PRACTICAL CONSIDERATIONS IN THE DESIGN OF A HIGH CURRENT COMMERCIAL H-MINUS CYCLOTRON

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Abstract

High current H^- cyclotrons (>1000 μA) are being developed and implemented for radioisotope production, radioactive therapeutic implants and other applications. The beam dynamics and general physics design of these cyclotron systems must be well done. However, to not compromise an elegant and effective physics design, engineering practicalities must be carefully considered and then implemented. Based on our experience in the design, upgrading, and maintenance of commercial H^- cyclotron systems, we offer practical issues and solutions to be considered in the engineering design and implementation of such high current systems.

INTRODUCTION

Of the modern commercial 30 MeV H^- cyclotrons utilizing axial injection, over thirty Cyclone30s, and about a half-dozen TRIUMF technology TR30s are installed.

Given the large number of Cyclone30s, this paper uses the Cyclone30 design circa the late 1990s and earlier as a baseline reference, and discusses practical engineering improvements to be made to this cyclotron to enable reliable and consistent operation at high current. This would increase radioisotope production yields, and operational cost-effectiveness.

ION SOURCE & INJECTION SYSTEM

The Cyclone30 ISIS is mounted on the moveable upper half of the cyclotron on a cantilevered support. Beam injection is downwards as shown in the left hand side (LHS) of Figure 1. This is problematic because the ISIS is moved each “lid-up” maintenance, and with a springy cantilevered support structure the ISIS frequently becomes misaligned and requires correction as shown in the right hand side (RHS) of Figure 1. The solution is to use a permanently aligned ISIS mounted to the lower fixed half of the cyclotron with a sturdy support structure.

The ISIS vacuum is provided by a diffusion pump system (Figure 2 LHS), which introduces hydro-carbon molecules into the ion source chamber [1,2]. The hydro-carbons interfere with H^- production, reduce filament life-time to ~80 hours within months, and over this time scale deposits 2 to 3 mm of material on the chamber walls. With the ion source emitting the beam downwards, debris from the deposits falls onto the grounded plasma electrode as shown in Figure 2 RHS. Some of this debris falls through the lens aperture into the injection line buncher wires, and onto the inflector electrodes. Cleaning a thick coating with a blunt instrument requires a great deal of force risking micro-cracking of the source chamber and concomitant water leaks.

An ion source mounted on the lower fixed side of the cyclotron stops debris falling into the cyclotron. Thick deposition and debris can effectively be eliminated by the use of the TRIUMF source [3]. The TRIUMF source utilizes Cryo/Turbo pumping for a clean environment, and only a very thin deposition layer must occasionally be cleaned using fine grit sandpaper.

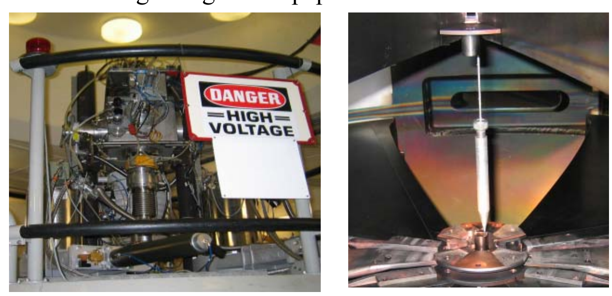

Figure 1: LHS shows ISIS on top of Cyclone30, and RHS shows ISIS out of alignment after several tank openings.

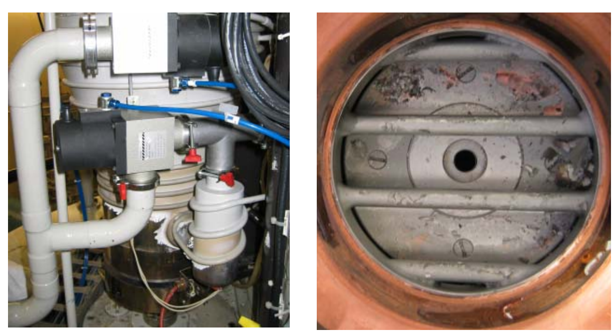

Figure 2: LHS shows Cyclone30 ISIS diffusion pump. RHS shows ion source with hydro-carbon debris.

