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Design of the prototype of a beam transport line for handling and selection of low energy laser-driven beams

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ABSTRACT

A first prototype of transport beam-line for laser-driven ion beams to be used for the handling of particles accelerated by high-power laser interacting with solid targets has been realized at INFN. The goal is the production of a controlled and stable beam in terms of energy and angular spread. The beam-line consists of two elements: an Energy Selection System (ESS), already realized and characterized with both conventional and laser-accelerated beams, and a Permanent Magnet Quadrupole system (PMQ) designed, in collaboration with SIGMAPHI (Fr), to improve the ESS performances. In this work a description of the ESS system and some results of its characterization with conventional beams are reported, in order to provide a complete explanation of the acceptance calculation. Then, the matching with the PMQ system is presented and, finally, the results of preliminary simulations with a realistic laser-driven energy spectrum are discussed demonstrating the possibility to provide a good quality beam downstream the systems.

1. Introduction

The charged particle acceleration is one of the main applications of high power lasers, in fact high current multi-MeV proton bunches are produced from ultra-intense ($>10^{18}$ W/cm^2) short-pulse (30 fs – 10 ps) lasers interacting with thin solid density foils [1,2]. Several acceleration regimes are discussed in literature even if most of the experiments expoilt the Target Normal Sheath Acceleration (TNSA) mechanism [3] showing proton energies up to some tens of MeV with good characteristics, in terms of maximum cutoff energy and particles abundance. However, the experimental results in this regime demonstrate an exponentially decaying spectrum (energy spread up to 100%) and a wide angular divergence of laser generated protons. This would require the development of a beam-line whose elements can collect most of the particles, correct their divergence and inject them in a selection system to make such beams suitable to different applications, specially medical ones. An Energy Selection System (ESS), based on four permanent magnet dipoles with alternating fields, have been already realized at INFN-LNS (Istituto di Fisica Nucleare – Laboratori Nazionali del Sud, Italy) and deeply described [4–6]. It can select particle beams with kinetic energy up to 60 MeV protons providing beams with a spread of a few MeVs. The selection and transmission efficiency of the ESS are strongly dependent on the angular divergence of the entering beam. Simulations and experimental results show that the transmission efficiency is below 1% and, until the beam has any directionality, the selected spectrum is much broader than the nominal resolution of the system. In order to improve the ESS performances and to have a stable and controllable beam as output, a Permanent Magnet Quadrupole system (PMQ) has been designed and realized at INFN-LNS [7–9], in collaboration with SIGMAPHI [10], and tested at LOA facility in Paris showing a good and predictable control of the beam, if the laser-produced protons are properly characterized [11]. PMQs lenses have the advantage to be relatively compact with an extremely high field gradient, around 100 T/m, within a reasonable big bore of a few centimeters. These are the main reasons of the increasing interest in the application of PMQs for the beam handling in laser based particles accelerators [12–14]. The realized system is made of two 80 mm long PMQs and two of 40 mm long PMQs. The net bore of 20 mm diameter and a gradient of about 100 T/m. The system has been designed to improve the transmission and selection efficiency of the magnetic Energy Selection System. In this work, we present the results of the ESS calibration with conventional monochromatic proton beams and the results are compared with an analytical model developed to simplify the

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energy selector in the simulations performed to setup the PMQs optics. Results for the whole beam-line simulations are also discussed showing the possibility to match the two system in order to maximize the selection and transmission efficiency producing, as output, a controllable beam.

2. Energy Selection System characterization

The ESS system, developed at INFN-LNS, is based on four permanent magnet dipoles with alternating fields, similar to a bunch compressor. Each dipole has a gap of 10 mm and it is 88 mm long, the drift spaces between the central and external dipoles are $d = 85$ mm long and the central dipoles are separated by a $d_s = 10$ mm drift. In this drift, particles with different energies are fully dispersed on the radial plane and a moving slit is used to select ions within a certain energy range. Fig. 1 shows a scheme of the ESS and the necessary parameters for the calculation of the path length of a proton inside the magnetic chicane, the calibration equation and the acceptance of the system. The treatment follows the bunch compressor study proposed by Castro [15]. In the next subsections the derivation of the calibration equation of the ESS is explained and comparison with experimental results is shown, then the ESS acceptance is calculated.

2.1. ESS calibration

The transverse displacement of the particle orbit in the central drift of the ESS, namely at the selection point, can be calculated using the main trajectory parameters shown in Fig. 1 which are the bending radius $r = p/Be$ and the bending angle $\alpha = \arcsin(l_{eff}/r)$, being p and e the momentum and charge of the particle, B and l_{eff} the magnetic field and the effective length of a dipole. The horizontal displacement of the trajectory inside a dipole, x_{arc} is:

$$x_{\rm arc} = r(1 - \cos\alpha) = l_{\rm eff}\frac{1 - \cos\alpha}{\sin\alpha} \quad (1)$$

The horizontal displacement x_d in the drift d between two dipoles is a straight line and depends on the ratio between the drift length d and the tangent of the bending angle α.

