# CONFIGURABLE 1 MeV TEST STAND CYCLOTRON FOR HIGH INTENSITY INJECTION SYSTEM DEVELOPMENT

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### *Abstract*

In order to study and optimize the ion source and injection system of our multiple cyclotron products, Best® Cyclotron Systems Inc. (BCSI) has assembled in its Vancouver office a 1 MeV cyclotron development platform.

To accommodate different injection line configurations, the main magnet median plane is vertically oriented and rail mounted which also allows easy access to the inner components. In addition, the main magnet central region is equipped with interchangeable magnetic poles, RF elements, and inflector electrodes in order to replicate the features of the simulated cyclotrons.

Multiple diagnostic devices are available to fully characterize the beam along the injection line and inside the cyclotron.

This paper will describe the design of two system configurations: the 60 MeV $H_2$+ for the DAEδALUS [1,2,3] experiment (MIT, BEST, INFN-LNS) and the BCSI 70 MeV $H^-$ cyclotron.

## INTRODUCTION

Over the last decade there has been an important increase in demand for medical radioactive isotopes production. BCSI has a goal to create a line of cyclotrons of differing energies and intensity specific to the isotope production needs of the customer.

Since each system has different cost, efficiency and ease of use requirements for the ion source and injection line, a development platform was assembled in Vancouver to study and optimize beam injection into the appropriate central region. The test stand consists of a fixed high voltage enclosure housing the ion source and a vertically oriented 1 MeV cyclotron mounted on rails to allow various injection line lengths. Other features include interchangeable magnetic poles, RF components, and beam optics, multiple diagnostic devices and a RF system with variable power and frequency.

Construction of the test stand started in November of 2012 and it has been operational since April 2013. The first injection system tested was for a 60 MeV $H_2^+$ cyclotron for the DAEδALUS experiment in collaboration with MIT and INFN-LNS followed by a 70 MeV $H^-$ cyclotron.

## TEST STAND

All elements of the injection system, as well as both halves of the main magnet, are sitting on 6 meter long rails allowing variable injection line configurations. Located at the far right end of the rail (not shown in the figure) is the high voltage enclosure which contains the ion source, its power supplies, and a 25 kW insulation transformer. Located in an insulated rack, the power supplies can be floated up to 40 kV.

An extraction system was not included in the cyclotron design. Instead, the 1 MeV beam is dumped into a copper beam stop bolted onto one of the magnet pole hill.

### *Main Magnet*

Weighing over 7 tons, the four sectors steel structure and both coils of the main magnet are responsible for the creation of the magnetic field. The target field of each platform is achieved through a combination of coil current adjustment and interchangeable elements of the magnetic structure (shims and centre plugs). The different components of the main magnet are shown in Fig. 1.

Having both halves of the cyclotron mounted on a rail facilitates access to its inner components.

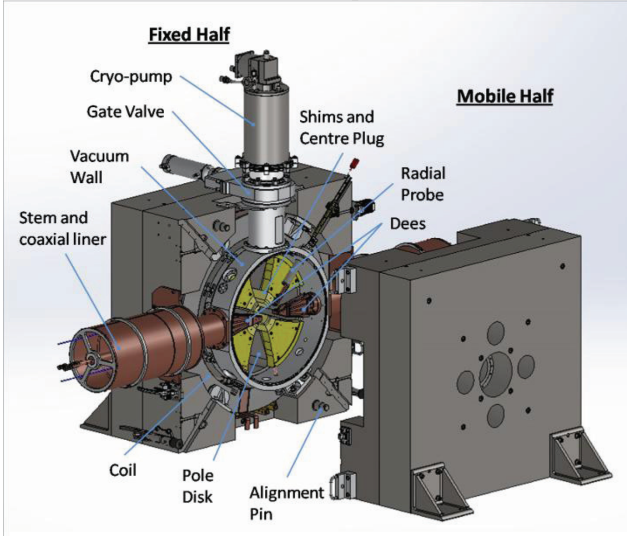

Figure 1: 1 MeV test stand cyclotron and its main components.

### *Magnetic Field Mapping*

To confirm that the target field is reached, a map of the relevant region is made using a temperature compensated hall probe mounted to a dual axis driving system.

Starting with oversized shims and centre plug, the target field is achieved by incremental machining of these elements, followed by field mapping.

Improvement to the mapper hardware and driver and data acquisition software reduced the time from 20 hours to 75 minutes for a 2 $mm^2$ resolution map.

### *RF System*

In order to accelerate $H^-$ or $H_2^+$ particles up to 1 MeV, the test stand is equipped with a tuneable multi-frequency resonator [4]. Coarse tuning is accomplished with manually adjusted shorting plates in the stems to match the different resonator geometries and frequencies. Fine tuning is carried out by motor driven tuner and coupler.

