RECIRCULATING ELECTRON BEAM PHOTO-CONVERTER FOR RARE ISOTOPE PRODUCTION*

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Abstract

The TRIUMF 50 MeV electron linac has the potential to drive cw beams of up to 0.5 MW to the ARIEL photo-fission facility for rare isotope science. Due to the cooling requirements, the use of a thick Bremsstrahlung target for electron to photon conversion is a difficult technical challenge in this intensity regime. Here we present a different concept in which electrons are injected into a small storage ring where they make multiple passes through a thin internal photo-conversion target, eventually depositing their remaining energy in a central core absorber which can be independently cooled. We discuss design requirements and propose a set of design parameters for the Fixed Field Alternating Gradient (FFAG) ring. Using particle simulation models, we estimate various beam properties, and electron loss control.

INTRODUCTION

In 1999 W.T. Diamond published a paper [1] stressing the possibility of producing high yields of neutron-rich radioactive ions, using a high power electron beam from an e-linac as the driver accelerator for a Radioactive Ion Beam (RIB) facility. The electron beam could be scanned over a large area of a high Z Bremsstrahlung-production target. This would significantly reduce the power density on the Bremsstrahlung-production target and on the isotope-production target. A big advantage is that, such a facility would come at low cost, compared with other beam accelerators.

As a result during the following decade a couple of laboratories around the world tried to capitalize on this idea. At Flerov Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research in Dubna, Russia, a 50 MeV compact accelerator of the microtron type MT-25 [2] was built and the first experimental results were published in 2002 [3]. From IPN Orsay, in France, the results of the ALTO facility [4] based on a linear accelerator at 50 MeV were published in 2008. Both facilities chose a low power regime of operation of 500 W of electron beam power. ARIEL (the Advanced Rare IsotopE Laboratory) started at TRIUMF in 2010, first with the e-linac design, fabrication and installation. This first phase was complete in 2014, followed by the start-up of the electron target station design, and other concomitant projects and accelerator energy upgrades. The challenging aspect of ARIEL is to design and build a target station capable of dissipating up to 500 kW (50 MeV, 10 mA) of electron beam power.

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In this paper we name the Bremsstrahlung production target, the converter and the isotope production target, the target.

Figure 1 shows experiment results from Dubna [3]. This graph shows that only the photons at energy around 10-20 MeV induce fission reactions by exciting the Giant Dipole Resonance (GDR) of the ^{238}U nucleus. The overlapping area on Figure 1 of the GDR and the γ-quanta spectrum contains the photons of interest. The power carried by photons with energies above 3 MeV will cause thermal loads onto the converter and target. Since this is an intrinsic property of the production of photonuclear reactions, it cannot be reduced without lowering the production of radioisotopes in the target.

The low energy photons undergo photoelectric absorption (between 1 keV and 1.5 MeV) and Rayleigh scattering (below 100 keV) depositing their energy in matter. On the high-energy side, photons contribute to Compton scattering (significant up to 10 MeV) and pair production (starting at 1.022 MeV and growing for increasing photon energies), which impacts the heating up of the converter and the target, without producing any fission reactions.

An ideal configuration would have only the intrinsic power of the produced Bremsstrahlung brought to interaction with the target, with neither charged particles (electrons and positrons) nor low energy photons reaching the target.

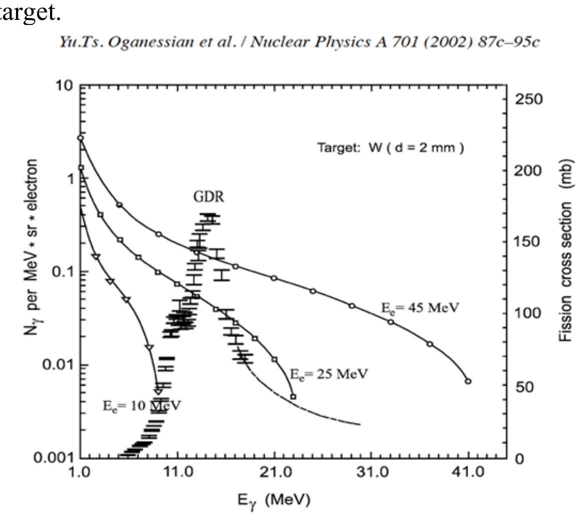

Figure 1: The γ-quanta spectrum (left scale) produced by electrons with various energies. The experimental points (right scale) correspond to the ^{238}U photo-fission cross-section [3, 5].

