DESIGN OF ULTRA-LIGHT SUPERCONDUCTING PROTON CYCLOTRON FOR PRODUCTION OF ISOTOPES FOR MEDICAL APPLICATIONS

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Abstract

A new design has been explored for a superconducting-coil-based compact cyclotron, which has many practical benefits over conventional superconducting cyclotrons. The iron yoke and poles in conventional superconducting cyclotrons have been avoided in this design. The azimuthally varying field is generated by superconducting sector-coils. The superconducting sector-coils and the circular main-coils have been housed in a single cryostat. It has resulted in an ultra-light 25 MeV proton cyclotron weighing about 2000 kg. Further, the sector coils and the main coils are fed by independent power supplies, which allow flexibility of operation through on-line magnetic field trimming. Here, we present design calculations and the engineering considerations, focused on making the cyclotron ideally suited for the production of radioisotopes for medical applications.

INTRODUCTION

Historically, various designs of cyclotron have evolved to adapt them to various applications, especially in medical applications, apart from its use as a research tool in atomic, nuclear and solid-state physics experiments [1]. Due to its compactness and the cost factor, the cyclotrons have become the ideal choice for the production of short-lived proton-rich radio-isotopes used in biomedical applications [2, 3, 4, 5]. More than 350 cyclotron installations worldwide are engaged in the production of radio-nuclides, mostly the PET and SPECT isotopes (^{11}C, ^{13}N, ^{15}O, ^{18}F, ^{123}I, ^{203}Tl, ^{67}Ga) used in medical diagnostics, as well as the isotopes for therapeutic applications, e.g., ^{64}Cu, ^{103}Pd, ^{186}Re etc. The production of ^{99m}Tc in a proton cyclotron is also a matter of great contemporary interest [6].

These installations generally use low energy cyclotrons (9 MeV to 30 MeV) with several hundred micro-ampere beam currents to satisfy user demand for these radioisotopes [7, 8, 9]. There has been ongoing effort since nineteen eighties towards developing new designs of such cyclotrons using superconducting magnets to lower the weight, power consumption and radiation background. The recent trend is to develop extremely compact superconducting cyclotron, optimized to produce unit does on demand [10].

One remarkable step towards an ultra-light cyclotron was the design proposed by Finlan, Kruip and Wilson using a superconducting magnet with iron sectors contained within the room temperature bore of the magnet was [11]. The major reduction of weight was obtained by getting rid of iron yoke enclosing the superconducting magnet. This was unique feature of this design over all other conventional superconducting cyclotrons [12, 13, 14, 15]. Oxford Instruments built 12 MeV H^- cyclotron based on this design weighing only 3.5 tons [16]. The isochronous field and adequate flutter was achieved three iron sectors placed in the warm bore of the superconducting main coils. Isochronous fields for protons or H^- ions up to 60 MeV can be produced in such an arrangement.

Moving ahead in the same direction, present authors proposed a design in which the iron sectors have been replaced by superconducting sector coils [17]. The isochronous field along with sufficient flutter is obtained by optimizing the sector coils and the superconducting circular coils. A magnetic field bump at the centre of the machine generated by a small superconducting circular coil provides the necessary magnetic focusing in this low flutter zone. Inside the main sector coils, sector shaped trim coils have been used for further fine tuning of the average field. Independent excitations of the main coils and trim coils allow the flexibility of operation through online magnetic field tuning. Thin iron shims have been used on the face of sector coils for finer shaping of the magnetic field. Magnetic shielding is done using separate a-few-mm thick iron cylinders outside the superconducting magnet. The weight of a 25 MeV H^- cyclotron based on this design is estimated to be about 2 tons. In this paper we present the design calculations for this cyclotron and the engineering aspects.

DESIGN FEATURES AND SPECIFICATION

The proposed design is for a fixed field, fixed frequency, compact superconducting cyclotron, accelerating negative hydrogen ions and extracting proton beams using stripper mechanism. The present design is for a maximum energy of 25MeV proton (H^-) beam, which is good enough for ^{99m}Tc production [6]. However, the concept can be applied for designing cyclotrons of other energies as well, from 12MeV to 30MeV or a little higher energy also.

