STATUS REPORT OF THE ACCEL 250 MEV MEDICAL CYCLOTRON

A. Geisler, C. Baumgarten, A. Hobl, U. Klein, D. Krischel, M. Schillo, J. Timmer,

ACCEL Instruments GmbH, Bergisch Gladbach, Germany

Abstract

Since 2001 a superconducting cyclotron for proton therapy has been designed in collaboration with the National Superconducting Cyclotron Laboratory (NSCL) at ACCEL Instruments GmbH [1]. The design is based on a NSCL proposal originating from 1993 [2]. In the recent years two cyclotrons of this type were built, tested as far as magnetic and cryogenic properties are concerned and installed at the customer's premises. In this paper we present design features, operating parameters and results of quality assessment tests as well as important issues taken into consideration when building such a machine for medical application.

INTRODUCTION

In spring and summer 2004 ACCEL has delivered two superconducting cyclotrons dedicated for cancer treatment with protons. Based on a conceptual design of NSCL these machines are the first of their kind being engineered and built in industry. The first cyclotron was installed at the Paul-Scherrer-Institut (PSI) in Switzerland in spring 2004. As an essential part of the PSI project PROSCAN it will substitute an existing machine in order to intensify the activities in the field of cancer treatment. The second cyclotron was installed at the Rinecker Proton Therapy Center (RPTC) in Munich, Germany, and is now in the final assembly phase. It is part of a complete proton therapy system build by ACCEL.

BASIC DESIGN CONCEPT

Important machine parameters

Important parameters of the 250 MeV proton cyclotron are listed in table 1. Starting from the NSCL proposal ACCEL has refined and finalized the design in close collaboration with NSCL. In particular the cryogenics had to be adapted to the needs of medical environment. Furthermore ACCEL was supported by PSI and KVI during the design phase.

The major design goals are defined by the requirements of the medical application:

- Fixed proton energy of 250 MeV (corresponding to approx. 40 cm range in water)
- Maximum possible beam current of 500 nA
- For beam scanning (used at PROSCAN and RPTC instead of scattering): stable beam current and fast intensity modulation
- High availability / up-time
- Fast and simple maintenance
- Low activation
- Closed cycle liquid He system
- Standard industrial cryo coolers

Fig. 1 shows a cut view on the main parts of the cyclotron. The most apparent part of the cyclotron is the pill box design of the iron yoke consisting of the flux return yoke rings and the motorized upper and lower pole cap. The rf-structures consist of 4 dees (two galvanically and two capacitively coupled satellites), four stems and a coupler. The system is driven by a 150 kW rf-amplifier.

Table 1: Key Parameters of the 250 MeV cyclotron

General properties	
type	isochronous sector
final energy of ions	250 MeV
extracted beam current	500 nA
expected extraction efficiency	80 %
number of turns	650
ion source	internal cold cathode
total weight	approx. 90 tons
outer diameter	3.1 m
Magnetic properties	
average magnetic field	2.4 T @ center
stored field energy	2.5 MJ
operating current	160 A
rated power of cryo coolers	40 kW
RF system	
frequency	72,8 MHz
operation	2nd harmonic
number of dees	4
rf power consumption	approx. 100 kW

The cryogenic system consists of a supply cryostat serving as a helium reservoir and the toroidal coil cryostat.

The use of a cyclotron for fixed energy and a single ion type simplifies the design significantly. The fixed

---

* A. Geisler, C. Baumgarten, A. Hobl, U. Klein, D. Krischel, M. Schillo, J. Timmer are with ACCEL Instruments GmbH, Friedrich-Ebert-Str. 1, D-51429 Bergisch Gladbach, Germany (e-mail: Geisler@accel.de).

energy and fixed particle concept enables to omit field trimming coils as well as costly remote controlled positioning systems of extraction elements and electro-static deflectors. The only remote controlled mechanical devices are magnetic rods for beam centering and de-centering before extraction, a pair of phase selection slits close to the center and the tuning mechanics for the dee stems.

