MAGNETIC FIELD DESIGN AND CALCULATIONS FOR THE IBA C70 CYCLOTRON

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Abstract

Presently IBA designs and produces a 70 MeV cyclotron for radiochemistry and nuclear medicine (C70) [1], [2], [3], [4], [5]. Main problems and solutions of the magnetic design and calculations are described. Two distinguished isochronous magnetic fields are necessary to accelerate both types of ions with charge to mass ratio $q/m = 1/1$ (H^-) and $1/2$ (D^-, α, HH^+). The isochronous magnetic field for $q/m = 1/1$ is created by appropriate shimming of iron. The second isochronous magnetic field is obtained using correction coils wound around magnet poles. There are three sets of correction coils, each with their own separate power supply and with an adapted radial density of windings to obtain the required spatial magnetic field modification. Negative ions are extracted by stripping; positive ions through electrostatic deflection and a subsequent Gradient Correcting Extension. Both beams converge to the same switching magnet. Two special shaped iron pieces will be added onto each magnet pole to create favorable beam optics for both extracted beams.

INTRODUCTION

C70 cyclotron will accelerate two types of ions described by the charge state q to mass m ratio:

- $q/m = 1/1$, H^- ions can be accelerated to 70 MeV
- $q/m = 1/2$, α particles can be accelerated also to the total kinetic energy of 70 MeV, giving 17.5 MeV/nucleon. D^- and HH^+ ions will be accelerated to 35 MeV. Due to small differences of the ion rest mass it was also necessary to verify that the isochronous magnetic field for α particles is also isochronous for D^- and HH^+ ions, however, the small shift of the RF system frequency was observed.

Two different methods of extraction will be applied for positive or negative accelerated ions:

- negatively charged ions H^- and D^- will be extracted by stripping, giving, for the stripper moving radially, the beam of protons with the kinetic energy between 30 and 70 MeV or extracted D^+ beam with energies between 15 and 35 MeV. The stripping extraction systems will be installed on opposite sides of the cyclotron permitting a dual beam extraction and a simultaneous irradiation of two targets.
- positively charges α particles and HH^+ ions will be extracted using an electrostatic deflector installed on one cyclotron side. HH^+ ions can pass by the stripper foil producing the beam of 17.5 MeV protons for PET radioisotopes production.

All calculations have been performed using Vector Fields [6] OPERA-2D and OPERA-3D software, different versions for Windows and Linux operating systems.

RESULTS

The conceptual design of the C70 cyclotron magnet has been changed many times. Initially the cyclotron was considered as a scaling-up of the existing IBA C30 cyclotron. Then the cyclotron magnet has become more and more complicated taking into account all requirements of the accelerated beam types, different types of the extraction from the cyclotron and other subsystems.

Calculations and the final geometry

The figure 1 shows the blown view of the cyclotron iron. The cyclotron median plane is on the extreme right.

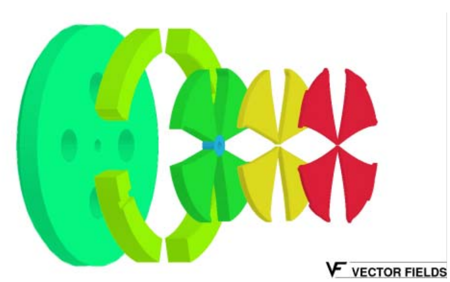

Figure 1: The blown view of the C70 cyclotron iron. From left to right: the upper return yoke, the lateral return yokes, the sectors and the central plug, the poles and the covers.

The $B-H$ magnetization curve of the lower and the upper yoke was measured on the extracted samples by one of the subcontractors and verified by the certified laboratory. All measured and used in calculations $B-H$ magnetization curves have been significantly better than the similar curves measured for typical magnetic steel used to produce IBA PET cyclotrons. These yokes are the biggest parts of the cyclotron magnet having the thickness and the diameter of 450 and 1910 mm respectively. The vacuum and RF ports diameter is 520 mm. The decision concerning the dimensions and the position of ports probably has been taken too early in the design process due to the fact that the RF system was developed by one of IBA subcontractors.

