UA9 2019-2024 Workshop

CpFM Results

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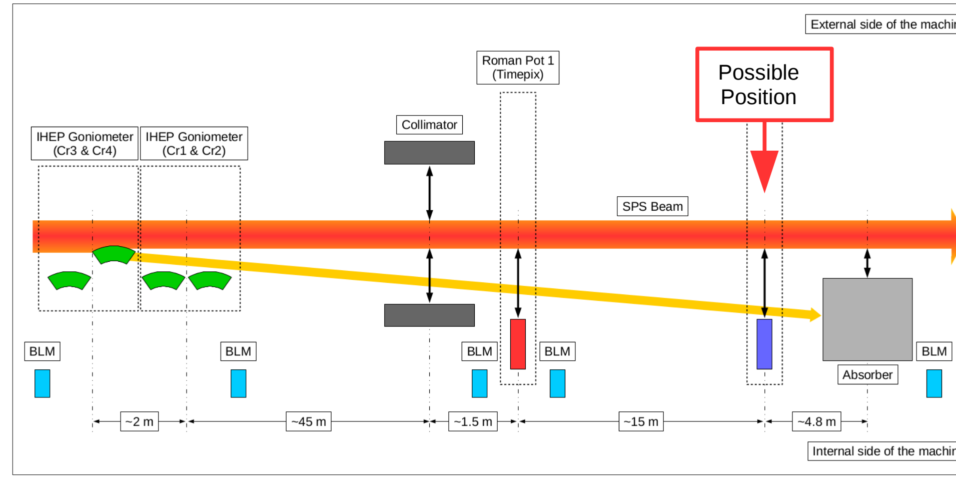
Orsay, France
12-13 March 2019

- Basic idea.
- Cherenkov detector.
- First detector calibration.
- SPS MD 2016.
- Characterization of the fused silica surface quality with a β-source.
- CpFM improvements.
- New CpFM. SPS installation.
- SPS MD 2018.
- CpFM progress.
- Double crystal setup at SPS 2018.
- Double crystal setup with a target at SPS 2018.
- Conclusions.

Basic idea



LSS5 zone of the SPS 2016

What do we have?

A bent crystal deflecting halo particles.

What do we want?

A device for quantitative characterization of the deflected particle beam.

What is the working environment

Circulating machine (SPS & LHC).

What are the requirements for this device?

1. Vacuum compatibility: **10^{-9} mbar** for SPS and **10^{-11} mbar** for LHC.

2. Fast enough detector response for the particle counting during a single bunch of **1-3 ns** duration (*it is not necessary to measure each bunch in a train*): revolution frequency of **43 kHz** for SPS and **11 kHz** for LHC.

3. Counting range: from 1 up to **10^3 particles/turn**.

4. Radiation hardness: neutron flux of about **10^{12}/cm^2** and **10^{15}/cm^2** for SPS and LHC, respectively. Integrated dose up to **kGy/year**.

Our proposals?

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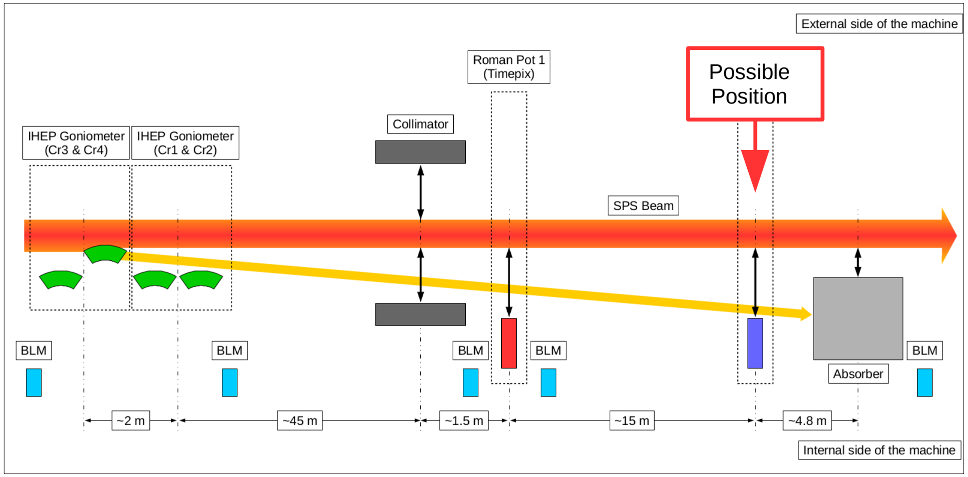
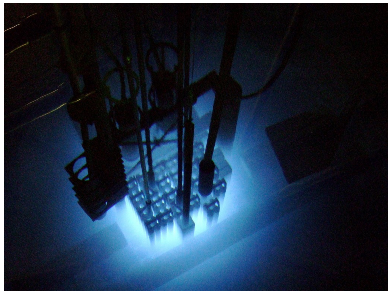
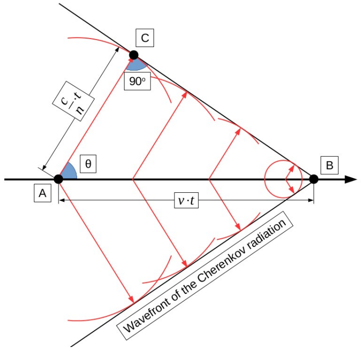


LSS5 zone of the SPS 2016

Our proposals?

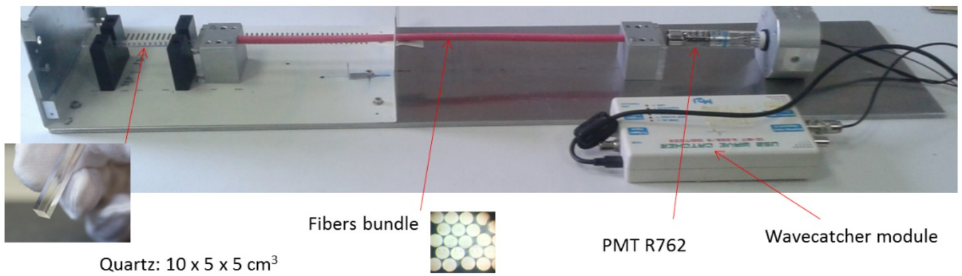
Cherenkov Detector !

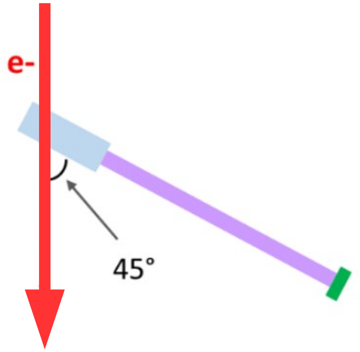


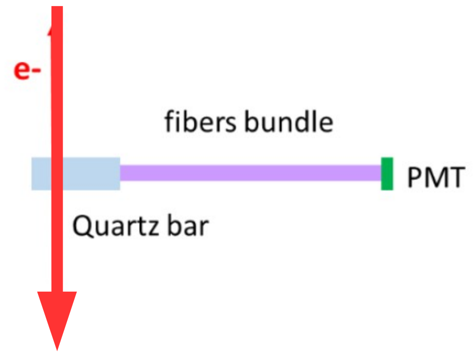


$$cos(\theta) = \frac{1}{n\beta}$$

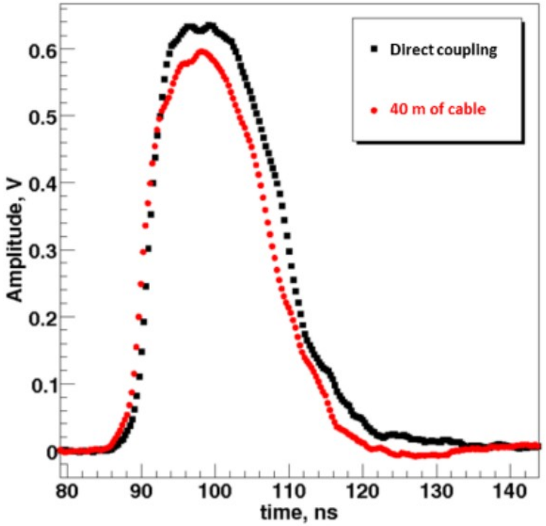
$$N = 2\pi\alpha Z^2 L \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)\left(1 - \frac{1}{n^2\beta^2}\right)$$





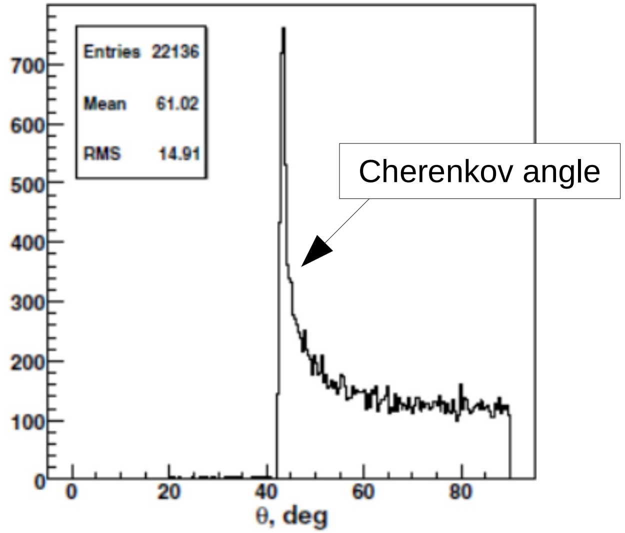


Measurements



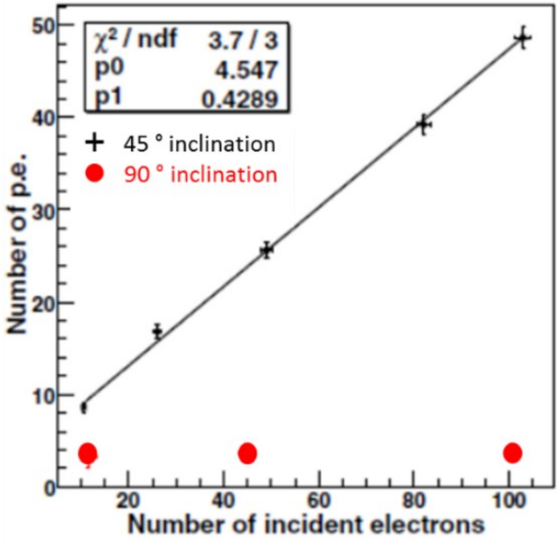
40 m long signal cable effect

Simulation



Distribution of the polar angle of the Cherenkov photons emerging from the read-out surface of the fused silica bar, when it intercepts at 90 degrees electrons of 450 MeV.

Measurements

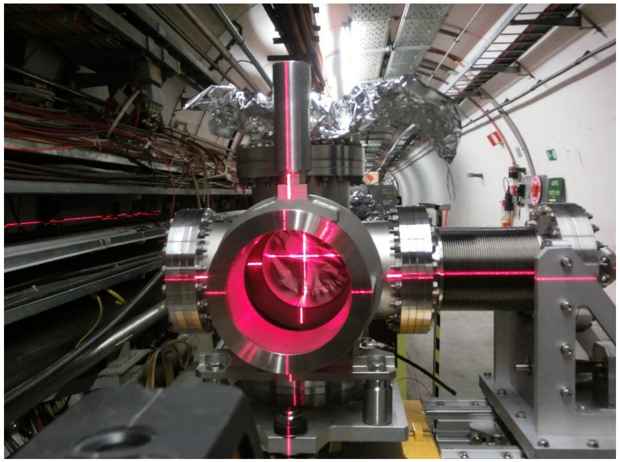


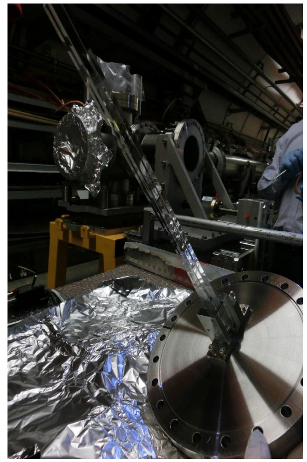
Measurement of the prototype response as a function of the incident electron flux

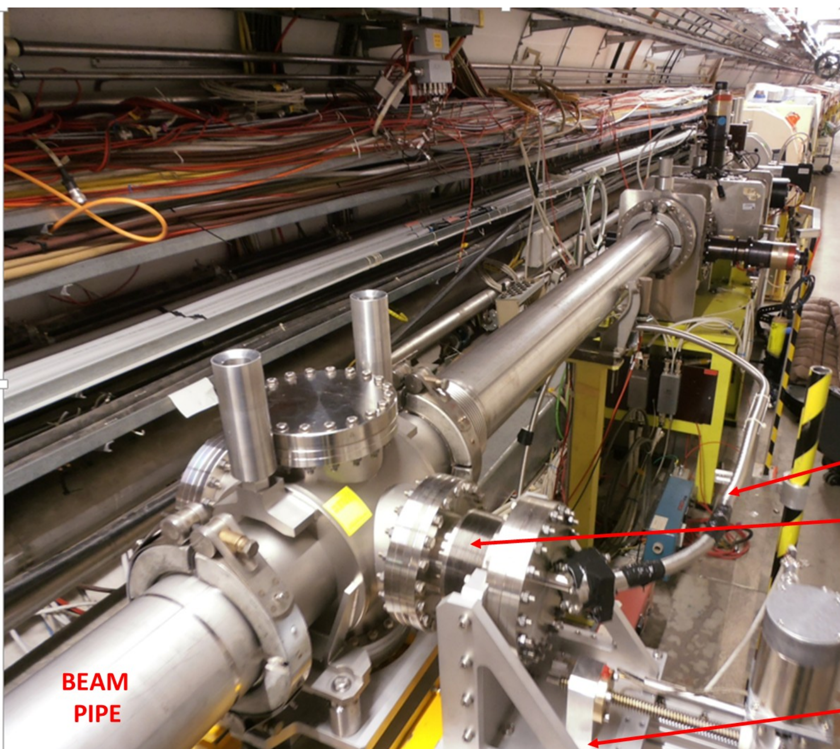
→ Bar has to be inclinated or with a cutted readout side
→ 40 m long singnal cable doeas not affect measurements
→ Configuration (Radiator + Fibers + PMT) works

