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Conceptual model of IMSIC-250 cyclotron magnet

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Abstract

Proton therapy with accelerator systems has been used in the last 30 years to destroy tumors by producing highly energetic ion beams. Although different systems have been introduced and designed to accelerate ions, the superconductive cyclotron accelerator is one of the most efficient treatment equipment compared to other systems. In this research, the design study of Iranian Medical Proton Superconducting Cyclotron (IMSIC-250) was considered. The IMSIC-250 system is a fixed frequency cyclotron with four spiral sector magnets designed to accelerate protons in the form of H_2^+ particles up to 250 MeV/amu. In the current study, the design process of the superconducting magnet and coil structure was reported. The 3D model of the spiral pole magnet alongside the superconducting coil was modeled. The main characteristics of the cyclotron magnet and coil structure were also studied. It was demonstrated that the designed magnet is capable of producing the desired isochronous magnetic field in order to accelerate protons up to 250 MeV. The stability of the acceleration process was achieved by a nonnegative value of flutter over the acceleration of particles. For coil structure, the current density over coil turns and the applied force was modeled. The flutter concept was also used to investigate the stability of the acceleration process. It was discovered that flutter has a nonnegative value when compared to particle acceleration. Finally, the stability of a magnetic coil against applied magnetics (Lorentz) force was investigated and it was demonstrated that the applied magnetic field on the coil would not have a destructive influence on the superconducting structure of the coil.

Keywords: proton therapy, superconducting cyclotron, cyclotron magnet, superconducting coil.

1. Introduction

Nowadays cancer is one of the main challenging diseases facing medical and biomedical scientists. According to the World Health Organization (WHO), cancer was responsible for 9.9 million deaths worldwide in 2020 [1]. During the course of treatment, a large number of cancer patients receive radiation therapy, either as the sole treatment or in combination with other therapy modalities. The absorbed dose is the fundamental physical quantity of interest for quantifying treatment outcomes. The main challenge in research and development of radiation treatment planning is to deliver an appropriate dose to the cancerous tissue, while minimizing the absorbed dose in the healthy tissues and organs at risk (OARs). Using proton or ion beams instead of photon beams in radiation therapy results in delivering higher dose to the tumor while maintaining the total dose of healthy tissues and OARs at the reduced orders [2].

Nowadays there are commercial cyclotron and synchrotron accelerators used clinically in proton and ion therapy. It has been proven that these clinical facilities can deliver a reliable and reproducible treatment in the clinical applications [3]. According to the Particle Therapy Co-Operative Group (PTCOG) in China, there are 80 operating and 46 under-construction clinical accelerator facilities worldwide. In addition, there are 25 other accelerators in planning stage. These accelerators include cyclotron, synchrotron, and synchro-cyclotron types. The majority of these facilities are cyclotrons accelerating proton to 220-250 MeV.

In the current study, the planning stage (conceptual design) of a new superconducting isochronous cyclotron, IMSIC-250 (Iranian Medical Superconducting Isochronous Cyclotron), is reported. The designed cyclotron is capable of accelerating protons in the form of H_2^+ particles up to 250 MeV/amu [4].

Table 1. The main properties of IMSIC-250 magnet and coil

Accelerator type	Superconducting cyclotron
Particle	Proton (in form of)H_2^+
End energy	250 MeV
Outer diameter	4.1 m
Average magnetic field	~2.4T @ center ~4.0T @ extraction radius
Fundamental frequency	23 MHz
Coil current	1.2 kA
Coil turns	1536
Coil current density	~45 A/mm^2
Coil diameter	2.35 m
Extraction radius	1.15 m

There are some advantages in using H_2^+ molecules instead of traditional H^- ions to accelerate in cyclotrons:

- The binding energy of electrons to H_2^+ molecule is much stronger than the electrons in H^- (about 14 eV for H_2^+ against only 0.7 eV for H^-). Therefore, it is possible to apply much higher magnetic field (as high as 10 T) on the particles without the risk of electrical stripping. This allows to design cyclotrons with significantly higher final energy.
- To have proton beam, it is necessary to strip only one electron from H_2^+ and produce two protons, compared to the case of two electrons stripping in H^- with production of only one proton. Therefore, it is possible to work with thinner stripper foil with longer expected life time (see section 5).
- Since the q/A ratio of H_2^+ beam is lower compared with protons, it has reduced space charge effect on the beam and hence we have better emittance and higher current of H_2^+ sources compared to the H^- ones.
- It can be also used to accelerate similar particles with charge to mass ratio $q/A = 0.5$ such as ${}^{12}C^{6+}$, ${}^{14}N^{7+}$ and ${}^{16}O^{8+}$.

