THE DESIGN OF THE SPECIAL MAGNETS FOR PIMMS/TERA

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Abstract

In the framework of a collaboration agreement with the TERA Foundation, CERN provided the design, drawings and engineering specifications for two kickers, one chopper and three bumper magnets as well as three magnetic and two electrostatic septa, power supplies for the electrostatic septa, kickers and bumpers including control electronics for the PIMMS/TERA proton and carbon ion medical synchrotron. The first application will be in the Italian National Centre for Hadrontherapy, to be constructed in Pavia. The main features of the devices are described along with the strategic design choices, directed by the demand for very high reliability and minimum maintenance.

INTRODUCTION

A synchrotron, capable to accelerate either carbon ions or protons, will be the basic instrument of the Centro Nazionale di Adroterapia Oncologica (CNAO), the medical centre for cancer therapy, to be built in Pavia, Italy (Fig. 1). The accelerator complex consists of a linac that will accelerate the particles to an energy of 7 MeV/u. An injection line will transfer them to the synchrotron where the injected particles will be accelerated and extracted with an energy ranging from 60 to 250 MeV for protons and from 120 to 400 MeV/u for carbon ions.

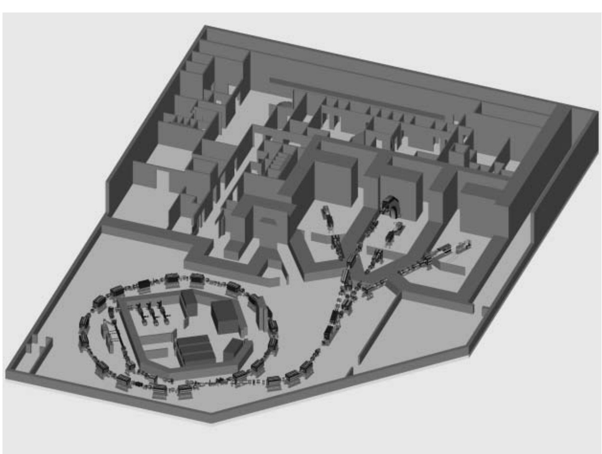

Figure 1: Schematic picture of the CNAO medical centre

The PIMMS/TERA design [1] comprises two magnetic septa in the injection line, one injection electrostatic septum, two injection bumpers, two dump bumpers and one extraction electrostatic septum in the synchrotron; three magnetic septa and four chopper magnets in the extraction line.

Eleven different designs have been produced [2], for a total of seventeen magnets to be built.

FAST PULSED MAGNETS

The parameters for the elements described in the following chapters, headed Bumpers, Chopper and Tune Kickers, are summarized in Table 1. All these magnets are placed outside the machine vacuum, have a metallized ceramic vacuum chamber and use a ferrite yoke.

Dump Bumpers

A beam-dumping scheme based on a rapid bump that is excited over a few tens of turns has been adopted. The rapid bump is excited by two bumper dipoles, powered in series. The two yokes are identical, but the coils are arranged so that one dipole gives half the kick of the other. The beam is deflected vertically. Due to the vertical dimension of the vacuum chamber, the magnet is constructed in one piece as an open C-core closed by an eddy-current screen. CAD views of these magnets are shown in Fig. 2.

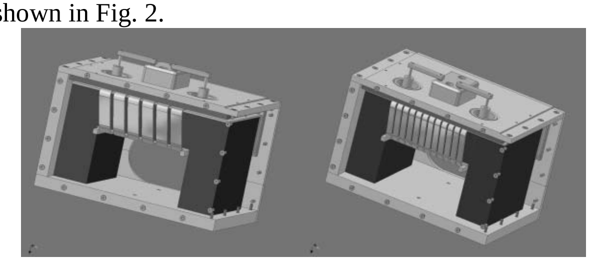

Figure 2: 6-and 12-turn Dump Bumpers, covers removed

The relatively moderate constraints on the linearity of the field rise allow to use a simple resonant power supply system, with third harmonic for flat top and a freewheel recovery branch. The choice of C1, C2 and L1 allows an under-damped sinusoidal current with enhanced ´flat top´ to flow. The freewheel branch D1/R1 allows the following current decay (Fig. 3).

