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THE ZGOUBIDOO PYTHON FRAMEWORK FOR RAY-TRACING SIMULATIONS WITH ZGOUBI: APPLICATIONS TO FIXED-FIELD ACCELERATORS

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Abstract

The study of beam dynamics in accelerators featuring main magnets with complex geometries such as Fixed Field Accelerators (FFAs) requires simulation codes allowing step-by-step particle tracking in complex magnetic fields, such as the Zgoubi ray-tracing code. To facilitate the use of Zgoubi and to allow readily processing the resulting tracking data, we developed a modern Python 3 interface, Zgoubidoo, using Zgoubi in the backend. In this work, the key features of Zgoubidoo are illustrated by detailing the main steps to obtain a non-scaling FFA accelerator from a scaling design. The results obtained are in excellent agreement with prior results, including the tune computation and orbit shifts. These results are enhanced by Zgoubidoo beam dynamics analysis and visualization tools, including the placement of lattice elements in a global coordinate system and the computation of linear step-by-step optics. The validation of Zgoubidoo on conventional scaling and non-scaling FFA designs paves the way for future uses in innovative FFA design studies.

INTRODUCTION

The magnetic field of FFAs is constant in time, which allows rapidly accelerating different kinds of beams, in particular high-intensity beams (high repetition rate), in a wide energy range (variable energy beam). Their magnetic structure also enables strong focusing, either focusing using alternating fields or focusing using spiral magnet edges. These key points allow FFAs to be accelerators of choice for some applications: FFAs have already been considered for neutron spallation, muon accelerators, and medical applications [1–5]. There are two main variants of FFAs: scaling FFAs and non-scaling FFAs. Scaling FFAs, which were the first to be studied, allow having constant tunes with energy by imposing a strong condition on the magnetic field, while non-scaling FFAs relax this condition to have easier to build magnets and to reduce the orbit shift at the expense of a non-zero tune variation. The complex geometry and magnetic fields and the absence of a true reference trajectory due to its energy dependence make simulation codes featuring step-by-step tracking the tools of choice. The Zgoubi ray-tracing code [6–8] allows tracking particles in any magnetic and electric field, particularly in highly non-linear magnetic fields, which is the case for FFAs. In addition, Zgoubi realistically models the magnet fringe fields and allows the user to implement complex and arbitrary misalignment of the magnetic elements, and shape of the magnet edges. It can be used for the optics study, helpful for the accelerator design, but also for the final study of the lattice, using measured field maps with realistic fringe fields and possible magnetic imperfections. Because of these advantages, Zgoubi has been extensively used to study FFA lattices [5, 9]. To facilitate the use of Zgoubi and allow data analyzes and simplified visualizations, we developed a modern Python 3 interface using Zgoubi in the backend: Zgoubidoo [10]. This library provides a fully featured and easy-to-use interface to Zgoubi. It can be used both to generate Zgoubi input files and run the simulations in parallel, as well as to perform more advanced tracking results analyzes, including linear and non-linear beam dynamics studies. Additionally, Zgoubidoo also has modules ensuring the correct placement of the lattice elements in space and the plotting of the beamline and tracking results, including particle trajectories in the global reference frame. Zgoubidoo thus has all the necessary tools to study all kinds of accelerators, especially FFAs. This work illustrates the main features of Zgoubidoo on well-known scaling and non-scaling FFA designs [11, 12]. First, the main steps to model and simulate a scaling lattice with a large field index [11] are presented. Then, the magnet simplification steps allowing to transform this scaling design into a non-scaling one following the steps presented in Ref. [12] are detailed. The complete analysis of conventional FFA lattices with Zgoubidoo, from the closed orbit search to the linear tune computation, validates its different modules and paves the way for further studies of FFA designs.

MODEL DEFINITION OF THE SCALING LATTICE

The first lattice studied with Zgoubidoo is scaling and consists of 12 identical triplet cells, with radial focusing (sector-alternating field) and a nominal energy of 250 MeV. The working point of this lattice is chosen in the second stability region of Hill's equations, with a phase advance per cell larger than 180°, which implies choosing a large field index. It allows reducing the orbit shift while remaining a scaling lattice and therefore having energy-independent tunes [11]. Zgoubidoo allows studying this lattice: closed orbit search, particle tracking, linear and non-linear beam dynamics, and parametric study to set the working point. Zgoubidoo's class structure makes it straightforward to create the lattice with a few efficient commands: it is possible to build a Zgoubi input file with realistic default values for the

