A CW microwave proton source and LEBT for the IUCF cyclotrons

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A high reliability and low maintenance proton injector for a 20 keV to 750 keV CW RFQ has been constructed and installed to supply beam for acceleration to 208 MeV by the Indiana University Cyclotron Facility (IUCF) cyclotrons. The injector includes a 6 mA 2.45 GHz microwave proton source, two solenoids to match the 20 keV beam to the RFQ, a third pulsed solenoid for modulating the beam intensity out of the RFQ and an electrostatic chopper that operates at 17.79 MHz to select only the beam that will match the RF phase acceptance of the 35.58 MHz cyclotrons. The injector has been nearly continuously and with no failures since June 2003.

29.25.Ni, 29.20.Hm, 29.27.Eg

Introduction

The IUCF accelerators have been upgraded and now provide fixed energy 208 MeV protons to the beam delivery system for the Midwest Proton Radiotherapy Institute (MPRI) cancer treatment clinic and to other applications[1]. A nuclear physics based research program previously used the cyclotron beam but has been replaced by MPRI. The clinic will demand beam for 8 to 10 hours a day between 0600h and 1800h. A requirement is that the beam delivery during a course of patient treatments meets or exceeds 98% reliability. To this end, a 600 kV Cockroft-Walton high-voltage terminal and polarized proton and deuteron ion source has been replaced by a much smaller and easier to maintain accelerator system that consists of a 20 keV microwave source based proton injector and an AccSys PL-1 20 keV to 750 keV CW RFQ[2].

The demands of the clinic make it difficult to perform maintenance or development work during normal working hours. Because of this, a simple and conservatively designed microwave ion source and two-solenoid beam matching section were designed and built as the 20 keV proton injector for the RFQ. In addition, an electrostatic chopper is used to select only the protons that will match the RF phase acceptance of the cyclotron. A pulsed solenoid installed between the two RFQ matching solenoids is being evaluated as a fast intensity adjustment that will be used when the 208 MeV beam is switched between treatment rooms. An additional focusing solenoid was added close to the ion source due to an unexpectedly large divergence of the beam. Injecting a background gas of N_2 reduces this divergence. Offline testing of the injector with the RFQ began in February 2003 while the high voltage terminal was still being used. Installation of the proton injector and RFQ began in April and has been used to deliver beam daily to the cyclotrons since June 2003.

Injector Design

The requirement of 98% reliability, long and short-term beam stability and infrequent access for maintenance or repairs define the criteria for choosing the type of proton source. At IUCF, the ECR ionizer from the polarized ion source in the high voltage terminal[3] was simplified and used as a proton source for several years with no breakdowns. Maintenance or repairs on this old ECR source were not required for a two-year period but it was large and didn't produce the 1 mA beam current required by the injector design. The new ion source design is based on the microwave proton source first built at Chalk River Laboratory[4] and later developed for testing high current CW accelerators at Los Alamos[5]. These designs were modified to have a 20 kV extraction system and smaller emission aperture to limit the beam current.

The microwave ion source has a 2.45 GHz magnetron that can supply 1.2 kW of RF power through a circulator to a WR284 waveguide. A directional coupler measures the forward and reflected powers and is followed by a three-stub tuner that is insulated from the source high voltage by a choke flange coupling with a 3mm thick Teflon spacer. A double-ridged tapered waveguide feeds power to the source body and improves the matching of the RF to the source plasma. An Aluminum Nitride RF window (Fig. 1), glued with Armstrong A2/E epoxy[6] to a rectangular stainless steel frame makes a vacuum seal to the source body end flange with a custom designed rectangular Helicoflex[7] metal gasket.

