AUTOMATED OPERATION AND OPTIMIZATION OF THE VARIAN 250 MeV SUPERCONDUCTING COMPACT PROTON CYCLOTRON

T. Stephani[#], H. Röcken, U. Behrens
VARIAN Medical Systems Particle Therapy GmbH, Bergisch Gladbach, Germany
C. Baumgarten, PSI, Villigen, Switzerland

Abstract

The 250 MeV superconducting compact proton cyclotron of Varian Medical Systems Particle Therapy is specially designed for the use within proton therapy systems. During medical operation typically no operator is required. Furthermore, several automated control system procedures guarantee a fast, simple and reliable startup as well as beam optimization after overnight shutdown or regular service actions. We report on the automated startup procedures, automated beam centering and automated optimization of extraction efficiency. Furthermore we present an automated beam current setting as used during medical operation by means of an electrostatic deflector located at the cyclotron center at low beam energies.

INTRODUCTION

The VARIAN medical proton accelerator is a compact four sector AVF isochronous cyclotron incorporating a superconducting main coil. The design of this compact machine, proposed by Henry Blosser and his team [1] and further developed and manufactured by VARIAN, proved to be very successful. The beam energy is 250 MeV, the maximum beam current during medical operation is 800 nA and the typical extraction efficiency is 80%. More detailed technical information and dedicated cyclotron parameters are provided in our last status report [2] which dealt with the commissioning of VARIAN's superconducting 250 MeV proton cyclotrons at PSI, Switzerland and RPTC, Germany.

Both machines are fully operational and are used to provide beam for proton therapy treatment systems with scanning techniques. Since the last report considerable progress has been made in the field of automation procedures for the control system. The announced optimization procedures for beam centering and extraction are operational and have proved reliable. For power saving reasons the standby condition of the RPTC cyclotron has been modified. Furthermore, a fast beam current variation procedure has been implemented and several new automatic characterization procedures are implemented in the cyclotron control system.

AUTOMATED CYCLOTRON STARTUP

Five cyclotron states have been defined and automatic transition routines have been introduced to guarantee reproducible system settings and a fast startup especially following overnight shutdown. Tab. 1 gives an overview on these cyclotron states and a short explanation of the respective cyclotron condition. An operator can easily change between the states by using automated transition procedures.

Table 1: Cyclotron States

Off	cyclotron vented, magnet off ⇒ cyclotron can be opened
Standby 1	cyclotron closed and evacuated ⇒ long shutdown period
Standby 2	additionally magnet energized, cooling water temperature increased ⇒ access to bunker, overnight shutdown
RF ready	additionally RF operating at reduced power ⇒ short standby period, alternative overnight shutdown
Beam ready	all active cyclotron components operating at predefined set values ⇒ cyclotron ready for beam operation

At RPTC currently "Standby 2" is used as overnight shutdown state. To reduce the power consumption of the system, all active components except the cryo-cooling, the superconducting magnet system, and the vacuum system are switched off. To maintain the thermal stability of the magnet iron the cooling water is set to an increased temperature. This minimizes the transient effects caused by heating from RF losses when coming back to standard beam operation. In addition this state enables access to the bunker to allow service actions if necessary.

Starting from "Standby 2" beam operation is possible within several minutes. With the transition to the state "RF ready" the RF amplifier is switched on and the RF system is set to operation at a reduced power of about 75 kW. A subsequent transition to the state "Beam ready" sets all other active components (ion source, extraction deflectors, …) to their nominal values. The time flow diagram in Fig. 1 illustrates this startup procedure for the important subsystems. The transition algorithm computes and sets the required magnet current as a function of the iron temperature. After setting the voltage of the vertical deflector – an electrostatic component located at the center of the cyclotron – to $U_{VD} = 0$ V (Fig. 1 at 8 min) beam is extracted from the cyclotron. A phase feedback loop ensures the optimal fine setting of the magnet current and also tunes the extraction efficiency and the beam current stability to its optimal values to ensure reliable and stable beam operation. The feedback system utilizes the signal of a non-destructive beam phase detector [4], mounted as the first beam line element. This phase pickup is designed to measure and quantify the effect of beam phase shifts due to magnetic field drifts.

[#] thomas.stephani@varian.com

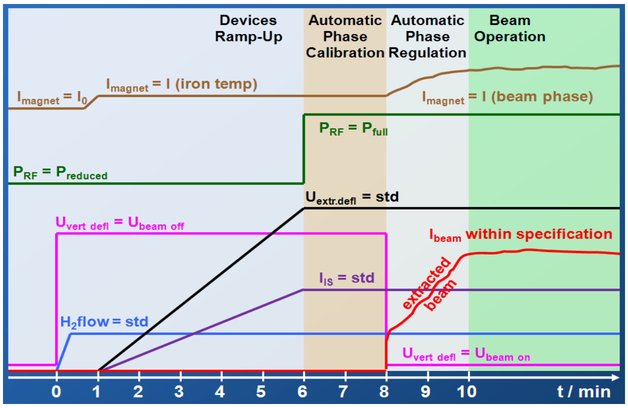

Figure 1: Timing diagram of the transition “RF ready” to “Beam ready”.

