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GANTRY DESIGN USING ACHROMATIC SCALING FIXED-FIELD MAGNETS

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Abstract

Proton therapy provides significant advantages over classic radiotherapy for specific cancerous diseases, notably by limiting the delivered dose to organs at risk (OARs). Novel treatment modalities such as flash and arc therapy require changing the energy delivered at the isocenter while providing a high dose rate. Fixed-field achromatic transport lattices satisfy both constraints, allowing ultra-fast energy modulation and excellent transmission efficiency while providing a compact footprint. Prior studies have shown that lattices using scaling fixed field magnets allow the achromatic transport of energies between 70 and 230 MeV. We investigate the use of straight scaling FFAG line that uses nonlinear fields, fulfilling the straight scaling conditions for achromatic transport, to be used as a matching section for the CASPRO ("Compact Achromatic System for Proton Therapy") project.

INTRODUCTION

Cancer treatment is a major challenge faced by society, and various techniques are being actively developed to address it, such as surgery (mechanical treatment), chemotherapy (chemical treatment), immunotherapy (biological treatment), or radiotherapy (physical treatment) [1]. Hadrontherapy uses charged particles, e.g., protons or carbon ions, that focus the beam on a specific position without irradiating healthy tissues. Moreover, novel proton therapy techniques such as flash and arc therapy have emerged to increase clinical efficiency and shorten treatment times. However, these advanced modalities pose new challenges for accelerator and beam delivery systems. They require more precise control of beam spot sizes at the isocenter, improved beam loss management, and higher beam currents. To address these challenges, gantry designs that offer achromatic transport with fixed-field magnets have been developed, enabling rapid energy scanning and providing an effective solution for the demands of these advanced proton therapy techniques [2–4].

In a previous study, we presented the CASPRO ("Compact Achromatic System for Proton Therapy") project, which designed an achromatic gantry without superconducting magnets (see Fig. 1). We have also shown that FFAG spiral magnets can transport a proton beam in an achromatic way [5]. In this paper, we will analyze the different possible technologies for the design of the matching section between the energy degrader and the entrance of the spiral magnets (block 1 in Fig. 1).

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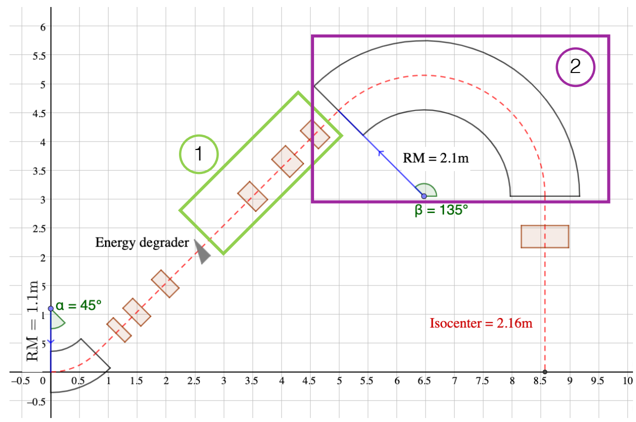

Figure 1: The proposed structure for the CASPRO achromatic gantry. The second block, in magenta, has already been studied in [5] and the purpose of this paper is the study of the block highlighted in green.

Two solutions can be intended for the design of the transport beamline between the degrader and the spiral section:

- Apochromatic beamline [6–8]
- Lines with a scaling fixed field alternating gradient magnet [9–12].

The use of apochromatic lines *i.e.*, beamline consisting in only of drifts and quadrupoles, enables the correction of chromatic effects with linear elements only. Such lines have been extensively investigated for beam distribution and transport lines design in the European X-Ray Free-Electron Laser (XFEL) facility and plasma wakefield acceleration applications. Nevertheless, the integration of these lines into a gantry can be challenging due to their relatively long (12 m) length.

