AN ALTERNATIVE DESIGN FOR THE RACCAM MAGNET WITH DISTRIBUTED CONDUCTORS*

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Abstract

This paper presents an alternative design of the magnet for the RACCAM project.

The magnet was first designed with a variable gap to produce the desired field law $B=B_0(r/r_0)^k$.

An alternative magnet design was then proposed with parallel gap and distributed conductors on the pole to create the required field variation. This solution requires about 40 conductors along the pole and much more power than the gap shaping solution. We expect a much better fringe field variation even without variable chamfer.

INTRODUCTION

The aim of RACCAM collaboration is to study and build a prototype of a scaling spiral FFAG as a possible medical machine for hadron therapy. The gap shaping solution has been the most investigated solution in this project [1] [2]. The key feature in the "scaling" behavior of the magnet is in getting the fringe field extent to be proportional to the radius. The gap shaping solution has a contradictory behaviour : the decreasing gap with radius leads to a decreasing fringe field although an increasing fringe field is required to satisfy the scaling condition. Could an alternative design with parallel gap and distributed conductors overcome this problem ?

THE IMPORTANCE OF FRINGE FIELD

This scaling condition means that the working point in the tune diagram is fixed during all the acceleration cycle.

Vertical focusing can, in the smooth approximation [3][4], be written as :

$$\frac{1}{\rho}\tan\left(\varepsilon - \frac{I_1.\lambda.(1+\sin^2(\varepsilon))}{\rho.\cos(\varepsilon)}\right) \qquad (1)$$

ρ = radius of curvature, ε = edge angle, I1 = constant, λ is the fringe field extent, which can be taken in first approximation equal to the magnetic gap g

Since ρ is proportional to the machine radius R, the fringe field length λ has to increase linearly with R to keep the vertical focusing constant with energy.

THE GAP SHAPING SOLUTION

Exhaustive beam dynamics studies have led to working parameters for the machine in terms of field index coefficient and spiral angle. 2D and 3D magnetic calculation have then been performed to determine a design for the magnet. A prototype has been built and tested.

As stated by equation 1, increasing fringe field is required to satisfy the scaling condition. This is obviously not the case for the gap shaped magnet (Fig. 1). This problem has mostly been solved by adding to the magnet field clamps and variable chamfer with the radius. Almost constant tunes have been achieved (Fig. 2).

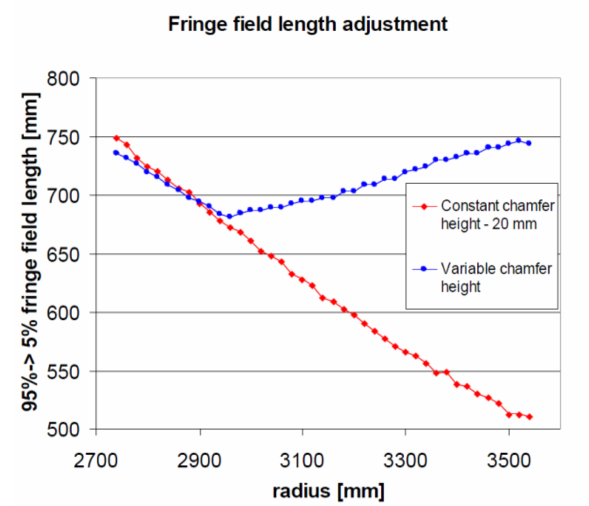

Figure 1: Total fringe field length in two models : with and without variable chamfer.

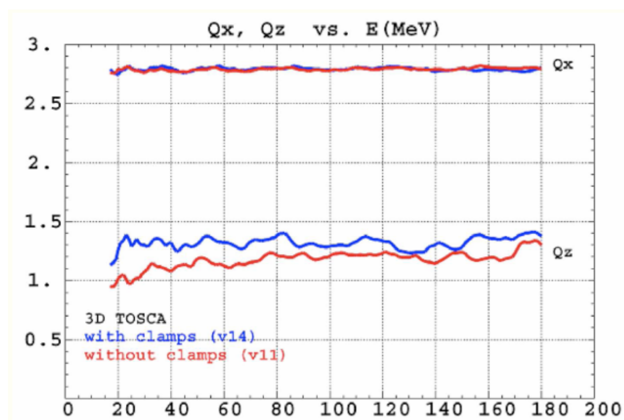

Figure 2: Horizontal and vertical tunes versus kinetic energy in two models : with and without field clamps.

