PERFORMANCE OF A CW RFQ INJECTOR FOR THE IUCF CYCLOTRON*

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Abstract

A 750 keV RFQ proton pre-injector was installed in place of a 600 keV Cockroft-Walton high voltage terminal for the *IUCF* k220 Cyclotron [1]. The pre-injector consists of a 20 keV microwave ion source and LEBT, a unique design 750 keV CW RFQ, and a short transfer beam line to the k15 injector cyclotron center region [2]. This pre-injector system was installed and commissioned in June of 2003 and is now in routine service as the sole injection system to the cyclotrons. This contribution will discuss the performance of the CW RFQ pre-injector and the transmission properties of the beam through the cyclotrons.

INTRODUCTION

The cyclotrons of the Indiana University Cyclotron Facility (IUCF) were in operation as a nuclear physics research center from 1975 until 2000 when its beam delivery system and experimental areas were rebuilt to provide a fixed energy proton beam to the Midwest Proton Radiotherapy Institute (MPRI) for cancer treatment and other applications [3]. The cyclotrons also deliver beam to a radiation effects research program (RERP) located in two rooms outside of the cancer clinic. As part of this construction, the 600 keV high voltage terminal was replaced with a compact 750 keV proton injector that consists of a microwave ion source generating a 20 keV beam that is injected into a 750 keV radio frequency quadrupole (RFQ) manufactured by AccSys Technology, Inc. The 750 keV beam is transported to the k15 "injector cyclotron" by a short beamline with three quadrupoles and a steerer. The central region of the k15 cyclotron and diagnostic probes were upgraded to accommodate the new higher energy beam.

The RFQ injector was installed in June of 2003 and is shown in Figure 1 with the k15 cyclotron. Patient treatments began the following January. The operating schedule is and will continue to be very demanding and allows little time for repairs or maintenance. Because of this, the 750 keV injector and other cyclotron systems have been designed or are being upgraded to require low levels of maintenance effort, minimum repair times after a failure and a system wide reliability that exceeds 95% or 98% during scheduled treatments.

In a typical two week operating period, beam is delivered to MPRI for treatments 5 days a week for two 8 hour shifts per day. In addition, MPRI requires beam outside of the planned treatment schedule for QA and testing. The RERP users take beam between patient treatments and during midnight shifts and weekends. Every second weekend is scheduled for maintenance and repair, usually beginning late Friday night with turn on scheduled for Sunday morning.

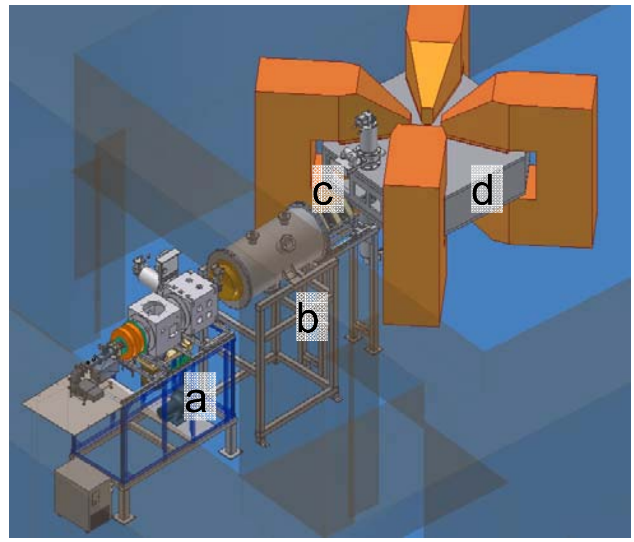

Figure 1: A 3D model of the 750 keV proton injector showing the 20 keV ion source and LEBT (a), the RFQ (b), the 750 keV beam line (c) and the k15 cyclotron (d).

* This work was supported by the State of Indiana, Indiana University, and the DOE (Grant No. DE-FG-02000ER62966). Operation of the cyclotrons is supported by the Midwest Proton Radiotherapy Institute.

750 KEV PROTON INJECTOR

Details of the 750 keV proton injector design and construction have already been reported [2] [4]. Changes have been made to the equipment or operating procedure as we have gained experience during long term beam delivery to the users.

Microwave Ion Source

The proton injector uses a 2.45 GHz microwave ion source [4] which produces several milliamperes of continuous proton current. The 20 keV proton beam is formed by a four element extraction system, then collimated and focused to match the acceptance of the RFQ by two solenoid lenses.

The proton beam intensity from the source far exceeds the maximum required for acceleration and so the collimating apertures are designed to intercept about 75% of the beam. The current draw on the 20 keV high voltage power supply is typically about 5 mA yet only 1 mA of peak proton current is required within the RF phase acceptance of the injector cyclotron.

 0-7803-8859-3/05/$20.00

A low noise Sairem microwave generator [5] with a maximum power output of 300 W replaced a 1.2 kW generator. Modulation of the beam intensity at 60 Hz and kHz switching supply frequencies was reduced from about 5% to 10% down to 1% to 2%. The plasma is very stable at 300 W and the total beam current dropped by only about 20% from 6.5 mA to 5.2 mA as measured by the extraction voltage power supply current draw. The change in proton fraction was not measured.

