PRAE International Workshop
Platform for Research and Applications with Electrons
October 8-10, 2018
LAL-IPNO-IMNC, Orsay

UA 9

The CpFM: a high-sensitivity charged particles flux-monitor for accelerators physics

The CpFM for the UA9 Experiment at CERN

PRAE International Workshop, LAL-IPNO-IMNC, Orsay – France, October 10, 2018

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Outline

I. Scope of the development: the UA9 Experiment

II. The CpFM concept

III. The CpFM in operation: main results and key technical issues

IV. Toward the development of a new high-sensitive flux monitor

- Ways to improve light collection
- Direct coupling
- Mechanical integration with a flange?
- Cherenkov radiator design and optimization
- Photodetector
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V. Results in operation

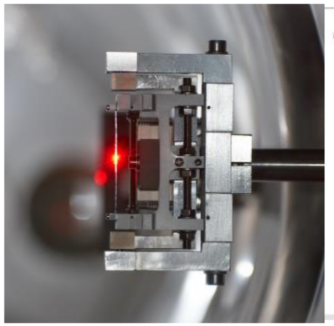
- MDs in SPS with protons
- Discussion

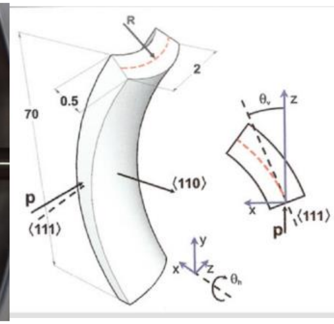
VI. Conclusions

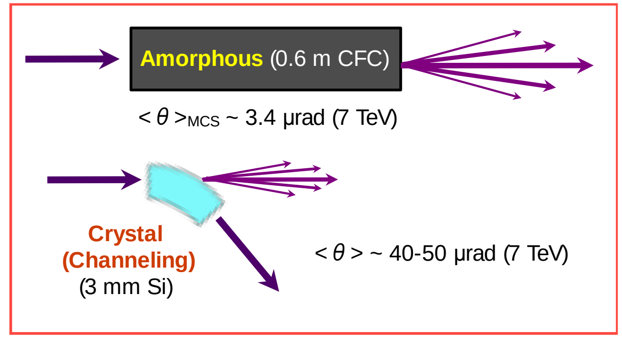
The UA9 experiment

Investigate bent crystals as primary collimators in hadron colliders

- Bent crystals work as a “smart deflectors” on primary halo particles



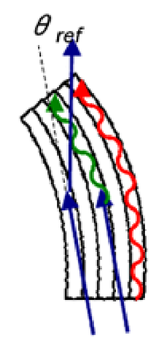




- If crystalline planes are correctly oriented, particles are subjected to a coherent interaction (channeling):

✓ large angle deflection also at high energy
✓ reduced interaction probability (e.g. diffractive events, ion fragmentation/dissociation)
✓ reduced impedance (less secondary collimators, larger gaps)

✗ small angular acceptance
✗ concentration of the losses on a single absorber



<u>The UA9 Collaboration is investigating how to use bent crystals as primary collimators/deflectors:</u>

- operational and machine protection concerns are considered in cooperation with the Collimation Team
- 3 installations (since 2014): SPS North Area (H8), SPS, LHC

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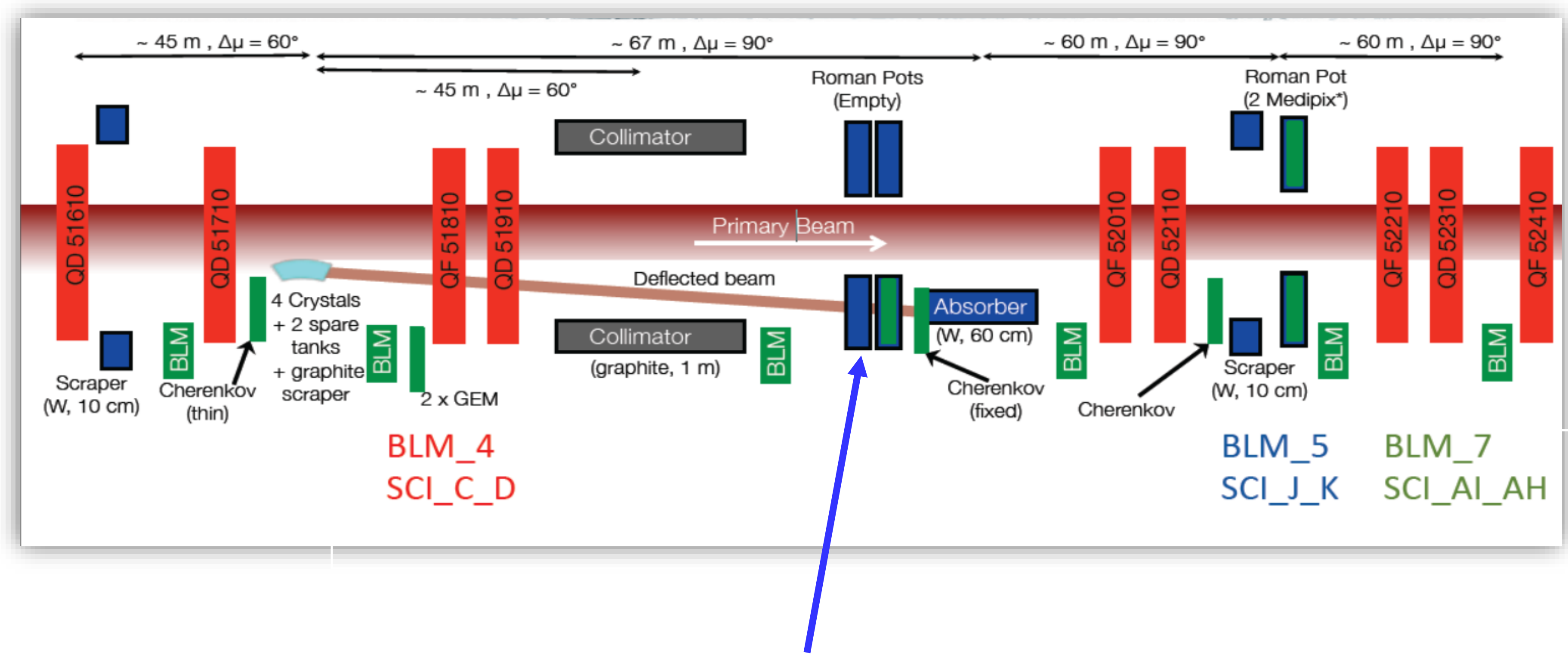
The CpFM

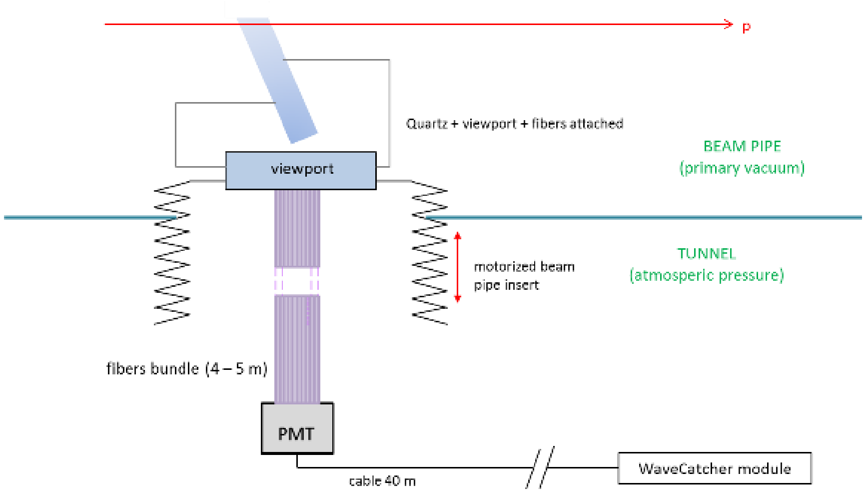
- **<u>C</u>herenkov detector for <u>p</u>roton <u>F</u>lux <u>M</u>easurement**
- **Main contribution of LAL Laboratory to the UA9 Experiment**

- **Goal of the CpFM: count the number of protons (or ions) from the halo - deflected by UA9 bent crystals - in the SPS or LHC environment**
- The CpFM is a part of the UA9 SPS instrumentation, 58 m downstream the crystal



CpFM

The CpFM: concept & first version

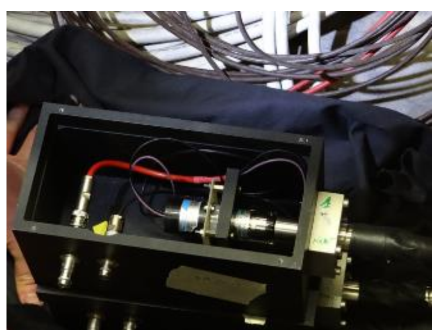


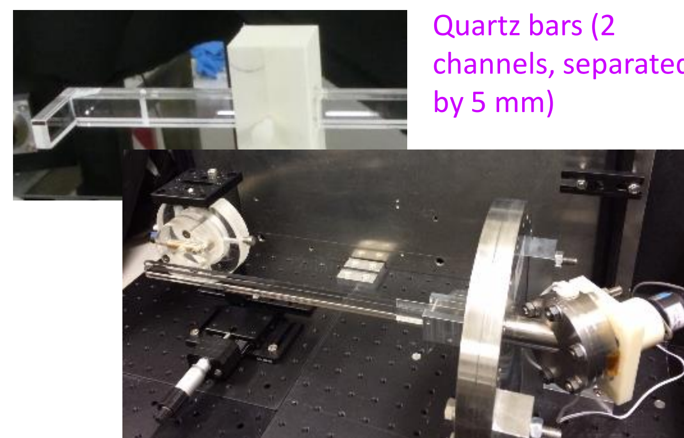
In vacuum, radiation hard detector:

- Interception of the channeled beam by a quartz radiator (2 channels)
- Emission of Cherenkov light
- Vacuum / air interface: quartz viewport
- 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 and working at 43 Hz (but revolution frequency at 43 kHz)
- 40 m cable between PMT and WaveCatcher (remotely controlled)

Fibres bundle

PMTs socket and housing

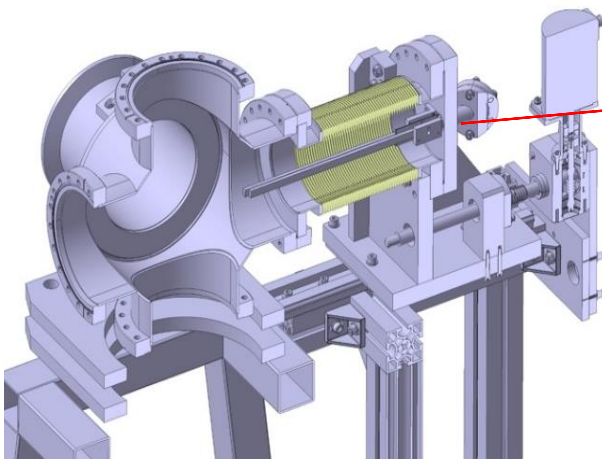


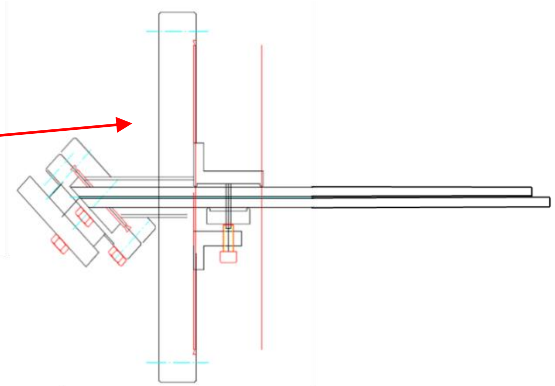


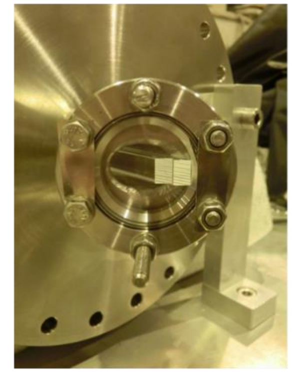
Quartz bars (2 channels, separated by 5 mm)

