low-x physics

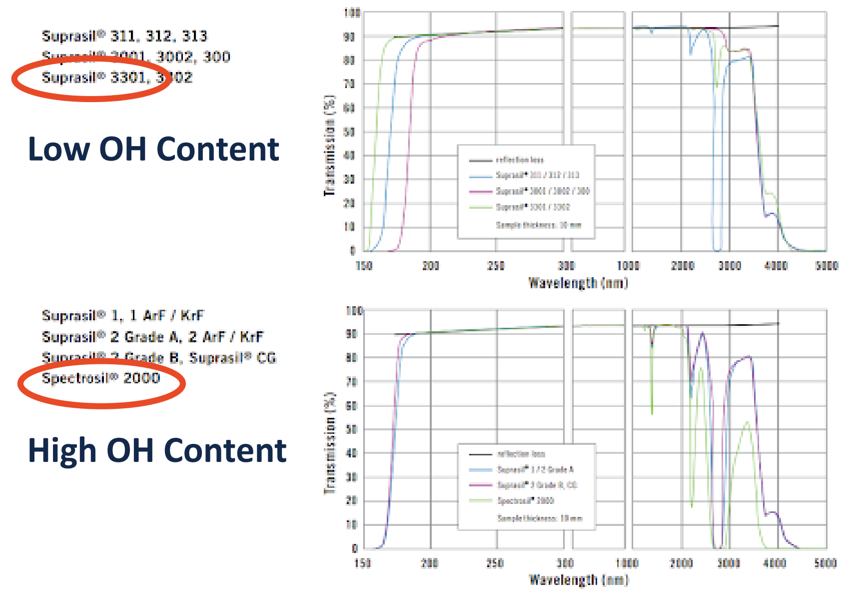
Irradiation Studies for an Upgraded ZDC



BRAN fused silica rods in the TAN

Photo courtesy of Marcus Palm

Rod #	Material	Irradiation Period
1	*Spectrosil 2000 Fused Silica (High OH)*	*Control*
2	*Spectrosil 2000 Fused Silica (High OH)*	*2 LHC year: 04/16 - 12/17*
3	*Spectrosil 2000 Fused Silica (High OH, high H_2)*	*1 LHC year: 04/16 - 12/16*
4	*Spectrosil 2000 Fused Silica (High OH, H_2 free)*	*2 LHC years: 04/16 - 12/17*
5	*Suprasil 3301 Fused Silica (Low OH, high H_2)*	*2 LHC years: 04/16 - 12/17*



