ACCELERATION IN SPIRAL FFAG USING FIELD MAP DATA

For the RACCAM Project :
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Abstract

This paper presents beam dynamics studies regarding the variable energy operation of a spiral scaling FFAG (Fixed Field Alternating Gradient) accelerator designed for producing 70 to 180 MeV protons and acceleration simulations for different operation modes, corresponding to different extraction energies.

INTRODUCTION

The RACCAM project [1] aims to design a protontherapy installation consisting of a variable energy H$^-$ cyclotron injector and a spiral FFAG ring [2]. This installation is designed to deliver protons between 70 and 180 MeV and is subject to other contributions [2, 3]. The FFAG ring parameters are presented and its variable energy scheme is discussed in this paper. From a TOSCA 3D magnetic modelling of the RACCAM prototype magnet [4], beam dynamics studies in the ring have been done and results will be shown for different extraction energies. Finally, acceleration simulations will be shown.

SPIRAL FFAG RING SPECIFICATIONS

The layout of the spiral FFAG ring is shown in Fig. 1 and its parameters are listed in Table 1.

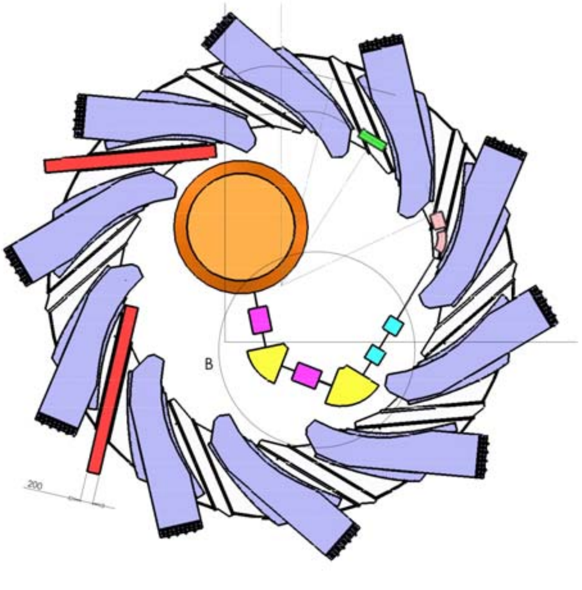

Figure 1: Layout of the spiral FFAG ring for protontherapy.

Table 1: Parameters of the spiral FFAG ring

Number of cells	10
Injection energy range	5.549 – 15 MeV
Extraction energy range	70 – 180 MeV
Field index k	5.00
Spiral angle ζ	53.7°
Packing factor	0.34
B_{max} on extraction orbit	1.7 T
Orbit radius (extr / inj)	3.46 m / 2.79 m
Gap at extr / inj radius	4 cm / 11.64 cm
(Q_H,Q_V): extr. orbit at 180 MeV	(2.761, 1.603)
(Q_H,Q_V): inj. orbit at 15 MeV	(2.758,1.549)
Maximum gap voltage	6 kV
Harmonic number	1
RF swing: 15 – 180 MeV	3.03 – 7.54 MHz
RF swing: 5.549 – 70 MeV	1.86 – 5.07 MHz
Cycle time, 180 MeV / 17 MeV	9.74 ms / 5.44 ms
Acceleration rate with 1 gap	> 100 Hz
Number of turns, 180 MeV / 70 MeV	55000 / 21500

The design of the FFAG magnet and ring [2] are based on several constraints:

- A spiral scaling lattice for compact size and zero chromaticity condition to avoid resonance crossing during acceleration.
- Maximum magnetic field of 1.7 T to reduce machine size and in view of testing magnet behaviour close to saturation limit.
- A rather small number of cells (10) in order to avoid fringing field dominated magnets.
- Field index large to reduce orbit excursion and magnet size, not too large so to limit the spiral angle.
- Spiral angle small enough for RF cavity placement between magnets.
- Working point located away from systematic resonances and yielding good dynamic apertures in both planes.
- Extraction energies between 70 and 180 MeV as a compromise between medical needs and injection / extraction momentum ratio of ≈3.6 allowed by the gap shaping magnet design.

