TRIUMF

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# ARIEL Facility Safety Report

This report is submitted to the CNSC in support of a licence to commission ARIEL to 10 kW of average electron beam power.

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# 1 General Information

The ARIEL (Advanced Rare IsotopE Laboratory) facility at TRIUMF is a new rare isotope beam (RIB) facility complementing the existing ISAC and ISAC-II facilities. This chapter describes the purpose and scope of this report.

## 1.1 Purpose

This report has been prepared for submission to the Canadian Nuclear Safety Commission (CNSC) in support of an application to commission ARIEL including a Class II electron linear accelerator (e-Linac) housed in the Electron Hall at TRIUMF, on the campus of the University of British Columbia (UBC) in Vancouver, BC. The report describes the facility and its environmental impact; the potential hazard associated with its operation and includes a safety assessment of the mitigation of those hazards.

## 1.2 Scope

This report describes the layout of the full ARIEL facility but otherwise the scope of the hazard analysis is limited to the e-Linac and its operation in the Electron Hall.

The safety analysis along with the additional assessments presented in the report demonstrates that the operation of this facility can be conducted in a safe manner.

## 1.3 Referenced Documents

- *Quality Manual (Document-611)*
- *TSOP-02 Nonconformity and Fault Reporting and Resolution (Document-4758)*
- *TSOP-10 Access to TRIUMF (Document-1733)*
- *Accelerator Operations Management - TSOP-11 (Document-5604)*
- IAEA Technical Report Series No. 188 (TRS188) Radiological Safety Aspects of the Operation of Electron Linear Accelerators, 1979
- National Council on Radiation Protection Report No. 51 (NCRP51) Radiation Protection Guidelines for 0.1 – 100 MeV Particle Accelerator Facilities, 1977
- National Council on Radiation Protection Report No. 144 (NCRP144) *Radiation Protection for Particle Accelerator Facilities, 2003*
- *Calibration, Inspection and Recurring Maintenance - TSOP-08 (Document-595)*
- *Commissioning - TSOP-13 (Document-5708)*
- *TSN 5.8 Electrical Safety at TRIUMF (Document-870)*
- *TSN 5.11 High Voltage Safety at TRIUMF (Document-10581)*

- *TSN 1.3 TRIUMF Lockout Policies and Procedures (Document-539)*
- *TSN 1.8 Policy for Maximum Allowable Dose Rates in Accessible Areas at TRIUMF (Document-544)*
- *TSN 1.2: TRIUMF Policy on Radiation Exposure (Document-545)*
- *TRIUMF Fire Protection Program (Document-29313)*
- *TRIUMF Emergency Response Plan (Document-5856)*
- *Design Note TRI-DN-13-11 Specifications for the ARIEL eHall Shielding (Document-77790)*
- *e-Linac Commissioning Plan (Document-108335)*
- *E-Linac Shielding and Radiological Assessment Plan (Document-108545)*
- *Commissioning Plan for the e-Linac Radiation Safety System (Document-108174)*
- *Human Factors Engineering Program Plan for the ARIEL E-Linac (Commissioning) Control Room (Document-108553)*
- *e-Hall & Compressor Building Oxygen Deficiency Hazard Assessment and Mitigation (Document-108576)*
- *Training Plan - Working in Exclusion Areas (Document-114192)*
- *Training Plan - E-LINAC Monitoring and Prerequisites for Beam Tuning (Document-118072)*
- *E-Linac Operating Envelope Current Monitor System (Document-117036)*
- *Design Note TRI-DN-13-03 Preliminary Design of Target/Cooling Plate and Raster Pattern for a 100kW Electron Beam Dump(EBP) at 25-75 MeV (Document-70781)*
- *Design Note TRI-DN-13-24 Design considerations for quadrant monitor for e-linac 100kW electron beam dump (Document-103722)*
- *E-Linac Electron High Energy Beam Dump (EHD) System Requirements Specification (Document-57707)*
- *Design Note TRI-DN-13-29 e-Linac 100 kW Tuning Beam Dump Local and Upstream (EHDT beamline) Shielding Design (Document-103968)*
- *Design Note TRI-DN-14-13 De-rated e-Linac Tuning Beam Dump Shielding Design, Prompt and Residual Dose Rates, and Activation (Document-111865)*
- *E-Linac Access Control System Functional Requirements (Document-43329)*
- *Review of MPS Detector Tests (Document-121169)*
- *TSN 3.7 Work Permit System (Document-851)*
- *List of Interlocks for the e-Linac Tuning Dump - P0104 (Document-112445)*
- *Human Factors Verification and Validation Plan for the ARIEL E-Linac (Commissioning) Control Room (Document-109159)*

- *Human Factors Verification Report for the ARIEL E-Linac Control Room (Document-121492)*
- *Human Factors Verification Report for the ARIEL E-Linac Control Room: Addendum (Document-124249)*
- *ARIEL E-Linac Control Room Human Factors Validation Survey Results (Document-133671)*
- *ARIEL E-Linac Control Room Human Factors Validation Observation Team Results (Document-133672)*
- *DR.P0104-24 - E-Linac 100kW Beam Dump Insert Design Review (Document-104082)*
- *e-Linac Beam Dump Maximum Un-Rastered Beam Power - Engineering Note (Document-115170)*
- *ARIEL e-Linac Machine Protection System Requirements - P0104 (Document-85636)*
- *TSOP-04 The TRIUMF Training Program (Document-609)*
- *TSN 1.5 - Policy and Procedures for the Implementation of Interlock Defeats and Device Disables (Document-541)*
- *Commissioning Test for the e-Linac Radiation Safety System (Document-109675)*
- *Record of Completed Tests for E-Hall Watchmans Stations and Beacons (Document- 114067)*
- *Verification of E-Hall Lock-up Search Path (Document-114264)*
- *E-Hall, Compressor Building & MAB Oxygen Deficiency Monitoring System Commissioning Plan (Document-110698)*
- *E-Hall, Compressor Building, & MAB Oxygen Deficiency Monitoring System Commissioning Report (Document-113818)*
- *e-Linac Tune Lock (Document-162960)*
- *Beam position interlock for the e-linac high-energy beam dump (EHD) (Document- 203990)*

# 2 Facility Description

This chapter provides a general description of the proposed ARIEL facility. It also contains a description of the TRIUMF site, and the facilities located on that site. The location of the ARIEL facility with relation to the existing cyclotron facilities is described and a general layout is provided. A description of the adjacent areas and assumed occupancy factors are included.

## 2.1 General Description

This document describes ARIEL (Advanced Rare IsotopE Laboratory), a complementary Isotope Separation On-Line (ISOL) facility that will provide additional rare-isotope beam (RIB). These beams will eventually be delivered to the existing ISAC (Isotope Separator and Accelerator) experimental areas through a combination of new and existing beamlines.

ARIEL is designed to be similar in many ways to the existing ISAC facility. At ISAC, high-energy protons from TRIUMF's main cyclotron are impinged on thick production targets to generate rare isotopes by spallation and other processes. These isotopes are then extracted and transported electrostatically to a low-energy research area or reaccelerated to several MeV/u for experiments at higher energies.

At ARIEL, a new electron linear accelerator (or "e-Linac") with a maximum design energy of 50 MeV[1] and a maximum design beam power of 500 kW will be used as a driver accelerator for the production of rare isotopes by photon-induced fission ("photofission") in one of two separate, new, target stations. New mass separator facilities and low-energy beam transport will couple the ARIEL target station to the ISAC experimental halls. This will allow the combined ISAC and ARIEL facilities to deliver multiple RIB to experiments at high and low energies simultaneously, greatly increasing TRIUMF's research capabilities. The technical aspects of the facility, including the new beamlines, target area, and RIB transport, are described in Section 3.3.

ARIEL includes about 3728 $m^2$ of constructed area. The location and layout of the facility and its associated infrastructure are described in Chapter 3.

TRIUMF is responsible for the manufacture of the SRF e-Linac, including beam transport lines, control system, installation, and commissioning.

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[1] 49 MeV is used in the report as the design energy for the e-Linac as it is licensed as a Class II facility and as such should not exceed 50 MeV beam energy. All the analysis has been done at 50 MeV for simplicity.

## 2.2 Design Objectives and Current Capabilities

The design objectives of the ARIEL project were to produce a 500 kW electron beam at an energy slightly under 50 MeV. However, the accelerator systems and vault shielding have been designed with extra contingency, in a way to allow for possible future energy upgrade of up to 75 MeV.

The e-linac, in its present configuration, is in principle capable of producing 100 kW of average beam power at a beam energy of 30 MeV. Beam energies slightly over 30 MeV, by 1 or 2 MeV are also, in principle, achievable.

The tuning dump (see Section 3.3.16), in its present configuration, is only capable to handle up to 10 kW of average beam power. For this reason, the scope of the current state of commissioning is limited to 10 kW (e-Linac Commissioning Plan).

During the current commissioning stage, it is valuable for understanding accelerator performance to be able to commission the accelerator at energies slightly higher than 30 MeV, some portion of the time. In support of that the commissioning license is for energies <40 MeV. The safety justification supporting the current 40 MeV energy limit is discussed in section 5.1.4.

Some components of the ARIEL project, located in the beamline tunnel and target areas, are still under construction. A brief description of these areas is included in the following section

## 2.3 ARIEL Site and Buildings

### 2.3.1 Location

The TRIUMF site is located at 4004 Wesbrook Mall in the South Campus Research Precinct of the University of British Columbia in Vancouver. The ARIEL facility is located near the North boundary of the TRIUMF site nested between the Main Office Building and the existing ISAC-I facility and Remote Handling Building to the East, as shown in Figure 2-1. The e-Linac is located below ground in the Electron Hall, the former Proton Hall of the Main Cyclotron Building. A 45 m long underground tunnel extends from the Electron Hall and encloses the electron transport line to the ARIEL Target Hall.

The ARIEL facility is located within the TRIUMF security fence as is the case for the existing ISAC-I and ISAC-II facilities and all other TRIUMF accelerators. Access to the area within the fence is restricted as described in TRIUMF Standard Operating Procedures, *TSOP-10 TRIUMF Site Access*.

Figure 2-1 Architect rendition of the ARIEL building nestled between the Main Office Building and the ISAC building

## 2.3.2 Layout

Architectural plans of ARIEL are shown in Figure 2-2 for a section at the B2 level and in Figure 2-3 for a section further east of the tunnel through the east part of the Electron Hall and the middle of the ARIEL building. ARIEL includes the following functional areas proceeding from South to North:

- Helium Compressor Building (not shown in Figure 2-2 and Figure 2-3)
- Electron Hall
- ARIEL Tunnel

ARIEL Building that includes again from South to North:

- Target Hall & Target Support Spaces
- RIB Building
- RIB Service Annex

### 2.3.3 Elevations

The site grade elevation is 289’ above sea level. Elevations for the different floors in TRIUMF buildings are commonly referred to using the floor designations B2, B1, G and L1. For the Service Annex on the south side of the Electron Hall these designations correspond to the following elevations in feet: B2 – 264’, B1 – 276’, G – 289’ and L1 – 301’. The top of the Electron Hall roof beams are at 297’ elevation, and the new lower roof area at the north end of the hall is at 284’ elevation. A service tunnel extends north south at the B3 level (255’ elevation) below the Electron Hall. Penetrations for accelerator services exist between the Electron Hall and the service tunnel.

The RIB Building on the north end of the ARIEL Building has the following elevations, B2 at 263’, B1 at 276’, G at 289’ and the Penthouse at 317’. The Target Preparation Annex on the south side of the ARIEL Building has B2 at 263’ elevation, B1 at 281’ to match the Target Hall B1 level, G at 293.75’, L1 at 306.75’ elevation and the penthouse above.

The beamline tunnel floor elevation is 264’.

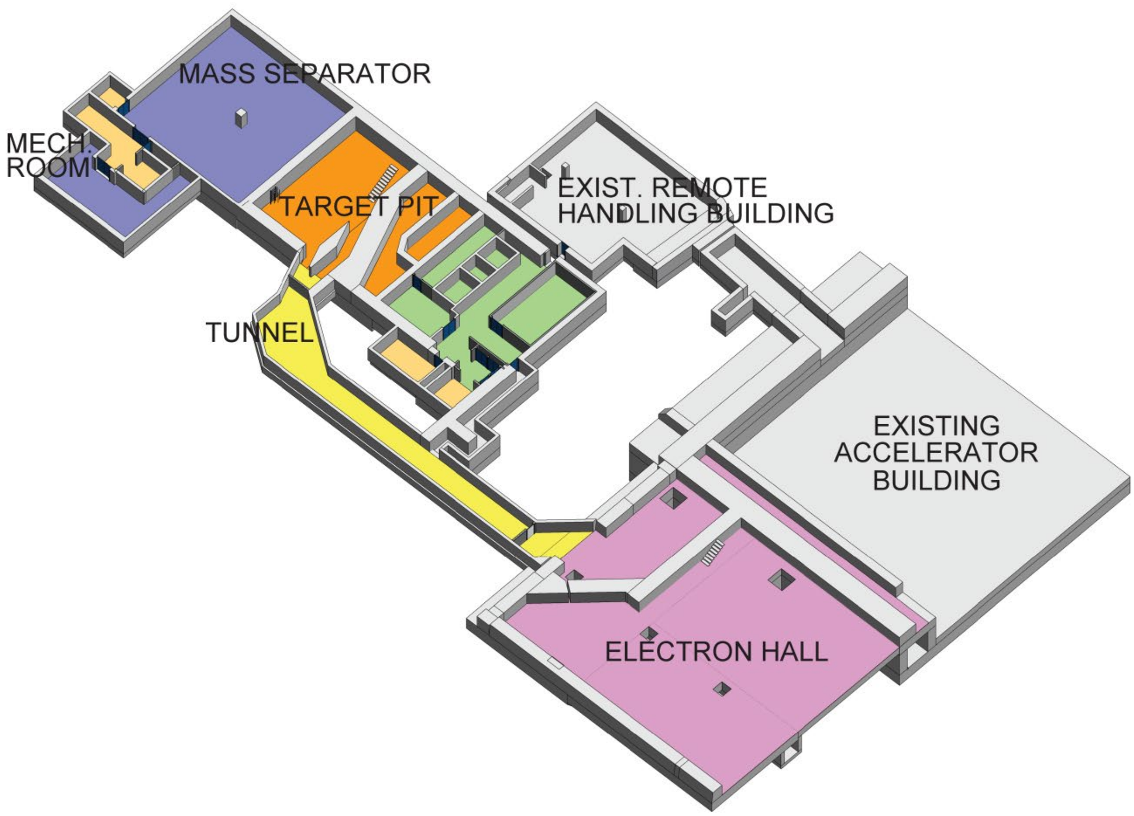


Figure 2-2 Architectural Plan at the B2 Level of ARIEL

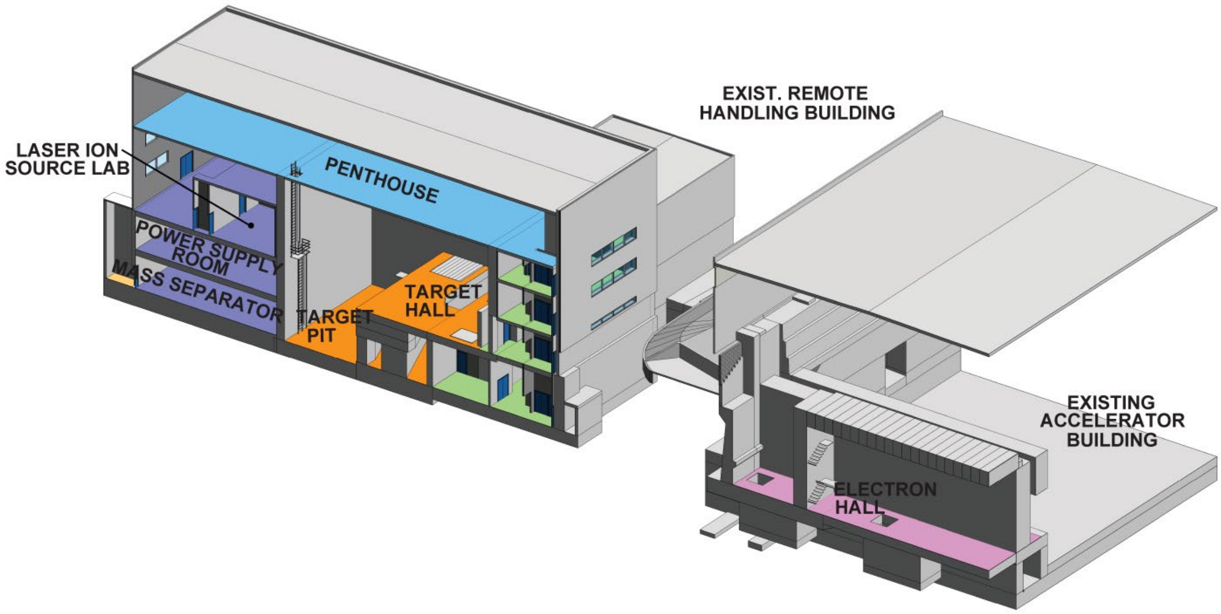


Figure 2-3 Architectural plan showing a section through the ARIEL building as well as the Electron Hall

## 2.3.4 Building Description

Appendix A contains drawings of ARIEL at each of the main floor elevations that can be consulted to help situate the areas described in this section.

