

A NOVEL DESIGN OF A CYCLOTRON BASED ACCELERATOR SYSTEM FOR MULTI-ION THERAPY

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Abstract

A cyclotron based system for hadron therapy is developed, which allows a phased installation: start with protons and Helium ions and add Carbon ions later. The concept is based on an accelerator system of two coupled cyclotrons. The first cyclotron provides protons or He-ions that can be used for the full spectrum of treatments and “low energy” C-ions, with a range of 12.7 cm in water for a subset of tumours and radiobiological experiments. For treatments at all tumor sites with C-ions, the C-ions can be boosted subsequently up to 450 AMeV in a separate sector cyclotron, consisting of six sector magnets with superconducting coils and three RF cavities. First studies of the separate sector cyclotron indicate a relatively robust design with straight forward beam dynamics. This system is smaller than corresponding synchrotrons and possesses the typical advantages for therapy applications of a cyclotron. Present efforts to optimize the design of the super conducting sector magnets indicate that the introduction of a radial gradient in the sector would have many advantages.

INTRODUCTION

Hospitals considering radiation therapy with protons, Helium or Carbon ions, often desire a phased approach: start with protons and add Carbon ions later. The

motivation to use carbon ions for radiation therapy is based on the ballistic properties (heavy, thus limited scatter) and the expected advantages of a higher Radio Biological Effect (RBE, the ratio of the dose given with ^{60}Co gamma rays to the dose given with the Carbon ions, for the same cell killing). Until now all clinical carbon therapy facilities are using an injector linac coupled to a synchrotron (typically $\varnothing \approx 25$ m) to accelerate particles. The advantage is the selectable energy, but the pulsed beam structure (the spills) and the relatively large fluctuations of the beam intensity during the slow extraction process prevent the application of fast pencil beam scanning methods. Such methods are suggested [1] to deal with organ motion and tumour motion during the administration of the irradiation dose. A cyclotron, however, offers a DC (actually CW) beam with a very stable beam intensity (also at kHz bandwidth [2]), fast (<80 ms) energy change (external energy degrader), fast (kHz) beam intensity control with an accuracy of a few percent, high extraction efficiency and no intensity problems. Since building a synchrotron does not allow for a phased approach, a solution based on two cyclotrons is proposed here, where the second cyclotron is coupled to the first one in the second installation phase of the project. Furthermore, this concept exploits the advantages typical for cyclotrons as mentioned above.

