APPLICATIONS OF ADVANCED SCALING FFAG ACCELERATOR

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Abstract

Until today, scaling FFAG accelerator were only designed in a ring shape. But a new criteria of the magnetic field configuration satisfying the scaling condition even for straight FFAG beam line has been recently found. Moreover, combining different types of cells can be used to imagine new lattices. Various applications using these recent developments are here examined: improvements of the PRISM project and the ERIT project, and a zero-chromatic carbon gantry concept are presented.

INTRODUCTION

Recent developments in scaling FFAGs have opened new ways for lattice design [1, 2]. Indeed, it is possible to guide particles with no overall bend in scaling FFAGs, with an exponential field law. Different types of cells can be combined in the same lattice. It offers possibilities in terms of shape for rings and transport lines, but also leads to the creation of new functions, such as dispersion suppressors. This concept can be applied to overcome problems like in the PRISM project, or to improve existing schemes, like the ERIT lattice. Finally, a scaling FFAG carbon gantry concept is briefly described.

INSERTION AND DISPERSION SUPPRESSOR

Insertion

It is possible to combine two different FFAG cells by matching the dispersion [1]. The periodic beta-functions of the cells have also to be matched to limit the amplitude of the betatron oscillations. If a correct matching is not achievable, then a transparent insertion with a phase advance multiple of 180 deg. can be done for one of the two different types of cells.

Dispersion Suppressor

A principle of a dispersion suppressor in scaling FFAGs is presented in Fig. 1. The components of this scheme are three types of scaling FFAG cells, straight or circular. The area 1 contains FFAG cells with a dispersion D_1 at the border, the area 2, constituting the dispersion suppressor itself, contains FFAG cells with a dispersion D_2 at the borders, and the area 3 contains FFAG cells with a dispersion D_3 at the border. The conditions to have a dispersion suppressor are a phase advance of 180 deg. for the cells of the area 2 and the dispersion D_2 has to verify

$$D_2 = \frac{D_1 + D_3}{2}. \tag{1}$$

This principle is based on the linear theory, so is valid as long as the effect of non-linearities is negligible.

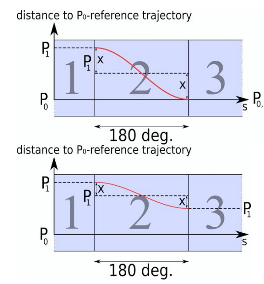

Figure 1: Principle of a dispersion suppressor with scaling FFAG cells. The upper scheme shows the case of a complete suppression of the dispersion, the lower one the case of a remaining dispersion after the dispersion suppressor.

PRISM CASE

The PRISM (Phase Rotated Intense Slow Muon beam) project aims to realize a low-energy muon beam with a high-intensity, narrow energy spread and high purity. For this purpose, a scaling FFAG ring has been proposed [3]. Requirements for the FFAG ring include a large transverse and longitudinal acceptance. The original design of the FFAG ring for PRISM is based on 10 identical DFD triplets. If this design fulfills the requirements of acceptance, the excursion is very large and the injection and extraction still remains difficult. To solve this problem, we consider the use of straight cells in the lattice and a new design is proposed (see Fig. 2). Parameters are summarized in table 1.

Particle tracking is done with Runge-Kutta integration in soft edge fields with linear fringe field falloffs. Components of the field off the mid-plane are obtained from a first order Taylor expansion, satisfying the Maxwell equations.

The original PRISM design has a very large dispersion function (~ 1.2 m) that makes difficult the injection and the extraction. The new proposal starts then from a smaller one (~ 0.8 m). After minimizing the mismatch of the beta-functions, the bending part of the ring is made transparent to limit the effect of the remaining mismatch on the

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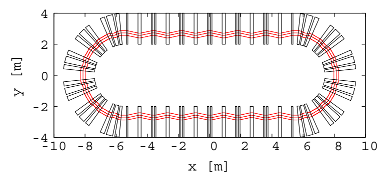

Figure 2: Closed orbits of 55 MeV/c, 68 MeV/c and 82 MeV/c muons μ^- in the PRISM lattice with straight sections.

