

ACCELERATOR DESIGN FOR A ½ MW ELECTRON LINAC FOR RARE ISOTOPE BEAM PRODUCTION

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Abstract

TRIUMF, in collaboration with university partners, proposes to construct a megawatt-class electron linear accelerator (e-linac) as a driver for radioactive beam production for nuclear structure and astrophysics [1] and material science. The design strategy, including upgrade path, for this cost-effective facility is elaborated. The 50 MeV, 10 mA, c.w. linac is based on TTF superconducting (SC) radiofrequency technology at 1.3 GHz & 2K. Many of the major sub-system components have been identified; where possible existing designs will be adopted.

E-LINAC DESIGN OVERVIEW

Facility Overview

The photo-fission source has two major components: a ½ mega-watt (MW) electron linac fission driver; and a ½ MW-capable target station, to be located in the western extension of the ISAC target hall, connected by a 60 metre long electron beamline that parallels the 4-North proton line. The major components of the fission driver are a 20 MeV *injector*, followed by a *main* linac section accelerating from 20-50 MeV. The linacs, Fig.1, will be housed in the existing Proton Hall – which provides ample space for the baseline machine and a small ring if so desired. Figure 1 of Ref. [2] provides an overview of the entire facility. Three goals have shaped the conceptual design of the e-linac: (1) c.w. operation at high average power; (2) the utilization of existing technology wherever possible; and (3) flexibility toward operation and re-configuration.

Relation of E-linac to TTF Cavity Unit

From the outset we have opted to base the E-linac design around Tesla Test Facility (TTF) technology developed for TESLA, XFEL [3] and ILC[4]. This is for two reasons: to benefit from the extensive SRF development for these electron accelerators, and to prepare TRIUMF and Canada for participation in International Linear Collider if that project proceeds. However, if given free rein from the start, we would have come to very similar conclusions: five 1.3 GHz SRF cavities housed in two cryomodules.

For a 50 MeV electron linac, high duty factor operation is inconceivable with normal conducting (NC) cavities: 4-8 MW of wall-plug power are required in addition to the ½ MW of beam power. But implemented in SC cavity technology, the wall-plug power (including cryogenic cooling) is less than 1.5 MW – a dramatic reduction resulting in enormous savings in operational costs.

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Theoretical considerations arising from the temperature and frequency dependence of SC cavities built from bulk niobium point to a cost minimum at ≈ 1.8 K and ≈ 1.3 GHz.

E-Linac HLRF Building Block and Gradient Choice

The ILC cavity unit (consisting of a 9-cell cavity, liquid helium vessel, mechanical tuner, RF input coupler, HOM coupler and 2-phase He pipe) has become a standard 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 unit. The ILC design is gradient limited, whereas e-linac is power-limited: the limitation arising from input coupler design and cryogenic heat loads. For ILC the per-cavity peak power is 300 kW; but because of the 0.5% duty factor, the average power is less than 16 kW. In the fission-driver linac, 500 kW of c.w. RF power has to propagate through the input couplers and cavities into the electron beam.

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, it is intended both to leave an upgrade path to an ERL operating at 20 MV/m and to have an intermediate stage of 15 MV/m running of the injector. We confine the gradient options to ≤ 20 MV/m because this is the limit achievable with chemical polishing. BCP is readily available at TRIUMF, whereas electro-polishing is not. The e-linac SRF 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 Nb quarter wave cavities for the ISAC-II project.

CW Operation: Challenges and Benefits

Continuous wave (c.w.) operation, which is required to limit the thermal shocking of the RIB production targets, has challenges beyond a limited choice of input couplers and klystrons. There are higher heat loads in all RF components. Indeed the cryogenic loads, at 2K and 80K, in the 5-cavity e-linac at 10 MV/m are five times those in the 12-cavity TESLA cryomodule at 23.4 MV/m. This thermal challenge, which requires a departure from the TTF cryomodule, is starting to be met by the designers of FEL drivers. The Cornell ERL Injector [5] will provide complementary combinations of current and energy ranging from 100 mA & 5 MeV to 30 mA & 15 MeV that

result in ½-MW beam power. Despite its unusual RF configuration (five 2-cell cavities operating at up to 14 MV/m), this injector provides an existence proof for a c.w. ½ MW cryomodule that could well form the basis of the e-linac cryovessel design. Nevertheless, c.w. operation does afford some benefits as compared with a pulsed machine: there are (i) no periodic beam-load transients; (ii) no periodic Lorentz-force detuning of the cavity; (iii) little or no need for piezo actuators; and (iv) the low-level RF is in principle simpler. In these respects, the e-linac specification is more relaxed than that of ILC.