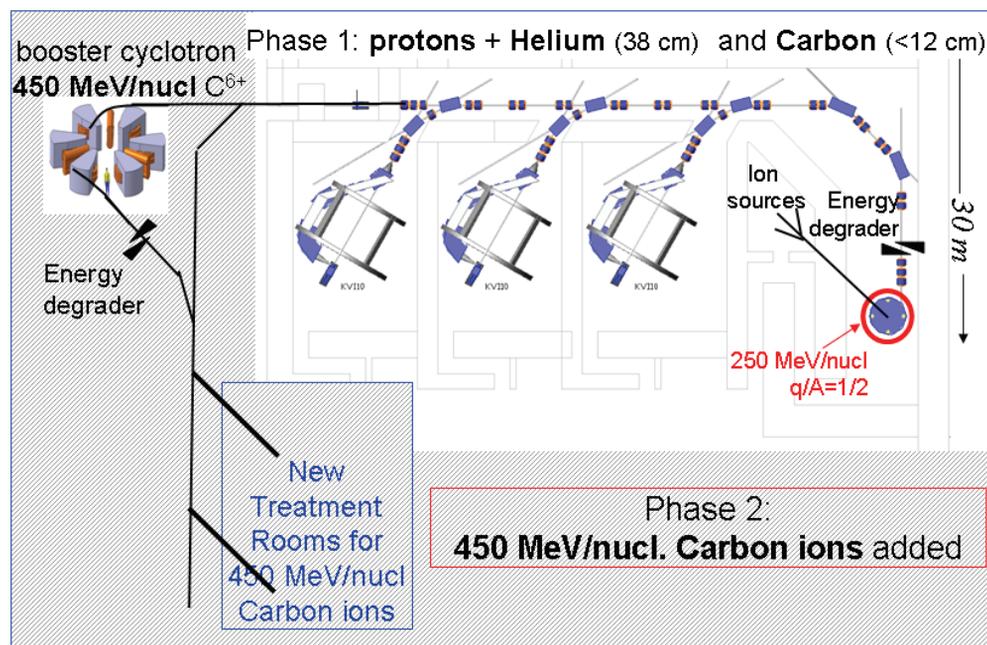


Figure 1: Possible layout for a multi-ion facility, based on two coupled cyclotrons, built in two phases.

Protons (H_2^+), He^{2+} , or C^{6+} -ions of 250 MeV/nucl will be accelerated in the first cyclotron, which is compact and has superconducting coils. Protons can be used for the full spectrum of treatments and the Helium ions, having the same water equivalent range of ~ 38 cm as the protons, also allow a full scale medical program, as well as radiobiology research with moderate RBE particles. For a subset of treatments, with a maximum water equivalent depth of ~ 12.7 cm, the “low energy” C-ions can be used for therapy, but also enable a sophisticated research program in radiobiology.

In the second phase of the project (Fig. 1), one can extend the treatment possibilities with C-ions to all sites (depth of 33 cm) by boosting the energy to 450 AMeV in the second cyclotron. For this booster we a separate sector cyclotron is proposed, consisting of six sector magnets with superconducting coils and three or four RF cavities.

In this paper the specifications of the total cyclotron system will be described first, followed by a detailed discussion of several design possibilities of the separated sector cyclotron.

SPECIFICATIONS AND GLOBAL DESIGN OF THE CYCLOTRON SYSTEM

Ion Sources and Injection

ECR sources for Helium and Carbon ions and a cusp source or ECR source for H_2^+ ions will be mounted in a separated vault (quick access) in close vicinity to the injector cyclotron. A typical injection energy is about 25 kV. A fast laminated switching magnet is used to select the ion source within a few seconds. The beam intensity can be switched off by means of a fast electrostatic deflector in the beam line to the axial injection system of the first cyclotron. Using a slit system down stream of the deflector, this system can be used for beam intensity modulation with kHz speed.

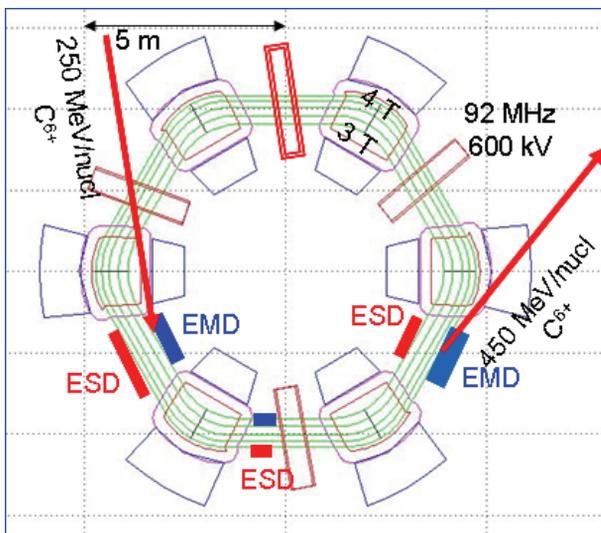


Figure 2: Injection and extraction in a 3(4) cavity layout of the 450 MeV/nucl booster cyclotron.

Injector Cyclotron

The choice of a superconducting “compact” cyclotron is based on the advantageous properties of and good experience with the COMET cyclotron [3] currently in use at PSI’s Center for Proton Therapy [4]. The optimal value for the beam energy must be found in the range 230-250 AMeV, with simplicity of the design as major criterion. Extraction of the Carbon ions will be by means of electrostatic elements. The extraction of the H_2^+ ions, however, could be done by stripping the ion and extracting the protons. The stripper option will give almost 100% extraction efficiency, but will most probably require a dedicated extraction channel and stripping foil technology. With the COMET 250 MeV proton cyclotron, the extraction efficiency is $>80\%$, resulting in a relatively low radioactivity in the cyclotron [3]. To achieve at least a similar extraction efficiency, is an important specification for the injector cyclotron.