The 250 MeV protons are capable of irradiation of tumors seated up to 30 cm depth (water phantom). The most important characteristics of the designed cyclotron are listed in table 1. The compactness of cyclotron is ensured by a high magnetic field provided by superconducting coil. All parts of such a cyclotron must be analyzed solely and in relation to each other to ensure the correct distribution of particles at the extraction point. The first stage of such a study is reported in the current work as magnet design.

2. Isochronous magnetic field

The average vertical magnetic field on the median plane of cyclotron which helps to evolve the particles in the correct cyclic pathway is calculated using the magnet model. The magnetic field should satisfy the isochronism conditions and the particle focusing requirements during acceleration. The isochronism conditions could be summarized as:

- The direction and intensity of the focusing magnetic field must be constant over evolution time of the particle (related to the continuous operation requirement);
- The betatron oscillation frequency should have no dependency on the evolving particle energy (related to the stability of the particle motion);
- The rotational frequency should have also no dependency on the evolving particle energy (related to the continuous operation requirement);

It is also necessary that the magnetic field provides the vertical and azimuthal focusing of the particle beam during acceleration and also guarantees an operation point away from resonance(s). At the higher (relativistic) energies, it is important that the isochronous magnetic field compensates the relativistic increase of mass during acceleration.

The magnitude of magnetic field; B, the bending radius; ρ, and the kinetic energy E_k, of accelerated particle are inter-related by [5]

$$B\rho = \sqrt{(E_tot^2 - E_0^2)}/300 = 1/300\sqrt{(E_k^2 + 2E_kE_0)} \quad (1)$$

where $E_{tot} = E_k + E_0$ in which E_k and E_0 are kinetic energy and the energy of rest mass of proton, respectively. The left-hand side of Eq. (1) is called “magnetic rigidity” in Tesla-meter, a parameter which indicates the values of the bending radius and the magnetic field at the given radius. The magnetic rigidity of 250 MeV proton is ~2.43 Tm.

The design of accelerator magnet is based on the isochronous and oscillation frequency equations. In isochronous cyclotrons the particle evolution frequency is constant which necessitates increasing the magnetic field with radius. These can be summarized in the following equation [5]:

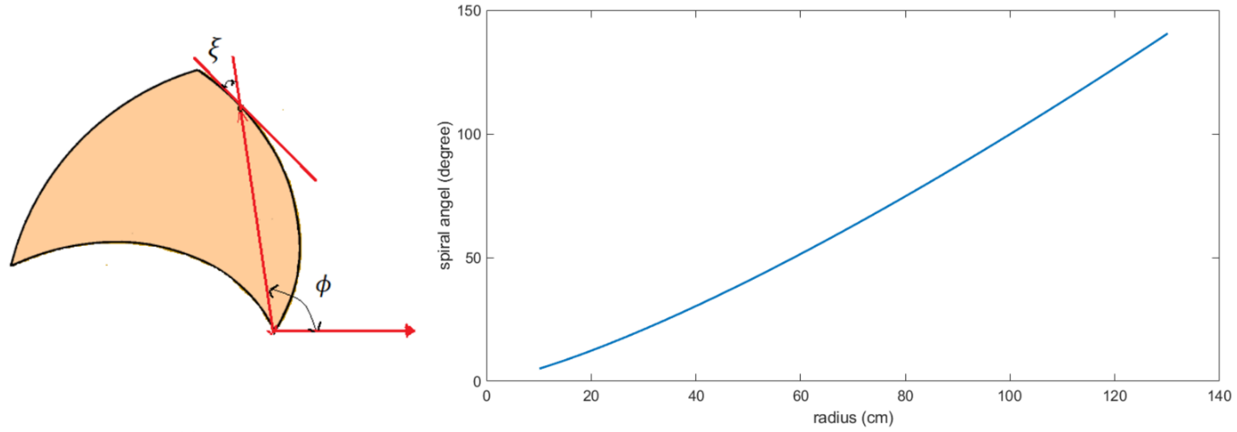
$$\langle B_0(R)\rangle = B_{center}\gamma(R) = Bcenter\sqrt{(c^2/(c^2-(\omega_0 R)^2))} \quad (2)$$

where $\langle B_0(R)\rangle$ is the average field at radius R, B_{center} is the magnetic field in the center of the magnet, ω_0 is the proton cyclotron frequency, and c is the speed of light.