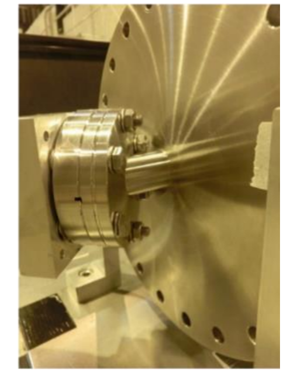
The CpFM: concept & first version

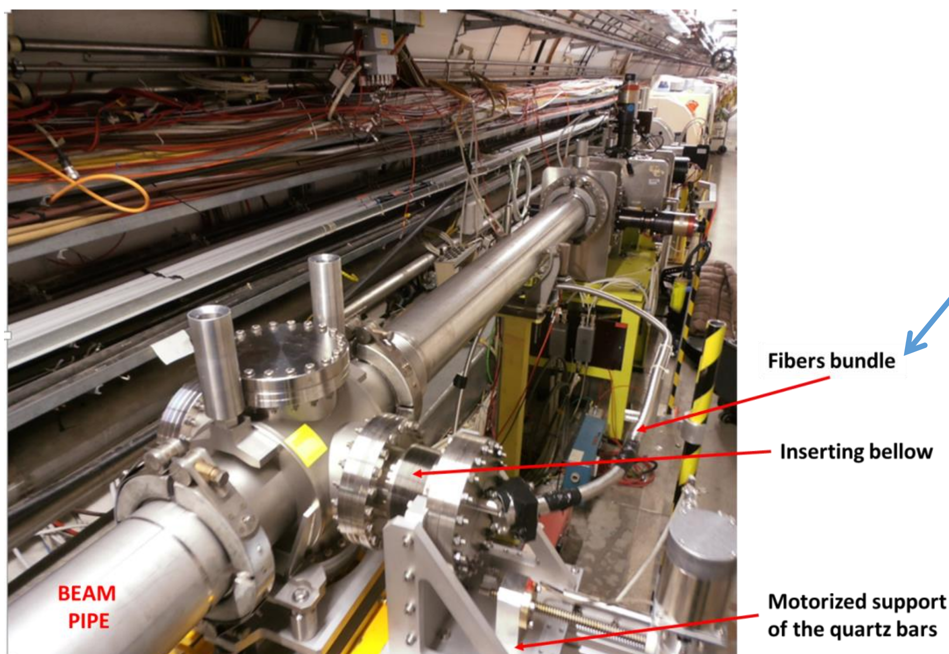
Quartz viewport is the interface between the bars and the PMT → signal loss, estimated by a factor 2











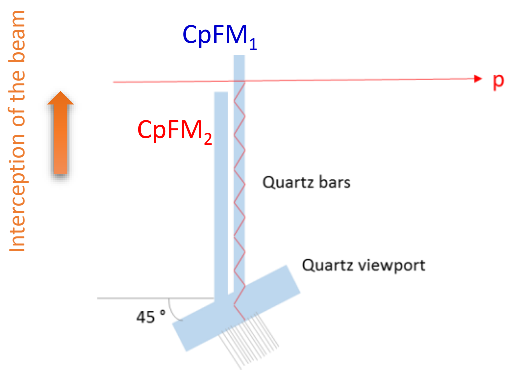
Coupling with Fibers bundle have to be improved (reduction by a factor 10 on light yield was shown).

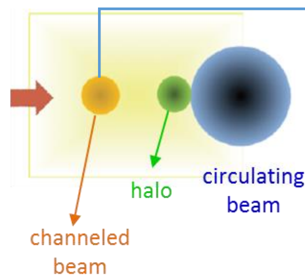
Previously calibrated with 446 MeV/c e^- (BTF, INFN Frascati), 400 GeV/c protons (H8, CERN)

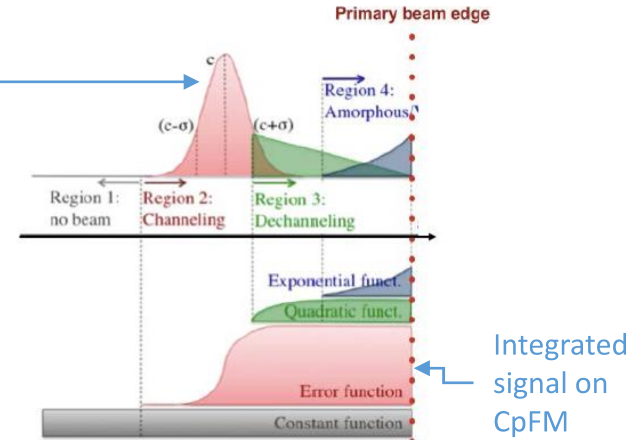
Outline

CpFM in operation

Linear scan: insertion of the bars in the beam pipe

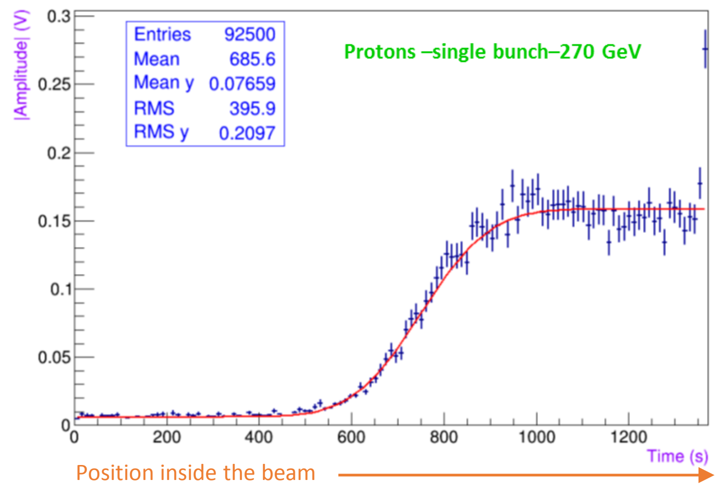






<u>CpFM **used** for:</u>

- **Finding channeled beam and its profile**
- *Counting particles*
- *Beam stability (relative flux)*



Fit of the amplitude distribution in the channeling region with an error function → its derivative corresponds to the Gaussian profile of the channeled beam.

→ σ → angular spread of the channeled beam: **12.8 μrad, in good agreement with the critical angle for 270 GeV proton (12,2 μrad)**

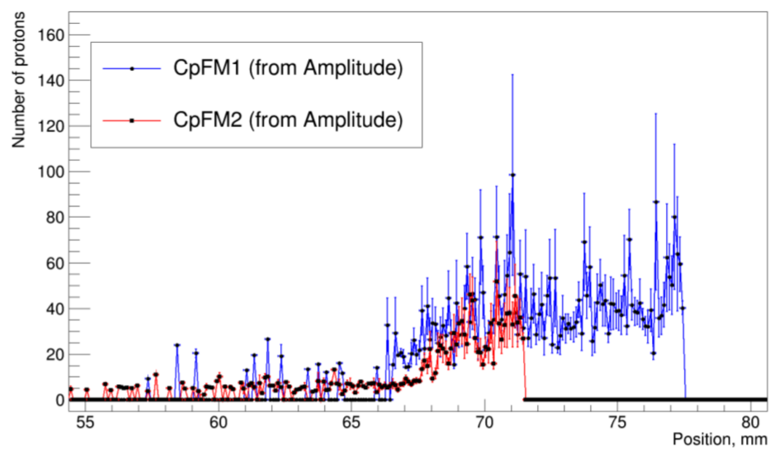
CpFM in operation

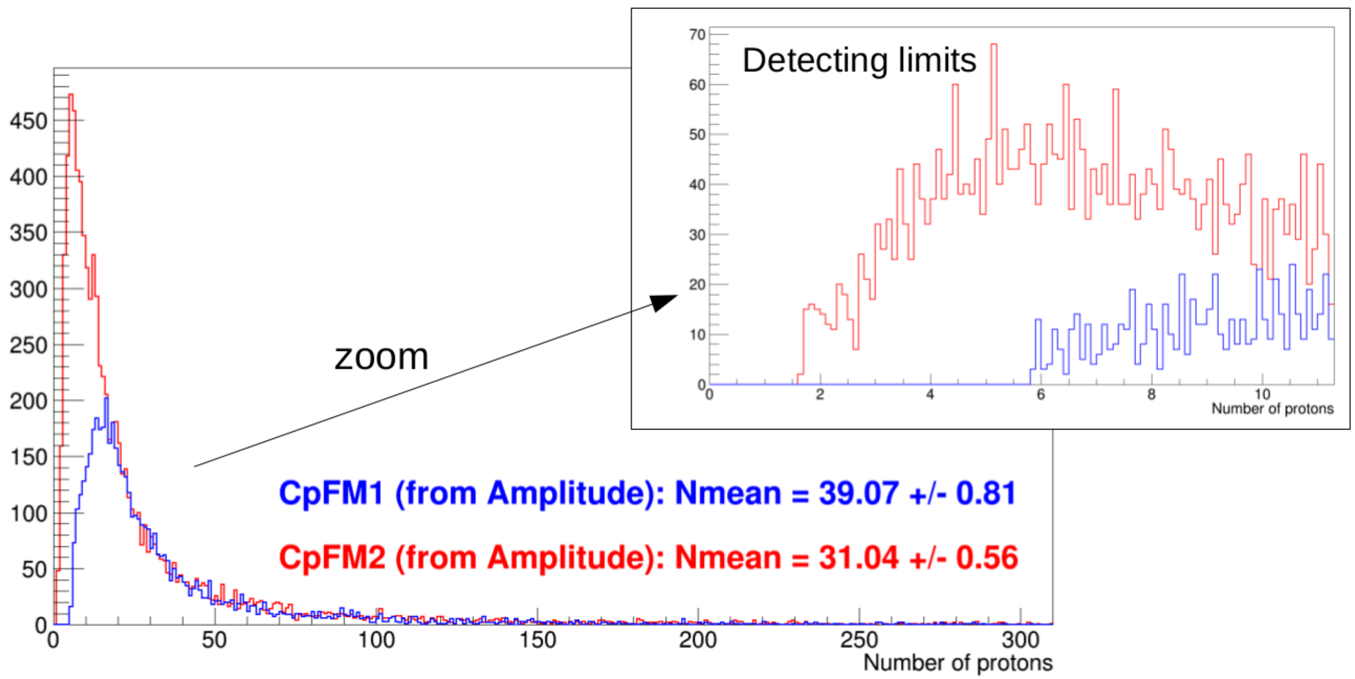
➡ Number of deflected protons as a function of the position & detecting limits:

<u>CpFM **used** for:</u>

- *Finding channeled beam and its profile*
- **Counting particles**
- *Beam stability (relative flux)*