Switching the setting of the cyclotron between different particles requires a slight ($\sim 0.8\%$) change of the RF-frequency and a small change of the magnetic field shape. Field changes can be made by using trim rods or correction coils. It is to be investigated how this can be done fast and reproducibly, also in view of the extraction method.

A possible candidate for the injector cyclotron could be the existing design of a cyclotron for 250 AMeV, made by the Catania group [5]. This design operates at 92 MHz, has a diameter of 4.9 m and a weight of 320 tons. However, an up scaling of the COMET cyclotron will also be considered.

Separated Sector Cyclotron

The application of superconducting magnets in a sector cyclotron has been demonstrated at the K2500 cyclotron at Riken (Japan) [6]. This cyclotron enables acceleration of many different isotopes in the radioactive beam facility at Riken. Since this is not needed in our case, this will strongly simplify the magnet. In order not to complicate the design of the superconducting coils, the beam dynamics of the cyclotron must be chosen such that no concave coil shapes are needed.

DESIGN STUDY OF THE BOOSTER: SEPARATED SECTOR CYCLOTRON

The first design studies presented here, have been confined to a six sector machine, using 92 MHz (12th harmonic) cavities with a peak voltage of 600 kV. A four sector machine would need larger magnets and may offer less flexibility and a more complicated injection or extraction.

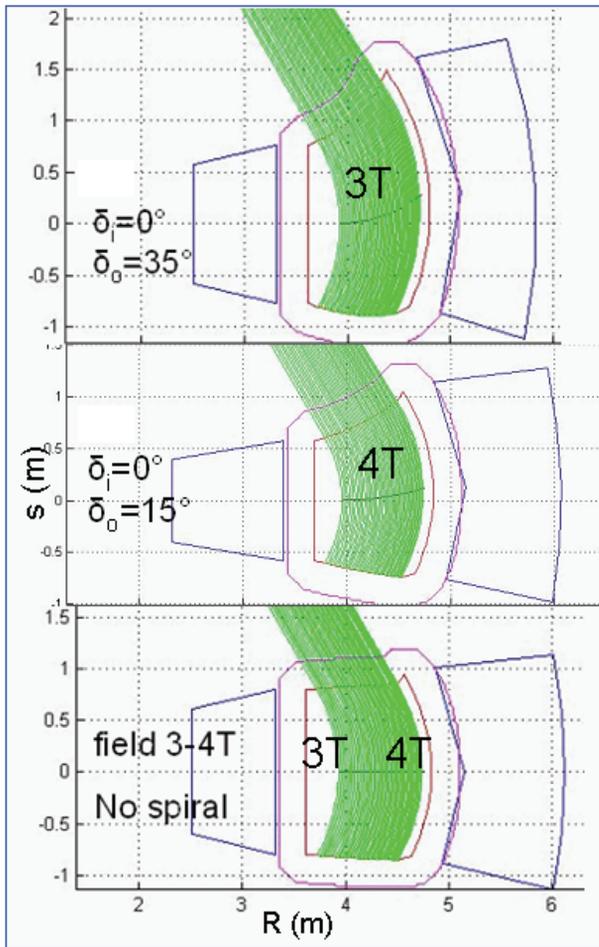


Figure 3: Magnet shapes and equilibrium orbits in the 3T, 4T and 3-4T designs, and their spiral angle at injection and extraction $\delta_{i,o}$.

Designs (see Table 1) with different magnetic fields in the sector magnets have been compared: 3 T, 4 T and one with a field varying from 3 T at injection to 4 T at extraction. Working at a lower harmonic number (e.g. 10 or 8) would reduce the magnet dimensions considerably. However, the space between the magnets would not allow enough room for the RF cavities or injection/extraction elements. Furthermore, a spiral angle up to 40° would be needed, which will be extremely difficult to construct in a 4 T magnet.