WHY ANOTHER SOLUTION FOR FIELD GENERATION?

As we have seen the fringe field natural variation for the gap shaping solution is contradictory. A magnet with parallel gap would normally give a constant fringe field length over all radii. Even better would be a linearly increasing gap that would produces increasing fringe field length as required by the beam dynamics. The different solutions can be compared in terms of tunes in figure 3.

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Moreover, the gap shaping solution has shown limitation at smaller radii and so large gaps. This would be even more difficult with a greater energy extent that would require greater gaps at low energy.

We have so decided to explore the solution of parallel gap with distributed conductors for the field law generation.

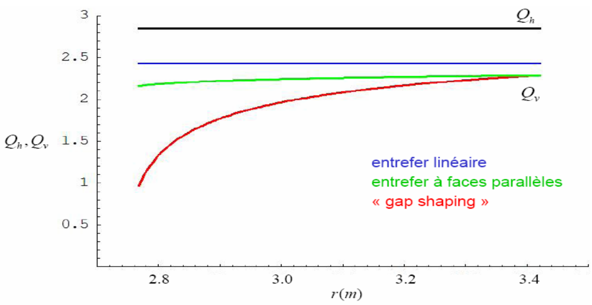

Figure 3: Tunes for various gap shapes in the model FFAG-spi [5].

DISTRIBUTED CONDUCTORS

Magnet Parameters

Main parameters are listed in table 1. The gap has been determined as the sum of the useful gap for the beam (30mm) plus the conductor dimension (2x5mm) and 1mm of play in between. As it requires large current densities the conductor has been chosen with a cross section of 5mmx15mm.

The number of conductors has been set to 40, a sufficiently large number to lower field fluctuations in between conductors to an acceptable level [6].

Table 1: Main Magnet Parameters

spiral angle (°)	53.7
field index coefficient	5.15
number of conductors	40
maximum field (T)	1.7
radius of maximum field (mm)	3300
gap between conductors (mm)	32
physical gap (mm)	44
conductor height (mm)	5
conductor width (mm)	15
minimum pole radius (mm)	2610
maximum pole radius (mm)	3610

2D Calculation

A first model has been done in 2D (Fig. 4) to get the initial input of the 3D model. The field law is created by distributed conductors on the pole. A main coil is also added to contribute to the constant field generation.

An iterative procedure has been used to determine the set of currents to achieve the required magnetic law. A first attempt has been done by linking directly the field to the current of the corresponding conductor. As the effect of a conductor is seen at every radius, it was very difficult to converge. A new scheme has been used by linking the current to the local field derivative.

The current law is shown in Figure 5 with a maximum of about 1600A in the last conductor. This important current density creates a high saturation in the yoke of more than 2T. The total ampere-turns needed are 46000At, 60% more than in the gap shaping solution.

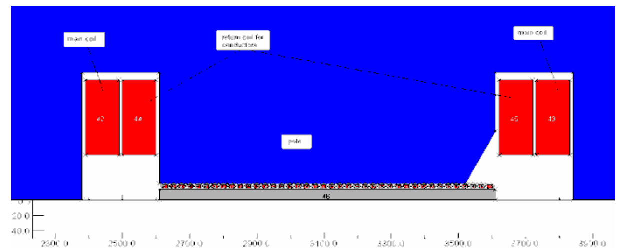

Figure 4: 2D model.

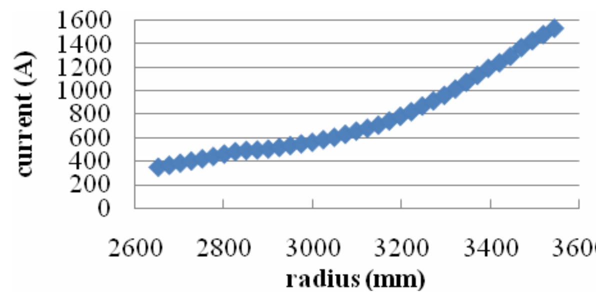

Figure 5: Current law.

3D Calculation

The previous current distribution law has been introduced in a 3D model (Fig. 6). In this case we have considered a constant chamfer of 20mm at 45°. As the saturation (Fig. 7) between 2D and 3D is different few iterations have been necessary to achieve the required field law (Fig. 8). The fringe field length can then be calculated.