As a solution, the CASPRO project has explored the possibility of scaling fixed field lines with large momentum acceptance and optical functions independent of energy. These magnets' magnetic profile resembles that of scaling FFAG magnets and is expressed as [11]:

$$B_z(x, y) = B_{z0} \left(\frac{y_0 + y}{y_0}\right)^k F(x), \quad (1)$$

where x, y, and z are, respectively, the longitudinal, horizontal, and vertical Cartesian coordinates, k is the field index and $F(x)$ is the fringe field factor and describes the field evolution with the longitudinal position. This function is 0 far from the magnet and unity in the core of the magnet. The

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decrease is modeled by a Enge function over the form [11]:

$$F(x) = \frac{1}{1 + \exp\left[\sum_{i=0}^{5} C_i (x/g)^i\right]}, \tag{2}$$

where C_i are the Enge coefficients, and g is the gap of the magnet.

Previous studies have demonstrated that Zgoubi [13, 14] is well-suited for investigating FFAG-type cells [5, 15, 16]. In this paper, we use the extended capabilities of Zgoubidoo [17], the Python interface to Zgoubi, to model the field directly using the analytic expression of the field (Eq.(1)) as input for Zgoubi. Figure 2 presents the code that generates the fieldmap, and the results are shown below.

```
fm_map = CartesianFieldMap.generate_from_expression(
   bz_expression=Bz,
   generate_3d_map=False,
   mesh=mesh,
)

FMagnet1 = fm_map(
      label1="MF1", binary=False, MOD=0, MOD2=0,
      generator=ToscaCartesian2D, load_map=True
)

kin = zgoubidoo.Kinematics(549 * _.MeV_c)
ref_beam = Objet2("BEAM", BORO=kin.brho)
ref_beam.add(np.array([[0, 0, 0, 0, 1.0]]))
zi = zgoubidoo.Input(
      name="BTL",
      line=[
         ref_beam,
         FMagnet1,
      ],
)
```

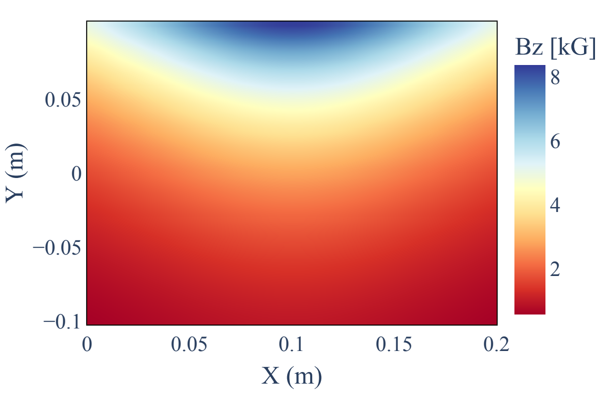

Figure 2: Code example (up) that builds the field map based on Eq. (1) to be direclty used in Zgoubi and its visual representation (bottom).

STRAIGHT SCALING FFAG BEAMLINE

Several studies have recently investigated straight Fixed-Field Alternating Gradient (FFAG) cells due to their significant acceptance and constant magnetic field. This paper compares the results from reference [12] computed with S-CODE [18] to those obtained using Zgoubidoo.

The transport beamline consists of four magnets in a DFFD configuration, each magnet measuring 20 cm length and separated by a 20 cm drift. The beamline's parameters are summarized in Tab. 1, and it aims to achromatically transport beams with momenta from 369 MeV/c to 729 MeV/c, corresponding to energies between 70 MeV and 250 MeV.

Table 1: Cell Parameters of the Straight FFA Beamline

Parameter	Value
Magnet length	0.2 m
Short drift length	0.2 cm
Long drift length	3.6 m
Cell length	5 m
Field index k / y_0	11 m^{-1}
B_{z0} at F	0.36 T
B_{z0} at D	−0.43 T
Gap of magnet	15 cm
Enge coefficients	0.146, 2.267, -0.64
C_i $(i = 0, 5)$	1.156, 0, 0

The first validation is determining the closed orbits for various energies within the beamline. For this purpose, a fit is performed for each energy to ensure that the input position in the beamline equals the output. The results in Fig. 3 show the trajectory's evolution within the cell and the magnetic field. As we observe, there is excellent agreement between the two software.

