THE JOINT ZERO DEGREE CALORIMETER PROJECT (JZCAP)

Joint CFNS & RBRC Workshop on
Physics and Detector Requirements
at Zero-Degree of Colliders

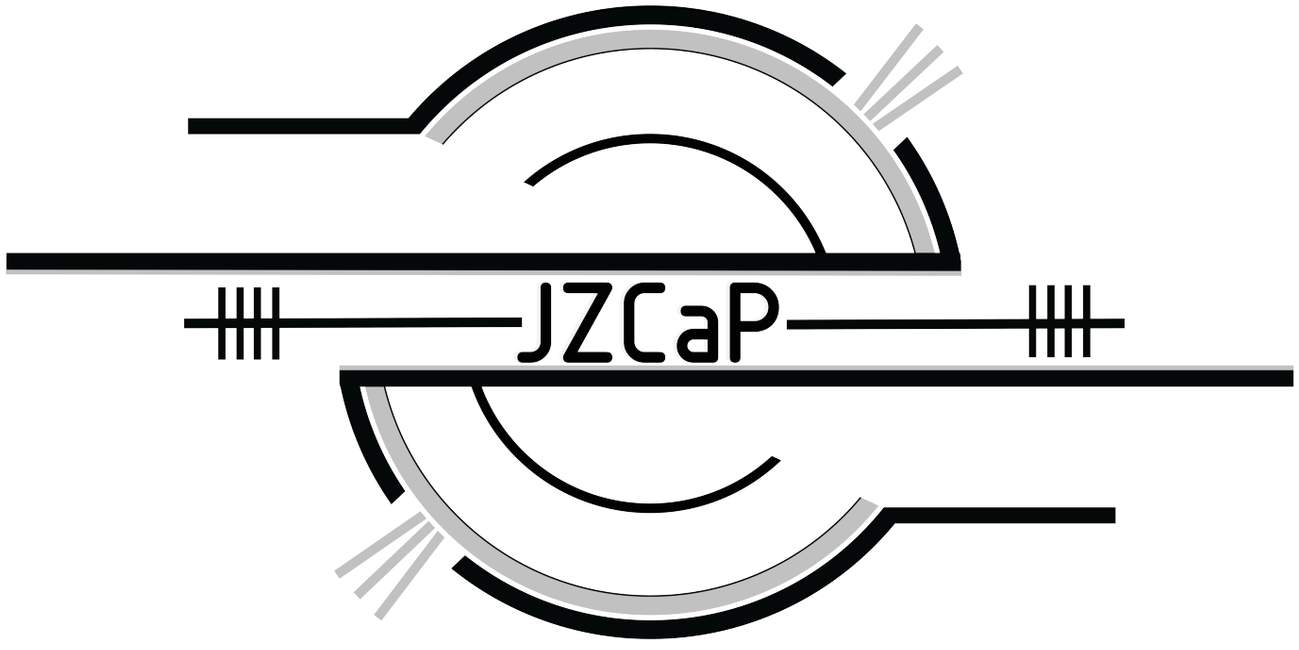
Stony Brook (NY)
24 - 26 September 2019

Riccardo Longo



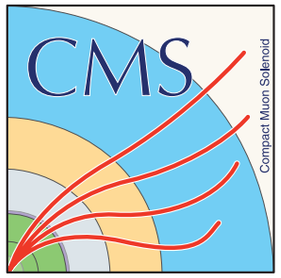
JZCaP

ILLINOIS



Joint **Z**ero degree **Ca**lorimeter **P**roject (**JZCaP**)

- ATLAS + CMS joint R&D effort
- In contact with LHCb and sPHENIX to expand the collaboration
- New collaborators are welcome! j.zdcrd@cern.ch



- University of Kansas
- University of Maryland

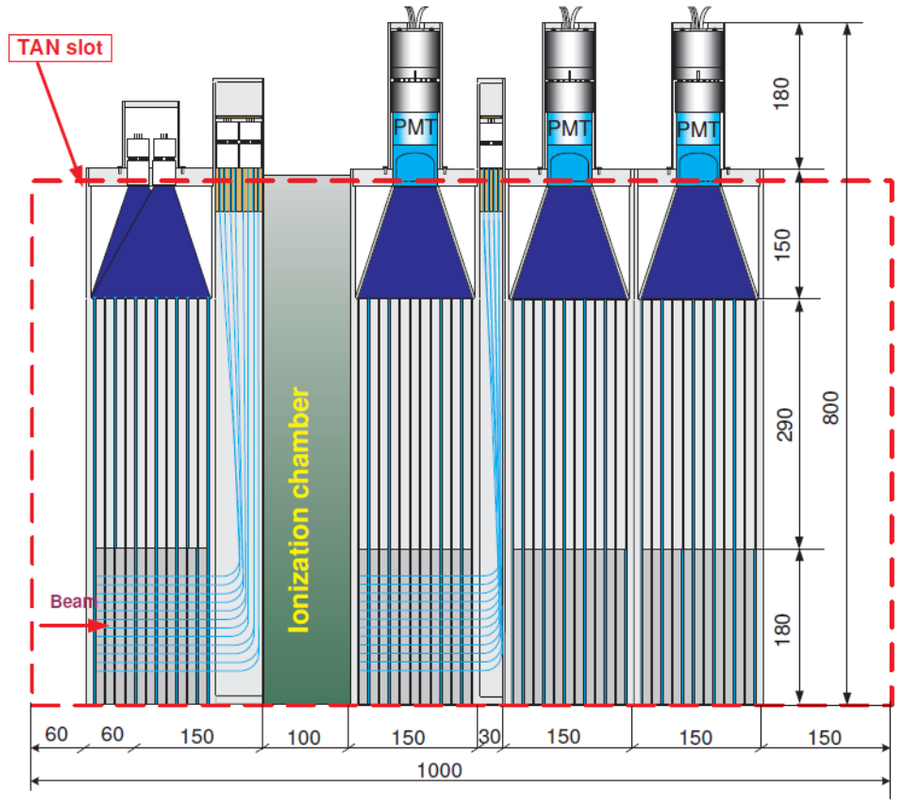


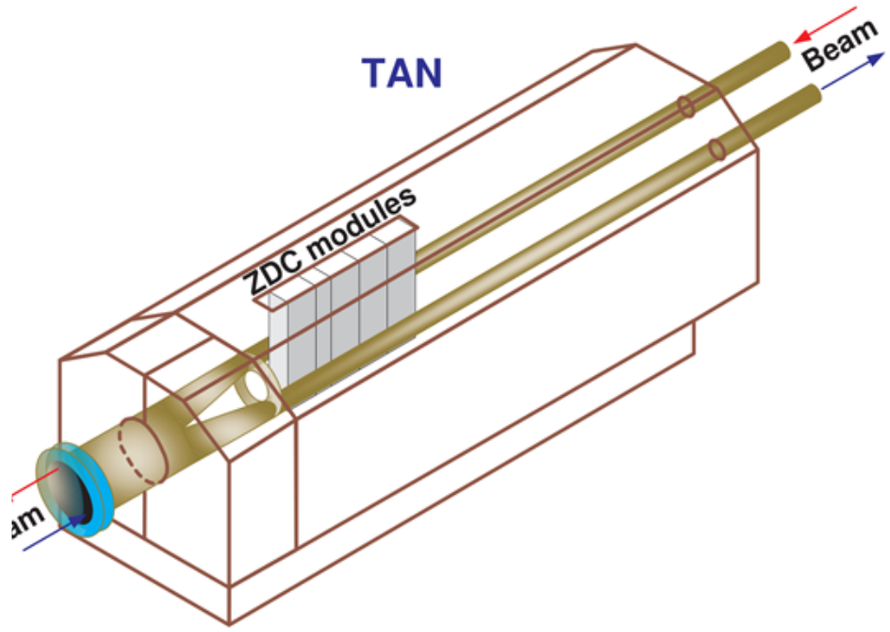
- Ben Gurion University
- BNL
- Columbia University
- University of Illinois

INTRODUCTION AND MOTIVATIONS

THE CURRENT ATLAS & CMS ZDCs

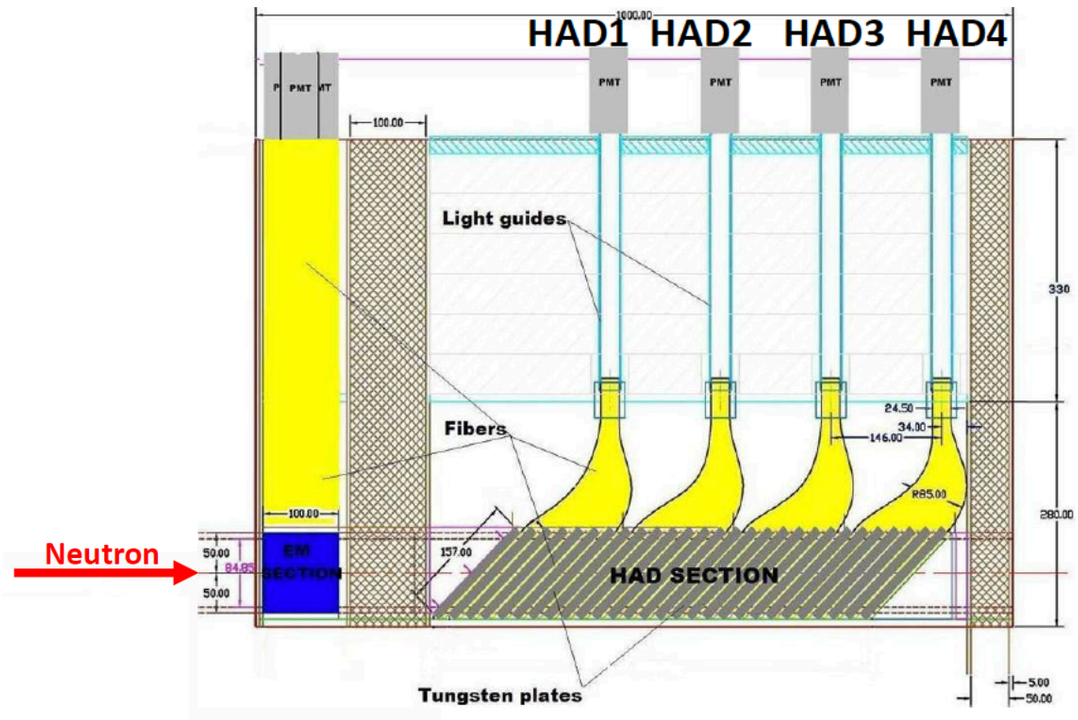
ATLAS EXPERIMENT





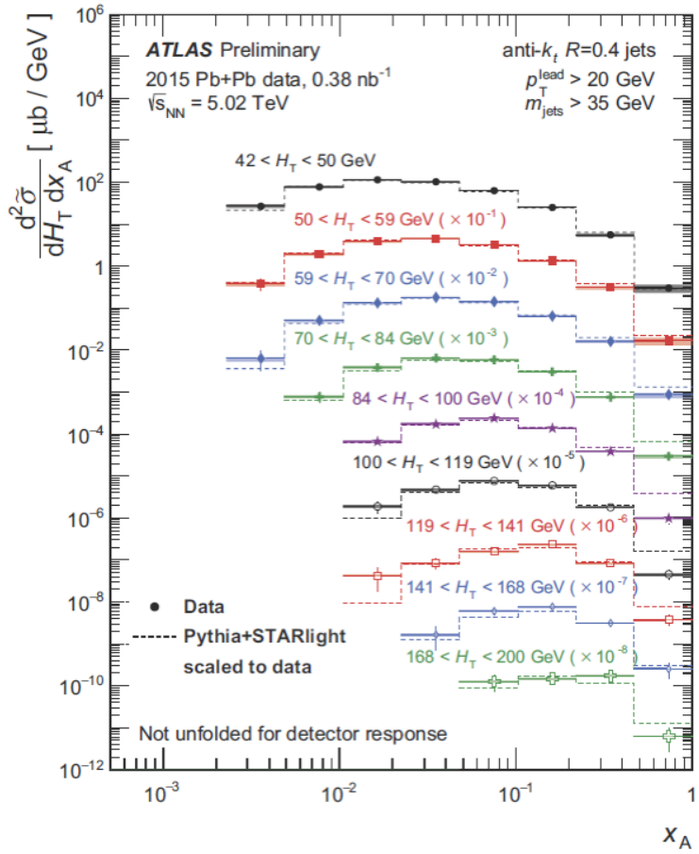
CMS Compact Muon Solenoid

See talk by E. Adams



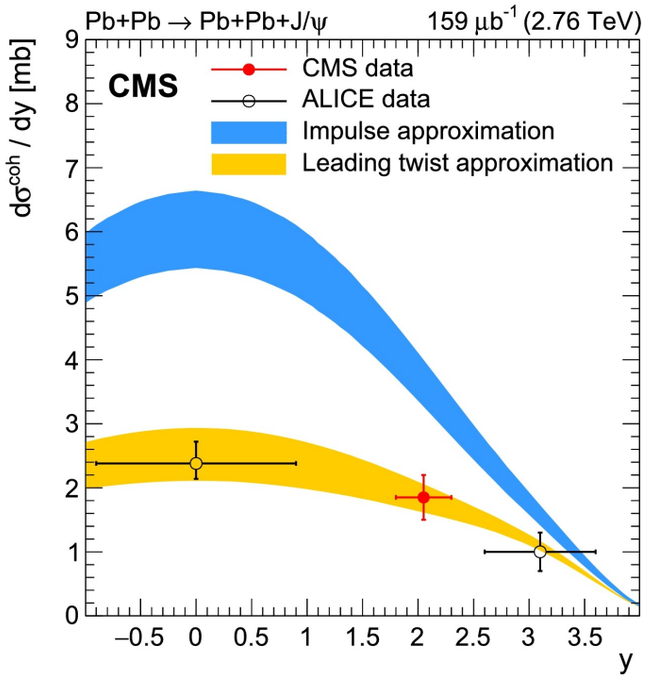
- ZDCs located in the **TAN** (140 m from IPs)
- W - quartz sampling calorimeters
- ATLAS: EM + 3 Hadronic modules
- CMS: EM + 4 Hadronic modules

MOTIVATION – PHYSICS



Photoproduction of jets $\sqrt{s_{NN}}$ = 5.02 TeV
ATLAS, Nuclear Physics A 967 (2017)

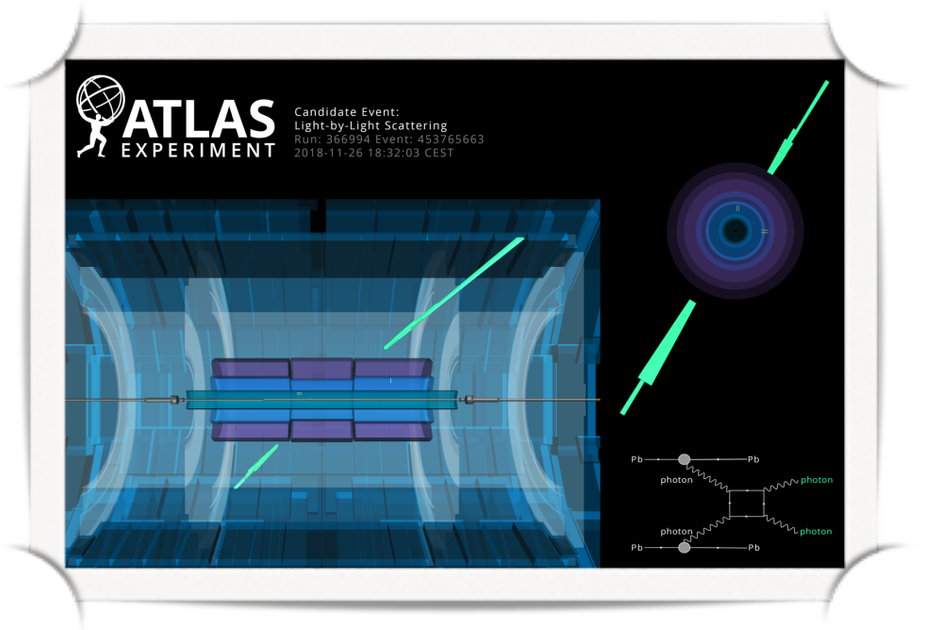
- Ultra Peripheral Collisions:
  - Photo production of jets as probe of nuclear parton structure (ZDC used for event tagging)
  - J/ψ photoproduction in ultra-peripheral PbPb collisions (ZDC used for triggering and event classification)



Coherent J/ψ photoproduction in ultra-peripheral PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV

CMS, Physics Letter B, 767 (2017)

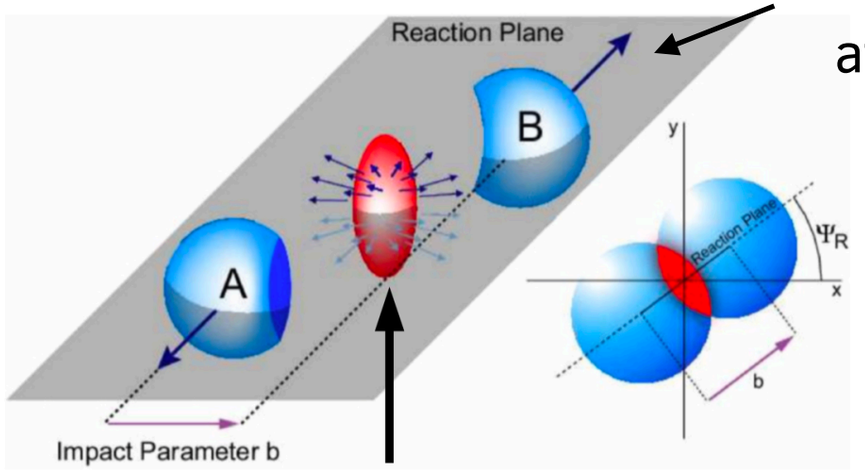
- Light-by-light scattering (ZDC used for event tagging and minimum bias triggering)



Evidence for light-by-light scattering in heavy-ion collisions
***Nature Physics* 13, 852–858 (2017)**

MOTIVATION – PHYSICS

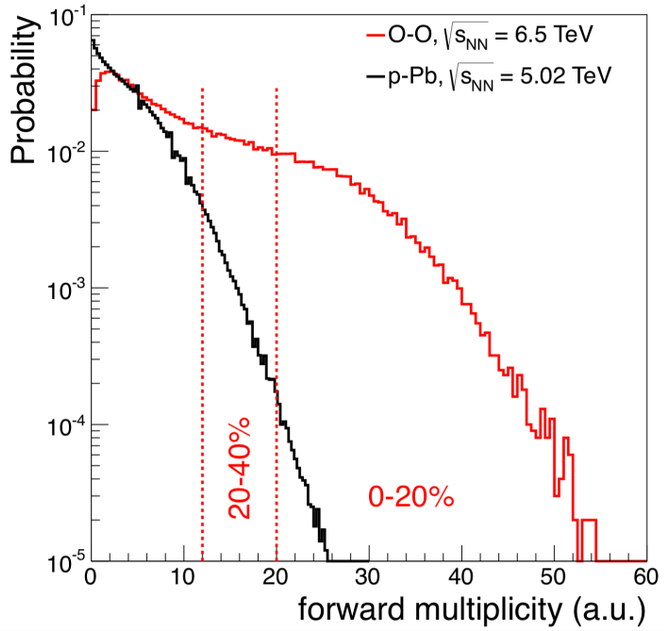
- Characterize geometry of the collision: centrality, flow and event plane measurements as input to analysis of Pb-Pb collisions (ZDC measures spectator nucleons).



RP Measurement at very forward rapidity

Flow Measurement

Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams
arXiv:1812.06772 [hep-ph]



- O-O measurements
  - Investigating the properties of low-multiplicity heavy-ion collisions with a well defined geometry
- p-O measurements
  - Crucial input to cosmic ray physics program
- Room to use the ZDC in pp forward measurements (e.g. veto in exclusive reaction measurements)

- Equipping both ATLAS and CMS with the same ZDC would bring a considerable advantage while **comparing results** obtained by the two experiments

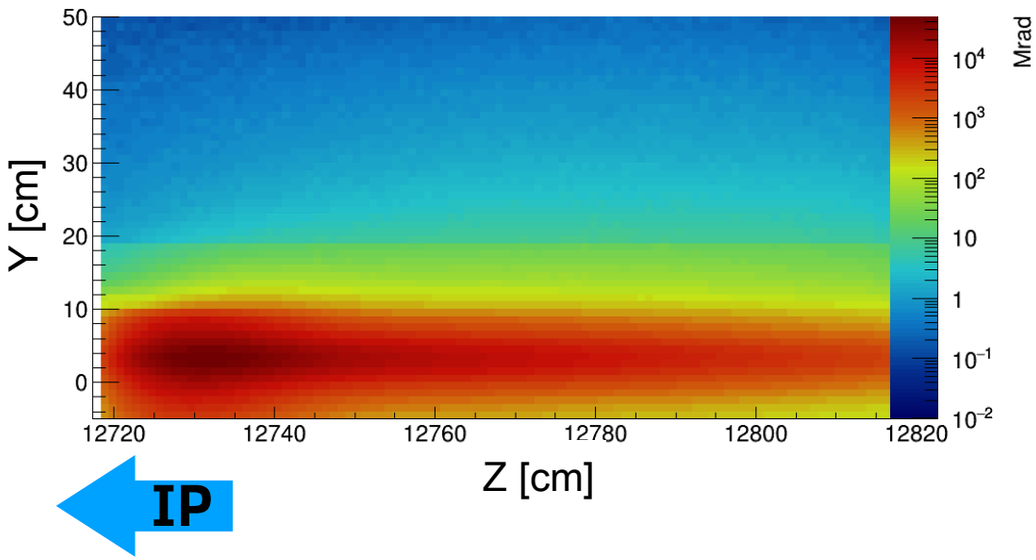
MOTIVATION – LHC LUMINOSITY UPGRADE

- The LHC upgrade during LS3 requires a rearrangement of the beam line.
- Less space left for the ZDC (from TAN - 10 cm, to TAXN, 5 cm) —> **Narrower ZDC** modules for Run4.
- TAXN ~ 15 m closer to the interaction point compared to TAN.
- Radiation levels will further increase.

		pp collisions	**Pb+Pb collisions**	**Low-μ pp collisions**
Run 2	Energy	13 TeV	5.02 TeV/n	5.02 TeV
	Total Int. Lumi	156 fb^{-1} (3 years)	1 nb^{-1}	334 pb^{-1} (2017)
	max dosage in TAN	**8 Grad/2017 *pp*** (FLUKA)	**8 Mrad/2018** PbPb (FLUKA)	**21 Mrad/year** (estimate)
Run 3	Energy	14 TeV	5.5 TeV/n	5.5 TeV
	Total Int. Lumi	270 fb^{-1} (3 years)	6 nb^{-1} (3 years)	
	max dosage in TAN	**15 Grad/year** (estimate)	**53 Mrad/year** (estimate)	
Run 4	Energy	14 TeV	5.5 TeV/n	5.5 TeV
	Total Int. Lumi	750 fb^{-1} (3 years)	7 nb^{-1} (3 years)	
	max dosage in TAN	**30 Grad/year** (FLUKA)	**62 Mrad/year** (estimate)	

- Radiation level simulations (LHC simulation group - using FLUKA) and estimates for Run2, Run3 and Run4

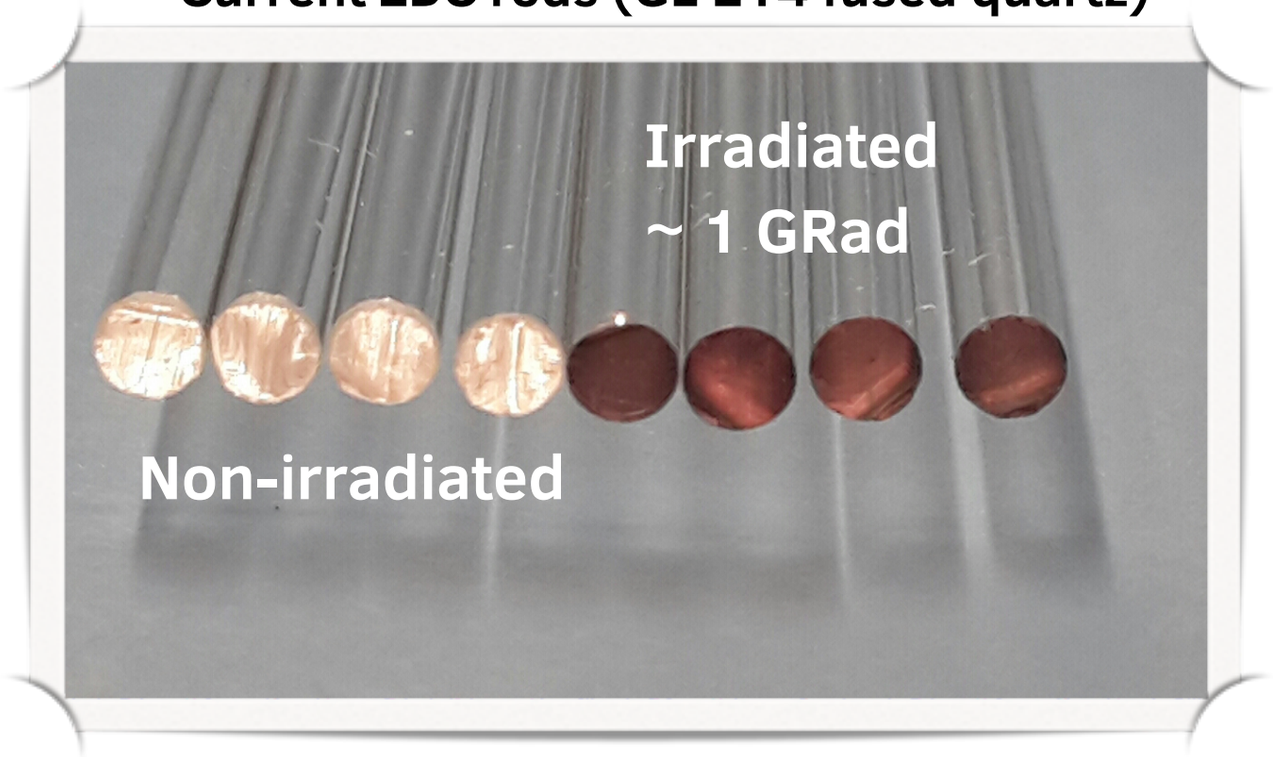
HL-LHC *pp* dose map (TAXN region - 1year)



MOTIVATION – RADIATION DAMAGE

- The LHC upgrade during LS3 requires a rearrangement of the beam line.
- Less space left for the ZDC (from TAN - 10 cm, to TAXN, 5 cm) —> **Narrower ZDC** modules for Run4.
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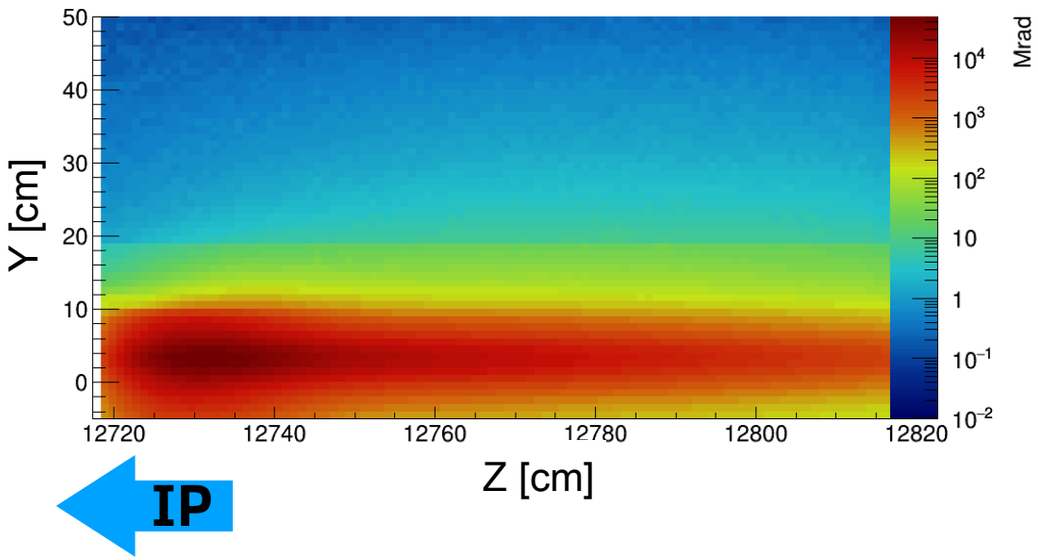
Current ZDC rods (GE 214 fused quartz)



- Fused quartz with high level of impurities inadequate for any pp running and damaged during PbPb running.

