THE IBA SUPERCONDUCTING SYNCHROCYCLOTRON PROJECT S2C2

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Abstract

In 2009 IBA started developing a compact superconducting synchrocyclotron as part of the small footprint proton therapy system ProteusOne®. The cyclotron has been completely designed and constructed and is currently under commissioning at the IBA factory. Its design and commissioning results are presented.

INTRODUCTION

The ProteusOne® is an innovative single treatment room solution for protontherapy. It consists of the S2C2 superconducting proton cyclotron [1], the new IBA compact gantry [2] and a state-of the-art patient treatment room facility; it is designed for lower cost and compactness to make proton therapy more widely accessible.

In the new gantry, the scanning magnets are placed upstream of the last bending magnet. Figure 1 shows the layout of this new gantry. This configuration offers the combined advantage of compactness and pencil beam scanning with reasonable SAD (source to gantry axis distance). The energy selection system is included in the straight inclined part of the gantry. This also gives a considerable reduction of the facility footprint.

Several presentations on the S2C2 were given at the 2012 European Cyclotron Progress Meeting (ECPM) at PSI [3].

GENERAL CONSIDERATIONS

The average field in an isochronous cyclotron is limited to about 2.5 Tesla. Above this value, the flutter quickly becomes too small to provide sufficient vertical focusing and simultaneously constant orbit frequency. Much higher fields can be used in the superconducting synchrocyclotron where the requirement of isochronism is unnecessary and weak focusing is obtained from the negative gradient of the rotationally symmetric magnetic field. Other important differences exist:

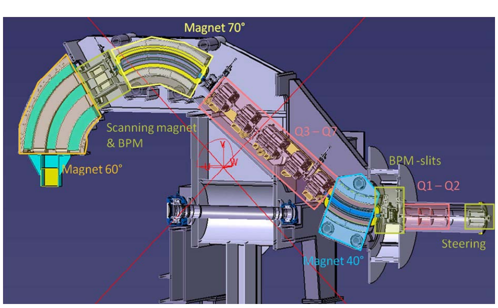

Figure 1: The ProteusOne® compact gantry.

Figure 2: The assembled cyclotron placed in the shielded beam-vault. It can be opened in the median plane as well as at the top of the cryostat. Also visible are the rotcoshield (left), the cryocooler-shield (middle) and the vacuum station (right).

i) the RF frequency is periodically modulated and the beam is pulsed, ii) longitudinal dynamics becomes a major aspect of the beam physics with energy-phase oscillations bound by a separatrix, iii) beam is captured at injection only during a limited time window, iv) regenerative extraction is needed to recover the beam which has a very small turn separation at extraction, v) the extracted beam has a relatively low intensity typically in the order of nAmps (this is perfectly sufficient for proton therapy applications), vi) the central region is strongly reduced in size compared to an equivalent isochronous cyclotron.

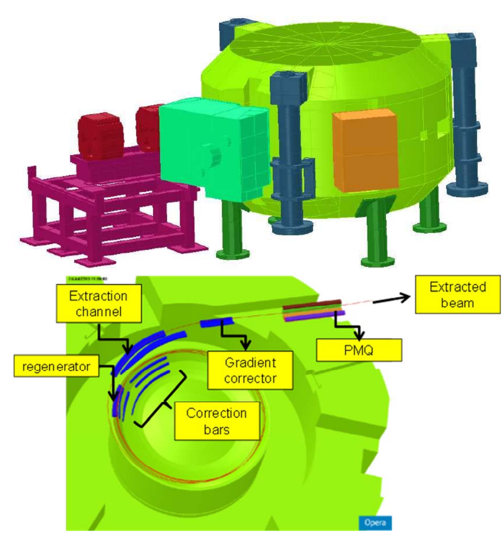

Figure 3: OPERA3D model of the cyclotron.