In the isochronous cyclotrons, the magnet is split into radial or spiral sectors. The spiral shape of the sector could be described by two different parameters at each radius: the spiral angle; ξ, and the angle ϕ of rotation of the hill central axis (figure 1a). These parameters are related by the geometric relation:

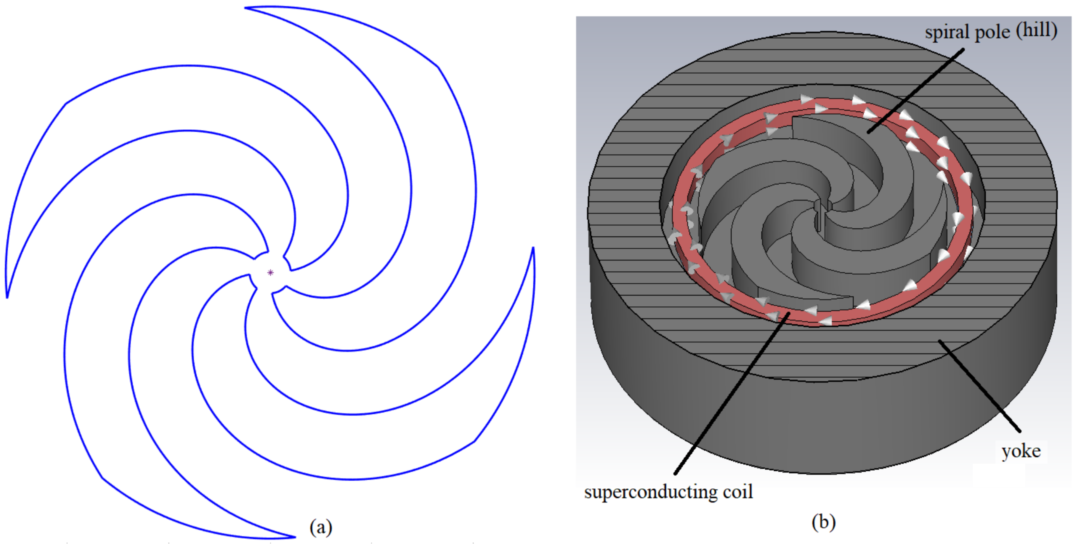
$$\tan\xi(r) = r\frac{d\phi(r)}{dr} \quad (3)$$

To achieve a good vertical focusing at high energies, the magnet pole is designed as spiral hill. The spiral angle of the sector will increase with radius. Figure 1b illustrates the variation of ξ with radius in IMSIC-250. This design is used to provide extra focusing forces to the evolving particles and to provide a radially variable



(a) (b)

Figure 1. (a) The overall shape of a spiral sector definition and (b) variation of spiral angle with radius in IMSIC-250 magnet.



(a) (b)

Figure 2. (a) 2D model of the spiral sector; (b) The 3D model of lower part of the four spiral sector configurations in the designed IMSIC-250 cyclotron.