In the current design (Fig. 2) three single-gap RF cavities are foreseen. Depending on the layout of the injection and extraction channels, it may be an option to use four cavities. In some layout options (e.g. in the one shown in Fig. 2) the symmetry in the cavity locations is distorted, which needs further study of the consequences for the beam dynamics. However, experiences with the 590 MeV proton ring cyclotron at PSI have shown, that this need not be a problem. Also the potential of having a redundancy in the RF cavities, is an interesting feature for therapy. The injection and extraction paths cover two or three sectors and can be performed with electrostatic deflectors and septa (ESD, ~ 100 kV/cm) and magnetic deflectors (EMD, ~ 0.4 T).

Table 1: Design Options for a Six Sector Cyclotron

Field in sector magnet:	3 T	4 T	3-4 T
Harmonic number (f_{RF}/f_{turn})	12	12	12
Weight 1 sector magnet (tons)	88	93	94
Diameter(m)	12	12	12
Spiral angle inj/extr (degr)	0/35	0/15	0/0
Orbit separation inj/extr (mm)	3.0/2.5	3.0/2.5	3.0/2.5

Beam Dynamics

The tune diagram has been calculated with a computer program employing analytical methods, which allow a review of different designs in rather short time. The effect of the magnetic field has been approached by a first order beam transport formalism in which a sector magnet is modeled by a transport matrix, which includes fringe field approximations and pole face rotations at entrance and exit of the magnet. At a series of radii between those of injection energy and extraction energy, the transport matrices of the magnet are calculated. Within the sector magnet a circular trajectory is assumed. At each radius the length along the arc of the trajectory and the spiral angle have been calculated, thus yielding the geometrical shape of the pole. In this way also a curved pole face and/or a radial gradient in the field could be taken into account. For the fringe field calculation several methods have been explored, all assuming more or less ‘‘classical’’ magnet field boundaries with a parameterization proposed by Kato [7]:

$$B(s) = \frac{B_{max}}{2} \left[1 - \frac{(s/g) - a}{\sqrt{((s/g) - a)^2 + b^2}} \right]^n.$$

Here s is the distance from the magnet’s effective field boundary and a is the distance of $B_{max}/2$ from the field boundary, b the softness of the edge, g the magnet gap and n the inverse of the tail extension. The effect of the fringe field is approximated as a correction ψ on the pole face rotation angle β , having only effect in the vertical plane [8]. In an alternative approach, giving almost the same results, the fringe field was approximated as a product of transport matrices, each representing a slice with thickness Δs of the fringe field.

From the beam transport matrix $M_{r,z}$ of a sector magnet and following drift space to the next sector magnet, the betatron frequencies in the radial and vertical plane have been calculated using

$$v_{r,z} = \frac{n_{sec}}{2\pi} \mu_{r,z}, \quad \mu_{r,z} = \arccos\left(\frac{1}{2} \text{trace}(M_{r,z})\right),$$

where $\mu_{r,z}$ is the phase advance in the section (one out of n_{sec}). Fig. 3 shows the thus obtained tune diagrams of the three designs.

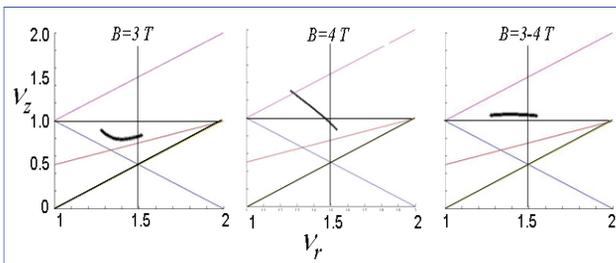


Figure 3: Tune diagrams and some resonances for the three design options.

