STUDY OF THE RADIATION DAMAGE ON A SCINTILLATING FIBERS BASED BEAM PROFILE MONITOR

E. Rojatti*, G. Calvi, L. Lanzavecchia, A. Parravicini, C. Viviani, CNAO, Pavia, Italy

Abstract

The Scintillating Fibers Harp (SFH) monitors are the beam profile detectors used in the High Energy Beam Transfer (HEBT) lines of the CNAO (Centro Nazionale Adroterapia Oncologica, Italy) machine. The use of scintillating fibers coupled with a high-resolution CCD camera makes the detector of simple architecture and with high performances; on the other hand, fibers radiation damage shall be faced after some years of operation. The damage appears in multiple ways, as efficiency loss in light production, delayed light emission, attenuation length reduction. The work presents measurements and analysis performed to understand the phenomenon, in such a way to deal with it as best as possible. The connection between dose rate, integral dose and damage level is investigated as well as the possible recovery after a period of no irradiation. The influence of the damage effects on profiles reconstruction and beam parameters calculation is studied. Data elaboration is modified in such a way to compensate radiation damage effects and protract the SFH lifetime, before the major intervention of fibers replacement. Methods and results are discussed.

THE SCINTILLATING FIBERS HARP MONITORS

The Scintillating Fibers Harp (SFH) monitors [1] are beam profile detectors installed along the High Energy Beam Transfer (HEBT) lines of the CNAO (Centro Nazionale di Adroterapia Oncologica) accelerator. Their active area is made up of two orthogonal harps of scintillating fibers (for the horizontal and the vertical beam profiles reconstruction) which are guided up to the chip of a CCD camera and mapped for the signal read out. The CCD output signal per fiber (12 bits digital signal) is proportional to the number of particles crossing the fiber, to their energy and depends on the camera configuration parameters. A different correction factor (called "calibration factor") is applied to each fiber at profiles reconstruction in order to equalize the different fibers response, which can vary due to fibers geometry, composition and coupling with camera chip.
The CNAO beam extraction takes 1 to 10 seconds, and thus several beam profile acquisitions, with a good compromise between acquisition rate[1] and integration time, are needed to monitor the beam longitudinal profile during the extraction time and to correctly measure beam parameters (barycenter and width). Fig.1 shows the 3D reconstruction, on the horizontal plane, of one extracted spill.

* elisa.rojatti@cnao.it

[1] The maximum camera acquisition rate is 50 Hz.

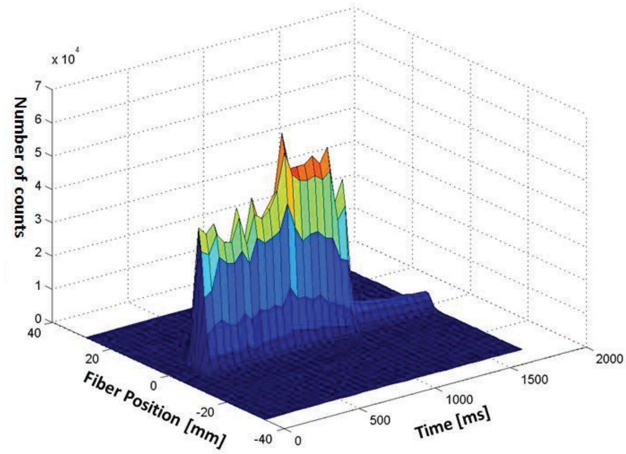

Figure 1: Example of one extracted spill longitudinal profile, reconstructed on the horizontal plane from one SFH measurement.

RADIATION DAMAGE ON SCINTILLATING FIBERS

Several studies concerning the radiation damage on scintillating fibers have been published [2]. The topic is very complex and far from being fully understood. In case of the SFH detectors, the radiation damage appears both as reduction of light production and as reduction of fibers transparency, mainly involving the central region of the SFH sensitive area which is mostly hit by the beam. The first effect emerges clearly taking one image of the beam profile after having enlarged the beam on purpose (Fig.2): the enlarged-beam profile shows a depression indicating a reduced light production efficiency for the most irradiated fibers.