Other cyclotron iron pieces have been produced and the measured $B - H$ magnetization curves provided by other subcontractor. This subcontractor have produced iron for many already constructed and tested IBA PET cyclotrons. All these cyclotrons confirm the good quality of the rolled iron and the good reproducibility of the production process.

Initially C70 was considered as the four-fold rotational symmetry cyclotron. The lateral return yoke consists of four pieces but creates two-fold rotational symmetry of the cyclotron due to the fact that only two opposite pieces have ports for stripping extraction system. Two other opposite return yokes have one corner cut to create the passage for the lower kinetic energy beam extracted by stripping.

Inside the vacuum chamber the cyclotron magnet has four-fold symmetry except the center up to the radius of 45 mm. The azimuthal variation of the magnetic field is created by sectors and the central plug then by poles and finally by covers located 15 mm from the cyclotron median plane. The 50 mm thick covers have the inner and the outer radius 15 and 1240 mm respectively. The cover edges close to the median plane and the cyclotron rotation axis are rounded to increase the available space for the inflector and its housing. The small region of the two-fold symmetry in the center facilitates the increase of the dee angle of the central region.

To improve beam optics after stripping extraction it was necessary to increase the volume of the cover to avoid the passage of the extracted beam by the regions with a high gradient of the magnetic field that is nearly parallel to the trajectory. One corner of each cover at the outer radius was increased by adding 40 mm Cover Extension.

An electrostatic deflector is placed in one valley of the magnetic field and the extracted beam will cross the outer edge of the cover placed directly downstream the deflector. Considerations of the beam optics after electrostatic deflection resulted in the addition of the Gradient Correcting Extension at the outer edge of covers. The gap between covers of 30 mm is linearly reduced to 20 mm at the Gradient Correcting Extension extremity.

The Cover Extension and the Gradient Correcting Extension are added to all eight covers to preserve the four-fold symmetry of the cyclotron. The figure 2 present one cover with the Cover Extension and the Gradient Correcting Extension.

Correction coils and more calculations

Different methods have been considered to obtain required two different isochronous magnetic fields:

- movable inserts in two opposite valleys as in IBA PET cyclotrons. This method was excluded because dimensions of inserts become too large taking into account that the isochronous field difference should be above 500 Gauss in the extraction region.

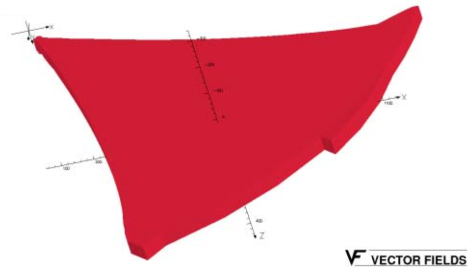

Figure 2: The view of the C70 cover from outside. The Cover Extension and the Gradient Correcting Extension are on a first plan.

- movable inserts in two opposite valleys moving along the lateral edge of the pole. This method was rejected due to probable mechanical friction and/or a grip between movable and fixed iron pieces that must be in contact to correctly transfer the magnetic flux.
- the well known classical correction coils placed on flat surface of the poles close to the median plane of the cyclotron. Only two isochronous fields are necessary in C70 cyclotron so the correction coils should be simplified.
- equidistant correction coils wound around poles of the cyclotron. Theoretically such correction coils create an additional magnetic field with a constant gradient as in a quadrupole. Practically the relative permeability of iron varies in the magnet so the quadrupolar field is distorted. This solution initially seemed to be attractive but requires similar number of power supplies as the number of correction coils and is too expensive.
- correction coils wound around poles of the cyclotron with a variable density of winding. This solution is interesting because theoretically it requires only one power supply when the correction coils are correctly placed around poles. This was rejected because it is risky to rely only on the correct placement of coils around eight poles and a practical application may need a lot of time when adjusting the coil positions.
- correction coils wound around poles of the cyclotron with a variable density of winding and using few (two, not more than three) power supplies. This solution was finally chosen. It adds, if necessary, the flexibility to the previous solution by giving the possibilities of adjustment of coils positions and to change the current of the one coil or of the block of correction coils.