- Hardening the detector for pp running allows flexibility in installation to accomodate special LHC runs (e.g. O+O, p+O in Run3) that take place in the middle of pp running

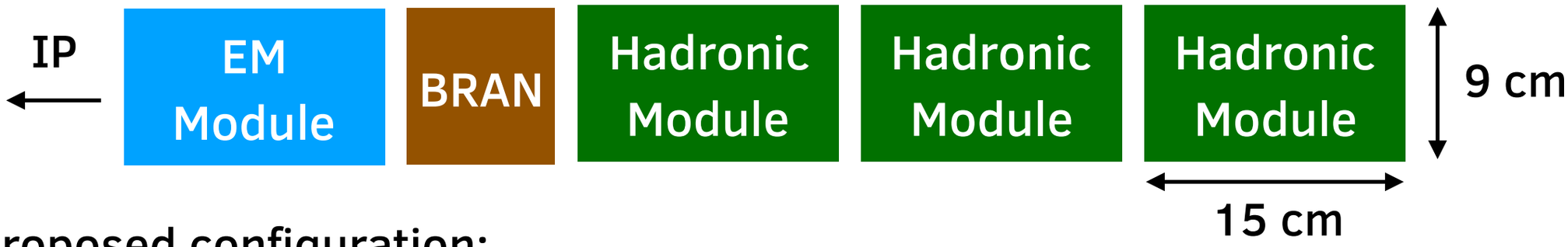
HL-LHC *pp* dose map (TAXN region - 1year)



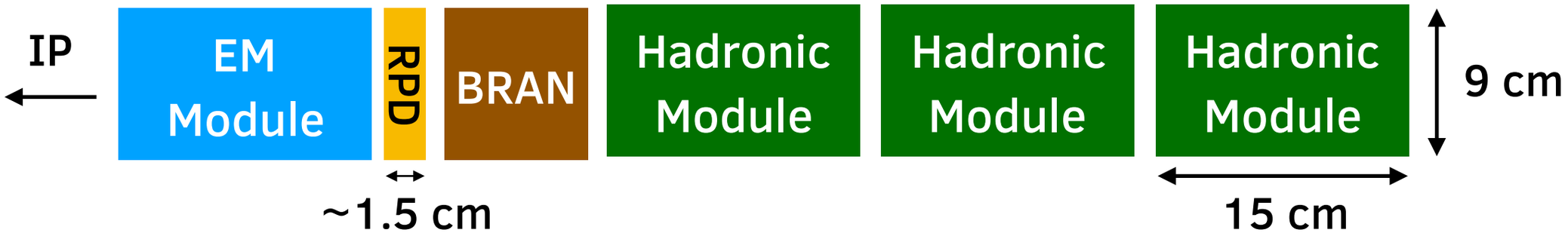
DETECTOR LAYOUT

RUN3: PRELIMINARY DETECTOR CONFIGURATION

Run2 configuration:



Run3 proposed configuration:



- For each arm:

  1 Electromagnetic Module [**EM**] +

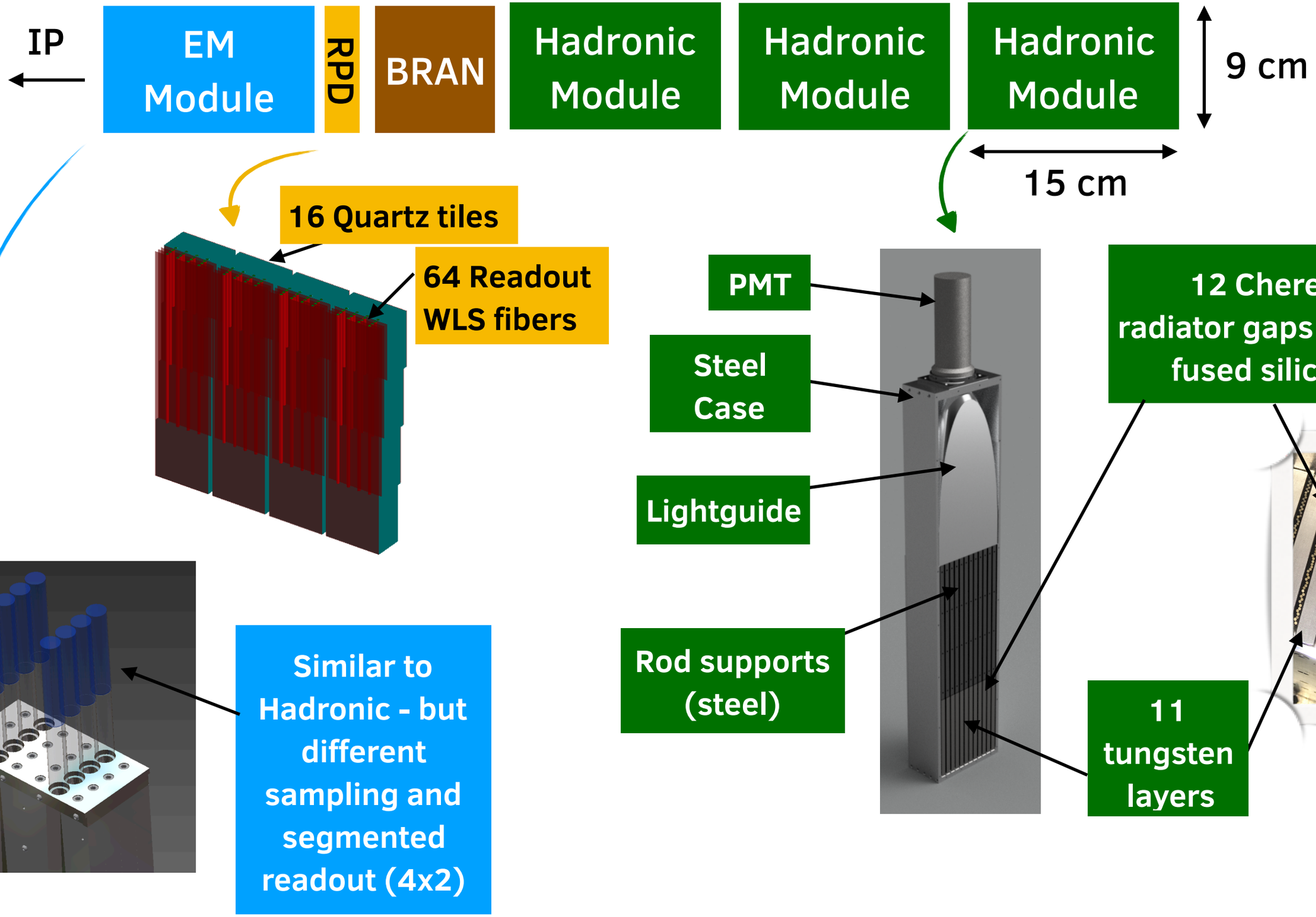
  1 Reaction Plane Detector [**RPD**] +

  3 Hadronic Modules [**HMs**]

- **RPD** placed at Cherenkov shower max;
- Upgrades to HMs and EM discussed in this talk;
- For Run4, the detector will be rebuilt (narrower space in TAN - 5cm).

RUN3: PRELIMINARY DETECTOR CONFIGURATION

Run3 proposed configuration:



RADIATION HARDNESS R&D

RADIATION-HARD FUSED SILICA RODS

- Fused silica supplier: **Heraeus** (Hanau, Germany).
- Joint effort between the University of Illinois at Urbana Champaign, the BRAN luminosity group and the LHC simulation group.

ILLINOIS

Matthias Perdekamp
Chad Lantz
Riccardo Longo
Michael Phipps
Nico Santiago
Aric Tate
Sheng Yang

LHC simulation group

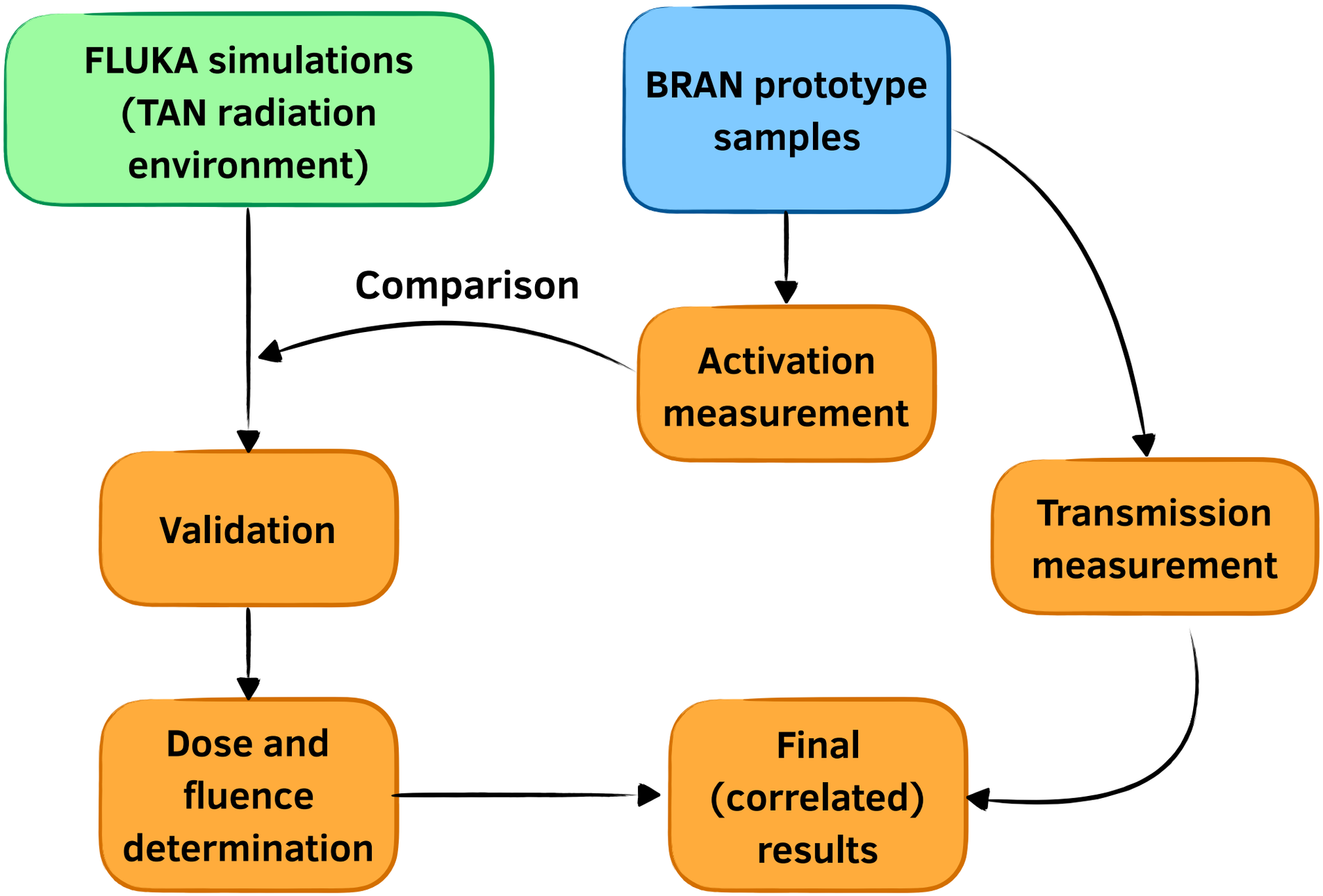
Francesco Cerutti
Marta Sabate Gilarte

BRAN luminosity group

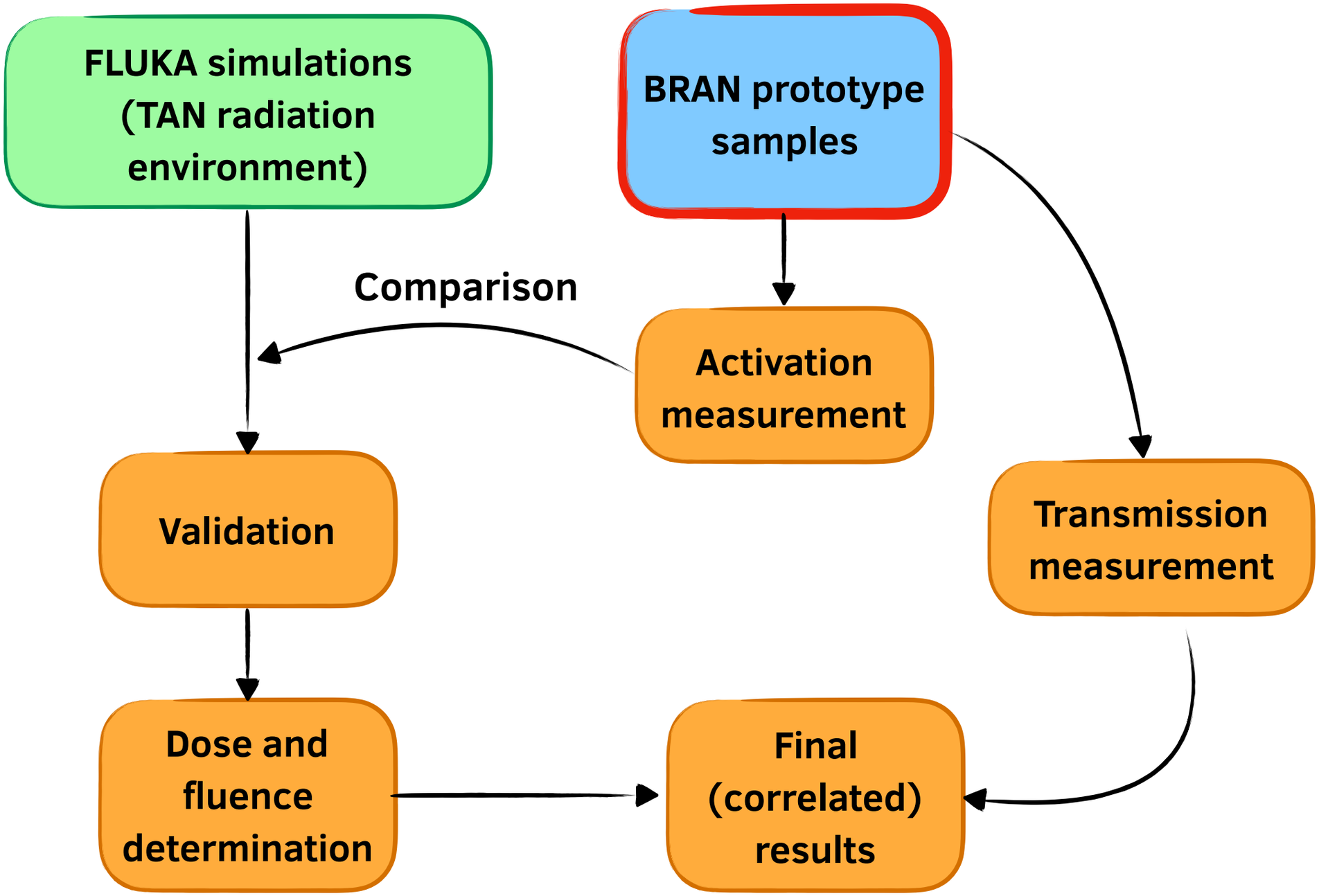
Marcus Palm
Enrico Bravin
Sune Jakobsen

- Heraeus fused silica rods irradiated by the BRAN experiment at the LHC, from 2016 - 2018.
- LHC simulation group provided FLUKA estimates of the radiation environment during the three years of run.

ANALYSIS BREAKDOWN

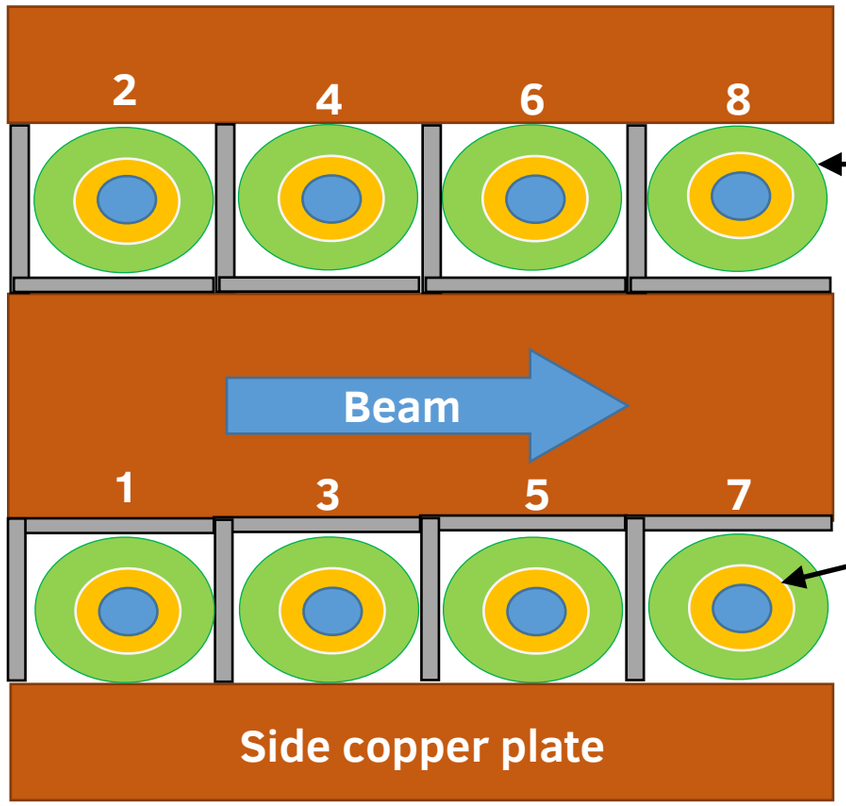


ANALYSIS BREAKDOWN



BRAN DETECTOR PROTOTYPE DURING RUN2

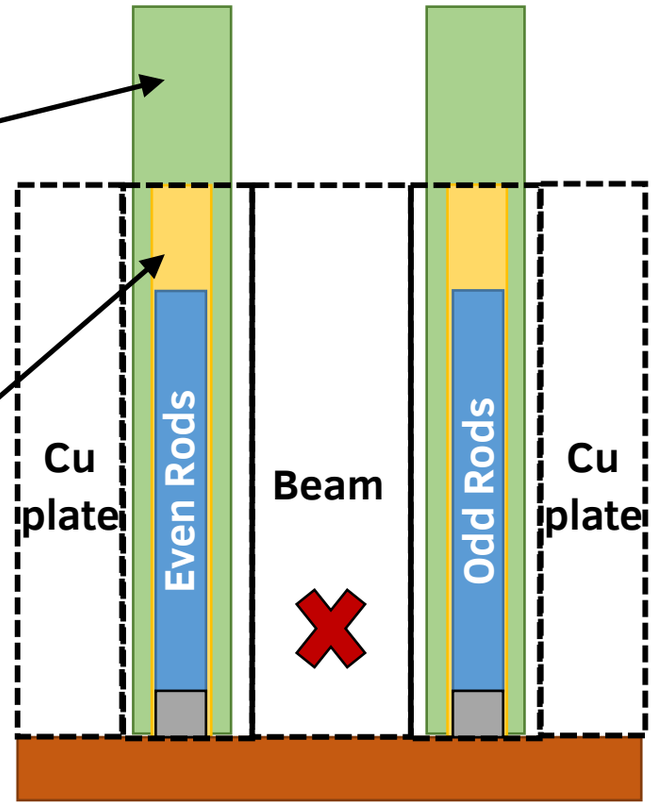
BRAN prototype top view



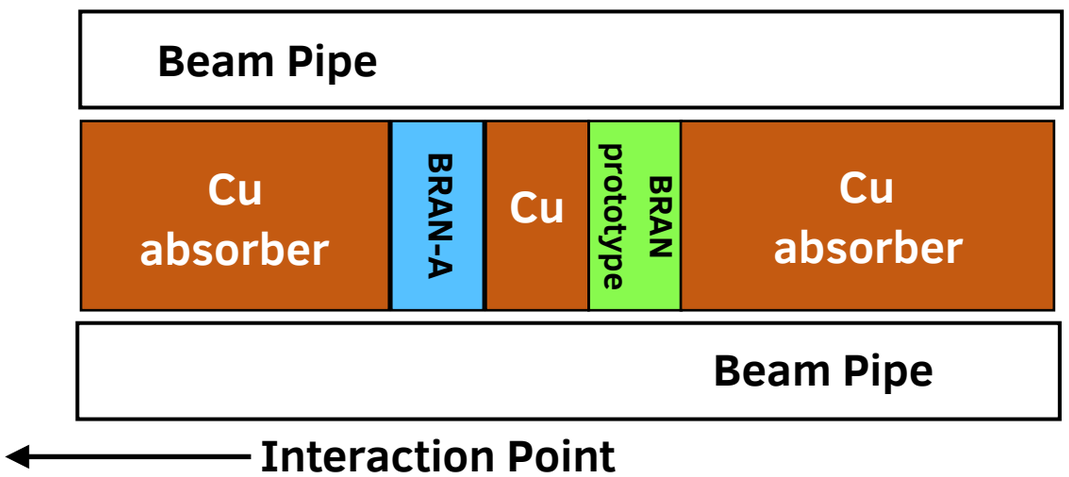
External Support tube (Aluminium)

Internal Support tube (Quartz)

BRAN prototype front view

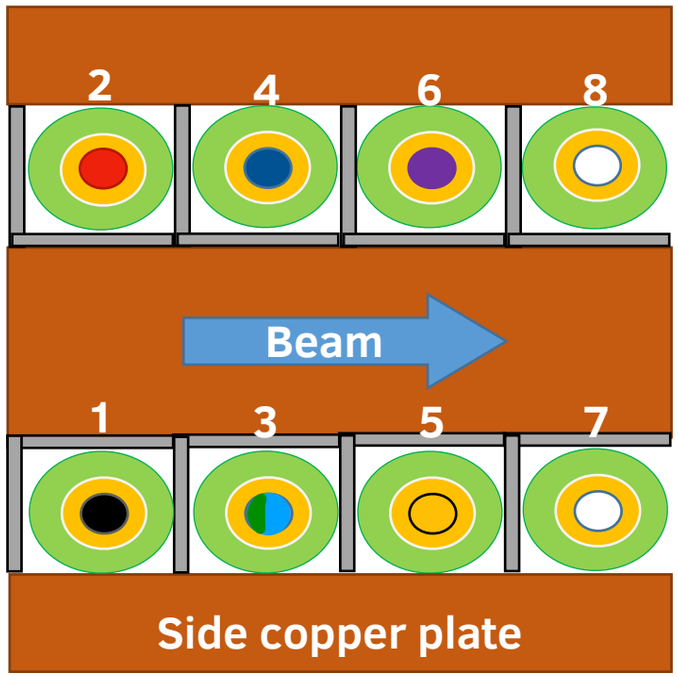


TAN top view (pp configuration)



- Two BRAN detectors installed during Run2: one regular detector and one prototype for High-Lumi LHC equipped with fused silica rods.
- Rod geometry:
  - ϕ = 1 cm
  - h = 40 cm

