Update on Luminosity monitoring for HL-LHC

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Outline

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

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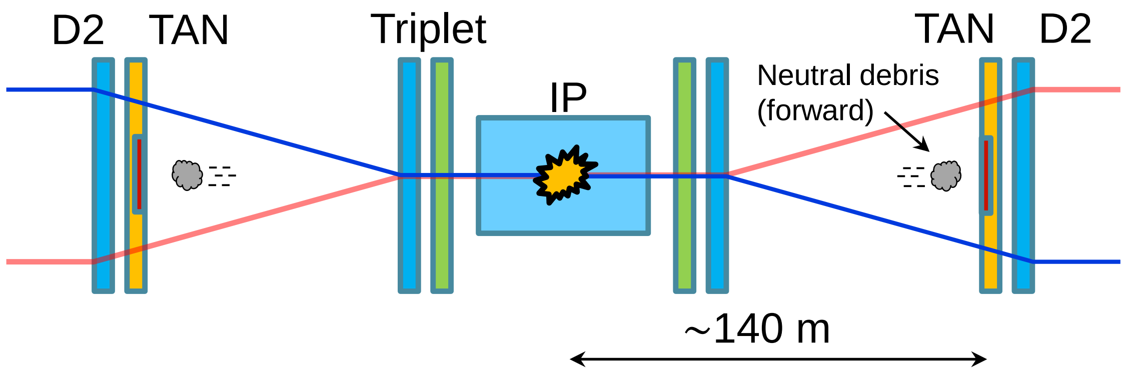
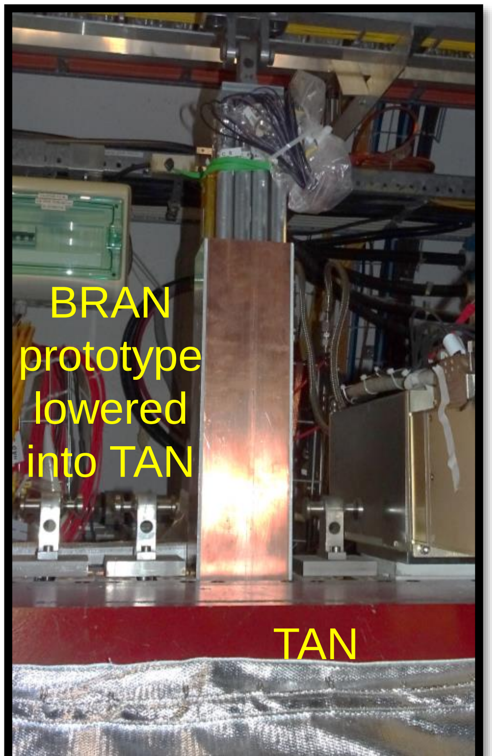
Overview

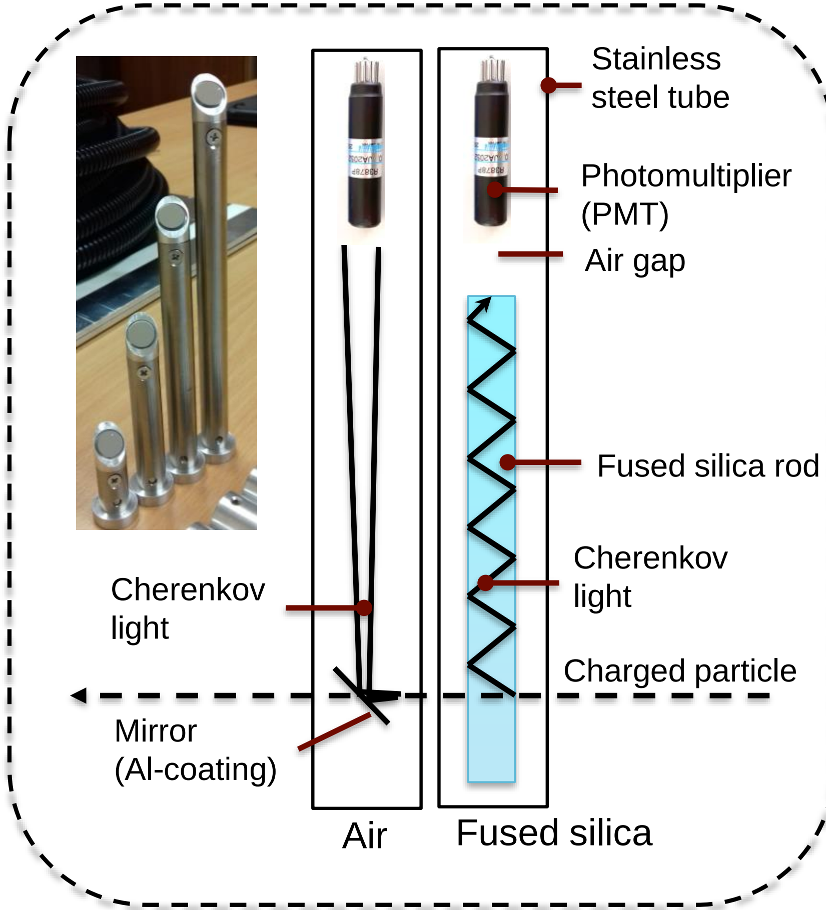


- **Where**: machine luminosity monitors around all IP1, IP2, IP5, IP8
- **Use cases**: Finding collisions, backup instrument for OP (if no data from experiments), cross-check experiments, sanity check, …
- **Precision**: ~1% @ 1 Hz (absolute luminosity not necessary)
- **Challenges**:
  - Large dynamic range
  - IP1 & IP5: radiation (180 MGy/year), limited space in TAN (only 5 cm width)
- HL-LHC upgrade: Cherenkov radiation based monitors

HL-LHC BRAN prototype

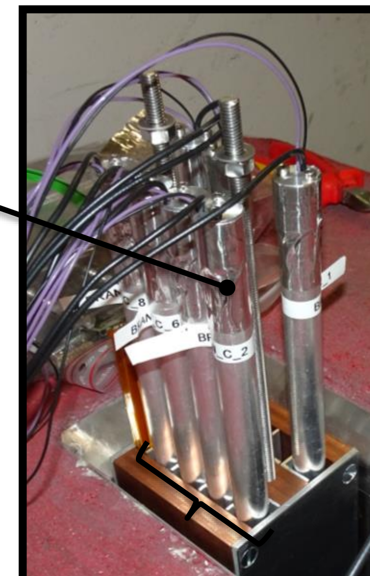


Principle



2 Cherenkov radiation-based
modules tested

8 channels



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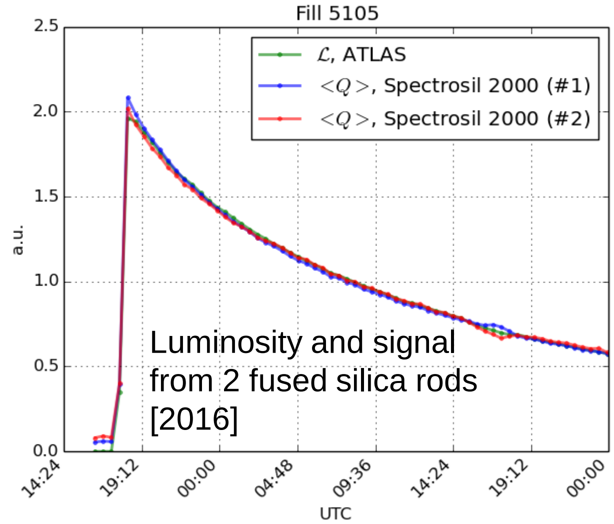
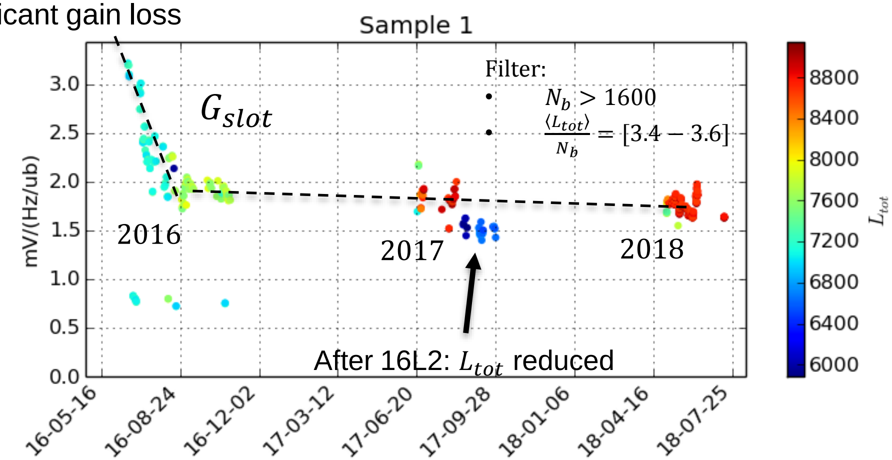
General performance