### 2.3.4.1 Compressor Building

A new two story Compressor Building (256 $m^2$) has been built South of the roadway bordering the South side of the Main Accelerator Building (MAB). A trunk consisting of three 2”-8” lines carrying pressurized helium to the Electron Hall and recycled warm helium gas back from the Electron Hall, travel South through the MAB Service Annex (SA) at the 287’ elevation and then at 3.5 m above the ground South from the Service Annex to the Compressor Building.

### 2.3.4.2 Electron Hall

The Electron Hall (e-Hall) is located in the old Proton Hall and is the underground space (600 $m^2$ at the 264’ elevation) adjacent to the West wall of the Cyclotron Vault inside the MAB. It includes a service tunnel at the 255’ elevation extending the full length of the e-Hall with an access door at the B3 level of the Main Accelerator Building Service Annex. A schematic of the e-Hall is included in Section 3, Figure 3-1. The e-Hall contains the e-Linac and its associated equipment, the shielded high energy beam dump and associated water and vacuum services, and the first stage of electron-beam transport to the Tunnel. The NE part of the electron hall is reserved for the future proton beam line BL4N that will provide a second driver for ARIEL. Access to this space is via the ARIEL tunnel for personnel and light material.

The shielding inside the e-Hall includes a shielding wall on the north end that separates the e-Hall proper from the future BL4N tunnel section[2]. The shielding wall is configured with a poured in place section and additional eighteen-foot removable blocks- have a minimum thickness of 3.7 m of concrete in order to allow occupancy of the e-Hall for maintenance when the future proton beam line is operational.

A 10 t crane[3] (1 t = 2240 lb) is installed in the e-Hall, whose capacity is sufficient to handle the heaviest piece of equipment inside the e-Hall.

The beam dump is housed behind dedicated local shielding. The beam dump is cooled via a dedicated High Active Low Conductivity Water package (HA-LCW) which is in turn cooled across a heat exchanger by the Low Active – LCW (LA-LCW). The dump has been designed so that the local shielding and servicing of the dump insert will be done with the MAB 50 t crane through the e-Hall north hatch. The hatch is filled with removable blocks equal in thickness to the 1.8 m thick ceiling over the dump.

Access to the e-Hall is from the South for both material and personnel. An exit at the NE corner of the e-Hall, up a staircase and out onto the 284’ elevation BL4N shielding blocks, provides a means of egress in case of emergency. The exit from the cyclotron vault into the electron hall has been retained, but the maze shielding has been reorganized to ensure safety for all modes of operation.

A larger opening is cut in the north wall where the electron beamline branches north and downwards to transport the beam from the e-Hall to the ARIEL Tunnel. Sufficient shielding has been added on the BL4N side of the dogleg shielding void in order to allow occupancy in the tunnel with electron beam operation to the dump in the e-Hall. With this shielding in place, there is no access from the Electron Hall to the ARIEL Tunnel. Access for services and cabling to the e-Hall is via existing penetrations in the West and South wall and several round penetrations built into the North wall.

[2] Reference documents: *E-Linac Electron High Energy Beam Dump (EHD) System Requirements Specification* [Document-57707], *Design Note TRI-DN-13-29 e-Linac 100 kW Tuning Beam Dump Local and Upstream (EHDT beamline) Shielding Design* [Document-103968], *Design Note TRI-DN-14-13 De-rated e-Linac Tuning Beam Dump Shielding Design, Prompt and Residual Dose Rates, and Activation* [Document-111865].

[3] Unless stated otherwise in the report, all references are to an Imperial ton.

The hall is kept at a slight depression with respect to atmospheric pressure in order to limit migration of air activation from chronic losses. The anticipated air activation levels are low (≤ 1 DAC) and an exhaust rate of approximately one volume per hour will limit migration out of the hall.

The roof of the e-Hall consists of 23 x 5 ft thick concrete beams weighing about 104 t each. The beams have been grouted in place to make a solid slab. The roof top of the e-Hall houses HV power supplies, the ARIEL/e-Linac 12.5 kV switchgear and the 480 V and 208 V distribution systems to support local loads. Located on the northwest corner of the roof are rows of racks for power supplies, controls and diagnostics systems, and beam monitoring and radiation monitoring systems required for operations and safety.

#### 2.3.4.3 ARIEL Tunnel

The Tunnel is a 3 m wide by 2.7 m high structure with a floor elevation at 264’, approximately 7.6 m below grade. It is ~ 45 m long and connects to the South with the Electron Hall and to the North with the Target Hall. Eventually, it will house both the electron beam and proton beam transport systems in a top-bottom arrangement. It is kept at a slight depression relative to atmospheric pressure. Access to this space is via the B2 level of the ARIEL building Target Preparation Annex.

Access for services from the South is through an array of 6” conduits that start just above grade outside the Main Accelerator Building and drop down following an S-shape into the top of the ARIEL Tunnel. Cabling and services from the North will come from the RIB Annex Power Supply room at the B1 level via an array of conduit external to the building and enter the North end of the ARIEL tunnel at an elevation below the proton beam plane.

#### 2.3.4.4 ARIEL – Target Hall

The Target Pit at the North end of the Target Hall will house the heavily shielded RIB production target stations into which electron beams will be directed. Once the target shielding is installed, the Hall will be a contained volume through which access to the top of the target assemblies and their service connections will be gained from the south B1 Level of the Target Preparation Annex. Access to the top of the target assemblies will be achieved by removing demountable shielding with a 20 t overhead crane.

The Target Hall will also house some of the target and basic service components such as air exhaust filters, closed-circuit target cooling water systems and vacuum system pumps and exhaust holding tanks. At the South end of the Hall there will be three hot cells for handling irradiated targets and target modules. The hall will also house a spent target storage facility where irradiated targets will decay before disposing off-site for long-term storage, as well as a shielded enclosure for the activated target modules. The Target Hall will be an access-controlled area with a PLC requiring that the area be secured before the crane controls are enabled for transport of target modules.

#### 2.3.4.5 ARIEL - RIB Building

The RIB Building located North of the Target Hall houses the Mass Separator Room (MSR) at the B2 level where beam extracted from the target stations in the Target Hall will be separated by mass/charge state before being directed up to the RIB General Purpose Hall on the ground floor and into the ISAC-I Experimental Hall. The Mass Separator Room will also eventually house the Laser Ion Source laser beam optics table. For full power operation, the MSR will be under access control.

At the B1 level above the MSR, is the Power Supply Room which will house the power supplies, controls and diagnostics, safety monitoring and HV stations for both the East and West target stations and low energy beam lines and components in the RIB building. In addition, space in this room is allocated to power supplies, controls, and diagnostics for the North sections of both the electron and proton beam lines. This area is designed for occupancy at full power operation.

The General Purpose Hall is on the ground floor of the RIB Building. RIB species separated in the MSR are directed via two vertical transport lines up to the grade level GP Hall, where they can be directed via a switchyard, or after being subject to further charge stripping by the ISAC ECR (electron cyclotron resonance) charge breeder, into the ISAC-I Experimental Hall. The RIB Building ground floor also includes the Laser Clean Room, a laboratory housing the laser beam equipment. The Laser beam is transported to the Target (both East and West) via a laser pipe going vertically down into the mass separator room and then horizontally South to the target stations through the laser ion source beam ports.

Access to the RIB Building will be via a staircase and elevator at the northwest corner of the building in the RIB Service Annex. This annex will also house electrical and ventilation chases supplying the B1 and B2 level of the RIB Building. The Mechanical Services Room located at the B2 level of the RIB Service Annex will contain the sumps for the ARIEL building. The Electrical Services Room located in the RIB Service Annex B1 level will house the ARIEL main 480 V distribution and 208 V services as well emergency and UPS panels.

#### 2.3.4.6 ARIEL – Target Preparation Area

This is a four-story wing on the South side of the Target Hall that contains a Target Preparation Room (B2 level), a Radiochemistry Lab

(B1 Level), a cold Chemistry Lab (G Level) and the Target Hall Crane Control Room for remote handling of target modules (L1 Level). At the B2 level adjacent to the Target Hall hot cells is the hot cell support area where the hot cell technician operates the manipulators. Located North of the Hot Cell Access Area, essentially below the B1 level of the Target Hall, are the Target Support Services areas. These areas will be locked out as part of the Target Hall lock up in preparation for moving an irradiated target module. The Radioactive Gas Storage room is below the shielded enclosure for the target modules and contains the hot cell HEPA and charcoal filters, as well as the decay storage tanks for the target station vacuum exhaust. The other area is the Target Pit Service Room that will contain the services for the high-power target station (east target) converter.

#### 2.3.4.7 ARIEL – Penthouse

The Penthouse houses HVAC services including the nuclear exhaust, and the building mechanical services. The room at the south end of the penthouse above the Target Preparation Area will house the continuous air monitors for the nuclear exhaust.

### 2.3.5 Occupancy in ARIEL

The Electron Hall is under access control to protect from the prompt radiation hazard associated with e-Linac beam commissioning activities. The shielding designed in the Target Pit allows for occupancy in the Target Hall during beam operation.

# 3 Accelerator Design

The layout of the Electron Hall and its attendant equipment gallery is shown in Figure 3-1.

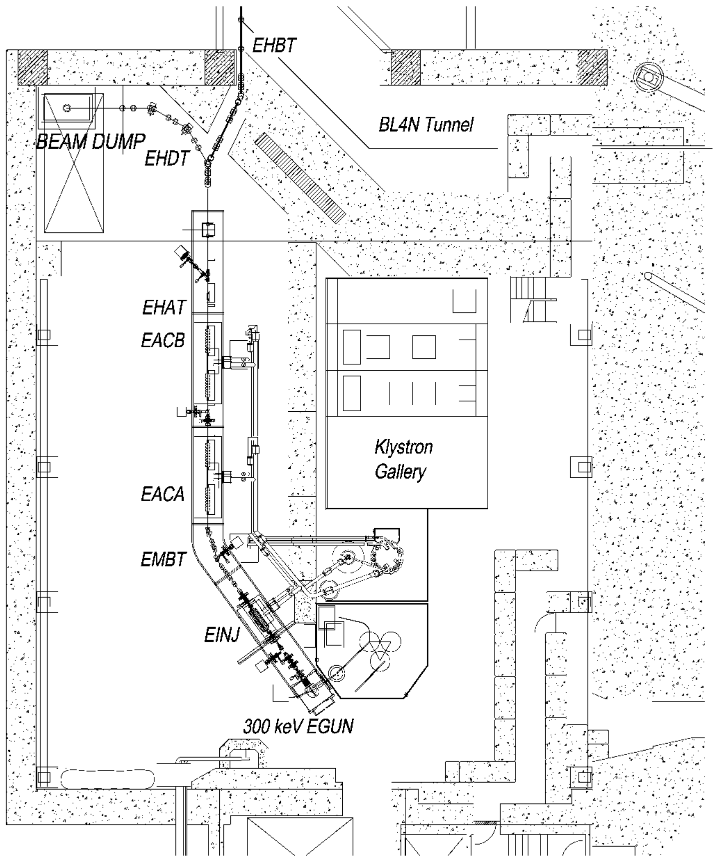


Figure 3-1 E-Linac equipment layout for the Electron Hall. The schematic is at the 264' elevation except for the maze exit in the NE (top right) corner which is at the 284' elevation on top of the BL4N shielding blocks. [An up-to-date beamline layout showing the locations of analyzing dumps is included in the Appendix A drawing list.]

## 3.1 Design

Three main goals have shaped the conceptual design of e-Linac:

- continuous wave (CW) operation at high average power;
- the utilization of existing technology wherever possible; and

- flexibility of operation and configuration.

A 10 mA beam current and a 10 MV/m accelerating gradient have been chosen as the baseline for the full power machine. This will furnish an electron beam of sufficient intensity at a useful energy for an ISOL type facility while still relying on conservative design settings for the accelerating gradient.

The e-Linac is being implemented in stages.

## 3.2 Staging

The initial e-Linac configuration is a 10 MeV injector cryomodule (EINJ) followed by a single accelerator cryomodule (EACA) providing a total nominal beam energy of 30 MeV. Commissioning is being done to a nominal energy of 30 MeV and a maximum energy <40MeV and a maximum beam power of 10 kW delivered inside the e-Hall to the high energy dump.

Operation on AETE (ARIEL Electron Target East) target will be phased according to the science plan and target engineering. First operation will be at 0-10 kW with a goal to ramp up the beam power systematically. Presently a 100 kW converter and target is being implemented.

The final anticipated configuration will include the injector and two accelerator cryomodules (EACA and EACB) delivering up to 49 MeV electrons with a total beam power capability of 500 kW (10 mA and 50 MeV). The injector comprises a 300 keV electron source (the “e-gun”), a buncher cavity, and the injector cryomodule (EINJ) along with low-energy beam transport (LEBT). Each of the accelerator cryomodules contain two multi-cell RF cavities each capable of increasing the beam energy by nominally 10 MeV. The EINJ and EACs are linked by short medium-energy beam transport (MEBT) sections. The accelerated electron beam is transported by a high-energy beam transport section either to a tuning dump in the north-west corner of the Electron Hall (EHDT) or eventually to the beamline tunnel (EHBT) and transported to the east target station (AETE) in the ARIEL Building.

In some cases shielding is considered for a maximum energy of 75 MeV that would correspond to a future upgrade where a recirculating ring would be added. These will be noted explicitly in the analysis.