L. Burmistrov et al., 2013 IEEE Nuclear Science Symposium and Medical Imaging Conference (2013 NSS/MIC).

Cherenkov detector for **p**roton **F**lux **M**easurement
>> CpFM <<



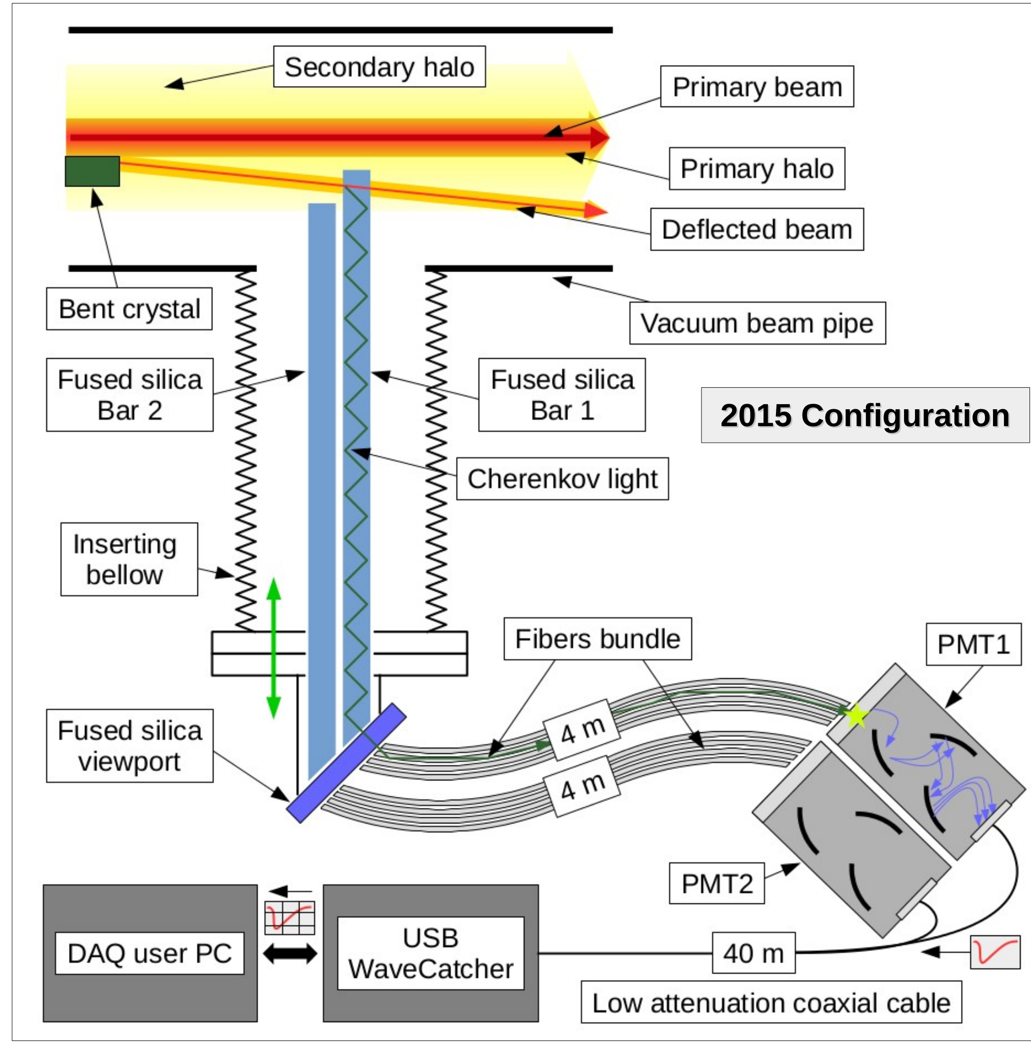


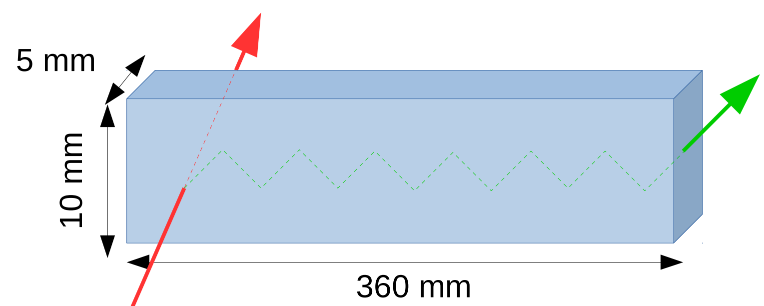


Fibers bundle

Inserting bellow

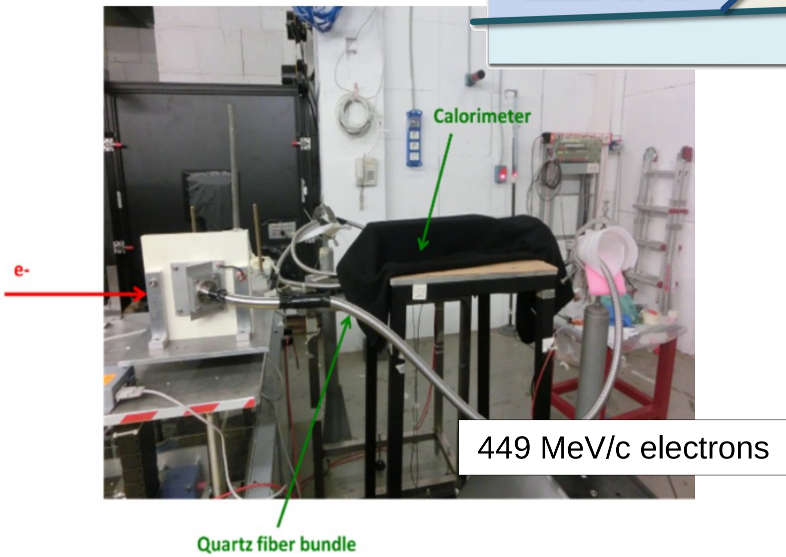
Motorized support of the quartz bars



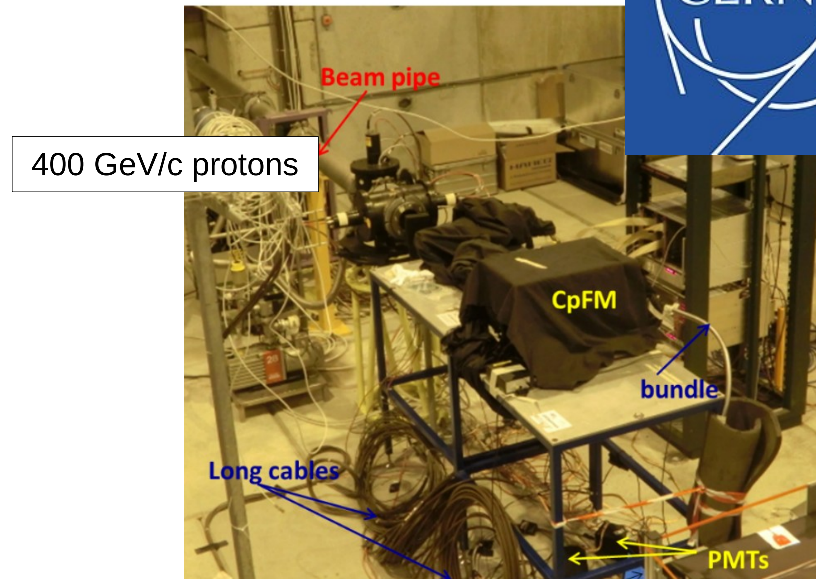


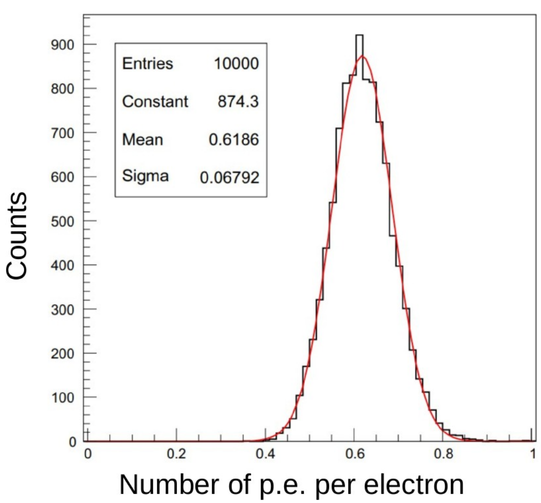
V. Puill et al.The CpFM, an in-vacuum Cherenkov beam monitor for UA9 at SPS. Journal of Instrumentation, 12:P04029, 2017.

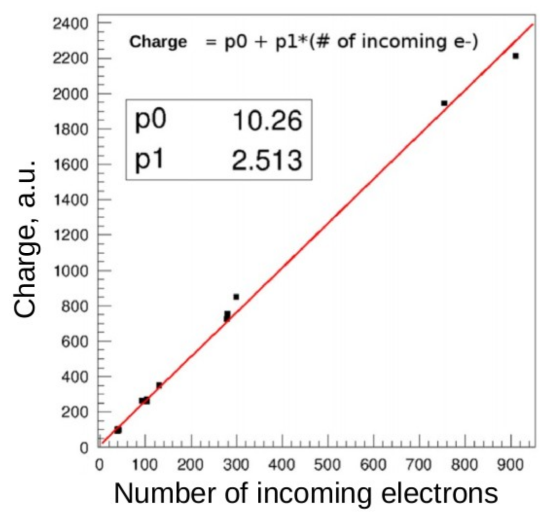
The DAFNE **B**eam-**T**est **F**acility



CERN SPS extraction line
H8 North Area







→ A good signal linearity with a number of incoming electrons.

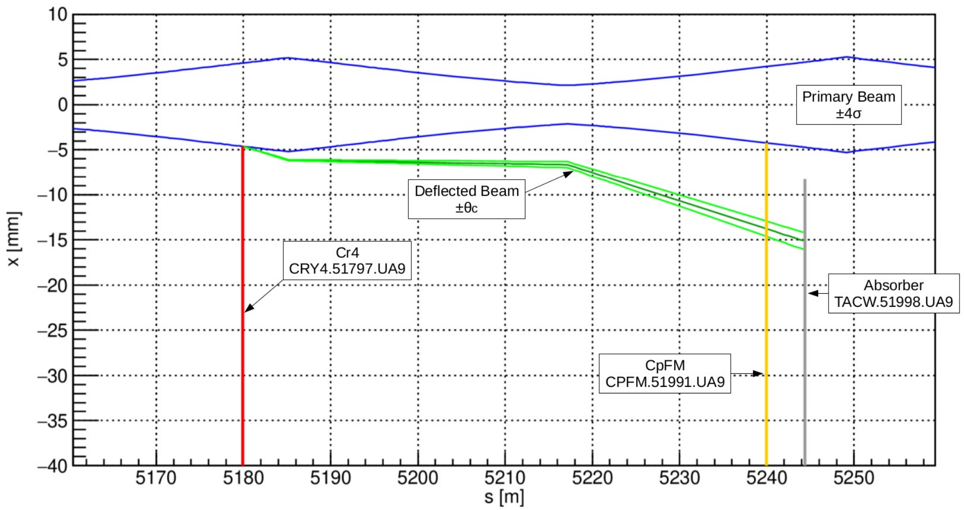
→ The measured resolution of the detector is **15%** for 100 electrons.

→ Calibration value of about **0.62-0.63 photoelectrons/particle**.

On SPS **40 cm** long bars have been installed (<u>not properly tested before</u>).

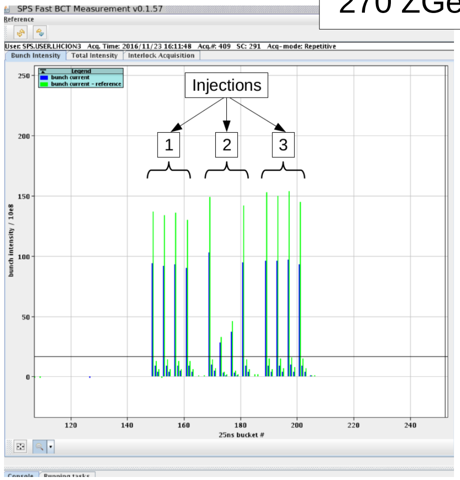
L. Burmistrov et al. Test of full size Cherenkov detector for proton Flux Measurements. Nuclear Instruments and Methods in Physics Research A, 787: 173 – 175, 2015.

SPS MD 2016. Self-calibration with ions

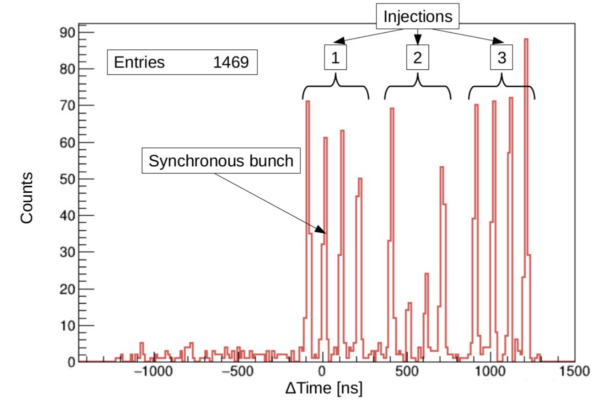


Beam optics at SPS LSS5

270 ZGeV/c Pb ions

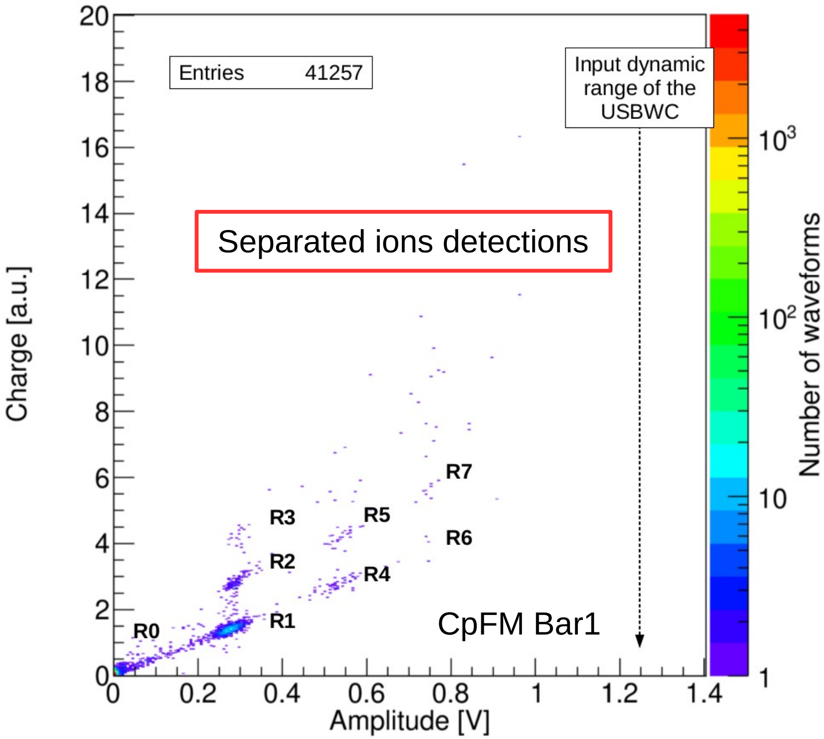


Fast BCT measurements



CpFM measurements

Excellent beam structure match



Waveform charge as a function of the maximum signal amplitude. Detection of the different number of ions.

Self-calibration with ions

Different detection sensitivity of the bars for the same amount of the produced Cherenkov light.

!

	Amplitude, mV	Charge, a.u.
CpFM Bar1	276.3±0.2	1.325±0.001
CpFM Bar2	990.3±0.2	6.247±0.002

Amplitude and charge per a single ion.
For 700 V of the CpFM PMTs voltage supply.