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MOTIVATION

Since the geometry and the design of the converter and target play an important role for the optimization of the radioisotopes production, a new conceptual design is proposed in this paper.

Conceptual Design

The proposed design consists of a spiral scaling FFAG magnetic structure [6] to inject a cw electron beam. The FFAG structure is used to provide suitable horizontal and vertical focusing to the circulating electron beam.

A thin converter is placed inside the FFAG. The simulations are performed using multi-particle transport Monte Carlo FLUKA [7], and crosschecked in GEANT4 [8]. In the FLUKA and GEANT4 simulations below (see Figures 2, 3 and 4) one can see the electron fluence and respectively the photon fluence of a 5-sector spiral scaling FFAG electron beam is making multiple passes through a 0.1 mm thick tantalum foil. By using a very thin convertor secondary electrons with low energies get trapped in the magnetic flux lines and deposit their energy in a central core absorber and in the vacuum chamber walls, which can be cooled externally. The isotope production target is placed outside of the magnet. In this way most photons will reach the target and induce the photo-fission reactions. The specifications of the 5-sector spiral scaling FFAG are summarized in Table 1.

To inject a cw electron beam at 50 MeV in horizontal direction a turn separation is necessary between the first turn and all the other turns of the electron beam. In this turn separation the injection septum is placed.

To get a turn separation we first choose a phase advance between the convertor and the injection point of ~180°, so that large angles from scattering through the foil do not contribute to the beam size at the injection point. Note: in this way the beam size at the injection point is dominated by dispersion.

The desire is to have a very thin converter foil so that secondary particles produced in the foil do not deposit their energy in the foil, in order to reduce the temperature of the converter. Secondary electrons and positrons, for instance, will escape the foil, spiral along the magnetic flux lines, and eventually deposit their energy on the vacuum chamber walls. To get additional turn separation we drive the $\nu_r = 1$ resonance using a controlled first harmonic field error. The effect of driving this resonance is illustrated in Figure 5. In this way we obtain a turn separation of about 5 mm (see Figures 2 and 4).

Table 1: Specifications of the 5-Sector Spiral Scaling FFAG

Geometrical field index	k = -0.1
Spiral angle	$\chi = 65°$
Maximum field	< 0.9 T
Radial tune	$\nu_r = 0.997$
Vertical tune	$\nu_{rz} = 1.23$

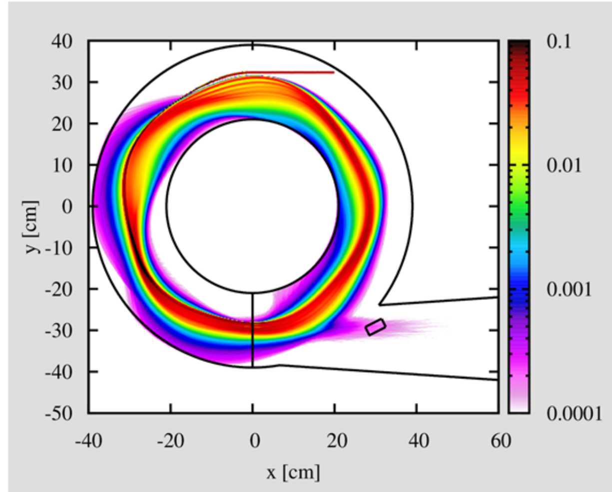

Figure 2: Electron Fluence (projected along z, arb. unit).

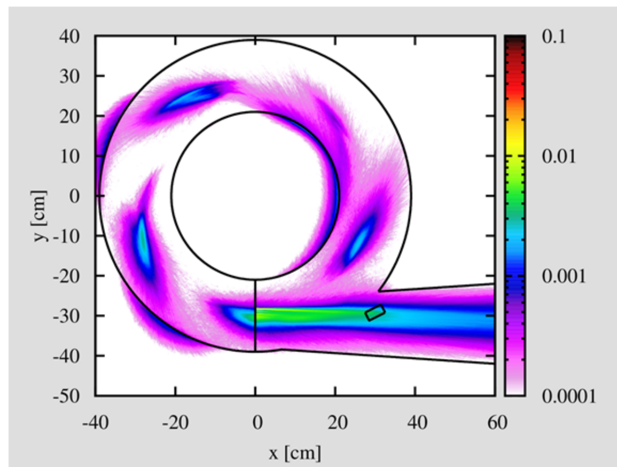

Figure 3: Photon Fluence (projected along z, arb. unit).