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Table 1: General Features of the S2C2

Maximum Energy	230/250 MeV
Size	
yoke/pole radius	1.25 m/0.50 m
weight	50 tons
Coil	NbTi - wire in channel
ramp up rate / time	2-3A/min / 4 hours
windings/coil	3145
stored energy	12 MJ
Magnetic field	
central/extraction	5.7 T/5.0 T
Cryo cooling	conductive
	4 cryocoolers 1.5 W
initial cooldown	12 days
recovery after quench	less than 1 day
Beam pulse	
rate/length	1000 Hz/7 μsec
RF system	self-oscillating
frequency	93-63 MHz
voltage	10 kV
Extraction	Passive regenerative
Ion source	PIG cold cathode
Central region	removable module

New computational tools where developed and existing tools improved, to be able to simulate all aspects of beam dynamics in this new accelerator [3]. Some main features and parameters of the cyclotron are listed in Table 1. The new mapping system that has been developed for this cyclotron is described in a separate paper [4]. Figure 2 shows the cyclotron in the beam-vault.

MAGNETIC DESIGN

The optimization of the magnetic circuit has been a long process carried out by the three main contributors to this development: IBA, AIMA and ASG (manufacturing company used for the coil and the cryostat). Many aspects have to be considered: i) optimization of the pole-gap profile, ii) definition of the pole radius and the 230 MeV extraction radius iii) optimization of coil current density and dimensions to assure a margin with respect to the critical surface and to allow operation up to 250 MeV iv) dimensioning of the yoke to reasonably balance the outside stray fields, v) dimensioning and placement of all horizontal and vertical yoke penetrations (ports are needed for RF, ion-source, vacuum, beam exit, cryocoolers, 3 horizontal and 2x3 vertical tierods) vi) the optimization of the extraction system vii) the shielding required for external systems such as the rotco and the cryo-coolers viii) the influence of the external iron systems on the accelerated beam ix) the influence of the fringe field on the external beam line x) median plane errors introduced by the vertical asymmetry in the magnetic design and compensation of these errors, xi) magnetic forces acting on the return yoke, the coils, the extraction system elements, external components etc. xii) design

