Simulation of Thomson Parabola spectrometer for charged particle diagnostics in the PETAL+ project

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The PETAL (PETawatt Aquitaine Laser) laser facility is a high energy multi-petawatt laser, which is able to generate pulses of up to 3.5 kJ energy with a duration of 0.5 to 20 ps. This petawatt laser will be coupled with LMJ (Laser MégaJoule) which will deliver shaped pulses from 0,7 ns to 25 ns with a maximum energy of 1,5 MJ. Such facility will provide unique tools for inertial confinement fusion (ICF) physics. PETAL is located on the site of the CEA/CESTA in the Barp, close to Bordeaux in France. The Petal+ project is aiming at designing and constructing the first diagnostics of the PETAL laser for the characterization of the Target Normal Sheath Acceleration (TNSA) particle source. Among them, SEPAGE (Spectometre Electrons Protons à Grandes Energies) is a two-Thomson Parabola (TP) diagnostic which will measure the electron, proton & ion energy spectra in the direction perpendicular to the PETAL target.
This paper presents the simulation by Finite Element Method of these twoThomson Parabolas: High Energy (HE) and Low Energy (LE) which work simultaneously. Each TP involves the use of a magnetic field generated by a pair of permanent magnets, and an electric field generated by a potential difference across a pair of electrodes.

LMJ is part of the French Simulation Program developed by the CEA. The Simulation program aims to improve the theoretical models and data used in various domains of physics, by means of high performance numerical simulations and experimental validations. The PETAL project consists of the addition of one high-energy multi-petawatt beam to LMJ. LMJ will deliver shaped pulses from 0,7 ns to 25 ns with a maximum energy of 1,5 MJ and a maximum power of 400 TW of UV light on the target at the center of the target chamber to reach ignition of a DT (Deuterium and Tritium) target. The target chamber [8] consists of a 10-meter diameter aluminum sphere, fitted with two hundred ports for the injection of the laser beams and the location of diagnostics. It is a 10 cm-thick aluminum sphere covered with a neutron shielding made of 40 cm-thick borated concrete. SEPAGE will be inserted inside the chamber close to the experimental target with a dedicated insertion system SID (System for Insertion of Diagnostic) which is a two-stage telescoping system that provides a precise positioning of a diagnostic close to the center of target chamber (see Fig. 1).

