

# FIRST TESTS OF A CW RFQ INJECTOR FOR THE IUCF CYCLOTRONS

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## Abstract

A 750 keV proton injector is being installed in place of a 600 kV Cockroft-Walton high voltage terminal at the Indiana University Cyclotron Facility [1]. The injector features a microwave ion source, a 20 keV to 750 keV CW RFQ and a quadrupole triplet to focus the beam into the 15 MeV injector cyclotron. Two solenoids and one pulsed lens are used to match the 20 keV proton beam to the RFQ and to rapidly change the beam intensity. The injector has been tested offline; the results will be described in this paper.

## INTRODUCTION

The Indiana University Cyclotron Facility (IUCF) is in the final phase of an upgrade program of the 210 MeV proton cyclotrons. These accelerators will be used to provide a fixed energy proton beam to the Midwest Proton Radiotherapy Institute (MPRI) for cancer treatment and other applications [2]. Part of this upgrade is to replace the 600 kV Cockroft-Walton high voltage terminal with an AccSys PL-1 20 keV to 750 keV CW radio frequency quadrupole (RFQ) accelerator [3]. This system is expected to operate with at least 95% reliability, should be easy and quick to repair and should have infrequent maintenance requirements.

The cancer clinic requires between 2 nA and 125 nA of 206.5 MeV beam delivered to the entrance one of three treatment rooms. The intensity should be stable to 5% and have ripple less than 5% for the two minute duration of each treatment plus a several minute setup time. Each treatment will require a unique beam intensity and will typically be different than the intensity the cyclotron operators will use to monitor the beam at a remote beam dump. A pulsed lens is used as a beam intensity modulation system (BIMS) to adjust the level of the beam intensity within 2 ms to 3 ms after a change is requested.

The proton injector, shown in Figure 1, consists of a 2.45 GHz microwave proton source [4] which is a modified version of the LEDA 100 mA CW source [5]. A 20 kV, four-electrode extraction system forms a beam that is then transported by two electromagnetic solenoids which match the beam to the RFQ acceptance parameters. An electrostatic chopper phase locked to one-half of the cyclotron frequency operates at 17.79 MHz to form beam pulses that match the  $\pm 6^\circ$  RF phase acceptance of the cyclotrons. The BIMS solenoid which adjusts the beam focusing at the entrance of the RFQ has a ferrite gap with return yoke and within 3 ms is changed to any requested current between 0 A and 400 A. The 750 keV beam from the RFQ is focused into the first electrostatic bend of the cyclotron by an NEC built quadrupole triplet [6].

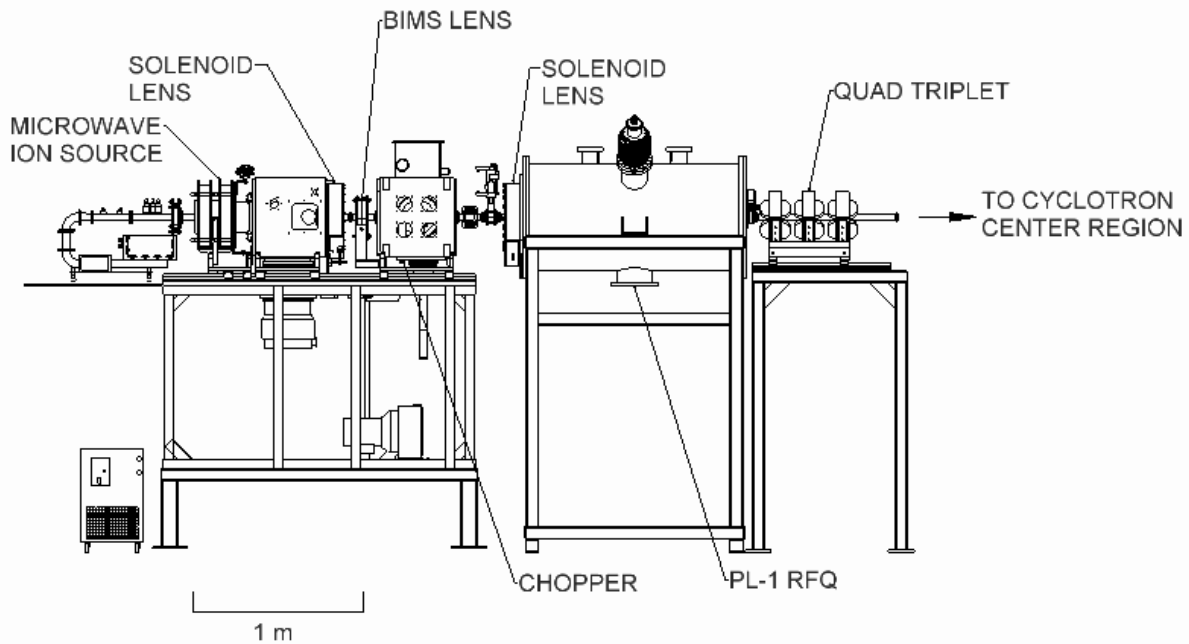


Figure 1: Schematic of the 750 keV proton injector. The beam height and centerline of the injector is 77.312 inches above the floor as shown by the dimension at the right side of the drawing.

