Cherenkov light in vacuum beam monitors for crystal-assisted beam manipulations

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Outline

- ✓ Crystal channeling
- ✓ The CpFM for Crystal assisted collimation in the UA9 experiment
  - ✓ CpFM requirements and layout
  - ✓ CpFM commissioning during operations: functionality test and detector characterization
- ✓ SE-CpFM: a second version of the CpFM to monitor the slow extraction spill of SPS
  - ✓ SE-CpFM requirements and layout
  - ✓ SE-CpFM efficiency test in H8-SPS extraction line
  - ✓ SE-CpFM preliminary validation of the readout electronic + analysis tool

Crystal Channeling

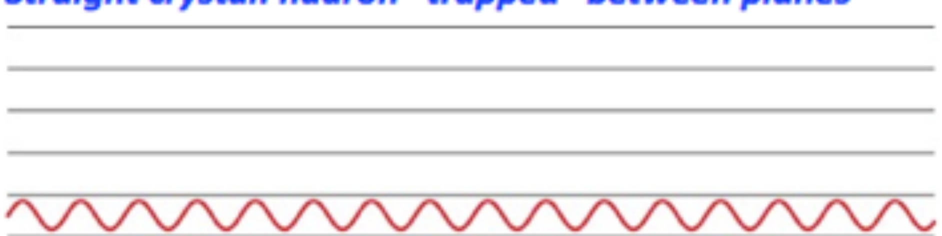
If the protons have $p_T < U_{max}$

$$\boxed{\theta_c = \sqrt{\frac{2U_{max}}{pv}}}$$

Critical angle in Si

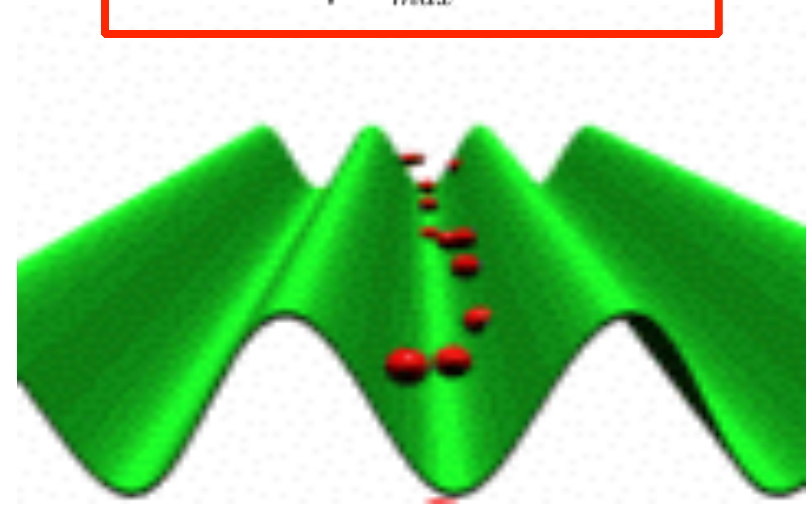
Case	Energy [GeV]	θ_c [μrad]	λ [μm]
SPS coast	120	18.3	33.0
SPS coast	270	12.2	49.6
H8	400	10.0	60.3
LHC inj.	450	9.4	64.0
LHC top	6500	2.5	243.2
LHC top	7000	2.4	252.3

Straight crystal: hadron "trapped" between planes

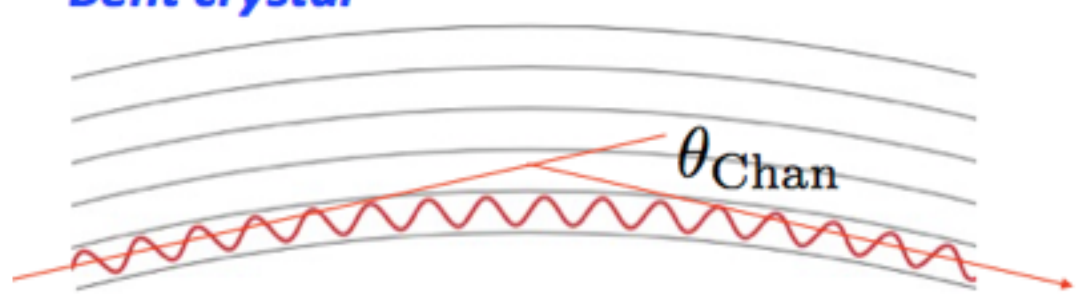


Forced to oscillate between crystalline planes

$$\boxed{x(z) = \frac{d_p}{2}\sqrt{\frac{E_t}{U_{max}}}\sin\left(\frac{2\pi z}{\lambda} + \phi\right)}$$



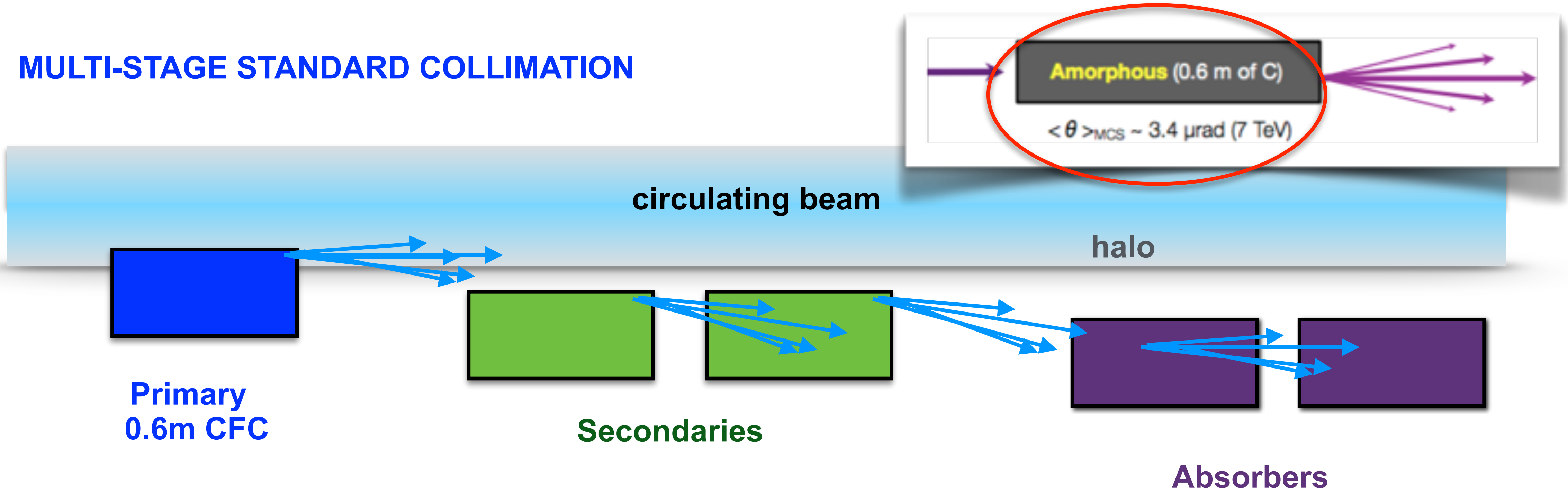
Bent crystal

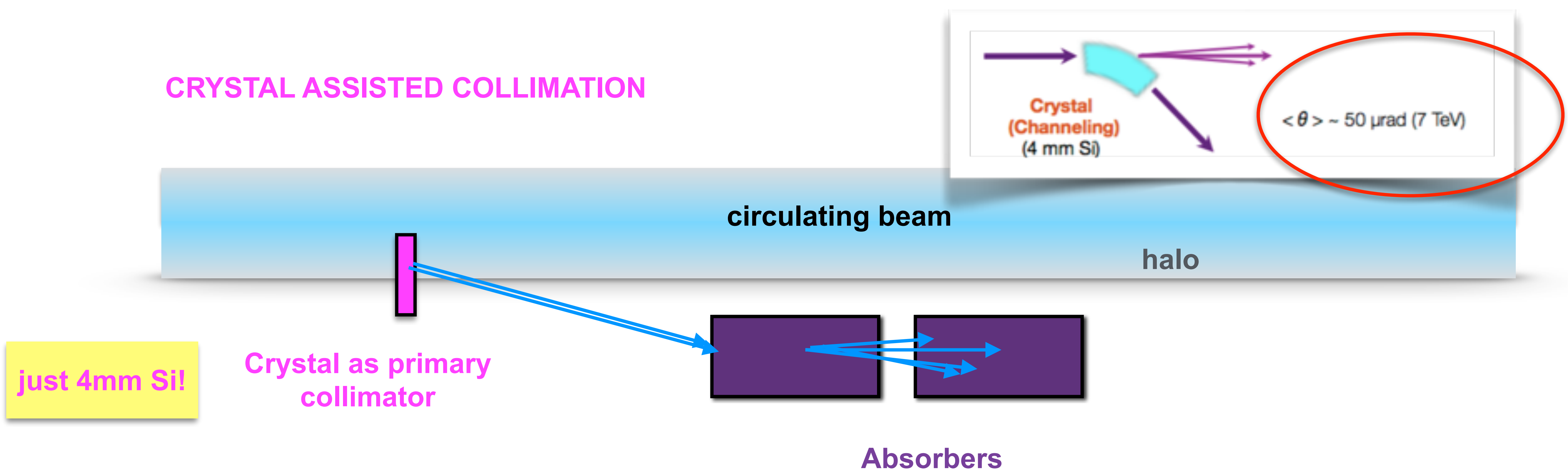


4 mm Si Crystal with a bending angle of 50urad produces the same kick of a 310T magnet!

UA9 experiment purpose

The main purpose of UA9 experiment at CERN-SPS is to demonstrate the feasibility of a bent crystal assisted collimation for hadron colliders

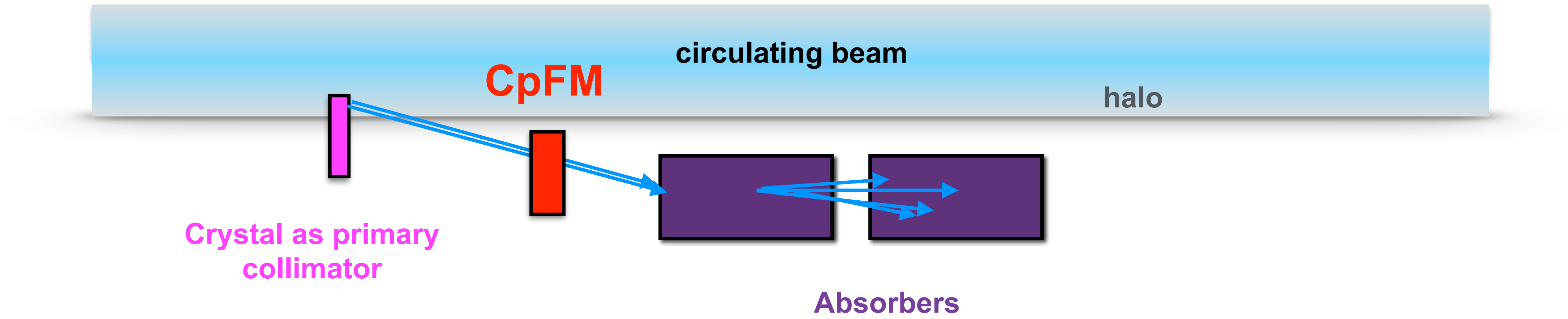




The Cherenkov for proton Flux Measurement detector for UA9 experiment

The Cerenkov proton Flux Measurement detector for UA9 experiment

To monitor the deflected halo a new concept in-vacuum detector is needed, sensitive to the single proton.