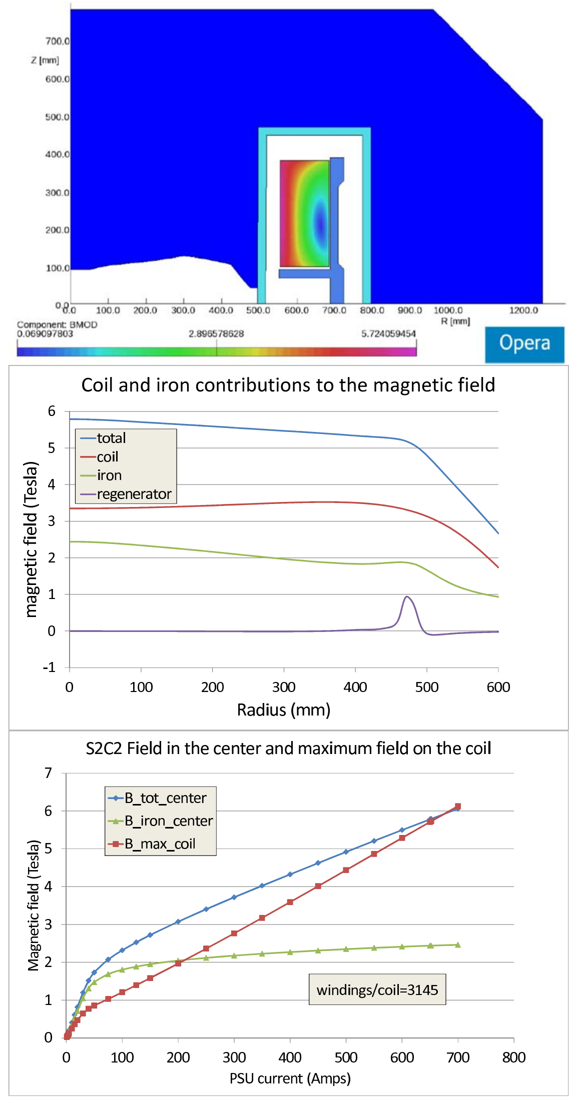

Figure 4: Upper => OPERA2D model showing the particular pole-gap shape that is used for obtaining the required focusing properties and the field distribution on the coil at nominal current. Middle => separate contributions of the iron and the coil to the average field; for comparison the field-profile at one fixed azimuth as produced by the regenerator is also shown. Lower => magnetization curve with the seperate contribution of the iron; the maximum field on the coil is also shown.

of the harmonic coils, xiii) compensation of first harmonic field errors, xiv) the influence of the cyclotron feet and the yoke lifting system xv) and many others. For the design of the superconducting coil, the transient behavior of the magnet with eddy currents and AC-losses and also the quench-behavior need to be studied in detail.

To make this optimization, magnetic finite element models were made in OPERA2D, OPERA3D and CST. Especially in OPERA3D, very detailed models were made as illustrated in Figure 3. Some main magnetic field properties as obtained with OPERA2D and shown in Figure 4.

CENTERING OF THE MAIN COIL

To accelerate the beam up to extraction during 40000 turns, correct horizontal and vertical centering of the coil is essential. An innovative method (patent pending EP13170532) permits to do this with millimeter to sub-millimeter precision. It is based on measurement of the vertical and radial field profiles between the two main coils, where the field is coil- dominated. Measurements are made in three radial ports (vacuum, rotco and source). For horizontal centering, the B_z-profiles are compared in the radial region where the radial fall-off is at maximum. For vertical centering, the B_r-profiles are measured in a region where $B_z \approx 0$ so that the tilt-error of the Hall-probe is not important. Results are shown in The upper of Figure 5 shows the deduced horizontal coil position (as a function of the radial position of the probe) in the initial configuration and in the final configuration where the coil is centered to better than 0.5 mm. The lower figure shows the vertical off-centering measured in each of the three ports. We estimate this positioning error to be about 1 mm or less, depending on the port.

The centering of the main coil was done hand-in-hand with measurements of the magnetic forces acting on the cold mass. These are obtained from strain gauges mounted in the tierod-assemblies. A special effort was made to reduce the total vertical force on the cold-mass by proper coil positioning and by placing iron shims on top of the return yoke. OPERA2D calculations indicate that the median plane error is reduced when this vertical force is compensated. Figure 6 shows the measured forces as function of the ramp-current. The vertical force in the final configuration (after shimming) is substantially lower than in the initial configuration. The horizontal forces are larger. This is due to the extraction system and the asymmetry of the yoke. During ramp-up the coil moves about 1.5 mm, to arrive at a centered position at nominal current.

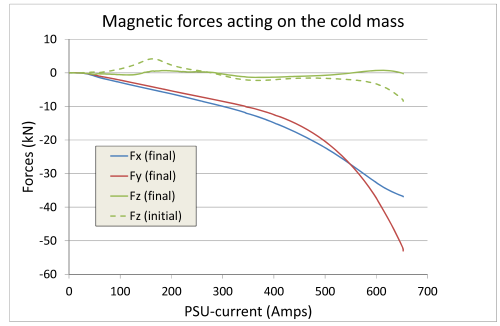

Figure 6: Measured forces acting on the cold mass.

BEAM EXTRACTION

Regenerative extraction based on on $2Q_h = 2$-resonance is used. The regenerator (lower Figure 3) creates a strong bump (middle Figure 4) which locally increases the radial focusing and locks Q_h to 1. It is essential to avoid the Walkinshaw resonance (upper Figure 7). Extraction sets in at this condition and a displacement of the beam towards the extraction channel steadily builds up (lower Figure 7). Correctors are used to compensate the undershoots of the regenerator and the extraction channel. A 3-bar corrector guides the beam through the fringe field.

