

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

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Abstract

In October 2008, TRIUMF in collaboration with university partners made a proposal to the federal government for the construction of an electron linear accelerator in support of its expanding rare isotope program, which targets nuclear structure and astrophysics studies as well as material science. In July 2009, that proposal was accepted and TRIUMF is embarking on the design phase. The 50 MeV, 10 mA, cw linac is based on super-conducting radiofrequency technology at 1.3 GHz & 2K. The first stage of the project a 25 MeV 5 mA, cw linac [matching the isotope production target power-handling capability in the next five-year plan] is planned to be completed in 2013. The injector cryomodule development, which is being fast tracked, is the subject of a scientific collaboration between TRIUMF and the VECC laboratory in Kolkata, India. This paper gives an overview of the facility, its motivation, and the accelerator design progress.

INTRODUCTION

State-of-the-art detector systems at ISAC have been deployed to address critical questions in nuclear physics. TRIUMF facilities and expertise for the development and deployment of rare isotope beams (RIBs) has created an overwhelming international demand for ISAC beam time. Regrettably, the present facility delivers the beam to a single user at a time, whereas there are in principle three experimental areas. TRIUMF's 2010–2015 Five-Year Plan outlines a strategy to at least double the RIB program. This will be realised by building an electron linear accelerator (e-linac) photo-fission driver coupled with a target station suitable for handling actinide targets and isotope separation on-line (ISOL). The plan, see Fig. 1, also envisages an additional proton beam line, extracting from the 4 north port of the existing H- ion 500 MeV, 200 μ A cyclotron, impinging on the same target in a time-shared manner.

The centre piece of this program is the high average current continuous-wave electron linear accelerator founded on superconducting RF technology. The linac, as a RIB driver complementary to the cyclotron, brings many benefits to the Five Year Plan.

- New Science: Nuclear physics with neutron-rich RIBs
- High purity radioisotope beams
- Complementary & independent RIB driver

- Enhanced science output: multiple beams to multiple users
- Steady RIB production: staggered e-linac & cyclotron shutdowns
- Leverages valuable existing infrastructure:
 - Proton Hall: available shielded vault with services
 - World-class RIB multiple experimental stations
 - Expands SCRF in-house expertise
- Prepares Canada for SCRF projects world-wide (International Linear Collider, CERN-SPL)
- Qualifies local (B.C.) commercial partner (PAVAC) to build elliptical SCRF cavities
- Provides entry path to a 4th generation light source test bed – Compton Scatter Source (x-rays), Coherent Synchrotron Radiation (IR, THz).

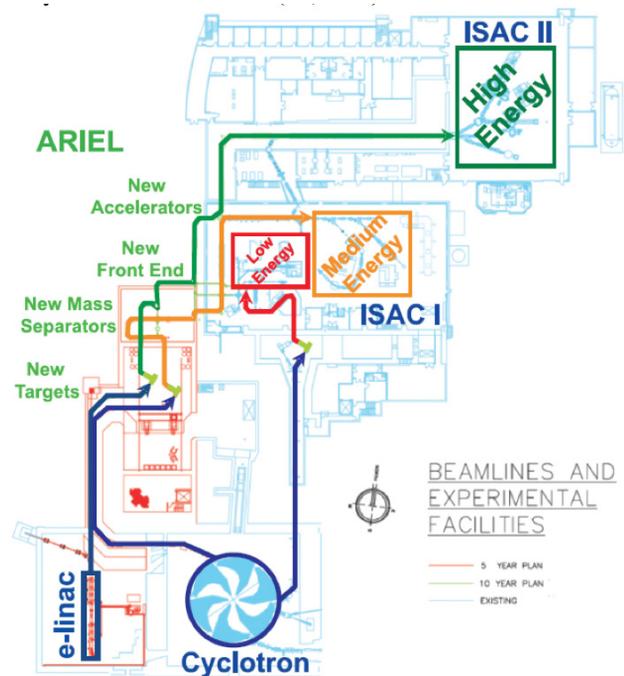


Figure 1: Overview of the present ISAC facility at TRIUMF and the future ARIEL expansion.

Complementarity of *e* & *p* for Neutron-Rich RIBs

Nature has an excellent way of producing neutron-rich radioactive isotopes: fission of the U nucleus using either a high-energy proton or an electron beam. The latter produces a limited range of isotopes, albeit in large quantities.

