MULTI-CODE MODELLING OF MOMENTUM COLLIMATION IN THE TRIUMF ARIEL LINAC

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Abstract

The electron linac of the TRIUMF ARIEL facility will provide CW beams of 50–75 MeV and up to 0.5 MW of beam power, with consequent requirements for low-loss operation. One factor in controlling beam quality is the reduction of the low-momentum tail which arises from the RF-modulated 300 kV electron gun. To study momentum collimation between the injector and the main linac, and its implications for downstream beam characteristics, a simulation model has been constructed using several tracking and optics codes, linked together by scripts and data converters. The model follows the evolution of the beam from the gun through the injector linac and the 10 MeV transfer line where the proposed collimator is located. The components, methods and results of this application are described.

INTRODUCTION

The injector for ARIEL[1] comprises a 300 kV thermionic gun followed by focusing and bunching elements and a superconducting 1.3 GHz RF cavity (ICM) boosting the energy to 10 MeV. Pulsed beam at an average current of 10 mA is obtained by RF-modulating the gun at 650 MHz resulting in a bunch charge of ∼16 pC.

Studies of the gun and LEBT predict that within the expected range of operating scenarios there will be a long sparsely-populated low-energy tail at the trailing end of the bunch (see Figure 1). This will persist through the ICM and lead to losses at various downstream locations.

The transport of electrons from the ICM to the main linac (ACM) is achieved by the EMBT transfer line. In Phase I of ARIEL the EMBT will be implemented in a 2-dipole configuration, with a possible future upgrade to a 3-dipole merger section for RLA and ERL applications. In both cases, it is proposed to place an electron collimator in the straight section after the first dipole of the EMBT. In the following we describe simulation studies of the collimator and of its efficacy in minimizing uncontrolled losses.

PROGRAM CHAIN

The effectiveness of momentum collimation depends critically on the structure of the low-momentum tail in relation to the core of good beam which must pass unimpeded. Additional factors of concern are the survival of primary (outscattered) and secondary electrons arising from the beam interactions in the collimator material, and the survival of the collimator itself under heating due to electron energy loss. The simulation study must therefore provide: (1) accurate particle coordinate data at the collimator location, (2) sufficient particles in the tail to measure performance, (3) a complete description of scattering and energy loss in the collimator, and (4) estimates of surviving low-momentum electrons.

To provide this level of detail we have chained together a series of codes as follows:

1. **GPT** (General Particle Tracer): Emission and tracking of electrons in the 300 kV gun
2. **Astra**: Tracking from 300 KeV to 10 MeV in the LEBT and injection cryomodule
3. **Accsim**: Tracking in the EMBT transfer line
4. **G4Beamline**: Interactions in the collimator jaw material and tracking of primary and secondary particles in the collimator region and the balance of the EMBT

To implement the above chain a series of scripts and small programs have been developed to provide the necessary data and units conversions. Auxiliary programs employed include Optim, for interactive optics design of the EMBT; DIMAD, utilizing Optim output to analyze the EMBT optics and obtain an element list and strength data for G4Beamline; and Matlab, where scripts have been developed to read Astra, G4Beamline and Accsim output for visualization and analysis of code results.

CONFIGURATION

GPT

Particle tracking in the gun structure, including a 3D treatment of space charge, is performed by GPT[2]. The cathode of the thermionic gun is modeled in GPT as a uniform disk of charge. Initial particle divergences are sampled from a Gaussian distribution and scaled to obtain a thermal emittance of 4.76 μm. Charges are pulled off the cathode by a 650 MHz RF-modulated grid with a maximum voltage difference of ∼+10 V. Particles surviving the grid are accelerated by the gun field to 300 keV. The GPT distribution at the gun exit is converted to Astra format using a conversion program "gpt2astra".

Astra

Transport from the gun exit through the 1.3 GHz buncher and 9-cell cavity of the ICM is performed by Astra[3] which provides efficient tracking of particles under external cylindrically symmetric static or oscillatory fields defined on-axis and paraxially expanded. Space charge effects are included with the option of full 3D or cylindrically symmetric grids for suitable distributions. For this application we found that the cylindrically symmetric feature of Astra is adequate and provided very efficient results.

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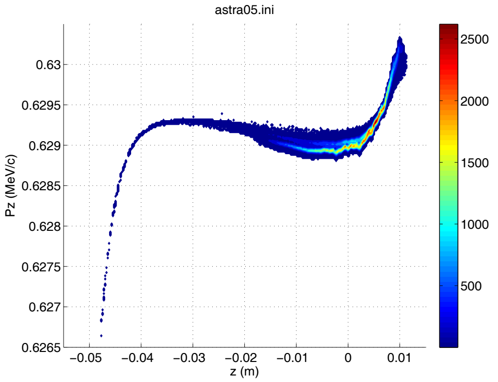

Figure 1: Density plot of (z, P_z) at the electron gun exit.