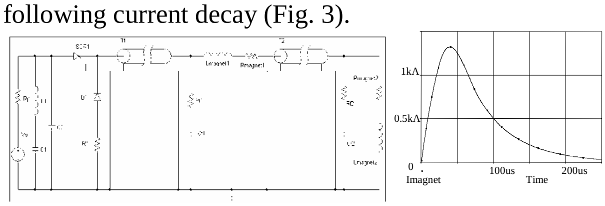

Figure 3: Dump Bumpers circuit and magnet current

Injection Bumpers

Two magnets will be constructed from two 3-piece ferrite C-cores, mounted face-to-face, to form a window frame magnet. The magnets are built up from identical 4-turn open C-magnet halves (Fig. 4). The four 4-turn magnet halves powered in series require a peak current of 454 A. The power supply is an IGBT driven resonant circuit (Fig. 5). To fulfil the requirement for a variable, quasi-linear decreasing current slope the values of C1 and R1 can be varied using relay-commutated parallel components. The use of controlled switching of the

Table 1 – Bumpers, Tune Kickers and Chopper parameter table.

Item	Dump Bumper		Injection Bumper	Tune Kicker Hor.	Tune Kicker Ver.	Chopper Dipole
	2 different items powered in series, resonant power supply generator		2 items, powered in series, resonant power supply generator	PFN-type generator with thyratrons		4 items powered in series, current controlled power converter and programmable with a resonant HV branch
Eff. magnetic length [m]	0.3	0.3	0.3	0.3	0.3	0.3
Max integ. Field ∫Bdl [T.m]	0.0173	0.0346	0.0076	0.0088	0.0095	0.0419
Aperture w × h [mm^2]	90 × 166	90 × 166	166 × 90	166 × 90	90 × 166	96 × 90
Coil	1, copper conductor, 6 turns	1, copper conductor, 12 turns	2 in series, copper conductor, 4 turns	1, copper conductor, 1 turn	1, copper conductor, 2 turns	2, copper conductor, water cooled, double layer pancake 2 × 4 turns, saddle-shaped
Good field (rectangle) [mm^2]	60 × 120	60 × 120	120 × 60	120 × 60	60 × 120	66 × 66
Field quality [%]	± 2.5	± 2.5	± 1	± 1	± 1	± 0.2
Current for max field [A]	1265	1265	454	2100	2100	644
Voltage [V] (nominal)	3300	3300	280	35000	35000	~ 5000 (pulsed) & 32 (DC)
Number of turns	6	12	8 (4 per coil)	1	2	16 (8 per coil)
Estimated inductance [μH]	8	32	20.0	1	1.4	120
Rise time [μs]	32 to 50, 48 pref.	32 to 50, 48 pref.	Whatever	0.101 (10-90)%	0.135 (10-90)%	90 (max)
Rise shape	Lin. shape or cosine	Lin. shape or cosine	Whatever shape			
Flat top [μs]	> 6	> 6	-	0.085 - 1.6	0.085 - 1.6	
Fall time [μs]	Some ms	Some ms	20 < t < 70 linearly selectable	0.115 (90-10%)	0.148 (90-10%)	90 (max)
Cycle period [sec]	1.2	1.2	1.2	-	-	0.1

primary current avoids the need for any high voltage resonant techniques to establish the peak current and allows the use of semiconductor switches and low voltage power supplies. The addition of R_{delay} creates the time delay needed between the pulsed magnetic fields.

