Converting an AEG Cyclotron to H^{-} Acceleration and Extraction

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Abstract Clinical Trials are under way to evaluate agents labeled with the nuclide ^{225}Ac and its decay product ^{213}Bi, in targeted alpha-immuno-therapy [1]. ^{225}Ac can be produced on a medium-energy cyclotron via the nuclear reaction ^{226}Ra(p,n)^{225}Ac. To demonstrate proof-of-principle, a vintage AEG cyclotron, Model E33 [2], with an internal target, had been employed in a pilot production program at the Technical University of Munich (TUM). To enhance production capability and further support the clinical studies, the TUM facility has recently been refurbished and upgraded, adding a new external beam-line, automated target irradiation and transport systems, new laboratories, hot cells, etc. [3]. An improved high-power rotating target has been built and installed [4]. The AEG cyclotron itself has also been modified and upgraded to accelerate and extract H^{-} ions. We have designed, built, and tested a new axial Penning-type ion source which is optimized for the production of H^{-} ions. The ion source has continued to evolve through experiment and experience. Steady improvements in materials and mechanics have led to enhanced source stability, life-time, and H^{-} production. We have also designed and built a precision H^{-} charge-exchange beam-extraction system which is equipped with a vacuum lock. To fit within the tight mechanical constraint imposed by the narrow magnet gap, the system incorporates a novel chain-drive foil holder and foil-changer mechanism. The reconfigured cyclotron system has now been in operation for more than 1 year. Three long-duration target irradiations have been conducted. The most recent bombardment ran 160 continuous hours at a beam on target of ~80 micro-amperes for a total yield of ~70 milli-curies of ^{225}Ac.

Key Words AEG Cyclotron, Negative ion conversion
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INTRODUCTION

The quantity of beam that can be started in the center of a cyclotron equipped with an internal ion source depends on many parameters, including ion source geometry, gas pressure within the source, arc current, position of the arc column relative to the anode extraction slit, electric potential used to extract the ions from the source, and arrangement of the electrodes in the first few turns in the center of the cyclotron [5]. At the start of our project, inspection of the interior of the AEG Cyclotron revealed that certain of the central-region components were highly etched on the median plane along the path of the first orbit: The beam itself was trying to tell us something! After a number of ‘cut-and-try’ experiments – opening and widening apertures and channels in the respective components – we were able to substantially increase central-region beam transmittance.

ION SOURCE

The AEG cyclotron had originally been equipped with a ‘Livingston’ filament-type ion source [6] intended for production of H^{+} ions, but the processes in any ion source produce both *plus* and *minus* charge species. The Livingston source could surely produce *some* H^{-} ions, albeit at low efficiency. Positive and negative H ions are extracted from the ion source during the negative and positive peaks, respectively, of the RF accelerating voltage, but ions of the ‘wrong’ polarity travel only a fraction of a turn – and in the wrong direction – before colliding onto the exterior of the ion source or onto other central-region components.

When we reversed the polarity of the cyclotron magnet power-supply connections, we were indeed able to accelerate a few micro-amperes of H^{-} ions. Following principles enunciated by Ehlers [7] we modified the internal geometry of the Livingston source to further enhance H^- production, but due to the high power required to heat the source filament (2.5V at 330A), the entire body and anode structure of the Livingston source ran incandescent – dull red – too high a temperature for efficient H^- production. Because of space constraints, adding extra cooling was not an option; we abandoned our effort to improve the Livingston source and instead began the design and development of a compact Penning-type H^- source.

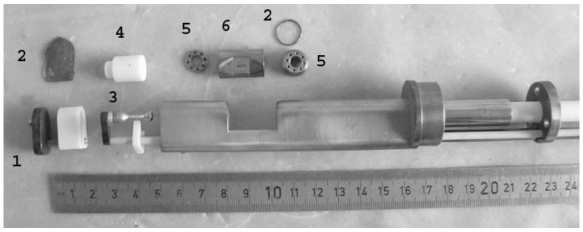

FIGURE 1. Partially-exploded view of axial Penning-type ion source: 1. Copper shield plate. 2. Flexible Graphite gas seals. 3. Lower cathode. 4. Alumina insulator to suppress ExB discharge on lower cathode stem. 5. Vented collimator. 6. Ion source anode.

