NEW HIGH INTENSITY COMPACT NEGATIVE HYDROGEN ION CYCLOTRONS

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Abstract

Best Cyclotron Systems Inc (BCSI) has been established in Springfield, Virginia, US, for the design and production of commercial cyclotrons. The company is a subsidiary of Best Medical International renowned in the field of medical instrumentation and radiation therapy. Cyclotrons are manufactured and tested at Best Theratronics, Ottawa. BCSI is initially focusing on three different energy cyclotrons 14, 35 and 70MeV negative hydrogen ion accelerators.

CYCLOTRON CHARACTERISTICS

Various small cyclotrons had successfully been developed with compact structure for isotopes production in 1990s. CIAE has dedicated to the exploration of the cyclotron physics and key technologies with the compact structure remained and the energy range extended to 70~100 MeV since late 1990s. The cyclotrons developed by BEST began with referring to 10 MeV CYCIAE-CRM, as well as the advanced design of CYCIAE-14[1] and CYCIAE-70[2]. As preceded by CIAE, the sophisticated technologies on compact cyclotrons with high intensity and relatively high energy have taken the lead in the developing trends to some extent, as the case of BEST.

All BEST's cyclotrons have room temperature magnets, deep valley design with four radial sectors, two dees in opposite valleys, external ion source and simultaneous beam extraction on opposite lines. The BEST 14 cyclotron is designed for both internal and external ion source configuration. The cyclotrons are illustrated in Figure 1.

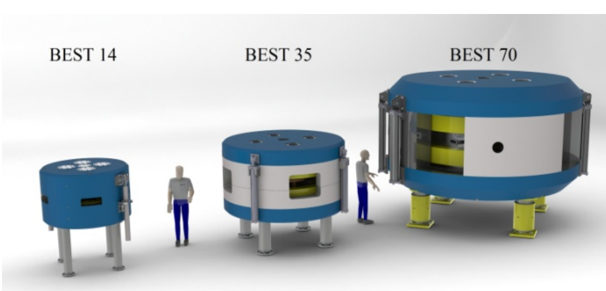

Figure 1: BCSI Cyclotrons

The main characteristics of the cyclotron magnets are shown in Table 1 with power specifications, including four beam lines each for the 35 and 70MeV cyclotrons.

Table 1: Comparative Specifications

Energy	Dimension (dia. x height)	Weight	Electric power
14MeV	1.7 m x 1.0 m	14 t	60KVA
35MeV	2.7 m x 1.5 m	55 t	280KVA
70MeV	4.5 m x 2.2 m	195 t	400KVA

BEST 14 CYCLOTRON

The BEST 14p cyclotron system is designed for negative hydrogen ion (H^-) acceleration and fixed energy 14MeV dual beam extraction using multi-foil extraction carousel. The cyclotron has the unique feature of compatibility between the uses of an internal or external ion source. The design allows for field upgrade from internal to external ion source.

Main Magnet

A strong axial focusing magnet design has been chosen to allow for future beam intensity increase with $\nu_z > 0.5$ and $> \nu_r/2$ as shown in Figure 2.

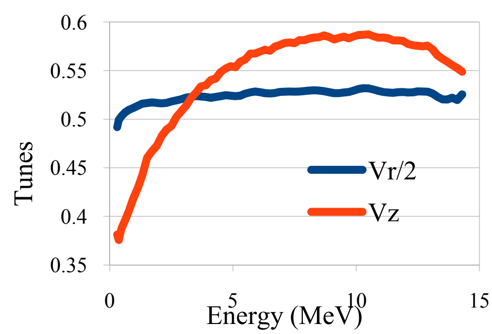

Figure 2: Tune diagram

Table 2: Magnet parameters

Number of sectors	4
Sector angle	52º
Average magnetic field	1.2T
Radius of sector magnet	50.0cm
Hill gap	2.6cm
Magnet coil	100kAT
Coil power	20kW

Ion Source

The internal ion source option is based on a PIG source as shown in Figure 3, designed to provide an extracted beam current in excess of 100μA.

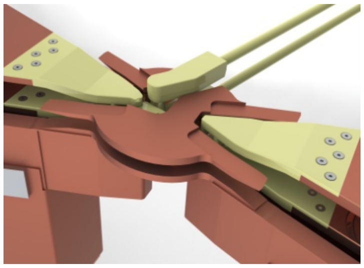

Figure 3: Internal ion source

The external ion source option is based on a multi-cusp ion source with a DC capability of 5mA ensuring a minimum of 400μA of extracted beam at an injection energy of 27keV. The plots in Figure 4 were obtained by accelerating the beam from the injection point after the inflector to the extractor and then to the target outside of the magnet. Ellipse containing 95% of the beam have normalized emittance of **Z**=6.2 mm mr, **X**=3.8 mm mr.

