BEST 70P CYCLOTRON COMMISSIONING AT INFN LN LEGNARO

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Abstract

Best Cyclotron Systems Inc (BCSI) has designed and manufactured a 70 MeV compact cyclotron for radioisotope production and research applications. The cyclotron has been built at the Best Theratronics facility in Ottawa, Canada for the INFN-LNL laboratory in Legnaro, Italy. The cyclotron has an 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 microamperes with variable extraction energy between 35 and 70 MeV. The beam commissioning performances at the customer site are reported.

BEAM COMISSIONING

The cyclotron and beam line equipment has been installed and commissioned at INFN LN Legnaro and the *Factory Acceptance Test* (FAT) has been successfully repeated before proceeding with high energy beam acceleration.

1 MeV Acceleration

The cyclotron is equipped with a low energy beam intercepting probe located at the 1 MeV radius. The probe is used to optimise the beam transport through the *Low Energy Beam Transport (*LEBT) line and characterise the beam injection efficiency and acceleration to 1 MeV. A complete characterisation up to 1 MeV has been done and reported [1] as part of the FAT.

Beam intensity and stability parameters have been confirmed to better values as shown in Table 1.

Table 1: Beam at 1 MeV Probe

Parameter	Value
Beam current	900 μA
Ion source current	8.5 mA (max. 15 mA)
Injection efficiency	10.3%.
Beam ripple	±1% of the average value stability better than 5 μA

High Energy Acceleration

Beam acceleration to high energy was scheduled in several steps to ensure that beam tuning on target was optimum while maintaining the beam losses to a minimum. The beam line layout as shown in Fig. 1 allowed us to install multiple low power Faraday cups at the exit of each beam line switching magnet in addition to the high power beam dump of 50 kW (INFN supply) installed in target vault A6. Tests on Faraday cups were conducted at low beam currents of 3 to 20 μA single and double beam extraction. Beam delivery operation and tunes were verified and optimised at 100 μA beam current on the beam dump.

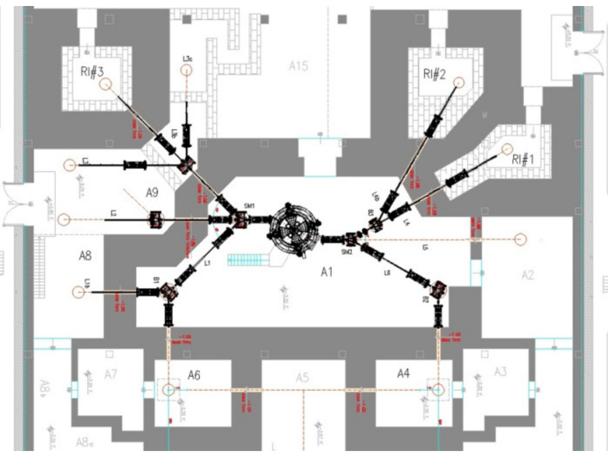

Figure 1: Beam line layout.

Beam Profile Measurement

Two helical wire beam scanners per beam line were installed to characterise the beam profile during the tuning process. Scans have been done up to maximum beam current by closely monitoring the power dissipation on the wire (increased rotation speed at higher beam powers). Figure 2 shows the beam profile (peak voltage) for wobbler off and on status versus *x* axis position.

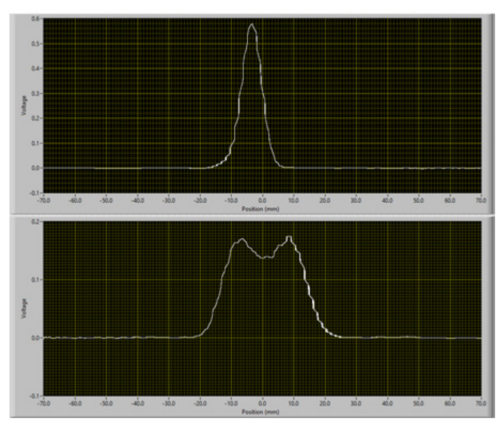

Figure 2: Beam profile (V), wobbler off/on versus *x* axis position.

Pulsed Beam

Two methods of pulsing the beam intensity were considered: amplitude and phase modulation. In either case the modulated parameter was switched between values:

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one that completely eliminates the beam and the other corresponding to the optimum operational setting.

