The Cherenkov Detector for Proton Flux Measurement (CpFM) in the UA9 Experiment

CpFM for double-crystal studies

6th French-Ukrainian Workshop on Instrumentation, LAL Orsay – France, September 26, 2018

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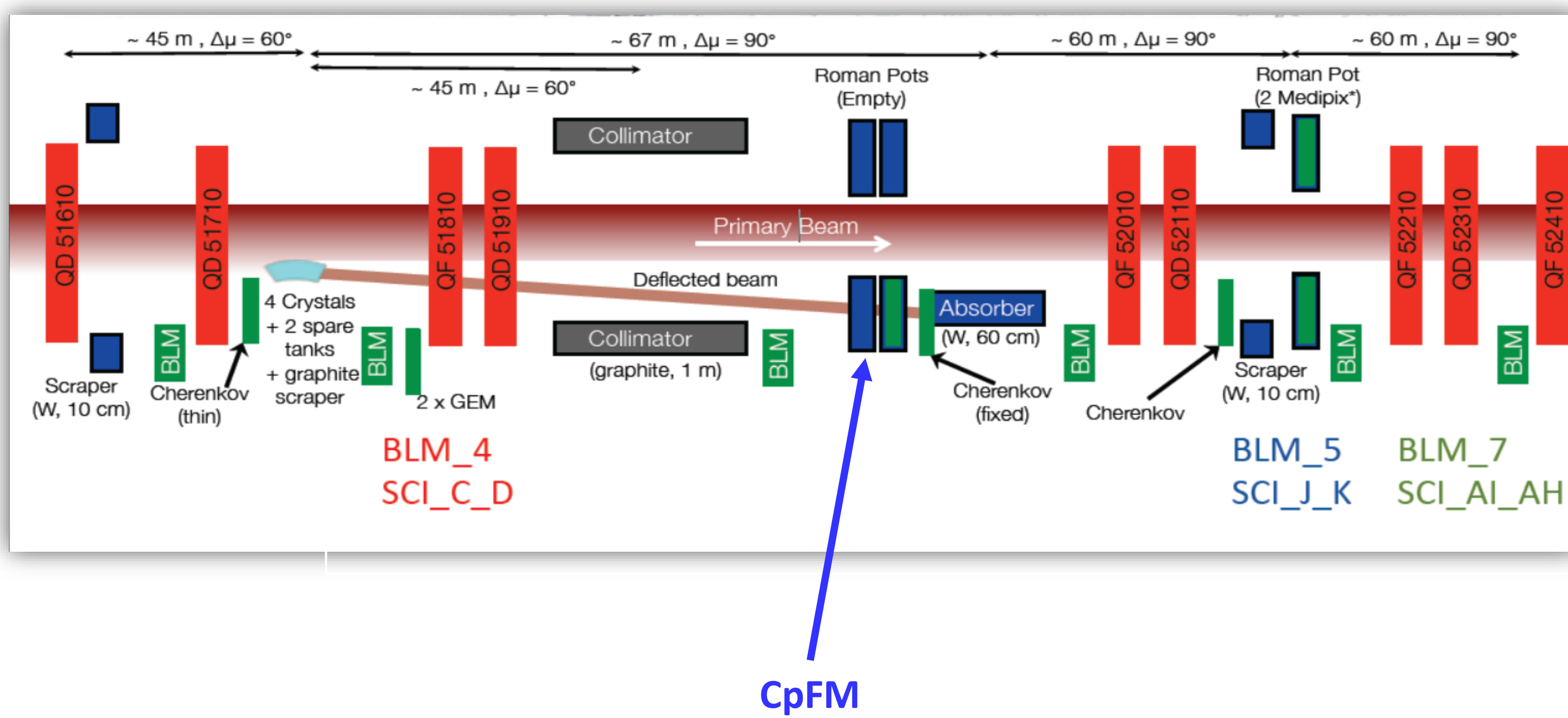
Outline

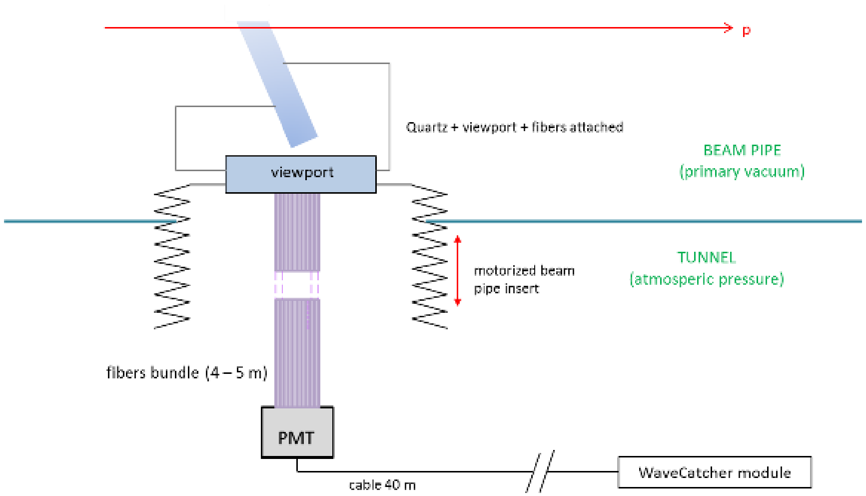
- Reminder: The CpFM
  - The CpFM for SPS
  - CpFM in operation
  - In-situ recalibration
  - Feedback, limits, and evolutions
- New development: CpFM for double-crystal studies
  - Layout
  - New requirements
  - Studies to improve light collection
  - New electronics
  - Monitoring system
  - H8 characterization
  - New mechanical setup
- Installation in SPS
- Firsts MDs: results in operation, online calibration & feedback / expectations
- Conclusions

Reminder: The CpFM

- **<u>C</u>herenkov detector for <u>p</u>roton <u>F</u>lux <u>M</u>easurement**
- **Main contribution of LAL Laboratory to the UA9 Experiment (CERN)**
- **Developed at LAL, calibrated at H8 (CERN), and BTF (INFN Frascati)**
- **Goal of the CpFM: count the number of protons (or ions) deflected by UA9 bent crystals with a precision of about 5% in the SPS or LHC environment (for <u>each bunch</u>, or <u>mean value over several bunches</u>, with expected values between 1 and 200 p/bunch)**
- The CpFM is now installed on the SPS, 58 m downstream the crystal



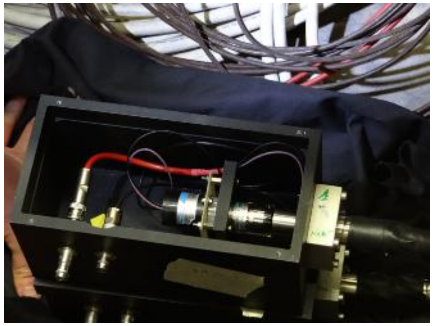
Reminder: The CpFM



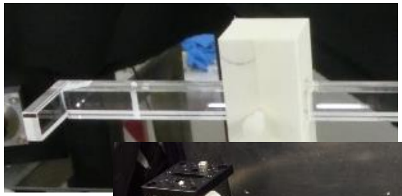
In vacuum, radiation hard detector:

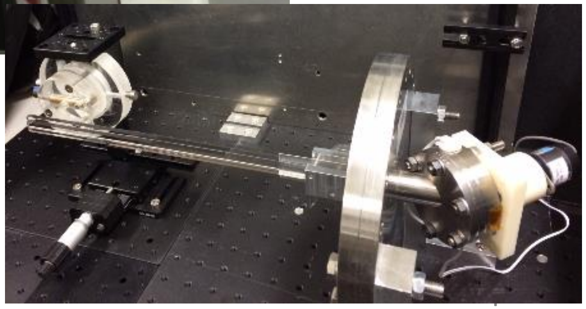
- Interception of the channeled beam by a quartz radiator (2 channels)
- Emission of Cherenkov light
- Readout by a PMT placed 1 m from the beam pipe (light brought by silica fibers)
- PMT amplified signal readout by the WaveCatcher module (3,2 GHz digitizer) integrated to the SPS acquisition system
- 40 m cable between PMT and WaveCatcher (remotely controlled)

Fibres bundle



PMTs socket and housing



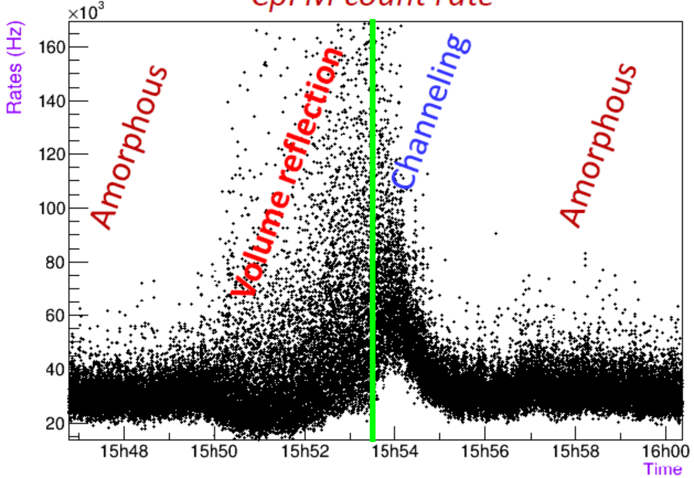


Quartz bars (2 channels, separated by 5 mm)

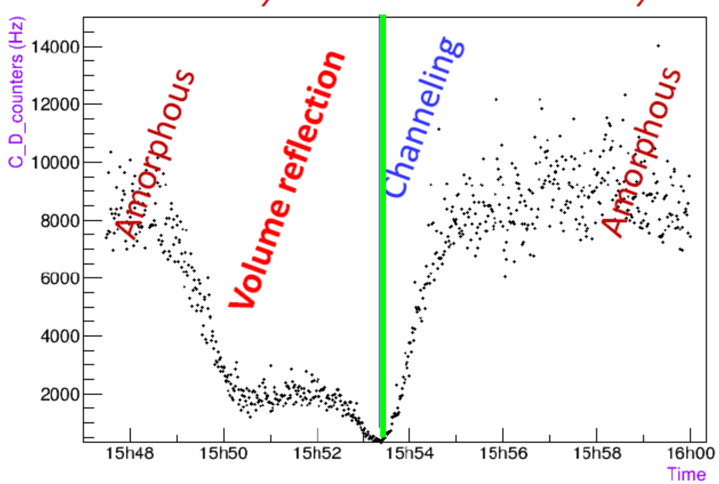
CpFM in operation

Angular scan: counting of the deflected proton when changing the angular orientation of the crystal (from 1800 to 900 µrad)

CpFM count rate



Losses measured by scintillators near the crystal



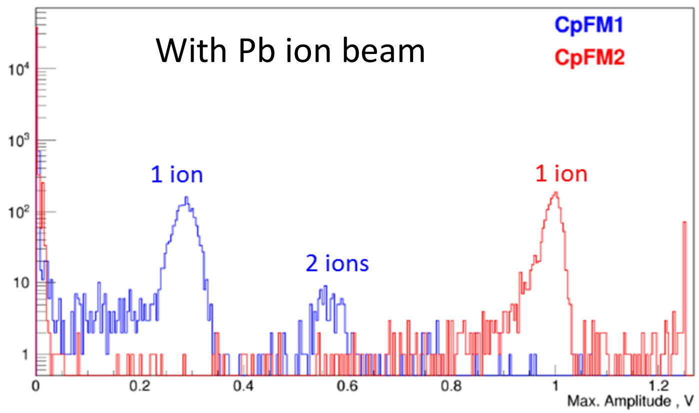
max signal on CpFM ⟷ min losses on the scintillator

Channeling angle found at 1432 µrad

→ good agreement bewteen the CpFM and the scintillator BLM

In situ calibration

Uncertainties about the number of deflected protons when inserting into channeled beam!



CpFM1 $_{750\,V}$ = 271 mV
CpFM2 $_{750\,V}$ = 995 mV

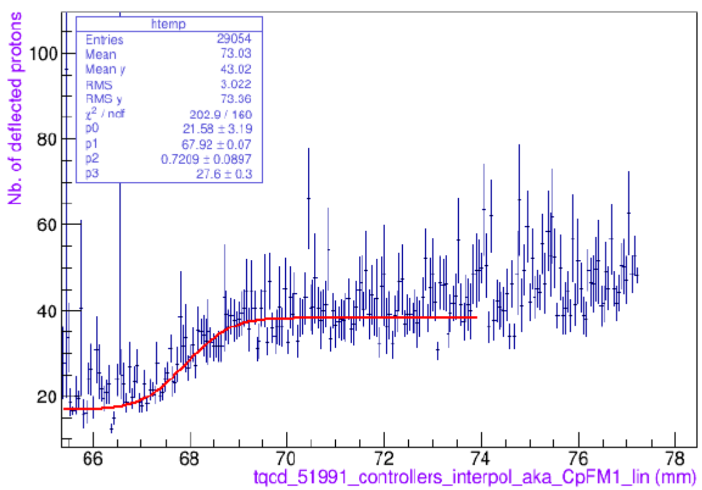
Pb ions generates 6724 times more Cherenkov light than protons (Z^2)

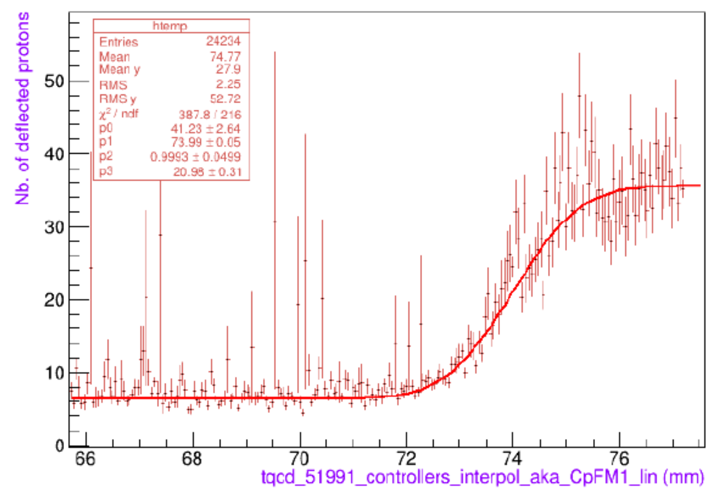
<u>Calibration coefficients:</u>

$CpFM_1$: 0.06 pe/part. 10 times less than expected
$CpFM_2$: 0.18 pe/part. 3,3 times less than expected

→ Factor 3 between the 2 channels

➡ Corrected number of deflected protons as a function of the position:



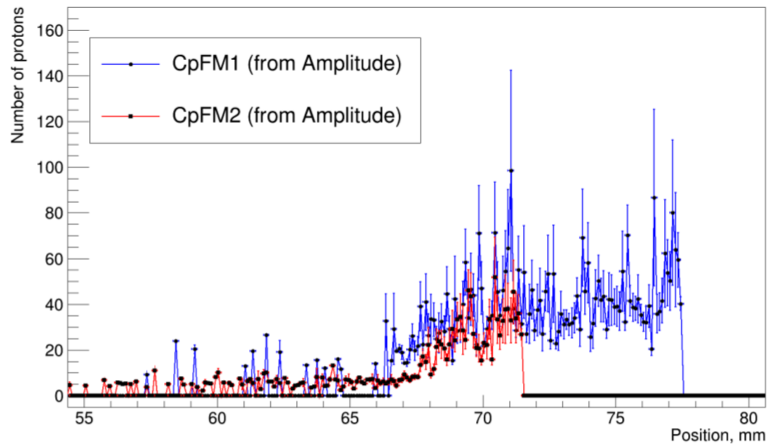


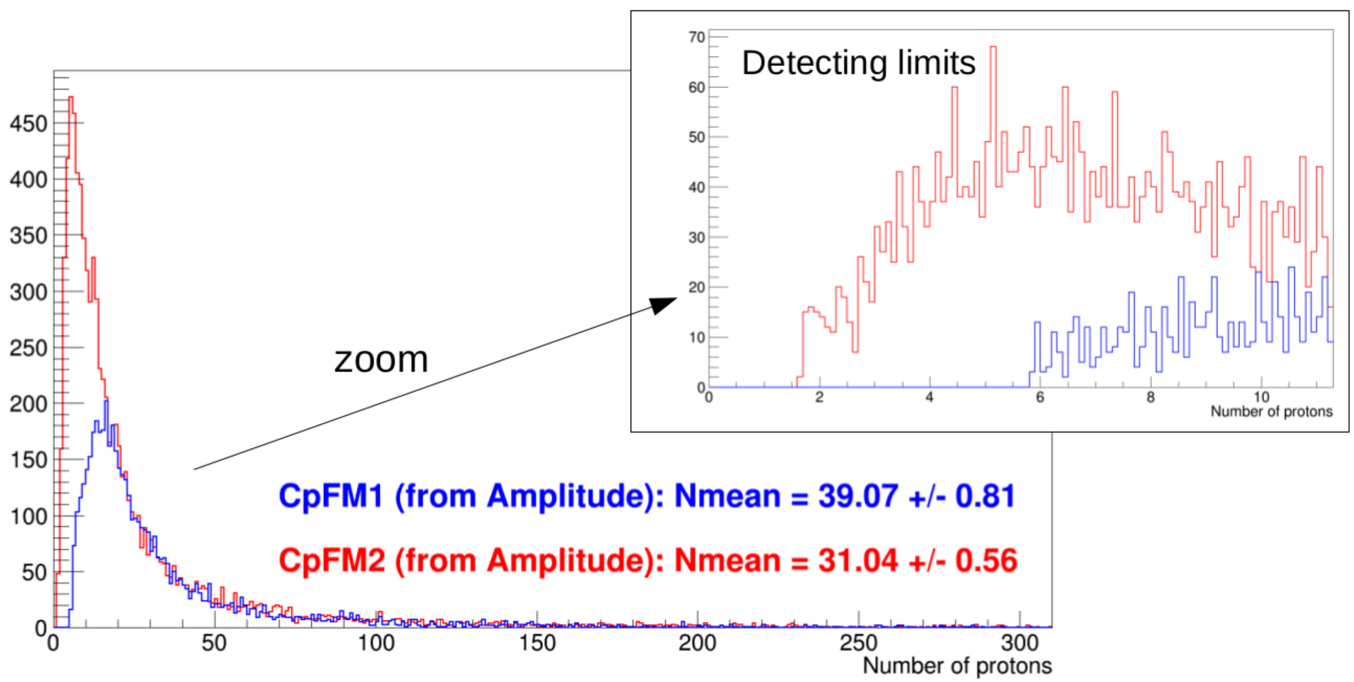
➡ Origin? Measurements performed with a β source shows that the polishing quality of the two quartz bars is not the same + some inefficient corner areas. Drastic effect on light collection!
See "Characterization of the quartz surface quality with β-source", by A. Natochii et al. (published just some days ago…)