Pb ions (Z = 82)

	Amplitude, mV	Charge, a.u.
CpFM Bar1	276.3±0.2	1.325±0.001
CpFM Bar2	990.3±0.2	6.247±0.002

Proton (Z = 1)

	Amplitude, mV	Charge, a.u.
CpFM Bar1	0.990±0.001	$0.005 \pm 3.6 \cdot 10^{-6}$
CpFM Bar2	2.910±0.001	$0.018 \pm 5.9 \cdot 10^{-6}$

Cherenkov photons number ~ particle Z^2

	From the Amplitude, p.e./proton
CpFM Bar1	0.047±0.002
CpFM Bar2	0.142±0.003

From H8/BTF ~0.63 p.e./p

!

WHY?

What have we done since H8/BTF calibration?

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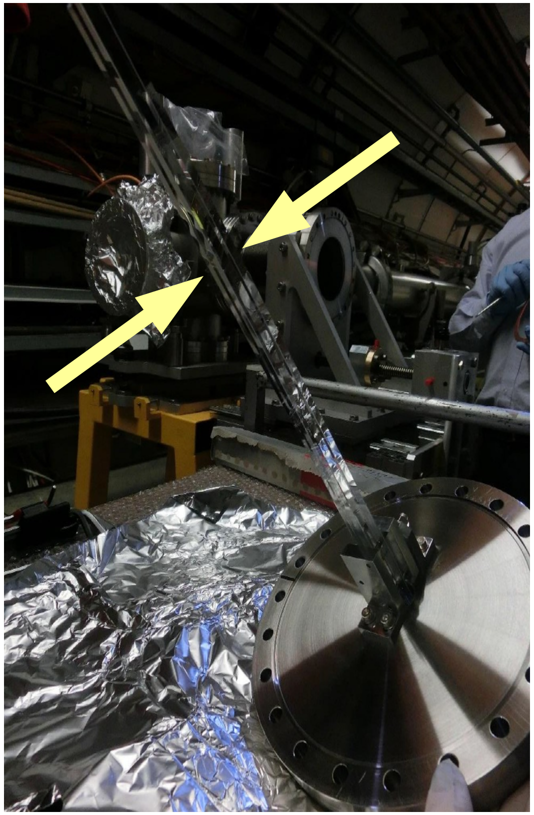
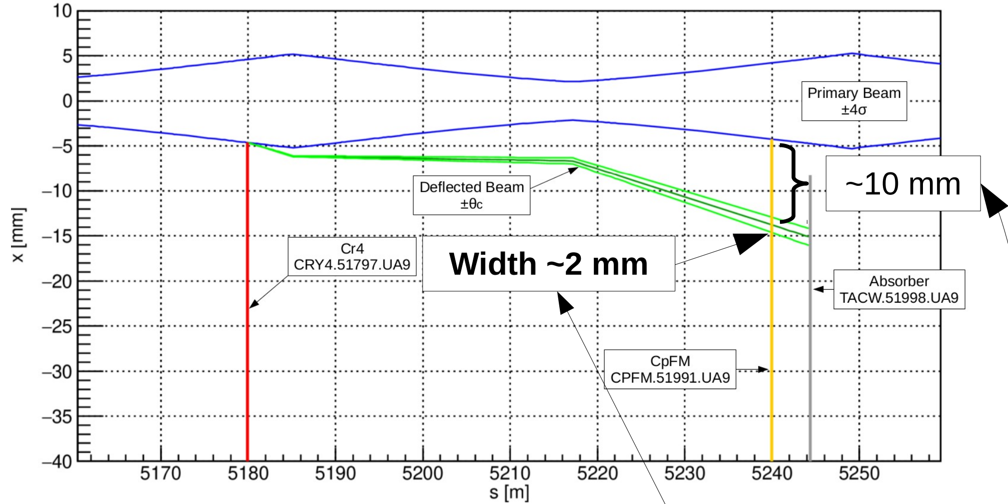
WHY?

Not properly tested new 40 cm long fused silica bars



?

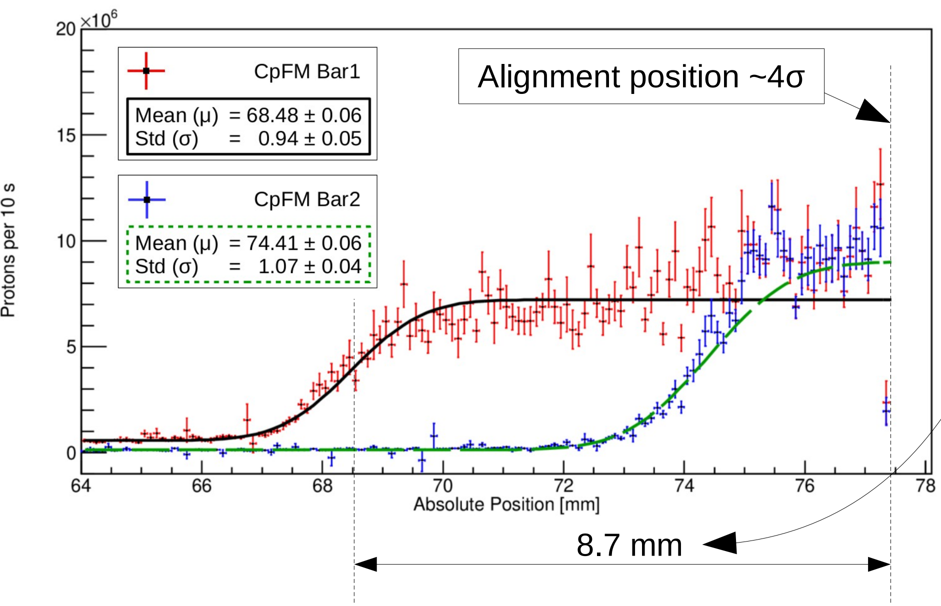
What have we done since H8/BTF calibration?



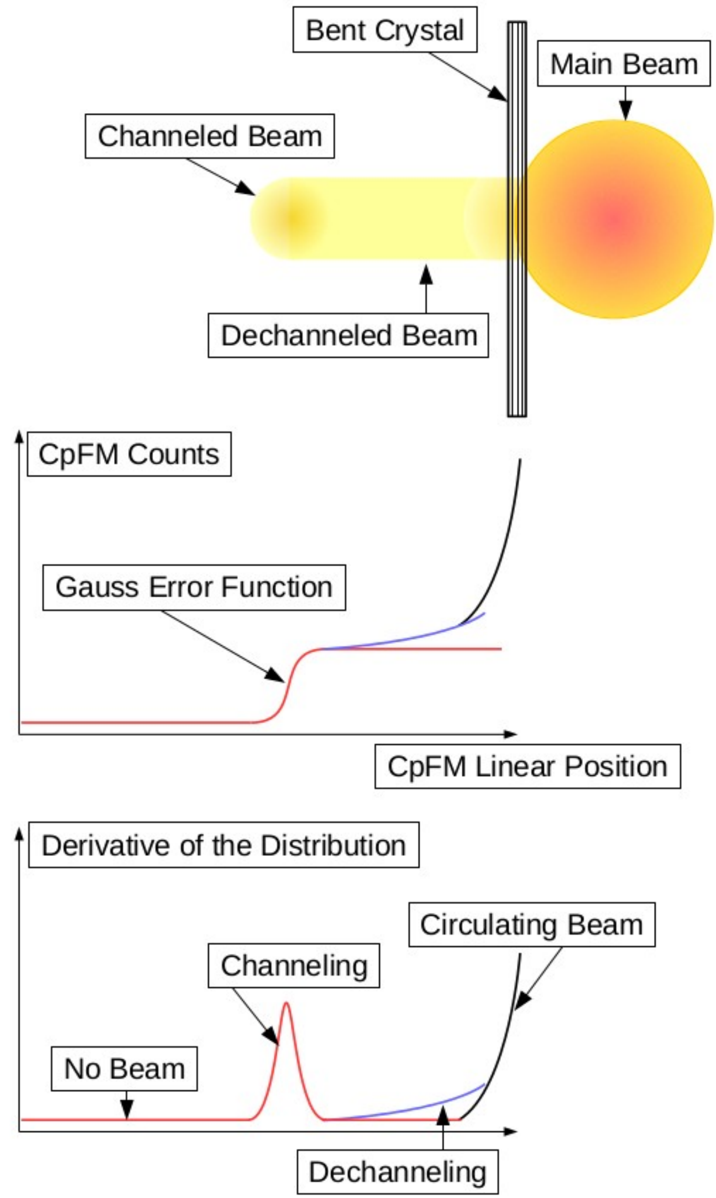
Beam optics at SPS LSS5

CpFM measurements with 270 GeV/c protons

FWHM = 2.355×Std = 2.355×0.94 = **2.2±0.1 mm**

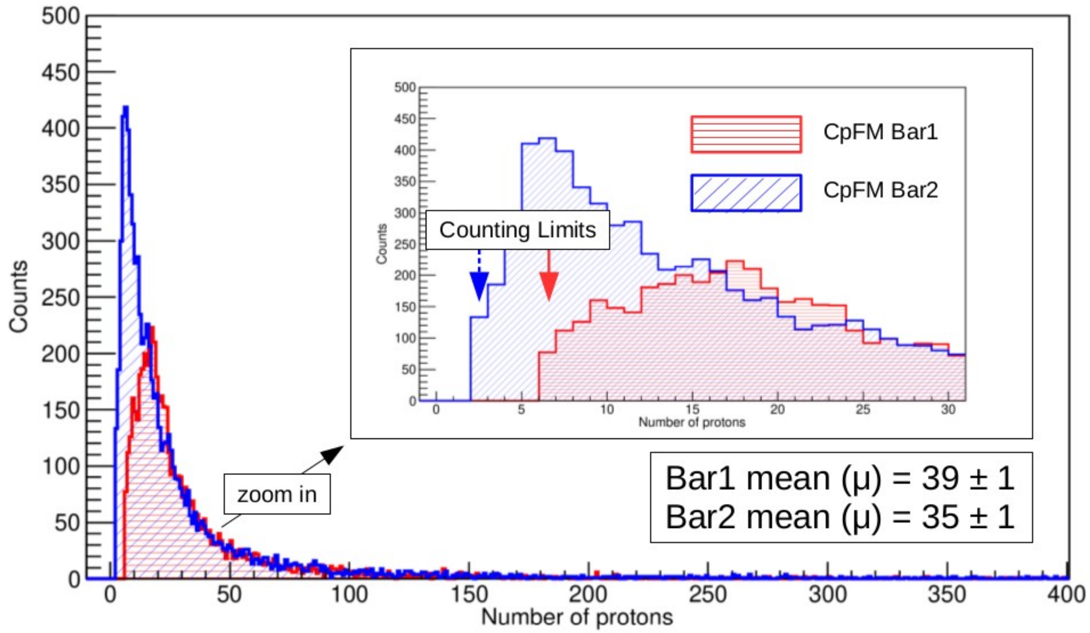


CpFM integrated counts along the linear scan.

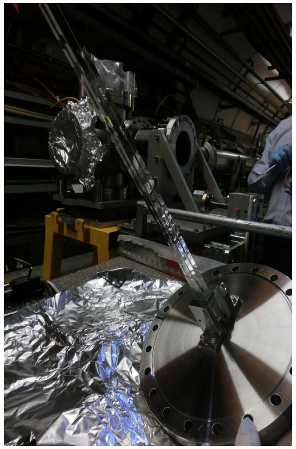


Amplitude per a single protons

	Amplitude, mV
CpFM Bar1	0.990±0.001
CpFM Bar2	2.910±0.001

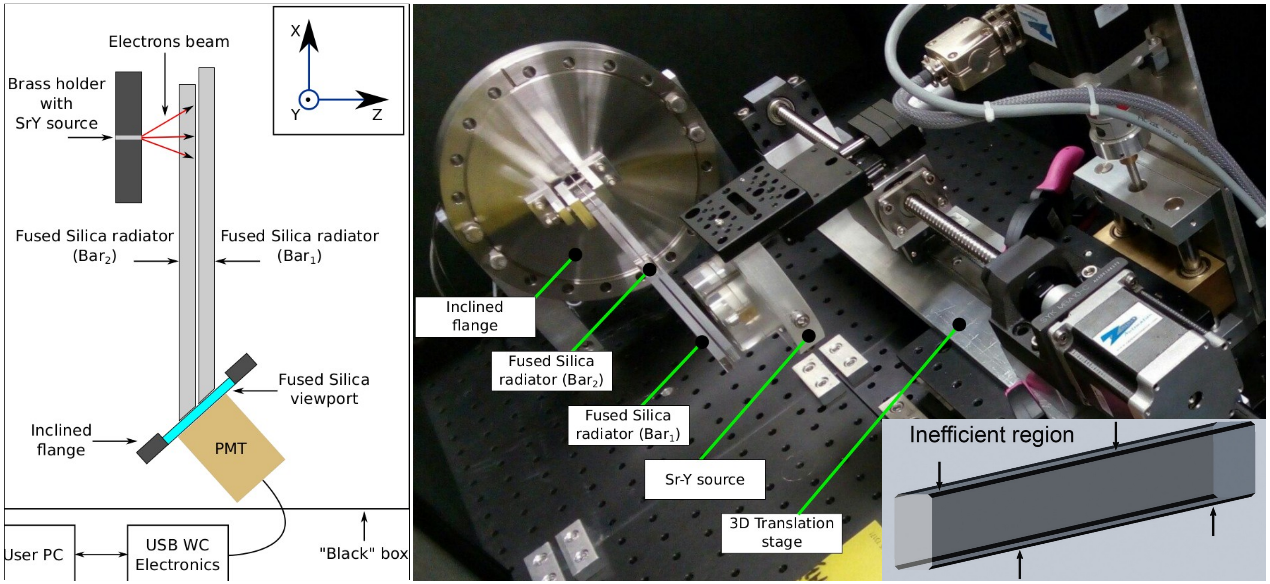


- Measured beam profile and channeled particles flux.
- Not sensitive to a single proton.
- Different parameters of the bars.