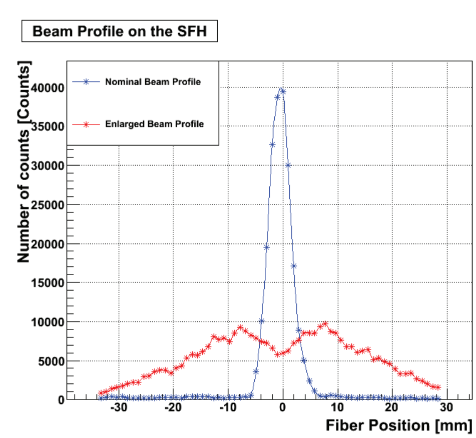

Figure 2: Nominal (blue line) and enlarged (red line) beam profiles on one SFH.

ISBN 978-3-95450-177-9

Both the effects are visible in Fig.3, which represents a 2D reconstruction (for simplicity called "intensity map" from this point on) of the detector response on the horizontal plane (vertically displaced fibers) to the same beam (with fixed parameters) moved up to different positions of the detector sensitive area by means of two scanning magnets[2]. More precisely a Proton beam with 8E+08 particles per spill, 10 mm FWHM and 60 MeV kinetic energy is displaced in 121 different positions uniformly spaced in both the dimensions. The integral signal per spill is computed and plotted in function of the spill barycenter position. The radiation damage appears, on the intensity map, as a depression located at about the center of the horizontal plane (X ≃ 0 mm) in correspondence of the vertical plane positive region (Y > 0 mm). The depression depth increases as the Y-coordinate increases and the deeper point, located at X ≃ 0 mm and Y ≃ 18 mm, corresponds to an efficiency loss of about 40% with respect to the peripheral fibers. This effect results mainly from fibers loss of transparency. Indeed, due to the detector geometry, the light produced on the positive region of the vertical plane has to cross the more damaged area (corresponding to the region which is mainly intercepted by the beam, around the active area center) before being read out by the camera. As a consequence, the detector response loss is observed, although the vertical plane positive region is not directly damaged by radiation.

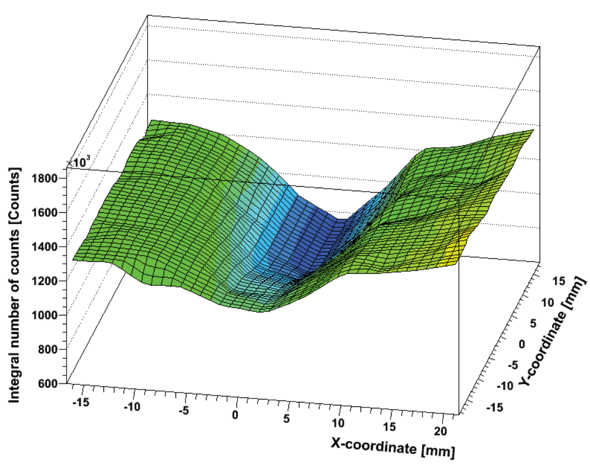

Figure 3: SFH response on the the horizontal plane to a Proton beam with 8E+08 particles per spill, 10 mm FWHM and 60 MeV fixed kinetic energy, moved up to 121 different positions on the detector active area.

Damage Dependence on the Amount of Dose

Measurements illustrated in this section have been aimed at investigating the fibers radiation damage level dependence on the amount of received dose. For this purpose two consecutive intensity maps were performed, then the active area was irradiated with a total dose of about 115 Gy, and after the irradiation two intensity maps more were performed: the first one immediately after the irradiation and the second one after 24 hours of no irradiation, in order to investigate the capability of scintillating fibers recovery. The irradiation was performed by means of 360 consecutive spills made up of 8E+08 Protons per spill, 10 mm FWHM, 60 MeV kinetic energy and beam barycenter fixed on the detector active area center. Fig.4 shows the integral number of counts per spill read out by the camera on one plane during the irradiation.