In situ calibration

➡ Corrected number of deflected protons as a function of the position & detecting limits

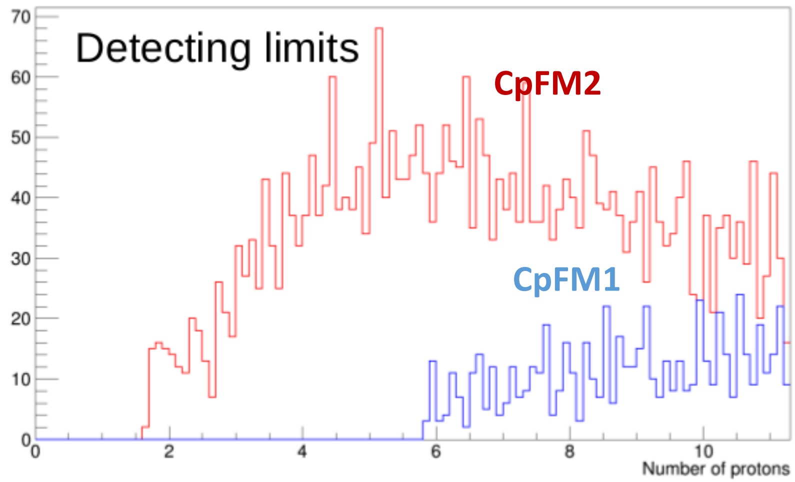
From WaveForms

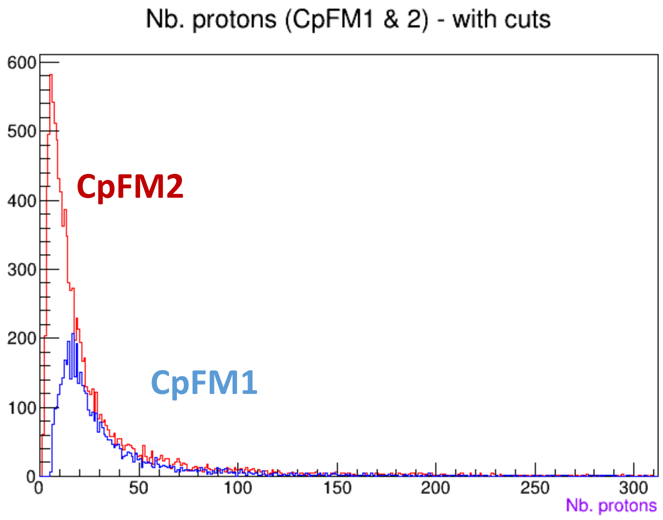




CpFM – Main characteristics, limits, evolutions

- ✓ Use of a fibre bundle -> light collected by the PMT reduced by about a factor 10 -> We could use direct coupling (PMT just disposed behind the viewport)
- ✓ "Simple" geometry for quartz radiators used (and low thickness) -> light production could be optimized with more complex geometries. We need to have enough light to see a single proton (detection threshold should be minimized)
- ✓ Light produced at the output of the quartz bar extremely dependent on the polishing and quartz quality (especially at its edges) -> We cannot completely rely on simulation; we should be very careful and experimentally characterize each bar produced (even from the same production batch)
- ✓ A monitoring system could be useful to check the evolution of the calibration with respect to time
- ✓ As the revolution frequency is 43 kHz, the measure of charge and amplitude is done at a frequency of 43 Hz (1 per 1000). Moreover, the number of deflected protons is drastically changing from one bunch to another. Instead of mean value, more interesting to measure each bunch individually -> Need of a new electronics, with a good time resolution and no dead-time.

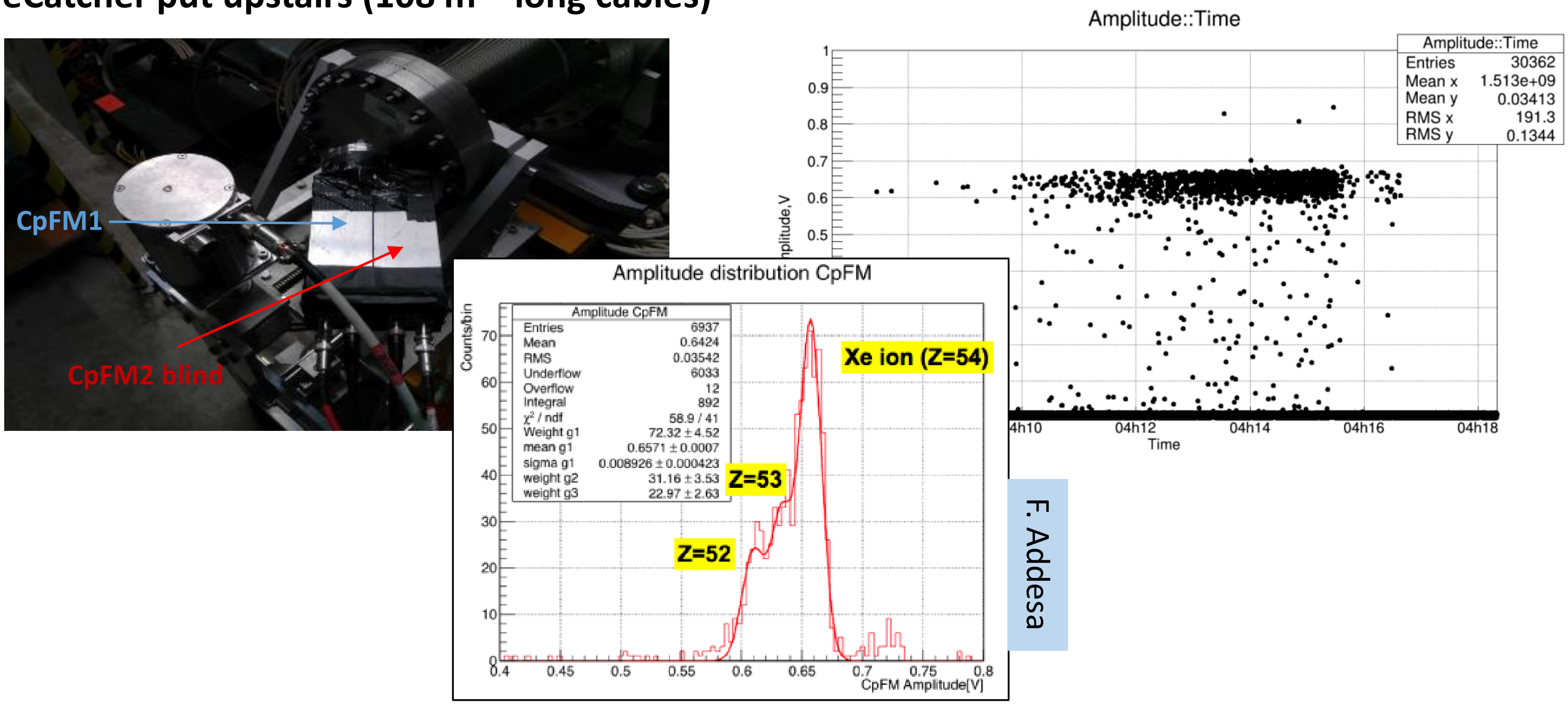




->Development of a new CpFM to fulfil requirements for double-crystal studies: each point addressed in parallel

Fast upgrade

- Very few time during 2017 winter TS: fast / simple updates
- **To have a better proton efficiency: bundle removed (PMT directly coupled with the viewport), bars inverted (more sensitive bar put close to the beam). Only one channel kept (second PMT is blind for electromagnetic pick up measurements). Electromagnetic shield added.**
- **WaveCatcher put upstairs (108 m – long cables)**



- **Checked during a MD with Xe ions (same procedure as explained before): 18.2 mV / proton at 1050 V (corresponds to 1.17 pe/proton). Before: 0.18 pe/proton (-> about 85% of light lost in the bundle)**

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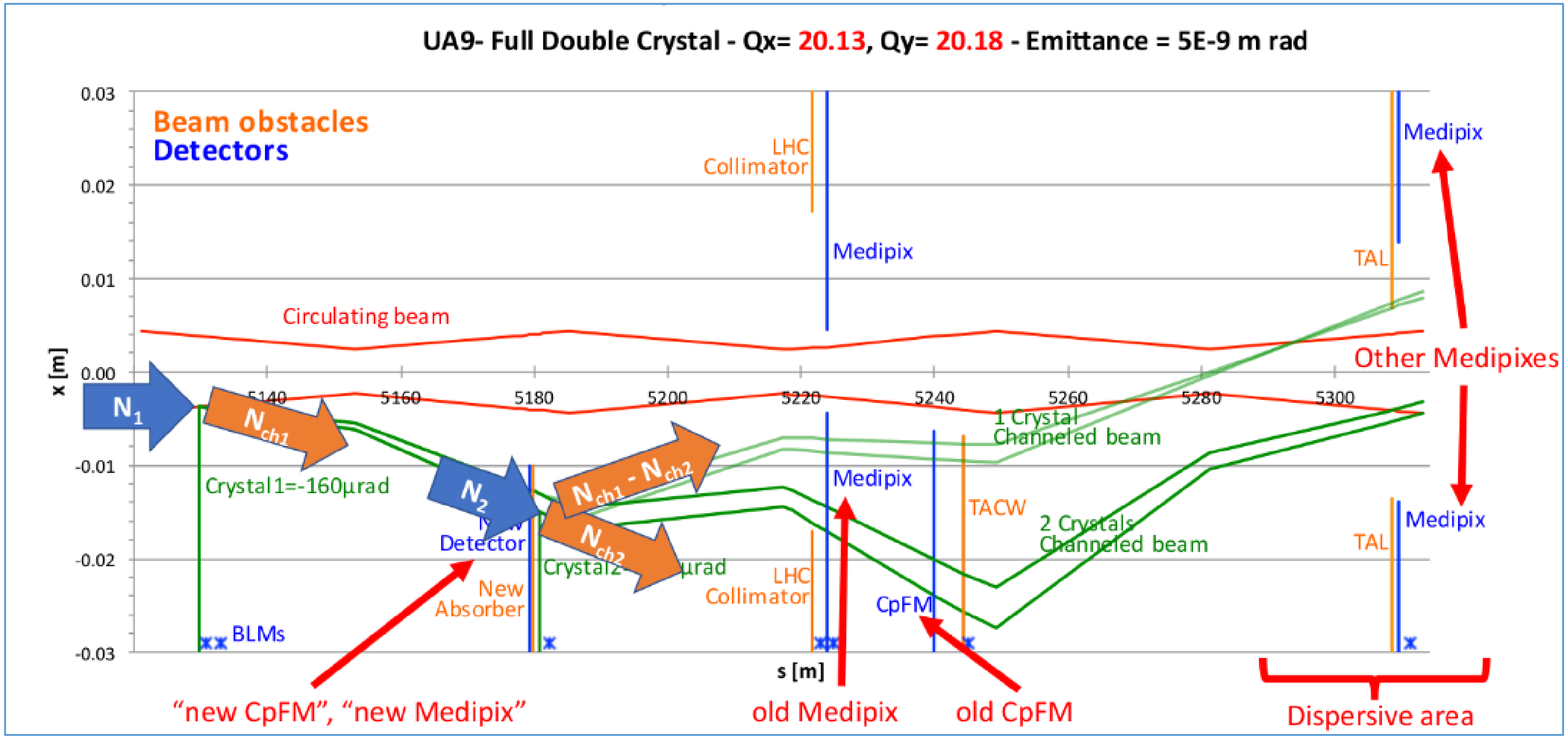
Layout for the Double Beam Splitting



❖ Need to measure combined efficiencies of Crystal 1 & 2:

- N_1: number of protons reaching Crystal 1 (estimated by lifetime / diffusion speed - BCTs)
- $N_{ch1} \approx N_2$: nb. of protons channeled by Crystal 1 and reaching Crystal 2 **-> To be measured by the new CpFM, for several seconds and <u>for all bunches</u>**
- N_{ch2}: nb. of protons channeled by Crystal 2 **-> Measured by the "old" (but updated) CpFM**

CpFM for the Double Beam Splitting

Typical beam properties

- Longitudinal parameters:
  - Revolution time: 23 us
  - N. of buckets: 4620
  - Bucket length: 5 ns
  - Bunch length: 1.5÷3 ns
- Intensity (per bunch):
  - INDIV → 1÷1.5 x 10^{11} p
  - PROBE → 5÷20 x 10^{9} p
- Beam emittance: 2÷25x10^{-9} m rad
- Lifetime 0.5÷8 h
- Tune:
  - Q_x = 20.13, Q_y = 20.18 ("double crystal")
  - Q_x = 26.13, Q_y = 26.18
  - Q_x = 26.62, Q_y = 26.58 ("extraction")
- Filling scheme (limitations for total intensity!)
  - Single → relax timing requirements
  - N x single with separation 23 us / N
  - N x 12 → N trains of bunches at 75 ns (N <= 4)
  - N x 48 → N trains of bunches at 25 ns (N <=4)
  - N x 36 → N trains of bunches at 50 ns (N <=4)
  - N x 72 → N trains of bunches at 25 ns (N <=4)

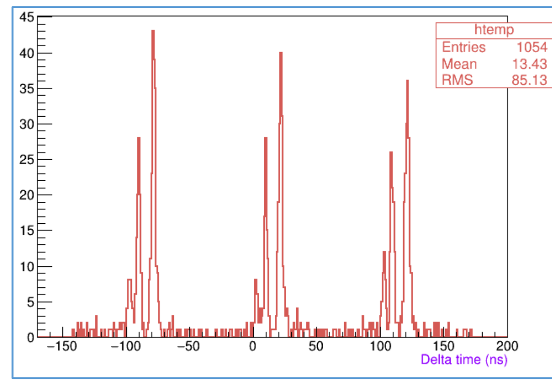
❖ **In old CpFM, one bunch every 23us (43 kHz), measure of 1/1000 by the WC (43 Hz) -> we loose the "history"**

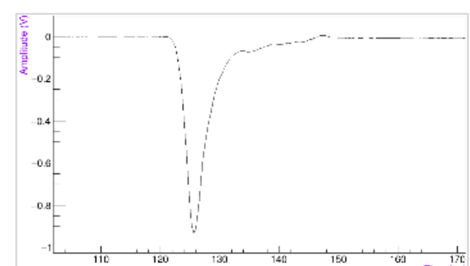
❖ Acquisition window between 312.5 ns and 2.5 us (400 MHz – 3.2 GHz WC sampling frequency)

❖ **For the new CpFM: minimum 1 bunch every 23 us (measure at 43 kHz), maximum of 4 trains of 72 bunches (each spaced by 25 ns) every 23 us -> We should work at 40 MHz to measure each bunch (a complete train: 1.8 us)**

❖ With the old CpFM, we are already able to separate successive bunches at 25 ns (possible to see a complete train), but still only 1/1000 (43 Hz) and not possible to measure charge and timing for *each bunch*

❖ **Need a dedicated and new electronics working at up to 40 MHz with no dead-time**

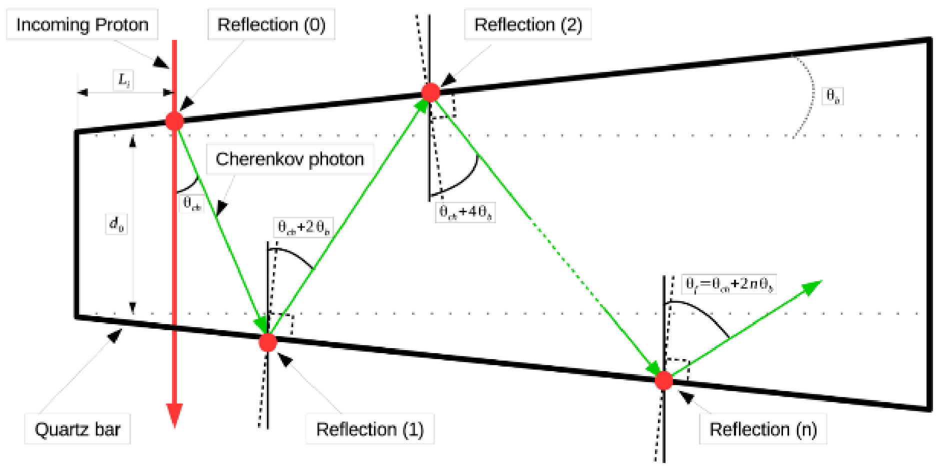




Study of new geometries for quartz radiator

✓ **How to improve light-collection?**

- **Bigger cross-section (instead of 5mm, maybe 10 mm?) -> More Cherenkov light produced and number of reflections divided per 2.**
- **Removing bundle (already done, see before)**
- **Brazing of bars through viewport (R&D, not ready -> *See Vincent Chaumat's talk tomorrow*)**
- **Better polishing quality (limitation of light-losses with total internal reflection)**
- **Shorter bars (less reflections, but not possible here)**
- **New geometries (less reflections, and more Cherenkov light). Example: pyramid-shape. Each time after single reflection initial angle will change by the double θ_b (θ_b - half pyramid opening angle) -> Number of reflections reduced.**