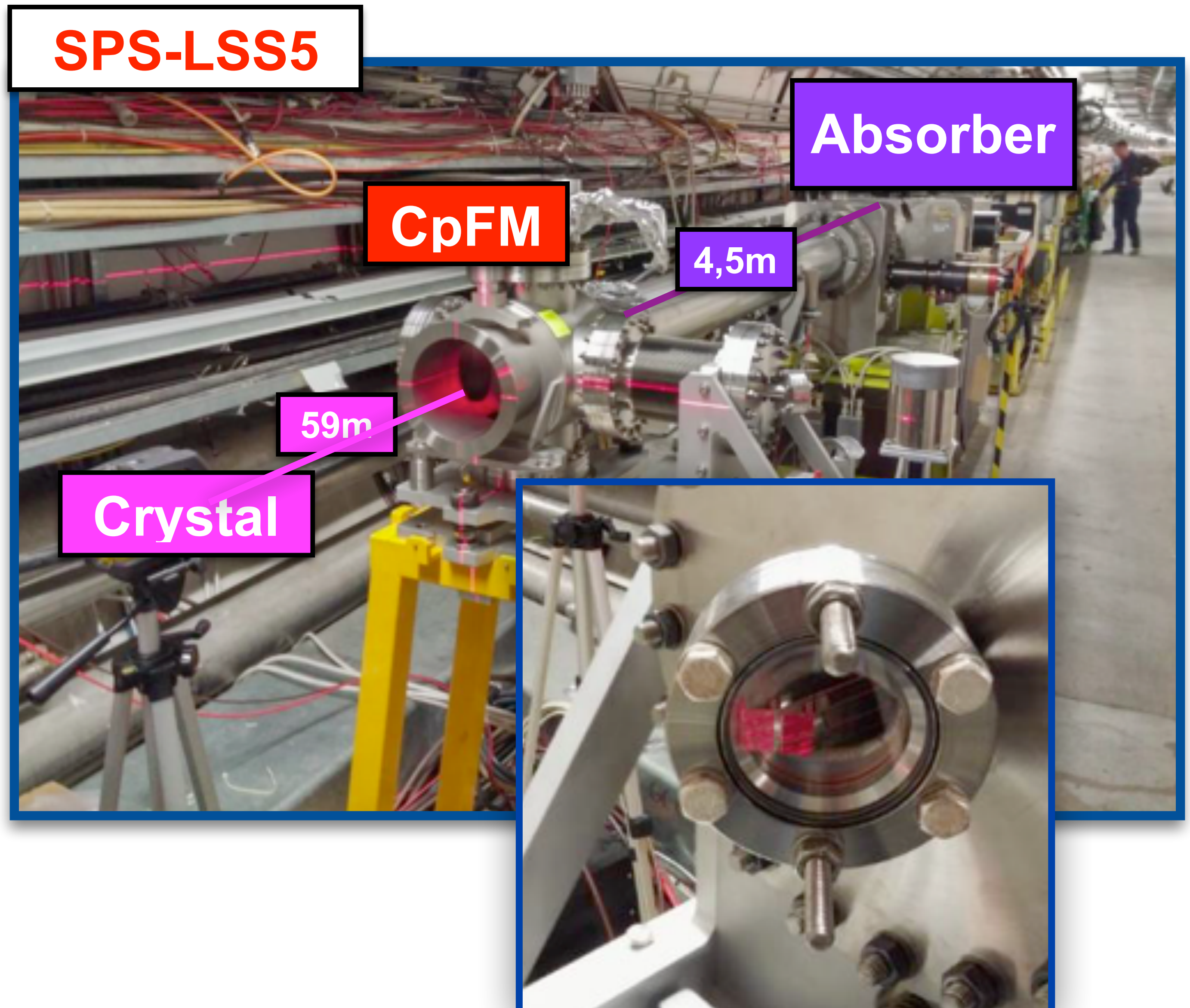


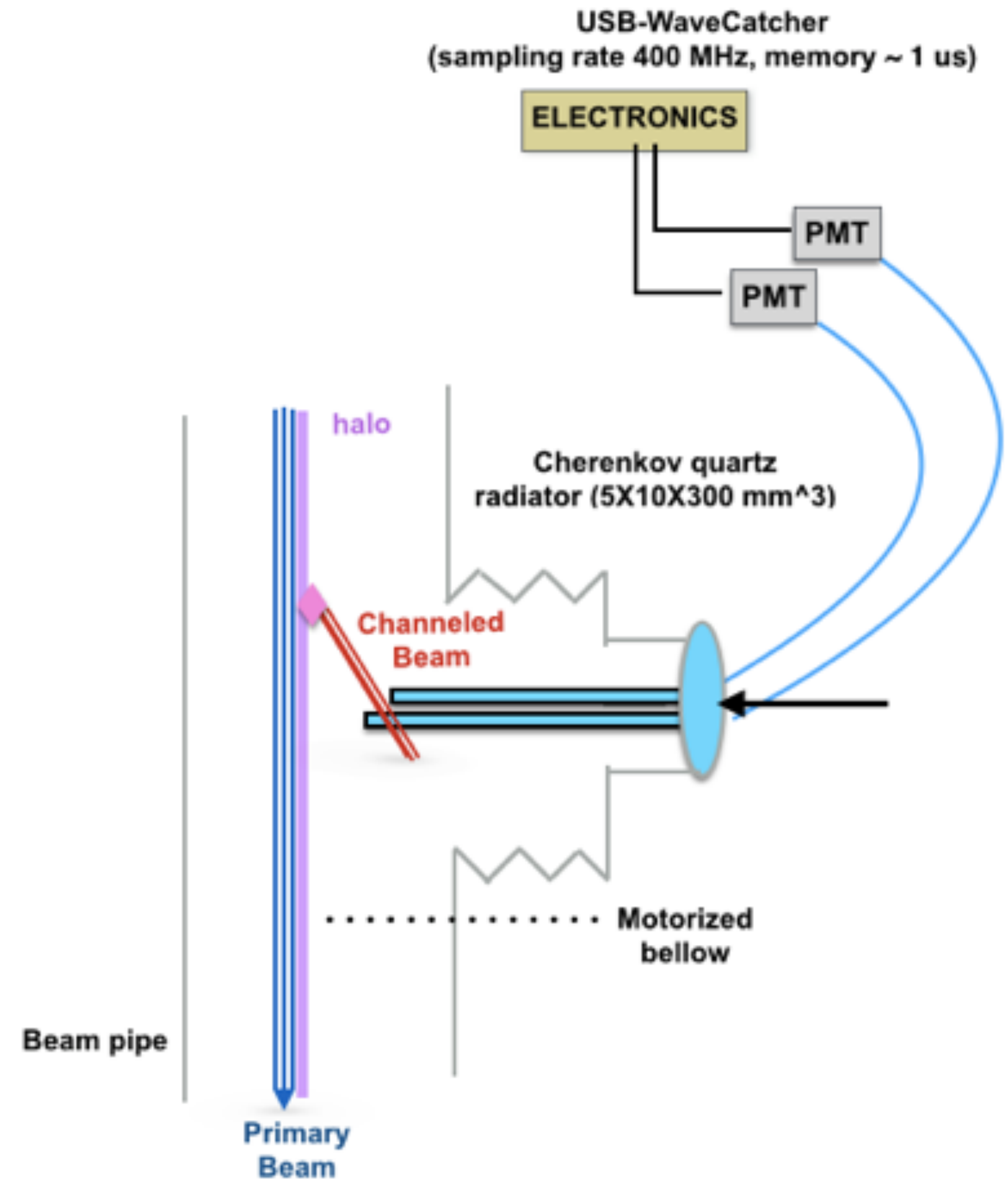
CpFM design requirements:

- **materials with no degassing (location: inside the primary vacuum)**
- **Radiation hardness of the detection chain (~ 100 Gy, 10^12 1-MeV-eq. neutrons/cm^2 per year)**
- **Compact radiator (small space available, inside the beam pipe)**
- **Timing: 3 ns bunches, 25 ns minimum distance**
- **Dynamic range: 1÷200 protons per pulse.**
  (extracted ~ 10^7-10^8 protons/s; Trev = 23 μs)

The Cerenkov proton Flux Measurement detector for UA9 experiment

CpFM detector has been installed in UA9 experimental area in LSS5 since December 2014

