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TRUNCATED COSINE THETA MAGNET AND THE APPLICATIONS*

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Abstract

Demand for superconducting septum magnets is growing. For realization of high energy accelerators such as Future Circular Collider (FCC) or future heavy ion synchrotron in the Facility for Antiproton and Ion Research in Europe (FAIR) accelerator complex, high field septum magnet technology is crucial. Furthermore, for a compact medical machine, reduction of injection or extraction line length by introducing high field septum magnet is favorable. Beyond a limitation of conventional iron-dominated septum magnets, truncated cosine theta magnets can generate magnetic field over 2 Tesla without severe stray magnetic field at the circulating beam area. After introduction of the design principle, several design studies are presented and discussed.

INTRODUCTION

Typically, septum magnets in an injection and extraction areas of particle accelerators are designed with a normal conducting coil and a C-shape iron return yoke. Therefore, the magnetic field strength of such a septum magnet is limited to around 2 T because magnetic field can leak at the circulating beam area in an undesired way due to iron saturation.

For future high energy machines like High Energy Large Hadron Collider (HE-LHC), Future Circular Collider (FCC) at CERN [1], or heavy ion synchrotron in future FAIR accelerator complex at GSI [2], the development of a high field superconducting septum magnet technology is a key for the realization. Since high field septum magnets enable to shorten the length for an injection or extraction areas and thus, the accelerator itself and the building can be constructed more compact. The application for medical therapy accelerators would be promising as well.

GSI has developed a novel septum design concept based on a cosine theta magnet [3–5]. This design enables to reach higher magnetic field with superconducting technology similarly to superconducting cosine theta magnets used in high energy accelerators, instead of normal conducting iron dominated magnets.

In the following section, the design principle is summarized and several conceptual designs are presented.

DESIGN PRINCIPLE

The novel concept was inspired by the truncated cosine-theta magnet concept (without iron yoke) [6]. This concept was realized for the magnet for the g-2 experiments [7]. The magnet was used in an external magnetic field. Therefore, the use of a dedicated iron yoke was not considered. By introducing an iron yoke, the magnet size and ampere×turn can be drastically reduced.

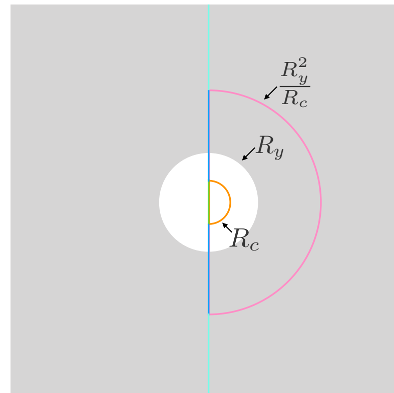

Figure 1: Layout of truncated cosine theta current distribution in a cross section of a magnet.

Figure 1 is a basics layout of a cross section of a truncated cosine theta magnet. The current distribution on the colored lines in the Fig.1 is expressed by following formulas.

- The cosine theta current distribution (orange) and image current of cosine theta current distribution (pink) is given by
$$j = -j_0 \cos\theta \tag{1}$$
- The truncation current distribution within the coil radius (green) is
$$j = \frac{j_0}{2}\left(\frac{1}{R_c} + \frac{R_c}{R_y^2}\right) \tag{2}$$
- The truncation current distribution between cosine theta current and its image current (blue) is
$$j = \frac{j_0}{2}\left(\frac{R_c}{y^2} + \frac{R_c}{R_y^2}\right) \tag{3}$$
- The truncation current distribution outside of image cosine theta current (light-blue) is
$$j = \frac{j_0}{2}\left(\frac{1}{R_c} + \frac{R_c}{R_y^2}\right)\left(\frac{R_y}{y}\right)^2 \tag{4}$$

Here R_c is a radius of a cosine theta coil, R_y is an iron yoke inner radius, and j_0 is current density. These combination of the sheet currents generates dipole field strength in the half-circular aperture of $B = \frac{\mu_0 j_o}{2}\left(\frac{1}{R_c} + \frac{R_c}{R_y^2}\right)$.

Figure 2 shows the flux lines delivered from analytical models, which consists of line currents and its image currents demonstrating the effect of iron yoke with infinite permeability, of both complete and truncated cosine theta magnets. The line currents are arranged to represent the current distribution in the formulae. For example, at the truncation line, distances between the line currents located from R_c to R_y increases toward the iron yoke. This is due to the magnetic

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field strength there decreases and thus, the current density to shield the field must be decrease (see equation (3)) as well by changing the distance of the line currents. As one can see, all flux lines are captured in the right part in case of the truncated cosine theta configuration.

