PROGRESS AT VARIAN'S SUPERCONDUCTING CYCLOTRONS: A BASE FOR THE PROBEAM™ PLATFORM

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Abstract

During the last 9 years, Varian's superconducting isochronous ProBeam™ medical proton cyclotrons proved their matureness when they accumulated more than 20 operational years at factory testing and patient treatment without any unscheduled down time caused by quenches or failures of the cryogenic supply systems. Their reliable superconductive technology features a fast initial cool-down and low operating costs. Besides the two machines which are in clinical operation in Switzerland and Germany, one more ProBeam™ cyclotron is already fully commissioned and delivering a 250 MeV proton beam at Scripps Proton Therapy Center in San Diego, USA. Several other ProBeam™ cyclotrons are under fabrication or in the phase of factory beam acceptance tests. We report on fast cool-down and time-to-beam-extraction achievements as well as on the latest status and operational experience with Varian's ProBeam™ cyclotrons. Additionally, we give an insight in new developments for further reduction of commissioning time and improvement of reliability.

INTRODUCTION

The driver of Varian's ProBeam™ Proton Therapy Platform is the 250 MeV superconducting (SC) cyclotron, which was already described in previous articles [1]. Since ProBeam™ Cyclotron #3 (delivered to Scripps Proton Treatment Center (SPTC), San Diego) we have the opportunity to pre-commission our cyclotrons with beam in a test cell of our production facility near Cologne (Germany). Up to date, we factory commissioned one more cyclotron (#4, to be shipped to customer site by November, 2013) and the next one (#5) is already moved into the test cell for RF and beam commissioning. Assembly of cyclotron #6 is running and at cyclotron #7 the coil winding is finished and the iron is already in the factory.

The production facility was set up to enable the production of three cyclotrons per year with the possibility of further ramp up.

CYCLOTRON COOL-DOWN

After final assembly and prior to beam commissioning, the cyclotron SC coils are cooled down to liquid helium temperature of 4.2 K on an assembly stand in our productions halls. In order to cool down from room temperature, around 160 MJ heat energy must be carried away from the cryostat. To remove this heat energy by using liquid helium (LHe), around 50.000 liters would be needed. Therefore we apply the reliable and more economical standard solution of cooling down not directly by LHe but via an intermediate step using liquid nitrogen (LN_2), which has a latent heat of evaporation ≈54 times higher than LHe. Cooling down the SC coils from room temperature to LN_2 temperature (77 K) by filling the vessel around the coils takes around 1.400 liters of LN_2. The system is then given some time to thermally settle before the LN_2 is expelled out. A thorough processing has to be followed to avoid any nitrogen freezing when starting the final cooling with LHe. This step then needs only around 1.000 liters of LHe.

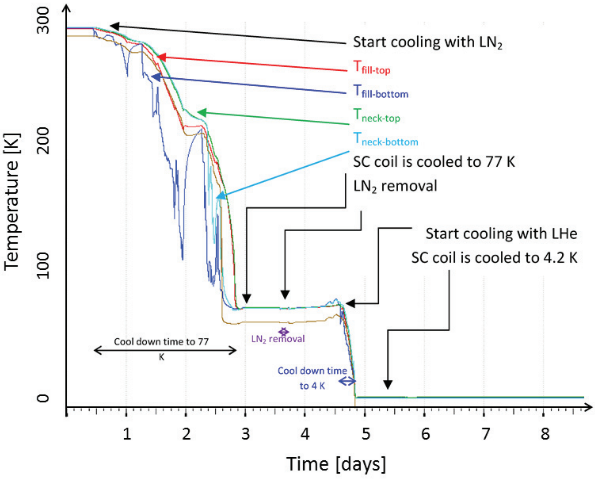

Figure 1: Cool down time of the SC coils from room temperature (300 K) to the LN2 temperature (77 K) and further to LHe temperature (4 K).

In this way the cool down process of the SC coils needs effectively only around 5 days (see Fig. 1), whereas for dry-cooled systems it could easily take several weeks. The time is an important factor because cooling of massive materials cannot be forced. The coils need time to be homogeneously and smoothly cooled to be protected from mechanical stresses due to the different shrinking coefficients at different temperatures all over the coils and LHe vessel. After completing the cyclotron cool-down process, the SC coils can directly be energized to excite the required magnetic field for the mapping and shimming process.