Accsim

The layout and optics of the 2-bend EMBT as calculated by DIMAD are shown in Figure 2. The dispersion at the proposed collimator location between B1 and QB is ∼15 cm. For tracking through the EMBT the simulation program Accsim[4] has convenient options for specifying apertures, allowing quantification of both the stopped beam and the retained beam for a given collimator configuration. The DIMAD-format element list produced by Optim can also be read by Accsim, and the starting beam is taken from the Astra beam coordinate output at the end of the ICM. A conversion program "astra2accsim" has been written to accomplish the coordinate and unit transformations.

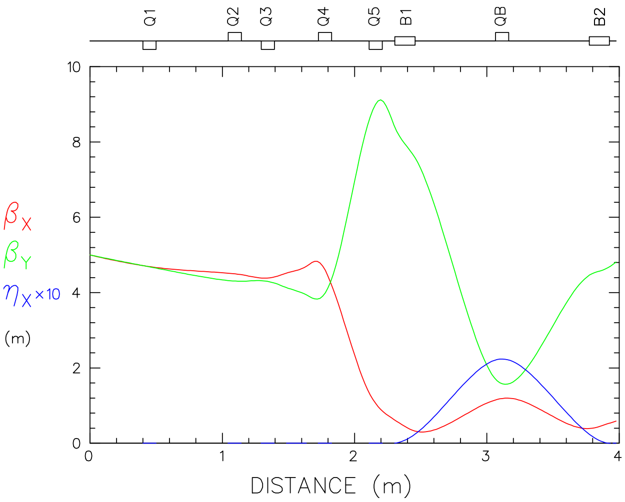

Figure 2: Optics of 2-bend transfer line from DIMAD.

G4Beamline

Based on a foundation of the simulation toolkit Geant4[5], the G4Beamline[6] application allows the collimator and downstream components of the EMBT to be modelled in a fully 3D geometry. The beam hitting the collimator, as determined by Accsim, acts as the input beam for G4Beamline. In Accsim a new procedure has been implemented to output this beam data in the required NTuple format for reading by G4Beamline. G4Beamline tracks this beam accounting for all electron interactions in the collimator material, including energy loss, multiple scattering, and production of gamma rays and secondary electrons.

Table 1: Collimator performance in two scenarios: 3-bend merger and denser tail and 2-bend transfer with sparse tail

	3-bend merger	2-bend transfer
Min ΔE	−7.83 MeV	−8.72 MeV
Max ΔE	0.057 MeV	0.173 MeV
RMS ΔE	0.0367 MeV	0.0578 MeV
Low-energy cut	−0.100 MeV	−0.0867 MeV
Fraction in tail	0.1097%	0.0220%
Jaw location	−4.63 mm	−2.62 mm
Fraction stopped	0.0747%	0.0170%
Fraction missed	0.0350%	0.0050%
Remainder min ΔE	−0.256 MeV	−0.262 MeV
Remainder min $\Delta p/p$	−0.0244	−0.0250

Via particle data output by G4Beamline and post-processing by Matlab scripts, the stopping of electrons in the collimator can be verified and any losses due to outscattered electrons can be detected.

COLLIMATOR PERFORMANCE

We have applied the program chain GPT-Astra-Accsim-G4Beamline, for the 2-bend and 3-bend EMBT configurations, to estimate the collimator performance. Since the low-energy tail is a small fraction of the beam, the simulations used ∼700,000 macroparticles, which represents the upper limit of GPT memory consumption. The gun structure has a fairly low yield of forward electrons, so more than 10 million initial particles were launched in GPT in order to obtain the necessary number exiting the gun.

Subsequent tracking of this ensemble by Astra and Accsim to the collimator location allowed us to analyze the effectiveness of the collimator, as shown in Table 1. The collimator jaw is positioned in order to collect as large a fraction as possible of the low-energy tail without interfering with the "good" beam. Since any interception of the beam core could cause rapid overheating of the collimator, a nominal 1 mm "safety" has been added to the jaw offset. In practice, this may vary depending on what automatic protection mechanisms are implemented and on the cooling capacity of the collimator system.