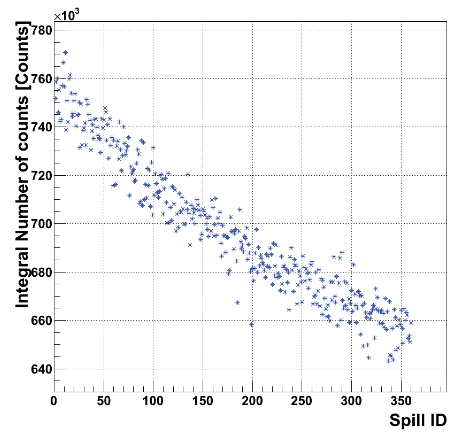

Figure 4: SFH response during the irradiation of the detector active area with 360 consecutive spills with 8E+08 Protons per spill, 10 mm FWHM, 60 MeV energy and fixed barycenter on the detector active area center (115 Gy of total dose delivered).

As one can observe the detector response decreases during the irradiation: the total number of counts is reduced of about 15% after the total amount of dose received (115 Gy). Fig.5 shows data extracted from the intensity maps performed before and after the detector irradiation. In particular it illustrates the detector response on the horizontal plane at fixed coordinate (Y = 0) on the vertical plane.

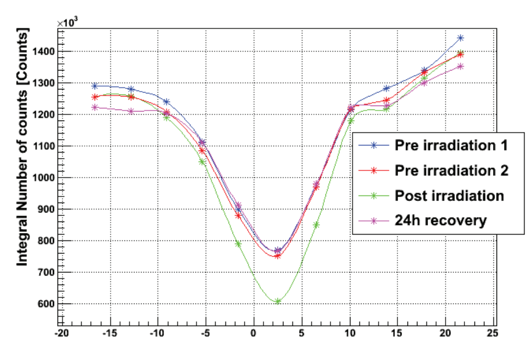

Figure 5: Detector response to 11 consecutive spills with equal features (8E+08 Protons per spill, 10 mm FWHM, 60 MeV kinetic energy) on the horizontal plane at fixed coordinate (Y=0) on the vertical plane, before and after an intense irradiation on the central region.

[2] The scanning magnets, at the end of each HEBT line, are commonly used for the "active scanning" method to "paint" each tumor slice area with the pencil beam.

ISBN 978-3-95450-177-9

The efficiency depression on the horizontal plane is visible both before and after the irradiation, as a permanent and irreversible damage. At the same time, as a consequence of the irradiation, the depression becomes deeper, but this additional efficiency reduction is restored after only 24 hours of no irradiation.
From these preliminary measurements a few conclusions can be drawn:

- The efficiency loss can affect measurements if one SFH is used continuously over a long time. The only procedure at CNAO which implies this kind of use of the SFH detectors is called "steering", and consists in irradiating the SFH active area center with 160 consecutive spills of increasing energies. The increase of beam energy implies a lower energy release in the scintillating fibers and thus a minor damage with respect to the damage level resulting from the irradiation with 160 consecutive spills of fixed energy as reported in Fig.4. For this reason the efficiency loss during the "steering" procedure can be considered negligible for a good profiles reconstruction and beam parameters computation;
- Thanks to the scintillating fibers recovery only the irreversible damage has to be taken into account for data processing and eventually corrected.

DATA CORRECTION

The best solution to face up to SFH scintillating fibers radiation damage would be fibers replacement on all the affected detectors after an arbitrary period depending on the amount of received dose. However this solution implies a major intervention in terms of time and cost, which one would like to postpone as far as possible. Alternatively a data correction software procedure has been implemented to compensate the radiation damage only by analyzing and manipulating the acquired data.
This procedure consists in processing a correction factors map on each detector plane. In order to extract the correction factors one SFH is placed at the isocenter[3] and one intensity map per plane is performed. The beam profiles acquired with different barycenter values on both planes are normalized with respect to the beam intensity. An appropriate fit is applied on each normalized beam profile. By fixing the beam position on one plane, the correction factors per each profile on the opposite plane are obtained, fiber by fiber, as the ratio between the fitting curve and the raw beam profile (not normalized). Although only a few discrete beam barycenter positions can be investigated ecause of obvious machine limitations, the correction factors per fiber on one plane for all the possible beam barycenter positions on the opposite plane can be extracted by means of mathematical extrapolation. The 2D correction factor map thus obtained for each plane is applied to the raw data after a rough beam barycenter estimation. Fig.6 shows the SFH output signal map obtained from the one in Fig.3 after the correction factors application to the acquired data. As one can observe the corrected SFH response to the beam is quite uniform throughout the whole active area.

