ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPGW011

FIELD-MAP AND BEAM TRANSPORT CALCULATIONS OF THE MAGNETIC SEPARATOR AT ALTO FACILITY AT ORSAY

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Abstract

The Institute of Nuclear Physics at Orsay (IPNO) has always been a major player in building accelerators for nuclear physics. The Accelerator Linear Tandem Orsay (ALTO) facility is powered by a 50 MeV/10uA linear electron accelerator dedicated to the production of radioactive beams [1]. The production mode is based on the photo-fission process of a thick UCx target heated up to 2000°C and using the Isotopes Separation On-Line (ISOL) technique [2]. For the ionization of the released fission fragments, three ion source types can be coupled to the target: a Febiad ion source, surface ion source, and laser ion source. The facility can deliver the radioactive ions beams (RIB) to six different experimental setups. The mass of the produced mono-charged Radioactive Ions Beam is selected using a magnetic dipole in order to select a nucleus before its transmission through electrostatic devices up to the experimental setups [3]. This paper is focused on the separator that was built and exploited with success since 43 years. The separator is located closely to the exit of the source of RIB production. We propose to revisit this dipole with a precise field-map calculation and particles transport simulations. These results will be used as a first brick for the understanding and reliability of the transmission along the RIB lines at the ALTO facility.

INTRODUCTION

The IPNO laboratory, created in 1956 at the initiative of Irène and Frédéric Joliot-Curie, is today at the heart of the scientific and technical pole of Greater Paris. It is one of the largest laboratories in the world for research in nuclear physics. Since its foundation, the laboratory focuses on the knowledge of matter and its ultimate components. Various and first class accelerator were build and operational at Orsay.

The ALTO facility is powered by a 50MeV/10uA linear electron accelerator dedicated to the production of radioactive beams (see Fig. 1). The production mode is based on the photo-fission process of a thick UCx target heated up to 2000°C and using the ISOL technique. For the ionization at 30keV (60keV in the near future) of the released fission fragments, three ion source types can be coupled to the target: a Febiad ion source, a surface ion source, and a laser ion source. The ISOL technic is commonly used at various facilities in the world: ISOLDE at CERN, ISAC at TRIUMF, SPIRAL1 at GANIL, RIKEN in Japan [4].

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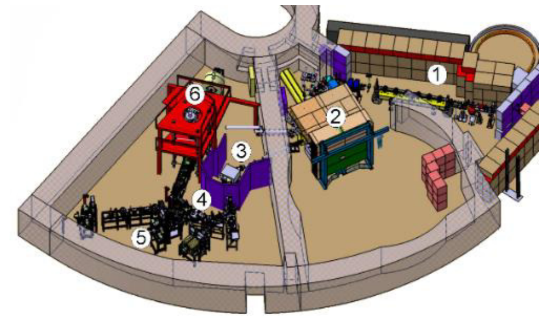

Figure 1: Scheme of the ISOL facility ALTO: 1. 50MeV Electron LINAC, 2. Target ion source vault, 3. Mass separator, 4. Transfer lines, 5. and 6. experimental setups in operation and under construction.

Various radioactive species are produced during the ISOL process. Prior to transport the ions of interest to the experimental setups, a magnetic separation must be ensured with a sufficient power. In this paper, we will describe the magnetic studies of the 43 years old separator using the existing mechanical design and simulation tools. The dipole plays a key role in the chain of beam transport of the low energy beam line. Today, experimental beam tuning is not well optimized and beam transmission is less than 50%. Therefore, that's why we plane to produce a precise and realistic end-to-end beam dynamic calculation in order to increase significantly the reliability.

DIPOLE DESIGN

The ALTO separator was built in 1975 in collaboration between IPNO and IPN-Lyon (see Fig. 2). The dipole was used intensively at different IPNO facilities in order to ensure separation [5]. The H-dipole is a 65° bending angle, radius to 600mm, gap to 66mm, faces angles to 21.5° with negligible index n=0.

Figure 2: Top view of the separator magnet (in red) in the dedicated room. Beam is coming from the top left corner of the figure.

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Unfortunately, during the last four decades, a weak material has passed through: few original 2D drawings, magnetic characteristics of the raw material and impurities, fringing field measurements. An excitation curve was measured in 1976 up to 265A with 8624Gauss that is sufficient for a mono-energetic beam up to 60keV. The field is linear in the working range. In order to fulfill our needs, we made some dimensional measurements directly on site concerning the yokes, coils, chamfer, coils fixations and holes in the yokes. With more precise geometrical specifications, we produced 3D model using the OPERA software [6] (see Fig. 3).