From WaveForms

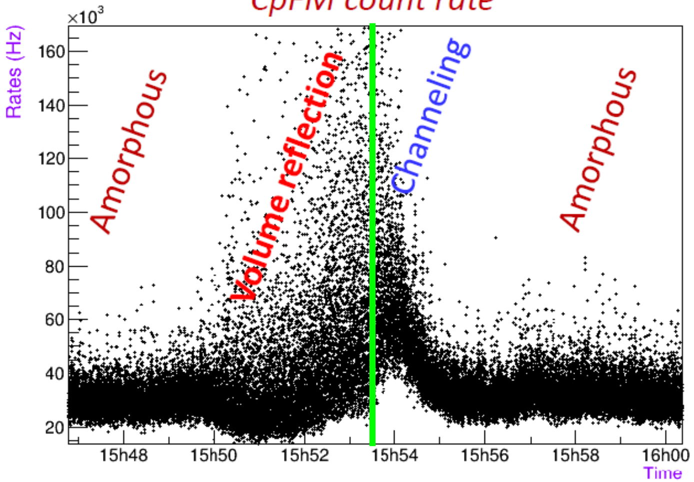




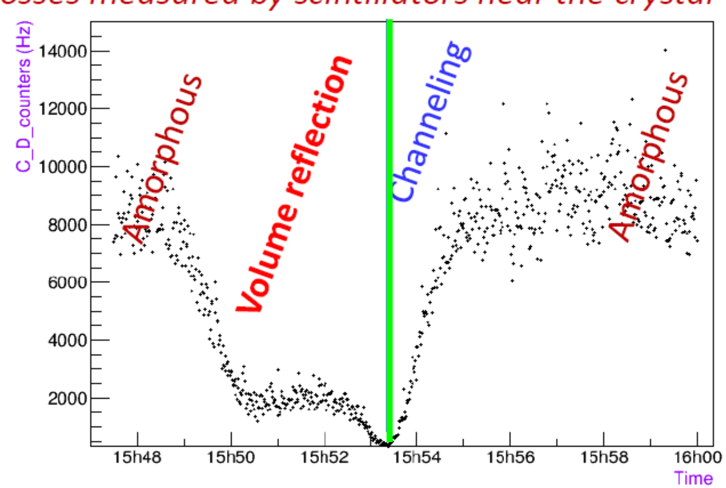
CpFM in operation

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

<u>CpFM **used** for:</u>

- *Finding channeled beam and its profile*
- *Counting particles*
- **Beam stability (relative flux)**

Channeling angle found!

→ good agreement bewteen the CpFM and the scintillator BLM

In situ calibration

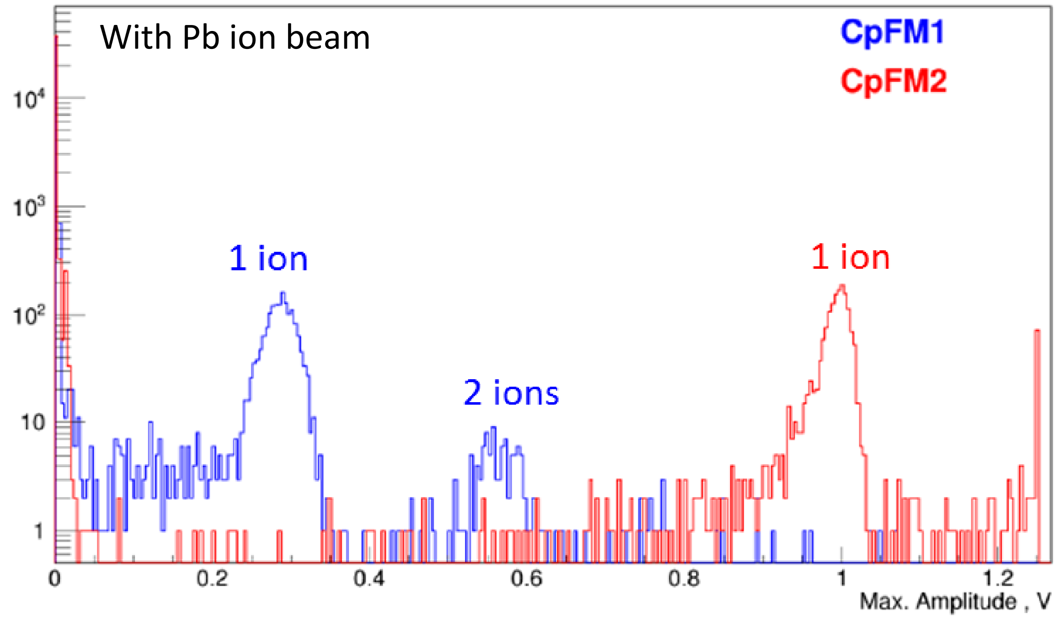
Possible to re-calibrate the instrument using the large amount of Cherenkov light produced by ions!

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

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

Calibration coefficients:

CpFM$_1$: 0.06 pe/part.
CpFM$_2$: 0.18 pe/part.



CpFM – Limits, evolutions

- ✓ We need to have enough light to see a single proton for a range of 1-200 protons/bunch (detection threshold should be minimized)
- ✓ 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
- ✓ New filling schemes: 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!

- ➢ **Development of a new electronics with charge & amplitude extracted at 40 MHz with no dead-time.**
- ➢ **Light collection improvement: huge work on all aspects (quartz optimization, optical coupling at the interfaces, mechanical integration…).**

Development of a new CpFM to fulfil requirements: each point addressed in parallel

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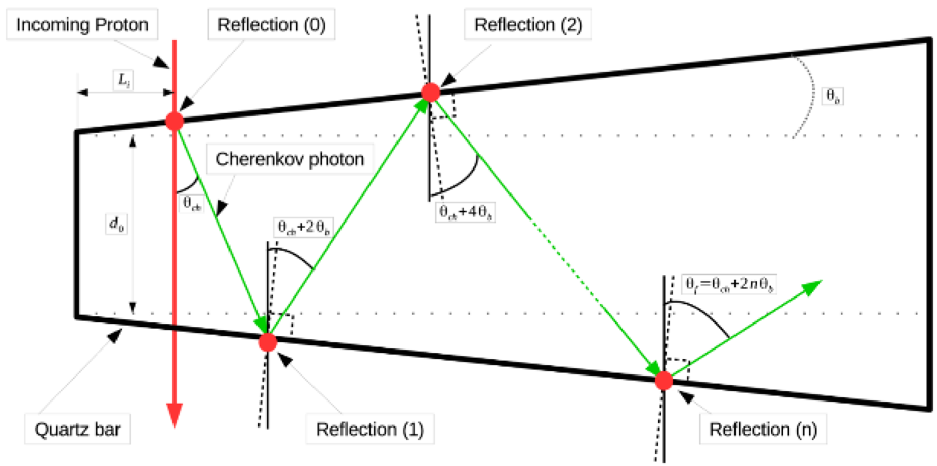
How to improve light-collection?

✓ Some solutions…

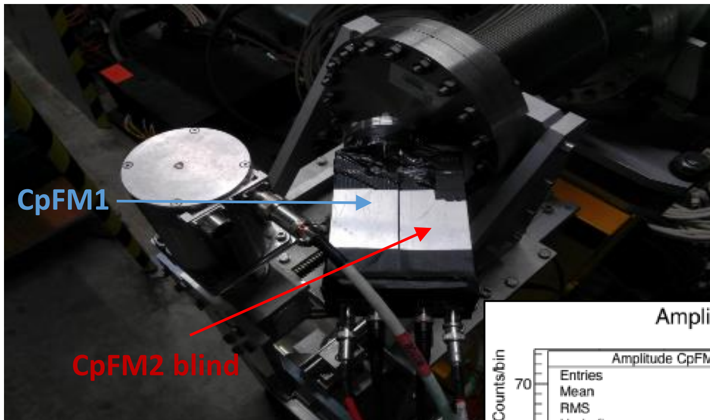
- Bigger cross-section for the radiator (instead of 5 mm, maybe 10 mm?) -> More Cherenkov light produced and number of reflections divided per 2.
- Removing bundle (direct-coupling, *already done, see after*).
- Brazing of bars through viewport (*R&D, not ready -> See after*)
- Better polishing and quartz 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 -> Number of reflections reduced.

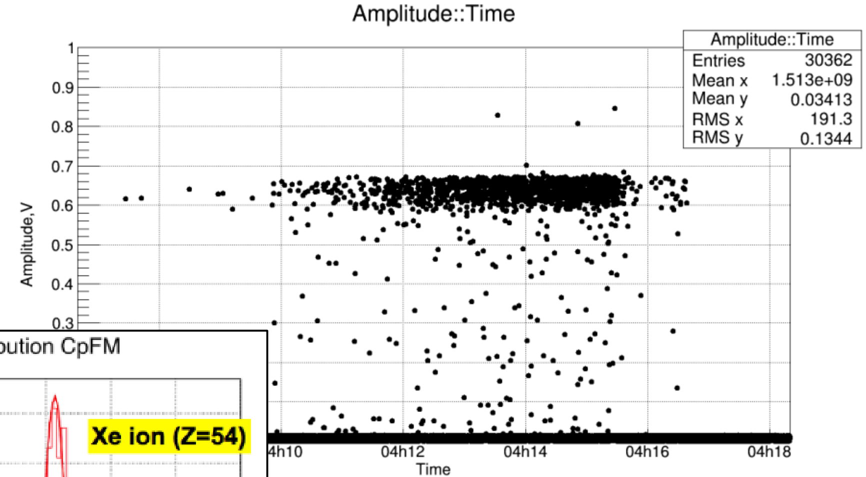


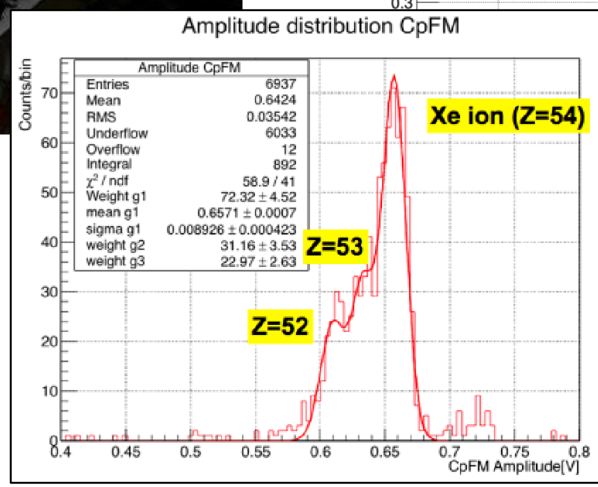
✓ Need tests & simulations!