## 3.3 E-linac Major Components

### 3.3.1 E-Gun

A simple, low-maintenance, 300 kV DC thermionic electron gun is employed to deliver a 10 mA (average) current. The source outputs 136 picosecond wide bunches each up to 16 picocoulomb charge with a bunch repetition rate of 650 MHz. The source consists of a gridded cathode at 300 kV potential separated from an anode at ground by a ceramic insulator. The grid electrode converts the source from diode to triode operation; together with a DC offset the modulation with an RF voltage of the grid causes the gun to be conducting for 16° of the RF cycle allowing a bunched beam to emerge at the anode. The modulation voltage and DC offset are at about 400 V. Additionally low frequency (up to several kHz) pulsing of the beam can be applied by modulating the RF voltage. This allows operation at a lower average power by applying a duty factor to the beam. The source electrodes and ceramic insulator sit in a vessel filled with up to 2 bar of $SF_6$ gas. The high voltage power supply is located in a locked enclosure or “cage”. The RF modulation electronics is near ground potential, and the few watts RF power is transmitted via a ceramic waveguide that penetrates through the vessel.

### 3.3.2 Low-Energy Beam Transport

The e-gun is followed by a LEBT section that uses low field (400 Gauss) solenoid magnets to provide transverse focusing and includes diagnostics to characterize the electron beam and a buncher cavity to shorten the bunches to match the 1.3GHz RF cavity in the injector cryomodule.

### 3.3.3 Buncher Cavity

The buncher, a normal conducting RF cavity excited at 1.3 GHz, develops a voltage of 11 kV AC. The buncher generates almost no acceleration, but rather imposes an energy modulation from head to tail of the bunch; as a result, its power requirements are modest and are met with a 200 W solid-state amplifier.

### 3.3.4 Injector Cryomodule (EINJ)

The purpose of the EINJ is to accelerate the electron beam to a nominal kinetic energy of 10 MeV. The EINJ contains a single SRF cavity operating at 2 K and 1.3 GHz contained within an insulating cryostat. The cryostat achieves thermal insulation and containment through an insulating vacuum and layers of thermal shielding. The outer layer is cooled to 80 K by liquid nitrogen, and the inner layer to 4 K by liquid helium. The multicell cavity is made from niobium and cooled with liquid helium inside a metal jacket.

The cavity which operates at a nominal gradient of 10 MV/m is similar in design to those developed at DESY for the XFEL but modified for operation at 100% duty factor and lower gradient; and with modified end groups for the input coupler and Higher Order Modes suppression. The cavity is driven initially by a klystron operating at 100 kW of RF power. This allows operation of the injector to beam currents of 10 mA at 10 MeV.

### 3.3.5 Medium-Energy Beam Transport (MEBT)

The Injector is followed by the first of two intermediate transport sections: EMBT and EABT. Each section is equipped with magnets for focusing and steering, and beam diagnostics for characterization of the electron beam, particularly its energy. The energy measurement are made in a stub beam line terminating in a Faraday cup.

### 3.3.6 Accelerator Cryomodule (EACA)

The purpose of the EACs is to accelerate the 10 MeV electron beam from the EINJ to higher energies. Each EAC provides a nominal energy gain of 20 MeV so that the beam will have an energy of about 30 MeV after EACA and 50 MeV after EACB. The two modules are identical in construction, and each consists of two multicell elliptical SRF cavities housed in an insulating cryostat similar to that used for the EINJ.

The cavities are each 1 m long and made of niobium. Each accelerator cryomodule approaches 4 m in length. The cavities operate at 2 K and 1.3 GHz with a nominal electric field gradient of 10 MV/m. Thermal shielding and cooling by liquid nitrogen and helium cryogens similar to that in the EINJ has been adopted. Each cavity supplies up to 100 kW of power, generated in a klystron, to the beam.

### 3.3.7 High-Energy Beam Transport

EACA is followed by the first of two high energy transport sections. EHDT leads to a beam dump used for accelerator tuning. And eventually, EHBT will lead off from EHAT, via a switching magnet, into the Tunnel leading to the RIB production targets located in the ARIEL Target Hall. Transverse focusing in both HEBT sections is provided by a series of DC quadrupole magnets. EHDT and EHBT will be approximately 10 m and 60 m long, respectively, with EHDT lying entirely within the Electron Hall while EHBT lies mostly within the Tunnel as shown in Figure 3-1.

### 3.3.8 Beam Diagnostics

Between the different types implemented at the ARIEL e-linac, diagnostics measure current, transverse beam position, beam profile, and time structure across a variety of physical scales.

Initial electron beam threading through the beamline is facilitated by profile monitors (a.k.a View Screens, VS). These devices intercept the beam and produce transverse 2D images that allow determination of beam position and size at their locations. The devices contain scintillators screens, and some also contain Optical Transition Radiation (OTR) screens that can handle average and instantaneous power of a few Watts; hence they are used at low duty factor. The cameras are triggered synchronously with the pulsing of the electron gun. There are 17 View Screens in the e-Hall, and 10 are planned for the ARIEL tunnel.

At power above few W, non-intercepting beam position monitors (BPMs) are used to measure the beam position. Each BPM is essentially four capacitive probes that read out horizontal and vertical position; they also give a relative measure of beam current. These are mated to acquisition electronics that can read beams both with pulsed and C.W. time structure. The BPMs form the backbone diagnostic system. There are 26 units in the e-Hall and 28 planned for the tunnel.

At power levels above a few W, fast wire scanners (FWS) are used to measure beam profile. Unlike the VS, the FWS scan across the beam and so measure profiles rather than provide 2D images. The scan speed is adjustable, and can accommodate beams up to 100 kW C.W. Moreover, they have a very large dynamic range such that (in stepping mode) they can resolve “beam halo” when scanned into the tails of the transverse beam intensity distribution. There are in total four installed in the e-Hall, and up to 3 planned for the tunnel.

The beam current is measured in order to quantify beam flux from the source and quantify transport along the beamlines. The beam may be C.W. or repetitively pulsed, and the measurements must cover both. At certain locations, beam intercepting Faraday Cups (FC) are used. Non-intercepting current monitors, capacitive probes (a.k.a. RF shields, RFSH) can be used for pulsed and C.W. over the entire power range from few W to 100 kW. These RFSH are not absolute and must be calibrated against a FC. Presently, there are 11 of these devices, but only 3 are instrumented with acquisition electronics. The beam current in the C.W. regime and with long beam pulses (hundreds of ms) are measured with DC current transformers, which offer high precision and absolute calibration. Presently, one unit is installed in the EHAT section.

The beam time structure has two scales: macro-pulses from the gun ranging from a few μs to hundreds of ms; and the micro-structure consisting of individual rf bunches. The individual bunches are much shorter than ns, and hard to resolve with probes. A transverse deflecting mode RF cavity located in the ELBD in combination with a VS is used to measure bunch lengths down to the 10 ps level.

### 3.3.9 Machine Protection System (MPS)

The Machine Protection System (MPS) is necessary for beams above 100 W average power. The MPS consists of beam spill monitors and purpose-built electronics that turns off the E-Gun within about 10 μs when a beam spill above threshold is detected. The threshold is 0.1 μC (of beam) in any 0.1 s period. Beam spills are detected using a series of 3 m Long Ion Chambers (LIC) along the beam pipe, and scintillators coupled to Photomultiplier Tubes (PMT) located where additional monitoring is required, typically expected to be at the main bending dipoles. The detectors have been tested at the injector linac of the Canadian Light Source in Saskatoon and have been shown to be satisfactory for the application (Document-121169). The MPS also interacts with the Control System to determine machine configuration and prevent potentially damaging operation. An operation mode is the combination of a "beam property" (essentially an accelerated power level) and a "beam path" (a start-through-end in-beamline equipment list). If the selected property is not compatible with path, then the mode is rejected by the control system. The "beam property" values follow a logarithmic scale (i.e. power of 10). For example, all beam-intercepting devices (except appropriately rated dumps) must be withdrawn from the beam pipe for power above 100 W C.W.; or 10 kW C.W. beam cannot be sent to any dump except EHD.

The machine protection system (MPS) interlocks required to protect the beam dump (EHD) and its associated systems depending on the type of failure and the associated harm which can result. Document-112445, *List of Interlocks and Alarms for the e-Linac Tuning Dump* specifies all the requirements for 10 kW beam dump operation and indicates others that are foreseen when operation above 10 kW with raster magnets is undertaken.

### 3.3.10 Operating Envelope Current Monitoring System– RF Shields

Operating within the beam current envelope prescribed in the licensing agreement is essential to personnel and machine safety and is necessary at all times. The license limit specifies the maximum beam power at a given energy, and the average current limit is the beam power divided by the maximum energy. The maximum current for accelerated beam is limited by at least one calibrated capacitive non-intercepting current monitors (CNIM) in the ELBT and associated threshold electronics that trips off the e-Gun if limits are exceeded. These CNIMs are known to the EPICS as instrumented RF shields (RFSH).

The electron beam has a periodic macro-pulse structure with a (constant) in-pulse beam current and an average current which is calculated as the product of the in-pulse current multiplied by the duty factor, the latter can be varied between ≈ $10^{-4}$ and 1. The RF shield produces a signal that is proportional to the in-pulse current. In order to obtain a current reading the RF shield must be calibrated against a Faraday cup. Two RF shields are used for CNIMs; EGUN:RFSH1 immediately downstream of the e-Gun and ELBT:RFSH0 before the bend to ELBD. Both RF shields are calibrated against the Faraday cup ELBT:FC2 downstream. The calibration is done to the current limit required either by the commissioning license limits or those defined for a particular beam mode. The beam current limits are defined within a control system interface for the CNIMs. Either exceeding a current limit, or failure of a CNIM results in removal of the interlock OK signal, turning off the beam at the e-Gun, and inserting Faraday cup ELBT:FC2. A complete description of the system is in *E-Linac Operating Envelope Current Monitoring System* (Document-117036).

### 3.3.11 RF Power Sources and Distribution

In the final e-Linac configuration, each multicell cavity delivers 100 kW of RF power to the electron beam. Klystrons, very high-gain RF amplifiers, are used to provide this power. These commercially produced devices operate by using a high current (~ 9 A) low energy (~ 60 keV) electron beam to amplify a low-power RF modulation (~ 20 W) to very high power (up to ~270 kW). Each klystron has a DC high voltage (60 kV) cathode, input and output coupling cavities for the RF waves, and a water-cooled anode and is powered by a DC high-voltage power supply and a low-power 1.3 GHz RF source. Presently two klystrons are used to power the three multicell cavities (one klystron for EINJ and one klystron for EACA). The klystrons are housed inside the e-Hall; their attendant power supplies are located on the e-Hall roof beams.

Power is transferred from the klystrons to the cavities by means of water-cooled rectangular waveguides coupled to air-cooled coaxial input couplers that penetrate the individual cavities inside each cryomodule. In addition to these main power distribution components, there are splitters to divide the power between the input couplers, and high-power circulators and resistive loads to protect the klystron from any reflected power.

### 3.3.12 Cryogenic System

The purpose of the cryogenic system is to supply 2 K and 4 K liquid helium and 80 K liquid nitrogen to the three e-linac cryomodules. The helium plant is a closed system with negligible losses in normal operation. Liquid nitrogen, on the other hand, is delivered periodically by a commercial vendor and the evaporated gas is not recovered.

The helium cryogenic system consists of the following main components:

- a pressurized He gas facility;
- refrigeration to 4 K and liquefaction;
- further refrigeration to 2 K;
- sub-atmospheric pumping; and
- purification and impurity control

The main and recovery compressor, He purifier and sub-atmospheric pumps are housed in the Compressor Building South of the Electron Hall. The 100 $m^3$ He gas storage tank is located adjacent to the Compressor building.

Pressurized He gas, at 14 bar, is transferred at ambient temperature (~ 300 K) through piping to the 4 K cold box in the Electron Hall where it is liquefied and collected in the dewar. 4 K liquid He is transported in vacuum-insulated trunk lines to the cryomodules. Inside each cryomodule a cryogenic insert receives the 4K liquid and produces 2K liquid by expansion through a JT valve. An array of sub-atmospheric pumps installed in the compressor building maintains the required pressure on the 2K side of the JT valve.

In practice, the cryoplant is more complicated than this brief description for two reasons: both the 2 K and 4 K He “spent” gas is used in heat exchangers to pre-cool inflowing gas before flowing out for recompression, and an 80 K liquid nitrogen bath is used both to pre-cool the helium and to cool directly the outer thermal shields of the cryomodules. Used nitrogen is warmed up in the ambient vaporizer and exhausted to the atmosphere outside the MAB.

### 3.3.13 Vacuum System

The vacuum system for the e-Linac beamline is divided into three parts with different requirements and volumes: a 5 m long source area operated at $10^{-9}$ Torr, a 15 m accelerator section composed of the cryomodules (at approx. $10^{-11}$ Torr) inter-connected by short beam lines at $10^{-8}$ Torr, and the 10 m and 60 m long respectively, EHDT and EHBT beam lines operated at $10^{-7}$ Torr. These requirements are standard ultra-high vacuum (UHV) practice at accelerator laboratories. The UHV is brought to the nominal pressure in successive steps: followed by a turbo pump to achieve high vacuum; and lastly by ion pumps to reach the UHV required for operation. The scroll pump exhaust for the dump section is directed to the HEPA filtered exhaust from the e-Hall. The ion pumps are self-contained and are regenerated periodically.

A 50 mm diameter vacuum pipe size is used for the EHBT sections based on molecular conductance and the need to keep beam halo losses small. The vacuum pressure in these regions is consistent with a total fractional beam loss, from residual gas scattering, summed over the entire beamline length below the $10^{-6}$ level.

### 3.3.14 Electrical Services

The dominant electrical loads are the high-power RF and cryogenic systems, magnet power supplies, and vacuum systems. Additional loads include controls, diagnostics, lighting, ventilation systems, water cooling pumps, and similar systems. Electrical service is provided by a hierarchical branched system starting with a tap from the 12.5 kV switchgear in the MAB Service Annex. From this point, the voltage is stepped down to 480 V and 208 V and distributed via breakout panels to e-Linac equipment loads. In the event of an interruption to site power, key linac components will receive power from a back-up diesel generator and uninterruptible power supply (UPS).

### 3.3.15 Control System

The ARIEL Control System software is based on the Engineering, Physics, and Industrial Control System (EPICS) toolkit, a multi-laboratory initiative to standardize and share controls device standards, protocols, and software.

The hardware includes a combination of commercial, in-house, and partner laboratory designs, and includes Programmable Logic Controllers (PLCs), a VMEbus based CPU and IO hardware, dedicated control system networking (especially CANbus) apparatus, and commodity CPU and networking apparatus.

### 3.3.16 Beam Dump (EHD) Design & Services

The beam dump is located in the NW corner of the Electron Hall. The roof slab above the dump at the 284’ elevation contains a hatch with removable shielding blocks in order to allow access to the dump with the Main Accelerator Building (MAB) crane. This crane can be used to unstack the dump shielding from the top so that the dump can be extracted and placed in a shielded flask for transfer to the Remote Handling work area at the east end of the MAB. The beam dump is cooled via a dedicated High Active Low Conductivity Water package (HA-LCW) which is in turn cooled by the Low Active – LCW (LA-LCW). The water package is located at the north end of the service tunnel at the B3 level. It has a separate surge tank to minimize the contact with air in the primary loop and keep the water conductivity low. A containment tray with a water sensor is used around the water package and a separate one around the connections and dump insert to contain water spills. The vent from the water package surge tank and that from the vacuum exhaust for the dump is piped separately into the filtered nuclear exhaust for the e-Hall.

