PROGRESS REPORT ON THE CONSTRUCTION OF THE PROTON THERAPY EQUIPMENT FOR MGH

Y. Jongen, M. Abs, J. Bailey, W. Beeckman, J.-L. Delvaux, M. Ladeuze, S. Laycock, D. Vandeplassche, A. Van Meerbeeck, S. Zaremba
Ion Beam Applications s.a. (IBA)
Chemin du Cyclotron 3, B-1348 Louvain-la-Neuve, Belgium

M. Sano, T. Satoh, T. Tachikawa
Sumitomo Heavy Industries (SHI)
Niihama-City, Japan

1 INTRODUCTION

IBA and SHI have jointly developed a 235 MeV proton isochronous cyclotron as part of a proton therapy system specifically designed for in-hospital operation. Besides the cyclotron, the system includes an energy selection system (transforming the fixed energy beam extracted from the cyclotron into a variable energy beam in the 235 to 70 MeV range), a beam transport and switching system, isocentric gantries with nozzles, horizontal beam lines, high precision robotic patient positioning systems, a global control system, and a global safety management system using hardwired interlocks to achieve a safety level meeting applicable standards. Two such systems are installed and almost completely tested, one at the Northeast Proton Therapy Center (NPTC) of the Massachusetts General Hospital (MGH) in Boston, MA, USA, the other at the National Cancer Center (NCC), Kashiwa, Chiba prefecture, Japan. Three more systems have been recently ordered to IBA for installation in USA, and are currently under construction. This paper presents a status report on the equipment construction and installation at MGH. Some interesting technical and beam dynamics problems were encountered and solved during the commissioning, and are explained in the paper.

2 THE PROTON THERAPY SYSTEM FOR THE NPTC

2.1 A cyclotron-based system

Our goal was to meet all the clinical specifications of a state-of-the-art proton therapy facility in the most simple, reliable and cost effective way. This is the reason for the choice of a fixed energy cyclotron followed by an energy selection system. With this choice, the proposed system is ideal for both the present and the new treatment modes currently under consideration such as pencil beam scanning for example. Indeed, our energy selection system allows for a comfortable 10% energy variation within 2 seconds, and the high intensity, continuous beam extracted from the cyclotron can be intensity controlled from the ion source within 15 µsec turn on/turn off time.

Fig. 1. CYCLONE 235 installed at the NPTC.

2.2 The energy selection system (ESS)

The energy variability of the system is achieved by means of a carbon wedge used as an energy degrader. As a result of the energy degradation, there is an increase in emittance and energy spread. Emittance slits are therefore used to define the emittance of the transmitted beam to a value adjustable between 10 and 35 π mm mrad, while an analysing magnet system limits the energy spread from 0.3 to 1%. Energy changes are completed in two seconds, using laminated magnets and quadrupoles.

2.3 The beam transport system

The beam transport and switching system connects the exit of the energy selection system to the entrance points of the gantries and the fixed beam lines. All bends are achromats. At strategic points along the beam transport system, the beam characteristics are monitored by beam profile monitors made of gridded ionization chambers. This information can be used for automatic tuning.

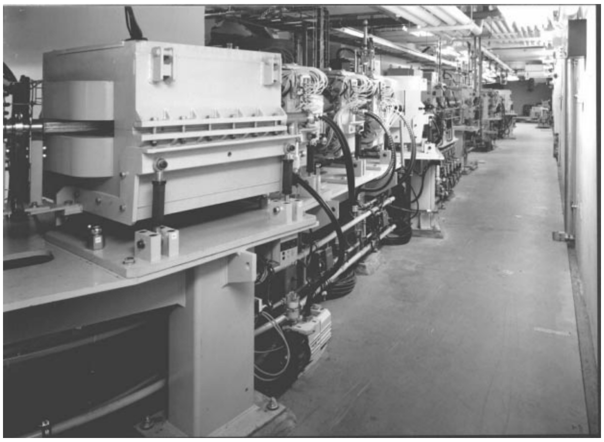

Fig. 2. Beam transport system at the NPTC

2.4 The gantries

The equipment for the NPTC includes two complete isocentric gantries fitted with a nozzle The gantry is the movable portion of the beam transport emerging from the cyclotron and terminating at the patient. The gantry structure is designed to minimize interference with the beam delivery system, provide maximum access to the patient, and maintain the isocenter position to within a sphere of confusion of radius 1 mm under all operating conditions, including all orientations, of the gantry. It includes a beam transport line which utilizes one 45° bending magnet, one 135° bending magnet, nine quadrupole magnets and a nozzle. A simple rotating seal connects the moving portion of the beam transport tube to the stationary portion at the end of a 60° achromatic bend leading to the gantry.

Fig. 3. Gantry and PPS under installation at the NPTC

The NPTC equipment includes two complete isocentric gantries. Each gantry is an achromatic system. Its optics can be tuned for either beam scattering/wobbling or for pencil beam scanning. As for the energy selection system and the beam transport system, the use of laminated magnets and quadrupoles allows for energy changes in two seconds.

2.5 The nozzles

The functions of the nozzles include the 3-D beam shaping to irradiate the target volume at a constant dose, the beam monitoring and dosimetry, the help for patient positioning and field alignment verification, and the support of patient specific devices. The spreading techniques provided by the IBA nozzle are the double scattering for small to moderate fields, and broad beam raster scanning for the largest and deepest fields. The nozzle is compatible with a future upgrade to pencil beam scanning.

