

RECIRCULATING ELECTRON BEAM PHOTO-CONVERTER FOR RARE ISOTOPE PRODUCTION*

A. Laxdal[†], R. Baartman, I. Bylinskii, A. Gottberg, F.W. Jones, P. Kunz, T. Planche[‡], A. Sen, TRIUMF, Vancouver, BC, Canada
 S. Ganesh, University of Waterloo, Canada
 L. Lopera, McMaster University, Canada

Abstract

The TRIUMF 30-75 MeV electron linac has the potential to provide 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, exploiting an optimized energy range for production of gamma rays used for photonuclear reactions inside of a secondary target. The remaining energy is then deposited 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 rates of neutron-rich radioactive isotopes through photo-fission of heavy target nuclei, 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, significantly reducing the power density on the Bremsstrahlung-production target, as well as, on the isotope-production target. A major advantage of an electron-driven production system is lower costs as compared to a high-energy hadrons accelerator.

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. The ARIEL (Advanced Rare Isotope Laboratory) facility started at TRIUMF in 2010, first with the e-linac design, fabrication and installation,

as well as with the construction of buildings for the target and RIB beamline systems. This first phase was completed in 2014, followed by the start-up of the electron target station design, and other concomitant projects and accelerator energy upgrades. In ARIEL one target station will be served by TRIUMF's main 500 MeV cyclotron, while a second target station will receive electron beam from the e-linac. The challenging aspect of the electron station is the requirement to dissipate up to 500 kW (50 MeV, 10 mA) of electron beam power.

In this paper we use the term 'converter' for the Bremsstrahlung production target, and the term 'target' for the isotope production target.

Figure 1 shows gamma intensities recorded for different electron beam energies in Dubna [3] together with experimental data for the photo-induced fission process in ^{238}U . Only the photons at energies between 8-30 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. All photons at lower energy will not contribute notably to the production of rare isotopes but will impose thermal load onto the target.

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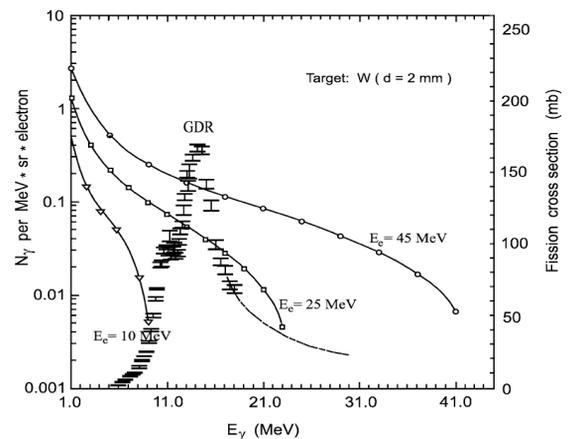


Figure 1: The γ -quanta spectrum (left scale) produced by electrons with various energies. The experimental points (right scale) correspond to the ^{238}U photo-fission cross-section [3, 5].

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

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[†] aureliat@triumf.ca [‡] tplanche@triumf.ca

increasing photon energies), being stopped in the target and depositing thermal power.

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

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 presented in this paper, which has potential to make use of the entire power of TRIUMF's electron linac.

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, thinner than in conventional designs, is placed inside the FFAG and the isotope production target is placed outside of the magnet. In this way electrons are deflected rather than stopped and mainly photons will reach the target and induce the photo-fission reactions.

The simulations are performed using the multi-particle transport Monte Carlo code FLUKA [7], and crosschecked in GEANT4 [8]. In the FLUKA and GEANT4 simulations below (see Figures 2 and 3) one can see the electron fluence and respectively the photon fluence of a 5-sector spiral scaling FFAG. The electron beam (at 50 MeV) is making multiple passes through a 0.1 mm thick tantalum foil. For electron beams at 50-70 MeV the photon beam becomes more collimated in forward direction, which allows placing the target further away from the converter foil. This is relevant for this design since the target requires additional services, such as high voltage, and operates preferably outside the magnetic field.

The specifications of the 5-sector spiral scaling FFAG are summarized in Table 1.

To inject a cw electron beam at 50-75 MeV in horizontal direction a turn separation is necessary between the first turn and all the other turns of the re-circulated electron beam. In this turn separation the injection septum is placed. To get a turn separation we first choose a phase advance between the converter and the injection point of $\sim 180^\circ$, 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. 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 4. In this way we obtain a turn separation of about 5 mm (see Figures 2).