Table 1: Parameters of the new PRISM lattice.

	Circular Section	Straight Section
Type	FDF	FDF
k-value or m-value	2.55	$1.3\,\mathrm{m}^{-1}$
Radius/Length	2.7 m	1.8 m
Horizontal phase advance	60 deg.	27 deg.
Vertical phase advance	90 deg.	97 deg.
Number of cells	2	3

amplitude of the betatron oscillations. The resulting beta-functions for a momentum of 68 MeV/c are presented in Fig. 3. The working point is chosen in the tune diagram so that it is far from the structural normal resonances. The present working point has a tune of 2.9 in horizontal and 6.3 in vertical.

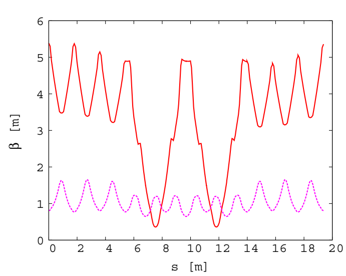

Figure 3: Horizontal (plain red) and vertical (dotted purple) beta-functions for half of the ring of the PRISM lattice.

The transverse acceptance in both planes is studied by tracking over 30 turns a particle with a displacement off the closed orbit and a small deviation in the other transverse direction (1 mm). Collimators ($\pm$ 1 m in horizontal, $\pm$ 30 cm in vertical) are used to identify the lost particles. The regions drawn by the particle with the largest initial stable amplitude in the horizontal and vertical phase spaces are respectively presented in Fig. 4 and 5. Horizontal ($\sim$ 24000 π.mm.mrad) and vertical ($\sim$ 6000 π.mm.mrad) acceptances are then measured by the area of the biggest ellipse included in this region.

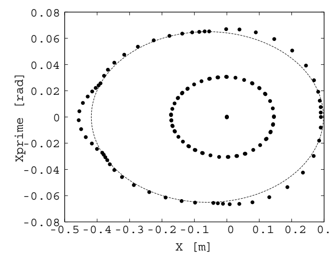

Figure 4: Horizontal phase space. Two particles with an initial displacement of 15 cm and 29 cm are tracked in the PRISM lattice over 30 turns. The dotted ellipse is the one used to measure the acceptance in the middle of the straight section.

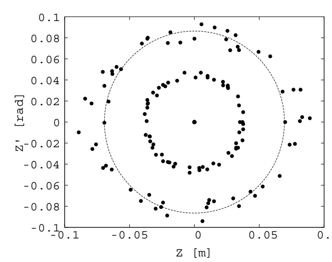

Figure 5: Vertical phase space. Two particles with an initial displacement of 3.5 cm and 7 cm are tracked in the PRISM lattice over 30 turns. The dotted ellipse is the one used to measure the acceptance in the middle of the straight section.

ERIT CASE

The ERIT (Energy/Emittance Recovery Internal Target) project with a scaling type of FFAG proton storage ring has been proposed as an accelerator-based intense thermal or epithermal neutron source (ABNS) for boron neutron capture therapy and constructed in KURRI [4]. Emittance blow up due to multiple scattering and energy straggling in the target is limited by ionization cooling. The results are promising [5], but since limitation of the survival rate of the protons comes from the emittance growth in the vertical plane, an insertion with a minimum of vertical betafunction could improve this scheme.

The purpose of the insertion is to decrease the value of the vertical betafunction at the target. In the existing scheme, the vertical betafunction is 0.8 m. The length of the insertion is settled from the RF frequency of the existing cavity (18.2 MHz). To minimize the effect of the mismatch on the amplitude of the betatron oscillations, the arc is modified by changing the k-value (from 1.92 to 2.57) to become transparent. This change in the design will have a small effect on dispersion (from 0.8 m to 0.65 m). The parameters of the new lattice are presented in table 2.

Particle tracking is done again with Runge-Kutta integration in the same conditions than in the PRISM case. The tune is 2.22 in horizontal and 2.82 in vertical.

Betafunctions are obtained with a small amplitude mo-

Table 2: Parameters of the new ERIT lattice.