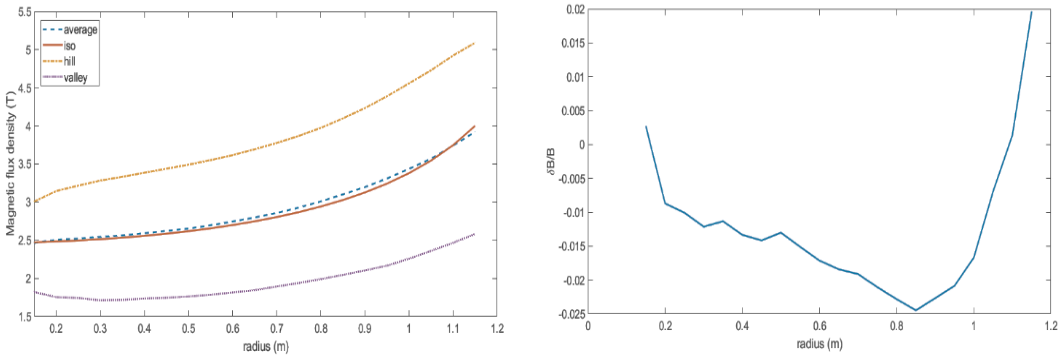


Figure 3. Magnetic field along the radius. The average magnetic flux density on the hill and on the valley (a|), the error of magnetic field compared to isochronous field (b).

magnetic field to guarantee isochronism, continuous wave operation, and high beam intensity for the designed cyclotron. In IMSIC-250, the magnet is designed with 4 spiral sectors (figure 2). Moreover, in order to reduce the overall weight and size of the cyclotron, the extraction radius is fixed to 1.15m. Therefore, the average magnetic field at the extraction point will be approximately 4 T.

To satisfy the isochronous conditions, the average magnetic field at the center of the machine must be compared alongside the ideal isochronous field [6]. The process of averaging is applied point by point over the 2π turn on the specified radius. In the current design, the average magnetic field at the center of the machine is approximately 2.4 T. Figure 3a shows variation of the average magnetic flux density with radius. The red line

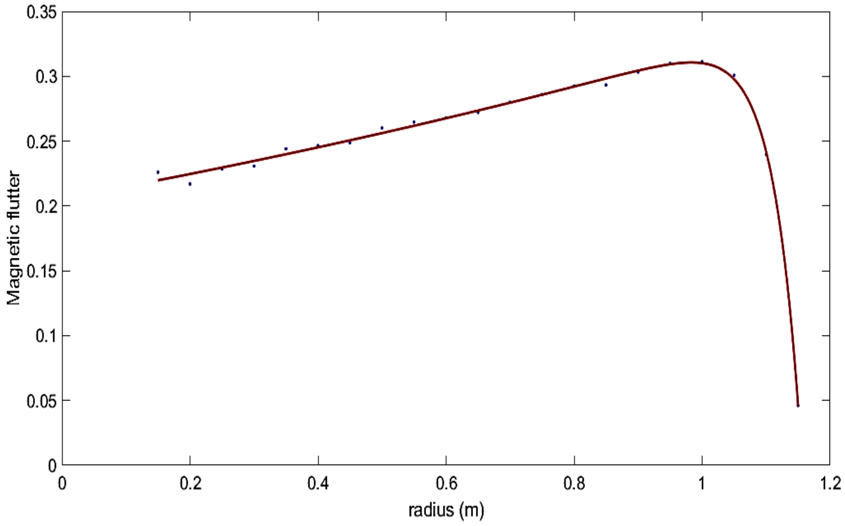


Figure 4. Flutter rises steadily by increasing the average magnetic field along radius and at the end of the beam trajectory it falls towards zero because the particles reach to high energies.

curve demonstrates the ideal isochronous field's flux density obtained from the analytic equation (2). The variation of average magnetic flux density on the pole (hill) and valley are also demonstrated in figure 3a which obtained point by point by averaging over the 2π turn. Final isochronous field of the system is the average of these two components (hill and valley fields) which fitted satisfactorily with ideal isochronous field flux density. Figure 3b demonstrates the deviation between the average filed from the ideal isochronous one.

In the spiral sector cyclotrons, the axial focusing is quantified by the flutter, F. Variation of the magnetic field flutter is defined as [7]

$$F = (\langle B^2(\theta)\rangle - \langle B\rangle_\theta^2) / (\langle B\rangle_\theta^2) \tag{4}$$

where $\langle B^2(\theta)\rangle$ is the average of square magnetic field on the trajectory, while $\langle B\rangle_\theta^2$ is the square of average magnetic field on a particular radius. The flutter must be high enough to compensate the negative axial focusing strength to a positive number. By evolution of the accelerated particle toward higher energies, flutter rises steadily by increasing the average magnetic field along radius and then at the end of the beam trajectory, it falls towards zero because the particles reach to high energies (figure 4). The aim of the magnet design is to maximize the provided flutter and therefore to achieve adequate beam focusing properties. Focusing should be ensured in both vertical and azimuthal direction. The good focusing condition helps removing the destructive resonance during the particle evolution and good betatron tuning properties.

