AN INDUSTRIAL CYCLOTRON ION SOURCE & INJECTION SYSTEM

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Abstract

This paper describes ion source and injection system (ISIS) concepts, and techniques for improving performance in industrial cyclotrons. A new ISIS design for increasing injected beam currents, and improving accelerated beam emittances is presented. The new system has the potential to significantly boost radioisotope production at facilities utilizing axial injection based H^- cyclotrons.

INTRODUCTION

The majority of commercial cyclotrons installed to date utilize ion sources internal to the main cyclotron vacuum tank. Of the modern commercial cyclotrons utilizing axial injection for H^- beams, there are about thirty IBA Cyclone 30s, fifteen ACS (formerly Ebco Technologies Inc.) TR30s & TR19s, and two Oxford cyclotrons.

The Cyclone30s installed up until the late 1990s utilize a Lawrence Berkeley Lab (LBL) style ion source dating to the early to mid-1980s similar to [1]. The H^- beam current output by this ion source technology is typically in the 2.5 mA range, and the beam unnormalized emittance has been quoted as 400 mm·mrad [2]. The TRIUMF style ion source licensed by Dehnel Consulting Ltd. is capable of producing 15 mA of H^- beam with an unnormalized 4 rms emittance of 100 mm·mrad [3].

This paper describes axial injection design followed by the introduction of a novel ISIS. This ISIS is shown as an upgrade to a Cyclone 30 cyclotron as an example. This new ISIS would boost accelerated beam in industrial cyclotrons, which would potentially yield significantly more beam current for radioisotope production.

AXIAL INJECTION DESIGN CONSIDERATIONS

The injection system is intended to provide the transport of the ion source H^- beam to the cyclotron centre region with a high transmission rate, and minimal beam quality degradation. In addition, the beam phase ellipses are ion-optically adjusted to be most appropriate for acceleration within the cyclotron (i.e. the beam central trajectory must be injected on a prescribed orbit, and the matching of the beam phase ellipses to the cyclotron acceptances must be optimized).

Belmont [4] offers a good summary of what to consider when designing an injection system. These include: (i) space (or lack thereof), (ii) reliability of elements, (iii) adaptation of emittances between elements, (iv) beam transmission, (v) vacuum quality, (vi) space charge, (vii) axial bore magnetic field, (viii) technology of fabrication, (ix) cost.

Injection of an H^- beam into a cyclotron requires a vacuum of ~1×10^{-6} Torr to maximize space charge neutralization and maintain stripping losses at less than 5% per metre [5] for the case of no electrostatic elements. It is also important to avoid aberrations by ensuring the beam sizes in the system remain small as compared to the apertures of optical elements. It is important to select optical elements which will yield a well-focused beam through the inflector. Due to unavoidable cross-plane coupling in spiral inflectors [6], asymmetric focusing element(s), such as quadrupole magnets with rotation capability [7, 8, 9], are required to counter-act the emittance growth through the spiral inflector, and to facilitate beam matching. Choosing the correct inflector electric bend radius, tilt parameter k', and electrode aspect ratio are also very important with regards to injecting the beam with the correct position and momentum co-ordinates, and minimizing emittance growth [10].

THE PROPOSED ISIS

A basic Cyclone 30 injection line upgrade would be to replace the early 1980's style LBL ion source with a low emittance TRIUMF style ion source including lenses, vacuum box and pumping elements, and to keep the remainder of the elements as is (i.e. a strictly vertical injection system with beam direction downward). This could be done relatively inexpensively. Such an upgrade would yield an improved ISIS with more beam current available for acceleration in the cyclotron [11].

The novel ISIS proposed here goes a step further. A strictly downward pointing ISIS is somewhat unsatisfactory since flakes from the ion source can fall into the buncher, and the cyclotron inflector. For the case of the TRIUMF style ion source used in this configuration there would also be some hazard of such flakes shorting the plasma lens. To avoid this issue, it is proposed that the ion source and first section of the ISIS be horizontal in orientation followed by a 90° bending magnet to direct the beam downwards through the cyclotron magnet yoke (refer to Figure 1).

The Cyclone 30 ISIS is on the move-able side of the cyclotron. This means with every lid-up operation for cyclotron main tank maintenance the entire ISIS is moved. A certain amount of ISIS shaking occurs, and the author has witnessed systems where alignment becomes altered (verified with plumb-bob). To minimize the risk of mis-alignment, the ISIS proposed here would incorporate a sturdy industrial support and alignment structure along both sides of the ISIS.