***Beam Dump Protection***

In its present de-rated 10 kW configuration (*Design Note TRI-DN-14-13 De-rated e-Linac Tuning Beam Dump Shielding Design, Prompt and Residual Dose Rates, and Activation*) the beam dump is protected by specified interlocks (*List of Interlocks for the e-Linac Tuning Dump - P0104).* Maintaining required beam size and position is enforced by the tune lock system (*e-Linac Tune Lock*) and beam position monitors.

After characterization of the beam spot size at low power, using beam diagnostics (see Section 3.3.8), the tune is “locked" as soon as a beam power over 100 W is requested. Every beam optics and rf device is monitored along the beam path, and the beam is automatically turned off if the output signal of any of these elements drift outside of predefined limits.

If the beam position is measured outside of predefined limits (as per *Beam position interlock for the e-linac high-energy beam dump (EHD)*), the beam is automatically turned off.

## 3.4 Electron Hall Building Services

In the Electron Hall, an air-handling unit and the exhaust fan are both located on the roof of the Main Accelerator Building (MAB). The exhaust blower has a variable frequency drive and is rated at 3000 l/s with a 3.5” water column of back pressure to simulate the impedance of dirty HEPA filters. The exhaust duct for the fan is in the northeast corner of the hall.

Cooling water for the E-linac beam line components and the ancillary equipment in the klystron gallery is supplied as part of the low-active cooling water system (LA-LCW) in the Main Accelerator Building. The beam dump has a separate high active cooling water package as described in Section 3.3.16 with a heat exchanger that is also cooled by the LA-LCW system.

## 3.5 E-linac Control Room & Human Factors Engineering

The e-Linac Control Room is inside the Driver Control Room.

ARIEL will follow the same processes for beam delivery and maintenance as those already used for existing accelerator facilities and described in *TSOP-11 Operations Management*.

A Human Factors Engineering Program Plan (HFEPP) has been released (Document-108553) for the design of the e-Linac Control Room (ELCR). The plan addresses the technical considerations for human-machine interface in the control room environment and identifies the methods by which verification is carried out to ensure compliance with known standards and validation exercises are completed to assess human factor engineering performance. The human factors analysis was based on required tasks and parallels the design of the ISAC Control Room, as both control rooms are similar from an operational stand point. Areas where operation of the accelerators differ were identified and these received a complete review for human factors design. Input and operational experience was also solicited from system experts.

The HFEPP identified both verification and validation processes to be followed and these are further described in the Human Factors Verification and Validation Plan (HFV&VP) for the ARIEL E-Linac Control Room (Document-109159). The verification process for the ELCR design is also based on that completed for the ISAC Control Room. It examines the physical working environment, the human-machine interface for control of the accelerator, components and safety systems and compares the design to accepted standards for human factors[4]. Validation of the design was accomplished with a written questionnaire to survey and obtain feedback from the ELCR users[5]. In addition, validation exercises involved observing the completion of different operational scenarios in the ELCR[6].

[4] Human Factors Verification Report for the ARIEL E-Linac Control Room (Document-121492); Human Factors Verification Report for the ARIEL E-Linac Control Room: Addendum (Document-124249)
[5] ARIEL E-Linac Control Room Human Factors Validation Survey Results (Document-133671)
[6] ARIEL E-Linac Control Room Human Factors Validation Observation Team Results (Document-133672)

# 4 Hazard Analysis

## 4.1 Electron Linear Accelerator Radiation Hazards

Prompt radiation from the electron accelerator comes from losses of the electron beam striking beam apertures; from x-rays from the RF-HV of the accelerating cavities; and from fields from the activation of air and cooling water.

Residual radiation fields are significantly less than the prompt fields and are mostly associated with areas of high beam loss such as the beam dump. These components are typically shielded and residual fields are only of concern when the shielding is removed.

The radiation hazard analysis has been estimated for the final configuration of 50 MeV and 500 kW. In some, cases an energy of 75 MeV is chosen in consideration of future potential upgrades.

### 4.1.1 Prompt Radiation – Photons

Energetic electrons incident on a target produce energetic photons called bremsstrahlung, or “braking” radiation. The emission of photons is a result of the conservation of energy that occurs when the relatively light electron is deflected and decelerated in the vicinity of the electromagnetic field of the target nucleus. Bremsstrahlung radiation is the dominant secondary radiation associated with energetic electrons.

The bremsstrahlung cross-section scales with $Z^2$ of the target nucleus and with increasing incident electron energy, $E_0$. At energies below 1 MeV, electrons lose most of their energy through direct ionization of the target material. At higher energies radiative losses, i.e. bremsstrahlung, dominate. The critical energy ( $E_C$ ) is defined for a given target material as the electron energy at which the energy loss from ionization is equal to that from radiation, and is given by the following expression:

$$E_C = \frac{800}{Z+1.2}\ MeV.$$

The critical energy for some standard materials such as aluminum, copper and lead are 51.0, 24.8 and 9.5 MeV respectively.

The interaction of high energy photons with matter is dominated by pair production, from which electrons and positron in turn generate lower energy bremsstrahlung resulting in an electromagnetic shower. The production of bremsstrahlung therefore results in a continuous energy spectrum which peaks at ~ $0.3E_0$ and diminishes down to zero at the incident electron beam energy, $E_0$. For electron energies above a few MeV bremsstrahlung radiation is significantly forward peaked. The half-width of the angular distribution, $\theta_{1/2}$, is described by the following equation:

$$E_0 \times \theta_{1/2} = 100\, MeV \cdot degrees$$

The photon spectrum in the forward direction is higher energy than in the lateral direction. These properties are important considerations when designing shielding for the accelerator.

The IAEA TRS188 report on the 'Radiological *Safety Aspects of the Operation of Electron Linear Accelerators'* provides some rules of thumb for bremsstrahlung dose rates from worst case thick targets. The absorbed dose rate at 0° for electrons above 20 MeV striking a thick high Z target is given to within a factor of two by:

$$H\left(\frac{Gy \cdot m^2}{hr \cdot kW}\right) = 300 \cdot E_0.$$

For the proposed ARIEL 500 kW, 49 MeV e-Linac, this works out to a worst-case unshielded dose rate at one meter in the forward direction of:

$$H_0(0°) = 1.5 \times 10^4 \, Gy \cdot m^2/hr \cdot kW \times 500 = 7.5 \times 10^6 \, Gy/hr.$$

TRS188 also provides an estimate for the dose rate laterally for the most penetrating bremsstrahlung component of:

$$H_0(90°) = 50 \, Gy \cdot m^2/hr \cdot kW \times 500 = 2.5 \times 10^4 \, Gy/hr.$$

The angular distribution in the forward direction for 50 MeV electrons striking a thick high Z target is shown in Figure 4-1 and is taken from data in the NCRP51 Report *Radiation Protection Guidelines for 0.1 – 100 MeV Particle Accelerator Facilities*.

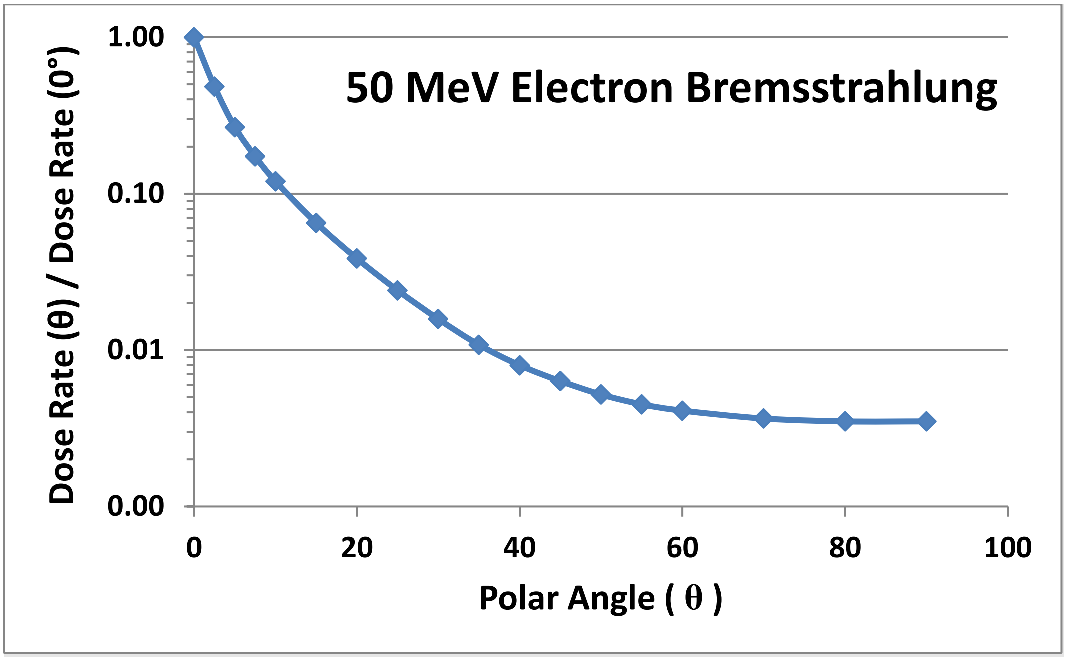


Figure 4-1 Bremsstrahlung dose rate angular distribution normalized to 0° for electrons striking a thick high Z target.

X-rays from the RF cavities also contribute to the prompt radiation field. Dose rates have been measured for these higher gradient cavities by the TRIUMF SRF group. At a gradient of 10.4 MV/m quiescent dose rates at 30 mSv/hr at 0.3 m are observed and during cavity and coupler conditioning when multipacting can occur, dose rates up to 400 mSv/hr at 0.3 m have been measured. Nevertheless, at the ten-meter distance of the overhead roof beams in the e-Hall, the additional contribution to the overall prompt radiation fields from these X-ray fields is negligible.

### 4.1.2 Prompt Radiation – Neutrons

Photons of energies in excess of 7-10 MeV when interacting with material produces neutrons. At photon energies less than 50 MeV the dominant photo-neutron production mechanism is the giant dipole resonance (GDR), an excited state of the nucleus comprising an oscillation of protons and neutrons which can result in the emission of a neutron.

The neutron production yield grows from threshold at 7-10 MeV and for most materials saturates at about 35-50 MeV incident electron energy. The saturation yield is higher for higher Z materials. TRS188 lists approximate neutron yields for 100 MeV electrons on thick targets of aluminum, copper and lead of 0.5, 1.0 and 1.8 × $10^{12}$ n/sec • kW respectively. The yield for uranium includes fission neutrons and is larger by about a factor of two at $3.9 \times 10^{12}$ n/sec • kW.

### 4.1.3 Air Activation for the Electron Hall

Air activation is produced by bremsstrahlung radiation, resulting from chronic losses along the electron linear accelerator, incident on constituent air nuclei in the electron hall. A maximum value for the chronic beam loss is $10^{-5}$ per meter (5 W/m) which for an approximate ten-meter length in the hall amounts to $10^{-4}$ of the total power, or a 50 W loss, or 1 μA at 50 MeV. This is a worst case as the highest operating beam loss, based on experience at other electron accelerator laboratories, is expected to be at least one order of magnitude less than this level, and typical quiescent operating losses would be two orders of magnitude lower than this worst-case level. The high-energy beam dump shielding has been designed to contribute less than 10% of the highest operating loss, and therefore will not add significantly to air activation from this worst-case chronic loss.

The saturation air activation production rate for an electron beam stopping on a thick high Z target from TRS188 is shown in column 3 of Table 4-1 for the long-lived air activation products. Except for Ar-41 which is produced by neutron capture on Ar-40, the production mechanisms are photo-nucleon and photo-spallation reactions. The values are per meter path length of bremsstrahlung in the electron hall. For the electron-hall the saturation air activity production rate can be calculated using a mean path length of ten meters and a total chronic power loss of 50 W or 0.05 kW.

Table 4-1 Air activation for a chronic beam loss of 1 μA in the Electron Hall for a 50 MeV beam.

| Isotope | $T_{1/2}$ (sec) | Saturation Activity (Bq/kw-m) | Derived Air Concentration (Bq/m3) | Equilibrium Activity Concentration (DAC) | Derived Release Limit (TBq) | Release Activity (DRL fraction) |
|---|---|---|---|---|---|---|
| ***H-3*** | 3.88E+08 | 5.00E+06 | 1.34E+06 | 2.72E-09 | 1.32E+05 | 1.07E-12 |
| ***Be-7*** | 4.58E+06 | 1.00E+06 | 1.67E+05 | 3.71E-07 | 7.53E+02 | 3.17E-09 |
| ***C-11*** | 1.20E+03 | 1.00E+07 | 5.68E+04 | 1.35E-02 | 6.07E+03 | 4.87E-06 |
| ***N-13*** | 5.94E+02 | 1.00E+08 | 5.67E+04 | 1.62E-01 | 7.53E+03 | 4.70E-05 |
| ***O-15*** | 1.20E+02 | 5.60E+07 | 5.66E+04 | 1.07E-01 | 1.46E+04 | 1.60E-05 |
| ***Cl-38*** | 2.22E+03 | 2.20E+05 | 3.53E+04 | 3.75E-04 | 3.39E+03 | 1.50E-07 |
| ***Cl-39*** | 3.30E+03 | 1.50E+06 | 3.81E+04 | 1.93E-03 | 3.48E+03 | 8.13E-07 |
| ***Ar-41*** | 6.59E+03 | 1.78E-03[7] | 4.27E+04 | 2.52E-06 | 4.40E+03 | 9.43E-10 |
| **Total** | | | | **2.85E-01** | | **6.88E-05** |

[7] The Ar-41 saturation activity is in units of Bq/kW-cc.

The equilibrium concentration air activity can be calculated by taking into account the production and removal rates. The production rate, $C_0$, is given by

$$C_0 = A_{sat} \times P \times L \times 1/V$$

where

$A_{sat}$ = saturation activity in Bq/kW-m

$P$ = beam power (0.05 kW)

$L$ = average path length of photons in the hall (10 m), and

$V$ = room volume (4400 $m^3$).

The Electron Hall dimensions assumed for estimating the air activity are 8.4 m height by 22 m length and 24 m width for a total volume of 4.4 $\times 10^3$ $m^3$. The exit of EACB is 6.5 m from the north wall and taken together with a distance from beam height to the underside of the roof beam of 7.7 m, yields a path length from the hypotenuse of ~ 10 m. This distance is also appropriate laterally since the effect of the north-south wall limits the extent of the direct photon path in the hall which is otherwise ± 12 m.

Using $n$ to represent the number of radioactive atoms per unit volume, the removal rate is made up of the decay rate, $\lambda n$, and the loss rate through ventilation, $Rn/V$, where $R/V$ is the exhaust rate in room exchange per unit time.

At equilibrium, the loss rate from decay and removal is equal to the production rate and

$$\lambda n + \frac{Rn}{V} = C_0$$

The equilibrium activity concentration, $C_{eq}$, is then

$$C_{eq} = \lambda n = \frac{\lambda C_0}{\lambda + R/V}.$$

The equilibrium concentration for the different isotopes in units of derived air concentration is shown in the left graph in Figure 4-2 as a function of the ventilation rate. In the limit of very few air changes the equilibrium concentration for all air activation products is expected to be about 0.3 Derived Air Concentration (DAC), with the dominant contributions coming from N-13 (9.9 min) and O-15 (2.0 min). The fifth column in Table 4-1 shows equilibrium concentrations in DAC units assuming one hall volume change per hour.

