TECHNICAL REPORT

Characterization of the ELIMED Permanent Magnets Quadrupole system prototype with laser-driven proton beams

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Abstract: Laser-based accelerators are gaining interest in recent years as an alternative to conventional machines [1]. In the actual ion acceleration scheme, energy and angular spread of the laser-driven beams are the main limiting factors for beam applications and different solutions for dedicated beam-transport lines have been proposed [2, 3]. In this context a system of Permanent Magnet Quadrupoles (PMQs) has been realized [4] by INFN-LNS (Laboratori Nazionali del Sud of the Instituto Nazionale di Fisica Nucleare) researchers, in collaboration with SIGMAPHI company in France, to be used as a collection and pre-selection system for laser driven proton beams. This system is meant to be a prototype to a more performing one [5] to be installed at ELI-Beamlines for the collection of ions. The final system is designed for protons and carbons up to 60 MeV/u. In order to validate the design and the performances of this large bore, compact, high gradient magnetic system prototype an experimental campaign have been carried out, in collaboration with the group of the SAPHIR experimental facility at LOA (Laboratoire d'Optique Appliquée) in Paris using a 200 TW Ti:Sapphire laser system. During this campaign a deep study of the quadrupole system optics has been performed, comparing the results with the simulation codes used to determine the

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setup of the PMQ system and to track protons with realistic TNSA-like divergence and spectrum. Experimental and simulation results are good agreement, demonstrating the possibility to have a good control on the magnet optics. The procedure used during the experimental campaign and the most relevant results are reported here.

KEYWORDS: Acceleration cavities and magnets superconducting (high-temperature superconductor; radiation hardened magnets; normal-conducting; permanent magnet devices; wigglers and undulators); Beam dynamics; Accelerator modelling and simulations (multi-particle dynamics; single-particle dynamics); Beam Optics

Contents

1 Introduction

The production of energetic particle beams from ultra-high intensity ($> 10^{18}$ W/cm^2) laser-matter interaction has been throughly investigated in the past few years [1, 6]. Technologies for a practical use of laser-generated proton/ion beams are currently under study, to enable precise control over the unique features of laser-generated particle beams. Although, the most reliable acceleration scheme remains the Target Normal Sheath Acceleration (TNSA) mechanism [7]. Proton bunches from TNSA are characterized with 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 for different applications, specially medical ones. Permanent Magnet Quadrupole (PMQ) lenses have the advantage to be relatively compact with an extremely high field gradient within a reasonable big bore. These are the main reasons of the increasing interest in the application of PMQs for beam handling in laser based particle accelerators [8–10]. A PMQ system have been designed and realized [4, 11, 12] by INFN-LNS researchers, in collaboration with SIGMAPHI. It consist of two PMQs of 80 mm length and two PMQs of 40 mm with a net bore of 20 mm and a gradient of about 100 T/m. The PMQ system has been characterized in collaboration with the group of the SAPHIR experimental facility at LOA (Laboratoire d'Optique Appliquée) in Paris using a 200 TW Ti:Sapphire laser system. The laser is based on Chirped Pulse Amplification (CPA), the central wavelength is of about 800 nm. It delivers pulses with 3 J of energy on target and duration of 25 fs at a repetition rate fo 5 Hz. During the experimental campaign the laser pulse was focused with a 30° off-axis parabolic mirror having an f-number of $f/1.8$. The focal spot size of 10 μm diameter at $1/e^2$ concentrate the laser beam at an intensity of $I_0 = 10^{20}$ W cm^{-2} and with a 45° incidence angle onto a 5 μm thick titanium foil. Protons are accelerated in the TNSA regime and they come from contaminants present on the target surface [13]. The experiment have been performed in single shot mode, but depending on the diagnostic used, mainly GafChromic films, one or several targets have been fired upon using the same PMQs setup in order to accumulate the recorded signal. In this work the results of the experimental characterization of the system are reported, starting from a precise description of the proton source. This was done to compare and validate the simulation codes used for the setup of the PMQ system and for the particle tracking with realistic TNSA-like proton. The agreement between experimental data and simulation is good, showing the possibility to properly adjust the magnetics lense setup and, hence, to have a good control on the particles transport. This aspect is crucial because the PMQ system have been realized not only to focus and preselect particles but also to improve the transmission and selection efficiency of the magnetic Energy Selection System already realized and deeply described in [14–16] and a proper matching between the two systems can be performed if the properties of the PMQ system are accurately known.

