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# RECENT PROGRESS IN R&D FOR IONETIX ION-12SC SUPERCONDUCTING CYCLOTRON FOR PRODUCTION OF MEDICAL ISOTOPES

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*Abstract*

The Ion-12SC is a sub-compact, 12.5 MeV proton superconducting isochronous cyclotron for commercial medical isotope production recently developed at Ionetix Corporation [1]. The machine features a patented cold steel and cryogen-free conduction cooling magnet, a low power internal cold-cathode PIG ion source, and an internal liquid target [2]. It was initially designed to produce N-13 ammonia for dose on-demand cardiology applications but can also be used to produce F-18, Ga-68 and other medical isotopes widely used in Positron Emission Tomography (PET). The 1st engineering prototype was completed and commissioned in September 2015, and four additional units have been completed since [3]. The first two units have been installed and operated at the University of Michigan and MIT. R&D efforts in physics and engineering have continued to improve machine performance, stability and reliability. These improvements include: 1) Water cooling added to the dummy dee to limit the operating temperature of the ion source to improve lifetime and performance, 2) Magnetic field maps, obtained with a Hall probe based mapper, were used to accurately measure the isochronism and provide information needed to compensate for any unwanted 1st harmonics and 3) Feedback based control methods applied to regulate the beam intensity on target by adjusting the ion source cathode current. The C1 unit installed at the University of Michigan Medical School early this year treated ~100 patients/month with N-13 ammonia. The machines are now capable of routinely producing > 21 doses/day with > 99% availability. The Ionetix manufacturing facility is capable of producing up to 30 machines per year.

## INTRODUCTION

R&D for the Ion-12SC superconducting cyclotron started in 2013 with the design goal to produce N-13 ammonia dose on-demand for cardiology applications. The beta engineering unit (T1) was installed at the University of Michigan Medical School in January 2016 to produce N-13 ammonia doses for patients. The beta unit was then replaced with the newest production unit (C1) for routine reliable production. C1, as shown in Figure 1, has now been moved to an Ionetix Isotope production facility in Sarasota, Fl.

Table 1 shows the main parameters of the Ion-12SC superconducting cyclotron. The superconducting magnet features a conduction-cooled, cryogen-free design cooled by a single PT-415 pulse tube cryo-cooler. It requires approximately two hours 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 and 3 hours to discharge. The cold steel design simplifies the magnet design while also eliminating tune drift due to yoke and pole steel temperature variation.

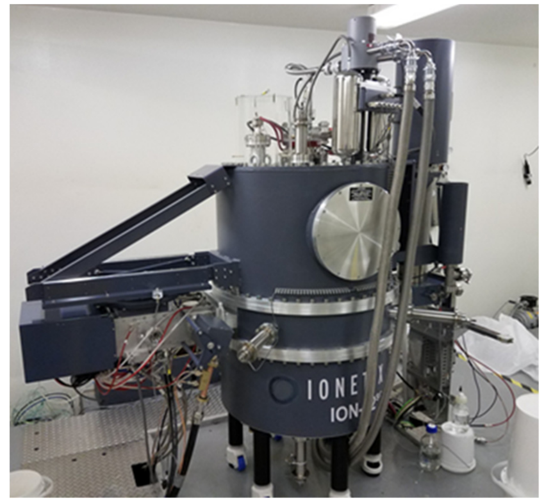


Figure 1: Ion-12SC unit C1 at the University of Michigan Medical School.

The experience obtained from operating multiple Ion-12SC units since 2016 has led to recent R&D efforts at Ionetix to improve the machine performance, stability and reliability, which will be discussed in the following sections of this paper.

Table 1: Ion-12SC Main Parameters

| Parameter | Value |
|---|---|
| Accelerated Ion | Proton |
| Final Energy | 12.5 MeV |
| Nominal Beam Intensity | 10 μA |
| Magnet Type | Superconducting, Cold-Steel |
| Injection Type | Internal, PIG |
| Target Type | Internal, Liquid |
| Central Magnetic Field | 4.5 Tesla |
| Installed Cyclotron Weight | ~ 2.3 tons |
| Cyclotron Diameter | 884 mm |
| Cyclotron Height | 1955 mm |

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## MAGNETIC FIELD MAPPING & CORRECTIONS

To accurately measure the magnetic field of each magnet upon receipt from the manufacturer, Ionetix designed and built a mapper using a Lakeshore 455 DSP Gaussmeter coupled to a transverse Hall probe driven by Zaber linear stage step motors on a square grid. The position accuracy is about 0.1 mm. The Hall probe has been recalibrated from the default maximum field of 3.5 T up to 4.5 T, with a field measurement accuracy of +/- 0.15 %. The mapper can be installed on either the RF or the target port of Ion-12SC cyclotron.

A number of possible effects on mapper accuracy and repeatability were explored, including grid size, grid centering, rest time between steps, and mapping path. The most significant effects came from ensuring the sample grid was accurately centred on the field, and from choosing a mapping path where the motors were always traveling in the same direction to reduce backlash effects.