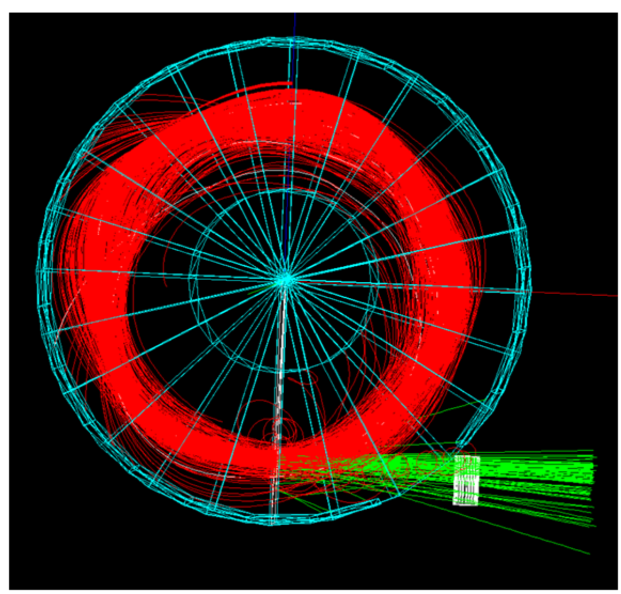

Figure 4: Visualization of electron and photon trajectories in Geant4 (top view).

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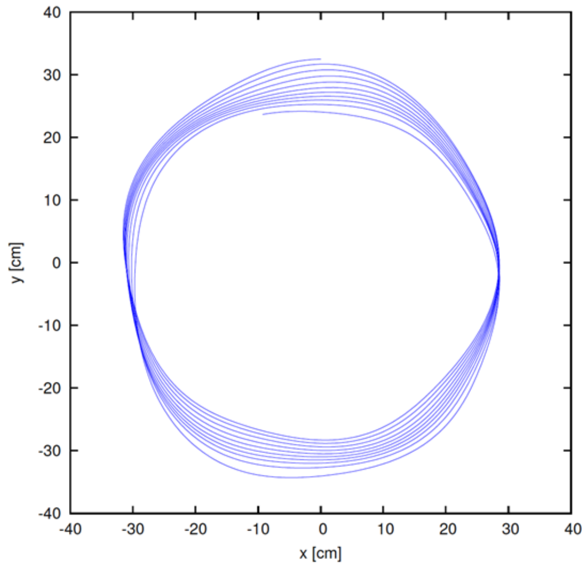

Figure 5: The orbit of a single electron (our reference particle) is shifted in the y direction using a controlled first harmonic field error that drives the $\nu_r = 1$ resonance.

THERMAL ANALYSIS

The energy deposition from FLUKA [7] is input in ANSYS [9] to perform the thermal analysis.

The thermal analysis is done for a 1 mA and 1.5 mA of electron beam at 50 MeV. The tantalum converter foil thickness is 0.1 mm and the size of the beam spot is 1 cm^2. The uranium carbide target density is $\rho = 3.5$ g/cm^3 and its volume 16 cm^3. The figure of merit is the fission rate in the uranium carbide target.

See simulation results in Table 2 and target temperature in ANSYS for 1.5 mA of primary electron beam in Figure 6.

An optimized setup would have: (1) a larger beam spot on the converter foil; (2) a reduced temperature gradient in the target and (3) a high fission rate in the target.

The temperature gradient in the target can be reduced using external ohmnic heaters, but the primary electron beam flux dictates the maximum temperature in the converter foil and the target. Using a FFAG structure, the optics can be adjusted to optimize the power density (and the beam size) on the converter and implicitly on the target. In an uranium carbide target the maximum operational temperature should be below 2100 °C [10]. The converter foil should operate at temperatures below 2500 °C although it can withstand temperatures up to 2700 °C but the foil has to be exchanged more often.

CONCLUSIONS

In this design the interaction of the charged particles with the uranium carbide target is significantly reduced. Mainly photons are interacting with the target and the energy deposition onto the target is reduced.

Since the electron beam is re-circulated, in case of a converter failure, the target is protected from a direct impact with the primary electron beam.

