COMPACT SUPERCONDUCTING 250 MeV PROTON CYCLOTRON FOR THE PSI PROSCAN PROTON THERAPY PROJECT

M. Schillo, A. Geisler, A. Hobl, H.U. Klein, D. Krischel, M. Meyer-Reumers, C.Piel, ACCEL
H. Blosser, J.-W. Kim, F. Marti, J. Vincent, NSCL
S. Brandenburg, J.P.M. Beijers, KVI

Abstract

A cyclotron for proton therapy has to fulfil many requirements set by the specific operational and safety needs of a medical facility and the medical environment. These are for instance high extraction efficiency, high availability and reliability, simple and robust operation. ACCEL Instruments GmbH has refined the design concept of a medical cyclotron for the PSI PROSCAN project with the objective to use this cyclotron as the standard accelerator in complete proton therapy facilities, which ACCEL intends to market.

Starting from the design in [1], we have carried out further detail clarifications, optimizations and adaptations to the needs of PSI [2]. The work was performed in a collaboration between ACCEL, NSCL and KVI in view of the requirements from the PSI PROSCAN project. An overview on the design will be given touching on subjects such as the 3D structural analysis of the coil, detailed magnetic modeling for optimization of the inner region and the spiral, optimization of the RF power, optimization of the cryogenic design based on available cryocoolers instead of a liquefaction plant and Monte Carlo simulations to estimate the heat balance produced by neutrons at 4K components.

1 INTRODUCTION

ACCEL Instruments GmbH has been chosen as the supplier for a dedicated 250 MeV Proton Cyclotron for the PSI PROSCAN Project. This Cyclotron Design is intended as a reference for future clinical proton therapy facilities. So in addition to the formal aspects of medical device certification and approval which have to be observed right from the beginning of the project, the design must be optimized for the intended usage and requirements of the medical facility.

The formal aspects of medical device approval or certification, e.g. the CE certification for the European market and FDA approval for the US market, require an adapted Quality Management System, containing rules for Documentation, Labeling, risk analysis etc.

Starting from the design described in [1], we have carried out further detail clarifications, optimizations and adaptations to the needs of PSI [2] in a collaboration between ACCEL, NSCL and KVI.

The most essential requirement for a medical facility is high reliability and availability of the complete system and especially the application of superconducting coils in a cyclotron design offers advantages which help to enhance the total reliability and availability of the accelerator.

The higher contribution of the coil field allows relaxed vertical gap dimensions, which in turn reduces the risk of higher order effects causing beam losses or unpredictable behavior at extraction. Based on the NSCL and KVI experience an extraction efficiency of above 80% is expected. This will reduce activation of components and improve the maintainability of the whole accelerator.

The iron yoke follows the pill-box configuration of presently operating sc. cyclotrons allowing a fast and easy access to all internal components of the cyclotron by raising the top with an internal jacking system. All critical internal components are designed for a fast and easy exchange. Highest emphasis was put on a safe and robust design. The coil design is based on a standard Low Temperature superconductor cooled by a helium bath at 4.2K. The maximum field at the coils is moderate (~ 4T) leaving a large safety margin. The objective was to bring in the benefits from a superconducting coil without pushing the design to the limits.

Special effort was directed towards keeping the cooling concept simple, redundant and reliable. Due to the advances in modern small cryocooler technology and optimizations of the heat flow to the 4K level, e.g. by incorporating HT_C current leads and other measures, the liquefaction plant could be reduced to a system of redundant small cryocoolers operating as internal reliquefiers in the cryostat. The coil and cryostat will continuously stay could for long periods as demonstrated by NSCL.

Various additional approaches to enhance the reliability and availability of the accelerator are included in the design. So for instance a spare part pool with the most critical components will be created for easy swapping in case of a failure. Regular preventive maintenance procedures will ensure a replacement of components before there typical failure period.

An additional consideration for a clinical facility, which will influence the commercial aspects, is the complexity and cost of installation and commissioning, operation, of decommissioning and waste disposal. Here the proposed

CP600, *Cyclotrons and Their Applications 2001, Sixteenth International Conference,* edited by F. Marti

design also offers various advantages. The usage of sc. coils drastically reduces the total weight of the cyclotron, thus reducing the requirements for transportation, reinforcements in the building and the weight of activated material for waste disposal. The power consumption of the coil is negligible, only the cooling power of the cryocoolers which is in the range of 40kW has to be compared to the power consumption of a normal conductive coil which typically will be above 200kW.