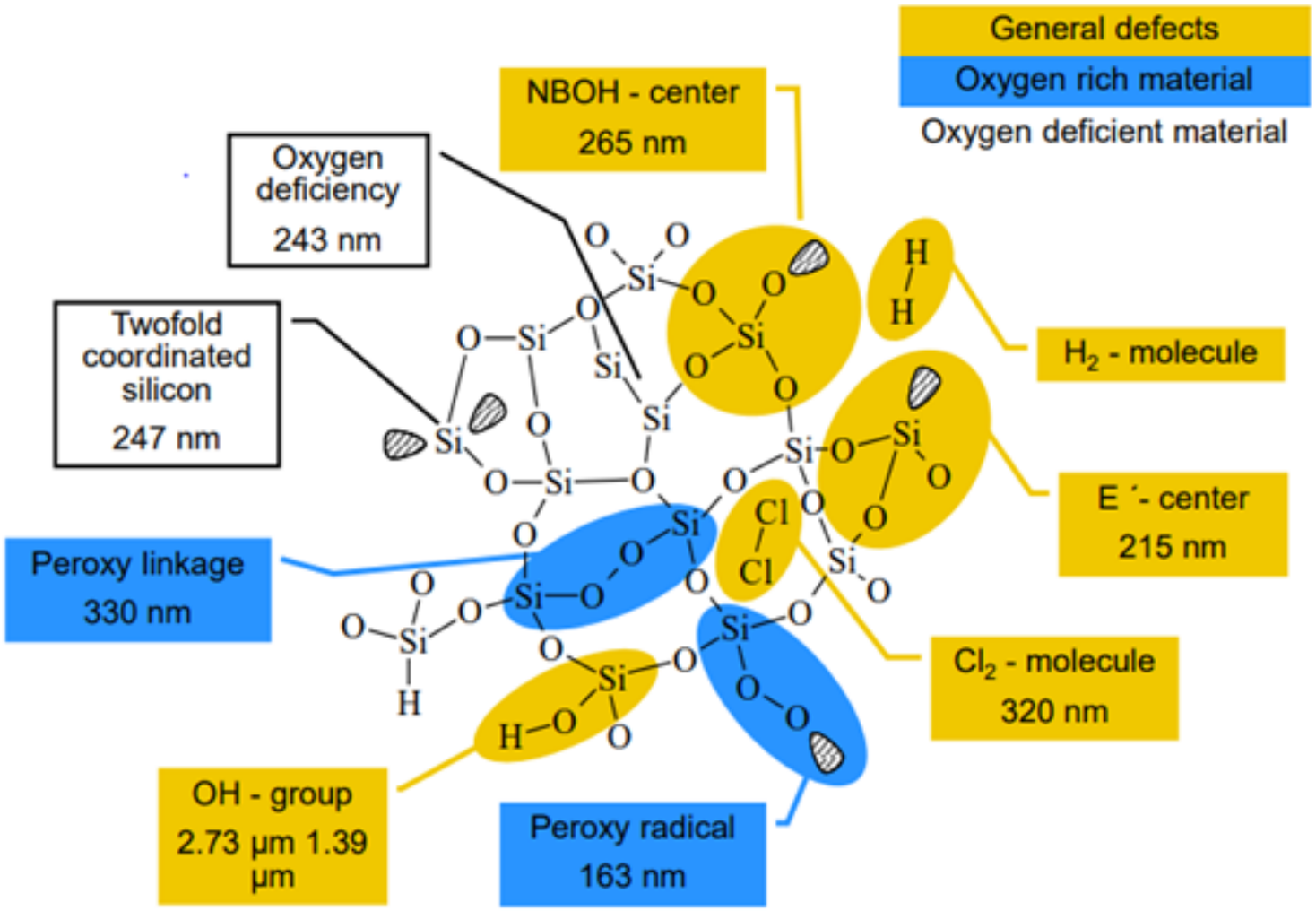
BRAN DETECTOR PROTOTYPE DURING RUN2



- Heraeus fused silica rods irradiated in the BRAN prototype at the LHC (2015 - 2018) and analyzed at UIUC.
- Samples have varied radiation histories and material properties

Bran Position	Irradiation period	Peak exposure (Grad)	Material	H_2 [mol/cm^3]	OH [ppm]
Control	None	0	Spectrosil 2000 (High H_2, Mid H_2)	7.20e17	1120
1	04/2016 - 12/2018	3	Spectrosil 2000 (High OH, Mid H2)	7.20e17	1120
2	04/2016 - 12/2017	1.5	Spectrosil 2000 (High OH, Mid H2)	7.20e17	1120
3a	04/2016 - 12/2016	0.5	Spectrosil 2000 (High OH, High H2)	2.80e18	1000
3b	04/2017 - 12/2018	2	Spectrosil 2000 (High OH, Mid H2)	7.20e17	1120
4	04/2016 - 12/2017	1	Spectrosil 2000 (High OH, H2 free)	0	1011
5	04/2016- 12/2017	1	Suprasil 3301 (Low OH, High H2)	3.00e18	15
6	04/2016 - 12/2018	2	Suprasil 3301 (Low OH, H2 free)	0	14

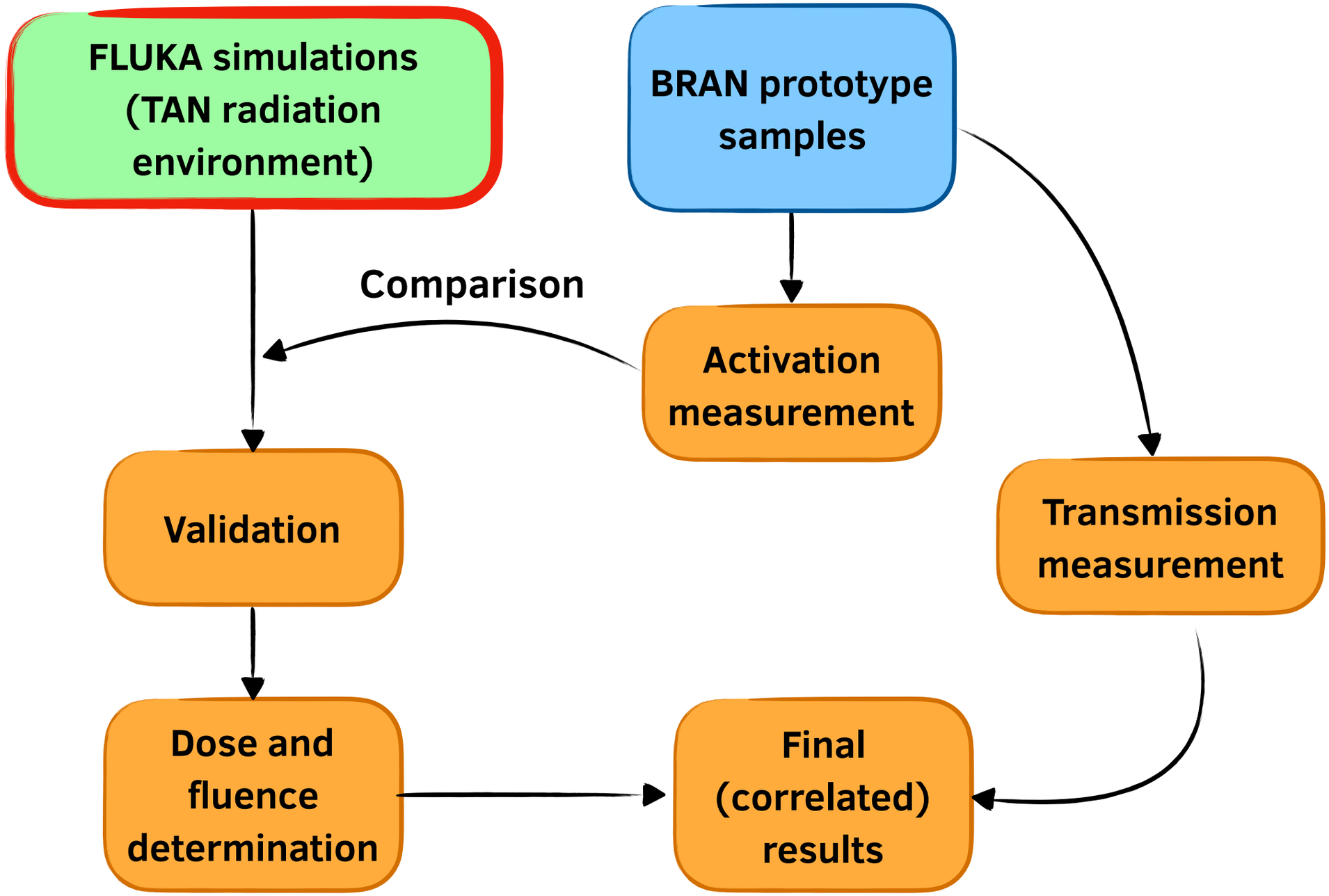
RADIATION DAMAGE IN FUSED SILICA



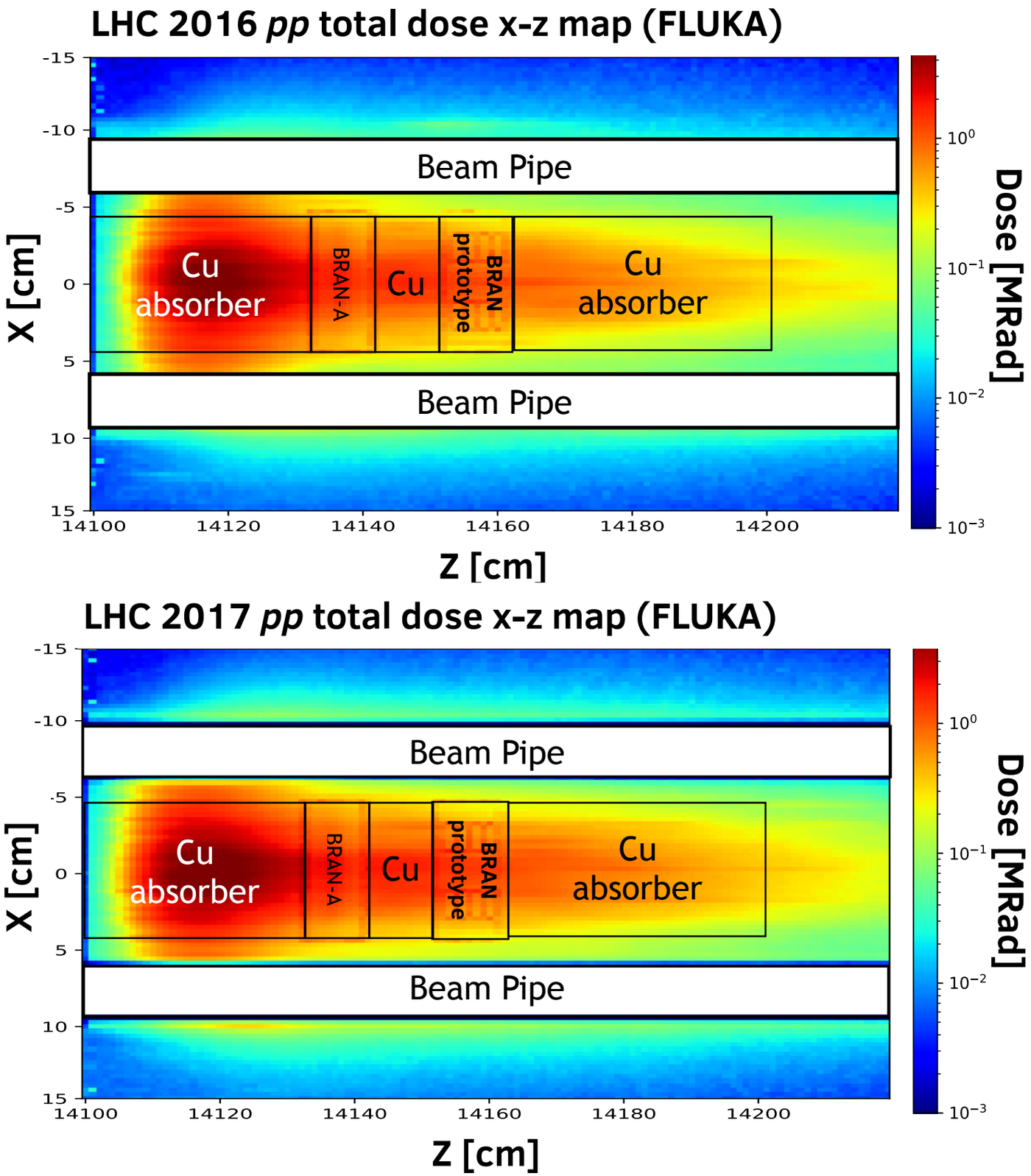
Schematics showing known defects to SiO4 tetrahedral characteristics (courtesy of Frank Nuernberg [Heraeus])

- Increasing number of defects and color centers induced by radiation damage decreases the transmission
- Materials with a high purity level show a lower absorption and a better radiation hardness.
- In the UV region:
  - Saturation of absorbing defects by H_2
  - Decrease in transmittance more pronounced/rapid
- Our results represent the first study of radiation hardness of fused silica exposed to **high energy hadron cocktail**

ANALYSIS BREAKDOWN



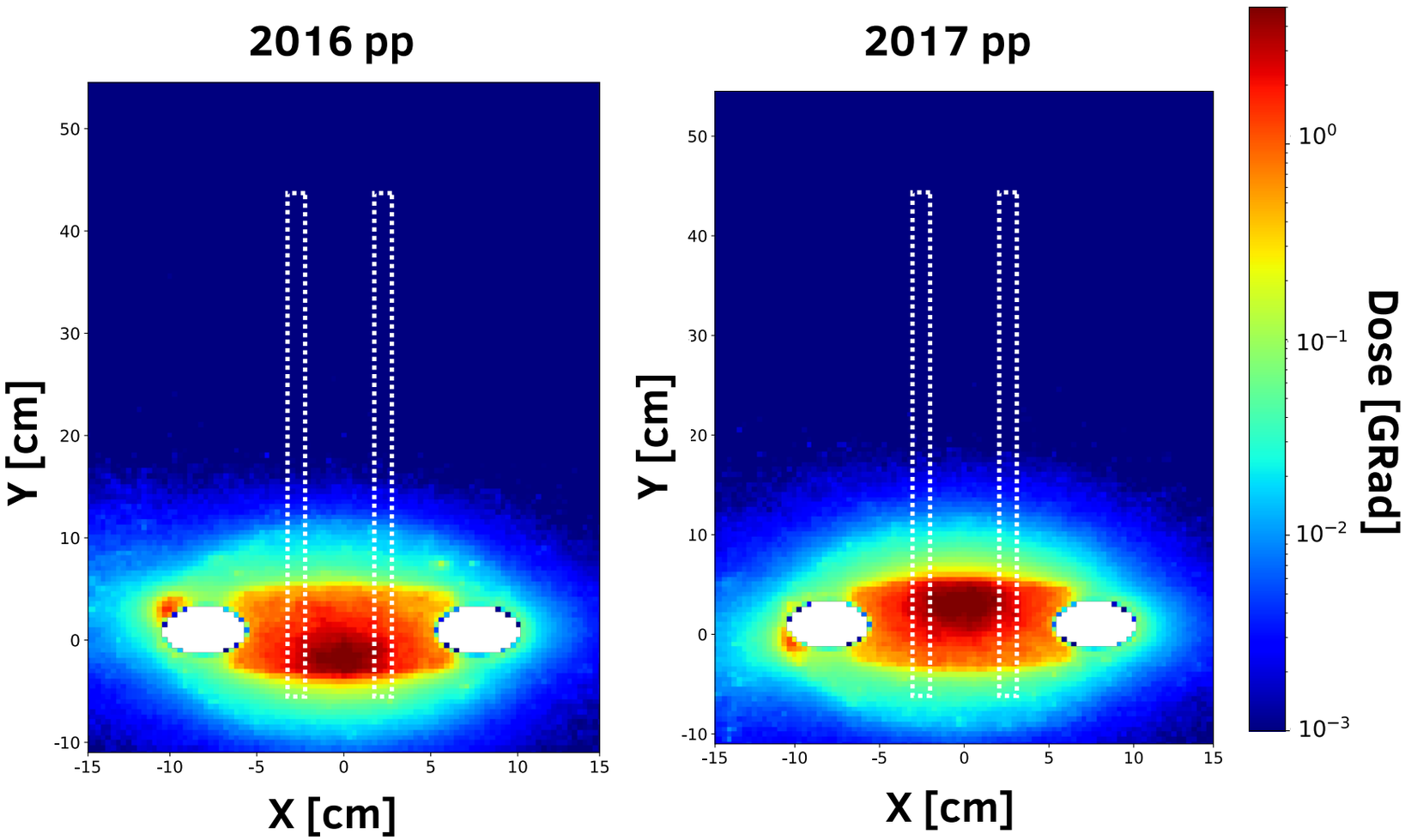
FLUKA SIMULATION OF RUN2 RADIATION ENVIRONMENT



- FLUKA simulations of the TAN provided by the LHC simulation group
- Different simulations for 2016 and 2017-18 to take into account different beam crossing angles
- Consequences:
  - Different shower max:
    - 2016: 0.5 cm from the bottom of the rod
    - 2017-18: 4.5 cm from the bottom of the rod
  - Different damage for the same part of the rods in the two years

FLUKA SIMULATION OF RUN2 RADIATION ENVIRONMENT

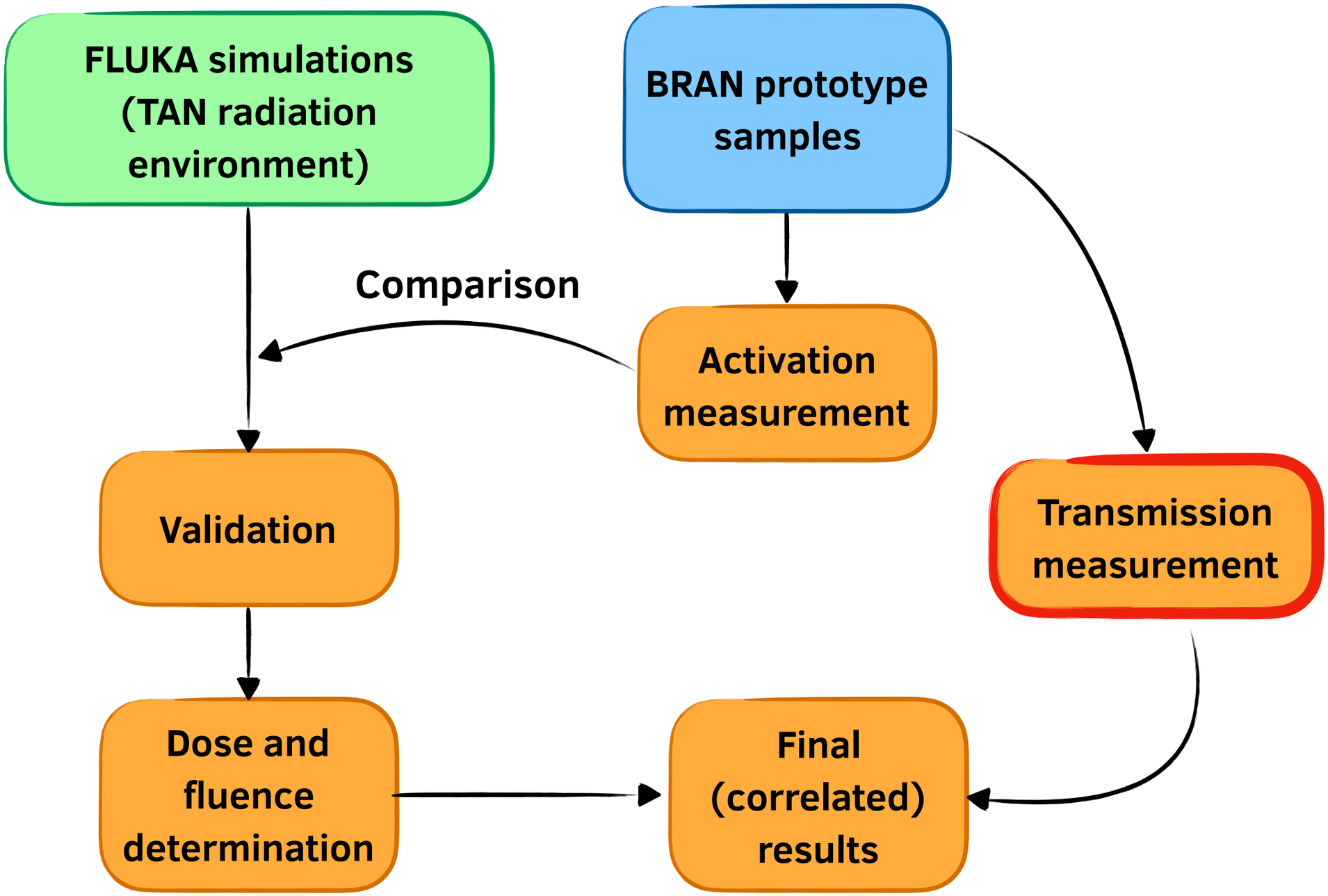
LHC *pp* total dose x-y map @ shower max (FLUKA)



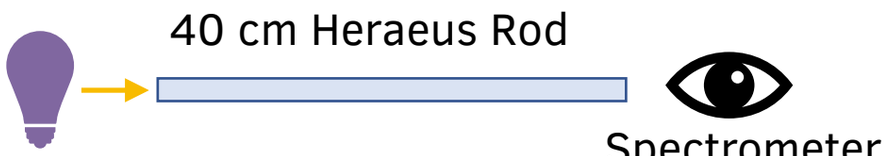
- pp Luminosity collected:
  - 2016 - 45 fb^{-1}
  - 2017 - 50 fb^{-1}
  - 2018 - 60 fb^{-1}

- FLUKA simulations of the TAN provided by the LHC simulation group
- Different simulations for 2016 and 2017-18 to take into account different beam crossing angles
- Consequences:
  - Different shower max:
    - 2016: 0.5 cm from the bottom of the rod
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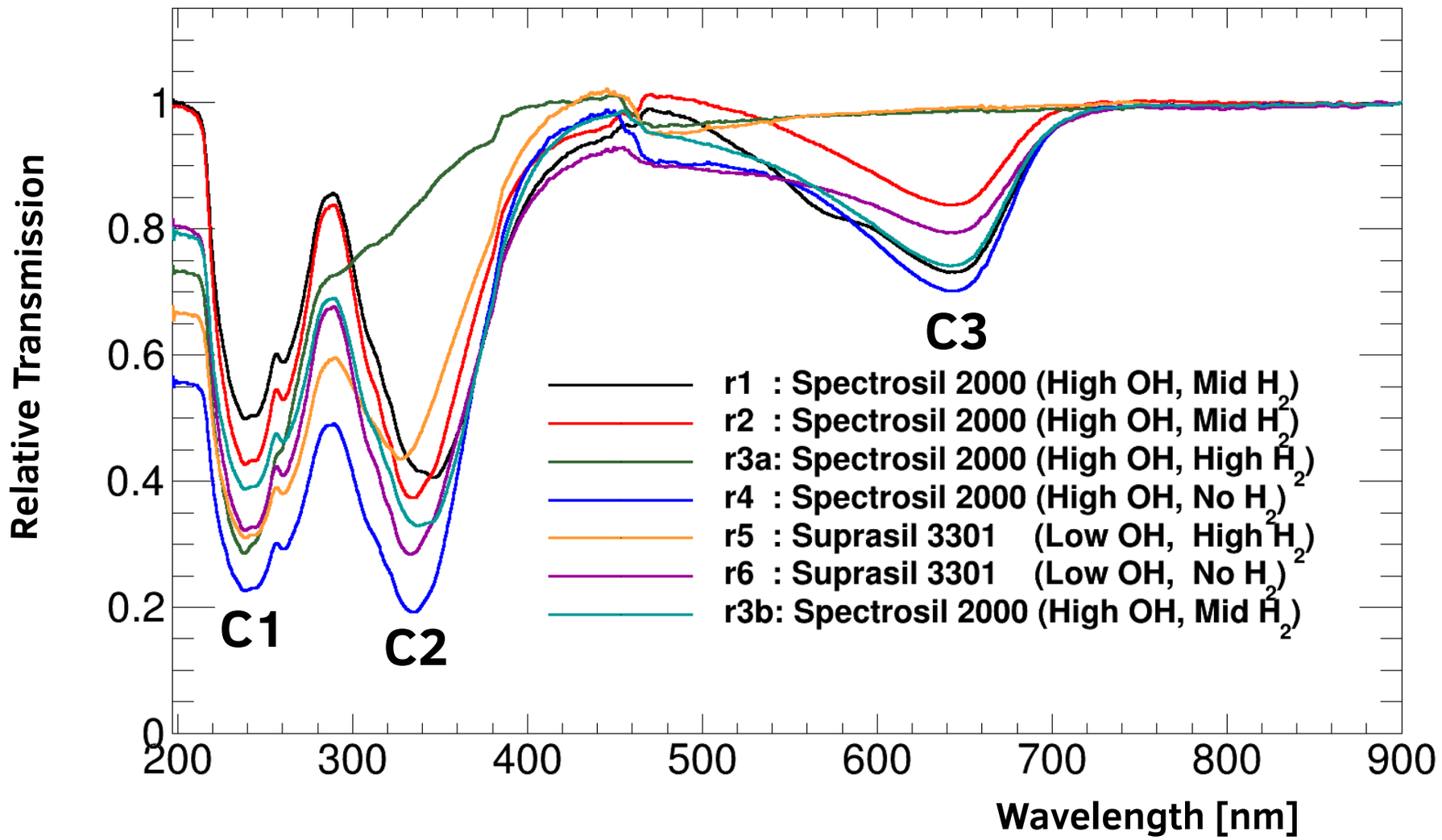
ANALYSIS BREAKDOWN



LONGITUDINAL TRANSMISSION MEASUREMENT

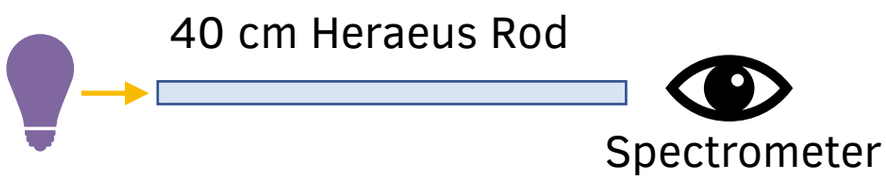


- Longitudinal transmission measurements allow to determine attenuation over similar scales relevant to ZDC and BRAN