3. Design tools

The magnetic design can be implemented on the CAD tools with FEM methods. Two computing packages are used to model the 3D structure of the magnet and the superconducting coil, including COMSOL Multiphysics [15] and CST Studio Suit [16]. The distribution of magnetic field in the central horizontal plane is demonstrated in figure 5. As can be seen, the magnetic field is increasing by radius in order to maintain isochronous characteristics and also to compensate the relativistic mass increase of the accelerated particles.

4. Superconducting coil

In the process of producing magnetic field, it can be said that the coils are the main tools. The magnitude and direction of the produced magnetic field is determined by the characteristics of the coil (current density, number of turns, radius, and etc.); and also by the properties of the metallic core. The most used metallic core in the coil design industry is iron. The iron core magnetization saturates at the magnetic flux density of approximately 2.1 T. By using an iron core, we cannot obtain a magnetic field larger than this saturation field value. For producing a larger magnetic field, a superconducting structure is required.

Superconducting coils do not need iron core and can produce a larger magnetic field by using a higher current density which is applicable to these structures [5]. In other words, in superconducting coils the magnetic field produced by the coil has a significant contribution to the total magnetic field compared to the normal-conductor-based structures. The larger producible magnetic field with superconducting structures is the critical field of the used materials. The use of a superconducting coil provides several advantages in medical applications including:

- Compactness of overall shape of cyclotron which facilitates transportation, reinforcements in the building, and reduces weight of the activated material for waste disposal;
- Reduced weight of cyclotron;
- Significant reduction of the electrical power consumption of the cyclotron.

The coil structure is modeled using the COMSOL package. Figure 6 illustrate the current density distribution inside the coil structure. The amount of the applied current density is approximately 45 A/mm^2.

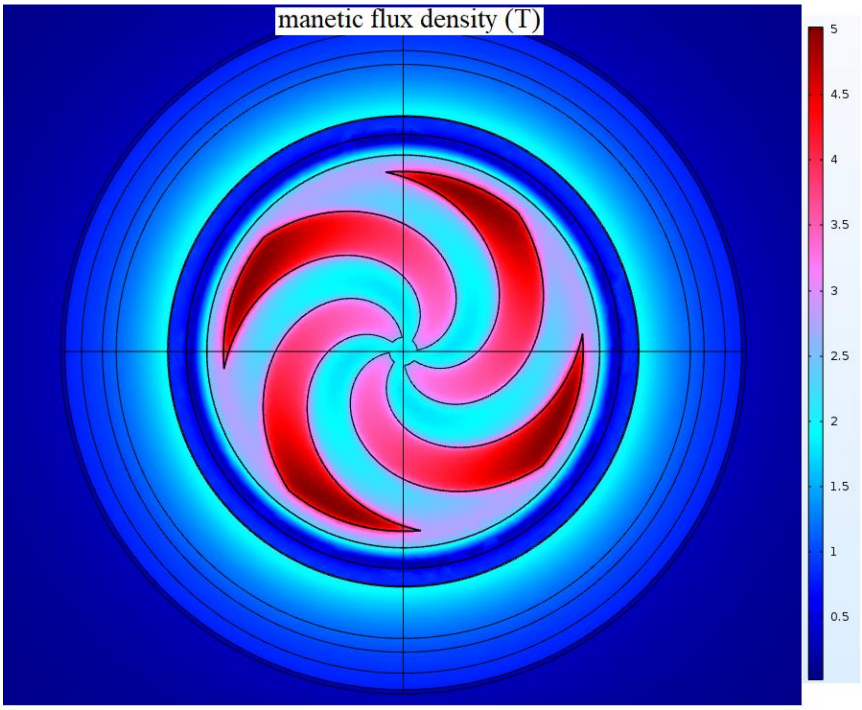


Figure 5. Distribution of the magnetic flux density (in Tesla) at the central horizontal plane of cyclotron.