The cyclotron magnet consists of two sets of circular main coils at the outer radius (MC1, MC2), four 45° sector coils, two trim coils inside each sector and two small circular coils at the centre (CC1, CC2). Figure 1 shows the geometry of sector and circular coils. All the coils are superconducting and they are contained in a single cryostat. In this design calculations we have considered NbTi superconducting wire (1.1×1.7 mm^2) from Bruker Advanced Supercon (4.2 K, 4 T, J~3000 A/mm^2, Cu:NbTi ratio from 10 to 20). The number of

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turns and the cross-sectional position of individual coils have been optimized to meet the isochronous condition on the field. Finer adjustment of the average magnetic field has been done by placing thin iron shims in appropriate positions near the median plane.

The basic design philosophy, like any medical cyclotron, is to make the machine suitable for a hospital environment. So, maintaining low radiation background and proper magnetic shielding are also important considerations apart from reducing the weight and power consumption. All the important design features of Oxford cyclotron to reduce the power consumption and low background radiation are common to this design also. For example, the open-bore magnet offers provision for efficient RF resonator design, unconstrained in the axial dimension; or, use of external ion-source permits differential pumping, maintaining high vacuum in the beam chamber, hence reducing partial stripping by residual gases. In the Oxford cyclotron, the magnetic shielding was achieved by using bucking coils. Same technique may be used here also. Alternatively, in this design we have used a separate thin iron cylinder sufficiently far away from the main machine to reduce the stray magnetic field below appreciable level. This iron cylinder may be assembled in two halves for easy access to the magnet. Some local shielding is required around the instrumentation ports.

The beam current loss due to Lorentz stripping of H^- ions is an important issue while designing a cyclotron accelerating negative hydrogen ions. To minimize Lorentz stripping of electrons from H^- ions and at the same time to optimize the size, average magnetic field is kept 1.73 T, so that field at the hill centre is less than 2.5 T. This also makes the central region geometry and the inflector size comfortable with typical injection energy of 28 kV. The residual gas stripping loss is less than 0.1% for an overall pressure of 10^{-7} torr [11]. To maintain high vacuum in the beam chamber an external H^- ion source and axial injection with spiral inflector is considered. The beam acceleration chamber geometry is such that the conductance to the vacuum pumps will be much higher than in conventional superconducting cyclotrons. The design specification of the superconducting coil cyclotron is given in table-1.

In 1.735 T average magnetic field, the extraction radius of 25 MeV proton beam is 415 mm. At this field level the sector coils provide sufficient flutter to ensure enough vertical focusing for the beam. The maximum attainable kinetic energy of an ion beam in a given magnetic field configuration is given by $T/A = K_f\eta$, where K_f is called the focusing energy limit [12], η is the ion's specific charge (charge state/mass number), T is the kinetic energy in MeV, A is the mass number. As shown in Figure 2, the major harmonic component B_4 = 0.78 T at extraction radius gives $K_f \cong$ 36 MeV/A. With a typical injection energy of 28 keV in an average magnetic field of 1.735 T, the spiral inflector has a magnetic radius of R_m = 14 mm.

Table 1: Design Specifications

Design Specifications	
No. of Sector Coils	4
Average magnetic field	1.735 T
Particle revolution frequency	26.42 MHz
Hill Field	2.48T
Valley field	1.2T
Injection & Acceleration	Negative Hydrogen Ion
Extraction	Proton with stripper foil, Dual beam
Extraction radius	Maximum energy at ~400 mm
Magnetic radius of spiral inflector	~14 mm
Injection energy	~28 keV
No. of Dees	2, in alternative valleys
Dee angle	~42° in outer radii
RF Frequency	~105.68 MHz
RF Mode of operation	4th harmonic

MAGNET DESIGN

Magnetic field modelling has been done using MATHEMATICA based software RADIA, a 3-dimensional magnetostatic computer code based on boundary integral method [18]. Figure-1 shows the RADIA model of the sector and circular coils.

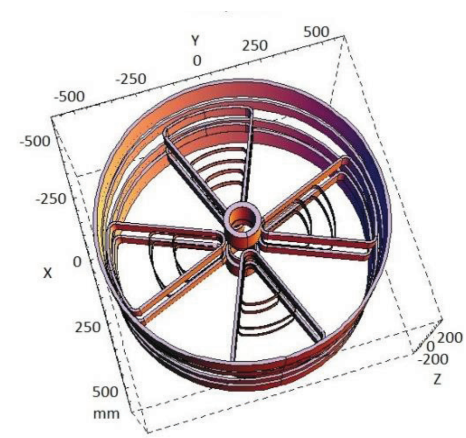

Figure 1: RADIA model of the superconducting coils.

