Laser induced proton acceleration at the FLAME facility in Frascati: LILIA experiment

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Abstract

A high power laser named FLAME with an intensity up to 10^{21} W/cm^2, a repetition rate of *10 Hz* and a contrast value (between main pulse and pre-pulse) of 10^{10} is being deployed at the LNF – INFN in Frascati and it is expected to be fully operative by the middle of 2012. In this frame an experiment of light ions acceleration through laser interaction with thin metal targets (LILIA) has been proposed and funded. The aim of LILIA experiment is to study, design and verify a scheme which foresees the production, the characterization and the transport of a proton beam toward a stage of post acceleration (high frequency compact Linac). Now the maximum operating laser intensity is limited to 10^{19} W/cm^2 due to the lack of a parabola with a focal length shorter that the current used. In this configuration, according to the interaction theory by short pulse laser and to performed numerical simulations, we expect a proton beam with maximum energy of a few *MeV* with a total dose up to 10^{10}-10^{12} protons/shot. Although these values are modest compared to the present state of art, their scientific relevance is very important due to the fact that we will have a real laser driven source in the next year. In this paper we present the experimental set-up and the first tests of diagnostic devices based on radio -chromic films, Thomson parabola, solid-state diodes arrays and solenoid current detectors. A scheme for the focusing and the transport of an emitted proton beam based on a pulsed solenoid feed by a custom designed power supply will be also presented.

INTRODUCTION

In the past few years, various interesting experiments have been started in order to study the interaction of ultrahigh-power laser pulses (with intensities beyond 10^{19} W/cm^2 and duration time ranging between *40 - 1000 fs*) with thin solid films (thickness of the order of *0.5 - 100 μm*) of different elements both metallic (Au, Cu, Pd, Al) and dielectric (polymers) [1]. These experiments have shown that, as a result of the laser-target interaction, protons and ions with energies up to *58 MeV* are emitted[1]. These protons, mostly originated by contaminated hydrocarbon surface used as target, are accelerated due to their higher charge-mass ratio with respect to other ions. Nevertheless, it is possible even to accelerate various species of ions by etching the target utilizing different methods. The total number of accelerated particles is strongly correlated to the specific target conditions and the experimental set-up: typical values are in the range from 10^9 to 10^{13} particles for laser pulse.

Laser driven acceleration is characterized by specific interesting properties, which mark a strong difference with respect to the traditional accelerating techniques. The most relevant features may be summarized in the following points: a) the possibility to accelerate ions at tens of *MeV* in very compact structures (of the order of a few tens of microns) due to the very high electric fields available with respect to the size of well known accelerators; b) an excellent beam quality with a transverse emittance less than 10^{-8} *mmrad* and a longitudinal energy spread less than *10 eV*. c) a very short duration of the proton bunch (of the order of a few *ps*); d) the possibility to synchronize the proton beam with the laser beam up to a scale of a few *fs* to obtaimultiple, synchronized sources of different particles (electrons, protons) and radiation (monochromatic *X* rays).

Due to these considerations laser driven acceleration holds the promise of compact accelerating structures which may be useful in different applications such as medicine (radioisotope production for PET, hadrontherapy), nuclear physics, inertial fusion (proton induced fast ignition), advanced diagnostic (proton imaging of fast electromagnetic fields) or material properties analysis and advanced imaging applications.

Materials and Methods

THEORY

In the majority of experiments for proton accelerations, the regime occurring is the so called TNSA (Target Normal Sheath Acceleration)[1, 2]. The laser pulse heats the electrons and ionizes the medium. Next the electrons diffuse around the target building an intense electric field. This field accelerates the free protons present on the target surfaces, both in the forward direction (from the rear side) and in the backward direction (from the front surface).