2 DESIGN HIGHLIGHTS FOR MEDICAL APPLICATION

In view of the intended usage of the accelerator in a proton therapy facility we summarize here the design features especially optimized for this purpose:

- Design optimized for single turn extraction, Multiturn extraction with >80% extraction efficiency
- Optimized extraction, <90KV/cm field strength at electrostatic deflector, Reduced higher order effects due to sc. design
- Standard low temperature superconducting coils, bath cooled by liquid helium at 4.2K
- Moderate field strength 2.38T in center ~4T maximum field at the coils
- State-of-the-art cryo design with HTC current leads low heat losses and redundant cryocoolers for internal reliquefaction of Helium. ~50% safety margin of cooling power.
- Pill-box yoke design, top lifting jacking system for easy access
- Compact design: Yoke Height ~1.7 m, Diameter ~3 m, Weight ~90t
- Coil power supply <3kW rated power
- Optimized accelerating gap for reduced RF power

3 DESIGN OPTIMIZATIONS

In the described further optimization process a number of design issues have been identified, which have a high potential for further optimization with regard to beam optics and rf-power consumption. Utilizing conservative design wherever possible directly affects the reliability and is thus a major guide line for the past and ongoing design work.

3.1 RF Optimizations

Since the superconducting coil is not the main power consumer (below 1 kW in normal operation mainly determined by the resistive cable) the rf-power is of high interest because the total system power needed during operation can be significantly reduced. Different approaches for rf-power reduction were considered:

- stem position
- two Dee stem solution
- reducing the rf peak voltage
- reducing spiral
- increasing the accelerating gap.

While some of these potential design changes have considerable disadvantages, as e.g. a reduced peak voltage increases the number of turns and thus implies higher demands on the field isochronism, the last design issue revealed to be highly effective for reducing the power, even when the peak voltage is increased to keep the original turn number [3].

The fast developing computational power led to more sophisticated magnetic design tools, and thus made it possible to perform more accurate calculations. The reduction of spiral mentioned above could be taken into considerations, because the vertical focussing was originally designed conservatively with the saturated iron approximation to be above $\nu z=0.2$. We now use 3D-FEM-codes to model the cyclotrons main field. However, some details that can be considered as disturbances of the main field are still implemented by means of the saturated iron approximation.

Further magnetic design issues, which have been and will be treated, are:

- central region for an optimal beam quality and centering,
- field isochronism
- edge field roll off
- stray field reduction
- extraction optimization

3.2 3D Structural Analysis of the Coil

In the design process of a sc. magnet it is a standard procedure to investigate the stress levels, deformations and movements of the coil in a structural analysis. A 3D FE model of the coil and coldmass was created to investigate the structural mechanics of the system under winding tension, cool down and Lorentz forces. The forces were imported from the 3D Tosca magnetic model. To keep the calculation time in a feasible range only a half section of the model was generated implicitly assuming by the imposed symmetry conditions a second extraction channel. Figure 2 shows the model with the color encoded stress distribution after applying the winding tension. First modeling and calculations have been performed. The detailed interpretation of the results and further detail modeling is in progress.

With a winding tension of 80N/mm² the stress levels in the coil will always stay in safe range. The azimuthal stress inside the winding is always tensile, the Lorentz forces result only in a small increase of this tensile stress. The wire movement in radial and axial directions due to the energization of the coil stay below 0.02mm. The behavior with and without bandage will be investigated in more detail.

The only critical deformation in the observed in model is an elliptical bending of the winding mandrel. The two extraction channels in the structure act as weak links between two stiff half circles. When the whole structure comes under pressure from the winding tension, the links will bulge out, resulting in a deviation from a circular coil in the order of 0.2mm. The effects of this deformation will be studied in more detail in the magnetic model. Further investigation will be carried out at a simplified 3D structural model with only one channel and alternatively introduced symmetric channels in the mandrel to obtain a fourfold symmetry of the deformation.