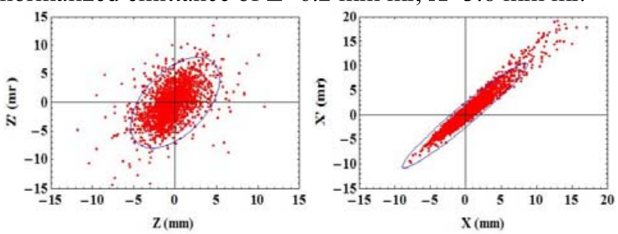

Figure 4: **Z** and **X** normalized emittances at target.

The centre region magnetic field configuration is capable of accelerating beam from both internal and external sources with minimal changes (factory mapped for both options). The upgrade to an external ion source requires replacing two magnet shims, the centre region assembly and ion source. The centre region includes the inflector and new dee tips.

RF System

The resonator is composed of two λ/4 resonant cavities connected at the centre as shown in Figure 5. This option optimises the resonator power dissipation with minimum dee voltage off balance between the lower and upper dee plates.

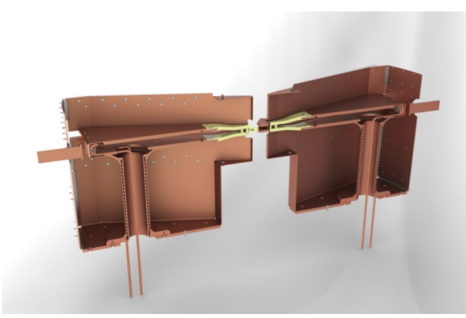

Figure 5: RF Resonators

Table 3: Main characteristics of the RF System

Frequency	73MHz, 4^{th} harmonic
Dee angle	30º
Dissipated power	8kW
Dee voltage	40kV
Quality factor	7000

The resonant cavity has been simulated with CST MWS to optimise the resonator characteristics and continues with coupling and tuning optimization. The final design will ensure identical resonator characteristics when replacing the centre region and dee tips for the external ion source.

Extraction Mechanism

The beam can be simultaneously delivered to two of the four target stations (two on each side) installed at the end of the vacuum wall extraction horns. Beam extraction is achieved with two diagonally opposite extraction probes each probe being equipped with two four-foil carousels as shown in Figure 6.

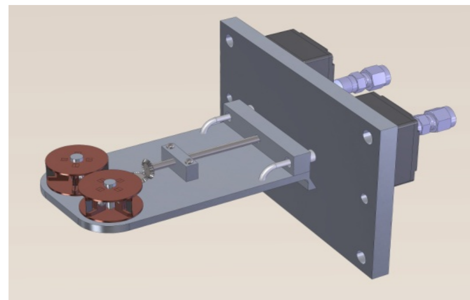

Figure 6: Extraction probe

Carousel rotation moves the beam in the horizontal plan and radial movement adjusts the beam ratio between extractors.

CONTROL SYSTEM

The main purpose of the Control System is to provide a fully integrated real-time operation and monitoring of the cyclotron systems, interlock and safety signals. The controller consists of a Siemens-based Programmable Logic Controller that analyzes all input and output signals. The graphical user interface, built on WinCC software, links the operator with the PLC as shown in Figure 7.

The daily operations of the cyclotron are simplified through built-in automated procedures like machine start-up, or machine shutdown for the basic users. Manual operation of the cyclotron is also available to fine-tune the machine by more experienced operators based on higher security level access.

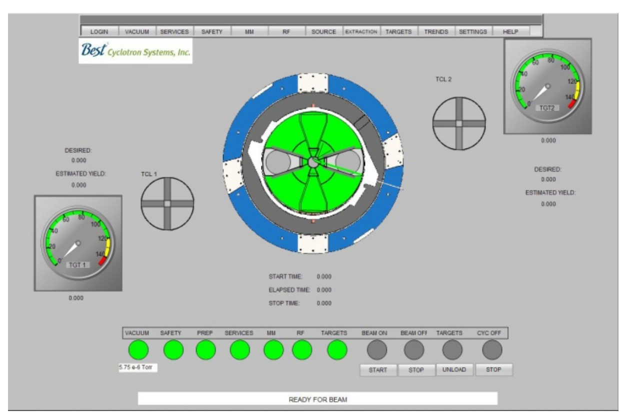

Figure 7: Control system interface

BEST 35 CYCLOTRON

The BEST 35p cyclotron is designed for negative hydrogen ion (H^-) acceleration and variable beam extraction between 15 and 35MeV. There is a broad range of single photon emitters that are used in nuclear diagnostic imaging and therapy that are accessible in this energy range. Typical characteristics of the cyclotron are presented in Table 4.