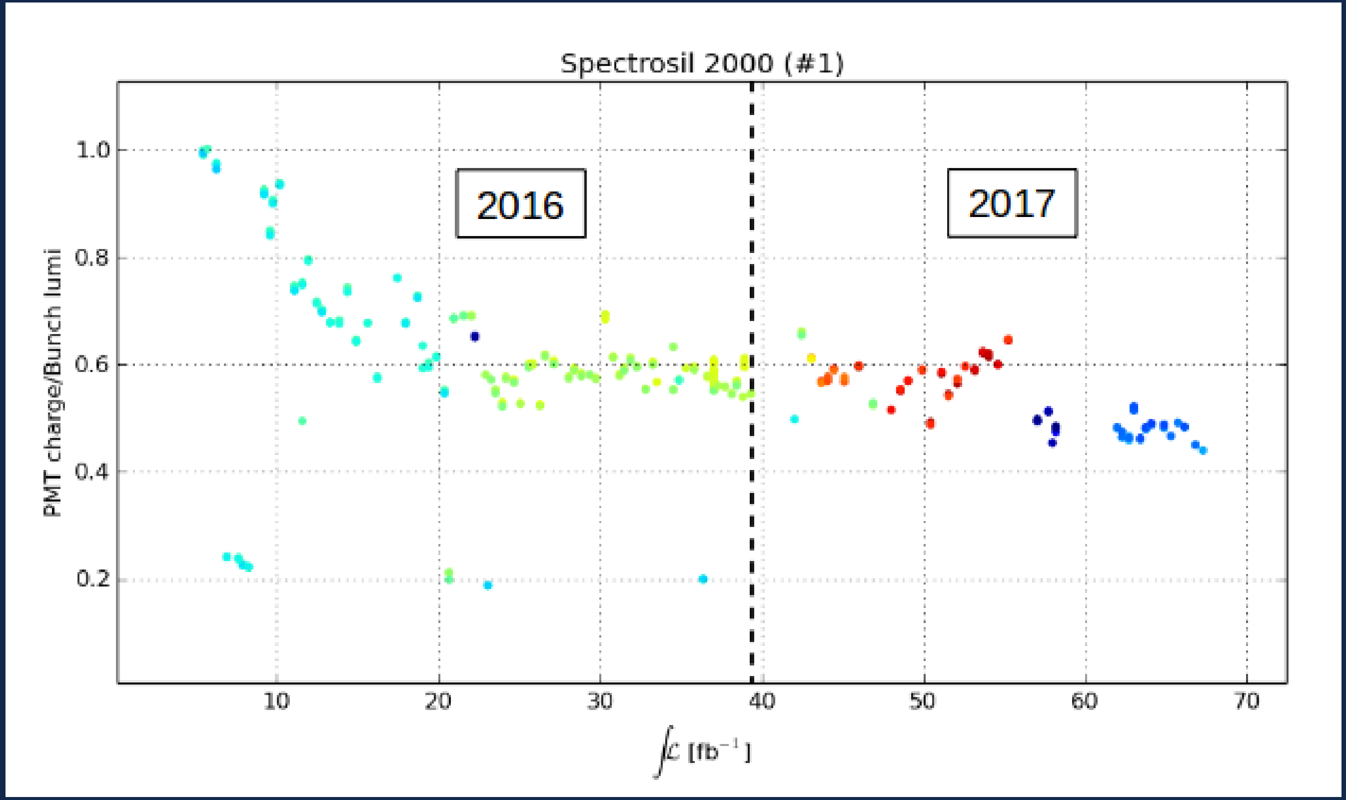
Transmission in undamaged fused silica

- 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

Is there a solution that can withstand *pp* radiation environment in HL-LHC?
➔ BRAN R&D on Fused Silica!

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

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



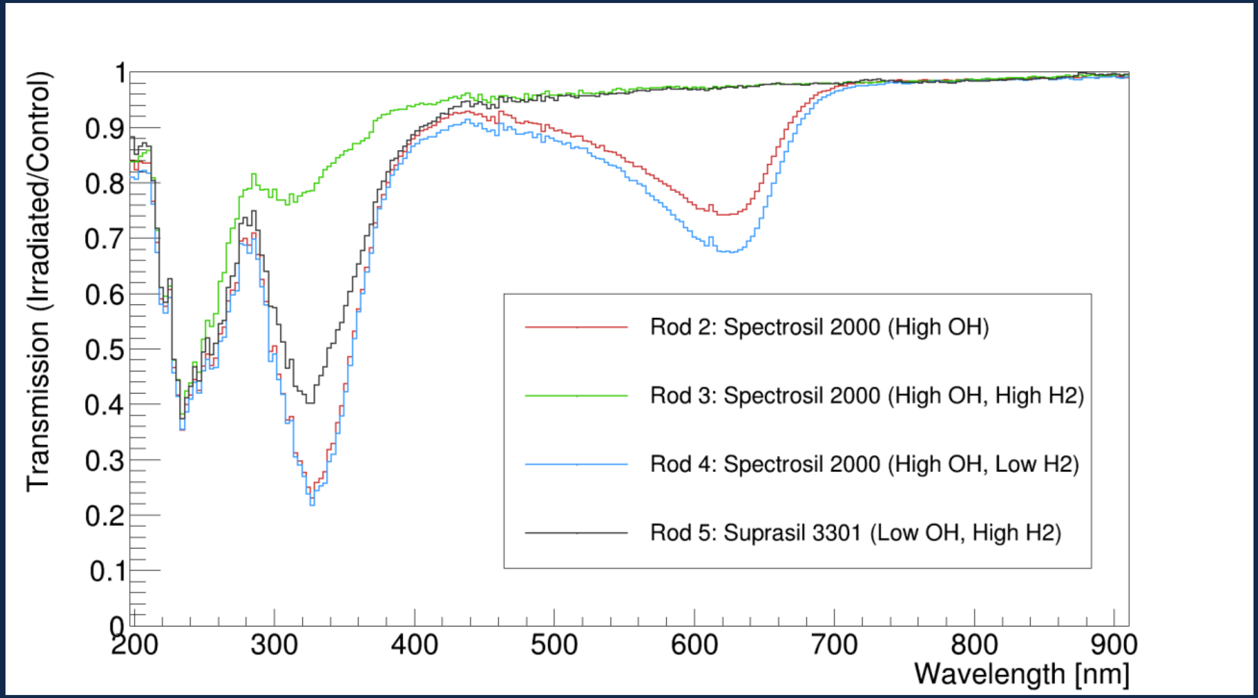
Result provided courtesy of Marcus Palm and BRAN Luminosity Monitor