The source body, end flange and the emission aperture are made from OFC copper and is water cooled only on the end flange and emission aperture assembly. The end flanges are bolted to the source body and sealed by circular Helicoflex Del-Seals[6]. In the interior of the source body, the Aluminum Nitride rf window end flange and emission aperture are lined by 10 mm thick AX05 Boron Nitride (BN)[8]. The emission aperture assembly is vacuum brazed to a low carbon steel plate that limits the magnetic field in the extraction region. An Alumina cylinder epoxied to the steel plate and aluminum vacuum chamber flange isolates the source high voltage from ground potential. Two solenoids, each made from five 30-turn 2-layer pancakes of hollow conductor are insulated from the 20 kV of the source body by a nylon bobbin. During normal operation the coils operate at about 90 A and produce a peak magnetic field of 90 mT close to the center of the source body. The hydrogen gas supply is adjusted by a needle valve attached to the source body end flange. The pressure in the insulated gas line to the needle valve is kept just slightly above atmospheric pressure. There are no power supplies or controls required at the ion source potential. Details of the source assembly are shown in Fig. 1 and ion source parameters are tabulated in Table I.

The beam forming system consists of an emission aperture, a grounded extractor, an electron stopper and a final ground electrode. All electrodes are machined with an 80 degree angle with respect to the beam axis. The diameter of the apertures are 3.5 mm in the copper emission electrode followed by the 5 mm and 6 mm diameter apertures of the stainless steel extraction and electron stopper electrodes. The 9 mm diameter final ground electrode is made from Molybdenum. This beam electrode system has now been replaced by a new design that has an angle of 54 degrees on all electrodes. The new angle was chosen after a wide range of extraction geometries were calculated using the PBGUNS[9] code. There is a calculated improvement of a factor of 2 in the beam size at the exit of the 54 degree extraction system.

The 1.9 m low energy beam transport line (LEBT) in Fig. 2 has two 38 kAt solenoid lenses, LENS_01 and LENS_02, with a maximum strength of 0.02 Tm to match the beam into the RFQ acceptance[2]. Tantalum apertures collimate the beam close to the entrance of each of the primary solenoids. The parallel plate chopper is mounted between the two solenoids in front of the downstream aperture. Beam current is stopped and measured on a movable Faraday cup. One electrode of the parallel plate chopper is biased at -150 V and serves the purpose of fully deflecting the beam out of the path of the RFQ. A 17.79 MHz RF voltage applied to the opposite electrode chops any of the protons off a Ta aperture into the RFQ acceptance. The beam is chopped into pulses less than 10 ns wide at one half of the cyclotron frequency. This pulse structure is sufficient to ensure a good match of the protons into the RF acceptance of the cyclotron. The beam intensity out of the RFQ can be varied smoothly over a wide range by adjusting the RF voltage on the chopper. Two additional solenoids are mounted in the LEBT. The first solenoid, LENS_00 is mounted inside the vacuum system and has a current limit of 15 kAt and 0.01 Tm generated in a gap 2.0 cm long and 3.0 cm in diameter. It is used to test additional focusing close to the source that would compensate for the unexpected large divergence of the beam. The second solenoid, the beam intensity modulating system (BIMS) lens has a 24 turn coil and a ferrite return path to allow rapid pulsing of the magnet. It has an inner diameter of 4.8 cm and length of 7.6 cm with a 1.8 cm long focusing gap. It is being evaluated as a method to modulate the beam intensity.

The ion source is attached to the first chamber of the LEBT and is pumped by a 1500 l/s turbopump backed by an oil free scroll pump. The second chamber has a 1500 l/s cryopump with activated charcoal to improve the hydrogen capacity of the cryopanels. Precaution is taken during operation to keep the source and RFQ oil and grease free. A 40 mm diameter 35 cm long tube that acts as a differential pumping aperture connects the chambers. The second chamber typically operates at 3 x 10^{-7} Torr, at ten times lower pressure than the ion source chamber. A needle valve feeds gas into the ion source chamber for beam space charge neutralization studies. The controls consist of VISTA software GUI running on LINUX workstations with VME based hardware and a PLC.