A parametric model of the sector coils and main coils has been used to optimize the geometry that produces near isochronous field, with the constraints coming from engineering point of view, e.g., the space required for the cryogenic system (multilayer thermal insulation, radiation shield etc.), rf system (dee, liner etc.), spiral inflector and radial penetrations for diagnostic probes, extraction elements etc. The $4n$ harmonics (n = 1, 2, .., 5) of the Fourier series analysis of the magnetic field data are shown in Figure 2. Two smaller size sector coils, placed within the main sector coil, will be used as trim coils. A cross-sectional view of the coils in the (*r*-*z*) plane is shown in Figure 3 and the coil dimensions are listed in table-2 and table-3.

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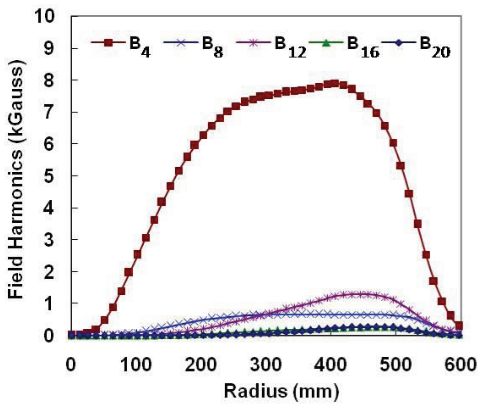

Figure 2: Fourier harmonic components of magnetic field.

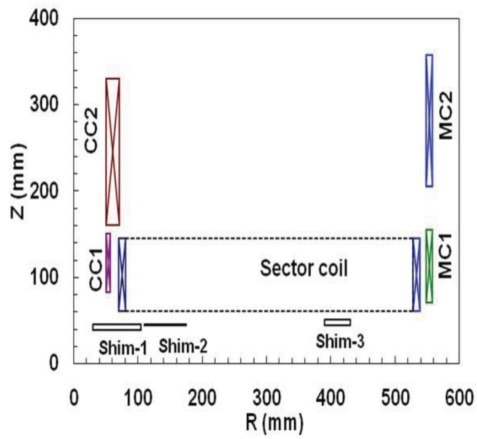

Figure 3: Sectional view of coils in the (*r*-*z*) plane.

Table 2

Sector Coil	Large	Medium	Smallest
Current		500 A	
Sector angle		22.5°	
Wire cross-section (mm^2)		1.1x1.7	
Inner Radius*	70.3	83.3	85.3
Outer Radius*	538.7	357.4	278.3
Radial length	468.4	273	193.0
No. of radial layers	10	1	1
No. of turns per layer	50	20	25
Distance from median plane*	60	60	60

Table 3

Circular coils	CC1	CC2	MC1
Current (A)		500	
Inner Radius*	50	50	587
Outer Radius*	57	71	597
No. of radial layers	7	19	9
No. of turns per layer	40	100	12
Distance from median plane*	82	160	70
Inner Radius*	50	50	587

* in mm.

Final adjustment of magnetic field, in the range of tens of Gauss, has been done by placing thin iron shims near the centre and the extraction zone. Figure 4 shows that after fine tuning the average field profile remains within 40G from the analytical isochronous field. A central field bump of about 70 G is added by adjusting the central coils and central shims. The shim dimensions are finalized iteratively on the basis of the equilibrium orbit properties [17].

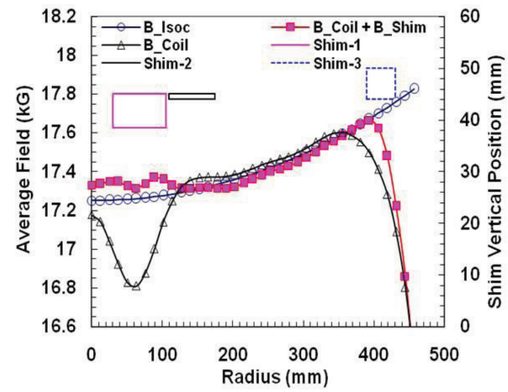

Figure 4: Average magnetic field before and after iron shimming, along with isochronous field (B_isoc).