Two-Three Cavity Split

The baseline configuration splits the five HLRF building blocks between a two-cavity injector linac, and a three-cavity main linac. This gives the opportunity to prototype some components in the injector, before employing their designs in or modifying then for the main linac. This same choice would allow the linacs to be re-configured at some later date, by the insertion of return arcs, as a test bed for Energy Recovery Linac (20 mA, 70 MeV) or Recirculating Linear Accelerator (2 mA, 160 MeV) technology. Little additional cost is incurred by this two-three cavity split. The return arcs are not costed in this proposal, nor a photo-cathode gun; but HOM absorbers, variable coupling ratio and piezo tuners (but not their drivers) form part of the baseline design.

Staging

Staging is more an issue of implementation than design. In principle, the ½-MW capable e-Linac could be completed by end of 2014. However, it is proposed to stage the linacs' construction – providing 5 mA, 30 MeV in mid 2013, and 10 mA, 50 MeV in 2017. This aligns e-linac with the RIB target staging and provides a useful driver beam at the earliest possible date. “Staging” drives the 2-3 cryomodule split, whereas consideration of ERL or RLA options favour a 1-4 split.

Fourth Generation Light Sources

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 Synchrotron Radiation source. E-linac provides a source of future possibility and opportunity to broaden light-source based research in Canada. For those reasons, we have gone to some pains to assure that e-linac is inclusive of those future options: no decisions made in the e-linac design will preclude diversification of the facility to a demonstrator of 4th generation light source technology.

E-LINAC TECHNICAL DESIGN

We now focus on some technical details of the e-linac.

Injector

The injector is composed of a 100 keV electron source, a 1st buncher cavity, a 0.5 MeV capture section, followed by a 0.5-20 MeV linac containing two 9-cell SRF cavities. There are optics matching sections between these components. The injector linac terminates in an electron

beam analysis section containing a 30° spectrometer. A short dog-leg (2 magnets) is envisioned immediately downstream of the injector linac for compatibility with later options, i.e. ERL or RLA.

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 and careful emittance preservation; this implies photo-cathodes, small emittance, high bunch charge and leads to extreme space-charge forces which must be overcome by rapid acceleration. By contrast, the fission driver eliminates its beam on target and so a simpler low-maintenance gun is employed. The source is a 100 kV DC thermionic gun, with a gridded cathode producing >10 mA (average) electron current. The modest extraction voltage is chosen to avoid the inconvenience of an SF₆ bath to avoid arcing, as occurs at higher voltage. The source outputs 170 ps FW bunches each of 16 pC with a bunch repetition rate of 650 MHz. The grid electrode converts the gun from diode to triode operation; modulating the grid causes the gun to be conducting for ≤ 45° of the RF cycle allowing the beam to emerge pre-bunched at the anode. Designs of this sort have been pursued successfully at NIKHEF-FELIX and the Mitsubishi Electric Corp. Microtron. The emittance typical of a thermionic gun at this current level is some 30 μm normalized; and is expected to rise to 100 μm during bunching and capture.

Buncher cavity

The buncher cavity is used to prepare the beam for efficient acceleration and additional bunching in the capture section. One takes advantage that while the beam is not yet relativistic, a small voltage modulation can achieve a significant bunching action. 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.

Capture Section

The capture section performs two functions: modest acceleration and additional bunching. Injecting a 100 keV beam ($\beta=0.55$) directly into a $\beta=1$ RF structure results in very inefficient acceleration because of the mis-match in transit time; for example, injection into a 10 MV/m 9-cell structure would result in ≈ 8 MeV energy gain, rather than 10 MeV. There are also deleterious transverse effects, leading to apparent emittance growth, associated with low energy injection into a high-gradient SRF structure.

The capture section accelerates the beam to ≥ 500 keV ($\beta=0.863$); the first cell imposes further energy modulation to improve the bunching throughout the remainder of the linacs. The capture section could be implemented either through an NC graded-beta structure; or 5 independently phased NC cells each operating at ≈ 110 kV and driven by Inductive Output Tubes (IOTs); or two SC low-gradient single cells within the entrance of the injector linac. Cost

favours the latter, but beam dynamics may favour the former lower-gradient option. A detailed analysis will be performed leading to a final choice between these options.

