THE IONETIX ION-12SC COMPACT SUPERCONDUCTING CYCLOTRON FOR PRODUCTION OF MEDICAL ISOTOPES

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Abstract

A 12.5 MeV, 25 μA, proton compact superconducting cyclotron for medical isotope production has been produced. The machine is initially aimed at producing 13N ammonia for Positron Emission Tomography (PET) cardiology applications. With an ultra-compact size and cost-effective price point, this system offers clinicians unprecedented access to the preferred radiopharmaceutical isotope for cardiac PET imaging. A systems approach that carefully balanced the subsystem requirements coupled to precise beam dynamics calculations was followed. The system is designed to irradiate a liquid target internal to the cyclotron and to minimize the unnecessary radiation. The scientific design of the machine has been described elsewhere.[1] The overall engineering, construction, commissioning, and experience at the first customer site will be described here.

INTRODUCTION

An ultra-compact, 12.5 MeV, proton, isochronous, sector focused, superconducting cyclotron for medical isotope production has been produced and large scale manufacturing is being ramped up. The cyclotron is designed to be auto-tuned and does not require a skilled dedicated operating or maintenance staff. As shown in Figure 1, the first installation on the customer site occurred on January 30, 2016 at the University of Michigan followed by the first production of N13 on February 28, 2016. The machine features a patented cold steel yoke and pole design [2] in conjunction with warm iron logarithmically spiralled focusing sectors. Initially a batch of three machines have been manufactured and tested, and three additional machines are under construction in a production facility currently capable of producing up to 32 machines per year.

Table 1: Cyclotron Parameters

Parameter	Value
ION Source	PIG, Cold Cathode
Central Magnetic Field	4.5 T
Number of Sectors	3
RF Frequency	68 MHz
Peak Dee Voltage	≤ 20 KV
Final Energy	12.5 MeV
Maximum Beam Intensity	25 μA
Installed Weight	~ 2.3 tons

The cyclotron will be discussed in terms of five systems consisting of 1) Magnet, 2) RF, 3) Ion Source, 4) Target, and 5) Controls & Instrumentation. Since this is a commercial project, details of the engineering will be described at a conceptual level.

Figure 1: Beta Installation at the University of Michigan.

SUPERCONDUCTING MAGNET

Figure 2 shows the structure of the superconducting magnet. It is a conduction cooled, cryogen free design cooled by a single PT-415 pulse tube cryo-cooler. It requires approximately two days to evacuate the cryo-vessel to below 10 mTorr followed by approximately ten days to fully cool it to operating values. The magnet is normally left continuously charged in persistence mode and requires approximately five hours to charge or discharge. The cold steel design simplifies the magnet design while also eliminating tune drift due to steel temperature fluctuations.[2] Although the conduction cooled cold steel magnet simplifies the design and improves stability, this comes at a cost of significantly increasing design complexity and tolerances while also decreasing the available space for other systems. This design requires a systems approach to ensure that one system component (e. g. beam dynamics, median plane spacing, etc.) is not overly optimised with the unintended detriment to another (e.g. RF, target, etc.).

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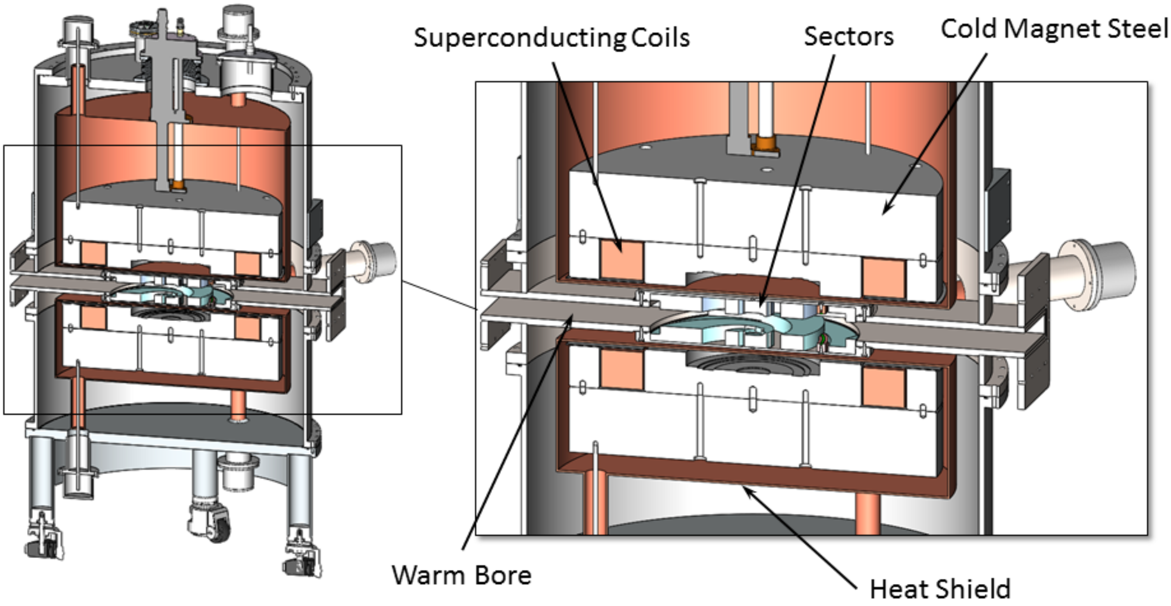