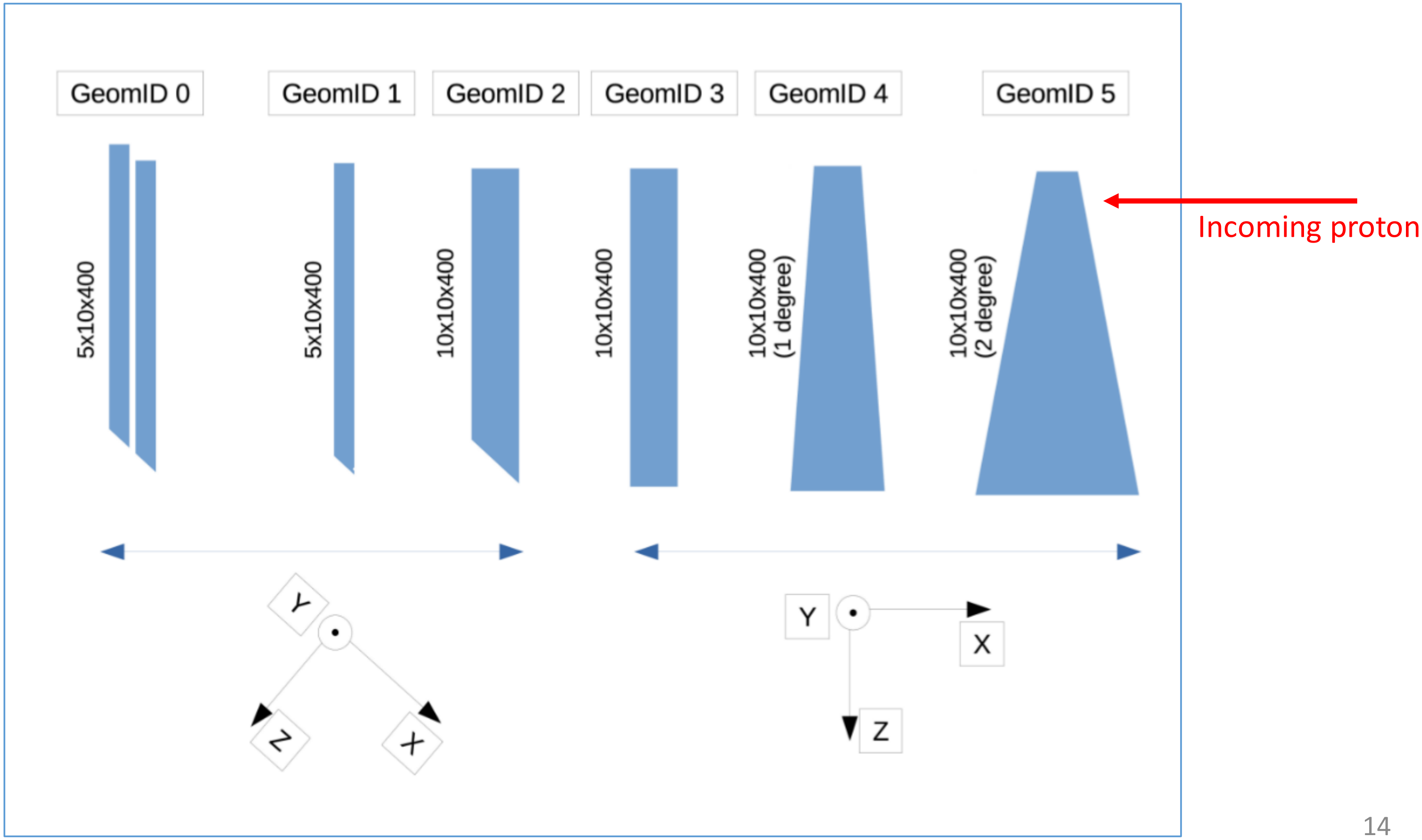


✓ **Need simulations!**

Study of new geometries for quartz radiator

Team work of Andrii Natochii & Leonid Burmistrov

- ✓ **Simulation of different quartz geometries (various thicknesses, 47° degrees cut or not, "I" or "pyramid" shape)**
- ✓ **Actual geometry: configuration #0 or #1 (length of 400 mm, kept for this simulation)**
- ✓ **With GEANT4: response to a flux of incoming protons impinging the extremity of the bars (close to the circulating beam)**



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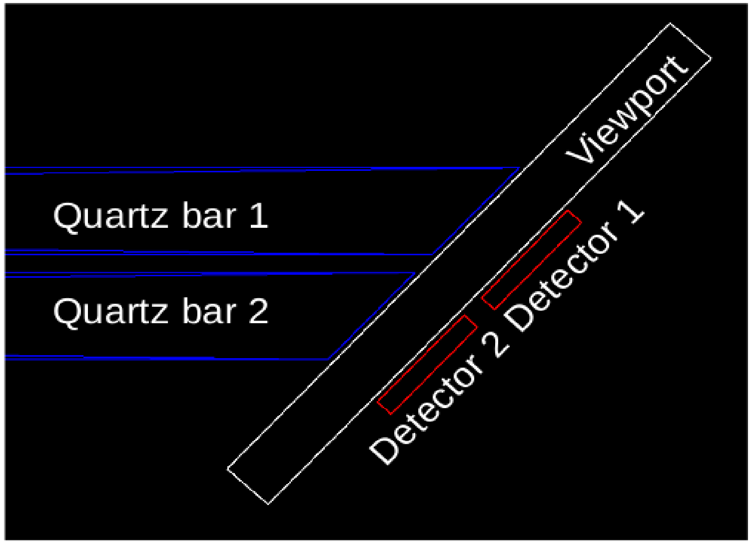
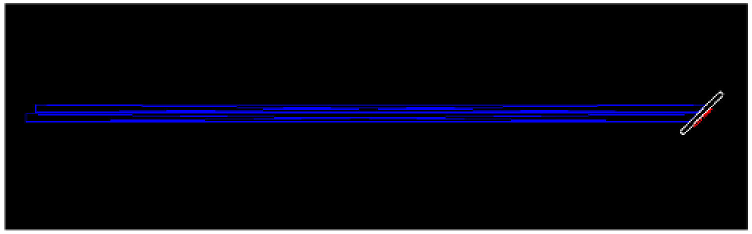
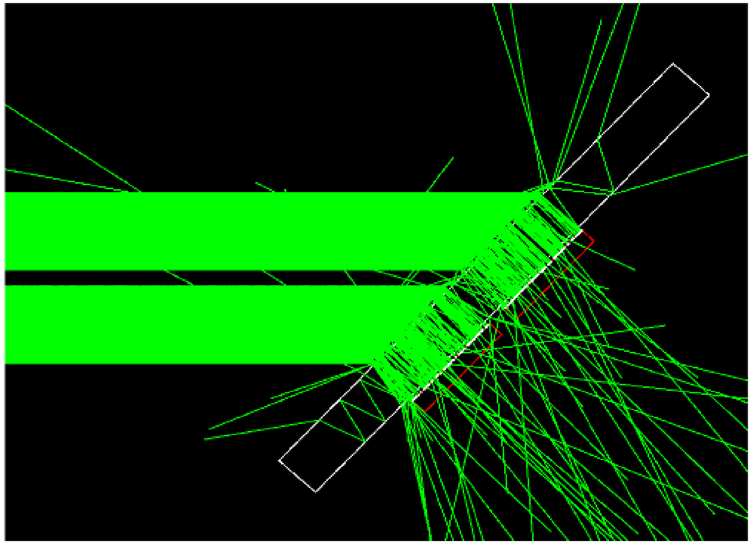


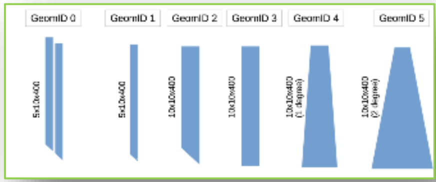


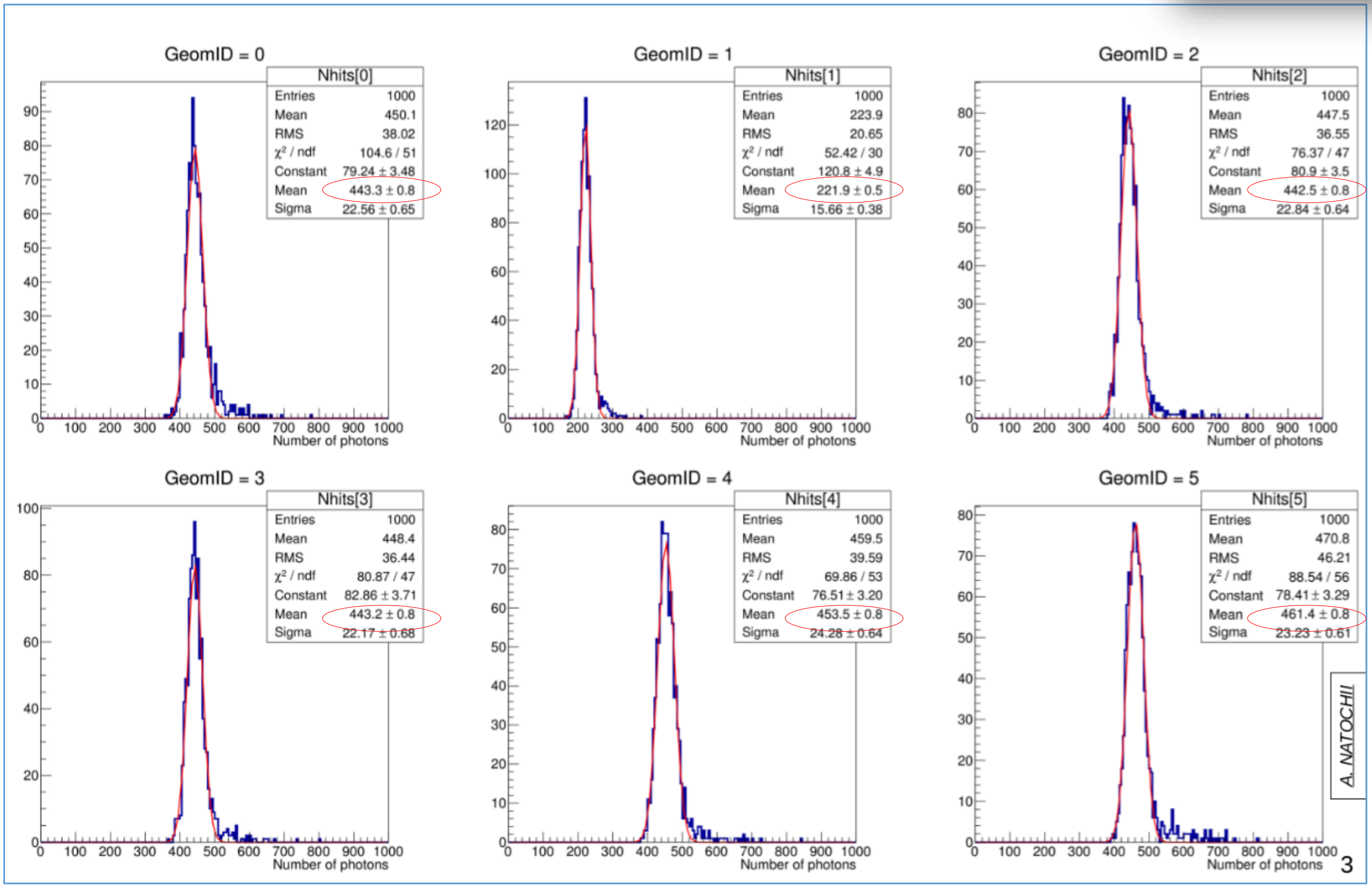


-> For each proton, tracking of all Cherenkov photons generated.
-> Transportation (reflections, absorption, diffraction) & detection (or not) by a photodetector

Study of new geometries for quartz radiator

- ✓ **Distribution of the number of photons hitting the detection surface:**
- ✓ **… between 443 and 461 photons / proton**
- ✓ **Nb. of reflections?**