The protons energy depends on the electrons temperature and it has an exponential spectrum due to the thermal distribution of the electron energy. For a given laser, the intensity is

$$I = \frac{2P}{\pi w^2}\left[W/cm^2\right] \qquad (1)$$

where P is the laser peak power and w is the pulse waist value. It is convenient to introduce the dimensionless parameter:

$$a = \frac{eA}{mc^2} = 0.85\times10^{-9} I^{1/2}\left[W^{1/2}/cm\right]\lambda[\mu m] \qquad (2)$$

where A is the maximum value of the vector potential. If $a > 1$, the electron quivering motion in the laser fields is relativistic. Let us consider a $1D$ laser pulse moving on the z direction, the electron temperature (expressed in eV) can be estimated from the kinetic energy as $T = mc^2(\gamma - 1)$ where $\gamma = [1 + (P_z / mc)^2 + a^2]^{1/2}$ and P_z is the longitudinal momentum [3]. If $a >> 1$ we obtain that $T / mc^2 \sim a$. In $1D$ geometry, the electrostatic potential can be computed by solving the Poisson equation for a Maxwellian electron distribution. The protons maximum energy can be obtained estimating the maximum value of the electrostatic potential at the target-vacuum interface [4]. After some simplification, the proton maximum energy results approximately proportional to:

$$E_{max}\,(MeV) \sim \xi_0\, a \qquad (3)$$

where $\xi_0 \sim 2$ for a simple one dimensional model[5]. For very short pulses, the scaling found theoretically and in recent experiments [6-8] is

$$E_{max} \sim I^{0.8}$$

with a proportionality constant depending on the power, focal spot and target thickness. As a consequence, eq. (3) should be replaced with

$$E_{max}\,(MeV) \sim \xi a^{1.6} \qquad (3)$$

where the ξ depends on the wavelength and strongly on the thickness. The constant value is $\xi \sim 0.16, 0.085, 0.02$ for a target of thickness $h = 0.5, 5, 20\ \mu m$, respectively according to the fitting reported in [8] related to the thickness dependence found in the Dresden experiments.

For the highest power $P = 100\ TW$ and a waist of $2.5\ \mu m$ corresponding to $I = 10^{21}\ W / cm^2$ and $a = 22$, the maximum energy obtained with a target of $5\ \mu m$ thickness is $E_{max} = 12\ MeV$ whereas the average energy is $E_0 = 1.7\ MeV$. Dresden experiments and numerical investigations (see Fig. 1) show how the proton maximum energy drops significantly increasing with the target thickness.

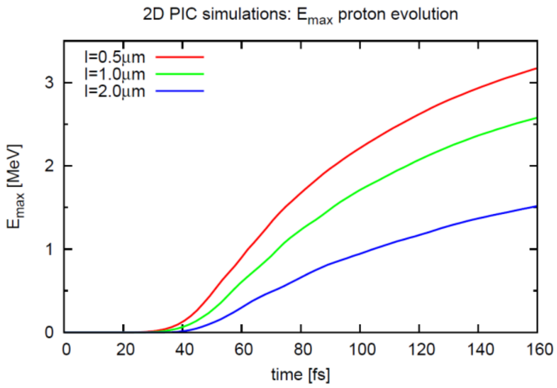


Fig. 1 Energy growth with time for a 2D simulation with P = 85 TW and a = 5 for a solid target with n = 80 n_c and a thin hydrogen layer. The 3D result can be expected to be one half of the present one.

One of the limits of the proton energy achievable in the TNSA regime is related to the fraction of the initial laser energy. absorbed by the electrons of the target. If a large enough layer of plasma near its critical density can be added in front of the solid target, the energy coupling between the laser pulse and the target is strongly enhanced resulting in higher energy protons. Recent numerical investigations[9,10] considered solid targets with a foam layer added on the front surface, showing that these targets allow to double the value of the highest proton energy reachable.

