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Design study of the ESS-Bilbao 50 MeV proton beam line for radiobiological studies

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ABSTRACT

The ESS-Bilbao proton accelerator facility has been designed fulfilling the European Spallation Source (ESS) specifications to serve as the Spanish contribution to the ESS construction. Furthermore, several applications of the ESS-Bilbao proton beam are being considered in order to contribute to the knowledge in the field of radiobiology, materials and aerospace components. Understanding of the interaction of radiation with biological systems is of vital importance as it affects important applications such as cancer treatment with ion beam therapy among others. ESS-Bilbao plans to house a facility exclusively dedicated to radiobiological experiments with protons up to 50 MeV. Beam line design, optimisation and initial calculations of flux densities and absorbed doses were undertaken using the Monte Carlo simulation package FLUKA. A proton beam with a flux density of about 10^6 protons/cm^2 s reaches the water sample with a flat lateral distribution of the dose. The absorbed dose at the pristine Bragg peak calculated with FLUKA is 2.4 ± 0.1 Gy in 1 min of irradiation time. This value agrees with the clinically meaningful dose rates, i.e. around 2 Gy/min, used in hadrontherapy. Optimisation and validation studies in the ESS-Bilbao line for radiobiological experiments are detailed in this article.

1. Introduction

Humans are exposed both to natural and artificial ionising radiation which makes the study of its impact on human health of vital importance. Radiobiology studies the biological effects of ionising radiation on living tissues and organisms. The applications of the radiobiological studies are various, from space mission planning (radiation effects in humans and materials) to cancer treatment. Hadrontherapy is an advanced radiation oncology technique that uses protons, heavy ions and neutrons to kill tumour cells, although neutrons are very rarely used for therapy nowadays due to their unfavourable dose deposition pattern. However, increasing numbers of patients suffering from cancer are treated with protons or heavy ions due to their greater specificity and higher biological effectiveness compared to treatment with photons [1–3]. Hadrontherapy is especially recommended in cases where the tumour is close to an organ at risk or in paediatrics. The intrinsic precision of the hadrons to deliver the dose in the tumour cells (the Bragg Peak) is the main advantage of the hadrontherapy technique respect to the conventional photon and electron cancer therapies. Therefore, ion beam therapy offers an excellent dosage localisation for tumour treatment while minimises radiation-associated damage in normal tissue. Moreover, the exposure to highly ionising radiation should be considered when planning manned space missions, not only due to the risk of cancer caused by radiation exposure but also to the chance of damage to the components [4].

The main parameters of the proton accelerator facility conceived to serve as the Spanish contribution to the European Spallation Source (ESS) [5] construction, named as ESS-Bilbao [6], are summarised in Table 1. This proton beam could be used to conduct experiments in the field of radiobiology, materials and aerospace components [7–9]. The Protons for Biology (P4B) laboratory is the facility envisaged to house radiobiological experiments, using small animals, tissue or cells. Although similar facilities already exist or are planned across Europe, the P4B laboratory would be the first of its kind to be built in Spain. This facility would therefore be very beneficial not only for international scientists but also essential for the increasingly Spanish scientific community working in the field of radiobiology.

In ESS-Bilbao, high current intensities are considered to fulfil ESS specifications. However, before getting to the P4B laboratory, these current intensities will be reduced from the design parameters to those required for radiobiological applications, i.e. current

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Table 1
Main parameters of the ESS-Bilbao accelerator.

Parameter	Value
Energy	50 MeV
Peak current	75 mA
Repetition rate	20 Hz
Pulse length	1.5 ms
Duty factor	3%
Average current	2.25 mA
RF frequency	352.2 MHz

intensities in the range of nA, which corresponds to clinically meaningful dose rates, of about 2 Gy/min [10]. Higher currents than nA are not safe in therapy due to the minimum feedback time required for machine control [10]. Different methods to decrease current intensities such as the use of beam splitters, fast kickers or collimators are being considered.

This article describes the process of designing a beamline for radiobiological studies. The process starts with beamline optimisation using FLUKA simulation package [11,12]. Moreover, this package has also been used to undertake simulations of the proton, neutron and photon flux densities in the room as well as the absorbed dose in the sample. FLUKA is a tool for calculation of particle transport and interactions with matter.

2. Beam line design

The first step in the beam line design involves defining the specifications for biological experiments. Then, the elements required to adjust the beam to the appropriate parameters are chosen and placed along the line. Finally, optimisation of the elements sizes and positions is carried out.