- 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 Fused Silica Rods: Optical spectrometry results

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)

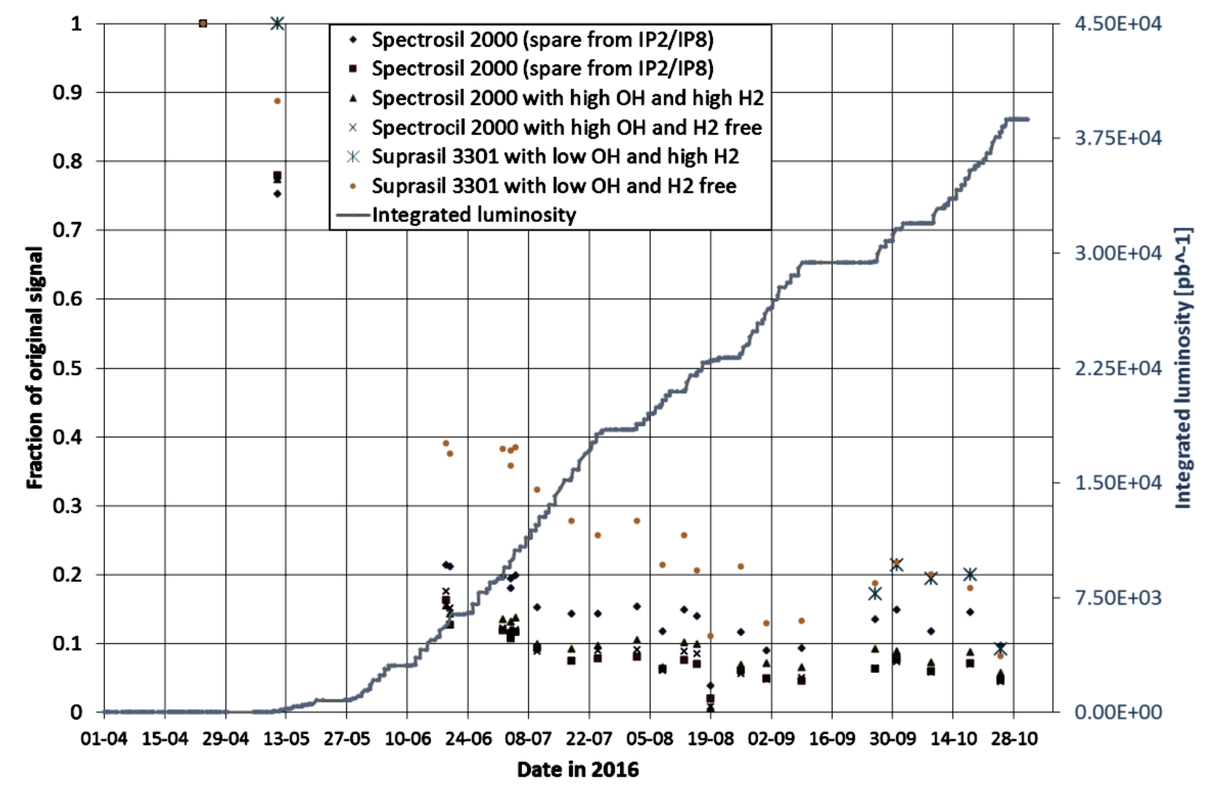
- 230 nm absorption center:
  - Possibly an E' center
    - ≡Si• (oxygen deficiency)
  - Rods irradiated for 2 years show same loss as rod irradiated for 1 year
    - Suggests saturation of the absorption site!?
    - Saturation of transmission loss might explain the observed early light losses followed 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)
    - ≡Si-O• (silicon deficiency)
  - Only shows up in OH-rich rods
  - Low OH rods show little visible radiation damage!