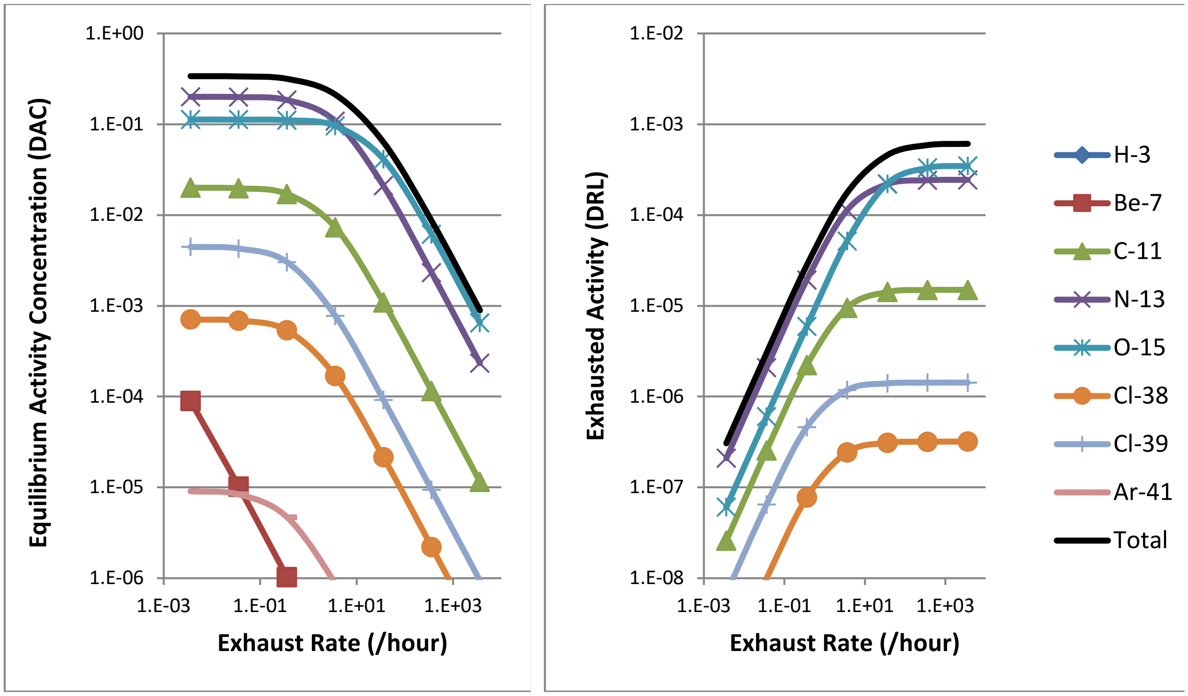


Figure 4-2 Equilibrium airborne activity concentration in DAC and total exhausted airborne activity in DRL as a function of Electron Hall exhaust rate.

The exhausted air activation can also be calculated as a function of the Derived Release Limit (DRL) for the site. Figure 4-2 shows the contribution of air activation products as a function of the exhaust rate. The level of releases at high ventilation rates saturates at 0.1% DRL, or about one tenth of the current site emissions. The exhausted activity for the planned ventilation rate of one volume change per hour are shown in the last column of Table 4-1 and total to less than 0.1% DRL.

Air activation was also examined using FLUKA for a 50 MeV electron beam on a 10 cm copper target in the center of the electron hall. The FLUKA saturation concentrations obtained were 10-20% of the worst-case values from that obtained from the TRS188 values used in Table 4-1. The above estimates can therefore be considered conservative.

## 4.1.4 Residual Radiation & Activation

Residual radiation results from activation products from photonuclear reactions in components in the proximity of high bremsstrahlung fields. The residual radiation fields are anticipated to be highest for the beam dump which is heavily shielded to reduce prompt radiation fields, and which will only be exposed during maintenance.

The high-energy dump in the Electron Hall consists of a water-cooled aluminum insert surrounded by a 10 cm thick lead shield followed by layers of steel and concrete. The shielding and simulations are described in detail in Chapter 6. Residual activation and dose rate information was also extracted from the simulations carried out for the shielding. A range of energies from 25 MeV to 75 MeV and a maximum beam power of 100 kW is used to check the dump residual radiation and activation. Note that this beam power is ten times higher than the 10 kW limit that TRIUMF has placed on present operation.

For 75 MeV electrons about three quarters of the total beam power is deposited in the aluminum and will contribute to activation. The anticipated long term operating scenario to the dump is one month per year for 20 years. Such a scenario was used in a Monte Carlo simulation to generate residual dose rates that personnel would be exposed to when changing out the beam dump. The dominant activation species in the aluminum alloy (Al-6061) are H-3, and Na-22 from aluminum and V-48 and 49, Cr-51, Mn-54, Fe-55, Co-58 and Zn-65 from the trace quantities of iron, manganese, zinc and other elements. The dose rate at 6 m from the uncovered beam dump insert and the remaining surrounding shielding are shown in Figure 4-3 assuming 100 kW operation. After 1 week decay the dose rate is 0.5 mSv/hr and is dominated by the dump insert activation products. A shielded hatch is located above the shielded dump and provides access with the MAB overhead crane for removing the dump insert. The crane will be used to place the dump insert in a shielded flask for transportation to the Remote Handling Hot Cell at the east end of the Main Accelerator Building for repair or replacement as required.

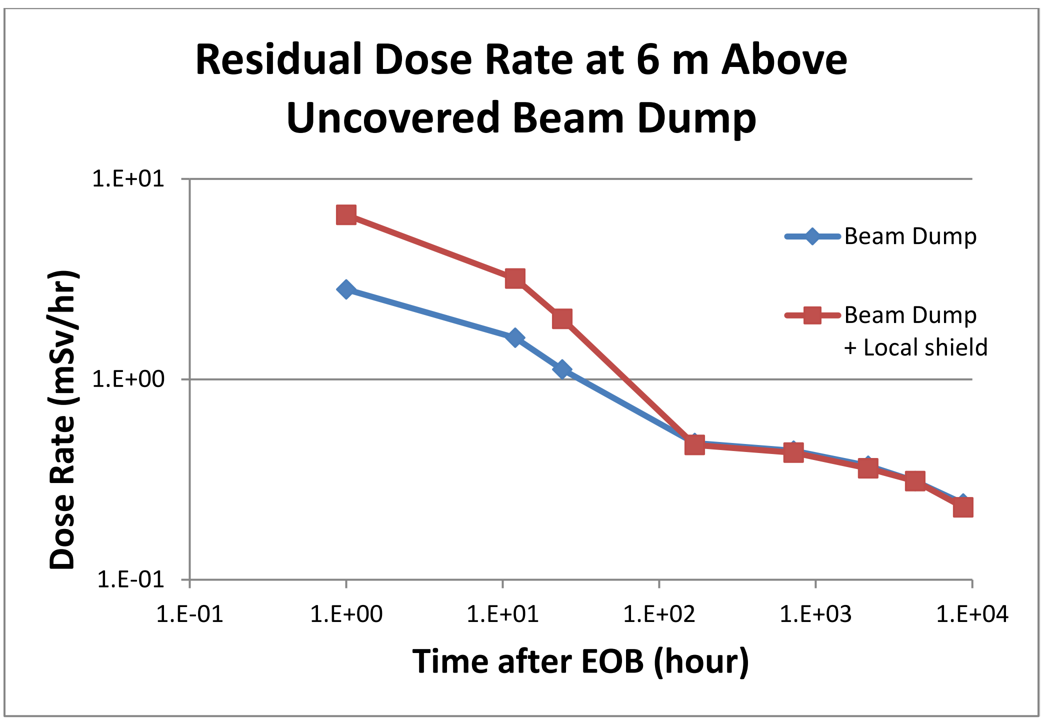

Figure 4-3 Dose rate at 6 m above the uncovered 100 kW beam dump as a function of time after the end of bombardment (EOB). The irradiation profile assumes twenty years of irradiation for 1 month annually with 1.33 mA, 75 MeV electrons.

Residual fields from water activation also need to be considered. The cooling water package resides at the north end of the West Service Tunnel below the e-Hall. The beam dump simulation showed that at lowest beam energies (25 MeV) one could expect up to 20% of the total beam power to be deposited in the water. The dose rate from the water package for the 25MeV and 100kW case after two months of continuous operation is shown in Figure 4-4. [N.b. Two months of continuous operation, rather than 1 month for 20 years used for the dump insert, provides a worst case to the nominal 1-month annual operation as there are no long-lived activation products that can build up and contribute significantly to the dose for water activation.] The production cross sections used are from the FLUKA simulation for 75 MeV electrons and the total worst case deposited cooling waterpower of 20 kW associated with the low energy 25 MeV electron operation, was used. In as much, this represents a worst-case activation level for the dump water package. Most of the water activation products are short lived, and the dose rate from the water package after 6 hours, when most of the C-11 ($T_{1/2}$=20min.) has decayed away, is dominated by Be-7 and is 2 μSv/hr at one meter. The total tritium content after two months of irradiation is 0.25 GBq, or less than a percent of the tritium activity produced in the 500 MeV proton target water packages. The high active water will be released to the MAB Service Annex active sump annually to limit the buildup of tritium in the water package.

Lastly, residual radiation dose rates for beamline components that are subject to chronic beam losses (5 W/m) are expected to be modest, at ~ 10-20 μSv/hr at half a meter.

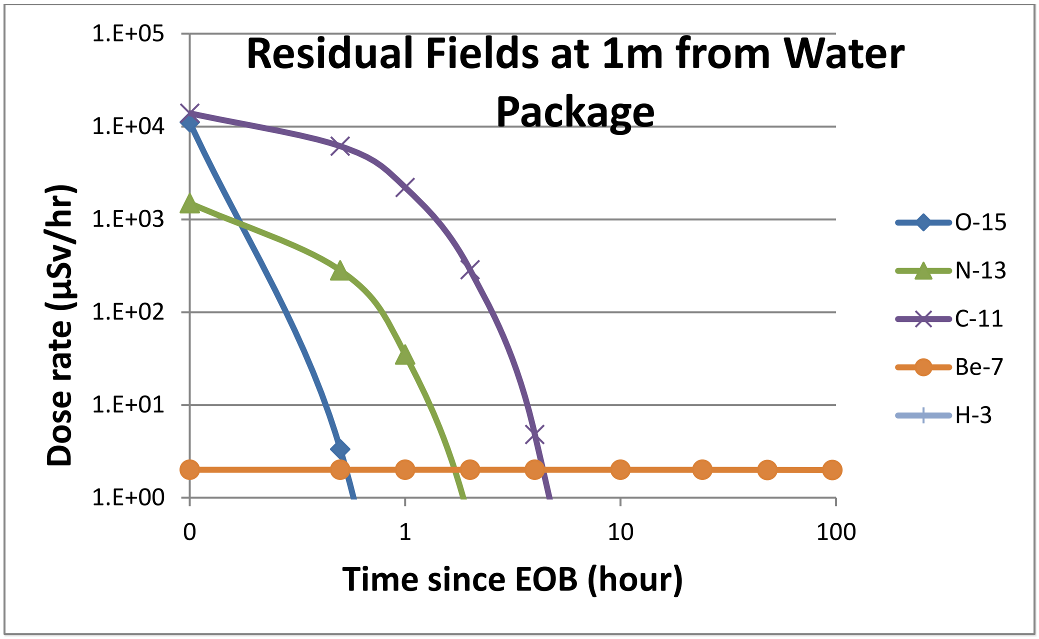


Figure 4-4 The dose rate at 1 m from the high energy dump water package as a function of time after the end of two months of bombardment (EOB). The calculation assumes a bombardment of 100 kW at 25 MeV.

## 4.2 Non-radiological Hazards

### 4.2.1 Seismic Hazard

The Electron Hall occupies the below-grade western portion of the existing Accelerator Building, with a link to the new ARIEL facility via tunnel. The existing below-grade Accelerator Building structure is reinforced concrete, with a thick raft slab and thick side walls. The Accelerator Building was constructed in 1970 and designed to the applicable codes and standards of that time. The works to create the Electron Hall constitute a renovation to the existing building. The additional works do not degrade the seismic performance of the existing building, but they also do not form a seismic upgrade to the existing building.

Structural and seismic analysis and design of the new structures within the Electron Hall complies with seismic provisions of BCBC 2006 (which is adopted from NBCC 2005) as well as the UBC Technical Guidelines (which refer to BCBC 2006). The new structures are designed for seismic loads and provisions corresponding to a Normal Importance building. Non-structural components and parts and portions of the building are designed and suitably restrained for seismic forces in accordance with Clause 4.18.17 of BCBC 2006. The additional structures within the Electron Hall include mass concrete shielding wall and suspended slab elements. These are sufficiently strong that they are not expected to yield during the design earthquake as defined below. These elements are connected to the existing building by epoxy adhesive doweled reinforcing connections, so as to prevent sliding or overturning during the design earthquake. The existing 25mm structural gap along the East side of the Electron Hall (Gridline 4) has been respected and maintained with the new construction.

### 4.2.2 Conventional Electrical Hazards

Conventional electrical hazards include both high voltage and high current AC and DC power. The major source of AC power is a 10 MW, 12.5 kV electrical distribution system. Electrical hazards during installation and operation is mitigated by strict compliance with both the Canadian and BC Electrical Codes as well as the WorkSafe BC requirements. Installations are inspected by the site electrical engineer who has responsibility for ensuring compliance with the BC Electrical Code.

All work carried out on electrical systems must comply with the TRIUMF electrical safety requirements as described in the following TRIUMF Safety Notes (TSN): *TSN 5.8 - Electrical Safety at TRIUMF* , *TSN 5.11 - High Voltage Safety*, and *TSN 1.3 - TRIUMF Lock-out Policy and Procedures* .

The high voltage supply for the 300 kV electron gun is enclosed in a high voltage cage. The high voltage supply is one of the beam inhibit devices for the e-Hall Access Control System. The engineered safety features incorporated into the design consist of the access control interlocks, disconnection of the supply power, and equipment for grounding the terminal before access to the cage.

### 4.2.3 Ozone Production

Under normal operation, at all times during acceleration and transport the electron beam is contained within the vacuum envelope. Therefore, the only potential for production of ozone during normal operation comes from the chronic beam losses which give rise to bremsstrahlung radiation. As described in Section 4.1.3, the total worst case chronic relative beam loss is expected to be $1 \times 10^{-4}$, or 1 microampere at 10 mA. A worst-case estimate for the ozone production is to assume that the electron beam loss directly ionizes the air. There are also loss mechanisms that need to be taken into account in order to arrive at a saturation quantity. Following the formalism laid out in NCRP144 and the references therein, the rate of change of the ozone concentration in air is given by

$$\frac{dn}{dt} = gI - \alpha n - \kappa I n - \frac{R}{V} n,$$

where

$g$ = # ozone molecules produced per eV (= 0.103/ eV)

$I$ = ionization energy deposited (eV / $m^3$-sec)

$\alpha$ = rate of decomposition of ozone molecules (/sec)

$\kappa$ = # of ozone molecules destroyed per unit energy and concentration $n$ ($eV^{-1}m^3$) and

$\frac{R}{V}$ = the room ventilation rate ($s^{-1}$).