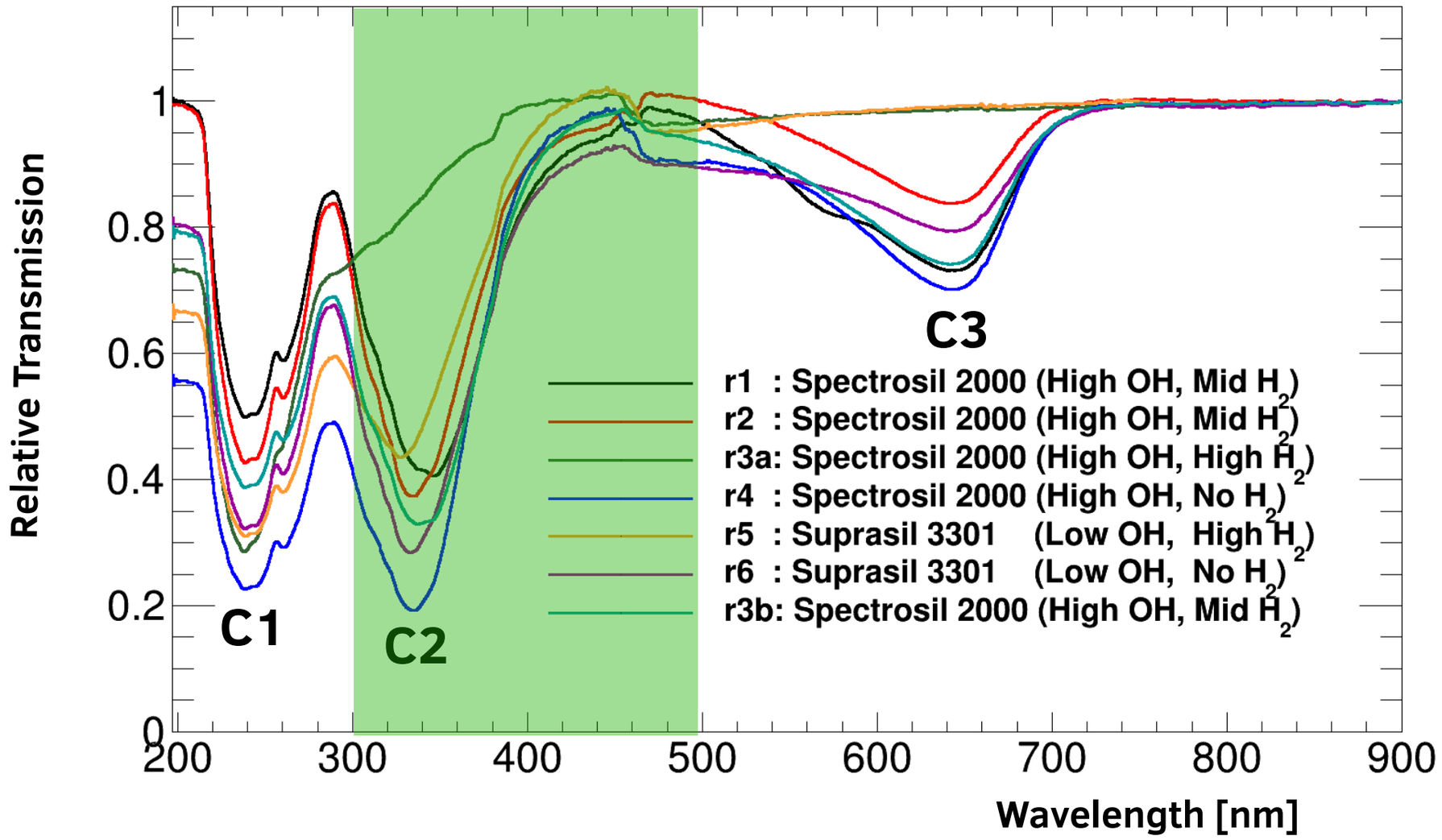
- Three main color centers observed: **C1** ~ 240 nm, **C2** ~ 310 nm , **C3** ~ 640 nm

LONGITUDINAL TRANSMISSION MEASUREMENT



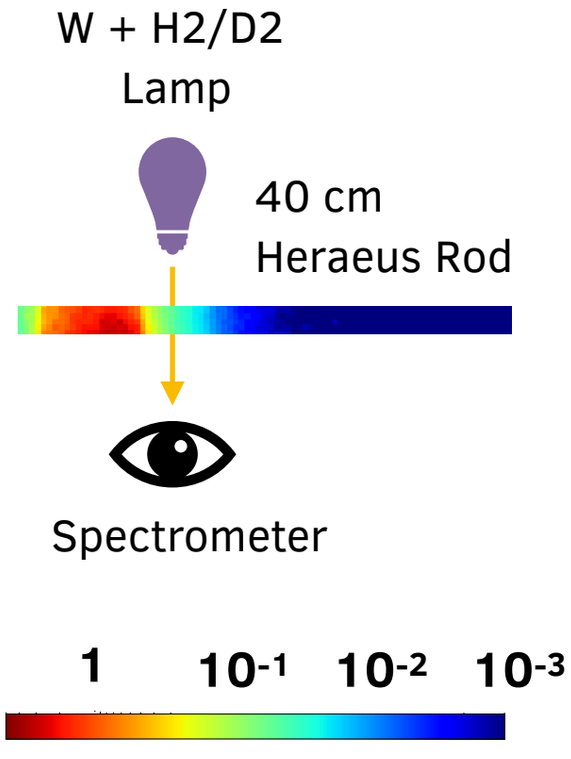
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Primary sensitivity region of the PMT [300 ; 500] nm



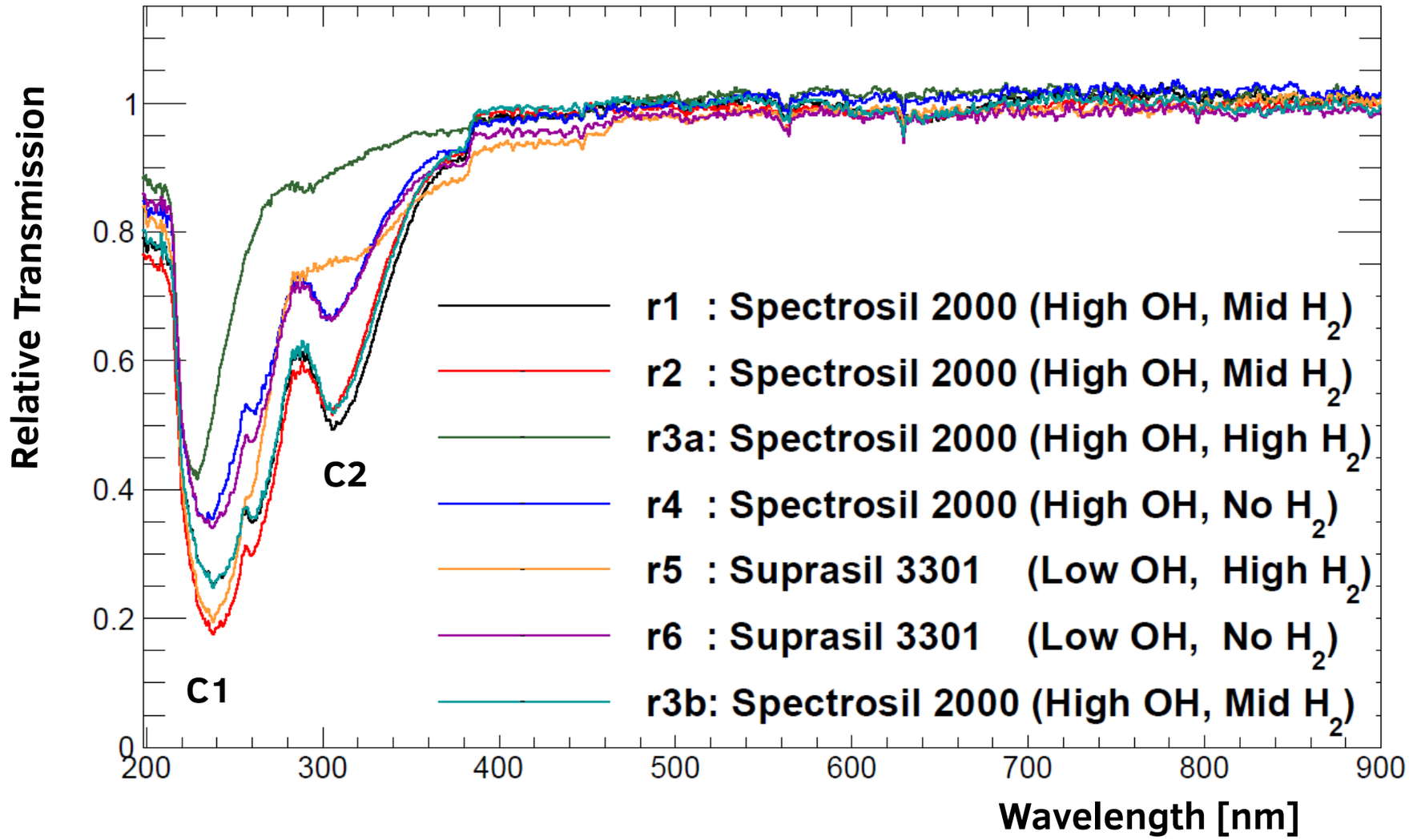
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TRANSVERSE TRANSMISSION MEASUREMENT

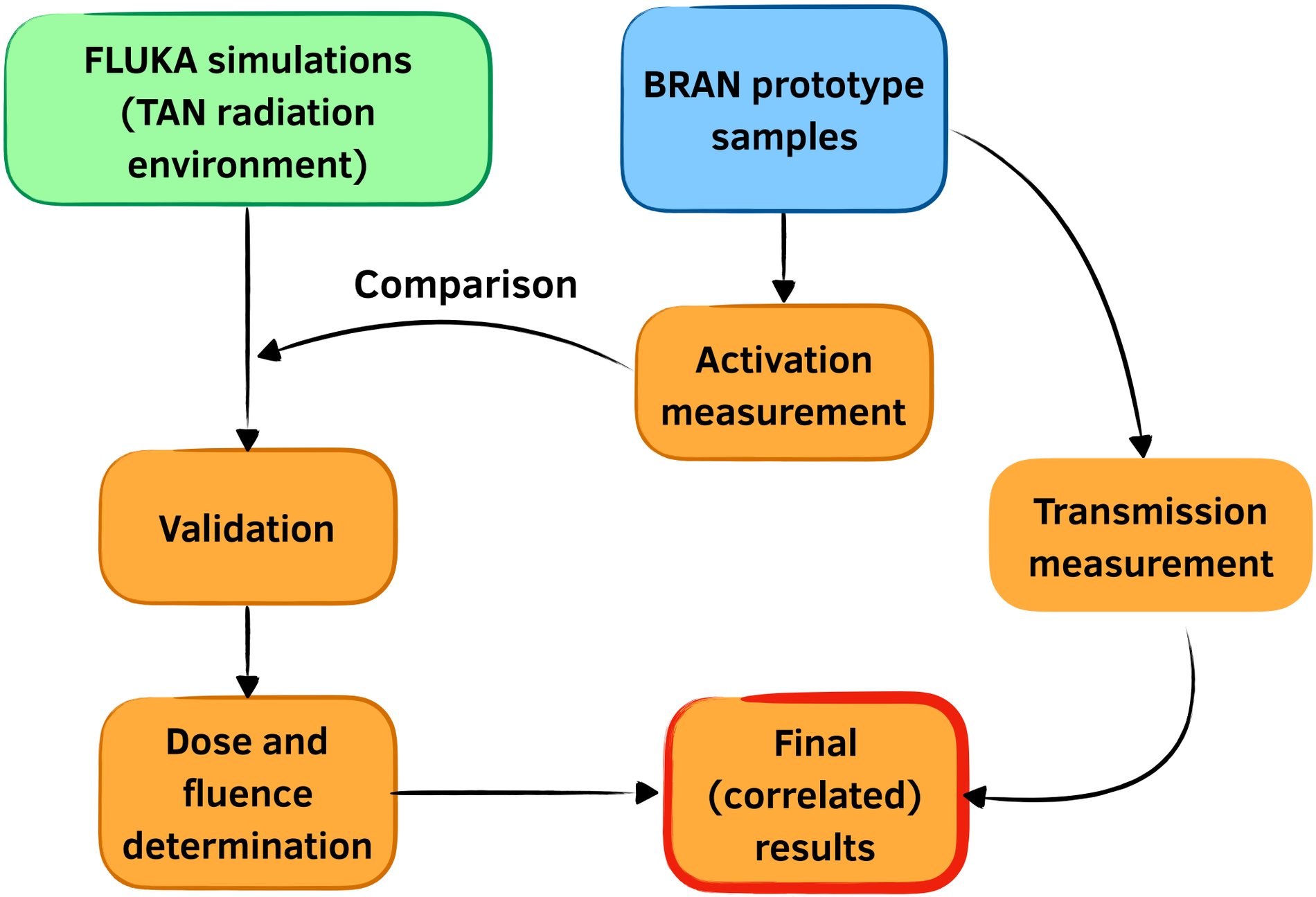


- Two color centers observed:
  - **C1** ~ 240 nm
  - **C2** ~ 310 nm
- Further studies on the path length dependence require cutting the rods

- Characterization of transmission loss as function of dosage/fluence (dose variations up to 10^4 in 40 cm)



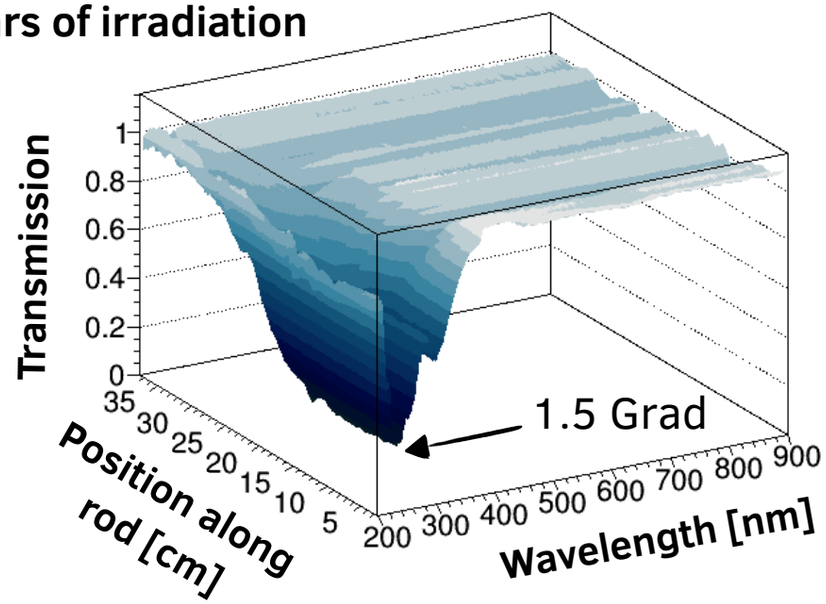
ANALYSIS BREAKDOWN



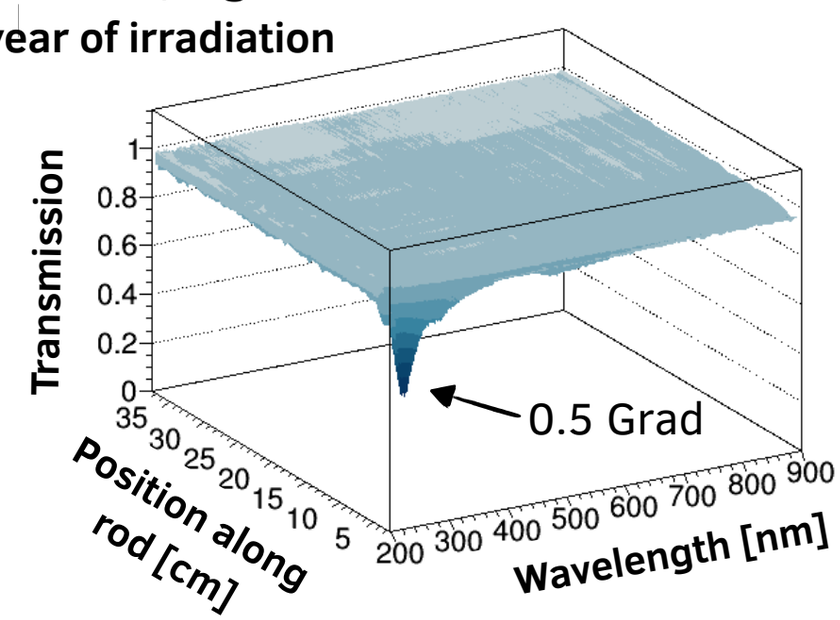
TRANSMISSION VS WAVELENGTH AND DOSE

- For each rod: transverse optical spectra measured in segments of 1 cm along the full length
- 3D map that correlates **position (<—> irradiation level)**, transmission and wavelength

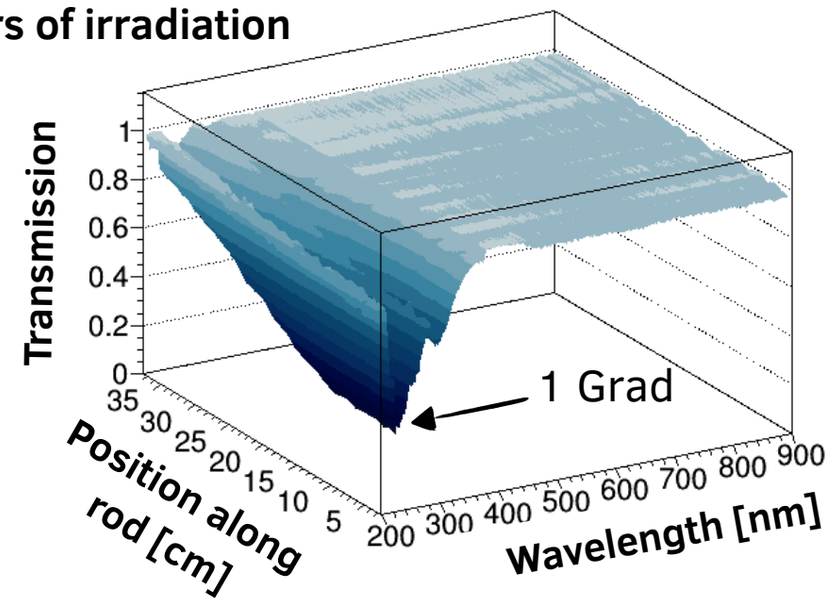
Rod 2: Spectrosil 2000, High OH, Low H_2, 2 years of irradiation



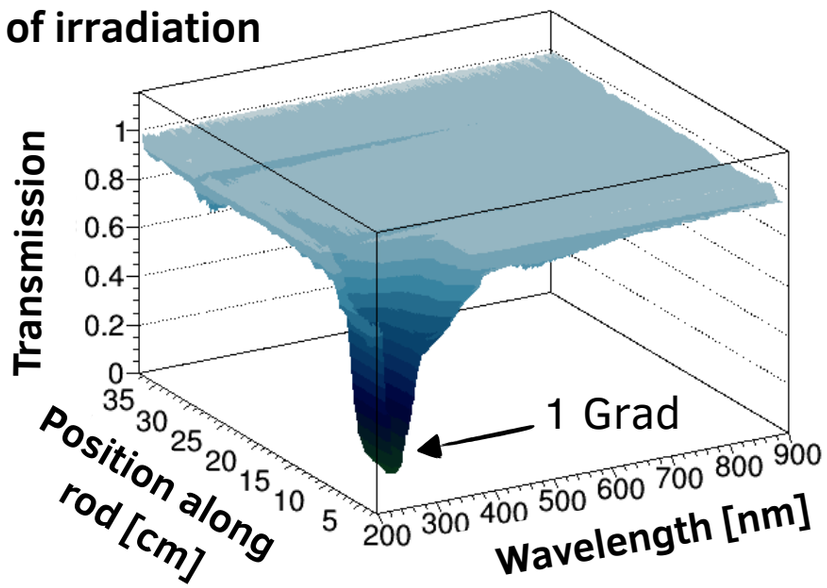
Rod 3a: Spectrosil 2000, High OH, High H_2, 1 year of irradiation



Rod 4: Spectrosil 2000, High OH, No H_2, 2 years of irradiation



Rod 5: Suprasil 3301, Low OH, High H_2, 2 years of irradiation

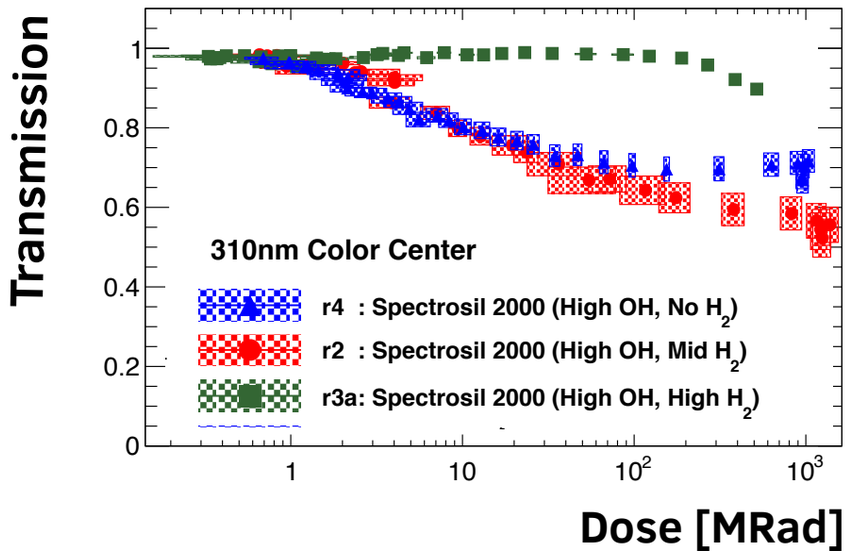


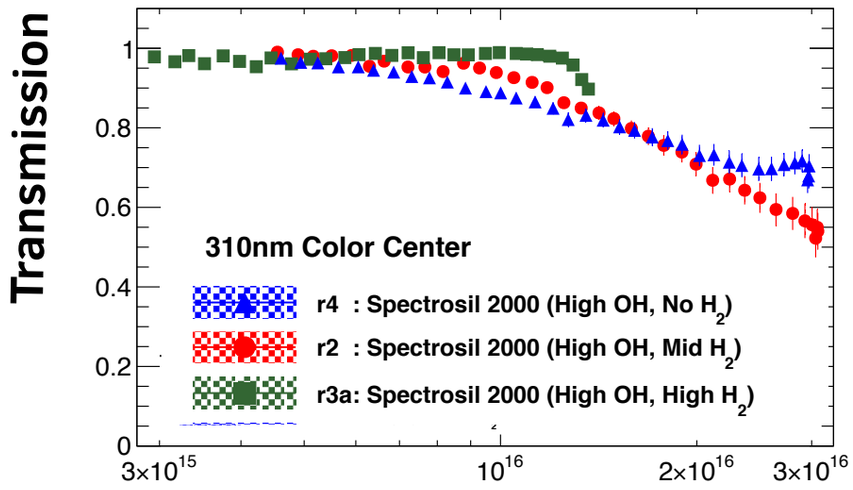
λ = 310 nm – DIFFERENT H_2 LEVEL

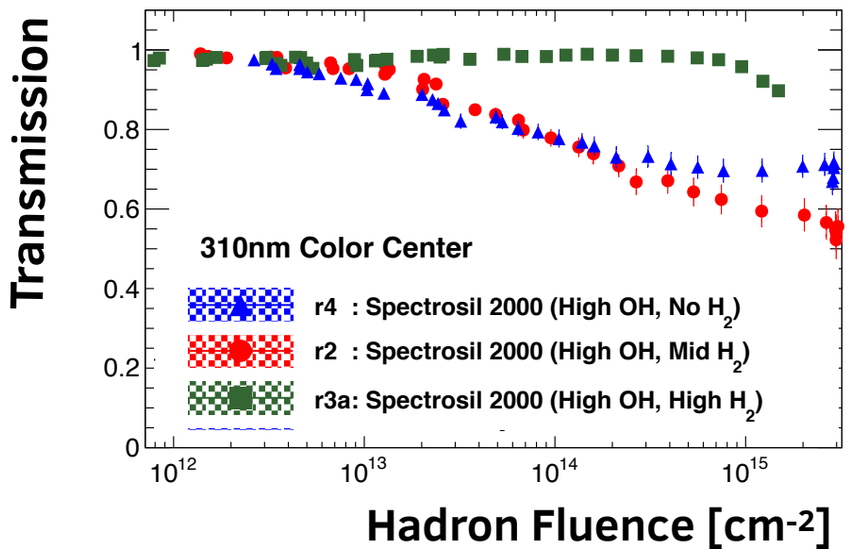
- Self-repairing effect observed with increasing H_2 concentration
- Hints for a cut-off of this effects (lack of H_2?)
- H_2 free rod shows initial loss but stable plateau above 100 MRad
- More irradiation needed to extend analysis to higher doses and confirm observed features

