ELECTRON LINAC PHOTO-FISSION DRIVER FOR THE RARE ISOTOPE PROGRAM AT TRIUMF

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Abstract

In July 2009 TRIUMF, in collaboration with the University of Victoria and other partners, was awarded Canadian federal government funds for the construction of an electron linear accelerator (e-linac) in support of its expanding rare isotope beam (RIB) program. The project anticipates Provincial funds for the construction of buildings to be announced in June 2010. TRIUMF has embarked on the detailed design for the 10 MeV Injector cryomodule and the first of two 20 MeV Accelerator cryomodules (ACMs), all rated at up to 10 mA. The project first stage, ICM and ACM1, providing 25 MeV 4 mA is planned to be completed in November 2013. The injector is being fast tracked in collaboration with the VECC in Kolkata, India. This paper gives an overview of the facility layout, and accelerator design progress including beam dynamics and cryomodule concept.

INTRODUCTION

The proposed TRIUMF on-site science program for 2010-2015 is based on multiple funding sources: (1) facilities and operations by the National Research Council of Canada (NRC); (2) construction of e-linac from the Canada Foundation for Innovation (CFI); and (3) new buildings from the B.C. Provincial government. These sources combined were to create a new centre for nuclear, materials and life sciences, called ARIEL; this facility and its ambitious science program are described in Ref.[1,2]. The key feature was to be a tripling of beam delivery to ISAC experiments via a second proton line (BL4N), the new electron linac (e-linac) and 2 target stations (E & W).

In July 2009 CFI awarded funds for the e-linac- with release contingent upon matching funds for labour from TRIUMF/NRC and buildings from the Province. In April 2010, the NRC contribution to the Five Year Plan became known, and is consistent with maintaining existing core operations, but not the foreseen ambitious expansion. It has recently been determined to re-stage the Plan: BL4N and E target are delayed to 2015, while the e-linac and W target station, and tunnel linking them, will proceed. The project anticipates Provincial funds for the construction of buildings to be announced in June 2010.

While awaiting Federal and Provincial government funding, ARIEL moved forward on two fronts: (1) a joint project to develop the 10 MeV, 10 mA Injector with the VECC (India); and (2) instigation of an ARIEL team to make final decisions on facility configuration and civil engineering. Key plans include: building excavation and construction sequence; selection of secant-pile shoring for the basements; extensive design of the target hall and hot cell and target storage complex, with full consideration of personnel access. In the canyon-type target hall design, the RIB line elements are installed and maintained from above using an overhead crane; vacuum connections are made by flexible joints developed for T2K. This allows a close packed shielding design, thus reducing the neutron fields in the RIB building. A detailed layout of the RIB front end systems was developed and space allocated for future upgrades, power supplies and services. Use of the west target is motivated as follows: no protons on target in this 5 years; best place for radiator development; shorter (cheaper) beam line. The electron beam is placed on the east wall of the tunnel, below (future) proton beam.

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E-LINAC Baseline Concept

The centre piece of ARIEL is the high average current continuous-wave electron linear accelerator founded on SRF technology at 1.3 GHz & 2K. The 10 mA, 50 MeV ultimate specification of the e-linac beam is a response to the desire for in-target photo-fission rates up to 10^{13} s^{-1}, and the production efficiency versus electron beam energy which falls steeply below 20 MeV. Major components of the e-linac are a 10 MeV *injector,* followed by a 10 to 50 MeV *accelerator* linac composed of two 20 MeV sections. The main reason for the injector-accelerator split is the possible later installation of return arcs and operation either in energy recovery mode for a light source, or energy doubler mode for photo-fission using bremsstrahlung with much smaller angular divergence. Bunch vital statistics are reported in Table 1 for the fission driver and light-source user, respectively.

Table 1: E-linac Beams Characteristics

	Fission at injection	Fission at extraction	Light source
Bunch charge (pC)	16	16	100
Bunch rep' rate	650 MHz	650 MHz	100 MHz
Transverse (norm) emittance (μm, 1σ)	5π	15π	≤10π
Longitudinal 1σ emittance (keV.ps)	≤20π	«750π	≈50π
Bunch length (ps)	<170 (FW)	≈35 (FW)	1 (rms)
Energy spread	0.3 keV (1σ)	≤1% (FW)	≤0.1% (σ)

Because the photo-fission beam is dumped on a target-convertor, the 6D emittances are relaxed compared with linac-based light sources. In the following, *low brightness* refers to the thermionic gun (16 pC, 100 keV), while *high brightness* refers to beam from a future photonic gun (100 pC, 200 keV). Machine main parameters and descriptions of the components can be found elsewhere [3, 4].

INJECTOR BASELINE CONCEPT

The goal of the VECC Collaboration Injector Cryomodule (ICM) systems integration test is to define, construct and test the e-linac from e-gun to 10 MeV, 25 kW at ISAC-II. There are two challenges for beam dynamics design: (1) world's first SC β <1 electron capture section; and (2) transport and acceleration compatible with both low and high brilliance beams to be delivered in alternating shifts. A 100 keV thermionic gridded gun was chosen as the electron source based on low cost, simplicity and ease of maintenance. This is followed by a 1.3 GHz NC bunching cavity of the Daresbury EMMA type – chosen over 650 MHz or ELBE 1.3 GHz types for lower emittance growth.