2 Experimental characterization of the PMQs system

The PMQ system is made of four Permanent Magnet Quadrupoles, based on a hybrid Halbach design [4, 17], with a 20 mm net bore diameter. Two quadrupoles are 80 mm long with a gradient of 103 T/m and the other two are 40 mm long with a gradient of 98 T/m. The magnetic features of the system have been deeply studied and described in [4], where are also reported the field quality, harmonic component and the related errors study. The PMQs are provided with carriages, guides and step motors remotely controlled, see figure 1, in order to change the relative distances between magnets and tune the system for the handling of different energies. The system modularity allows, using different setups, to focus protons in a relative big energy range from a few MeV up to 20 MeV.

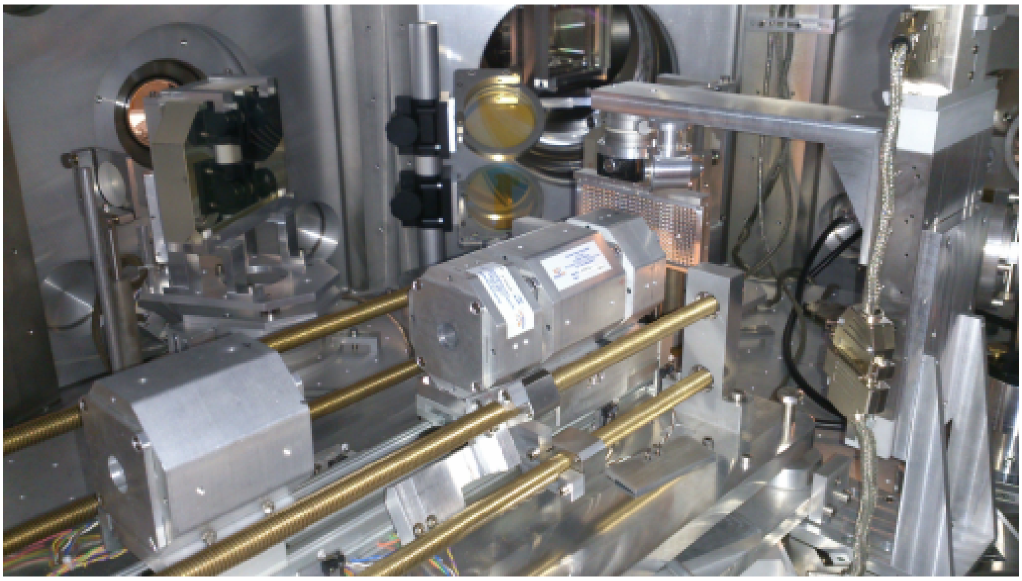


Figure 1. Complete PMQ system with mechanics set inside the SAPHIR interaction chamber. At the input, on the right side, is the target grid.

In the following subsections, two different PMQ setups are discussed. The first has been chosen in order to focus the 8 MeV energy component in one point at 440 mm downstream from the source, and the effects of the magnetic lenses on several energy components has been studied using a stack of GafChromic film. The second setup has been chosen in order to have a beam with a size of about 10 mm diameter and uniform profile to be used for fluence measurements. In this configuration the quadrupole optics has also been investigated. The method used to study and validate the experimental results involves comparison with simulations obtained with two codes: TraceWin [18], used to define the system setup for the reference energy component transport, and Simion [19], in which the resulting setup of TraceWin is used to transport the realistic TNSA beam. For the sake of precision, in both codes the quadrupole field maps are introduced (calculated with COMSOL [20] and validated by magnetic measurement [4]). Moreover, in order to simulate a beam as close as possible to the real beam produced at SAPHIR, the first step of the experimental campaign has been the proton beam analysis, in terms of energy spectrum and angular aperture. This first step is described in the next subsection, then the two different configurations are studied.

2.1 Ion source characterization

The diagnostic systems used for ion source characterization are a Thomson Parabola Spectrometer (TPS) and GafChromic HDV2 films. Using both diagnostics it is possible to retrieve proton spectrum and angular distribution. TPS are well established diagnostic devices for laser driven ion beams [21–26] as it can give on-line shot-to-shot information on charge-to-mass ratio and charge-to-momentum ratio. The TPS used during the experiment and developed by the SAPHIR team, was set 960 mm downstream the target, in the forward direction.

GafChromic HD-V2 films are used to record the transverse beam profile thanks to the particle energy deposition on the active layer of the detector. A stack of 8 layers of GafChromic HDV2 films has been set 40 mm downstream the laser-target interaction point and the spatial profile of the accelerated particles on the transverse plane has been recorded firing 25 shots in order to accumulate energy deposition in the layers.