- Good agreement between prototype voltage-integral and ATLAS luminosity



- Signal gain:
  - $G_{slot} = \frac{\langle U_{slot} \rangle}{L_{tot}/N_b}$
- Fairly stable gain from mid-2016 until today

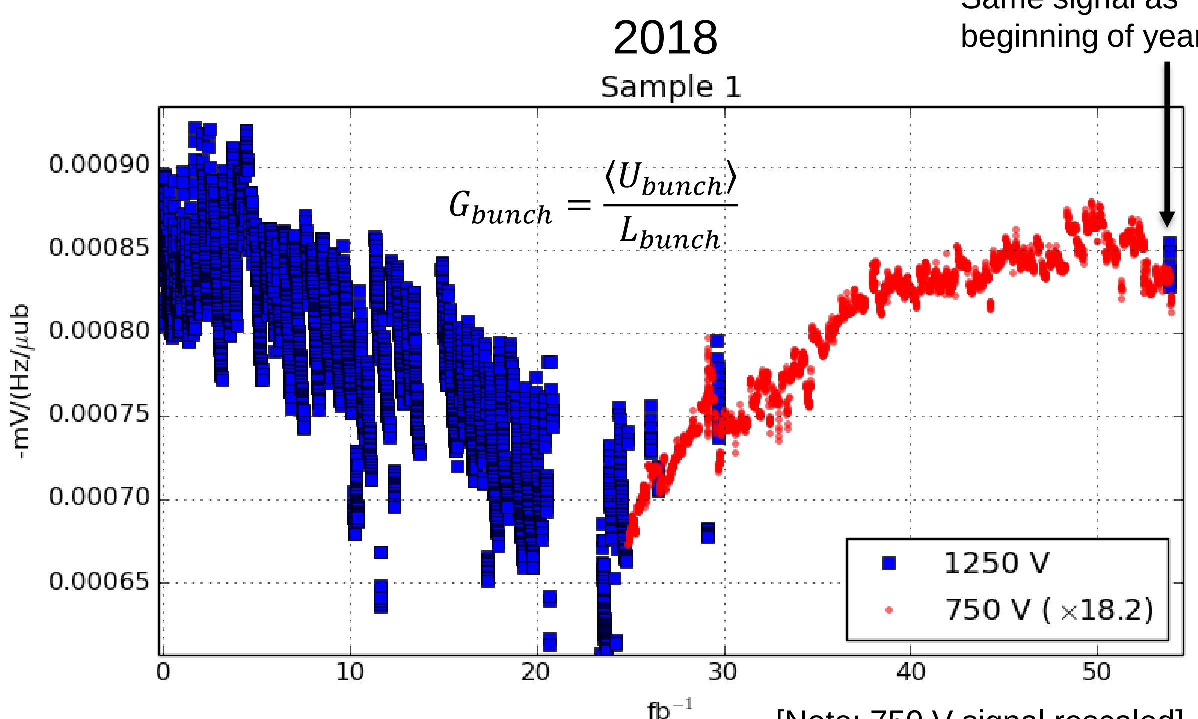
First few fb[-1]: significant gain loss



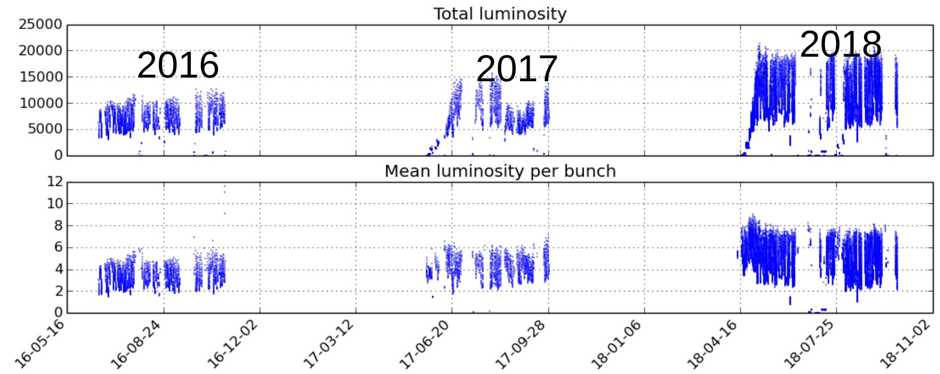
PMT saturation

- Gain loss during 2018
- 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

Same signal as beginning of year



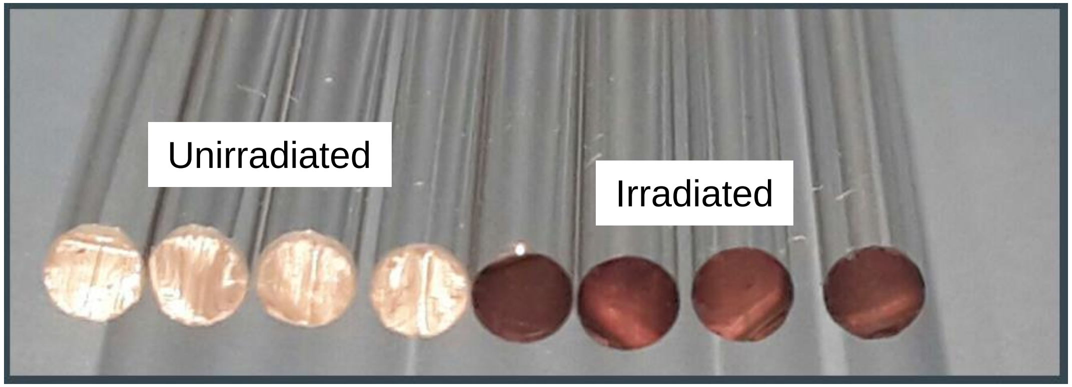
[Note: 750 V signal rescaled]