Direct coupling

- **Already tested: <u>bundle removed</u> (PMT directly coupled with the viewport), electromagnetic shield added.**







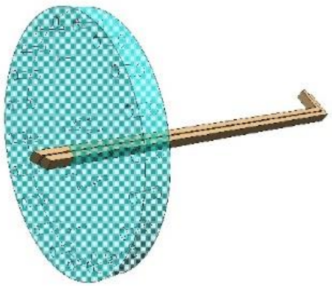
F. Addesa

- **Calibration checked with Xe ions: 18.2 mV / proton at 1050 V (corresponds to 1.17 pe/proton). Before: 0.18 pe/proton (-> <u>about 85% of light lost in the bundle</u>)**
- **No EM pick-up**

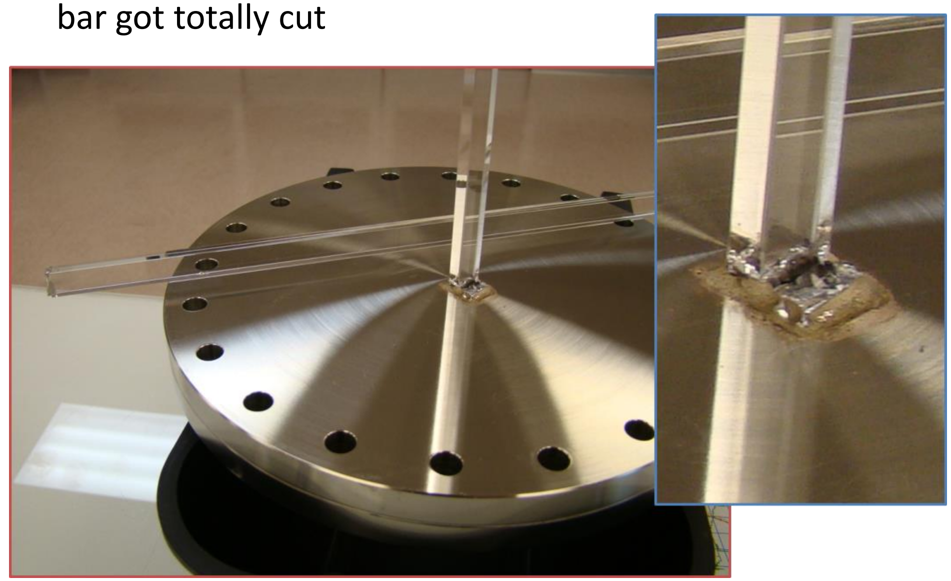
Mechanical integration of a Quartz bar in a flange

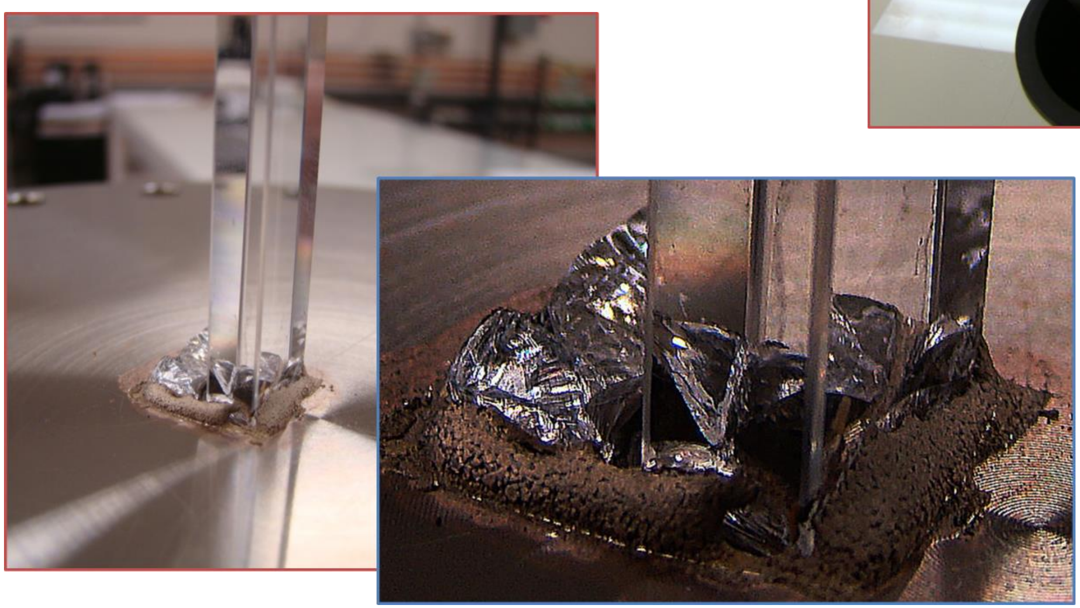
In principle very interesting for optimizing light collection (less interfaces)
But… First brazing disaster when designing the first CpFM!!

Initial design : the bars are brazed to the flange



Even if company ran a very slow thermal cycle to minimize the thermal mismatch between the parts, one of the quartz bar got totally cut



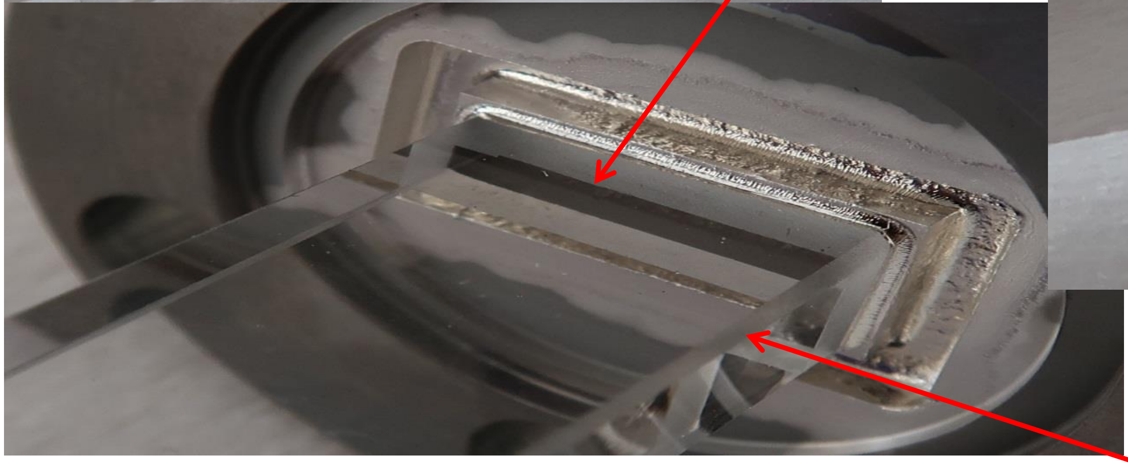


The last bar was not cut and hold on the flange but it is cracked

The issue seems to be the CTE gap (coefficient of thermal expansion) between the metal and the fused silica

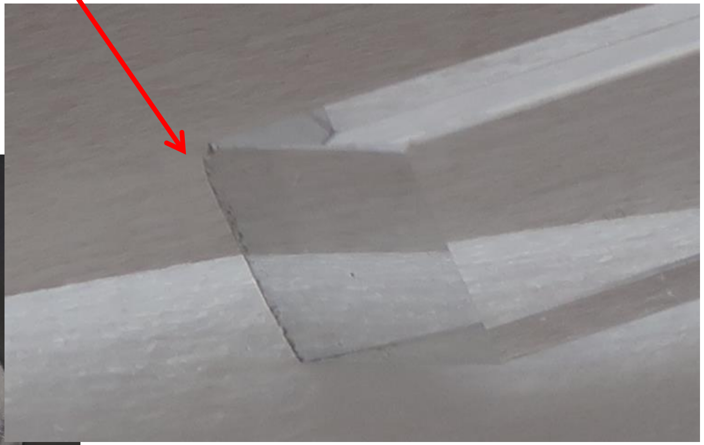
Mechanical integration of a Quartz bar in a flange

Just now (weeks ago), first success with a mini-bar (R&D from *Cherenkov Lab* project)



Brazing through a Ti flange by PNL company.
Depth of brazing: 2mm
Helium vacuum test achieved

Problems that appear with brazing process
-Depolished surface
-Damaged end



Undesired chamfer

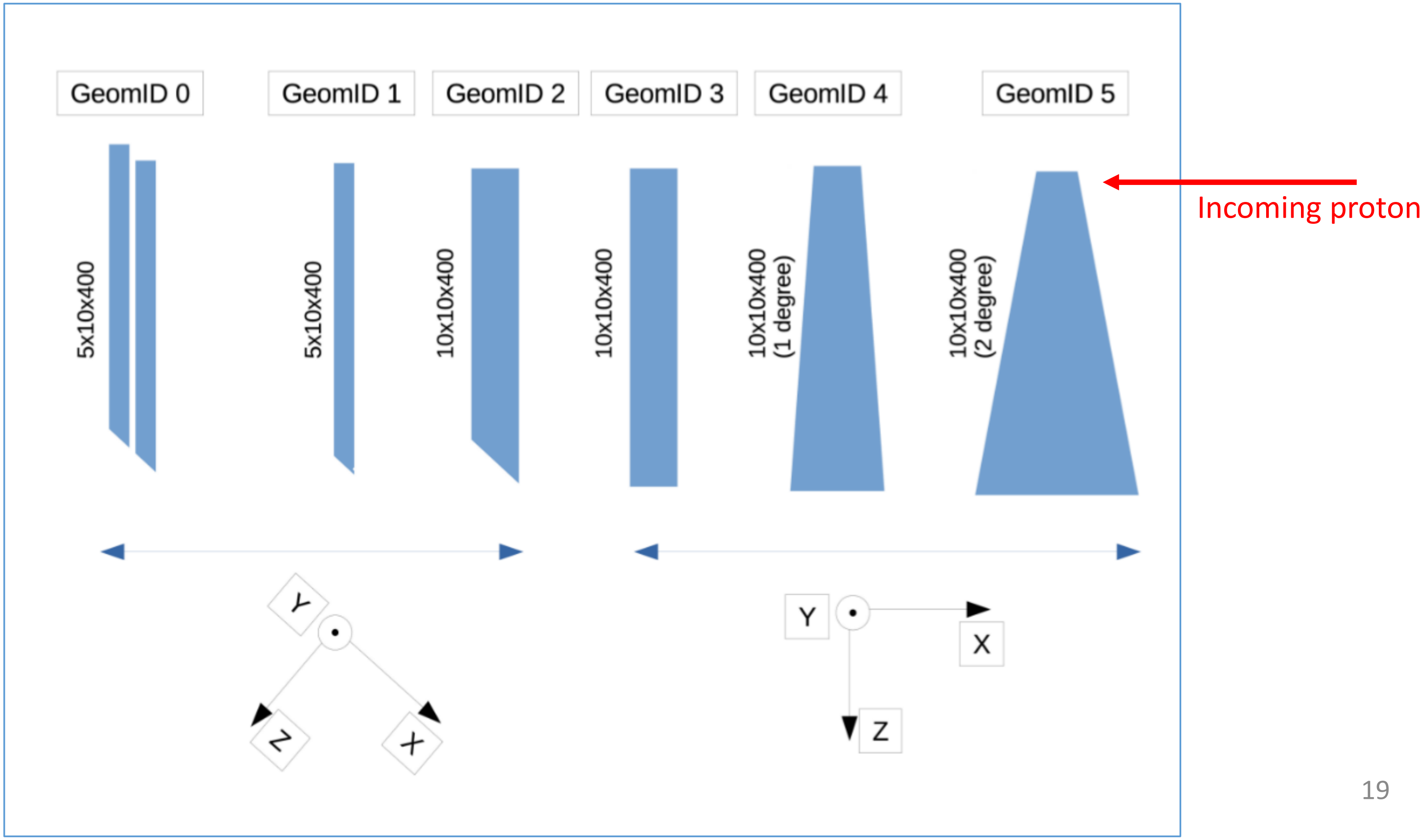
Needs of brazing process improvement

First test with particles (pions): about 70% of light losses… Up to now, <u>viewport still a better solution</u>!