Combining data of TPS and GafChromic films, the spectrum of the protons and their angular divergence are calculated. The spectrum can be described as an exponential function [27]:

$$N(E) = A\exp(-0.15\mathrm{E}) \tag{2.1}$$

being A a normalization factor related to the total number of particles (about 5×10^9 proton per pulse as calculated from the energy deposited on each GafChromic). The cutoff of the proton energy has been calculated to be at about 8.9 MeV. Assuming a point-like source term, the half angular aperture, in *mrad*, has been modelled using second order functions, 2.2, that relate the beam angular aperture θ on both x and y planes, with the proton energy E.

$$\begin{aligned} \theta_y &= -3.5E^2 - 4.6E + 3.2e^2 \\ \theta_x &= -4.1E^2 - 5.4E + 2.8e^2 \,. \end{aligned} \tag{2.2}$$

These data provide a precise characterization of the produced proton beams. In fact, each energy component is well defined and the previous functions allow to calculate emittance and twiss parameters, necessary to produce the monochromatic reference beam in the TraceWin code used to define the PMQ system setup. The functions in formulas (2.1), (2.2) are directly used in Simion to reproduce the realistic TNSA beam. This two steps are fundamental for the proposed optics study.

2.2 PMQ setup for focusing 8 MeV protons

The PMQ system has been optimized, using TraceWin code, in order to focus 8 MeV protons 440 mm behind the laser-target interaction point (details on the relative distance among the elements of the beam-line are in figure 2). A stack of six GafChromic films HD-810 has been set at the expected focal point. These films have a low sensitivity, in fact 25 laser shots have been fired in order to accumulate enough energy deposition to have visible traces. On the other hand, they are thin enough to guarantee a good energy resolution when they are used in a stack. The stack has been shielded with an aluminum foil 130 μm thick for filtering heavy ions and protons with energy lower than 3.98 MeV.

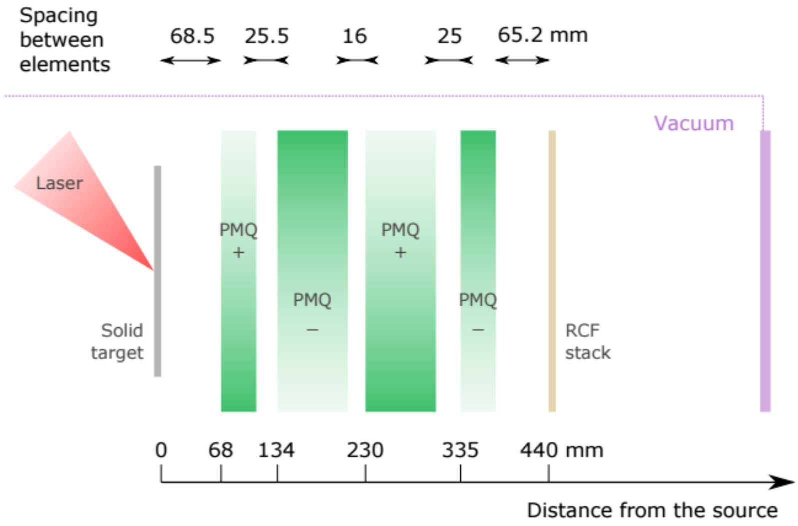


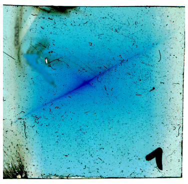
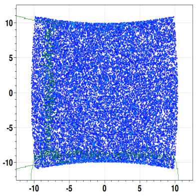
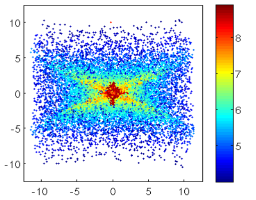
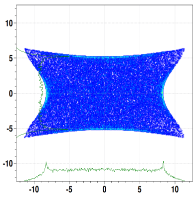
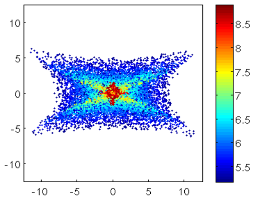
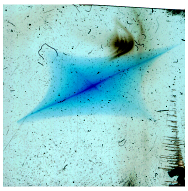
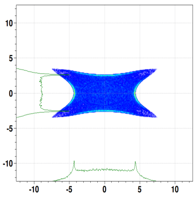
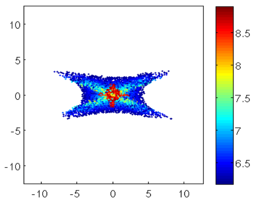
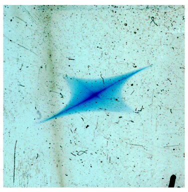
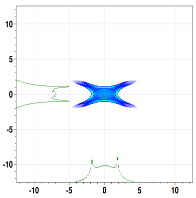
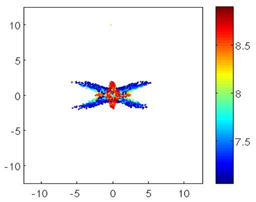
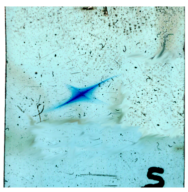
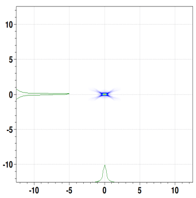
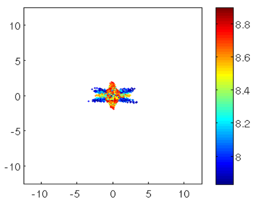
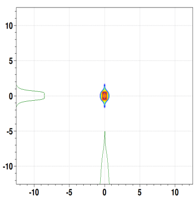
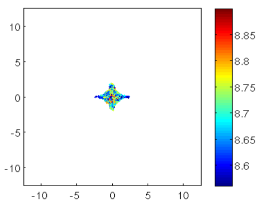
Figure 2. PMQs setup for 8 MeV proton beam focusing.

