ISBN: 978-3-95450-205-9 doi:10.18429/JACoW-Cyclotrons2019-TUP029

A 15-20 MeV/NUCLEON ISO-CYCLOTRON FOR SECURITY AND RADIOISOTOPE PRODUCTION*

C. Johnstone†, R. Agustsson, S. Boucher, S. Kutsaev, A. Y. Smirnov
Radiabeam, Santa Monica, CA, USA
R. C. Lanza, Massachusetts Inst. of Technology, Cambridge, MA, USA

Abstract

Cargo inspection systems exploit the broad bremsstrahlung spectrum from a 6 - 10 MeV, low-duty cycle electron accelerator which in the presence of significant backgrounds presents challenges in image and material identification. An alternative approach is to use ions which can excite nuclear states either directly, or through generation of secondary high-energy signature gammas which are produced from nuclear interactions in a target. RadiaBeam is designing a compact sector isocyclotron ~1.2 - 1.5 m extraction radius, with high-gradient cavities to accelerate multi-ion species up to 15 - 20 MeV/u, respectively, with large turn-to turn, centimeter-level separation for low-loss extraction without lossy foil stripping. A strong-focusing radial field profile will be optimized in a separated-sector format for control over machine tune simultaneous with isochronous orbit requirements for high-current (~0.5 mA) operation. Innovation in injection will be introduced to replace the high-loss central region. Non-security applications of the cyclotron include medical isotope production, ion radiobiology, as well as material science research and ion instrumentation development.

INTRODUCTION

In cargo scanning for Special nuclear material (SNM), detection can be performed by either passive or active interrogation. The approach proposed here is an active, accelerator-based interrogation systems based on an ion accelerator capable of 15 - 20 MeV/nucleon.

Commercially-available accelerator-based security inspection systems generally exploit the broad bremsstrahlung spectrum generated using a 6 - 10 MeV, pulsed, low-duty cycle electron accelerator (i.e. linac or betatron) which in the presence of significant backgrounds presents difficulties in image and material identification which can make precise analysis challenging [1, 2]. An alternative approach is to use low energy (10 - 20 MeV/u) ions, which can excite nuclear states either directly, or through generation of secondary high-energy signature gammas produced from nuclear interactions in a target [3]. In the presence of nuclear materials, a beam of ions or secondary gammas will excite characteristic nuclear states which can be selectively identified by an appropriate detector array via spectral absorption or emissions eliminating the broad bremsstrahlung photon background that can avalanche a detector. The multiple monoenergetic gammas can be used in transmission to differentiate materials based on density and Z. Further, the Continuous Wave (CW) beam proposed here is well matched to detector systems in both collection and response times, facilitating low-dose scans and/or a much higher gamma ray energy spectrum for signature nuclear state excitation and applying established gamma-ray spectroscopy techniques. The idea is to use low energy nuclear reactions to produce mononenergetic gammas to improve the measurement of average density and Z; improving identification of lead and uranium, for example.

Designing for a charge to mass of ½ as proposed in Table 1 would allow either protons in the form of H_2+ or deuteron beams to be accelerated, for example, and delivered using the same system with deuterons adding neutron scanning capability. Another active detection approach which uses a CW accelerator for interrogation relies on measurement of delayed radiation [4] from induced photofission uniquely identifying SNM. What is unique to beam in a CW accelerator is that it can be triggered/inhibited on an RF timescale (~25 to 50 ns) through RF control systems, optimally tailoring to detection and maximizing signal to noise ratio by controlling both the strength and duration of the delayed radiation.