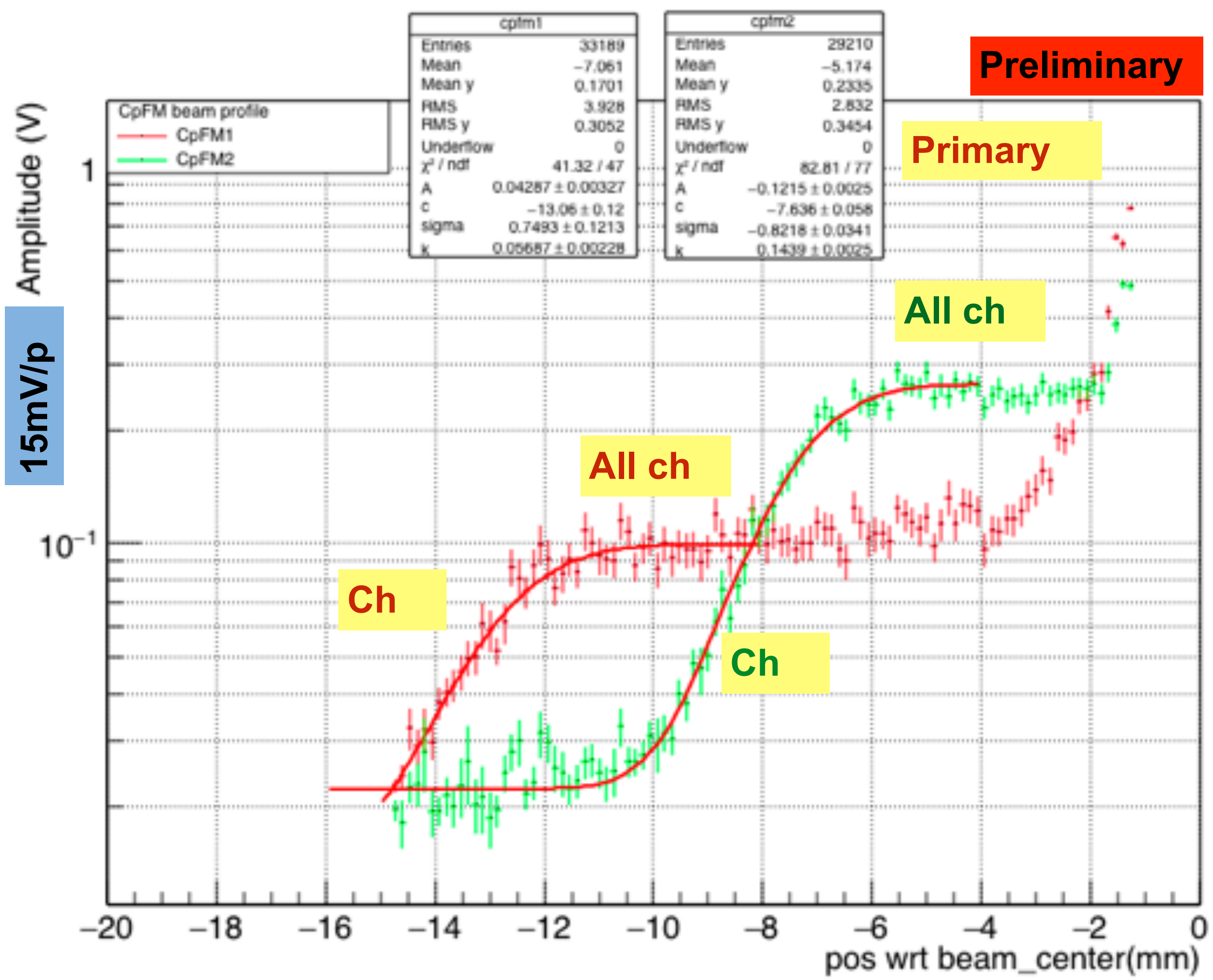


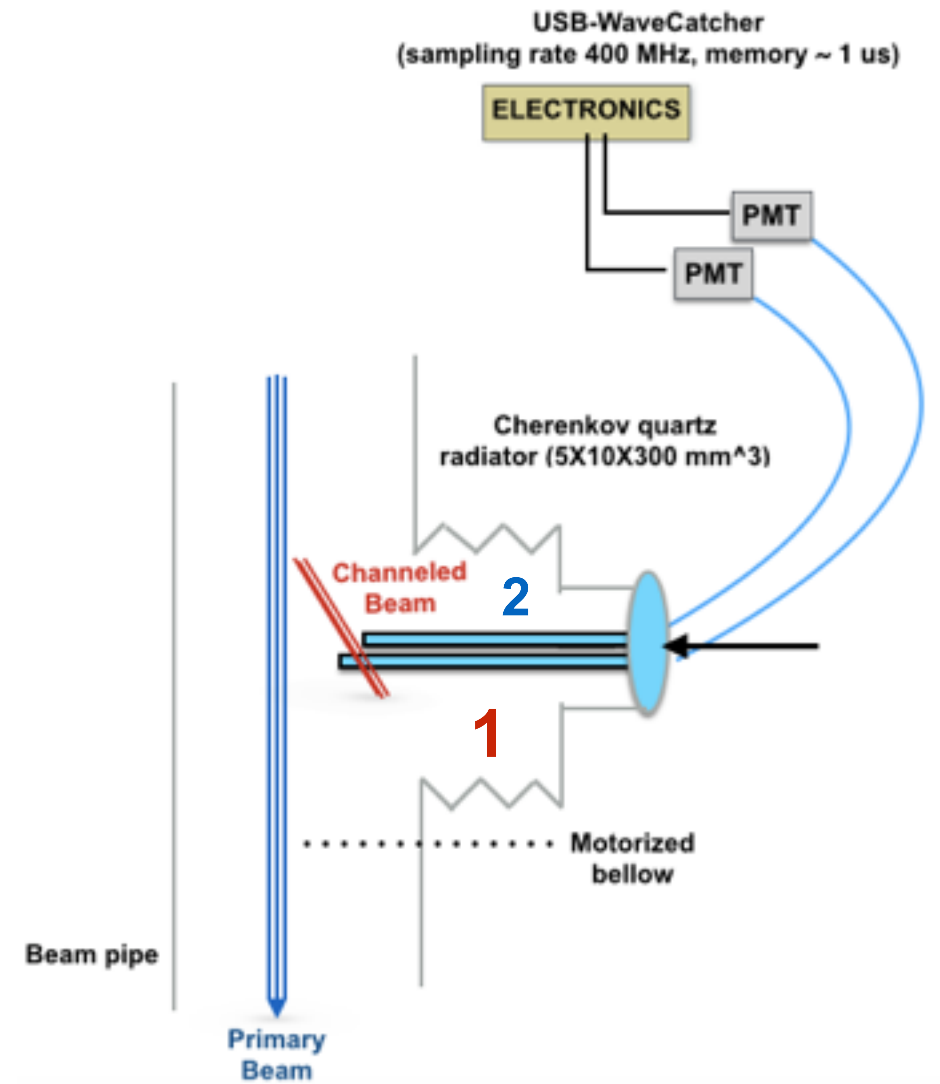


Calibrated at BTF with 500MeV/c electrons:
efficiency to single electron = 63%

The Cerenkov proton Flux Measurement during operations

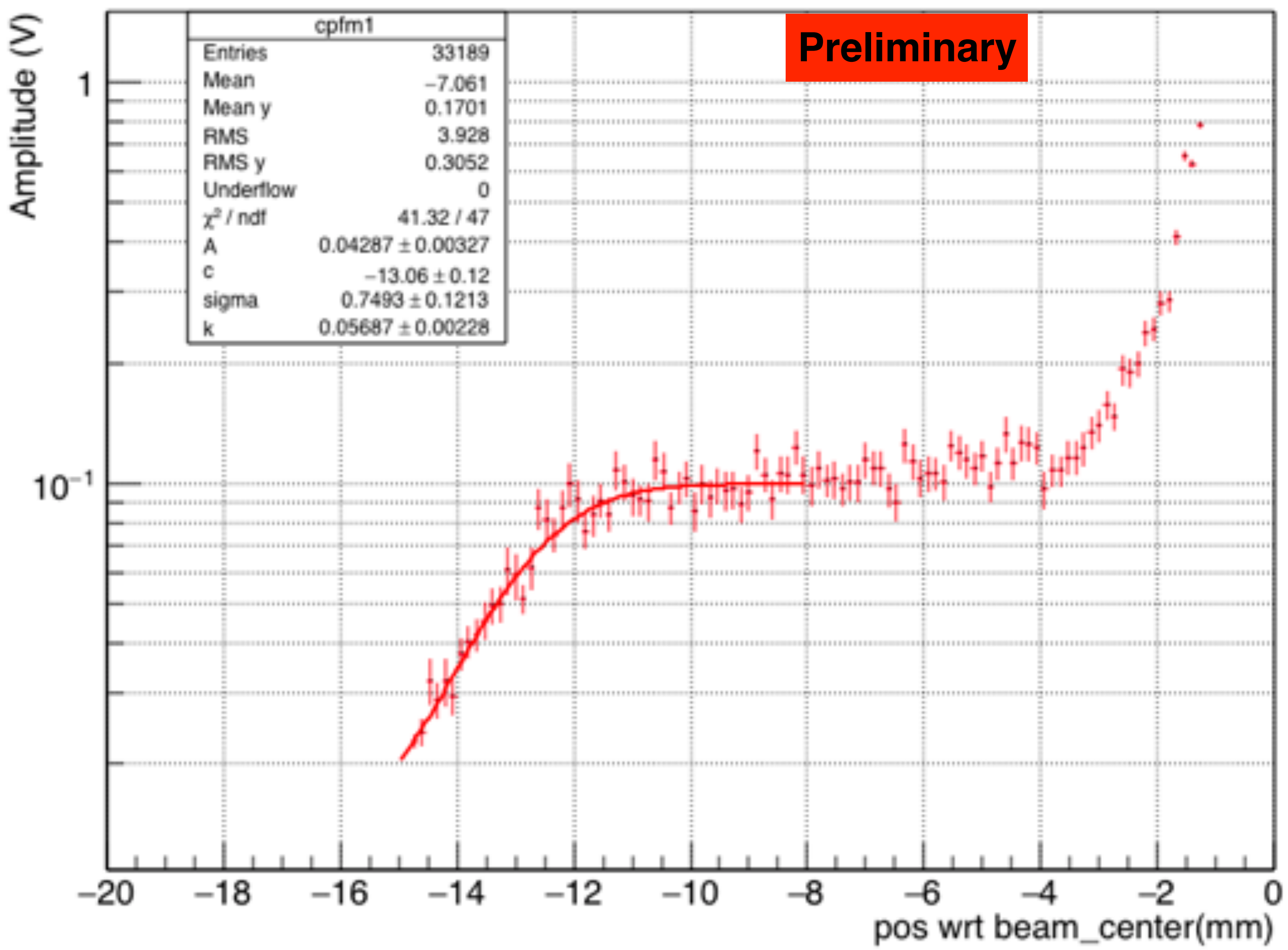
CpFM detector operation during Oct 2015 UA9 test- single bunch 270 GeV protons

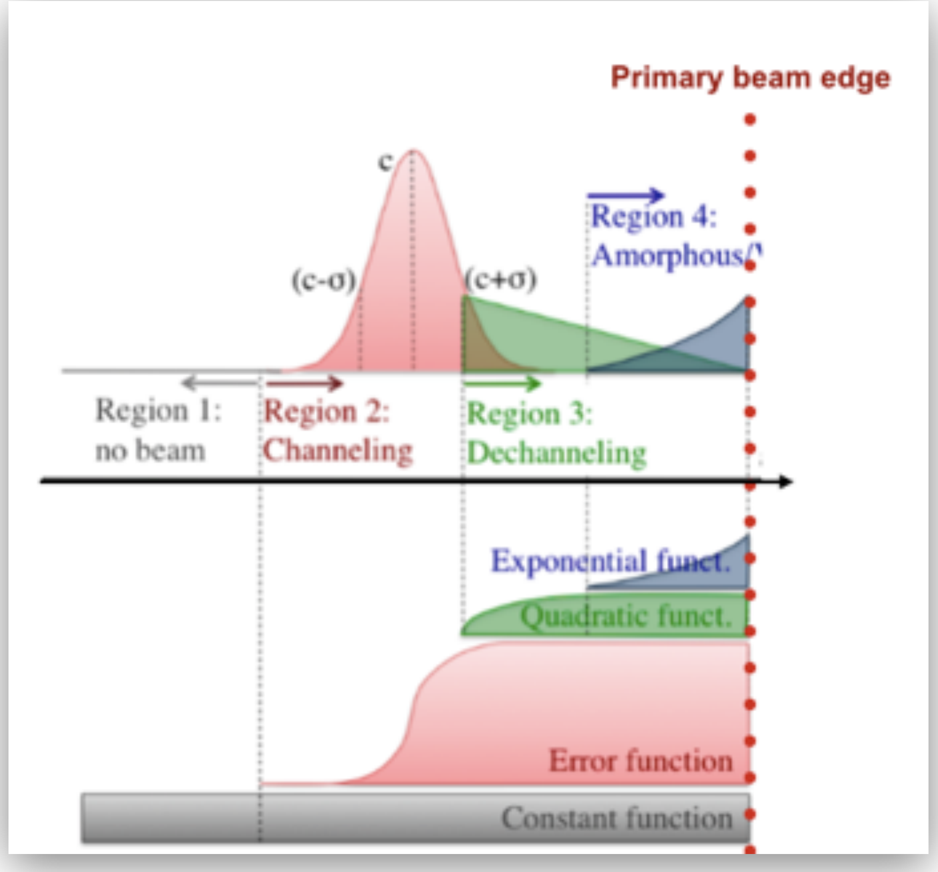




UA9 Crystal as a primary collimator. As the bars approach the channeled beam, the amplitude of the signal increases, until the channeled beam is fully intercepted. Moving the bars further, the first one touches the edge of the primary beam.The shift of the fit peaks is due to the relative shift of the bars (5,5 mm)

CpFM functionality test: channeled beam parameters extrapolation





Fitting function: $A \cdot \frac{1}{\sigma\sqrt{2\pi}} \int_0^x e^{-\frac{(t-c)^2}{2\sigma^2}} dt$ + k