For each layer, the lower energy cutoffs for protons, calculated using SRIM [28], are reported in the first column of table 1. The table also reports the experimental results and comparison with simulations. GafChromic films and simulation plots have the same scale and units are in *mm*.

The proper characterization of the proton source, both in terms of energy and spatial distribution, and hence emittance, allows to simulate with good precision the system and the results in table 1 demonstrate the possibility to have a very precise control on the beam optics. Small discrepancies in shape and dimensions can be related to different factors discussed below. The experimental beam profile in the first two films is bigger than simulations and it has the same shape as the PMQ bore. In these films, the cross-like trace, due to the high energy components, is well visible and in agreement with polychromatic beam simulations. The films in rows three, four and five have slightly bigger beam spot size. The differences are due to the fact that several shots have been accumulated on the films and the initial particle distribution has a low and unpredictable reproducibility. This determines the bigger halo in the experimental data, in fact, what is recorded on the films is an average behavior of several different beams.

In row six, the low amount of particle interacting with the film leads to a low energy deposition and the apparently smaller dimensions of the beam spot size than in the Simion simulation. Moreover, 25 different bunches have been fired on the stack, and shot-to-shot fluctuation of the laser can affect the spectrum cutoff position shifting it to slightly lower energies, hence reducing the amount of particles interacting with the last two films. The PMQ field quality [4] can also be responsible for the differences in beam shape and dimensions. The cross-like shape, which reflect the magnetic

Table 1. Comparison of experimental results at the focus point with the PMQ system for a TNSA proton beam (2nd column) and simulations with monochromatic beams (3rd column, colors represent the particle density) and with a realistic beam (4th column, color scale is energy in MeV). The three columns show the transverse beam profile 440 mm behind the source for different energies (units in mm). The lower energy cutoff of the H^+ beam reaching the considered layer is specified in first column. The cutoff energy value is used for monochromatic TraceWin simulations.

Low Energy cutoff	GafChromic	Tracewin simulation	Simion simulation
4 MeV			
5.18 MeV			
6.17 MeV			
7.05 MeV			
7.83 MeV			
8.56 MeV			

field of the quadrupoles, is due to the fact that the amount of particles moving outside the good field region of the PMQs (which has 6 mm radius) is significant. Also non-linear effects on the beam optics cannot be neglected, but considering the fluctuation in the source, cannot be reproduced with higher precision. They are anyway reproduced with simulations and can be easily predicted and corrected using collimators, if required.

2.3 PMQs setup for the optics study and fluence measurements

The second setup has been chosen in order to have a wide and almost uniform proton beam with a central energy of 6.5 MeV transmitted outside the interaction chamber with the goal to perform an in-air beam characterization. For this setup, an accurate optics study have been carried out, recording the beam spot at several positions along the PMQ system. This central energy have been chosen because the amount of particles after quadrupoles should be reasonably high to perform fluence estimations. The PMQ setup is detailed in figure 3. Figure 4 shows the reference beam envelope obtained with the TraceWin Multiparticle calculation. GafChromic EBT3 films are used in stacks of two layers, shielded with a 26 μm thick aluminum layer. The energy resolution is worst than in the previous case (the lower cutoff energy is 3.66 MeV and 6.48 MeV, for layer 1 and 2 respectively) but the films are more sensitive and only 6 laser shots were fired.