Amplitude and Phase Modulation The separated resonator design and digital Low Level Radio Frequency (LLRF) [2, 3] controller allows for the amplitude and phase of the accelerating voltage to operate in pulsed mode of various configurations (in phase or phase modulation). Both features allow for the beam current intensity to be controlled in pulse peak power and/or ramp-up mode as may be required by the target power management. Features can also be used to compensate for beam loading effects in addition to the movable coupler design. Figure 3 shows the in phase amplitude modulation of the dee voltage between 40 to 60 kV (100 ms period 50% duty factor, 70 MeV, 100 µA average, 200 µA peak beam).

When using amplitude modulation at higher beam currents, we investigated and confirmed spills on beam line during the transient time of the accelerating voltage by monitoring one of the four slits in first beam line section.

The spills increased with the peak current as illustrated in Fig. 4, at the same time showing the induced RF amplitude instability due to the strain of a sudden increase in beam loading (400 µA peak current, 100 ms period 50% duty factor). The trace in the middle (magenta) corresponds to the current on one of the slits, showing a burst during this transition.

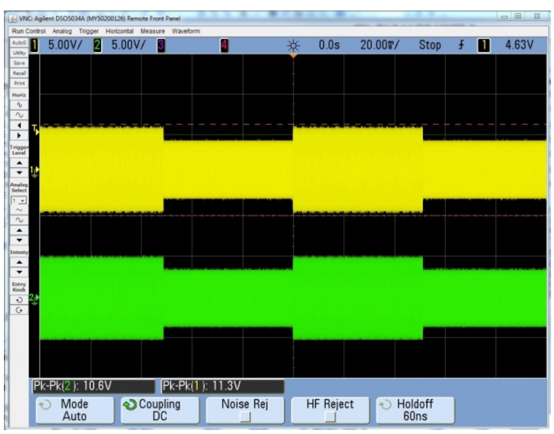

Figure 3: Amplitude modulation (sample) versus time.

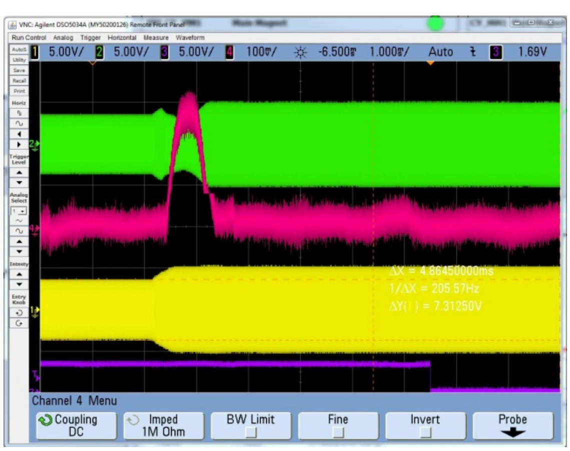

Figure 4: Amplitude modulation, peak current (400 µA) versus time.

Amplitude versus Phase Modulation In order to determine if any beam losses occur during the acceleration when either the accelerating voltage or phase between resonators is changed, a comparative measurement was done between the 1 MeV and extraction probe currents.

The characteristic of beam transmission versus the accelerating voltage shows both currents being identical. Therefore, no losses in the cyclotron occur when using an amplitude ramp-up procedure. Results are shown in Fig. 5 where it can also be noted that when the acceleration voltage was decreased to 40kV, the beam reduced to zero.

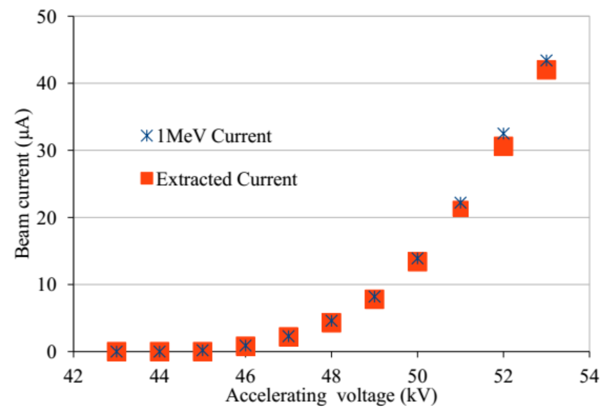

Figure 5: Beam transmission with amplitude.