The highest energy value $E_{max} = 12\ MeV$ for the bare metal target agrees with the scaling (4) of Dresden experiments. The proton energy spectrum in the TNSA regime is exponential with a cut-off

$$\rho(E) = \frac{dN}{dE} = \frac{N_0}{E_0} e^{-E/E_0} \theta(E_{\max} - E) \tag{5}$$

where N_0 is the total number of protons while $\langle E \rangle = E_0$ is the average energy. The number of protons in a given small energy interval is

$$n(E, E + \Delta E) = \int E\left(\frac{dN}{dE}\right) dE \cong N_0 \left(\frac{\Delta E}{E_0}\right) e^{-E/E_0} \tag{6}$$

The average energy is related to the electron temperature and $N_0 \sim a$, but it is considerably smaller than the maximum energy. As a consequence, if a quasi monochromatic bunch has to be selected close to the maximum energy, the corresponding number of protons is a small fraction of the total. In the case of the Dresden experiment reported in Ref. [8] it has been shown that for $E_{max} = 12\ MeV$ and $N_0 = 10^{12}$ with $E_0 = 1.7\ MeV$, the fraction of particle with $E = 10\ MeV$ and $\Delta E = 0.1\ MeV$ would have only 1.6×10^8 protons.

THE LILIA EXPERIMENT

A high power laser (FLAME) has been deployed in the Frascati National Laboratories (LNF) of the INFN (Italian National Institute for Nuclear Physics). The main features of the apparatus are the following:

- $\lambda = 0.80\ \mu m$;
- pulse length: *20 fs*;
- pulse repetition rate: *10 Hz*;
- pulse energy: *6 J*;
- medium power: *60 W*;
- laser beam waist = *2.5 μm*.

At the present time, a target area is currently operating, allowing the first test experiments of electron Laser Wakefield Acceleration (LWFA) to be carried out in a safe, radiation shielded environment. The FLAME facility will be fully operational in the middle of 2012, as well as for the proton acceleration experiment (LILIA).

Concerning the experiments with LILIA, the following pulse parameters are expected:

1. in the first phase, the power will be in the range $100 < P < 200\ TW$, so that with a w of $10\ \mu m$, the intensity range is $0.64 \times 10^{20} < I < 1.3 \times 10^{20}\ W/cm^2$ and the dimensionless parameter range is $5.4 < a < 7.7$. As a consequence, supposing a linear scaling holds, the highest protons energy that might be reached for $a = 5.4$ is *2.4 MeV* for a very thin (*0.5 μm*) target and *13 MeV* for a medium target (*5 μm*). For a very thin target the maximum energy reachable results to be *4 MeV* at the power of *200 TW* on the target surface. The scaling (3) was confirmed by systematic 2D simulations with the *AlaDyn* code[11] and by experiments carried in similar experimental conditions[12];
2. in the second phase, full power of *200 TW* should be reached and the use a new off-axis parabola would allow a much tighter focusing with a waist of *2.5 μm*, so that intensities up to $2 \times 10^{21}\ W/cm^2$ and $a \sim 30$ might be reached. In case of a thin target (*0.5 - 1 μm*), we would expect a maximum energy above *30 MeV*, which could be further enhanced by using a structured target[13] .

As a consequence, one might select a bunch at $E = 30\ MeV$ with a narrow energy spread ΔE and still have a reasonable number of protons (10^7 - 10^8). This opens a very interesting perspective for applications such as hadrontherapy in connection with a post-acceleration stage in order to reach energies up and beyond *100 MeV*. Indeed if a sufficient current intensity can be reached at *30 MeV* with narrow spread $\Delta E / E \sim 1\ \%$, good beam quality, energy selection and collimation, then the proton bunch might be post-accelerated after injection in a high field linac, as the one developed for the INFN ACLIP project [10] (Fig. 2).

During the first phase, we will focus on two main aspects.

a) A parametric study of the correlation of the maximum TNSA accelerated proton energy, with respect to the following parameters:
   - Laser pulse intensity (in the range of 10^{18} - $10^{19}\ W/cm^2$);
   - Laser pulse energy (in the range of *0.1 - 5 J*);
   - Laser pulse length (in the range of *25 fs - 1 ps*);
   - Metallic target thickness (in the range of *1 - 100 μm*).

   In such a frame, we would like to deeply investigate the experimental scale rules within the possibilities offered by the FLAME facility.

