THE CHERENKOV DETECTOR FOR PROTON FLUX MEASUREMENT (CpFM) IN THE UA9 EXPERIMENT

S. Montesano*, W. Scandale[1], CERN, 1211 Geneva 23, Switzerland
F. M. Addesa, G. Cavoto, F. Iacoangeli, INFN Sezione di Roma, Rome, Italy
L. Burmistrov, S. Dubos, V. Puill, A. Stocchi, LAL, Orsay, France
[1] also at LAL, Orsay, France

Abstract

The UA9 experiment at the CERN SPS investigates the possibility to use bent crystals to steer particles in high energy accelerators. In this framework the CpFM have been developed to measure the beam particle flux in different experimental situations. Thin movable fused-silica bars installed in the SPS primary vacuum and intercepting the incoming particles are used to radiate Cherenkov light. The light signal is collected outside the beam pipe through a quartz optical window by radiation hard PMTs. The PMT signal is readout by the WaveCatcher acquisition board, which provides count rate as well as waveform information over a configurable time window. A bundle of optical fibers can be used to transport the light signal far from the beam pipe, allowing to reduce the radiation dose to the PMT. A first version of the CpFM has been successfully commissioned during the data taking runs of the UA9 Experiment in 2015, while a second version has been installed in the TT20 extraction line of the SPS in 2016. In this contribution the design choices will be presented and the final version of the detector will be described in detail.

INTRODUCTION

Since 2009, the UA9 Experiment investigates the possibility to use bent silicon crystals to steer beams of charged particles, and in particular to improve the performance of a multi-stage collimation system [1]. The main installation of the experiment is in the Long Straight Section 5 (LSS5) of the CERN SPS and includes three goniometers to operate five different crystals, one dedicated movable absorber, several scrapers, detectors and beam loss monitors (BLM) to probe the effect of the crystal on the beam halo [2]. A schematic representation of the layout of the experiment is reported in Fig. 1.

The main process that is investigated is the so-called "planar channeling": particles impinging on a crystals with a direction close to the one of the lattice planes are forced to move between the planes by the atomic potential, with high efficiency; if the crystal is bent, the trapped particles follow the bending and are deflected. When an optimized crystal intercepts the beam halo to act like a collimator, about 80% of the particles are channeled, coherently deflected and dumped on the absorber (see Fig. 1), effectively reducing the beam losses in the sensitive areas of the accelerator [3–8].

Requirements for the Detector

In order to fully characterise this system, the flux of the particles diffusing to the crystal should be characterized, as well as the "deflected beam" due to the particles extracted towards the absorber by the crystal. Initial estimations are performed using the variation of the primary beam intensity measured by the Beam Current Transformer (BCT) and intercepting the extracted beam with a Medipix detector enclosed in a Roman Pot [3, 9].

The existing instrumentation allowed to perform several measurements, however, the optimal detector for these measurements would be:

- installed directly in the beam pipe vacuum, to avoid the interaction of the protons with the Roman Pot window;
- able to measure the number of protons extracted from a single SPS bunch (during UA9 operations the bunch length is 3 ns and the minimal bunch distance is 25 ns);
- able to resolve the signal generated by a single proton up to few tens of protons (the estimated extraction rate is of the order of 10^7 p/s with a revolution time of 23 µs - i.e. few protons extracted per machine turn);
- radiation-hard in order to reliably operate in the accelerator tunnel;
- movable in the direction transversal to the beam, to allow measurements at different apertures of the collimation system and to avoid interfering with the beam during standard machine operations.

THE CHERENKOV DETECTOR FOR PROTON FLUX MEASUREMENT

In order to comply with the requirements listed above, the concept of the CpFM was conceived. A sketch of the detector is reported in Fig. 2, with its main elements: a radiator that intercept particles inside the beam pipe and create the Cherenkov light, a bellow to allow moving the radiator, an interface transmitting the light outside the beam pipe, a photomultiplier (PMT) to collect the light and electronics to readout the PMT signal. Several investigations and measurements [10] performed in the last few years have allowed to carefully select all the components of the chain.

