Simulations for the future converter of the e-linac for the TRIUMF ARIEL facility

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Abstract. In the next years, TRIUMF activity will be focused on building a new facility to produce very intense neutron rich radioactive ion beams. Unlike others ISOL facilities, the e-linac primary beam, that will induce the fission, is an intense electron beam (50 MeV energy and 10 mA intensity). This challenging choice, which make this installation unique, despite the ALTO facility, makes an average fission rate of \(10^{13} \text{--} 14\) fissions/s in the target. This beam is sent on an uranium carbide target (UC\(_x\)), but due to its power, it is essential to insert a “converter” on the beam path to avoid a target overheating. The purpose of this converter is to convert electrons into Bremsstrahlung radiation. The \(\gamma\) rays produce excite the dipole resonance of \(^{238}\text{U}\) (15 MeV) inducing fission. Energy deposition, fission rate and thermal behavior were simulated using Monte Carlo techniques are presented in this paper.

1. Introduction

From fundamental nuclear research to nuclear medicine, Rare Ion Beams (RIB) represents the future of these research fields. TRIUMF exploits the ISAC facility since more than ten years now. In order to deliver more RIB to physics experiment, TRIUMF is proposing to add two new target stations. One will be driven by a new electron linear accelerator while the second on will utilize proton beam from the H\textsuperscript{−} cyclotron. The new proton beam will come from an unused extraction port, BL4. The upgrade will come in two phases, the first phase will utilize the electron for producing photo-fission, the second phase will utilize the proton beam for producing rare isotopes. This expansion presents the particularity to use the photo-fission as the reaction mechanism used to produce exotic nuclei. This makes, with the ALTO facility [1], the only two installations in the world to use this specific process for RIB production.

The actual ISAC facility at TRIUMF is an ISOL facility using the cyclotron proton beam (500 MeV and 100 \(\mu\)A) on several target material, mainly refractory foils or carbide target for rare isotope beam production. The facility has two independent target stations. This allow service on one while producing and delivering radioactive beam on the other. The ARIEL (see fig. 1) new facility includes a driver, two target stations, two mass separators and a post acceleration section.

2. Presentation of the ARIEL facility
The main goal of the ARIEL facility is to provide more RIB for physics experiments, the actual ISAC facility is one user only. The installation of an electron LINAC will provide a second driver to produce RIB. The use of electron beam can induce photo fission via the giant resonance or producing $^8\text{Li}$ via $^9\text{Be}(\gamma,p)^8\text{Li}$. The later one can be used for material science. The facility can be easily divided in two section the target hall and the separator hall. Like for ISAC the target hall will house the target station, the hot-cell for target exchange and maintenance, the nuclear ventilation, the vacuum system and cooling system. Like it is the case for ISAC the new facility will utilize target module to shield the key component from radiation. But, unlike ISAC there will be no other module, the target module is directly connected to the proton beam line, beam dump and heavy ion beam line using flexible joint for ease of services. The extracted beam will be analyzed via a series of mass separators and will be directed to the actual ISAC experimental hall to be accelerated by the room temperature LINAC or to the final stage by the ISAC-II superconducting LINAC.

The future e-linac utilises superconducting technology for the accelerating cavities. The general layout of the machine is composed of an injector cryomodule (ICM) followed by four 9-cells cavities (10 MV/m) to raise the electron kinetic energy up to 50 MeV. The ICM is the part where the electrons are accelerated from 100 keV to 5 MeV. The injector module has a capture section consisting of two single cells and an injector cavity to match the beam to the accelerating section downstream. The electron beam is produced with a modified thermionic gun. The beam is bunched using a normal conducting buncher before being injected into the ICM. All the main parameters of the linac are presented in M. Marchetto et al. work [2].

3. Detailed description of the future converter

Beyond 2015, the ARIEL facility will be tooled up with a 500 kW electron beam. Considering such power, it is impossible to send it directly on the uranium carbide (UC$_x$) target like other photo-fission facilities with smaller beam intensity [1]. To avoid target deterioration, it is necessary to convert the electron in photon. This apparatus is designed to convert the electron energy into gamma rays via the bremsstrahlung radiation. The photons will enter the target and induce the fission of $^{238}\text{U}$. In the following sections, we will present the results from from simulations to draw a suitable converter geometry.