The nominal Cyclone30 ISIS utilizes symmetric focusing elements (einzel and glaser lenses) which do not compensate for cross-plane coupling in the inflector. This

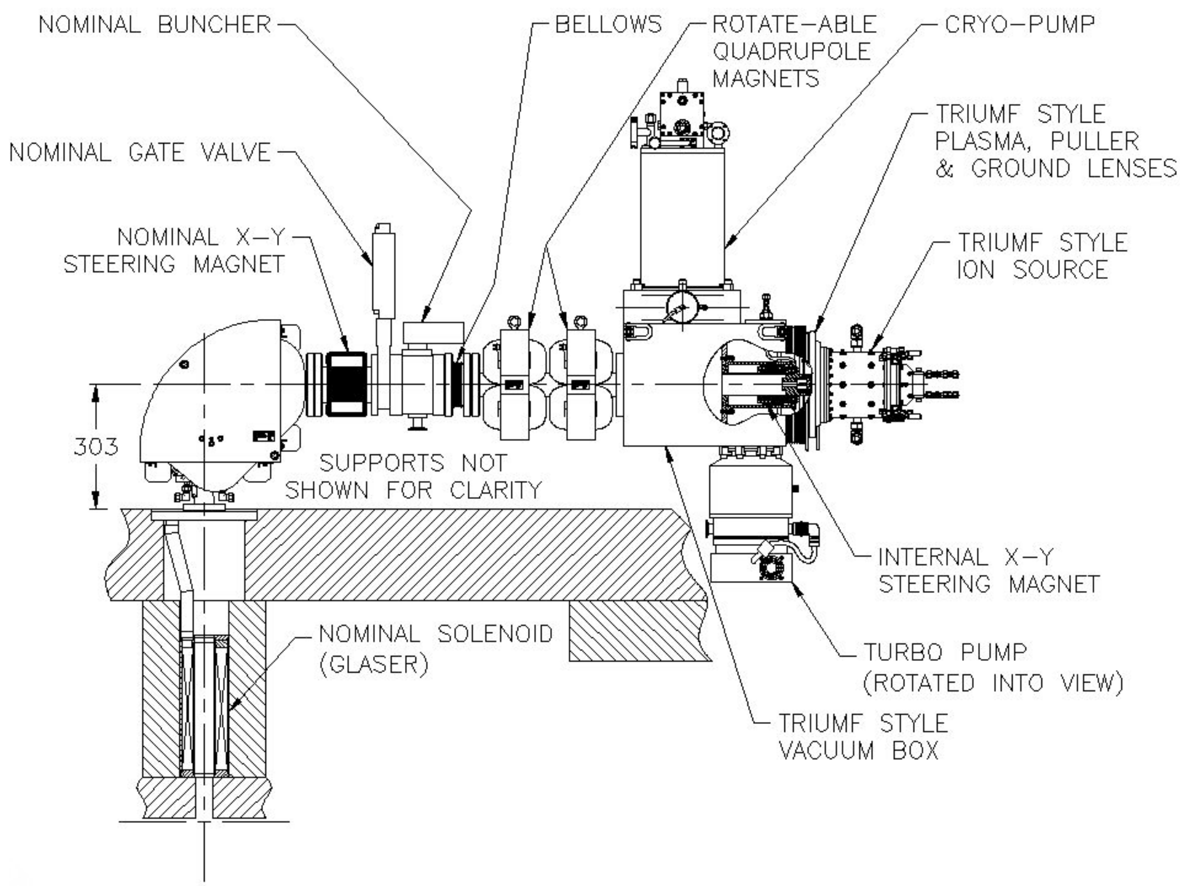

Figure 1: Layout of proposed ISIS. Dimensions in mm.

results in emittance growth. The ISIS upgrade proposed here uses rotate-able quadrupole magnet (asymmetric) focusing elements in place of the nominal einzel lens. In addition, the 90° bending magnet utilizes edge focusing.

The TRIUMF style ion source has a 15 mA H^- beam current [3] and can be run at 30 keV as required on a Cyclone 30. The 4 rms emittance at this high current output level has been measured as 100 mm·mrad unnormalized [3]. The plasma electrode is biased as compared to the unbiased Cyclone 30 plasma electrode, which enables the plasma electrode voltage to be adjusted in an iterative fashion with the puller electrode voltage to achieve both a high beam current and about a factor of 4 fewer extracted electrons as can be achieved in the non-biased case. In addition, the TRIUMF puller is very short (~21 mm), as compared to the Cyclone 30 ion source puller (~52 mm). The resultant lens action is such that in the TRIUMF case the beam receives a focusing action at the upstream end of the puller, followed by an almost immediate focusing action at the downstream end of the puller. This means that the extracted beam is transported through the puller without loss, and, thus, without puller erosion. As shown in [11], the Cyclone 30 upstream to downstream lens action is too far apart and beam strike on the inner walls of the puller causes erosion, and part replacement is required every 6-12 months. Also, the Cyclone 30 puller electron filter is a single direction magnetic dipole which significantly deflects the extracted beam off-course which causes a tear drop shaped erosion pattern in the ground lens, and part replacement every 6-12 months. This erosion is avoided in the TRIUMF design by using a double dipole magnetic filter that first deflects the beam (and removes electrons), and then corrects the beam so that it exits on axis.

