

BEST 70P CYCLOTRON FACTORY TEST

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Abstract

Best Cyclotron Systems Inc (BCSI) designed and manufactured a 70MeV compact cyclotron for radioisotope production and research applications. The cyclotron has been built at Best Theratronics facility in Ottawa, Canada for the INFN-LNL laboratory in Legnaro, Italy. The cyclotron has external negative hydrogen ion source, four radial sectors with two separated dees in opposite valleys, cryogenic vacuum system and simultaneous beam extraction on opposite lines. The beam intensity is 700 μ A with variable extraction energy between 35 and 70MeV. The beam acceleration to 1MeV results are reported as well as confirming the individual cyclotron systems performance.

ION SOURCE

The ion source for the BEST 70p cyclotron is a multi-cusp filament driven arc discharge ion source. The design parameters are chosen to closely follow, where possible, the published design parameters of the de facto reference design of this type of ion sources, the TRIUMF ion source [1]. Following the reference design, the walls of the plasma chamber contain 10-cusp magnetic structure confining the plasma to the centre portion of the chamber. The ion source emittance was found to be similar to that reported for the TRIUMF source as seen in Fig. 1. During the commissioning the ion source was operated at output currents greater than 8mA [3].

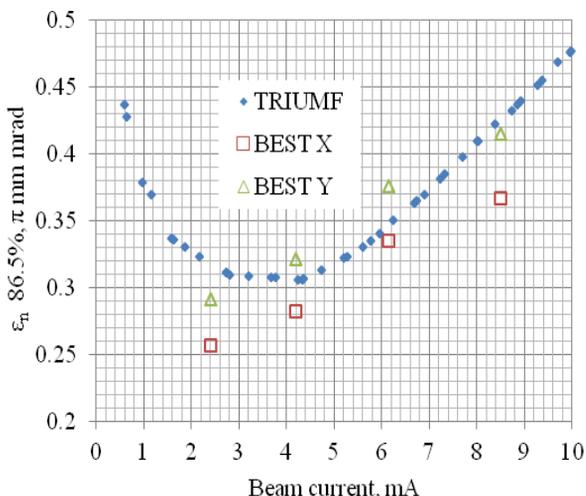


Figure 1: Emittance measurements (normalized emittance shown).

The ion source emittance was measured at the injection energy (40keV) in two perpendicular directions, one of them along the direction of the electron filter deflection. Sample emittance data is shown in Fig. 2, the “X” axis along the deflection direction. The dashed line boundaries outline emittance ellipses of 1 σ , 4 σ , and 9 σ inclusion. While there are slight differences in the beam properties in x- and y- directions, they are not significant for transporting the beam through the injection line.

Further development of the ion source is continuing, a more detailed account of the ion source studies will be reported elsewhere.

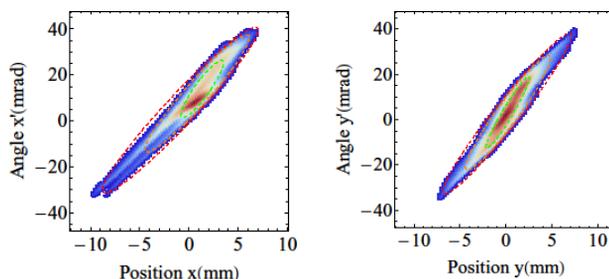


Figure 2: Ion source emittance at 6mA output (X and Y).

MAIN MAGNET

The magnet design has a good vertical focusing $v_z > 0.25$ after the first few turns (0.4 at full extraction energy) and minimum magnet gap of 45mm to ensure low beam losses and high beam current acceleration. For a valley gap of 700mm the magnet operates with B Hill $\approx 1.6T$ and B Valley $\approx 0.12T$.

The 70MeV magnet is shown in Fig. 3.



Figure 3: B70p Magnet.

The magnet has been commissioned and operated for extensive periods of time over a six months period [3]. Figure 4 is presenting the magnetic field data log over 12 hours stability test performed as part of the *Factory Acceptance Test (FAT)*. The field has been measured in the middle of a hill using an NMR probe.

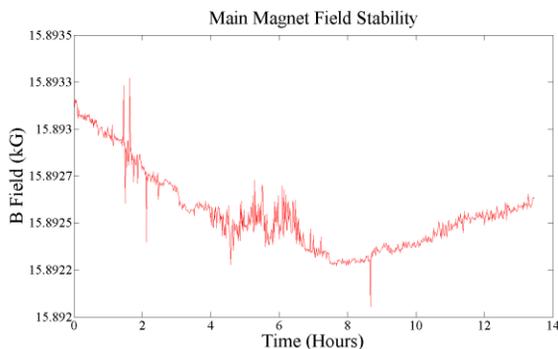


Figure 4: Magnetic field stability data log.

The magnetic field stability over the 12 hour period of the test was determined to be less than 1 Gauss that calculates at 6.0×10^{-5} and exceeding by one order of magnitude the specification of 5.0×10^{-4} .