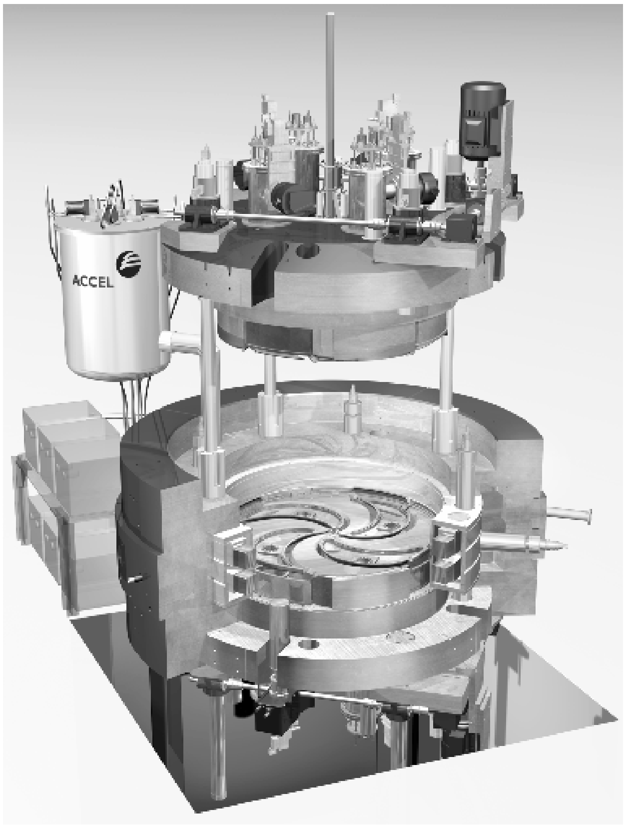

Figure 1: 3D CAD view of the superconducting cyclotron. Main components are the iron yoke with its motorized pole caps (the upper one is in open position), the rf-structures, the supply cryostat and the coil cryostat. Only the latter one contains the superconducting coil, so in general the accelerator with its inner parts is at room temperature.

Advantages of superconducting cyclotrons

The use of a superconducting main coil for cyclotrons is not new. There are many examples e.g. at NSCL, INFN (Italy), and KVI (Netherlands) where this technique was successfully applied. In all cases individual designs were made by scientific institutes. The high contribution of the coil to the magnetic field has several advantages which are particularly beneficial in a machine used for medical purposes. Superconductivity provides the option for a more compact, less power consuming, and less risky design over normal conducting cyclotrons. Bath cooling is achieved by 4 multi stage cryo coolers with a total power of about 6 Watts in a closed cycle operation. In addition two separate single stage shield coolers are used to cool the radiation shield of the main coil.

COMMISSIONING OF CRYOSYSTEM

Cool Down

The commissioning of the cryogenic system of the PSI cyclotron started in November ’03. The cold mass is hooked up to the cryostat by 12 adjustable support links – 4 on top, 4 from bottom and 4 radial - that are equipped with force gauges. The cool down required about a week, 4 days and 1400 litre N_2 to reach liquid nitrogen temperature, 2 days and about 1000 litre H_2 to reach liquid helium temperature.

First Excitation of Magnet

During the first magnetic excitation, the force gauge readings were carefully observed. The change of the force balance due to the current in the main coil was then minimized by appropriate adjustments of the tension links. In Dec. 12th 2003, the coil was excited the first time and the maximum current of 170 A was reached within a few hours without problems. The central field measured with an NMR probe at 160 A coil current was 2.45 T in close agreement with TOSCA computations.

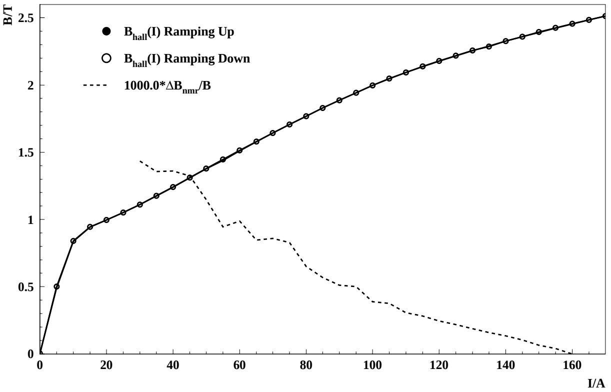

Figure 2: Measurement of the field in the cyclotron center with NMR and hall probe (low field region only). The difference in the magnetic field measurement between ramping up and ramping down is also shown. It is below 10^{-4} close to the nominal current.

The cooling power of the cold heads is in total 6 Watt. In order to keep the helium pressure constant, the heater circuit has to be operated with 3.5 to 4 Watt. This gives a heat balance of about 2.5 Watt, which agrees with the most optimistic estimations. This value is the same with or without current in the main coil. Only during the ramping process, the required heater power is reduced due to the heat induced by eddy currents.

The magnetic field in the cyclotron center in dependence of the coil current was measured with hall and NMR probes, respectively. The results are shown in

Fig. 2. They indicate a high purity and quality of the magnet iron by the small hysteresis effect.