Moreover, this will provide the opportunity to get experience in the development of iagnostic techniques and in target optimization

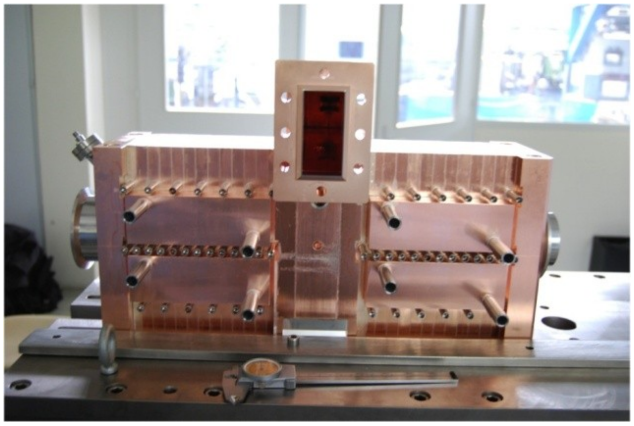


Fig. 2 *The INFN ACLIP Linac*

diagnostic techniques and in target optimization.

b) The possibility to produce a real proton beam able to be driven for significant distances (*50 - 75 cm*) away from the interaction point and which will act as a source for further accelerating structures.

THE LILIA SETUP

The mechanical setup

The LILIA experiment has been designed to be housed in the interaction chamber available at the exit of the laser compressor in the FLAME bunker. The layout of the first phase of the experiment is shown in Fig. 3 and it foresees:

- a special designed optical breadboard, with standard metric holes format, to allow the definition of a common reference plane level and the assembly of components within the chamber;
- a multi shot target holder able to be remotely moved in x-y-z directions and rotated along the z-axis with respect to the laser beam. This will allow a very accurate positioning of the targets with respect to the laser beam and the possibility to perform multi shot experiments without having to open the vent of the chamber to replace the already used targets. The target holder has been designed for the use of aluminium foils (pure up to *99.0 %*) with thickness as low as $1 \mu m$ and the possibility to provide up to 30 usable shots. The position accuracy of the targets with respect to the laser beam is of the order of $20 \mu m$ for the translation stages and of *0.1* degrees for the rotation stage. The alignment of the targets with respect to the power laser beam will be accomplished using alignment lasers and devoted optical windows in the chamber;
- a remotely movable multi-detector holder able to house *8* stacks of radio-chromic detectors to be used close (*50 mm*) to the interaction point. A fixed lead foil (*3 mm* thick) is used to avoid the damage of stacks adjacent to the one of interest for a specific laser shot;
- the availability of multiple detectors copes with the possibility to perform multiple experiments on different targets in a very short time, minimizing the fluctuations in the laser beam characteristics;
- a more accurate analysis of the energy distribution of the produced ions will be carried out at a fixed emission angle with a Thomson parabola (TP) spectrometer with its related detectors. A *150 mm* diameter vacuum movable window in the interaction chamber at an angle of *120* degree with respect to the laser beam will allow the positioning of the TP.