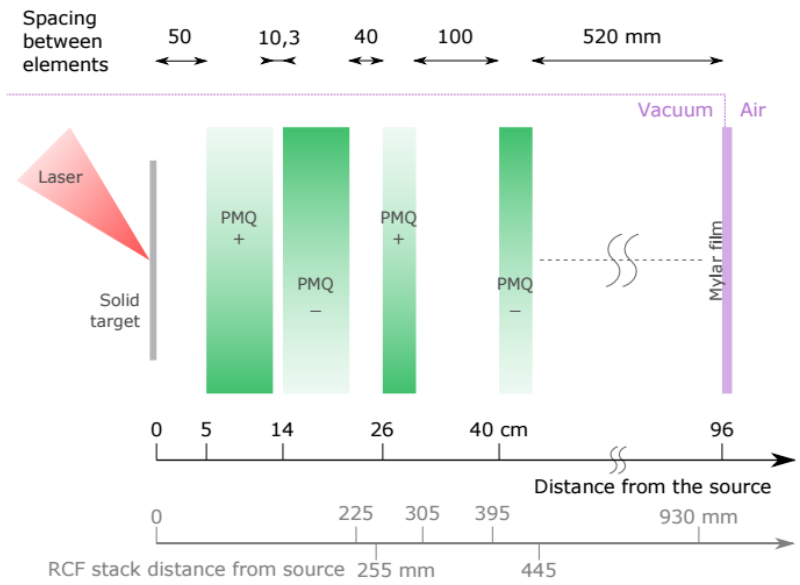


Figure 3. PMQ setup with details on relative distances marked on the black scale. The gray scale marks the positions of the GafChromic films. In the in-air part the yellow line indicate the ionization chamber position and the double pink line the position of the last image plate position.

The results of the PMQs optics on each GafChromic film are reported in tables 2 and 3, with comparison of simulations done with TraceWin and Simion. In particular, table 2 refers only to the first film of each stack, whose lower energy cutoff is 3.66 MeV. Table 3 refers only to the second film of each stack, whose lower energy cutoff is 6.48 MeV. The agreement between experimental results and monochromatic beam simulations run with TraceWin is more evident in the second layer of the stack (see table 3) as here the energy range of particles loosing energy in

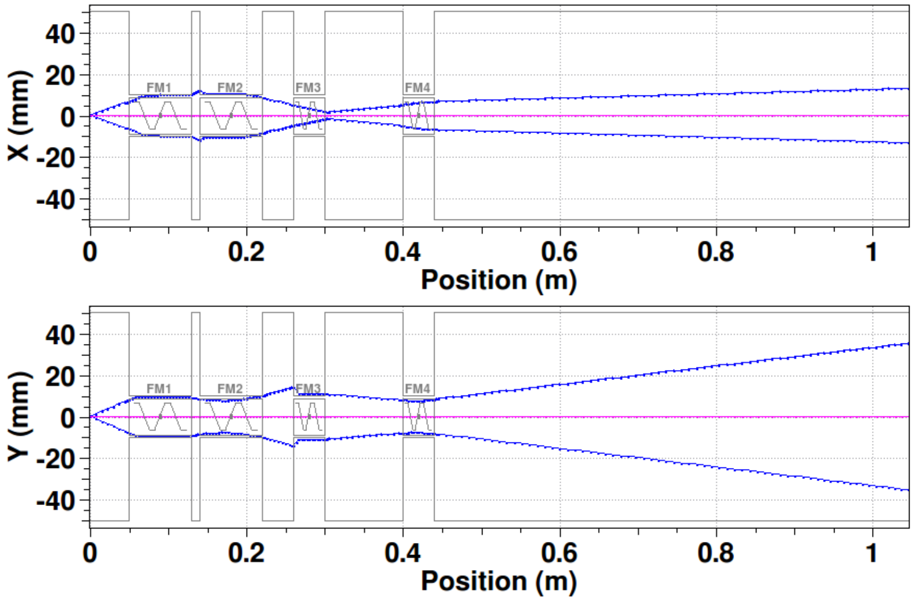


Figure 4. 6.48 MeV proton beam envelope calculated with the TraceWin Multiparticle tool in the described PMQ setup.