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## ION SOURCE

The 2.45 GHz microwave ion source has many similarities to the LEDA source [5] but with much lower intensity and beam energy requirements. A 3D cutaway view in Figure 2 illustrates the primary components of the source. A four electrode 20 kV extraction system forms a beam more than 5 mA of protons. A 2.45 GHz magnetron supplies 1.2 kW of RF power through a circulator to a WR284 waveguide. A directional coupler connected to a three-stub tuner measures the forward and reflected powers. A choke flange coupling with a 3mm thick TFL spacer insulates the three-stub tuner from the source components that are elevated to the 20 kV extraction potential. A double-ridged tapered waveguide between the choke flange and the source body improves the matching of the RF to the source plasma. The microwaves are launched into the source volume through an Aluminum Nitride and Boron Nitride layered vacuum window [5]. A vacuum seal is made with a rectangular shaped metal gasket [7] that requires 5.6 N·m of Torque on the fasteners of a modified WR284 rectangular flange.

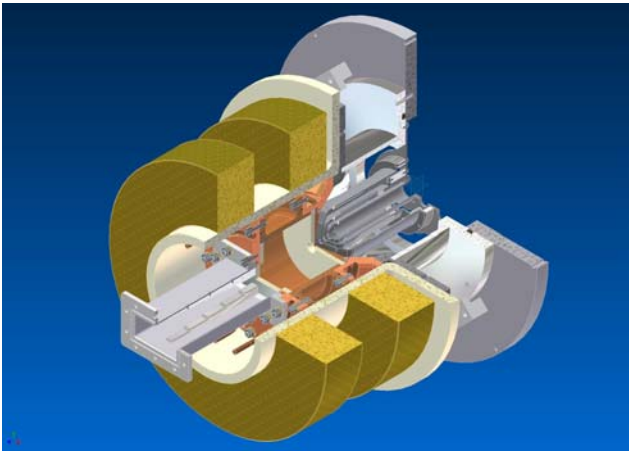


Figure 2: A 3D model of the ion source with a cutaway to show the internal components. The tapered ridged waveguide and source body are insulated from the two solenoid coils by a large nylon insulator and from the vacuum chamber by a ceramic cylinder.

The OFHC copper source body and end flanges are assembled with metal vacuum seals. A pure Boron Nitride (BN) liner covers the two inside ends of the source but the inner diameter of the chamber remains copper. The plasma is extracted via a hole in the BN through a 3.5 mm diameter emission aperture in the plasma electrode. Positive ions are accelerated to a grounded electrode with a 5 mm aperture then pass through a negatively biased electron stopper electrode. A final grounded electrode signals the entrance to the low energy beam transport line (LEBT).

The source has operated for a total of about 26 days including one 14 day period during which the source was vented to add a diagnostic, pumped down and operation recovered in less than 2 hours.

With the H<sub>2</sub> gas flow at 0.15 sccm and the ion source coils set to produce a nominal 900 Gauss field, the plasma self starts at about 300 W of RF power. Nominal operation is with 750 W of RF power with only 10 W to 15 W reflected. Typically, the extraction current is 6 mA and more than 5 mA of beam current is observed 50 cm downstream. The electron topping electrode operates at negative 150 V.

## 20 KEV BEAM TRANSPORT

The beam transport and matching section to the RFQ serves three purposes. Two solenoid lenses and Tantalum apertures collimate and focus the beam into the RFQ acceptance. The BIMS solenoid placed between the two matching solenoids is used to modulate the beam intensity according to the needs of the users. A pair of electrostatic plates chops the beam at 17.79 MHz to limit the beam injected outside of the phase acceptance of the cyclotrons.

The RFQ acceptance dictates that at the matching point, the beam must have a spot size of 3.2 mm and a 160 mrad angle of convergence. The symmetrical spot has Twiss parameters of  $\alpha = 1.69$  and  $\beta = 0.043$  mm/mrad and an emittance of  $0.5 \pi$ -mm-mrad normalized to  $\beta\gamma$  for 90% of the beam. The 20 keV beam emittance was measured upstream of the final solenoid lens and after a 1 cm collimator. At this location the emittance is  $0.25 \pi$ -mm-mrad normalized to  $\beta\gamma$  for 90% of the 1 mA beam. Heavier ions were clearly separated in phase space and comprised less than 15% of the total beam.