2.6 The patient positioning system (PPS)

Patient positioners for proton therapy should be submillimeter precision instruments and the equipment therefore includes a patient positioner specifically designed for proton therapy. It positions the patient to permit the beam to be delivered with great accuracy to any point in the patient from any angle. Coupled with the gantry which provides 360° rotation of the beam about one vertical axis, the patient positioner must provide a minimum of four axis of motion (three translations and one rotation) to accomplish this objective. In fact, the patient positioner for the NPTC has six degrees of freedom - four axes as defined here above, and couch pitch and roll to accomplish fine scale adjustments. The PPS has demonstrated a reproducibility of 0.08 mm (one sigma). A load cell measures the forces and moments caused by the patient weight, and a computer algorithm allows to correct the PPS deformations and reproducible errors.

2.7 The control system

The NPTC Control System is developed on three levels: the equipment control level where we have the process controllers close to the equipment, the management level, which is responsible for the operation of a set of high level functions, and the user interface level with the operator interface. Networks provide the connection between the different levels and between units at the same level. The process controllers, using VME crates or industrial PLCs, are connected through an industrial bus (CANBus). An Ethernet network allows the connection of the different nodes of the system.

3 BEAM DYNAMICS ISSUES

The main beam dynamics issues along the acceleration are the resonance crossings. In order to illustrate this discussion, CYCLONE235's tune diagram is shown in fig. 4.

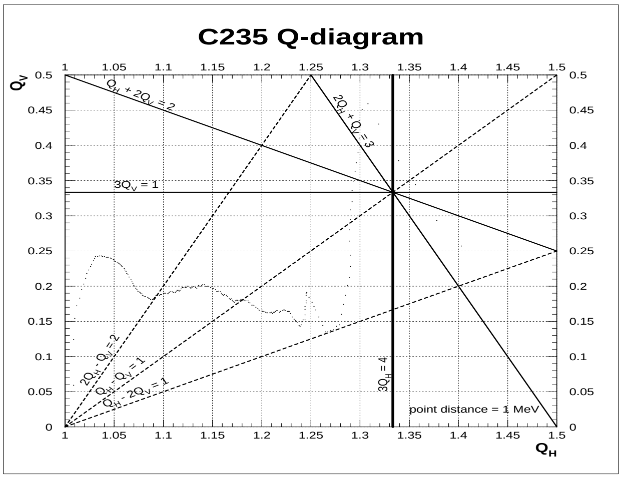

Fig. 4. Working diagram throughout the acceleration in CYCLONE 235, as obtained from closed orbits in the final field map.

The working diagram shows several resonances that have to be crossed or touched during acceleration. Also, it is well known from cyclotron literature that especially the quadrupolar coupling resonance is potentially dangerous. This resonance occurs in CYCLONE235 at 139 MeV, at an average radius of 0.88 m.

Historically, the rationale to discard the $Q_H - Q_V = 1$ coupling resonance as being harmful was based on the following motivation: in theory CYCLONE235 is a machine with a broken 4-fold azimuthal symmetry due to the extraction system (inducing an important first harmonic distortion field), but with a fully preserved mirror symmetry with respect to the median plane. Hence all the multipole components describing the magnetic field are of the normal type, and no skew components are expected. If this is true the coupling resonance would not be excited, even if the harmonic contents of the field does correspond to that of the resonance.

In reality, however, already early beam tests have shown vertical beam displacements to occur, both in the central region and in the region around $r = 0.8$ m. Although these displacements are not fully understood, they undoubtedly indicate the presence of sizeable skew field components. As a consequence, the coupling resonance becomes excited, and this is entirely confirmed by visual observation of the beam on a fluorescent screen. In fact, the excitation was strong enough to loose an important fraction of the beam at its crossing.

Inspection of the working diagram tells that the crossing of this resonance lasts for several turns. Since the crossing is unavoidable, the working line had to be changed in such a way that it crosses the resonance line perpendicularly. Therefore it was necessary to rise the vertical tune right before the crossing point, and to lower it right after the crossing, both these effects with respect to the standard machine.

It has been possible to realize this correction by adding a small (9x4 mm) iron corrector bar to 2 of the non-removable pole edges. The effect of these Q-correctors had been simulated by TOSCA calculations, and their exact positioning along the pole edge was obtained by closed orbit calculations.

The correctors turned out to be fully effective.

4 STATUS OF THE NPTC PROJECT

The installation of most of the subsystems is reaching completion. The cyclotron and the ESS were shipped to Boston at the end of March 1997, after successful completion of all cyclotron and ESS factory tests in IBA's assembly hall, including Bragg peak measurements. As far as the cyclotron is concerned, beam was accelerated up to the maximum energy, with extracted beam intensities up to 1 µA. This equipment arrived at the NPTC mid-April 1997 and is now running since months. The beam transport system was completely mounted and ready to accept beam (on site) in September 1997. Shipment of the first gantry took place at the middle of last year, after factory tests with the magnets installed. Installation of the gantry and PPS is now almost complete, and beam has been produced at the isocenter since April 98. This gantry is now rotating normally at almost full load (nozzle not yet fully installed). The first nozzle is being installed on it, after extensive tests at the IBA assembly hall. The second gantry arrived in Boston at the end of May 98, after undergoing all necessary factory tests in Belgium. Installation of the second PPS will start as soon as the second gantry is installed. Finally, work on the control system and on the safety system is reaching completion. The whole system final acceptance tests on site are expected to begin around September 1998.

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