VARIABLE ENERGY PROTONTHERAPY FFAG ACCELERATOR [*]

For the RACCAM Project :
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Abstract

This paper presents the design of a variable energy spiral scaling FFAG (Fixed Field Alternating Gradient) accelerator installation, sized for producing 70 to 180 MeV protons. A prototype of the spiral magnet has been designed and is being constructed at SIGMAPHI, magnetic measurements to be performed next August September.

INTRODUCTION

The RACCAM project [1] aims at contributing to the on-going worldwide R&D activity regarding the use of the FFAG method for the neutrino factory [3, 4], and at exploring the domain of medical applications.

This paper focuses on the second domain. It presents a principle design study of a medical spiral scaling FFAG installation, schemed in Fig. 1, capable of producing variable energy proton beams with potentially high repetition and dose delivery rates. General parameters are given in Tab. 1. This work is far from completion, on contrary on some aspects it tends to raise questions rather than bringing answers. However it is believed that in its present state it allows establishing principles regarding FFAG protontherapy beam production, and can serve as a basis for further R&D. The accelerator assembly (Fig. 1) comprises an H^- variable extraction energy cyclotron that fits inside the main ring, a short beam line, a kicker-septum injection system (with provision for multiturn injection), the FFAG ring with two RF cavities whose design is now under study [5], and two single-turn extraction ports.

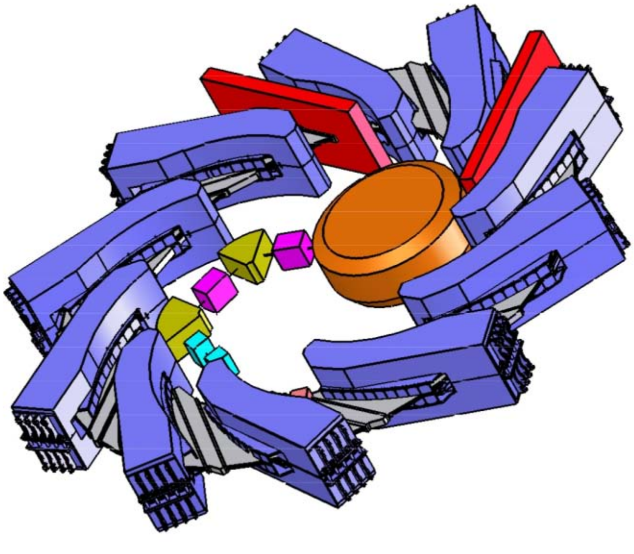

Figure 1: Layout of the RACCAM installation.

Table 1: Medical proton FFAG accelerator parameters.

Energy, variable	MeV	$70 \rightarrow 180$
Average intensity	nA	> 100
Extraction efficiency	%	> 95
Extraction mode		bunch-to-pixel
Rep. Rate	Hz	> 100
Treatment time	min	~ 1
Dose	Gy×l/min	> 5
Size	m	<10
Patients/year	/2 shifts	> 1000
Power at plug	kW	≈ 200
Weight	tons	< 200
Particle desirable		p
at lower Bragg range, w/ proper injector		He, C, O
Extraction ports		2

SPECIFICATIONS

Medical specifications that yield the parameters displayed in Tabs. 1, 3 have been established in collaboration with the MEDICYC team of the anti-cancer Center Antoine Lacassagne (CAL). At present, the 65MeV cyclotron at CAL performs eye treatment, however a 180 MeV (20 cm Bragg range, plus some margin) upgrade is being discussed, in view of widening treatment possibilities.

With the aim of exploiting FFAG potentialities, challenging properties are foreseen, as (i) dose rate of 5 Gy.liter/minute and beyond ; (ii) in order to allow for space charge free working regime ($< 10^9$p/pulse or less), this constrains the repetition rate in the 100-200 Hz range ; (iii) multiport extraction, etc.

INJECTOR

Preliminary studies have been carried out to demonstrate the feasibility a simple variable energy azimuthally varying field (AVF) compact cyclotron injector to feed the FFAG ring [6]. General parameters are given in Tab. 2. Extraction based on a fast switch multi-stripper has been successfully simulated (Fig. 2) (it allows Bragg peak depth steps within cm range) ; angular separation between min. and max. energies at focus point is 22 degrees. Fast acceleration yields good turn separation, leading to transverse optical properties appropriate for injection into the FFAG, reduction of

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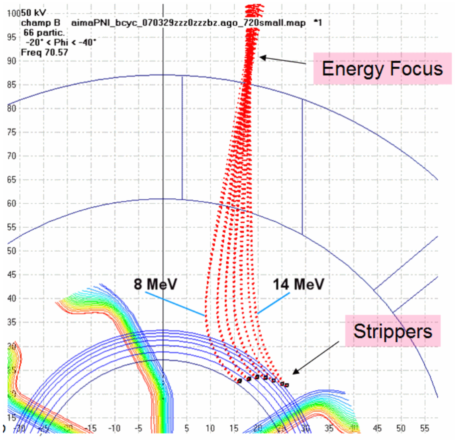

Figure 2: Path of the extracted beams.