the sensitive layer of the film is narrower than in the case of the first layer. In order to highlight the agreement between experimental data and simulations, in the fifth column of table 2 the realistic beam simulated in Simion. Plots have a density scale for particle above the cutoff energy. Particles within [3.66–4] MeV are considered as reference and are plotted in blue. In the fifth column of table 3, the plots have a density scale for all particles at the cutoff energy, as higher energies are less abundant and their contribution to the film blackening is not relevant. The experimental traces have an evident rotation, which is due to a imperfect alignment of the PMQ system with the input beam, emphasizing the skew quadrupole components already considered in the maps used for the simulations, see [4] for details. What is not reproduced in the simulations are random shot-to-shot fluctuations in the initial particle distribution due to the different laser-target interactions. Anyway beam shape, dimensions and filamentation are well predicted in the simulation. Last film in table 2 shows a poor beam uniformity, probably because the skew components act on the beam in an unpredictable way on the lower energy component. The beam rotation is present on the last film in table 3, but here the beam shape is more uniform as predicted by simulations. In this setup, the beam transported with the PMQ system have been also analyzed with the TPS, following the method proposed in [26]. The detected proton spectrum, retrieved from the spectrogram shown in the l.h.s. of table 4, is compared with the proton spectrum obtained setting the TPS directly downstream the source, r.h.s. of the same figure.

It is important to notice the increase of particles in the energy range around 6 MeV, which means that the particle fluence is actually boosted by the PMQs. Same result has been confirmed by simulations.

The transmission efficiency of the PMQs in the present setup is shown in figure 5. For the high energy components the number of lost particle is low and, considering that the beam is compressed on the transverse plane, this justify the result obtained with the spectra analysis. The particle

Table 2. Transverse beam profile at different positions behind the source (specified in the first column). Comparison of experimental results for the beam transport in the second PMQ setup (third column) and simulations with monochromatic beam (fourth column, colors are related to the particle density) and TNSA beam (fifth column, color scale is the density of particle above 4 MeV, particles below this energy are in blue). This table reports, for different positions, only the first GafChrominc film of each stack and its lower cutoff energy is 3.66 MeV, in the second column is specified the real dimension of the corresponding film. Simulations plot have scales in mm.

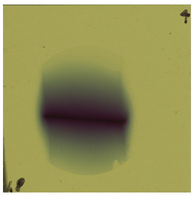
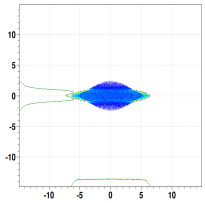
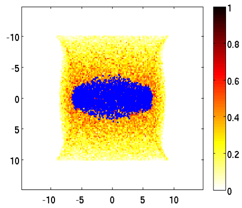
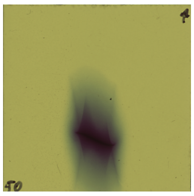
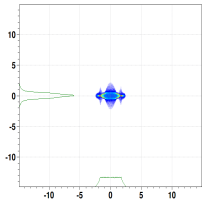
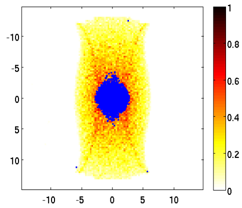
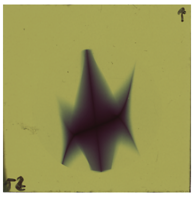
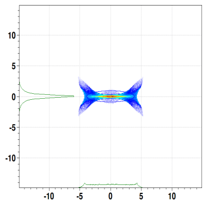
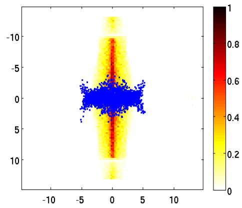
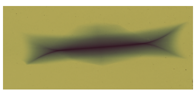
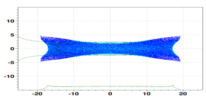
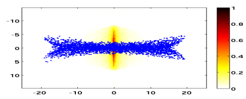
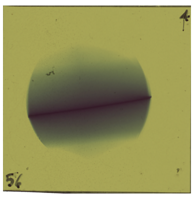
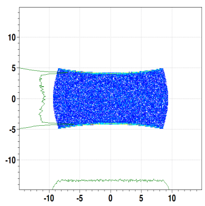
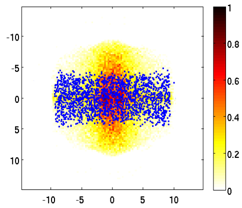
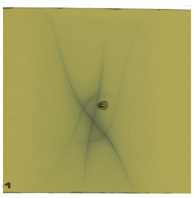
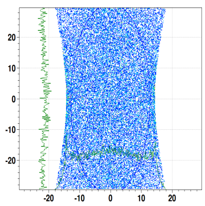
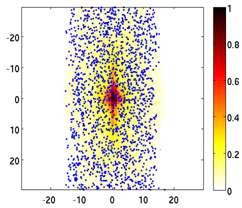
Gaf Position	Film dimension	GafChromic	TraceWin simulation	Simion simulation
225 mm	29.6x29.6 mm			
255 mm	29.6x29.6 mm			
305 mm	29.6x29.6 mm			
395 mm	29.6x51.6 mm			
445 mm	29.6x29.6 mm			
930 mm	57.8x57.8 mm			