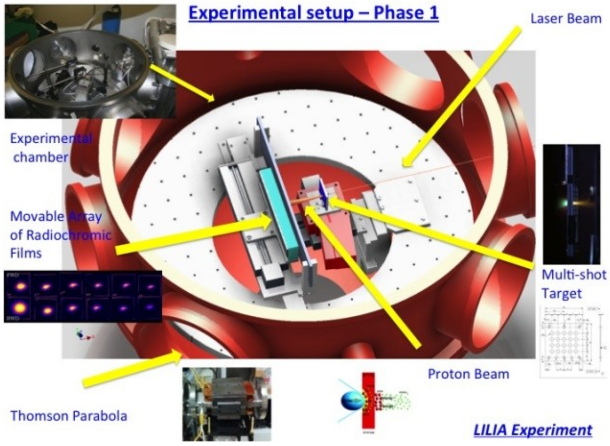


Fig. 3 Sketch of the LILIA mechanical setup

The ion detectors

Radio-chromic films

Radio-chromic detectors involve the direct impression of a material by the absorption of energetic radiation, without requiring latent chemical, optical, or thermal development or amplification. Detectors based on this phenomenon are available as films of different shape and build. They are obtainable as stacks of one or more subtle layer of sensitive material (usually few microns thick) with intermediate polyester and adhesive layers to act as mechanical support. A radio-chromic film changes its optical density as a function of the absorbed dose. This property, along with the relative ease of use, led to adopt these detectors as simple ion beam transverse properties diagnostic tools. More sophisticated analysis procedures and more complex configuration of these detectors (usually stacks of many films) may give an estimation of energy distribution of the ions in the beam[14]. Two specific commercially available detectors have been considered for the first measurements we are going to do: they are provided by Gafchromic company and named HD-810 and MD-55. The first type is a single layer film with a dynamic range from *0* to *250 Gy* while the second one is a double layer film with a *60 Gy* maximum dose value. An analysis procedure based on the reading of the exposed films using a commercial scanner (Epson V750 Pro, maximum optical density 0-4), a calibration correlation with a ISO21550 reference target, along with the conversion curves optical density-dose provided by Gafchromic, lead us to an evaluation of the maximum error in the determination of the true dose of the order of *20 %*. This value is rather large and it is due both to intrinsic fluctuations in the film sensitivity in the production process and to errors in the image measurements.

A model has been developed for the reconstruction of the ion beam energy spectrum from readings of films arranged in a stack. For a maximum energy of *10 MeV* and a stack of 10 films, test cases give up energy distribution characterized by errors of the order of *25 - 30 %*.

The above considerations lead us to the idea to use radio-chromic films just in the first stages of the measurements, in order to provide us a rough idea of the emission process and of the dynamic range of energies and intensities we'll have to deal with.

<u>Thomson Parabola spectrometer</u>

A Thomson spectrometer has been designed and realized within the LILIA collaboration. An extensive description can be found in [15].

The main characteristics may be so summarized:

- Analysis of proton and carbon beams ($Q = +1$ to $+6$) from *0.1* to *10 MeV*;
- very compact design [$160 \times 144 \times 150\ mm^3$];
- high magnetic field (tunable) up to *1850 gauss*;
- high electric field (tunable) up to *20 kV / cm*.

<u>Solid state detectors</u>

In addition to the more traditional passive radio-chromic films, or MCP detectors, active solid-state detectors have been studied and tested. They would give a real time information which of course is extremely important to control and change the experiment parameters.

Our basic aim has been the possibility to study and develop a silicon based detector, position sensitive and based on a matrix of simple PIN diodes. These detectors are thought for the focal plane of the Thomson Parabola Spectrometer, being possible to arrange a 2D array with proper spatial resolution. After a laser shot, a pulse of ions reaches a single pixel of this matrix after being deflected by the TP. The pixel identifies ions with the same Z/A ratio and the same energy. The measure from the pixel is done by integration, with a delayed coincidence with respect to the laser pulse.