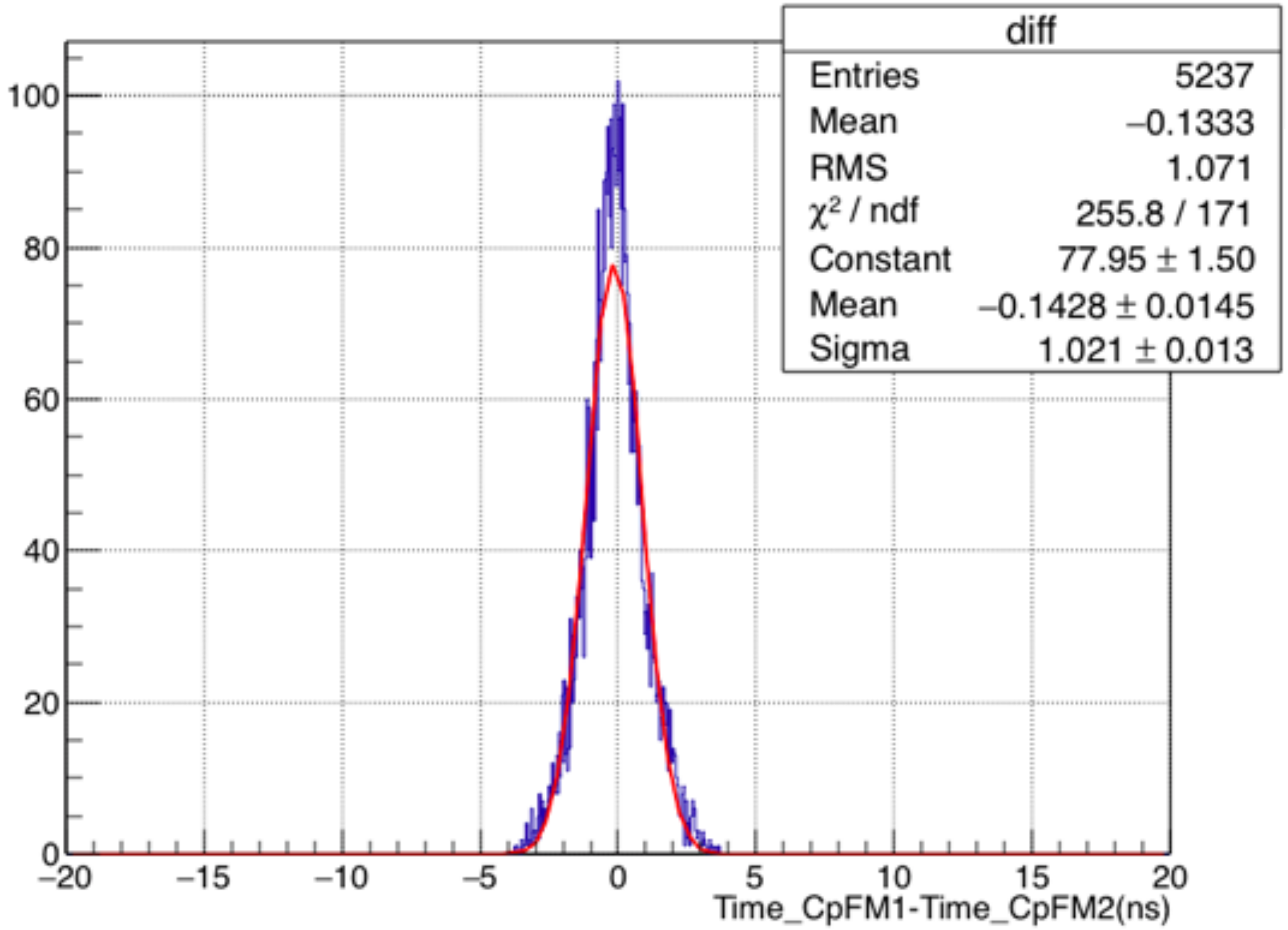
- ✓ The amplitude distribution in the channeling region can be fitted with an error function. The derivative of this function corresponds to the gaussian profile of the channeled beam. From the sigma value is possible derive the angular spread of the channeled beam that, in our case, well reproduce the critical angle for 270 GeV protons(12.2 urad).

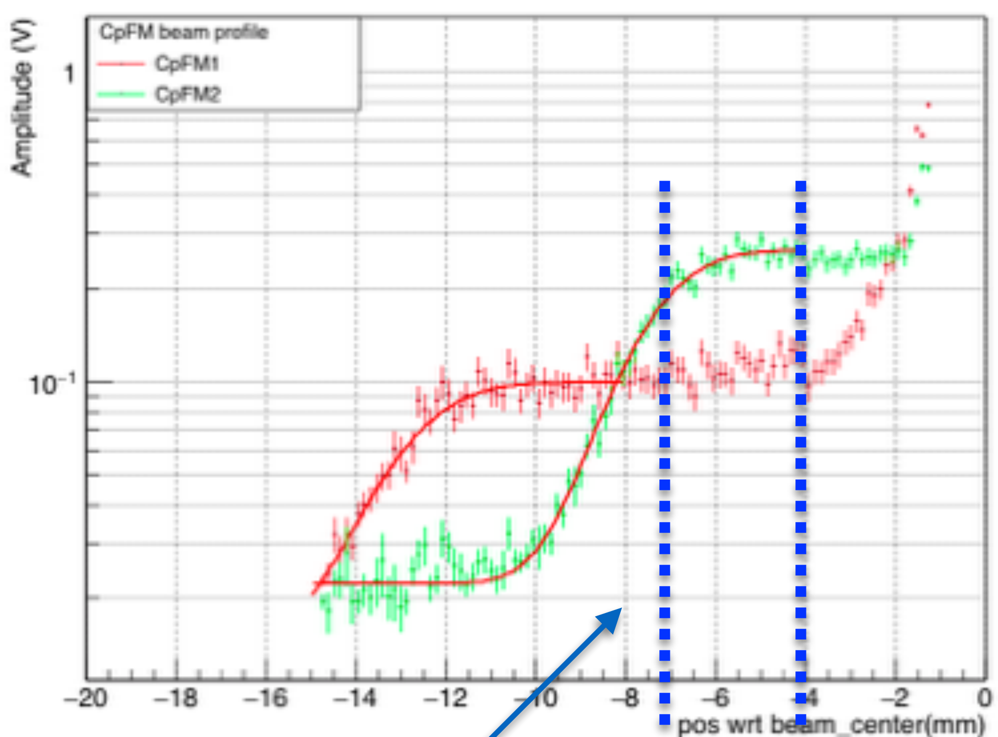
$$\theta_{spread} = (12,8 \pm 1,3)\mu rad$$

- ✓ Estimation of the bending angle through the knwoledge of the channeling peak position.

$$\theta_{ch(cry4)} = (153 \pm 11)\mu rad$$

CpFM detector characterization: Time resolution





To extrapolate time resolution we need to be sure that both the bars detect the same particles so we need to consider just the case in which both bars intercept the whole channelled beam (plateau position). Supposing that the time resolution for the two bars is the same:

Time resolution of CpFM= $(722 \pm 9)ps$

Summary: CpFM for the UA9 experiment

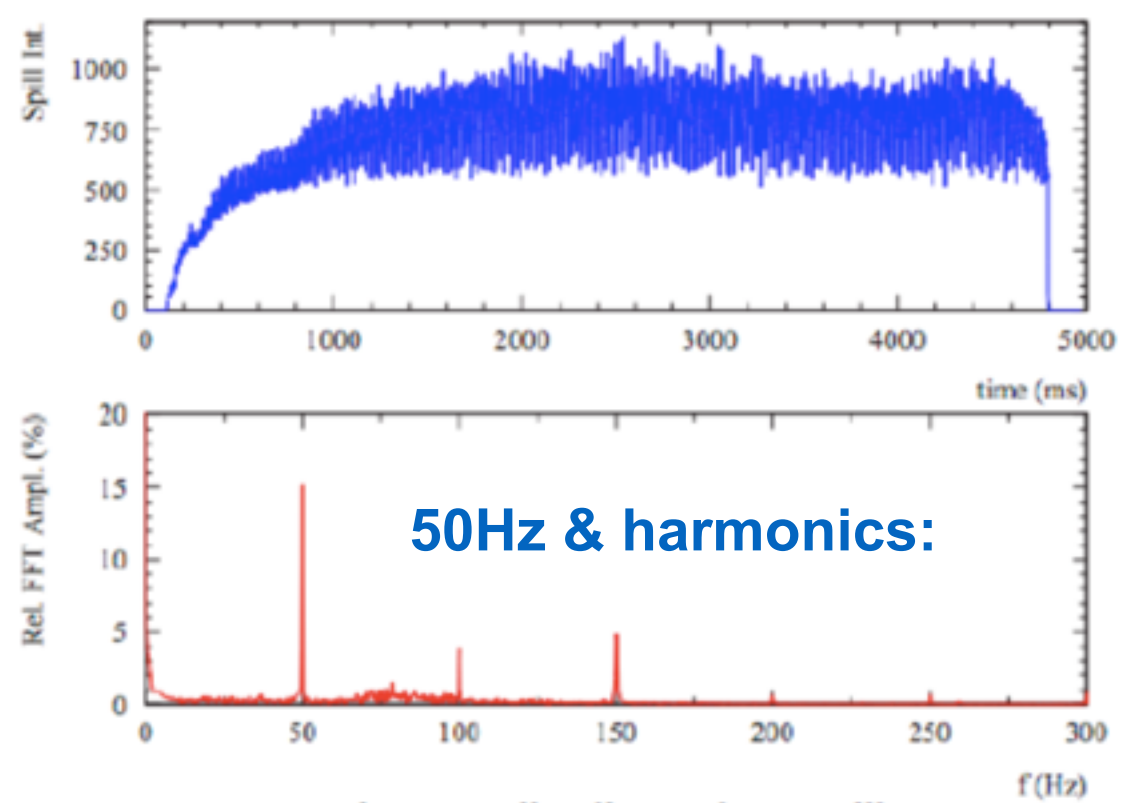
- ✓ A new concept of Cherenkov detector has been designed to perform proton flux measurements in the framework of UA9 experiment.
- ✓ The device has been commissioned during 2015 and 2016: Linear scan procedure has been used for both, testing the functionality of the CpFM detector and to characterize the detector itself.
- ✓ Because of a problem in the collection of the light at the vacuum-air interface it was not possible until now, converting the amplitude of the CpFM in the number of protons. The problem has been solved last September
- ✓ However a solid method of analysis of the CpFM signal has been developed and is going to be used for next data taking (18/10/16 with protons and in November with Pb ions)
- ✓ The R&D of the CpFM detector is still undergoing for what concerns the fused silica radiators in terms of geometrical shape and radiation resistant.

The Slow Extraction CpFM to monitor the slow extraction spill of SPS

The SE-CpFM detector to monitor the Slow extraction Spill of SPS.

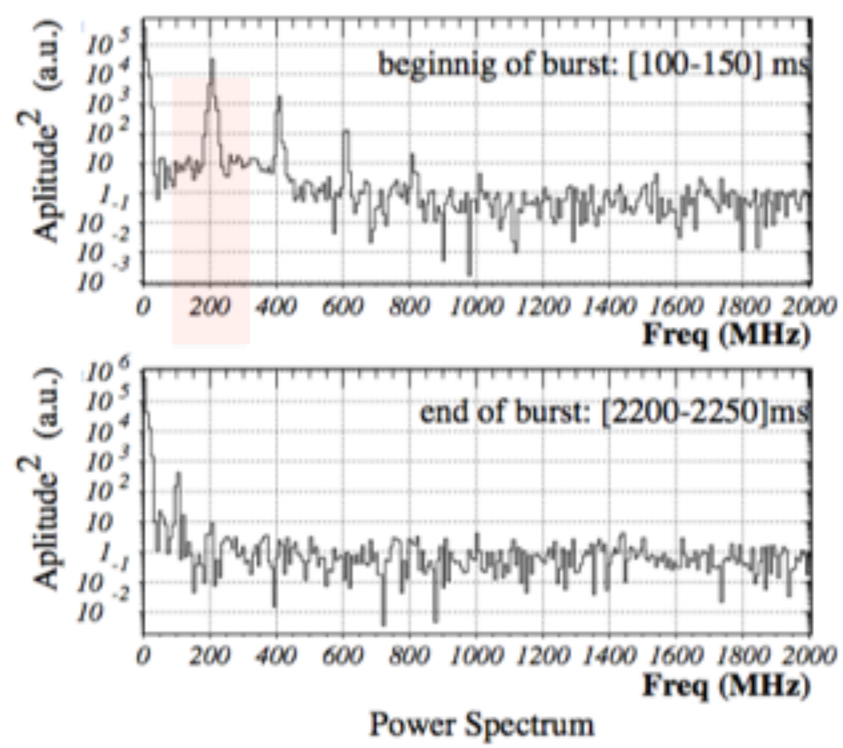
- ✓ The SE-CpFM is a second version of the CpFM detector conceived to monitor the time structure and the quality of the slow extraction spill of SPS .
- ✓ The Slow extraction SPS spill is controlled by the Servo-spill system. This is a closed loop feedback measuring the extracted current and acting on four dedicated quadrupoles to stabilize the extracted beam intensity. However the spill is characterized by high intensity spikes at the beginning and keeps some time structures typical of the machine (50Hz, 43KHz, 200MHz)

Spill intensity vs time



Less well-adjusted p+ spill

SPS RF 200MHz harmonic time evolution



last several 100 ms!

Figure 8.13: *The Fourier transform of the proton time distributions at the beginnning and end of the burst (see figure 8.12).* G. Colazzuol,PhD thesis, NA8

Mitigate now by a feed-forward system

No correction is possible in this case but it's anyway fundamental delivering to the experiments this information.