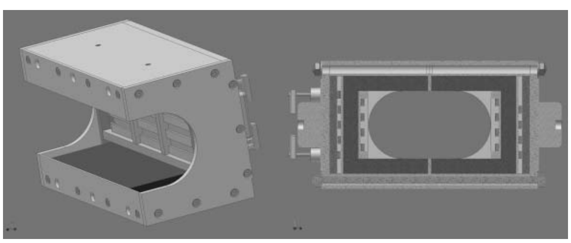

Figure 4: Injection Bumper half and cut view

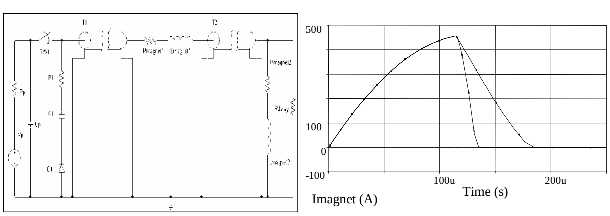

Figure 5: Injection Bumper circuit and magnet current

Chopper dipoles

All treatment rooms will be able to switch the beam on and off routinely during operation by means of the beam chopper. The chopper works by making a closed-orbit bump that bypasses a dump block mounted inside the vacuum chamber. The very narrow beam and the absence of tails on the 'bar' of charge makes the horizontal plane the preferred choice for the bump that is excited by four equal bumper dipoles in series. Since the four dipoles sit in a common drift space, the bump is perfectly closed and the downstream trajectory of the beam is unaffected at all times. For this reason, the stability and over-shoot of the power converter are not critical issues. The magnet uses a window frame construction with two water cooled saddle coils of 8 turns each (Fig. 6).

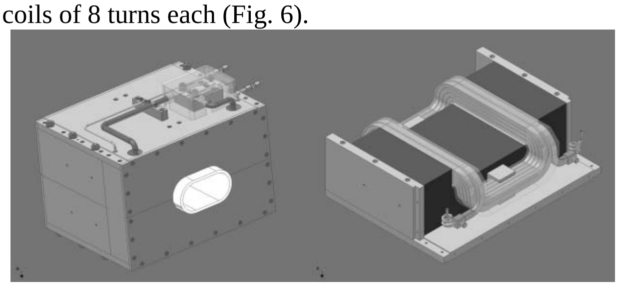

Figure 6: Chopper dipole, full and half cut view

Tune kickers

The synchrotron will be equipped with one Horizontal and one Vertical Tune Kicker. The 2-turn Vertical Tune and 1-turn Horizontal Tune magnets are open C-core closed by an eddy-current screen, using a mica-epoxy insulated coil. In order to be able to scan the maximum area of the dynamic aperture with full pulse width control, it was decided to opt for a thyratron switched cable PFN type pulse generator designed such that this generator can pulse either the Horizontal or Vertical Tune Kicker at a time.

SEPTA

Five different designs of injection and extraction septa were developed. Their parameters are summarized in Table 2.

Magnetic Septa (MS)

All MS use 1.5 mm thick laminated yokes to allow the magnets to be ramped. The magnets can be split horizontally and removed from the vacuum chamber for maintenance purposes using a special mechanical support.

Table 2 - Septa parameter table.

Item	Injection MS	Injection ES	Extraction ES	Extraction MS	
	2 powered in series	Foils, angled by 60 mrad	Foil	1 thin, 2 thick all powered in series	
Equivalent magnetic length [mm]	444	600	800	650	975
Physical length [mm]	486	855 (to flanges)	1055 (to flanges)	692	1017
Deflection angle [mrad]	250	60	2.5	50	150
Septum thickness + screen [mm]	10.3 + 1.1	0.1	0.1	10.4 + 3.0	20.2 + 1.1
Gap aperture w × h [mm^2]	80 × 40	-	-	80 × 40	75 × 40
Gap width [mm] (min., max.)	-	25 (15,35)	15 (10,25)	-	-
Cathode length [mm]	-	555	770	-	-
Number of turns	4	-	-	4	8
I nom [A]	3416	$< 10^{-4}$	$< 10^{-4}$	3881	3881
B nom [T]	0.429	-	-	0.488	0.975
∫Bdl [T.m]	0.186	-	-	0.317	0.951
V nom [kV]	-	69.7	63.7	-	-
E nom = E max [MV/m]	-	2.79	4.26	-	-
Good Field w × h [mm^2]	49 × 33	25 × 33	15 × 28.8	31 × 26	49 × 30
Field quality [%]	± 1	± 1	± 0.5	± 1	± 1