The Cherenkov Radiator

When choosing the technology of the sensor, different options were considered: silicon and gas detectors posed important issues with respect to operation in the beam pipe vacuum, while scintillator materials were considered not

* simone.montesano@cern.ch

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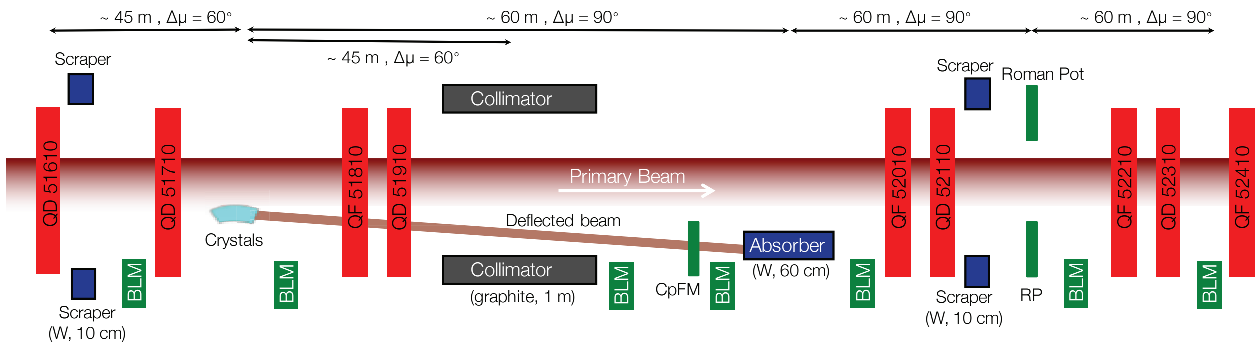

Figure 1: Schematic layout of the UA9 Experiment in the SPS LSS5. The quadrupoles defining the phase advance among different elements are represented by red boxes.

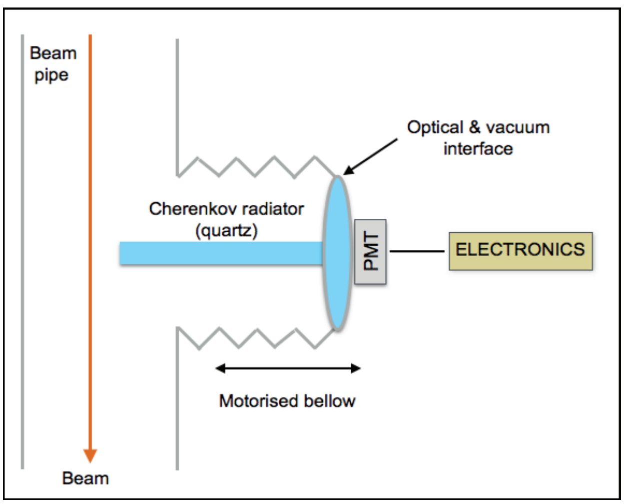

Figure 2: Conceptual sketch of the CpFM.

enough resistant to radiation. Finally it was decided to use a Fused Silica radiator to produce Cherenkov light.

Fused Silica is a synthetically made quartz which has been studied during the R&D for several detectors. The requirement to move the sensor completely out of the beam pipe during normal machine operations set a minimum length for the radiator, which should also transport the generated light through internal reflection from the tip intercepting the beam to the other end of the bar, interfaced with the external of the beam pipe. An extensive simulation campaign has been performed comparing different shapes for the radiator (L-shape, J-shape and I-shape bars were compared, as well as bars with round or rectangular sections) and defining the required polishing (100 nm RMS) and flatness (100 nm). While the best light yield is obtained for L-shaped bars, it turned out difficult to obtain L-bars with the required polishing. Therefore the produced detectors were equipped with I-bars with rectangular section and 5 mm length in the beam direction.

Cherenkov photons are generated with an angle $\theta_c = 47°$ with respect to the direction of the incoming particles, which can be assumed to be parallel to the beam pipe. After multiple reflection inside the radiator, photons reach the end of the bar where they are collected (see Fig. 3). In order to maximise the photons collected, the collection surface should be perpendicular to the direction of the photons. Measurements where performed interfacing a bundle of optical fibres to the end of the radiator and confirmed that the signal is collected with good efficiency only when the bar has an angle of ~47° with respect to incoming particles. Since the integration of an inclined bar requires a large aperture in the tank hosting the detector, it was chosen to cut the end of the bar with an end surface inclined by 47° and to keep the radiator perpendicular to the beam direction.