Table 3. Transverse beam profile at different positions behind the source (specified in the first column). Comparison of experimental results of the beam transport in the second PMQ setup (third column) and simulations with monochromatic beam (fourth column, colors are related to the particle density) and TNSA beam (fifth column, color scale is the density of particle around the cutoff energy). This table reports, for different positions, only the second GafChrominc film of each stack and its lower cutoff energy is 6.48 MeV, in the second column is specified the real dimension of the corresponding film. GafChromic at position 930 mm has enhanced contrast, for better view of the beam spot. Simulations plot have scales in mm.

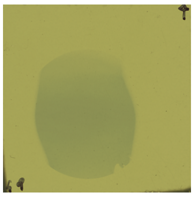
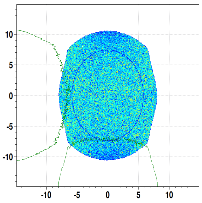
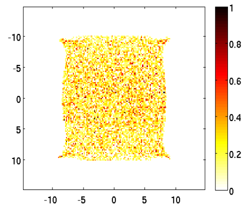
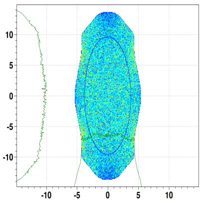
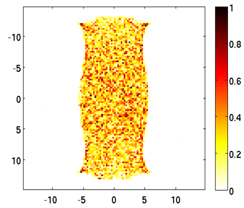
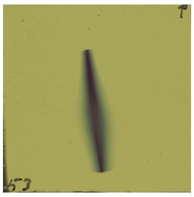
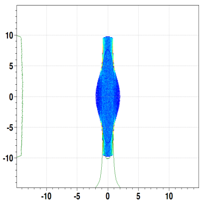
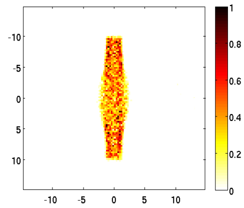
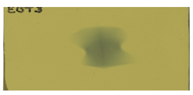
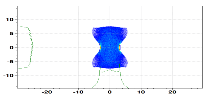
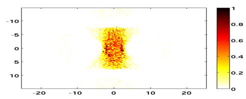
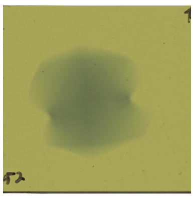
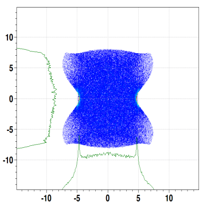
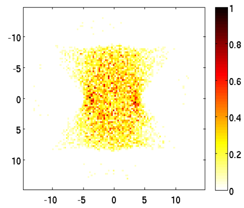
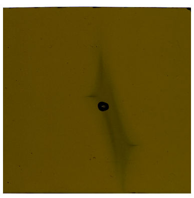
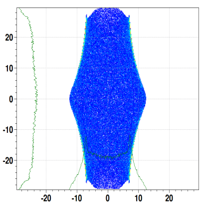
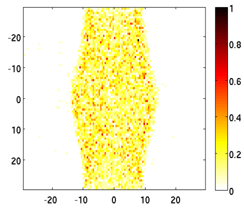
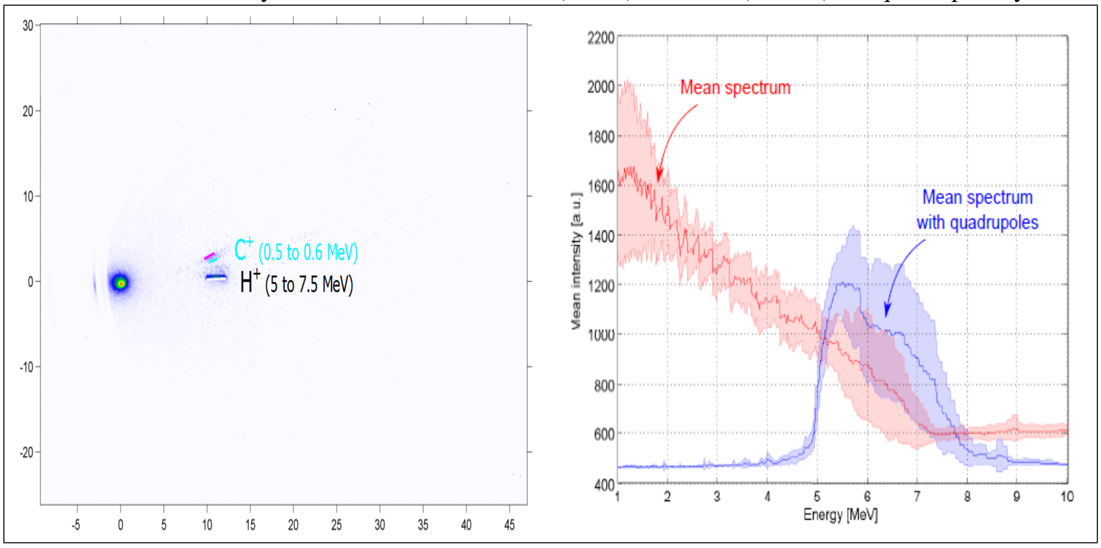
Gaf Position	Film dimension	GafChromic	TraceWin simulation	Simion simulation
225 mm	29.6x29.6 mm			
255 mm	29.6x29.6 mm			
305 mm	29.6x29.6 mm			
395 mm	29.6x51.6 mm			
445 mm	29.6x29.6 mm			
930 mm	57.8x57.8mm			