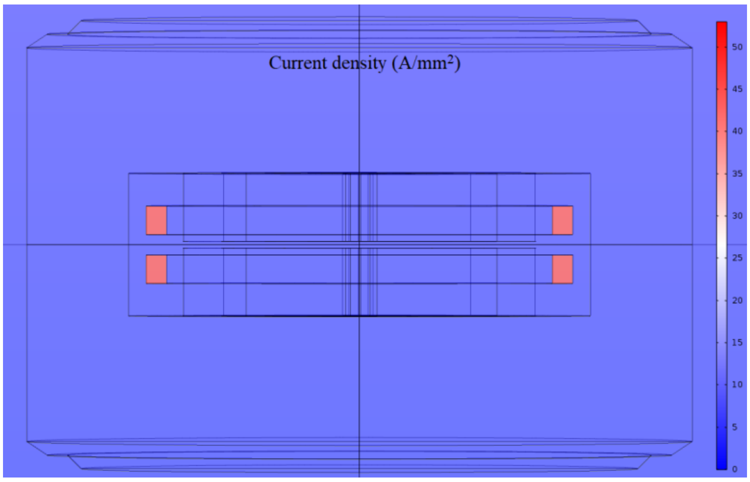


Figure 6. Current density distribution inside the two coils.

In design of superconducting coils, the main problems are the magnitude and direction of the applied magnetic force from the produced magnetic field in the coil structure. This force can lead to overall instability of the system and failure of machine. Figure 7 demonstrates the magnitude and direction of the volume force density on the coil on the central vertical plane. It indicates that the applied force on the surfaces of coil structure is toward the center of superconducting coil which acts as a stabilizing factor.

5. Preliminary discussion on extraction process

One of the main decisive choices in design of the isochronous cyclotrons is the extraction method. The aim of the extraction system is to transfer desired beam (with acceptable dynamic properties and particle distributions) from an internal confined orbits to a target outside the confining magnetic field. Since the beam losses in the extraction process could activate the mechanical component of the machine, it should be considered more carefully, especially in the case of machines capable to accelerate high intensity beams with significant particle energies. The whole process of extraction associated with some difficulties arises from two main sources [8]:

(a) *Confining magnetic field*: magnetic field has two major effects on the extraction process. To extract the beam, we should overcome the confining force in the first step. Second, the whole extraction process should occur on the edges of this field with significant nonlinearity and very large gradients (fringe field) which could easily result in the beam losses, beam blow-up, and/or loss of beam quality.

(b) *Turn separation of accelerated particles*: walking toward the outer radius of cyclotrons makes the particle revolve orbits closer to each other and thus piles up the turns near the extraction radius. As a result, separation of the desired particles on the last orbit from the inner undesired ones become more difficult.