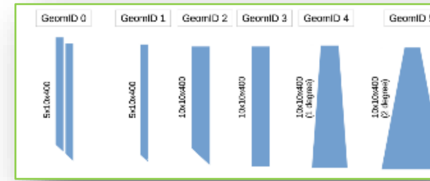


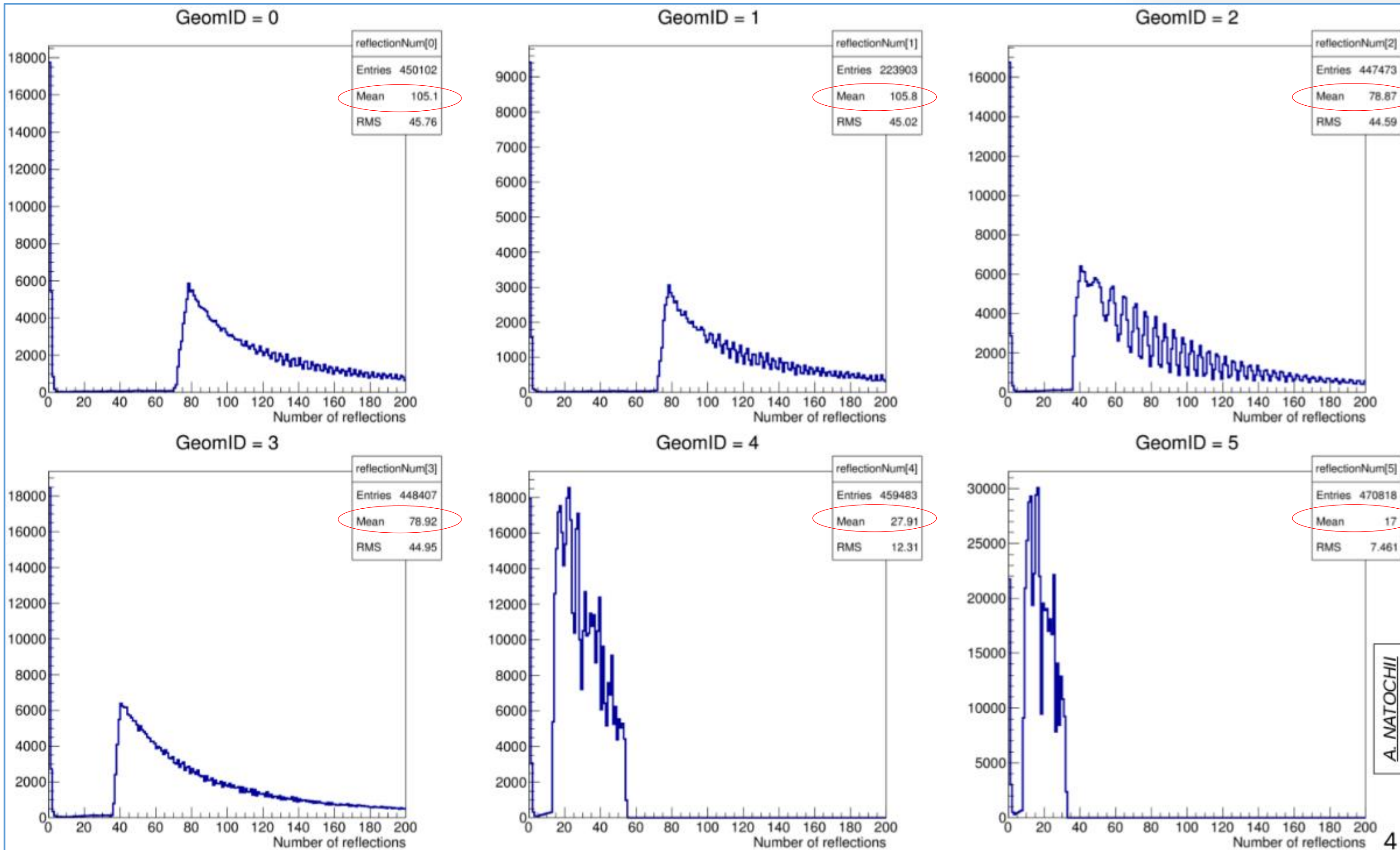


Team work of Andrii Natochii & Leonid Burmistrov

Study of new geometries for quartz radiator

- ✓ **Distribution of the number of reflections for each Cherenkov photon:**



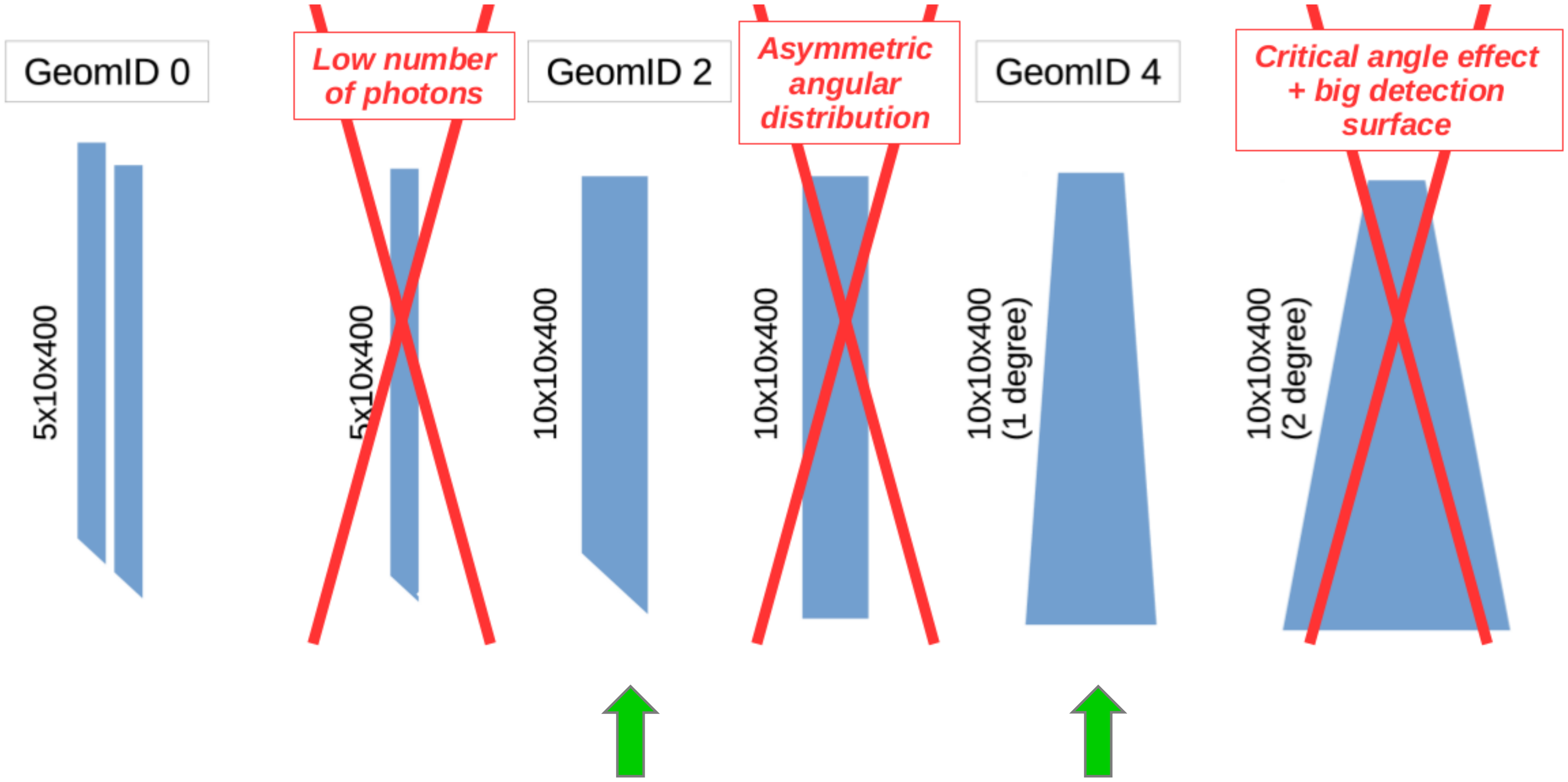


Team work of Andrii Natochii & Leonid Burmistrov

Study of new geometries for quartz radiator

✓ **Conclusions for the design of a new detector:**

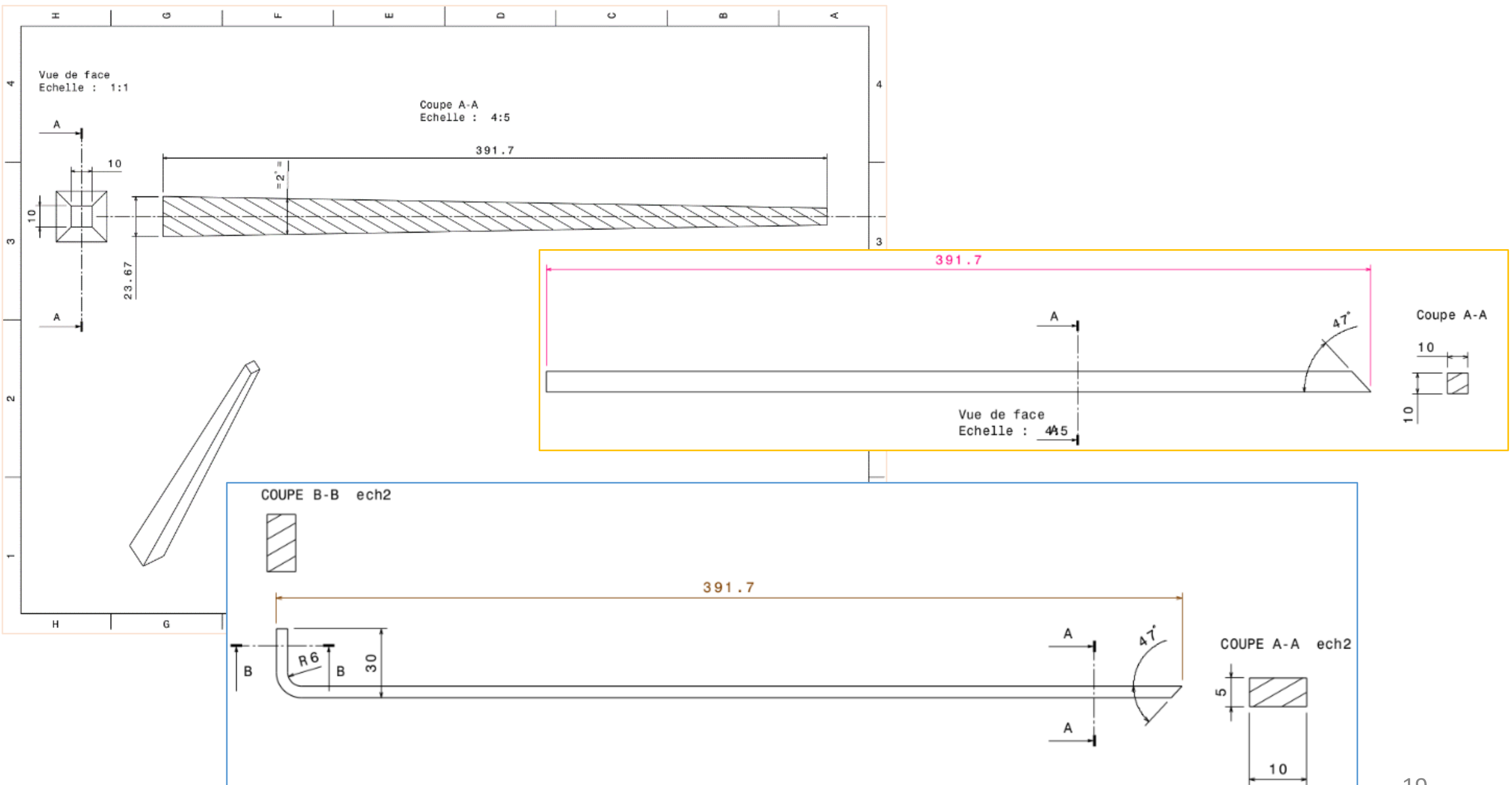
- **Geometry #0: installed**
- **Geometry #2: more Cherenkov photons generated (compared to #1) and less reflections (compared to #0), adapted to the using of a fibers bundle**
- **Geometry #4: high number of Cherenkov photons produced, low number of reflections, photons focussed on a "small" surface (2.4 * 2.4 cm^2). Also, suitable for direct coupling.**



Study of new geometries for quartz radiator

✓ **For the new CpFM, we decided to order (from Optico AG, with surface roughness of < 1 nm rms):**

- **Two "pyramid"-shape bars of 0.8°, to be used without bundle (direct coupling)**
- **One "I"-shape bar of 10*10 mm^2 , as a backup or an update for the "old" CpFM**
- **One additional "banana"-shape bar (nose of 3 cm, thickness of 0.5 cm), as a backup or an update for the "old" CpFM**



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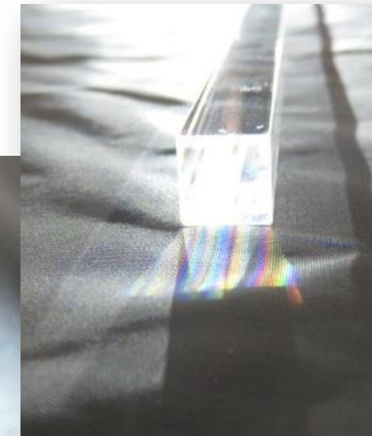
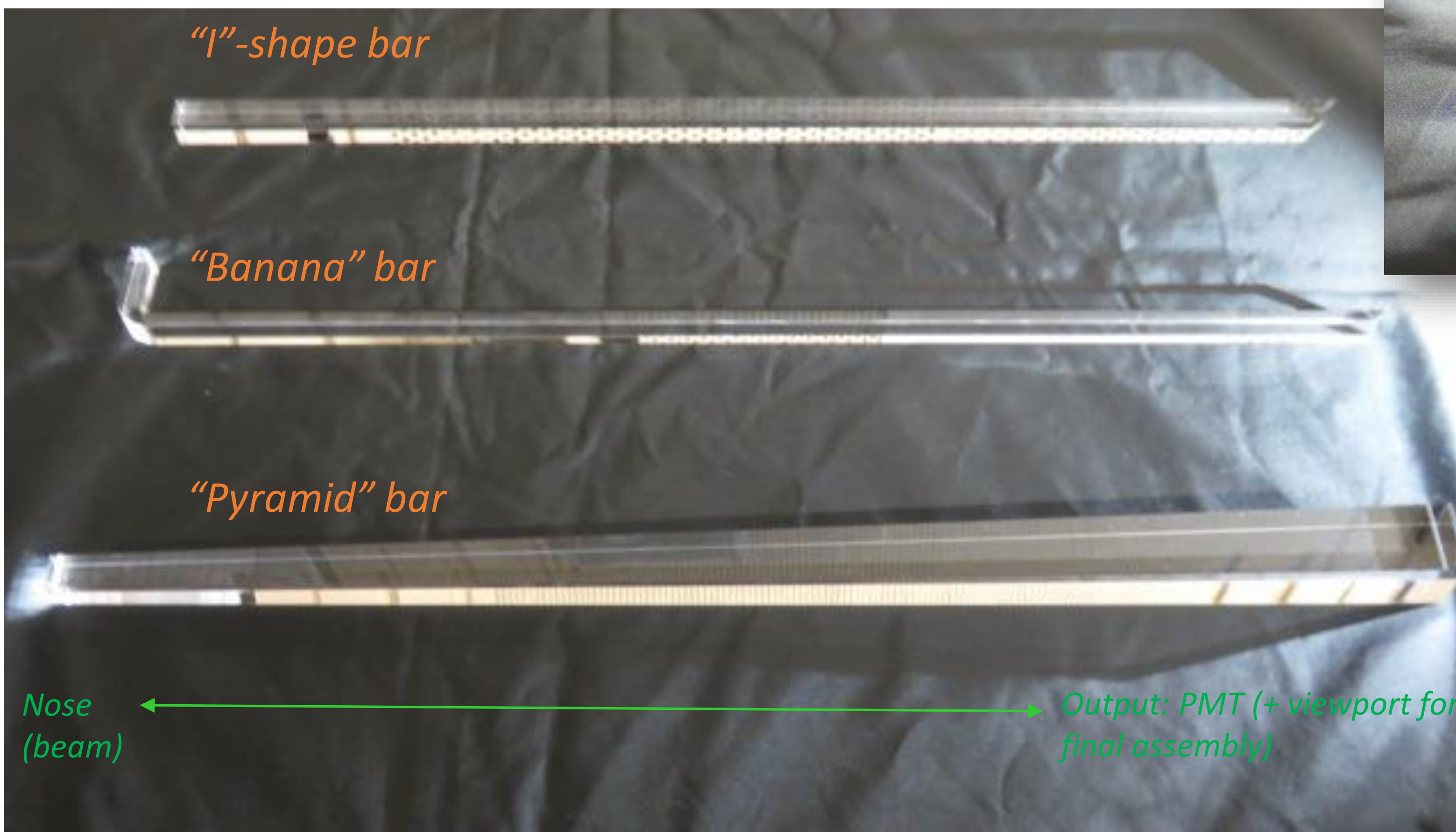
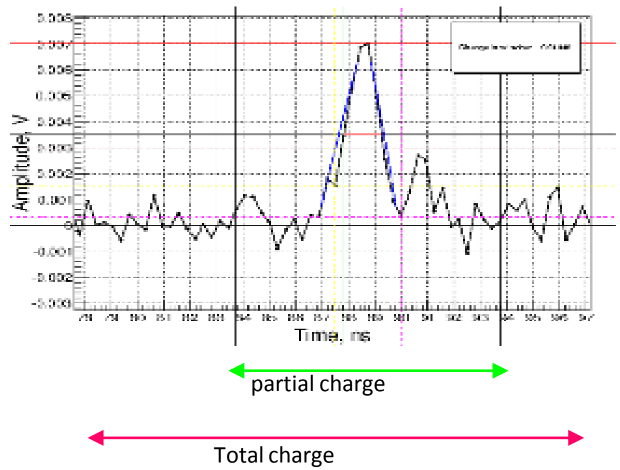


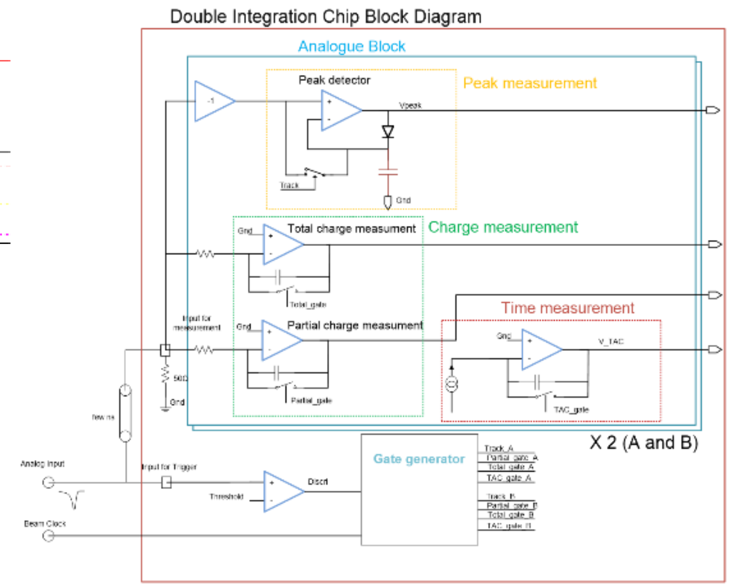


New electronics

✓ **Design** of a new electronics (dedicated ASIC): measurement of the charge, the amplitude and the time at 40 MHz without dead-time

- **Evaluation of both partial and total charge, plus amplitude and timing, every 25 ns (every bunch measured in any case in SPS or LHC environment)**



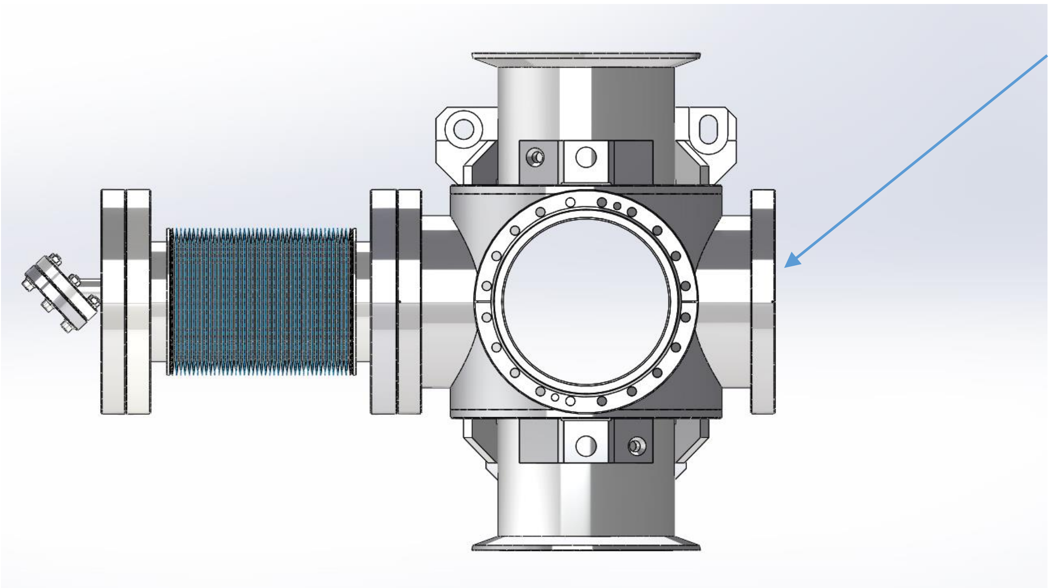


- Design under study (close collaboration with SERDI, Philippe Vallerand)
- Some choices to do: technology used, ways to estimate partial and total charge (sampling, delays…), back-end (from WaveCatcher or redesigned)… **Merged with the ASIC developped in parallel for Cherenkov Lab project**

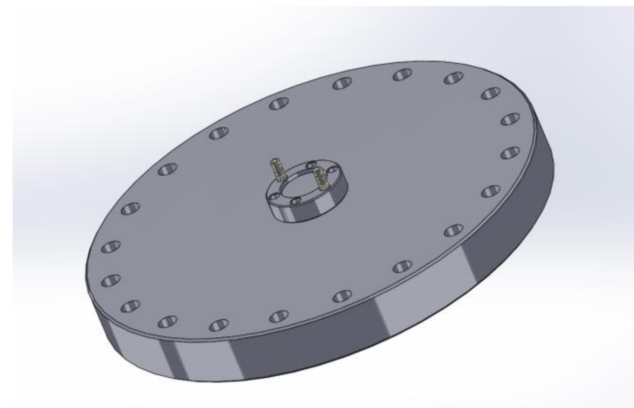
- **Before, and in any case, we can use the COBRA electronics, able to register waveforms without discontinuity for several seconds (and analysis software already available in the laboratory).**

Monitoring system

- ✓ **We proposed to install in the CpFM tank a LED-light source.**
- ✓ **Possible to inject the light to the CpFM tank, to check/follow the gain calibration of CpFM**

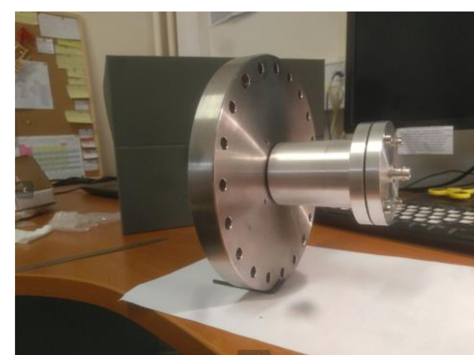


Proposal for the installation of the LED system



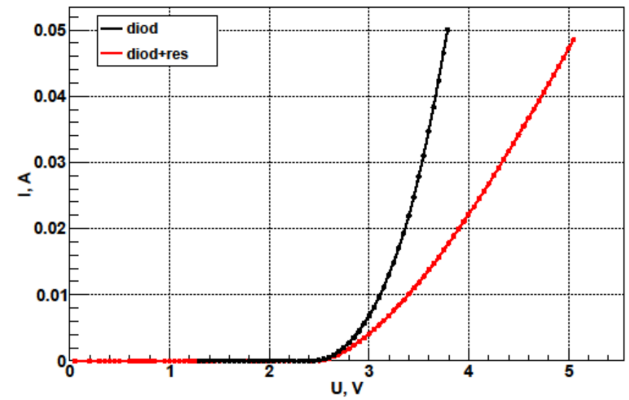
- ✓ **Flange with hole for viewport. Could be easily adapted for possible other purposes (in the future).**
- ✓ **We developed a system for attaching the LED to the viewport**

