ARIEL AND THE TRIUMF E-LINAC INITIATIVE, A ½-MW ELECTRON LINAC FOR RARE ISOTOPE BEAM PRODUCTION

S. Koscielniak, F. Ames, R. Baartman, R. Dawson, J. Drozdoff, Y. Bylinsky, K. Fong, A. Hurst,
D. Karlen, R. Keitel, R. Laxdal, F. Mammarella, M. Marchetto, L. Merminga, A.K. Mitra,
K. Reiniger, T. Ries, R. Ruegg, I. Sekachev, G. Stinson, V. Verzilov
TRIUMF*, 4004 Wesbrook Mall, Vancouver, BC V6T 2A3, Canada

Abstract

TRIUMF, in collaboration with university partners, proposes to construct a megawatt-class electron linear accelerator (e-linac) as a driver for U(γ,f) of actinide targets for nuclear astrophysics studies, and ^{9}Be(γ,p)^{8}Li for beta-NMR materials science. The e-linac is part of a broader proposal for an expansion of the TRIUMF rare isotope beams capability through a new facility to be named ARIEL. The e-linac design and prospects for funding are elaborated.

INTRODUCTION

TRIUMF, in its Five Year Plan 2010-2015 proposes to build the Advanced Rare IsotopE Laboratory (ARIEL) to augment the Rare Isotope Beam (RIB) science program at the ISAC facility. ARIEL, Figure 1, will have four major components: (i) an electron linac photo-fission driver, (ii) a new target hall to be located in a western extension of the existing ISAC building, (iii) a new proton beam line from the H- cyclotron, and (iv) a new RIB "front end". The accelerators and target station(s) will be connected by new 60 metre long beam lines in a common tunnel. The project will be staged. In the first stage, a 100 kW capable linac, a single target station, the e and p beam lines, ion sources and mass analyzers and RIB transport lines to the existing ISAC RFQ and linacs will be constructed. The second stage occurs in the 2015-2020 Plan: the electron linac and target station are upgraded to the full 1/2 –MW capability, an additional target station is added, and the "front end" is completed by the addition of new RIB accelerators, thus facilitating up to three simultaneous RIB, two of which may be accelerated beams. The science program is sketched in Ref.[1] and concepts for the e-linac design and RIB front end are presented in Refs.[2,3].

Ariel is a fictional sprite who appears in Shakespeare's play *The Tempest*. The counterpart of Ariel's master *Prospero* is the ISAC science program with its suite of world-class experimental apparatus eager to command the production of more beams and new beams. Adding the electron linac will double the RIBs, and adding the new proton beam line and second target station will triple the RIB production and science output. The '-el' ending of Ariel translates in Hebrew as 'God,' placing Ariel inline with benevolent spirits; and indeed the new accelerator will bring many benefits to TRIUMF.