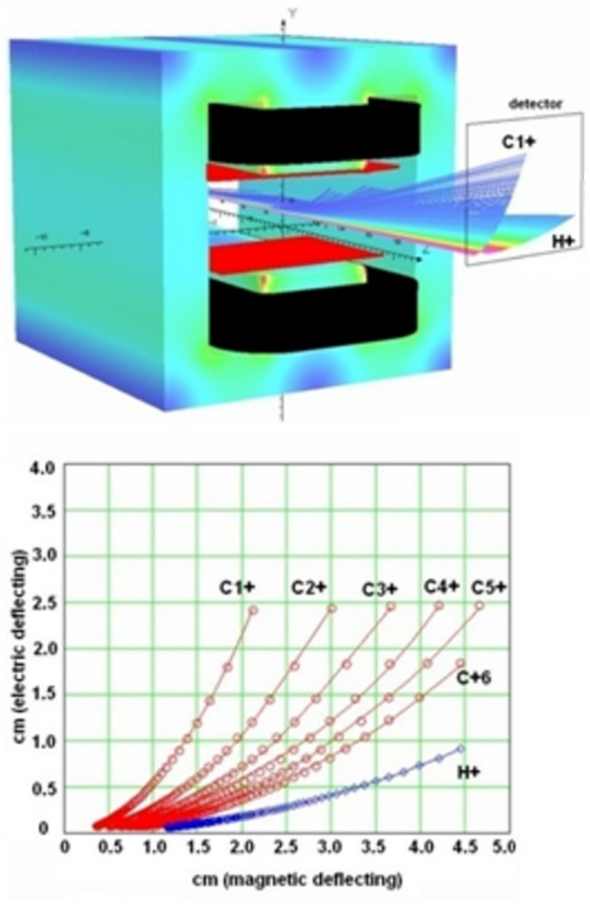


Fig. 4 Thomson Spectrometer for laser plasma facility

The main advantages of this sort of detectors with respect to a scheme that foresees a MCP and a CCD camera, may be pointed out in the following:

- the lower sensitivity of the detector is as low as a single proton charge ;
- the capability to work in a rough vacuum environment;
- the availability of low-medium cost detectors;
- the flexibility to design specific geometric configurations able to suit the experimental requirements.

Different materials and structures have been considered and partly characterised: silicon photodiodes (PD), monolithic silicon telescope (MST) and SiC diodes.

Different materials and structures have been considered and partly characterised: silicon photodiodes (PD), monolithic silicon telescope (MST) and SiC diodes. diodes for optimum particle discrimination and large energy range, SiC diodes are radiation hard. Tests have been performed on the two silicon structures at INFN-LNS and INFN-LNL with *30 MeV* proton beam for the first (PD) and *1 - 5 MeV* proton beam and *60 MeV / u* carbon beam for the second (MST).

The results show that charge collection is optimal in the fully depleted structure (MST), being the other affected by long tails and partial collection.

SiC diodes are built on a low doped epitaxial layer and their response to high energy ions passing through will be verified soon.

We plan to further develop and test some of these detectors, but we still have to face the problems which arise from their use in an extremely high noise environment, as the one present in the surroundings of the laser-target interaction.

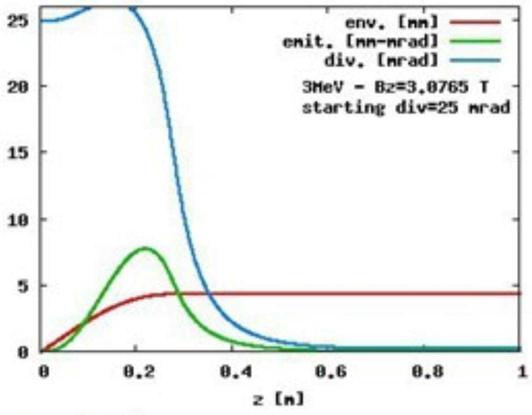
Beam Focusing and Transport

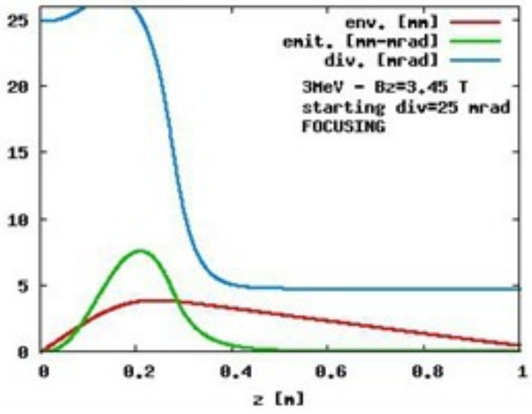
The problem to immediately focus the emitted protons in order to obtain a useful beam and to transport it from the interaction region toward external measurement or post-acceleration facilities will be faced both from the numerical computation and experimental point of view. The following general considerations must be taken into account to deal with this item. The excellent emittance is the result of very short initial burst duration and very small “virtual” source size. However, proton beams emerging from a laser-driven target have typically a broad energy spectrum and large, energy dependent, divergence angle (typically *40 - 60* degree depending on laser and target parameters). The inherent large divergence and the energy spread can make it hard to utilize the full flux of the proton beam for applications and indeed for further transport and beam manipulation. The manipulation of proton beams gives new challenges due to the high bunch charge and nature of the beams. This means it requires innovative approaches to enable beam control. The possibility to drive a laser emitted proton beam using a scheme based on a pulsed solenoid has been reported in literature[16]. We considered this approach really interesting and we carried out very preliminary simulation runs to define the main features of the components involved.