During normal operation, the ion source requires maintenance every 6 months to replace a Boron Nitride protective shield on the RF window. This maintenance schedule was determined over the last two years of operation. After two years of operation, the extraction system began to spark and cause unacceptable interruptions during patient treatment. To eliminate this sparking, a shield was added close to a metal-vacuum-ceramic electron emitting “triple point” [6] on the 20 kV alumina insulator. This shield covers a ceramic to grounded metal joint and stopped electrons from streaming between the joint onto parts connected to the source potential at 20 kV. Typical operating parameters are listed in Table 1.

Table 1. Typical operating parameters for the DC ion source on the IUCF 750 keV proton injector.

Ion source parameter	Value
H_2 gas flow (mbar l/s)	8.9
Microwave power, 2.45 GHz (kW)	0.30
Extraction supply current (mA)	5.2
Extraction voltage (kV)	20.0
Electron suppression voltage (V)	-160
Emission aperture diameter (mm)	3.5
Extraction gap distance (mm)	8.5
Extraction electrode diameter (mm)	5.0
Total beam current (mA)	>4.0
Duty factor (%)	100
Emittance (π mm mrad, rms normalized)	<0.10

20 keV Beam Transport

The 20 keV proton beam is transported and matched to the Linac using three magnetic solenoid lenses. In the original design [2] only two lenses were installed. A current limiting aperture and third solenoid lens were added close to the ion source in order to control where the beam is reduced in the beam line. A Tantalum water cooled aperture is installed at the entrance of each lens.

The IUCF cyclotrons operate at 35.58 MHz but the beam is chopped and accelerated only on the second harmonic at 17.79 MHz. The DC beam from the ion source is deflected by an electrostatic chopper mounted between the final two solenoids. One plate of the chopper is at several hundred volts DC and acts to deflect the beam completely out of the path of the RFQ. The second plate oscillates at 17.79 MHz with peak to peak voltages of a few volts to several hundred volts and can be easily adjusted by the operators. The electrostatic chopper modulates the beam so that it more closely matches the ± 6º RF phase acceptance of the cyclotrons.

The two upstream solenoid lenses are adjusted so that the beam entering the chopper is 2 cm in diameter, matching the hole in the aperture. The operators control the beam intensity out of the cyclotrons over a range of more than 1:200 by adjusting the RF voltage on the chopper. The chopper, along with fast switching and septum magnets in the 208 MeV trunk line, will be used at IUCF to rapidly switch the beam between end stations where users require different intensities. This electrostatic chopper replaces the ferrite pulsed solenoid lens which could only produce a dynamic range of 1:5 of the beam intensity.

CW Radio Frequency Quadrupole Linac

The AccSys Technology Inc. [7] PL-1 radio frequency quadrupole accelerates the 20 keV protons to 750 keV. It is powered with a 20 kW CW, 213.48 MHz amplifier built by Amplifier Systems Inc. [8]. The basic design of this CW RFQ is described elsewhere [1, 9].

Several upgrades were made to the amplifier and the RFQ to improve reliability and beam stability. Operating the RFQ at a fixed frequency and fixed phase with respect to the cyclotron operation has been a challenge. Small changes in relative phase are compensated electronically. Larger changes in the phase are compensated by retuning the RFQ cavity with a motorized tuning slug. Despite this control, the beam intensity would drift or change abruptly as the phase changed and tuning slug moved.

As the cavity warmed or cooled, the tuning slug would move to compensate. The temperature was controlled within a range of ±1°F but this proved too large for beam stability and caused the tuning slug to move frequently. Eventually, the tuning slug surface wore down and the sliding RF contacts failed, causing the cavity to spark and shut down.

To resolve this problem, a ±0.1°F cooling system was installed. The tuning slug material was changed from soft copper to silver plated Beryllium copper, a much harder material. This system has operated for more than 6 months without a failure and with adequate beam stability.

The 213.48 MHz amplifier was also upgraded to improve reliability. The two major improvements were replacing the anode high voltage power supply and rebuilding the final cavity. It has now worked reliably for more than 6 months.

750 keV Beam Transport and Inflection

The beam exiting the RFQ is transported and matched to the injector cyclotron through a quadrupole triplet. Horizontal and vertical steerers allow for some small adjustment of the beam position at the entrance of the first inflector in the injector cyclotron. The inflectors bend the beam into the first orbit of the injector cyclotron. It was necessary to design a new set of electrostatic inflectors that matched the higher energy of 750 keV from the RFQ compared to the old high voltage terminals which produced a beam with a nominal energy of 600 keV. The higher beam energy was chosen so that the first turn in the cyclotron would have a wide margin of clearance to the inflector assemblies. The design of the inflectors, curvature and operating voltage, was determined by modeling the electric fields including the RF voltage on the Dees and using measurements of the magnetic field to track the particle trajectories. The first inflector operates at -25 kV across a gap of 0.385" and the second inflector is set to +65 kV across a gap of 0.185". A model of the inflectors is shown in Figure 2. The grey elements in the Figure 2 inflectors are the electrodes at high voltage whereas the copper colored plates are at ground potential.