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```
kin = zgoubidoo.Kinematics(250 * units.MeV)
beam_for_tracks = Objet2('BUNCH', BORO=kin.brho)
beam_for_tracks.add(np.array(closed_orbit))
FDF_cell = FFAG(f"FDF_cell",
    N= 3, RM = r0, AT = cell_angle,
    ACN=[10.20, 15.0045, 19.80741, 0, 0] * units.degree,
    BZO=[BOF, BOD, BOF, 0.0, 0.0] * units.kilogauss,
    K=[k, k, k, 0.0, 0.0],
    OMEGA_E=[1.2, 1.2, 1.2, 0, 0] * units.degree,
    OMEGA_S=[-1.2, -1.2, -1.2, 0.0, 0.0] * units.degree,
)
zi = zgoubidoo.Input(name ="FDF_cell",
    line = [beam_for_tracks, FDF_cell])
```

Figure 1: Code example that builds the lattice cell consisting of three FFA scaling magnets and the reference particle with a few Zgoubidoo commands. The magnet parameters are given in the form of lists, allowing to readily manage Zgoubi keywords with several magnets in their integration zone.

element parameters in Zgoubidoo. As an example, Figure 1 shows the simple creation of a cell consisting of three FFA magnets.

For FFA components, Zgoubi allows having up to 5 FFA magnets in the same element (keyword 'FFA' [13]). In the Zgoubi input file, it involves duplicating blocks of lines to have the required number of magnets and changing the desired parameters in the right place, which is error-prone. Zgoubidoo allows to readily define FFA elements by giving the magnet parameters in the form of lists. After running the simulations on the previously created beamline, Zgoubidoo allows the automatic tracking result collection and the plotting of the retrieved tracks along with a 2D representation of the beamline. The Zgoubidoo plotting module represents the FFA elements with their magnets (and magnet shape) and their entire integration zone. The user can thus verify the correct magnet placement in the FFA element and the correct shape for the magnet edges. Figure 2 shows one of the cells of the considered scaling lattice.

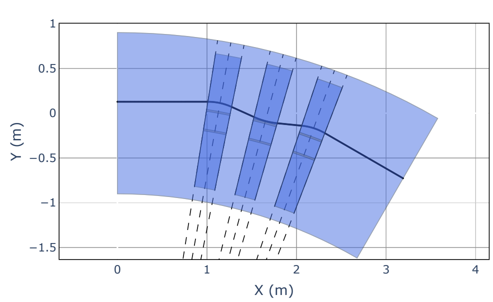

Figure 2: One cell of the model scaling FFA lattice. Zgoubidoo's plotting module allows a 2D representation of the cell. The FFA magnets are shown in dark blue, while the FFA element integration zone is shown in light blue. The dotted lines indicate the straight magnet faces and the mean radius of the FFA element.

In addition to this plotting module, Zgoubidoo has a powerful survey module that associates a global reference to the ring and thus places all the elements in space. Contrary to Zgoubi, which only uses local frames, Zgoubidoo makes it possible to know the global geometry of the ring, allowing better visualization of the lattice. Figure 3 shows the entire accelerator ring, along with the closed orbits for different energies. We can observe the horizontal orbit shifts and the geometric similarity of the orbits of the particles at different energies, which characterizes a scaling machine. Additionally, this figure shows the difference in orbit shift between working points set in the two stability regions: the orbit shift for the working point in the second stability region is equal to 0.17 m, which is significantly reduced compared to the orbit shift in the first stability region (~ 0.83 m). These results correspond perfectly to prior results [11].

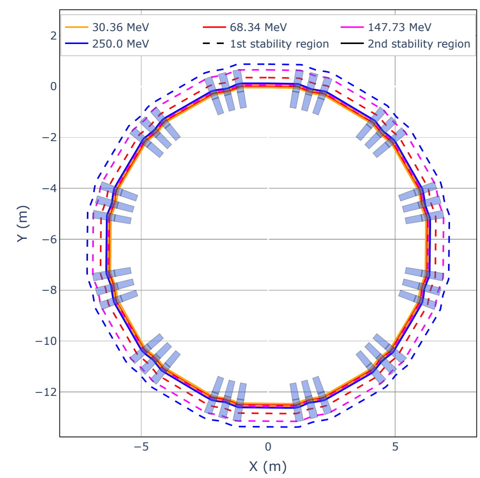

Figure 3: Representation of the entire ring. Zgoubidoo's survey module correctly places the elements and the particle trajectories in a global reference frame.

FROM A SCALING TO A NON-SCALING DESIGN