Study of new geometries for quartz radiator

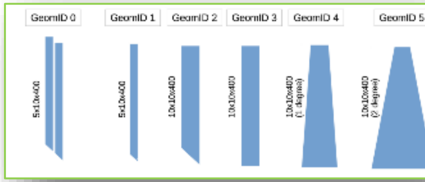
Team work of Andrii Natochii & Leonid Burmistrov

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

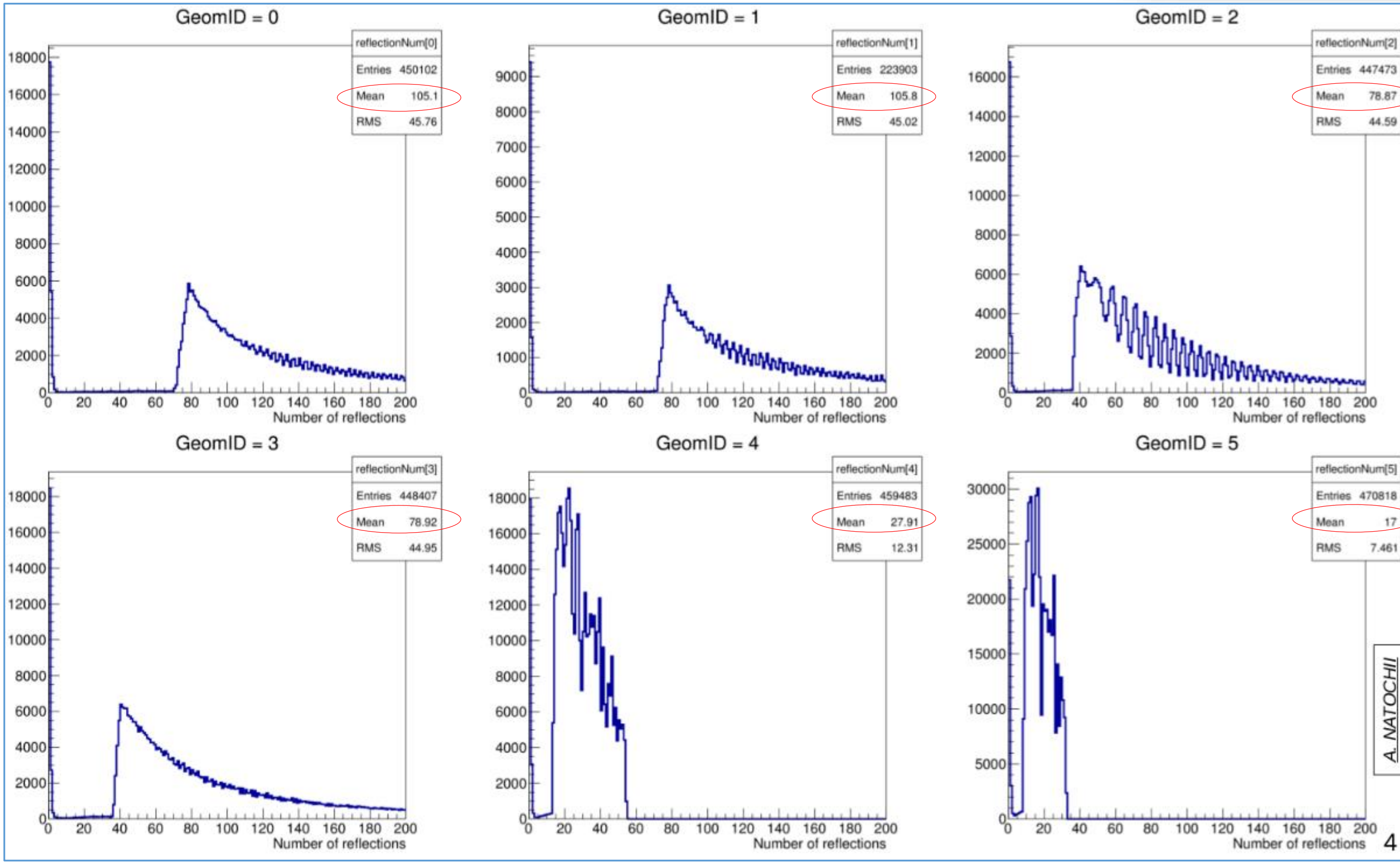


Study of new geometries for quartz radiator

- ✓ **Distribution of the number of photons hitting the detection surface: not so interesting here … between 443 and 461 photons / proton**



- ✓ **<u>More pertinent: distribution of the number of reflections for each Cherenkov photon:</u>**

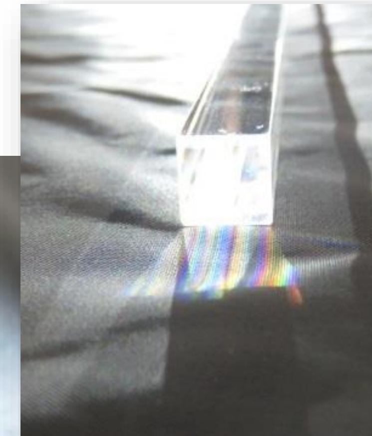


Team work of Andrii Natochii & Leonid Burmistrov

Study of new geometries for quartz radiator

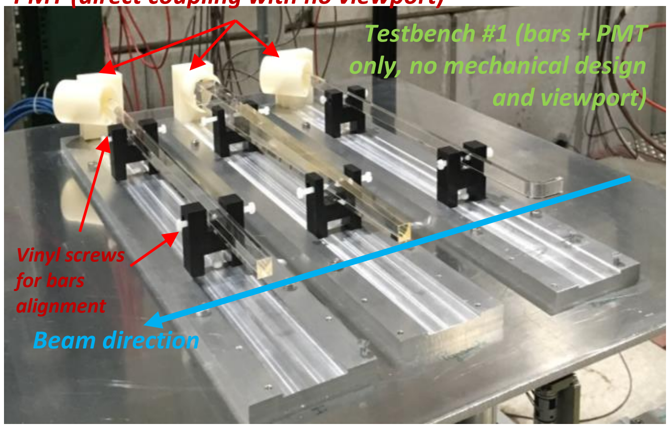
✓ **For the new CpFM, we decided to order (from Optico AG, Switzerland, with surface roughness of < 1 nm rms, their best quality):**

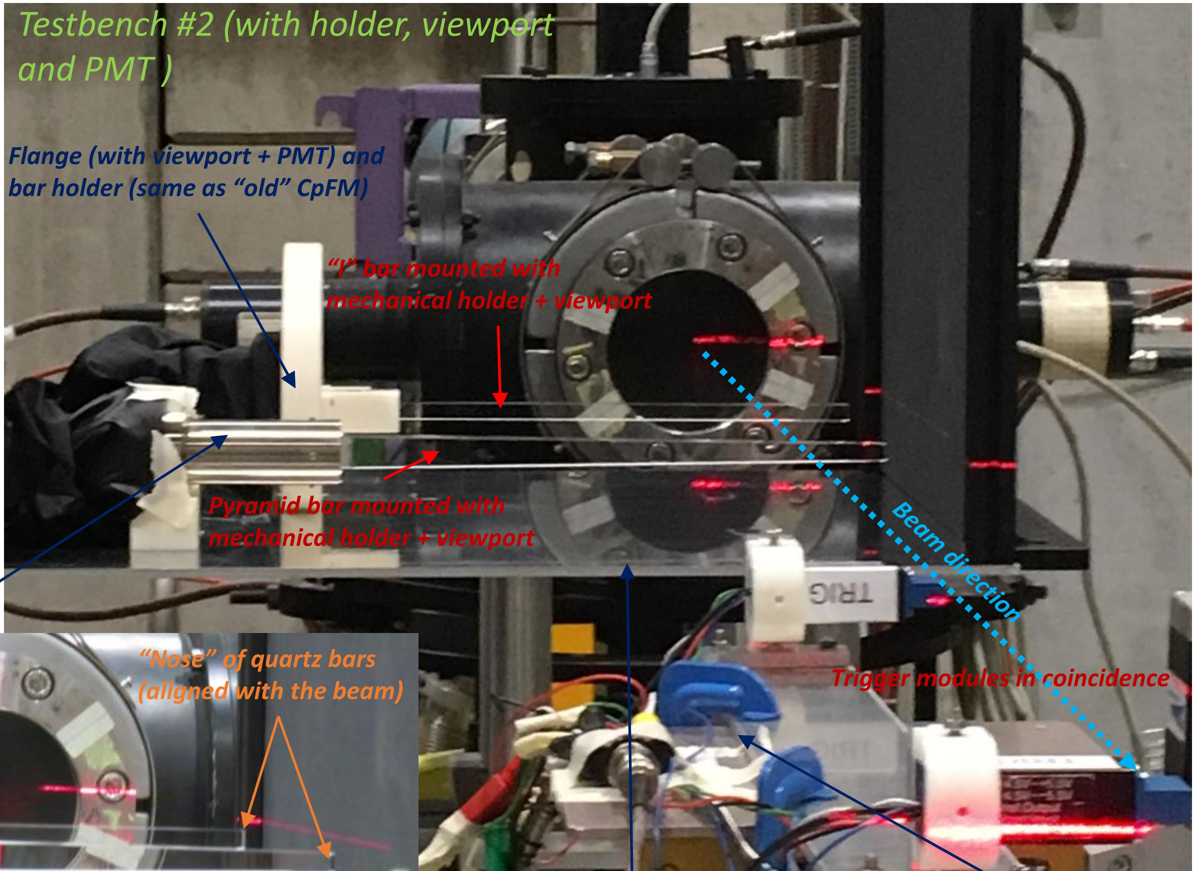
- One "pyramid"-shape bar, as first choice
- One "I"-shape bar of 10*10 mm^2, and an additional "banana"-shape bar (nose of 3 cm, thickness of 0.5 cm), as a backup

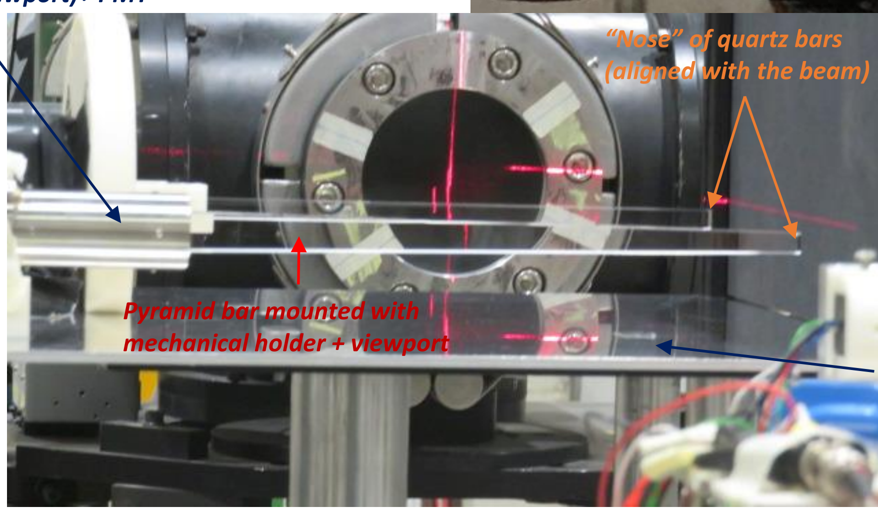


Study of new geometries for quartz radiator

✓ **Tested in H8 (CERN) with 180 GeV/c pions, in various mechanical configurations.**