Table 4. Left panel: TPS traces of the transported beam. Carbon ions are not considered because they are stopped in the first dead layer of the GafChromic films. Right panel: average proton beam spectra extracted from the traces recorded by the forward TPS, without (in red) and with (in blue) the quadrupole system.



fluence is also affected by the PMQs, in fact, on a beam spot size of 30 mm radius set 1020 mm far from the ion source, the number of particle per surface unit (cm^2) obtained after the PMQs is $4.6 \times 10^3\,H^+/cm^2$ (having 2×10^6 particle at the source in the simulation or $1.13 \times 10^7\,H^+/cm^2$ if there are 5×10^9 protons produced at the source). If no PMQs are used the fluence on the same beam-spot size is $2.2 \times 10^3\,H^+/cm^2$ (having 2×10^6 particle at the source in the simulation or $6.5 \times 10^6\,H^+/cm^2$ if there are 5×10^9 protons produced at the source). This means that the PMQ system helps in increasing the particle fluence for the higher energy components, as the lower energy particle are removed. The fluence evaluated from the last film of table 3 is in agreement with this estimation ($1.2 \times 10^7\,H^+/cm^2$, corresponding to a dose of 0.1 Gy per bunch). More details on the dosimetric characterization of the transmitted beam will be given in a separated work.

3 Conclusion

An experimental campaign for the characterization of a PMQ system designed for the collection of laser-driven proton beams have been carried out and the results shows a very good agreement with simulations. This aspect is crucial as the computational results are validated demonstrating the possibility to have a precise control on the system as long as the proton source is know with good precision. Moreover, the fluence calculation results demonstrate that a certain energy component can be efficiently collected improving the beam quality, not only in terms of angular aperture but also in terms of particle density and, hence, dose. The spectrum transmitted by the PMQs is not perfectly controlled and selected, this is not an issue as the system as been designed to inject a certain energy component in a permanent magnet dipoles chicane used as Energy Selection System (ESS). The reported results demonstrate that the matching between the two devices can be accomplished with good precision using the simulation codes and, in the next months the whole beam-line (PMQs+ESS) will be characterized in order to study its performances. Finally, the increase in the

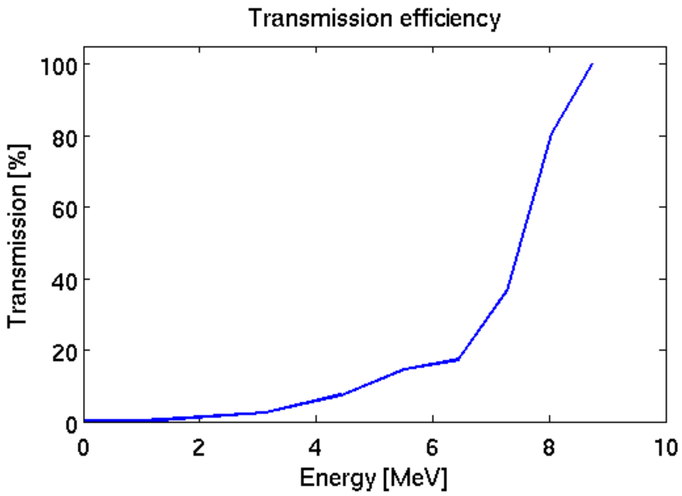


Figure 5. PMQs transmission efficiency for different energies.

particle fluence due to the PMQ system measured with IC and TPS confirms that the collection system can improve the beam quality, also in terms of particle density for a narrow energy range. This justify the use of the PMQs ahead of the selection system.

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