The solution to this equation is

$$n(t) = n_{SAT}\left[1 - e^{-(\alpha+\kappa I+R/V)t}\right].$$

For a long irradiation time the concentration reaches saturation

$$n_{SAT} = \frac{gI}{\alpha+\kappa I+R/V}.$$

Using the chronic beam loss current and the electron ionization in air ( $\mu_{coll}$ = 2 MeV • $cm^2$ / g) one obtains

$$I = \mu_{coll}\,\rho\frac{L}{V}\,i_{chronic}$$

where $\rho$ is the air density and $L$ / $V$ is the path length in air divided by the room volume. Using 10 m for the path length and 2000 $m^3$ for the volume yields

$$I = 7.85\times 10^{14}\ eV/s\cdot m^3.$$

Conservative values for the rates of decomposition are = $2.3 \times 10^{-4}$ $s^{-1}$, and $\kappa = 1.4 \times 10^{-22}$ $eV^{-1}$ $m^3$.[8] Using one e-Hall volume change per hour ($R/V = 2.78 \times 10^{-4}$) as in Section 4.1.3 and plugging in values into the equation above yields an ozone saturation concentration of $3.51 \times 10^{17}$ $m^{-3}$. Dividing by the ideal gas molecular oxygen concentration at room temperature and pressure of $6.02 \times 10^{23}$ • 0.21 / 0.0245 $m^3$, yields a saturation concentration of 0.068 ppm. This concentration is just below the ozone threshold limit value (TLV = 0.1 ppm), above which remediation measures are recommended. In conclusion, additional remediation measures are not anticipated to be required for ozone production. Sampling will be carried out to confirm the ozone concentration levels.

### 4.2.4 Radiolysis for the Beam Dump

The deposited beam power in the cooling water for the cooled aluminum beam dump can result in radiolysis of the water generating ions and some gases. Experience with the 500 MeV production targets and beam dump has shown that these ionization products can be minimized by maintaining low conductivity for the primary cooling water loop. This

[8] The value given for κ in NCRP144 is in error. The value used here is from the original source is Hoeffert, M. CERN-TIS-RP-175-CF breport, 1986

is achieved with a closed primary loop that includes an ion-exchange resin that is devoid of water/air boundaries. In addition, the primary loop is connected via a supply line to a secondary surge tank. The capping volume of air atop the water in the surge tank is exhausted to the nuclear exhaust. A similar water package design has been used for the water-cooled dump. The beam dump system requirements have been captured in Document-57707.

Radiolysis of water occurs when deposited energy from charged particles result in splitting water molecules into free radicals. The average energy per dissociation is ~ 100 keV. Depending on the conditions the free radicals can then form $H_2$ and $O_2$ gas in the water which eventually collects in the capping volume at the top of the water package. The production of $H_2$ gas has been measured for different systems and is between 0.8-3.2 l $H_2$/MJ. [9] This value will depend on the water purity (high purity reduces the production) and 1.6 l/MJ is used here. [N.b. NCRP 144 has a value of 0.44 l/MJ.]

Using 1.6 l/MJ, and 10 kW of deposited power in the beam dump cooling water results in (10E-3 MJ/s • 1.6 l/MJ * 3600 s/hr) 57.6 l/hr of $H_2$ gas. The explosive limit for hydrogen gas is 4%. The air volume above the tank is monitored and the gases vented to the hall exhaust to keep the maximum $H_2$ gas operating level below 1%. Assuming that none of the $H_2$ gas remains dissolved the required exhaust flow from the top of the surge tank would be 60 • 100 = 6E3 l/hr (100 Lpm).

### 4.2.5 Thermal Considerations for the Beam Dump

This section addresses the design considerations taken to minimize the risk of damage to the beam dump. These risks do not pose an immediate personnel hazard but any work recovering from a failure would involve exposure to residual radiation fields and/or potential contamination.

***<u>100 kW Operation</u>***

This beam power is 10 times higher than the present TRIUMF internal limit for beam delivery to the high energy dump. Energies of 25 to 75 MeV are considered. At this power raster magnets would be installed to distribute the beam through a 4 by 4 cm square aperture onto the (aluminum) dump incident plate angled at 3° to the beam direction. The incident instantaneous spot size of 1 mm radius is spread over an ellipse with semi axes 1 mm and 19 mm. Through the raster pattern, the beam is painted over a rectangular area roughly 3 cm by 80 cm.

The thermal requirement for the dump insert is two-fold: (i) keep the maximum temperature of the cooling water below 90 °C to remain well

[9] Walz et al. SLAC-PUB-0279 Beam Dumps, Energy Slits and Collimators at SLAC – Final Versions and First Performance Data

below the boiling point; and (ii) keep the incident aluminum plate temperature of the dump insert, the location where the power density is highest, below 150 °C. This design limit provides a margin of 30 °C above which material ageing effects can start to affect the material strength of 6061-T6 aluminum.

The thermal analysis was the subject of a design review (Document-104082) where two independent analyses were compared and found to agree within ≈ 10%. The maximum temperatures predicted for the beam dump insert at 25 (75) MeV incident electrons was 93 (114) °C, with the maximum observed at the beam spot for 25 MeV and at the lower surface centered along the length for 75 MeV electrons. The highest temperature away from the beam spot at 75 MeV is a result of the larger radiative fraction – 38% at 75 MeV as compared with 17.5% at 25 MeV. Yield stresses were also examined and found to be better than a factor of safety of two of the yield strength for the solid sections and better than a safety factor of three for the weld areas. A one third size prototype was also built to verify procedures for manufacturing and assembly as well as to check the integrity of the weld design through pressure tests and sectioning of the weld.

***10 kW Operation***

At power levels up to 10 kW (present commissioning limit), the dump may be operated without a raster provided that the beam spot size is increased up to 6 mm r.m.s. The quadrupoles EHDT:Q5,Q6 and the wire scanner FWS6 are used to adjust and measure the spot size at low duty factor.

The same beam dump insert is used for 10 kW operation, except that instead of rastering, the Gaussian beam is defocused to a size of 1.41 cm FWHM ($\sigma_{rms}$ = 0.6 cm) . A thermal analysis was performed using a uniform cylindrical incident power deposition having the same peak and r.m.s. power density (W/m$^2$) and total power as that of the Gaussian beam shape. The analysis demonstrates that the dump insert and cooling water temperature requirements are satisfied for a Gaussian beam with total power up to 26 kW. The maximum temperature observed (T = 119 °C) for 26 kW and no raster is slightly greater than that for the 100 kW rastered operation. However, the analysis has a comfortable safety factor of more than two for operating the dump at 10 kW: the thermal stress is lower because at 10 kW both the maximum temperature (67 °C) and the width of the heated zone are significantly less than at 100 kW. The thermal analysis for the de-rated beam conditions is included in E-Linac Beam Dump Maximum Un-Rastered Beam Power (Document-115170) .

### 4.2.6 Oxygen Deficiency Hazard

The accelerator superconducting RF cavities are enclosed in two cryomodules that operate at or below 4 K. A cryomodule consists of an outer enclosure cooled with liquid nitrogen ($LN_2$) and a smaller inner enclosure filled with liquid helium (LHe). The nitrogen exhaust is released to the atmosphere outside the Main Accelerator Building, whilst the helium gas is captured and circulated back to the Compressor Building for recompression. By eliminating the release of all evaporated cryogenic liquid from the hall, a defense in depth approach has been adopted to minimize an oxygen deficiency hazard.

The hazard assessment for oxygen deficiency in the e-Hall and Compressor Building is described elsewhere (Document-108576). Table 4-2 summarizes the relevant quantities to assess the oxygen deficiency hazard in these areas, an oxygen deficiency hazard is said to exist when the 20.95% $O_2$ level normally present in air is depleted to below 18%. The first column includes the type of cryogenic liquid and the area in question. The second column is the volume of the area where personnel could be impacted; a conservative 1.4 m height above the floor for $LN_2$ since the cool $N_2$ gas tends to pool at low elevations, and a 1.4 m depth below the ceiling for LHe in the e-Hall since that is 1 m above the elevation of the exit door and maze. The third column is the air exhaust rate from the area. The fourth column is the volume of cryogenic liquid that when released in the area would result in an OD hazard (≤18% $O_2$). The conversion from liquid to gas for $LN_2$ is a factor of 700 and for LHe a factor of 750. The two right-most columns are the amount of liquid cryogen available in the area and the potential supply of cryogenic liquid to the area.

Table 4-2 Cryogenic liquid and gas volumes required to create an oxygen deficiency hazard in the e-Hall and Compressor Building. $LN_2$ is not shaded and LHe is in the shaded rows,

| AREA | Volume of Occupied Area[1] ($m^3$) | AREA air Exchange Rate (/hr) | Cryo Liquid Volume Necessary for ODH[2] (l) | Cryo Liquid Available in the AREA[3] (l) | Cryo Liquid supplied to the AREA[4] (l/hr) |
|---|---|---|---|---|---|
| $LN_2$ in e-Hall (B2 Level) | 720 | 1.3 | 192 | 330 | 3000 |
| LHe in e-Hall (284' elevation) | 720 | 1.3 | 1100 | 1150 | 0 |

| | | | | | |
|---|---|---|---|---|---|
| $LN_2$ in West Service Tunnel (B3 Level) | 67 | N/A | 13 | 330 | 3000 |
| LHe in West Service Tunnel (B3 Level) | 67 | N/A | 12 | 0.45 | 0 |
| $LN_2$ in Compressor Bldg. | 200 | Return | 39 | 50 | 3000 |
| LHe in Compressor Bldg. | 500 | Return | 93 | 0.45 | 3.6 |

1) Only consider the lower 1.4 m for the relevant volume as cold $N_2$ gas will not mix readily with air. For the LHe include the top 1.4 m below the e-Hall ceiling.

2) Cryogenic liquid volume required to lower the $O_2$ concentration below 18%. Includes the hourly exhaust air rate where applicable.

3) Includes the largest volume of the cryogenic liquid in the area. In the case of the Service Tunnel, the He from the hall is not included as it will rise in the hall and never penetrate the apertures into the tunnel below the hall.

4) Flow rates into the area are based on the connecting line diameter from the 34000 l dewar to the area. As for the LHe it is based on a rupture of a 24 m long pipe carrying 14 bar He gas from the compressor building to the e-Hall and converted to an effective LHe volume for comparison with the ODH volume in column 4. Similarly, the supply for the compressor building is based on 0.75 cc-atm/s He gas flow rate at the compressor converted to an effective cryogenic volume.

A comparison of the cryogenic liquid volumes required in each area to create an oxygen deficiency hazard (column 4) and the volumes and flow rates available in those areas (columns 5 and 6) indicates that for $LN_2$ all the areas in a worst-case release have the potential for the oxygen to drop below 18% in the occupied region. Whereas for LHe the service tunnel and the compressor building do not have an oxygen deficiency hazard, and the top of the Electron Hall would only result in a concentration that is marginally below 18% in a worst-case scenario. The last column shows the flow rate in effective cryogenic liquid volumes possible in the area. It is important to note that the 3000 l/hr $LN_2$ flow rate would only be possible if the control valve, on each of the lines, to the e-Hall via the service tunnel and/or the compressor building, failed to shut on an interlock signal from the oxygen deficiency monitor. Details of the engineering controls to limit the hazard are included in Chapter 6.

Lastly, there is three cubic meter-atm of sulphur hexafluoride ($SF_6$) in a vessel containing the e-gun high voltage electrodes located at the south end of the Electron Hall. This is a relatively small volume and $SF_6$, which is heavy compared with air, will tend to migrate to the lowest elevations. For more information, see Section 5.7.4.

# 5 Mitigation Measures

## 5.1 Shielding for the Electron Hall

Shielding which is described in this section is the primary level of passive personnel protection from prompt radiation hazard. In addition to shielding, active personnel protection is provided with access control and radiation monitoring systems which are described in section 5.2.

The fixed shielding analysis has been estimated for the final configuration of 50 MeV and 500 kW.

### 5.1.1 Shielding Requirements

Target dose rate limits for the shielding design are governed by *TRIUMF's Policy for Maximum Allowable Dose Rates in Accessible Areas TSN 1.8*. Prompt radiation dose rates outside shielding need to be considered for both normal and abnormal beam loss conditions when designing shielding. The requirements are that:

- under normal operation, for a chronic beam loss, the shielding must be sufficient to limit dose rates in high (low) occupancy areas to 0.5 (10) μSv/hr; and
- under an abnormal or accidental beam loss condition the dose rate be limited to 50 mSv/hr.

The anticipated worst case chronic beam loss for the 500 kW e-Linac is 5 W/m which, over a 10 m length of the e-Linac, amounts to 50 W, or a relative loss of $1 \times 10^{-4}$ of the full power. When one designs with a safety margin of two and uses a chronic dose rate for low occupancy areas of 5 instead of 10 μSv/hr, the ratio of chronic over accidental loss dose rate limits (5 μSv/hr / 50 mSv/hr = $10^{-4}$) is then equal to the fraction of full power for total chronic losses in the Electron Hall. Therefore, using the target dose rate of ≤ 50 mSv/hr for a full accidental loss in designing shielding provides sufficient shielding to remain below 5 μSv/hr for chronic losses.

Additional information from other CW electron accelerator laboratories indicate that the above chronic loss level is high and that maximum losses associated with normal operation are expected to be at least an order of magnitude lower. This would then bring the chronic loss dose rate ceiling to 0.5 μSv/hr in the low occupancy areas and allow for higher occupancy while remaining below the annual dose threshold of 1 mSv (2000 hours). There are high occupancy areas located further away from the electron hall and these have dose rates that are correspondingly lower as well. These low occupancy areas are also examined in the shielding analysis below. An order of magnitude lower dose rate limit means that for an accidental full loss the dose rate should be below 5 mSv/hr.

The above shielding requirements need to take into account both bremsstrahlung photons and the resultant photonuclear neutrons generated by photon interactions with materials in the Electron Hall. The strong forward-peaked bremsstrahlung distribution as compared to the isotropic neutron distribution means that neutrons have the potential to constrain the shielding requirements in the lateral direction. Even then, as will be shown below, with 50 MeV electrons incident on a moderate Z target such as steel or copper, the neutrons contribute less than ten percent of the dose in the lateral direction. Where neutrons become the dominant contributor to radiation fields outside shielding is at maze openings, as neutron transmission along a maze is superior to that for photons.

A plan view of the 49 MeV, 500 kW electron linear accelerator housed in the Electron Hall is shown in Figure 5-1.