In our Penning-type source, shown in a partially-exploded view (Figure 1), ionization and dissociation of H_2 gas takes place via a process [8] in which H+ ions are produced in the hot, central core of a plasma column between a pair of tantalum cathodes biased at a high negative potential. Our source-cathodes are tantalum buttons, supported on stems designed to optimize heat flow and hence cathode temperature and arc voltage [9]. The cathodes are aligned axially and placed symmetrically above and below the median plane in a cylindrical anode at the center of the cyclotron. H^- ions are produced in a relatively cooler annulus surrounding the hot central plasma column. Low-energy electrons in this cooler annulus facilitate formation of H^- ions in the presence of molecular hydrogen [10]. Internal collimators place the surface of the arc column at an optimum distance (~0.7 mm) from the anode's extraction slit. H^- ions near the extraction slit encounter a strong radial electric field generated by the cyclotron's RF extraction potential. H^- ions are thus extracted through the slit into the cyclotron's central region.

Our original goal was to achieve a beam current of ~30 µA at the target. Our beam current objective was quickly met, but source stability and lifetime were, at first, not sufficient for the long-duration irradiations that would ultimately be required.

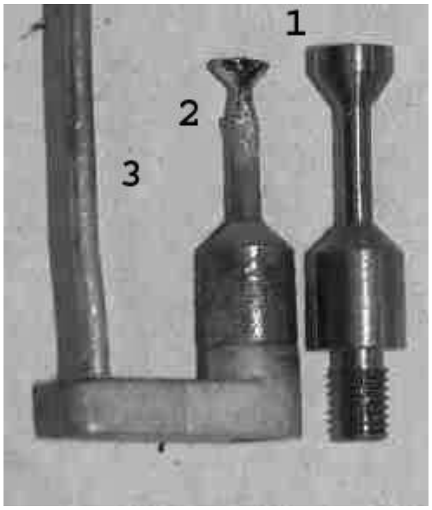

FIGURE 2. First ion source trials: 1. New, un-used ion source cathode. 2. Initial, early failure due to ExB discharge. 3. Evidence of overheating of lower cathode support during early trials.

The primary failure mode in the early trials (see Figure 2) was manifest as overheating and melting of the lower cathode stem caused by a tightly concentrated ***‘ExB’*** plasma discharge around the stem, just below the cathode tip. This was solved by embedding the lower cathode in an alumina ceramic insulator. Additional heat stress in the lower source structure was caused – not by self-heating in the source itself – but by excess power coupled into the ion source structure from nearby RF accelerating electrodes (Dees). Adding a copper bottom plate, and grounding of the lower end of the lower end of the ion source by means of a spring-loaded contact finger, has alleviated this problem. Further attention to details such as improved sealing of the ion source structure against H_2 gas leaks with flexible graphite gaskets, equalizing the partial pressure of H_2 throughout the active volume of the source by means of ‘vented collimators’, and further optimization of the central- region first-turn acceleration channel, have resulted in a steady improvement in H^- beam so that, as of July, 2008, the cyclotron is able to reliably deliver 100 µA of proton-beam current on target at the end of our beam line.

CHARGE-EXCHANGE EXTRACTION SYSTEM

Extraction of the proton beam from the outer radius of the cyclotron is accomplished by passing the H^- beam through a thin (approximately 5 micron) carbon foil which strips off both of the H^- ion's two electrons, reversing the charge state and hence the direction of the ion beam's radius of curvature. The extraction foil is positioned in the interior of a magnet hill, as shown in figure 3. The AEG cyclotron's magnet hills are pentagonal: The inner portion of each hill is a radial wedge – straight, with no spiral – out to the radius of extraction. Beyond the radius of extraction, the hill edges are parallel to a line of bisection. This is fortuitous, since it allows the extracted beam to exit almost exactly perpendicular to the edge of the hill, thus minimizing the effects of the steep field-gradient at the edge that could otherwise cause substantial distortion and de-focusing of the beam as it reverses curvature and leaves the acceleration region.

The cyclotron originally had large access ports (20 x 60 cm) on opposite sides of the vacuum tank. The port facing in the direction of our proposed beam-line extension gave us convenient access to the interior of the cyclotron's acceleration region. In a series of tests, we established trajectories for the extracted beam by mounting a thin carbon foil on a temporary arm. The carbon foil was centered on the median plane and positioned inside the magnet hill nearest the exit port, at a radius consistent with the desired energy of extraction (~22 MeV). We tuned up our H^- beam on the cyclotron's internal beam probe before letting the beam reach the radius of our temporary extraction foil. The extracted proton (H^+) beam was then allowed to exit the acceleration region and strike a copper strip that had been affixed to the inside of the access port, thus forming an activated radiologic 'hot spot' which we could subsequently measure and locate with good precision after each test bombardment. This procedure was repeated several times, moving the carbon foil in small increments in radius and azimuth to establish a locus of beam-spot location versus extractor foil position.