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

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

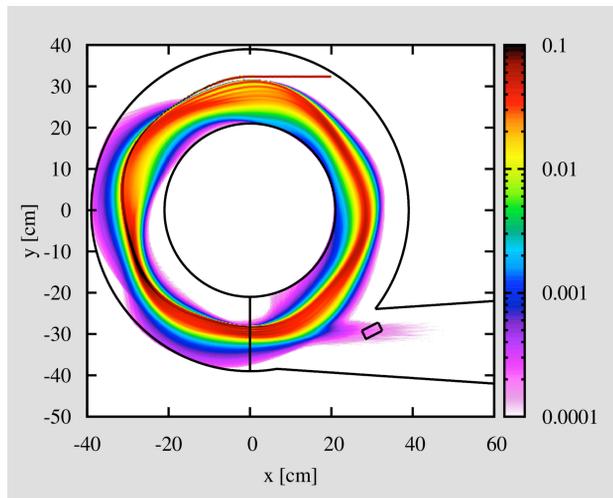


Figure 2: Electron Fluence (projected along z, arb. unit).

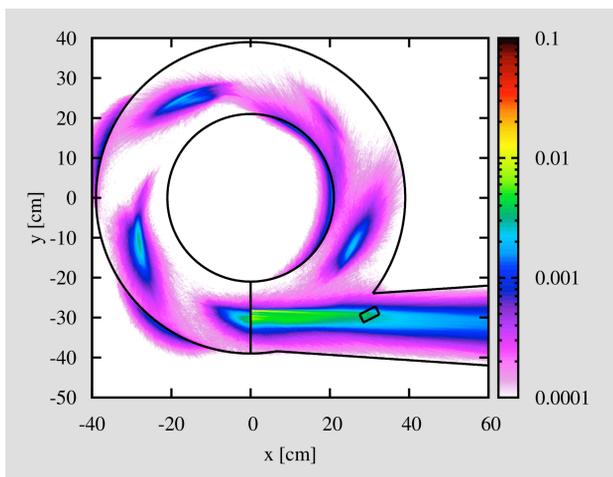


Figure 3: Photon Fluence (projected along z, arb. unit).

The desire is to have a very thin converter foil for maintaining its temperature low. By doing so, the secondary electrons and positrons produced, will escape the foil, spiral along the magnetic flux lines, and eventually deposit their energy in a central core absorber and on the vacuum chamber walls, cooled externally.

Further optimizing the FFAG tune would allow to: minimize the losses of effective photons in the poles of the magnet; enlarge the beam spot on the converter foil and, in turn, accept higher electron beam intensity; reduce the temperature gradient in the target and produce a further increased fission rate in the target.

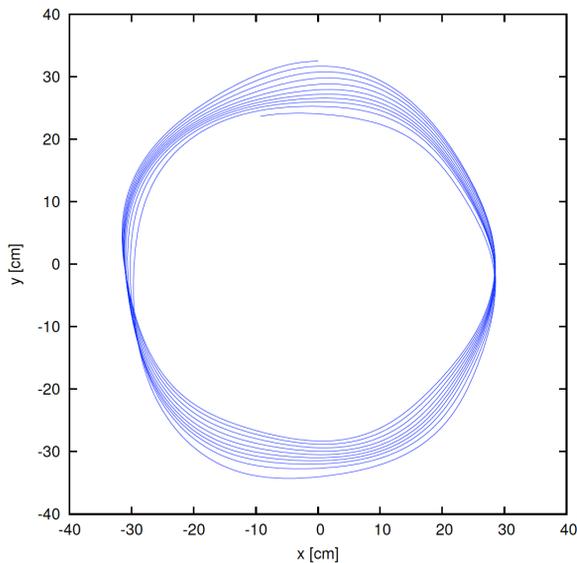


Figure 4: The orbit of a single electron (our reference particle) is shifted in the y direction using a controlled first harmonic field error that drives the $\nu_r = 1$ resonance.