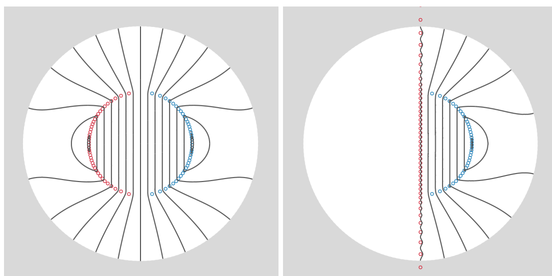

Figure 2: Flux line calculated by line currents and image currents. Left: complete cosine theta model, right: truncated cosine theta model.

A calculation code have been developed to quickly estimate magnet design parameters and crosscheck results of finite element simulations. Input parameters are

- Magnetic field strength in the half-circular aperture,
- Radius of the cosine theta coil,
- Iron yoke radius or peak field at the iron yoke,
- Number of the line currents (turn/pole),

and from this

- Necessary current, ampere×turns,
- Position of the line currents (and image currents),
- Magnetic field distribution in the aperture and the other side of the septum.

are delivered.

MAGNET DESIGN

In the following section, several studies are presented and discussed.

Cross Section Design

For high field septum magnets, magnetic length of several meters (e.g. 4 m for FCC and FAIR) would be needed. Therefore a design starts from the cross section in a 2-dimensional design. From experience on several design trials, the following design procedure is proposed.

1. A cross section of a complete cosine theta magnet with iron yoke is designed taking into account the geometrical requirements for the injected/extracted beam area, septum width, vacuum chamber etc. Field quality must be optimized to an extent which depends on the requirement (at a reference radius, which include the extracted beam area).
2. The complete cosine theta is truncated by the y-axis and a block coil is introduced. The cable center of the block coil would be on the y-axis. The cable vertical position in the block coil should follow the estimation with an analytical model of the line current. Especially amount of the cables in the cosine theta coil radius is important to shield the magnetic field properly.
3. Field quality in the aperture and the leak field for the circulating beam area is optimized by adjusting the cable positions.

One can note that the beam is exposed to the magnetic field of septum magnet only one time during injection or extraction. Therefore, the demand for the magnetic field quality is not as high as that of magnets in an accelerator ring. On the other hand, the stray field has to be controlled, because the circulating beam sees many times.

Figure 3 shows the conceptual preliminary cross section design for the FCC and FAIR septum magnets. FCC septum coil is designed with a one layer coil with the LHC superconducting cable [8] of 31 turns with 6.3 kA. For FAIR septum, small Rutherford cable similarly to Super-KEKB QCS magnets [9] are selected to two layers coil design of 100 turns with 2.1 kA. In the half-circular aperture, the magnetic field strength is 4 T for FCC and 3.65 T for FAIR and stray magnetic field have been suppressed around a few tens of milli-Tesla.

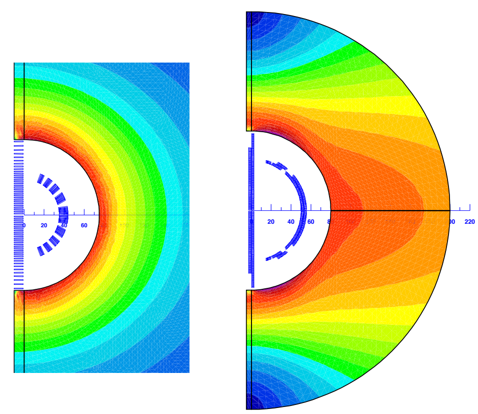

Figure 3: Conceptual cross section design for FCC (left) and FAIR (right).

Coil Head Design

One of difficulties of the coil manufacturing according to the concept given above is the coil head design so that one can wind a cable in designed positions in the cross section. The combination of a typical saddle coil head and subsequent vertical cable bending in the block coil would be a solution for a Rutherford cable coil. In this case, by introducing inclined cable in the block coil, one can avoid additional twists of the cable. Figure 4 shows the design adjustment of the cross section and the cross section just after the coil head for the FCC septum design. By introducing such cable arrangement in the cross section, conventional cosine theta coil winding technique would be applicable. Besides special 3-dimensional shape winding mandrel and spacers, support structures, and winding tools and so on have to be developed. Stray field and field quality in the half-circular aperture can be optimized in the same way as the original cross section design case. Figure 5 shows a conceptual model of the coil

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head winding. The vertical bending of the cables in the block coil has to be integrated.