Two Injection MS (Fig. 7) are connected electrically in series to supply the required total deflection of 500 mrad. In the front of the magnet yokes, stainless steel bars are located in special slots in the lamination for alignment and clamp fixation purposes and also to reduce the fringe field. The 4-turn septum coils are based on a 9.5 mm square section conductor with a ø 3 mm water cooling hole. The cross-section of the rear conductor is doubled to reduce power dissipation. Insulation is provided by glass fibre spacers between the turns and by glass fibre tape that is half lapped and moulded afterwards with Araldite®. Both half coils are electrically interconnected in series at the back of the magnet, while water blocks will assure that the coil is cooled on each turn. Three Magnetic Extraction Septa that are electrically in series are used to provide the required total deflection of 350 mrad. The first septum (Extraction Thin MS) is a stretched version of the Injection MS. However, to keep the coil in place and stay within the space constraints imposed, the orbiting beam vacuum chamber is modified. A vertical wall made of highly magnetic steel is part of this vacuum chamber. It is bolted against the magnet to maintain mechanically the septum coil in position and at the same time to act as a magnetic screen to reduce the fringe field. Downstream of this septum two Extraction Thick MS are positioned, based on the same technology as the Injection MS, but using an 8-turn coil. This coil is cooled per half turn, with adjacent turns having opposite water flow directions to limit temperature peaks in the coil.

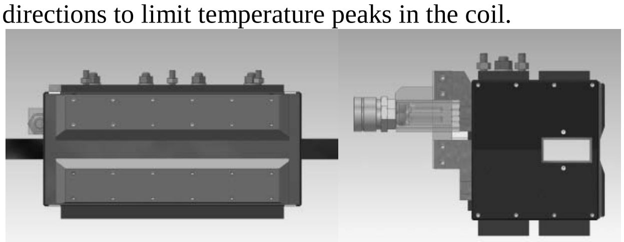

Figure 7: Injection Magnetic Septum

Electrostatic Septa (ES)

The Injection ES (Fig. 8) is housed in a vacuum vessel, allowing the orbiting beam to pass in a beam screen, to preserve as much as possible the RF impedance. Septum and cathode displacement systems together with the High Voltage (HV) feedthrough are positioned inside the ring.

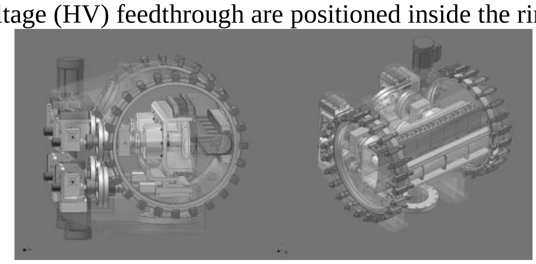

Figure 8: Injection Electrostatic Septum

The septum is made of two sets of 330 mm long and 0.1 mm thin molybdenum foils aligned at an angle of 60 mrad with respect to each other. The foils are fixed onto a machined and polished C-shaped stainless steel septum support. Inside this support is the HV stainless steel cathode. Their shapes are chosen such as to reach the required field quality. The septum support, hence the septum itself, can be remotely displaced in the radial as well as angular position. Septum and cathode support systems are mechanically linked, and a remote positioning system is foreseen to modify the gap width. Installed vacuum pumps reach the 10^{-9} mbar range. The design of the Extraction ES is similar. The septum is a straight foil of molybdenum 860 mm long. Due to higher electrical stress the cathode cannot be made of stainless steel; instead anodized Peraluman 300 is foreseen.

CONCLUSION

The design of the special magnets and their power supplies for CNAO has been completed by CERN. Engineering specifications have been submitted to industry for tendering. Accelerator commissioning is planned for fall 2006.

REFERENCES

[1] P. Bryant (ed.) et al., "Proton-Ion Medical Machine Study (PIMMS) Part II", CERN/PS 2000-007 (DR), 7/2000.

[2] J. Borburgh et al., "Special Magnets, Engineering Specifications", CNA-SPDF-007WXX-00232 to 00236, 00238, 00239, 04/2004.