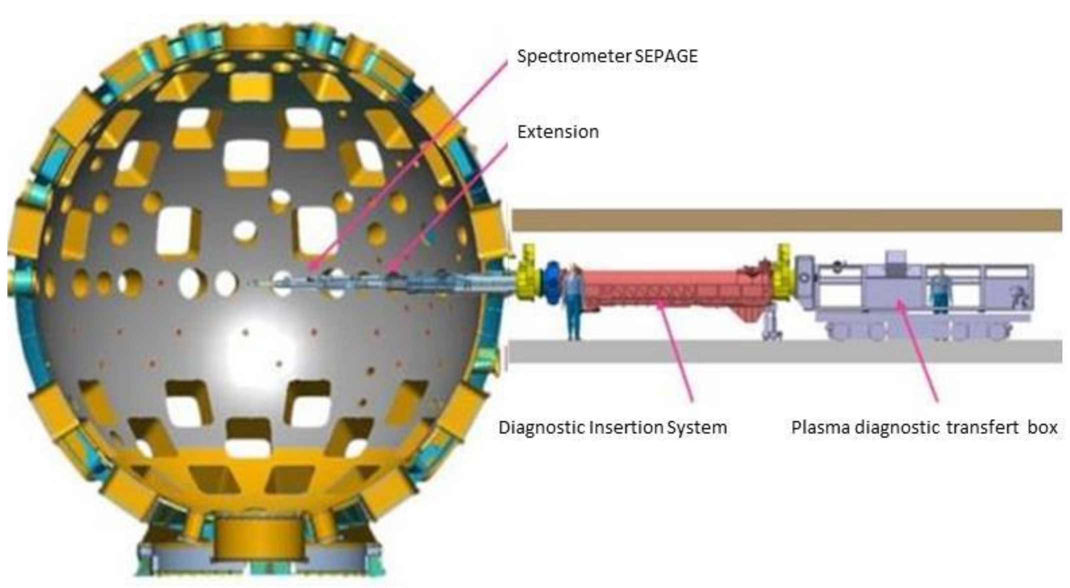

Fig. 1. Presentation of SEPAGE diagnostic during shot position

The current design of SEPAGE diagnostic is shown in Fig. 2

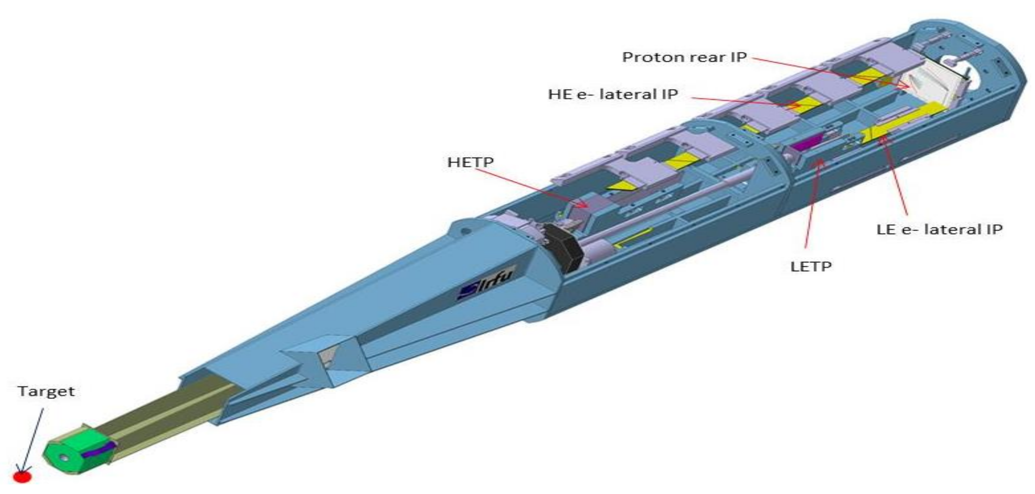

Fig. 2. SEPAGE spectrometer

SEPAGE has been equipped with two channels: A high energy one and low energy one, as described in the table below.

	Electrons	Protons (ions)
High energy TP	8 – 150 MeV	10 – 200 MeV
Low energy TP	0.1 – 20 MeV	0.1 – 20 MeV

Each of the two Thomson Parabolas (see Fig. 3) utilizes a pair of permanent magnets to generate the magnetic field at the front behind the pinhole, followed by a pair of high-voltage electric plates with both pairs being parallel.

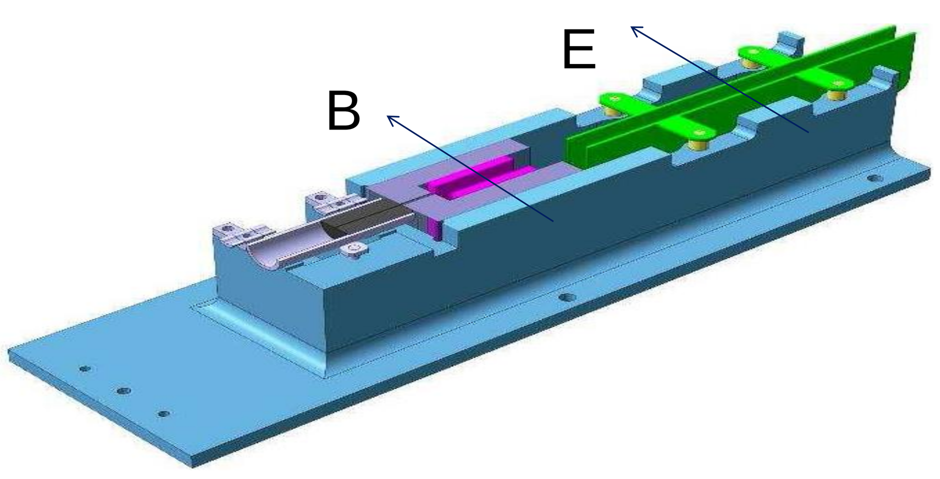

Fig. 3. Thomson Parabola

1. Magnetic and Electric Models

The magnetic and electric Finite Element Analysis of these two Thomson Parabolas was carried out using OPERA-3d software. This software uses its Geometric Modeler to mesh the geometry and create the database necessary for analysis, its analysis program TOSCA to solve non-linear magnetostatic and electrostatic field, and its Post-Processor to display and perform further calculations on results from analysis program TOSCA.