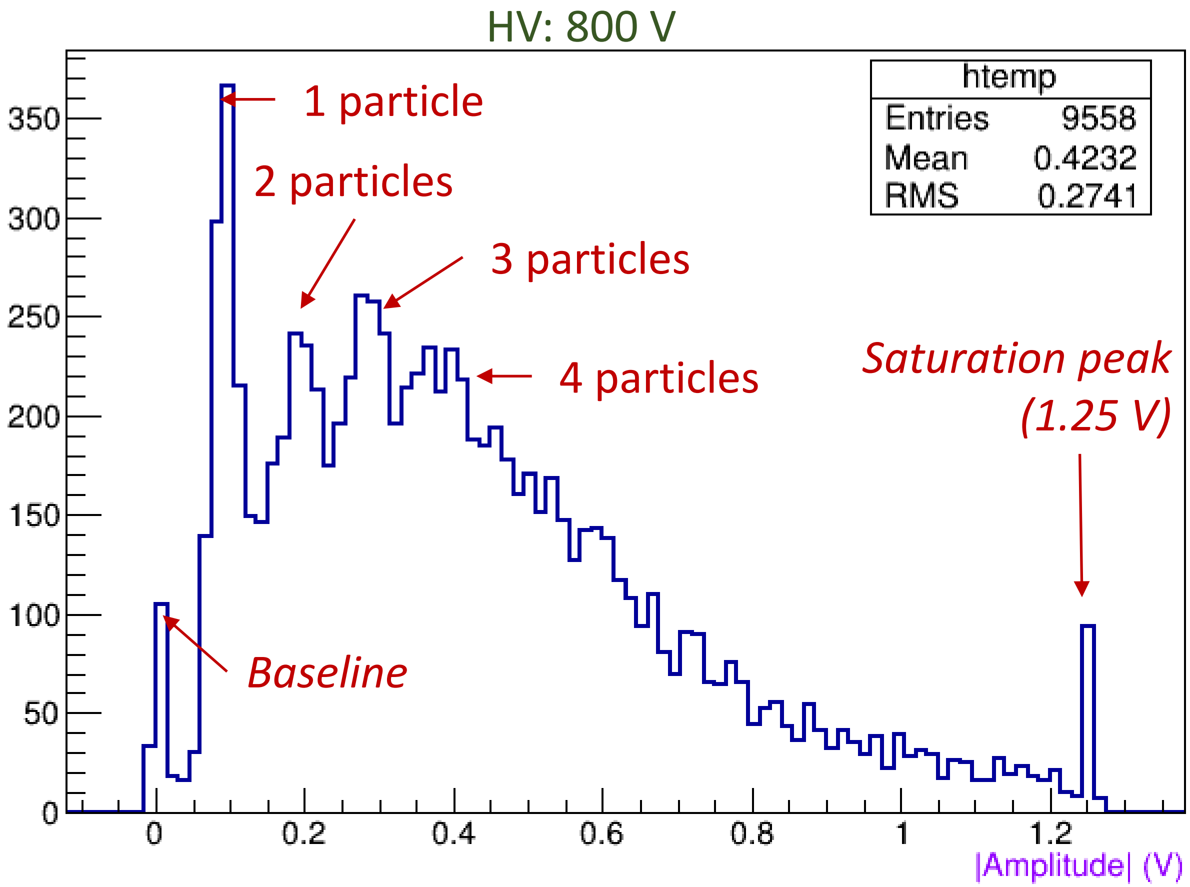


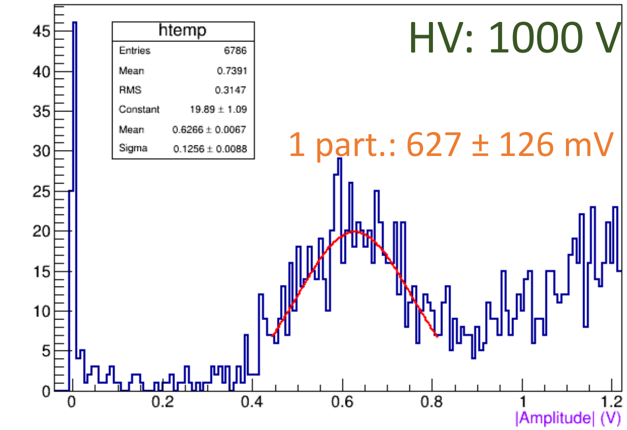


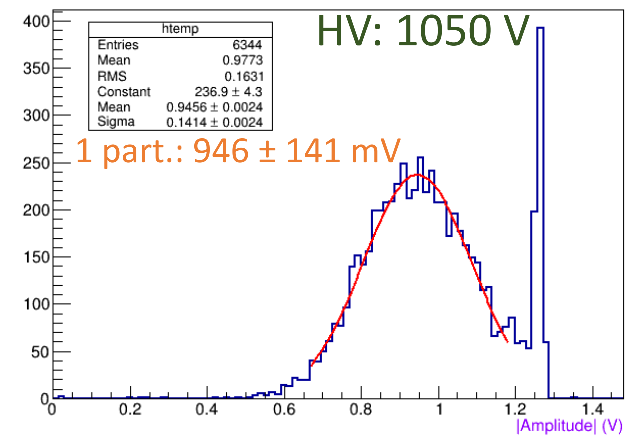


Study of new geometries for quartz radiator

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



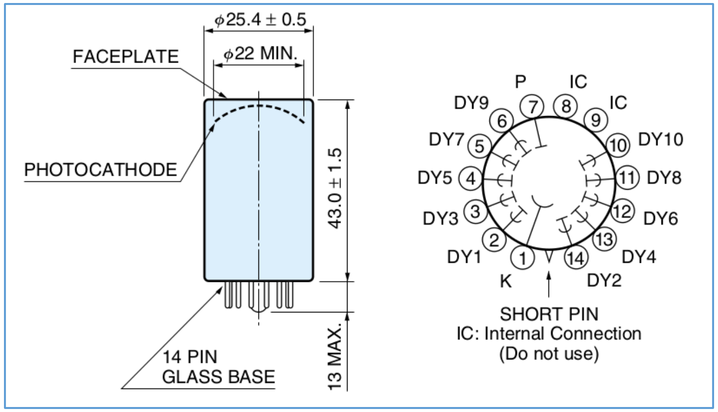




-> Up to 60 p.e./proton (1.17 before)!

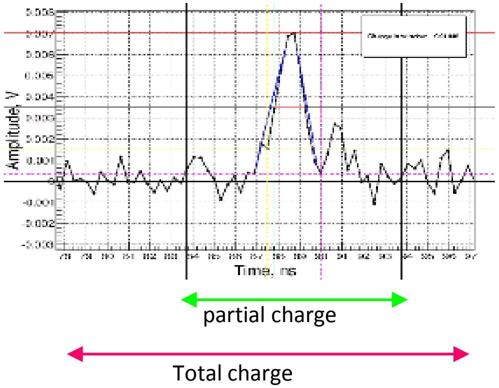
Photodetectors & electronics

- ✓ **Hamamatsu R7378A (already used for CpFM)**
- ✓ **Bialkali photocathode, synthetic silica window, glass base**
- ✓ **HV up to 1250 V (typical gain: 2.0 * 10^6)**
- ✓ **Quantum efficiency of about 20%**
- ✓ **22 mm for the diameter of the photocathode**
- ✓ **Performed at LAL: Linearity / saturation tests**



✓ **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)



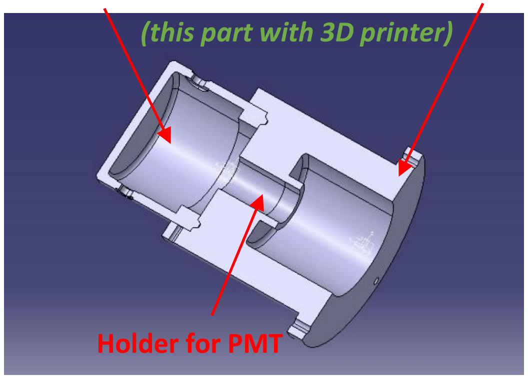
- Work in progress (close collaboration with SERDI, Philippe Vallerand), not ready yet.
- **Before, and in any case, we can use the COBRA electronics, able to register waveforms without discontinuity for several seconds (and analysis software already available in the laboratory).**
- **Storage / bandwidth issue (several Gb/s…)**

Mechanical setup

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

Space for PMT cables and connectors output

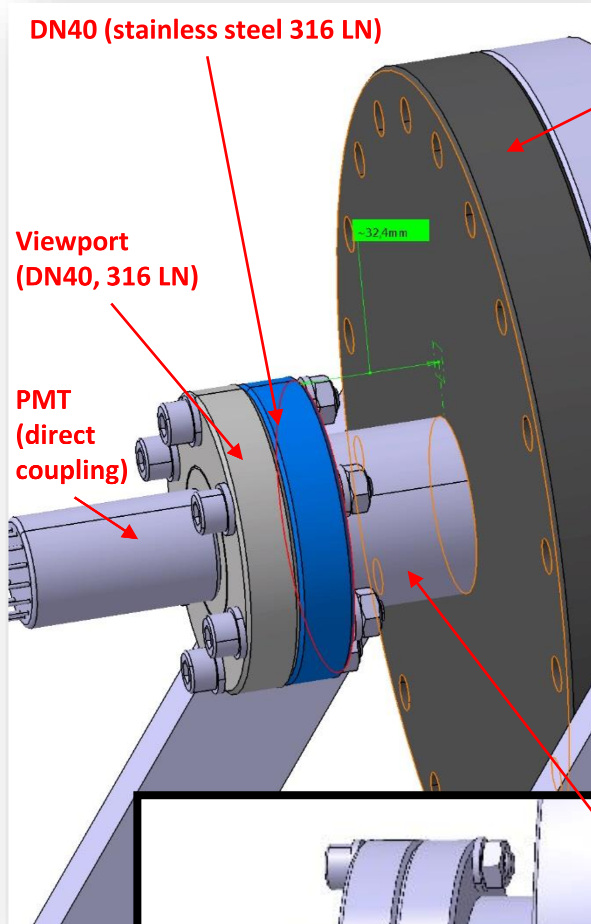
Cover for viewport and DN40 (fixed at DN150)

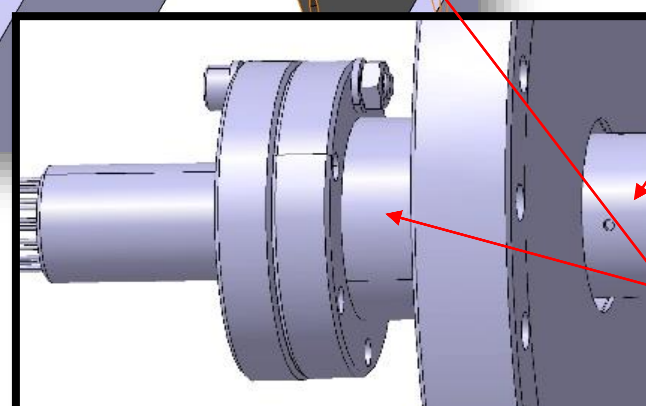


DN40 (stainless steel 316 LN)

Viewport (DN40, 316 LN)

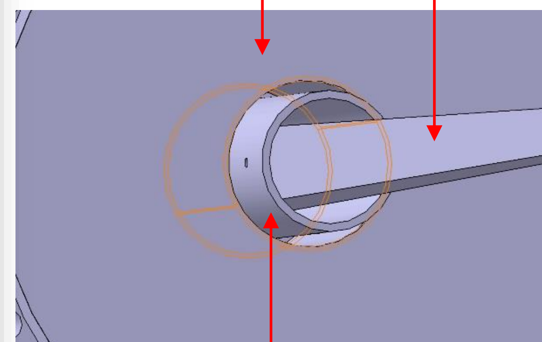
PMT (direct coupling)