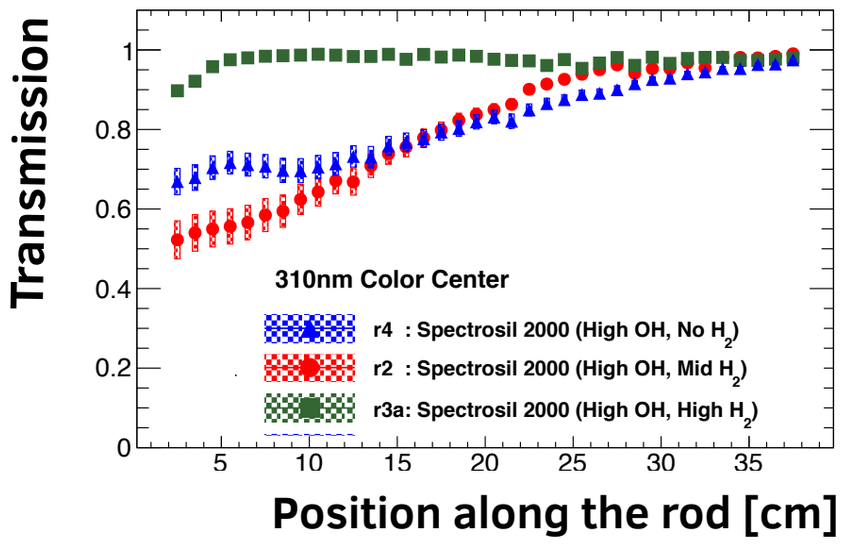
Increasing level of H_2

Rod	Irr. Period	Peak exp.	Material	H_2 [mol/cm³]	OH [ppm]
4	04/2016 - 12/2017	1 Grad	Spectrosil 2000 (High OH, H2 free)	0	1011
2	04/2016 - 12/2017	1.5 Grad	Spectrosil 2000 (High OH, Mid H2)	7.20e17	1120
3a	04/2016 - 12/2016	0.5 Grad	Spectrosil 2000 (High OH, High H2)	2.80e18	1000









PLANS FOR FURTHER IRRADIATION TESTS

- Ongoing arrangements with different laboratories / nuclear reactors to **further irradiate segments of the rods** and instrumentation components (connectors, cables)

- n
  - n flux ~1.9*10^{10} cm^{-2} s^{-1}
  - ~ 0.05 MRad/hour
- γ
  - Secondary γ
  - ~ 2 MRad/hour

- n
  - n flux ~2.5*10^{13} cm^{-2} s^{-1}
  - ~ 0.1 GRad/hour
- γ
  - Secondary γ
  - ~ 0.1 GRad/shift

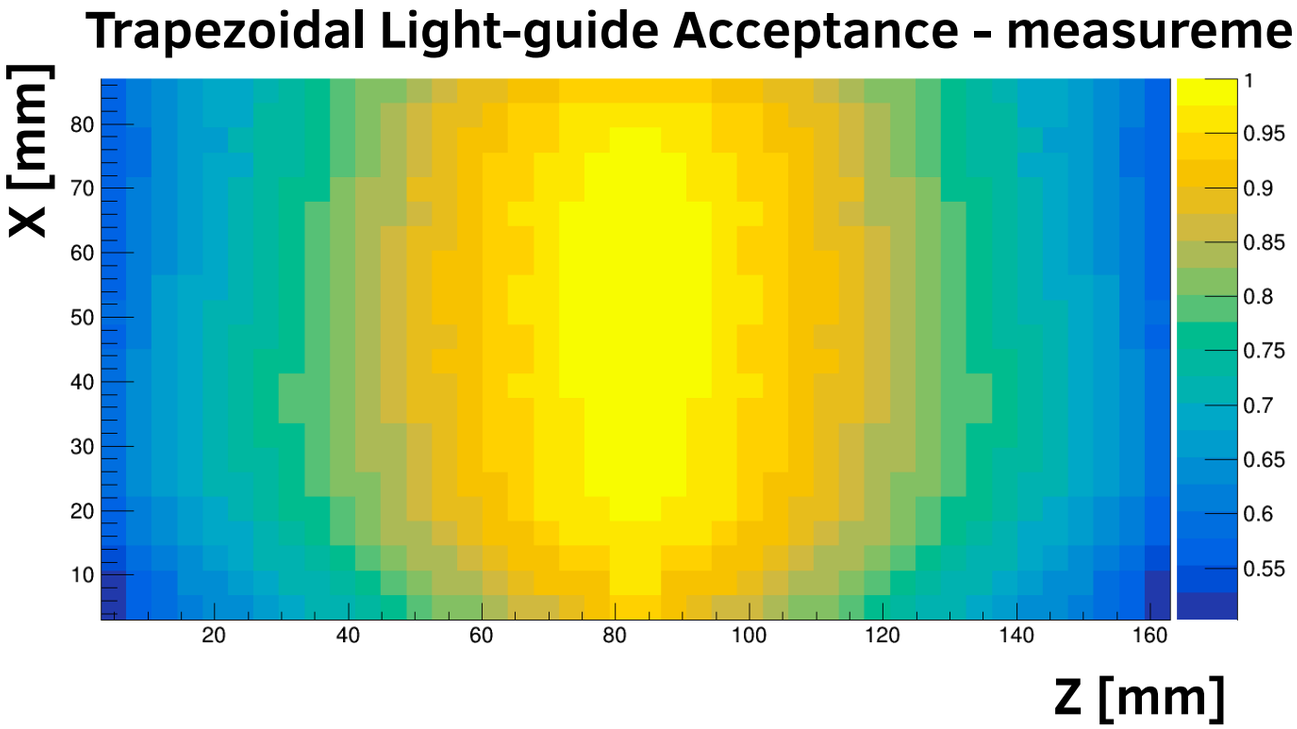
- 3 MeV Van de Graaff accelerator
- e$^-$
  - Up to ~0.6 GRad/hour
- γ
  - ~ 1.3 MRad/hour

- Study of radiation damage induced by different types of radiation (except of charged hadrons)
- Increase irradiation a few Grad (3-4) to extend the investigation of the transmission degradation

LIGHT-GUIDE R&D

TRAPEZOIDAL LIGHT-GUIDE STUDIES

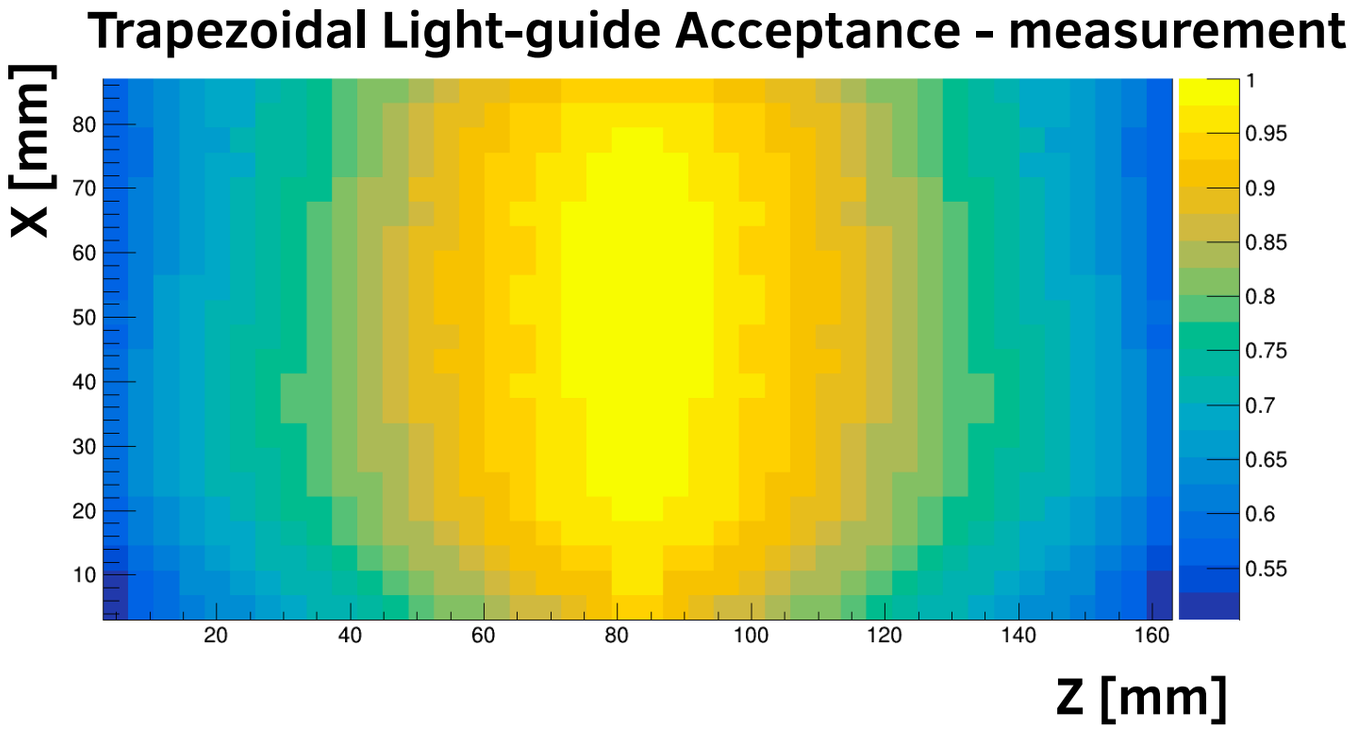
- Also the collection of the light generated in the quartz rods can be further optimized
- Measurement of relative light acceptance for trapezoidal light-guide design



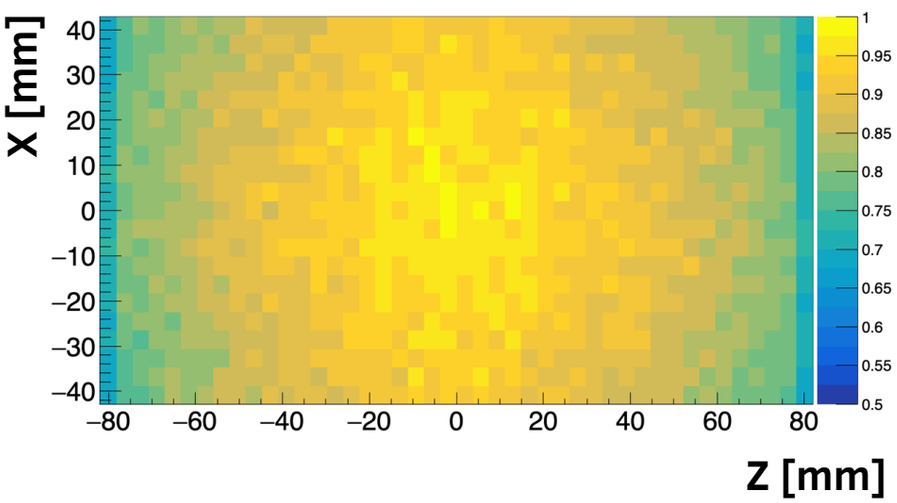
- Clear **modulation of the collected light** along the beam axis

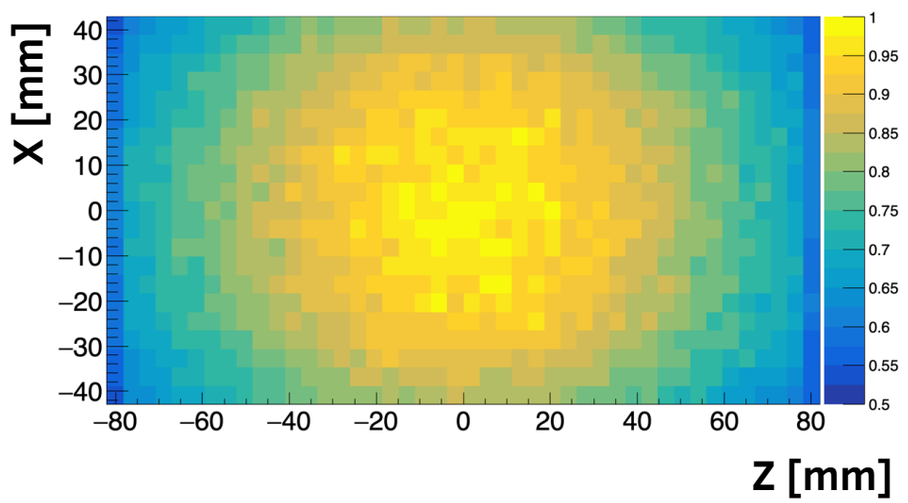
TRAPEZOIDAL LIGHT-GUIDE STUDIES

- Also the collection of the light generated in the quartz rods can be further optimized
- Measurement of relative light acceptance for trapezoidal light-guide design

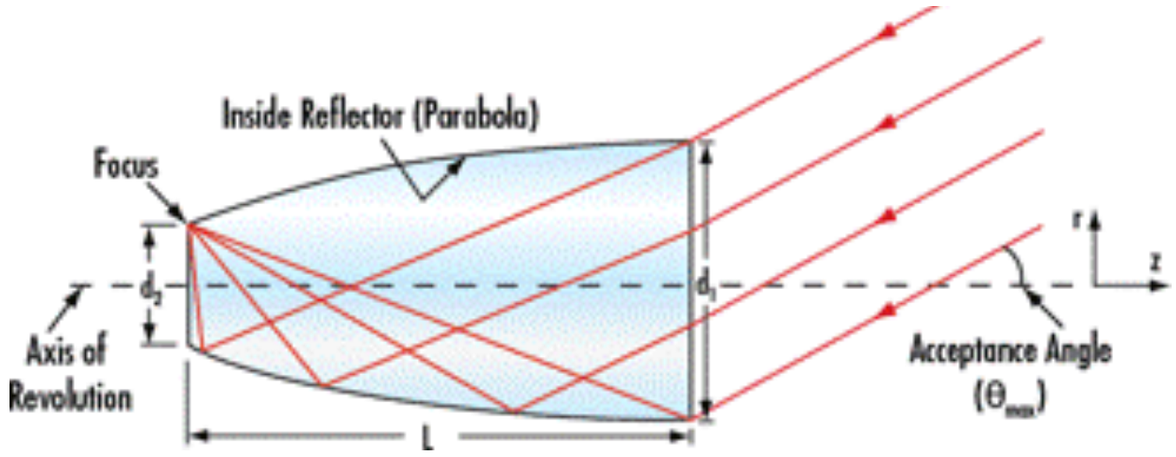


- Clear **modulation of the collected light** along the beam axis
- GEANT4 simulations carried out to evaluate performances of different light-guides
- Trapezoidal light-guide simulated to validate GEANT4 results
- Level of polishing of the internal mirror affects the light-acceptance results





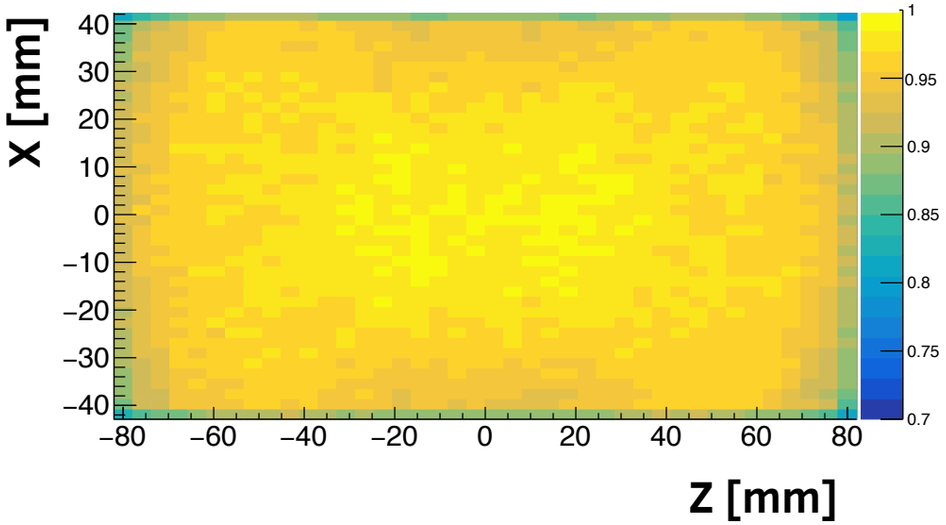
WINSTON CONE LIGHT-GUIDE



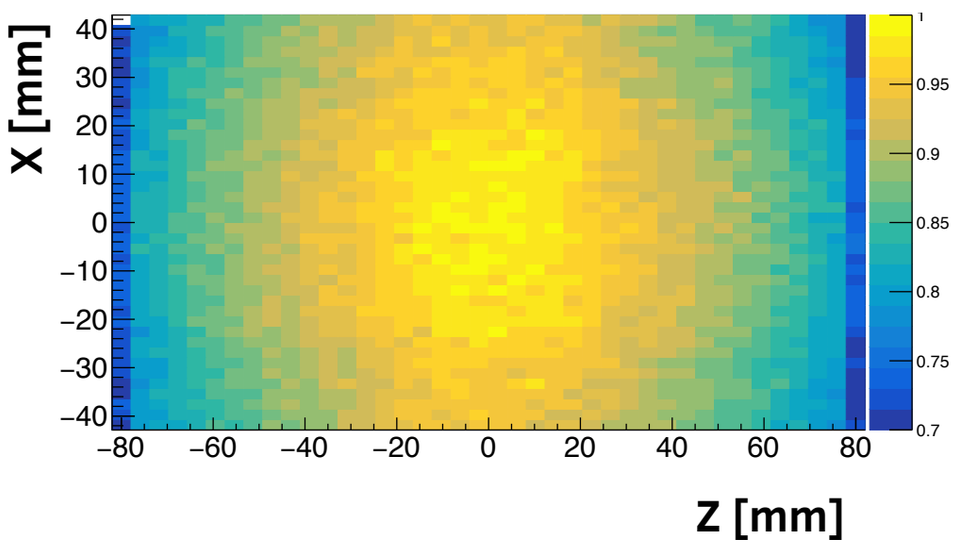
$$\sin\theta_{max} = \frac{d_2}{d_1} \qquad L = \frac{d_1 + d_2}{\tan\theta_{max}}$$

- Winston cone shaped light guide to improve light acceptance and **uniformity** of the light collection
- Length fixed by the aperture of the two extremities

Winston Cone Light Acceptance



Trapezoidal Light-guide Acceptance



- Different machining options being evaluated to produce a Winston Cone
- Simulation results show interesting **improvements** wrt trapezoidal-shape, in particular in **uniformity along the beam direction**.

EM MODULE AND RPD

RUN3 UPGRADED ZDC: EM MODULE

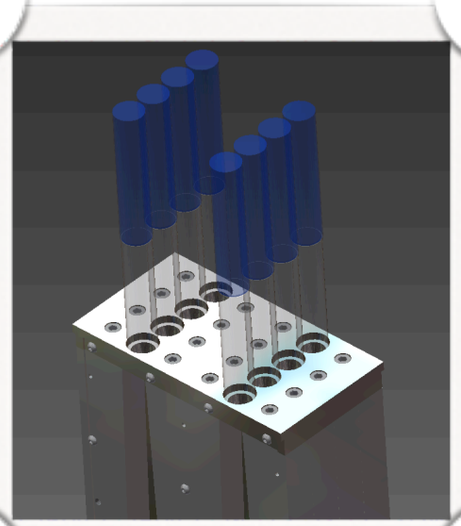
- **Segmented design**: 4 segments in x, 2 in z.
- Small (Run4 like size) prototype tested during July test-beam @ Fermilab.
- Different sampling ratio were tested. Data analysis ongoing @ KU.



EM module
2 mm sampling



EM module
4 mm sampling



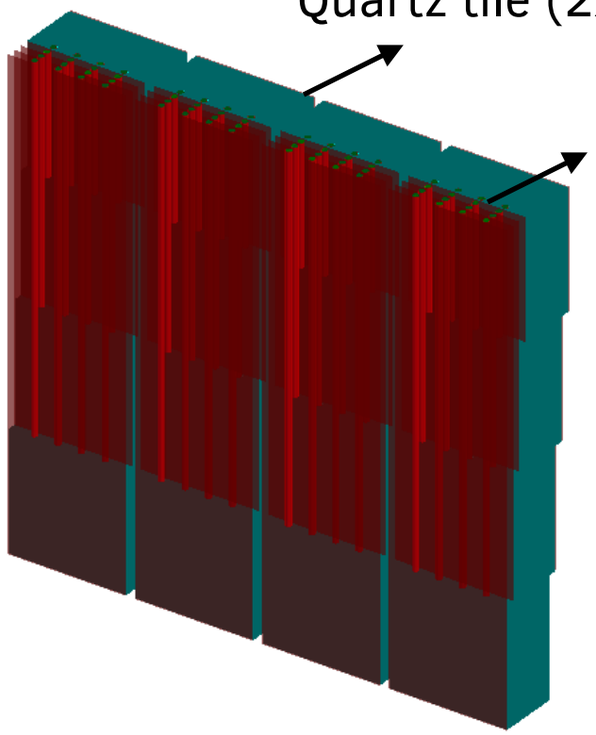
Segmented PMT readout



Light-guides of two z-segments

- The detector will be equipped **Radiation-hard fused silica rods**
- **Winston Cone light-guides** will be tested in 2020 test beam
- Final design for Run3 under discussion

REACTION PLANE DETECTOR

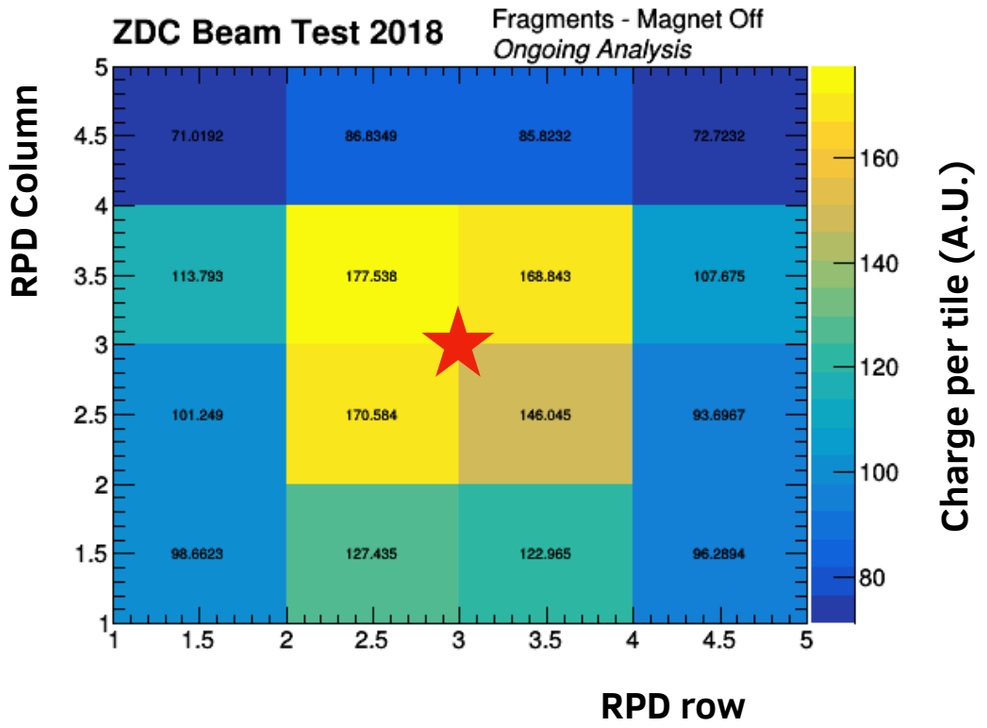


RPD - 2018 Test beam and CMS 2018 HI run configuration

- 4 x 4 array of quartz tiles (16 readout channels)
- Background signal induced in the WLS fibers running behind other tiles
- WLS fibers currently not radiation hard
- Dimensions 8.5 x 8.5 x 1.5 cm³
- Experience: CMS 2018 HI data analysis & SPS Test beam

RPD analysis, 2018 Test Beam data

Beam position denoted by the red star ★



- Different designs considered
- **Final implementation with radiation hard materials**
- Coupled with a segmented EM allows one to reconstruct the reaction plane in a different rapidity range wrt the flow measurement

See also talk by E. Adams

SUMMARY

- A Joint R&D effort between **ATLAS** and **CMS** is currently ongoing to build a new **radiation-hard ZDC** for **Run3** and **Run4**
- Interested in **collaborating** with other experiments (j.zdcrd@cern.ch)
- **Fused Silica** rod samples irradiated by the CERN **BRAN** group in the LHC during Run2 represent a unique input towards the understanding of radiation hardness of the material
  - H_2 rich fused silica better for applications up to ~1 GRad
  - H_2 free fused silica shows initial loss but stable plateau above 100 MRad
- **Further irradiation tests** are scheduled in the near future at different facilities to extend the range of our observations
- A **Winston Cone** light guide seems to considerably improve the uniformity of the light collection along the beam axis
  - Different machining options are being evaluated - prototypes will be built
- Run3 detector planned to be built using radiation-hard rods and including an **RPD** for each arm

JZCAP PEOPLE & CO – THANKS !

ATLAS EXPERIMENT

Ben Gurion University
BNL
Columbia University
University of Illinois

Senior Physicists: Zvi Citron, Brian Cole, Matthias Grosse-Perdekamp, Peter Steinberg.

Post-docs: Riccardo Longo, Raveendrababu Karanam.

Grad Students: Chad Lantz, Michael Phipps, Nico Santiago, Taylor Shimek, Aric Tate, Sheng Yang.

Undergrad Students: Yuval Bashir, Xinyue Cui, Andi Mankolli, Daniel McLean, Shier Shenkar, Tiansu Zhang.

Technical Staff: Giulio Avoni, John Blackburn, Eric Thorsland.

CMS Compact Muon Solenoid

University of Kansas
University of Maryland

Senior Physicists: Michael Murray, Sorina Popescu, Alice Mignerey, Timothy Koeth.

Post-docs: Quan Wang.

Grad Students: Matthew Nickel, Eric Adams, Samuel Lascio.

Undergrad Students: Grant Bogler, Casey Butler.

Technical Staff: KU machinists.