Figure 2 shows a magnetic field map of an Ion-12SC magnet measured with the mapper along with the design field and an isochronous field for reference. The field is designed to match the isochronous field while providing some weak focusing in the central region before AG focusing is established. The significant force applied on both Ion-12SC superconducting coils could create larger gaps than the design tolerance of 0.2 mm. These would appear in the field map as deviations from isochronism, particularly at larger radii.

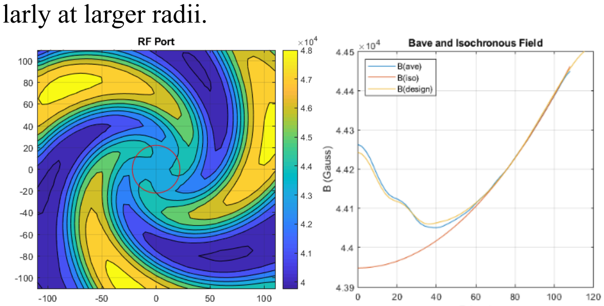


Figure 2: Measured magnetic field map (left), and resultant average field vs. the isochronous field (right).

The 1st harmonics of the magnetic field that result from manufacturing errors of the coils and sectors will lead to the orbit moving off center. If significant enough, compensation is required to allow acceleration to full energy and intensity. For one of the Ion-12SC magnets, the solution was to install a pair of 0.5 mm thickness steel strips on the RF covers of as shown in Figure 3.

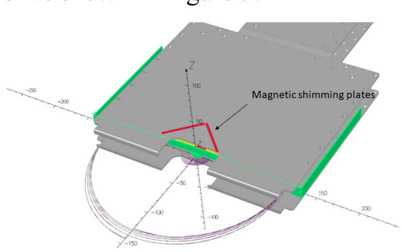


Figure 3: Example of magnetic shims for 1st harmonic magnetic field compensation.

Figure 4 shows the amplitude of the magnetic field 1st harmonic, measured before and after the shimming. The ~20 Gauss 1st harmonic bump at ~ 30 mm was reduced to ~ 5 Gauss after the shimming. As a result, ~ 100% beam transmission was restored. The 1st harmonic bump at large radius does not seem to have any significant impact on the beam transmission.

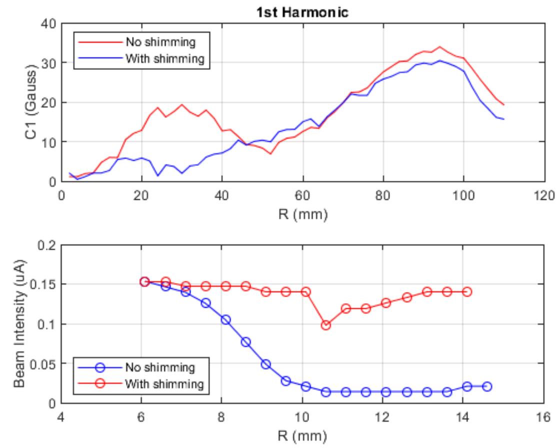


Figure 4: Magnetic field 1st harmonic amplitudes (top) and beam transmissions before and after the shimming.

## WATER COOLING FOR ION SOURCE

The Ion-12SC 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 with no direct water cooling, as shown in Figure 5. Early operation experience showed that, although the required power consumption of the Ion-12SC ion source is very low (< 10 watts), the performance and lifetime of the ion source were not consistent as expected. This was found to be due to the significant temperature rise at the ion source as a result of RF heating of the indirectly cooled dummy dee. In 2018, a new dummy dee with direct cooling supplied by additional water-cooling channels in the RF structure was designed and tested to mitigate the problem as shown in Figure 6. This was found to significantly improve the ion source performance and lifetime as well as the overall performance of the cyclotron. Figure 7 shows the measured beam intensity on target as a function of the ion source cathode current after the upgrade.

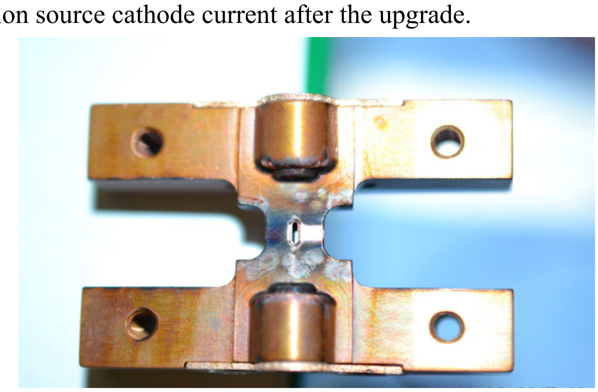

Figure 5: The Ion-12SC cold-cathode low power internal PIG ion source.