DN150 (stainless steel 316 LN)

Quartz bar (pyramid)

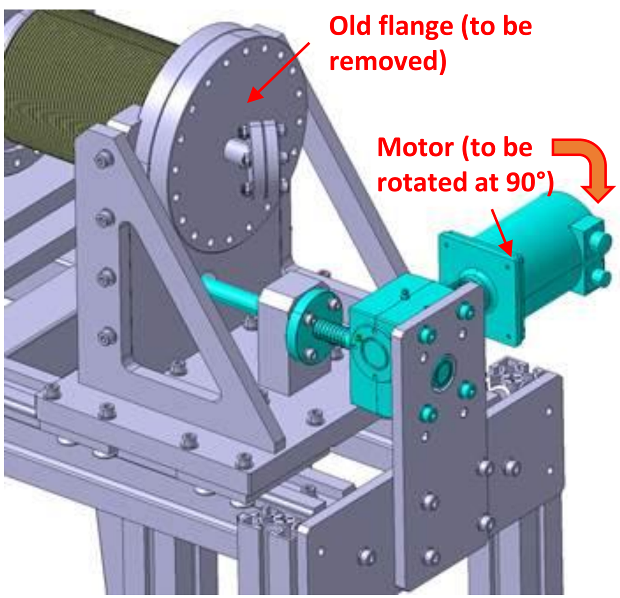


"Small" tube (316 LN, 36 cm), holding the bar with 8 screws (and attached to the viewport)

"Big" tube (316 LN, 42 cm), junction between DN40 and DN150 flanges)

Old flange (to be removed)

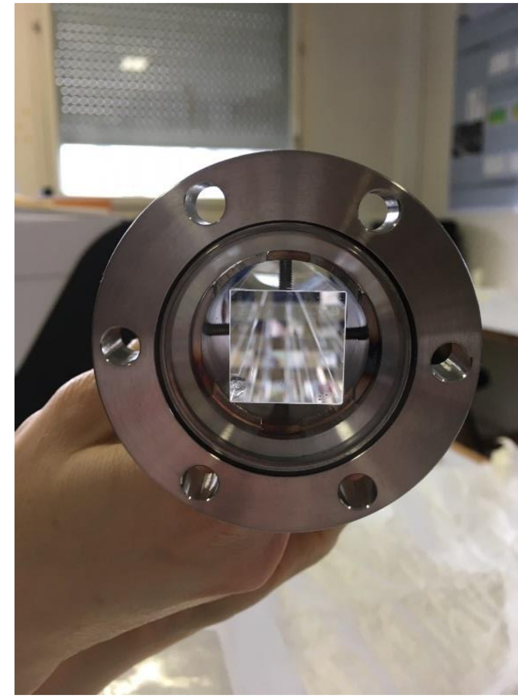
Motor (to be rotated at 90°)



(discussed with Simone Montesano & Regis Seidenbinder, CERN)

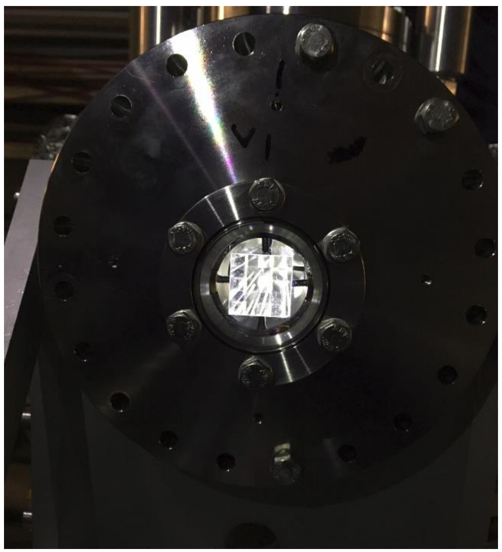
Mechanical setup

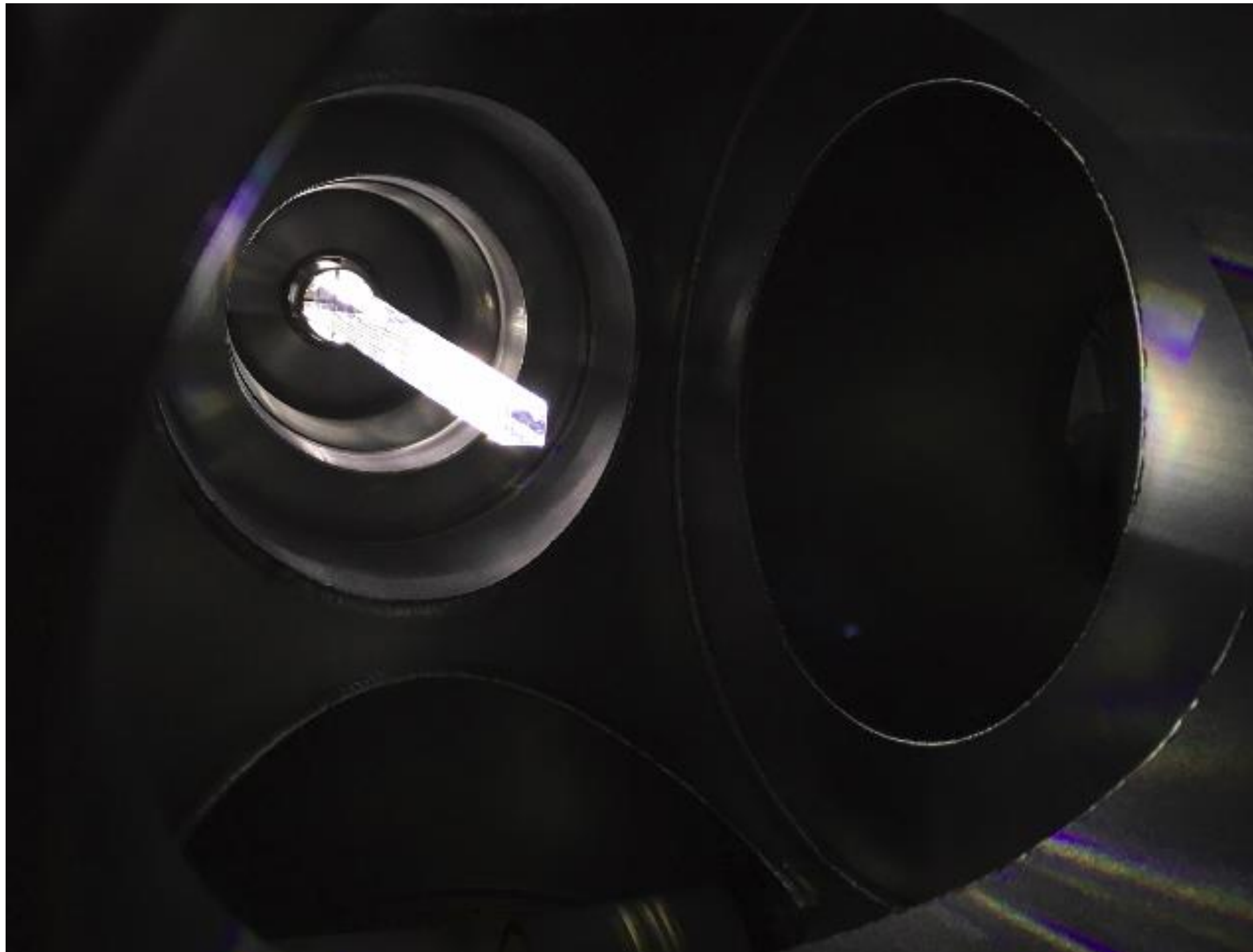
✓ **Mechanical realization (viewport + “small tube” (bar holder) + quartz):**



Installation in SPS (YETS 17-18)

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





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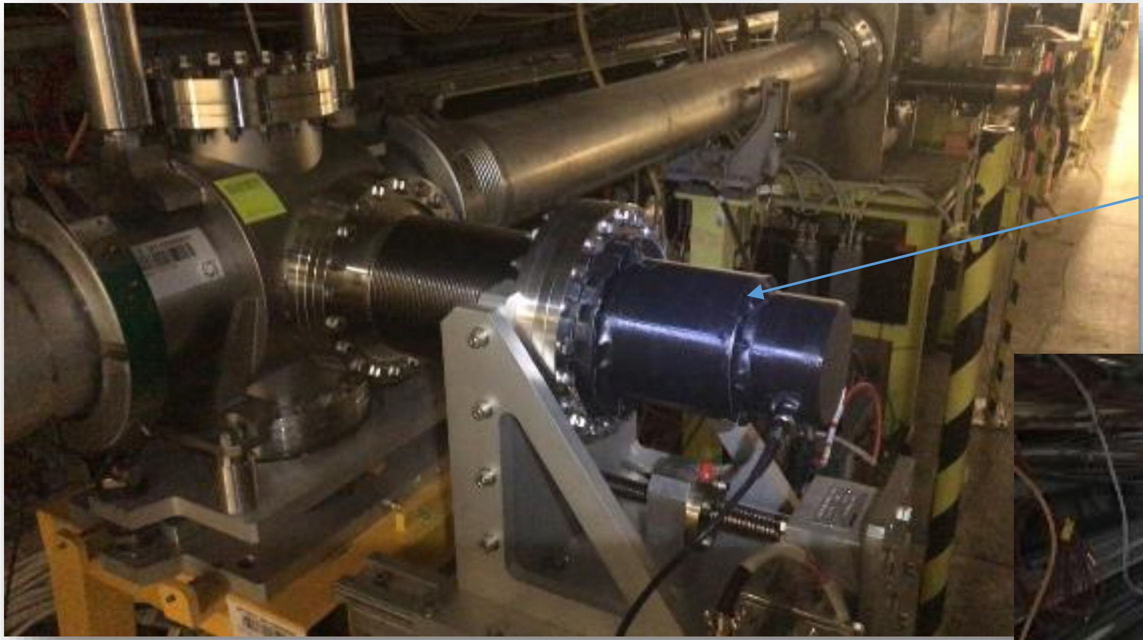

CpFM installed

Monitoring system installed

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III. The CpFM in operation: main results and key technical issues

IV. Toward the development of a new high-sensitive flux monitor

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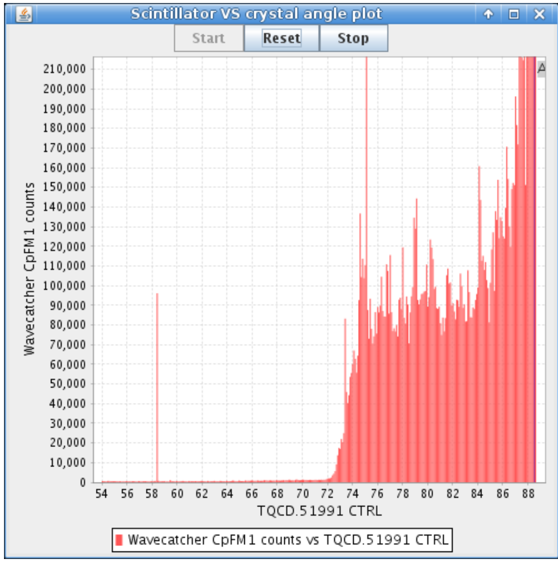
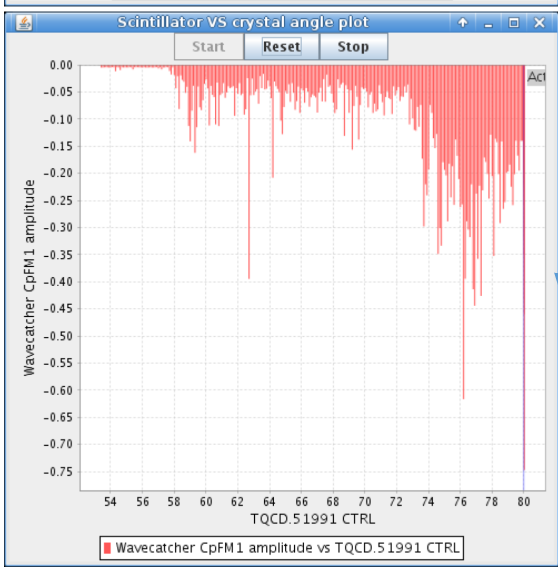
VI. Conclusions