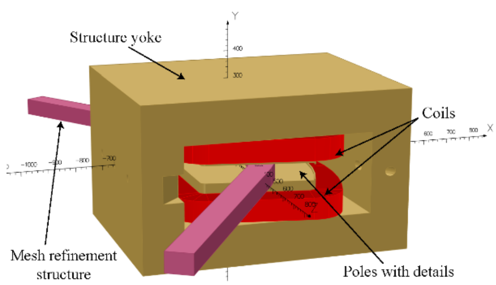

Figure 3: Conception of the H-dipole with OPERA.

A three times larger than yokes external volume is built with tangential magnetic surface limit conditions and maximum mesh elements size to 30mm. For mesh refinement along the central beam trajectory, a volume with rectangular section to 90x66mm² is modeled with maximum mesh elements size to 2mm. For the yoke, the maximum elements sizes are fixed to 20mm. Magnetic permeability of 1293G/Oe and current density of 1.99A/mm² are used corresponding to 6000G field at 185A and 172 turns/coil. Symmetries of the model are used in order to have a calculation by quarter.

We use a HP EliteBook 840 G2 with Intel® Core(TM) i5-5300 CPU at 2.30GHz with 8Go RAM. Calculation duration is 78 minutes (surface mesh, volume mesh and solving). The model had in total 6x10^6 nodes and 5.2x10^6 edges.

FIELD ANALYSIS

A first analysis can be a 3D drawing which illustrates the variation of the magnetic field at the centre of the dipole of the horizontal plans (see Fig. 4). Yoke is well identified (in green); the region of the field at 6000G inside the dipole can be also clearly located (in red).

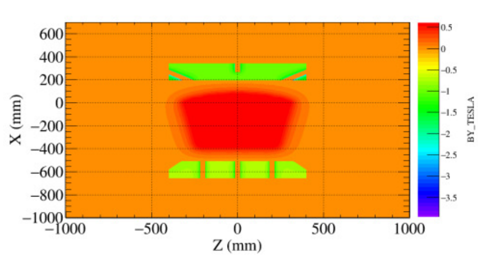

Figure 4: Horizontal plane field-map of the dipole.

Along the theoretical path of the central particle, the magnetic field can be extracted (see Fig. 5). The magnetic length is 676mm long determined from $L_m = \int B\, dl/B_0$.

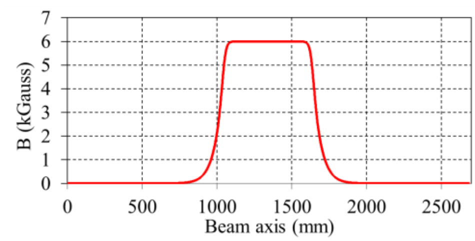

Figure 5: Magnetic field along the central theoretical path of a perfect align particle.

We also studied the magnet fringe field, thanks to existing measurements made in 1976. Figure 6 shows the comparison of the fringe field measured, the OPERA calculation and adjustment with the following function [7]:

$$\frac{B}{B_0} = 1/\left(1 + exp\left(\sum_0^4 \left(C_i \times (x+\delta)\right)\right)\right) \qquad (1)$$

With $\delta = -0.663$ $C_0 = 0.4747$, $C_1 = 2.2252$, $C_2 = -1.0931$, $C_3 = 0.67805$, $C_4 = -0.14198$. The parameters were determined by fitting the experimental curve. An excellent agreement is observe from -2cm up to 3.5cm around the limit of the edge of the magnet.

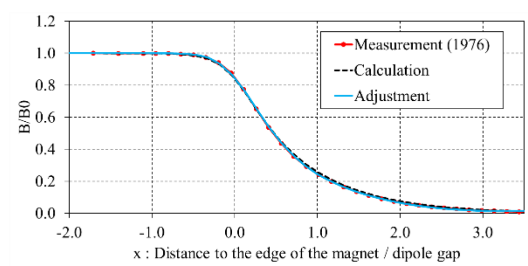

Figure 6: Fringed field of the dipole: the 1976 measurement (in red), the OPERA calculation (in black), and the fitting of the experimental data (in blue).

BEAM DYNAMICS

A fundamental aspect to know about the dipole is the particle trajectories along the magnet.

Centred Magnet Particle Tracking

For the 6kG field fixed in the OPERA calculation, single protons is tracked directly using the OPERA post-processor. This single particle is fully centered (x=y=0, x'=y'=0). The particle started at 1000mm up to the entrance face of the dipole. At 1000mm downstream the exit face for the bending angle to $\theta = 65°$ and radius $\rho = 600mm$, the optimum energy of the centre Proton is $\bar{E}_{Protons} = 5.95MeV$ $(B\rho = 0.353T.m)$. Particle divergence is $x'_{out} = -2.7 \times 10^{-5} mrad$ at 1000mm down to the exit face of the dipole. In the mid-plane of the magnet, we have $x_{mid} = 2.3mm$ and $x'_{mid} = 7 \times 10^{-6} mrad$. Trajectory length calculated using the real configuration is

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2.72mm lower than a pure theoretical description of the dipole ($L_{tot\ th.} = 1000 + \rho\theta + 1000 \sim 2681mm$). A good agreement and understanding of the zero order of the magnet is observed.