Using the automatic transition procedures it takes only 10 minutes to extract a quality proton beam starting from the overnight shutdown while only 2 buttons at the control system have to be pressed. It is expected that further optimization of the timing parameters will reduce this startup time to approximately 5 minutes.

AUTOMATED CYCLOTRON OPTIMIZATION

To ensure a stable and reliable cyclotron operation with a minimum of downtime the cyclotron settings have to be optimized after service of major components. Several automatic procedures have been implemented in the control system that enable a fast optimization of the cyclotron.

Automated Beam Centering

Beam centering is one key issue in optimization of the cyclotron performance. Only with a well centered beam a reliable operation is possible and high extraction efficiency can be reached.

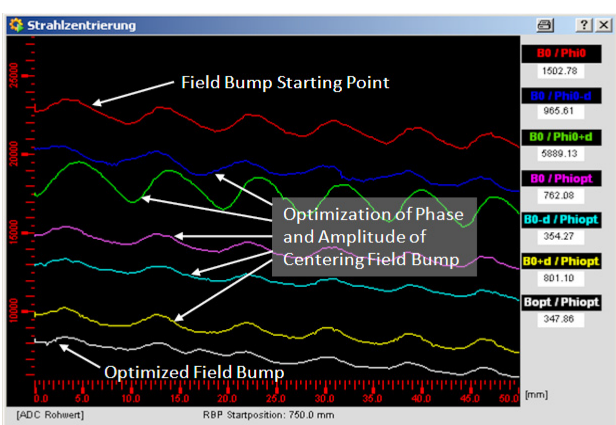

Figure 2: Graphical output display of the automatic beam centering procedure.

The beam is centered by proper positioning of 8 iron trim rods near the center of the cyclotron (inner trim rods). These rods are used to adjust the amplitude and the phase of the first field harmonic which allows minimizing the radial beam precession. A measure of the beam precession is the oscillation of the beam current as measured with a radial probe. The automation procedure takes several probe scans and computes the optimal inner trim rod settings based on these measurements using a dedicated algorithm [3]. Fig. 2 shows a graphical output display of this procedure with the beam current signals for the different scans.

Automated Optimization of the Extraction Efficiency

The extraction efficiency is also automatically optimized. A second set of movable trim rods placed at the extraction radius (outer trim rods) is used to excite some beam precession before extraction in order to increase the turn separation at the two electrostatic deflectors. Together with an automated optimization of the extractor voltages this procedure reliably optimizes the extraction efficiency up to 80% and sometimes above, see Fig. 3.

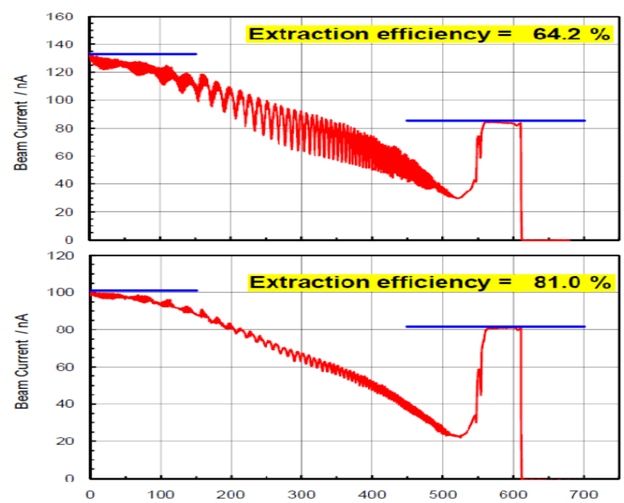

Figure 3: Radial beam probe scan with non-optimized (upper) and optimized (lower) cyclotron settings.

Automated Optimization of the Radial Phase Slit Positions

Internal beam losses can be minimized by proper positioning of two movable phase slits that are used for beam current adjustment during medical operation. A control system procedure measures the beam currents captured by the phase slits with respect to their radial positions. The optimal radial positions for the phase slits are computed and they are positioned automatically by the control system.

AUTOMATED CYCLOTRON CHARACTERIZATION

A predefined set of performance characterizations is recorded on a regular basis. The data are part of the quality checks and enable prediction of upcoming service actions required to keep the beam quality at the desired level. The following cyclotron characterization measurements are automated in the control system:

- beam current dependence on phase slits positions
- beam current dependence on vertical deflector voltage
- beam current dependence on RF power
- beam phase dependence on magnetic field settings
- plausibility check for current losses on center slits

AUTOMATED CYCLOTRON OPERATION

All the presented procedures help to set up the cyclotron in a well defined state that supports the automated operation of the system.

