Magnetic Design of a Compact GaToroid for Very High Energy Electron and Pre-Clinical Hadron Beams

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***Abstract*—GaToroid is a novel configuration of a beam delivery system for charged particles therapy based on a steady-state, axis-symmetric field configuration. The basic idea is to use fixed toroidal magnets, producing an axis-symmetric (or periodical axis-symmetric) field configuration that can bend beams from several directions onto the patient location. In principle, neither magnets nor patient need to be moved. In addition, the field of the magnets of this toroidal gantry is static. Such system is perfectly adapted to FLASH therapy, a novel method of beam dose delivery that has shown benefits for electrons and potential for hadrons. In this paper we describe the magnetic design of a "compact GaToroid", which could be built with iron-dominated magnets, suitable for 200 MeV electron beams, as well as protons at 70 MeV. The gantry profits from the use of toroidal quadrupoles, which greatly simplify the beam transmission. An additional novelty is the use of a resonant kicker as the vector magnet. Starting from the requirements for beam transmission, we derive first the magnet main characteristics (strength, aperture, size and mass) and report the detailed magnetic field calculations in support of the design.**

***Index Terms*—Particle therapy, hadron therapy, gantry, FLASH effect.**

I. Introduction

CHARGED particle therapy, using hadron and electron beams, is a pioneering approach in cancer treatment [1], [2], [3], [4]. Protons, helium and carbon ions, along with high-energy electrons, provide precise radiation to cancer cells while minimizing harm to healthy tissue. A crucial advantage of charged particle beams compared to photons is that they can be accurately shaped and guided using magnetic fields [4]. In the most advanced installations, gantries are used to achieve conformal mapping of the area to be irradiated [5]. Present gantries are rotating beam transfer lines that direct the beam precisely around the patient, allowing for optimal tumor targeting and minimal exposure to healthy tissue. The rotation capability of gantries is used to cover arbitrary beam angles, achieving conformality, thus enhancing treatment efficacy while minimizing side effects.

Standard particle therapy is usually performed by delivering small dose fractions, at low rate of 0.1 Gy/s, often over days and weeks. In recent years, however, the possibility of a new technique named *FLASH* has emerged [6], [7]. The FLASH effect refers to the fact that an ultra-high dose of radiation delivered in an extremely short duration, typically in a fraction of a second at rates up to 100 Gy/s, appears to spare healthy tissues while effectively treating cancerous cells, thus enhancing the treatment capability. The FLASH effect was observed in very high energy electrons (VHEE) [6] and protons [7], which are both suitable for treatment of deep-seated tumors. Research on FLASH, and in particular on VHEE, is a very exciting topic of present radiation oncology, with on-going construction of dedicated therapy and research installations [8], [9].

To go beyond the state-of-the-art, it would be of particular interest to combine FLASH therapy with conformal beam delivery, hence achieving the benefits of both: maximizing treatment efficacy while minimizing exposure to healthy tissues. Conformal FLASH therapy could hold the promise of transforming cancer treatment paradigms. The speed at which a FLASH beam is delivered, however, makes it physically impossible to change the beam delivery direction using a rotating gantry. Gantries tend to be bulky because of the required of mechanical stability, weighing several tens to hundreds of tons. A different concept is hence required to achieve conformal delivery of FLASH beams.

A possibility is to build dedicated beam delivery lines, and selecting beams for each line based on energy. This is the concept used in the realization of the VHEE FLASH therapy center built as a collaboration of CHUV, CERN and THERYQ [8]. This configuration has the disadvantage of using different energies for different directions, and being limited in the number of directions.

An alternative to single magnets is to exploit the rotational symmetry of a torus to design a magnetic configuration which can be more compact and offer more flexibility in terms of geometry and number of lines, selecting directions with a fast kicker magnet. This is in fact the original idea behind the GaToroid [10], [11]. The basic idea is to use fixed toroidal gantry magnets (one, or several), producing a steady state, axis-symmetric (or periodical axis-symmetric) field configuration that can bend

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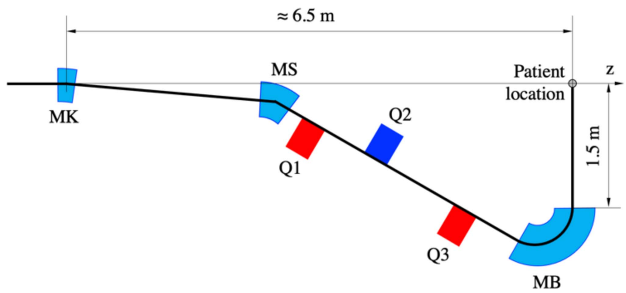

Fig. 1. Schematic layout of the beam delivery line design, indicating the position of the resonant kicker (MK), the septum (MS), focusing (Q2), and defocusing (Q1, Q3) quadrupoles and final bending dipole MB).