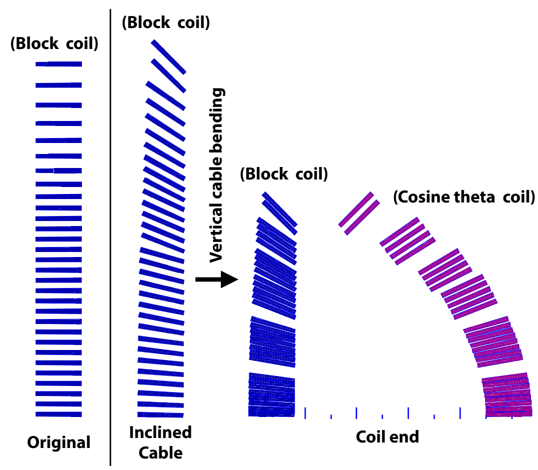

Figure 4: Improvement of the cross section design for the coil winding. Only upper half part is shown.

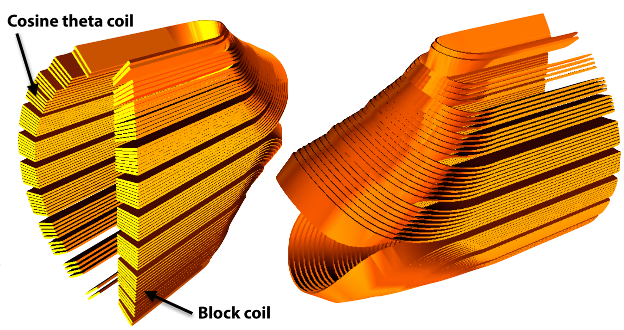

Figure 5: Conceptual coil head design consists of saddle coil head.

The other solution would be a single strand coil winding. Figure 6 shows a conceptual design with a single layer coil. Such a magnet can be operated with a low current. However, due to high inductance, quench protection would be an issue. For the medical therapy accelerators, such a magnet would be favorable to shorten the length of the injection and extraction lines in order to reduce the size and cost of the accelerator building.

FUTURE WORK

Mechanical design studies are already started. Preliminary study shows that the Lorentz forces on the cosine theta part is very similar to that of a complete cosine theta magnet because the magnetic field on the cable is almost identical. At the block coil side, the magnetic forces, which is horizontal, are almost equally distributed. A mechanical structure to support this force have to be properly designed. As usual, series of mechanical analyses from the manufacturing (at room temperature, with pre-stress) to the excitation phase (at cryogenic temperature, with Lorentz forces) has to be done. Cooling design has to be worked out to keep the magnet at

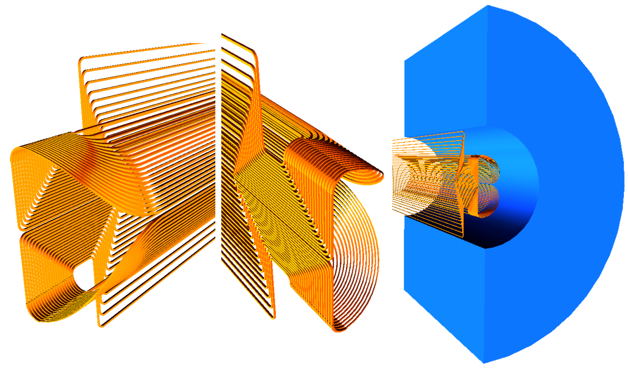

Figure 6: Conceptual coil head design for a single strand winding technique.

stable temperature with requested current ramping condition. Cooling channels must be designed both in the cosine theta and block coil. Comprehensive engineering design by iteration of electromagnetic, mechanical, and cooling studies will be continued.

SUMMARY

A novel concept of a septum magnet for high magnetic field application with superconducting technology is presented. Theoretical and analytical calculations prove attractive magnetic feature of the truncated cosine theta configuration for applications for septum magnets. Electromagnetic cross section design shows sufficiently good field quality in the half-circular aperture and well suppressed stray field at the circulating beam area. A conceptual design of the coil head was developed. The proposed winding techniques with Rutherford cable and single strand would be applicable. Further design study will be continued.

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