Figure 2: ION-12SC superconducting magnet structure.

RF SYSTEM

The RF system consists of 1) a resonator, 2) a solid-state amplifier, and 3) a digital RF controller.

RF Resonator

The resonator shown in Figure 3 is a vacuum insulated stripline structure using a finger contact based sliding tuner, an adjustable loop coupler, and a classic ~175 degree dee. The support structure is normally connected to the cyclotron such that the resonator may be inserted or retracted smoothly and rotated for service without discharging the magnet. The so-called dummy dee is simply a slotted bar connected to the resonator that both provides the precision accelerating gap and a mount for the ION source. Spring loaded pins couple the dummy dee bar to internal constructs in the cyclotron to ensure the ion source gap and ion source are precisely aligned with the cyclotron. The ion source gap may be precisely adjusted external to the cyclotron with the resonator fully installed and under vacuum.

Table 2: RF Parameters

Parameter	Value
Drive Power	< 6 KW
Nominal Input Impedance	50 Ohms
VSWR	< 1.5
Tuning Range	66 – 69 MHz
Water Cooling	4 GPM
Dee Angle	~175 degrees

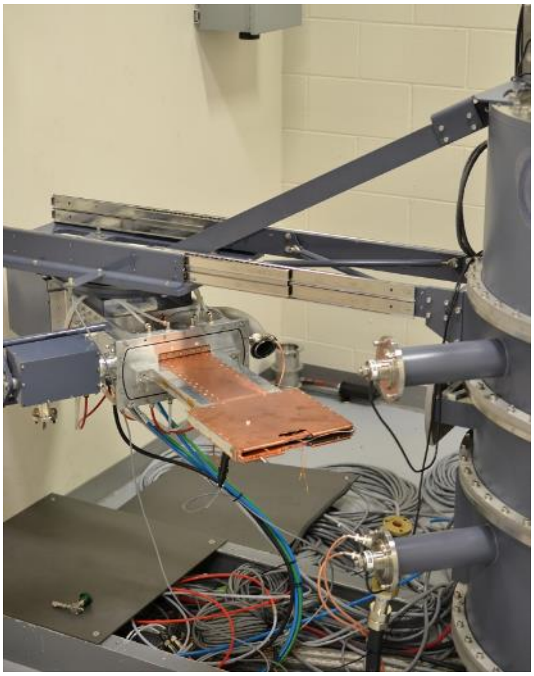

Figure 3: RF cavity shown on support structure.

RF Solid State Amplifier

The solid state amplifier is a 6 KW commercial unit built to Ionetix specifications. It consists of two rack mounted 5U water cooled 3KW amplifiers as shown in Figure 4 combined through an air cooled 4U rack mounted unit. The amplifier features a 62 dB of gain, a full power operating efficiency of 72 %, a 66.5 – 70.5 MHz bandwidth, and may be into a VSWR of up to 1.5. The amplifier is housed in the control rack.