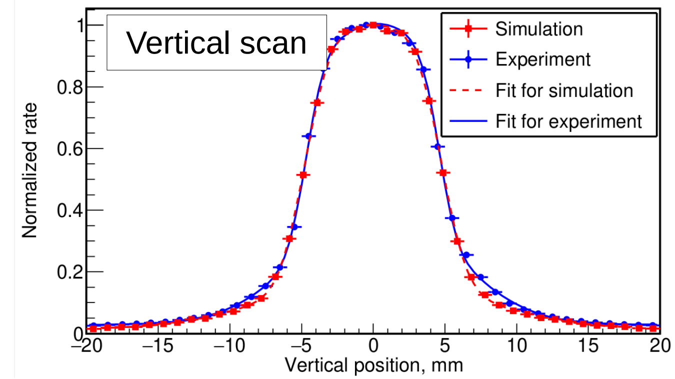


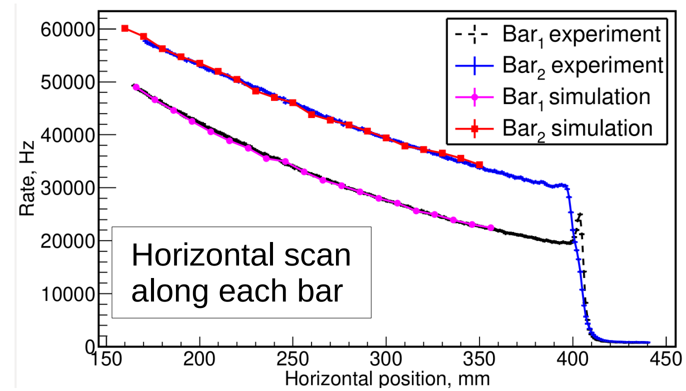
<u>Characterization of the bars is needed !</u>

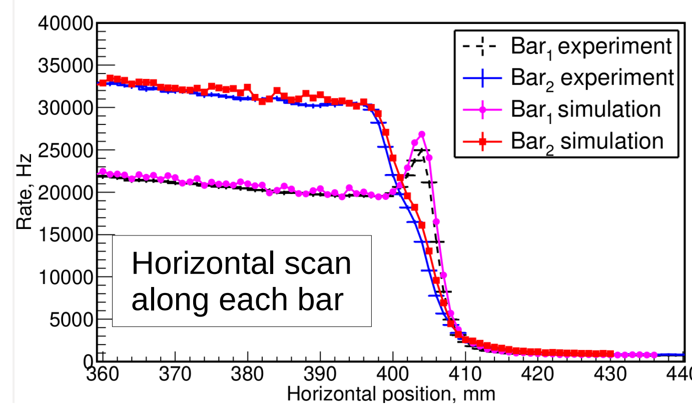
Characterisation of the fused silica surface quality with a β-source



February 2017







Geant4 Monte-Carlo simulation:

→ realistic electron distribution produced by the source

→ refractive index and total internal reflection probability behavior of the fused silica for different photon energies

→ quantum efficiency of the PMT Bialkali photocathode

The model well-describes the experimental data obtained by scanning the bars with the source and measuring the Cherenkov light signal output with a PMT

	Bar1	Bar2
Probability of total internal reflection	96.4 ± 0.1 %	95.9 ± 0.1 %
Fraction of ineffective area at the edges of the bars	2.7 ± 0.7 %	0.0 ± 0.7 %

Verdict

Bad production quality **!**

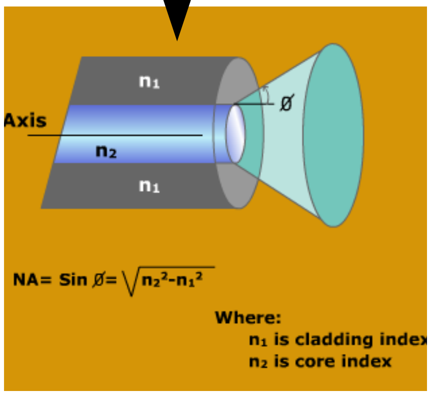
13

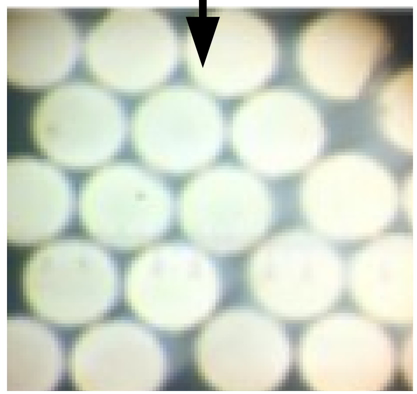
A. Natochii et al. Characterisation of the fused silica surface quality with a β-source. Nuclear Instruments and Methods in Physics Research A, 910:15 –21, 2018.

SPS MD 2017

10 times reduction of the the detected Cherenkov photons:

1. Numerical aperture of the fiber ∼ 8°.
2. Fibers fill factor.

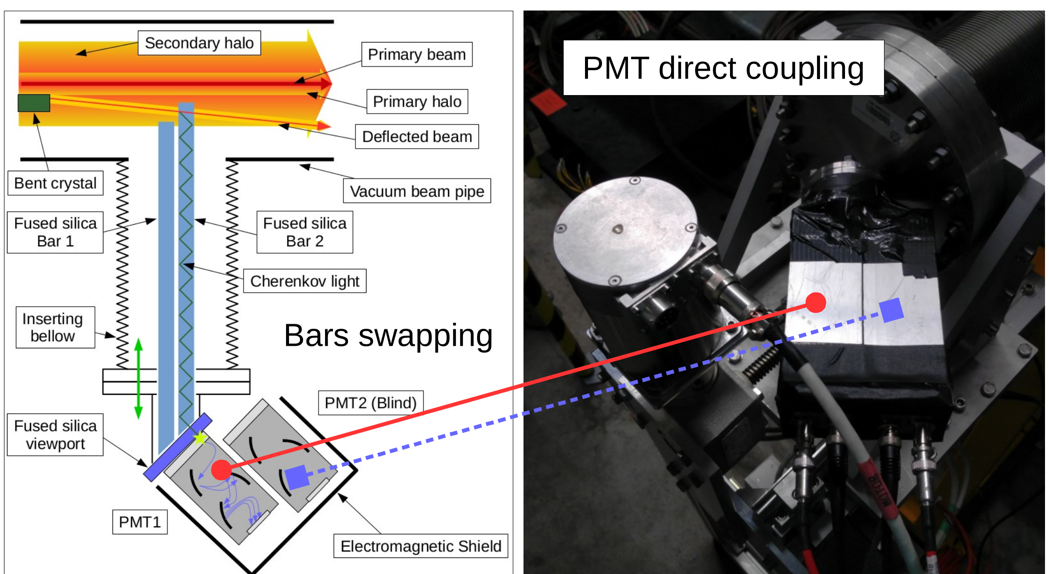




Why did we put the bundle?

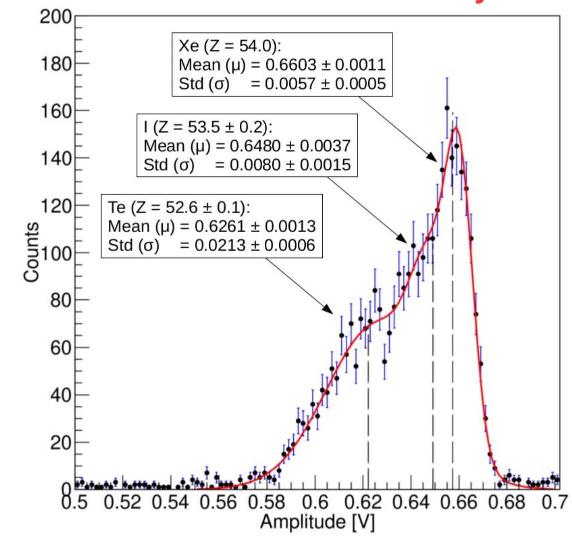
1. To reduce the radiation dose on the PMT.
2. PMT EM pick-up, close to the beam-pipe.

Solution



Operational PMT

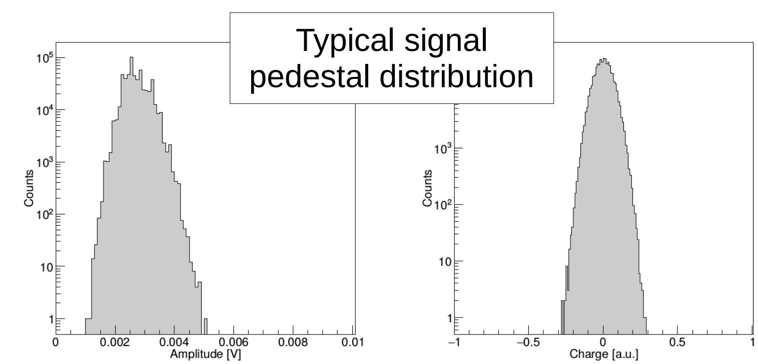
New Xe ion calibration at SPS
Beam contamination study



	Amplitude, mV	Charge, a.u.
CpFM Bar2	660.3±1.1	5.3723±0.0215

No EM pick-up has been observed.

Blind PMT



(a) Amplitude distribution. (b) Charge distribution.

CpFM improvements. Direct coupling

Single proton amplitude → Calibration value

	Amplitude, mV
CpFM Bar2	18.294±0.0055

	From the Amplitude, p.e./proton
CpFM Bar2	1.418±0.022

2015-2016 H8/BTF	→ 0.63 p.e./proton	→ resolution ~ 150 %/proton
2016-2017 SPS	→ 0.05 p.e./proton	→ resolution ~ 300 %/proton
2017 SPS direct coupling	→ 1.42 p.e./proton	→ resolution ~ 55 %/proton

- Improved amount of the detected Cherenkov light.
- Improved a single proton resolution.
- Checked the direct coupling configuration (EM pick-up).

Better Resolution
< 20 %/proton

What do we want?

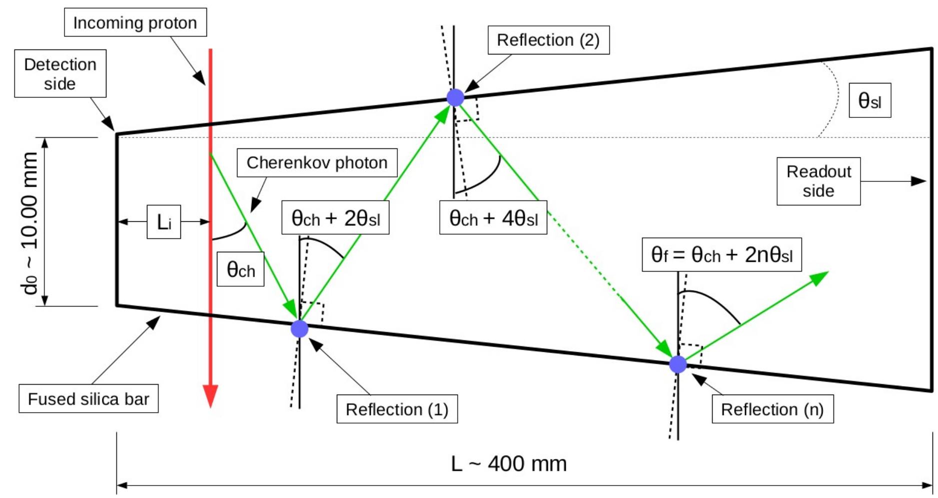
1. To increase the particle detection efficiency.
2. To be sensitive to a single proton with a good resolution (10÷20%).

What we have to do?

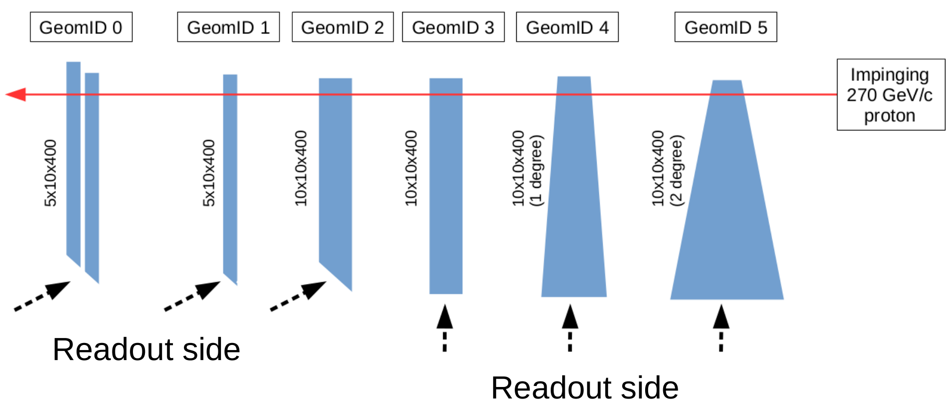
1. Increase the number of the produced Cherenkov photons.
2. Decrease the number of the photons internal reflections from the surface of the bar.
3. Improve the quality of the fused silica bar surface.

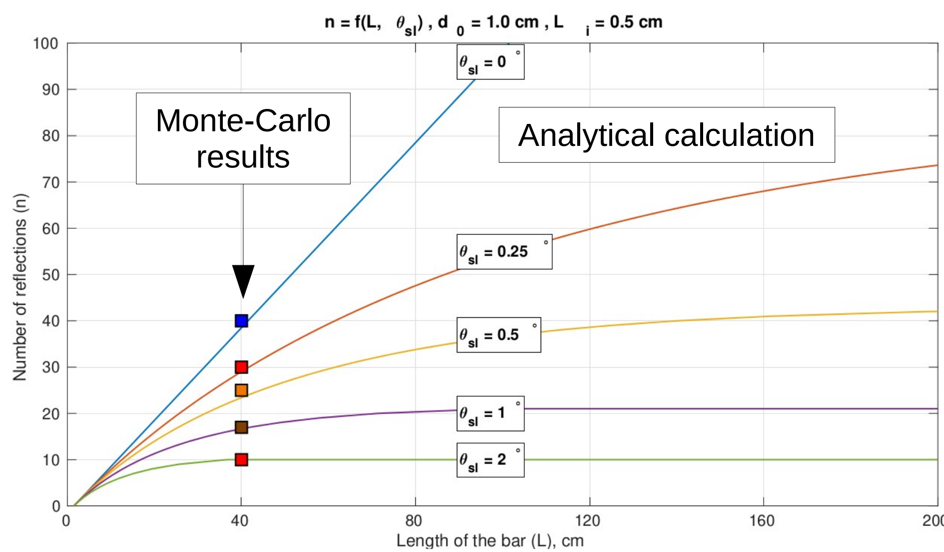
Solution

A new radiator geometry.

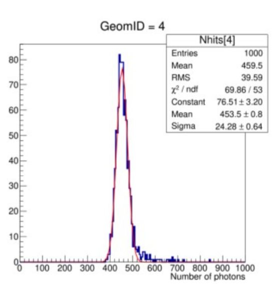


Pyramid slant angle makes all work!

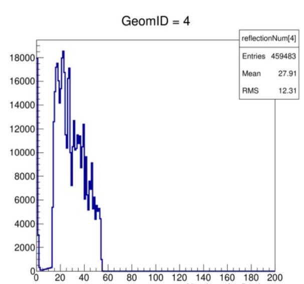




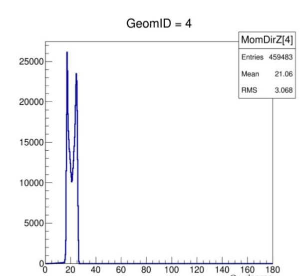
Analytical and Monte-Carlo approaches have been used to find the most efficient geometry.