Quench Test

The superconducting coils of both cyclotrons were quenched at nominal current in order to verify the robustness of the system. For this purpose the coils are equipped with a local quench heater attached to the windings. The heater had to be operated with about 6 Watts in order to quench the main coil. It was not possible to quench the coil by fast ramping of the magnetic field.

No changes of the magnetic and cryogenic properties were observed after the quench tests.

Figure 3: The 250 MeV medical cyclotron at ACCEL during cryogenic and magnetic tests.

CYCLOTRON ISOCHRONISATION

The isochronisation was done in 3 iteration cycles of field mapping and shimming. The shimming is done by removal of iron from top of shimplates mounted on top of the hills. It was successfully finished for both machines in July 2004. The last verification measurements were performed beginning of September 2004.

Magnetic Design Goals

The first measured field map matched the computed field models with a precision of about 500 ppm. The required precision of the average magnetic field and hence of the mapper is 20 ppm.

The field has to be adjusted to match the extraction energy of 250 MeV at the radial frequency of about ν_r=0.75. It is the goal to match a given RF phase curve $\phi(E)$ and to maximize the axial betatron frequency ν_z. Furthermore it is a goal of the isochronization to produce a phase curve for which the integral of $\sin(\phi)$ over the energy vanishes at extraction [3]. This facilitates the extraction since it minimizes the energy spread of the beam.

Besides the determination of shim steps, the field maps are used to compute the field harmonics. The first field harmonic has to be minimized by small radial displacements of the main coil.

Principle Method of Field Mapping

The concept of the field mapping machine is similar to the design previously used at NSCL. The median plane region close to the axis of the cyclotron has a highly homogeneous field that can be measured by NMR probes to a precision of better than 10ppm. The field difference relative to this central value is measured by the voltage integral of the moving search coil.

In addition two other regions – one in the valley and one on top of the hills – were identified, where the field homogeneity allows NMR measurements for the calibration of the search coil.

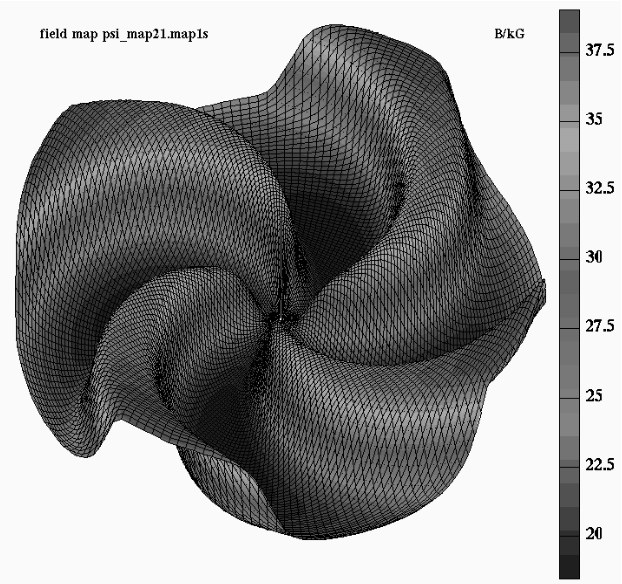

Figure 4: 3D-plot of the measured field map of the medical cyclotron after the last shim iteration at PSI. The field ranges from 18 to 38 kG.

The search coil is mounted on a carriage that can be moved between -280 and +940 mm in the radial direction along rails installed in the measuring arm. This arm sits on top of an axis connected to a rotational drive system which is hooked from below to the lower pole cap. The rotational (azimuthal) angle is measured by an angular encoder attached to the axis. Two stepper motor drives enable to move the search coil freely to any location within the median plane from remote.

During a field map measurement the search coil is first moved radially outwards at constant velocity and then back in. The voltage is integrated in both directions, so that a comparison of the data taken during the outward and the inward movement allows to derive a correction of the integrator drift. Besides the voltage measurement, a linear encoder and a fast timer are triggered simultaneously to allow the determination of the velocity and the exact position of the measurement. Small positioning errors due to variations in the velocity of the search coil are corrected.

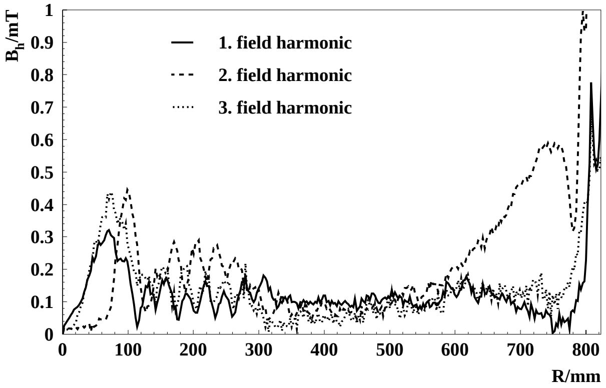

Figure 5: Amplitude of the first 3 field harmonics of the PSI superconducting cyclotron after isochronization and radial adjustment of main coil.

