ON-LINE BEAM LOSS POSITION MONITORS FOR SPARC

D. Di Giovenale*, L. Catani, INFN Roma Tor Vergata, Roma, Italy
A. Cianchi, INFN and University Tor Vergata, Roma, Italy
G. Di Pirro, INFN-LNF, Frascati, Italy
F. Broggi, INFN-MI LASA, Milano, Italy

Abstract

Beam Loss Position Monitors (BLPM) are diagnostic systems that give hint of accidental interaction of beam, or part of it, with pipe walls typically caused by either steering errors or beam lost particle. Intensity of beam losses is measured by detecting anomalous quantity of particles in proximity of the beam pipe and, by using appropriate particle detector configuration, measurements provide also information about the longitudinal position where the loss originated. This paper describes the design and results of the preliminary tests of the BLPM system proposed for the SPARC accelerator providing real-time information on the intensity and position of beam losses that might occur along the undulator section. The BLPM system will consist of three stretched 300μm quartz optic fibers aligned to the undulator hanging few centimeters from the beam pipe. Solid state MPPC from Hamamatsu are used to convert the Cerenkov light produced by electrons traversing the fiber into a proportional time dependent signal. By analyzing its temporal structure and by comparing the intensities between the different fibers information about the sources of the beam loss can be obtained. Laboratory characterization of detectors are underway while the test of a preliminary set-up installed in the accelerator hall during the recent SPARC run [1] which was concluded in summer 2009.

INTRODUCTION

The aim of the SPARC [2] project is to promote R&D towards high brightness photo-injectors to drive a SASE-FEL experiment. The 150 MeV SPARC photo-injector consists of a 1.6 cell RF gun operated at S-band (2.856 GHz, of the BNL/UCLA/SLAC type) and high-peak field on the cathode incorporated metallic photo-cathode of 120 MV/m, generating a 5.6 MeV, 100 A (1 nC, 10 ps) beam.

The beam is then focused and matched into 3 SLAC-type accelerating sections, which boost its energy to 150-200 MeV and then driven into an undulator section composed by six, variable gap, undulators.

Being permanent magnets made of radiation sensitive material is important to equip the undulator section with an appropriate protection system aiming at detecting anomalous level of particles in proximity of the beam pipe. Since these are typically caused by either steering errors or beam lost particles, measurement of ionising radiation outside the accelerator vacuum chamber can give hints to detect and locate the origin of beam losses.

* domenico.digiovenale@roma2.infn.it

DETAILS ON THE SPARC BLPM SYSTEM

A simple, though efficient, solution for implementing a Beam Loss Position Monitor (BLPM) is based on optical fibers generating Cerenkov light when particles traverse them with a velocity higher than that of light in this matter [3]. A fraction of the light generated by the passing electrons is trapped in the fiber via total reflection and travels in both directions through the end of the fiber where read out of the light pulse is done by photon detectors. The time structure of the light pulse, its delay with respect to the beam trigger and the pulse length and shape, will provide information about the longitudinal position(s) where beam loss(es) occur. The installation of multiple fibers, all parallel to each other and to the beamline, allows a more efficient detection of the losses and, provided the fibers are quasi-uniformly distributed in the transverse plane, the possibility to get information about the transverse direction of the particle showers by comparing the intensities of light pulses in the different fibers. Refer to Fig. 1 for a schematic drawing showing the position of a sample fiber with respect to the beamline and the Cerenkov light pulses generation and propagation.