JZCaP

Argonne NATIONAL LABORATORY

Michael D. Kaminsky

CERN **LHC simulation group**

Francesco Cerutti, Marta Sabate Gilarte

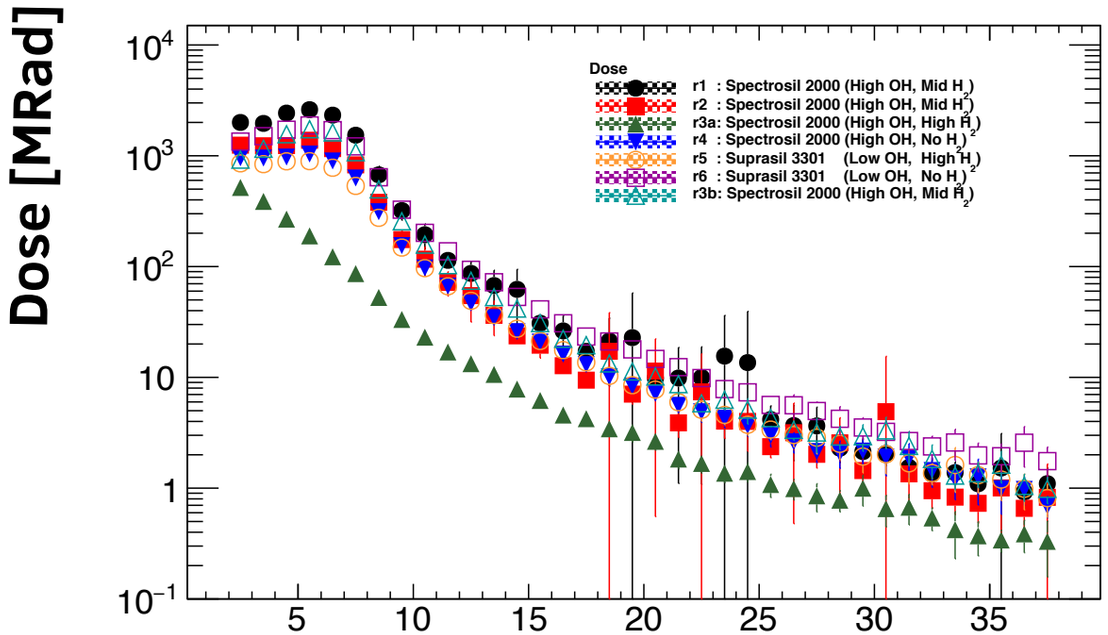
CERN **BRAN luminosity group**

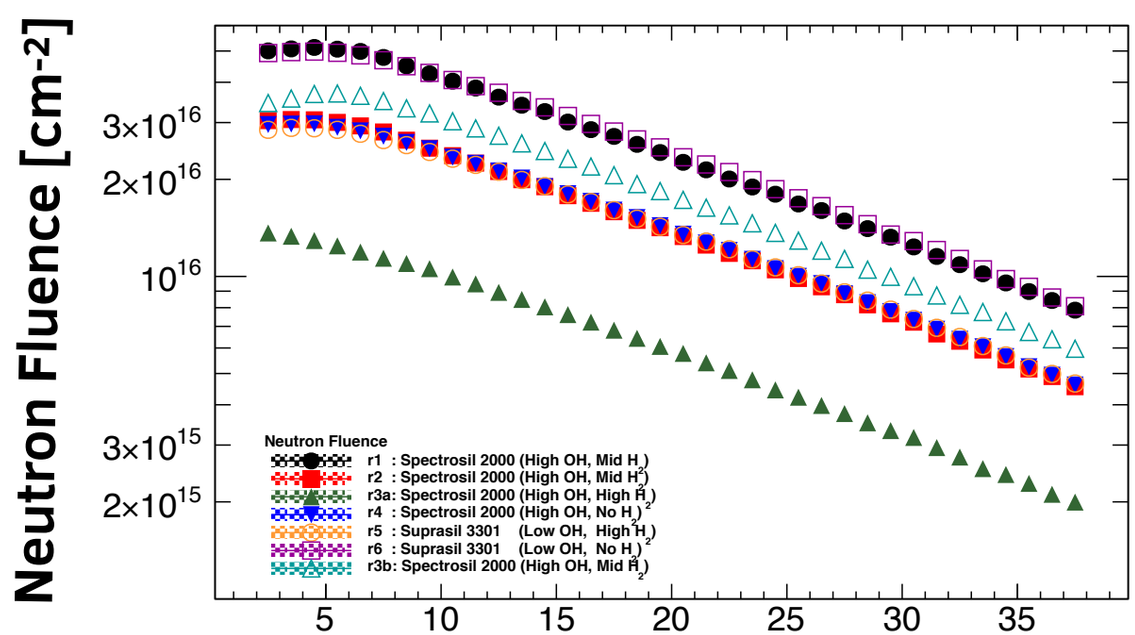
Marcus Palm, Enrico Bravin, Sune Jackobsen

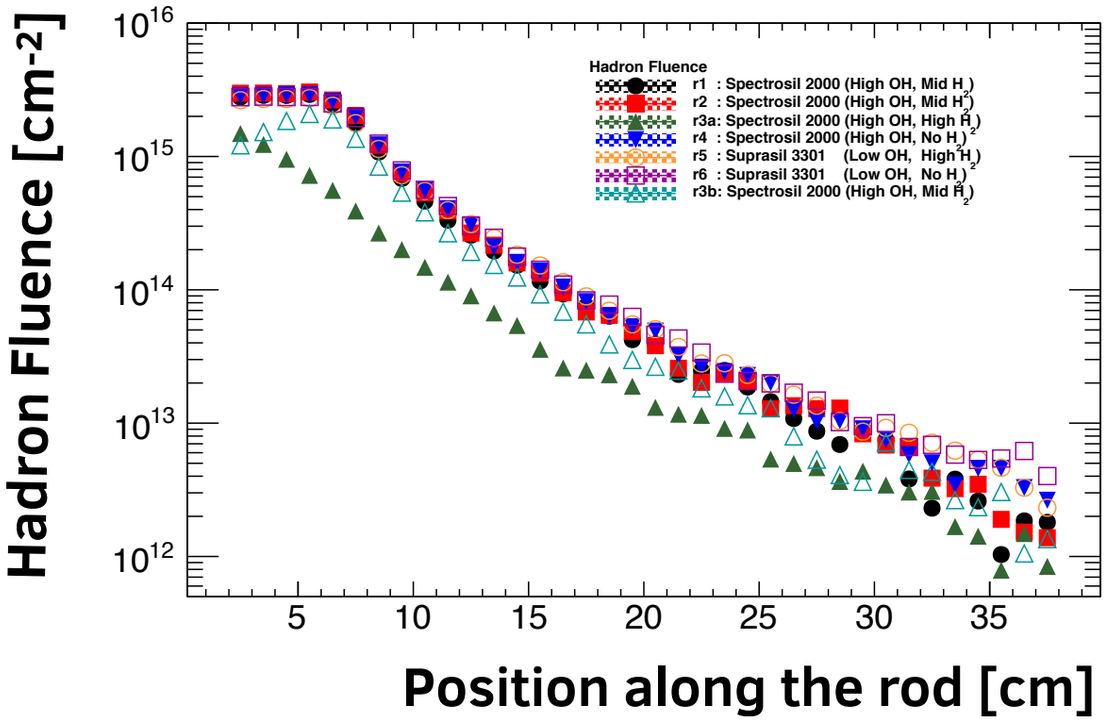
THANK YOU FOR YOUR ATTENTION!

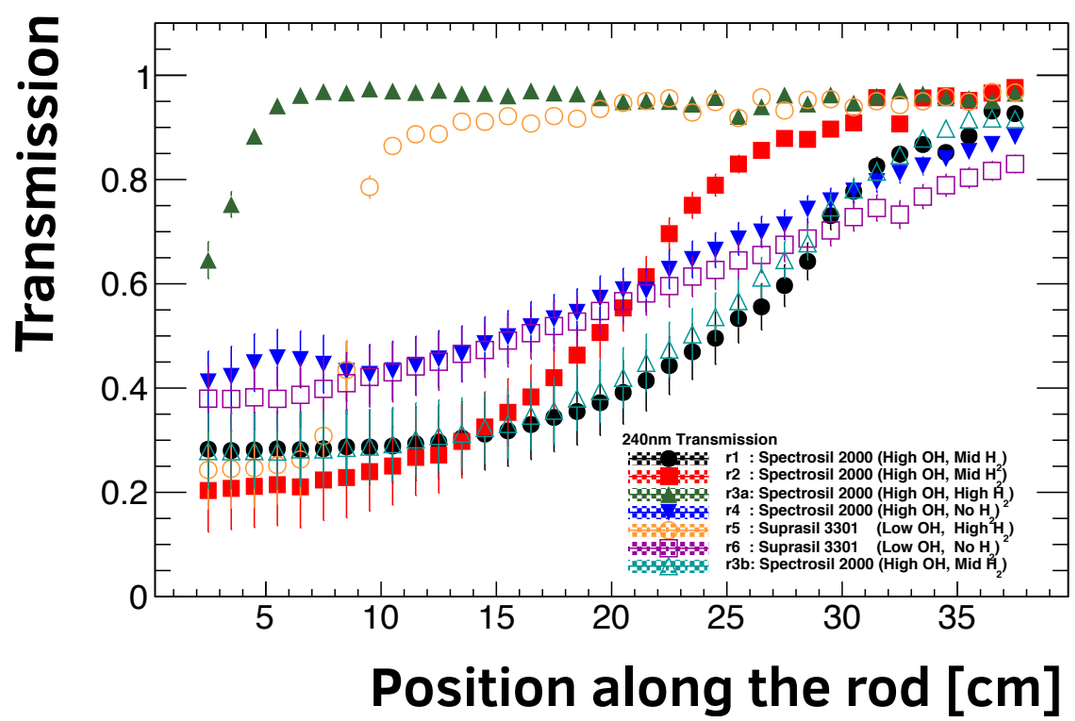
BACKUP SLIDES

FROM POSITION TO DOSE AND FLUENCE







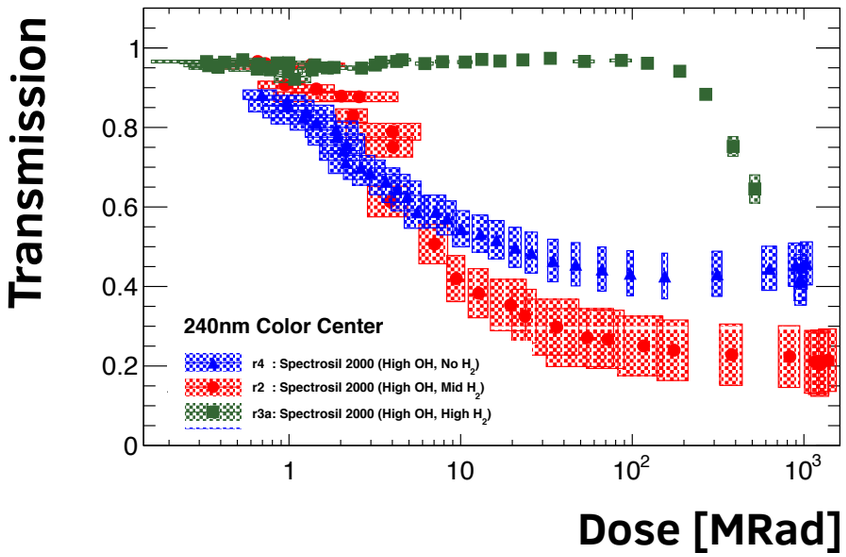


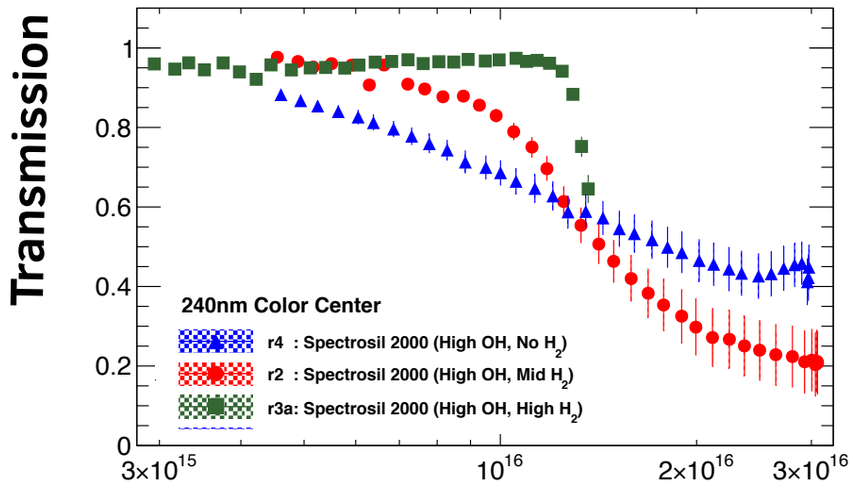
λ = 240 nm – DIFFERENT H_2 LEVEL

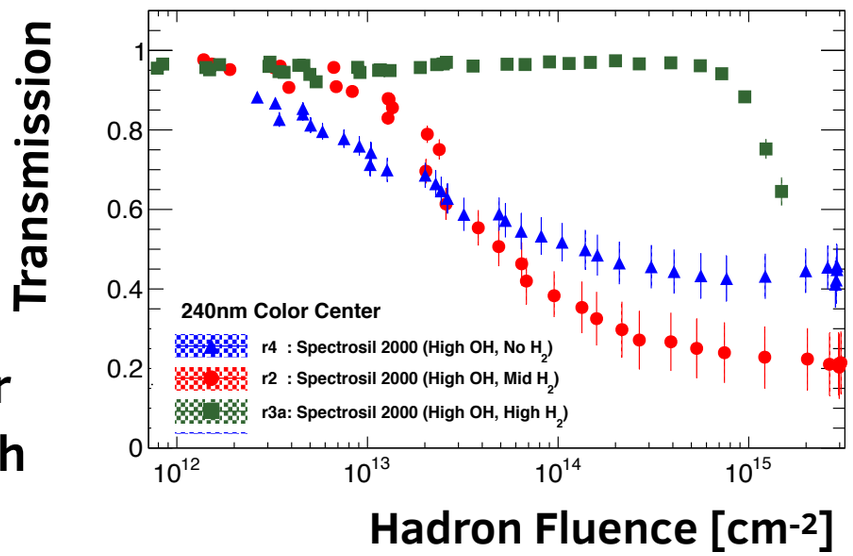
- Similar trends to 310 nm, but higher level of damage
- Transmission cut-off for high H_2 confirmed at 240 nm

Increasing level of H_2

Rod	Irr. Period	Peak exp.	Material	H_2 [mol/cm³]	OH [ppm]
4	04/2016 - 12/2017	1 Grad	Spectrosil 2000 (High OH, H2 free)	0	1011
2	04/2016 - 12/2017	1.5 Grad	Spectrosil 2000 (High OH, Low H2)	7.20e17	1120
3a	04/2016 - 12/2016	0.5 Grad	Spectrosil 2000 (High OH, High H2)	2.80e18	1000







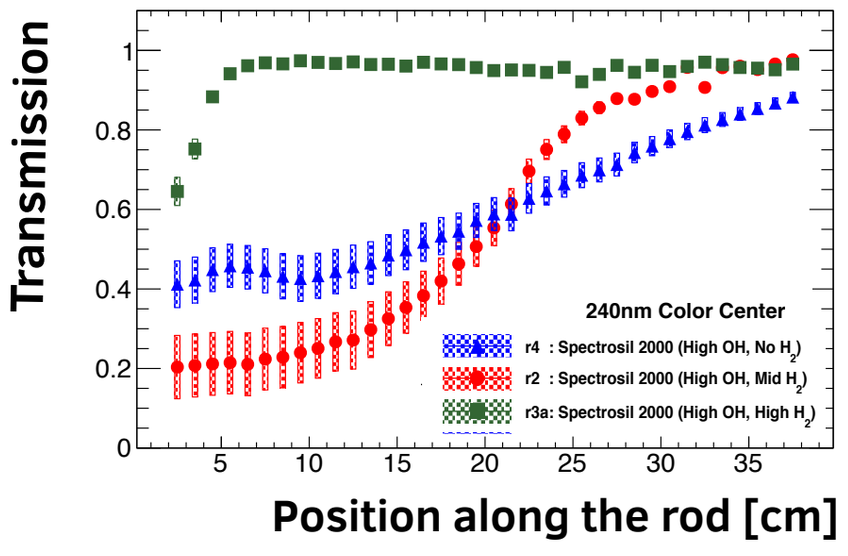


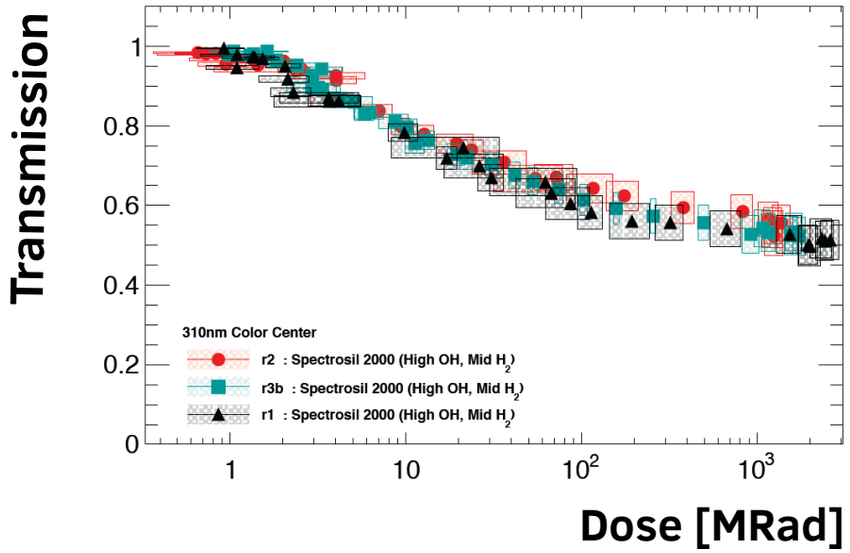
Fig.19: Transmission for λ = 240 nm for rods with different H_2 level

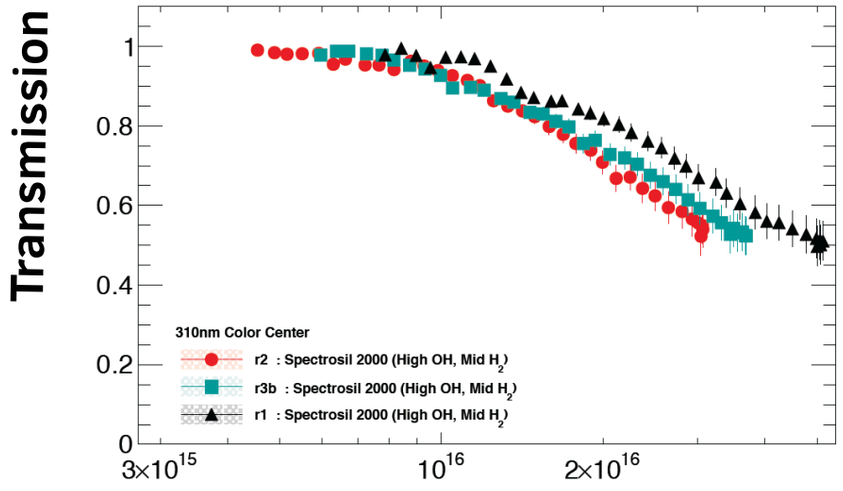
λ = 310 nm – SAME MATERIAL

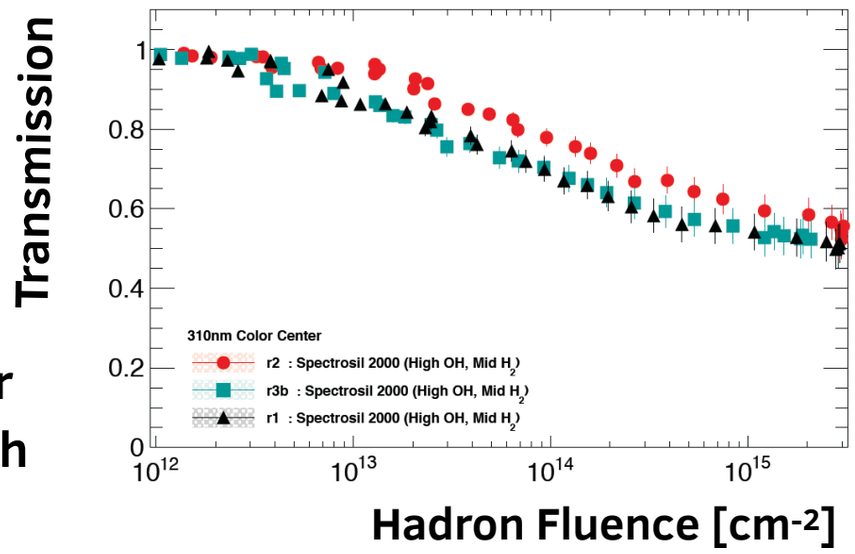
- Self-repairing effect observed with increasing H_2 concentration
- Hints for a cut-off of this effects (lack of H_2?)
- Measurement of remaining H_2 quite difficult. Different possibilities being inspected
- H_2 free rod shows initial loss but stable plateau above 100 MRad

Increasing dose

Rod	Irr. Period	Peak exp.	Material	H_2 [mol/cm³]	OH [ppm]
1	04/2016 - 12/2018	3 GRad	Spectrosil 2000 (High OH, Mid H2)	7.20e17	1120
3b	04/2017 - 12/2018	2 GRad	Spectrosil 2000 (High OH, Mid H2)	7.20e17	1120
2	04/2016 - 12/2017	1.5 GRad	Spectrosil 2000 (High OH, Mid H2)	7.20e17	1120







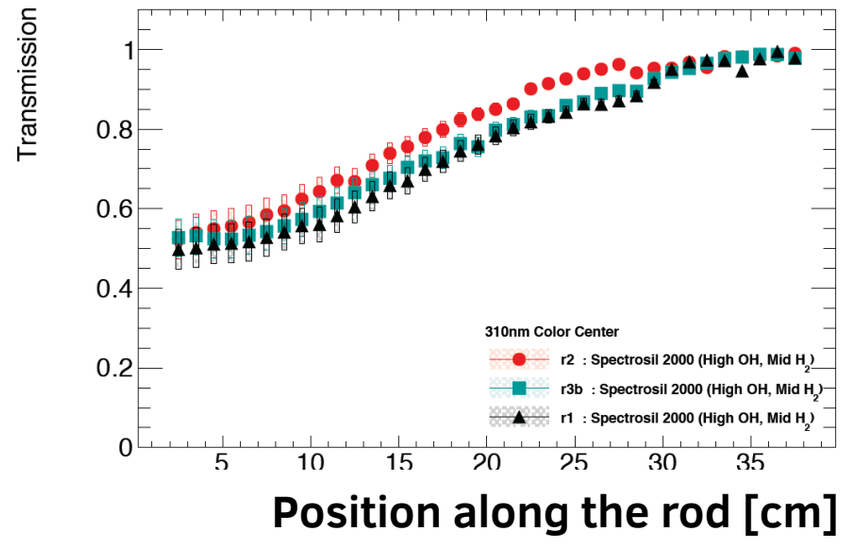
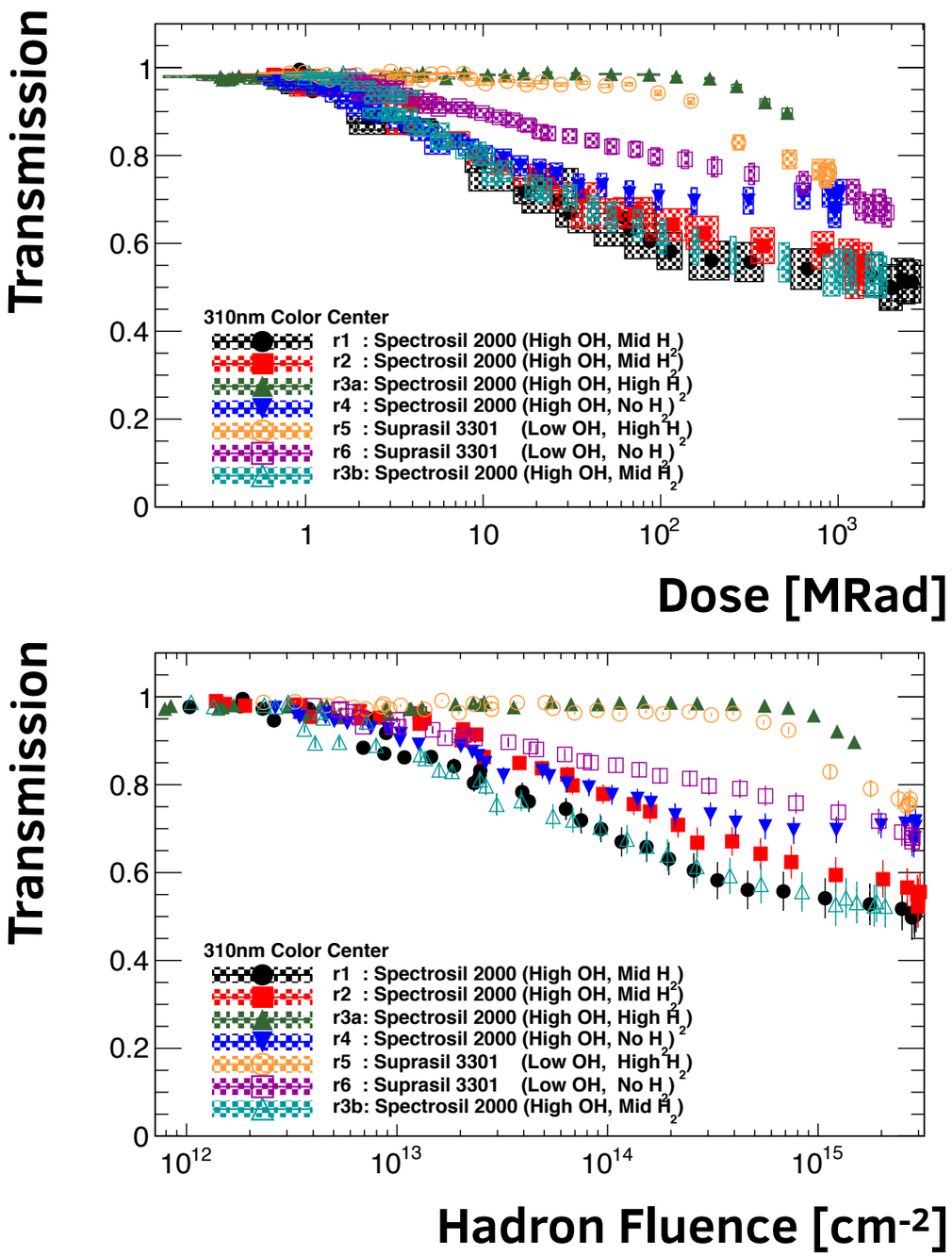
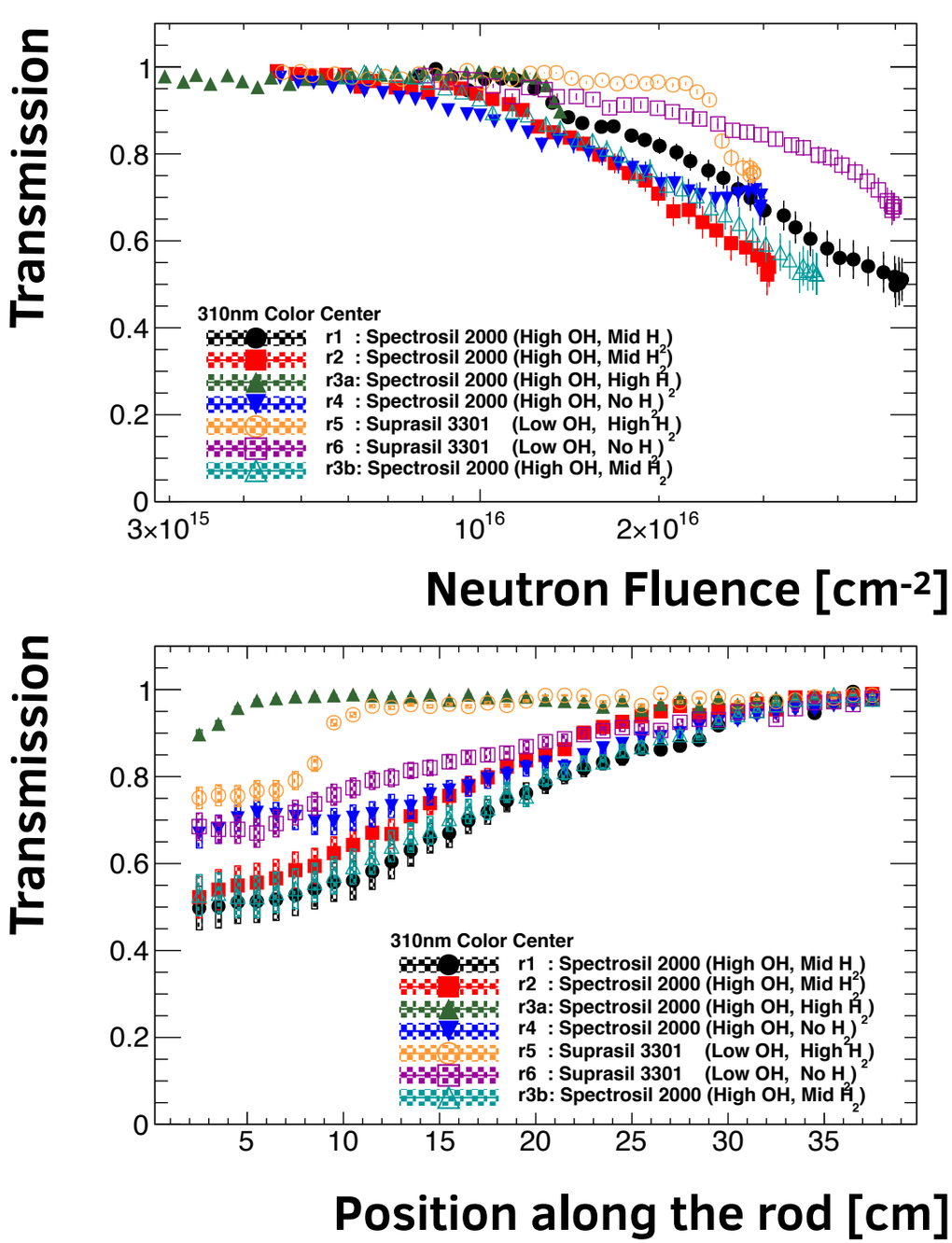


