CONCEPTUAL DESIGN OF SUPERCONDUCTING COMBINED-FUNCTION MAGNETS FOR THE NEXT GENERATION OF BEAM CANCER THERAPY GANTRY

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Abstract

An increasing number of proton therapy facilities are being planned and built at hospital based centers. Many facilities use rotatable gantry beamlines to direct the proton or ion-beam at the patient from different angles. A key issue is the need to make future gantries lighter and more compact with the use of cryogen-free superconducting magnets, in particular for the final bending section which can be of large aperture. Benefits of using the superconducting technology are: (1) the possibility to have a large momentum acceptance, hence reducing the need to ramp the magnet and enabling new treatment techniques, (2) the size reduction due to a lower bend radius and (3) the weight reduction up to a factor ten. The latter will also significantly reduce the costs of the supporting structure. We present a conceptual design based on Nb_3Sn superconducting combined function magnets (dipole, quadrupole, sextupole). The geometry using racetracks, the superconducting strand and cable parameters and the results of the thermal and the mechanical studies are reported. These magnets will work at a temperature of about 4.2 K cooled with cryocoolers.

INTRODUCTION

The number of the centres offering proton therapy has grown significantly over the past years and the number of hospitals and research institutions delivering protons or carbon ions for tumour treatment is following also an increasing trend. For the next generation of these machines, the superconducting technology applied to magnet development will play a key role as it will enable developping compact and light gantries. A gantry is the final section of a proton therapy facility, which consists of beamline magnets, beam diagnostics elements and the mechanical support structure. The gantry rotates around the patient and irradiates the tumour from different directions. The increased field strengths using superconducting magnets will decrease the bending radius, decrease the overall weight of the system and reduce the demands on the mechanical structure. More-over superconducting magnets allow increasing the momentum acceptance, hence reducing the need to ramp the magnet and enabling new treatment techniques [1].

The present concept is based on an isocentric gantry design with the transverse scanning performed downstream of the final bending magnet (Fig.1). A transverse scanning field of 30 cm x 40 cm with a beam spot size of $2\sigma \approx 5$ mm at the isocenter is required. The gantry should also allow a beam energy modulation between 70 MeV and 230 MeV (corresponding to a magnetic rigidity $B\rho$ of 1.2 Tm and 2.3 Tm, respectively). In our gantry layout, the last bending section aims at deflecting the proton beam by 135°. An achromatic layout is chosen with a very large momentum acceptance ($\Delta p/p \sim \pm 12\%$). Energy change between two layers will be performed in less than 100 ms, within the momentum acceptance window, keeping a ramping speed of magnetic field between these windows below 0.1T/s.

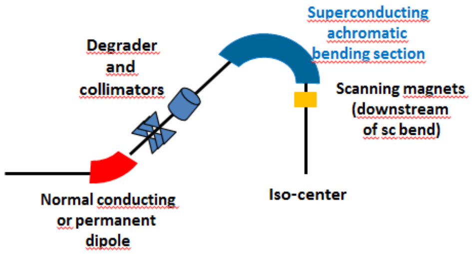

Figure 1: Gantry based on achromatic superconducting combined function magnets for the bending section.

The bending section consists of a series of superconducting combined function magnets described in this work, resulting from the conclusions of a preliminary study based on an upstream design [2]. The magnet geometry, the field maps, the conductor characteristics and the results of the thermo-mechanical calculations are discussed. Each dipole is cooled using two stage cryocoolers working at 4.2 K. To enable a sufficient temperature margin avoiding quenches after four consecutive current cycles (the treatment for the maximal target size), Nb_3Sn cables are used in the coils.

LAYOUT AND MAGNET DESIGN

Bending Section layout

The transport section is a curved, compact and locally achromatic, to minimize the proton beam dispersion. The section consists of three types of combined function magnets: (1) two superconducting combined dipoles-quadrupole and sextupole magnets (SDC1, SDC2), (2) a superconducting combined quadrupole-sextupole magnet (SCQ), (3) two tuneable normal conducting quadrupoles (Q1&2) at each side to meet with the beam optic conditions [1]. All the geometries are based on racetrack coils to keep the manufacturing as easy as possible. The design is optimized in different steps. From the magnets 3D field maps, the field harmonics are calculated and compared with the ones required by theoretical first order calculations. Tracking simulations including all orders are then performed and the beam parameters are analysed.

Magnet Specifications

Table 1 describes the specifications of the three types of magnets (x and y directions are shown in Fig.2).