Using the model described above, sensitivity calculations were performed to study the effect of the fringe field and the spiral angle. Variations of ν_z were typically within a range of 0.22, when varying the fringe field between “clamped Rogowsky” and very soft edge magnets. Similar variations were observed when varying the pole face rotations from 14 to 20 degree at injection and 30 to 35 degree at extraction radius. These “free” parameters can be used to force the vertical tune into a convenient value between 1.0 and 1.5. As can be seen in Fig. 3, such an adjustment (e.g. by slightly rotating the sector magnets along their vertical axis) is needed in the 3-4 T design to avoid the $\nu_z=1$ resonance.

In the horizontal plane, ν_r is about 1.3 at injection and 1.5-1.7 at extraction. The approximate phase advance of 100° and 80° per sector respectively, can be exploited in the extraction and at the extraction to increase the orbit separation (see Fig. 2).

The tune diagram needs to be confirmed in more detail by tracking calculations. As Fig. 3 shows, dangerous resonance crossings are not expected, but optimizations are still needed for the vertical focusing (e.g. move away from $\nu_z=1$, prevent concave sector magnet boundaries) and to establish the injection and extraction trajectories more accurate.

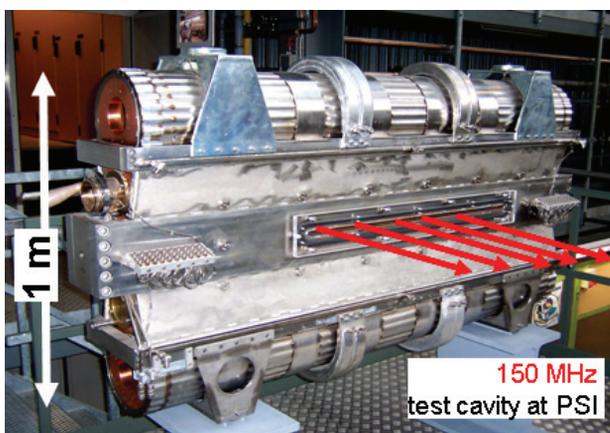


Figure 4: 150 MHz test cavity (single gap). A 92 MHz cavity is approx 1.5 times higher.

RF Cavities

We have chosen four single gap RF-cavities. A 1.5 times larger version of the existing test cavity (150 MHz) for the 590 MeV ring cyclotron at PSI could be used (see Fig. 4). The advantages with respect to a dual gap system are the relatively small space needed in the azimuthal direction and the small volume to be pumped. Based on the experience with this test cavity, a gap voltage of 600 kV can be expected, so that at extraction radius an orbit separation of 2.5 mm can be achieved, not taking the additional effect of the $\nu_r=1.5$ resonance into account. A fourth cavity could be added, ensuring redundancy but also allowing operation with lower power per cavity. Here some trade-off studies must be made.

Superconducting Sector Magnets

The main motivation for a super conducting coil is the possibility to achieve fairly strong magnetic fields. The advantages are the reproducibility of the magnetic field and the relative independence of the field from small artifacts in the iron. A study has been started to design the super conducting sector magnet. An advantage of the currently chosen size of the cyclotron is the possibility to use H-magnets. Fig. 5 shows the result of preliminary TOSCA calculations of a simplified 4 T magnet with a 3 cm gap. The coil has been modeled such that there are no concave sections. Compared to the original estimate, the size of the magnet has been increased to 215 tons, to limit the field in the yoke to 2.3 T. Using a separate iron layer with air gaps will allow a weight reduction. The totally stored energy is 24 MJ and radial forces of 150-300 tons are acting on the coil. In the model the poles are flat but have a concave shape at one end. Fig. 5 clearly shows that quite some shimming is needed.