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Figure 2a shows the fission products distribution for 50 MeV, 10 mA e-beam & Hg converter on a 14 g/cm^2 ^{238}U target. The limited range about the fission-mass peaks implies the beams are cleaner, i.e. fewer isobaric contaminants. By contrast, the proton beam produces a broader range of isotopes, see Fig. 2b; this leads to RIBs with significantly more isobaric contaminants. Thus, the strengths and weaknesses of the two drivers (e & p) are coupled. Proton-induced fission is clearly unbeatable for certain regions. While γ -induced fission production may decline more rapidly far from stability on the neutron-rich side, it does possess the strong advantage of comparative cleanliness. This will prove decisive in forays towards the neutron drip line: most experiments that seek to go far from stability are limited not by the low production of the most exotic nuclides, but rather by large isobar contamination.

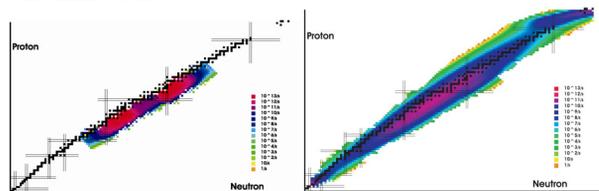


Figure 2: In-target production assuming 4.6×10^{13} photo-fission, Fig. 2a (left); and $10 \mu\text{A}$, 500 MeV proton beam on to a 25 g/cm^2 UC_x target, Fig. 2b (right).

NEW SCIENCE

The science programs to be conducted at ARIEL are presented in Ref. [1]; a synopsis follows.

Nuclear Structure

The outstanding questions in nuclear structure are:

- What is the structure of nuclei and nuclear matter?
- What are the limits of nuclear existence? (where are the proton/neutron drip lines?)
- What are nuclear properties as a function of neutron-to-proton asymmetry?
- How does the proton and neutron shell structure evolve along a chain of isotopes?
- Nuclear matrix elements for extracting neutrino masses.

In each case, theory needs experimental input to refine the models. An example of this is mass spectroscopy, which is key to determining binding energies and magic numbers. The e-linac program will focus on those neutron-rich nuclei with the peak yields.

Nuclear Astrophysics

There is a similar list of key questions in astrophysics:

- How, when, and where were the heavy elements produced?
- What role do nuclei play in the liberation of energy in stars and stellar explosions?
- How are nuclear properties related to astronomical observables:
 - solar neutrino flux,
 - γ -rays emitted by astrophysical sources,
 - light curves of novae, supernovae,

- and x-ray bursts of neutron stars/accretion disks?

The most neutron-rich and the heaviest nuclei are produced by the *r-process*, a series of rapid neutron captures, interspersed with photodisintegrations and β decays. E-linac will focus on nuclear astrophysics with neutron-rich nuclei at closed shells, particularly mass and decay lifetime measurements.

Beta-NMR for Materials Science

Beta-detected NMR (β -NMR) employs implanted particles that sense their magnetic environment and report this information through their spin-dependent anisotropic beta decay, thus acting as sensitive magnetic probes for fundamental studies of matter at the atomic scale.

Over the last 5 year period, TRIUMF β -NMR received about 4 weeks of beam per year. With such limited time, there is no chance for β -NMR to grow into a broad-based research tool like μSR . To make the leap to user facility, it is essential to implement a parallel source of ^8Li – this may be produced directly by photo-disintegration, e.g. the $^9\text{Be}(\gamma, p)^8\text{Li}$ reaction is estimated to yield at least as much ^8Li as the conventional ISAC target. With the proposed new e-linac source, the beam time available for β -NMR will quadruple.

ACCELERATOR BASELINE CONCEPT

Photofission of ^{238}U as an alternative production method for RIB was proposed by Diamond [2] in 1999. The electron beam falls on a converter target (W or Hg), to produce bremsstrahlung which in turn falls on a U target. The fission fragments are then ionized and mass-separated before transport to the RIB users.

The 10 mA, 50 MeV specification of e-linac is a response to the desire for in-target fission rates up to 10^{13} , and the production efficiency versus electron beam energy which falls steeply below 20 MeV and saturates above 50 MeV; it is a better investment to increase the electron flux than their kinetic energy.