	Circular Section	Straight Section
Type	FDF	DFFD
k-value or m-value	2.57	1.52 m^{-1}
Radius/Length	2.35 m	1.4 m
Horizontal phase advance	90 deg.	41 deg.
Vertical phase advance	90 deg.	148 deg.
Number of cells	8	2

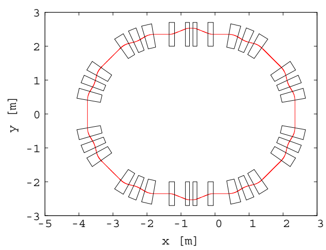

Figure 6: Closed orbit of 11 MeV proton in the ERIT lattice with the insertion.

tion (see Fig. 7): at the target, the horizontal betafunction is 3.2 m and the vertical one 0.29 m. The vertical betafunction is thus smaller by a factor 3 at the target, but the horizontal one is bigger by a factor 2.5 compared with the original lattice. Further study must be realized to check if the horizontal acceptance (more than 10000π mm.mrad, see Fig. 8) is enough to handle the overheating due to the increase of the betafunction.

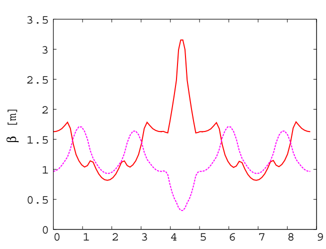

Figure 7: Horizontal (plain red) and vertical (dotted purple) beta-functions for half of the ring of the ERIT lattice.

TRANSPORT LINE AND CARBON GANTRY

FFAG transport line could be useful to transport different momenta in a short time in the same line, like in hadron therapy gantries. In zero-chromatic FFAGs, each momentum has a different reference trajectory. Dispersion suppressors are then necessary at the beginning and at the end of the gantry since all different momenta come from and arrive at the same point. Another constraint comes from the reverse bend in the line. It induces to reverse the dispersion

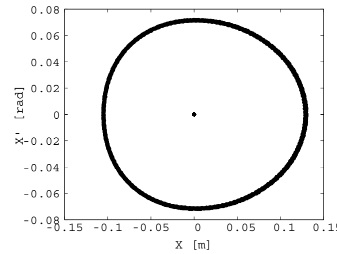

Figure 8: Horizontal phase space. An 11 MeV proton with an initial displacement of 13 cm is tracked in the ERIT lattice over 1000 turns.

between the two bends, or to use a negative-k lattice in one of the bends. A schematic layout is presented in Fig. 9.

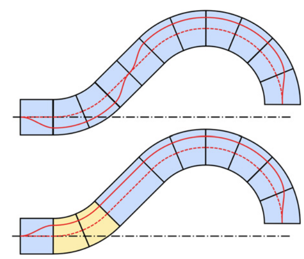

Figure 9: Schematic layout of a zero-chromatic FFAG gantry. The dotted red line represents the trajectory of a middle momentum, and the plain red line the maximum momentum. The mixed lines represents the rotation axis. The upper scheme shows the case of a reverse dispersion, the lower one the case of a negative-k lattice (in yellow).

SUMMARY

To overcome the problem of injection/extraction in the PRISM project, a new lattice using straight sections is proposed. An improvement of the ERIT scheme is then presented with a low-betafunction insertion in the ring. Finally the concept of a zero-chromatic FFAG carbon gantry is described. if these proposals need further studies, they open a promising way to improve lattices and schemes.

REFERENCES

[1] JB. Lagrange et al, "Straight section in scaling FFAG accelerator", PAC'09, Vancouver, FR5PFP002 (2009).

[2] JB. Lagrange et al, "Zero-chromatic FFAG straight section", FFAG'09, Fermilab (2009).

[3] "The PRISM Project - A Muon Source of the World-Highest Brightness by Phase Rotation -, *LOI for Nuclear and Particle Physics Experiments at the J-PARC* 217 (2003).

[4] Y. Mori, "Development of FFAG accelerators and their applications for intense secondary particle production", Nucl. Instrum. Methods Phys. Res. , Sect. A 562, 591-595 (2006).

[5] K. Okabe et al, "Study for FFAG-ERIT neutron source", IPAC'10 , Kyoto (2010).