Figure 3 LHS shows a hairpin tungsten filament with eroded supports due to exposure to the plasma, and RHS shows the backplate with two cusp magnet rows. The TRIUMF source utilizes tantalum ring filaments, recessed support posts, and four backplate cusp magnet rows for improved H^- performance. The absence of a filament induced magnetic field in the TRIUMF ion source centre contributes to a quiescent plasma [4].

The plasma lens (Figure 2 RHS) is at the same electric potential as the source body, whereas in the TRIUMF case it is electrically biased for optimized H^- production and a three-fold reduction in extracted electrons [1]. In addition, the TRIUMF puller lens utilizes a double-dipole magnetic electron filter with ($\int Bdl = 0$), whereas the Cyclone30 typically utilizes a single dipole magnetic field

($\int Bdl \sim 4000$ Gauss·mm). This means that the H^- beam is deflected after electron filtering and substantial beam loss occurs on the ground lens causing significant wear as shown in Figure 4 LHS. To compensate for the mis-steered beam a permanent magnet steering magnet is used internal to the vacuum (Figure 4 RHS). This structure requires several source ventings in order to be aligned correctly for centred beam. This can take several hours. The TRIUMF double-dipole magnet electron filter enables a centred beam to exit the ground lens, so no asymmetric wear is evident [4]. For steering corrections TRIUMF uses an in vacuum wire wound XY steering magnet for easy tuning through the control system [4].

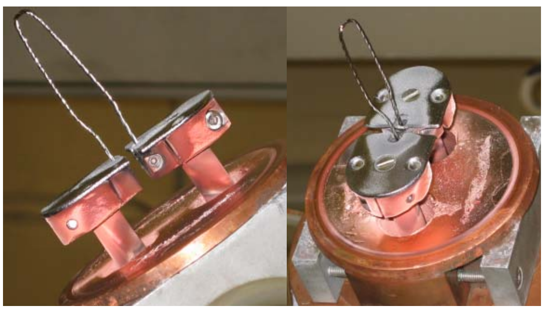

Figure 3: LHS shows hairpin tungsten filament and exposed support posts. RHS shows backplate with two cusp magnet rows used in the Cyclone30.

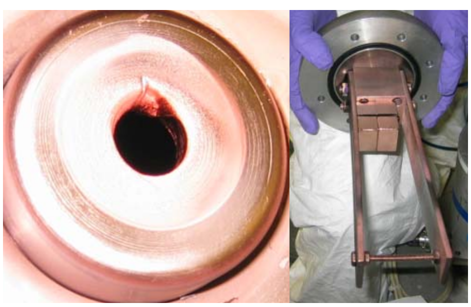

Figure 4: LHS shows wear in source ground lens. RHS shows permanent steering magnet in Cyclone30.

The typical Cyclone30 ion source of this era does not have a hydrogen flow controller. This device is required for optimizing the plasma density and beam production. The vacuum level in the injection line must be optimized at about the micro-Torr level for effective space-charge neutralization without excessive beam stripping [5].

The nominal Cyclone30 injection line utilizes an electrostatic einzel lens, XY steering magnets, a buncher, and a solenoid magnet. There is no asymmetric focusing. It is important to utilize rotate-able quadrupole magnets to ensure asymmetric focusing to de-couple the cross-plane coupling introduced by the inflector [7,8,9].

The typical Cyclone30 injection line provides little beam diagnostic information. An ion source Faraday Cup is typically provided, and a 1 MeV beamstop is optional (customers should select this option). It is our recommendation that 4-jawed collimators be located at the exit of the ion source vacuum box, at the entrance of the solenoid magnet and at the entrance to the inflector, so that beam focusing/centring can be easily carried out.