RF SYSTEM

The RF System of the 70MeV cyclotron comprises of two independent resonators each driven by its own power amplifier and controlled with a digital LLRF control system on a Master/Slave configuration as previously reported on [2]. The assembled resonators are shown in Fig. 5.

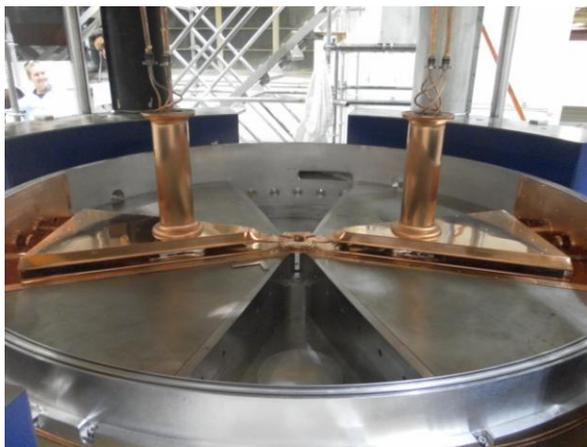


Figure 5: RF Resonators.

The RF system operates at 56.2MHz on 4th harmonic of the cyclotron frequency. The dee voltage at the centre dee tip is 60kV and increasing to 72kV at the outer radius.

After commissioning the RF System operated very stable over a four months period during which time endurance tests in excess of 48 hours were performed in fully automated mode [3]. Figures 6 shows the dee voltage endurance test data log over a period of 40 hours run as part of the FAT. Figure 7 shows a 10 minutes sample of the same voltage where the stability has been

determined to be 2×10^{-4} versus the specification of 5×10^{-4} .

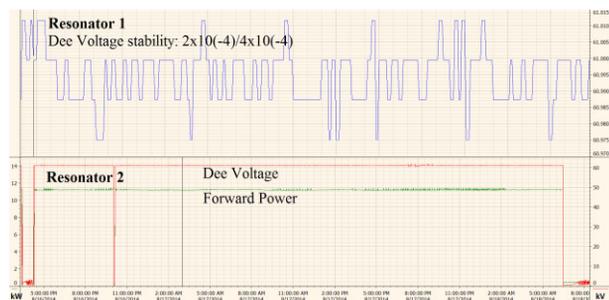


Figure 6: RF 40 hours endurance test.

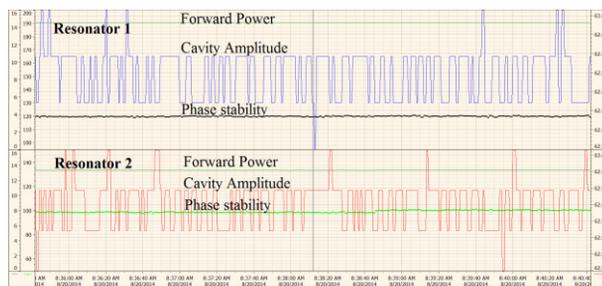


Figure 7: Dee voltage stability test 10 minutes sample.

The phase stability between the two resonators is automatically controlled through a digital phase control loop implemented at the level of the LLRF (internal FPGA programmed). The phase error between resonators was measured with Agilent DSA-X 92504A, 25GHz Digital Signal Analyzer and found to be 50 picoseconds. This accounts as ± 0.5 degrees of phase error between resonators. A 10 minutes sample from an 8 hour test is shown in Fig. 8.

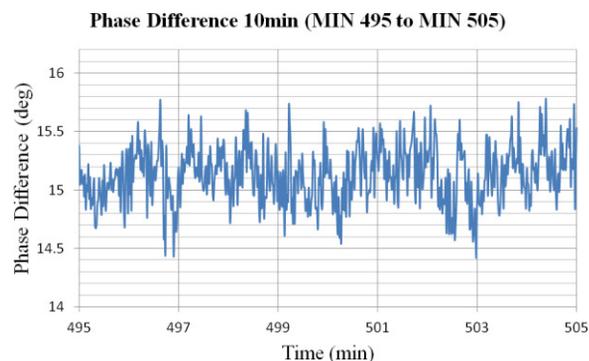


Figure 8: Phase stability test 10 minutes sample.

VACUUM PUMP DOWN

The main tank vacuum system operates with four cryo-pumps and achieved the following pressure:

- 7.5×10^{-7} Torr reached within 2 hours from start
- 7.5×10^{-8} Torr within 11 hours from start
- Falling below 7.5×10^{-8} Torr after 12 hours.

The full pump down cycle is shown in Fig. 9. A Residual Gas Analyzer (RGA) has been used for the entire 12 hours duration of the test to determine any tank contamination. All contaminants gases or water molecules

were measured below 10^{-7} for water and hydrogen and below 10^{-8} for other gases.