Radiation effects - Transmission

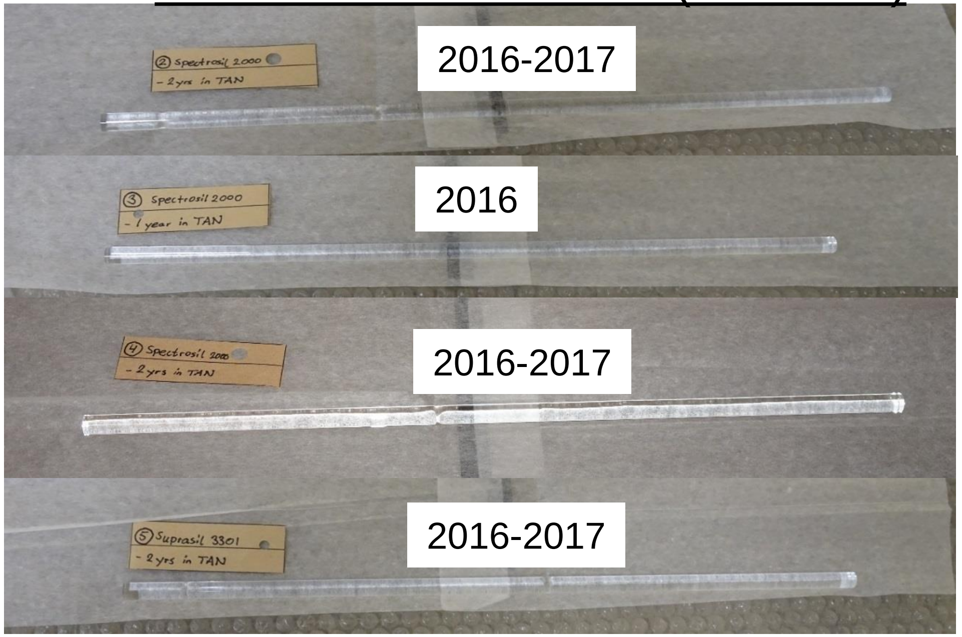
- Main radiation concern: reduced optical transmission
- 4 rods recuperated from TAN after 1-2 years of LHC operation
  - No visible discoloration or opacity (by eye)
- Shipped to ZDC group at University of Illinois for measurements

ZDC Quartz rods



[Courtesy: M. Phipps - "ZDC Upgrade: Spectroscopic Results"]

BRAN Fused silica rods (irradiated)

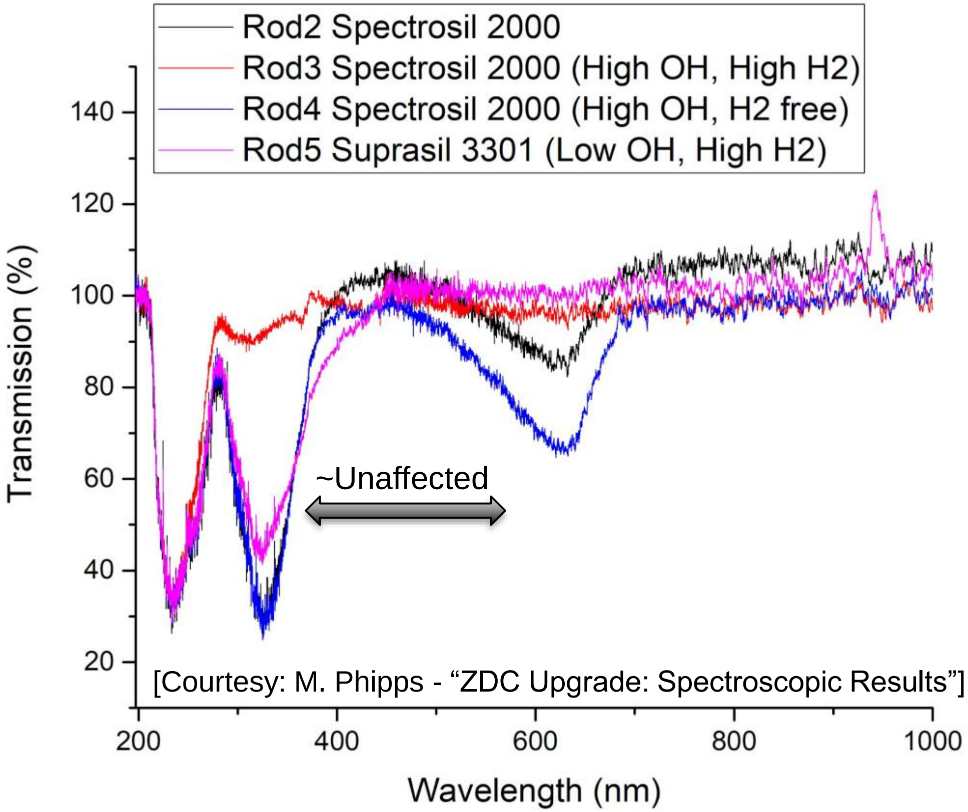


Measured rod transmission

- 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"



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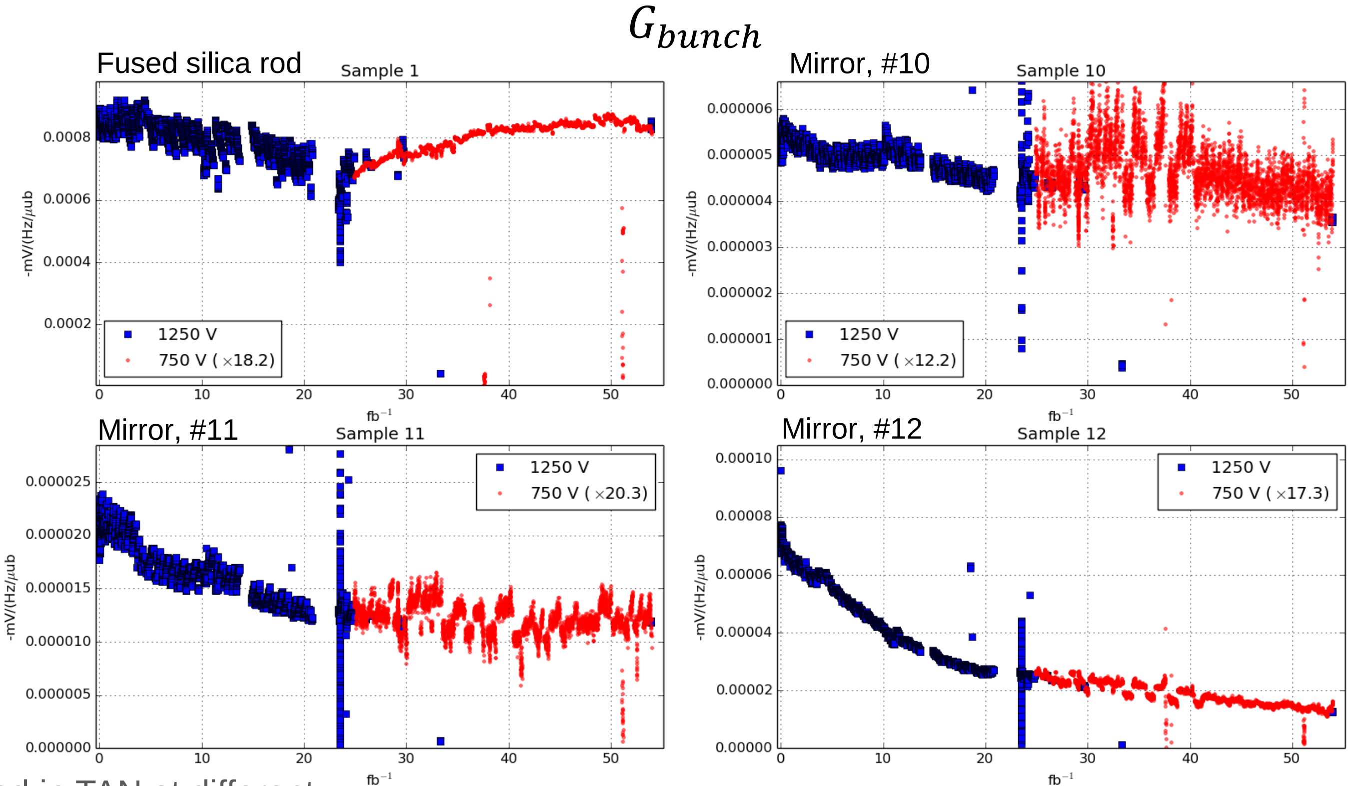
Aluminum mirrors