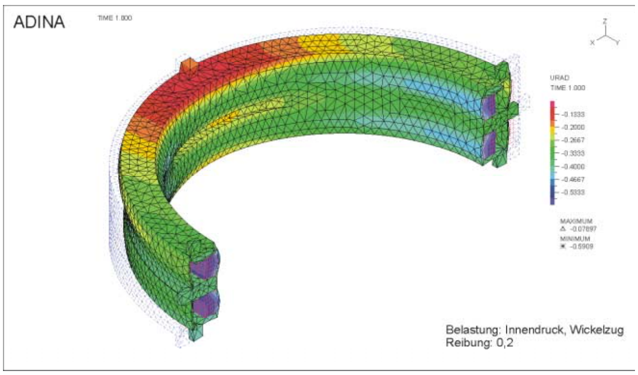

Figure1: Radial deformation

3.3 Cryogenic Design and Neutron Heating

Internal beam losses (e.g. along the extraction path) and stopping the beam on a measuring device such as the radial probe results in a significant neutron fluence passing through the superconducting coils of the cyclotron. Stopping 250 MeV protons in a heavy material such as tungsten results on average in two neutrons per stopped proton.

A fraction of these neutrons will penetrate into the 4K-mass consisting of the coils and their mechanical support. The slowing down of these neutrons and the energy release in neutron-induced nuclear reactions represent a heat-load, which may be significant in comparison to the heat-load due to radiation and conduction.

In order to quantify the neutron-induced heat-load calculations were made with the Monte Carlo code systems MCNP-X and FLUKA. In these calculations 250 MeV protons impinge on the center of the frontface of a tungsten block with a thickness of 45 mm. The frontface of the block has a width of 40 mm and a height of 25 mm. The block is placed in the symmetry plane of two concentric iron cylinders, which represent the inner cryostat wall and the 4K-mass, respectively.

In table 1 the results of the calculations are summarized. The energy deposited in the stopping block, the inner cryostat wall and the 4K-mass of the average 2.3 neutrons produced per incident proton are shown. The energy of the escaping neutrons is 10MeV and the binding energy 17.3MeV.

Table 1: Energy deposit as calculated with MCNP-X and FLUKA

	Stopping block	**cryostat wall**	**4K-mass**
MCNP-X	217.1 ± 0.1 MeV	1.5 ± 0.1 MeV	2.2 ± 0.1 MeV
FLUKA	218 ± 1 MeV	1.9 ± 0.1 MeV	2.5 ± 0.1 MeV

The error margins quoted are statistical only. They are internally calculated in the MCNP-X code, while for the FLUKA code they have been obtained from the results of five individual runs.

The calculation shows that the neutron-induced heat-load in the 4K-mass amounts to about 1.25 W when the full beam intensity of 500nA is stopped in the radial probe head at extraction radius.

The calculations give an upper limit of the energy deposit in the 4K-mass because they do not take into account the absorption of neutrons in the hill sectors of the magnet poles. Further investigations and measurements will follow to obtain a more precise value.

The analysis of the total heat balance for the cryostat was performed including considerations on radiation, all relevant conduction paths and the neutron heating. A careful cryogenic design of all components results in a heat leak to the liquid helium level small enough to be covered by small scale refrigerators. High temperature superconductor current leads help to reduce the thermal load at 4 K to 2.4 W in total. The re-liquefaction capacity of 4 GM cold heads or 2 small JT-reliquefiers today available gives about 6 W and thus is sufficient for the stable operation of the cyclotron including reserve. Even in case of failure of one of the reliquefaction systems the redundancy allows the normal operation of the cyclotron. The radiation shields and thermal intercepts of the current leads will be cooled by single stage GM cold heads. Due to these shield coolers no liquid nitrogen is necessary in the cryostat.

REFERENCES

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

[2] H. Reist, S. Adam, T. Blumer, A. Mezger, E. Pedroni, P. Sigg, P.A. Schmelzbach, T. Stammbach and J. Zichy; Specifications for the PSI Medical Accelerator, PSI Technical Note TM-85-01-01, 2001

[3] Design of a K250 proton cyclotron for radiotherapy, J. Kim and H.Blosser, This Conference.