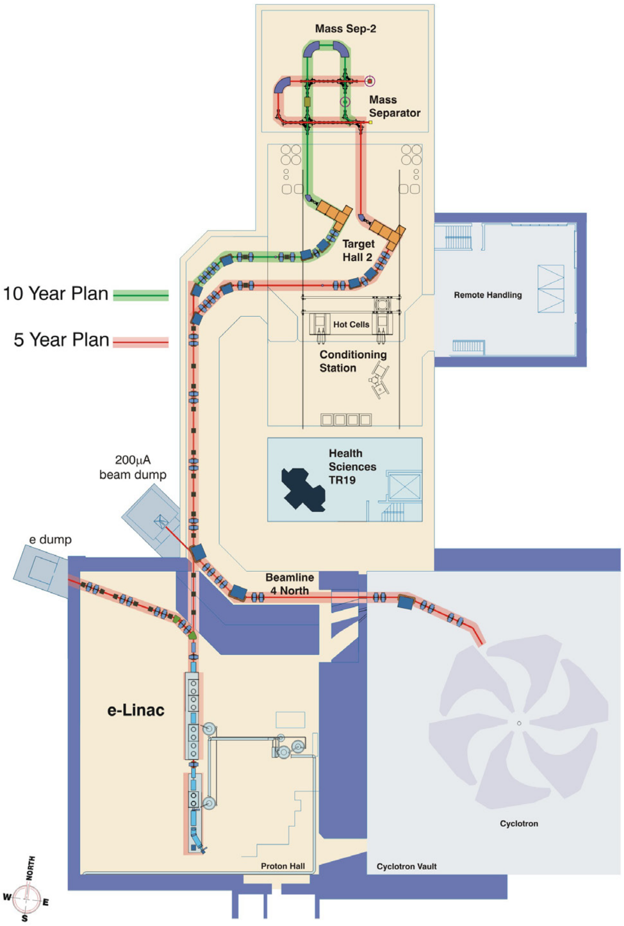

Figure 1: ARIEL infrastructure and layout.

- New Science: nuclear physics with neutron-rich RIBs, and ^{9}Be(γ,p)^{8}Li production for β-NMR studies in Materials and Molecular Sciences.
- An independent driver for RIB production that complements the cyclotron proton driver.
    - Implements strategy of multiple beams (e, p) to multiple users to accelerate science output.
    - E-linac will operate through annual cyclotron shutdowns providing a strong year-round RIB experimental program.
- Leverages valuable existing infrastructure:
    - Proton Hall, shielded vault with services
    - World-class experimental apparatus (detectors)
    - Builds further SCRF expertise base from β«1, 100 MHz, 4K quarter-wave structures to β=1, 1 GHz, 2K elliptical structures.

---

*TRIUMF receives federal funding via a contribution agreement through the National Research Council of Canada.

- Prepares Canada for SCRF projects world-wide (e.g. CERN-Superconducting Proton Linac, ILC).
- Qualifies a Canadian commercial partner (PAVAC) to build SCRF elliptical cavities.
- Test bed for 4th generation light source technologies.

The centre piece of this program is the high average current continuous-wave electron linear accelerator (e-linac) founded on superconducting RF technology.

E-LINAC DESIGN OVERVIEW

Three goals have shaped the conceptual design of the e-linac: (1) the utilization of existing technology wherever possible; (2) c.w. operation at high average power; and (3) flexibility toward operation and re-configuration.

From the outset we have opted to base the e-linac design around Tesla Test Facility (TTF) technology developed for TESLA, XFEL [5] and ILC[6]. This is for two reasons: to benefit from the extensive SRF development for these accelerators, and to prepare Canada for participation in high-energy physics projects such as CERN-SPL and the International Linear Collider. However, if given free rein we would have come to similar conclusions.

The TESLA/ILC cavity unit has become a building block for SRF linac design. Though it is the starting point for the e-linac design, commonality with the ILC stops at the cavity level and does not extend to cryovessel or RF power sources. The ILC is a low duty factor machine whose design is limited by the achievable gradient. The e-linac design is driven by the challenges of continuous operation at high average current. Particular challenges are the input coupler design and the 2 Kelvin heat loads. For example, the average power sustained by an ILC input coupler is $\leq$ 16 kW. In the fission-driver linac, 500 kW of CW RF power has to propagate through the input couplers and cavities into the electron beam. CW operation poses some challenges compared with XFEL or ILC designs, but these challenges are starting to be met in light source designs[4].

Basing the design on existing technology, the e-linac adopts a High-Level RF (HLRF) building block of one 130 kW klystron, two 60 kW couplers and one 9-cell cavity. Five such units operated at 10 MV/m coupled with 10 mA beam current consume 100 kW/cavity and result in a beam energy of 50 MeV. Though the gradient planned for e-linac is a modest 10 MV/m, we intend to leave an upgrade path to an Energy Recovery Linac (ERL) or Recirculating Linear Accelerator (RLA) operated at 20 MV/m; and the cavity fabrication and niobium surface preparation will be consistent with that goal.