The figure 9 shows the variation of fringe field with machine radius. They decrease from 664mm to 865mm. In the case of the gap shaping magnet the maximum fringe field was about 734mm.The variation with radius of 201mm should be compared to the gap shaping case where it was 222mm. We were expecting a much smaller variation than the gap shaping case and we find about the same.

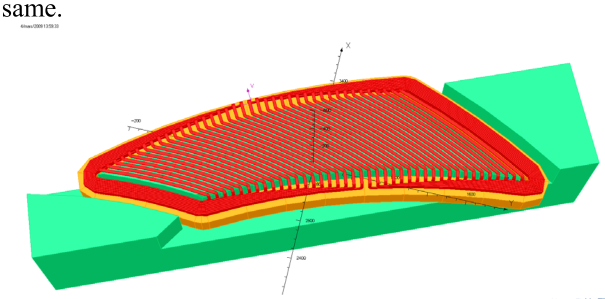

Figure 6: 3D model. Distributed conductors in red, main coil in yellow.

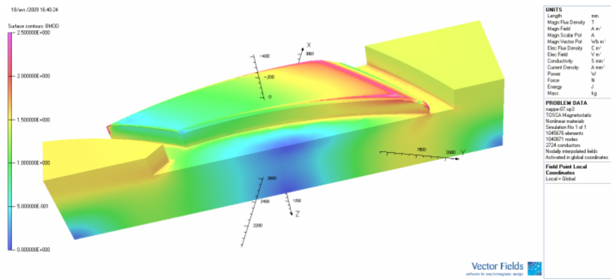

Figure 7: Saturation in the 3D model.

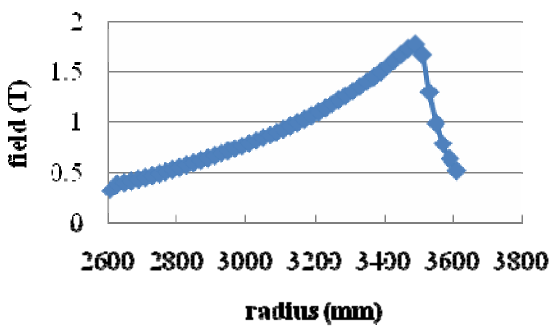

Figure 8: Achieved field law.

Calculating the same model but with a much lower current will show the effect of saturation. Figure 9 shows that there is very little differences between full and 20% of maximum current. Pole saturation could not explain the length variation.

Reducing the spiral angle to 30° decreases the maximum fringe field length to 480mm but without changing the slope.

It seems that the slope is related to the field gradient in the magnet. To test it, a calculation has been done with only the main coil without any distributed conductors in order to get a constant field in the gap. We find in this case a constant fringe field.

The fringe field variation is related to the field law in the magnet. The maximum fringe field length is influenced by the spiral angle and the gap shape. The parallel gap solution allows reducing the maximum fringe field length. One could think about an hybrid solution with a parallel gap at small radii and gap shaping afterward. This would allow reducing fringe field at small radii and take advantage of the gap shaping solution in term of required ampere-turns

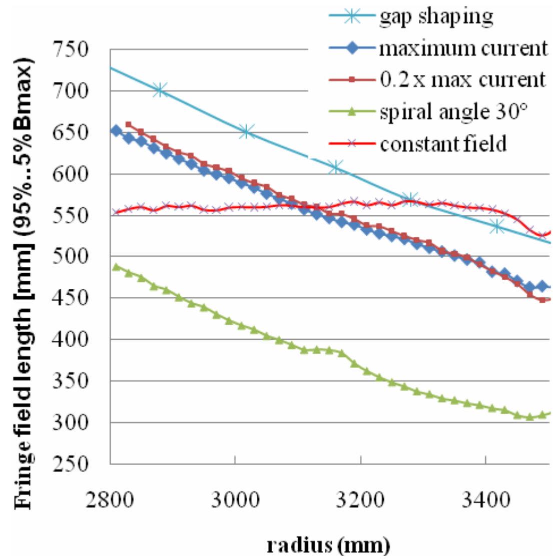

Figure 9: Fringe field length for various cases.

CONCLUSION

A model of a spiral scaling FFAG with distributed conductors has been achieved in order to compare to the gap shaping solution.

The total ampere-turns needed in the parallel gap solution is 46000 and is 60% more than in the gap shaping solution.

The fringe field variation is the same as in the gap shaping magnet with slightly reduced maximum value.

The fringe field variation is related to the field gradient, its absolute figure to the gap shape and spiral angle.

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