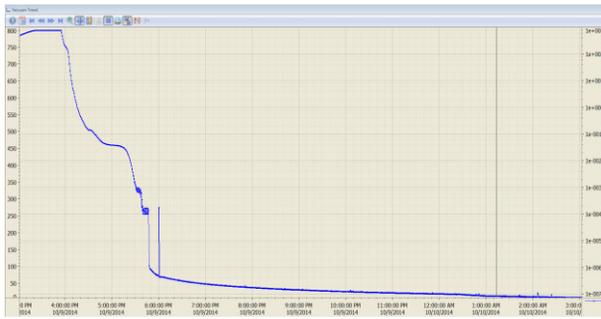


Figure 9: Vacuum pump down cycle.

BEAM STABILITY TEST

A complete set of beam stability tests have been done as part of the FAT to confirm the machine performance [3]. The cyclotron was operated and beam run on a beam stop positioned in the injection line that characterises the ion source DC output, transported through the *Low Energy Beam Transport (LEBT)*, spiral inflector electrode and injected into the cyclotron at the first dee gap. The beam was accelerated to 1MeV probe and injection parameters have been measured as follows:

- Beam current on LEBT probe from 4.5 to 8.5mA DC negative hydrogen ions,
- Beam was measured on the 1MeV probe for three value steps of 450, 600 and 700 μ A for various period of time.

A two hour run at 450 μ A on the 1MeV probe was successfully completed as seen in Fig. 10 (red data). The test started with the ion source from cold state and stable operation reached approximate 10 minutes later.

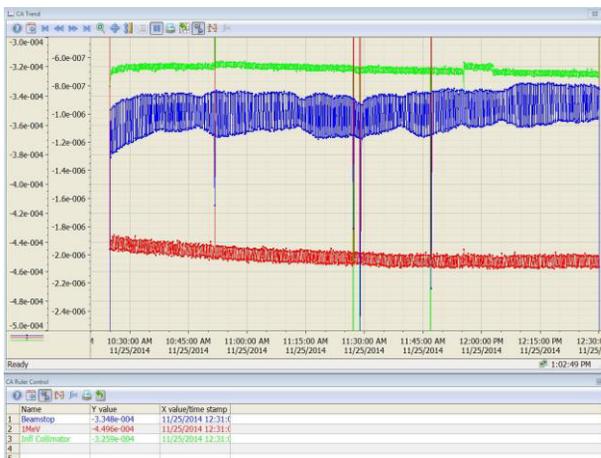


Figure 10: Beam stability test, 450 μ A.

Beam jitter was measured within $\pm 5\mu$ A (or $\pm 1\%$) of the average beam current over a two hour period. Beam stability over same period of time is better than 5 μ A.

The 600 μ A and 700 μ A runs have been operated for periods of 1 hour and correspondingly 10 to 15 minutes periods due to technical problems we encountered with

the high voltage separation transformer supplying the ion source system. The beam jitter and stability remained below $\pm 1\%$ at these higher beam currents. Figure 11 shows the 700 μ A beam tune data log (red data) discontinued due the transformer problems.

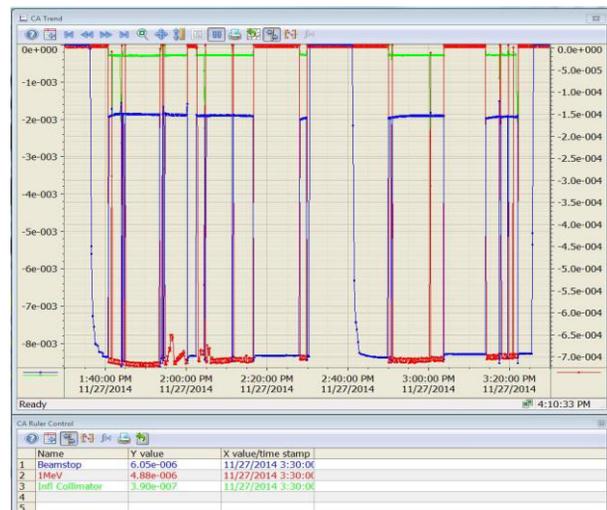


Figure 11: Beam test, 700 μ A.

The beam injection efficiency defined as the ratio between the beam current measured at 1MeV probe and the injection line beam stop is as expected from theoretical calculations (10%). The actual beam currents measured at few ion source tunes are presented in Table 1.

Table 1: Beam Current Transmission to 1MeV Probe

1MeV	Beam stop	Injection efficiency
450 μ A	3.97mA	11.3%
635 μ A	6.20mA	10.2%
715 μ A	8.09mA	8.8%

CONCLUSION

The BEST70p cyclotron FAT comprised of an extensive set of tests of each individual cyclotron system, performance and endurance tests that span over six months time and concluded with a detail beam current acceleration to 1MeV test. The collective sets of tests have been successfully completed up to 700 μ A of beam current accelerated to the 1MeV probe.

REFERENCES

- [1] T. Kuo, et al, Rev. Sci. Instrum. 69, 959 (1998).
- [2] V. Sabaiduc et al, "Resonator System for the BEST 70MeV Cyclotron", TU2PB04, ICCA 2013, Vancouver, Canada, September 2013
- [3] BEST 70P Factory Acceptance Test reports, Best Theratronics Ltd., August to November 2014, Ottawa, Canada.