- 3 Al-mirrors installed in TAN at different heights
- Mirror with largest signal (#12) has also degraded the most
  - >80% gain loss during 2018
  - Currently: -20%/10 fb^{-1}
  - No sign of flattening out…
- → Al-mirrors do not seem feasible for HL-LHC
- **⇒ We will go for quartz rods.**

	Mirror #10	Mirror #11	Mirror #12
Initial gain [compared to quartz rod]	0.6%	2.8%	**8.3%**
Gain loss up to 54 fb^{-1}	-32%	-43%	**-83%**

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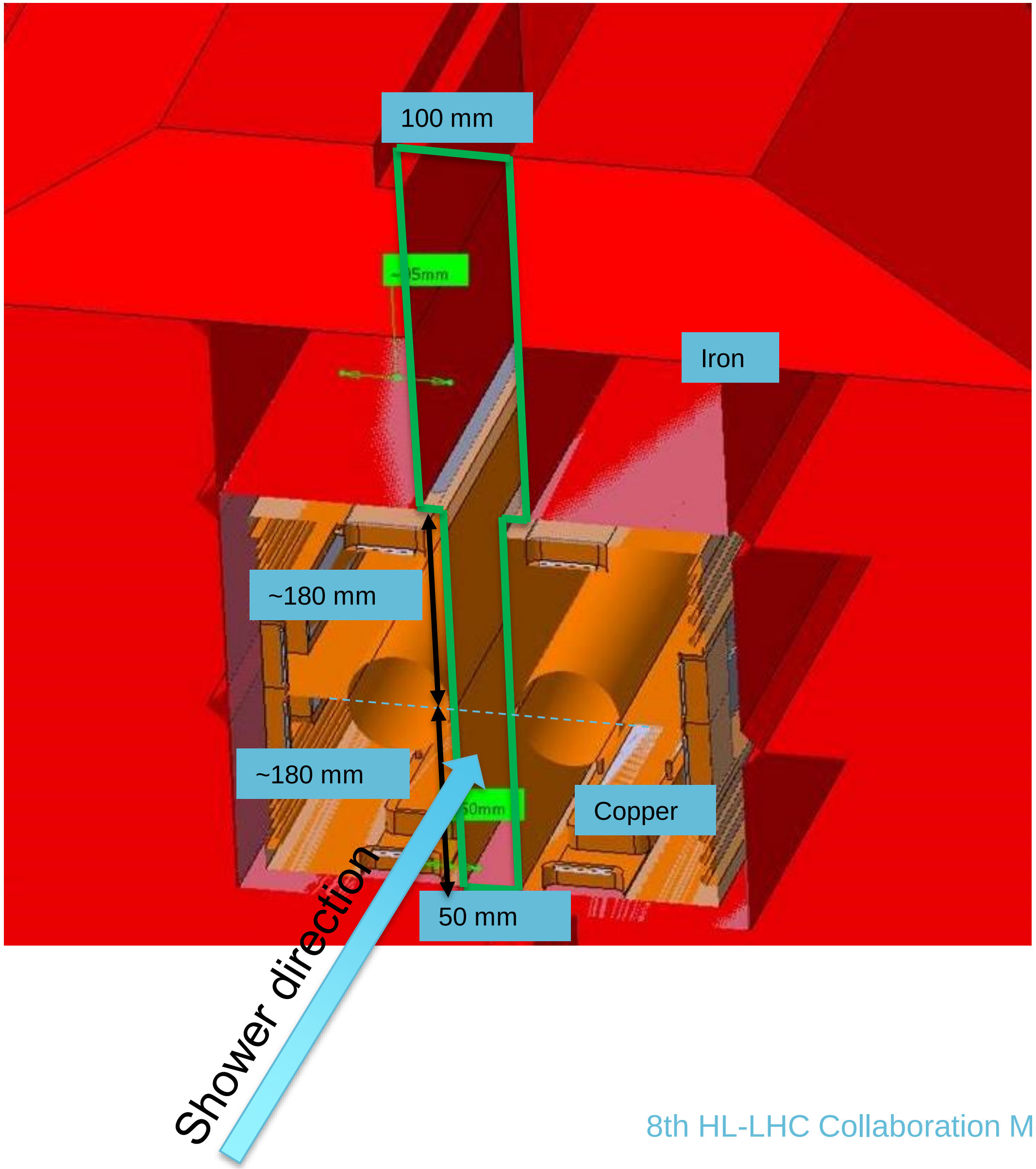
- <u>Design considerations</u>
  - Available space
  - X-ing angle
  - Dynamic range