SE-CpFM REQUIREMENTS

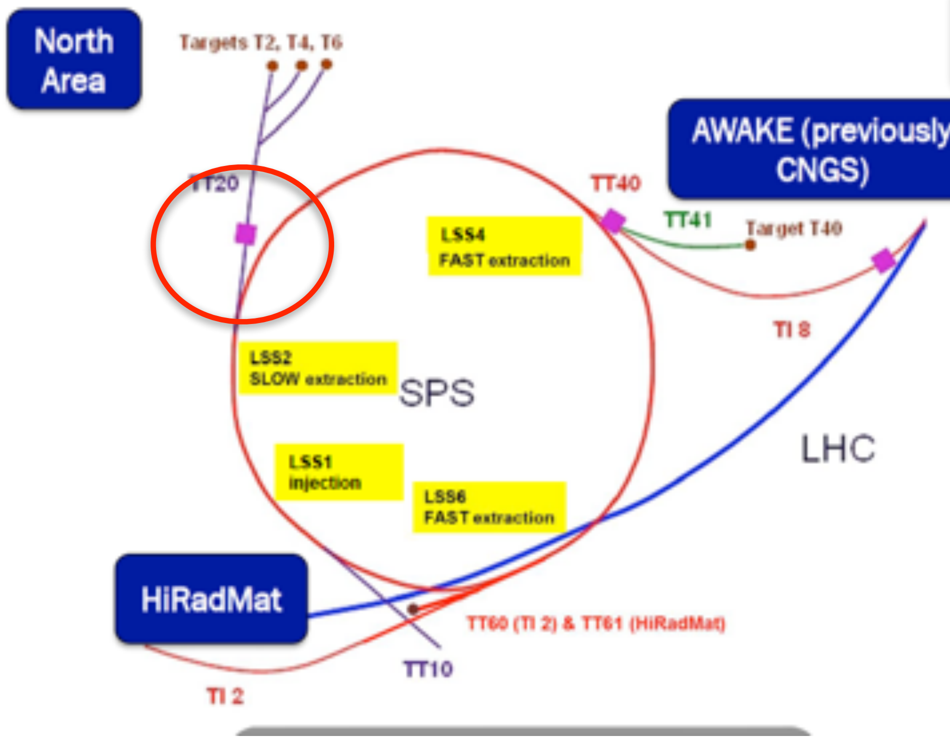
BEAM CHARACTERISTICS

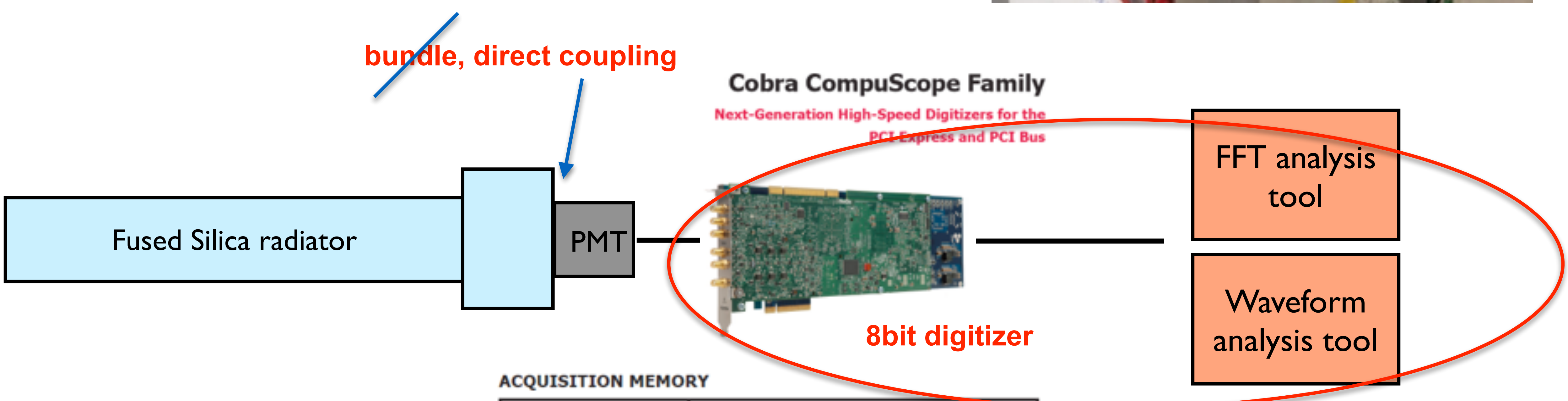
- Beam Intensity :1×10^{12} to 5×10^{13} p^+/spill
- Peak beam intensity: Expect spikes up to 3 times average intensity during the spill, i.e. up to 15×10^{13} p^+/s (max).
- Total beam intensity: $1>4\times10^{19}$ p^+/year
- Spill lenght: 1 to 4 sec
- High frequency content up to 200MHz

DETECTOR REQUIREMENTS:

- High dynamic range
- Radiaton hard detector
- large data buffering
- High speed digitizer

SE-CpFM detector location adn layout



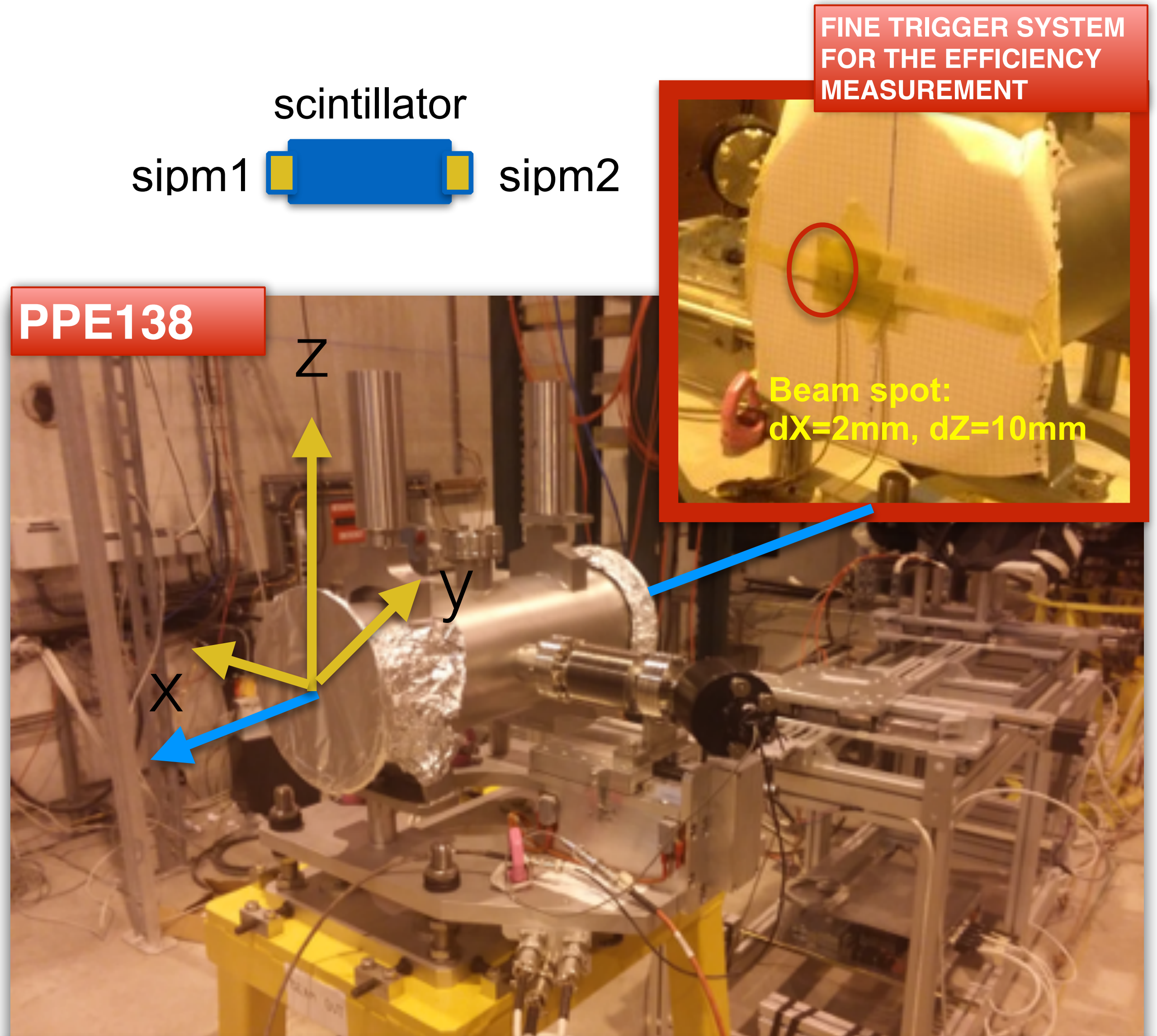


ACQUISITION MEMORY

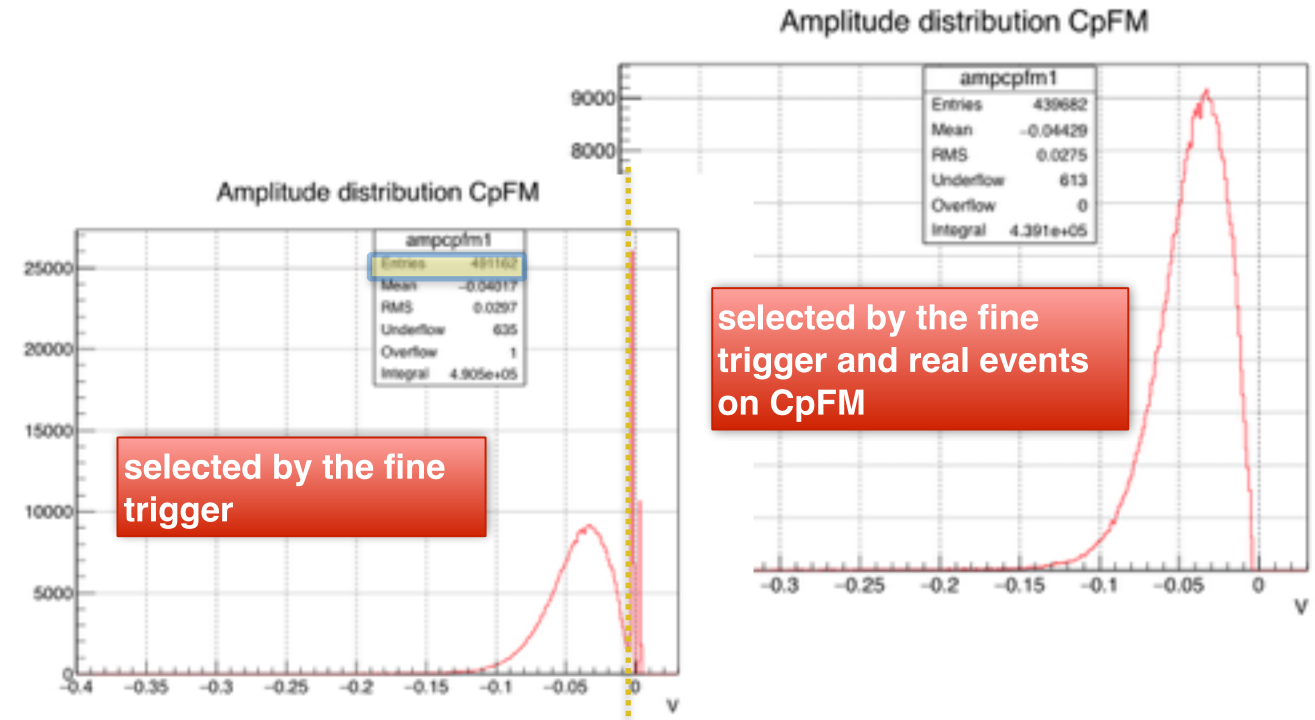
Cobra Model	Available memory options				
PCI Cobra	256 MS	512 MS	1 GS	2 GS	4 GS
PCI Express Cobra	2 GS	4 GS	8 GS	16 GS	32 GS

Validation performed using a pulse patter generator and a wide range of frequency