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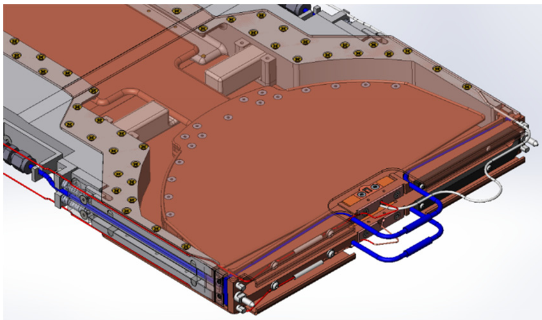

Figure 6: New direct water-cooled dummy dee circuit for Ion-12SC.

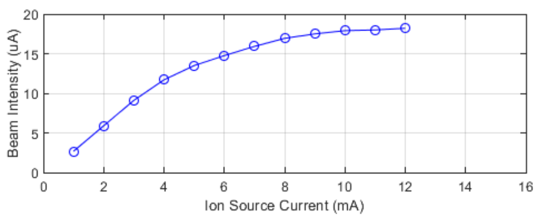


Figure 7: Measured Ion-12SC beam intensity on target as function of the ion source current.

## BEAM INTENSITY ON TARGET FEEDBACK CONTROL

To achieve predictable isotope production on a dose-to-dose basis in a hospital environment, the proton beam on target must maintain a constant and predictable intensity. Figure 8 shows the Ion-12SC target with the carbon shield installed. A beam current control feedback system was developed to obtain the stable beam intensity on the target. Assuming the cyclotron RF voltage remains constant, the beam current can in theory be viewed as a linear time variant system with respect to ion source current. Time varying behaviour is mainly due to heating of the ion source and its surrounding structures. The control logic has three main aspects: control during normal operation, calculation of the initial output, and logic to inhibit control when necessary (e.g. RF spark). The warmup behaviour of the system is repeatable, and it was found that the ion source current at 10 seconds is a close match to the ideal turn-on current. Therefore, the controller saves the current at 10 seconds each run and uses that value for the initial turn-on settings for the subsequent run. The effect of the control system is clearly demonstrated in Figure 9, where stable beam currents were achieved for 15 consecutive runs.

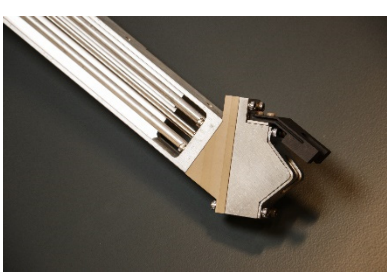

Figure 8: Ion-12SC internal liquid target with aluminum window.

## ION-12SC MEDICAL DOSE PRODUCTION RUNS AT UM

The recent progress in R&D for the Ion-12SC has had significant impact on the performance, stability and reliability of the cyclotron. The newest production unit, C1, was installed at the UM Medical School in 2018 and was successfully used to produce ~100 doses of N-13 ammonia for cardiac PET scan patients in early 2019. After the successful tests at UM ended, C1 was moved to the new Ionetix isotope production facility in Sarasota, Florida in May 2019.

Figure 9 shows the Ion-12SC cyclotron beam intensity on target and required ion source power for 15 runs in a routine day at the University of Michigan Medical School. Each production run lasts for 10 minutes with constant beam intensity on target of 10 uA. Figure 10 shows the corresponding N-13 dose at the End of Beam time (EOB) and after additional 15 minutes synthesis process/transportation time before the dose is ready for patient injection. The Ion-12SC cyclotron has demonstrated the capability to satisfy the customer requirement of an N-13 dose >20 mCi.

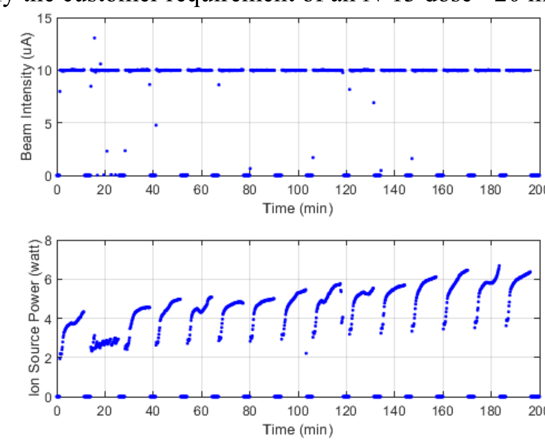


Figure 9: Beam intensity on target (top) and ion source power (bottom) of production runs in a day at UM.

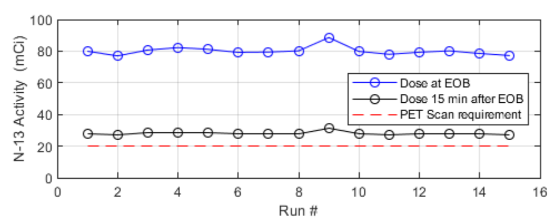


Figure 10: Measured N-13 dose at EOB and after 15 minutes from 15 production runs at UM.

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