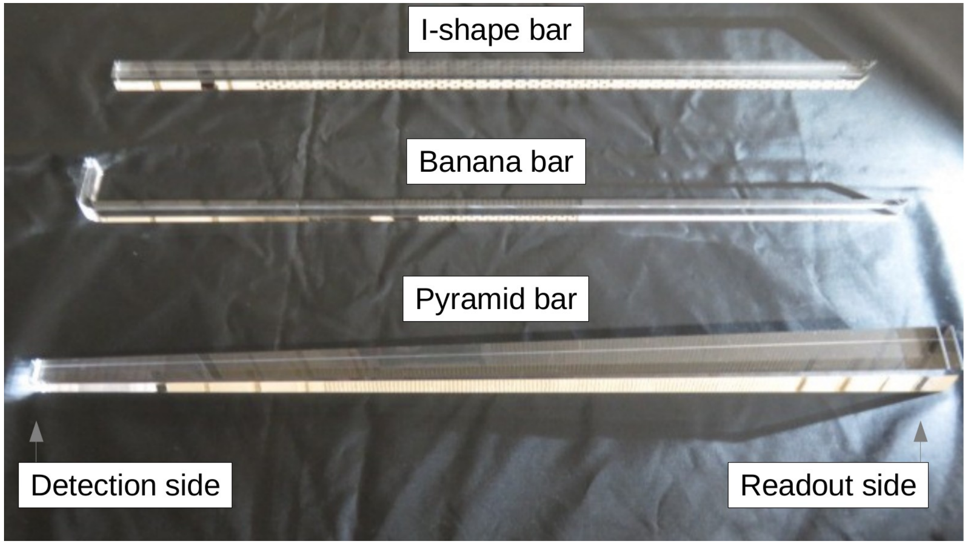
Number of photons

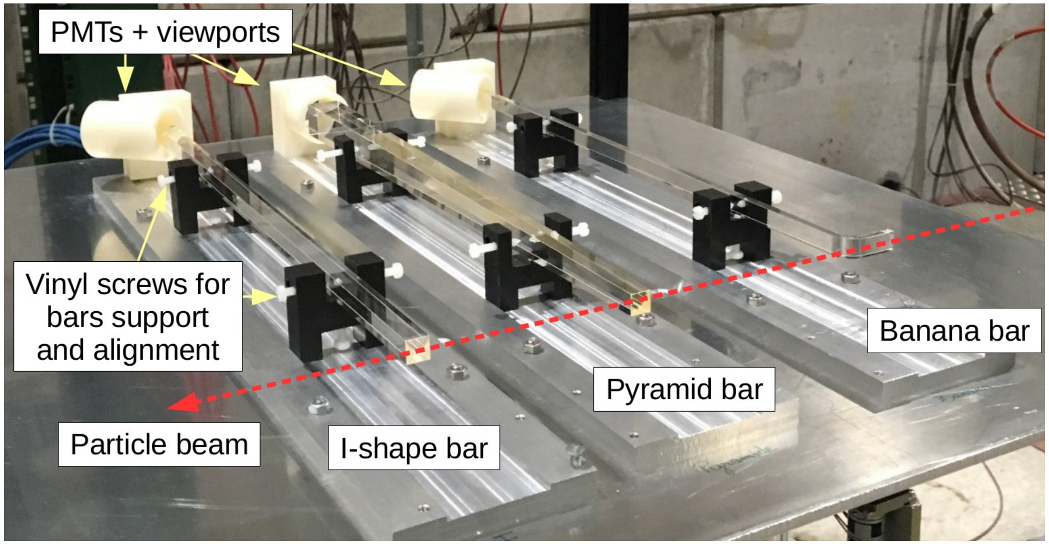


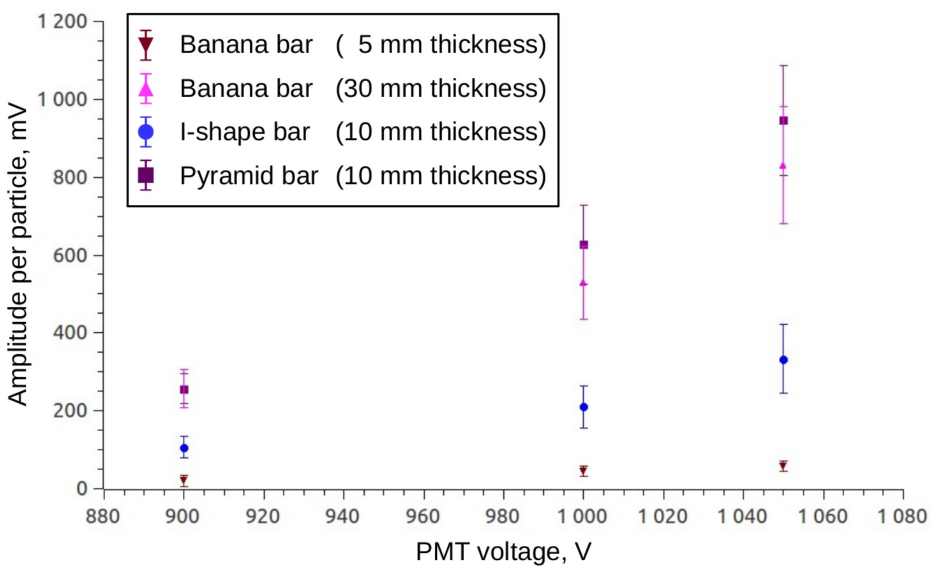
Number of reflections



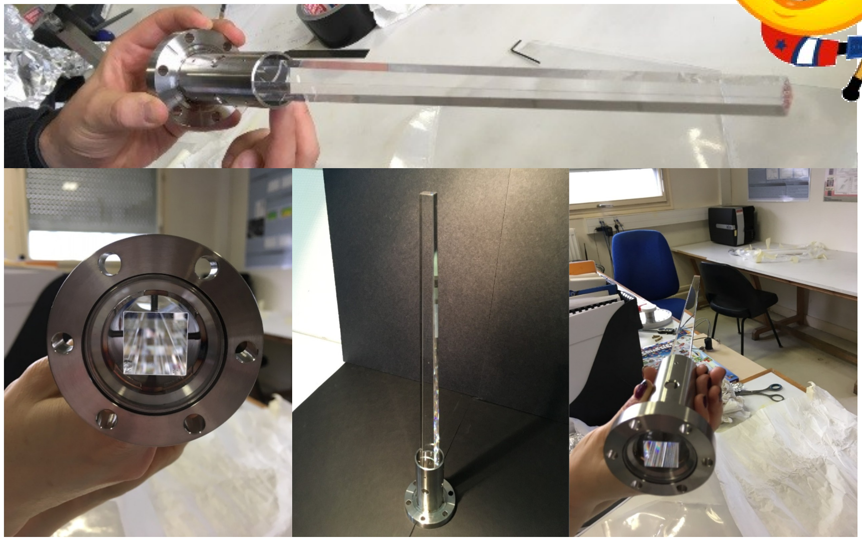
Polar Angle


I-shape bar
Banana bar
Pyramid bar
Detection side
Readout side

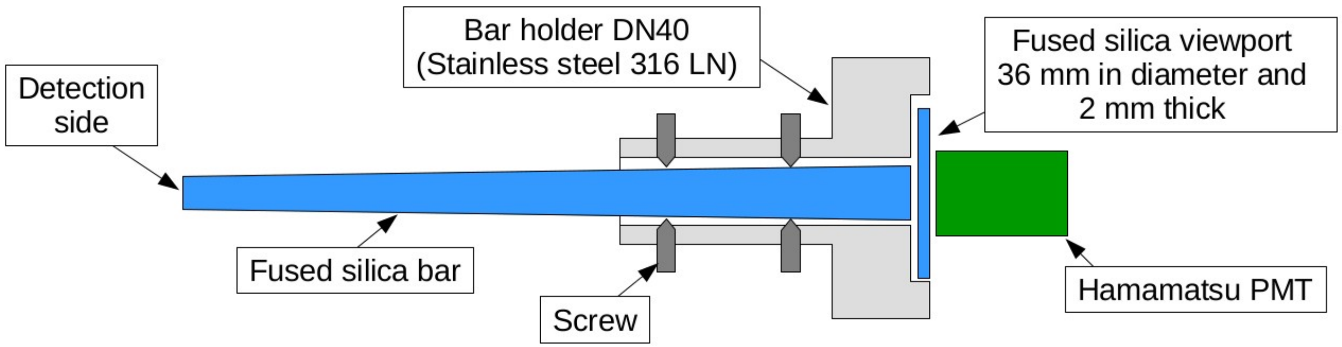

PMTs + viewports
Vinyl screws for bars support and alignment
Particle beam
I-shape bar
Pyramid bar
Banana bar

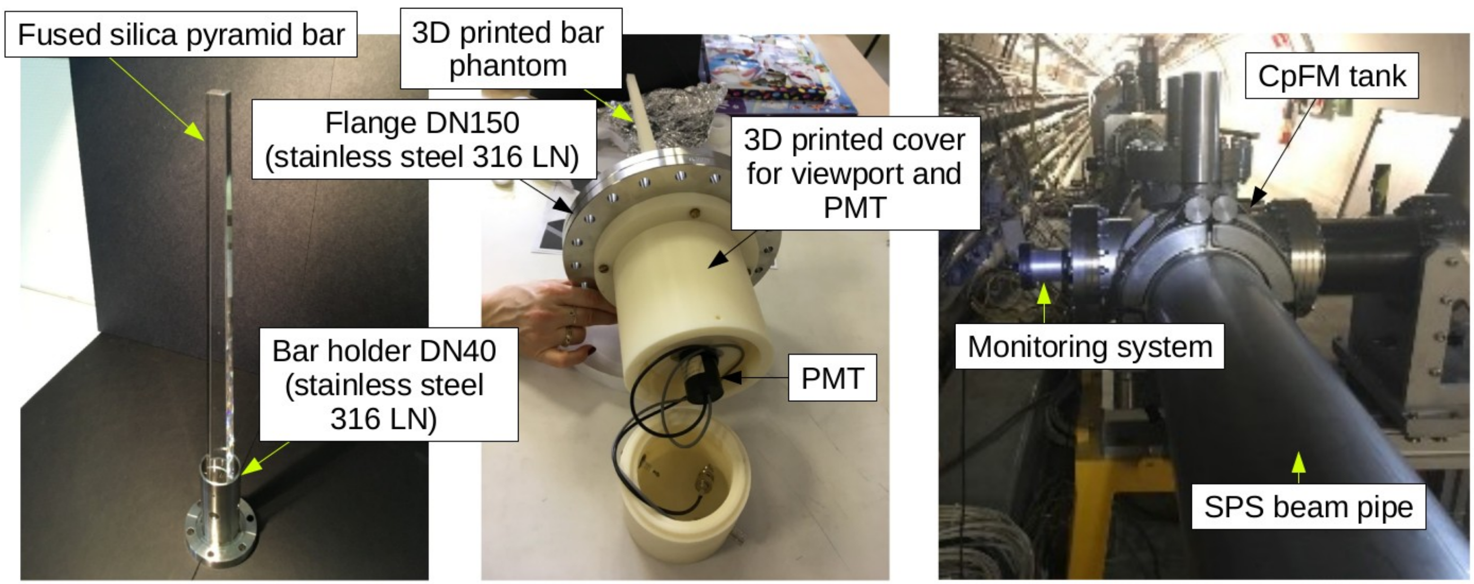

Banana bar (5 mm thickness)
Banana bar (30 mm thickness)
I-shape bar (10 mm thickness)
Pyramid bar (10 mm thickness)
Amplitude per particle, mV
0
200
400
600
800
1 000
1 200
PMT voltage, V
880
900
920
940
960
980
1 000
1 020
1 040
1 060
1 080

THE WINNER!



January 2018





What did we want?

1. Increase the number of the produced Cherenkov photons. → 1. Two times bigger thickness (10 mm)

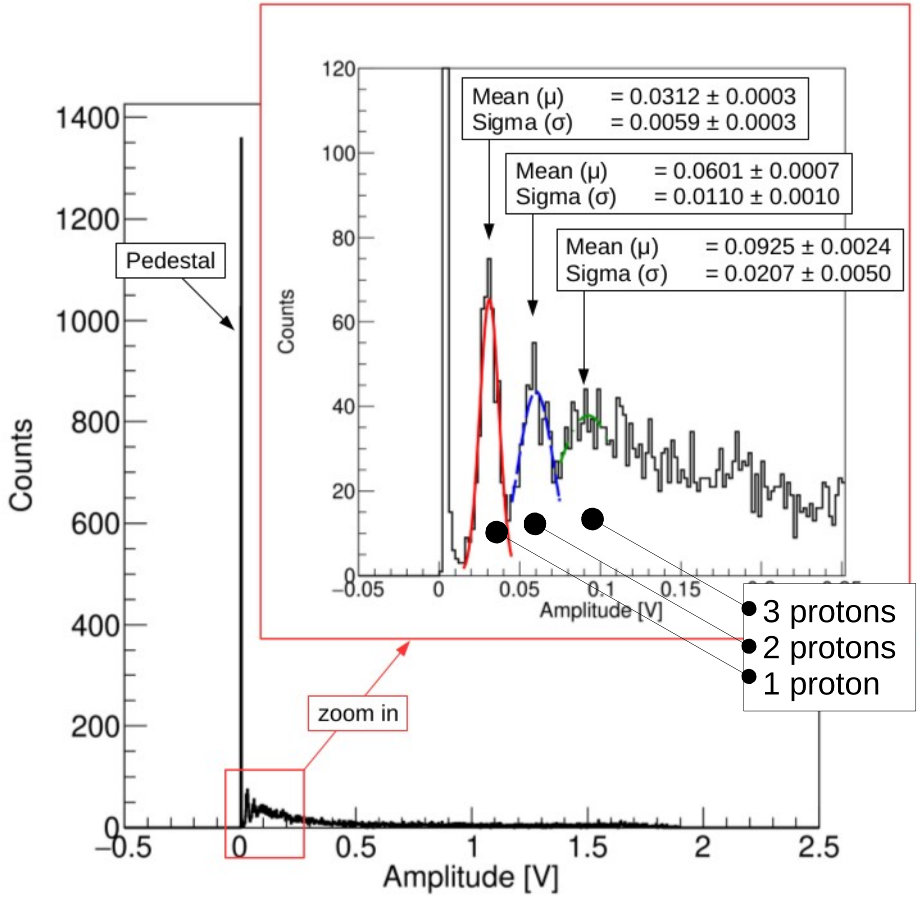
2. Decrease the number of the photons internal reflections from the surface of the bar. → 2. Pyramid shape (1 degree of the slant angle)

3. Improve the quality of the fused silica bar surface. → 3. We have asked the bar producing company for the best possible surface polishing quality and the smallest achievable ineffective area at the edges of the bar.

What have we done?