1.1. High Energy Thomson Parabola (HETP)

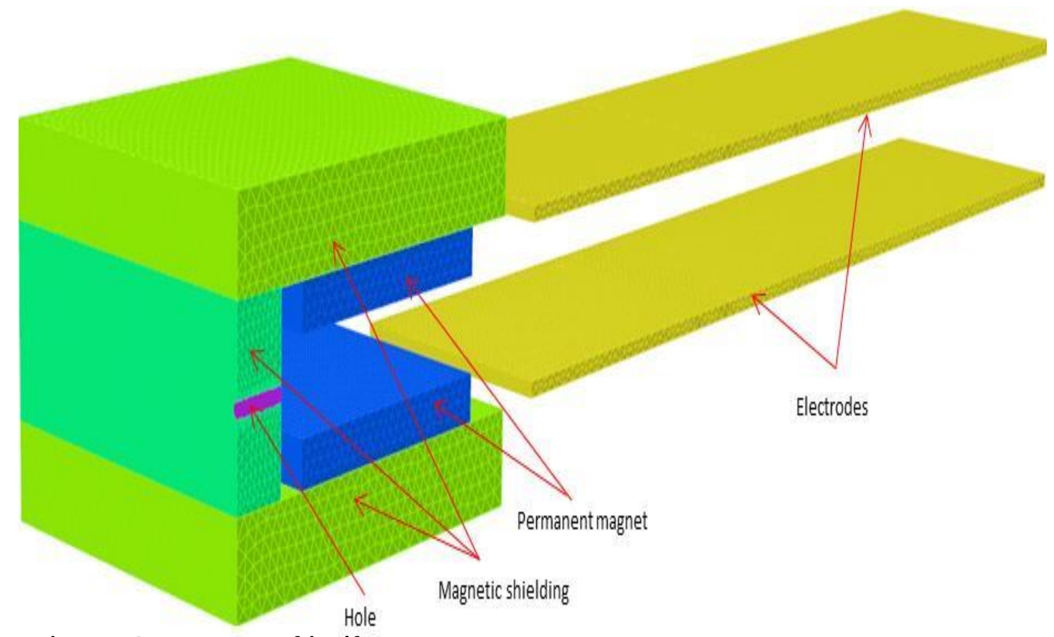

Fig. 4. Geometry of half-HETP.

The magnetic shielding was constituted of a material qualified by TOSCA as "good quality magnet steel" which has a nonlinear magnetic behavior. It is represented by the B-H curve shown in Fig. 5. The permanent magnet was constituted of neodymium boron iron material whose magnetization curve is presented in Fig. 5 (right).

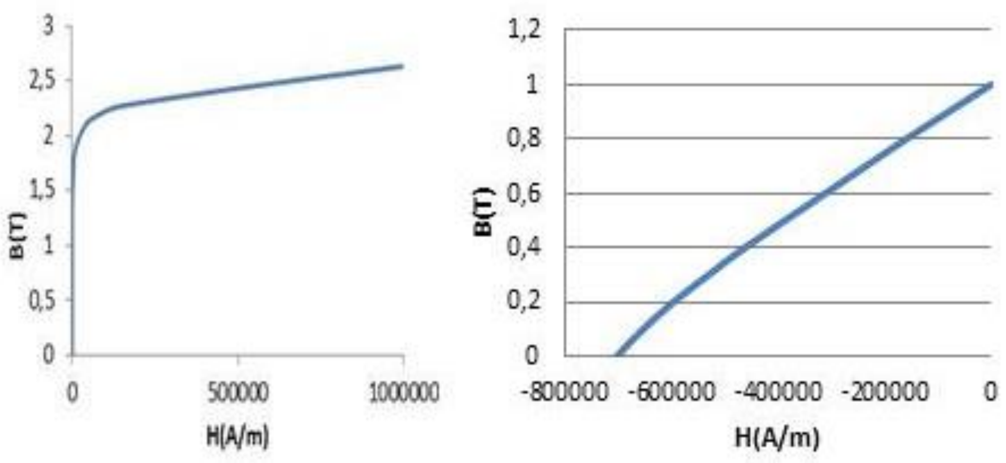

Fig. 5. Left ; B-H curve of magnetic shielding. Right; magnetization of permanent magnet