Historically, in pulsed-operation linacs, the transition from low β = v/c to β =1 has been achieved with an NC capture system that accelerates and provides additional bunching. However, for this CW application, substantial power savings are achieved with a SC capture section (two, independent single cells) before the first SC 9-cell cavity. This unusual configuration has motivated a careful beam dynamics study using genetic algorithm techniques. The choice of components and their locations was finalized through an optimization program aimed at achieving design objectives in beam parameters under constraints set by geometry, operational requirements and hardware limitations; see Ref[2].

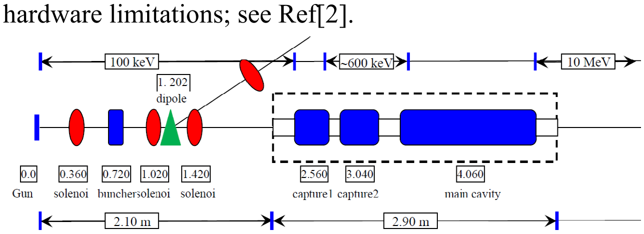

Figure 1: Injector schematic.

The major components forming the *injector* baseline design, namely RF cavities (represented by solid blue rectangles) and solenoid magnets (solid red ovals), are shown in Fig.1. The 20 cm field-length solenoids are excited at 400 Gauss. Preliminary solenoid and dipole magnet designs for beams up to 200 keV have been obtained from DPACE consulting. Intuitively, one might expect that capture cell#1 bunches while capture #2 accelerates; but optimization indicates that emittance is best if the roles are reversed. The cavities are arranged as in the following table.

	Energy Gain - Nominal		Voltage
Cavity	Low brightness	High brightness	
Buncher	2.5 keV	18 keV	110kV
Capture 1	0.40 MeV	0.42 MeV	0.88 MV
Capture 2	-0.10 MeV	-0.18 MeV	0.60 MV
Main	10.0 MeV	10.0	

The specified emittances, Table 1, have been achieved or bettered; this success is a major achievement of 2009. However, detailed engineering of the capture cavities, in particular their custom tuners, begins to reveal that their cost and time to manufacture has been under-estimated. For that reason, warm capture using a custom graded beta structure has been re-evaluated, as has a "no-capture" option with a higher gun voltage. Moreover, simultaneous fission and light source operation is now considered, and points to two independent injectors.

Coupler Transverse Kicks

The capture section contains two β=0.7 elliptical cavities independently driven through TTF-III type coaxial couplers. This was scrutinized closely for the effects of coupler kicks and HOMs. As was anticipated for a single-cell cavity, there are no offensive higher order modes – all modes propagate into the beam pipe.

The couplers break the axial symmetry and their transverse impulses (kicks) can lead to growth of the projected emittance due to the phase dependence of the kicks. The first step was to minimize the coupler penetration (and kick strength) by bringing them close to each cell for strong coupling. The second step was to attempt a cancellation of the kicks by choice of coupler locations. Let "u" and "d" denote up- and down-stream of the cavity; "a" and "b" denote above and below a reference plane. An *a-a* configuration has both couplers on the same side, while in *a-b* they are diametrically opposite. While the Panofsky-Wenzel theorem allows trivial calculation of the kicks when β=1, it is difficult to apply for varying β=v/c. Moreover, this theorem cannot predict the net position offset after passage through the two cells. Thus cases were evaluated by particle tracking.

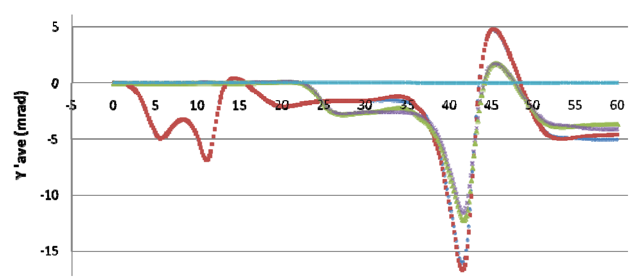

Figure 2: steering versus distance (cm) in capture section. u-d (blue), u-u (red), d-u (green), d-d (brown), none (cyan).

Fig.2 shows net divergence for 4 placements of the 2nd coupler for given location of the 1st coupler on the *d*-side of the 1st capture cell. The minimum kick would be achieved in the d(b)-u(b) case, but this is prevented by mechanical interference. The second best case is d(b)-d(b), but the mechanically preferred is d(b)-u(a). The projected emittance fractional growth, $\Delta\varepsilon$, was obtained by particle tracking from the gun to injector-exit. All values are within acceptable limits. Configuration d(b)-d(b) gives $\Delta\varepsilon$(xx') =1.87% and $\Delta\varepsilon$(yy') =0.76%, while d(b)-u(a) gives $\Delta\varepsilon$(xx') =6% and $\Delta\varepsilon$(yy') =1.6%.