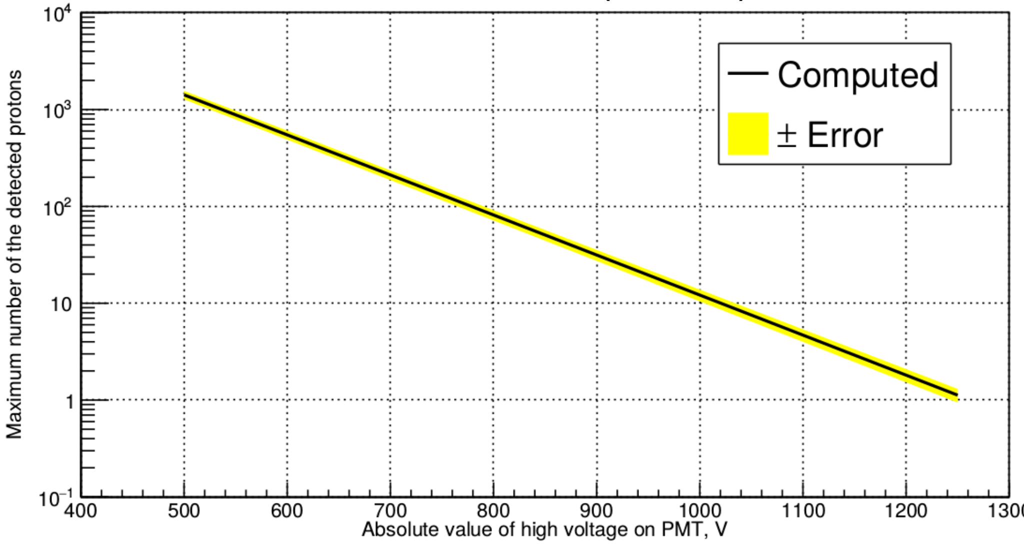
+ PMT direct coupling

Amplitude distribution of the signals. The pedestal indicates the number of the machine turns without particle extraction and makes up 24% of the total.



CpFM detector signal distributions for the 270 GeV/c channeled proton beam on SPS. The data are collected with HV = 800 V, and sampling frequency = 3.2 HGz.

Counting limitation due to the dynamic range of the USB-WaveCatcher (±1.25 V)

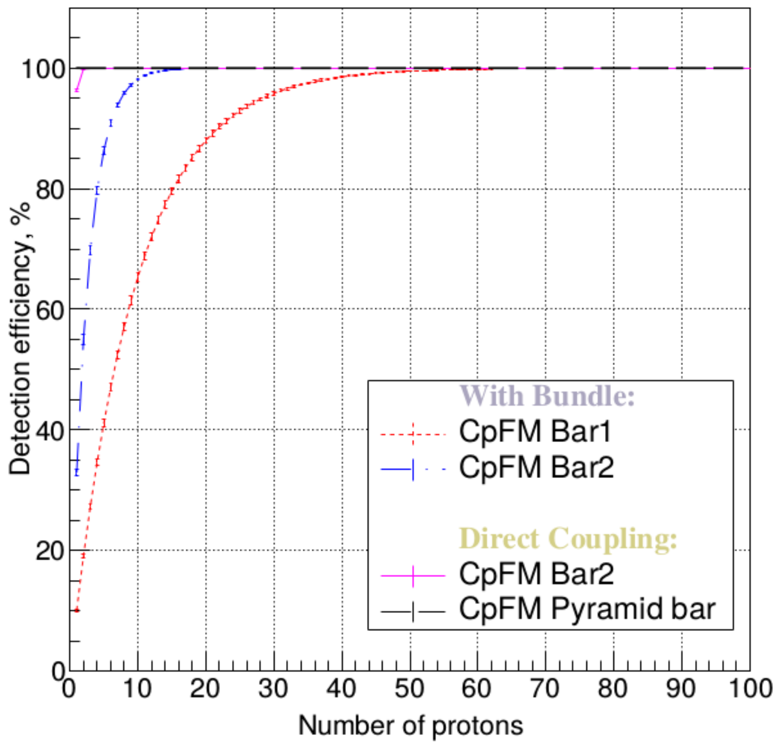


PMT voltage, V	Gain	Amplitude, mV
700	$3.58226 \cdot 10^5$	11.7±0.1
750	$5.76659 \cdot 10^5$	19.2±0.4
800	$9.00185 \cdot 10^5$	31.2±0.3
900	$2.02914 \cdot 10^6$	77.8±1.3

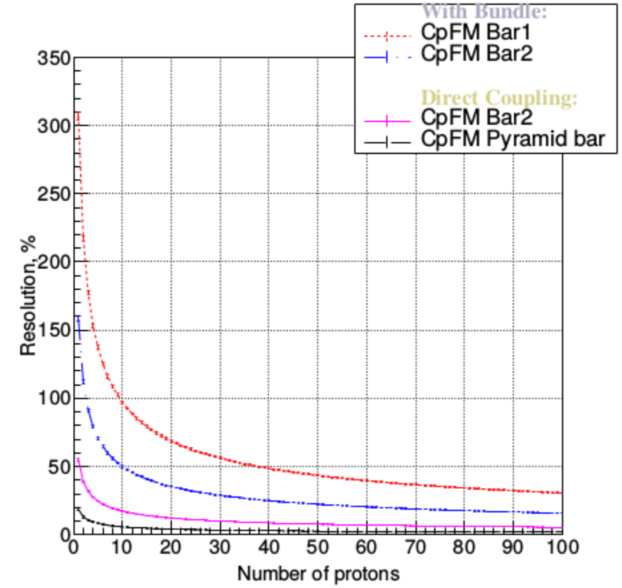
Single proton amplitude

The probability (P) for a single proton to produce a certain number of the photoelectrons (N) can be described using a Poisson distribution function:

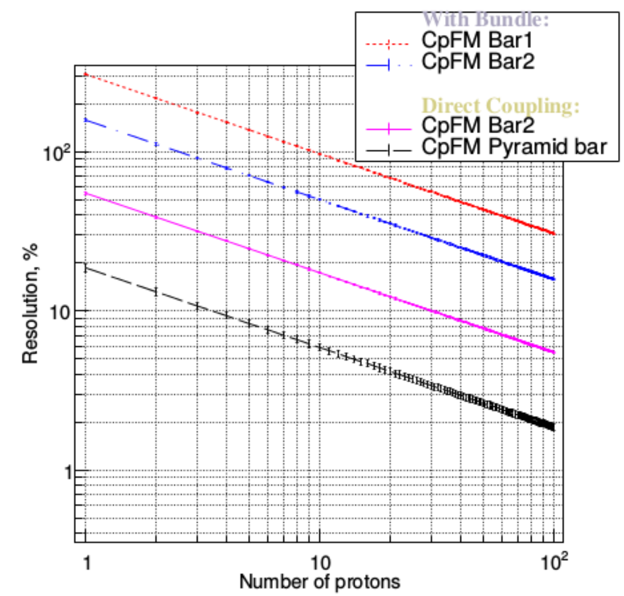
$$P(N) = \exp^{-\lambda} \frac{\lambda^N}{N!}$$



CpFM detection efficiency as a function of the impinging protons number.



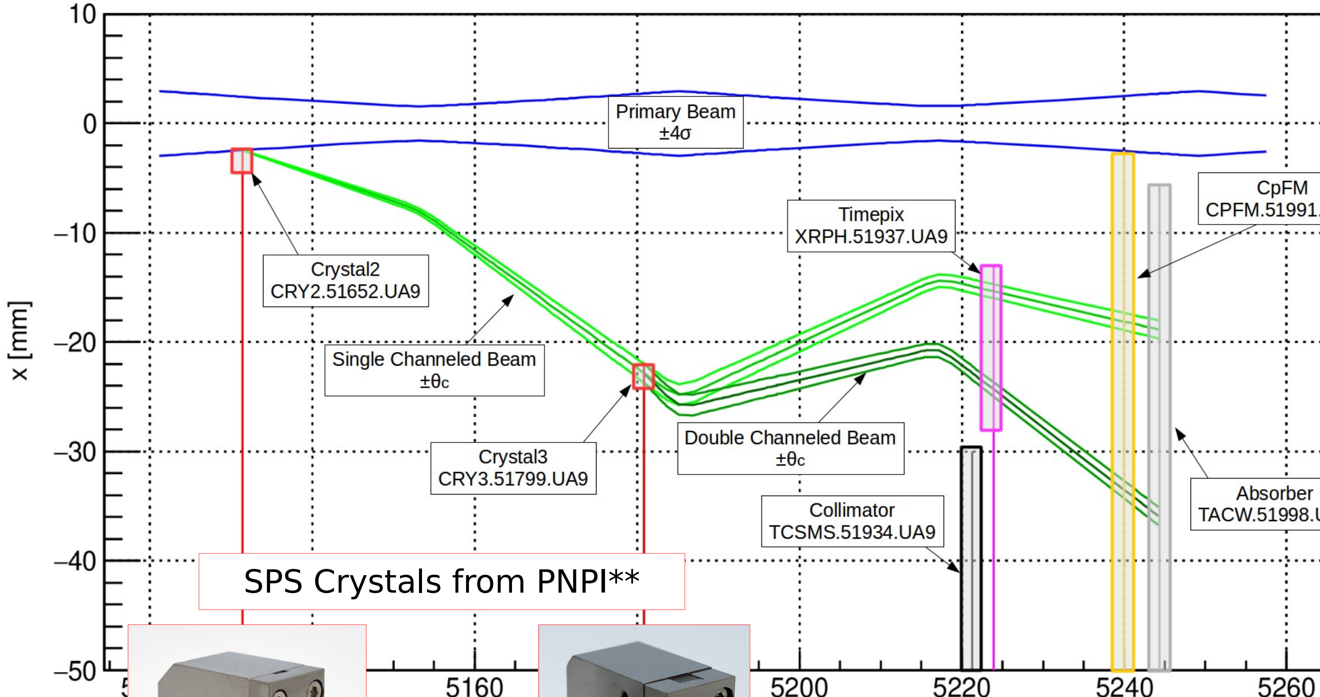
(a) Linear scale.



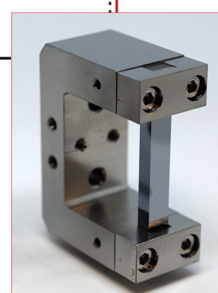
(b) Logarithmic scale in X-axis and Y-axis.

CpFM detection resolution as a function of the impinging protons number.

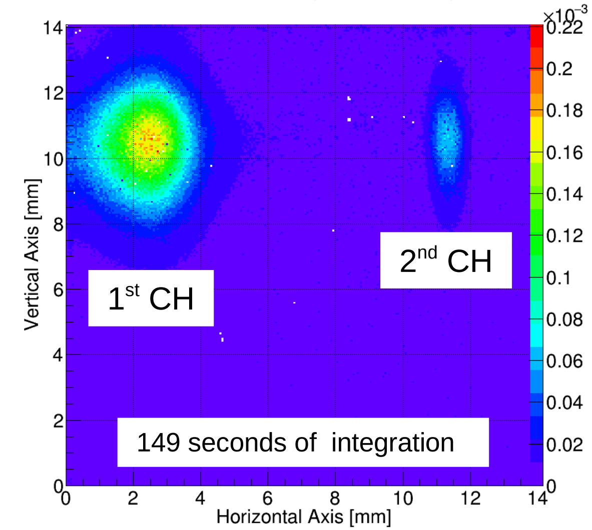
Beam optics configuration of the setup



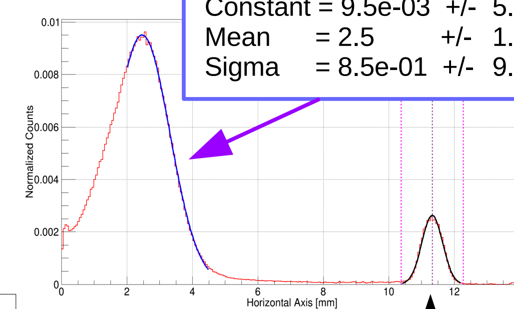
SPS Crystals from PNPI**



Timepix integrated image



"***normalized***" *means that each frame (0.5 sec) is normalized by the total number of hits.*



Constant = 9.5e-03 +/- 5.5e-07
Mean = 2.5 +/- 1.2e-04
Sigma = 8.5e-01 +/- 9.4e-05

Constant = 2.6e-03 +/- 5.3e-07
Mean = 11.3 +/- 6.7e-05
Sigma = 3.2e-01 +/- 6.0e-05

Secondary Wide Aperture SPS Crystal TCP78 (upgraded TCP74)

Bending angle:	**301 ±3urad**
Thickness:	4 ±0.02mm
With:	1.5 ±0.01mm
Torsion:	3 ±0.5 urad/mm

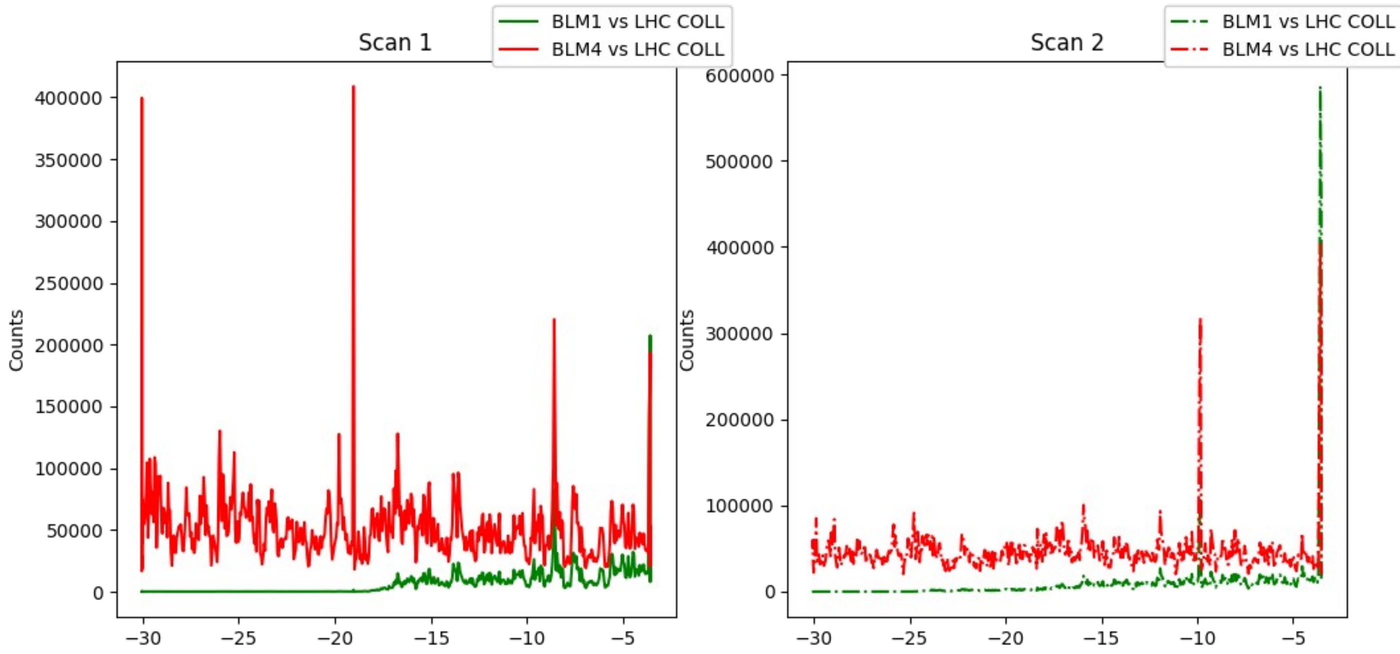
Secondary Wide Aperture SPS Crystal TCP75 (upgraded TCP72)