- *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

Design Conclusions

Backups

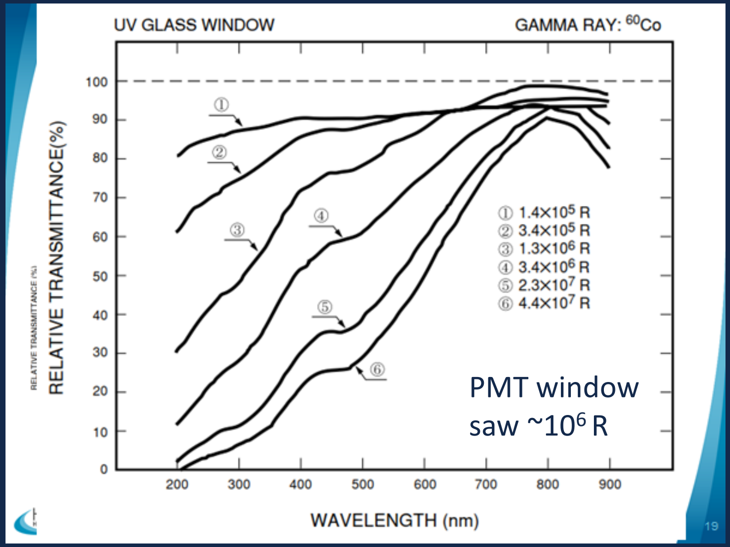
PMT signal size for different BRAN rods during 2016 LHC run



- 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

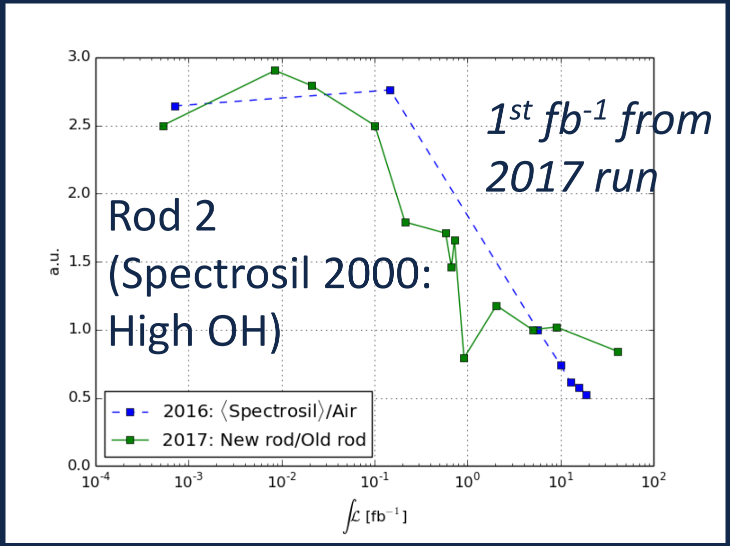
Significant PMT Window Damage



PMT window saw ~10^6 R

- PMT window used during runs suffered significant damage
- Significant portion of transmission loss seen in BRAN attributable to PMT window

Attempt to Unravel PMT-Independent Damage



1st fb^{-1} from 2017 run

Rod 2 (Spectrosil 2000: High OH)