Forces on coils in tons

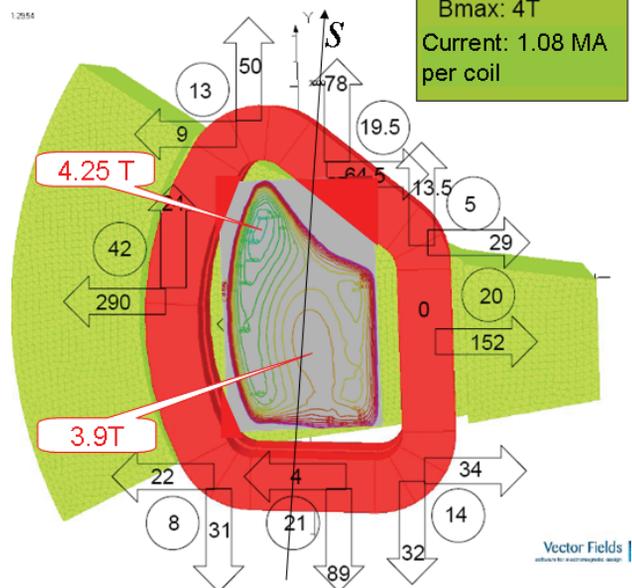


Figure 5: Magnetic forces and iso-field lines in a model of the 4T sector magnet, calculated with TOSCA.

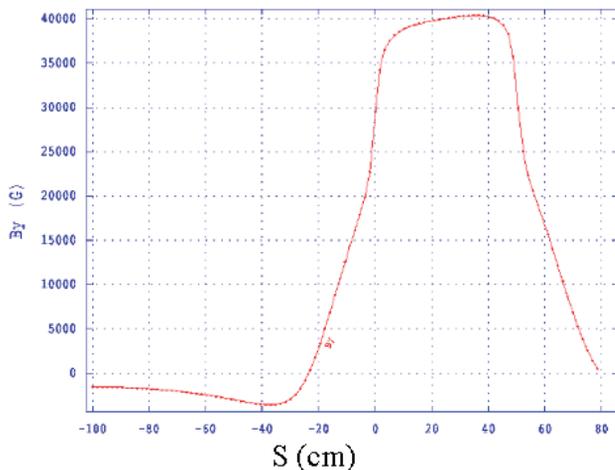


Figure 6: Magnetic field of one sector magnet along a line in the azimuthal direction, calculated with TOSCA.

The shape of the magnetic field is largely determined by the field from the coil. The vertical and horizontal position of the coils can thus be optimized to help the field shaping. In the magnet with the gradient an optimized coil location and orientation will be of major importance. The larger distance of the coil to the inner trajectories (3 T) compared to the coil distance to the outer trajectories (4 T) may be used advantageously. A design with a tilted coil is under investigation. The profile of the magnetic field along the line in Fig. 5 in the azimuthal directions shows some interesting features. First of all the top is not flat and the edges are not sharp due to saturation of the iron. Between -20 and 0 cm the slope of the field is shallow due to the coil field. The coil field is apparently so strong that a negative field of 0.2 T exists between the sector magnets. Although this makes the design sensitive for iron in the direct environment of the magnet, it may also be an advantage, since it increases flutter and thus focusing.

CONCLUSIONS

The study of various design options of a separated sector cyclotron for the acceleration of 250 AMeV C^{6+} ions until 450 AMeV indicated that the version with the radial gradient offers very favourable characteristics and advantages for the magnet engineering. The magnet can be rotated slightly in the horizontal plane to increase the vertical focussing. Furthermore its length is short enough to allow ample space for injection/extraction elements and

RF cavities. Beam dynamics studies indicate a relatively robust design with straight forward beam dynamics.

Present efforts to optimize the design of the superconducting sector magnets indicate no principal problems. However, work still needs to be done on minimizing the amount of iron, shaping of the field and the design of the coil.

The concept of two cyclotrons presented here, indicate that the proposed solution may turn to become an excellent solution for a combined - light and heavy particle - therapy machine for the following reasons:

- the robust and simple design allows a machine with a high reliability,
- it has the advantage of a CW cyclotron ion beam,
- the external ion source simplifies fast beam current variations necessary for optimal scanning and organ motion synchronization,
- the concept of two cyclotron offers an attractive two-phase realization. In the first step protons and helium ions are available for the full range. In particular helium ions have less angular spreading, which is important for deep seated tumors. Carbon ions with a range of up to 12.7 cm are attractive for cases where extreme localization is necessary. In a second stage the booster cyclotron can be added and the corresponding treatment rooms can be dedicated to heavy ion treatment.

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