RF COMMISSIONING

After shimming the cyclotron is moved in cold state into the test cell on an air film mover (see Fig. 2). Prior to beam commissioning the RF resonator has to be conditioned. Within approx. 100 h of pulse and cw RF operation, the RF power is stepwise increased to its operational value of nearly 120 kW.

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Figure 2: A ProBeam™ cyclotron on its way into the test cell.

High Power Solid State Amplifier

The RF power is generated by a high power solid state amplifier system designed to Varian's specifications by Cryoelectra GmbH, Germany. It consists of 120 amplifier modules, each delivering 1.25 kW at 72 MHz, connected by a combiner network. Each module is equipped with four high power LDMOS transistors which are driven at about 60% of their maximum power capability.

One important design consideration for amplifiers driving accelerator cavities is reflected power protection. Especially at frequencies below 100 MHz reflection protection by circulators becomes difficult and no standard components are commercially available. Therefore, the reflection hardness of the transistors is decisive for minimizing RF conditioning time and down times due to reflection events during normal cyclotron operation. Compared to tetrode amplifiers as used previously, we could increase the reflected power protection threshold from 5% to 10% of the maximum forward power. This resulted in a significantly reduced commissioning time for initial RF cavity processing.

RF Control

The feedback loops for RF amplitude and phase stabilization are combined in a digital Low Level RF control system (dLLRF). The signals from the RF pickup loops, including spare signals, are digitized by AD converters and further processed on a FPGA board. Beside the basic feedback functionality also high level functions for pulse processing and machine protection are integrated. The flexibility in re-programming of the FPGA allowed fast optimization of machine protection procedures and implementation of new operational features in order to improve the overall RF system stability.

CYCLOTRON BEAM COMMISSIONING

The factory and on-site beam commissioning phase represents the final stage of the series production of a cyclotron. In order to minimize the cyclotron´s activation with respect to radiation safety regulations for the transport, the typical beam intensity during the pre-commissioning phase (approx. 6 weeks) in the test cell is restricted to a few nA.

The factory beam commissioning includes typically:

- HV conditioning of extraction deflectors
- Start-up of ion source
- Start-up of all diagnostic systems (beam and viewer probe, external beam profile monitor)
- Beam production and optimization
- Adjustment of central region (ion source injection position, several slits)
- Adjustment of all beam focusing and guiding elements in the extraction region

Cyclotron #3

One acceptance criterion for a pre-commissioned cyclotron in the test cell is a beam extraction efficiency of at least 25%. As shown in Fig. 3, we were able to bring the efficiency of cyclotron #3 up to ~40% before it had to leave the test cell for shipping.

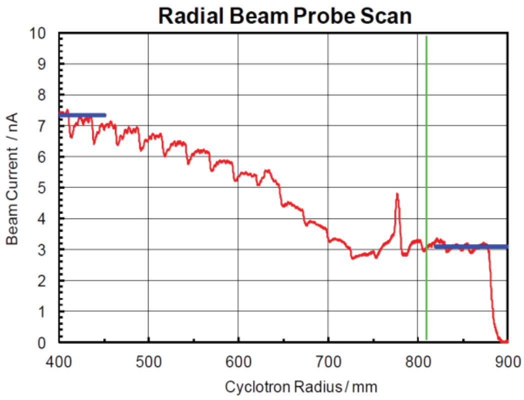

Figure 3: Beam probe scan of cyclotron #3measured at the end of the factory beam commissioning phase.

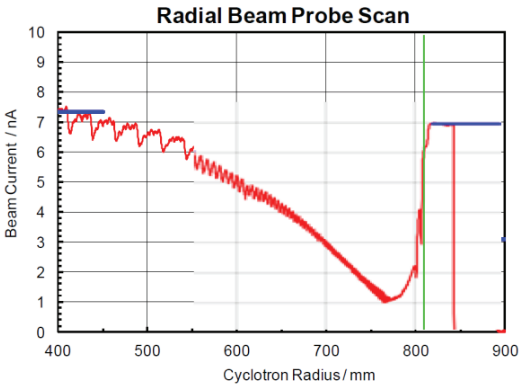

Figure 4: Beam probe scan of cyclotron #3 measured at the end of the on-site beam commissioning phase.

After shipment and installation at the customer site, first beam was extracted with known factory settings shortly after re-starting the RF. Beam operation then was optimized successfully via fine adjustments of extraction elements (position of electrostatic deflectors, focusing and compensation bars). Tilts of the main coil optimized extraction efficiency and beam position to match beamline acceptance. Overall, we achieved an extraction efficiency of about 80% as shown in Fig. 4.