The major components of the e-linac are a 10 MeV injector, followed by a main linac section accelerating from 10 to 50 MeV (see Fig. 3). Three goals have shaped the conceptual design of the e-linac: (1) cw operation at high average power; (2) the utilization of existing technology wherever possible; and (3) flexibility towards operation and re-configuration. Splitting the machine into injector and main linac will ease injector tuning and allow for an expansion to a test bed for Energy Recovery Linac (ERL) with beam intensity of 20 mA at 80 MeV, or Recirculating Linear Accelerator (RLA) with corresponding beam parameters of 2 mA and 160 MeV.

Machine main parameters and bunch vital statistics are reported in Table 1 & 2. Detailed description of the components can be found elsewhere [3, 4].

One of the major constraints affecting the accelerator layout was a power limitation of available RF power couplers and klystrons. Reference components of the design were 50 kW coupler design of Cornell ERL injector

Table 1: E-linac Baseline Major Parameters

| | |
|------------------------|-----------|
| Final energy | 50 MeV |
| Beam current | 10 mA |
| Beam power | 0.5 MW |
| Bunch repetition rate | 650 MHz |
| Accelerating frequency | 1.3 GHz |
| Accelerating gradient | 10 MV/m |
| Cavity quality factor | 10^{10} |
| Duty factor | 100 % |

Table 2: Bunch Vital Statistics for Photo-Fission

| Parameter | inject |
|--|--------------|
| Normalized emittance (μm) 4σ | $\leq 30\pi$ |
| Longitudinal emittance (keV.ps) 4σ | $\leq 80\pi$ |
| Bunch length (ps) FW | < 170 |
| Energy spread (keV) FW | < 1 |
| Bunch charge (pC) | 16 |

and 135 kW E2V klystron. In this configuration one RF unit would feed one 9-cell superconducting cavity via 2 high power couplers, delivering 100 kW of RF power to the beam per cavity. Coupled with the 10 mA requirement, this leads to the 10 MV/m gradient. The modest gradients and quality factor are consistent with chemical etching alone of the niobium surfaces. TRIUMF has an existing BCP facility, but no plans for electro-polishing.

Because the beam is dumped on a target, the 6D emittances are relaxed compared with linac-based light sources. A 100 keV thermionic gridded gun has been chosen as the electron source based on low cost, simplicity and ease of maintenance. This is followed by an NC bunching cavity. Historically, in pulsed-operation linacs, the transition from low $\beta = v/c$ to $\beta = 1$ has been achieved with an NC capture system that accelerates and

provides additional bunching. However, for this cw application, substantial cost/power savings will be achieved by incorporating an SC capture section (two, independent single cells) before the first SC multi-cell cavity. This configuration is unusual and has motivated a careful beam dynamics study using advanced design techniques as discussed below. The main linac adopts TTF type multi-cell cavities, but with modified end cells terminating in large bore beam pipes and beamline type higher-order-mode absorbers.

Upgrade Path: Light Source

A strong case exists for linac-based photon sources from the far infrared to hard x-rays. Compton scattering source (CSS) offers the possibility to produce hard x-rays research, industrial or medical applications at a fraction of the cost of ring or FEL-based facilities. The CSS is based on the scattering of photons from an intense laser by a relativistic electron beam. Retro-fitted with a photo-cathode electron gun and equipped with a bunch-compression magnet chicane and low-beta beam optics insertion, the e-linac could provide a 100 MeV capable electron source for this R&D effort.

Alternatively, configured as an ERL by the addition of return arcs and boosted cryogenic capacity, and coupled to a suitable high-Q cavity FEL, the e-linac could produce hundreds-watts-level infrared radiation in the range 2–200 μm . The SRF-linac offers the advantage of highly stable operation and high average power.

Terra-Hertz radiation is a frontier area for research in the physical sciences, biology and medicine. With a number of modifications, a 10–20 MeV the e-linac could be configured as a THz source: either a narrow-band FEL-based source similar to FELIX, or Coherent Synchrotron Radiation source similar to the one at the TJNAF.

This range of applications has motivated a parallel beam dynamics study with the aim of ensuring that the ICM design is compatible with a high-brilliance beam, in addition to the low brightness beam for the photo-fission RIB application. Beam parameters for this exercise are selected as follows: 100 pC/bunch, source kinetic energy 200 keV, repetition rate 100 MHz, transverse r.m.s.