Table 1: Preliminary Accelerator Parameters for Q/A = ½

Parameter	Value
Accelerated Ions	H_2^+ (p), deuterons, He, B, Li, C, O, Ne, Si
Sectors	4
Extraction Energy	15-20 MeV/u
Injection Energy	0.5-1 MeV/u
Peak Current (avg)	0.5-1 mA (CW)
Inject/Extract Radius	0.1 / 1.3-1.5m
Field @ extraction	1.3T
Acceleration	400 kV/turn (2 cavities)
RF frequency	~40 MHz (8th harmonic)

The high-current machine under design (Table 1) is also ideal for producing radioisotopes with many applications in medicine, biology, physics, chemistry, agriculture, national security and environmental and materials science. The most direct benefits are realized in medical diagnosis and therapy – expanding the availability of key or currently rare isotopes domestically is considered a high, even critical priority. One medical application is Radioimmunotherapy (RIT), a promising, new modality that selectively delivers radionuclides that emit α-particles, β-particles, or Auger electrons to tumours. The isotope group of the Nuclear Science Advisory Committee (NSAC), recognizing the gap between production and demand of α-particle-

* Work supported by U.S. Department of Energy, Office of Defense Nuclear Nonproliferation under SBIR grant DE-SC0020009
†johnstone29w@gmail.com

ISBN: 978-3-95450-205-9 doi:10.18429/JACoW-Cyclotrons2019-TUP029

emitters, advises in their long-range plan that the United States should "invest in new production approaches of ^{211}At emitters with high priority for ^{211}At and ^{225}Ac"; the latter, Actinium 225 is produced using a proton beam and Astatine 211 with an alpha beam both of which can be produced with the machine proposed here. Other isotopes in high demand in the U.S. in medical research, clinical nuclear medicine, science, oil exploration, construction, homeland security, national security, and defense include: Americium-241 Californium-252 Molybdenum-99 Uranium-232 Gadolinium-153 Promethium-147 Copper-67 Zirconium-89 Tin 117m.

In response, RadiaBeam is developing a novel compact sector iso-cyclotron, with dual, high-gradient, 0.2 MV cavities to accelerate ion species with charge to mass of ½ up to 20 MeV/u with large turn-to turn, centimeter-level separation for low-loss extraction removing the need for foil charge-changing extraction. The design will be optimized for radioisotope production and nuclear security applications – with a size and weight that allows transport between inspection sites on a truck. The higher extraction energy of 20 MeV/u and high currents are preferred for radioisotope production. The use of separated sectors allows extraction or insertion of targets at optimal energies for isotope production. With multi-ion capability (H_2^+ and He^{2+}) both ^{211}At and ^{225}Ac can be mass produced. Additionally, an intense neutron beam can be generated using a high current of protons on a Be target for production of Moly-99. This reaction requires less energy per secondary neutron than a current approach which uses a DT source – the Be target can be located inside the sub-critical assembly generating more neutrons and increasing the effective shielding.

TECHNICAL APPROACH

Two established approaches are available for ion acceleration: a linear or a recirculating machine. Ion linear accelerators (or linacs) have limited transportability and represent the highest cost due to the size of the accelerator and number of independent components and power sources needed to accelerate a hadron beam to the energies required for cargo inspection. For neutrons this is 14 MeV, or 14 MeV/u when applied to ions [5].

At these energies, AVF cyclotrons are a proven commercial and cost-effective technology for high current and compact proton applications. In this low-energy, non-relativistic regime (unlike electrons), cyclotrons can be designed with isochronous orbits and therefore can deliver a continuous beam in bunches spaced at the RF cavity frequency; a distinct advantage over low duty cycle pulsed systems and they have lower power requirements than a CW linac. AVF cyclotrons, however, have unavoidable high losses – 80% at injection during beam capture from the source in the central region and up to 60 - 80% at extraction due to closely-spaced proximate, turn-to-turn orbits; an artifact of low-gradient acceleration attributed to Dee cavities (which must fit in the gap between the poles, usually in the valley region [6]). Due to the closely spaced orbits, H^- is nominally accelerated in compact AVF machines instead of protons because foil stripping of electrons is required to charge change in order to extract. For ions, charge-changing extraction is not a practical option due to the already decreased charge to mass available for acceleration – for compact acceleration ions must be in their highest charge state. For light ions, a charge to mass of ½ is the highest charge state and allows a range of ions, H_2^+; or protons, through potentially to Ca^{20+}, to be accelerated in the same high-gradient accelerator.