ENGINEERING DETAILS

The focus of the engineering considerations has been on ease of fabrication, assembly, maintenance and operation. The weights of the major components are: former: 250 kg; coils: 200 kg; radiation shield: 150 kg; vacuum chamber: 550 kg; RF system: 200 kg; and external magnetic shield: 630 kg. A 3D conceptual design is shown in Figure 5.

Important engineering features of the main components of the cyclotron are discussed below.

Coil and Cryostat

The conductor has a 20:1 copper to superconductor ratio resulting in high stability against quenching. There are two 'formers' (bobbins), precisely machined out of high-strength aluminium alloy blocks. All circular and sector coils are placed on the formers with the necessary clamps and supporting fixtures for preventing their movement during ramping of the coils. The maximum magnetic field in the coils is 3.7 T. The forces are estimated on the coils and the formers are designed accordingly. It is also very important that the resultant horizontal forces on the former balance out because of symmetric geometry. As there are no iron poles, the interaction force on the coils, which is an important consideration in conventional superconducting cyclotron design, is comparatively insignificant. The support links, made out of glass epoxy, hold the former inside the vacuum chamber. A 50 K thermal intercept from the cryo-cooler 1st stage is provided to the support links for reducing the heat load to the coils. The optimised cold mass is about 450 kg at 4.2 K and 150 kg at 50 K.

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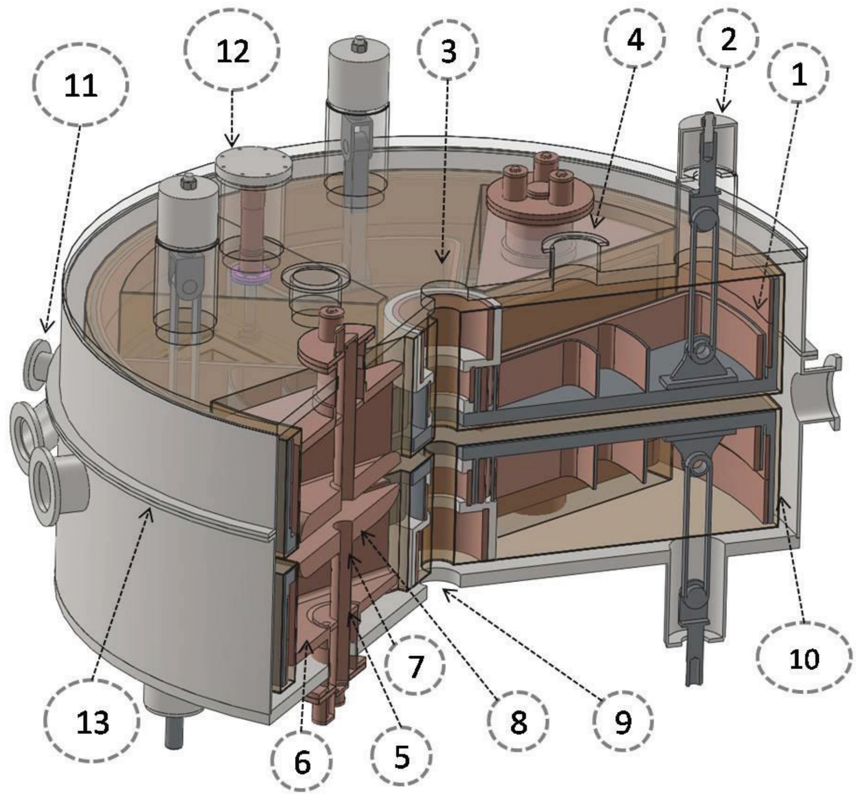

Figure 5: 3D model of superconducting coil cyclotron, showing different subsystems, as follows: 1. Coil-cryostat, 2. Support link, 3. Beam injection port, 4. Vacuum port, 5. Sliding short between cavity outer and inner conductors, 6. RF liner (outer conductor), 7. Dee stem, 8. Dee, 9. Port for spiral inflector, 10. Liquid nitrogen shield, 11. Median plane ports for beam extraction, stripper holder, beam diagnostics, 12. Port for Cryo-cooler, 13. Median plane O-ring joint.

