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Proton beam characterization in the experimental room of the Trento Proton Therapy facility

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ABSTRACT

As proton therapy is becoming an established treatment methodology for cancer patients, the number of proton centres is gradually growing worldwide. The economical effort for building these facilities is motivated by the clinical aspects, but might be also supported by the potential relevance for the research community. Experiments with high-energy protons are needed not only for medical physics applications, but represent also an essential part of activities dedicated to detector development, space research, radiation hardness tests, as well as of fundamental research in nuclear and particle physics.

Here we present the characterization of the beam line installed in the experimental room of the Trento Proton Therapy Centre (Italy). Measurements of beam spot size and envelope, range verification and proton flux were performed in the energy range between 70 and 228 MeV. Methods for reducing the proton flux from typical treatments values of 10^6–10^9 particles/s down to 10^1–10^5 particles/s were also investigated. These data confirm that a proton beam produced in a clinical centre build by a commercial company can be exploited for a broad spectrum of experimental activities. The results presented here will be used as a reference for future experiments.

1. Introduction

The Trento Proton Therapy facility, which is part of the Trentino Healthcare Agency (Azienda Provinciale per i Servizi Sanitari — APSS, Italy), started clinical operations in October 2014. A cyclotron (IBA, Proteus 235) serves two medical treatment rooms both equipped with rotating gantries, where more than 300 patients have been treated (number updated at March 2017) including paediatric patients [1].

The facility is also equipped with an experimental area where the beam line is split in two branches, both dedicated to a large spectrum of scientific applications, including medical physics, detector testing, radiation hardness measurements, space research and radiobiology. Following an institutional agreement with APSS, the beam is available in the experimental room outside clinical hours and all activities are managed and supervised by the Trento Institute for Fundamental Physics and Applications (TIFPA), which is part of the Italian National Institute for Nuclear Physics (INFN). Access to the research beam line is open to external users, in the framework of scientific collaborations or industrial applications, provided acceptance by the Program Advisory Committee (PAC) organized by TIFPA (http://www.tifpa.infn.it/sc-init/med-tech/p-beam-research/).

In parallel with the development and spread of charged particle therapy, several experimental irradiation rooms with ion beams at therapeutic energies have been setup worldwide in the last decades. The configuration where a pure clinical centre is hosting a research-dedicated beam line is very attractive for several reasons. First, it allows a close connection between experts dedicated to standardize clinical protocols and those involved in cutting-edge research for advancing proton therapy. Moreover, extending the use of ion beams to other

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types of research lower the cost burden of the facility itself. In Europe, experimental rooms are available at the Heavy Ion Therapy centre (HIT) of Heidelberg (Germany) [2], the University Proton Therapy Dresden (UPTD, Germany) [3], the Krakow Proton Therapy facility (IFJ PAN, Krakow, Poland) [4] and the CATANA line at the INFN-LNS (Laboratori Nazionali del Sud, Catania, Italy) [5]. While the first two are part of clinical centres, those located in Krakow and Catania were developed in the context of nuclear physics facilities, and started treating patients with ocular cancers [4,6]. All centres offer a proton beam, while heavier ions are available only at HIT and CATANA. Experimental rooms in other irradiation facilities are currently under commissioning, as in the National Centre for Oncological Hadrontherapy (CNAO, Pavia, Italy) [7]. At the same time, also USA [8] and Japan [9] are heavily investing in these types of combined centres.

The current solutions offered by commercial companies for proton centres setups are attracting a growing interest worldwide. This work shows how these types of facilities can be used beyond their clinical aim, paving the way for a new concept of combined radiotherapy and multidisciplinary research-oriented centre.

In this manuscript, the infrastructure of the experimental area will be shortly described. The procedure and results of the beam characterization of the Trento Proton Therapy centre will be also presented. This includes measurements of beam spot profiles in air, envelope, range verification and flux. These data represent a reference database that can be used by the scientific community for planning experimental activities as well as for future upgrades of the facility.