With energy of 50 MeV and 10 mA intensity, the energy deposit (∼ 90 J/mm$^3$) in a high Z material like lead is really larger to enthalpy of vaporization (9.732 J/mm$^3$). is to use have moving geometry in order to dissipate the energy over a larger volume. Furthermore with such beam power, the amount of energy deposited in the target is to high to maintain its integrity. The converter has to stop most of the beam energy to limit the deposited power in the target. TRIUMF has developed for the ISAC facility a 25 kW target [3], so in this work, we limited the target energy to 50 MeV.
ourselves to 25 kW of dissipated power in the target. The breaking radiation intensity increases with the square of the atomic number, so the ideal material is one with high Z. For smaller beam power (50 kW and 100 kW), tantalum, with its high Z (=73) and high melting point (3017 °C), is a suitable material for a converter. But in this particular case a heavier material was needed to stop the beam more efficiently. Unfortunately, all those have lower melting points and may turn to liquid state. To avoid their dispersion, they will have to be embedded in a tantalum shell. There is in practice two choices, mercury or lead. Lead is preferable since it is a solid at room temperature while mercury is much more difficult to use due to its environmental issues. For the mobile part, we will have a tantalum ring with lead embedded inside.

Cooling system will have to deal with slightly active water system. To do so, a hull containing a cooling fluid like water and the tantalum and lead converter was studied. To minimize the beam interaction with the hull, very light materials were chosen. Two graphite windows are added at the beam entry and exit point (see fig.2). The hull can be made of standard material like aluminium. A conceptual drawing is shown in figure 2. In this geometry along the beam axis is composed of 1 mm of graphite, 5.8 mm of water, 1mm of tantalum, 8 mm of lead, 1 mm of tantalum, 5.8 mm of water, 1 mm of graphite and 27.2 mm of vacuum before entering the target. For future Monte Carlo simulations, geometry files were generated using SolidWorks® in the STEP format. Then using the FASTRAD software [4], STEP files were converted to a GEANT4 readable format (gdml). Then GEANT4 will be used to calculate the spatial distribution of energy deposit and the fission rate in the target. In a second step, the thermal evolution of this converter will be tested through an ANSYS® simulation.

4. The GEANT4 simulations

GEANT4 [5, 6] is a C++ software toolkit for the simulation of the passage of particles through matter. It includes a complete range of functionality including tracking, geometry, physics models and hits. This program presents all the characteristics required to perform the wanted simulations. It takes explicitly and successfully the Bremsstrahlung process into account [7]. Furthermore, it is designed to insert new physics processes like the ones used to detail the photo-fission itself.

The interaction of the electron with the converter nucleus produces a continuous spectra with the maximum energy equal to the initial electron energy [8]. The angular distribution of the
Bremsstrahlung spectrum is anisotropic [9] with a maximum emission in the beam direction. The photons can excite the giant dipole resonance of $^{238}$U and then induce fission. This process is then called photo-fission. The $\gamma$ absorption by the nuclei that composed the target, implies different photo-nuclear reactions: $(\gamma, F)$, $(\gamma, n)$ and $(\gamma, 2n)$. These are the main processes to absorb photons in the target. In their work, J. T. Caldwell et al. [10] give a detailed description of the total $\gamma$ absorption cross-section: $\sigma(\gamma, \text{tot}) = (\gamma, F) + (\gamma, n) + (\gamma, 2n)$ with $(\gamma, F) = (\gamma, f) + (\gamma, nf)$. To be introduced in GEANT4, the three photo nuclear processes cross-section were fitted using experimental data as shown in figure 3 and than the fit were included in GEANT4 libraries. The purpose of these simulations was to determine the number of fissions in the target. The insertion of $(\gamma, n)$ and $(\gamma, 2n)$ processes needed more caution. These reactions produce neutrons which can induce fission. Their emission had to be explicitly declared in GEANT4 library. For this, phase space calculation packages, provided with ROOT, were used to determine the outgoing neutrons quadri-vector. Using pre-existing libraries, we were able to include fissions from these neutrons. All these processes were tested by reproducing existing results. In his work, M. C. Mhamed [12] performed shielding calculations for the ALTO project. Using FLUKA, he simulated photo-fission as a multi-step process ($\gamma$ absorption and fission of the compound nucleus) using 14 MeV neutron induced fission cross-sections. These simulations were successfully compared to experimental measurements. And these experimental results were successfully reproduced with the new GEANT4 libraries.