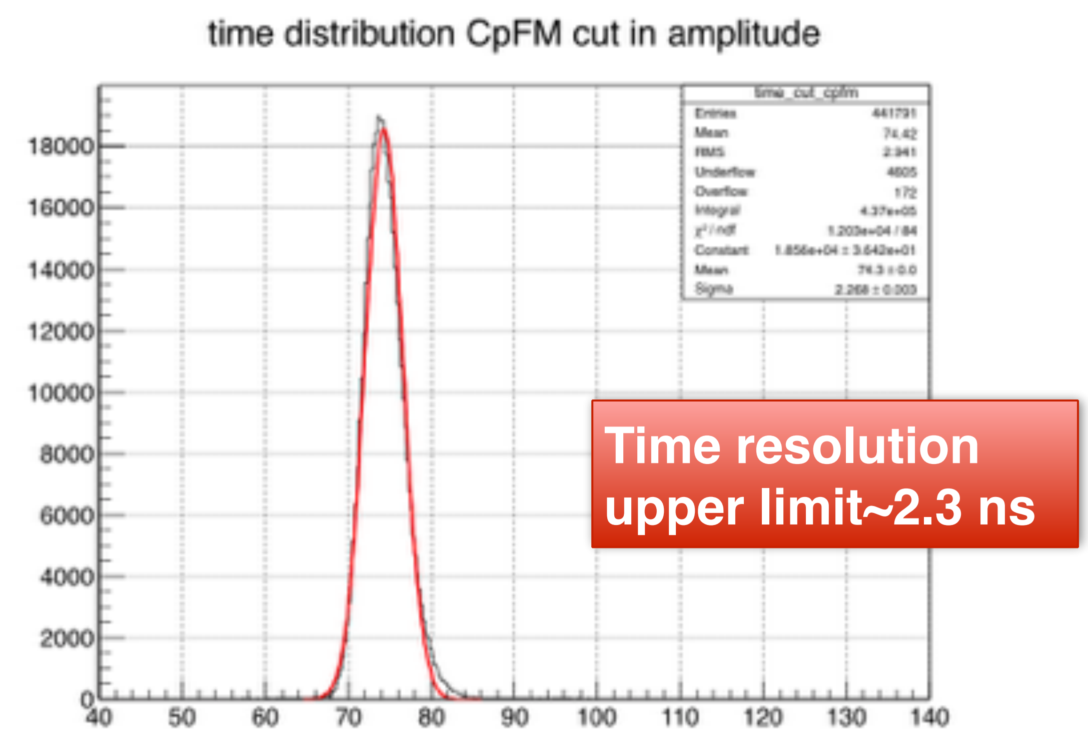
SE-CpFM efficiency test in the SPS-H8 extraction line



SE-CpFMefficiency test: 3-4/05/2016
180 GeV Pions / 2-6x10^5 pi/spill



CpFM single particle efficiency:89.5%

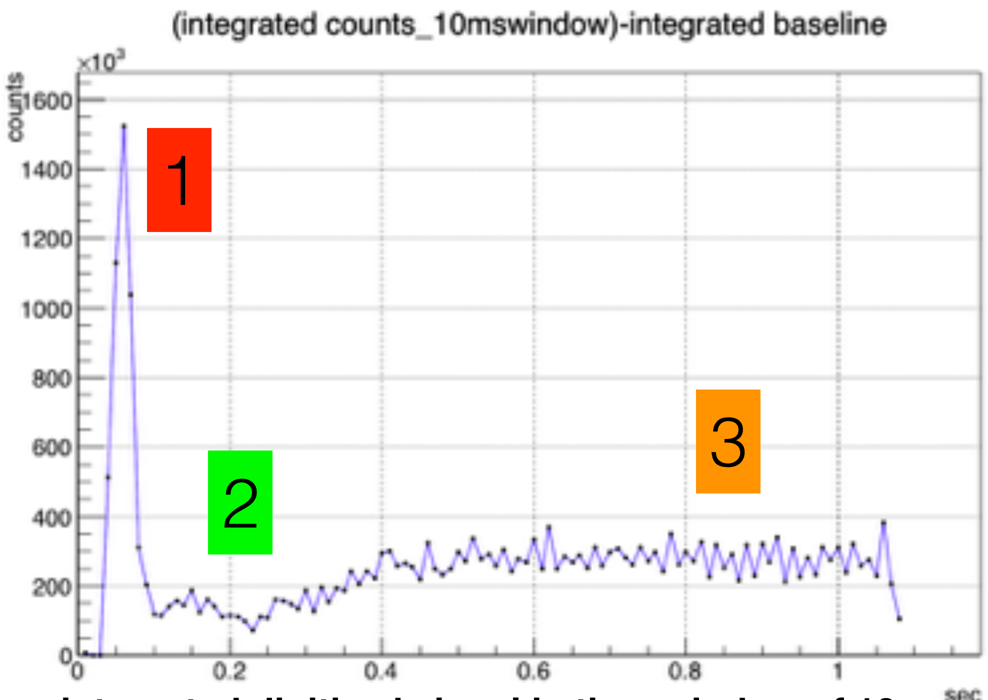


CpFM readout electronics:WaveCatcher board
3.2 GHz sampling freq, 320 ns time windows

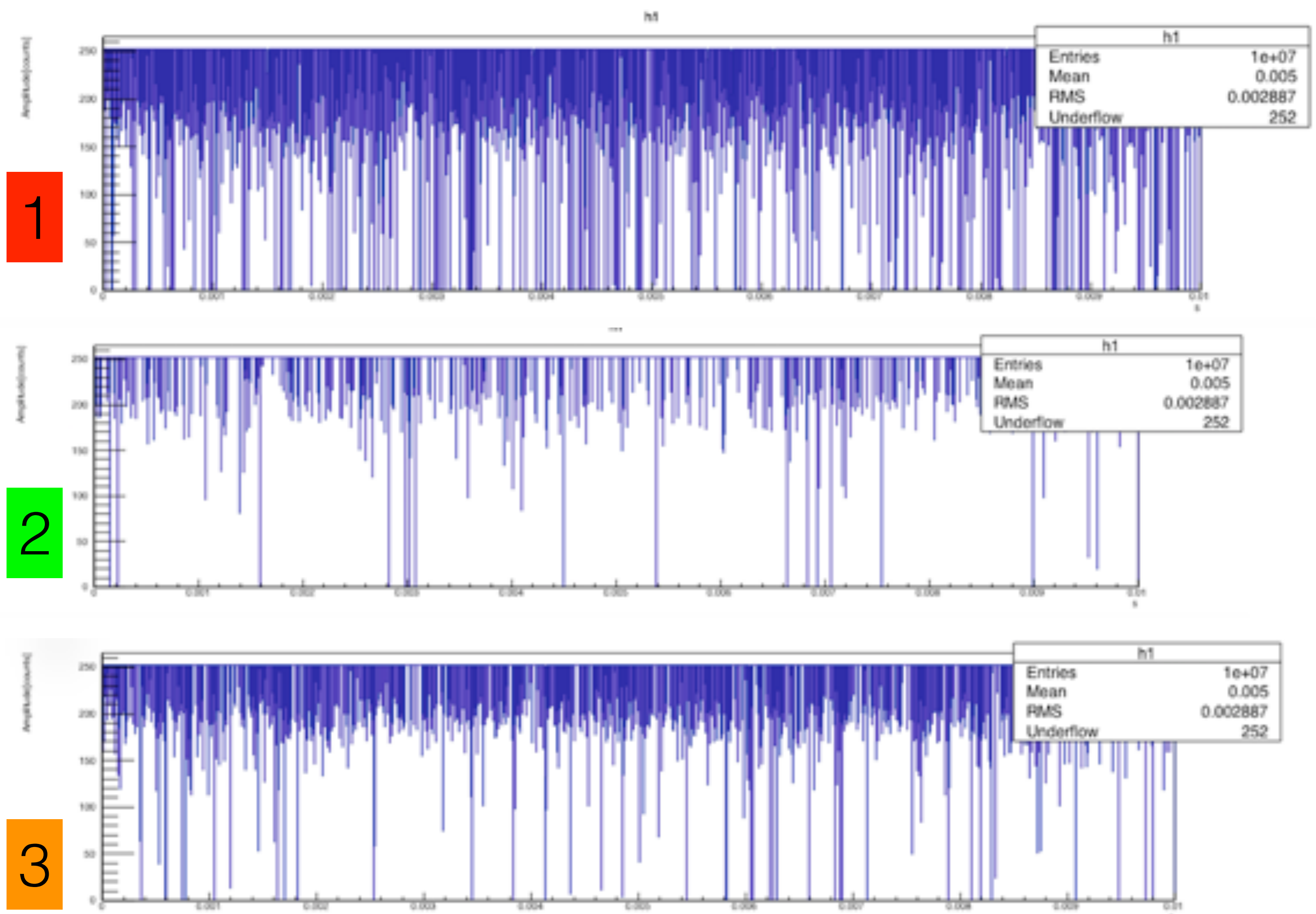
SE-CpFM Cabra card digitizer and analysis tool validation in H8

Cobra card sampling freq = 2GHz

SE-CpFM electronic readout test 1-6/07/2016
180 GeV Pions / 2-6x10^5 pi/spill



integrated digitized signal in time window of 10 ms, for 1 sec of spill: Is it clearly visible a huge intensity spike at the beginning of the spill. After first 400ms ,as expected, the intensity becomes quite stable

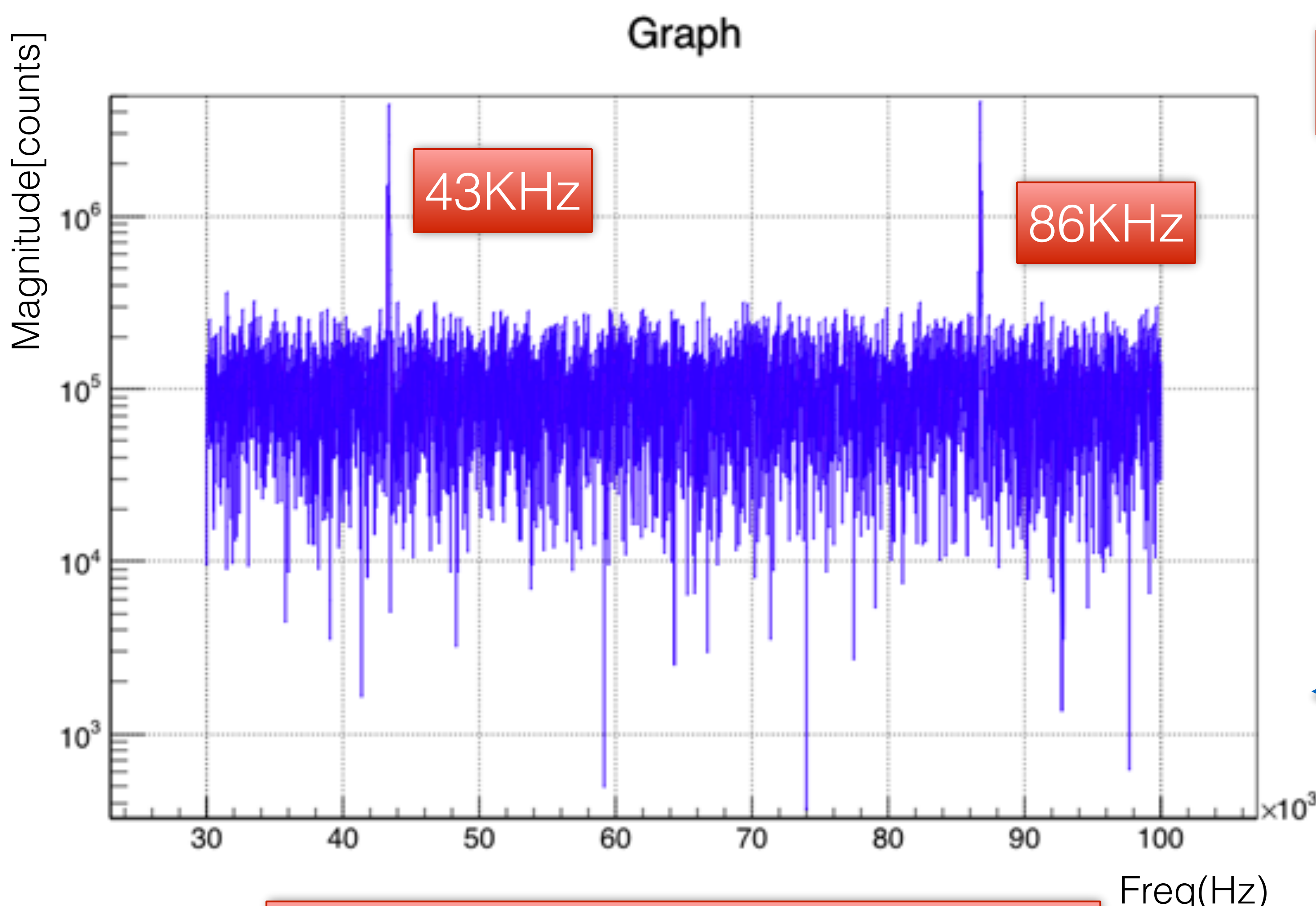


Digitized 10 ms waveforms, corresponding to different pion flux during the same spill.

dedicated Waveform analysis tool

SE-CpFM Cabra card digitizer and analysis tool validation in H8

43 KHz (SPS revolution frequency) harmonic component during first 100ms of the spill



0-100 ms

Cobra card sampling freq = 2GHz

FFT analysis tool based on FFTW3 class

SE-CpFM electronic readout test 1-6/07/2016
180 GeV Pions / 2-6x10^5 pi/spill

The validation of the Cobra card in terms of Dynamic range is still to be completed. No evidence for the 200 MHz harmonic has been found in H8; we are investigating about it.