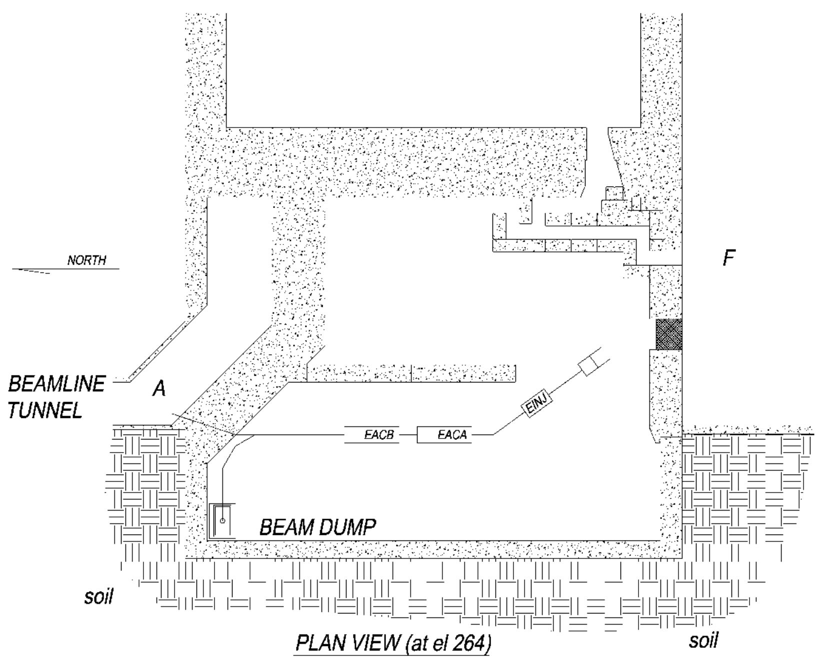


Figure 5-1 Plan view of the e-Linac and the shielding enclosure that makes up the Electron Hall. The inner north-south shielding wall is ten feet tall and provides prompt radiation shielding for the equipment gallery on the east side of the wall.

Additional shielding added to the south wall to protect occupants at the B2 level (location F) is also shown.

### 5.1.2 Photon and Neutron Shielding Requirements

Attenuation lengths in tenth value layers (TVL) for different shielding materials for bremsstrahlung spectra produced by 50 MeV electrons striking a thick, high-Z target are shown in

Table 5-1 and were obtained from figures in TRS188 (Fig. 46 and 47) and NCRP 51 (Appendix E). Concrete has a slightly larger initial TVL than for successive layers and is shown separately in the table. TVLs for shielding in the lateral direction are also included.

The dose rate outside shielding is given by:

$$H = H_0(\theta) \times 10^{-\left[1 + \frac{(t - TVL_1)}{TVL_n}\right]} \times {}^{1}\!/_{d^2}$$

where $H_0(\theta)$ is the source dose rate at one meter as given in the previous section, $t$ (> $TVL_1$) is the thickness of shielding and $d$ is the total distance to the beam loss point, both in meters and each a function of theta.

The source term dose rates for bremsstrahlung photons at zero and ninety degrees given in the previous chapter and scaled for a chronic loss of 0.05 kW (500 kW ×$10^{-4}$) are:

$$H_0(0°) = 1.5 \times 10^4\ Gy \cdot m^2/hr \cdot kW \times 0.05\ kW = 7.5 \times 10^2\ Gy \cdot m^2/hr$$

$$H_0(90°) = 50\ Gy \cdot m^2/hr \cdot kW \times 0.05\ kW = 2.5\ Gy \cdot m^2/hr$$

The neutron source term is isotropic and is correspondingly:

$$H_0(0°) = 1.0 \times 10^{12}\ n/s \cdot kW \times 0.05\ kW = 50.0 \times 10^{10}\ n/s$$

Table 5-1 Different material Tenth Value Layer (TVL) thicknesses for 50 MeV electrons incident on a thick, high-Z target

| Material | 0° -TVL (meter) | | 90° - TVL (meter) | |
| --- | --- | --- | --- | --- |
| | $TVL_1$ | $TVL_n$ | $TVL_1$ | $TVL_n$ |
| **Bremsstrahlung photons** | | | | |
| Concrete | 0.56 | 0.49 | 0.51 | 0.46 |
| Steel | -- | 0.11 | -- | 0.11 |
| Lead | -- | 0.053 | -- | 0.053 |

| Bremsstrahlung neutrons | | | | |
|---|---|---|---|---|
| Concrete | 53.2 | 36.6 | 53.2 | 36.6 |

TRS188 Fig. 54 data, reproduced in Figure 5-2 below, show the attenuation of neutrons for 55 and 65 MeV electrons incident on various targets as a function of concrete thickness. The abscissa (Bn) is the dose equivalent per incident neutron fluence in units of pSv·cm2 / neutron. The neutron attenuation lengths obtained from these data are shown in

Table 5-1. The emission of neutrons is isotropic, and the attenuation is therefore the same at zero and ninety degrees.

The shielding for the e-Linac was assessed for chronic losses in both the forward and lateral directions. Figure 5-1 shows a plan view and Figure 5-3 an elevation view of the accelerator in the hall.

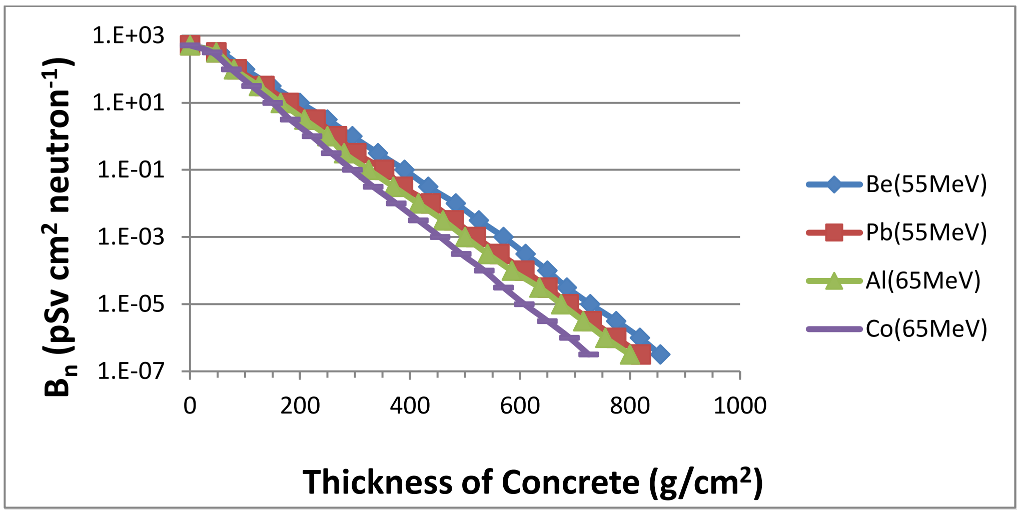


Figure 5-2 Attenuation of neutrons in concrete from different energy electrons impinging on different material targets

The accelerator is housed at the B2 level in the Electron Hall which is largely surrounded by soil to the northwest, west and southwest, and the 5 m thick cyclotron accelerator vault to the east. The only locations for occupancy at the B2 level are in the beam line tunnel directly ahead (Location A) and in the backward direction, Service Annex (Location F in Figure 5-1). In the lateral direction Figure 5-3 shows the locations B, C, D and E which also need to be assessed. Table 5-2 summarizes the relevant distance, concrete shielding thickness, gamma and neutron attenuation as well as the total dose rate for each of these areas.

Table 5-2 Attenuation factors for gamma and neutron through the thickness shielding for different locations and the associated dose rates outside shielding for a chronic loss of 50W at 50MeV.

| Location | Distance (m) | Concrete Thickness (cm) | Gamma Attenuation | Gamma Dose (µSv/hr) | Neutron Attenuation | Neutron Dose (µSv/hr) | Total Dose (µSv/hr) |
| --- | --- | --- | --- | --- | --- | --- | --- |
| A (0°) | 4.6 | 360 | 6.25E-08 | 2.22E+00 | 4.13E-10 | 1.69E-05 | 2.22E+00 |
| B (90°) | 6.3 | 180 | 1.57E-04 | 1.00E+01 | 3.43E-05 | 7.60E-01 | 1.08E+01 |
| C (90°) | 10.2 | 150 | 7.04E-04 | 1.71E+01 | 2.26E-04 | 1.90E+00 | 1.90E+01 |
| D (90°) | 24.9 | 192 | 8.61E-05 | 3.47E-01 | 1.61E-05 | 2.25E-02 | 3.70E-01 |
| E1 (90°) | 29 | 340 | 5.22E-08 | 1.55E-04 | 1.45E-09 | 1.50E-06 | 1.57E-04 |
| E2 (90°) | 33.1 | 192 | 8.61E-05 | 1.96E-01 | 1.61E-05 | 1.27E-02 | 2.09E-01 |
| F (90°) | 23.4 | 240 | 7.79E-06 | 3.55E-02 | 7.86E-07 | 1.24E-03 | 3.68E-02 |
| A (90°) (+60 cm) | 3.9 | 255 | 8.69E-06 | 1.43E+00 | 3.06E-07 | 1.74E-02 | 1.44E+00 |

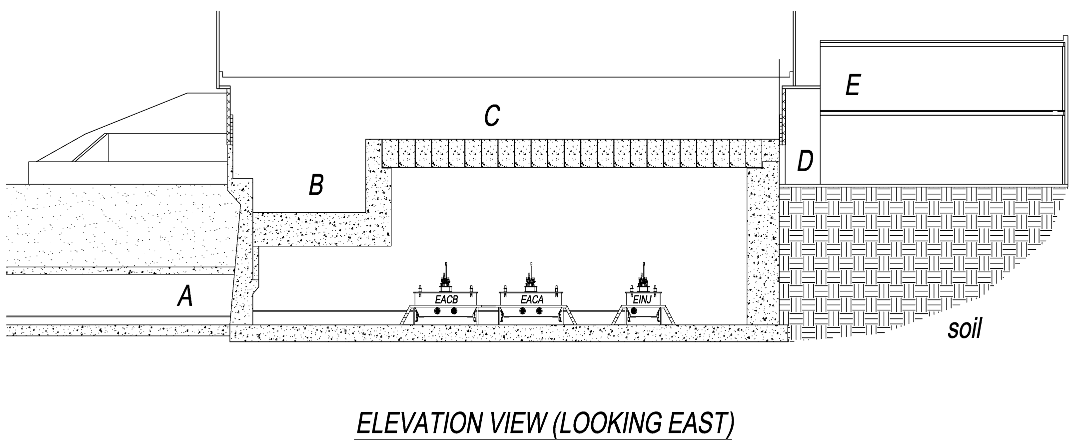


Figure 5-3 Elevation view taken at the accelerator axis looking towards the Cyclotron Vault. The tunnel extending North of the Electron Hall can be seen on the left. The letters refer to locations discussed in the text. This section is to the West of the Service Annex space to the South of the Hall, and as a result shows the soil fill at the B2 and B1 level.

All locations except E are low occupancy areas where the design dose rate limit is 5 μSv/hr for a chronic loss or 50 mSv/hr for a full point loss. The point kernel method indicates that the dose rate for locations B and C, i.e. the roof beams and the slab, exceed this limit. Note that the Monte Carlo analysis described in the next section shows that, in fact, the expected dose rate at these two locations are well below 5 μSv/hr for chronic loss. Location E is an office area and there the design dose rate limit is 0.5 μSv/hr. The table shows the dose rate assessed at the north end of the area (E1) where the shine is through the roof beams, and at the south end of the area where the shine is through the south shielding wall (E2). In both cases the dose rate falls within the limit.

The Monte Carlo analysis described in the next section addresses locations B and C where the point kernel method shows an excess of 5 μSv/hr for a chronic point loss or 50 mSv/hr for an accidental full point loss.

Figure 5-4 shows an elevation view of the Electron Hall looking north and includes the West Service Tunnel. The tunnel is part of the access-controlled area and will not be accessible during e-Linac operation.

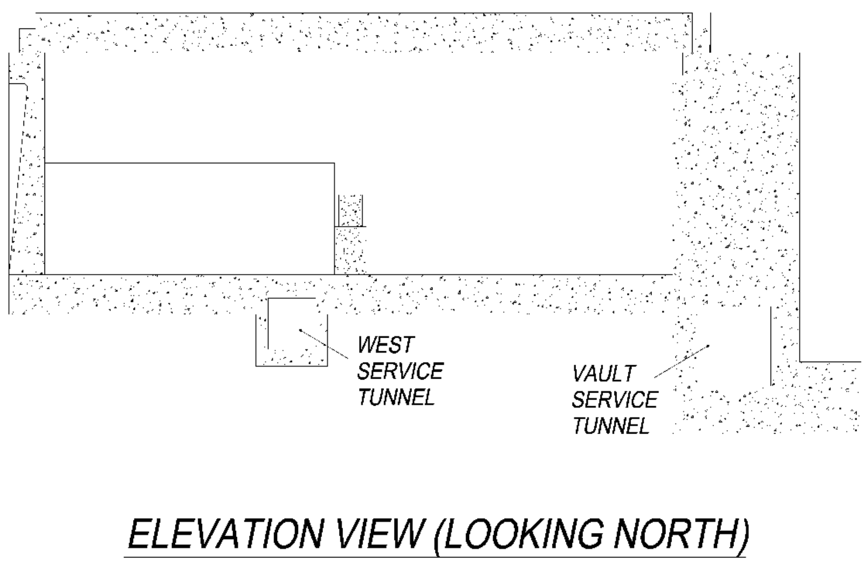


Figure 5-4 Elevation view looking North showing the West Service Tunnel located below the Electron Hall. It will be used for routing North to South cryogenic pipes and cable trays for the electrical services for the e-Linac. The inside concrete shielding wall is shown in the middle of the hall. The additional shielding at the ends of the roof beams is also shown.

### 5.1.3 100 kW Beam Dump Shielding

This beam power is 10 times higher than the present TRIUMF internal limit for beam delivery to the high energy dump. Energies of 25 to 75 MeV are considered. Simulations to optimize the local shielding for the

100 kW dump have been conducted and are summarized in TRI-DN-13-29. The simulations used FLUKA[10,11], a Monte Carlo code optimized for modeling accelerator shielding problems.

The configuration that proved optimum for the shielding footprint is a layered steel and concrete structure as shown in Figure 5-5. The electron beam is directed west which is to the left in the figure. The dump insert is water cooled aluminum which is surrounded by a water cooled lead shield that is 10 cm thick azimuthally and 13.5 cm thick in the forward direction.

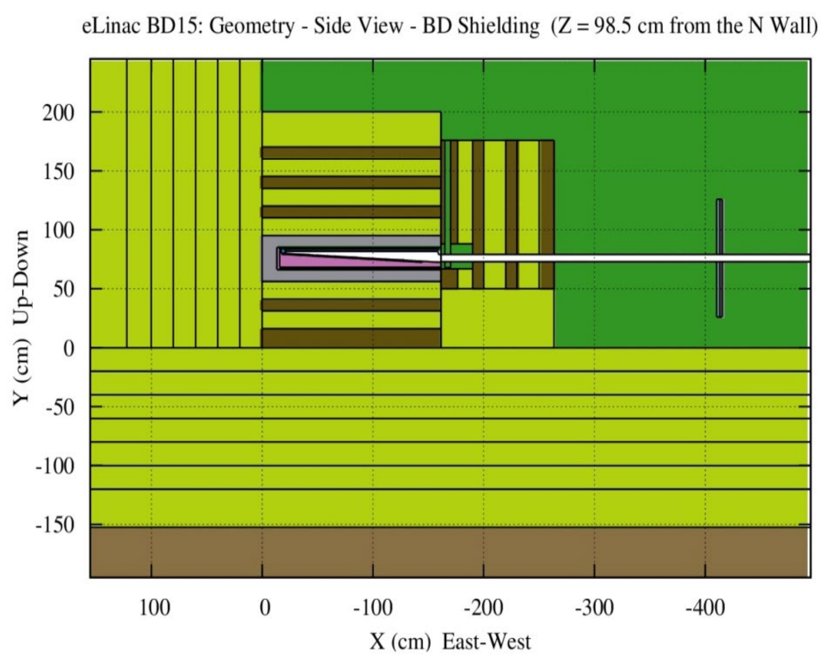


Figure 5-5 Elevation view of the simulation geometry for the shielded dump showing the layers of steel (brown), concrete (light green), and air (dark green). The layers in the Electron Hall poured-in-place concrete for the west wall and floor were used for biasing in the simulation.