TABLE I
CHARACTERISTICS OF THE MAGNETS OF THE REFERENCE BEAMLINE CONFIGURATION REPORTED IN FIG. 1

		Field|Gradient (T | T/m)	Magnetic length (mm)	Beam aperture (mm)
MK	Kicker	0.15	400	50
MS	Septum	0.5		3.5 x 3.5
Q1	Quadrupole	−4.2		4.2
Q2	Quadrupole	3.6		11.3
Q3	Quadrupole	−16.4		12.3
MB	Final Bend	1.47 | 2.6		23.4 x 31.9

beams from several directions onto the patient location. Neither magnets nor patient need to be moved. A single upstream "vector magnet" provides the beam steering, which depends on the beam energy (in the original version) and the direction of irradiation. The steady state operation allows quasi-simultaneous irradiations from different directions (also at different energies), with the only limitation imposed by the ability of the accelerator to deliver such beams, and the vector magnet to follow the desired changes. This makes the GaToroid configuration especially interesting for FLASH therapy application.

In this paper we describe the magnetic design of a GaToroid configuration suitable for VHEE in the range of 100 MeV to 200 MeV. Magnet specifications are derived from beam optics studies [12], [13], [14]. Because the rigidity of electrons at 200 MeV is comparable to that of protons at 70 MeV, the concepts presented here apply with minor modifications and adjustments to proton beams in the range of 70 …90 MeV. This is the typical energy range used for pre-clinical research. This study is hence also paving a possible path towards a unique research installation capable of conformal proton FLASH.

II. VHEE Beam Line Specifications

We have performed beam dynamics studies of electron beams at 200 MeV, showing that it is possible to produce beams with flat profile and relatively large (100 to 200 mm diameter) as desired for VHEE FLASH therapy [6]. One of the beam line configurations obtained, and satisfying above requirements, is reported schematically in Fig. 1. The beam line consists of a resonant kicker, a septum, focusing and defocusing quadrupoles and a final bending dipole. The magnet strengths (field for dipoles and field gradients for quadrupoles) and beam apertures required are listed in Table I. Aperture values are intended as the minimum required diameter for round bore magnets (kicker and quadrupoles) and minimum required gap x width for rectangular bore magnets (septum and final bend).

The resonant kicker receives the horizontal beam from the accelerator, and bends it to an angle of 5 degrees, towards the septum. The septum then amplifies this kick to 30 degrees, which provides sufficient space for the quadrupoles and, eventually, the final bending dipole. In this design, the beam arrives at 90 degrees angle on the patient, though this is not a constraint and could be changed as suitable.

The novelty we have introduced is that the kicker is powered in resonant mode, at a modest frequency (e.g., 10 Hz). The accelerator extracts beam at the time when the field in the kicker is the one needed to achieve the desired kick. This is possible with an accelerator based on RF cavities, where the control of beam energy and intensity is very fast, at ps time scale. The advantage of putting the kicker in resonant mode is that we avoid the difficulty of a fast and precise single field pulse, and simplify the control of the powering to providing a stable amplitude and phase.

After the septum, the beam is shaped by the quadrupole triplet Q1, Q2 and Q3. Aperture required in the quadrupoles are small, and the required gradients result in modest fields. The beam is finally bent by the dipole MB onto the patient location. Note that the MB is a combined function magnet with a specified dipole strength of 1.5 T and a gradient of 2.6 T/m. Given the small aperture required, though, the peak field in the magnet bore is well below 1.6 T.

The overall size is modest, i.e., 4 m outer diameter and 6.5 m length, with a free bore for the treatment area and required instrumentation of 3 m diameter. Such space would allow ample freedom in the positioning of the couch, as often required by treatment planning.