Proposed by
Volodymyr Levsheniuk
& Leonid Burmistrov



Monitoring system

- ✓ **Added a series resistor to limit the current (below 50 mA)**
- ✓ **Set-up to have a probability to measure only singles photoelectrons (or 0 p.e.)**
- ✓ **Checked the gain of a well-known PMT used in the lab -> OK**



Calculation Gain for High voltage 1000V:
test #1

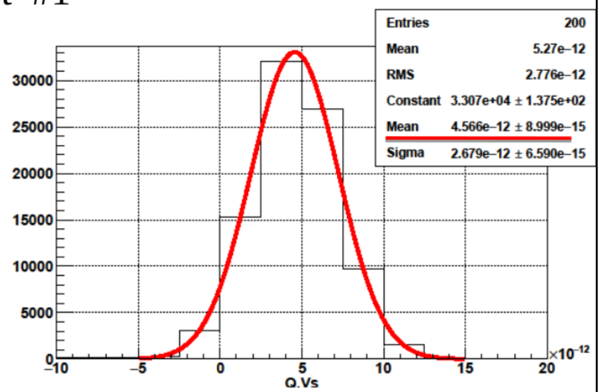
$$Q = \int I(t)dt$$

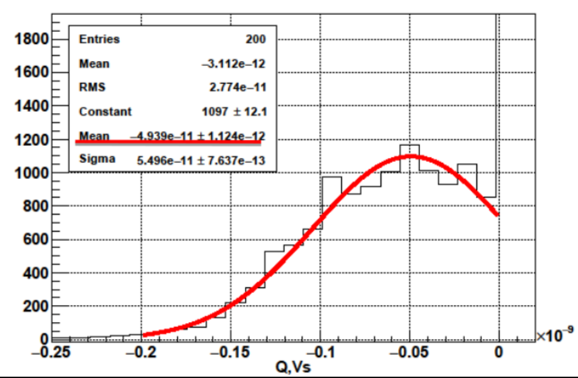
$$I(t) = \frac{U(t)}{R}$$

$$Q = \int \frac{U(t)dt}{R}$$

$$R = 50\Omega, e^{-} = 1.6 \cdot 10^{-19} q$$

$$G = \frac{Q}{e^{-}}$$





For HV 1000V :

$$G = (6.832 \pm 0.014) \cdot 10^{6}$$

Calculation probability for different number of photoelectron (test #1)

$$P = \frac{\lambda^{k} e^{-\lambda}}{k!}$$

$$p(0) = \frac{N(0)}{N} = 0.8852 \rightarrow 88.52\%$$

$$p(0) = e^{-\lambda} \rightarrow \lambda = 0.12$$

$$p(1) = \lambda \cdot e^{-\lambda} = 0.1062 \rightarrow 10.62\%$$

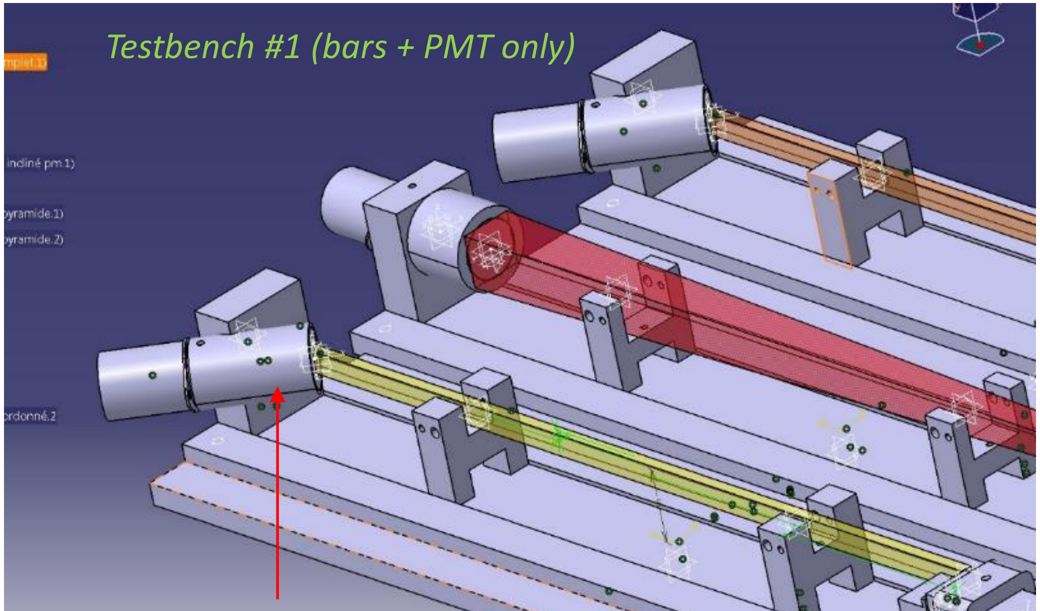
$$p(2) = \frac{\lambda^{2}}{2!} e^{-\lambda} = 0.0072 \rightarrow 0.72\%$$

$$p(3) = \frac{\lambda^{3}}{3!} e^{-\lambda} = 0.0003 \rightarrow 0.03\%$$

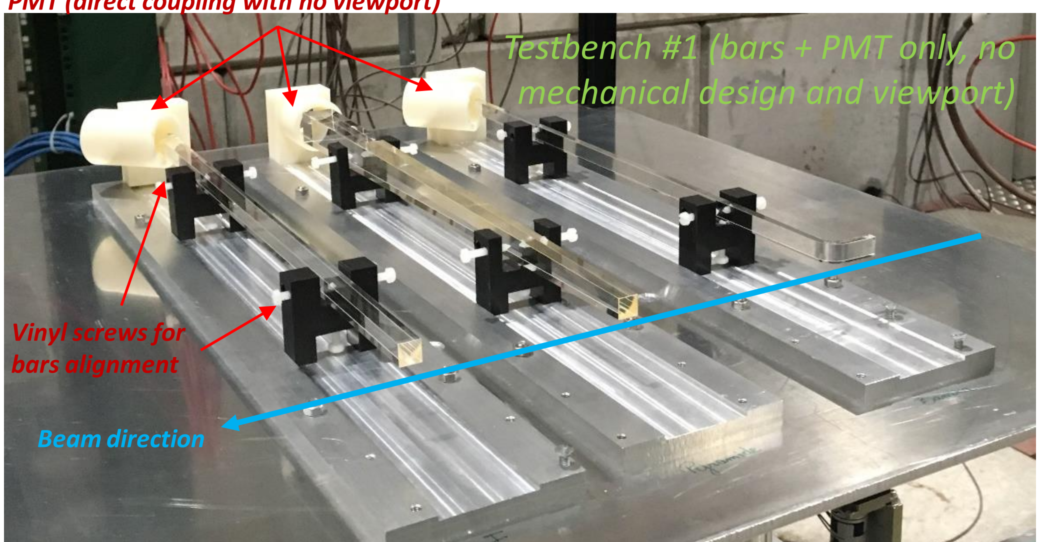
Part of work of Dariia Frondzei (student at LAL)

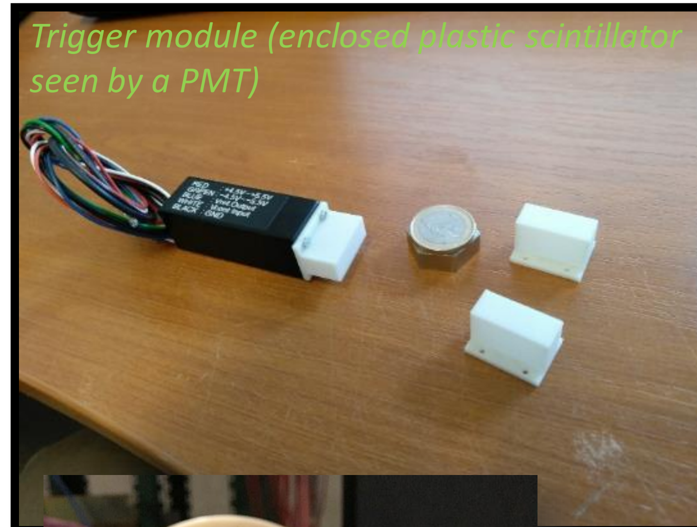
Test setup for H8 beam-tests

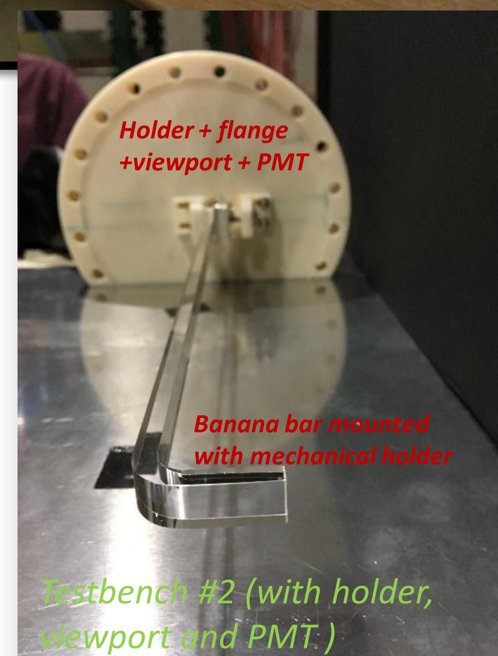
✓ **Mechanical pieces fabricated (holder, boards) or made with the LAL 3D printer (PMT holder, scintillator package)**



PMT (direct coupling with no viewport)

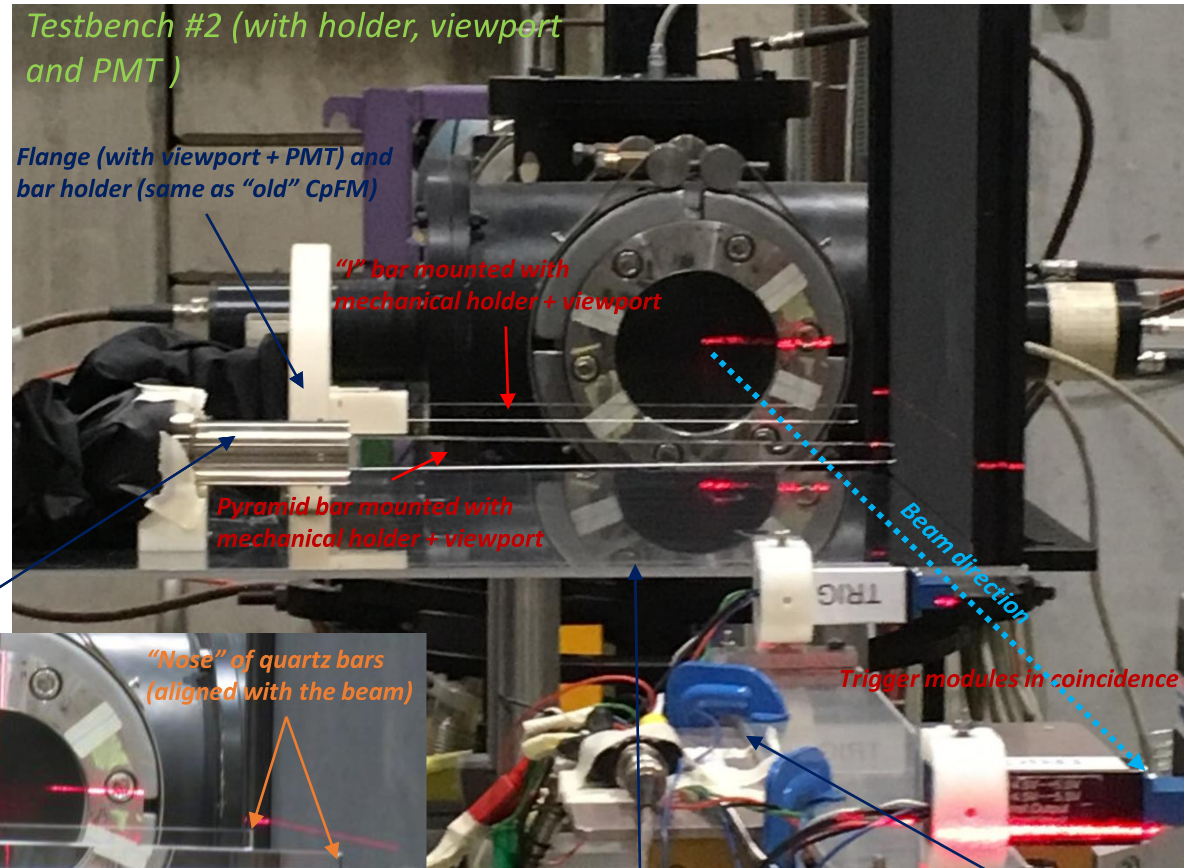




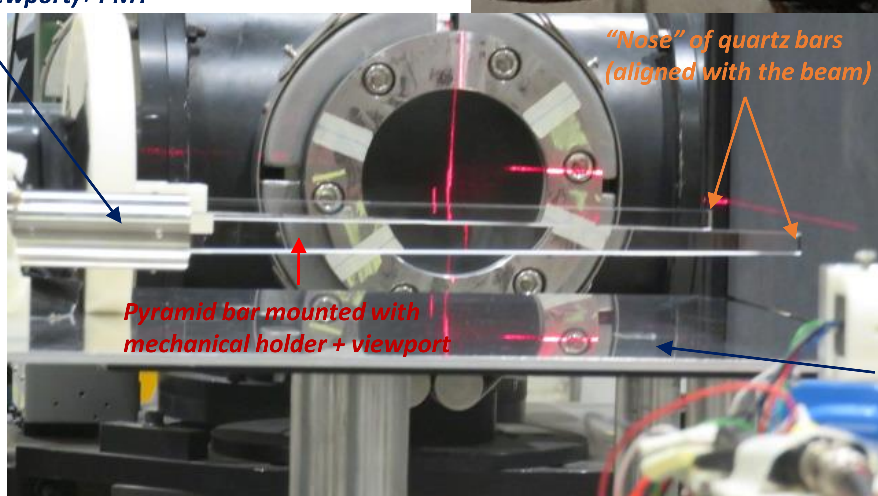


Test setup for H8 beam-tests

- ✓ **Not only characterization of quartz… But also complete comparison in a "final" configuration (bar + viewport + holder+ PMT & its socket)!**



Bar holder for pyramid (metallic tube with 8 screws attached to a viewport)+ PMT

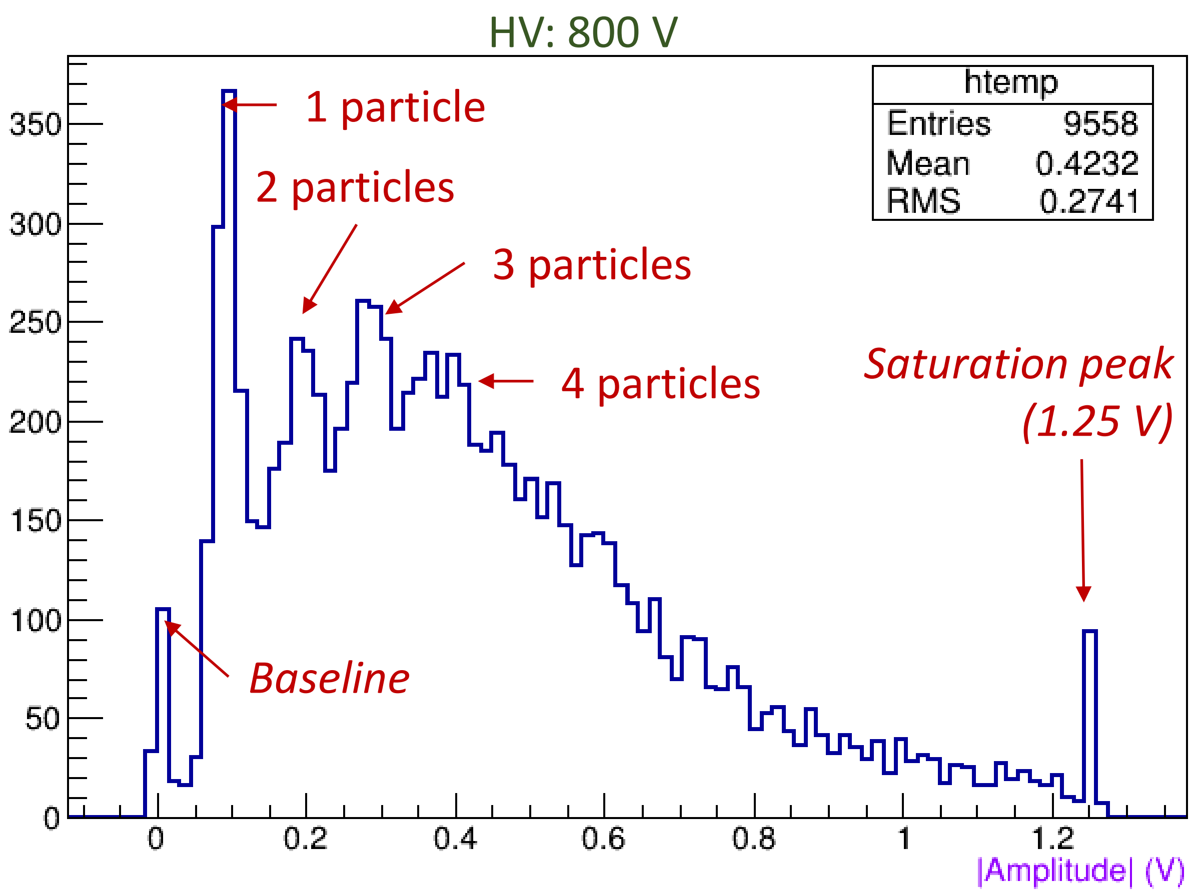


3D translation stage (for aligning triggers with the beam)