Superconducting cyclotrons are similarly compact and much lighter than conventional AVF cyclotrons, but the associated cryogenics systems are not mobile nor insignificant [7, 8]. The iron-free cyclotron [9] must be superconducting as air-core normal conducting coils cannot generate strong magnetic fields without iron to reach MeV energies. As in the AVF cyclotron, only low-gradient cavities can be integrated into the accelerator, but H^- stripping extraction is unlikely to be an option at high currents to avoid potentially quenching the coils. Further, the degree of isochronism required for acceleration, and coil/machine tolerances depend directly on the accelerating voltage and therefore the type of cavity deployed.

For preferred CW operation, only separated-sector cyclotrons support high-gradient accelerating cavities (inserted in the gaps between sector magnets), high beam intensities with acceptable losses, and can accelerate multi-species of ions with the same charge to mass ratio without operational or configurational changes. The sector cyclotron was therefore chosen to allow insertion of high-gradient cavities, achieve the orbit separation required to support low-loss injection and extraction channels, and reduce costly precision machine-manufacturing tolerances.

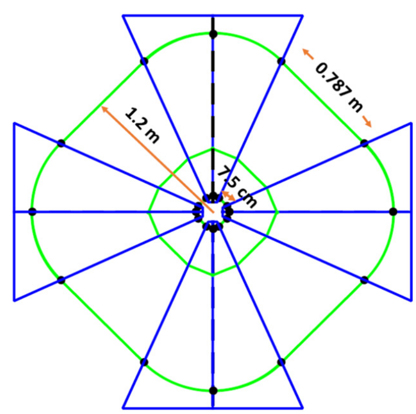

Figure 1: Schematic of the proposed cyclotron with injection drift (7.5 cm), extraction drift (0.8 m) at the extraction radius of 1.2 m

General Concept

RadiaBeam is developing a compact sector iso-cyclotron, 1.25 – 1.5 meters at the extraction radius as shown in Figure 1, with dual, high-gradient, 0.2 MV cavities to accelerate multi-ion species up to 15 - 20 MeV/u with large turn-to turn, centimeter-level separation for low-loss extraction eliminating the need for problematic ion charge changing via foil stripping. The focusing and compact foot-

ISBN: 978-3-95450-205-9 doi:10.18429/JACoW-Cyclotrons2019-TUP029

print of the AVF cyclotron will be reproduced by optimizing a radial field gradient in a sector, linear-edge magnet format with harmonic coils. Conventional shimming will attain the required isochronism for high-current (~0.5 mA) operation.

The injection energy to the cyclotron will be around 1 MeV at a radius of 12 cm, past the high-beam-loss central region plug of compact AVF and conventional cyclotrons. An innovative solid-state tandem system or RFQ with an ECR source is proposed to replace the high-loss central region – a critical design upgrade required to support high-current ion beams. Injection will occur in one of the unoccupied straight sections between sector magnets and use an inflector-type injector. The large acceleration gradient supports single-turn CW injection as the next energy orbit does not overlap the injector. A 2 mm extraction septum has been selected, given the large, meter spacing between sector magnets at extraction. A high-current, cost-effective and compact ion cyclotron based on high-gradient acceleration and low loss injection has not been built to date and the anticipated beam intensity could potentially achieve an order of magnitude higher intensity than existing ion cyclotrons.