The BIMS solenoid is a 24 turn coil with a ferrite return path. It has an inner diameter of 4.8 cm and length of 7.6 cm with a future plan to install a 1.8 cm long focusing gap. During operation, the strength of the first lens will be lowered to decrease the transmission through the RFQ to the lowest requested level. The BIMS lens will be switched on with a 3 ms rise time at a strength that will give the required beam current out of the RFQ. The beam intensity is adjusted to a ratio of at least 30:1 at the exit of the cyclotrons. Should the lens fail to pulse on or fail off during a patient treatment, it will fail in a low current safe mode. The lens has been tested with 20 keV beam into a stop with a 1 cm aperture 25 cm downstream. As expected, the intensity was modulated by a modest 2:1 at that measurement location.

## RADIO FREQUENCY QUADRUPOLE

The 20 keV to 750 keV accelerator is a radio frequency quadrupole (RFQ) built by AccSys Technology Inc. [3] and excited by 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].

Beam was accelerated through the RFQ in DC mode and chopped mode. As much as 0.6 mAdc of protons was measured after acceleration. The total beam transmission from a stop 30 cm upstream of the RFQ matching point was 70% and the proton transmission calculated to be about 90% after taking into account the 15% heavy ion fraction at the stop. The optimal transmission through the

RFQ occurred with an output power of about 12.5 kW from the amplifier. Figure 3 shows a plot of the output power and relative vane voltage vs. the beam transmission through the RFQ.

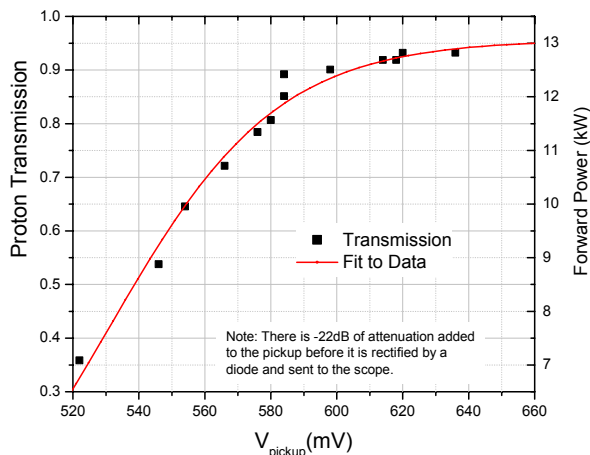


Figure 3: The proton transmission is plotted against a voltage derived from an RF pickup close to a vane. The forward power is plotted on the right-hand side.

The beam chopper was turned on and by adjusting a steerer upstream of the chopper, pulse selection of nearly 1:12 of the RF time structure was obtained. Figure 4 shows the signal of the chopped beam as measured by a gridded pick-up downstream of the quadrupoles and displayed on a 1 GHz bandwidth oscilloscope. The pick-up amplifier is AC coupled so each beam pulse has some undershoot. A 2<sup>nd</sup> harmonic RFQ RF signal is also observed as background noise.

Development of the RFQ operation will continue after



Figure 4: 750 keV chopped beam signal from a gridded pick-up observed on a 1 GHz bandwidth oscilloscope. The central peak of each bunch falls within the RF phase acceptance of the cyclotrons.

its installation. A water cooled coupling loop will replace an air cooled version in order to improve the reliability of the vacuum window. A circulator is being added to the 50 ohm line between the amplifier and RFQ. Finally, a  $\pm 0.1^\circ\text{C}$  regulated chiller will be used to better regulate the vane temperature and hence the matching to the amplifier.

## 750 KEV BEAMLINE

The beam exiting the RFQ is strongly divergent vertically and convergent horizontally. A quadrupole triplet refocuses the beam so that it matches the acceptance of the cyclotron. The three quadrupoles are NEC [6] model MQS17L. The pole tips have a diameter of 4.47 cm, a physical length of 7.62 cm and are designed to operate with a pole tip strength of 0.27 T with an excitation of 30 A. The quadrupoles matched these specifications but water cooling had to be added to the coils for long term operation at 30 A.

The quadrupoles operate at their predicted values to bring the beam to a symmetric focus 40 cm downstream of the triplet. A wire scanner at this location is used to measure the beam width while the strength of the third quadrupole is adjusted. The results are used to calculate the area and orientation of the phase space ellipse of the beam at the entrance of the quadrupole. The vertical emittance was measured to have an rms emittance of  $\epsilon_y = 0.14 \pi \cdot \text{mm} \cdot \text{mrad}$  normalized to  $\beta\gamma$  and a horizontal emittance of  $\epsilon_x = 0.12 \pi \cdot \text{mm} \cdot \text{mrad}$ . This agrees well with the predicted [1] emittances of  $0.5 \pi \cdot \text{mm} \cdot \text{mrad}$  normalized for 95% of the beam.

## CONCLUSIONS

The 750 keV CW proton injector for the IUCF cyclotrons was tested offline and produces and accelerates the beam as predicted. The injector is being installed at the time of this conference. Development and commissioning will continue after the installation is complete. This work was supported by the State of Indiana, Indiana University, and the DOE (Grant No. DE-FG-02000ER62966).

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