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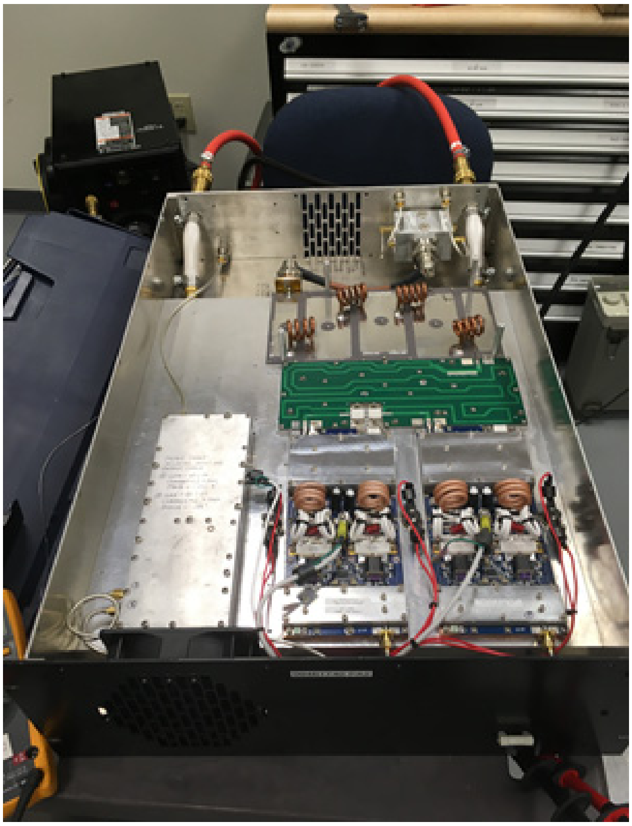

Figure 4: 3KW amplifier unit being tested.

RF Instrumentation and Control

The RF control unit is an Ionetix custom designed unit. The controller automatically tunes, regulates, and protects the resonator and amplifier. It applies direct digital sampling to read the cavity voltage from a pickup loop, and the forward and reflected power from an inline directional coupler at the cavity input port. The controller provides an output to drive the amplifier with up to 13 dBm of signal. The ADRC control algorithm [3] is applied to ramp and maintain the cavity amplitude. Additionally, the cavity tune is found and maintained by applying a PID algorithm to monitor and maintain the forward power to cavity phase to a pre-set value by actuating the stepper motor based cavity tuner.

ION SOURCE

The ion source is a cold cathode design using Tantalum cathodes and Boron nitride insulators. It has a single piece body and chimney manufactured from Beryllium Copper that measures 40mm wide by 25 mm tall as shown in Figure 5. The source opening is a 1.65 x 0.5 mm slit with a 30-degree bevel through a 0.2mm wall. It is a current controlled device that may be adjusted to operate from 0.1 to 15 mA at voltages that follow varying from 600 to 1.6 KV with gas flows from 0.3 to 0.9 sccm respectively. With the current cyclotron tune, the nominal operating point is ~5mA arc at <1KV necessary to produce ~10 uA of beam on target as shown in figure 10. The source has been tested in a test stand for up to 400 hours of continuous operation without failure and over 1100 cycles of 20 minute on and 20 minute off operation. The testing exceeds the operation expected between the nominal 3-month maintenance cycles. In operation, the ion source is fastened to the indirectly cooled so-called dummy dee that is a component of the overall rf assembly.

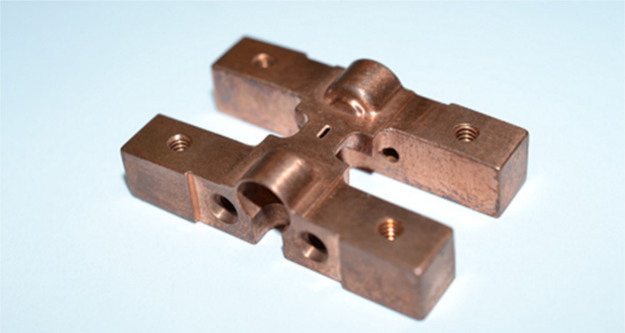

Figure 5: The Ion Source Body.

TARGET & BEAM PROBE

The port on the opposite side of the RF system is used for both the beam probe and the internal liquid target, shown in Figures 6 and 7. The beam probe covers the radial path from 4.6 cm to 15.1 cm, and can be fitted with a carbon block or stack of thin borosilicate glasses for beam current and energy measurement during the commissioning. The internal liquid target is designed to maximise transmission into the water while reducing neutron radiation. The target uses a thin graphene window and has a volume of ~3.0 ml of O^{16} water for N^{13} or O^{18} water for F^{18} isotope production. Both the beam probe and the target have a graphite shield to prevent the aluminium frame from being exposed to the beam.

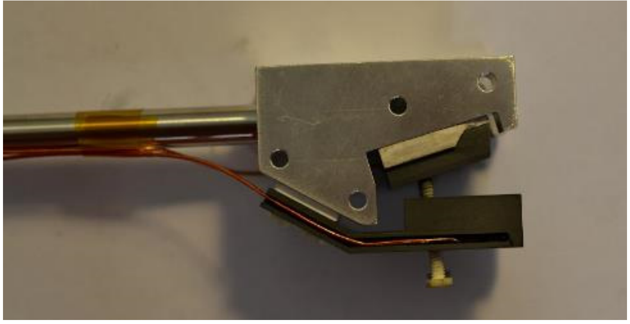

Figure 6: Beam probe.