The upper and lower formers are rigidly supported at the median plane, outside the beam acceleration zone, with four solid blocks to take care of the magnetic force between the upper and lower coils. These supports are demountable so that two halves are easily separable for access to the median plane.

In the absence of iron pole-tips, the magnetic field varies linearly with current, thus reducing the effort in the magnetic field measurement. This is particularly important, because the magnetic field configurations can be scaled up from only one set of measurements.

An external iron cylinder is used for magnetic shielding. With a 6 mm thick iron cylinder of 900 mm radius and 1500 mm height (weight 630 kg), the fringing field is reduced to 137 G at 0.5 m outside the shield. This is a value suitable for cyclotron operation with some local shielding for magnetic elements, pumps, and other instruments situated nearby. The advantage of using the external iron cylinder for magnetic shielding is that it is at room temperature, unlike the Oxford Instrument's cyclotron, where the iron cylinder in association with a bucking coil is within the liquid helium cryostat. So the cold-mass in this design is substantially reduced. Calculations have shown that, if further shielding is necessary, the field at 0.5 m (outside the first shield) may be reduced to 20 G by adding another iron cylinder of 6 mm thickness and 1200 mm radius weighing about 820 kg around the first one. The shielding cylinders are external to the main cyclotron. They can be made in two halves, allowing easy access to the cyclotron. In fact, these double wall iron cylinders may also be used as structure for neutron shielding material, e.g., borated polythene etc.

Cooling

There are four cryo-coolers, two at the top and two at the bottom, for cooling the coil-blocks. Each of the cryo-coolers will have cooling capacity of 35 W at 50 K (1st stage) and 1.5 W at 4.2 K (2nd stage). The 1st stage will be used to cool the thermal shield and the intercepts. This design is done based on re-condensation type bath cooling technique. But one can consider conduction cooling also, which is more interesting for its simplicity and robustness, apart from leading to a lesser weight. If the coils are conduction cooled, the liquid helium vessel is not required. One can thus avoid complications of leak tight welding that need to survive at cryogenic temperature. This also avoids the process of cold shocking, leak testing, etc. reducing the effort and cost of producing this machine. This way the possibility of a cold leak, as seen in some of the conventional superconducting cyclotrons, can also be reduced. The mechanical vibrations can be isolated from the coils with flexible thermal connections. The heat load for this configuration is estimated to be about 4 W at 4.2 K with a 50 K radiation shield and 50 K intercepts for the conduction links. The eddy current power dissipation in the Al-alloy former is calculated to be about 4 mW when the coils are ramped to 500 A in 2 hours. The heat load can be reduced with further optimisation. The redundancy in the number of cryo-coolers will allow the cyclotron to run in case any one of the cryo-coolers fails. This is important for its medical use so that the cyclotron up-time is high. It is also necessary to make demountable joints for the cryo-coolers for easy replacement. With all the four cryo-coolers on, the cooling capacity is about 6 watts at 4.2 K.

RF Cavity

The rf cavity will operate at ~106 MHz, and will have a coaxial TEM structure. The cavity will be made out of normal conducting copper structure operating at room temperature. Water cooling will be provided to the parts of the inner and outer conductors where the radio frequency currents are high.

Assembly and Maintenance

A central hole provides the path for entry of the ion-beam into the centre of the cyclotron from an external H^- ion source. The vacuum chamber would be made in two halves, with a large O-ring sealing near the median plane of the cyclotron. All the components, e.g., supports for coil-formers, rf cavities etc. will be attached to the top and bottom plate of this chamber. This will help in installation and maintenance of the cyclotron just by splitting the two halves of the vacuum chamber, which will allow full access to the median plane. The assembly of this cyclotron is easier than for a conventional superconducting cyclotron, as the latter's iron poles and return yoke restrict the approach to different parts.

CONCLUSION

A new design is proposed of an ultra-light, superconducting medical cyclotron for isotope production, weighing only about 2000 kg. In this design the iron yoke and the poles both have been eliminated. The azimuthal varying field is generated by superconducting sector coils. Independently powered superconducting circular coils and sector coils are used to generate the desired magnetic field shape. This further provides flexibility of operation through on-line tuning of the magnetic field. All the coils are accommodated in a single cryostat. A conceptual engineering design has also been worked out to check the feasibility of the design from the engineering point of view.

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