It is possible to transform the design of the scaling lattice to obtain a non-scaling lattice with simplified and more compact magnets. We have reproduced with Zgoubidoo different magnet simplification steps allowing such a design transformation [12]: the first step consists in expanding the scaling FFA non-linear field in terms of multipoles and truncating this series at the lowest orders (up to n=5 for a dodecapole); The second step transforms the sector-magnets into rectangular-shaped magnets; The last simplification consists in the alignment of the three magnets parallel to each other with different transverse offsets between the magnets. Figure 4 shows the three simplifications on the baseline cell.

To adapt the lattice for each simplification, in addition to changing the magnet shape and type, it is necessary to fit the magnetic field and radius of each element to have the same integrated magnetic field as in the scaling FFA element. Zgoubidoo simplifies the use of the complex Zgoubi FIT command, especially by managing the numbering associated with the parameters of each magnet. Zgoubidoo also allows

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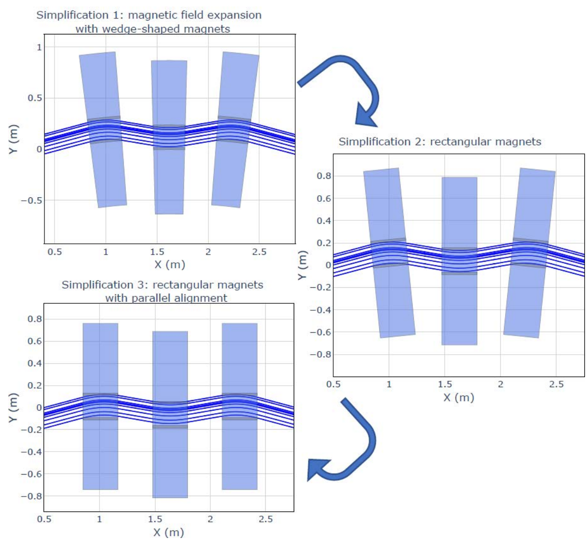

Figure 4: Non-scaling cell evolution with the different magnet simplifications presented in Ref. [12]. The cell consists of three magnets whose field is a truncated multipolar expansion. The magnets are first sector then rectangular, either facing the ring center or aligned with each other.

to readily retrieve the results of a FIT command by storing them in easily usable data structures in Python. By looking for the appropriate magnet parameters (nominal magnetic fields and offsets), it is possible to have an integrated field equivalent to that obtained in a scaling FFA. Figure 5 shows, for the first simplification, the magnetic field seen by particles at different energies, either in a scaling FFA element or in a magnet whose magnetic field is truncated at order 5. By correctly adapting the magnet parameters, the magnetic field is very similar in both cases. The magnets being rectangular for the other two simplifications, it is no longer possible to have closed orbits comparable to those in the scaling FFA. The magnetic field seen by the particles will thus be different, but the integral of the magnetic field in the successive magnets will always remain close to the scaling value.

Finally, Zgoubidoo allows the computation of linear optics at each integration step. Tracking results from Zgoubi are stored in data frames for data analysis: the user no longer has to read text files but can do everything using Python 3 and associated libraries (pandas, NumPy). From the tracking results in the Frenet-Serret reference frame, Zgoubidoo can compute the transfer matrices at each integration step, as well as the Twiss parameters. As an example, Fig. 6 shows the β-functions for two energies and a truncation of the multipole expansion at the 3rd order or the 5th order. We observe that the β-functions are more similar for a higher-order truncation because a particle with an offset will see the influence of higher-order terms in the magnetic field.

Finally, it is also possible to compute the cell and ring tunes for different energies and for all the simplifications. Figure 7 shows the excellent agreement between the tune evolution obtained with Zgoubidoo and the original results obtained in Ref [12].

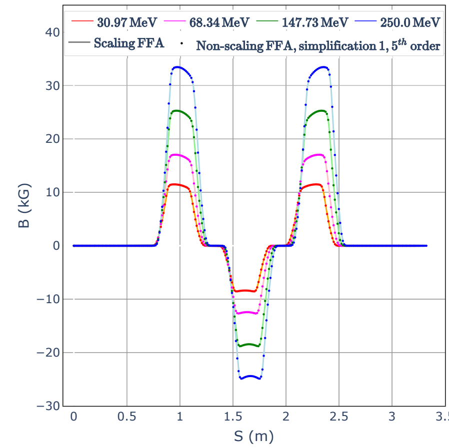

Figure 5: Magnetic field along the particle trajectory at different energies in a cell composed of scaling FFA elements and a cell with magnets whose magnetic field is truncated at the 5th order.

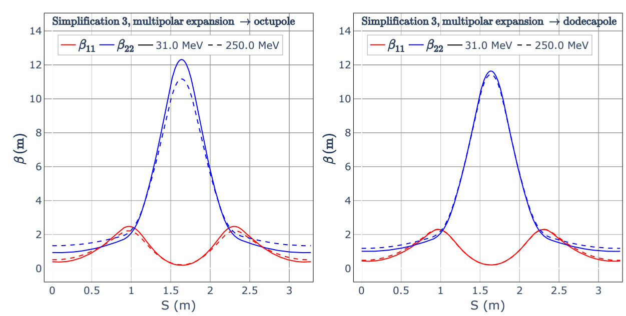

Figure 6: Horizontal and vertical β-functions (respectively β_{11} and β_{22}) for different energies obtained for the third simplification and a multipolar expansion truncated at the 3rd or 5th order.

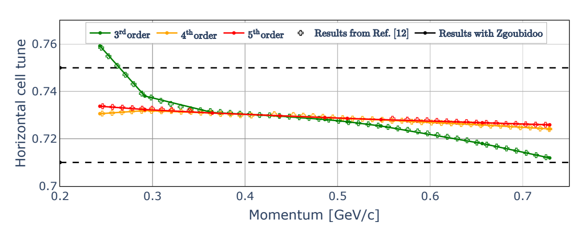