The experiment was repeated by incrementally changing the delay between resonators while the accelerating voltage was fixed at an optimum value. The measurement started from the 120 degree (out-of-phase) condition where it has been established that the beam is completely off; zero beam on the 1 MeV probe. Results were immediately observed when reducing the phase difference between resonators as shown in Fig. 6. There was a significant difference between the 1 MeV and extraction probe currents indicating losses in the acceleration, 16.6 versus 3.1 µA. The immediate conclusion was to not use the phase modulation for beam control at high intensity currents.

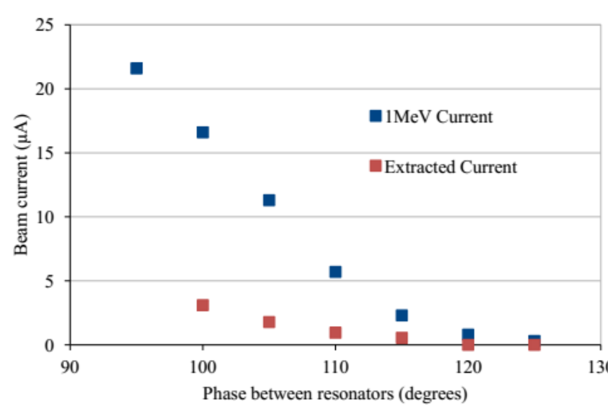

Figure 6: Beam transmission versus phase difference.

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500 µA Beam on Target

After exploring beamline operation at 100 µA, the current on the beam dump was gradually increased and sustained at every 100 µA increment to confirm stable, problem-free operation at each level before the next increase.

Figure 7 illustrates this ramp up to 400 µA of beam on target, followed by a ramp up to 500 µA on the next day (see Fig. 8). At that time the INFN beam dump developed a vacuum leak and the operation was stopped.

BEAM LINE LOSSES

Beam losses along beam line have been measured at various current levels with the tune optimised to minimise the losses. The value is measured as a percentage of unaccounted currents versus the extractor probe current. Unaccounted currents have been measured as the difference between extractor probe current and sum of all beam line currents (slits, baffles and target currents). Values are given in Table 2 for several beam current levels.

Vacuum at high beam power The vacuum level has been consistently stable at values near 5x10^{-8} Torr with all systems operating and no beam acceleration. Accelerating and extracting 500 µA of beam caused the vacuum level to increase to approximately 6.5x10^{-8} Torr as shown in Fig. 8.

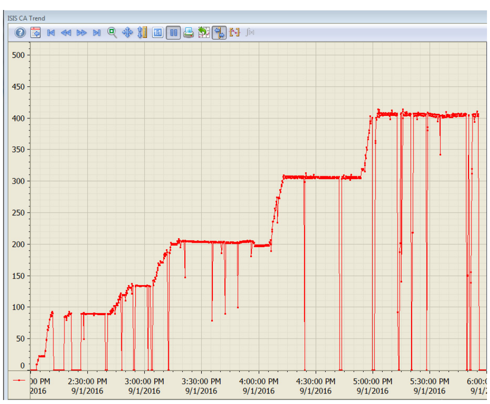

Figure 7: Beam current on target ramp-up (µA), versus time.

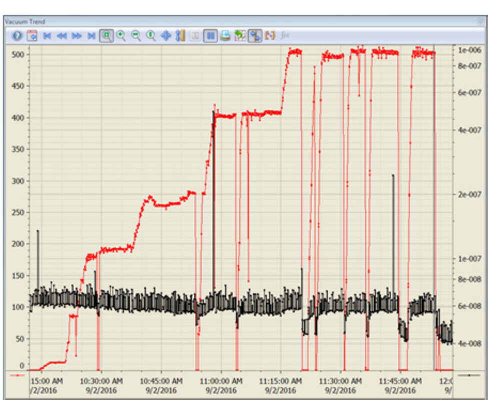

Figure 8: Vacuum and beam current (µA) versus time.

Table 2: Beam Line Losses

Beam Current on Target	Value
300 µA	0.2%
400 µA	0.5%
500 µA	0.5%

RADIATION LEVELS

Radiation surveys were periodically done after most significant runs. Activity levels have been noted at the typical locations at and around the Faraday cups and first set of beam line slits. No significant active spots have been detected along the beam line pipe. Some small activation spots have been found after pulsed beam operation. Those are most likely associated with increased slit spills observed during pulsed operation

The facility radiation survey system monitors in real time the level of radiation in vaults, air exhaust chimney and cooling water for the cyclotron. It was noted that all activity levels sensitively decreased when tuning was optimised and beamline slits current were reduced. Detail results are presented in [4].

ACKNOWLEDGMENT

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