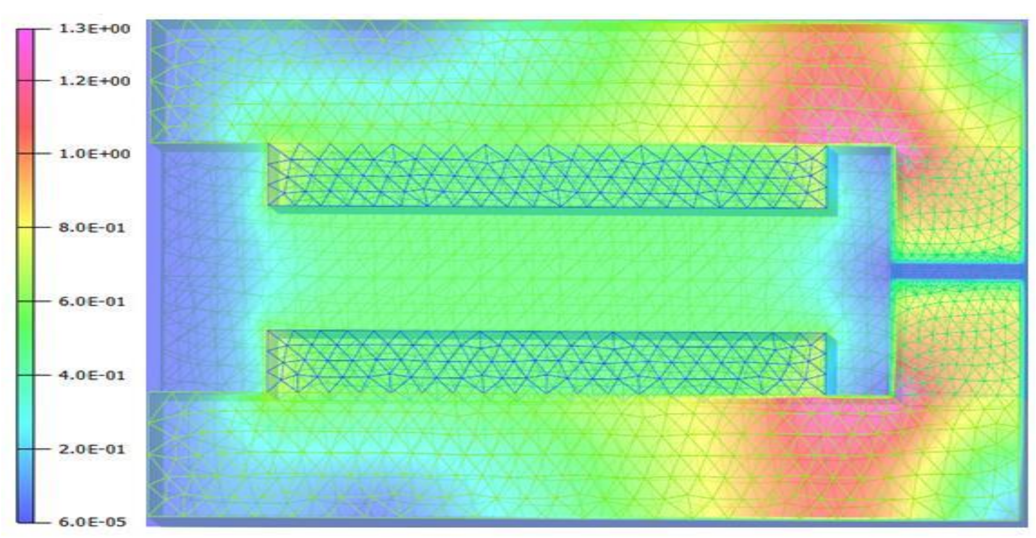

Fig. 6. Field map (in Tesla) on a vertical median plane XZ parallel to the emitted particle direction.

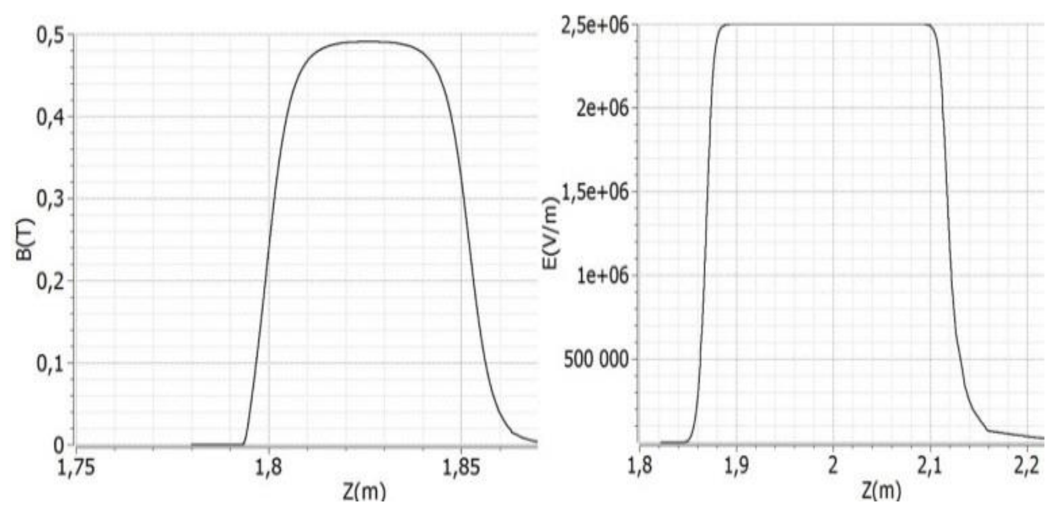

Fig. 7. Left ; Evolution of magnetic field along the magnet's axis. Right; evolution of electric field along the magnet's axis