With geometry files provided by FASTRAD and new physics processes, spatial distribution of energy deposit was calculated. During the simulation procedure, a careful look was given to maximize the number of fission in the target and to limit power dissipation in the target to 25 kW. The spatial distribution given on figure 4 was obtained. The converter structure is easily recognizable. The highest deposit takes place in the lead layer as expected. The highest temperature part of this distribution receives 187 W per cubic mm. This is by far beyond the vaporization enthalpy ($\sim 10$ J/mm$^3$) for lead. It indicates, that without any rotation of the wheel, elements would be vaporized in the beam path. The distance between the target and the converter is assumed to be 35 mm between the exit of the lead layer and the target entry. With this setup, the number of fission in the target is estimated to be $6.5 \times 10^{13}$ fissions/s. The total power deposited in the target-converter ensemble is 340 kW. The 160 kW missing are mainly transported by photons, scattered electrons which are isotropically (due to diffusion in the target) emitted in space after passing through the converter or the target. The proposed
5. The ANSYS simulations

For this, the ANSYS® workbench interface was used. Geometry was imported from Solidworks®. Then, using the interface, heat exchange processes (called loads) were defined. Convection loads were added on the tantalum wheel faces and on the inner faces of the hull. The film coefficient (convection main parameter) was calculated using different approaches [13]. Then radiation loads were applied on all the external surfaces of the converter as it may be placed under vacuum. An ANSYS macro was written to apply the energy deposit as a heat generation load. The macro used the spatial distribution written from GEANT4 into a text file.

In this simulation, the wheel has to move. Due to this, calculations were split in two steps. First, energy deposit was only applied to the hull without any rotation. Then, the wheel rotation was taken into account by applying this load only to the tantalum and lead structure. Thanks to the ANSYS® macro, the spatial distribution was rotated around the wheel axis with a rotational speed chosen as a parameter. Thermal simulation results for the hull are presented on figure 5. The temperature distribution on fig.5 corresponds to the steady state after 8 s of beam exposure. Maximum temperature (1124 °C) is reached on the graphite window center. Just as a reminder, graphite melting point is 3550 °C: the graphite window can resist constant beam exposure. The hottest point on the hull itself is at the interface between graphite window and the aluminium: the temperature in this region is below 180 °C. This result shows that the hull is well designed to resist the beam exposure without altering its integrity. For the mobile part, the last thing to determine is the wheel rotation speed. The beam spot is $2 \times 10^{-2}$ rad large. The hottest point on the wheel receive 256 W in a mm$^3$. Fusion energy for tantalum is 74 J/mm$^3$: tantalum layers melt in 0.3 seconds. To avoid this, the hottest spot need to go through the beam in less than 0.3 s. Then rotation speed for the wheel needs to be larger than $2 \times 10^{-2}$ rad / 0.3 s that is to say 0.6 rpm. The temperature distribution, calculated for a rotation speed of 1.5 rpm, presented on figure 6, present a maximum of 229 °C in the lead layer. Outside the beam spot, the wheel surface have a temperature close to the water temperature (about 10 °C). The only exception is a cold spot that appear just before the beam impact. This value appear on one node on the wheel surface is considered to be a numerical discontinuity.

From GEANT4 to ANSYS®, we have checked the validity of this geometry in term of number of fissions/s and thermal behavior. To move forward we will perform real engineering and start experimental tests of the converter and cooling system. In term of temperature, simulations shows, with a correct rotation speed, that the wheel can be exposed to the beam over long period of time as it is expected. As a consequence, this geometry is suitable for the future e-linac.

geometry fulfill the mandatory criteria to move forward to the thermal simulation step.

Figure 5. Front view of the ANSYS® result for the thermal analysis of the beam exposed hull. The total beam power is 500 kW.
Figure 6. Temperature distribution calculated with ANSYS® result for the thermal analysis of the rotating wheel.
The time is 10 s after the starting of calculation. The rotation speed was set to 1.5 rpm.

6. Conclusions
With the ARIEL facility, TRIUMF is about to start an ambitious project for a future installation using photo-fission and reach up to several $10^{13}$ fissions/s in the target. If the technological challenge of building a superconducting linac is about to be overcome, the use of this intense electron beam remains bounded to the converter and these simulations show that we have a concept that can be the base of an engineering test. A suitable geometry has been determined, some tests are necessary to confirm those results. It can be performed at the same rhythm as the linac construction. Some interesting additional outcomes appeared in this work. First of all, new physics library were computed for GEANT4. Photo-nuclear processes are now more carefully taken into account, and can be used for photo-fission simulations. The next development should be to integrate the fragment fission mass distribution for the $^{238}$U in these libraries. For example, it will allow simulations of production yields. The second interesting outcome is the discovery of the FASTRAD software. It is a surprising footbridge beyond the CAD systems and GEANT4. Its use will, certainly, change the way of introducing more complicated geometries in GEANT4.

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