Table 2: Properties of injector cyclotron.

energy, variable	MeV	5.5 → 15
RF frequency (h=3)	MHz	70.6
number of dees, gaps		3, 6
acceleration rate, time	keV/turn, μs	270, <1
		(60 turns at 15 MeV)
multi-stripper extraction :		
num. of turns		1
efficiency	%	> 80
$\epsilon_{x,z}/\pi$, max., norm.	10^{-6}m	0.3, 0.5
dp/p, total		$3\,10^{-3}$
con's for multiturn injection into FFAG :		
num. of turns		10
protons/cyclo. bunch		$1.5\,10^{7}$
num. of cyclo. bunches		200
cyclo. d.c. current	μA	170
pulse duration	μs	3

momentum spread needs further work. An external high brightness multicusp ion source provides the H$^-$ beam, 10 mA/cm, 5 mA dc (to accelerate 350μA), with possibility of fast modulation of the injected intensity, compatible with the bunch-to-pixel patient irradiation approach.

FFAG RING

The ring is schemed in Fig. 1. Parameters as spiral angle ζ, field index k, packing factor pf, number of cells, etc., have been subject to thorough optimization studies so to yield appropriate working point, large enough dynamic apertures, etc. These studies have been subject to earlier communications [1, 2], requiring the development of dedicated numerical tools and extensive simulation work [8, 9, 10], and resulted in the present design, with properties summarized in Tab. 3, and in the following.

The field index k has been taken large enough to limit the radial extent of the magnet, small enough to avoid large spiral angle ζ. The working point has been adjusted (via (k, ζ) adjustment) so to allow efficient multi-turn injection, while preventing strong non-linear coupling, and yielding large enough dynamic aperture, which results in $Q_x = 2.75$ at all energy, while $Q_z : 1.55 \rightarrow 1.65$ from injection to extraction (vertical tune can be made constant by appropriate fringe field extent, namely proportional to orbit radius r, however the present variation purposely mimics the prototype magnet behavior [8]). Fig. 3 shows the closed orbits, from both arc of circles modelling (solid lines) and stepwise ray-tracing (dots). Resulting optical functions on extreme orbits, from matrix modelling, are shown in Fig. 4,

Table 3: Medical proton FFAG ring parameters.

		injection	extraction
energy, variable	MeV	5.5 – 15	70 – 180
field on orbit	T	0.35 – 0.58	1.03 – 1.7
average radius	m	2.79	3.46
drift length	m	1.16	1.44
RF freq. (h=1)	MHz	1.86 – 3.03	5.07 – 7.54
bunch parameters (10-turn injection) :			
num. of protons		$3\,10^8$	
ϵ_x/π, max.	10^{-6}m	30 – 15	8 – 4
ϵ_z/π, max.	10^{-6}m	5 – 2.5	1.5 – 0.7
dp/p, required		10^{-3}	10^{-3}
lattice :		spiral	
field index, k		5	
spiral angle, ζ	deg.	53.7	
flutter, $R/\rho - 1$		1.94	
num. of cells		10	
tunes, Q_r, Q_z		2.76, ∼1.60	

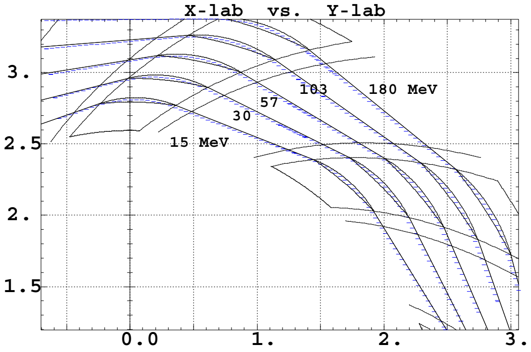

Figure 3: Closed orbits.

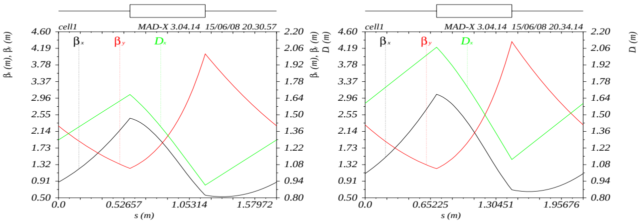

Figure 4: Optical function on inj. and extrac. orbits.