1.2. Low Energy Thomson Parabola (LETP)

The ferromagnetic material used for magnetic shielding for LETP was the same than that used for HETP whose nonlinear magnetic behavior is shown in Fig. 5. On the other hand the material which constituted the LETP permanent magnet was of type "ceramic ferrite permanent magnet" obtained by the University of Liverpool in 1986. Its magnetization curve is shown in Fig. 9 (right)

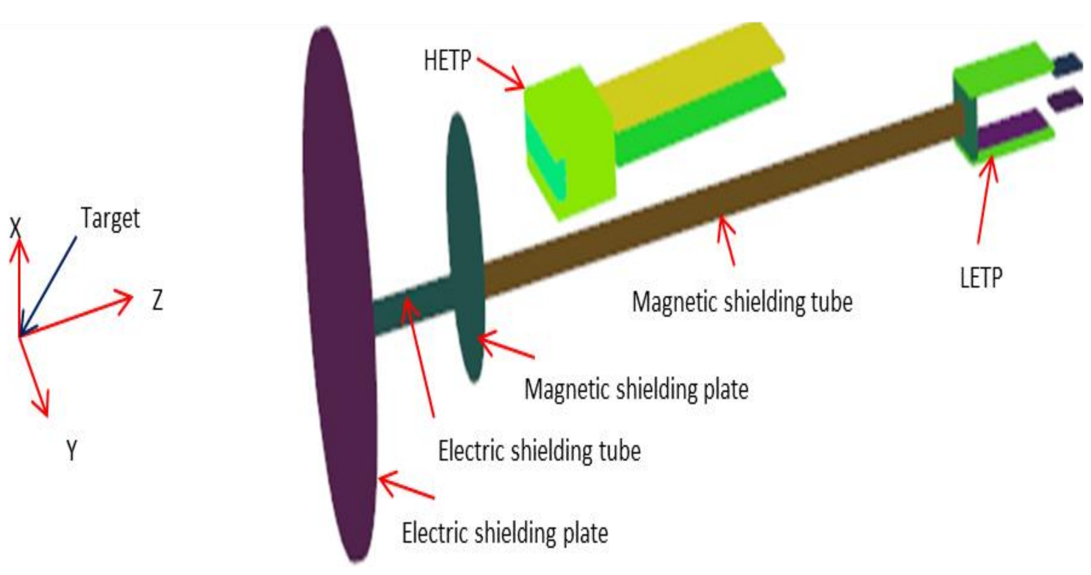

Fig. 8. Sketch of geometry of HETP and LETP and their magnetic shielding.