III. VHEE GaToroid Magnet Design

To achieve conformal treatment we need to have multiple beam delivery lines, ideally *rotating* the line described in the previous section around the z axis of Fig. 1 by a given delivery angle in the full range of [0 …360] degrees. In reality, a few delivery angles are already sufficient to achieve a good degree of conformality. We have chosen seven angles equally distributed in the full circle for this design exercise.

Such configuration could be built, in principle, as seven independent beam delivery lines, each equipped with the required dipoles and quadrupoles. In reality it may not be possible to fit independent lines in the limited space (e.g., at the septum location), nor it may be convenient to have separate magnets for each line. Following the gaToroid idea, we can improve on this concept by exploiting toroidal symmetry, i.e., designing toroidal magnets that produce the required dipole and quadrupole fields. The kicker, on the z axis, is evidently a special case, treated separately.

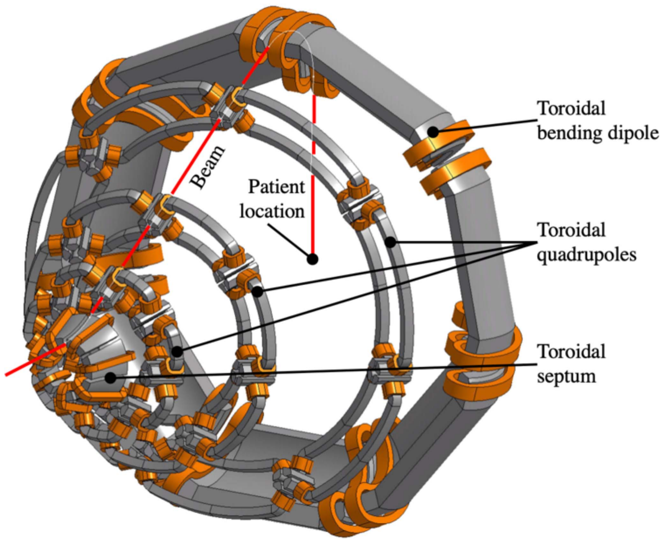

Fig. 2. Rendering of the toroidal magnets forming the seven beam delivery lines, showing iron yokes and coils. One beam line is highlighted for clarity. Design work by courtesy of T. Lehtinen, T. Capelli, A. Kolehmainen (CERN).

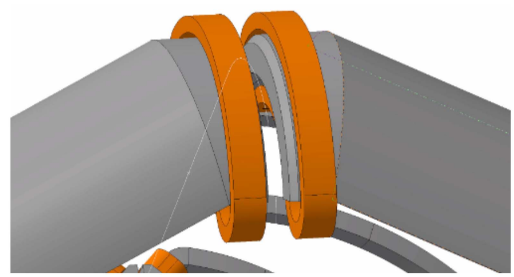

Fig. 3. Detail of the pole region of the final bending dipole, showing tapered poles and coil position. Design work by courtesy of T. Lehtinen, T. Capelli, A. Kolehmainen (CERN).

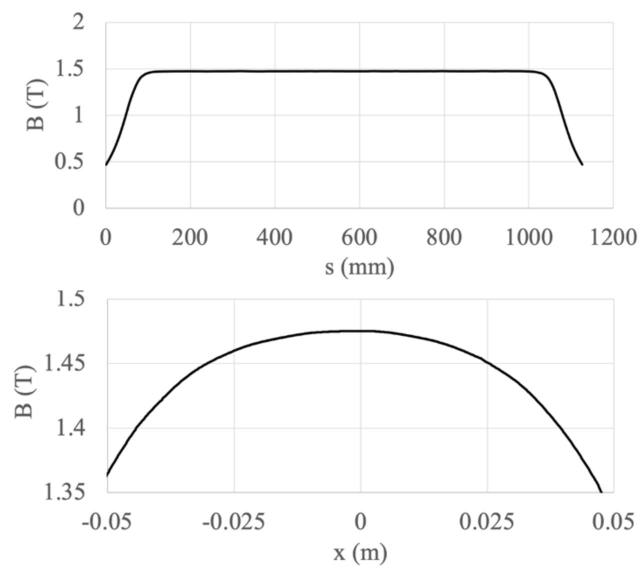

Fig. 4. Field profiles in the pole are of the final bending dipole. Longitudinal field profile (top) and transverse field profile (bottom).