In both cases shown, the collimator is able to collect about 75% of the tail population. Figure 3 shows the stopped portion of the tail as well as the portion missed, which is in effect hiding inside the beam core. The lower limit of $\Delta p/p$ in the retained beam thus remains quite high, around −2.5%, however the missed tail is at most 0.035% of the beam so that any downstream losses will be well within acceptable limits. After Accsim tracks the beam to the collimator surface, it exports the coordinates of all

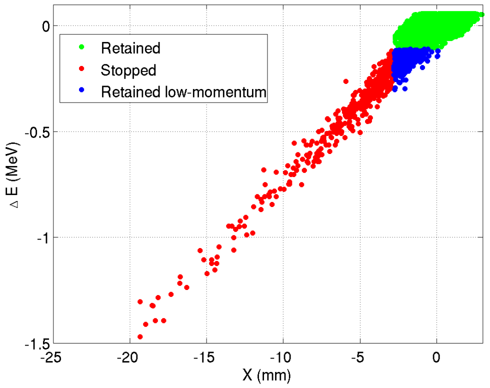

Figure 3: Collimated and missed beam fractions.

collected electrons in the BLTrackFile format for input to G4Beamline. As shown in Figure 4, the 3D geometry of the collimator jaw (here simplified to a block of copper) and the remainder of the EMBT is constructed in G4Beamline. The primary electrons are tracked into the collimator and all secondary particles are also tracked. In addition to the copious production of X-rays, the collimator material will cause some outscattering of primary electrons and production of secondary electrons. However, the G4Beamline simulation reveals that the collimation of 10 MeV electrons in copper is very effective: the great majority of primary electrons are stopped in the copper. Even with more than 2 million primary electrons we observed no outscattered or secondary electrons that entered the aperture of the beam pipe and survived to the end of the EMBT. By re-seeding events in G4Beamline we escalated the number of collimator hits until a few survivors were observed, but these were below the 10^{-4} level, or less than 10^{-7} of the total beam.

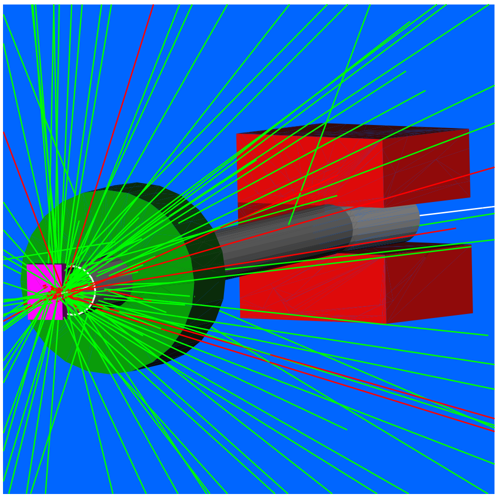

Figure 4: G4Beamline visualization of collimator jaw (purple) and downstream portion of EMBT. Green tracks are gammas, red tracks are outscattered and secondary electrons, and the white track is a central reference particle.

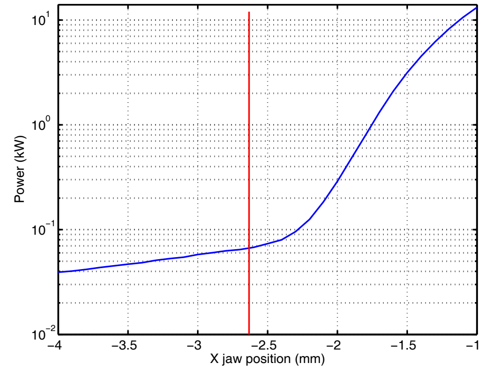

Figure 5: Beam power deposited in collimator jaw. The red line indicates the nominal operating jaw position.

The ARIEL Linac complex is designed to deliver high intensity (up to 500 kW) electron beams to the photofission target. For the collimator this entails careful attention to the heat load and positioning of the jaw. Figure 5 shows, for the 2-bend moderate tail scenario, the beam power load on the collimator jaw as a function of jaw position. The G4Beamline study shows that ∼95% of the electron beam energy is deposited within the first 5 mm of depth in the copper. While the nominal heat load is only about 70 Watts, it is seen that there is only about 1 mm of "safety" before the heat load has escalated to 1 kW. We anticipate that the hardware implementation will require protection mechanisms including covering of the front copper surface with a tungsten layer and extended cooling capacity.

CONCLUSIONS

These studies indicate that a simple momentum collimation system placed in the first dispersive region of the transfer line between the injector and the main linac of ARIEL, will be effective in removing a substantial portion of the low-energy tail coming from the injector.

The G4Beamline model shows that collateral electron losses due to the collimator itself will be well localised and at a low intensity. Moreover, downstream losses of the surviving portion of the tail will be limited to an acceptably small fraction of the transmitted beam.

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