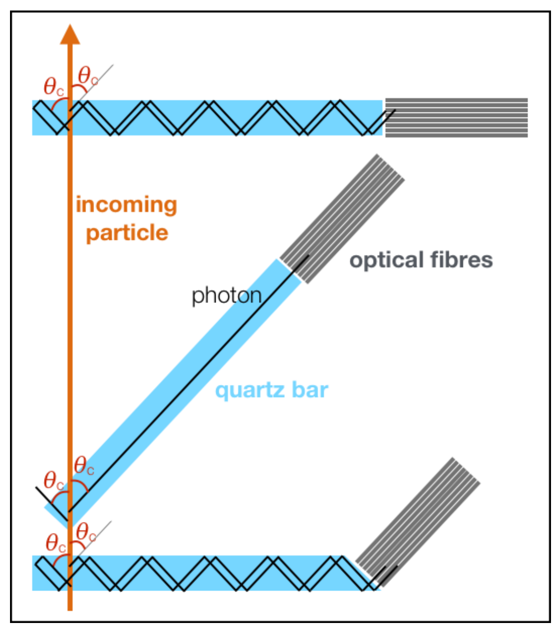

Figure 3: Effect of the Cherenkov angle on the collection of the signal at the end of the radiator.

The Optical and Vacuum Interface

The light generated in the radiator must be transmitted outside the beam pipe and collected by a PMT. In order to limit the number of interfaces traversed by the light it was attempted to feed the quartz bar through a vacuum flange and braze the ensemble to ensure vacuum tightness. The

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issue did not have an easy solution, therefore it was chosen to use a commercial quartz viewport to ensure the interface for vacuum and light. Measurements allowed to estimate a reduction of the signal by a factor maximum 2 when using a glass slab as interface. In order to match the 47° inclination of the end surface of the radiator, a special flange had to be designed (see Fig. 4).

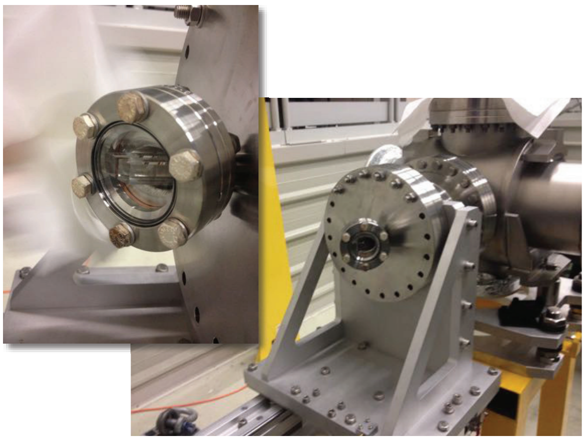

Figure 4: The tilted optical window of the CpFM.

The Photomultiplier

In order to choose a PMT for the CpFM, few radiation-hard devices were considered. Extensive tests were performed for two of them (HAMAMATSU R762 and R7378A, see Table 1 for the main characteristics) that showed good timing properties and sensitivity for the needed wavelengths. In the end the R7378A was chosen for its higher quantum efficiency and, given the good linearity and the low expected proton flux during UA9 data taking, it was decided to use a standard voltage divider to power it.

Table 1: Main Characteristics of the PMTs Under Test

	R762	**R7378A**
Window material	Synthetic Silica	Synthetic Silica
Photocathode diameter (mm)	15	22
Photocathode material	Bialkali	Bialkali
Typical gain	10^6	2×10^6
Typical dark current (nA)	1	1
Maximum sensitivity (nm)	420	420
Typical radiant sensitivity (mA/W)	85	85
Rising Time (ns)	2.5	1.5

THE CpFM FOR UA9 IN SPS

The first CpFM device was designed and built for installation in SPS at the beginning of 2015. It was chosen to use a general purpose tank with large flanges and to design a motorization system that could adapt to it (see Fig. 5, left).

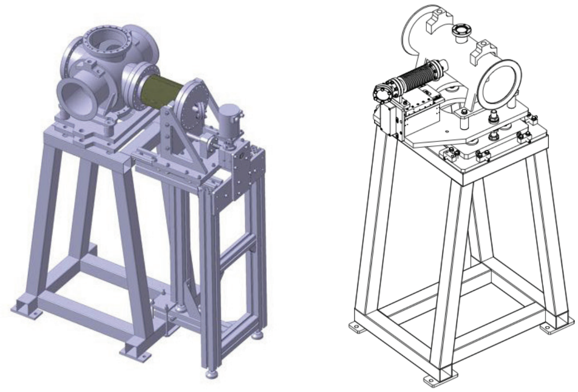

Figure 5: 3D model of the tank hosting the CpFM in the LSS5 of SPS (on the left) and in TT20 (on the right).