3D translation stage (for aligning nose of different barswith the beam)

Pyramid characterization with holder + viewport (final configuration). Multiple particles

- ✓ **Best results: Pyramid + holder (metallic tube with screws) + quartz viewport + PMT ZN2207 and its socket (AB 1216)**
- ✓ **Amplitude distribution for different HV**
- ✓ **Trigger: coincidence Trigg #0 + Trigg #1 + bar**



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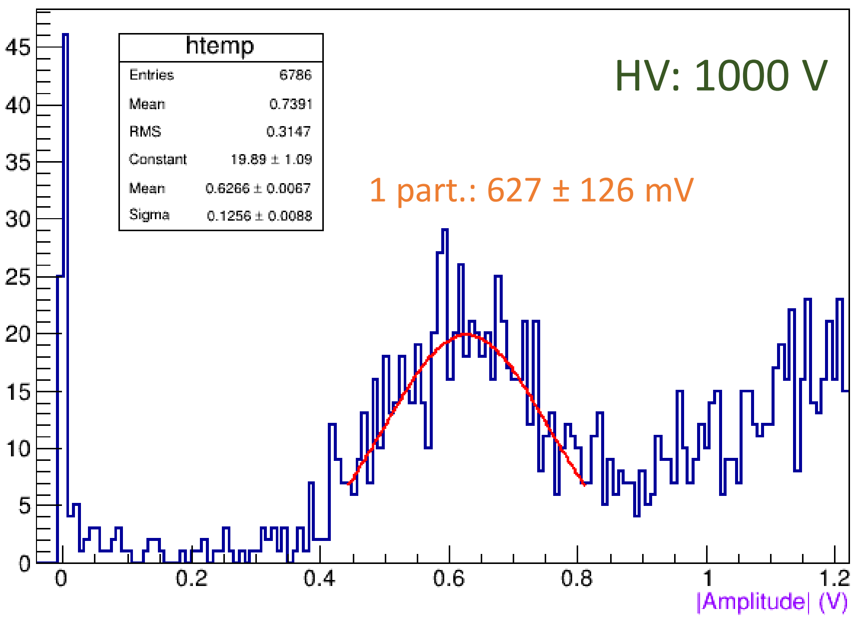
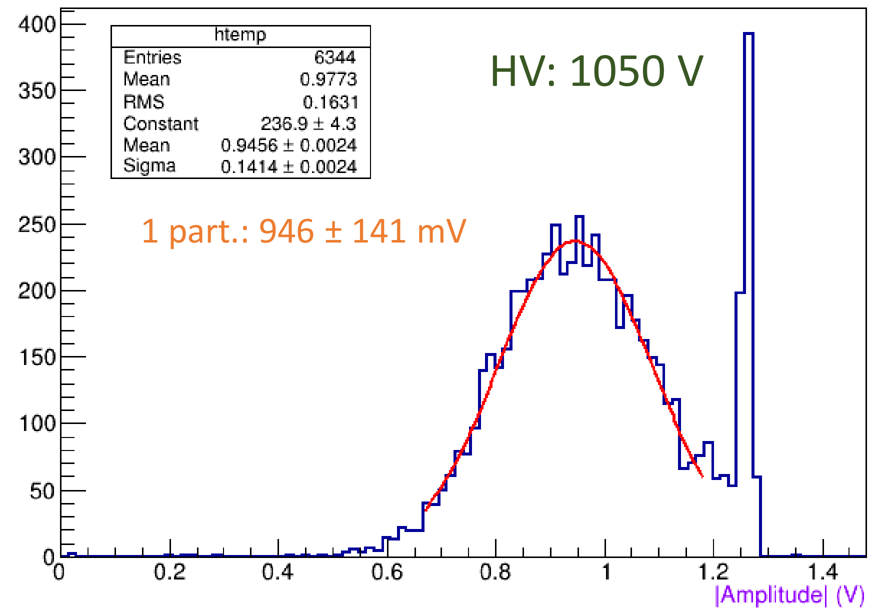
- ✓ **Amplitude distribution for different HV**
- ✓ **Trigger: coincidence Trigg #0 + Trigg #1 + bar**

-> At high gain (1000 V & 1050 V):



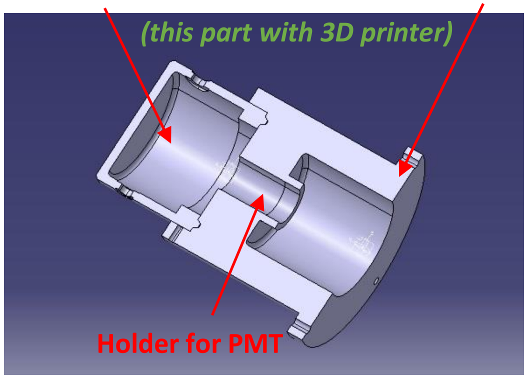


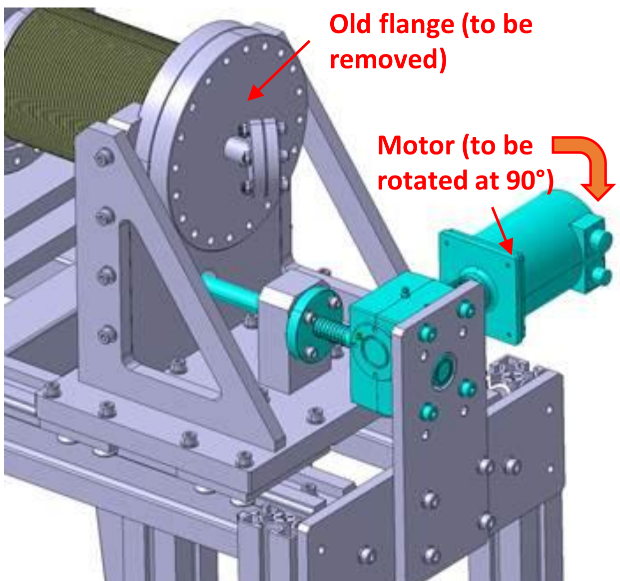
-> Reminder from "old" CpFM: At 1050 V, 1.03 mV (CpFM1) & 3.58 mV (CpFM2)

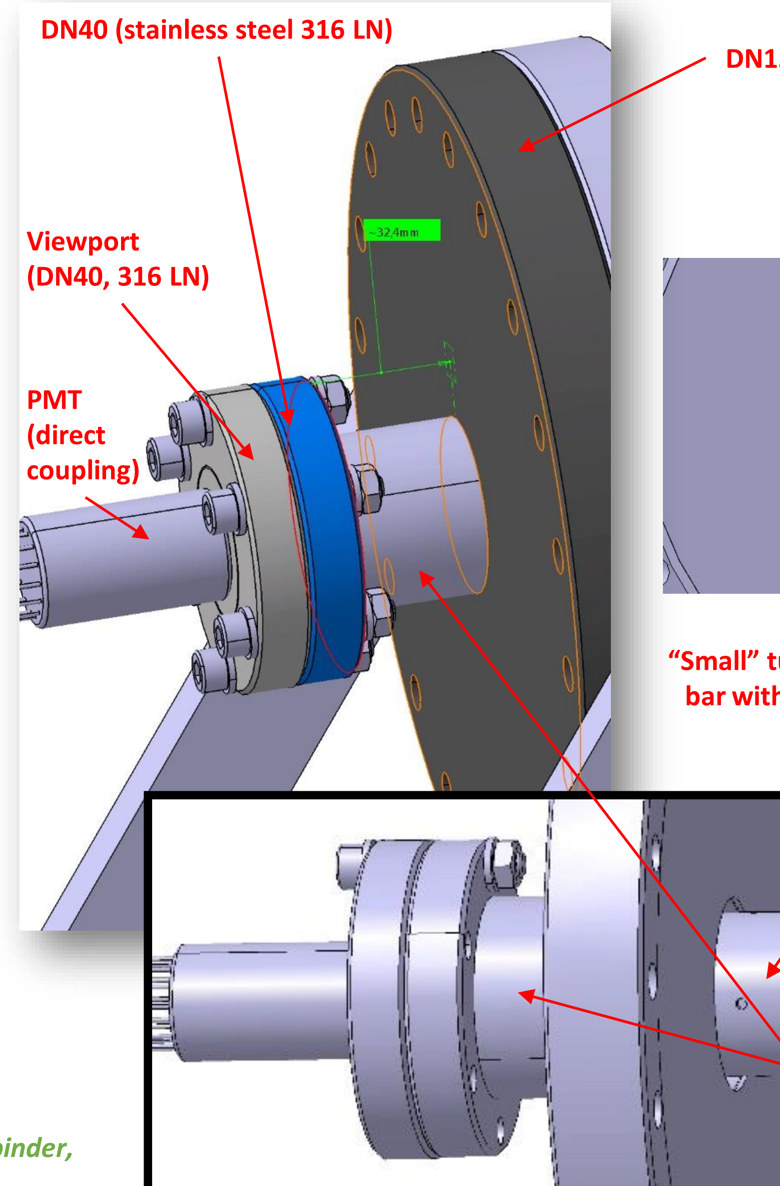
-> Up to 60 p.e./proton!

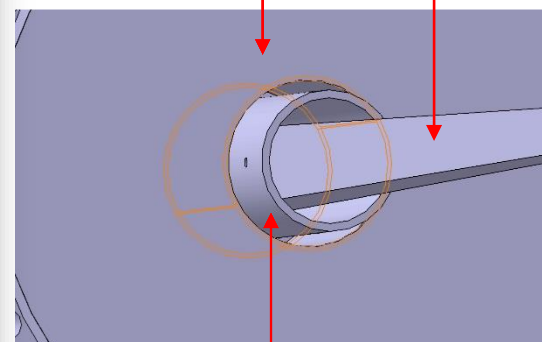
New setup installed

- ✓ **Designed and realized at LAL (M. Brière & F. Rudnyckyj)**





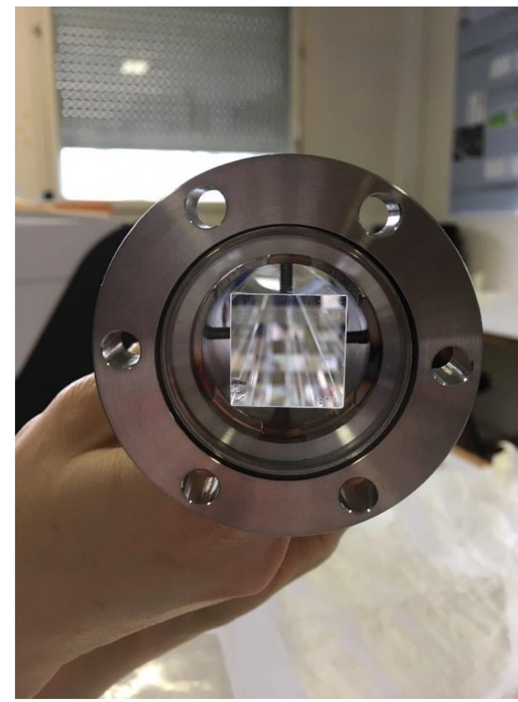




(discussed with Simone Montesano & Regis Seidenbinder, CERN)

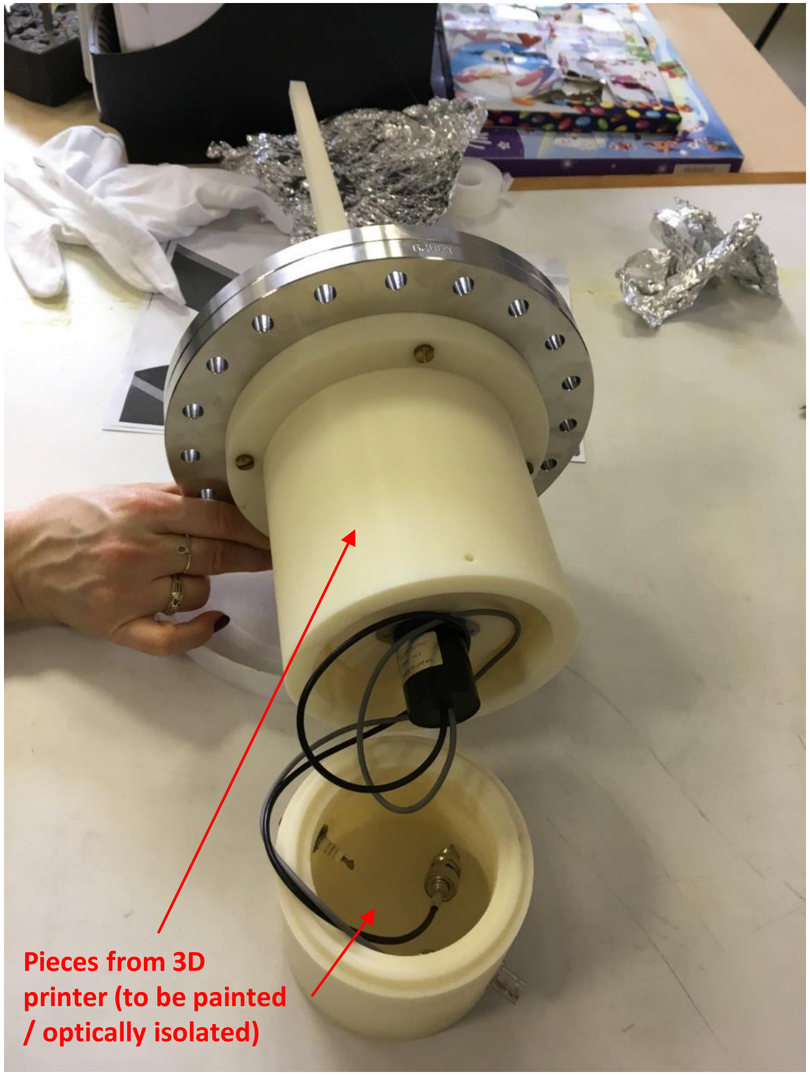
New setup installed

- ✓ **Mechanical realization (viewport + “small tube” (bar holder) + quartz):**



New setup installed

- ✓ **Mechanical realization (with DN150 flange and covers / PMT holders):**



Outline

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  - In-situ recalibration
  - Feedback, limits, and evolutions

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  - Layout
  - New requirements
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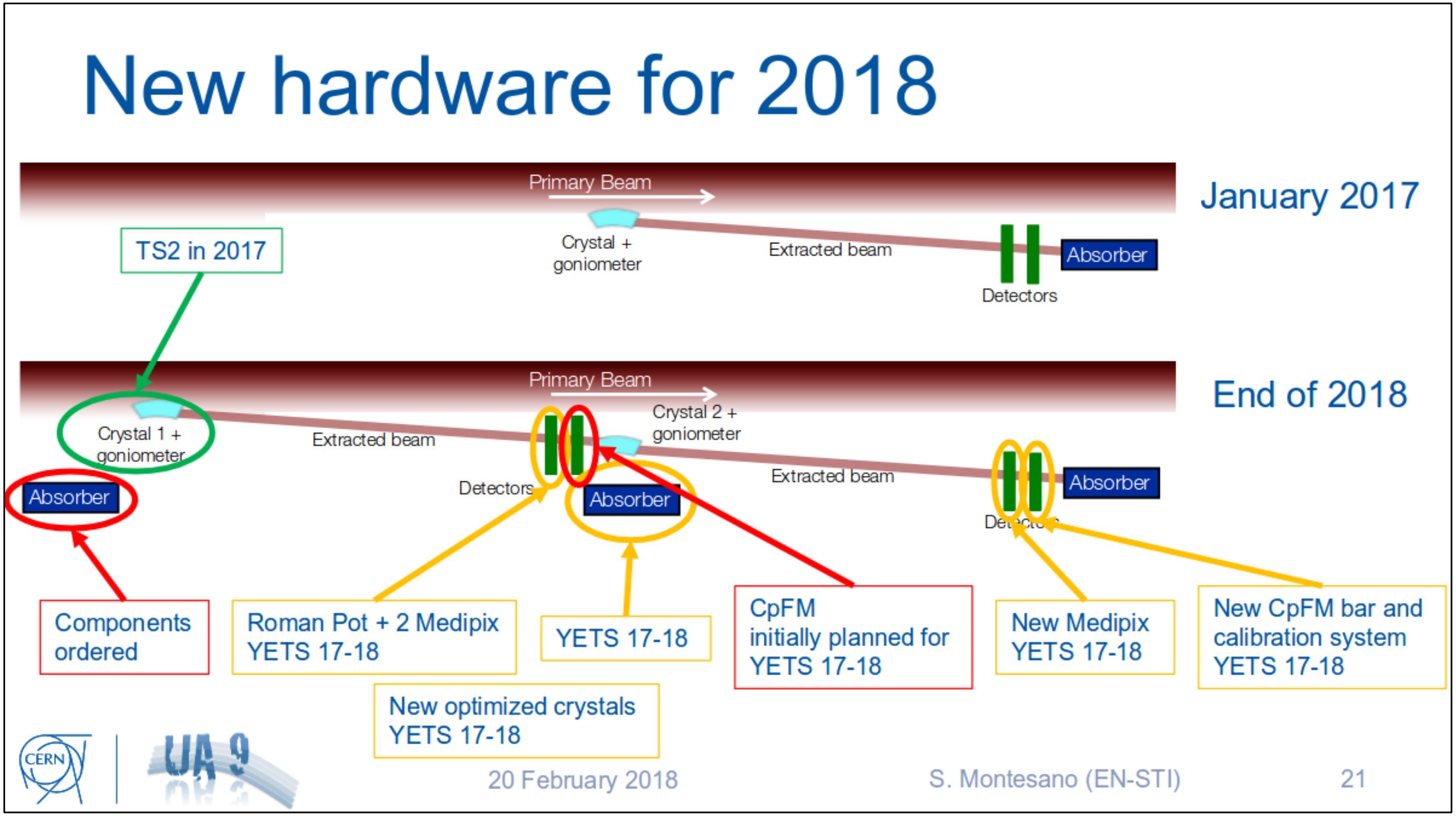
- Firsts MDs: results in operation, online calibration & feedback / expectations