2.1. Radiobiological beam line specifications

Beam line design starts with a thorough review of the specifications for biological studies. For this purpose, the following parameters were considered: particle type, particle kinetic energy, beam current, dose required in the sample and sample size. These specifications must be met throughout the beamline design.

The particle type and kinetic energy are fixed by the parameters of the ESS-Bilbao accelerator. The ion source produces only protons which will be accelerated up to 50 MeV at the exit of the last accelerating cavity and deliver into the P4B room. Consequently, the beam used to perform the simulations is a 50 MeV proton beam with Gaussian dimensions, divergence and momentum. The proton beam has 1% FWHM momentum spread and 5° divergence. The initial radius of the beam is 6 mm (FWHM of 4.71 mm) while the current intensity is set to be 1 nA (6.242×10^9 protons/s). This beam is used in the simulation of 1 min irradiation of a water sample of dimensions 5 cm (height) × 5 cm (width) × 2 cm (depth).

As mentioned before, ESS-Bilbao radiobiological line must deliver an acceptable dose rate, i.e. around 2 Gy/min [10], in order to reproduce proton therapy conditions. Hence, the initial beam parameters will be adjusted using passive elements appropriately placed along the beam line.

2.2. Beam line layout

Once the initial and final parameters have been defined, elements of the line have to be set. The beam window is the interface between vacuum and air. It should be thin enough to minimise beam losses and firm enough to stand the air pressure. A double-scattering method, using a central beam stopper, is implemented in the layout in order to obtain a broader uniform dose distribution at the isocenter. Additionally, an energy degrader and a beam profile monitor are also placed along the line for energy reduction and beam monitoring respectively. Since the proton beam will be scattered to a greater or lesser extend due to elements in its path, a collimator will be placed after each component of the beam line. In order to start with a simplified idea, three different units were arranged in successive order in the beam line:

- Unit 1: beam stopper + second scattering foil + collimator;
- Unit 2: energy degraders + collimator;
- Unit 3: monitor chambers + collimator,

a schematic representation of this idea can be seen in Fig. 1.

The beam line includes a kapton beam window to allow passage of the beam from vacuum to air. Moreover, a two scattering foils system with a beam stopper is implemented in the design. The scattering foils are made of tantalum and their function is to spread out the beam. The first scattering foil is placed in vacuum, right before the window. The second scattering foil is placed after the beam window and preceded by a beam stopper based on a cylinder made of brass with dimensions 6 mm (high) × 5 mm (radius). These dimensions were defined using the SRIM-TRIM [13] ion stopping and range tables, where the maximum projected range of 50 MeV protons in brass is established to be 4.23 mm. Consequently, the height of the stopper was decided to be 6 mm in order to assure the total absorption of the protons in the central part of the beam. The optimal radius was determined through the calculation of the lateral distribution of the dose in the sample, presented later in Fig. 9. The radius was modified until the calculated lateral distribution was observed to be flat enough to assure an uniform dose distribution along the direction of beam propagation in the sample. A general idea of the performance of the double-scattering method is presented in Fig. 2.

Energy degraders are required in passive beam lines in order to have a wide range of energies for different experiments. The ultimate idea is to place a device in the line capable of moving in-and-out a number of energy degraders to adjust the energy of

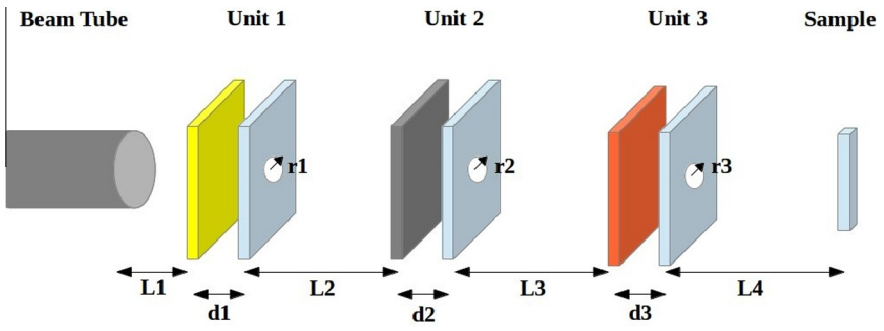

Fig. 1. Schematic representation of the ESS-Bilbao 50 MeV proton beam line for radiobiological studies prior to spacing and apertures optimisation.