The Cyclone 30 system usually employs a permanent magnet dog-leg to centre the beam after it has been extracted from the source. This magnet must be manually adjusted from time to time after lens part replacements. This requires a source venting and a trial and error process to centre the beam. In the TRIUMF ion source system, adjustments to the beam direction are made by an in-vacuum adjustable x-y steering magnet. This x-y steering magnet's settings are adjusted from the control room at any time to ensure that the beam is centred along the injection line. A beamstop and collimator (not shown in Figure 1) are used to provide diagnostic feedback to determine the extracted beam current and the beam centring.

The beam ion-optics plots are shown in Figures 2 and 3. The source beam waist parameters were taken to be x = y = 4 mm, x' = y' = 25 mrad. Beam transport is comfortably achieved without loss for the emittance envelope chosen, and a beamspot diameter at the inflector entrance of 4.6 mm is achieved (the inflector gap is 8 mm). Beamline Simulator produced the plots [12].

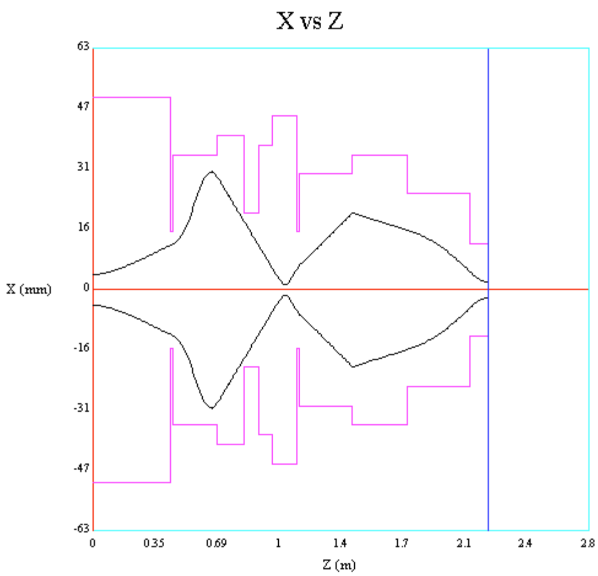

Figure 2: Horizontal H^- beam profile for proposed ISIS.

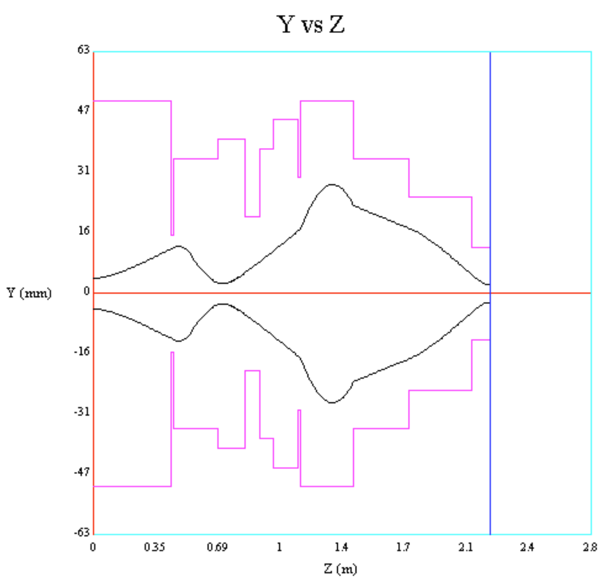

Figure 3: Vertical H^- beam profile for proposed ISIS.

Turbo pumping (900 l/s for hydrogen) is utilized for the ion source lens region, and a cryo-pump with a 200 mm flange is utilized for pumping the injection line (2,500 l/s for hydrogen). The turbo-pump and cryo-regions are physically separated in the vacuum box.

The quadrupole magnets have effective lengths of 100 mm, and apertures of 70 mm. The upstream quadrupole magnet is vertically focusing with a pole-tip field of 659 Gauss, and the downstream quadrupole magnet is horizontally focusing with a pole-tip field of 630 Gauss. The rotation angle of the quadrupole magnets may be adjusted and set during commissioning [8] to best match the injected beam to the cyclotron acceptances and for best beam transmission. The nominal Cyclone 30 bellows, buncher, gate valve and solenoid may be used. The solenoid was set at 1380 Gauss to obtain the beam profiles shown in Figures 2 & 3.

The 90 degree bending magnet was set at 1328 Gauss with an entrance pole-face angle of 43° and an exit pole-face angle of 30°. The bending magnet gap is 60 mm.

CONCLUSION

A horizontal ISIS for a high current Cyclone 30 application is proposed. It utilizes a TRIUMF style 15 mA, 30 keV H^- volume-cusp ion source, quadrupole magnet focusing elements, a 90 degree bending magnet, turbo/cryo pumping and nominal Cyclone 30 injection equipment. The authors wish to thank TRIUMF, and SICEAI-WEDC for financing.

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