- 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

BRAN Luminosity Monitor Live Data

Light-by-Light Scattering

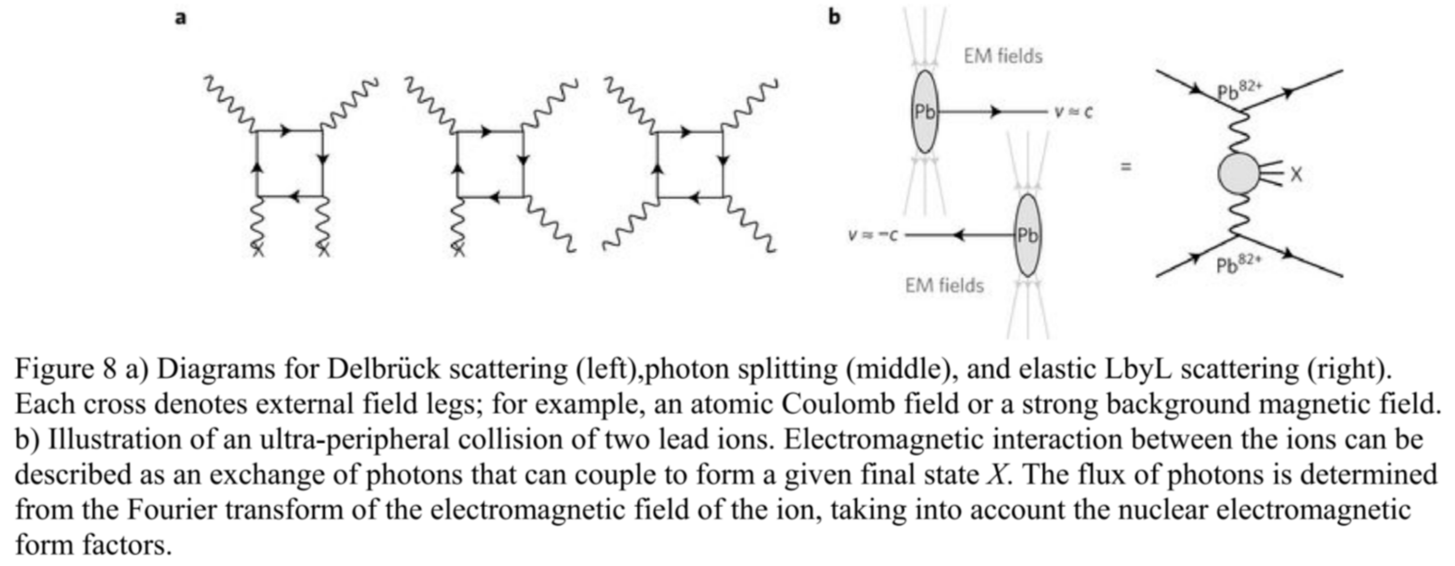


Figure 8 a) Diagrams for Delbrück scattering (left),photon splitting (middle), and elastic LbyL scattering (right). Each cross denotes external field legs; for example, an atomic Coulomb field or a strong background magnetic field. b) Illustration of an ultra-peripheral collision of two lead ions. Electromagnetic interaction between the ions can be described as an exchange of photons that can couple to form a given final state *X*. The flux of photons is determined from the Fourier transform of the electromagnetic field of the ion, taking into account the nuclear electromagnetic form factors.

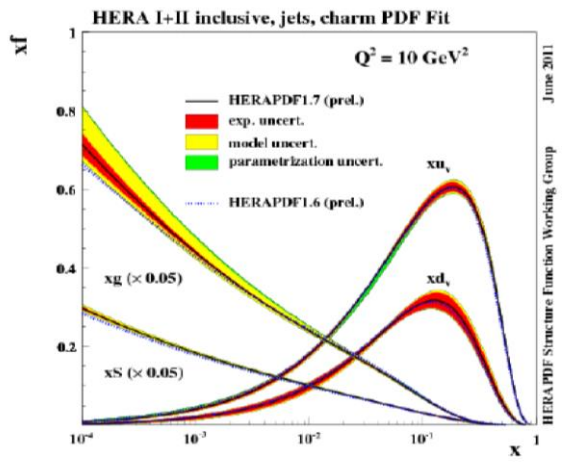
ATLAS Collaboration *in Nature Physics* **13**, 852-858 (2017)

- 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

See following publications:

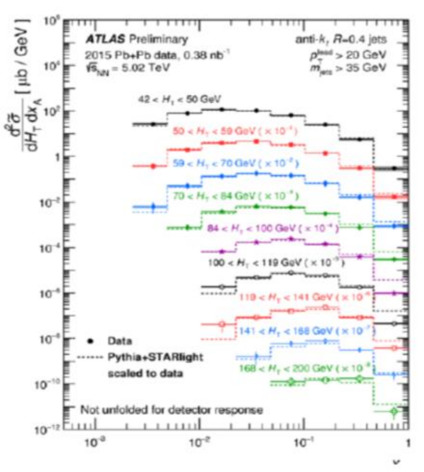
- C. Baldenegro, et al. "Probing the anomalous γγγZ coupling at the LHC with proton tagging"
- S. Fichet. "Probing new physics in diphoton production with proton tagging at the Large Hadron Collider"
- S. Fichet, et al. "Light-by-light scattering with intact protons at the LHC: from Standard Model to New Physics"
- O. Kepka, et al. "Anomalous WWγ coupling in photon-induced processes using forward detectors at the LHC"