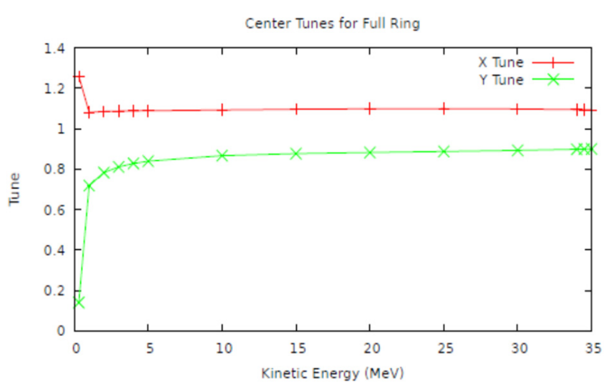

Figure 2: Design lattice machine tunes for charge to mass of ½ up to ~18 MeV/u.

Cyclotron Design

A 4-sector radial-gradient design lattice is being developed with a linear edge profile using an Enge-function end-field expansion to an isochronous specification of 10^{-5} to 10^{-4} in the Time-of-Flight (ToF) as a function of energy. Even-fold periodicity is important for the transverse dynamics and optimal when RF cavities are placed in opposing straight sections between sector magnets. The isochronous field profile will be designed for ions with a charge to mass of ½ which allows for acceleration over a wide range of light ions from protons in the form of H^{2+}, deuterons, and alphas up to Si as listed in Table 1. With strong acceleration gradients (400 keV/turn, 200 keV/cavity) and the specified field ToF field tolerance, ions with charge to mass of ½ can be accelerated in this machine without re-shimming, strong trim coils, or hardware reconfiguration of the accelerator and with fixed-frequency RF (fixed frequency RF can be retuned at the 1% level if needed). The rapid acceleration compensates for the very small changes in nuclear mass due to the nuclear binding energy. Radial field profile will not only support the ToF tolerance, linear edge-angle design and body field will be adapted to support strong, constant machine tunes in both the horizontal and vertical. The gradient radial field profile will perform the tune function of the spiral AVF pole design, serving to increase the flutter, or vertical tune (which typically decreases with radial compactness). Projected machine tunes for a preliminary concept are given in Fig. 2 for ions with a charge to mass of ½ up to ~18 MeV/u. Orbit separation at extraction for this acceleration gradient is currently estimated to be ~0.7 cm, center-to-center; sufficient for a 2 mm extraction septum. Additional extraction techniques can be applied such as inducing a betatron oscillation, as is done at PSI or a field fall-off near the extraction radius to increase the orbit to orbit separation if needed.

RF Concept

The electromagnetic design of the accelerating cavities will be driven by the cyclotron beam dynamics and magnet design. We estimate that the cavities should provide acceleration of at least 200 keV/u for the particles with charge-to-mass ratio of ½. The optimal frequency is ~40 MHz; a trade-off between acceleration gradient, stable longitudinal emittance and physical cavity size.

There are several types of RF cavities with large apertures for separate sector cyclotrons. They can be divided into two groups: double-gap (λ/4 or λ/2 transmission line type) resonators, also called 'coaxial' resonators and single-gap, waveguide-type resonators [10]. Coaxial resonators in particular can be made wide at outer radii (piece-of-pie shape, see Fig. 3, left). Double-gap coaxial type resonators can be made compact since they operate in TEM mode. However, the energy gain can vary along the aperture due to the phase difference between two gaps (transit-time factor) [11] (see Fig. 3, right).

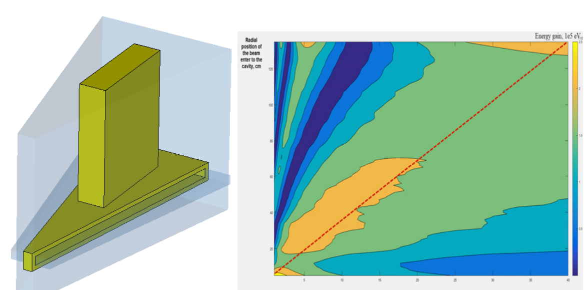

Figure 3: Quarter-wave double-gap (left) sector RF cavity, and the energy gain of the particle depending on the aperture position in a quarter-wave resonator (right), calculated in CST Particle Studio. Red line corresponds to the expected positions of the beam for the designed energy gain.