Corresponding to the beam probe scans, Fig. 5 shows the beam spot on a fluorescence screen of a so-called viewer probe within the cyclotron acceleration area (Fig. 5, left) and within the extraction channel (Fig. 5, right). Those spot observations provide important information: (i) beam shape and dimension, (ii) vertical beam position and oscillations, if present, relative to the median plane of the cyclotron. The common procedure to compensate vertical beam position offsets is either a vertical position correction of the main coil [2] which is, however, more effective if the offset is observed before beam extraction, or by tilts of the main coil [3] if the vertical beam position needs adjustment in the extraction path. By means of appropriate coil tilts we were indeed able to correct the position of the extracted beam as shown in the bottom of Fig. 5 (extraction channel) where the red line indicates the cyclotron median plane

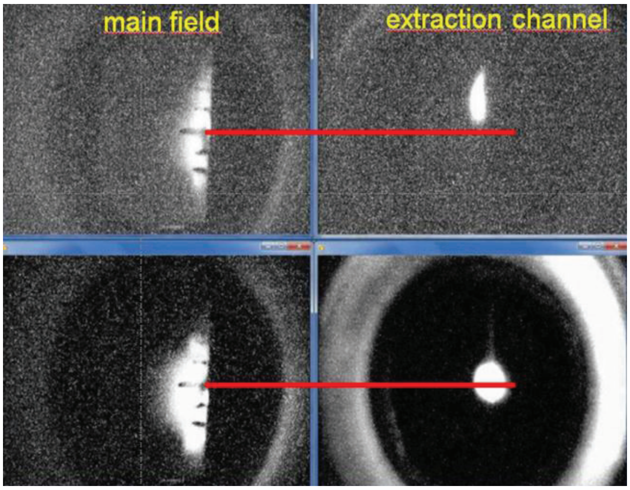

Figure 5: Beam profile observed with a viewer probe at cyclotron #3 before and after coil tilt. Left: beam in the acceleration region. Right: beam in the extraction channel.

Cyclotron #4

From the experience gained during commissioning of the last cyclotrons we were able to extract beam from cyclotron #4 within one week after starting the beam commissioning phase in the test cell. After two weeks we measured an extraction efficiency of about 40%. This gave us the possibility to use the remaining testing time for optimization of the intensity and position stability of the extracted beam already in the factory test cell.

Figure 6 shows the final measurement of the beam current using a Faraday cup (FC) at the end of the extraction beam line as well as the beam position observed by a beam profile monitor versus the coil current. Overall, we obtained a nearly constant vertical position of the extracted beam and stability of about 0.1 mm/mA for the horizontal position.

During the on-site installation and commissioning phase, the well-known horizontal and vertical displacements of extracted beam will be compensated by respective positioning of the cyclotron relative to the beam line and by fine adjustment of the magnetic extraction elements.

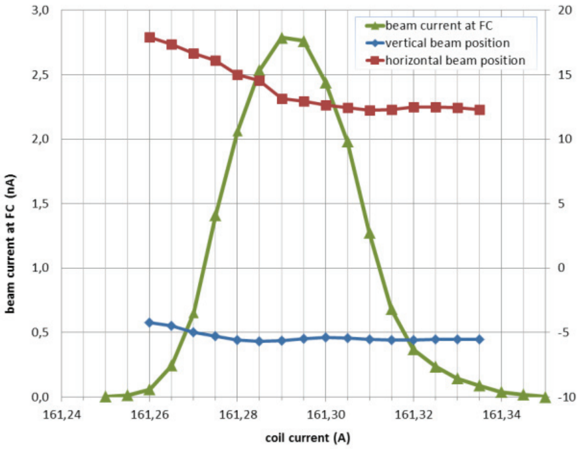

Figure 6: Characterization of extracted beam of cyclotron #4: beam current at Faraday cup (FC), horizontal and vertical beam position versus SC main coil current.

CONCLUSION

For its superconducting 250 MeV ProBeam™ cyclotrons, Varian has established a fast commissioning process using a factory test cell for accelerator pre-commissioning with beam. A new solid state high power RF amplifier with high reflected power tolerance enables fast RF commissioning in pulsed mode. The extracted 250 MeV proton beam is optimized for extraction efficiency and beam position. All operational parameters are then transferred from the factory to the installation site and allow a short time-to-beam. After a successful proof of this concept with cyclotron #3, the results for the already factory commissioned cyclotron #4 are even more promising.

REFERENCES

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