Table 4: BEST 35p Main characteristics

Main magnet	four sectors coil current: ≈ 98000AT
RF resonators	two resonators connected frequency: 70MHz harmonic: 4^{th} dissipated power: 20-22kW dee voltage:50kV
External ion source and injection line	multi-cusp H^-, 15mA DC combined beam current in excess of 1.5mA axial injection, spiral inflector
Vacuum	ion source: < 1 x 10^{-5} Torr main tank: < 5 x 10^{-7} Torr
Extraction	simultaneous dual beam 2 stripping multi-foil carousels variable energy 15-35MeV
Beam lines	2 or 3 way switching magnet 4 to 6 beam lines

BEST 70 CYCLOTRON

The BEST 70p cyclotron is designed for negative hydrogen ion (H^-) acceleration and variable energy extraction up to 70MeV with a combined beam current of 800µA. It may be used as a research accelerator as well as a radioisotope production cyclotron.

Typical characteristics are presented in Table 5.

Table 5: BEST 70p Main characteristics

Main magnet	B_{max} field: 1.6T coil current: ≈ 127kAT 4 sectors, deep valley hill sector angle: 50º varying hill gap: 6 – 4.69 cm
RF resonators (two resonators connected)	frequency: 58MHz, harmonic: 4^{th} dissipated power: 28kW dee voltage: 60 - 81kV dee angle 36º
External ion source and injection line	multi-cusp H^-, 15-20mA DC beam current: 800µA axial injection, 40kV spiral inflector
Vacuum	ion source: < 1 x 10^{-5} Torr main tank: < 1.5 x 10^{-7} Torr
Extraction	simultaneous dual beam 2 stripping multi-foil carousels variable energy 35-70MeV
Beam lines	2 way switching magnet Up to 4 beam lines

The illustration in Figure 8 shows the cyclotron, one side switching magnet and beam line.

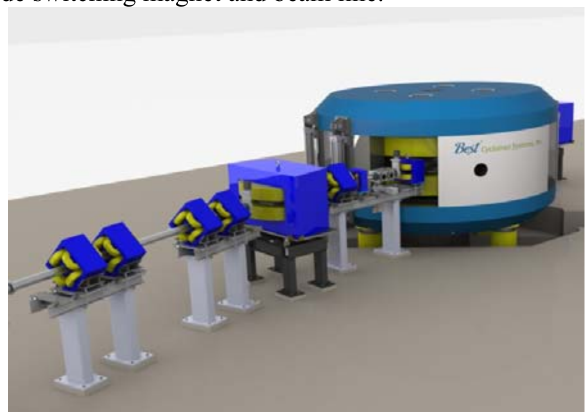

Figure 8: BEST 70p Cyclotron and beam line

Stripping Losses

The design goal is to keep the total H^- vacuum and E.M. stripping losses ≤2%. At 70MeV the gas stripping losses approximates at 2% and E.M. stripping losses at 0.2%, as shown in Figure 9.

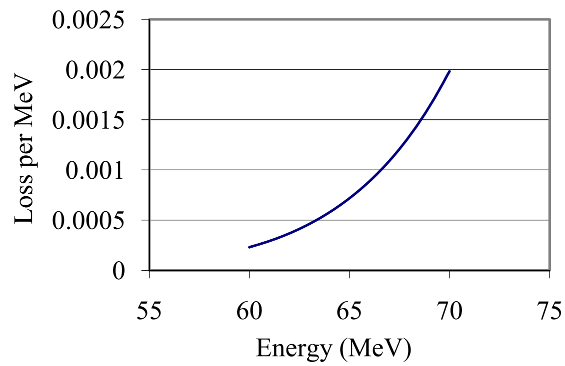

Figure 9: E.M. Stripping losses

RF Resonators

A two separated cavities solution has been chosen driven by individual amplifiers and LLRF digital control. The cavity design adopts the “triangular” stem structure for increase dee voltage distribution toward outer radii (reduce Lorentz stripping).

ACKNOWLEDGMENTS

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[3] George H. Mackenzie, *private communications*