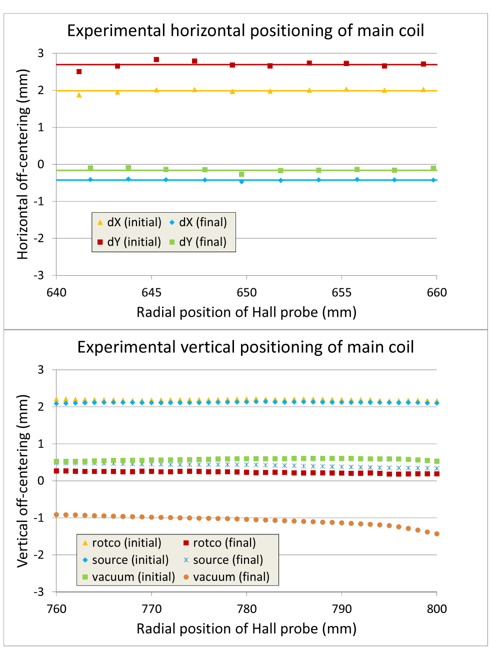

Figure 5: Measured coil positions as a function of the radial position of the Hall probes.

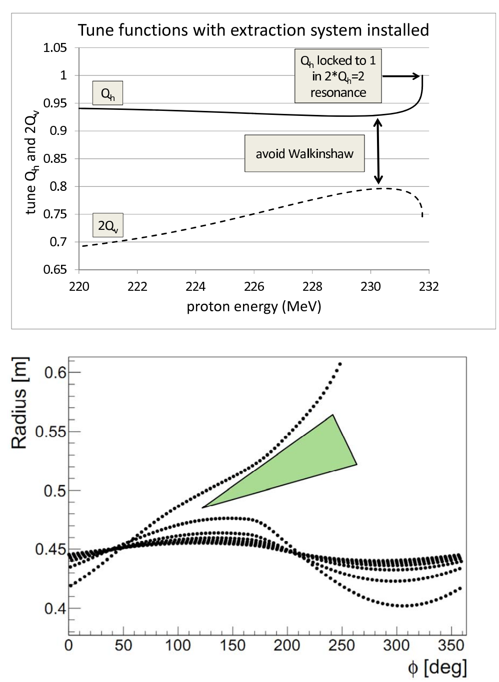

Figure 7: Extraction is based on the $2Q_h = 2$ resonance.

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RF SYSTEM

The RF resonator (Figure 8) operates as a half-wave transmission line terminated on one side by the 180° dee and on the opposite side by the rotco. The rotco is an innovative patented design having 8-fold symmetry. This allows excellent mechanical stability and very good reproducibility of the RF pulse. It rotates at 7500 rpm giving a 1 kHz repetition rate. The measured RF-frequency curve (Figure 9) agrees very well with the CST-model that was developed. The structure is coupled to a triode tube and operates in self-oscillating mode. The dee and the center-dummy dee are biased at 1 kVolt, to suppress the multipactor. Two side-stubs provide fine-tuning of df/dt during capture. To avoid eddy currents, the rotco and the triode are placed in a shielded volume, outside of the yoke.

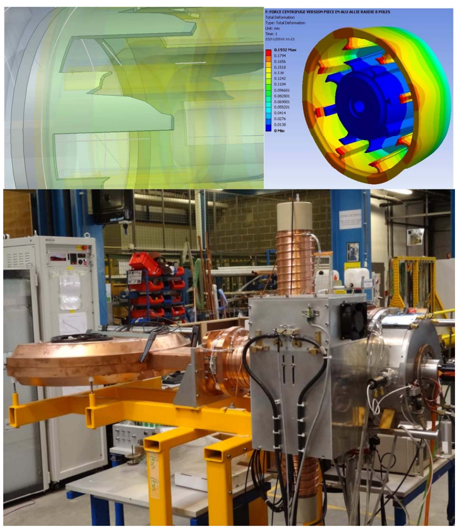

Figure 8: The fully assembled RF-system mounted on a test-bench. Detail of the rotco modeling in CST (top).