Table 1: Magnet specifications

Type	Q1&2	SDC1&2	SCQ
Length (cm) /bending angle (°)	10	67.5	35
Bending radius (m)		0.8	
Half-aperture (cm) (Half good field region)	25	10 (x) 4 (y)	12.5(x) 2 (y)
Dipole field (T)	0	2.57	0
Quadrupole (T/m)	25.7	-5.3	21.4
Sextupole (T/m^2)	0	-9.8	21.9
Operating current in superconducting magnets (A)		1700	1700
Number turns / turns per layers		36/28	20/30

Magnet Design and Field quality

The field distribution of the bending section magnets is calculated using OPERA3D^{TM} and the positioning of each component is optimized through tracking studies using OPAL, a tool for charged-particle optics in accelerator structures and beam lines [3]. Fig.2 shows the field map in each magnet of the bending section.

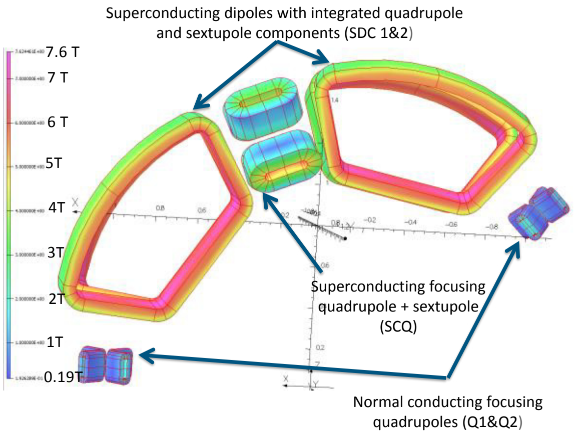

Figure 2: Field distribution in the Q1&2, SDC1&2 and SCQ magnets at operating current.

Peak fields at the conductor location are 7.62 T and 7.12 T for the SDC1&2 and SCQ respectively, three times higher w.r.t the average magnetic field in the good field region (GFR). Field quality is evaluated in several transverse cross sections with respect to the beam path. The multipole expansion was calculated in a circle of diameter equal to the smaller side of the GFR. The three components of the fields along the circle were projected onto the radial direction and using the Fourier transformation, the normal and skew multipoles were obtained. More details on the field quality determination can be found in [2]. The field quality in the superconducting magnets displays octupoles and 14-poles below 0.4% of the dipole field, matching well with the specifications.

SUPERCONDUCTING CABLE

The peak field values, the additional effect of the losses when the magnets are ramped up and down and the practical need of using dry systems for the cooling, have led to select Nb_3Sn for the coils. A reasonable temperature margin of about 4 Kelvins at operating conditions (fields of 7-8 T and temperature of 4.2 K) is pursued. In addition Nb_3Sn strands are well characterized by now. Accurate critical current scaling laws are available in the literature and the conductor is available on the market in large quantities. The Bronze routed Nb_3Sn strand developed for the ITER project [4] by the company Bruker-EAS is selected because it has shown good mechanical properties and low filament size. It withstands an axial tensile stress up to 180 MPa and bending strain up to 0.4-0.5% without breakages. Such strands feature also small filaments size, below 10 µm, minimizing the hysteresis losses. The strand parameters are summarized in table 2. For one single turn carrying 1.7 kA, a cable has to be wound. Rutherford cables provide a good current distribution reducing the field errors and guaranteeing a sufficient stability during operation. The cable will be made by 12 Nb_3Sn strands.

Table 2: Strand parameters for SDC and SCQ magnets

Parameter	Value
Strand diameter (mm)	0.82
Filaments twist pitch (mm)	14
Filaments diameter (µm)	≈6-7
N. of filaments	8305
Cu to non-Cu ratio	0.93
RRR	>100
I_c @ 4.5 T, 4.2 K and 0.2% strain (A)	200

The coils will be layer wound and impregnated to guarantee a good mechanical stability. The coils operating current was optimized aiming at a peak voltage in case of quench below 1.5 kV (per coil). A corresponding operating current value of 1700 A was selected, which allows also keeping the hot spot temperature below 150 K in case of quench. The J_c limits are based on the ITER Nb_3Sn critical surface parametrization [5] and the fields evaluated with the program OPERA 3D^{TM}. The proposed operating point corresponds to a magnetic field at the conductor position of 7.62 T (for a current of 1.7 kA) and an operating temperature of 4.2 K. For an intrinsic strain value below 0.3% the margin along the load-line is more than 25 % and in temperature around 5 K.