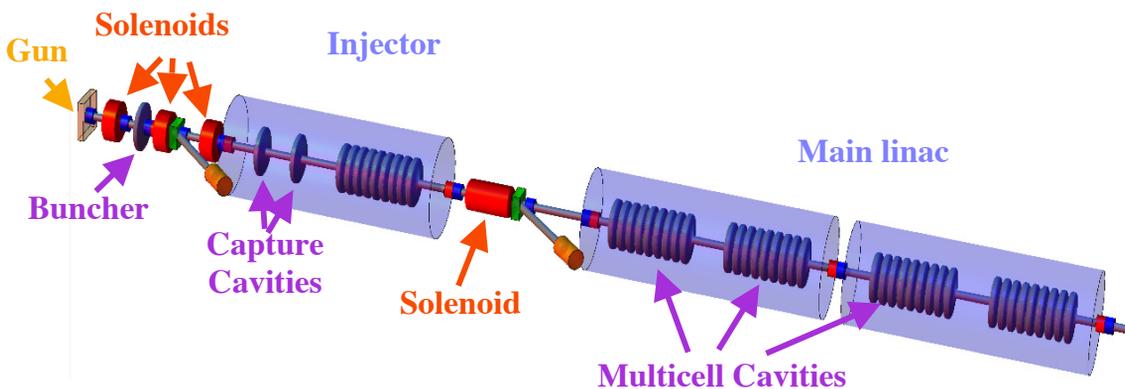


Figure 3: E-linac schematic layout.

emittances of 10 μm and r.m.s bunch length of 1 ps at the user.

SIMULATION METHOD APPROACH

The components of the e-linac injector and their operating parameters are being determined by a design process taking into account beam dynamics [5] and operational considerations as well as future upgrade path to a high brightness light source. The final design reflects a balance between performance goals and realistic constraints such as space and cost. The beam dynamics modelling is done with simulation codes ASTRA [6], PARMELA [7] and TRACK [8]. Early on it was realized that the design requirements for the photo-fission driver (16 pC bunch charge) were sufficiently forgiving, therefore the test of viability for any machine layout will rest with the high brightness case (100 pC) where space charge issues limit the geometry options. An iterative process has resulted in the current machine geometry, which can support quality transport of beams with both 16 pC and 100 pC bunch charge, while allowing implementation of sound schemes of tuning, monitoring and machine studies.

The capture has been simulated for cavities of different design beta. The objective is to avoid tail formation in the longitudinal phase space as well as to minimize the 6D emittance growth. Relevant to this goal is the bunch length at the entrance of the injector, which is modified by varying the distance between the buncher and the ICM. Some configurations of the ICM capture section are listed in Table 3. Downstream of the capture section, a 9-cell cavity completes the ICM RF elements. The four main linac 9-cell cavities are also included in the simulations. Output r.m.s. emittance growth profiles are represented in Fig. 4.

Table 3: Examples of ICM capture section configurations simulated in PARMELA.

| Solution | Capture 1 | | Capture 2 | |
|----------|-----------|------|-----------|------|
| | β | MV/m | β | MV/m |
| 1 | 1 | 6 | 1 | 10 |
| 2 | 1 | 6 | 1 | 11 |
| 3 | 1 | 6 | 1 | 12 |
| 4 | 0.7 | 7 | 1 | 14 |
| 5 | 0.7 | 3.5 | 1 | 10 |
| 6 | 0.7 | 7 | 0.7 | 14 |

Design and operating parameters in some cases are obtained using a genetic optimization program, originally adapted for accelerator design at Cornell University [9], with extended features developed locally for the e-linac design. A genetic algorithm is superior in its robustness against near singularities in the modeling process. The particular algorithm used allows multiple competing objectives and has proved competent in homing in onto globally optimal solutions in reasonable time. Each solution set is graphed as a Pareto front.

For example, Fig. 5 shows that the occupied beam phase space diminishes as the buncher to capture distance is reduced from 1.55 to 1.05 m.