The baseline configuration splits the entire e-linac into a low energy injector and the main linac; driven by one and four HLRF blocks, respectively. This choice would allow the linacs to be re-configured at some later date, by the insertion of return arcs, as a test bed for ERL (20 mA, 80 MeV) or RLA (2 mA, 160 MeV) technology. With marginal incremental investments, e-linac could serve as a test-bed for a Compton Scatter Source of hard x-rays or a staging post to an IR or THz FEL or Coherent Synchroton Radiation source. The return arcs are not costed in this proposal, nor a photo-cathode gun; but HOM absorbers, variable coupling ratio and piezo tuners form part of the baseline design.

E-LINAC TECHNICAL DESIGN

The 50 MeV, 10 mA, capable CW linac is based on TTF super-conducting radio-frequency (SRF) technology at 1.3 GHz and 2K; and consists of an electron gun, buncher, injector cryomodule, and two main-linac cryomodules. Figure 2 shows the e-linac baseline layout as it will appear in 2017. The injector module contains a capture section, followed by acceleration in a 9-cell cavity to a few MeV. Each of the main linac cryomodules, accelerating by 20 MeV, contains two 9-cell cavities.

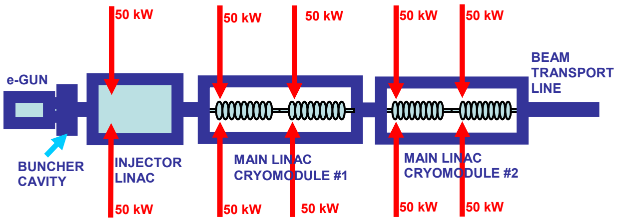

Figure 2: E-linac layout and power distribution.

In the first stage, to be completed mid-2013, the injector the first of the main linac modules, and single IOT and klystron drivers are installed providing 25 MeV, 4 mA. In the second stage, to be implemented 2017, the second of the main linac modules is added along with additional high-power RF sources to achieve the final ½-MW goal. The decision to divide the main linac into two modules stems mainly from the anticipated funding envelope.

We now focus on some technical details of the e-linac. Multiple stages of bunching are required to prepare the beam for on-crest acceleration in the main linac. There is progressive bunching at the source, buncher cavity and capture section at entrance of the injector linac.

Electron Source

The fission-driver specification is more relaxed than a comparable ERL injector to a Free Electron Laser. Light sources need 6D high-brilliance beams. By contrast, the fission driver eliminates its beam on target and so a 100 kV thermionic gun (30 μm normalized) is employed. A diode type gun has been received from TJNAF and will be converted to triode operation; modulating the grid causes the gun to be conducting for $\leq 45^{o}$ of the RF cycle allowing the beam to emerge pre-bunched at the anode.

Figure 3 shows the gun test bed at TRIUMF; vacuum components and HV power supplies are on order. The final source will output 170 ps FW bunches each of 16 pC with a bunch repetition rate of 650 MHz.

Buncher Cavity

The buncher cavity is used to prepare the beam for the injector linac. The buncher is a normal conducting RF cavity excited at 650 MHz with an amplitude of 15 kV and phased at 90° with respect to the beam. The power requirements are modest and are met with a commercial solid-state amplifier.

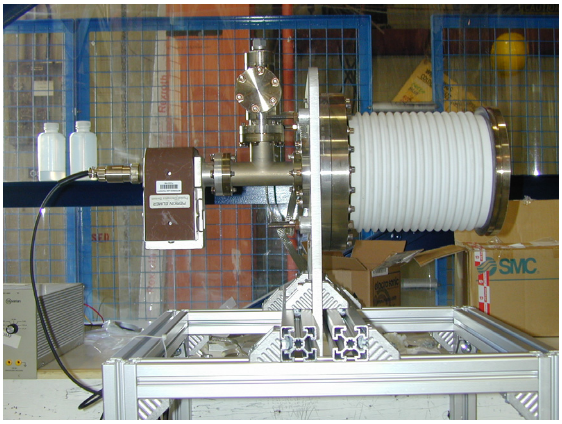

Figure 3: Ex-TJNAF thermionic gun at TRIUMF.

Injector Linac

The injector linac is composed of a capture section, followed a 9-cell SRF cavity. The injector terminates in an electron beam analysis section. A short, 2-magnet dog-leg is envisioned immediately downstream of the injector linac for compatibility with later ERL or RLA options.