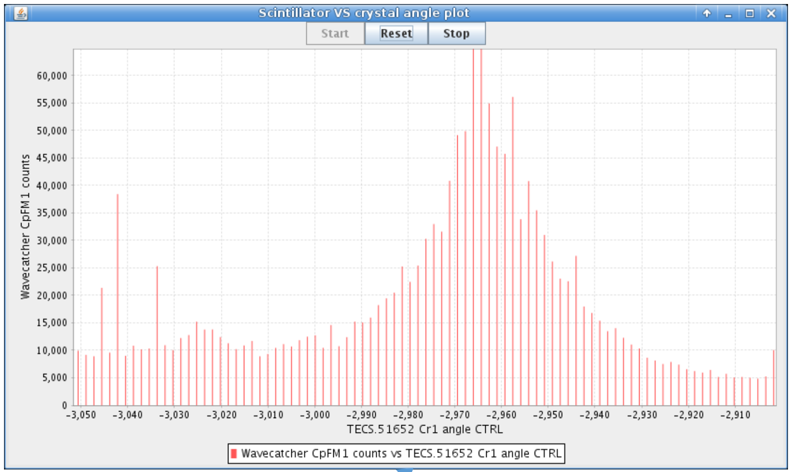
First MDs with the new CpFM

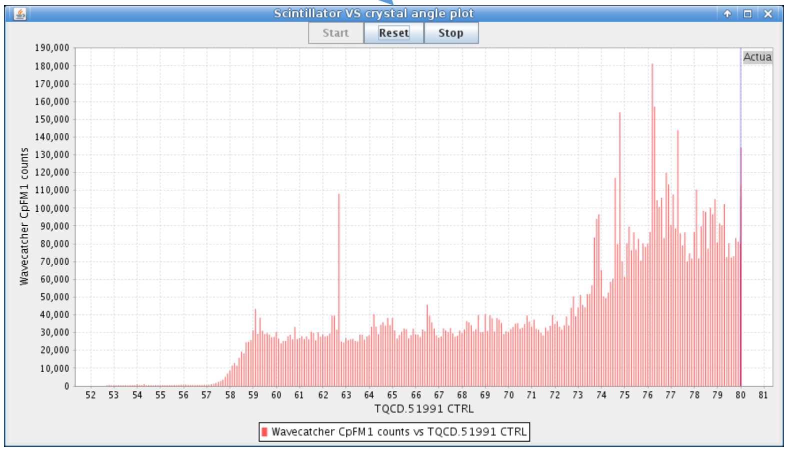
- **270 GeV/c protons**
- **Linear & angular scan: channeled beam & channeling found**





Linear scan

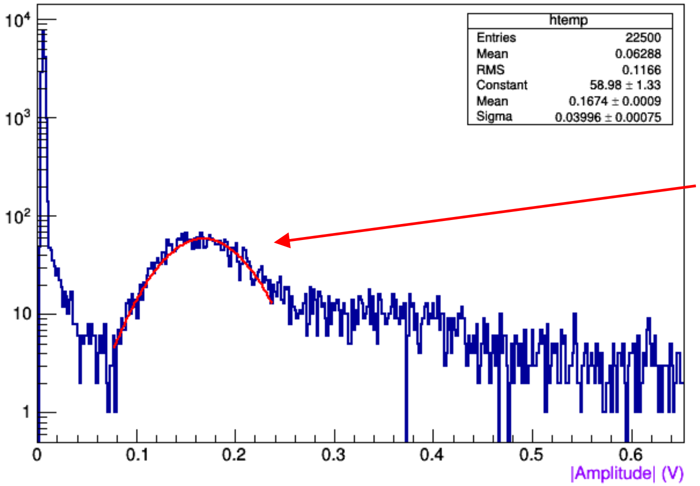




Angular scan

First MDs with the new CpFM

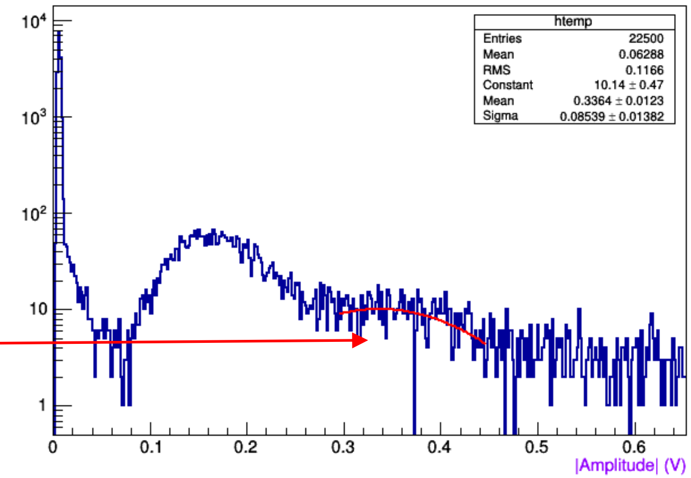
Amplitude distribution: one proton signal clearly visible (<u>self-calibration!</u>)



HV 1000 V

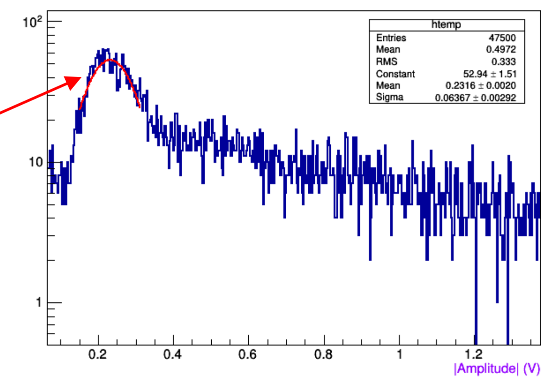
One proton (167 mV)

Two protons at 336 mV (≈ 2 × 167 mV)



HV 1050 V (maximum gain)

One proton (232 mV)



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

Conclusions - Expectations

- ✓ **Signal lower than expected from H8 results… Probably related to 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!**

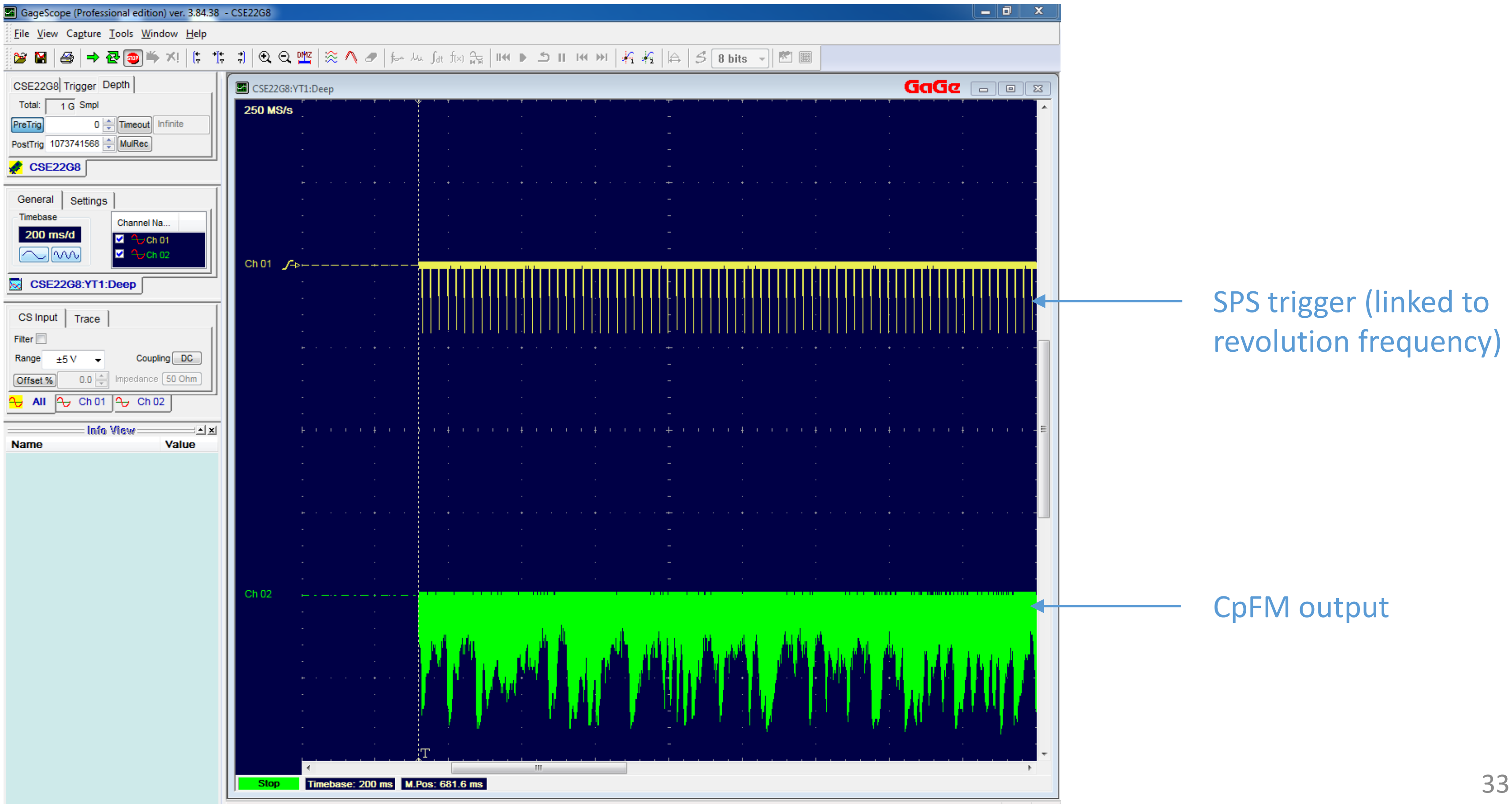
- ✓ **Measured performances (examples), with real on-line calibration:**

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 <u>able to register a complete train of 172000 successive bunches (4 s of acquisition, with a revolution frequency of 43 kHz)</u> -> Still to be analyzed…



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Conclusions

- ✓ Different versions / iterations of the CpFM developed, driven by new requirements and feedback from the experiment: first version, updated version with direct coupling, and at the end a new version with extended sensitivity and ability to count each bunch.

- ✓ Able to work in different configurations, to detect a beam, measure variations or count individual particles crossing, with a very low threshold (one proton).

- ✓ Used or tested with various charged particles: e^-, pions, protons, Pb and Xe ions…

- ✓ Design compatible with vacuum & SPS conditions.

- ✓ Could be modified / updated to be used as a particle flux-monitor in a beam line, like PRAE…
- ✓ … continuous developments on our side!