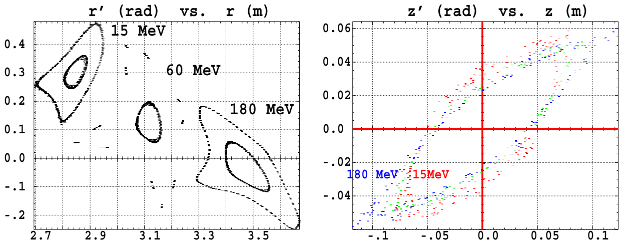

Figure 5: Horizontal (left) and vertical (right) DAs.

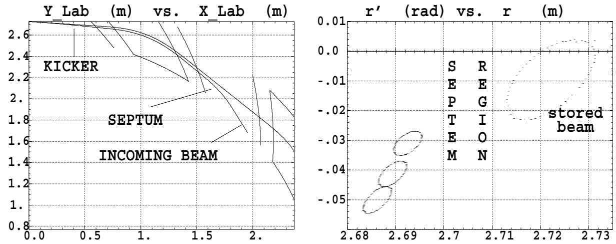

Figure 6: Injection geometry (left), septum exit (right).

Fig. 5 shows the dynamic apertures at three different energies, horizontal (for zero z-motion, the largest invariants, and in presence of very small z-motion, the inner invariants) and vertical, obtained from stepwise ray-tracing ; numerical simulations show that the present optics does not induce strongly constraining field and positioning accuracies, therefore these DAs are large enough for the beam emittances of concern (Tab. 3).

Injection has been simulated in both multi-turn and single-turn cases. The first method [11] employs two bumper magnets with π betatron phase separation, a septum magnet and an electrostatic kicker, it features more than 50% efficiency, and would permit reaching the dose rate necessary (and beyond) for the deeper layer in a 5 J/minute regime, in a $10\times10\times10$ cm^3 volume. The second method requires a septum and a kicker, it would be appropriate for lower dose or multiple painting. Fig. 6 shows the geometry in the second case, and the beam separation in phase-space at septum exit, for three different positions of the kicker along the drift ; the injected ellipses are $\epsilon_x = 10\,\pi$mm.mrad, the stored ellipse is $\epsilon_x = 100\,\pi$mm.mrad.

Extraction geometry, single-turn mode, using kicker and septum, is shown in Fig. 7, together with beam separation in phase-space at septum entrance for three different positions of the kicker.

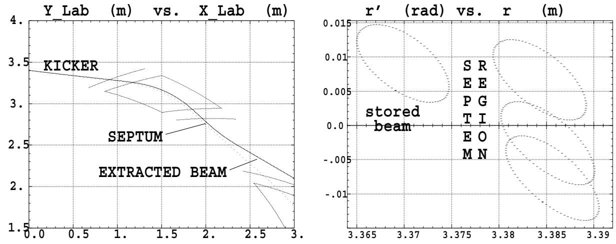

Figure 7: Extraction geometry (left), septum entrance (right) (note that the figure is flipped).

Table 4: Kicker and septum data, typical.

	length (m)	$\int B\,dl$ (G.m)	rise time (ns)
inj. kicker	~ 0.5	~ 150	→50
inj. septum	~ 0.3	$1.5\,10^3$	
extr. kicker	< 1	~ 250	<100
extr. septum		$5\,10^3$	

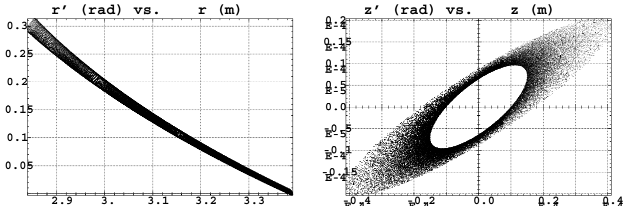

Figure 8: Transverse phase-spaces, and damping, upon 15 → 180 MeV acceleration.

Injection and extraction magnets typical data are summarized in Tab. 4.

Acceleration over a full cycle, 9.74 ms, from 15 to 180 MeV, has been simulated. The accelerating gap is supposed to be along a radius, normal to the high energy drift so to reduce transverse E-field effects (see Refs. [5]). Observation in H and V phase-spaces at the gap is shown in Fig. 8. More details can be found in Refs. [5, 7, 10].

CONCLUSION

Optimization work is carried on, concerning acceleration, injection and extraction, and in parallel with RF design and tracking simulation studies exploiting TOSCA field maps, prior to magnetice field measurements.

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