ICM ENGINEERING DESIGN

A parallel activity of the VECC collaboration has been to pursue a detailed engineering study for the Injector cryomodule design which will set the pattern for ACMs also. We present here motivations for design choices.

Cryomodule Concept

The TTF/XFEL type cryomodule (CM) has become the template for high peak power, low duty factor SRF at 1.3 GHz and 2K. Cornell [5] has developed this into a high average power & current CM for light source operations; the 2-phase He gas return pipe (GRP) and G10 supports are retained as the backbone, but many CW features were introduced and the input couplers each given a fixed-point location. Minimization of static heat loads is far less of an issue for CW as opposed to pulsed operation; the 4 K thermal shield is not needed and the suspension heat load can be larger. TTF, XFEL and ILC have ~ 10 cavities per CM, and in this case the combined GRP/strong-back is an effective solution. However, for a small number of cavities per CM, say two 9-cells as for e-linac, a separate GRP and strong back is appealing, Fig.3.

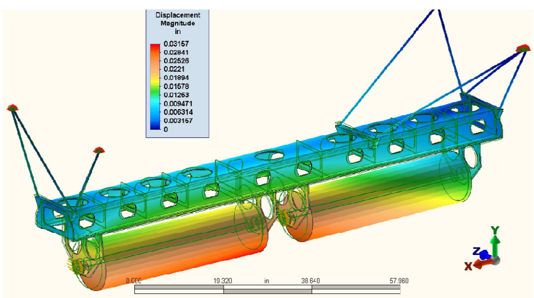

Figure 3: Cold mass (cavity string and 2 phase He pipe) supported from strong back slung from the ICM lid.

One may argue that the template for CW operation is the CEBAF at Jefferson laboratory, though at 200μA the beam current is modest compared with proposed linac light sources (~100 mA). At CEBAF and SNS, cavities are suspended from a cylindrical space frame by crossed struts; a sometimes perceived weakness of this system is the awkwardness of cavity alignment due to the counter-posed struts. In both these types (TTF, CEBAF) the CMs are end-loaded into a cylindrical vacuum vessel leading to an extensible design. Another possible template are the so-called bath-tub (or coffin) designs employed for ¼-wave resonators (~100 MHz) at the RIB facilities. In this case, the cold mass is suspended from a top-plate forming the lid of a rectangular vessel, see Fig.4. TRIUMF, through its ISAC program, has much experience with this style of CM. For the e-linac project, the ISAC CM must be made compatible with 2K (rather than 4K), elliptical cavities, 10 mA average current (rather than ~10nA), the fixed location of horizontally mounted input couplers, and a different cavity tuning mechanism.

Cavity Tuner

The ISAC CMs have a single-stage tuner delivering the entire dynamic range, while the TTF and ILC designs (at 2K) have two stages: coarse mechanical followed by fine piezos. The piezos are useful in pulsed operation (XFEL, ILC with dynamic Lorentz forces) but less so in CW mode. Thus CEBAF employ a (piezo-less) screw-jack tuner; this design offers the advantage of a room temperature stepper motor, albeit at the cost of more feed throughs. While CW energy recovery linacs operate at low power levels and high loaded Q and demand piezo actuators, linac applications with high power and beam current, such as photo-fission, operate in a heavily beam loaded regime leading to comparatively lower loaded Q, and wider cavity-bandwidth, obviating the need for piezos. For these reasons, a modified screw-jack (a.k.a scissor) tuner is adopted for the e-linac CM.

Cold Mass

Pending results of BBU calculations, the e-linac baseline adopts TTF style 9-cell cavities with modified end cells, large bore pipes and beamline HOM absorbers.

CW operation leads to high dynamic loads on the input couplers and 9-cell niobium cavities. At an early stage, the Cornell/CPI 50-60 kW couplers were adopted over the TTF-type. The cavity heat load is dealt with by employing two chimneys per cavity and adopting the 90 mm ID chimney dimensions proposed at BESSY.

Regarding the cryo-coolants, one question was whether to use He gas or LN2 to cool the 80 K shield. At an early stage it was found, given the low cost of LN2, that the high capital cost of a He refrigerator with 80 K cooling capacity would not be recouped for many years; and that a simple approach for LN2 direct cooling should be taken.

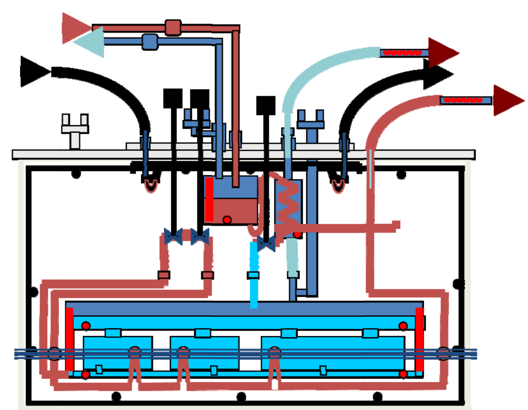

Figure 4:Top-load, box–type ICM with phase separator, 2K heat exchanger and JT expansion valve.

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