Operation and Reliability

The beam emittance was measured between LENS_01 and LENS_02, 70 cm downstream of a 1.9 cm aperture. A slit with a gap of 0.25 mm was scanned across the beam in steps of 0.25 mm. A wire scanner measured the beam profile 28 cm downstream of the slit. At the slit location, the rms emittance was measured to be less than 0.10 π mm mrad normalized. Heavier ions were clearly separated in phase space and comprised less than 15% of the total beam. However, during this measurement the current measured on the aperture was four to five times the beam current transmitted to the emittance device and indicating that the beam from the source had a large divergence upstream of the collimator. To compensate for this divergence, LENS_00 was installed at the exit of the extraction system. In addition, exposed electrodes that could have acted as an electron drain were shielded from the beam. Finally, the extraction system was inspected and the extraction electrode gap was found to be 35% smaller than the design value and restored to its design value. The PBGUNS code was used to model this extraction system and showed that the smaller gap results in an overfocused beam. These efforts gave some improvements but calculations show that LENS_00 must be stronger to focus the beam through the aperture. The biggest improvement was discovered when the transmission through the aperture increased with a pressure increase in the ion source chamber. Measurements of the current on the Faraday cup beam stop as a function of pressure is plotted in Fig. 3 for two different values of the electron stopper electrode. For these measurements the extraction current was 5.5 mA and the current on the aperture was 1.0 mA when the stop current was 4.0 mA. There is a qualitative improvement with the 54 degree extraction system but no measurements have been made.

The injector has operated 11.5 weeks continuously, except for three short breaks due to holidays or maintenance periods. The source parameters were not adjusted during this period and were always recovered to their original values even after venting to air. From the start of a pumpdown, beam is recovered in less than one hour, longer with new BN parts. The extraction current dropped gradually and reached 5.2 mA compared with 6.2 mA at the beginning of the schedule. At the end of the running period the source was disassembled, internal components inspected and the 54 degree extraction system installed. Portions of the BN protecting the RF window were corroded to a depth of 8.5 mm, the BN parts were replaced. There was a hard glassy black deposit on all of the cold surfaces. The final goal is to achieve one year of continuous operation with no maintenance or breakdowns due to the source.

Future Development

The effort to reach one year of continuous operation with no maintenance or breakdowns will continue. In addition, IUCF has received a grant from the National Science Foundation to build a low energy neutron source (LENS). LENS will use a 50 mA peak current beam of 15 MeV protons incident on a Be target and moderator to produce neutrons with energies of a few meV. The accelerator must operate at 5% duty factor with pulses ranging from 3 μs to 1 ms width. A new 25 keV injector will be designed and built to meet the first phase of this project that requires only 20 mA of peak current. The ultimate requirements will be met with a 60 keV, 75 mA proton injector. The design of both of these injectors is underway.

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TABLE 1. Summary of the microwave ion source properties.

Ion source parameter	Value
H_2 gas flow (sccm)	0.15
Microwave power, 2.45 GHz (kW)	0.75
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
Extraction supply current (mA)	6.2
Total beam current (mA)	5.5
Duty factor (%)	100
Chopper frequency = ½ $F_{cyclotron}$ (MHz)	17.79
Dynamic range of intensity modulation by chopper	>100
Measured beam emittance for 1 mA (π mm mrad, rms normalized)	<0.10
RFQ acceptance, 95% norm (π mm mrad)	0.5

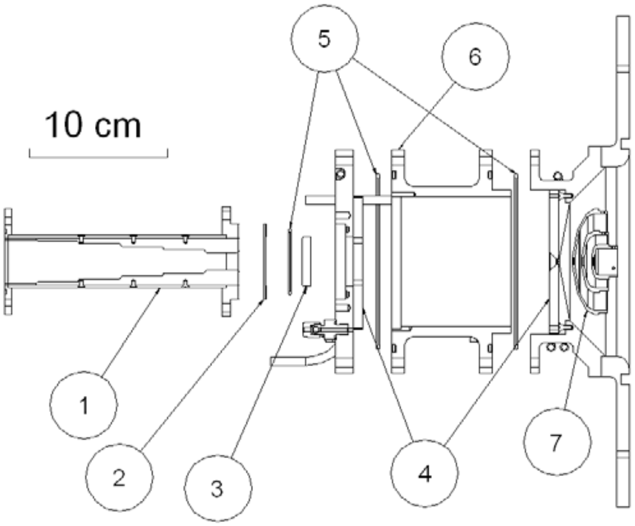

FIG. 1. An exploded view of the source body; 1) tapered ridge waveguide, 2) AlN window with 304 SS frame, 3,4) BN shields, 5) Helicoflex seals, 6) source body, 7) extraction system.