Available space

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

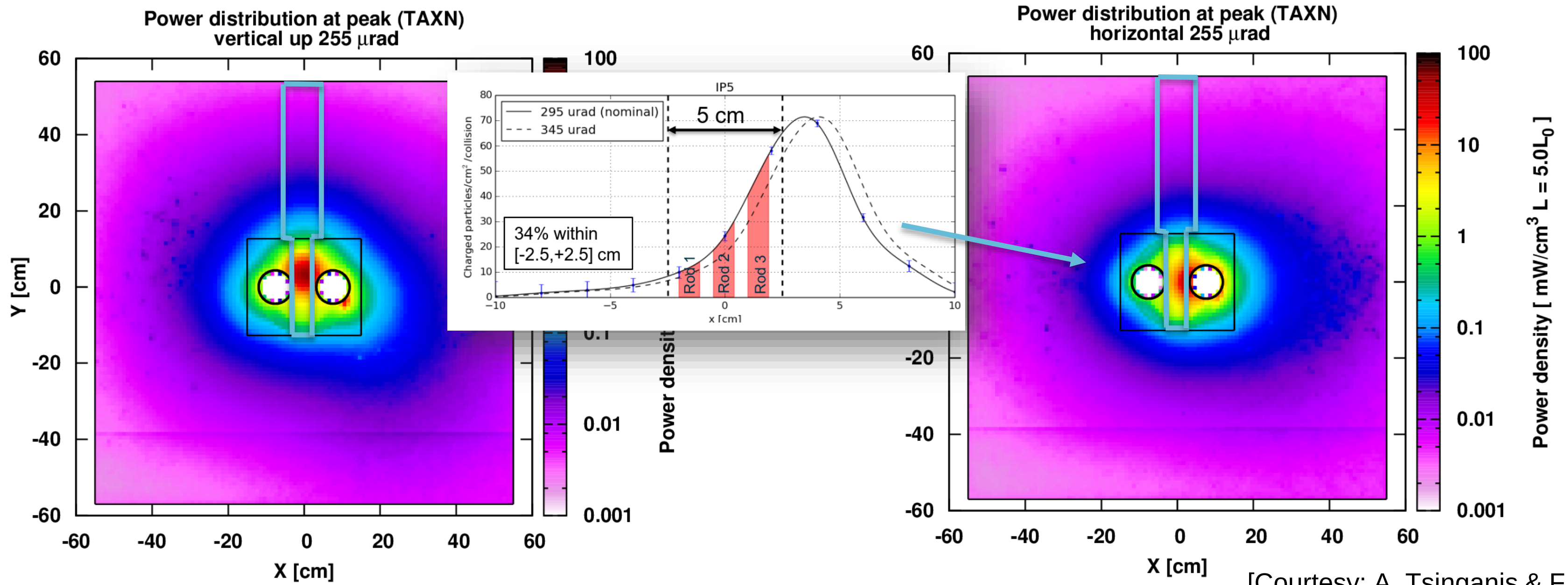
TAXN cross section



X-ing angle

Vertical X-ing

Horizontal X-ing



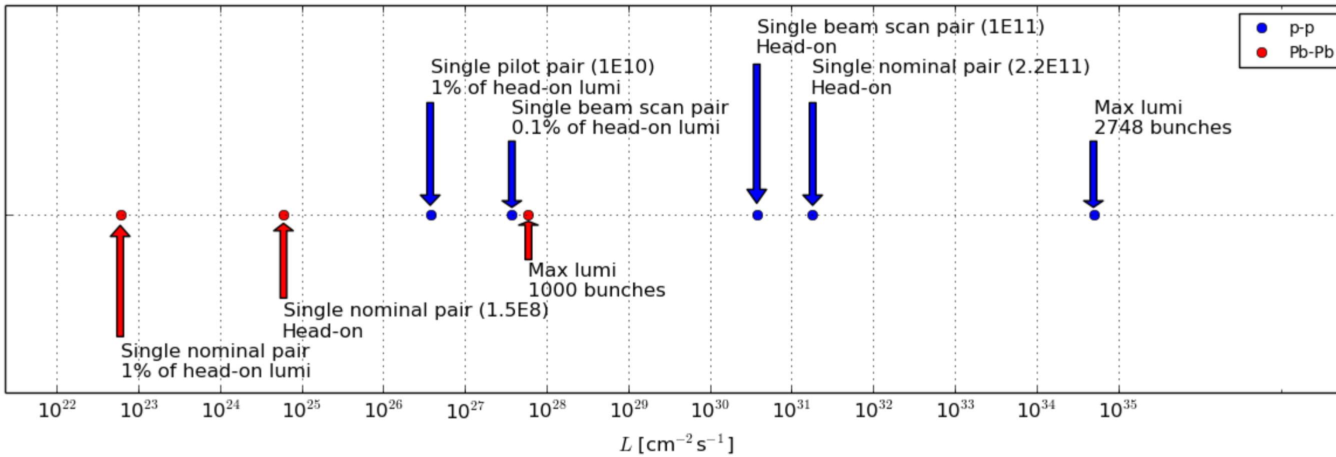
[Courtesy: A. Tsinganis & F. Cerutti]

- Vertical X-ing: Shower is centered between beam pipes.
  - Change of X-ing angle will have little impact on BRAN signal (%-level)
- Horizontal X-ing: Dose peak is outside 50 mm gap
  - Change of X-ing angle will change BRAN signal amplitude, which is indistinguishable from a change in luminosity
  - Not feasible to compensate for this by measuring X-ing angle
  - In addition: dose rate in left/right rods is different => transmission will change at different rate => many recalibrations would be needed before transmission is stabilized

- Above copper block: 100 mm space available
  - … but profile is also much wider => less precision
  - Dose rate ~3 orders of magnitude lower => Rod transmission would continuously degrade during first ~1000 fb^{-1}, instead of during first ~10 fb^{-1}.
  - Very impractical.
- **Conclusion: for horizontal X-ing, the measured BRAN luminosity will have a X-ing angle dependence**

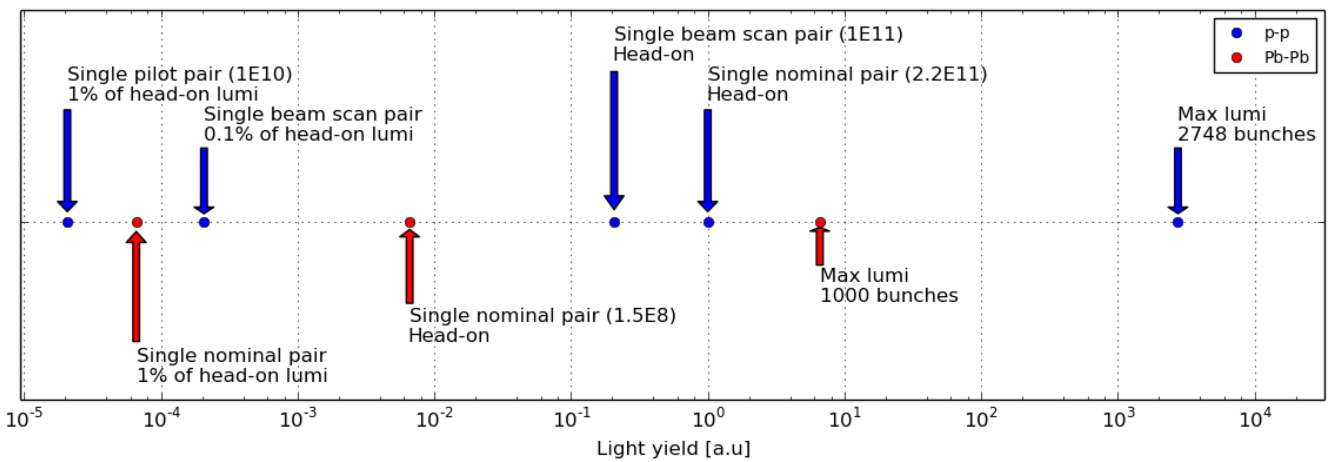
Dynamic range (1)

- Luminosity range (p-p & Pb-Pb)



Total luminosity: 12 orders of magnitude

- Signal range
  - Note: ~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.



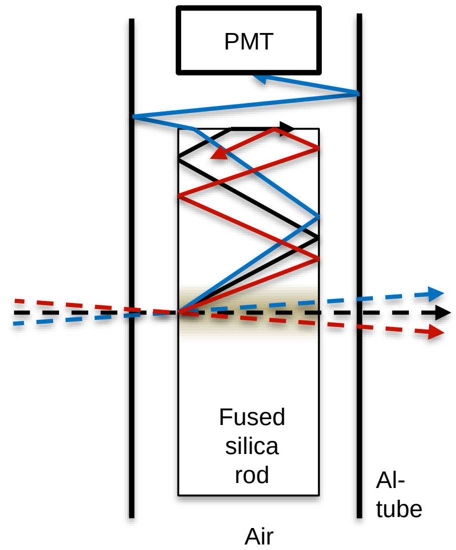
Total light yield: 8 orders of magnitude

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

Available signal

- 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 $\neq 0$
  - Each collision at μ=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

Track length/event (charged particles) @ Dose peak	98 cm/cm^3
Photon yield, quartz	1003 photons/cm^3
Equivalent PMT counts (incl. QE)	145 counts/cm^3
PMT counts/event	**14210**
Nominal pile-up, HL-LHC	138
PMT counts/crossing (1 cm^3 fused silica at dose peak)	=> 2,000,000



