THE VARIAN 250 MeV SUPERCONDUCTING COMPACT PROTON CYCLOTRON: MEDICAL OPERATION OF THE 2nd MACHINE, PRODUCTION AND COMMISSIONING STATUS OF MACHINES No. 3 TO 7

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Abstract

Varian Medical Systems Particle Therapy has successfully commissioned its 2nd superconducting compact proton cyclotron for use in proton therapy in 2008. The 250 MeV machine serves as proton source for treatments at the first clinical proton therapy center in Germany which opened in early 2009. Furthermore, Varian is currently commissioning and factory testing its 3rd machine.

We report on the operation and performance of the 2nd machine as well as on the successful cool-down, quench testing, and magnetic shimming of the 3rd machine.

In addition we present RF commissioning plans using a newly developed solid state amplifier, and plans for the upcoming factory beam commissioning in the new Varian cyclotron scanning nozzle test cell, scheduled for October 2010. Finally we provide a brief status and outlook on machines no. 4 to 7.

INTRODUCTION

VARIAN's superconducting compact cyclotron for use in proton therapy is an azimuthally varying field isochronous machine which delivers a 250 MeV cw beam of up to 800 nA. The use of superconduction technology with its closed cycle, zero boil-off liquid helium cryosystem allows a high induction that completely saturates the iron yoke of the compact machine. This results in a reproducible and stable magnetic field which is essential for a reliable beam operation during medical use. The initial design proposal [1] was worked out in detail by ACCEL Instruments GmbH. Some key features of this machine type are listed in Tab. 1; more details are given in our previous status report [2].

In 2007, Varian Medical Systems, Inc. bought ACCEL which had built at that time - amongst diverse advanced technology equipment for research and commercial users - two cyclotrons for use in proton therapy. In early 2009, the respective VARIAN business was re-structured and the particle therapy part is now pursued by the newly formed Varian Medical Systems Particle Therapy GmbH (VMS-PT).

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Table 1: Technical specifications of the VMS-PT cyclotron (engineering goals)

Beam	
Energy	250 MeV
Extracted current	800 nA (more on short term)
Emittance (hor./vert.)	$< 3 / 5\ \pi$ mm mrad (2σ)
Momentum spread	±0.04%
Number of turns	650
Extraction efficiency	~80%
Dynamic range for intensity modulation	1:800
Fast intensity modulation	via electrostatic deflector, >10% in 100 μs
Iron Yoke	
Outer diameter	3.1 m (3.2 m for the first two machines)
Height	1.6 m
Weight	<90 t
4 Sectors AVF SC Magnet	
Stored energy	2.5 MJ
Induction at center	2.4 T
Induction at coil	<4 T
Operating current	160 A
Rated power of cryocoolers	40 kW
RF System	
Frequency	72.8 MHz (2nd harmonic)
Voltage @ center / @ extraction radius	80 kV / 130 kV
RF power	≤115 kW

CYCLOTRONS IN OPERATION

Currently there are two VMS-PT cyclotrons in operation. The first one is located at Paul Scherrer Institute (PSI) in Switzerland as part of the PROSCAN project [3], which is treating patients since the beginning of 2007. The second one passed its commissioning phase in 2008 at the Rinecker Proton Therapy Center (RPTC) in Germany, the first and to date only European proton radiation center that provides since early 2009 a complete hospital setting for the treatment of cancer [4]. Besides the cyclotron this facility is equipped with VARIAN's proton therapy technology, like a degrader for energy adjustment, an energy selection system for the energy filtering, a beam line for beam transportation, four rotational isocentric gantries for 360° irradiation plus one fixed beam station for head / neck treatments, delivery nozzles providing the modern pencil beam spot scanning, safety systems, treatment control software and so on. The clinical user treats patients six days per week, for eight to ten hours per day, in the three gantries that have been handed over. Work to hand over the remaining treatment rooms is ongoing. Currently, the beam commissioning required to hand over the remaining rooms is performed during nights and weekends by VMS-PT. This means that the treatment facility, including the cyclotron, is operated 24 hours per day on six to seven days per week. Service actions are typically performed every Sunday. According to the clinical user, the uptime of the whole facility for patient treatment during the first six months of operation was 97% [5]. The uptime of the cyclotron itself was even higher. The cyclotron startup, diagnostics, and performance tuning is highly automated through the dedicated control system [6]. During clinical operation normally no cyclotron operator is required.

CYCLOTRONS AND SUBSYSTEMS UNDER COMMISSIONING

In contrast to the first two machines that were assembled and commissioned at the customer's site, cyclotrons no. 3 and following will be widely assembled and tested with beam already in the customized factory near Cologne, Germany. After this pre-commissioning and factory acceptance testing (FAT), the machines will be shipped to their destinations in only two large lots each, essentially parted into the upper and the lower half. Cyclotron no. 3 is currently in the final stage of assembly and is undergoing FATs in parallel.

Cool Down, Magnet Ramping, Test Quench, and Field Mapping of 3rd Machine

In May 2010 the superconductive (sc) magnet of cyclotron no. 3 was cooled down to LHe temperature without any problems. The first ramping of the sc coil up to and beyond its nominal operating current of 160 A took place on May 18 at the first attempt. All forces on mounting suspensions of the coil and cryostat were continuously monitored and exhibited the expected magnitude.