02 Future projects

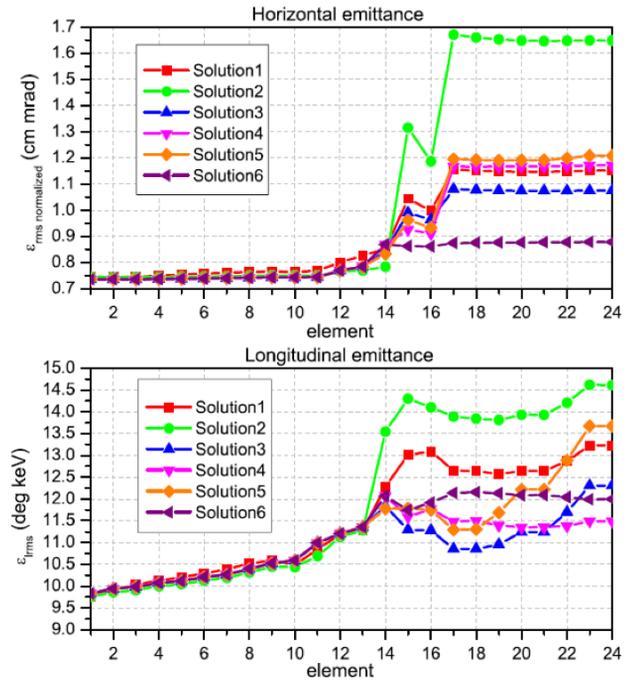


Figure 4: Transverse (top) and longitudinal (bottom) emittance growth for configurations (see Table 2) as function of the linac element: buncher =10, capture1 =14, capture2 =15, injector =17 and cavity1-4 =19-20-22-23.

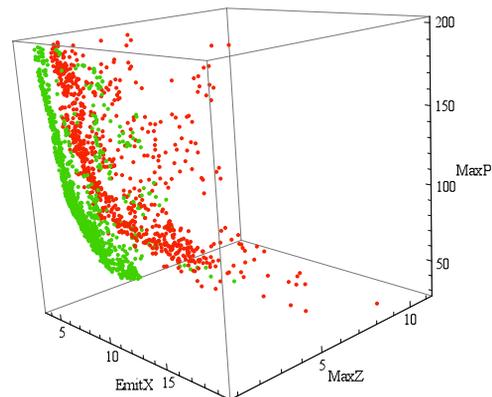


Figure 5: Pareto fronts for 1.55 m (red) buncher-to-capture distance and 1.05 m distance (green)

For example, Fig. 6 shows the performance in transverse and longitudinal emittance space as functions of the single-cell configurations including fault cases where only one cell is operative.

Figure 7 is a plot of the solution space; it summarizes many possible operating points and where one particular PARMELA tracking, solution 6, intersects the possible space of operating points consistent with equipment hardware parameters. The colours distinguished the data in the 3D space (blue points) from the projections (orange ϵ , red σ_z , green σ_E) on the three planes of the same data.

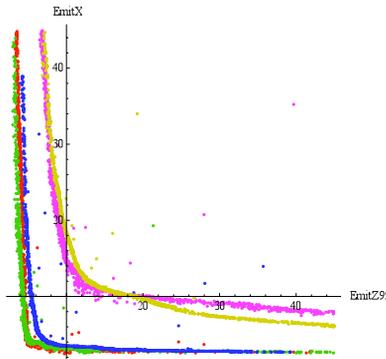


Figure 6: Performance comparison between normal and exception cases: red: $\beta=0.7+\beta=1.0$ capture cavities, green: $\beta=0.7+\beta=0.7$, blue: 1st capture only ($\beta=0.7$), pink: 2nd capture only ($\beta=1.0$), olive: 2nd capture only ($\beta=0.7$).

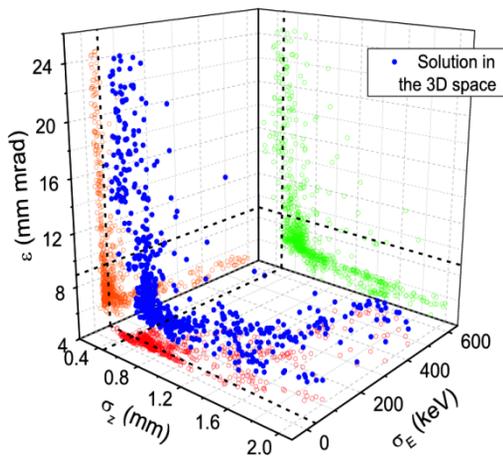


Figure 7: The 3D graph shows a population of ASTRA optimized solutions. The dotted lines on the three projection planes represent the PARMELA solution 6.

This graph shows that the independent solution found in PARMELA is in good agreement with the bulk of solutions found through the optimization routine in ASTRA. This give confidence in the final solution we are going to choose.