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 2.5 mA and 1.5 mA of electron beam at 50 MeV and 75 MeV respectively. The tungsten converter foil thickness is 0.1 mm and the size of the beam spot is 1 cm². The uranium carbide target density is $\rho = 3.5$ g/cm³ and its volume 15.9 cm³. The figure of merit is the fission rate in the uranium carbide target.

Using a FFAG structure, the optics can be adjusted to optimize the primary beam size, and implicitly the power density on the converter and on the target. The electron beam flux dictates the maximum temperature in the converter foil and the target. The temperature gradient in the target can be reduced by increasing the electron beam size or by rastering the beam in front of the converter foil. If additional heating is required to maintain the target at its desired temperature and temperature homogeneity external ohmic heating is applied. In a uranium carbide target the (optimum) maximum operational temperature should be around 2000 °C [10], before the vapour pressure becomes detrimental for the operation of the adjacent ion source.

The intrinsic limitation of a high-power target for ISOL beam production is the amount of power that can be dissipated from the target. Currently, only radiative cooling has led to sustainable target temperature profiles and reliable release of short-lived isotopes, limiting the in-target power deposition to below 20 kW. The converter foil should operate at temperatures below 2500 °C or 2700 °C if the foil can be exchanged regularly. By using a 60 μ m thick commercial black rhenium coating [11] on the converter foil and on the target, one would push the effective emissivity to $\epsilon > 0.9$ (see temperature results in Table 2 and Figure 5). In the FFAG concept design, the

power deposition in the isotope production target is well below 1 kW, even at a primary electron beam power beyond 100 kW. This is significantly lower than in routine ISAC-TRIUMF high power targets where the 500 MeV, 50 kW proton beam deposits approximately 8 kW thermal power, giving room for further increase of electron beam intensity or target thickness.

Table 2: Simulation results from FLUKA [7] and ANSYS [9] for 0.1 mm tungsten converter foil and the uranium carbide target of 14 g/cm² target thickness, with emissivity $\epsilon = 0.9$ (60 μ m black rhenium coating), cool only through thermal radiation.

Electron Beam Energy [MeV]	50	75
Electron Beam Intensity [mA]	2.5	1.5
Fission Rate [fis/sec]	2.35×10^{11}	3×10^{11}
Max Temperature Converter [°C]	2451	2094
Power in Converter [W]	1540	1210
Max Temperature Target [°C]	1834	2172
Power in Target [W]	670	849
Total Power [kW]	87.5	112.5

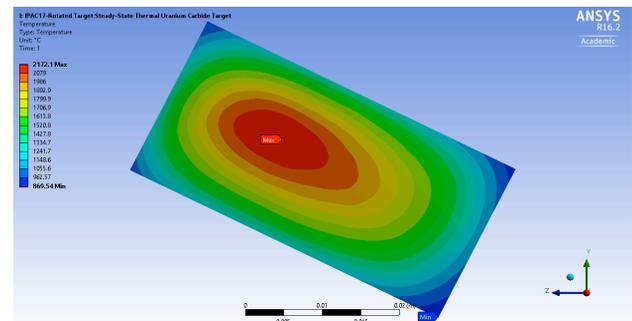


Figure 5: ANSYS thermal analysis for an uranium carbide target heated by photons generated from a primary electron beam of 1.5 mA at 75 MeV.

CONCLUSIONS

The concept of combining a re-circulating electron beam with an ISOL-type production target appears to be a feasible solution to address the enormous power deposition of a high-intensity electron beam when impinging directly onto an isotope production target. In multiple passages through the converter foil an optimized gamma spectrum is emitted to the photo-fission target, before low energy electrons are deflected and absorbed internally. Therefore, the interaction of the charged particles with the uranium carbide target is reduced. The resulting energy deposition in the target decreased significantly, allowing accepting higher electron beam intensities, leading to improved fission and isotope production rates. For an electron driver beam at 75 MeV only 0.75% of the total power is deposited in the uranium carbide target and 11% in the internal converter foil. The

rest of the power is dumped in the central core absorber and on the vacuum chamber. 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. The water-cooling system can be placed outside of the vacuum chamber, away from the electron beam, to lower the water radiolysis and the production of hydrogen gas. The photon cone is transformed into a photon band, which means a more homogenous geometrical distribution of the photons 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. Implementation studies are planned in order to allow experimental concept studies in the future.

[11] ULTRAMET Advanced Materials Solutions - <http://www.ultramet.com/>

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