The whole cryo- and magnet system is conservative in design. As a consequence, the obligatory factory test quench could not be forced by a fast ramping of the coil current at the limits of the power supply. Instead, it had to be triggered at full operating current by powering dedicated quench heaters that were mounted directly on the coil windings during manufacturing. The re-cooling proceeded very smoothly, and after only 5 hours the system was fully operable again. All suspension forces came back to their previous values and a detailed field map revealed that the magnet system did not alter in any way, thus proved being a stable, quench proof and also quench tolerant system.

Field mapping for fine magnetic shimming of the isochronous machine is a sophisticated task. To avoid spurious effects from the slight temperature dependence of the yoke iron's saturation magnetization we perform the mapping in a temperature stabilized cell (see Fig. 1) using a specially developed field mapping device. With this setup, a first harmonic in the 4-fold symmetrically field of up to 29 Gauss was initially determined. This was easily brought down to less than the target value of 2 Gauss by moving the coil. Releasing and tightening the suspension links a few tenth of a mm takes only a few minutes. However, some field disturbances in the order of 6 Gauss remained on outer radius and have to be shimmed locally.

Figure 1: VMS-PT cyclotron no. 3 in a temperature stabilized cell (front cover removed for photo) during FATs

Solid State RF Power Amplifier

RF power for the first two cyclotrons is provided by a 3-stage tetrode tube amplifier consisting of several electrical cabinets for power transformers and high voltage supplies. While this is an established technique, it suffers from some design drawbacks, namely the internal use of high voltages, missing redundancy, aging of tubes with high replacement costs, and less suitability for pulse operation then is desirable during cavity conditioning. Most important of these drawbacks is the redundancy issue, which has a direct influence on the potential uptime during clinical operation. Our efforts trying to resolve this potential issue raised the idea of using a transistor based "solid state" amplifier (SSA) with many identical amplification modules working in parallel. A test station with 20 modules was built in 2009 and has successfully passed a 1000 hours test at the full output power of 25 kW. First tests have shown the capability of the system to withstand a >15% continuous power reflection. Currently a full scale SSA consisting of 120 modules for a total output power of >150 kW is finalized and undergoing FATs at VARIAN [7]. This power is much higher than the cyclotron RF operation power of ≤115 kW, and the design allows uninterrupted operation in case one or more modules fail. Through its redundancy the new amplifier features a higher availability and maintainability. This will contribute to the overall system uptime and will also have a cost reduction effect. Moreover, the digitally controlled and modularized system provides extended diagnostics capabilities.

Digital Low Level RF Electronics

The next VARIAN cyclotrons will make use of a digital low level RF control electronics (dLLRF). All modules of this new development have already passed factory performance tests [7] and the system will be used for cyclotron no. 3 commissioning in September 2010. Like the SSA, the dLLRF is designed for high redundancy with parallel signal processing of redundant pickups and automatic switchover in case of failure of a signal path. This yields a high fault tolerance and further increases system uptime. Additionally, the dLLRF is faster than the previously used system and provides more remote input and output signals.

CYCLOTRON PRODUCTION

VARIAN has converted its >4,000 m^2 production halls near Cologne, Germany into a customized cyclotron manufacturing line, suitable for the assembly and system testing of several cyclotrons per year.

Cyclotrons No. 4 to 7

All major components for the production of cyclotron no. 4 are ready in the factory. Coil winding and assembly of pole caps is underway. We expect first system tests in late 2010. The fine machined yoke iron parts for no. 5 currently undergo dimensional and other QA inspections in the factory. Assembly will start shortly. Iron for no. 6 and 7 as well as the respective long lead items are ordered. The expected cyclotron production rate is about two cyclotrons per year for the near future. This can be increased according to market needs if necessary.

Test Cell

Directly adjacent to the manufacturing line VARIAN has built a radiation shielding concrete bunker providing the complete infrastructure for cyclotron and scanning nozzle beam testing, the so-called "test cell". Cyclotron no. 3 will be moved into the test cell after magnetic shimming. We plan to have tested all RF components, the ion source, slit systems, extractors, diagnostics, software etc. during a system integration and FAT with proton beam by the end this year. This enables the delivery of integrally factory beam tested systems.

CONCLUSION

Based on the proven design of a 250 MeV superconducting compact proton cyclotron, two machines have demonstrated remarkable performance during medical operation in the last years. The use for patient treatment started in 2007 at PSI and is a success in the PROSCAN project. A fully integrated clinical installation is operating at RPTC since 2008. VARIAN is now continuously improving the design with regard to reliability, maintainability, performance, cost reduction, and integration into the company's radiological treatment environment. This applies to nearly all hardware and software components, ranging from specially designed components such as ion source, RF amplifier, and dLLRF to more common system components such as the vacuum and media supply systems, which appeared to be an opportunity for considerable cost reduction.

Cyclotron no. 3 is currently undergoing magnetic shimming. RF commissioning, system integration tests with beam and FATs are planned to be completed by the end of 2010. Assembly of No. 4 is advanced and no. 5 will follow shortly. Irons for no. 6 and no. 7 are currently being casted and forged. The production process has been designed so that it can be adapted to market needs.

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