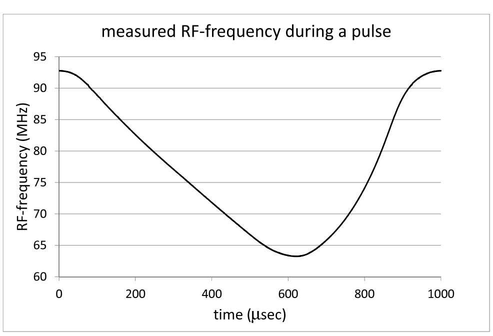

Figure 9: The measured RF-frequency curve.

ION SOURCE

Fast and precise pencil beam scanning (PBS) requires a high dynamic range (a factor 100) in the charge per pulse and also good pulse repeatability. A cold-cathode PIG-source is used because of its fast response, long cathode life-time and good pulse stability. The source is pulsed during 50 µsec, in synchrony with the RF. The source was initially characterized in a 1 Tesla test-stand [3], where a DC extracted beam current up to 6 mA was demonstrated (much more than required). Subsequent tests in the S2C2 at 5 Tesla confirm a very good arc-stability as a function of arc-current (Figure 10). This promises the good beam-pulse reproducibility as required.

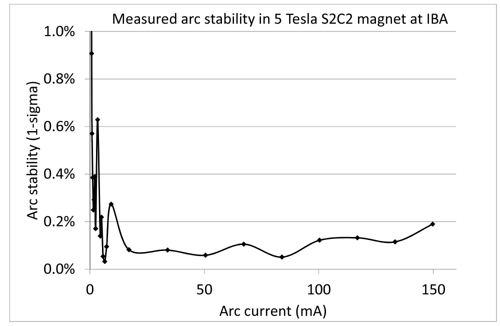

Figure 10: The very good ion source arc-stability as measured at 5 Tesla in the S2C2 also promises good beam pulse reproducibility.

CENTRAL REGION

The central region (CR) is extremely compact with a first turn radius less than 2.5 mm and the first 100 turns within a radius of about 3 cm. The vertical gap tapers in a cone to enable better vertical focusing and transit time factors during the first turns. The CR and ion source are removable as one sub-system for easy maintenance and precise alignment (Figure 11). Detailed modeling of the full accelerating structure was done in OPERA3D as well as CST. Particle tracking in 3D was done, to optimize the geometry and to predict the accelerated beam quality and properties as needed for the simulation of the extraction process. Good internal beam quality is predicted, as shown in Figure 12.

EXTRACTED BEAM LINE

A permanent magnet quadrupole in the return yoke matches the cyclotron to the beam line. The beam is focused by a quadrupole doublet on a 1x1 mm^2 (1-sigma) beam spot on the degrader placed at 2 meters from the yoke exit (see Figure 13). In between the two quads is an adjustable horizontal collimator that cuts the horizontal beam divergence at the degrader, to provide constant optical conditions independent of the gantry rotation angle.

CURRENT STATUS

The cyclotron is now fully assembled and installed in a shielded bunker for beam testing. The magnet cools down correctly. The magnetic field has been mapped and found to be in very good agreement with OPERA3D-simulations [4]. The coil has been centered correctly and