Design considerations: summary

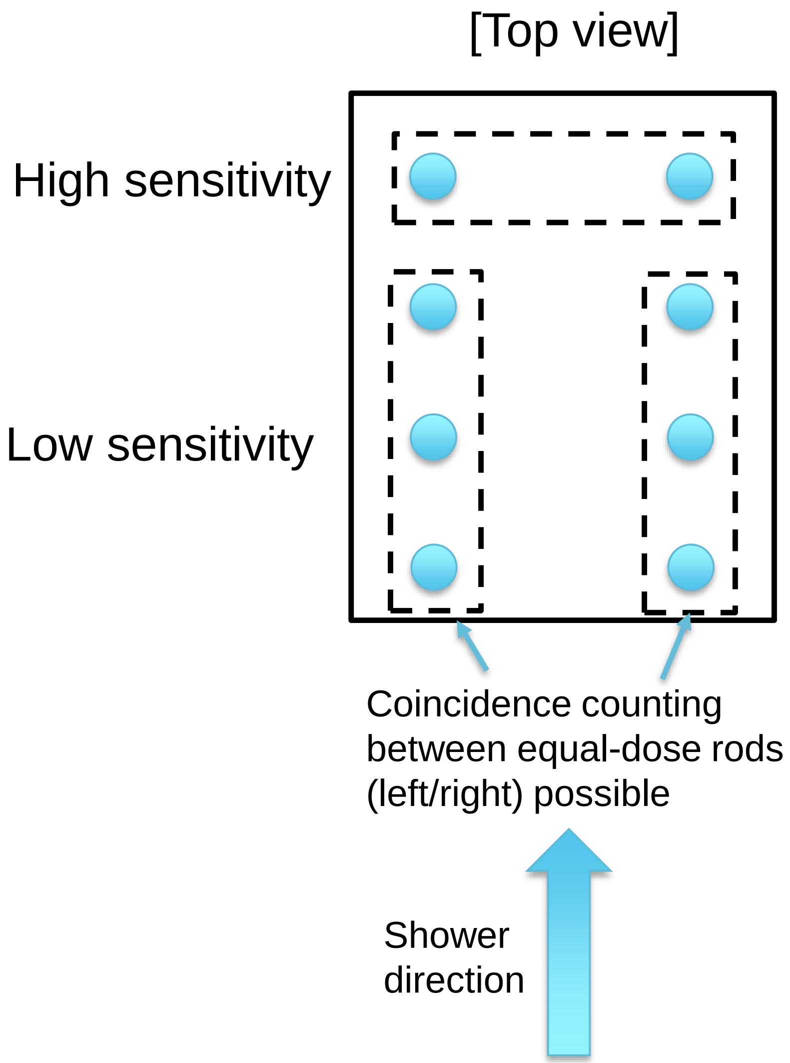
- Fused silica rods/~~Aluminum mirrors?~~
- X-ing angle dependence (horizontal)
  - We have to live with it.
  - Make sure operators know about it.
- Physical space constraints
  - Difficult to fit more than two parallel quartz rods + PMT + "cross-talk shielding" in 50 mm
- Dynamic range
  - 4-5 orders of magnitude in terms of photons/collision should be covered
  - 3.5 orders of magnitude more from number of bunches
- Available light
  - If we extract a sufficient fraction of light from the quartz 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.

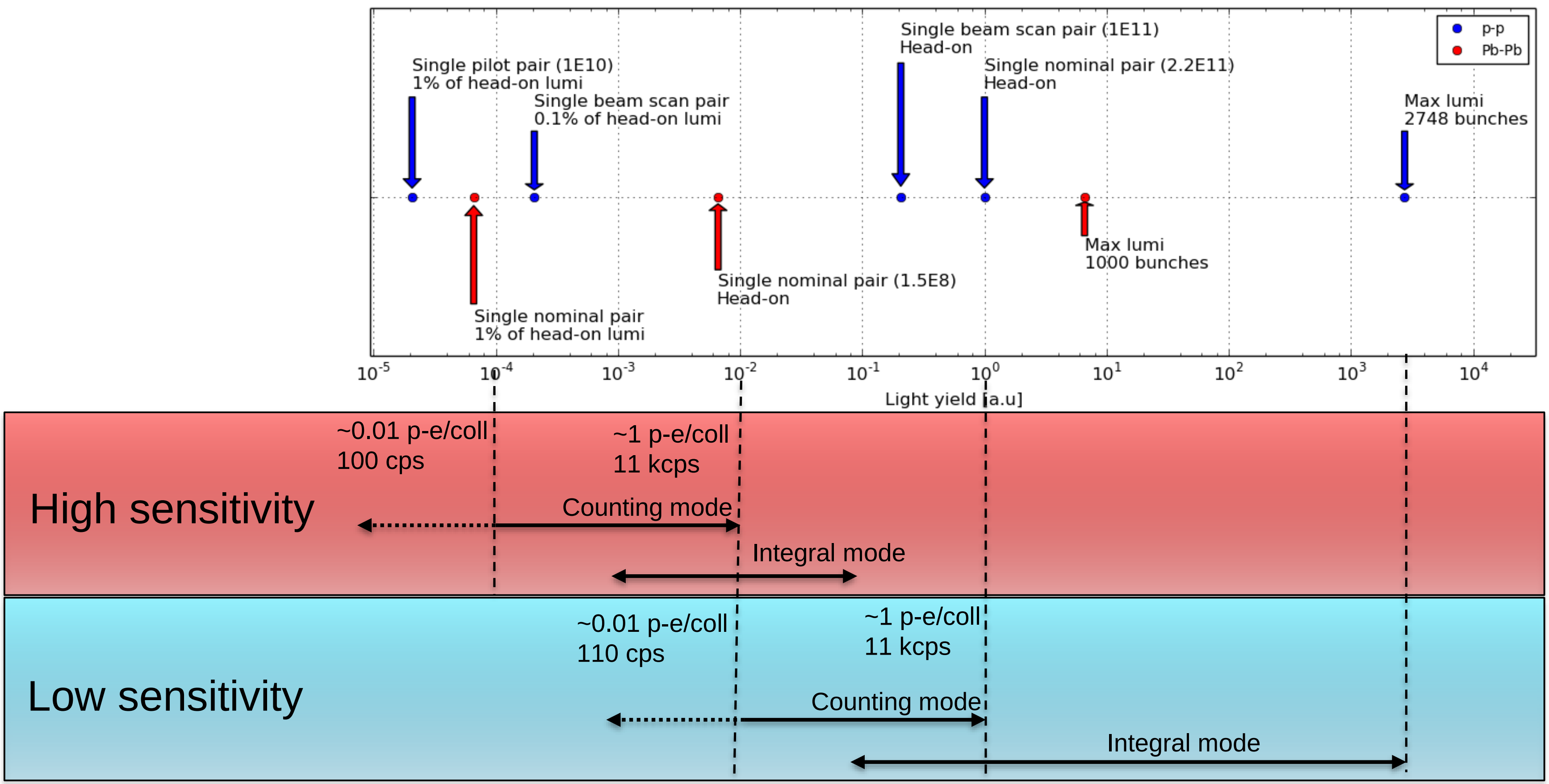
- Warning: the TAN/TAXN is a beast against which many detectors have failed…
  - **"Simple but reliable" better than "Perfect but complex"**

Channel configuration

- Tight fit between beam pipes: reduce quartz rod diameter from 10 to 5 mm
- 6 Low-sensitivity channels
  - = Multiple backup channels
  - Working point: Physics , high bunch luminosity
- 2 High-sensitivity channels
  - Working point: finding collision, low-μ runs