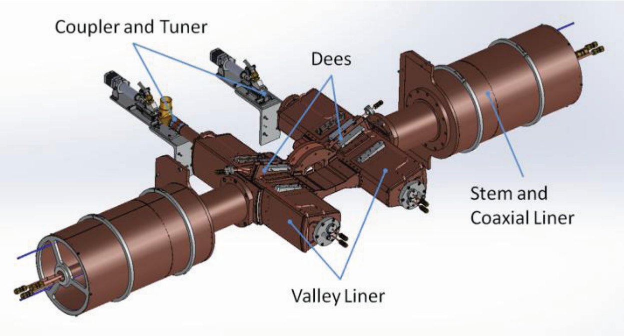

Figure 2: Test stand RF system assembly.

The accelerating gaps and resonators geometry is determined by a set of dees, centre post, and centre liners that are specific for each platform. These elements are thus removable so an exact replica of the actual cyclotrons elements can be installed on the base RF structure that consists of variable length radial stems, axial coupler and tuner elements located in the valley floor, and base liners. A model of the test stand RF system is shown in Fig. 2.

The front end stage of the 20 kW RF amplifier is a solid-state driver with circulator and the final stage is based upon a strip line so the impedance of the strip line is easily modified by changing a single mechanical part to cover frequencies between 49-80 MHz and dee voltages up to 70 kV.

Due to unforeseen delays in some parts manufacturing, the RF system should be ready for integration and commissioning in the first half of October 2013.

### *Vacuum System and Services*

An operating pressure of $10^{-5}$ Torr in the main tank and the injection line is maintained by a set of cryo-pumps. Each cryo-pump can be isolated from the system by a gate valve and kept at low temperature. This setup reduces the pump down time when vacuum is broken allowing rapid changes in the setup.

The main tank vacuum wall is fastened to the fixed half magnet and seal is made when the magnet is closed. The wall has many radial ports needed for RF coaxial stems, probes, and electrical and cooling feedthroughs.

The test stand devices are powered by a 75 kW 3-phase, 208 V and a 75 kW 3-phase, 400 V transformers for both North American and European electrical AC standards.

The cooling is handled by a 760 kPa, 60 l/s closed loop circuit that combines a heat exchanger unit with a capacity of 54 kW and a de-ionization system.

### *Diagnostics*

Beam characterisation can be done along the injection line and in the cyclotron up to 1 MeV by a selection of devices. Among those devices are an Allison scanner [5] and a rotating wire profiler which respectively measure the beam emittance and intensity profile. Other devices located on the injection line are a set of X-Y slits with current readback and a Faraday cup.

In the cyclotron, the beam profile and intensity is measured by radial probes that move along the median plane. Three probes can be installed at five different locations around the main tank vacuum wall; four at every 90° and one at 45°. Each probe has a specific design for various measuring modes:

- Single probe – for total beam interception and reading.
- Differential probe – for radial beam profiling.
- Five fingers head – for axial beam profiling.

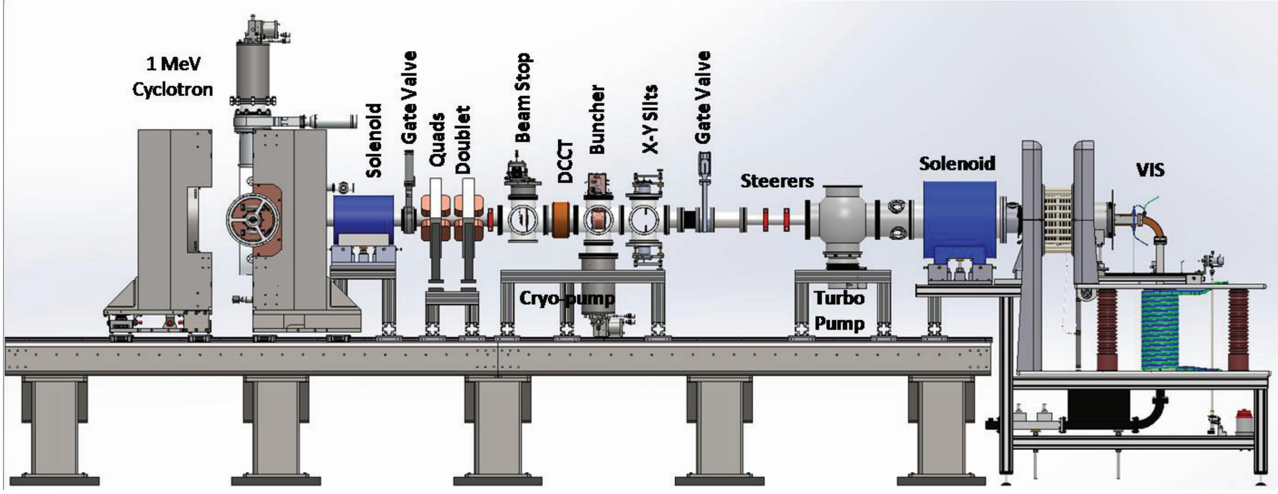

Figure 3: Test stand layout of the 60 MeV H2+ injection line.