Figure 7: Horizontal tune evolution with momentum, for the last magnet simplification step and different truncation orders for the field multipolar expansion. There is an excellent agreement between original results using Zgoubi [12] and results obtained with Zgoubidoo.

CONCLUSION

We used Zgoubidoo to study FFA lattices and illustrate the steps to transform a scaling FFA design into a non-scaling one. It has been shown that Zgoubidoo significantly enhances the use of Zgoubi, from the preparation of parametrized input files to the processing of tracking data, while offering additional advanced analysis and visualization. Zgoubidoo provides a set of numerical tracking

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methods and tools allowing the beam dynamics analysis, from the search for closed orbits to the computation of the linear and non-linear beam dynamics. The study of conventional FFA lattices with Zgoubidoo provides results in excellent agreement with prior results, including the correct linear optics computation, which shows that Zgoubidoo can be used extensively for further studies of FFAs accelerators.

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REFERENCES

[1] S. Machida, "FFA Options for ISIS upgrade and the feasibility study," in *Proc. 3rd J-PARC Symposium (J-PARC2019)*, 2021, p. 011 005, doi:10.7566/JPSCP.33.011005

[2] S. L. Sheehy, "High intensity and other world wide developments in FFAG," in *Proc. Cyclotrons'16*, Zurich, Switzerland, Sep. 2016, pp. 374–379, doi:10.18429/JACoW-Cyclotrons2016-THD01

[3] F. Méot, "RACCAM: An example of spiral sector scaling FFA technology," Tech. Rep. BNL–211536-2019-NEWS, 1507116, 2019, https://www.osti.gov/servlets/purl/1507116, doi:10.2172/1507116, BNL–211536-2019-NEWS, 1 507 116, doi:10.2172/1507116

[4] S. Antoine *et al.*, "Principle design of a protontherapy, rapid-cycling, variable energy spiral FFAG," *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 602, no. 2, pp. 293–305, 2009, doi:10.1016/j.nima.2009.01.025, doi:10.1016/j.nima.2009.01.025

[5] K. J. Peach *et al.*, "Conceptual design of a nonscaling fixed field alternating gradient accelerator for protons and carbon ions for charged particle therapy," *Phys. Rev. ST Accel. Beams*, vol. 16, no. 3, p. 030 101, 2013, doi:10.1103/PhysRevSTAB.16.030101, doi:10.1103/PhysRevSTAB.16.030101

[6] F. Méot, "The ray-tracing code Zgoubi," *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 427, no. 1-2, pp. 353–356, 1999, doi:10.1016/S0168-9002(98)01508-3, doi:10.1016/S0168-9002(98)01508-3

[7] F. Méot and J. Berg, *Zgoubi*, http://sourceforge.net/projects/zgoubi/, 2020.

[8] F. Méot, "The ray-tracing code Zgoubi – Status," *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 767, pp. 112–125, 2014, doi:10.1016/j.nima.2014.07.022, doi:10.1016/j.nima.2014.07.022

[9] J. Fourrier, F. Martinache, F. Méot, and J. Pasternak, "Spiral FFAG lattice design tools. Application to 6-D tracking in a proton-therapy class lattice," *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 589, no. 2, pp. 133–142, 2008, doi:10.1016/j.nima.2008.01.082, doi:10.1016/j.nima.2008.01.082

[10] C. Hernalsteens, R. Tesse, and M. Vanwelde, *Zgoubidoo*, https://ulb-metronu.github.io/zgoubidoo/, 2022.

[11] S. Machida, "Scaling fixed-field alternating gradient accelerators with a small orbit excursion," *Phys. Rev. Lett.*, vol. 103, no. 16, p. 164 801, 2009, doi:10.1103/PhysRevLett.103.164801, doi:10.1103/PhysRevLett.103.164801

[12] S. Sheehy, K. Peach, H. Witte, D. Kelliher, and S. Machida, "Fixed field alternating gradient accelerator with small orbit shift and tune excursion," *Phys. Rev. ST Accel. Beams*, vol. 13, no. 4, p. 040 101, 2010, doi:10.1103/PhysRevSTAB.13.040101, doi:10.1103/PhysRevSTAB.13.040101

[13] F. Méot, "Zgoubi users' guide," Technical Report BNL-98726-2012-IR, 2012, https://www.bnl.gov/isd/documents/79375.pdf