Injecting a 100 keV beam (β=0.55) directly into a β=1 RF structure results in inefficient acceleration because of the mis-match in transit time. There are also possible deleterious transverse effects associated with such low energy injection into a high-gradient SRF structure. So the capture section performs two functions: additional bunching and modest acceleration. The capture section could be implemented as either a graded-beta structure; or independently phased cells. Both NC and SC structures are possible; cost favours the latter. A detailed analysis will be performed leading to a final choice between these options. The capture section is driven by Inductive Output Tubes (IOTs).

Main Linac

The main linac consists of four 9-cell TTF-style SRF cavities housed in two cryomodules. The cavities operate at 10 MV/m, and each has an active length of 1 m.

We confine the gradient options to $\leq$ 20 MV/m because this is the limit achievable with buffer chemical polishing (BCP) alone of the niobium surfaces. BCP is readily available at TRIUMF, whereas electro-polishing is not. The e-linac cavities will be constructed in collaboration with a BC-based engineering company, PAVAC, with the intention of introducing to Canada the capability to fabricate and process elliptical Nb cavities. The company presently makes bulk-niobium quarter-wave cavities [7] for the ISAC-II project.

RF Power Source

A variety of manufacturers offer pulsed klystrons rated at up to 5 MW peak and 100–250 kW average power, but the reduced duty factor means they are not applicable to the fission driver. Several manufacturers at present have the capability to build a 120 kW CW klystron, but only *e2V* has recently delivered such a product – six units for the Cornell ERL injector[4]. The *e2V* K3415LS klystrons match the e-linac baseline specification. However, *e2V* has recently redirected its business strategy and ceased production of these klystrons. For the e-linac RF source we rely on the offer from *CPI Microwave Power Products*. Their device will be based on the 1.5 GHz, 110 kW klystron developed for the FEL injector at TJNAF. With minor modification, this will be capable to deliver up to 150 kW of RF power at 1.3 GHz in CW operation.

At present, the highest power-rated commercially available CW input coupler at 1.3 GHz is the 60 kW Cornell-designed coaxial coupler available from *CPI-Eimac*; and this is chosen for the baseline.

Funding Prospects

The ARIEL facility is a major component of the 2010-2015 TRIUMF Five Year Plan (5YP), and its funding will be pursued in that context with the National Research Council Canada. There exists also another funding route for e-linac: the Canada Foundation for Innovation (CFI) which proceeds by bi-annual competitions. The University of Victoria, TRIUMF and other Canadian universities actively propose to obtain CFI funding to leverage the 5YP and submitted the Letter of Intent January 15th 2008.

On June 23rd, CFI designated the e-linac proposal as a National Project Application, not subject to institutional caps. On June 30th, a collaboration of 14 universities submitted the official Notification of Intent, and CFI responded by inviting the submission of the Full Proposal by October 3rd 2008, the final day of this conference. The CFI competition results are to be made public in June 2009, and an announcement of the TRIUMF five year funding is expected in February 2010.

Conclusion

E-linac will be an exemplar CW high-power, high-current linac. Due to the intrinsic power efficiency of SRF technology and the compactness and high accelerating gradient of L-band structures, their adoption provides a cost effective approach to a MW-class fission driver. Many of the major sub-system components have been identified. There are cell, cavity, input coupler, klystron, mechanical tuner, HOM damper and cryostat designs either pre-existing or close to the e-linac requirements; and their adoption will speed project completion and reduce R&D costs.

REFERENCES

[1] S. Koscielniak *et al*, Proc. EPAC 2008, Genoa, Italy, p 985.
[2] S. Koscielniak *et al*, ibid p 2728.
[3] R.E. Laxdal *et al*, ibid p 3635.
[4] S. Belomestnykh *et al*, ibid p 832.
[5] H. Weise: Proc. EPAC2004, Lucerne, Switzerland, p 11.
[6] B. Barish: Proc. EPAC 2006, Edinburgh, Scotland, p 1.
[7] R.E. Laxdal *et al*, these proceedings THP003.