Furthermore, examining the magnet requirements described above we see that field and gradients are well within the reach of iron-dominated electro-magnets. Iron-dominated magnets are simple technology, with known manufacturing and performance. We have hence opted for this solution for the toroidal part of the beam transfer line, from the septum to the main bending dipole. The only exception is the resonant kicker, which is designed as an air-core magnet to limit losses and field errors generated by eddy currents.

Fig. 2 shows a rendering of the design of the toroidal magnets, with the beam trajectory for one delivery line highlighted. We can distinguish the toroidal septum, receiving the beam from the kicker, the sequence of three toroidal quadrupoles and the final bending toroidal dipole. All iron circuits are closed rings, with gaps and poles shaped to generate the desired dipole and quadrupole fields. The total system mass is approximately 21 tons, of which the iron yokes account for 17 tons and the remaining 4 tons are coils. The design of the magnetic system is described in more detail in the sections below.

A. *Toroidal Dipole Magnets*

The field in a gap of constant size in a ferromagnetic torus powered by discrete coils is uniform, i.e., a dipole. The same applies to a torus cut at several locations, as shown in Fig. 2 for the septum and final bending dipole. In our case, in addition, the ferromagnetic circuit is shaped according to the beam trajectory, thus saving in terms of iron mass and weight.

The magnet apertures are 80 mm $\times$ 200 mm for the final bending dipole and 50 mm $\times$ 100 mm for the septum, much larger than the minimum size required to accommodate the beam (see Table I). The desired field in the final bending dipole, 1.47 T is generated by a magnetomotive force of 665 kAturn, while for the septum 100 kAturn are necessary. Values are modest for an installation of this type, and well within reach of standard copper coil technology. At this stage of conceptual design, we have not yet considered the need for a quadrupole component in the final bend, i.e., the field is homogeneous in the gap. The quadrupole required is small, corresponding to about 0.1 T at the pole, and will be added during the pole optimization (see later).

A detail of the coils and pole area of the final bending dipole for one of the lines is shown in Fig. 3, where we note the tapering of the poles and the fact that the coils are placed parallel to each other next to the gap. This is necessary to achieve the field homogeneity, and reduce the reluctance of the return yoke with respect to the gap, thus avoiding flux leakage. A last detail is the fact that the ferromagnetic torus is formed by assembly of straight yoke segments, which eases manufacturing, e.g., stacking laminations.

The field profiles in the pole area of the final bending dipole are finally shown in Fig. 4. The profiles are taken along the curved beam trajectory, i.e., in longitudinal direction, as well as normal to the beam trajectory, i.e., in transverse direction. The results show homogeneous field along the trajectory, with end effects limited to about 200 mm in the beam direction, and a homogeneity better than 1% over the beam width of 32 mm.

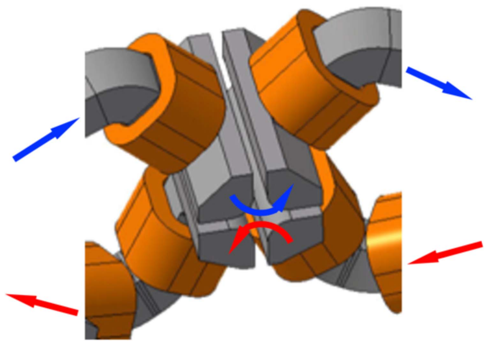

Fig. 5. Detail of the poles and return yoke of a toroidal quadrupole showing the direction of the magnetic flux in the iron and in the gap. Design work by courtesy of T. Lehtinen, T. Capelli, A. Kolehmainen (CERN).

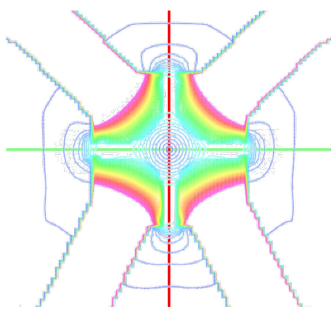

Fig. 6. Field map in a toroidal quadrupole at nominal gradient.