Between 180 and 720 radial scans at different azimuthal angles are used in a field map. The measurement of a high resolution field map can take up to 12 hours. In order to stabilize the conditions during the measurement, the iron is kept on constant temperature within +/- 0.5° C by radiators and iron heaters. The field change observed by NMR within 48 hours of magnet operation and field mapping measurements was typically less than a Gauss.

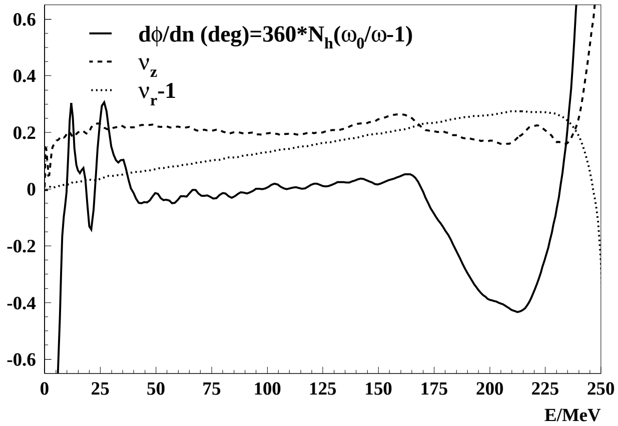

Figure 6: Phase shift per turn dϕ/dn, axial and radial betatron frequency ν_z and ν_r vs. energy. Compare to Fig. 1 in [3].

The radial scans are starting at negative radii, so that the search coil passes the cyclotron center twice. The redundancy of the data in the field map allows to compute corrections that are required due to small mechanical alignment errors. The method is based on the comparison of B(θ,r) with B(θ+π,-r) and is independent from the properties of the measured field values. The following corrections are considered:

- Linear encoder offset.
- Search coil missing the rotational axis.
- Mismatch between rotational axis of the field mapper and the iron axis.

The statistical precision of the field mapper was determined by the evaluation of a few hundred scans taken at the same azimuth and is about +/- 0.6 Gauss.

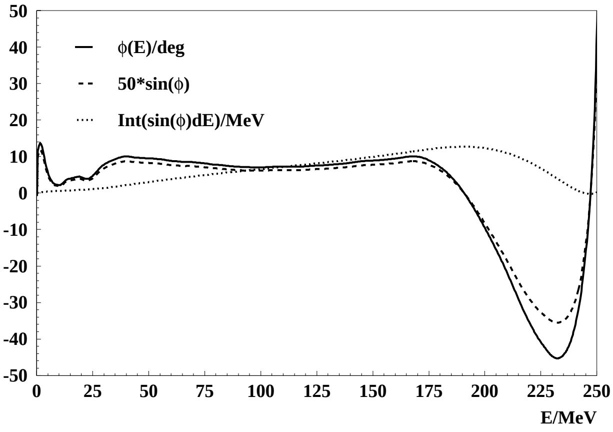

Figure 7: Final phase curves of the protons as computed for a nominal dee voltage of 80 kV.

Magnetic Properties After Shimming

The properties of the field maps are analysed by a program code that computes the equilibrium orbits, the field harmonics, the phase shift per turn and the betatron frequencies ν_z and ν_r. Furthermore the phase curve is computed by a particle tracking module that starts the orbit calculation from the ion source. The program also computes the rf phase ϕ(E) and integral of sin(ϕ). This code is a new development based on a merger of several old and proven NSCL programs.

The following results were obtained:

- $-45° < \phi(E) < 45°$
- $\nu_z>0.15$ for E > 5 MeV
- $\nu_z>0$ at all energies
- $\int_0^{250MeV} \sin(\phi(E))dE = 0$
- Amplitude of 1st harmonic < 2 Gauss
- Amplitude of 2nd harmonic < 6 Gauss
- Amplitude of 3rd harmonic typ. < 2 Gauss

Fig. 4 shows a 3D-plot of the final field map of the PSI cyclotron, Fig. 5 shows the resulting first 3 field harmonics of the PSI cyclotron. The first harmonic is below 0.2 mT for most of the energy range. The phase curve of the median ray computed by orbit tracking with the measured field starting at the ion source is shown in Fig. 6. The tracking code uses 2-dim. field maps of the accelerating electric fields including the H-field resulting from rf-currents in the dees and stems. The computed ion phase excursion is calibrated such that the energy gain is proportional to cos(ϕ) in consideration of the difference between the accelerating voltages of the dees at entrance and exit.