The new extractor drive assembly, shown on the left side of the cyclotron in figure 3, is installed through a penetration duct formerly used by one of the original diffusion pumps. The original pumps are now both removed and replaced by larger pumps mounted below new plenum boxes attached to the original 20 x 60 cm access ports. The plenum box shown in Figure 3 also incorporates a beam exit port and a mounting flange for the new beam-line.

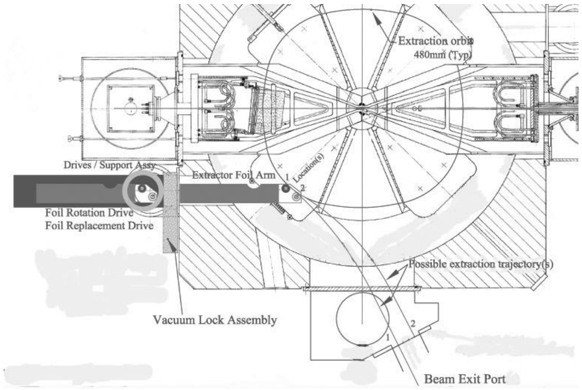

FIGURE 3. Partial plan-view of AEG cyclotron showing mounting of extractor drive assembly, placement of extraction foil, and estimated beam exit trajectory.

Tune-up and transmission of the extracted beam down a long beam-pipe requires precise adjustment and continuous control of the azimuthal position of the extractor foil. Placement of any sort of mechanical apparatus at the point of extraction is severely constrained by the narrow (~22 mm) gap between the field-correction coils occupying the space between the poles of the magnet. We therefore devised a novel, low-profile chain-driven foil-holder and drive mechanism (Figure 4) mounted on the end of a ram assembly.

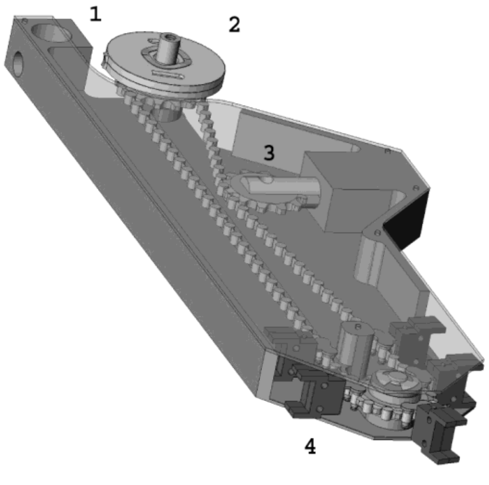

FIGURE 4. Cut-Away view of extractor foil-drive assembly showing: 1. Swivel joint for attachment to ram assembly. 2. Worm drive and sprocket. 3. Drive-chain tensioner.
4. Graphite foil-holder blocks mounted on modified chain links.

Coarse (first time) position adjustment is by means of a locking swivel joint. Fine (real time operational) adjustment is via a motor-driven worm-gear plus sprocket drive controlled from the cyclotron console.

Extractor foils have a finite service life – eventually failing due to material loss from sublimation at high temperature and/or cracking, curling, and deformation from radiation-damage-induced disruption of the graphite-material's crystalline structure. To allow for rapid changing of foils during long-duration bombardments, up to 6 foils may be mounted on special links modified to support out graphite foil holders.

The drive chain is made of type 304 stainless steel. Type 316 stainless would have been preferred, but such was available at the time. Type 304 is supposed to be 'non-magnetic' but we found there was a slight magnetic response due to work-hardening during the stamping and metal-forming process that could severely impair performance in a high magnetic field. We were able to eliminate the magnetic response by annealing the chain at ~1000 deg. F for 30 minutes, but this also caused the chain to shrink slightly, necessitating some last-minute revisions in the chain-tensioning apparatus.

WORK-IN-PROGRESS

After several hundreds of hours of operation, the stainless-steel foil-drive chain has become activated due to impinging neutral beam from gas-stripping of H—ions from the interior of the cyclotron. This makes service and maintenance problematic, but this will soon be mitigated by adding graphie neutral-beam shields to the chain links which are between each of the present foil-holding links.

ACKNOWLEDGEMENTS

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