THERMO MECHANICAL STUDY

Mechanical Analysis

The critical current of the strain-sensitive Nb_3Sn is strongly reduced under the applied mechanical load; therefore, the right choice of the mechanical support and a careful estimation of the deformations on the coils are carried out. The winding pack is wound around a stainless steel (316 LN) former. CuBe rings are placed around the coil to give a pre-compression and guarantee a thermal path to the cryocoolers cold heads. The two parts of the support structure are maintained by four 316LN stainless steel columns and anchored to the gantry through six G10 supports, four on the bottom and two on the sides. The (von Misses) stress distribution on the coil is calculated using the Multiphysics Code COMSOL (see Fig.3).

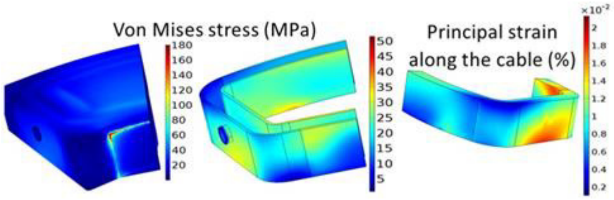

Fig.3: Von Mises stress distribution in MPa calculated in a SDC magnet support structure (left and middle) and principal strain along the cable direction (on the right).

The stress seen by the structure is below 180 MPa. This stress level leads to strain on the strands of the superconducting Nb_3Sn wires of around below 0.1%.

Thermal Analysis

Bath cooling at saturation temperature and ambient pressure is the most efficient cooling solution. The manufacturing of a rotating cryostat with inlet and outlet cold connections and an external re-condensing unit that liquefies the helium vapour coming from the magnet remains, however, extremely challenging. A "cryogen-free" solution is therefore adopted with all the SDC and SCQ magnets cooled by conduction using cryocoolers. The cooling sources are two stages cryocoolers producing a power of 1.4 W at 4.2 K. For the SDC, the first stage will be anchored to a Cu shield and the second stage to the CuBe rings. The first stage of the cryocooler is used to intercept the heat load from the normal conducting part of the current leads, as well as the thermal radiation from the room temperature environment. The second stage cools down the coil and intercepts the heat deposited by a pair of 2 kA high temperature superconducting current leads. In addition to the joule heating, the effect of the AC losses has to be considered. The SDC and SQC magnets will be designed to operate with typical ramp rates ranging up to 0.1 T/s. The considered treatment cycle is composed of four consecutive current cycles. Thermal analysis includes the following contributions: Losses occurring in the conductors and induced eddy currents in the structure, radiation from the thermal shield and heat input from the mechanical support. The losses in the conductor originate from a) eddy current losses in the matrix, b) hysteresis losses in the superconductor itself, and c) losses from coupling of the different strands and of the filaments of the composite conductor. The results of this study will be reported in details in a future separate contribution. In this work only the coils temperature distribution calculated after four cycles (i.e. 462 s) is presented. As shown in Fig.4 (right), the coil temperature does not exceed 6.6 K, allowing a comfortable temperature margin, well below the current sharing temperature T_{cs}. The total losses are of about 140 W/m^3, strongly dominated by the hysteresis contribution.

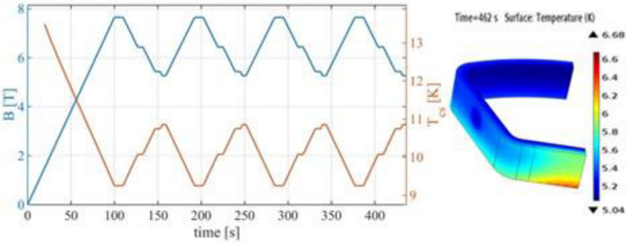

Fig.4: On the left: treatment cycle for a target of maximal size. Peak fields at the conductor along with the current sharing temperature are shown. On the right: Temperature distribution in the winding pack (only one quarter) at the end of the cycles.

CONCLUSION

The conceptual design of a superconducting achromatic bending section for a compact gantry is reported. The magnets will operate at 4.2 K, cooled down by cryocoolers. Using race-track geometry, peak fields at the conductor are showing a maximum value of 7.6 T. For the winding pack, Nb_3Sn Rutherford cables were designed to operate the magnet with a sufficient temperature margin. Thermo-mechanical analyses confirm this choice with temperatures not exceeding 6.6 K.

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