PROJECT TIMELINE

The University of Victoria and TRIUMF applied to the Canadian Foundation for Innovation (CFI), a federal agency for infrastructure projects, to fund the e-linac project in October 2008. The application for \$17.8 million Canadian was approved in July 2009, contingent on matching funds for the civil construction from the Provincial government. A final decision on the latter is expected autumn 2009. The e-linac project also represents an integral part of TRIUMF’s 5-Year Plan in support of the laboratory flagship RIB program at ISAC. This plan envisages early “new physics” outcome based on an intermediate phase of e-linac construction. This first stage will produce 100 kW beam power at 25 MeV, which will

02 Future projects

provide sufficient amount of photo-fissions to initiate a neutron-rich physics program in 2013. In order to further fast track this already challenging schedule TRIUMF has entered into a collaborative agreement with Variable Energy Cyclotron Centre (VECC) in Kolkata for development of 1.3 GHz SCRF technology. The e-linac Injector Cryomodule (ICM) development and beam test is a subject of the present stage of collaboration. Two identical ICM’s, one for each collaborator, will be constructed and the first unit beam tested in 2011. Intensive beam dynamics studies[5] are almost completed, and engineering design has just started for cryomodule development. The final 0.5 MW machine specification and matching photo-fission converter-target capability (yet to be developed) will be achieved in 2017.

Accelerator Components Design

TRIUMF decided to initiate an early start in development of the crucial components of the accelerator. The collaboration with VECC has allowed fast progress in the development of a 1.3 GHz SRF vertical test stand and the injector design and prototyping. The following sections summarise some recent achievements.

Electron Gun

An electron source test stand is being constructed based on the 100 keV thermionic gun obtained from the TJNAF. The gun has been modified from diode to triode operation to allow modulation at 650 MHz and individually formed bunches of 170 ps FW. The method was previously developed at the FELIX facility[10].

Simulations of the beam parameters have been performed with the code SIMION 3D Ver. 8.0 which allows tracking of particle bunches including space-charge forces and application of variable electrical potentials. Particle tracing through the electrical field of the extraction electrodes quantifies the beam pulses shown in Fig. 8: at a bunch charge of 29 pC, almost double the requested one, the normalized transversal rms emittance is $2.76 \pi \mu\text{rad}$ and the normalized longitudinal rms emittance is $28 \pi \text{keV}\cdot\text{ps}$.

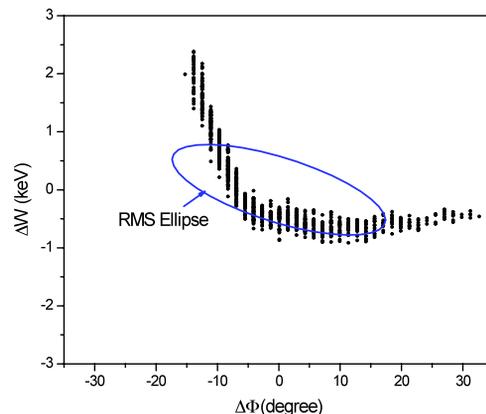


Figure 8: Particle distribution in the energy RF-phase space (ΔW , $\Delta\Phi$) at the gun exit.

Elliptical Cavity

Pursuing the 1.3 GHz technology, TRIUMF joined the Tesla Technology Collaboration (TTC) in 2007. In addition to SRF knowledge exchange in a framework of this agreement, TRIUMF has obtained from DESY and Fermilab two niobium cavities to gain expertise in a 1.3 GHz domain through cavity cold tests. Collaboration with VECC has pushed the e-linac development forward and helped setting up a vertical test stand. A single cell cavity test at 2K has validated the infrastructure required for the cavity development. The Richmond B.C. based company PAVAC is in the process of fabricating a couple of single cell and one 9-cell cavities in a framework of the e-linac cavity development program.

LLRF

The 1.3 GHz LLRF control system is based on the existing ISAC-2 106/144 MHz design, which operates under self-excited phase-locked mode.

The 1.3 GHz signal is first down-converted to an IF of 138 MHz, and then converted to base band to separate amplitude and phase detection. An IF is necessary because the digital phase detector, a Type 4 phase/frequency detector built using a Xilinx Spartan FPGA, provide only 300 degree phase detection at less than 250 MHz. The demodulated signals are sampled by two separate 18-bit ADCs to eliminate crosstalk between channels. The digitized signals are then processed by a Freescale 24-bit integer DSP. The processed signals are first up-converted to 138 MHz and then to 1.3 GHz. A prototype system has been built and tested using the single-cell cavity; closed-loop amplitude regulation was achieved.

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