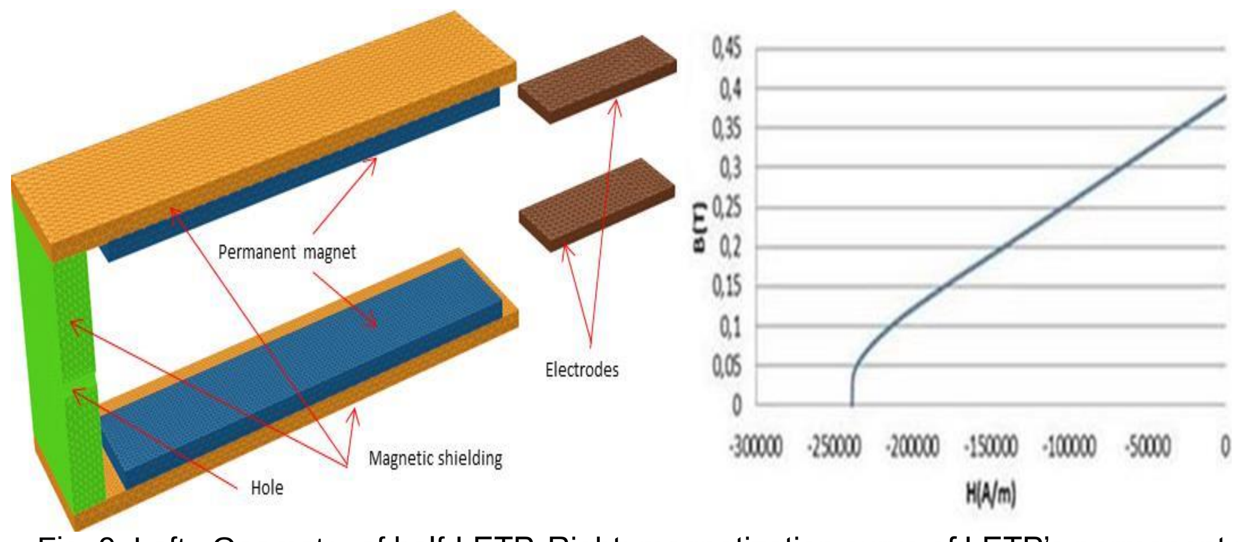

Fig. 9. Left ; Geometry of half-LETP. Right; magnetization curve of LETP's permanent magnet.

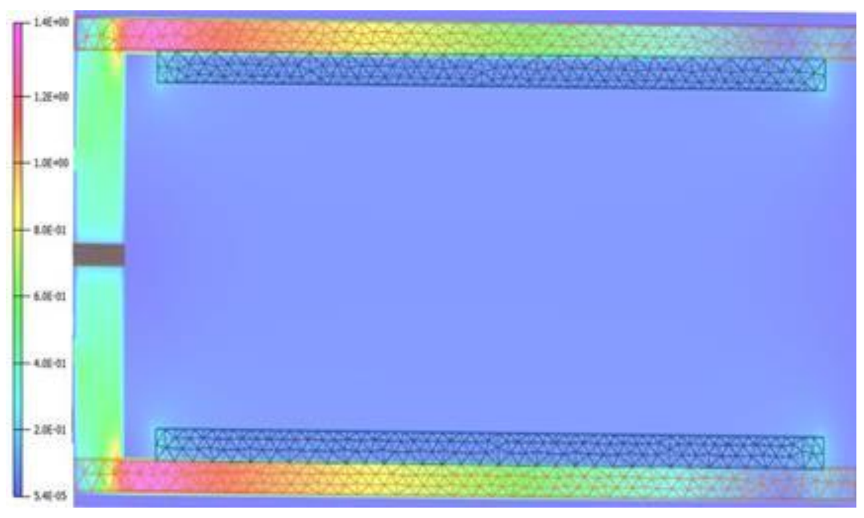

Fig. 10. Field map (in Tesla) on a vertical median plane XZ parallel to the beam's axis.

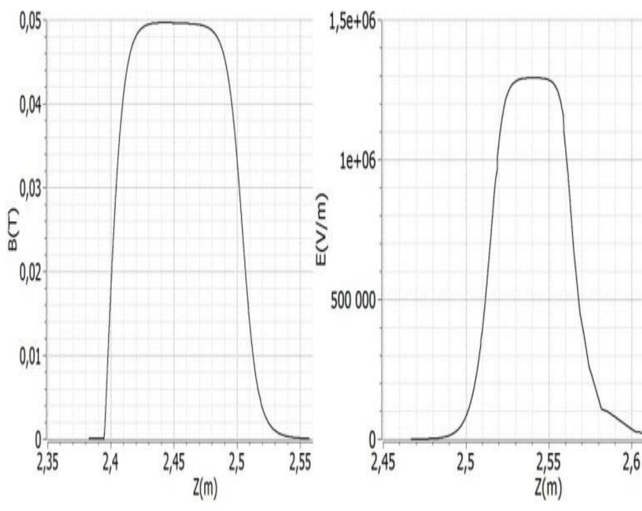

Fig. 11. Left ; Evolution of magnetic field along the magnet's axis. Right; evolution of electric field along the beam's axis

2. Particle trajectories

Inside the TP the protons, electrons & ions are deflected by the Lorentz force, $\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$, parallel to the electric field ($\vec{E}$) and perpendicular to the magnetic field ($\vec{B}$). $\vec{v}$ is the velocity of ions and q=Z × e is the ion charge