In our research we will focus on a scheme that foreseen a pulsed high field solenoid to collimate the beam directly behind the target foil. This method will provide a first formation of the proton beam very close to the target. Then, it would be necessary to add a second stage to accomplish the final formation of the beam and its transport to a reasonable distance from the source (*500 - 750 mm*). This goal may be reached using a magnetic chicane to filter the unwanted beam component and a conventional beam transport scheme based on high gradient permanent quadrupoles.

Elements characterized by gradient values up to *200 T / m* with small sizes (*8 mm* internal bore and *30 mm* external diameter), are commercially available.

Very preliminary simulations have been carried out looking at a proton beam of *3 MeV* with a diver





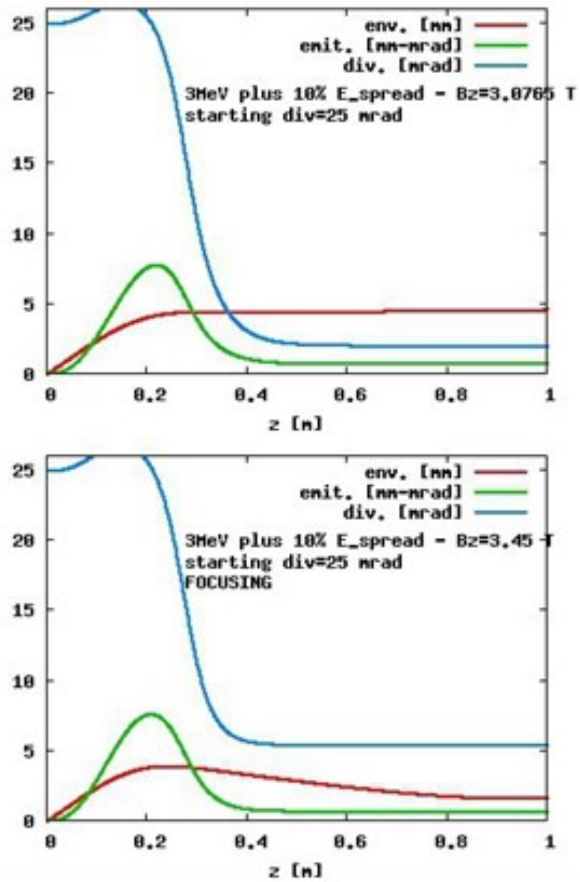


Fig. 5 Beam transport simulation results with a solenoid.

Fig. 6 Prototype of the pulsed solenoid for beam focusing

gence of *25 mrad* injected in a solenoid (*50 mm* internal bore, length *200 mm*) located at *50 mm* from the laser-target interaction point. An energy spread of the order of *10 %* has been considered in separate simulations to provide a more realistic approach to the phenomenon.

Fig. 5 summarizes the results so far obtained. It is noticeable that fields of the order of *3.0 - 3.5 T* may result in a good shaping of the beam at the distances of interests. Further work is undergoing to look at a more detailed understanding of the emission and transport processes of the proton beams in the presence of the solenoid.

From the experimental point of view we are constructing a pulsed power supply like charge transfer circuit. The main characteristics of this power supply are: max. voltage *40 kV*; max. current *2 kA*; pulse length *1 ms*; repetition rate *1 Hz*. It will be able to feed a solenoid as the one used in the simulation. Fig. 6 shows a first prototype of the solenoid. It has been constructed and it will be mainly used to test the high voltage insulation. A Rogowski coil [17] and a resistive shunt to measure the current behaviour of the power supply have been developed and calibrated.

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