During medical operation the complete beam handling is managed by a higher level control system including the requests for dedicated beam currents. There are no planned interventions of an operator during the standard operation of the cyclotron after setting up the system.

The maximum beam current for each patient treatment is adjusted by means of two movable phase slits based on an automatically generated look-up table. Beam current adjustment starts by setting the slit widths to defined values. The slits are then opened and allow a precise tuning of the maximal beam current in the range between 1 nA to 800 nA. After the adjustment of the phase slits the dependency of the beam current on the voltage of the vertical deflector is recorded online at the RPTC machine. The complete sequence takes about 20s. Based on this suppression curve later on the beam current can be changed within milliseconds over a wide dynamic range by changing the voltage setting of the vertical deflector during the irradiation. Fig. 4 shows the extracted beam current during an irradiation.

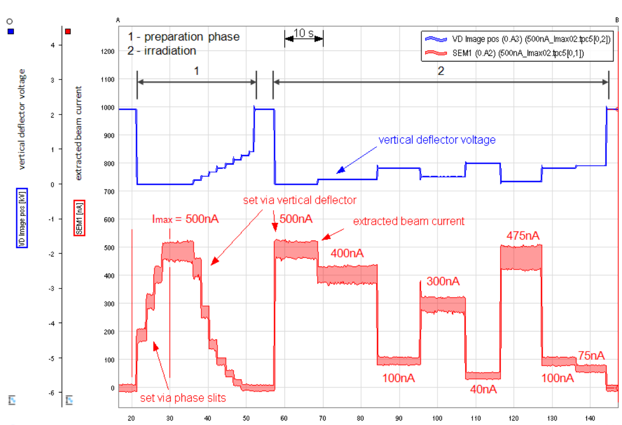

Figure 4: Sequence of the beam current setting procedure.

Fig. 5 gives a more detailed view on the timing behavior when the beam current is changed.

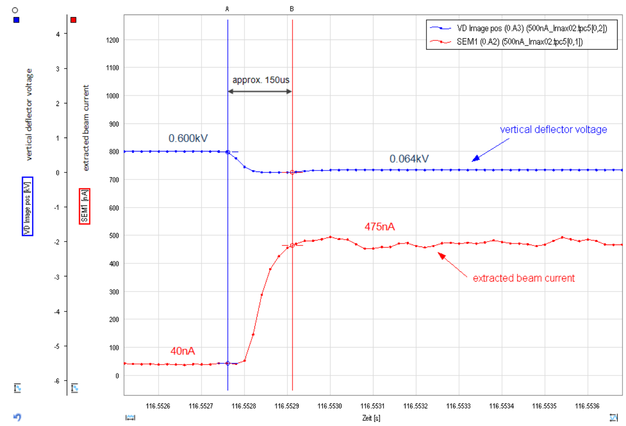

Figure 5: Fast beam current setting using the vertical deflector.

CONCLUSION

We have optimized the accelerator control system to ensure a reproducible and reliable beam operation during daily patient treatment and especially after service actions. The implementation comprises several software routines: an automatic routine for beam centering; an automatic optimization of the beam extraction efficiency; an automatic optimization of the radial positions of the two movable inner phase slits and a fast beam current setting procedure based on an automatically generated look-up table for slit widths and the vertical deflector induced beam suppression.

In addition we have successfully implemented and tested automatic routines for daily startup and regularly system characterization. All these routines have a simple user interface and allow a non-expert operator to perform a morning startup including standard QA procedures. During regular medical operation usually no operator interactions are necessary. As a result, the VARIAN 250 MeV superconducting compact proton cyclotron can be operated as a real “turn-key system”.

REFERENCES

[1] H. Blosser et al., “Proposal for a Manufacturing Prototype Superconducting Cyclotron for Advanced Cancer Therapy”, NSCL internal report MSUCL-874, East Lansing, Mi USA (1993).

[2] A.E. Geisler, J. Hottenbacher, H.-U. Klein, D. Krischel, H. Röcken, M. Schillo, T. Stephani, J.H. Timmer, “COMMISSIONING OF THE ACCEL 250 MEV PROTON CYCLOTRON”, Proc. of 18th Int. Conf. on Cycl. and their Appl., Giardini Naxos, Italy, p. 9-14 (2007).

[3] C. Baumgarten, “Beam Centering Calculation Algorithm”, Internal Report, ACCEL Instruments GmbH, Bergisch Gladbach, Germany (1997, unpublished).

[4] J.H. Timmer, H. Röcken, T. Stephani, C. Baumgarten, A.E. Geisler, “Automated cyclotron tuning using beam phase measurements”, Nucl. Instr. and Meth. A 568 (2006) 532 - 536.