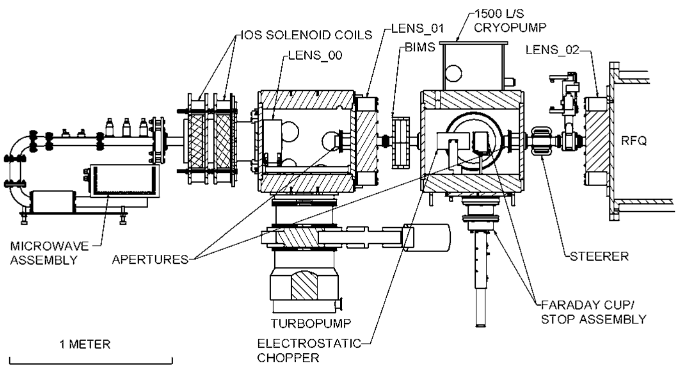

FIG. 2. A line drawing of the 20 keV proton injector.

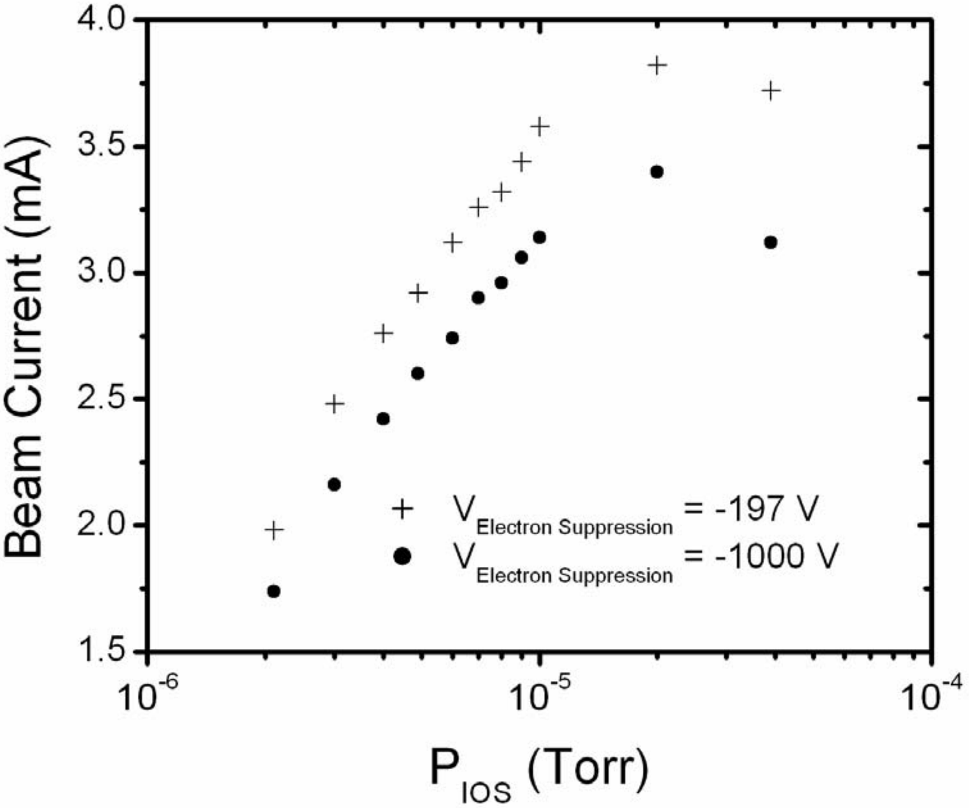

FIG. 3. Beam current on Faraday cup versus gas pressure.

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