VARIABLE ENERGY PRINCIPLE

As the depth of the proton Bragg peak inside the human body, which should be located inside the irradiated tumor, depends on energy, the variable energy operation for the protontherapy installation is crucial. It can be achieved in the following way:

- The cyclotron injector delivers variable energy proton beams for injection into the FFAG ring. It can be achieved with H- stripping extraction in the cyclotron by changing the position of the stripper [5].
- The magnetic field is changed in the FFAG ring by means of the main coils keeping the magnetic field index k unchanged. As the machine optics is defined by k, ζ and the ring geometry, the tunes should be conserved and the injection and extraction radii will be the same for all operation modes. This should be valid if the behaviour of the magnet is linear and far from saturation conditions. Beam dynamics results will later show limitations of the magnet behaviour.

BEAM DYNAMICS

The success of variable energy operation is based on the linear behaviour of the magnets. A TOSCA 3D magnet modelling has been developed within the RACCAM project, in view of building a magnet prototype, now in fabrication at SIGMAPHI. Step-by-step particle tracking can be done using TOSCA 3D field maps and the ray-tracing code Zgoubi [6] to study beam dynamics inside the FFAG ring for different operation modes [7].

Table 2: Operation modes studied and corresponding inj. / extr. energies (MeV) and B_{max} (T).

Mode	Inj/Extr E	B_{max}	Mode	Inj/Extr E	B_{max}
100%	15 – 180	1.71	70%	9 – 102	1.25
90%	13 – 157	1.59	60%	6 – 76	1.07
80%	11 – 130	1.43			

The working point has to be conserved and equal to the designed one for all operation modes in order to keep the beam far from systematic resonances. Fig. 2 presents horizontal and vertical tunes as a function of the machine radius for 5 operation modes. These modes correspond to reduced electrical current in the magnet coils. Current for acceleration between 15 and 180 MeV being the reference, the other modes studied are 90, 80, 70, 60% of this nominal current. Table 2 summarizes the injection / extraction energies for the different modes.

The horizontal tune behaviour is somewhat unchanged for the different modes while the vertical tune increases when the current is at 90 and 100% of the nominal one. This can be explained with the Fig. 3 showing the magnetic field seen by the particles on a series of closed orbits inside the TOSCA model for different modes.

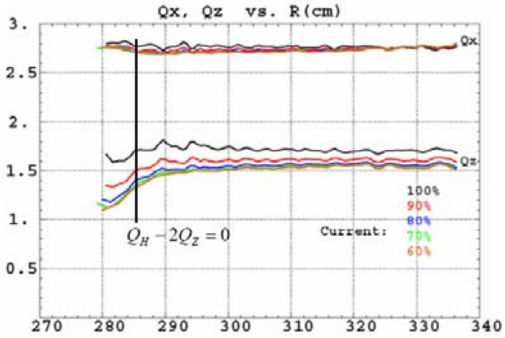

Figure 2: Tunes versus machine radius for different variable energy operation modes.

Particle energies corresponding to the fields are indicated. The 90 and 100% modes present magnetic field undershoots which change the fringing field shape and the flutter, modify vertical edge focusing of the magnet faces and vary the vertical tune. The 80 and 60% modes have no such undershoots and the vertical tune evolution is the same for these two modes. Undershoots are due to magnet saturation which appears when the magnetic field on extraction radius is above 1.5 T. As a consequence, the linear behaviour of the magnet is not guaranteed and, unless correction methods are advised, the maximum magnetic field should be limited to 1.5 T leading to an increase of the machine size. The vertical tune change between modes will also have consequences on the acceleration of protons as we will see in the next section.

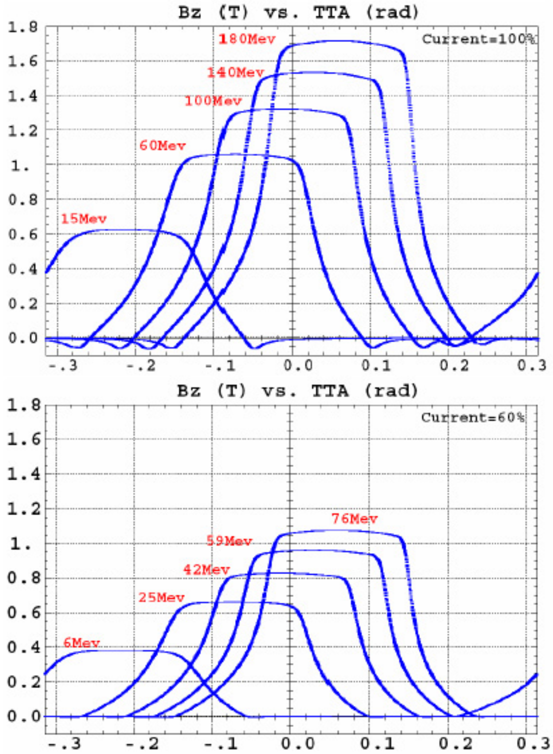

Figure 3: Magnetic field seen by protons on closed orbits for 100 and 60% operation modes.