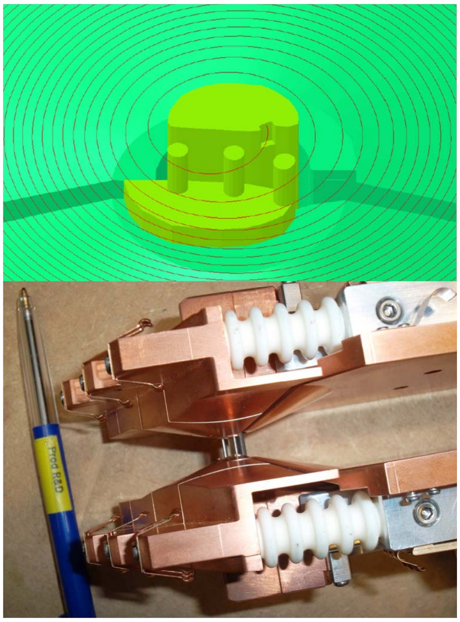

Figure 11: Upper: the CR as well as the full dee-structure are modelled in detail in OPERA3D, allowing precise tracking of the accelerated beam. Lower: the ion source and CR can be removed as one sub-system for easy maintanance and alignment.

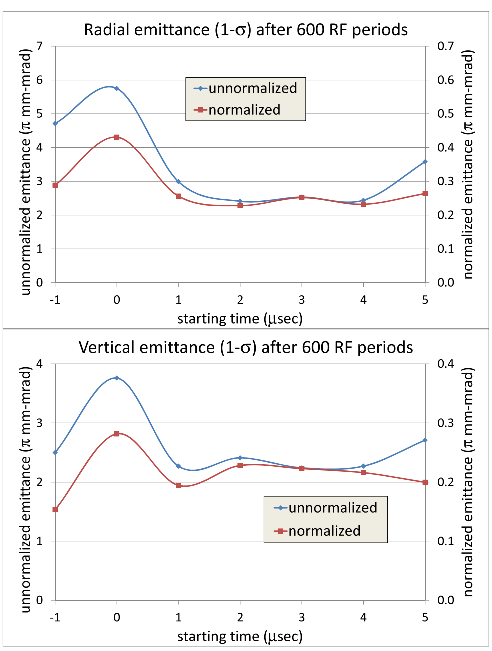

Figure 12: Radial and vertical beam emittances at 2 MeV as obtained by particle tracking.

the vertical forces on the cold mass have been substantially reduced by asymmetric shims placed on top of the yoke. The RF-system, the ion source and the central region have all been tested and are performing well. The external beam line up to the degrader has been fully designed and is under construction. At the end of August 2013 (a few days

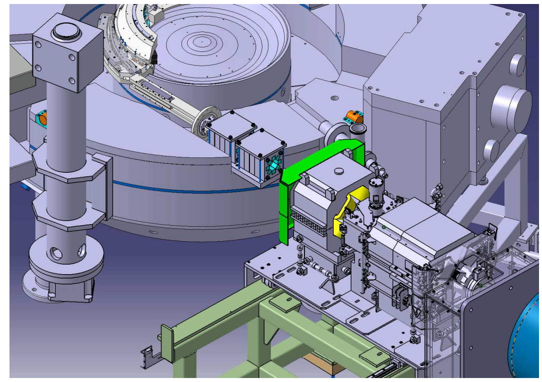

Figure 13: Extracted beam line and degrader placed 2 meters from the yoke.

after the beginning of beam tests) we have observed the beam extracted from the cyclotron by the colouring of a thin dose-sensitive foil placed at the end of the beam tube (Figure 14). This was obtained without any re-adjustment of subsystems in the cyclotron. Currently internal measurements are in progress to characterize the beam quality and to fine-tune the central region and the extraction system.

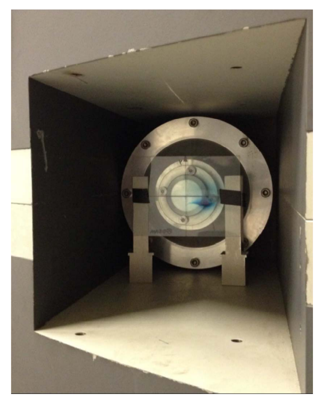

Figure 14: The extracted beam observed by a radiation sensitive foil.

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