Summary: SE-CpFM to monitor the slow extraction spill of SPS

- ✓ A second version of the CpFM detector has been designed to perform monitoring of the time structure and quality of the slow extraction spill of SPS

- ✓ The readout electronic of the SE-CpFM is realized by a High speed digitizer. This card has been preliminary validated together with a dedicated FFT analysis tool both, using a pulse patter generator and with the H8 beam test.

- ✓ The whole detector chain has been succesfully tested with 180 GeV/C pions beam at H8.

- ✓ The device has been installed in May 2016 in TT20-SPS transfer line and the commissioning has just begun.

BACK UP

Bending angle formula

We assume on-momentum particles hitting the edge of the crystal at their maximum betatron extension:

$$\begin{pmatrix} x_0 \\ x'_0 \end{pmatrix}_{cry} = \begin{pmatrix} x_{cry} \\ -\frac{\alpha_{cry}}{\beta_{cry}} x_{cry} \end{pmatrix} \tag{3.16}$$

where x_{cry} is the aperture of the crystal and α_{cry}, β_{cry} are the twiss parameters at the crystal location. After a kick θ_k from the crystal, the coordinates at the crystal are:

$$\begin{pmatrix} x_1 \\ x'_1 \end{pmatrix}_{cry} = \begin{pmatrix} x_{cry} \\ -\frac{\alpha_{cry}}{\beta_{cry}} x_{cry} + \theta_k \end{pmatrix} \tag{3.17}$$

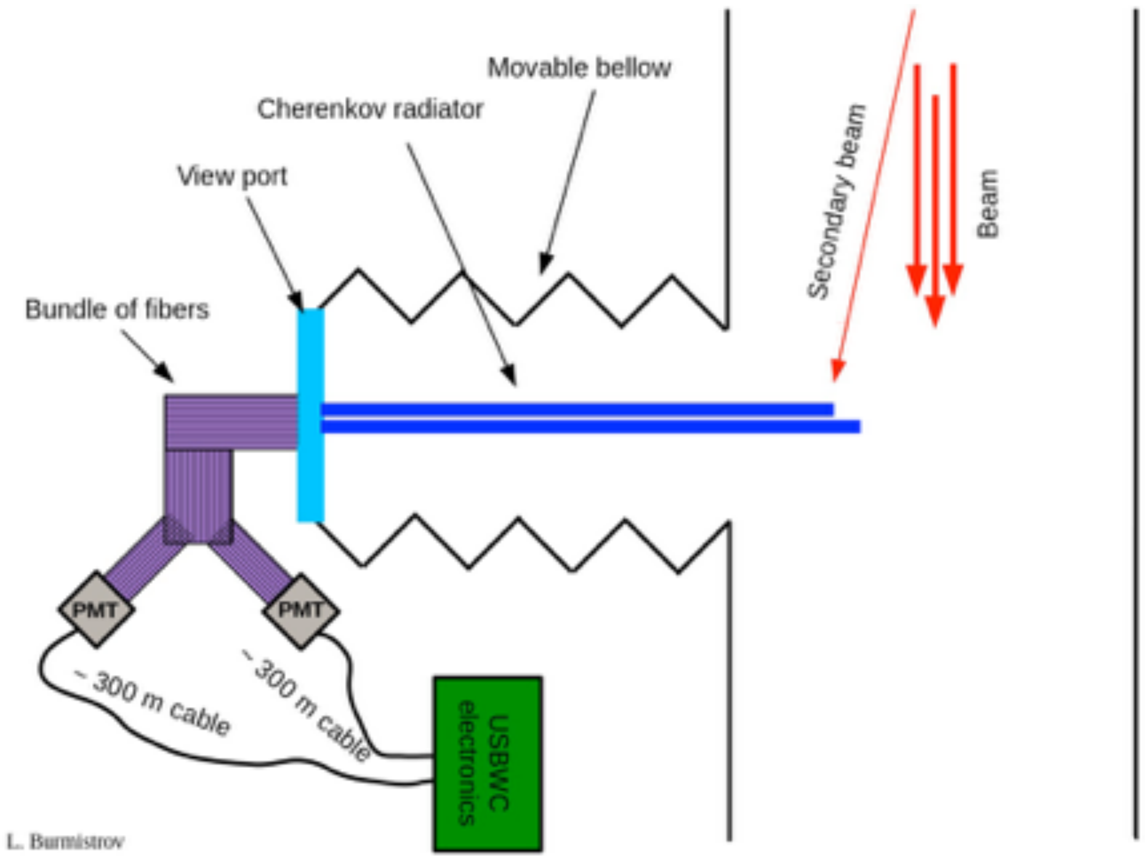
One can calculate the transverse coordinate $x(s_{coll})$ at the collimator location applying the standard transformation matrix M

$$M = \begin{pmatrix} \sqrt{\frac{\beta_{coll}}{\beta_{cry}}}(\cos\Delta\phi + \alpha_{cry}\sin\Delta\phi) & \sqrt{\beta_{cry}\beta_{coll}}\sin\Delta\phi \\ \frac{(1+\alpha_{coll}\alpha_{cry})\sin\Delta\phi + (\alpha_{coll}-\alpha_{cry})\cos\Delta\phi}{\sqrt{\beta_{cry}\beta_{coll}}} & \sqrt{\frac{\beta_{cry}}{\beta_{coll}}}\cos\Delta\phi - \alpha_{coll}\sin\Delta\phi \end{pmatrix} \tag{3.18}$$

$$\theta_k(s_{coll}) = \frac{x(s_{coll}) - \sqrt{\beta_{coll}/\beta_{cry}}\, x_{cry}\cos(\Delta\phi)}{\sqrt{\beta_{cry}\beta_{coll}}\sin(\Delta\phi)} \tag{3.20}$$

By calculating the equivalent kick associated to the center of the channeling peak c, one then obtains the channeling angle $\theta_{chan} = \theta_k(c)$.

CpFM layout in SPS BA5 Area



- Radiators: two fused silica I-shape bars (5x10x300mm) 6 mm staggered one from the other.

- Flange with a fused silica window to realize the air/vacuum interface

- Quartz fiber bundle coupled to PMTs (200 fibers, 4 m long)

- PMTs: HAMAMATSU PMT (R7378A) with radiation hard fused silica window.

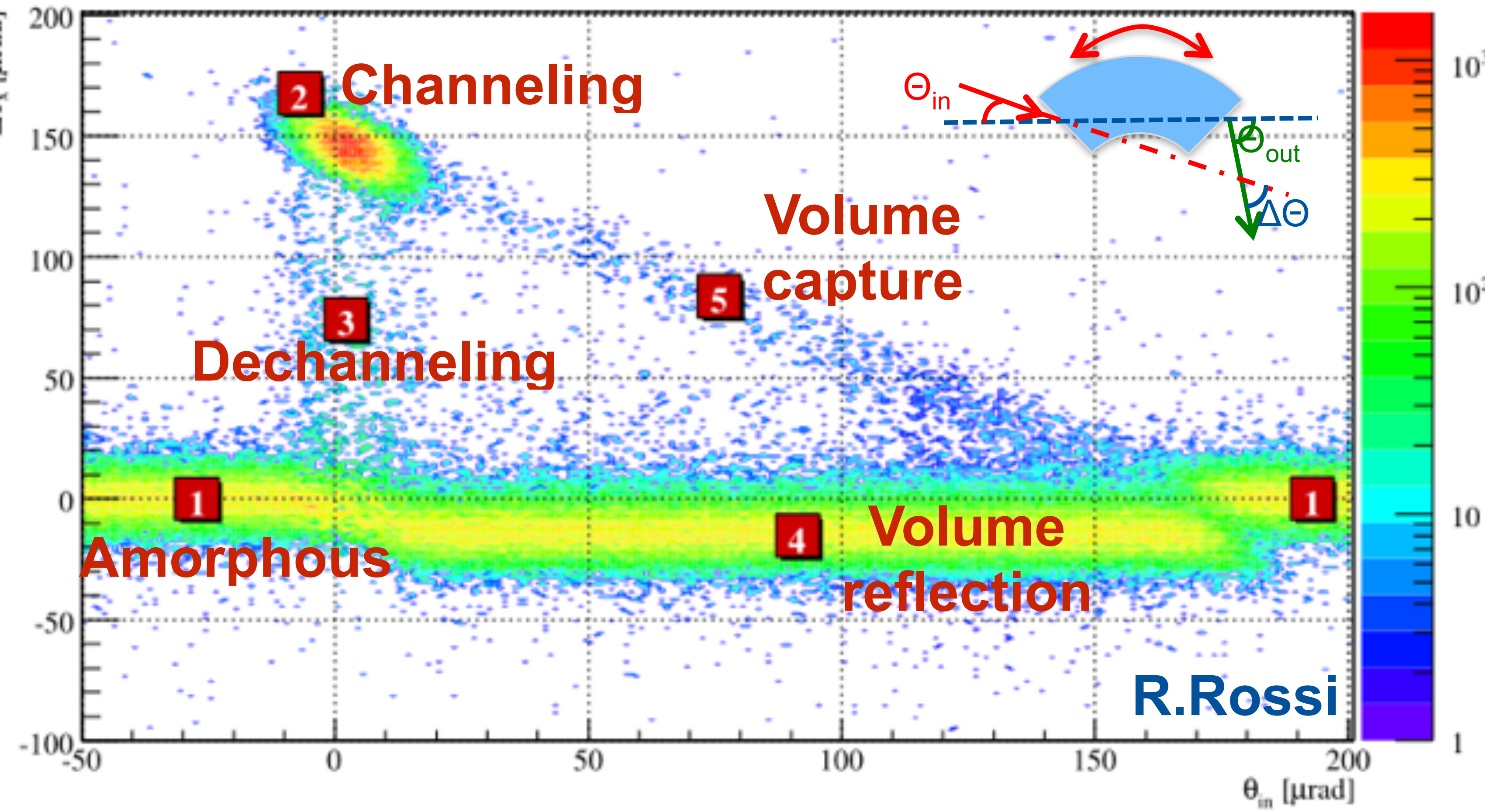
- PMTs readout by USB-WaveCatcher (sampling rate 400 MHz, memory ~ 1 us)

Radiators are pushed into the deflected beam through a movable flange.