Gluon Saturation in Pb Nuclei

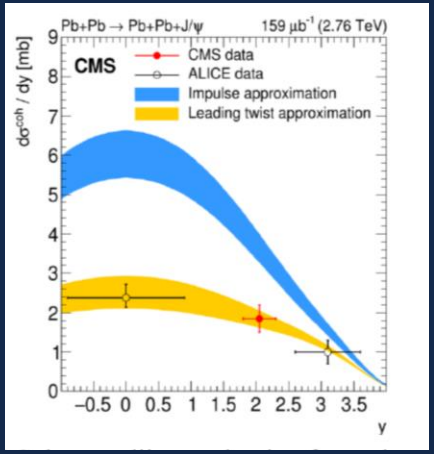


At low x gluon density diverges. Expectation is for saturation to occur at some point creating glass-like state of matter described by classical field equations

- 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 colisions
- 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

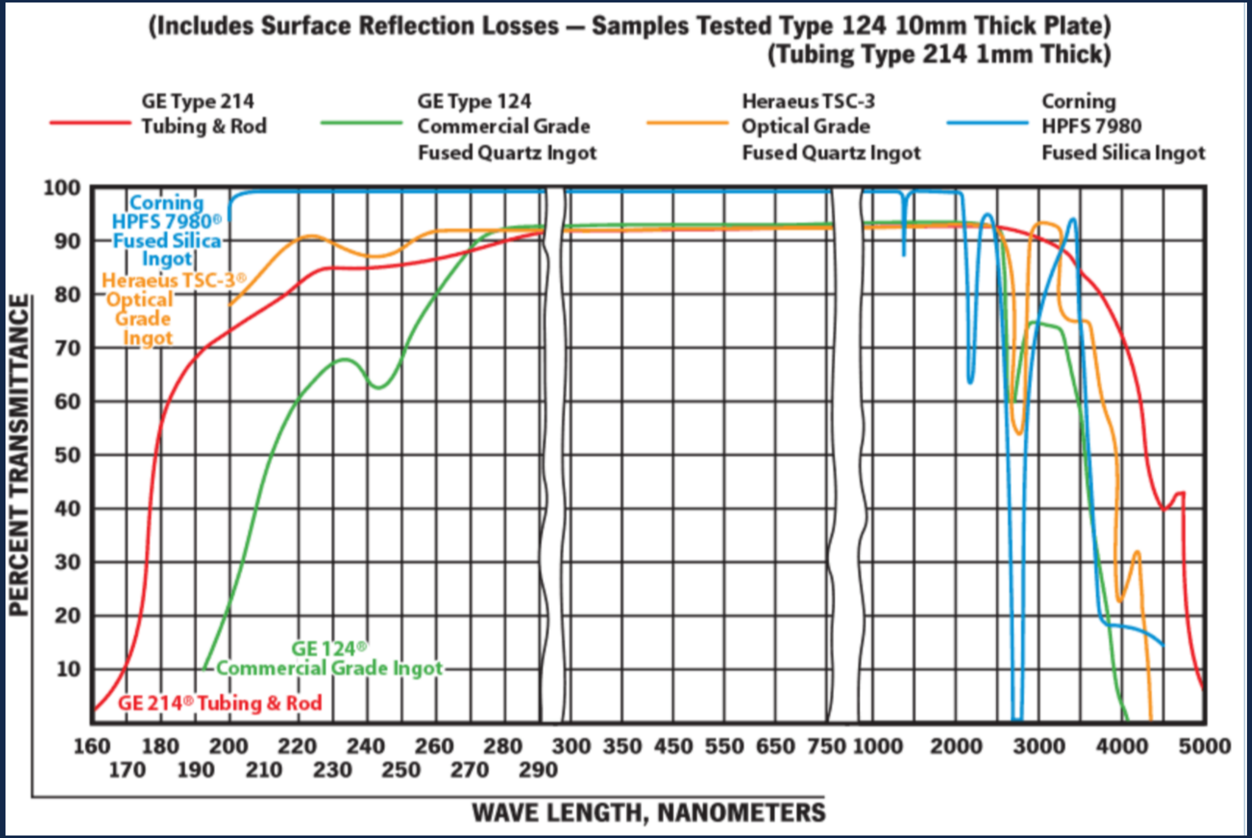