Fig.18: Transmission for λ = 310 nm for rods with different H_2 level

RESULTS: λ = 310 nm

- Using FLUKA simulations we can transform from transmission vs position along the rod to transmission vs [dose, hadron fluence and neutron fluence]





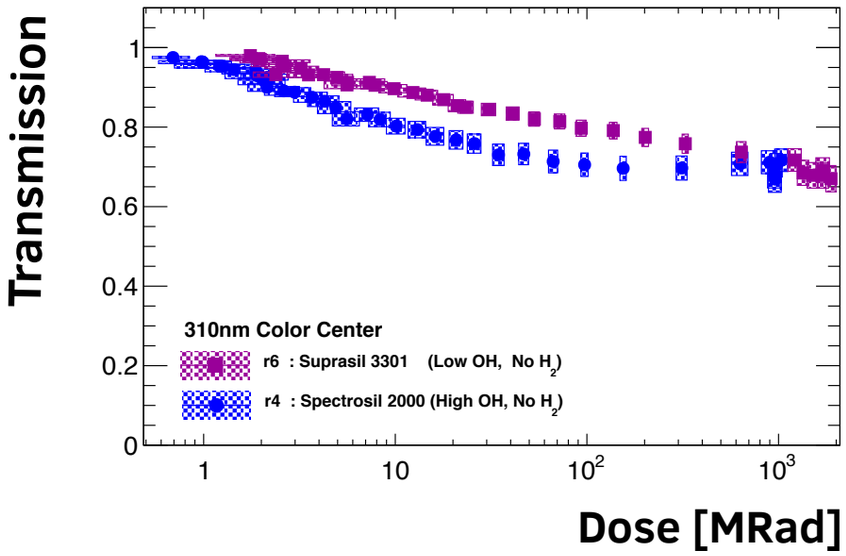
λ = 310 nm – DIFFERENT OH LEVEL

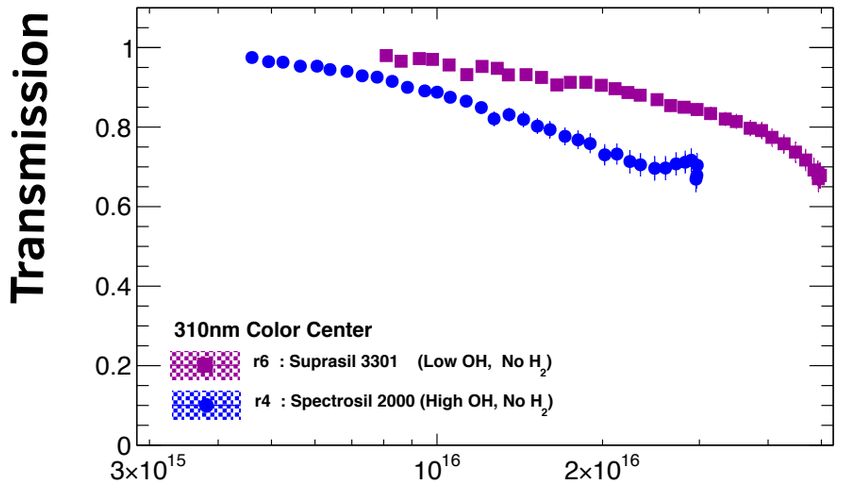
Increasing level of OH ↓

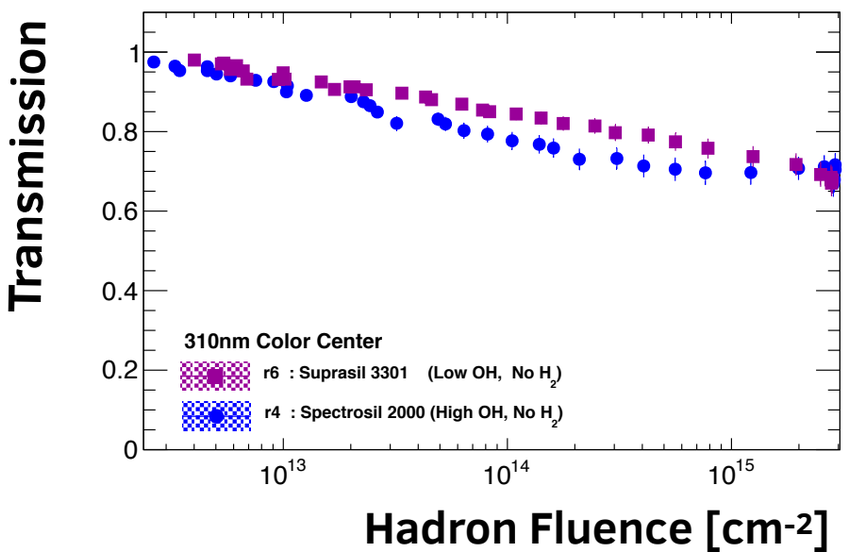
Rod	Irr. Period	Peak exp.	Material	H_2 [mol/cm³]	OH [ppm]
6	04/2016 - 12/2018	2 GRad	Suprasil 3301 (Low OH, H2 free)	0	14
4	04/2016 - 12/2017	1 GRad	Spectrosil 2000 (High OH, H2 free)	0	1011

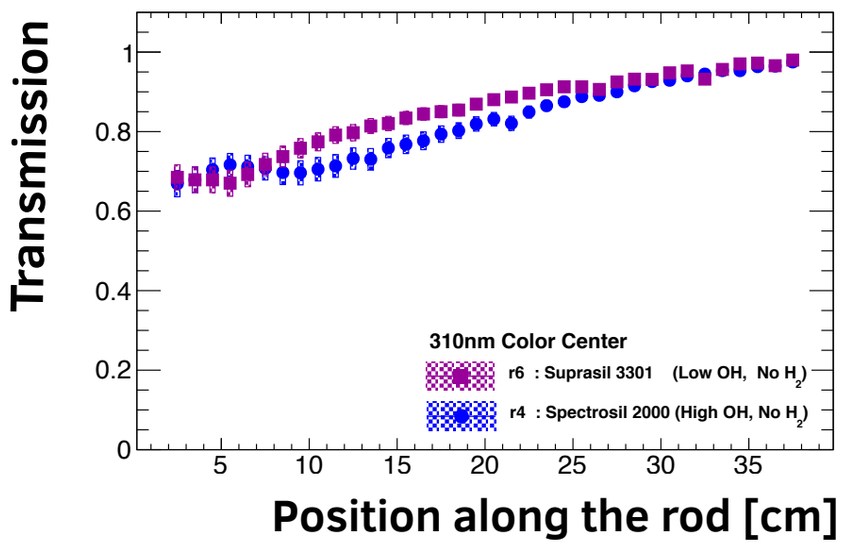
- Rod with lower level of OH shows better transparency up to 1 GRad
- Hints for crossing point around 1 GRad
- More irradiation needed to extend analysis to higher doses and confirm interesting features (e.g. plateau for

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

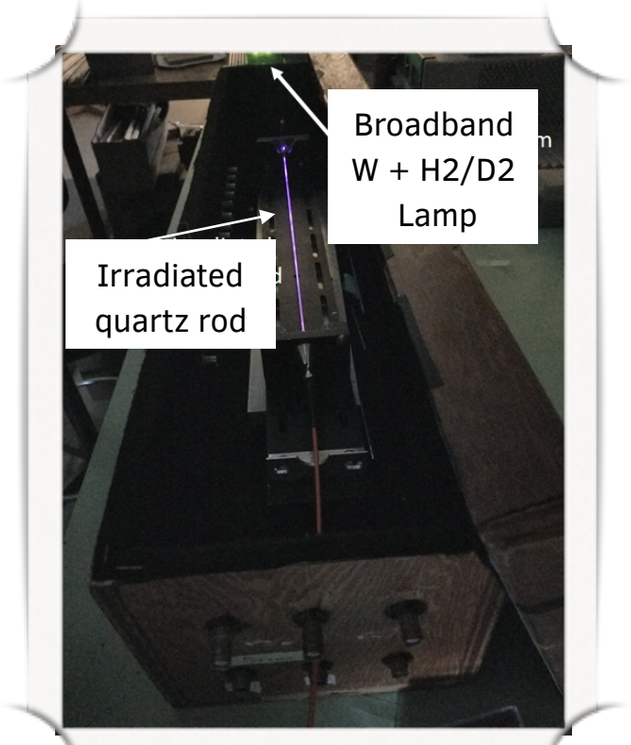


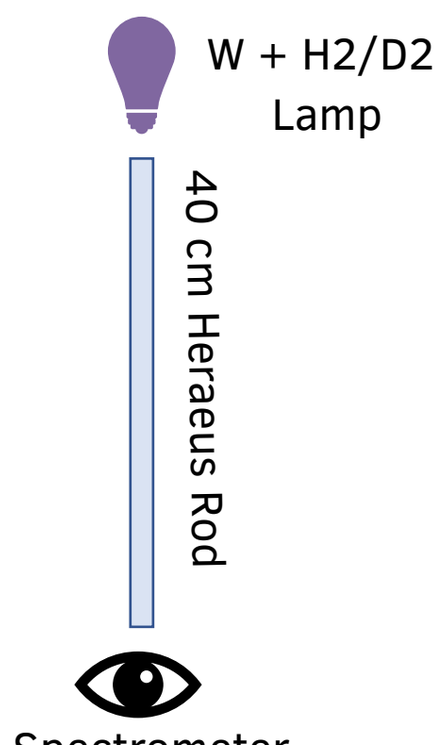






LONGITUDINAL TRANSMISSION MEASUREMENT

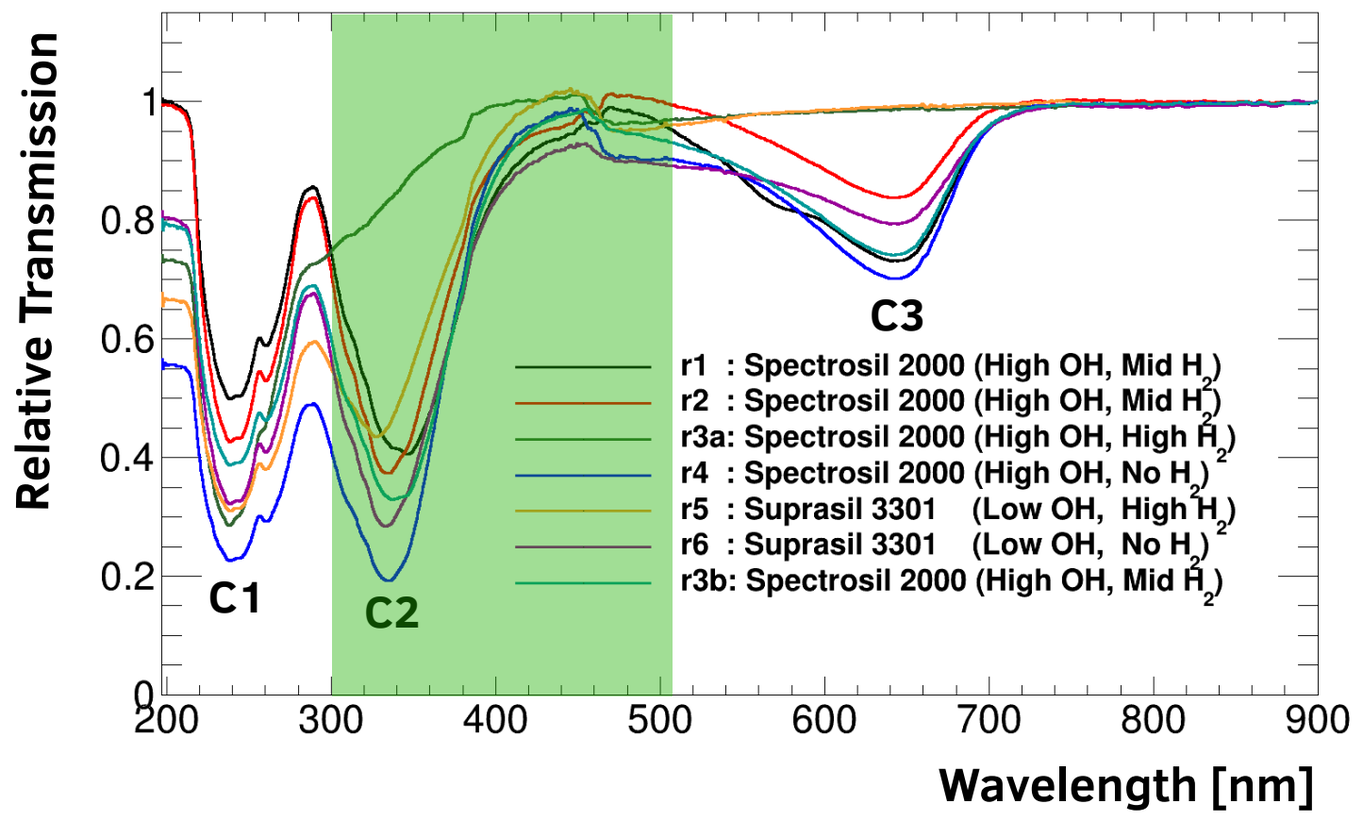




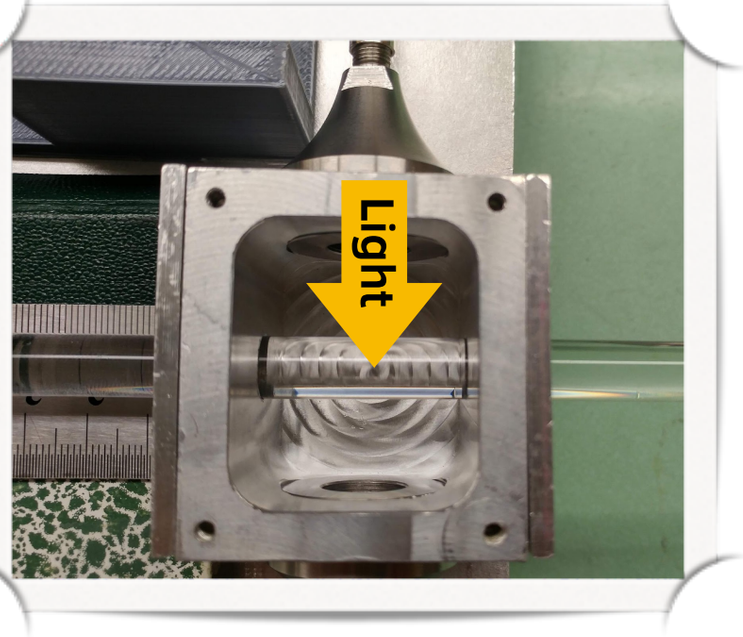
- Longitudinal transmission measurements allow to determine attenuation over similar scales relevant to ZDC and BRAN
- Tungsten-Deuterium lamp and spectrometer setup allow transmission characterization over a broad range of wavelengths (200nm - 900nm)

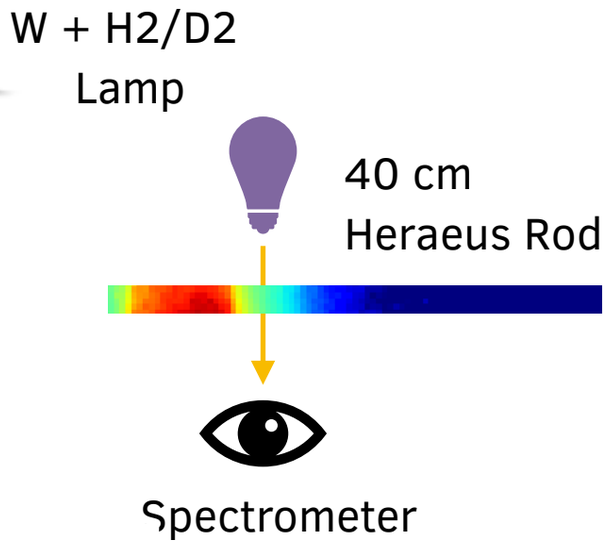
Primary sensitivity region of the PMT [300 ; 500] nm

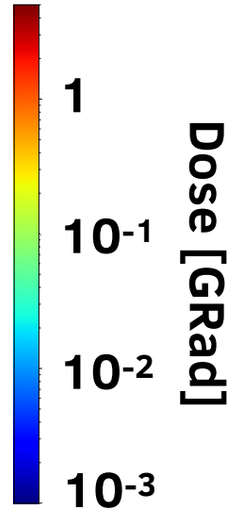
- Transmission evaluated obtaining an optical spectrum for each sample and comparing it with a non-irradiated rod (“control”)
- Three main color centers observed:
  - **C1** ~ 240 nm
  - **C2** ~ 310 nm
  - **C3** ~ 640 nm



TRANSVERSE TRANSMISSION MEASUREMENT

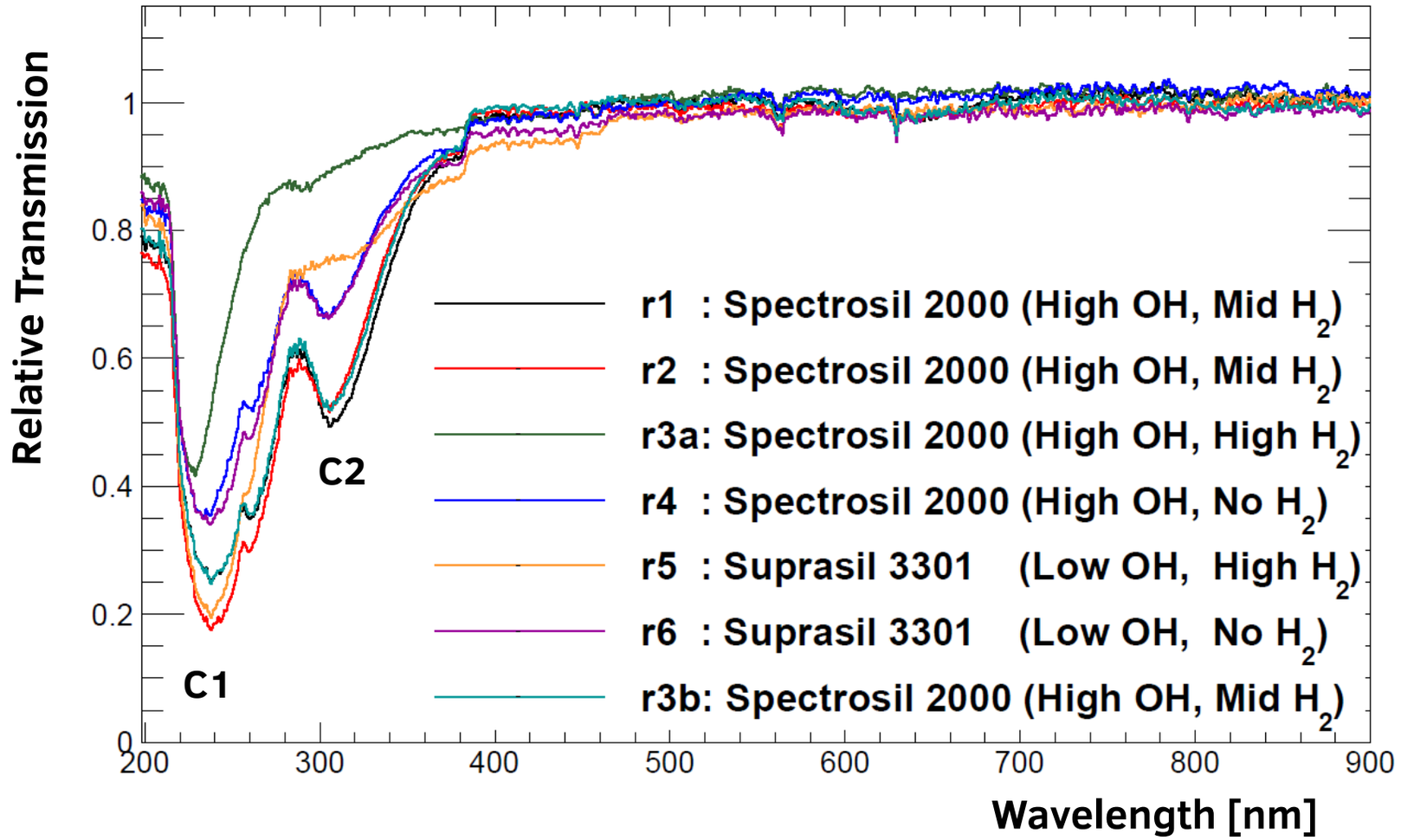






- Characterization of transmission loss as function of dosage/fluence (dose variations up to 10^4 in 40 cm)

- Two color centers observed:
  - **C1** ~ 240 nm
  - **C2** ~ 310 nm
- Further studies on the path length dependence require cutting the rods