For the SPARC set-up, compatibly with the mechanical constraints, we plan to install three fibers as shown in Fig. 2. Expected longitudinal resolution depends mainly on the sampling frequency of the digitizer and on the refraction index n of the fiber. Defining $\Delta\tau$ as the time needed for the light pulse to reach the end of the fiber

$$\tau_0 = \tfrac{s_0}{\beta c}; \quad \Delta\tau = \tfrac{s_0}{v} = \tfrac{s_0}{c} n;$$

$$\tau_0 + \Delta\tau = \frac{s_0}{c}\left(1/\beta + n\right) = kT$$

the value $\tau_0 + \Delta\tau$ gives its delay with respect to the beam trigger at the digitizer input whose sampling frequency is

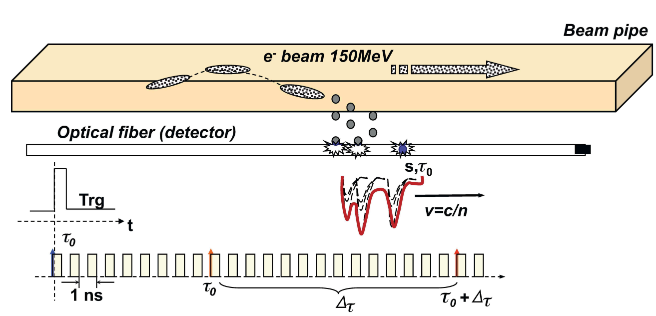

Figure 1: Schematic drawing of a Beam Loss position monitor.

$f = 1/T$. Since in our case $T = 1ns$ we can get an estimation of the longitudinal resolution limit for our set-up

$$\begin{array}{l} s_0 \approx \frac{cT}{1/\beta+n}k \\ \delta s_0 \approx \frac{cT}{1/\beta+n}\delta k \end{array} \quad \overset{\delta k=1}{\Rightarrow} \quad \delta s_0 \approx \frac{cT}{1/\beta+n} \approx 13cm$$

Intensity of light pulse traveling along the fiber will be attenuated exponentially as function of the distance. Attenuation, as well as MPPC photon detection efficiency, depends on the light wavelength. We chosen the wavelength range between 400 nm and 500 nm to estimate the signal expected at the detector.

The Cerenkov Radiator

Simulations have been performed to evaluate the expected electron shower emerging from the beam pipe in the case of a non optimal beam transport causing the beam to be driven towards the pipe wall. Figure 2 shows results of simulations made with FLUKA of the electron fluence outside the undulator beam pipe generated by 150 MeV electron beam hitting the side walls with a small incidence angle (3.5 deg).

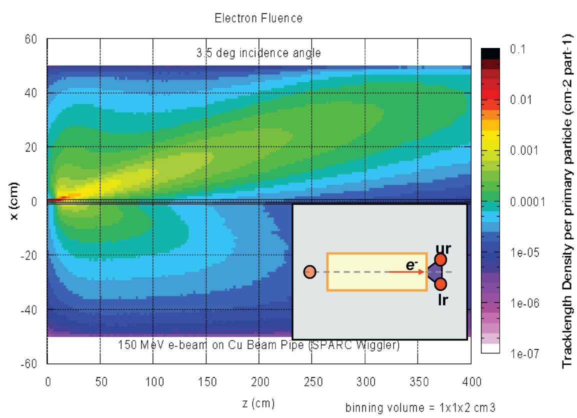

Figure 2: Simulation of the electron distribution outside the beam pipe as consequence of a misaligned beam hitting the pipe wall. The drawing superimposed to the intensity map shows a section of the rectangular beam pipe and the positions of the fibers (orange dots).

The number of Cerenkov photons (N_γ) with λ in the range (λ_1, λ_2) =(400 nm, 500 nm), emitted by the electron with $\beta \geq$ 1/n passing through an optical fiber is, for an estimated mean path s:

$$N_\gamma = s \cdot \frac{dN}{dx} = s \cdot 2\pi\alpha \cdot \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right) \cdot \sin^2\theta_c$$

$$\text{where } \sin^2\theta_c = \left(1 - \frac{1}{(\beta n)^2}\right) \quad \text{and}$$

$$n \cong 1.47 \quad \alpha = 1/137 \quad \beta \geq 1/n \approx 0.68$$

Giving to β sample expected values we obtain:

$$\beta \approx 0.7\,(E_{Kin} \approx 200KeV) \quad \Rightarrow \quad N_\gamma \approx 5ph$$
$$\beta \approx 0.999985\,(E_{Kin} \approx 90MeV) \quad \Rightarrow \quad N_\gamma \approx 48ph$$