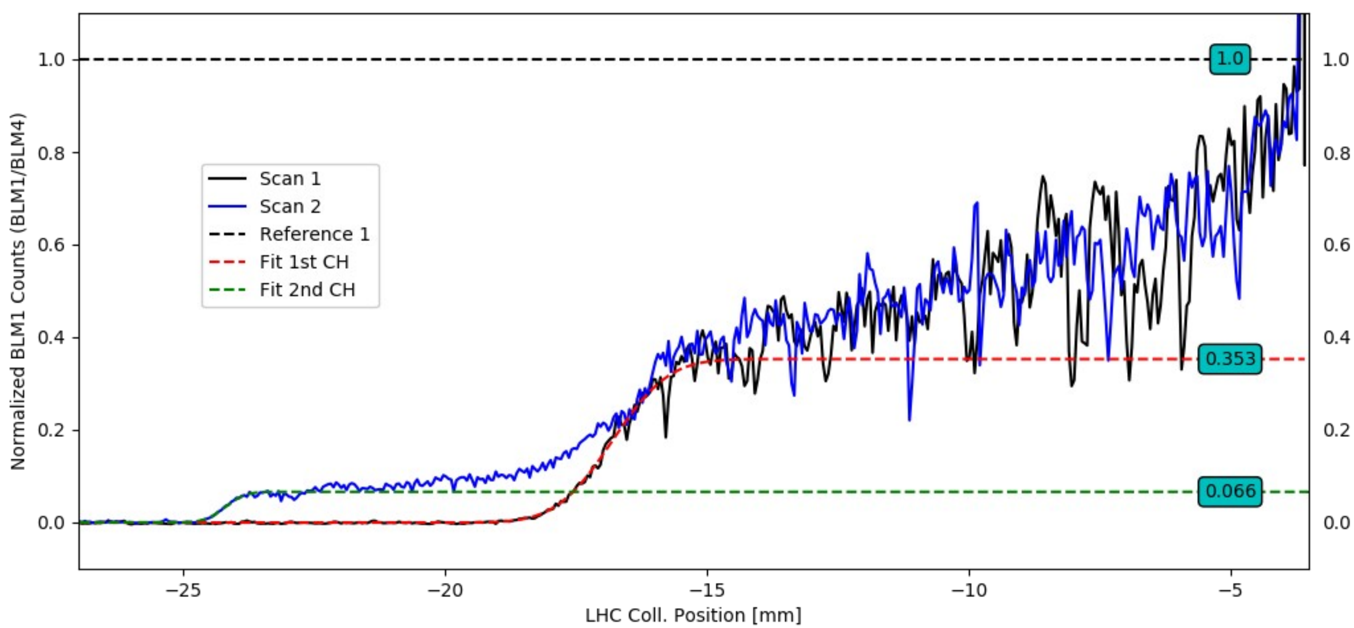
Deflection angle:	**197 ± 8 urad**
Torsion:	4 ±0.5urad/mm
Deflecting width:	4 ±0.02mm
Thickness:	6 ±0.02mm

Efficiency (Xe ions, 40GeV/nucl): 41 %

***UA9 Collaborating meeting, 20-21 February 2018. Yu. GAVRIKOV, Yu. IVANOV*

Double crystal setup at SPS 2018. LHC collimator linear scan





<u>For the BLM measurements during LHC-type collimator linear scan:</u>

CRYSTAL2 Multi Turn CH efficiency:
0.353
CRYSTAL3 Single Pass CH efficiency for the fixed orientation *<u>(-1810 urad)</u>*:
0.066 / 0.353 = **0.187**

Double-Crystal efficiency:
0.066

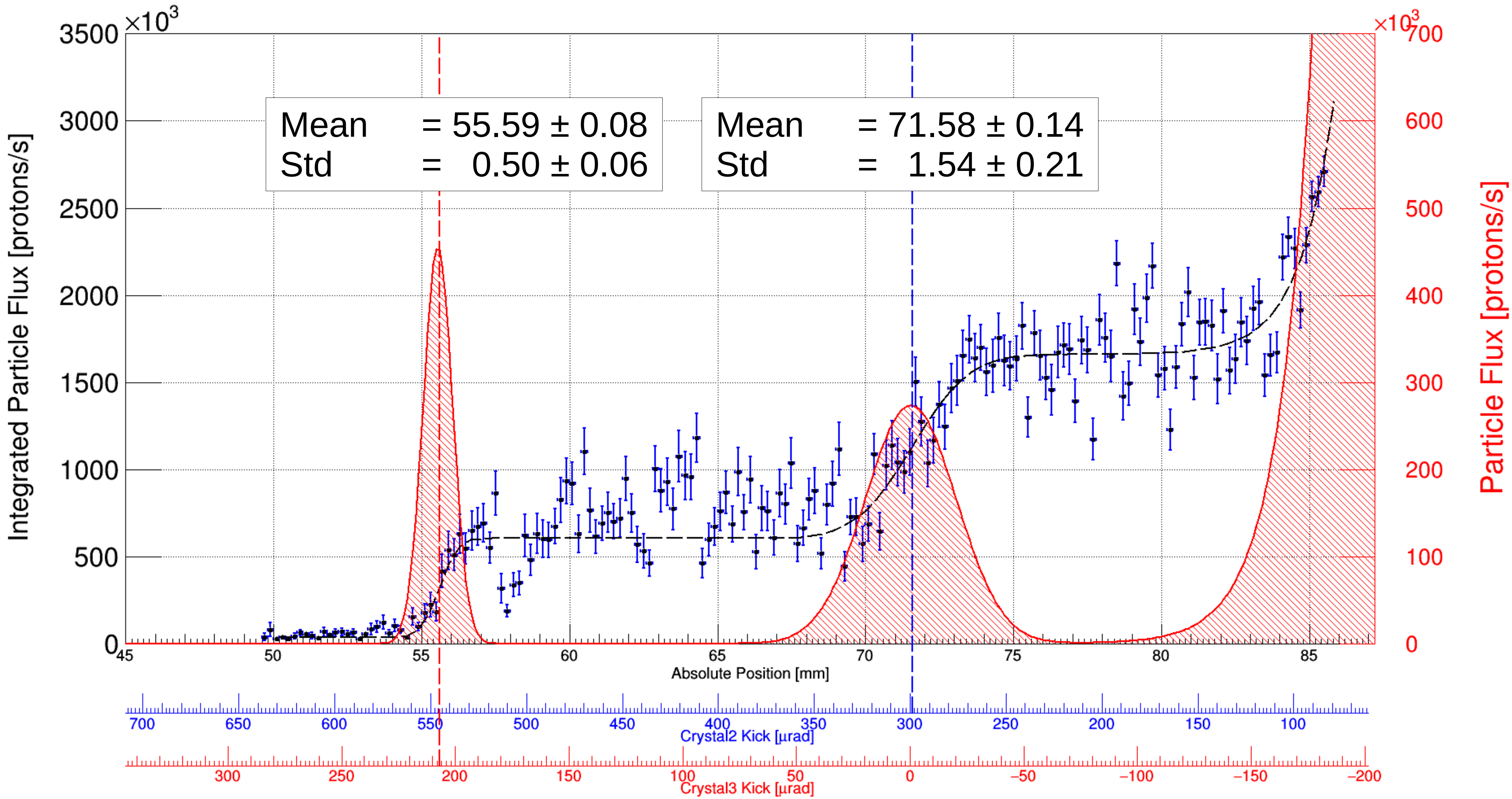
<u>For the same crystals position and orientation we got from the Timepix analysis:</u>

CRYSTAL3 Single Pass CH efficiency for the fixed orientation *<u>(-1820 urad)</u>*:
0.195

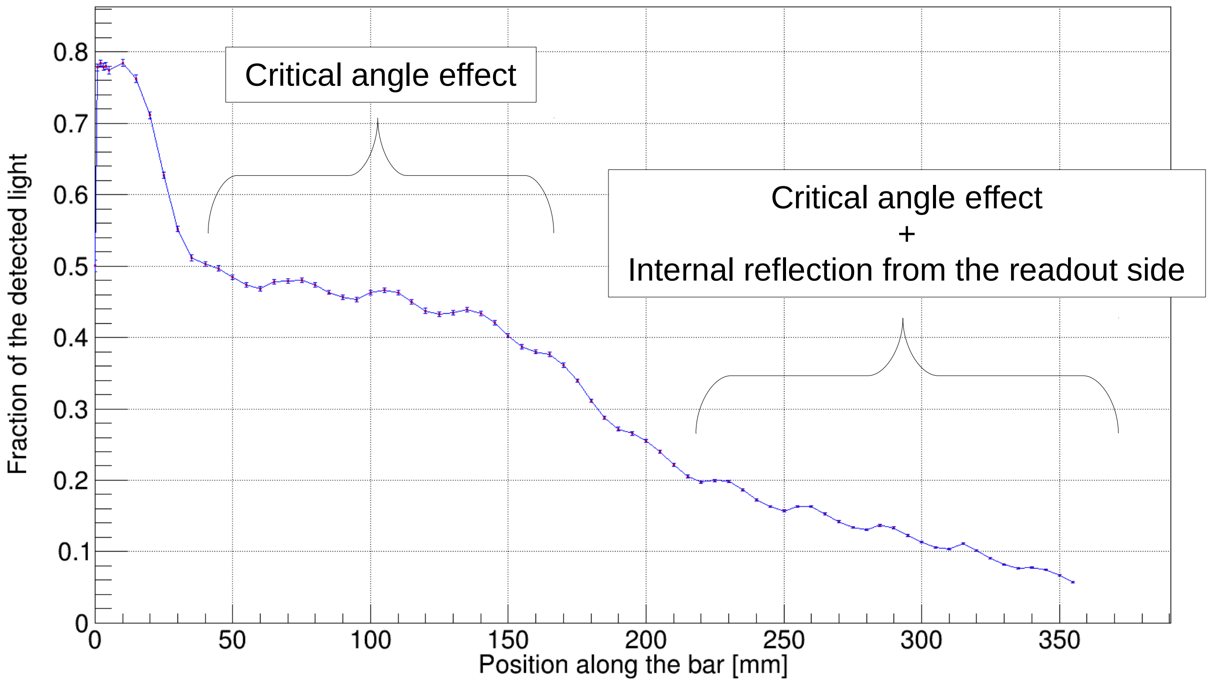
Fit 1st CH:
Mean = -16.8 +/- 0.05 mm
Sigma = 0.85 +/- 0.07 mm

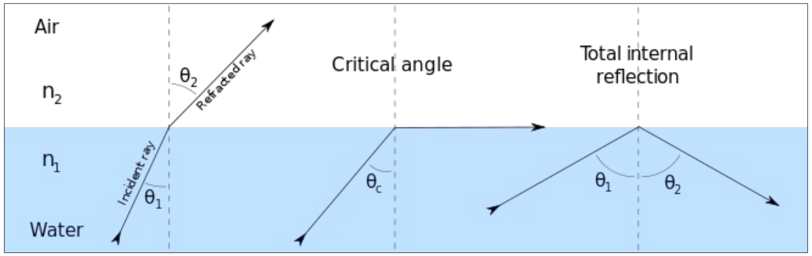
Fit 2nd CH:
Mean = -24.2 +/- 0.03 mm
Sigma = 0.31 +/- 0.04 mm

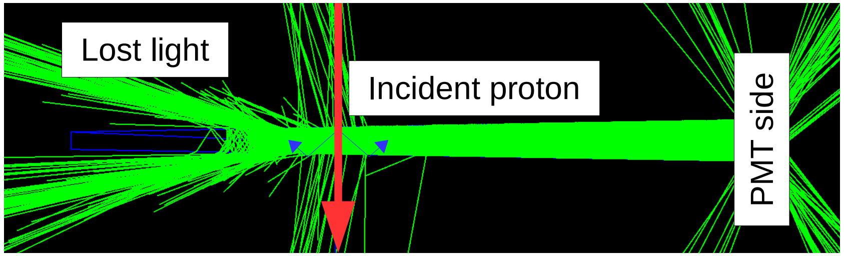
Double crystal setup at SPS 2018. CpFM linear scan

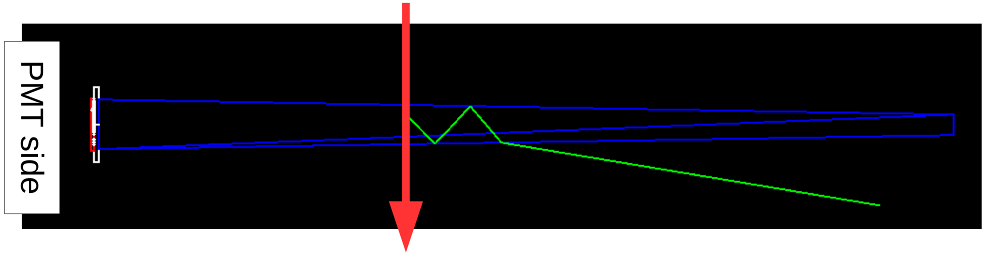


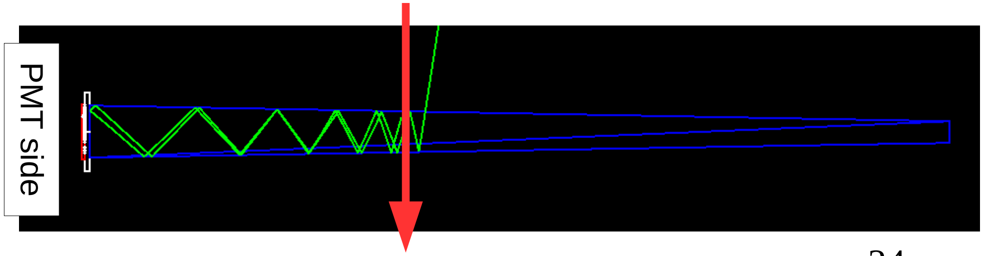
Binning 0.2 mm


Critical angle effect
Critical angle effect
+
Internal reflection from the readout side
Fraction of the detected light
Position along the bar [mm]
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
50
100
150
200
250
300
350