Two quartz radiators are used in this detector (see Fig. 6, left) to allow an estimation of the background. At the beam position, one of the bar is 5 mm closer to the beam and is meant to intercept the flux of protons to be measured. The other bar, being retracted from the beam to be measured, should provide a measurement of the background. The bars are supported by a clamping system: one side of the clamp is attached to the flange, while the other is provided by a short aluminum plate kept in position by a screw. Both sides touch the quartz bar only with two 0.5 mm-thick shoulders perpendicular to the long direction of the bars, to minimize the interface between metal and quartz and reduce the loss of light. The distance between the bars is defined by a 0.2 mm-thick aluminum plate clamped between them.

It was decided to reduce the radiation dose to the PMTs, moving them at the floor level, far from the beam pipe. The light signal is therefore transported by an optical fibre bundle composed of 2 channels of 100 fibres each. Fibres are radiation resistant and made of Fused Silica, in order to be transparent to the wavelengths of interest. The bundle is shielded from light by a flexible, stainless steel pipe.

The electronics chosen to readout the detector is the WaveCatcher [11]. This board is able to sample the analog signal of the detector over a configurable time interval (from 320 ns up to 2.4 μs) and to perform simple measurements on the signal. In addition, it counts the number of times that the signal in each channel crosses a user defined threshold. The usual trigger for the UA9 Experiment is used to read out the board (i.e. the SPS revolution signal downscaled by a factor 1000, and synchronised with the passage of the filled bunch in LSS5). Since the WaveCatcher is not radiation resistant, low attenuation cables are used to bring the signal of the PMTs to a shielded area in the SPS tunnel, where the WaveCatcher is installed. The board is then connected to a

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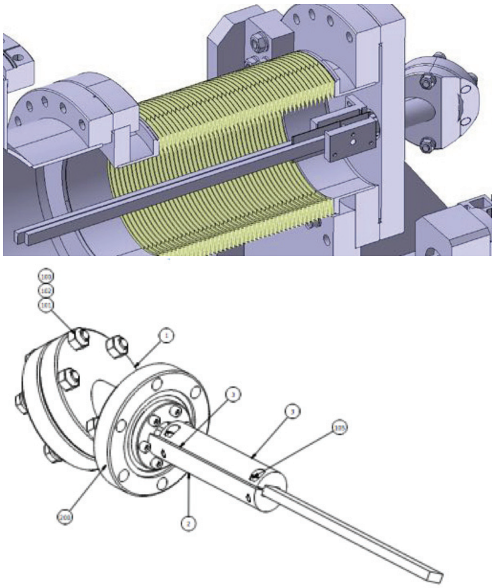

Figure 6: Bar holder and tilted optical window of the CpFM in the LSS5 of SPS (on top) and in TT20 (on the bottom).

standard PC outside the accelerator through USB protocol over an optical link.

The CpFM detector has undergone a detailed commissioning during the data taking runs of the UA9 Experiment and is routinely used for measurements during 2016.

THE CpFM FOR TT20

A second version of the CpFM was built to study the proton flux extracted from the SPS towards the North Area facility and was installed in the TT20 extraction line during 2016. The beam is substantially different with respect to the LSS5 situation, since a constant spill of the order of 10^{13} p over 4 s is expected. For this reason the electronics used for acquisition must to be changed and few different decisions have been taken, such as installing long low attenuation cables that bring the PMT signal directly outside the accelerator.

The tank hosting the detector has been redesigned from scratch, which allowed to build a more compact device, easier to install and to align in the beam line (see Fig. 5). The size of the bellow and of the flanges has been reduced and the optical fibre bundle has been removed, connecting the PMT directly to the optical window.

Assuming that the background will be negligible with respect to the beam to be measured, the design is based on a single quartz bar. The clamping system that holds the bar is therefore simplified, the plates have been changed to two hollow half-cylinders to reduce the risk to damage the bar during installation and transport (see Fig. 6, right). The contact points between quartz and metal are still provided by thin shoulders, but the distance between them has been increased.

The detector is entering the commissioning phase, the first signals have been acquired and are being analysed.

CONCLUSION

A new concept of Cherenkov detector has been designed to perform proton flux measurements in the framework of the UA9 Experiment. The detector is compatible with the vacuum and radiation hardness requirements for CERN accelerators.

During the development of the detector few interesting technological issues were raised but not solved: their solution would allow to build a detector with improved performance. A detailed paper describing all the simulation effort, the measurements and the beam tests that led to the final design is in preparation.

A first version of the device has been installed in the LSS5 of the SPS, has been commissioned and is routinely used by the UA9 Collaboration. A second version of the detector with few changes in the design has been installed in the TT20 extraction line and is entering the commissioning phase.

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