In the transverse field profile we see in particular the presence of a significant sextupole component which could be further reduced by adding pole shims, as is done customarily. During this pole optimization we will introduce the required quadrupole component.

B. Toroidal Quadrupole Magnets

It is also possible to generate a quadrupole field in a ferromagnetic torus with rotational symmetry, though this seems at first view nonobvious. To do this we separate the limbs of the flux return of an iron dominated quadrupole yoke, and connect them based on the flux direction, as shown schematically in Fig. 5. The result is the field map shown in Fig. 6, which shows the transverse field map and flux lines in the aperture. The quadrupoles are designed with an aperture of 58 mm, again largely in excess of the required beam apertures from Table I. In order to attain the nominal gradient of 16.4 T/m each toroidal quadrupole requires about 166 kAturn of magneto-motive force, once again well within standard coil technology. Though the result is already satisfactory, further optimization is possible and planned to improve on field homogeneity and simplify design, as done for the dipoles.

C. Resonant Kicker

The resonant kicker is a special case, being on the axis of injection into the beam delivery system. This magnet needs to provide a kick to steer the beam into the beam delivery lines, covering in principle any angle in the [0 …360] degrees range. This can be achieved combining two dipole fields at 90 degrees, and modulating their amplitude so that the total kick has the desired angle. Rather than separating the two dipoles, we have chosen to design a combined function magnets with two nested windings. In addition, as we anticipated, we wish to avoid the difficulty of powering each winding with a pulse of well controlled shape, amplitude and timing. The proposed solution is to power each nested winding in resonant mode, at constant amplitude, identical frequency and a 90 degree phase shift. Resonant powering can be controlled to high precision by acting on the amplitude and phase through active feed-back. Also, because the magnet is in harmonic mode, it is also easy to compensate for screening effects from eddy currents in metallic components.

The resulting field is a dipole with constant amplitude, rotating around the z axis by 360 degrees at each cycle. This set-up generates the field required for a kick in any direction, provided the beam is sent at the appropriate time. The time selection is delegated to the accelerator and extraction system. For an electron LINAC, such as the system being developed in collaboration among CHUV, CERN and THERYQ [15], the beam energy and delivery can be selected at ps time scale, i.e., with a precision largely sufficient to match the timing of the kicker field.

A magnet design similar to the one proposed was developed in the past to correct orbit variations in the ELENA accelerator [16]. The design is based on cos-theta coils wound with a copper conductor and nested in a structure that can be assembled directly onto the beam pipe. Extrapolating this design for a beam aperture of 60 mm, once again largely in excess of the beam aperture of Table I, we can produce the required 60 mT m kick with windings operating at 10 A/mm^2. We have chosen a 10 Hz operating frequency for the resonant kicker, which allows covering the whole [0 …360] degrees range within 100 ms, as necessary for the FLASH effect. With the computed inductances of the two nested windings, powering at 1 kA would require about 10 V of inductive voltage, i.e., a rather modest power converter. Also, at this frequency the field variation during the delivery of a train of beam packets, lasting a few tens of μs, remains within few 10^{-3}.

IV. Conclusion

We have described in this paper a novel configuration of a beam delivery system that can achieve conformal treatment of tumors using Very High Energy Electrons at 200 MeV in a time scale compatible with the FLASH effect, i.e., 100 ms. The system is largely based on the GaToroid concept, though in this study we make use of iron-dominated magnets for its majority. We have introduced two technical novelties, namely toroidal quadrupoles, exploiting rotational symmetry for the flux return to make the magnet simpler and the system more compact, and the use of a kicker magnet in resonant mode to take the functions of the vector magnet in the original GaToroid design, which was an issue identified at the time. Finally, this configuration is suitable for protons in the range of 70 to 90 MeV, and could provide a unique research facility, worldwide, for conformal hadron therapy at FLASH time scale.

We plan to continue with the optimization of the magnet design, e.g., introducing shims and pole shaping, simplifying powering and optimizing geometry for minimum mass. We are also progressing with the engineering, addressing mechanical supports and tolerances, cooling, as well as the option of using superconducting coils, preferably cryocooled HTS. At the same time, studies are on-going for proton beams, devising suitable optics and a magnetic design that matches new requirements.

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