It is necessary to shield correction coils from the beam and from the RF currents. Therefore there is a choice between two different solutions:

- the shielded poles with correction coils are placed close to the cyclotron median plane. The shielding plates have to cover all poles and on the lateral edges they have to be connected with the RF cavities.

- the poles with the correction coils are placed farther from the median plane. The shielding between the median plane of the cyclotron and the correction coils is created by adding the iron element to the magnet. The thickness of the added pieces of iron can be greater than the thickness of shielding plate. The added pieces can be used to shape one isochronous magnetic field without any necessity to add the removable lateral pole edges that are used to create the isochronous magnetic field in IBA C30 cyclotron. This solution was chosen, iron covers have been created.

These pieces of iron added between the median plane and the poles with correction coils have one disadvantage. They act like a short circuit in the cyclotron magnet and a fraction of the magnetic flux passes in the covers instead of the gap where the beam is accelerated. The fraction of the useful magnetic flux diminishes with increase of the cover thickness. Therefore the thinner cover is preferred but at the same time the mechanical rigidity of covers increases with the thickness.

Effects of the cover thickness have been studied using 2D model of the cyclotron magnet. Such calculations are about 20 times faster than 3D calculations. The obtained magnetic field differences confirm that the cover thickness of 50 mm can be accepted and the magnetic field changes are easier when the magnetic field diminishes.

The figure 3 presents the correction coils around one pole of the cyclotron.

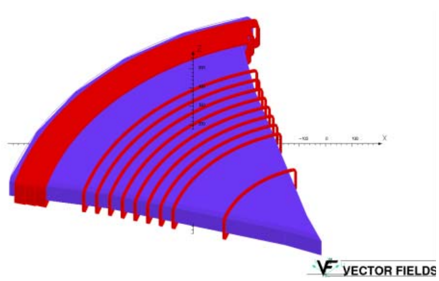

Figure 3: correction coils around one pole of the cyclotron.

The initial positions of correction coils have been determined assuming linear effects of coils. These results have been improved by an extensive study of effects of the correction coils, of the nonlinear iron behaviour and the changes of the magnetic field due to changes of the main coil current $dB/dI(r)$.

Field measurements and more calculations

First measurements allowed the comparisons between the measured and calculated magnetic field. The absolute values of the magnetic field of the models was in agreement with the measured values (typical absolute differences about 2 percent, more in the regions of a high field gradient). The magnetic field was very far from the isochronism due to the very conservative initial shape of the covers.

The first correction of covers has been performed based on the calculated matrix of the magnetic field changes due to cutting of the cover edges ($dB/dx(r)$) and aimed to obtain the isochronous field immediately. The measured magnetic field after the first correction still is not isochronous because the quantity of milled iron was enormous. At teh same time we noticed that the measured field differences are identical as the calculated field differences of two model geometries. This should diminish the number of necessary iterations to obtain the isochronism.

The comparison of the measured and calculated effects of the correction coils shows a good agreement. Produced changes of the magnetic field are also close to the theoretical difference of isochronous magnetic fields for H^- and α ions except the central region that probably will require other correction approach than the rest of the cyclotron.

CONCLUSIONS

- design of the C70 magnet based on the experience acquired at IBA took into account the presence of other important cyclotron subsystems. Therefore further development of the C70 cyclotron will not force to changes of the machine concept due to lack of the compatibility between subsystems. The cyclotron should be isochronous for two types of accelerated ions but a small adjustment of (between 30.2 and 30.5 MHz) RF system frequency will be necessary.

- the design of the C70 cyclotron has been done keeping in mind that the high beam intensity was required for H^- ions. The isochronous magnetic field for this ion will be created correcting the iron i.e. using well mastered technologies already applied for many IBA cyclotrons.

- the calculated and measured effects of the correction coils are in good agreement. This indicates that the creation of the isochronous magnetic field for α particles will be possible by applying the correction coils effects on the isochronous magnetic field of H^- ions.

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[6] Vector Fields Limited, 24 Bankside, Kidlington, Oxford OX5 1JE, England