Injector Linac

In final operation, at 10 MV/m gradient, the injector will produce a 10 mA electron beam at 20 MeV. In the proposed staging, the injector is the only module completed by mid 2013. Using the available headroom in the cryogenic cooling capacity, this linac can be run at 15 MV/m and apply a 30 MeV beam to the RIB production target. 15 MV/m operation is a conservative estimate based on $Q_0 = 10^{10}$; if the operating Q_0 attains 2×10^{10} , then 20 MV/m operation and 40 MeV beam energy is possible.

Main Linac

The main linac consists of three 9-cell TTF-style SRF cavities housed in a single cryomodule. The cavities operate at 10 MV/m, and each has an active length of 1 m. If the beam energy falls from 50 to 40 MeV, the rate of photo-fissioning drops from by $< 15\%$, an acceptable reduction. Consequently, there is no imperative to consider a fourth cavity to improve the fault tolerance

RF Power Source

There are a total of 5 TTF cavities, 5 klystrons and 10 input couplers. Presently, the closest match to the baseline specification are K3415LS klystrons manufactured by *e2v*. This 7-cavity, factory-tuned, high-efficiency, high-gain, broad-band, water-cooled klystron amplifier, with designed saturated output power of 135 kW, is designed to allow rebuilding up to three times during its operating life, thus reducing the need for a large spares inventory.

Input Couplers

At present, the highest power-rated commercially available c.w. 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. The main requirements for the e-linac coupler(s) are to deliver 100 kW c.w. RF power to the beam (per cavity). There are two options: waveguide and coaxial couplers. Both have a large set of (differing) merits and demerits. But, only the coaxial type offers a large, variable coupling range, lower chance of multipactoring, compactness and smaller penetration into the cryomodule resulting in lower heat load.

Higher Order Modes

Cavity Higher Order Modes (HOM) excitation in e-linac will be minimal: the bunch charge is low, beam frequency components are widely spaced compared to the spectrum of cavity resonances; and the bunches are long, so their power spectrum does not extend to very high frequency. These properties alone are probably insufficient to overcome HOM effects entirely, and will be supplemented by counter measures. HOMs will be damped to safe levels by opening up the beam pipe to 90 mm diameter, from the TTF standard 76 mm, thus allowing almost all damaging modes above 2.6 GHz to propagate to a ceramic absorber – designed for the DESY XFEL. Dedicated loop couplers,

targeted at particular groups of modes will be installed as needed; again XFEL designs are available. In the event of an ERL and short-bunch operation, the ceramic absorbers would be replaced with the Cornell ferrite design.

BPM Acquisition Frequency

Signal acquisition at 1.3 GHz is a costly business: signal attenuation in cables is large, and processing electronics is not commercially available at low cost. It is also wise not to acquire beam signals at the frequency of the HLRF; RF leakage can contaminate the beam-induced signals. These problems all diminish when the bunch repetition and acquisition frequency is set at 650 MHz.

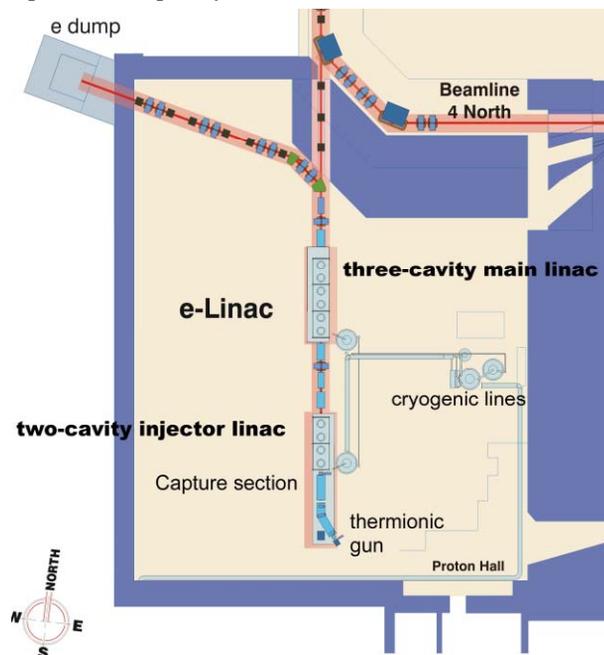


Figure 1: Proposed e-linac for RIB production.

Conclusion

E-linac will be an exemplar c.w. 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. 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 this eliminates substantial R&D cost. C.W. operation poses some challenges compared with XFEL or ILC designs, for instance the higher thermal loading of the cryomodule and the limited choice of klystrons and input couplers – but these challenges are starting to be met in some light source designs. Nevertheless, some cryomodule R&D will be required for the frontier parameters of the e-linac; also attention must be given to mitigation of beam halos.

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