ATLAS-CONF-2017-011

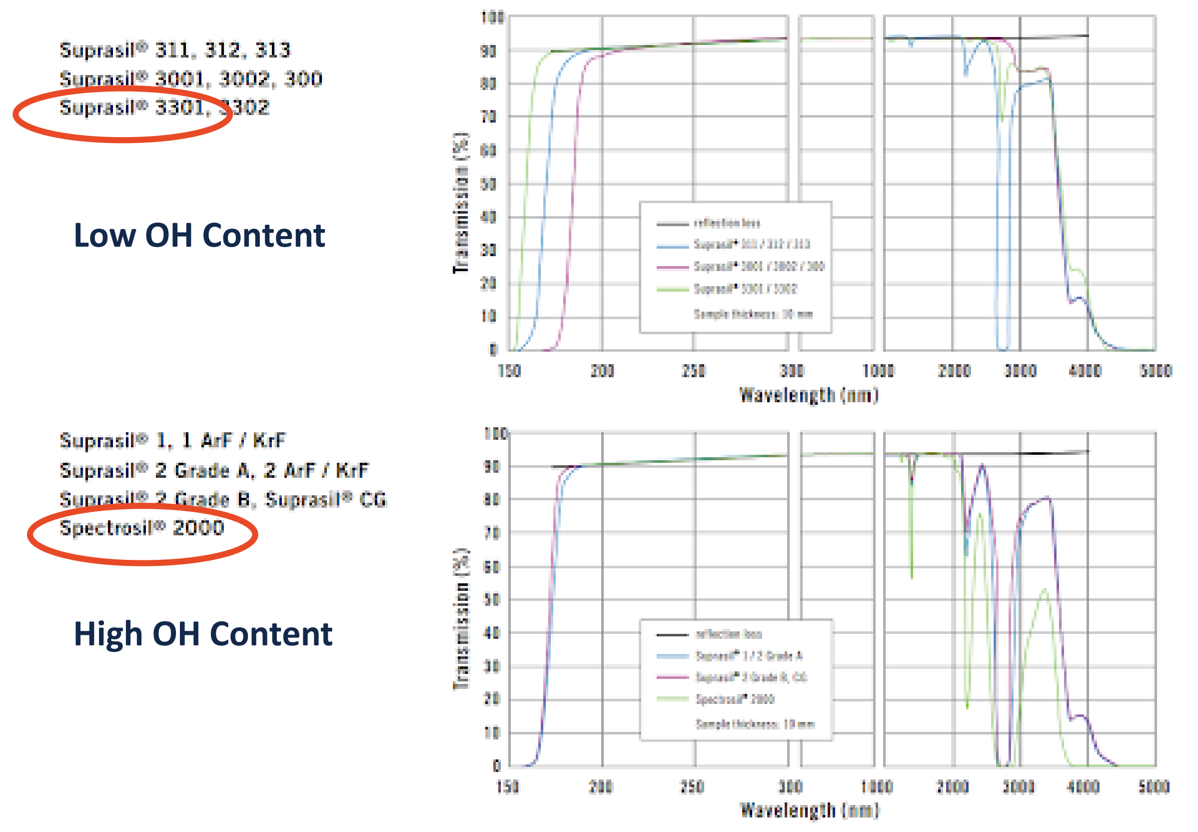


CMS Collaboration in *Phys. Lett. B 772 (2017) 489.*

Fused Quartz Transmission Curve (GE 214)



Fused Silica Transmission Curves



Unirradiated Transmission Curves

Fused Silica Defects

- **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” 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” https://aip.scitation.org/doi/abs/10.1063/1.346719