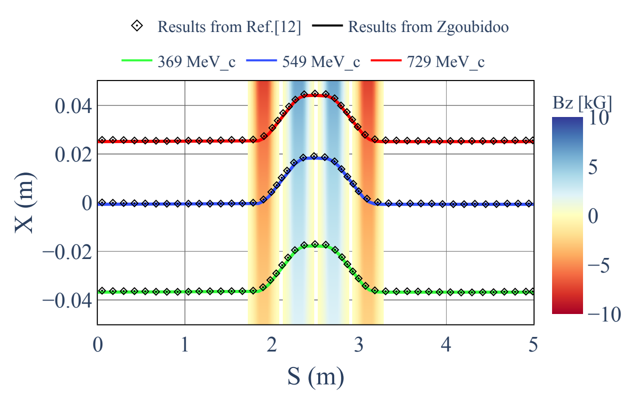

Figure 3: Closed orbits in a cell for different momentum. The dots correspond to the data from Ref. [12] and the lines are Zgoubidoo results.

We also verified that the magnetic field saw by the particles are in accordance between S-CODE and Zgoubidoo. And as for the orbits, we observe that results in Fig. 4 are in excellent agreement.

The last validation that has been carried out concerns the comparison of the evolution of the beta functions in the beamline. The results obtained are presented in Fig. 5. We also observe an excellent agreement between the two softwares although there are slight differences that are under investigations.

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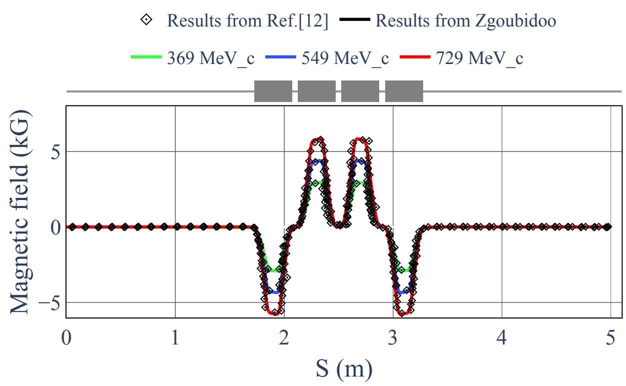

Figure 4: Magnetic field along the particle trajectory at different momentum in a cell. The dots correspond to the data from Ref. [12] and the lines are Zgoubidoo results. We observe an excellent agreement between S-Code and Zgoubidoo.

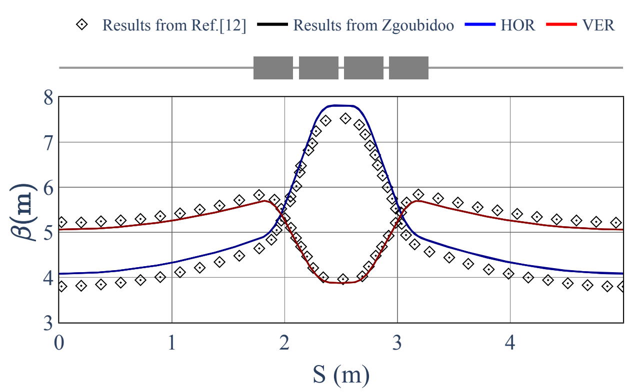

Figure 5: Beta functions in a cell for different momentum. The dots correspond to the data from Ref. [12] and the lines are Zgoubidoo results.

We have shown that straight FFA beamlines can be an interesting technology to match the energy degrader and the entrance of the spiral section of the proposed gantry for the CASPRO project. Indeed, they achromatically transport beams with energies in the 70-250 MeV range while using normal-conducting magnets.

CONCLUSION

This paper demonstrates that Zgoubi(doo) accurately reproduces the results obtained for a straight Fixed Field Alternating Gradient (FFAG) beamline. These FFAG lines are expected to be highly valuable in the CASPRO project, which aims to design an achromatic gantry for proton therapy. We have computed the closed orbits and the magnetic field experienced by particles along the entire beamline and show that they are in excellent agreement. Furthermore, we have shown excellent agreement between the beta functions obtained from Ref. [12] and Zgoubidoo. The next phase of this project involves compacting this cell to integrate before the bending section of the gantry.

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