Practically,

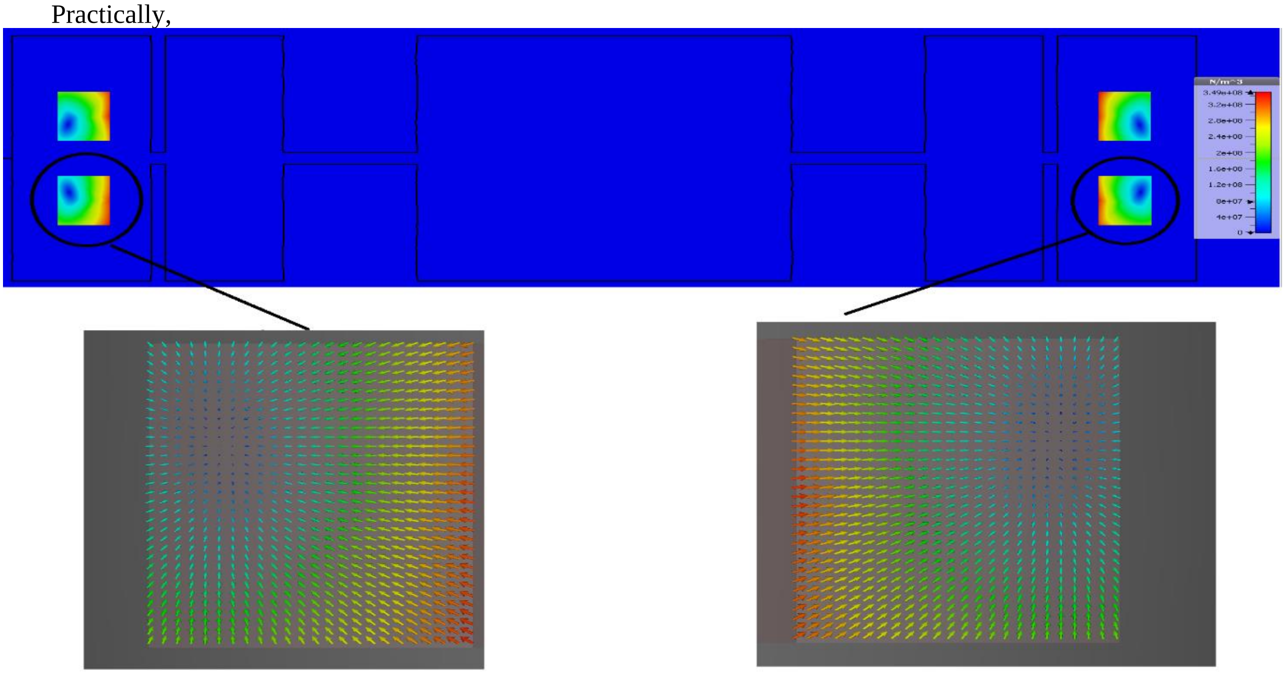


Figure 7. The magnitude and direction of applied magnetic force on central vertical plane on the coil structure in IMSIC-250.

Practically, two main procedures were used frequently to solve these problems and extract the desired beam: *stripping extraction* [9,10] and extraction by *electrostatic deflectors* [11].

Ion beams that are not fully stripped, like H^- ions or H_2^+ molecules, are prone to loss electrons when passing through a thin stripper foil. This process is used in stripping extraction system to change the charge state of the accelerated particles and consequently change the confining properties in magnetic field and transport dynamics of the ions (for instance, change the rotation direction of H^- ion or decrease the rotation radius of H_2^+ molecules) and finally extract them. This method is mostly used for negative beam extraction, but is also applicable in H_2^+ to have the proton beam.

For the fully stripped ions like C^{6+}, we cannot use the mentioned method and need to apply electrostatic defectors in which good turn separation is practically required to place the septum electrode in-between the turns. In isochronous superconducting cyclotrons the turn separation is usually smaller than the beam size [12]. Therefore, electrostatic extractors mostly rely on a conjugate method, such as extraction by acceleration or resonance extraction, to increase turn separation beyond the primary values.

In IMSIC-250, to have the proton beam, it is necessary to use the stripping process of H_2^+ molecular beam with thin carbon foil ($H_2^+ \rightarrow 2H^+ + e^-$). Using this stripping process, it is possible to extract particles with a wide energy range just by changing the radial position of the stripper foil. The H_2^+ molecules that transmit the foil without stripping will revolve another turn and hit again the stripper and this could be repeated until it is stripped. Therefore, this method is applicable for large internal beam currents (typically up to 500 µA) with extraction efficiency of ~ 100 % [8]. On the other hands, it is possible to extract proton beam with two separate channels with different beam energy and/or current. For therapy, we need typically beam current of the order 1 nA at patient site (but in practice higher beam currents, of up to 1 µA, are used to compensate all of the possible losses), therefore it is possible to design multiple channels to have simultaneous exposure [13].

To use IMSIC-250 with other particles than H_2^+, like C^{6+}, it is necessary to equipped it with the electrostatic deflector. The designed system is more like the IBA C400 hadron therapy system with two separate channels for proton and other particles [14].

6. Conclusions

In this article the conceptual design phase of IMSIC-250 was reported. As a first step, the design process of the superconducting magnet of IMSIC-250 and coil structure were considered. The 3D model of spiral pole magnet alongside the superconducting coil were modeled. It was demonstrated that the designed magnet is capable of producing the desired isochronous magnetic field. Stability of the acceleration process was also studied using the flutter concept. It was shown that the flutter has a nonnegative value over the acceleration of particles. Finally, the stability of magnetic coil against the applied magnetic (Lorentz) force was studied and it was demonstrated that the applied magnet field on coil would not be a destructive factor on the coil superconducting structure.

Statements and declarations
competing interests:

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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