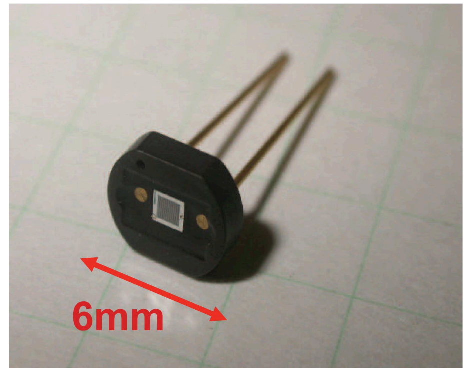

Figure 3: Picture of Hamamatsu MPPC used for the test application.

Nevertheless, considering for the MPPC a mean detection efficiency of 45% and an attenuation of 0.5 dB due to the 20 m of the transmission optical fiber (25dB/km*20 m), the fraction of Cerenkov photons that will produce a signal is about 41% that gives real number of γ detected being:

$$\tilde{N}_\gamma \approx N_\gamma \cdot 0.41 \Rightarrow \left\{ \begin{array}{ll} \beta \approx 0.7 & \tilde{N}_\gamma \approx 2ph \\ \beta \approx 0.999985 & \tilde{N}_\gamma \approx 20ph \end{array} \right.$$

For this application we chosen a step index type optic fibers with 300 μm core diameter and refractive index n=1.47. They are radiation resistant and UV enhanced to match MPPC characteristics.

The MPPC Photon Detector

The MPPC (Multi-Pixel-Photon-Counter) is a relatively new type of photon-counting device made of multiple APD (Avalanche-Photo- Diode) pixels operated in Geiger mode. Each pixel outputs a signal when it detects a photon. The signal output from the MPPC is the total sum of the outputs of all APD pixels.

These devices present a number of convenient features:

- compact size and low-cost;
- room temperature operation;
- insensitive to magnetic field;
- high gain($\approx 10^5$ to 10^6), low bias voltage($\approx$70V);
- high photon detection efficiency (25% to 65% at 400 nm);
- good time resolution: $\approx 10^2$ ps;

The relatively high dark count rate ($\approx 10^2$ kcps/mm^2) is not particularly relevant for our application since the expected signal exceed by far the average noise level.
In order to operate in Geiger mode the MPPC needs to be biased with a DC voltage exceeding the breakdown voltage, typically in the range (-70$\pm$10) V. Since characteristics and performance slightly changes in each device, the bias voltage needs to be adjusted and set independently to achieve a uniform response. Moreover, being the gain of MPPC temperature dependent, it is important to regulate the bias

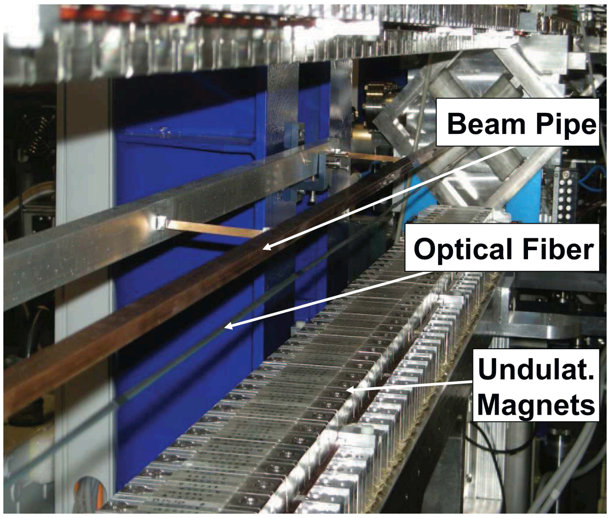

Figure 4: Picture of the fiber for beam loss detection system installed in the first undulator section at SPARC (gap is fully opened for installation).