CONCLUSION

Ion accelerators have lagged technically behind advances in compact, high intensity proton accelerators. The light ion accelerator proposed here represents an innovative advance in accelerator technology for nuclear security applications including material interrogation and special

ISBN: 978-3-95450-205-9 doi:10.18429/JACoW-Cyclotrons2019-TUP029

nuclear maetrials non-proliferation which require a compact transportable and cost-efficient CW accelerator capable of producing high current ion beams with energies of 10 - 20 MeV/u and the intensities up to ~mA. This accelerator will further be an enabling technology for the commercial production of critical and currently rare radioisotopes such as At-211 and Ac-225 and also Moly-99. The most common method for producing At-211 is the bombardment of natural bismuth with α-particles. Since the threshold for the reaction is approximately 20 MeV and then peaks near 31 MeV (or 15.5 MeV/u [12]), this production channel can be accessed with the proposed cyclotron. The proposed accelerator can also be used as the injector for an ion therapy machine.

REFERENCES

[1] S. Ogorodnikov and V. Petrunin, "Processing of interlaced images in 4 - 10 MeV dual energy customs system for material recognition", *Phys. Rev. Spec. Top. Accel. Beams*, vol. 5, p. 104701, Oct. 2002.

[2] F. D. McDaniel *et al*., "Understanding X-ray cargo imaging", *Nucl. Instrum. Methods Phys. Res., Sect. B*, vol. 241, no. 1, pp. 810-815, 2005.

[3] E. S. Marshall, "New considerations for compact cyclotrons", Master Thesis, Massachusetts Institute of Technology, Massachusetts, USA, 2012.

[4] G. R. Keepin, T. F. Wimmett, and R. K. Zeigler, "Delayed neutrons from fissionable isotopes of Uranium, Plutonium, and Thorium", *Phys. Rev.*, vol. 107, p. 1044, Aug. 1957.

[5] V. Valkovic, *14 MeV Neutrons: Physics and Applications*, Boca Raton, FL, USA, CRC Press, 2015.

[6] J. H. Oh, J.-S. Chai, H. W. Kim, and B. N. Lee, "Design of RF system for compact AVF cyclotron", in *Proc. 19th Int. Conf. on Cyclotrons and their Applications (Cyclotrons'10)*, Lanzhou, China, Sep. 2010, paper MOPCP024, pp. 99-101.

[7] M. M. Maggiore, L. Bromberg, C. E. Miller, J. V. Minervini, and A. Radovinsky, "Study of a superconducting compact cyclotron for delivering 20 MeV high current proton beam", in *Proc. 20th Int. Conf. on Cyclotrons and their Applications (Cyclotrons'13)*, Vancouver, Canada, Sep. 2013, paper MOPPT020, pp. 76-78.

[8] L. García-Tabarés, "Superconducting compact cyclotrons for isotope production", presented at Academia industry matching event on superconductivity CEIMAT, May 27-28, 2013.

[9] A. L. Radovinsky *et al.,* "Variable energy acceleration in a single iron-free synchrocyclotron", MIT, Cambridge, MA, USA, Rep. PSFC/RR-13-9, Sep. 2013.

[10] P. K. Sigg, "RF for cyclotrons", *CAS - CERN Accelerator School and KVI: Specialised CAS Course on Small Accelerators*, May-Jun. 2005, Zeegse, The Netherlands, pp. 231-251. doi:10.5170/CERN-2006-012.231

[11] T. Wangler, *Principles of RF Linear Accelerators*, Wiley, New York, USA, May 1998.

[12] M. R. Zalutsky and M. Pruszynski, "Astatine-211: Production and Availability", *Current Radiopharmaceuticals*, vol. 4, no. 3, pp. 177-185, 2011. doi:10.2174/1874471011104030177