Combining Eq. (1) with the expression of x_d, and considering that the four dipoles have slightly different fields B, the horizontal displacement at the selection point can be expressed as follows, where the subscripts are referred to the dipole number:

$$\Delta x = \sum_{i=1}^{2} l_{\rm eff_i}\frac{1 - \cos\alpha_i}{\sin\alpha_i} + d\,\tan\alpha_1 \quad (2)$$

The bending radius and angle depend on the particle momentum, hence on the energy, and the calibration equation of the ESS, in which the kinetic energy can be expressed as a function of the displacement, is :

$$T = \sqrt{\left(\frac{q\,c(\Delta x - {\rm d}\tan\alpha_2)}{\frac{1-\cos\alpha_1}{B_1} + \frac{1-\cos\alpha_2}{B_2}}\right)^2 + M_0^2c^4} - E_0 \quad (3)$$

where q, M_0 and E_0 are the charge, mass and the particle rest energy and c is the speed of light.

Eq. (3) has been experimentally verified during the calibration performed with the low energy proton beams produced at the INFN-LNL with the CN Van De Graaff accelerator. Experimental data and fit with Eq. (3) are shown in Fig. 2, lower panel. Data have been acquired using a small collimator (100 μm diameter) fixed at the entrance of the selector and a GafChromic film set at the selection point. The film has been exposed to the beam for 10 min. All the distances have been measured with respect to the dipole edge, pointed as reference edge in Fig. 2, upper panel, and then rescaled to the beam axis position. Fig. 3 is a magnification of the lower panel of Fig. 2, where the experimental points are represented with error bars.

The derivative of Eq. (3), $(dT/d(\Delta x))$, times the slit aperture size, gives the ESS energy resolution, namely the precision of the device to select a certain energy. Fig. 4 shows the ESS energy resolution for a slit aperture size on 1 mm, as actually used in the system. The energy range expected as ESS output can be estimated from this curve, for a beam with no angular dispersion injected in the chicane.

2.2. ESS acceptance

The ESS acceptance, crucial for the matching with the PMQs, can be calculated starting from simple geometric consideration and using the results from a back-trace of the particles in the magnetic chicane. The procedure is here reported.

The path length of a particle in the selection system can be calculated using the main trajectory parameters r and α. In fact, the product $r\alpha$ gives the length of the trajectory inside the dipole effective length, l_{arc}, while the path length in the drift d between the dipoles D_1 and D_2, namely l_{d1}, or D_4 and D_3, namely l_{d2}, are given by the ratio between the drift length d and the cosine of the bending angle α.

The ESS system has slightly different magnetic fields for each dipole, hence, the full path length is given by the sum of four terms, one per dipole, expressing the path length l_{arc}, and two terms expressing the path length l_{di} in the drifts. Moreover, the drift d_s has to be considered. The path length equations can be written as follows (the subscript i is referred to the dipole

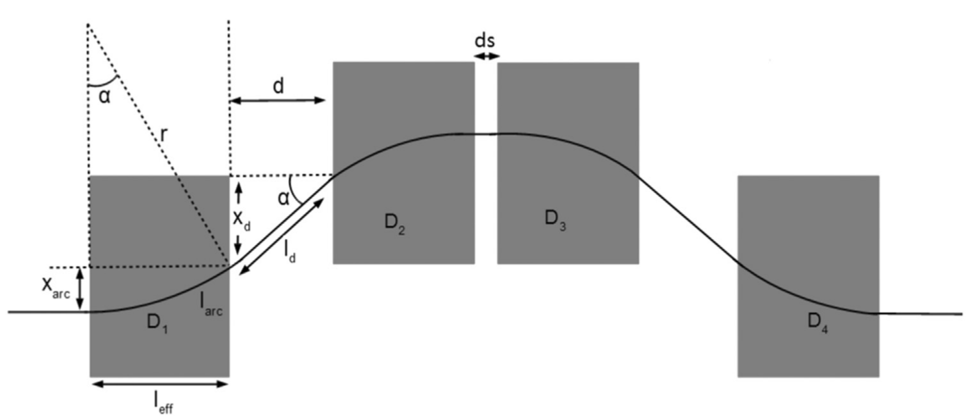

Fig. 1. Scheme of the Energy Selection System (not in scale). Parameters are explained in the text.