In addition to the new inflectors a phase slit was added at the radius of the 4th injector cyclotron turn. Beyond this slit all of the beam was accelerated and extracted at 15 MeV.

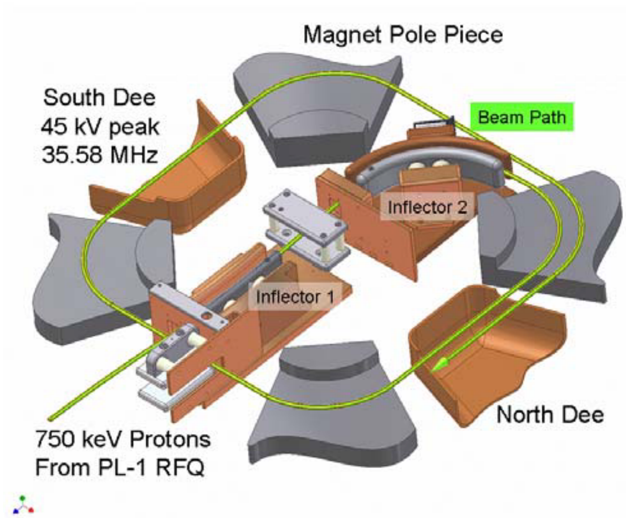

Figure 2. A 3D model of the electrostatic inflectors mounted in the center of the k15 injector cyclotron. The inflectors are very reliable and require maintenance only every 6 months or longer.

OPERATING CHARACTERISTICS

The proton injector came online on July 6th, 2003 and has since been scheduled for over 90% of all possible shifts. In 2004, the first full year of operation with the proton injector, the cyclotrons were scheduled for 7,925 hours out of a possible 8,736 hours in a year. Since 2003, the reliability of all IUCF proton delivery systems has improved from 84% to 92% in 2005 (through April 17th). Breakdowns of the RFQ and other systems in the proton injector have been a significant contributor to this statistic and improvements due to the upgrades described are certainly helping to better the performance.

The MPRI and RERP users require a wide range of beam intensities, stability and time on target. The cancer clinic requires a maximum of 30 nA or as little as 0.5 nA for any given treatment which will last between 1 and 2 minutes and with a minimum stability of ±5%. The RERP users may sometimes require very high beam intensities and would prefer up to 500 nA, perhaps for 1 hour at a time. Adjusting the electrostatic chopper in the 20 keV beamline provides a direct method of adjusting the intensity through such a large range. During one test, the operator briefly demonstrated a beam current of 750 nA at 208 MeV.

One way to measure how the RFQ injector performs relative to the old 600 keV high voltage terminal is to compare their beam transmission through the cyclotrons. On May 5th, 2005, the operators carefully tuned the cyclotrons then measured the transmission from the 20 keV beam line through to a stop on the 208 MeV trunk line. As expected, the transmission from the ion source through the RFQ was very low, due to the effect of the electrostatic chopper. Out of the total of the 750 keV beam, more than 50% was inflected into the k15 cyclotron. Slightly less than 50% of that beam, or 55 nA out of 120 nA makes it through to 208 MeV. Similar but no better transmission results were obtained after careful tuning when the high voltage terminal was providing beam.

CONCLUSIONS

The 750 keV CW proton injector for the IUCF cyclotrons has been in operation since July 6th, 2003. Some upgrades were made to the ion source, RFQ and amplifier system that should result in improved reliability. The characteristics of the proton beam from the injector suit the requirements of the cyclotrons and users. Beam transmission through the cyclotrons after inflection into the injector cyclotron, is similar to the 600 keV HV terminal. Special mention should be made of individuals that worked hard to make the operation of the injector a success; Steven L. Anderson, Mark Ball, Robert J. Brown, Ron Kupper, Mark Luxnat and Doug McCammon.

REFERENCES

[1] D.L.Friesel, et. al., App. of Acc. in Res. and Ind., eds. J.L. Duggan and I.L. Morgan, Denton, 651(2000).
[2] V.P.Derenchuk, et. al., Proc. 2003 Particle Accelerator Conf., eds., A. Jackson and E. Lee. pp. 1563-1565 Portland, OR, (2003).
[3] V. Anferov, et. al., Proc. 2003 Particle Accelerator Conf., Portland, OR, (2003), eds., A. Jackson and E. Lee. pp. 699-701.
[4] V.P.Derenchuk, Rev. Sci. Instrum. **75**, 1851 (2004).
[5] Sairem, S.A., 12 Porte du Grand Lyon, Neyron 01707 France. Model GMP-03 KED.
[6] L.D. Hansborough, et. al., Proc. 1997 Particle Accelerator Conf., **IEEE 97CH37167**, 2740(1998).
[7] AccSys Technology, Inc., 1177 Quarry Lane, Pleasanton, CA 94566-4757.
[8] Amplifier Systems, Inc., 18307 Napa St., Northridge, CA 91325.
[9] J.W. Staples, Proc. of the 1994 Linac Conference, Published by the National Laboratory for High Energy Physics, Tsukuba, Japan, 755(1994).

 0-7803-8859-3/05/$20.00 ©2005 IEEE