## 60 MeV $H_2^+$ INJECTION LINE

The commissioning of the test stand was done in parallel with the characterization of the high intensity $H_2^+$ injection line of the DAEδALUS and IsoDAR 60 MeV cyclotron. The test stand layout for this configuration is shown in Fig. 3.

To achieve the accelerated 10 mA proton beam required for the experiment, the 2.45 GHz non-resonant ECR source VIS (Versatile Ion Source) was shipped from Catania and adapted to the test stand. Prior measurements have shown that the VIS can produce up to 15 mA of $H_2^+$.

The first part of the experiment was to characterize the $H_2^+$ beam up to the beam stop [6]. Once the protons were removed from the $H_2^+$ beam (via solenoid focusing), a beam intensity of 10-12 mA at 60 kV was measured through a DCCT and Faraday cup. Emittance measurements with an Allison scanner were also performed (Fig.4).

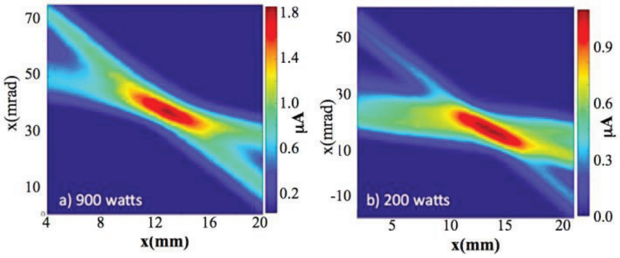

Figure 4: Emittance plots at the buncher location for combined $H_2^+$ and protons, a) at 900 watts microwave power, b) for 200 watts.

For the second part of the experiment, the beam will be characterized at the inflector entrance and exit and then accelerated to 1 MeV. The experiment will be resumed after the commissioning of the BCSI RF system.

## 70 MeV $H^-$ INJECTION LINE

The 70 MeV $H^-$ cyclotron is the first BCSI product to be tested in Vancouver. The final design of its injection line will depend on the results of the experiment.

With a maximum length of 3 meters, the injection line will constitute of a combination of solenoids, steerers, and quadrupole magnets. Diagnostics will consist of beam profiler, Faraday cup, and emittance scanner.

The 12 mA beam of $H^-$ required in the product specification will be produced by the BCSI LIS (Large Ion Source). The source is a variation of a filament-discharge multi-cusp H- ion source and will be operating at 40 kV.

The commissioning of the test stand RF system will be done in conjunction with the development of the 70 MeV platform.

## OTHER DEVELOPMENT PLATFORMS

Once the design of the 70 MeV platform is satisfactory, the second part of the 60 MeV $H_2^+$ experiment will resume.

To fill the gap left by the delayed RF system integration, the injection line of the BCSI 15 MeV cyclotron was installed on the test stand. Beam characterization was done after each optical element up to the exit of the inflector in order to optimize beam transmission. The setup of the ion source and injection line followed by diagnostics is shown in Fig. 5. From receiving to shipping, the experiment was completed in a mere 6 weeks showing the high versatility of the test stand.

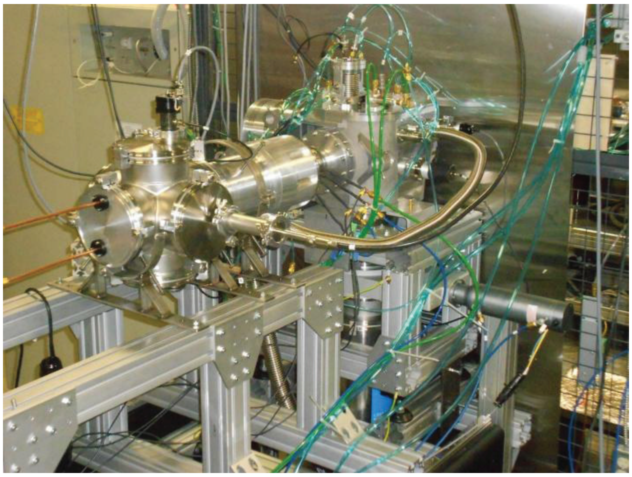

Figure 5: 15 MeV injection line and diagnostics setup.

Future development on the test stand will involve any new BCSI products and any future collaboration.

## ACKNOWLEDGMENT

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