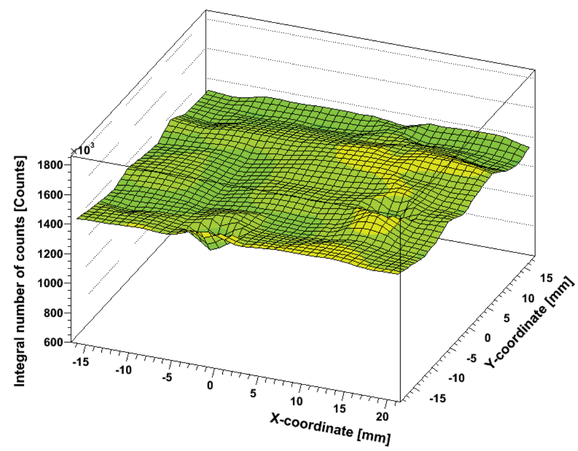

Figure 6: SFH output signal map extracted after correction factors application to the acquired data.

The procedure here above illustrated, although rigorous and reliable, is quite demanding and time consuming from an operational point of view. Indeed it requires to dismantle one SFH from the beam line and to place it at the isocenter. A more empirical procedure has been implemented to quickly and easily correct the effect of the radiation damage on the SFH detectors installed on the beam lines. It consists in scanning the beam in 4 or 5 positions on the horizontal (vertical) plane, keeping the vertical (horizontal) position around the center. The scanning is performed with the nominal or the enlarged beam in such a way to be able to identify the depression position on the beam profile (as illustrated in Fig.2) per each beam position. The response of the central damaged fibers can be corrected by multiplying the fiber output signal for an appropriate factor. This procedure allows to extract only one set of correction factors for the horizontal (vertical) plane which may compensate adequately the radiation damage only in case the beam is quite centered on the detector, that is usually true. This method, although far less rigorous than the one previously described, represents a quick and feasible solution to face the fibers damage, as shown in Fig.7.

Beam Parameters Computation Before and After Data Correction

The main use of the SFH detectors is the beam barycenter determination from reconstructed beam profiles. Fig.8 shows the beam barycenter values computed on both the planes before and after data correction by means of the 2D correction factors map. Values are compared with those acquired by the Dose Delivery (DD) which is a ionization detector installed at the end of each extraction line, in charge of checking the beam position during patients treatment.

[3] The isocenter is the point in which the target to be irradiated shall be positioned. The exact number of delivered particles may be know at the isocenter.

ISBN 978-3-95450-177-9

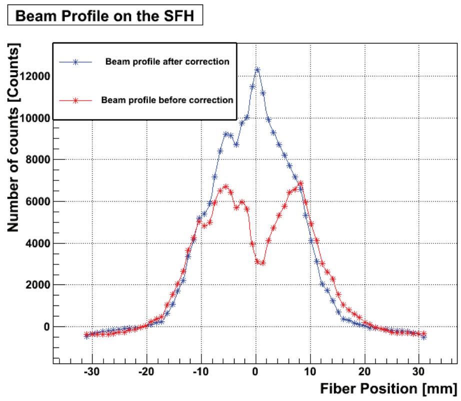

Figure 7: Beam profiles acquired before and after data correction by means of the empirical method.