Extraction Channel Measurement

Besides the internal median plane field map, the field along the extraction trajectory and through the magnetic extraction elements ("focusing bars") was measured with a device using an array of 3 hall probes as sensing element.

The extraction system consists of two electrostatic deflectors, up to seven magnetic extraction elements – focusing bars – and two compensation bars. The hall probes are attached to a guidance rail designed especially for the purpose of this measurement. The probes are tracked by a stepper motor control unit along the extraction trajectory. The measured field and resulting gradients are in good agreement with the expectations.

RF - COMMISSIONING

All rf structures, i.e. liner, dees, dee-stems and coupler are installed in both cyclotrons and the commissioning of the rf system is in progress. As a first step the system is connected to a network analyser and the rf parameters are determined. The agreement between computed and measured resonance frequencies and the mode separation is excellent, i.e. typically < 0.1%. It should be noted, that no hardware model of the rf system was built. However, very detailed and extensive FEM-calculations were performed in cooperation with the PSI using different eigen-mode codes (Omega3P, Microwave Studio, see Fig. 8).

The field balance was measured with rf pickups and the different modes were found with the help of and in good agreement with a tuning algorithm - which was successfully tested in this way.

SUMMARY AND OUTLOOK

The status of the PSI and RPTC cyclotron projects were reported. Several miles stones were passed with distinction especially in the recent year:

- The successful and fast cool down of the coil in Nov. '03.
- The value of the heat balance of the cryogenic system close to the theoretical optimum.
- Fast and unproblematic excitation of the coil.
- The unspectacular passing of the quench test.
- The good agreement between the TOSCA field model and the measured field map.
- The field shimming and isochronization.
- The first results of the low power measurements of the frequencies and modes of the rf-system are in excellent agreement of with the simulation results.

Not all of these mile stones were passed without problems, but all problems that occurred so far were solved within short time.

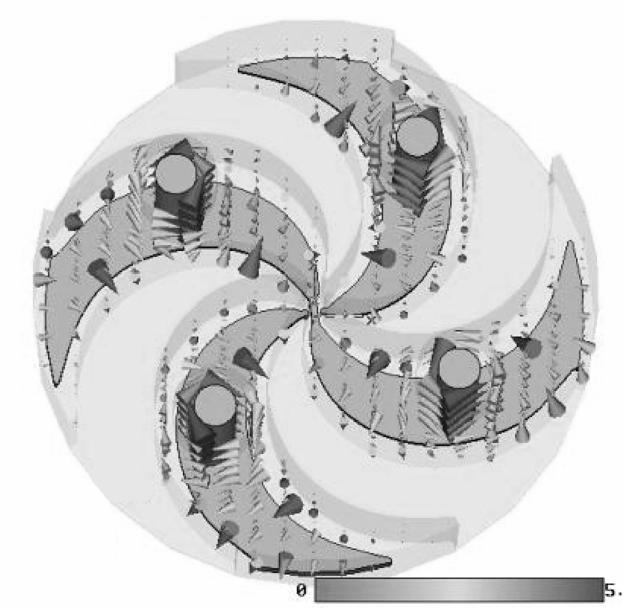

Figure 8: Simulation results of the rf system showing the dees, the liner and the stems.

The next step in both projects is the commissioning of the rf power amplifier followed by the high power rf commissioning. Afterwards - but still in this year - it is planned to switch on the ion source and to continue commissioning with beam.

At PROSCAN, the commissioning of the beam transport system will be done by PSI personnel. But at the RPTC project, ACCEL has the responsibility for the complete technical equipment of the radiotherapy facility, e.g. the energy selection system, the beam transport system, the gantries, the safety system, the scanning nozzles, the eye treatment room etc.

The first patient treatment at RPTC is planned for spring 2005.

REFERENCES

[1] M. Schillo *et al*: Compact Superconducting 250 MeV Proton Cyclotron For The PSI PROSCAN Therapy Project, Proc. of the 16th Int. Conf. on Cycl. and Their Applications, East Lansing 2001, pp 37-39.

[2] Proposal for a Manufacturing Prototype Superconducting Cyclotron for Advanced Cancer Therapy -- MSUCL-874, (1993).

[3] J. Kim and H. Blosser: Optimized Magnet for a 250 MeV Proton Radiotherapy Cyclotron, Proc. of the 16th Int. Conf. on Cycl. and Their Applications, East Lansing 2001, pp 345-347.