- Conclusions

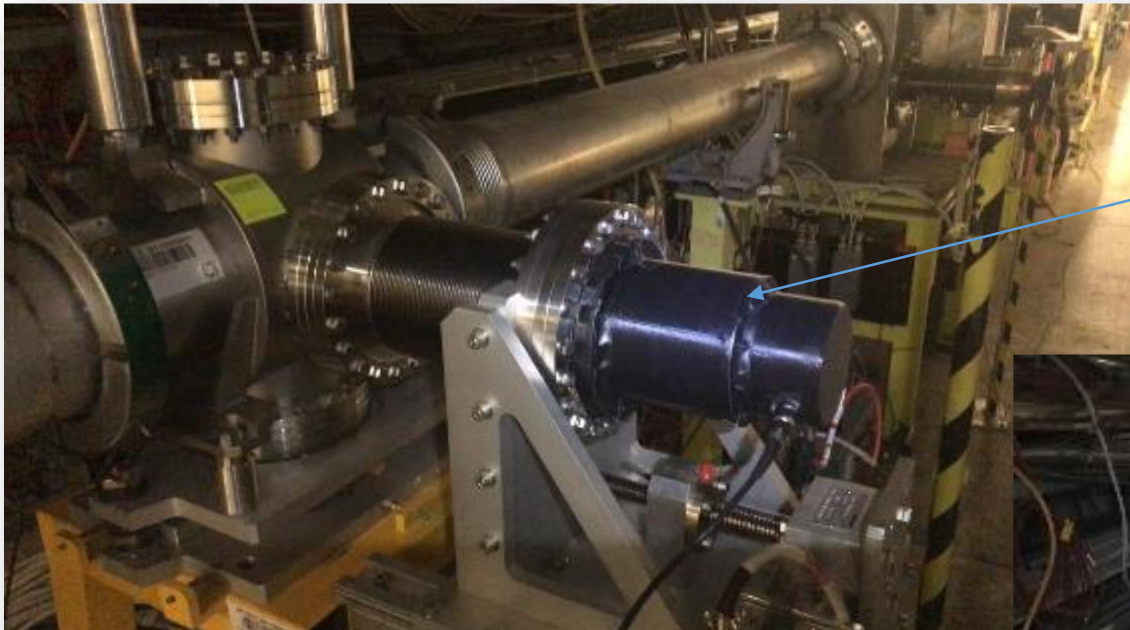
Installation in SPS (YETS 17-18)

✓ **Due to resources availability and priorities at CERN, the new CpFM not installed (need a new tank that doesn't exist). We decided to unmount the "old" CpFM and to replace it with the new-one, at the same place (after crystal 2).**



Installation in SPS (YETS 17-18)

- ✓ **New CpFM and monitoring system installed the 15 February**
- ✓ **Everything went WELL ☺**



CpFM installed

Monitoring system installed

Installation in SPS (YETS 17-18)

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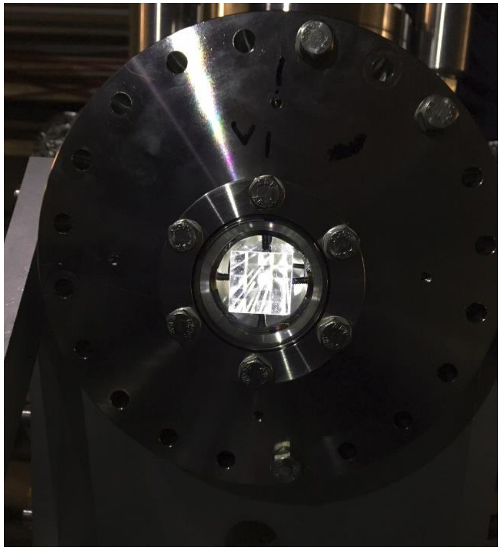

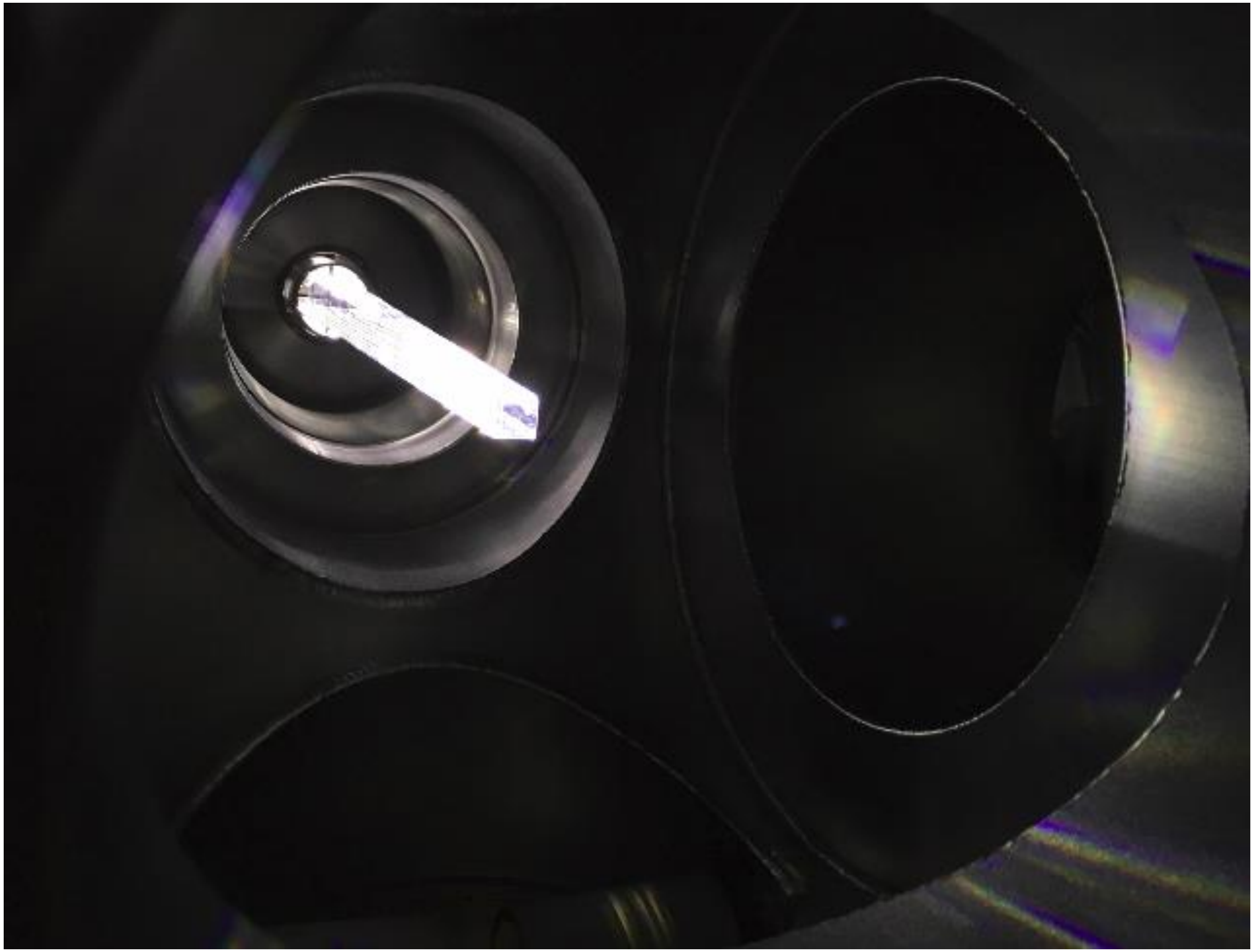

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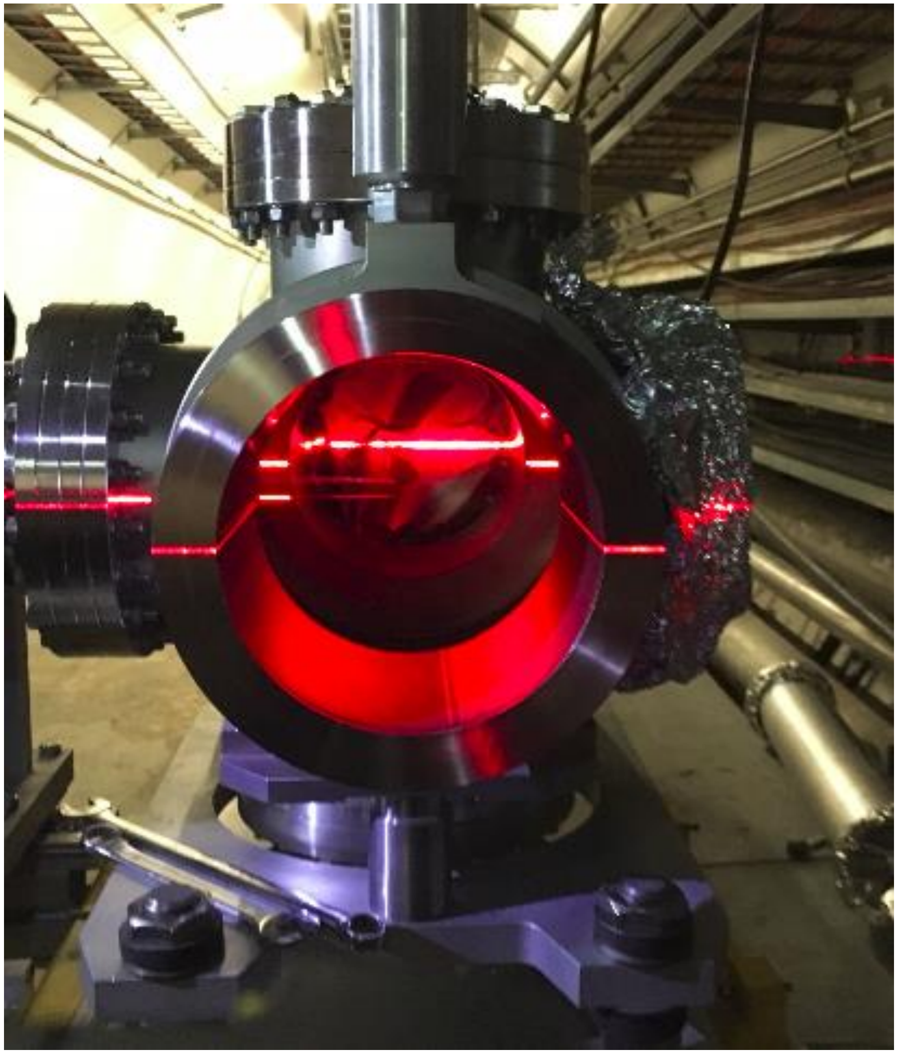

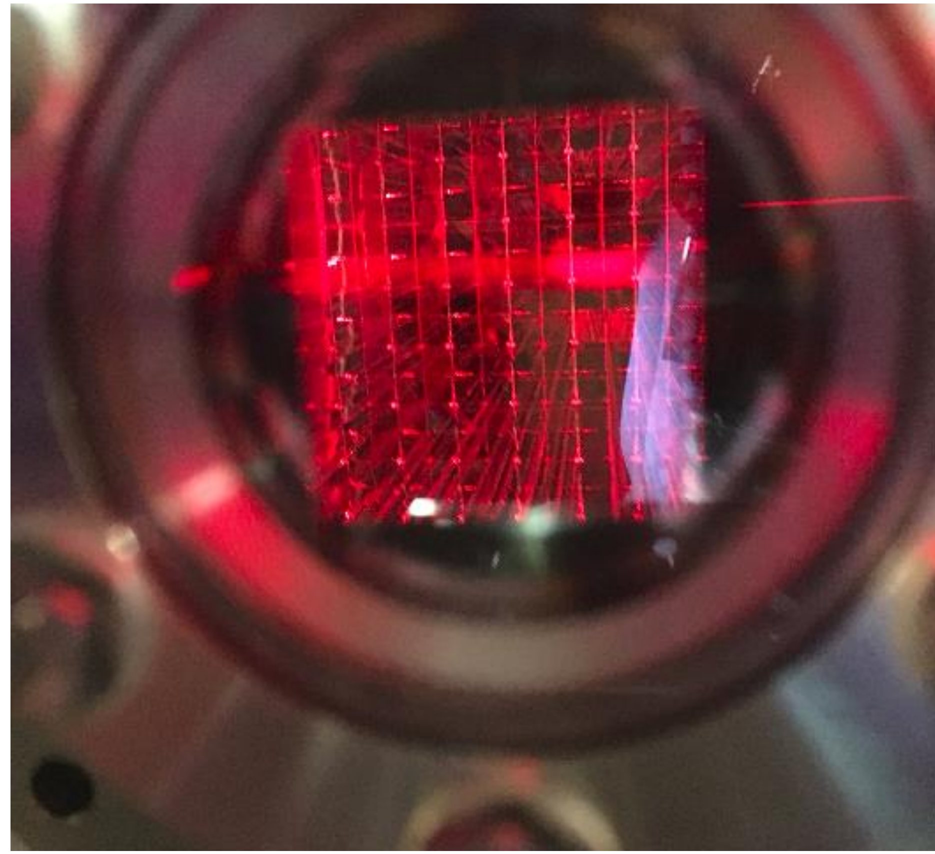

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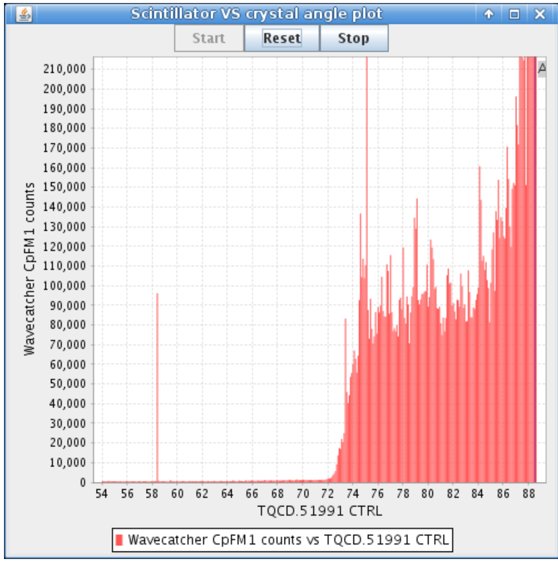
First MDs with the new CpFM

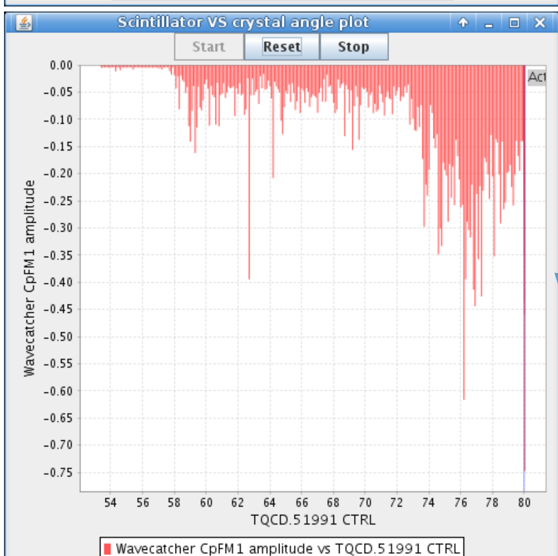
- ✓ Up to now… 2 dedicated MDs for UA9: June 18-19 + September 17-18 (24 Hours each)

- ✓ First light on the new CpFM -> functional tests, commissioning:
  1. No electromagnetic pickup when the beam is circulating (even with the PMT not shielded)
  2. No significant noise / background seen in parking position (no trigger with a threshold as low as 10 mV)
  3. Losses on the CpFM compatible with losses estimated with AD&I scintillators (seen with rates counters when setting up the optics / beam before the MD)
  4. Trigger (from SPS machine) well synchronized with the signal
  5. Offset of the electronics working well: range up to 2.5 V (instead of 1.25 V)
  6. PMT current as estimated: 244 uA at 1050 V (maximum gain)
  7. Channelled beam found (and primary beam too…) when inserting the CpFM inside the beam-pipe (linear scan)
  8. Angular scan: CpFM used to find the channeling angle and working well with other UA9 instrumentation (Medipix, scintillators)
  9. BUT… signal (amplitude) seems to be 3 times lower than expected (but still largely enough -> The CpFM is auto-calibrated!)