CENTRAL REGION

The Cyclone30's inflector electrodes are not enclosed in a grounded enclosure, nor is an electrically isolated collimator with beam current readback provided, as shown in Figure 5 LHS. This means that it is not straightforward to centre the beam at the inflector entrance, and ions or electrons from the source or injection line region strike and erode the inflector electrodes. It is our experience that inflector entrance collimators with beam current readback are useful, and it is important that the inflector insulators be properly shadowed, so that shorts due to sputtering do not occur. The inflector ground enclosure should only have a small opening at the entrance and exit, and the structure should be water-cooled to accommodate beam loss in the first turns. Figure 5 RHS shows the inflector electrode wires. The high voltage connection to the inflectors should be an automatic connection rather than a hand connection. In addition, inflector pieces should be mounted into the cyclotron in a manner which ensures a high tolerance fit, so there is no possibility of adjustable insertion available to maintenance personnel who likely have little training in the area of centre region optics. Figure 5 RHS also shows the bottom half of the Cyclone30 dees, as the top half are connected to the upper yoke of the cyclotron magnet. Separation of the dees introduces an unnecessary risk of misalignment error. It is our recommendation that the upper and lower dees be built as a single permanently aligned structure as in the TRIUMF 30 MeV cyclotron.

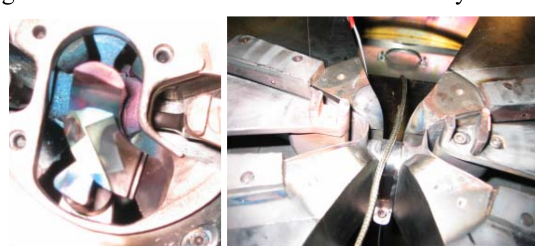

Figure 5: LHS shows inflector entrance with open ground enclosure. RHS shows dee bottoms in centre region.

A 1 MeV beamstop enables transmission to be determined between 1 MeV and the source Faraday Cup, and 1 MeV and the strippers. A neutral beam current measuring device is also useful.

MAIN CYCLOTRON SYSTEMS

Figure 6 shows the basic layout of the Cyclone30 magnet steel. O-rings are located throughout the magnet steel, and this is a very serious shortcoming of this design. When these o-rings harden and fail, it is a major operation first to locate the vacuum leak, and second to disassemble the magnet steel, particularly when an o-ring in the lower half fails. Magnet steel is relatively soft and can bind easily, ice baths have been used to permit concentric pieces to slide past each other. The TRIUMF 30 MeV cyclotron technology avoids this problem by having double o-ring seals between the vacuum tank top/bottom and the magnet steel surfaces immediately above and below the median plane. In the TRIUMF technique only four o-rings are required, and these are easily accessible when the cyclotron is opened for maintenance.

Clean Cryo or Turbo pumping is recommended rather than diffusion pumping to prevent hydro-carbon contamination. Nickel-plated poles with pumping to achieve the low 10^{-7} Torr range is recommended.

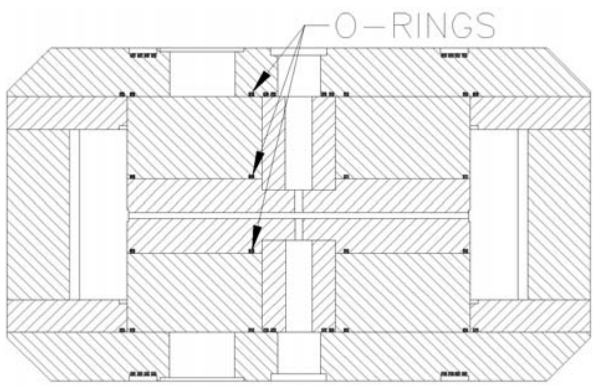

Figure 6: Cyclone30 magnet steel & o-ring arrangement. Fasteners/dowels are not shown. O-rings are not to scale.