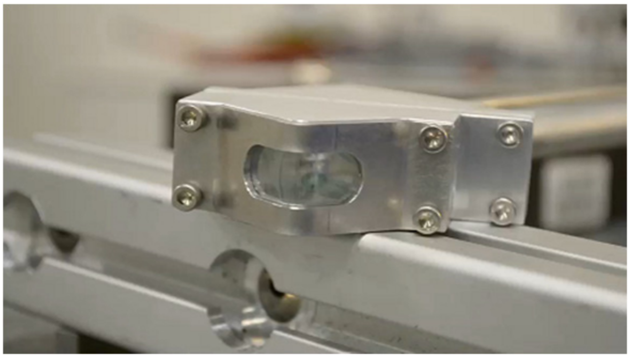

Figure 7: Internal liquid target.

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CONTROLS & INSTRUMENTATION

All of the system electronics, not specifically built into a remote component, are contained in a standard 19” electronics rack as shown in Figure 8. This includes the rf amplifier and controller as shown in figure 8. The controls are based on a standard industrial Programmable Logic Controller (PLC) coupled through a custom interconnecting Printed Circuit Board (PCB). The PCB contains intervening signal conditioners as required. In this manner, point-to-point wiring is replaced by quality controlled manufactured cables thus reducing wiring errors and manufacturing time to a minimum.

Figure 8: Electronics rack installed at the University of Michigan Medical School.

OPERATION EXPERIENCE

In addition to the beta unit installed at the University of Michigan, the 2nd manufactured unit was installed at the Ionetix facility in Lansing, Michigan in June, 2016. Extensive beam commissioning was performed that included adjustments made to magnet position, RF gap and ion source position to optimize the cyclotron performance.

Figure 9 shows the Ion-12SCcyclotron beam intensity vs. radius measured with the beam probe at a RF frequency of 67.123 MHz and voltage of 17 kV. The beam intensity drops between ~80 mm to 110 mm is correlated nicely with the neutron radiation observed. This is caused by reduction in beam turn separation during beam acceleration, causing a portion of the proton beam to pass through the edge of the carbon block and hit the metal parts nearby. Adjusting the edge angle of the carbon block leads to smaller measured intensity drops and therefore less neutron radiation observed.

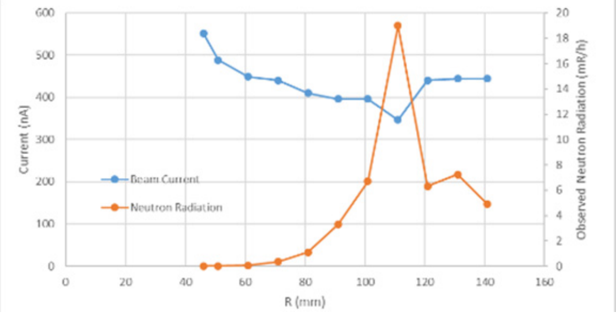

Figure 9: Measured beam current and neutron radiation vs. radius.

As one can see from Figure 9, the beam transmission from radius of 60 mm to the target position of 141 mm is about ~95%. The estimated maximum beam energy based the range of beam penetration through the borosilicate glasses is about ~12.1 MeV. Based on our beam commissioning experience both at UM site and Ionetix facility, the projected beam intensity on the target is well within reach of the design goal of 25 uA, as shown in Figure 10.

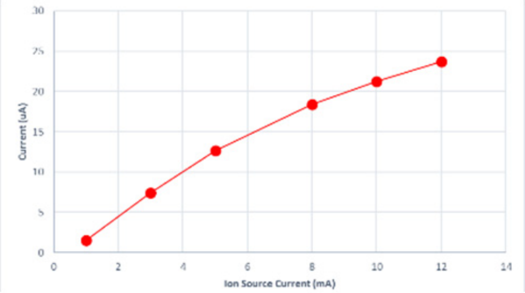

Figure 10: Projected beam intensity on target vs. ion source current.

CONCLUSION

The R&D and commissioning for the ION-12SC ultra-compact superconducting cyclotron for medical isotope production has been successfully completed at Ionetix, and large scale manufacturing is being ramped up to satisfy the expected market demand.

ACKNOWLEDGMENT

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