voltage in order to follow the temperature changes and obtain a stable output. A multichannel DC/DC converter has been designed and constructed for this purpose having the possibility to independently control the output DC voltages by means of corresponding input signals generated by software. This allows to set the proper bias voltage to each MPPC and adjust it, according to the operating temperature, to stabilize the gain. The MPPC analog output signal, after the amplification stage, is then connected to the input of a PXI-5154 from National Instruments for AD conversion. Two of this 2 channels, 2 GS/s, 1GHz bandwidth digitizers are housed in a PXI chassis together with a PXI-8106 controller running the configuration and read-out software.

Tests Results

Figure 4 shows the fiber (one of three foreseen for the final set-up) installed close to the beam pipe in the SPARC undulator (gap is wide open). This initial set-up allowed to perform the measurements that are shown in Fig. 5. The lower graph shows the signal provided by the digitizer (orange solid curve). Typical amplitude is in the order of 1 V. A portion of the curve, highlighted in green, is then expanded in the upper graph showing the instantaneous (green line) and averaged signal (red line). The values in abscissa are quoted in meters according to the evaluation presented in the previous paragraph. More precise calibration are needed to optimize the time to space conversion as well as the position of the abscissa with respect to the undulator position. The test has been performed when the beam transport along the the undulator was not optimized, nevertheless the monitoring of the MPPC signal evidenced the correlation with the changes of beam trajectory and different focusing of the beam envelope.

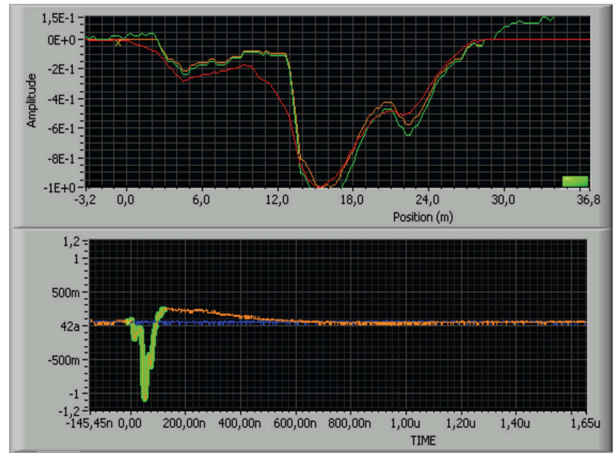

Figure 5: Sample measurement obtained during the tests. The top curves are expanded from the full signal (lower graph) read by digitizer. Green line represents a single event while red curve is obtained by averaging over a number of pulses.

CONCLUSION

The test presented, although they have been performed with a temporary and incomplete set-up, demonstrated the possibility to obtain a BLPM system with the expected performances in terms of sensitivity and time resolution (i.e. longitudinal position). Another major benefit of this design is the simplicity of installation mainly due to the flexibility and reduced size of the fibers that allow to easily adapt their positioning to mechanical constrains in different parts of the accelerator. Future improvements on the way to the final set-up will include the optimization of the electronic parts, in particular the amplification stage, and the development of software tools to facilitate the interpretation of the signals produced by the beam losses.

We acknowledge V. Lollo for his support in designing and constructing the mechanical components of the system.

REFERENCES

[1] M. Ferrario, "Commissioning Results of the SPARC FEL", THOB01, Proceedings of FEL2009, (2009).

[2] D. Alesini et al., Nucl. Instr. & Meth. In Phys. Res. A 507 (2003) 345-349C.

[3] M. Körfer, W. Göttmann, F. Wulf, J. Kuhnhenn, "Beam Loss Position Monitoring using Cerenkov Radiation in Optical Fibers", POW026, Proceedings of DIPAC2005, (2005).