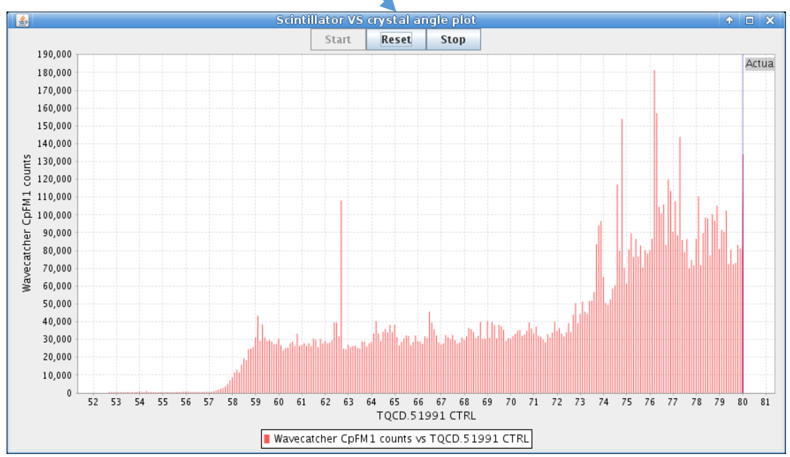
First MDs with the new CpFM

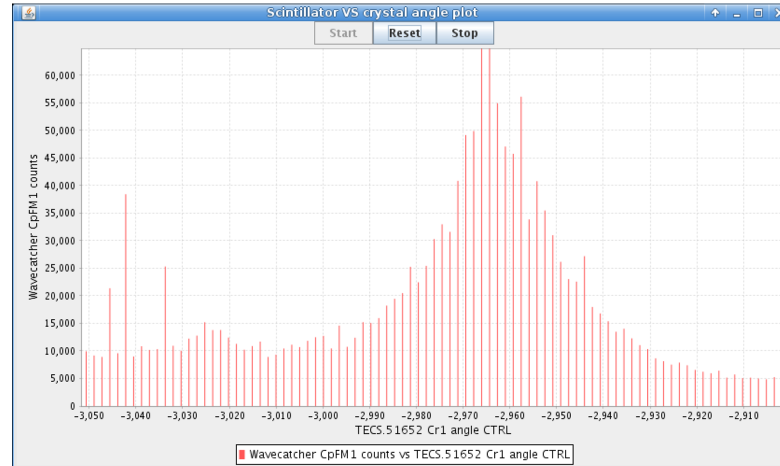
Linear & angular scan: channeled beam & channeling found using rates counters





Linear scan



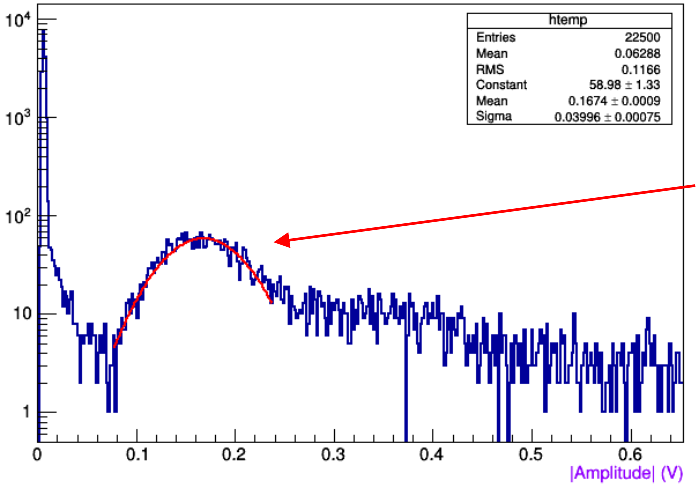


Angular scan

First MDs with the new CpFM

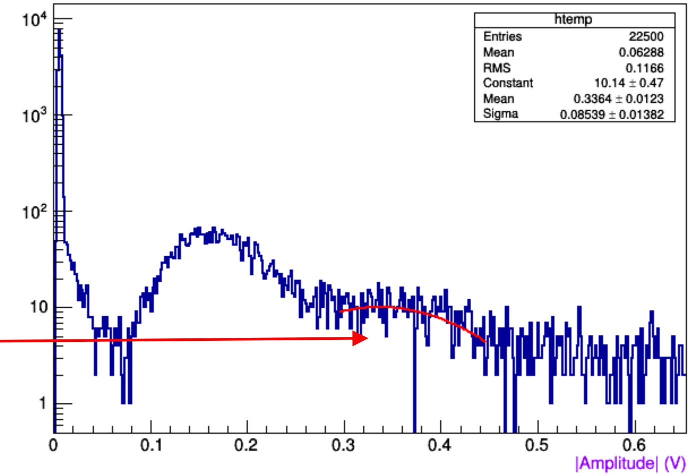
Amplitude distribution: one proton signal clearly visible (self-calibration!)

HV 1000 V



One proton (167 mV)

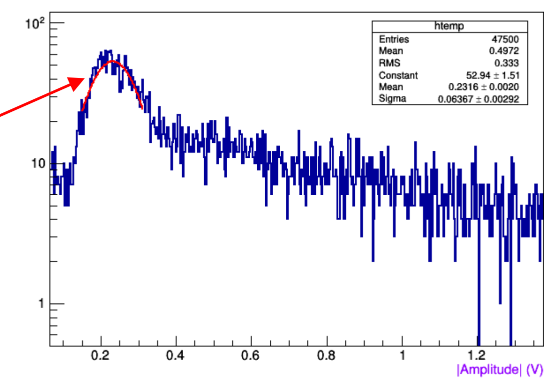
Two protons at 336 mV (≈ 2 × 167 mV)



-> Signal from one or two protons easily discriminated… but amplitude 3.7 times lower than initially expected with measures made in H8 (for this gain, expected 627 mV, 76.3% less)

HV 1050 V (maximum gain)

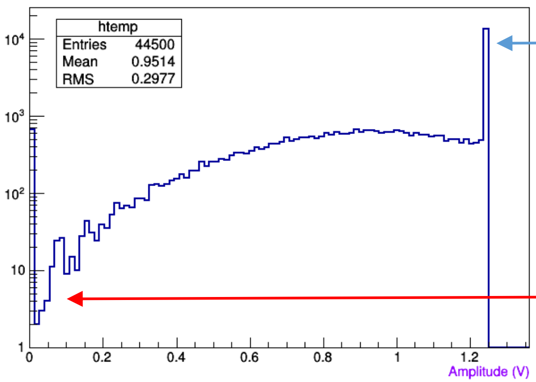
One proton (232 mV)



-> Same result: amplitude 4 times lower than expected with first measurements made in H8 (for this gain, expected 946 mV, 75.5% less)

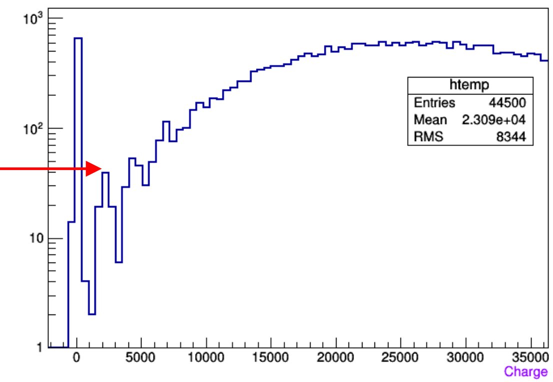
First MDs with the new CpFM

HV 900 V (crystal in channeling)

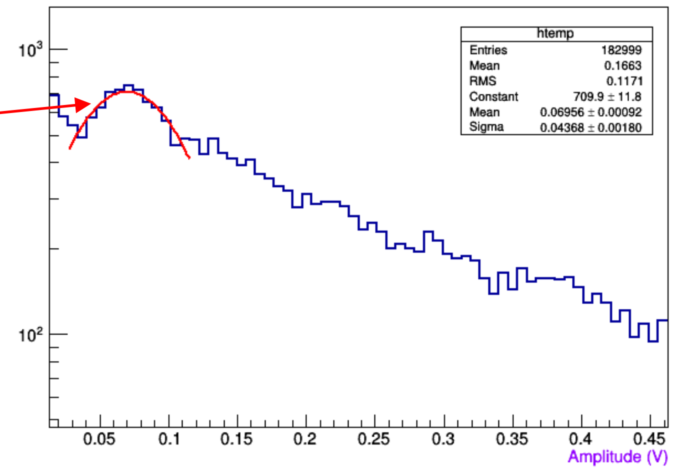


Saturation peak at 1.25 V (range can be extended with offset up to 2.50 V)

Proton signals (1, 2, 3 protons…) easily distinguishable on amplitude & charge distributions



One proton at 70 mV



-> Possible to recalibrate entirely the CpFM for all gains and in real conditions, and to follow its evolution

First conclusions

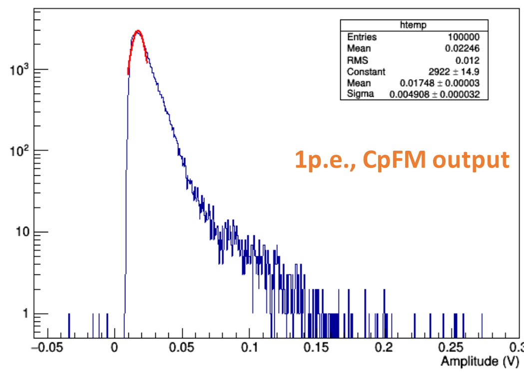
- ✓ Still a difference in response between H8 and SPS measurements.
- ✓ Origin?
- ✓ Checked the validity of calibration made with pi+ and validity for protons -> G4 Simulation (A. Natochii): exactly same results obtained with 180 GeV/c pi+, 270 GeV/c and 400 GeV/c protons.
- ✓ Setup? Same PMT, divider, and quartz bar. Not exactly the same viewport (needed a 316LN stainless steel for SPS, not available during H8 characterizations… but in principle similar quartz window). Holder a little bit different, but similar interfaces with the quartz (8 point of contact with 8 screws).
- ✓ Same response of the e between the WaveCatcher module used in H8 and the one installed for SPS (checked).
- ✓ Impedence adaptation between electronics, cables, and PMTs in SPS: checked.

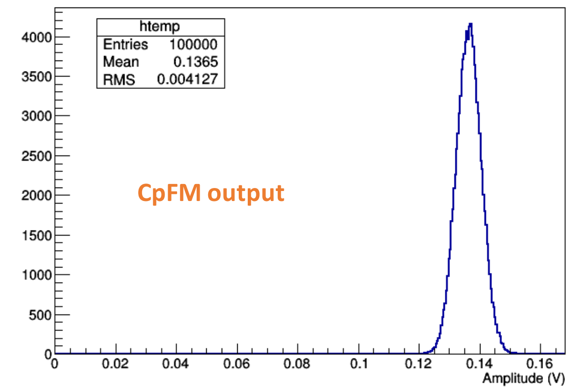
- ✓ Cables? In SPS, we use a 104 m-long low-attenuation cable. Previously estimated a loss of about 5-10% maximum, but not in real conditions. We had the opportunity to test it during an unplaned access in SPS in mid-August, using the LED installed during the last TS. When sending light in the CpFM with the LED system, we compared the response at the output of the CpFM and upstairs, after the cable.

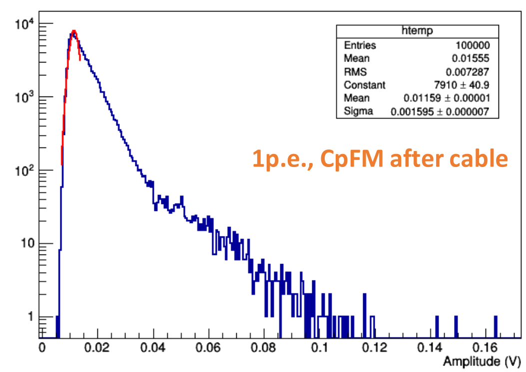
Test with LED system

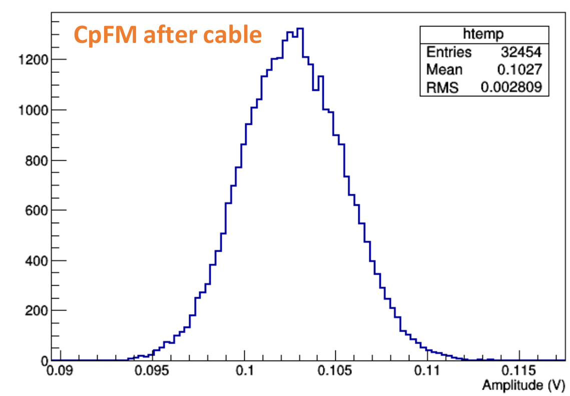
- ✓ **Two types of signals sent with the LED: a fast “low-amplitude” signal (producing one single p.e. on the PMT), and a “high-amplitude” signal.**
- ✓ **Results:**

- **1 single p.e. (1050 V): from 17.5 mV (CpFM output) to 11.6 mV (after cable) -> Factor 1.51, 33.7% lost.**
- **High amplitude LED signal: from 137 mV to 103 mV (factor 1.33, 24.8% lost).**









- ➢ **<u>Not enough to explain the difference that we observe (still about 40% lost…).</u>**
- ➢ **Comes from the bandwith limit of the low attenuation cable: very low attenuation for long signals, but starts to be critical with very short signals (high-frequency) of less than 10 ns.**

Conclusions - Expectations

- ✓ **Investigation still ongoing to find the origin of this difference. Probably related to the setup (window?) or the alignment of quartz bar with the window when installing (a small tilt between the base of the pyramid bar and the flat surface of the window could explain).**
- ✓ **Nevertheless… This system is self-calibrated. Even with less light collection than expected, we can find a single particle and count them!**

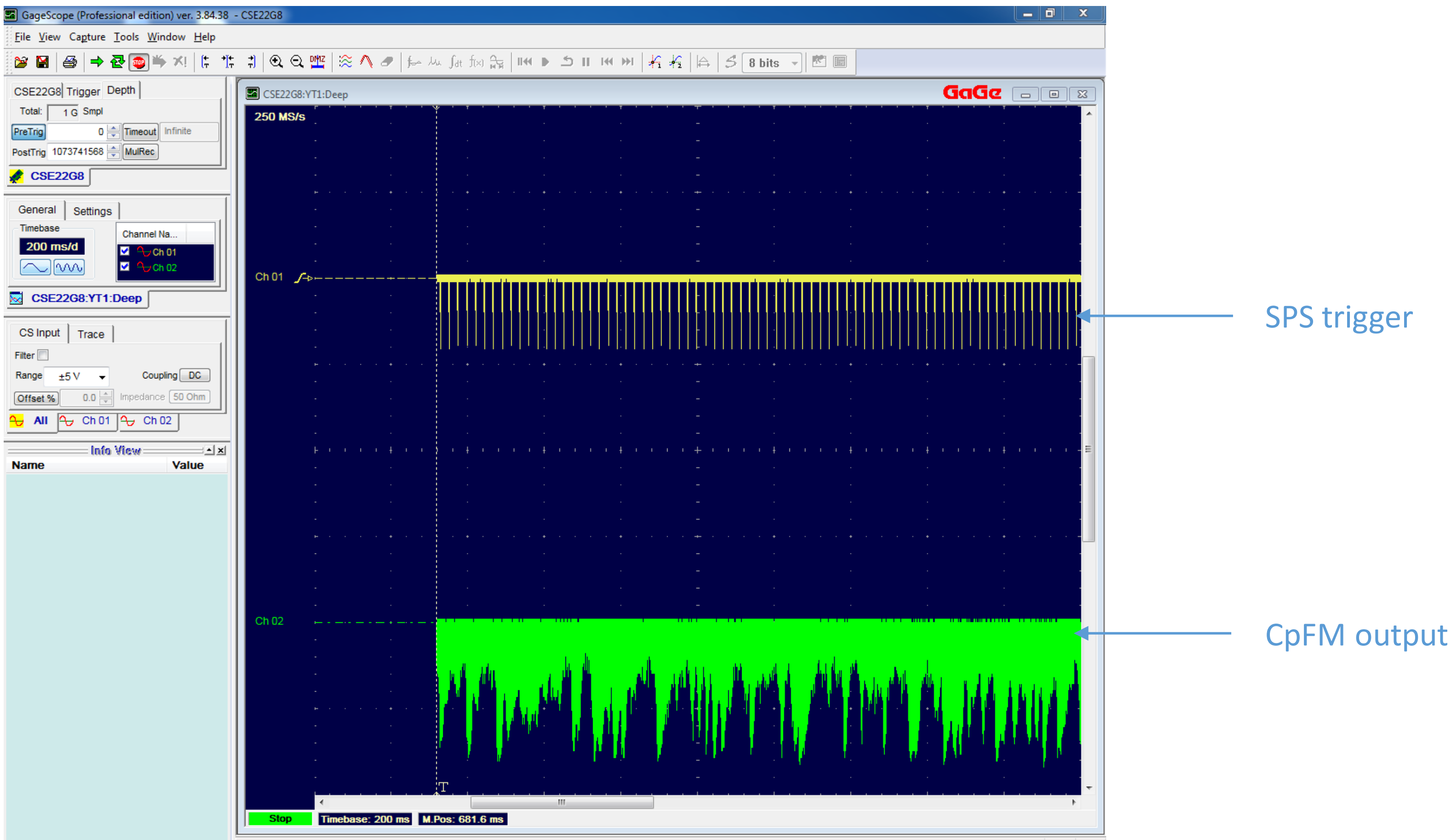
- ✓ **Measured performances (examples), with real on-line calibration:**

HV (V)	Amplitude for one part. (mV)	Range for counting (with offset)
700	8.09 ± 1.34	From 1 to 309 part. / bunch
750	18.8 ± 4.04	From 1 to 132 part. / bunch
800	30.6 ± 5.72	From 1 to 81 part. / bunch
900	72.9 ± 18.7	From 1 to 35 part. / bunch
1000	167.4 ± 39.9	From 1 to 15 part. / bunch
1050 (max.)	231.6 ± 63.7	From 1 to 10 part. / bunch

- ✓ **Possible to work at lower gains to increase the range (PMT gain response known for HV as low as 500 V)**

Conclusions - Expectations

- ✓ **Still working at 43 Hz (one bunch over 1000 counted), as the dedicated ASIC is not ready.**
- ✓ **But, using the COBRA digitizer, we were able to register a complete train of 172000 successive bunches (4 s of acquisition, with a revolution frequency of 43 kHz) -> Still to be analyzed (done last week)…**



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Conclusions

- ✓ **Different versions / iterations of the CpFM developed, following new requirements and feedback from the experiment: first version, updated version with direct coupling, and at the end a new version for double-crystal studies with extended sensitivity and ability to count each bunch**

- ✓ **New studies, conducted in parallel, to fulfill this requirement: new bars with improved quality, innovative geometries, new fast electronics, new mechanical holder / flange / viewport and vacuum interface (+ photodetector), and a monitoring system (LED).**

- ✓ **Everything tested and calibrated in the "almost" final configuration, with excellent results and a large safety margin.**

- ✓ **System installed and ready, to be used with suitable electronics (easy to change or replace, as it's upstairs): WaveCatcher (integrated with UA9 DAQ), COBRA or a new electronics when available.**

- ✓ **First results very positive… but things to be understood! Calibration needed to be done online. But full-working system anyway!**