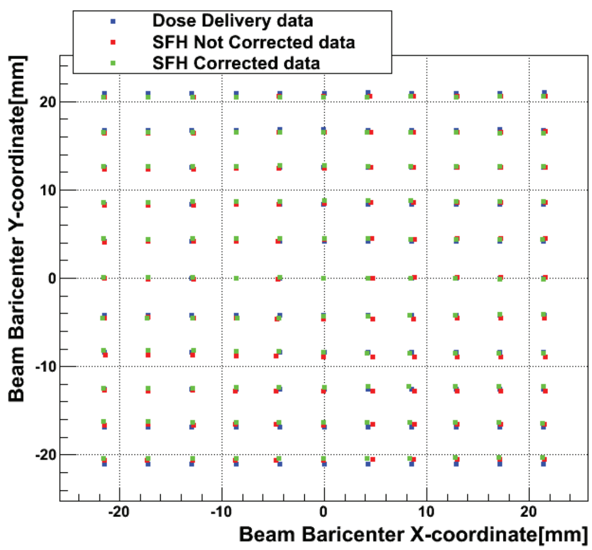

Figure 8: Beam barycenter values on the horizontal and vertical plane extracted from data before and after the correction factors application to the 2D intensity map. Comparison with reference values acquired by the Dose Delivery.

Fig.9 illustrates the difference (for simplicity called "Delta"), on the horizontal plane, between the beam barycenter values coming from the DD acquisition and, respectively, the not corrected and corrected values extracted from the SFH acquisition. Only the two outer fixed positions on the vertical plane (Y = -20 mm and Y = 20 mm) are taken into account here to compute the differences. Data points connected by the solid line are computed before SFH data correction, while those connected by the dashed line are computed after data correction. The systematic error introduced by the radiation damage, calculated as the standard deviation of the sample made up by the Delta values, is ~0.15 mm in case of not corrected data and ~0.07 mm after data correction. This result demonstrates the increase of the measurement accuracy after data correction as a consequence of the goodness of the algorithm used.

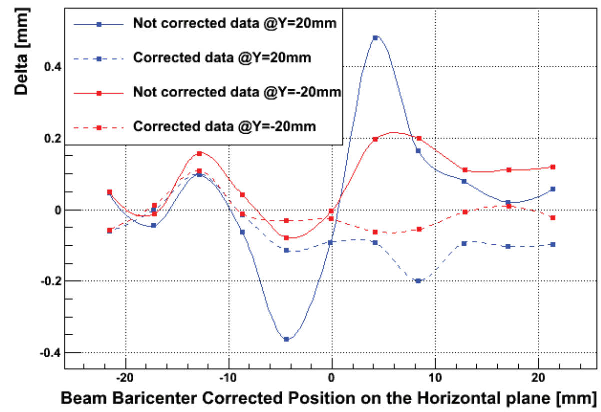

Figure 9: Differences (Delta [mm]) on the horizontal plane between barycenter values coming from the DD acquisition and values coming from one SFH acquisition before (solid line) and after (dashed line) data correction, for the two outer positions on the vertical plane (Y= -20 mm and Y = 20 mm).

CONCLUSION

Several studies on the radiation effects on the SFH scintillating fibers have been performed at CNAO. The main goal has been to find a method to manage the radiation damage effects on the scintillating fibers before the major intervention of fibers replacing. A robust procedure has been implemented: it is based on the determination of a map of correction factors per each plane of one detector. Each factor is computed taking into account the beam position on the active area and is used for off-line data correction. Consecutive tests on profiles reconstruction have demonstrated that thanks to the correction, applied on raw data, the beam barycenter can be measured with a major accuracy than the one obtained without data correction. Although reliable and efficient, this procedure presents a few operational difficulties. Consequently a less robust, but quicker and easier method to compute correction factor, has been implemented. It can be applied on all the SFH detectors. The goal of radiation damage handling and managing has been reached in both cases.

ACKNOWLEDGEMENT

We would like to thank Sir M. Haguenauer and Sir J. Bosser for their technical support during the years of operation of the SFH detectors and for their suggestions in facing up to the radiation damage phenomenon.

REFERENCES

[1] E. Rojatti et al., "Scintillating fibers used as profile monitors for the CNAO HEBT lines", in Proc. of IPAC, Richmond, Virginia, USA (2015).

[2] H.A.Klose et al., "On the measurement of degradation and recovery of scintillating plastic fibers", NIMB, Volume 135, Issues 1-4, (1998).

ISBN 978-3-95450-177-9