Table 2: Simulation results from FLUKA [7] and ANSYS [9] for fission rate, temperature and power deposition in 0.1 mm tantalum converter foil and the uranium carbide target. Convertor and target are cooled only through thermal radiation. Electron beam energy is 50 MeV.

Simulation	1 mA	1.5 mA
Fission Rate [fis/sec]	1×10^{11}	1.5×10^{11}
Max Temperature Converter [°C]	2370	2722
Power in Converter [W]	614	921
Max Temperature Target [°C]	1549	1840
Power in Target [W]	276	414
Total Power [kW]	50	75

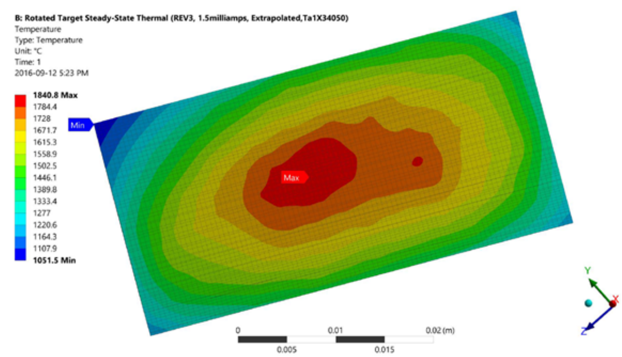

Figure 6: ANSYS thermal analysis for an uranium carbide target heated by photons generated from a primary electron beam of 1.5 mA.

The water-cooling system can be placed on outside of the vacuum chamber, so away from the electron beam, to reduce the water radiolysis.

The photon cone is transformed into a photon band, which means a more homogenous photons distribution on the target.

The proposed design should be further optimized to be compatible with the full beam power that the ARIEL electron linac can deliver.

REFERENCES

[1] William T. Diamond, "A radioactive ion beam facility using photofission", *Nuclear Instruments and Methods in Physics Research* A, vol. 432, issue no. 2–3, pp. 471–482, 1999.

[2] A. G. Belov *et al.*, in: Yu.P. Gangrsky (Ed.), *Workshop on Application of Microtrons in Nuclear Physics*, JINR Preprint D-15-93-80, 1993, p. 20.

[3] Yu. Ts. Oganessian, S. N. Dmitriev, J. Kliman, O. A. Maslov, G. Ya. Starodub, A. G. Belov and S. P. Tretiakova, "RIB product ion with photofission of uranium", *Nuclear Physics* A, vol. 701, issue no. 1–4, pp. 87–95, 2002.

[4] M. Cheikh Mhamed, S. Essabaa, C. Lau, M. Lebois, B. Roussiere, M. Ducourtieux, S. Franchoo, D. Guillemaud Mueller, F. Ibrahim, J. F. LeDu, J. Lesrel, A. C. Mueller, M. Raynaud, A. Said,

ISBN 978-3-95450-167-0

D. Verney, and S. Wurth, “RIB production by photofission in the framework of the ALTO project: First experimental measurements and Monte-Carlo simulations”, *Nuclear Instruments and Methods in Physics Research,* vol. B 266, pp. 4092–4096, 2008.

[5] J.T. Caldwell *et al.*, *Phys. Rev.* vol. C 21 p. 1215, 1980.

[6] K. R. Symon, D. W. Kerst, L. W. Jones, L. J. Laslett, and K. M. Terwilliger, “Fixed-Field alternating-gradient particle accelerators”, *Phys. Rev.* vol. 103, p. 1837, published 15 September 1956.

[7] A. Ferrari *et al.*, “FLUKA: a multi-particle transport code”, Internal Reports, CERN-2005-10, 2005, INFN/TC_05/11, SLAC-R-773.

[8] S. Agostinelli *et al.*, “Geant4 - A simulation toolkit", *Nuclear Instruments and Methods,* vol. A 506, pp. 250-303, 2003; J. Allison *et al.*, “Geant4 Developments and Applications”, *IEEE Transactions on Nuclear Science,* vol. 53, issue no. 1, pp. 270-278, 2006.

[9] ANSYS® Academic Research, Release 16.0.

[10] Y. Zhang and G. D. Alton, “Design of high-power ISOL targets for radioactive ion beam generation”, *Nuclear Instruments and Methods in Physics. Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 521, issue no. 1, pp. 72–107, 21 March 2004.

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