TRIUMF 30 MeV cyclotron technology utilizes AISI 1006 as rolled annealed steel. This is electric furnace quality vacuum improved plate ultrasonically tested to ASTM Specification #A578/A 578M-85. Cast or forged steel, and voids of any sort are not permitted. In addition, the cyclotron magnet must be mapped and shimmed in an iterative procedure to ensure a high degree of isochronism is obtained. Phase excursions must be kept within ± 10° of the RF.

It is important that a magnet lid-up procedure is developed that ensures a level closure of the magnet. With the Cyclone30 RF dees separately attached to the upper and lower yokes, it is essential that these delicate structures re-connect in a controlled manner upon lid closure. We have observed damaged dee structures when such procedures are not adhered to. RF ground liners that are single contiguous copper pieces mounted to the hill edge steel rather than plated, as is done for some commercial cyclotrons, is highly recommended.

An extraction stripper that can be retracted for foil changes and sealed by a gate valve to avoid main tank venting is essential. Strippers with several TRIUMF long-life diamond like foils are recommended, as is radial, azimuthal and rotational degrees of freedom. The stripper must be water-cooled, and capable of capturing the stripped electrons for an accurate accounting of the extracted beam current. The beamline switching dipole magnet should not utilize a return yoke that is shared with the cyclotron magnet as is often done in Cyclone30 installations as shown in Figure 7. This introduces unwanted harmonics into the cyclotron magnetic field, and makes dual beam extraction tuning quite difficult.

The Cyclone30 beamlines are generally well made, but it is our recommendation additional water-cooled 4-jaw collimators with beam current readback be installed to facilitate easy beam tuning as described in [10,11,12].

Figure 7: Cyclone30 switching magnet.

CONCLUSION

This document presents practical improvements to the Cyclone30 for consistent reliable high-current operation.

REFERENCES

[1] M.P. Dehnel *et al*, "An Ion Source Upgrade for an Axial Injection Based Commercial Cyclotron", NIM B 241, 2005, p. 896.

[2] M.P. Dehnel et al, "An Industrial Cyclotron Ion Source & Injection System", 17th Int'l Conf. On Cyclotrons and their App's, Tokyo, 2004, p. 293.

[3] T. Kuo et al, "Injection Study for High Current H− Cyclotrons," Proc. 15th Int'l Conf. Cyc. & Apps., Caen, 1998, p. 381.

[4] T. Kuo et al, "A 15 mA DC H¯ Multicusp Source for Cyclotron Injection," Proc. 14th Int'l Conf. Cyc. & Apps., Cape Town, 1995.

[5] R. Baartman and D. Yuan, "Space Charge Neutralization Studies of an H− Beam," EPAC'88, Rome, 1988, Vol. 2, p. 949.

[7] W. Kleeven and R. Baartman, "Beam Matching and Emittance Growth Resulting from Spiral Inflectors for Cyclotrons," Part. Acc. 41, 1993, p. 55.

[8] M.P. Dehnel et al, "Injection System Design and Tests for the TR13 Cyclotron," EPAC'94, London, 1994, Vol. 3, p. 2367.

[9] M.P. Dehnel et al, "The Experimental Characterization of a Compact H− Cyclotron's Spiral Inflector," NIMA, 396, 1997, p.35.

[10] M.P. Dehnel et al, "A Compact Cost-Effective Beamline for a PET Cyclotron", CAARI, in press, Fort Worth, Texas, USA, 2006.

[11] M.P. Dehnel et al, "Beamline Developments in Commercial Cyclotron Facilities", NIMB 241 2005, p. 655.

[12] M.P. Dehnel et al, "Industrial Beamline Design for Radioisotope Production", 17th Int'l Conf. On Cyclotrons and their App's, Tokyo, Japan, 2004, p. 486.