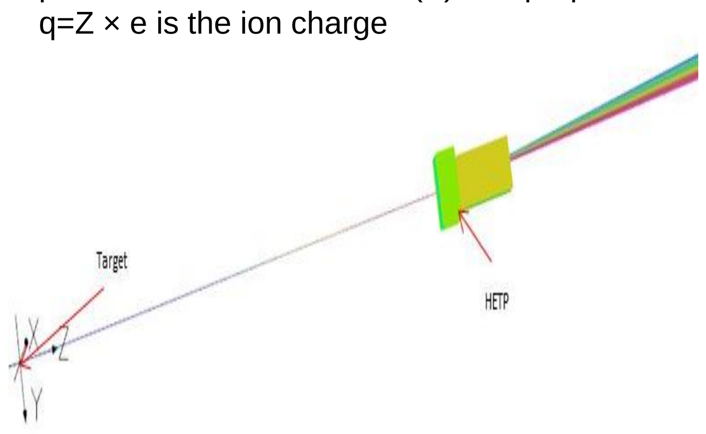

Fig. 12. Trajectories of high energy protons deflected by HETP.

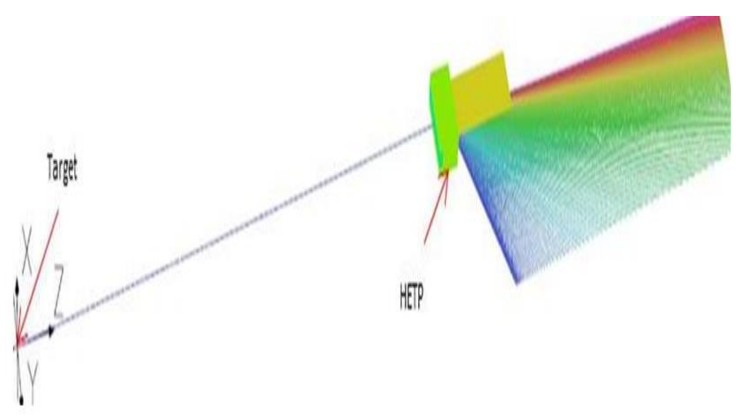

Fig. 13. Trajectories of high energy electrons deviated by HETP

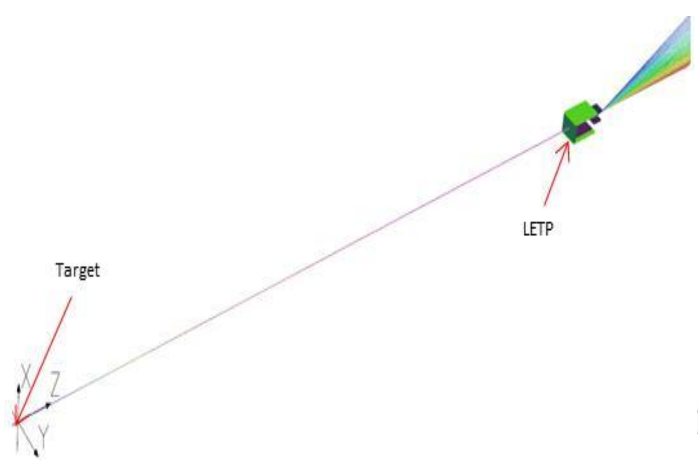

Fig. 14. Trajectories of low energy protons deflected by LETP

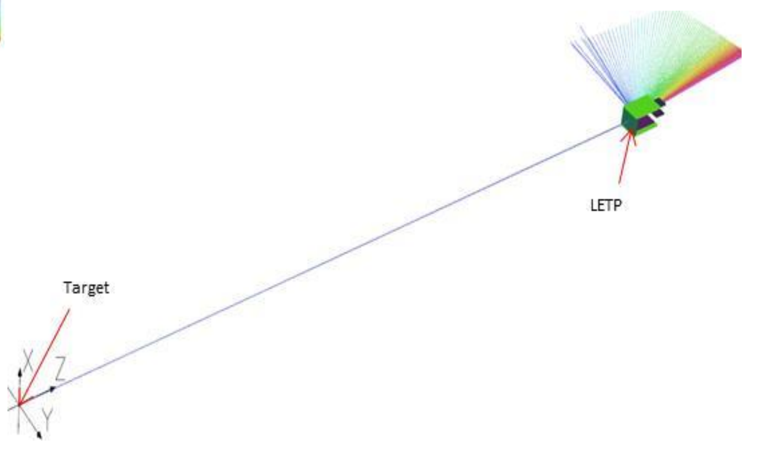

Fig. 15. Trajectories of low energy electrons by LETP

Particles are deflected toward Imaging Plates (IP) by Thomson Parabola. The intersections with rear IP and lateral IP of high energy electron trajectories are shown in Fig. 16 and 17. These trajectories were calculated numerically using OPERA3d (TOSCA) and analytically.

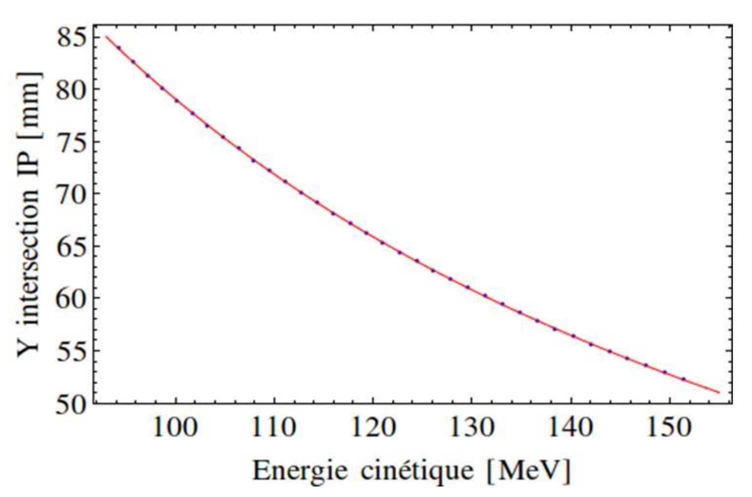

Fig. 16. Intersection, with rear IP, of high energy electron trajectories

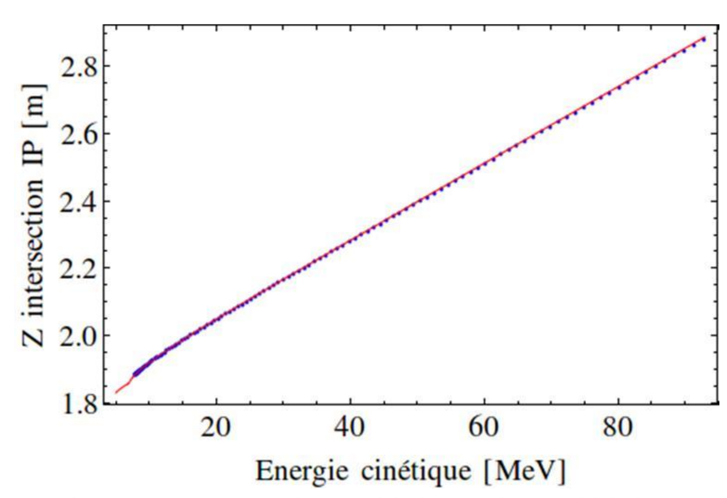

Fig. 17. Intersection, with latéral IP, of high energy electron trajectories

3. Conclusion

The SEPAGE diagnostic, made of two Thomson Parabolas for particle energy ranges (electrons, protons and ions) have been designed and constructed in order to characterize particles and radiation yields that can be created by PETAL; this is PETAL+ project. Full three-dimensional (3D) magnetic and electric computations using OPERA 3d (TOSCA) software were carried out in order to obtain magnetic and electric fields for the transport of charged particles in SEPAGE. Analysis of particle tracks from this spectrometer shows a good agreement between analytic and numerical solutions for high energy particles. The same computations have been performed for the low energy particles; but the agreement between the analytic and numerical results were not as good. These computations have been completed by a calibration experiment of the low energy Thomson Parabola with the proton and carbon ion beams of the ALTO-Tandem facility of the nuclear physics institute of Orsay and by a 3D magnetic field mapping of the SEPAGE permanent dipole magnets. These measurements are still being analyzed.