ACCELERATION

Acceleration simulations have been performed using TOSCA models and Zgoubi tracking code [8]. In the whole section, particles are launched with the following starting conditions:

- Particle on a 100 π mm.mrad Courant-Snyder invariant in horizontal to confirm the correct transmission of medical beams ($\varepsilon_H < 50\pi$ mm.mrad)
- Particle on a small vertical Courant-Snyder invariant ($10^{-3}\,\pi$ mm.mrad) to reveal possible coupling between motions in both transverse planes for these preliminary studies.
- Longitudinal synchronous phase ϕ_S =30° [8].

A single accelerating cavity is considered. To achieve the acceleration cycle from 15 to 180 MeV, the RF frequency is increased from 3.03 to 7.54 MHz, the synchronous phase ϕ_S =30° and the peak voltage $\hat{V}$ =6kV are maintained constant so that 55000 turns are needed.

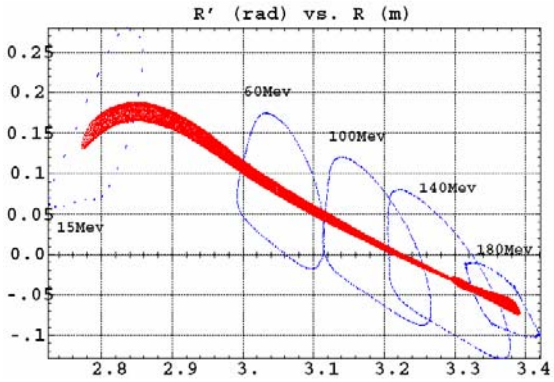

Figure 4: Accelerated particle trajectory in horizontal phase space and dynamic apertures.

Fig. 4 shows the accelerated particle from 15 to 180 MeV in the horizontal phase space. The horizontal dynamic apertures at 15, 60, 100, 140 and 180 MeV are indicated for comparison: the accelerated beam is well within admittance. The elbow shape of the red curve below 2.9m and the smaller dynamic aperture at 180 MeV are due to prototype magnet imperfection close to the injection and extraction orbit radius. Improvements on TOSCA models are on their way. Despite this, we can see that the transmission behaves correctly in the good field region (between 2.9 and 3.3 m) without losing the particle.

Fig. 5 shows the position of a particle accelerated from 6 to 76 MeV (mode 60%). The vertical amplitude increases because the particle crosses the sextupolar systematic resonance $Q_H - 2Q_Z = 0$ (see Fig. 2) which introduces strong coupling between horizontal and vertical motions. This resonance crossing is due to the vertical tune change produced by the saturation issues shown on Fig. 3.

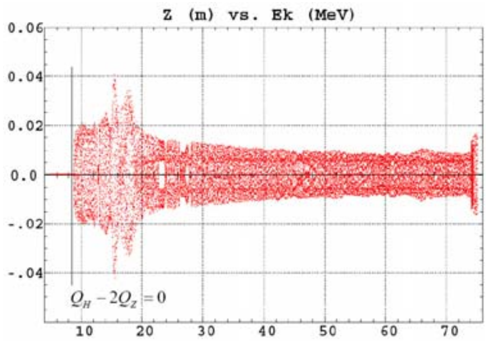

Figure 5: Vertical coordinate Z of the particle during acceleration from 6 to 76 MeV (60% mode).

CONCLUSION

Beam dynamics studies for several operation modes show the geometrical limits of the magnet prototype. Magnet improvements need to be done to take care of this tune change between operation modes and maximum magnetic field may have to be limited to 1.5 T to avoid saturation. Magnets with larger good field region, variable spiral angle, correction coils on the pole or active field clamps are possible solutions which are under investigation to keep the tunes constant during acceleration. In the mean time, further investigations will also be done by tracking particles on realistic vertical Courant-Snyder invariant in order to assess coupling effects between horizontal and vertical motions and 6D particle tracking will be performed to validate the acceleration.

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