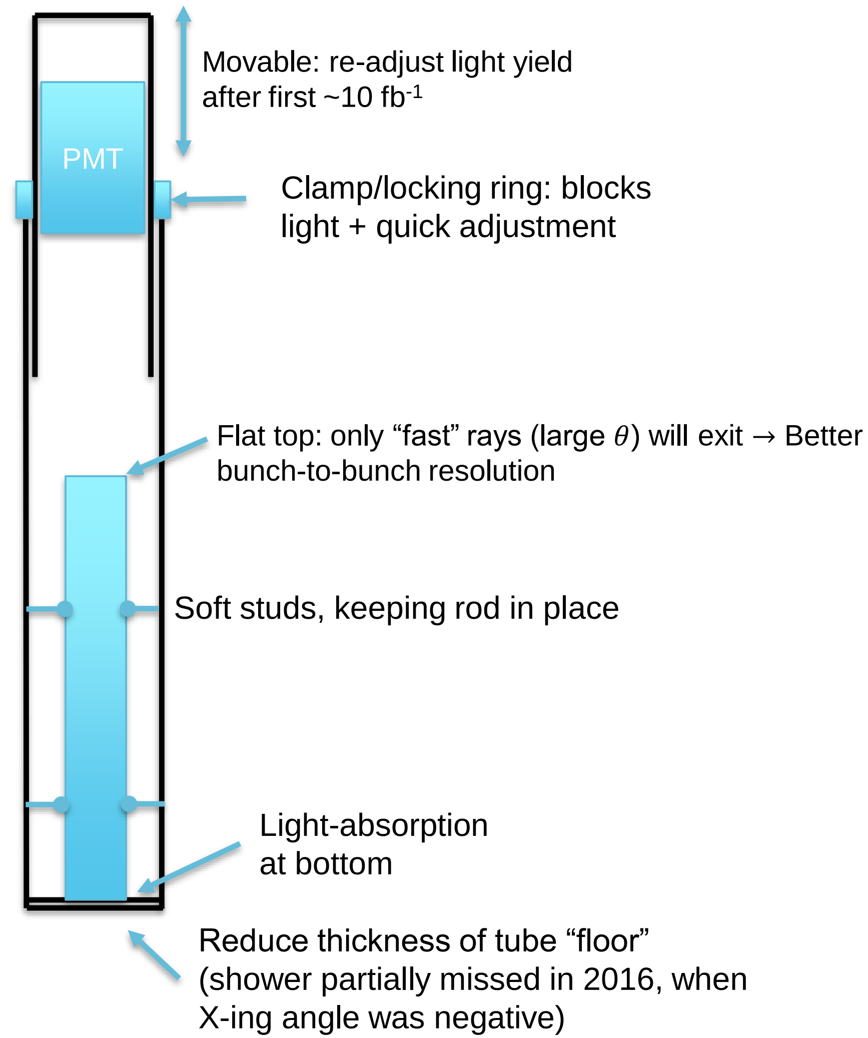
Channel sensitivity range



p-e = photoelectron
cps = counts per second

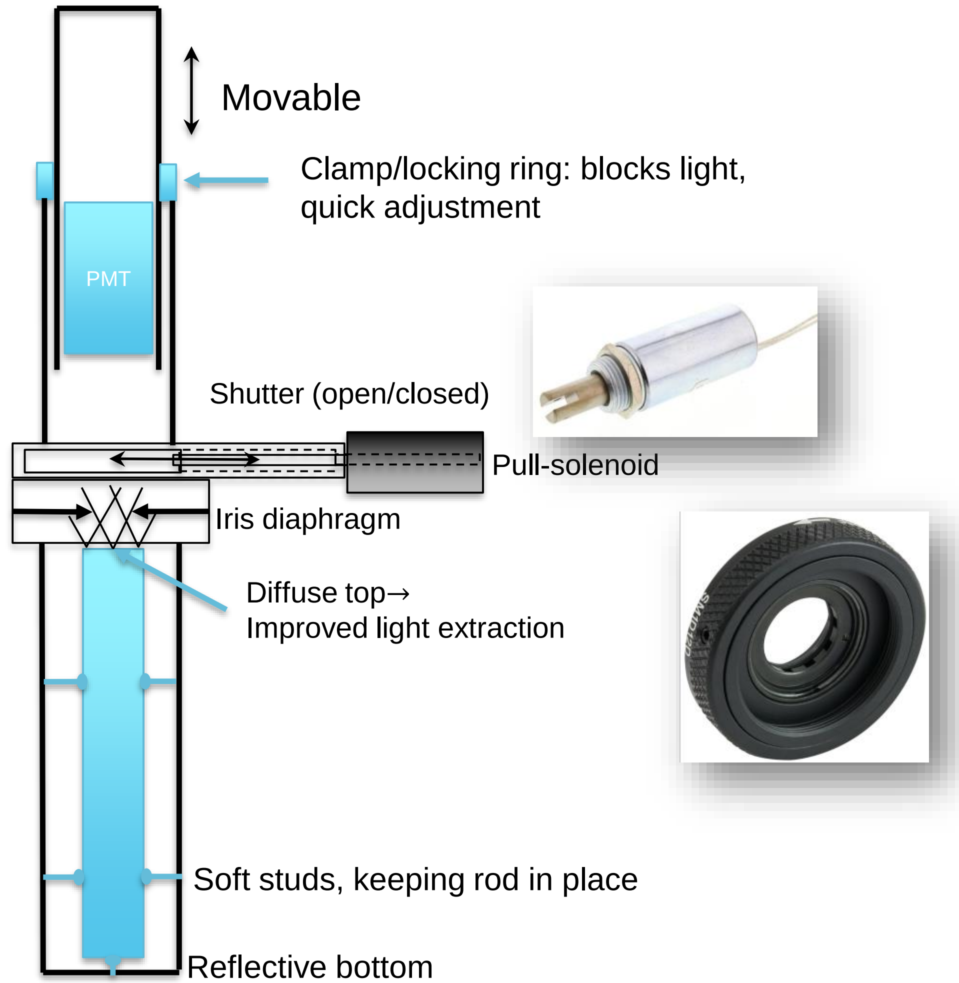
Low sensitivity channel

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



High sensitivity channels

- PMT will be killed if not shielded at high luminosity
  - Add pull-solenoid shutter
- Light yield tuning:
  - PMT-Rod distance
  - Graduated iris diaphragm



Summary

- Fused silica is a feasible Cherenkov medium for the TAXN environment
- Aluminum mirrors still degrading
- X-ing angle dependence at IP1
  - Make sure OP is aware
  - Cosmetics: apply X-ing angle dependent scaling factor
- HL-LHC BRAN will measure luminosity over 12 orders of magnitude

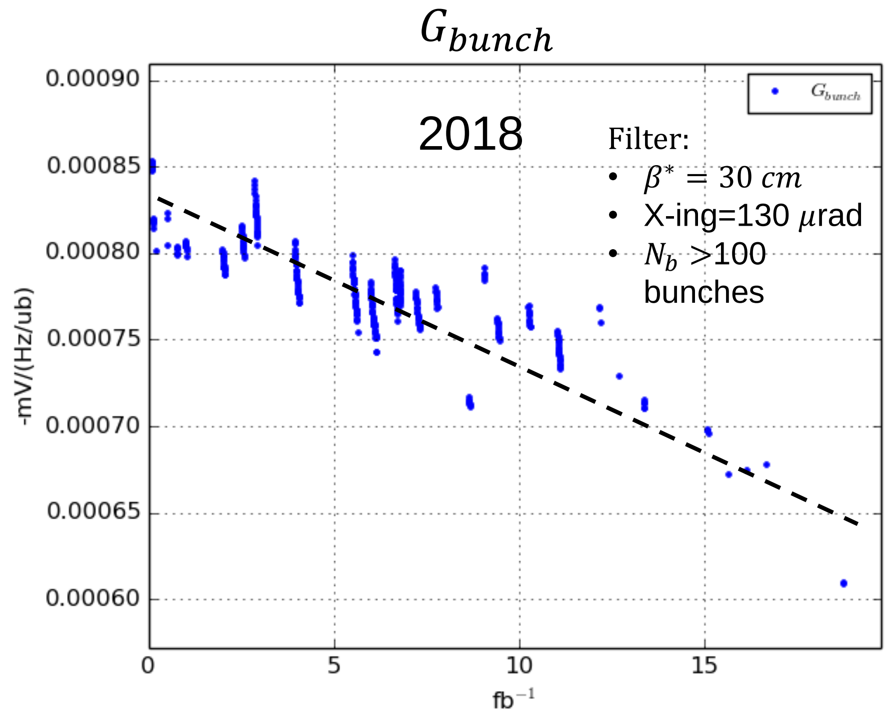
- Thank you for your attention

Backups

PMT saturation (1)

Ideally $\propto L_{bunch}$

- Bunch gain
  - $\langle U_{slot}\rangle = \langle U_0\rangle + \langle U_{tot}\rangle + \boldsymbol{\langle U_{bunch}\rangle}$
- Gain: $G_{bunch} = \dfrac{\langle U_{bunch}\rangle}{L_{bunch}}$
- ~10% intra-fill drop
- Decreasing inter-fill trend during 2018
- Cause?
  - Luminosity is higher now, compared to 2016 → More light → Larger current



Filter:

2016

2017

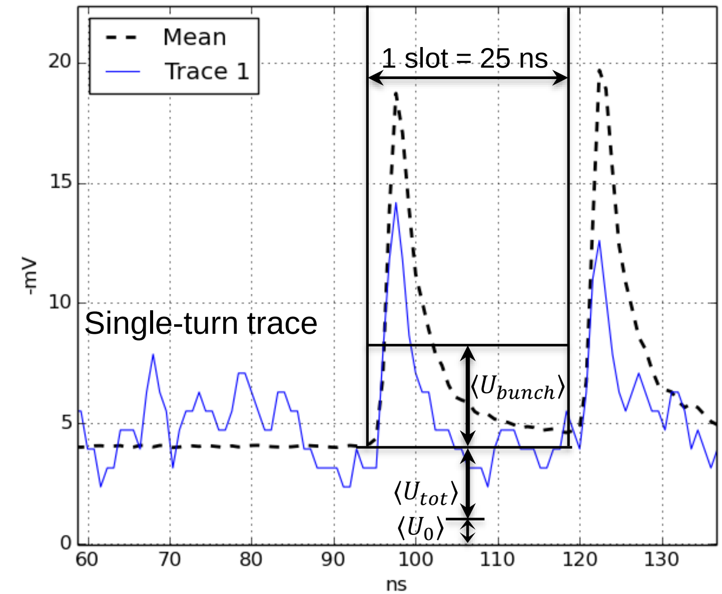
2018

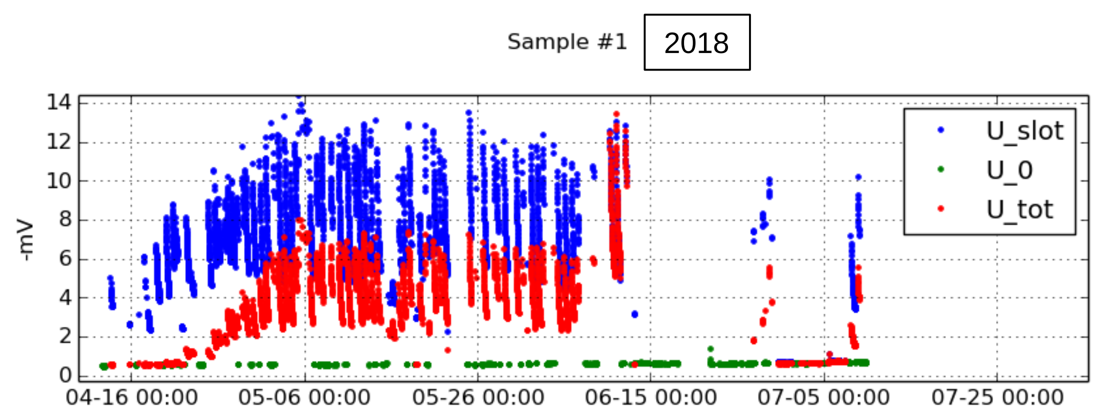
- $\beta^* = 30\ cm$
- X-ing=130 μrad
- N_b >100 bunches

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
  - $\propto I_{mean}$
  - ~Half(!) the voltage integral comes from baseline (red) at high luminosity
  - Not logged 2016-2017
  - 2018: detailed logging
  - →Restrict long-term evaluation to data points with similar luminosity



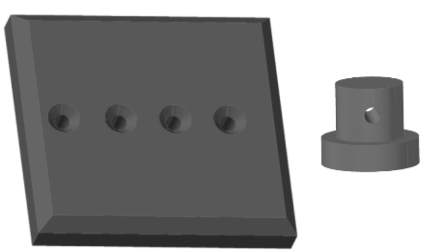


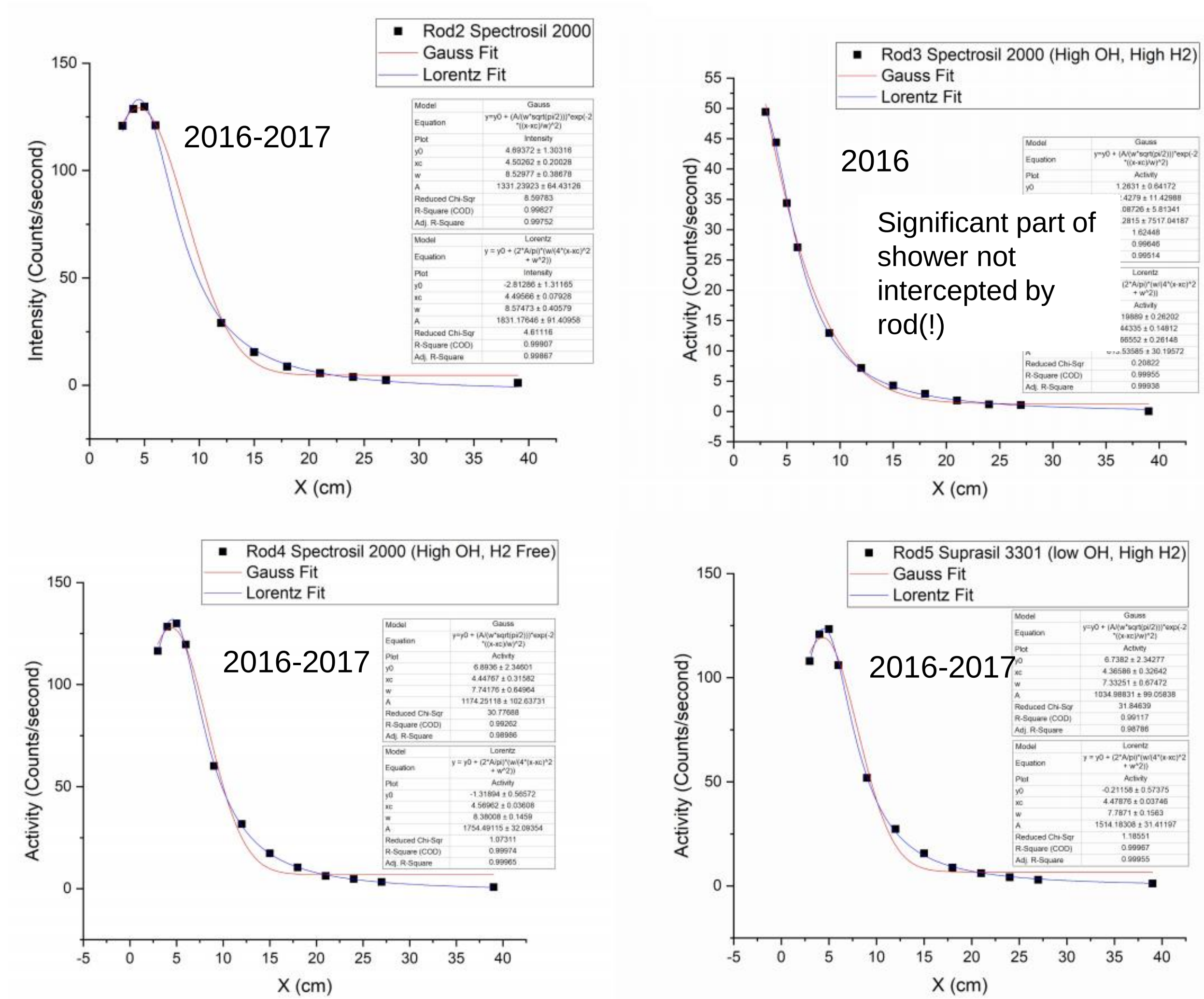
Terminology

- Quartz
  - Natural or synthetic
  - ***Crystalline*** SiO_2
  - Purity: case-by-case
- Fused quartz
  - ***Amorphous*** SiO_2
  - Made from natural crushed quartz
  - Natural impurities may persist into finished product
- Fused silica
  - Synthetic amorphous 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.





Activity vs. vertical rod coordinate (0 = bottom of rod)