UA9 Experiment: Single-pass measurements observation of channeling in SPS-H8

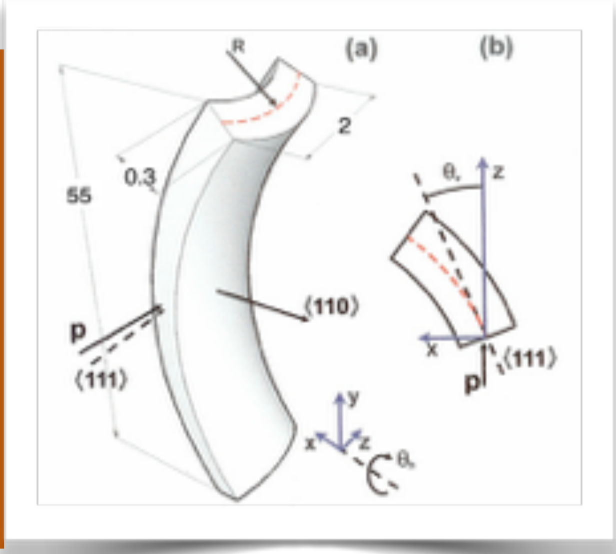
Since 2009 the UA9 Experiment investigates channeling effect and the feasibility to use bent crystals to steer hadron beams at CERN-SPS.

400 GeV protons H8 beam test

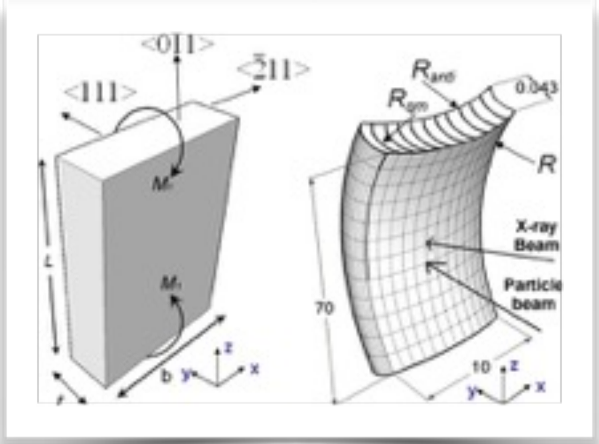


For a LHC designed crystal the channeling efficiency measured in H8 is around 60%

Strip Crystals

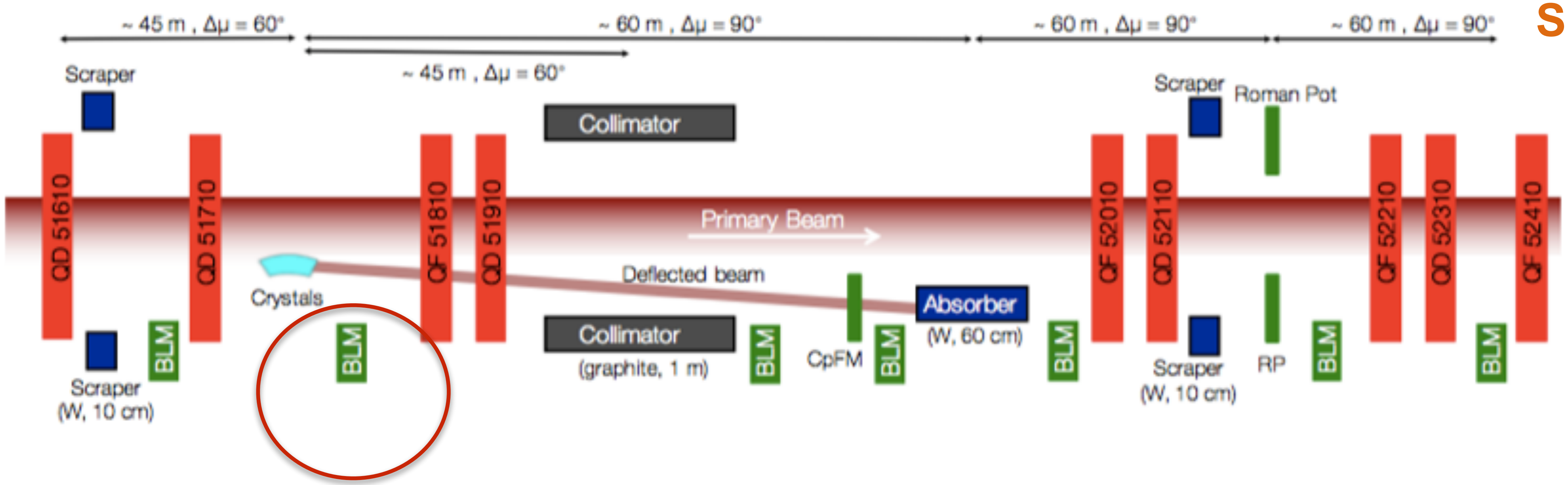


Quasi-mosaic crystals



UA9 Experiment: SPS channeling observations in circulating beams

SPS-LSS5

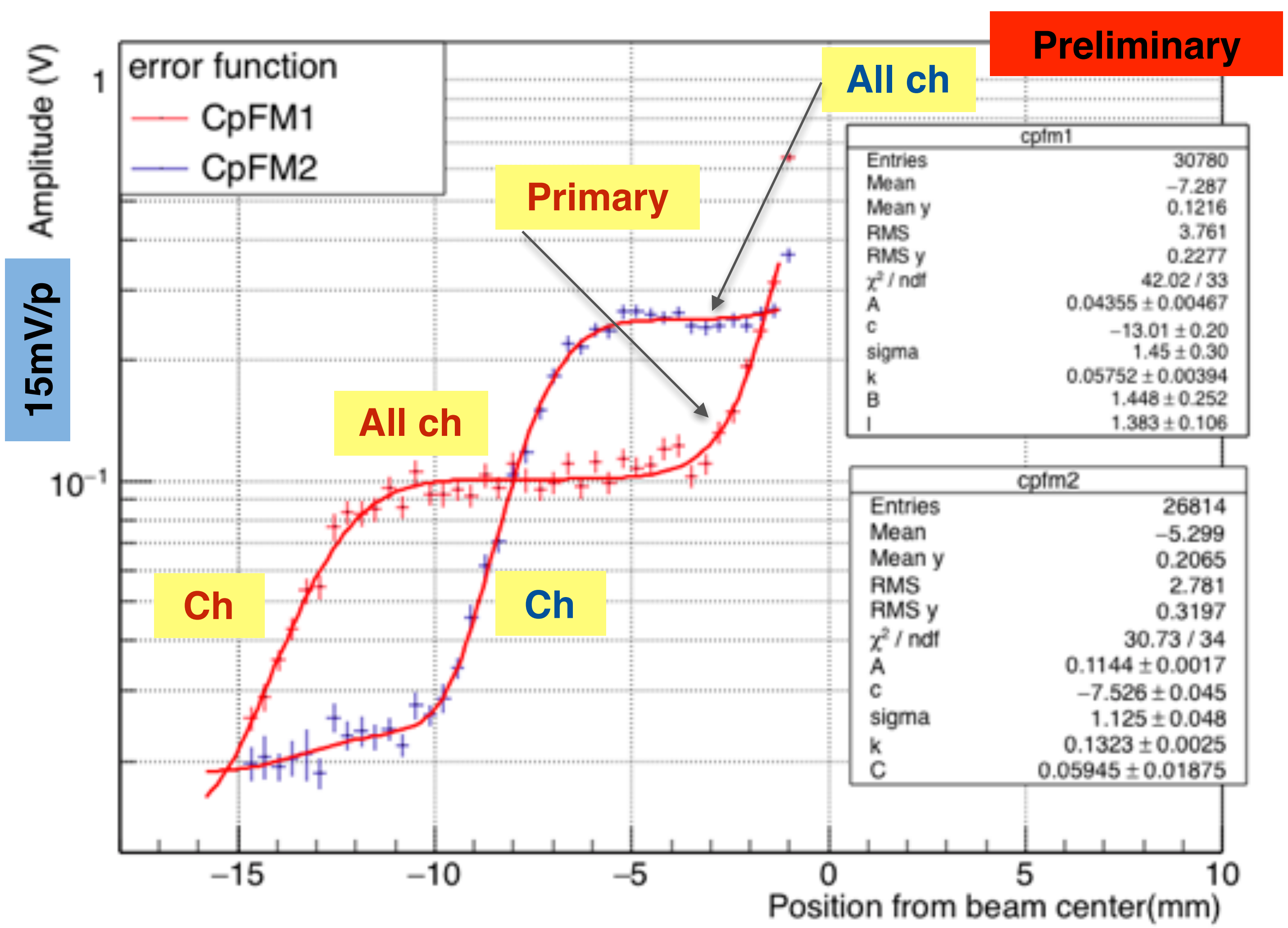


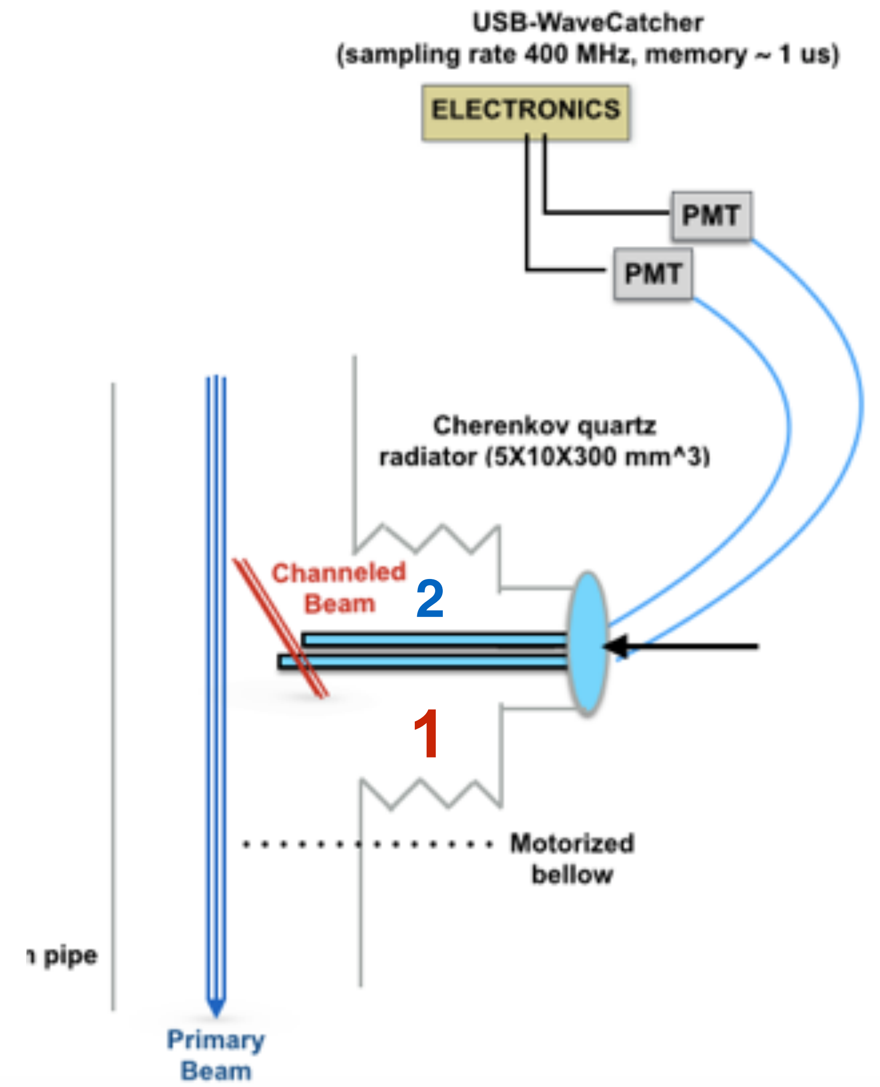
Channeling efficiency up to 80% in circulating beam (considering also multi-turn effect)

Channeling

The Cerenkov proton Flux Measurement during operations

CpFM detector operation during Oct 2015 UA9 test- single bunch 270 GeV protons





UA9 Crystal as a primary collimator. As the bars approach the channeled beam, the amplitude of the signal increases, until the channeled beam is fully intercepted. Moving the bars further, the first one touches the edge of the primary beam.

SPS-BA5 setup