2. Materials and methods

2.1. Beam production and transport

Proton beam production and transport in the Trento facility are under the responsibility of the IBA company (Ion Beam Applications, Louvain-La-Neuve, Belgium), which produced and installed the related infrastructure. IBA is also responsible for beam operations and has a resident staff in the facility. The cyclotron accelerates the beam up to a maximum energy of 228 MeV. Shortly after the cyclotron exit, a coarse energy selection is carried-out by a rotating degrader of different thicknesses and materials in order to reduce the beam energy down to its minimum value of 70 MeV. This is part of an Energy Selection System (ESS) that allows the fine selection of the desired energy to be transported downstream. Two branches of the main line transport the beam to the gantries, while a third branch connects it to the experimental room. The beam cannot be shared simultaneously among the different rooms and can only be requested alternately in either the gantries or the research area. Different beam intensities can be requested at the exit of the cyclotron, in a range spanning between 1 and 320 nA. The proton beam current will be modulated by a 50% duty-cycle square wave, with a 100 ms period. These current values correspond to the charge collected by an ionization chamber that can be inserted in the beam line shortly after the cyclotron exit and before the ESS. Depending on the requested energy, a significant part of the beam could be lost during the selection process. Therefore, the intensity values reported above provide an indication of the dynamic range available but, because of the variable transport efficiency, do not always correspond to the number of protons delivered in the rooms. While calibrated monitor Ionization Chambers (IC) are installed in the gantries, dedicated measurements have been performed in the experimental room for evaluating proton flux in air at different energies.

A dedicated effort was done to investigate a methodology for delivering low beam intensities (i.e. fluxes in the order of $10^1 - 10^5$ particles/s) that are needed for a broad spectrum of experiments. This requires the accelerator to work in an operational regime that is different from the standard (clinical) one. In fact, such low intensities are obtained by exploiting the so-called accelerator “dark current”, achieved by decreasing the high voltage of the accelerator source below the threshold used for standard operations. In this condition, a significantly smaller fraction of protons is extracted from the cyclotron and the monitoring devices along the beam line are not able to detect the particles. In this regime, a dedicated measurement system is needed for quantifying the proton flux (see Detectors Section below for details) within a range of 10^1–10^5 particles per second. When operating in this condition, the proton beam flux can be adjusted by fine-tuning the accelerator radio frequency voltage. This process can be done online by the operators, and usually only few minutes are required to find the optimal settings for the desired rate.

2.2. The experimental area

The experimental area consists of two different spaces: a multi-functional preparation room and the irradiation cave. The former is equipped with a control station for monitoring the activities inside the cave via remote control cameras and alignment lasers. Additionally, a patch panel equipped with 32 BNC, 12 SHV (max voltage 5 kV), 8 D-SUB and 8 Ethernet (1 Gb) cables connects the preparation room with the irradiation cave allowing the electronics installation for the data acquisition inside or outside the cave, according to the specific needs of the experiment. In case additional cables are needed, the path between the preparation room and the irradiation cave measures about 25 m.

The main beam line is split into two additional sub-branches at 0° and 30° with respect to its initial direction by a dipole magnet (Fig. 1(A)). This allows the simultaneous setup of two different experiments if necessary but the beam cannot be transported along the two branches at the same time. We refer to the 0° and to the 30° lines as the “Biology” and “Physics” beam line, respectively (Fig. 1(B)), since they are intended for different purposes and thus will be implemented with different hardware. In particular, the Biology line will require a broad homogeneous beam, able to homogeneously irradiate biological samples, while the Physics will mostly use a narrow spot. Results of Physics beam line characterization are presented in this work.

A fixed pencil beam is available at the Physics line with energies between 70 and 228 MeV selectable with the ESS. Further energy reduction is possible inside the cave using dedicated in-air degraders. Protons exit the beam pipe by traversing a 70 μm thickness titanium layer. Lasers are available for target alignment at 1.25 m from the exit window, which we define as “Isocenter” in analogy to the treatment rooms. Tables with adjustable heights are used for target positioning.

2.3. Detectors

A short description of the detectors used in this study and the corresponding measurements for which they were employed is reported below. Dedicated references are provided for additional information on the specific detector.

- Lynx (IBA-Dosimetry): scintillating screen coupled with charge-coupled device (CCD) cameras, sensitive area 30 cm × 30 cm, resolution of 0.5 mm in both X–Y plane, used for in air spot profile measurements [10].
- Giraffe (IBA-Dosimetry): multilayer IC, consisting of a stack of 180 independent parallel-plate IC with a 2 mm gap from each other (the gap also defines the raw data resolution), sensitive area of 10 cm diameter, used for range measurements [11].
- Mini-Q (DE.TEC.TOR): stack of coupled strips and integral IC for measuring profiles on the plane perpendicular to the beam direction, sensitive area of 14.7 cm × 14.7 cm; it was also used to quantify the proton flux after an appropriate calibration [12].
- Faraday Cup: in-house built basic configuration consisting of a shielded and insulated 6.35 cm thick Brass block, coupled with an electrometer for charge measurements (so-called “poor man Faraday Cup” [13]), adopted for cross calibration of the Mini-Q detector.