Full Bunch Particles Tracking

A realistic particles distribution of ALTO beam have been constructed. The transverse characteristics were $80\pi.mm.mrad$ marginal emittance and 7mm marginal beam size. 1000 particles are randomly generated in four-dimensional transverse hyperspace with $Size_{Max}/Size_{RMS} = \sqrt{6}$. We take a continuous beam and the same value of $\bar{E}_{Protons} = 5.95MeV$ for the distribution. Realistic energy dispersion at the exit of an ISOL source is $\delta E/\bar{E} = 0.02\%$ [8]. We choose on purpose $\delta E/\bar{E} = 2\%$ in order to push the magnet analysis. Additionally, we construct a first order transfer matrix knowing the parameters (ρ, θ, faces angles, dipole index, gap) of the magnet surrounded by two drifts. The same entrance particles distribution is used to construct the output distributions at the end of the system. First order optimisation of the magnet parameters (ρ, θ, faces angles), entrance and output drifts were done in order to obtain as close as possible pure matrix distribution and OPERA tracking distribution (see Fig. 7 and Fig. 8).

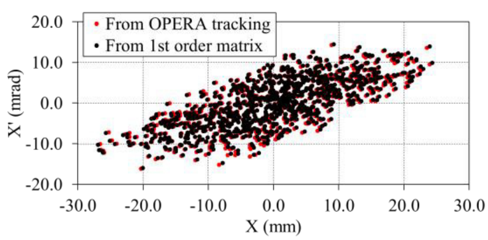

Figure 7: (X, X') emittances of 1000 particles track in the ALTO separator using OPERA and optimized pure 1st order matrix transfer.

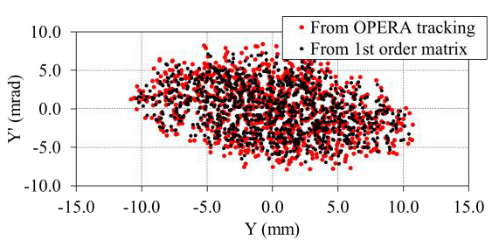

Figure 8: (Y, Y') emittances of 1000 particles track in the ALTO separator using OPERA and optimized pure 1st order matrix transfer.

The optimization gave a bending angle to 65°, a curvature to 597.6mm, face angles to 21.5°, entrance and exit drifts to 1001. 4mm, K1=0.3rad and K2=2.8rad^{-1} [9, 10]. Dispersion is 1.48m. System resolution is $R = \left|\frac{T_{16}}{2\langle x\rangle T_{11}}\right| = 5479$. We can observe an excellent agreement in the bending horizontal plane. Small discrepancies occur in the vertical plane where Twiss parameter γ for OPERA is 0.797π.mrad/mm and for the first order matrix calculation is 0.714π.mrad/mm. Therefore, small discrepancies are observed in the vertical plane. This study is not yet fully finalized.

From the OPERA post-processor, a large 5mm step 3D linear field-map was extracted and converted to TraceWin code [11]. The same methodology is used for particle tracking. We observed an excellent agreement between TraceWin calculation and the OPERA tracking.

CONCLUSION

These studies take place in the current reliability process of the radioactive ion beams installation at IPNO. In order to make the selection of the mass of the nucleus of interest for nuclear physic research produced by the ISOL technique, an old magnet separator is used. Because of historical reasons, poor material has passed in the last four decades.

We made a detail conception and calculation studies of this dipole in order to get updated knowledge. Using OPERA software, we constructed the real magnet design in term of geometry, materials and magnetic properties. Using the post-processing of the tool, we analyze in detail the field-map structure. We obtained an excellent agreement of the fringing field between the OPERA calculation and 1976 measurement. We did also the particles tracking. We produced first order matrix by fitting the basic parameters of the magnet based on the results of the particles distribution downstream the dipole obtained by the particles tracking in the field-map. A relatively good agreement was obtained.

Other bricks of the transfer beam lines like electrostatic quadrupoles, steerers and deflectors will be calculated with OPERA. All field-maps of beams optic devices to the transfer line will be inject in the TraceWin code. A full end-to-end beam calculation will be produced in order to significantly increase the experimental reliability of the RIB transport lines of ALTO facility.

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