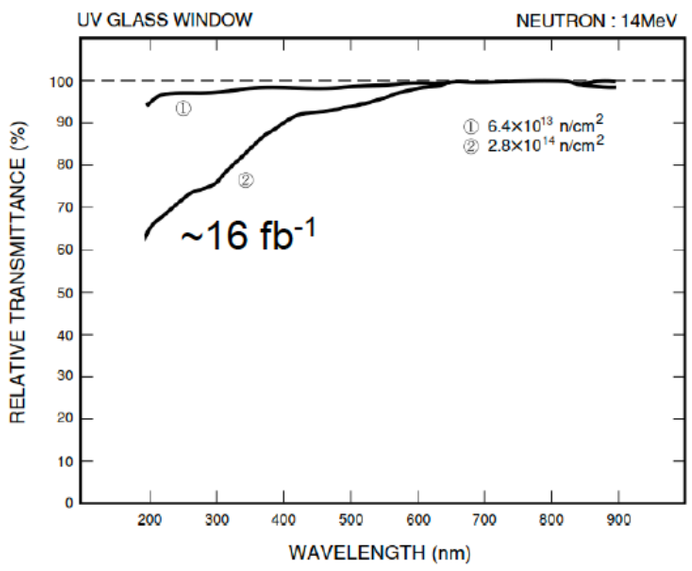


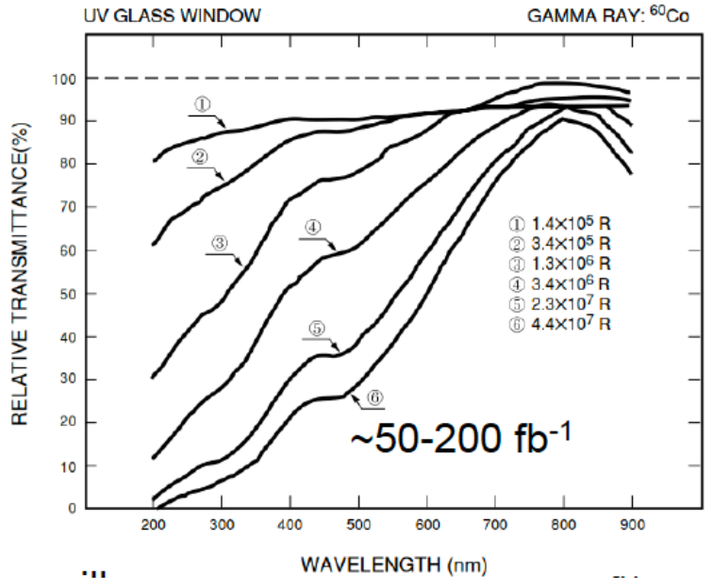
PMT WINDOW DAMAGE

Estimated dose on BRAN PMTs - HL LHC

Integrated luminosity	Neutrons [n/cm^2]	Dose [Gy]
1 fb^{-1}	1.7×10^{13}	8.8×10^{3}
1 year (250 fb^{-1})	4.3×10^{15}	2.2×10^{6}

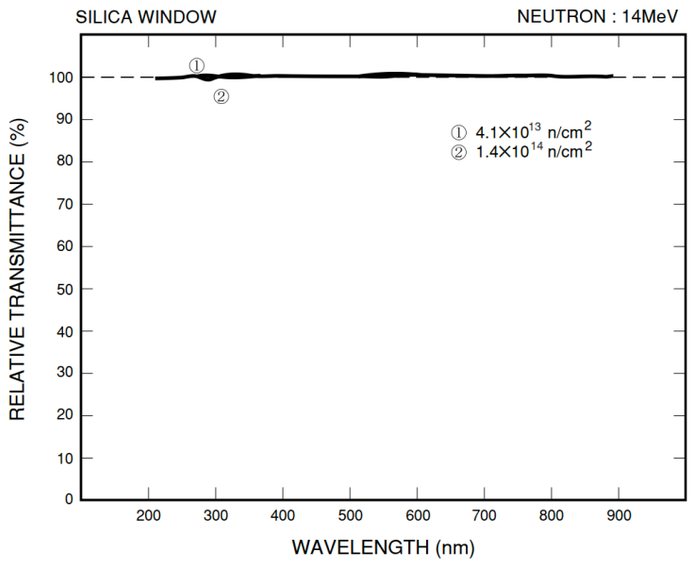
UV glass window will suffer significant transmission loss in 1 year of Run4 (pp, HL LHC)

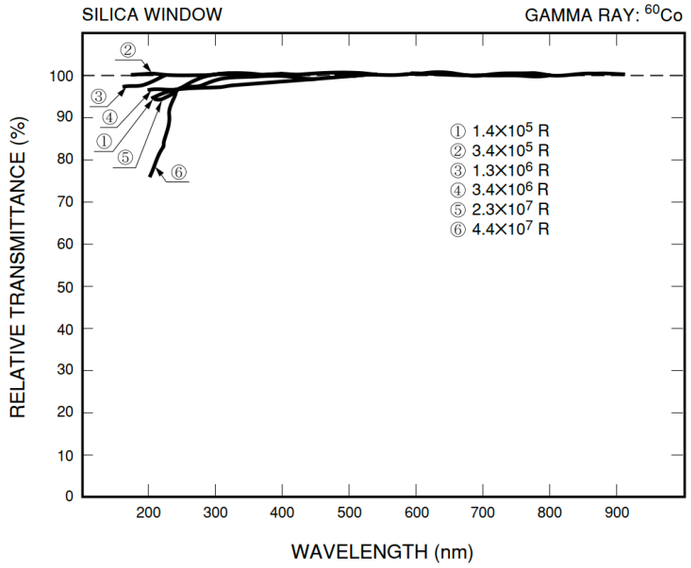




[Hamamatsu]

Fused Silica Window is a better option





Slide courtesy of M.Palm - HL LHC BRAN project

ACTIVATION MEASUREMENT

- Unique and unprecedented radiation environment in the world. Simulations needs validation.
- Two independent activation measurements carried out at UIUC and Argonne National Lab.

ILLINOIS

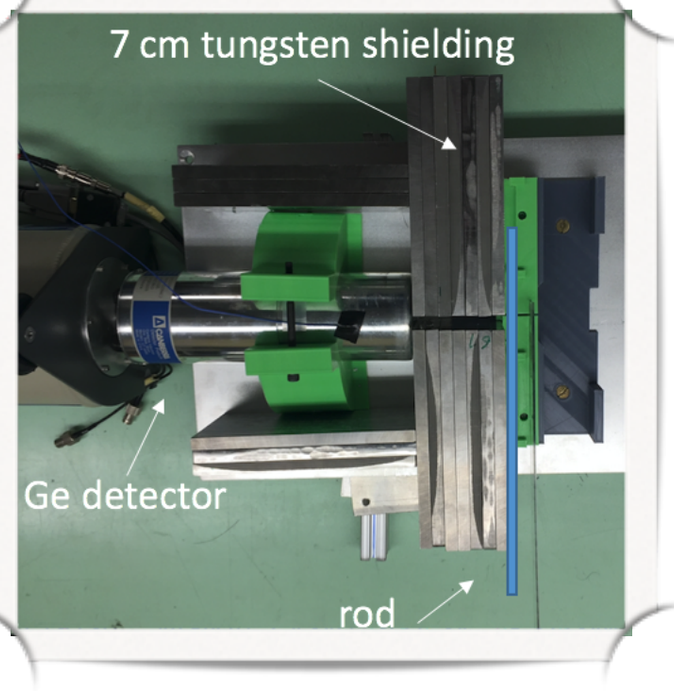


Fig10: UIUC setup

- HPGe detector (Canberra GC1519)
- 7 cm tungsten plates to collimate the rods
- 1 cm segment measured each time

Argonne NATIONAL LABORATORY

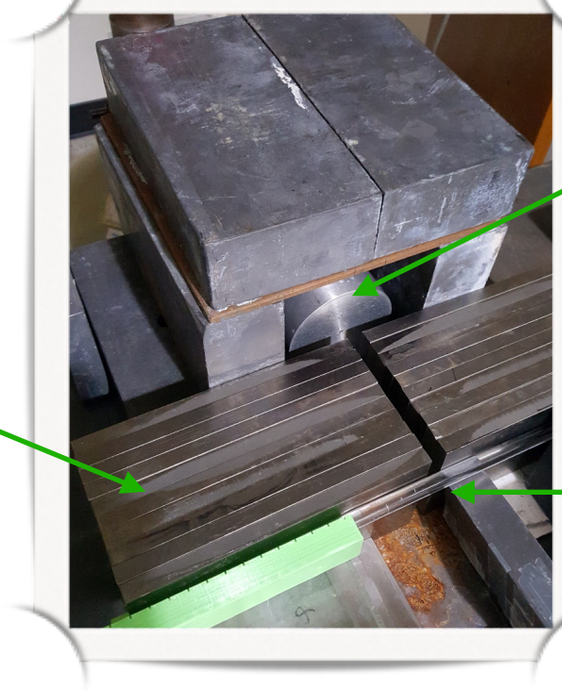
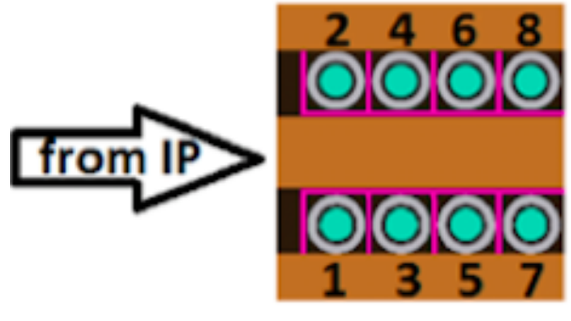


Fig11: Argonne setup

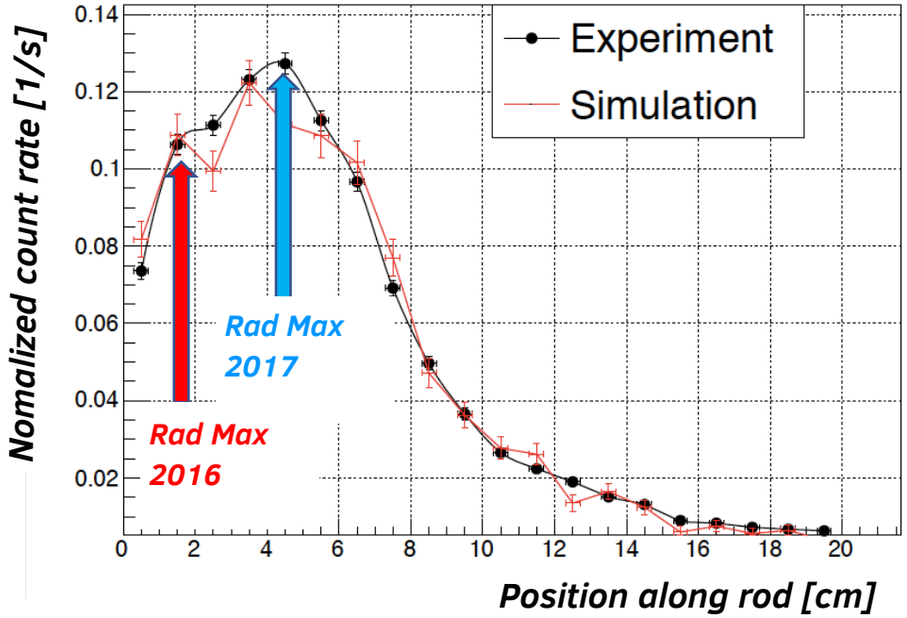
- Collaboration with Prof. M. Kaminsky
- Collimator detector
- 10 cm tungsten plates to collimate the rods
- 1 cm segment measured each time

ACTIVATION MEASUREMENT

- The radiation environment reached in LHC TANs during Run2 is unique. Simulations needs validation.
- Two independent activation measurements carried out at UIUC and Argonne National Lab.
- Example of results and comparison with FLUKA:
  - Rod2: irradiated for 2 years (04/2016 - 12/2017)
  - Rod3a: irradiated for 1 year (04/2016 - 12/2016)
- Results normalized wrt integral.



1.2 MeV gamma (Na-22) of Rod 2



1.2 MeV gamma (Na-22) of Rod 3a

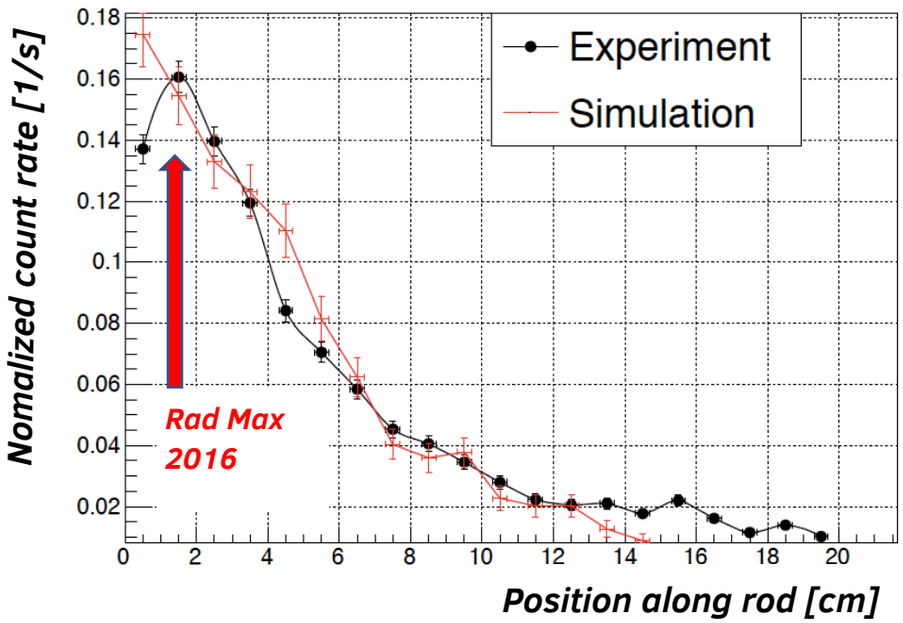


Fig12: measured activity of Rod2 and Rod3a compared with FLUKA simulations results

- Na- 22 half life: 2.6 years
- Effect of different crossing angles in 2016 and 2017 clearly visible
- Absolute normalization currently being determined

FLUKA SIMULATION OF RUN2 RADIATION ENVIRONMENT: HI

Fig7: LHC 2016 *PbPb* total dose map (FLUKA)

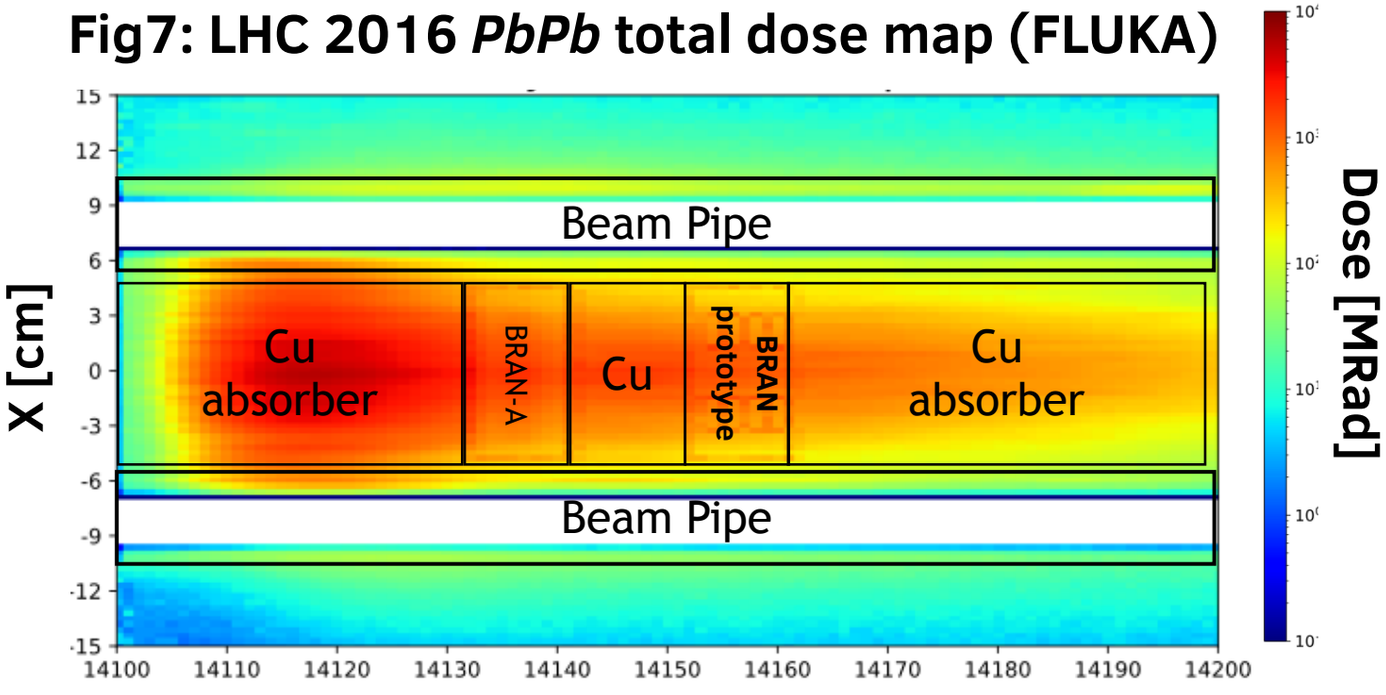
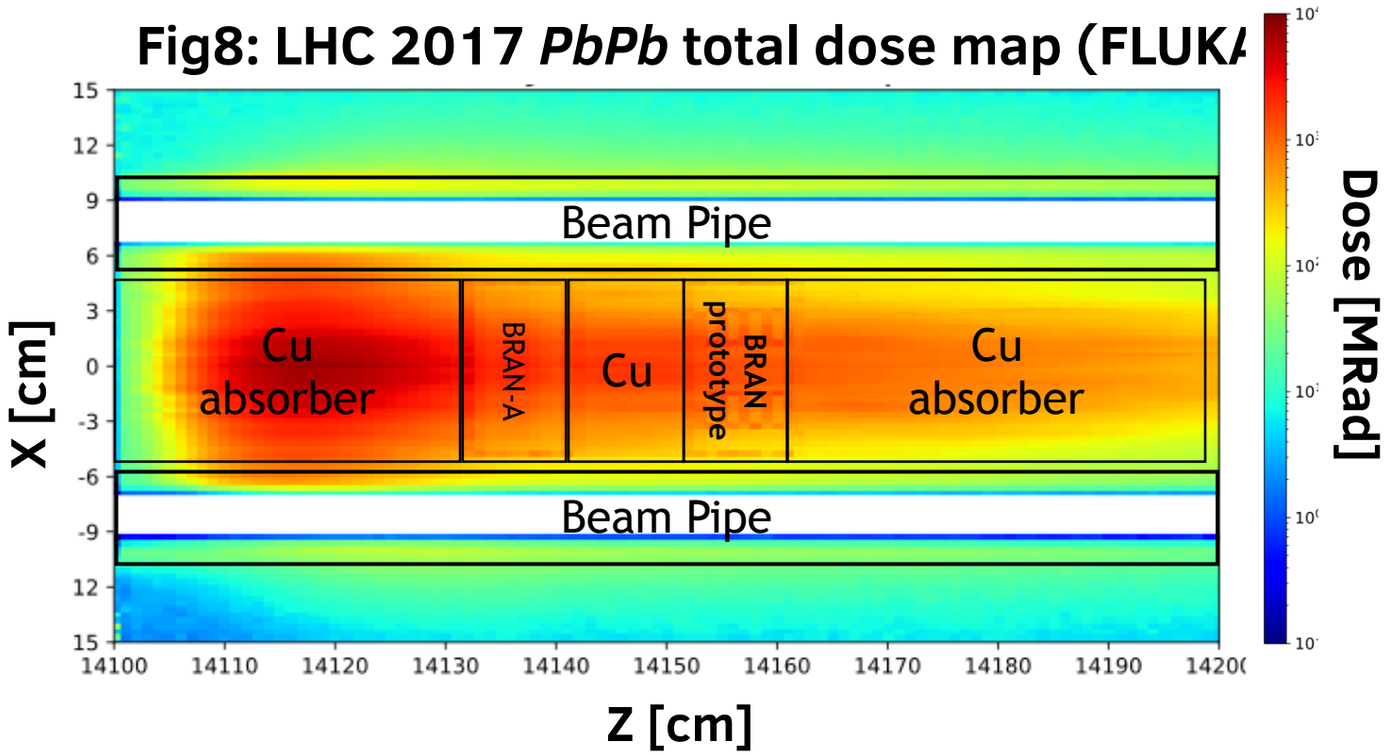


Fig8: LHC 2017 *PbPb* total dose map (FLUKA

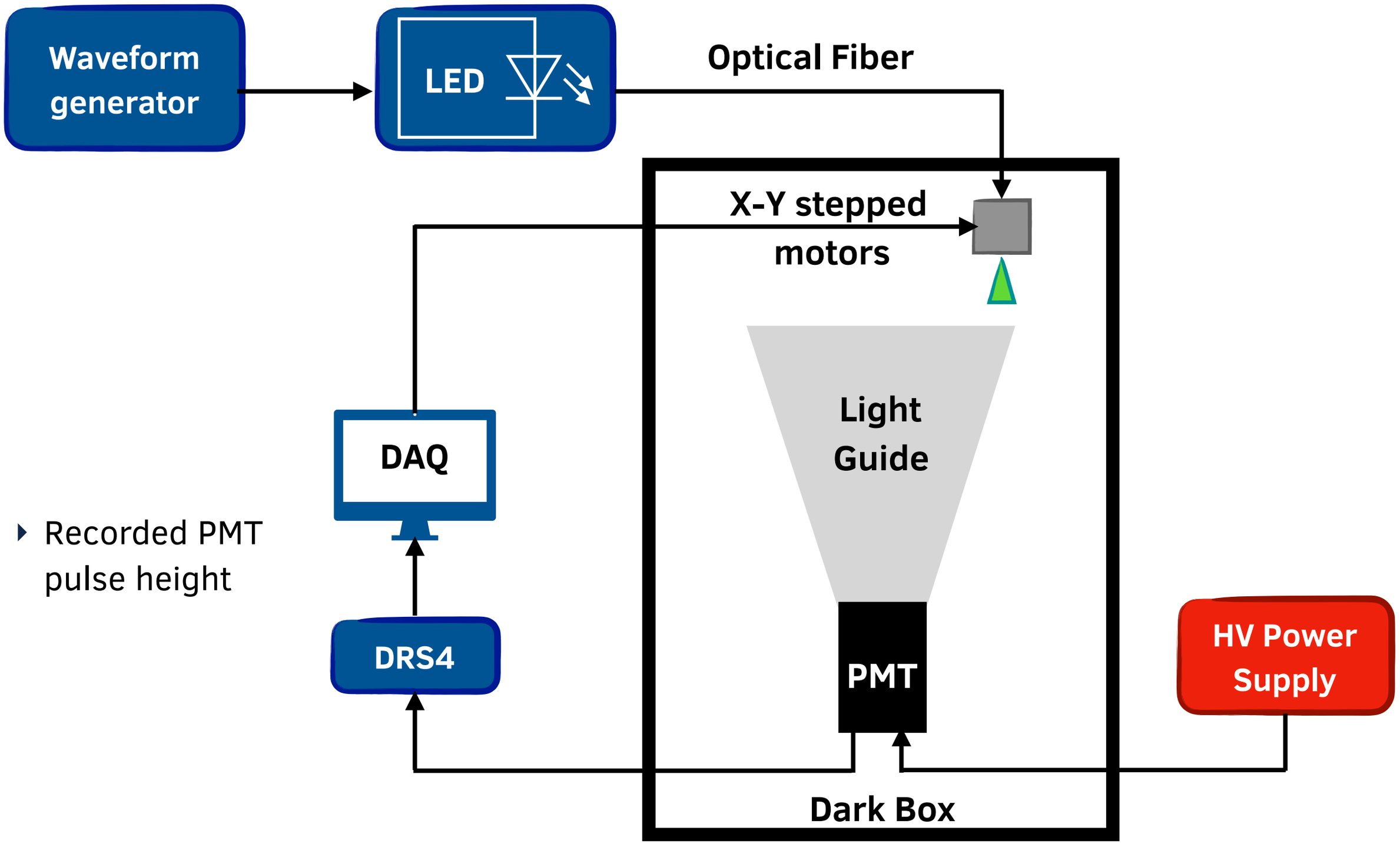


- FLUKA simulations of the TAN provided by the LHC simulation group
- Heavy Ion data taking (TAN in pp configuration - no ZDC - quantitative estimation of the expected dose)

TRAPEZOIDAL LIGHT-GUIDE STUDIES

- Also the collection of the light generated in the quartz rods can be further optimized
- Measurement of relative light acceptance for trapezoidal light-guide design

- Recorded PMT pulse height



RUN3-4 HI RUNS PLANS

Year	Systems, $\sqrt{s_{\mathrm{NN}}}$	Time	L_{int}
2021	Pb–Pb 5.5 TeV	3 weeks	$2.3\ \mathrm{nb}^{-1}$
	pp 5.5 TeV	1 week	$3\ \mathrm{pb}^{-1}$ (ALICE), $300\ \mathrm{pb}^{-1}$ (ATLAS, CMS), $25\ \mathrm{pb}^{-1}$ (LHCb)
2022	Pb–Pb 5.5 TeV	5 weeks	$3.9\ \mathrm{nb}^{-1}$
	O–O, p–O	1 week	$500\ \mu\mathrm{b}^{-1}$ and $200\ \mu\mathrm{b}^{-1}$
2023	p–Pb 8.8 TeV	3 weeks	$0.6\ \mathrm{pb}^{-1}$ (ATLAS, CMS), $0.3\ \mathrm{pb}^{-1}$ (ALICE, LHCb)
	pp 8.8 TeV	few days	$1.5\ \mathrm{pb}^{-1}$ (ALICE), $100\ \mathrm{pb}^{-1}$ (ATLAS, CMS, LHCb)
2027	Pb–Pb 5.5 TeV	5 weeks	$3.8\ \mathrm{nb}^{-1}$
	pp 5.5 TeV	1 week	$3\ \mathrm{pb}^{-1}$ (ALICE), $300\ \mathrm{pb}^{-1}$ (ATLAS, CMS), $25\ \mathrm{pb}^{-1}$ (LHCb)
2028	p–Pb 8.8 TeV	3 weeks	$0.6\ \mathrm{pb}^{-1}$ (ATLAS, CMS), $0.3\ \mathrm{pb}^{-1}$ (ALICE, LHCb)
	pp 8.8 TeV	few days	$1.5\ \mathrm{pb}^{-1}$ (ALICE), $100\ \mathrm{pb}^{-1}$ (ATLAS, CMS, LHCb)
2029	Pb–Pb 5.5 TeV	4 weeks	$3\ \mathrm{nb}^{-1}$
Run-5	Intermediate AA	11 weeks	e.g. Ar–Ar 3–9 pb^{-1} (optimal species to be defined)
	pp reference	1 week	

Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams
arXiv:1812.06772 [hep-ph]

- Goal: Operate the ZDC during O-O and p-O w/o being forced to remove the detector immediately after
- That means that the detector must stand ~2-3 months of pp running that will be in between the special runs and the HI run. For Run3, that corresponds to ~ 5 GRad. For Run4, it would correspond to ~ 10 Grad