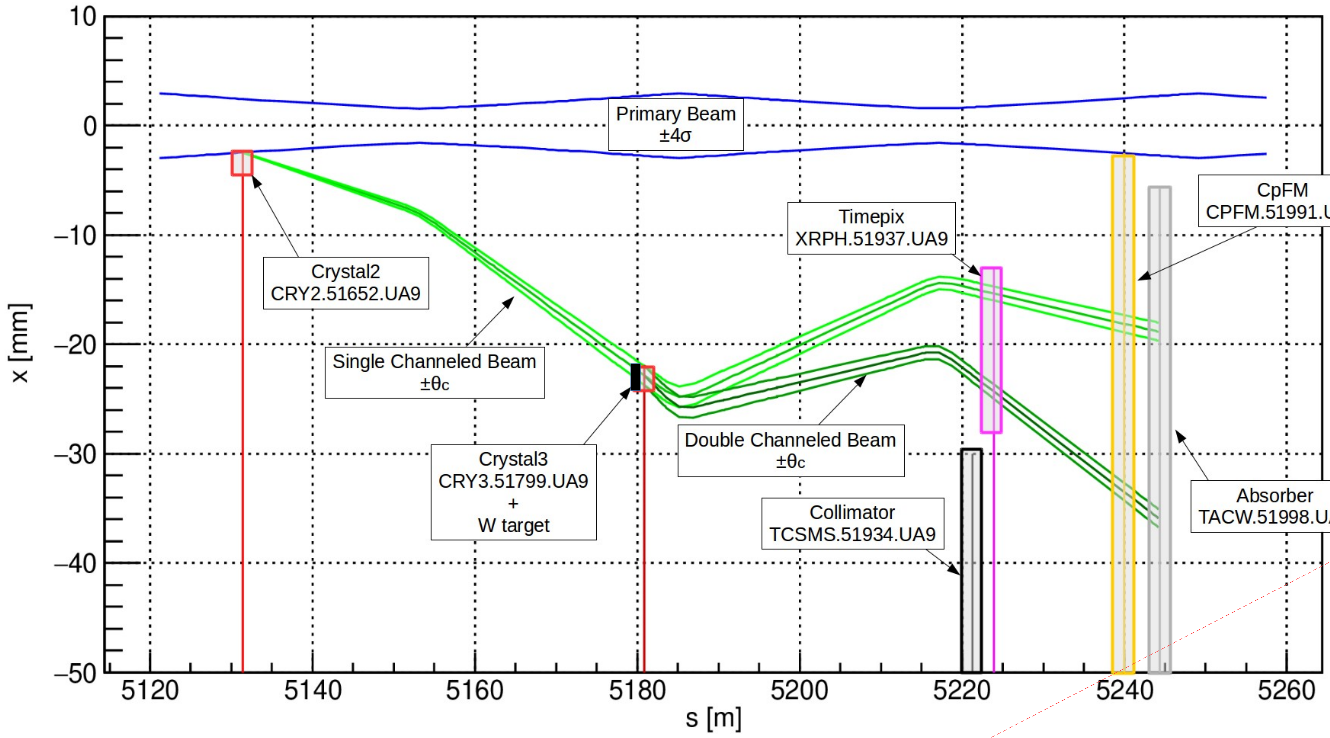

Air
n_2
n_1
Water
θ_2
Refracted ray
Incident ray
θ_1
Critical angle
θ_c
Total internal
reflection
θ_1
θ_2


Lost light
Incident proton
PMT side


PMT side

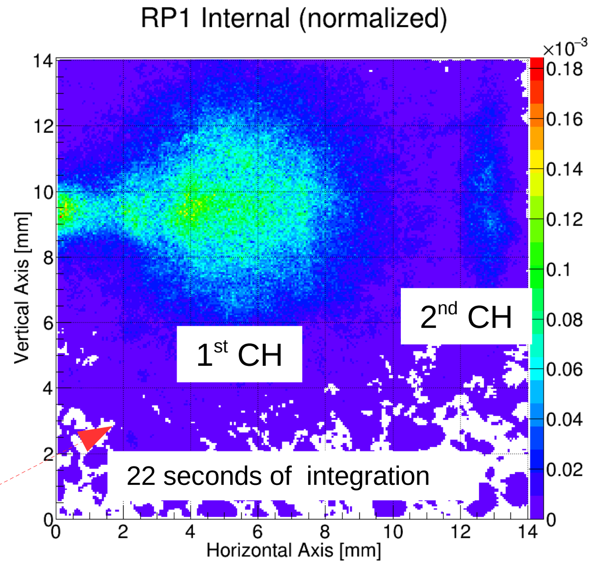

PMT side

Beam optics configuration of the setup

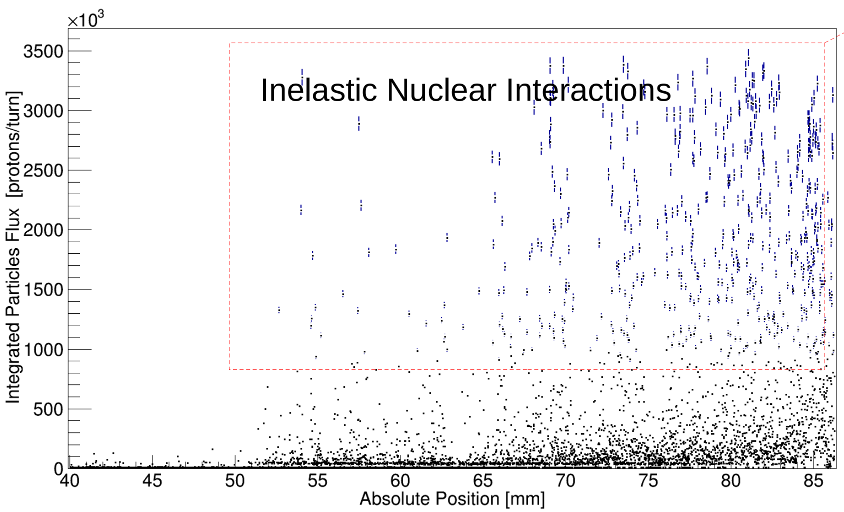


Not optimized for double channeling

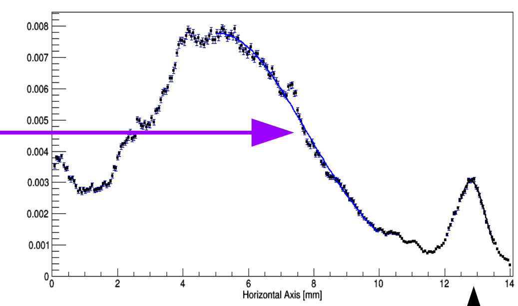
Timepix integrated image



*"**normalized**" means that each frame (0.1 sec) is normalized by the total number of hits.*

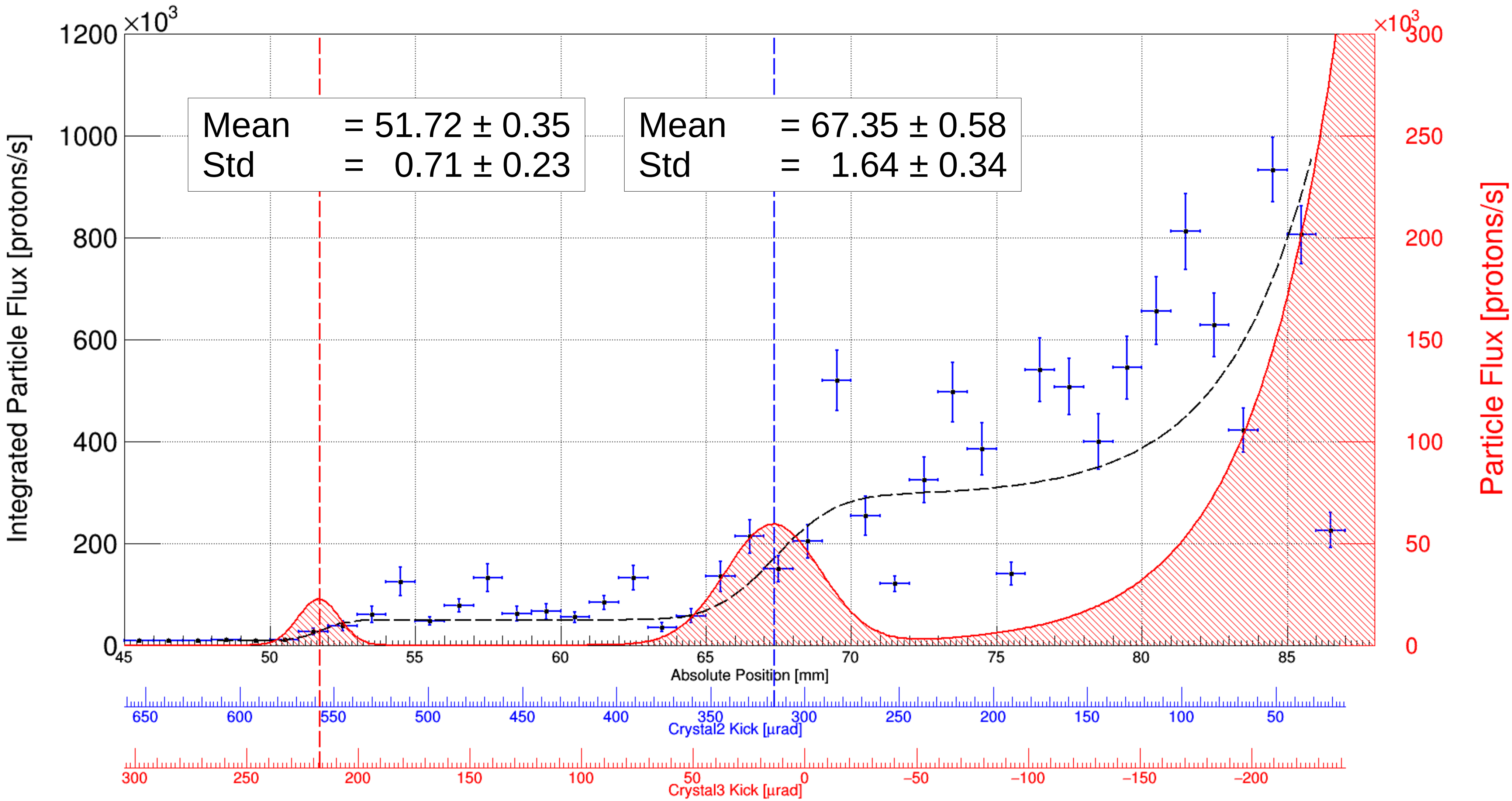


Constant = 7.8e-03 +/- 3.4e-05
Mean = 5.1 +/- 2.5e-02
Sigma = 2.6 +/- 2.1e-02



Constant = 3.0e-03 +/- 2.4e-05
Mean = 12.8 +/- 7.7e-03
Sigma = 4.7e-01 +/- 9.3e-03

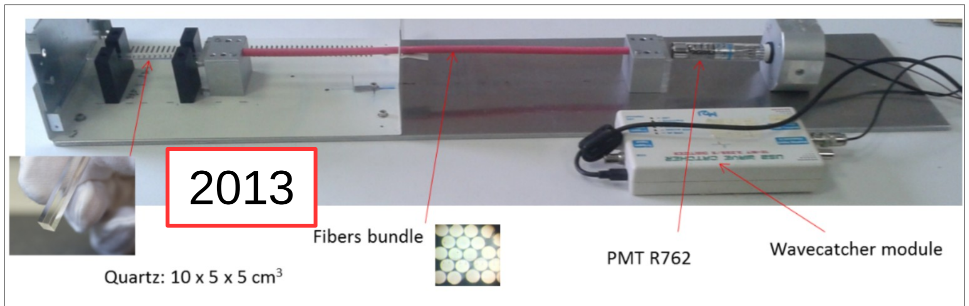
Double crystal setup with a target at SPS 2018. CpFM linear scan

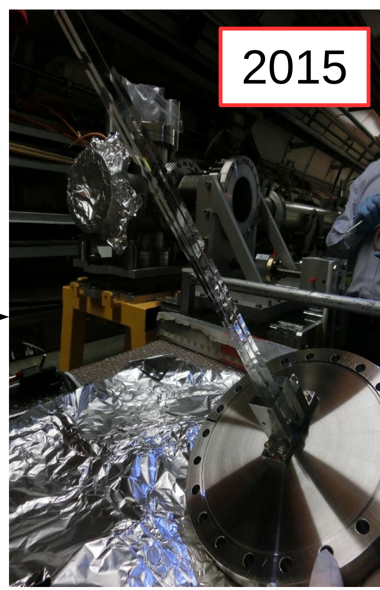


Binning 1.0 mm

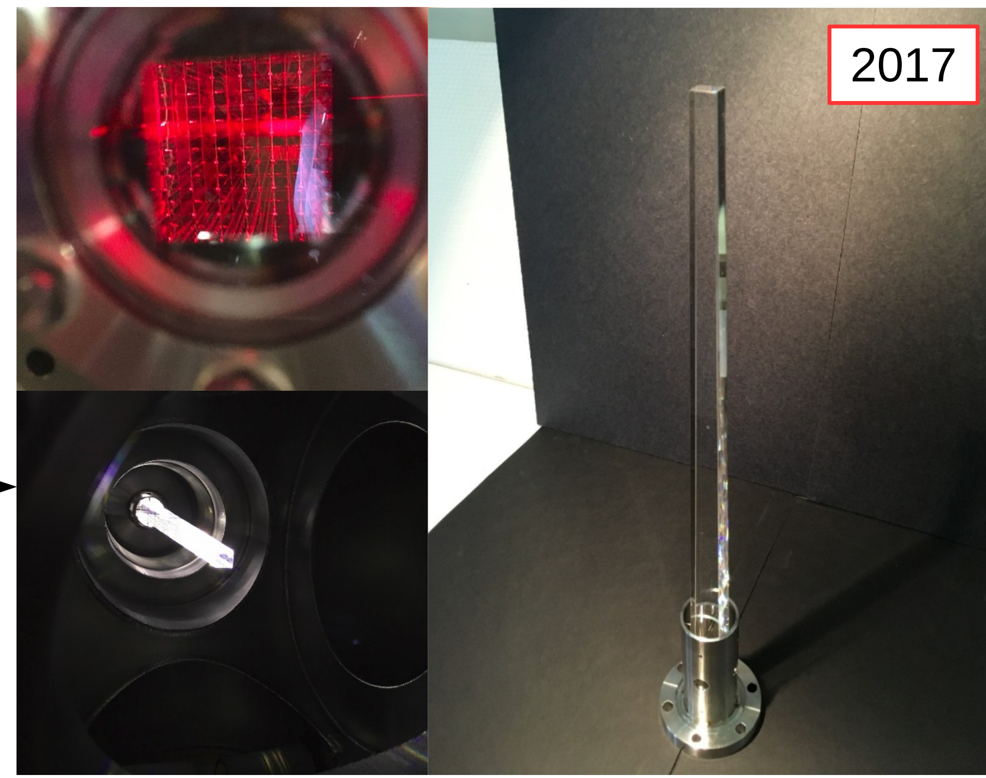
Unfortunately, very low statistics have been collected.

1. The final configuration of the CpFM detector has been developed.
2. The device is sensitive to a single proton with a resolution less than 20 %/proton.
3. Depending on the PMT voltage, particles detection range is 1 – 10^3 protons/turn (23 μs).
4. Due to the high amount of the produced Cherenkov light, a self-calibration with protons can be performed “on fly”.





Cherenkov detector for proton Flux Measurement
Pyramid fused silica radiator with a PMT direct coupling



Thanks for your attention !