The total thicknesses for the dump shielding materials are captured in Table 5-3.

Table 5-3 Local shielding thickness for the 100 kW dump

| | Total Shielding Material Thickness (cm) |
|---|---|

[10] G. Battistoni, S. Muraro, P.R. Scala, F. Ceruti, A. Ferrari, S. Roesler, A. Fasso, J. Ranft, The FLUKA code: description and benchmarking, 2006

[11] A. Ferrari, P.R. Sala, A. Fasso, and J. Ranft, FLUKA: a multi-particle transport code, CERN-2005-10, INFN/TC_05/11, SLAC-R-773, 2005

| | Above | Below | North | South | West | East |
|---|---|---|---|---|---|---|
| | Outside | Inside | Outside | Inside | Outside | Inside |
| Lead | 10 | 10 | 10 | 10 | 13.5 | 0 |
| Concrete | 75 | 30 | 60.25 | 85 | 0 | 53.6 |
| Steel | 30 | 36.2 | 20 | 20 | 0 | 48.3 |

The shielding requirements included in the 100 kW dump system specification document (Document-57707) are itemized below as well as a summary of the simulation results from TRI-DN-13-29.

**Requirement (RS 10)** The beam dump prompt radiation shielding shall attenuate the prompt neutron fluence in the soil to less than $1 \times 10^4$ neutrons/cm$^2$-sec for high energy neutrons (Energy > 20 MeV) and less than $1 \times 10^5$ neutrons /cm$^2$-sec for low energy neutrons.

**Rationale**: To limit soil and ground water activation.

**Results**: The neutron fluence in the soil was limited to 10 mSv/hr in all directions. Given the electron beam energy and the moderation through the shielding, this is largely a low energy neutron spectrum and for the most conservative energies corresponds to a fluence limit of $4 \times 10^3$ neutrons/cm$^2$-sec and easily meets the requirement above. The dose rates at the soil boundary are captured in Table 5-4. The requirement is met for all soil boundaries.

Table 5-4 Maximum dose rates at the inner and outer boundary of the poured-in-place concrete in the Electron Hall.

| | Dose Rate (mSv/hr) | | | | | |
|---|---|---|---|---|---|---|
| | West Wall | | Floor Slab | | North Wall | |
| | Outside | Inside | Outside | Inside | Outside | Inside |
| Total | 110 | 1.4E7 | < 0.01 | 7.1E3 | << 0.01 | 305 |
| Neutrons | 1.7 | 1.4E7 | -- | 6.9E3 | -- | 196 |
| Photons | 63 | 9.4E5 | -- | 220 | -- | 87 |

**Requirement (RS 11)** The beam dump prompt radiation shielding in the vertical direction at a distance of 3 meters outside the shielding shall attenuate neutrons to a dose rate of 50 mSv/hr and photons to a dose rate of 5 mSv/hr.

**Rationale**: To meet a design limit for the total chronic loss dose rates outside the 1.8 m concrete roof shielding of 5 μSv/hr for a low occupancy area. The above dose rate requirements will result in a combined neutron and gamma dose rate of 1 μSv/hr to the area immediately above the dump. In addition, this area will have a contribution from chronic losses along the accelerator shining through the vertical wall of ~ 2 μSv/hr, thereby keeping the total dose below 5 μSv/hr. [The TRIUMF policy on dose limits for a low occupancy area is 10 μSv/hr TRIUMF Safety Note 1.8 – Document-544]

**Results**: The dose rate above the dump had to be kept lower than this requirement in order to also meet the requirement RS 13 for dose rate limits in the Electron Hall for radiation-sensitive components. The total, neutron and gamma dose rates above the dump local shielding are 6, 1.5 and 4.5 mSv/hr.

**Requirement (RS 12)** The neutron dose rate outside the dump shielding shall be limited to 10 mSv/hr, in order to keep long-lived concrete activation below the CNSC regulatory Unconditional Clearance Level (UCL) of 0.1 Bq/g.

**Rationale**: Trace quantities of naturally occurring Europium in the Main Accelerator Building concrete (~ 0.25 ppm), when exposed to thermal neutrons leads to long-lived activation products. The Electron Hall wall activation should be kept below the UCL to limit the cool-down time at the time of decommissioning.

**Results:** The maximum dose rates at the inner boundary of the poured in place concrete in the Electron Hall are shown in Table 5-4. For none of the concrete surfaces in the vicinity of the dump was this requirement able to be met. The north wall is within a factor of twenty of the requirement and the west wall and the floor both exceed the requirement. This means that the poured-in-place concrete in the vicinity of the dump will need to be considered as activated material in the decommissioning of the Electron Hall.

**Requirement (RS 13)** The beam dump prompt radiation shielding shall result in a combined neutron and gamma dose rate outside the dump shielding of less than 1 mSv/hour, at 3 meters in the upstream direction from the outside of the beam dump shielding.

**Rationale**: To limit the additional contribution to the chronic loss dose rate in the hall to less than 10%. The latter is required to protect radiation-sensitive components such as CCD cameras.

**Results**: This requirement does not affect personnel protection or the radiological environment for the hall. It is the requirement, however, that drives the size of the local shielding for the dump. The total material thickness in the dump as well as an elevation view of the dump is shown in Figure 5-5.

The simulation examined the dose rate at a distance of 6 m from the exposed beam dump and shielding to provide a dose rate estimate for personnel carrying out remote handling tasks above the dump. After one week of cool down the dose rate is 0.5 mSv/hr and comes entirely from the Na-22 activation in the aluminum beam dump insert. Residual fields from the dump insert will be shielded with a lead lined transport flask. A 5 cm thickness of lead will attenuate the residual fields after one week of cool down to less than 10 µSv/hr.

### 5.1.4 De-rated (10kW) Beam Dump Shielding

Due to budget constraints, it was decided to operate on a de-rated beam dump at a maximum beam power of 10 kW with an un-rastered beam. The bulk shielding for the dump including the upstream shielding could then be made more economically from off-the-shelf concrete blocks rather than the layered steel concrete shown in Figure 5-5. The only steel retained is a collimator embedded in the upstream shielding that is 18 cm thick and 0.5 m × 0.5 m in the lateral direction to reduce the backscattered bremsstrahlung from the beam dump. Figure 5-6 shows the aluminum insert on which the beam is incident, the surrounding lead shielding, and the bulk and upstream concrete shielding. The layering through the concrete shielding is for purposes of variance reduction used in the FLUKA simulation to assess the shielding and is not intended to delineate block dimensions. The shielding is made of large removable concrete blocks whose total volume and outer extent are equivalent to that shown in the figure.

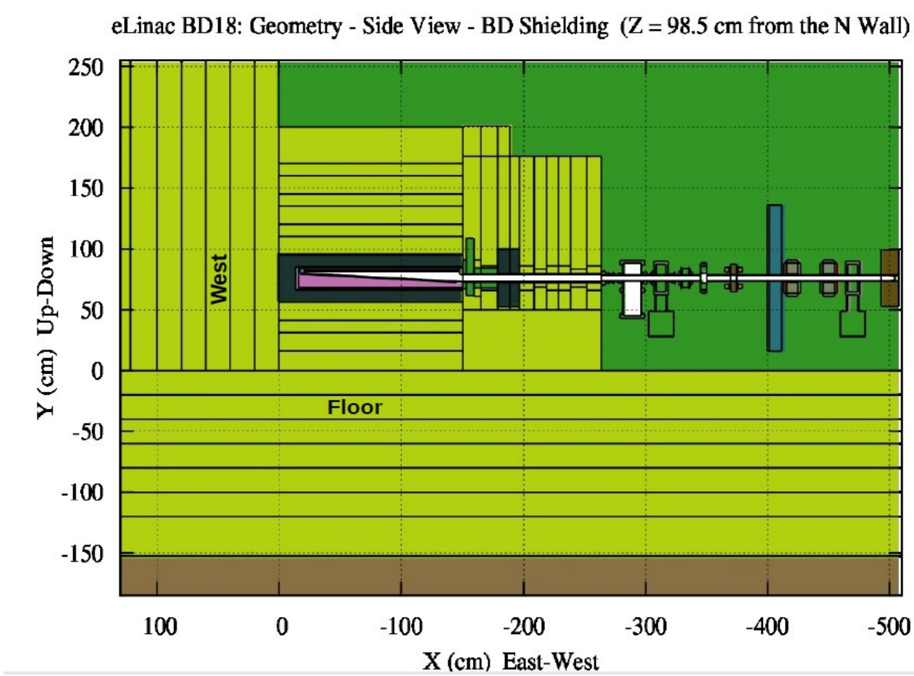


Figure 5-6 Elevation view of the 10kW dump shielding sectioned through the beam line showing the aluminum insert, the surrounding lead shielding, and the bulk and upstream concrete shielding.

The bulk shielding thicknesses for the lead and concrete are captured in Table 5-5.

Table 5-5 10 kW dump shielding thicknesses.

| | Total Shielding Material Thickness (cm) | | | | | |
|---|---|---|---|---|---|---|
| | Above | Below | North | South | West | East |
| Lead | 10 | 10 | 10 | 10 | 13.5 | 0 |
| Concrete | 105 | 56.2 | 80.25 | 105 | 0 | 101.9 |

FLUKA Simulations were completed using 25 MeV electrons and quantified to 10 kW which corresponds to 400 µA beam current. A Gaussian beam distribution was used in both directions with a FWHM = 1.41 cm. Figure 5-7 and Figure 5-8 show the results of the FLUKA simulation completed with 1.56 billion primaries. These results have been summarized in the Design Note TRI-DN-14-13.

A summary of the shielding results compared with the requirements as presented in Section 5.1.3 for the 100 kW dump is included here. The requirements are repeated to facilitate comparison with the results of the simulation.

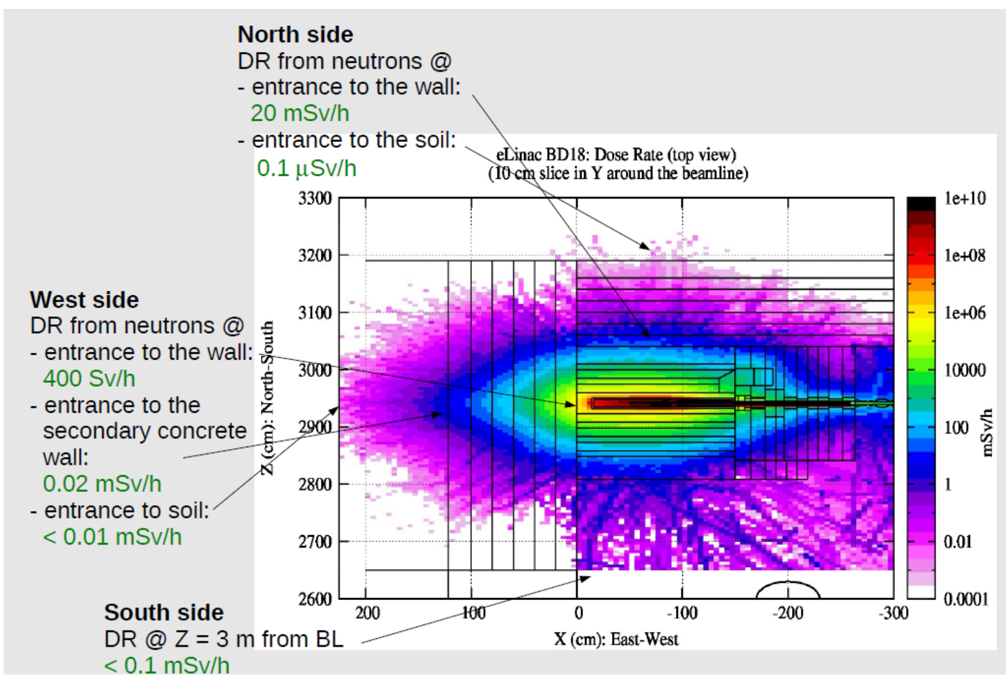


Figure 5-7 Plan view showing the total dose rate for the 10 kW dump bulk and upstream shielding. Neutron dose rates at concrete and soil boundaries are noted. The south side dose rate is a total dose rate.

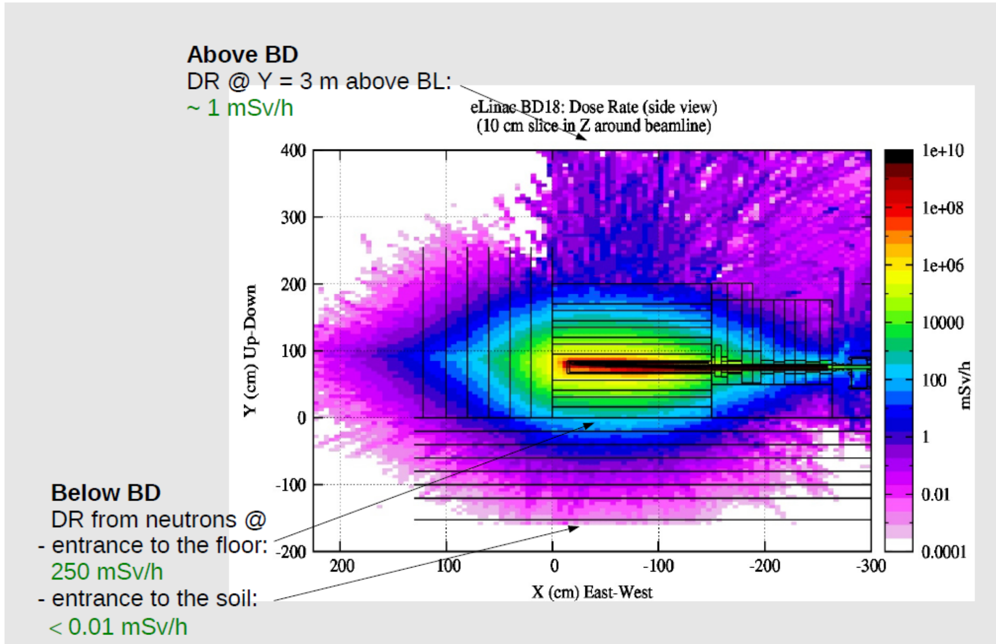


Figure 5-8 Elevation view showing the total dose rate for the 10 kW dump bulk and upstream shielding. Neutron dose rates at concrete and soil boundaries are noted. The dose rate above is a total dose rate.

**Requirement (RS 10)** The beam dump prompt radiation shielding shall attenuate the prompt neutron fluence in the soil to less than $1 \times 10^4$ neutrons/cm$^2$-sec for high energy neutrons (Energy > 20 MeV) and less than $1 \times 10^5$ neutrons /cm$^2$-sec for low energy neutrons.

**Results**: A neutron dose rate limit at the soil boundary of 10 mSv/hr meets the above requirements. The neutron dose rates for the 10 kW dump, summarized in Table 5-6, meet this requirement at the outside wall-soil boundary. The last row of the table are the neutrons dose rates for the 75 MeV, 100 kW dump shielding configuration as reported in Table 5-4. All inside wall dose rates with the concrete bulk shielding for 25 MeV, 10 kW are less by at least an order of magnitude than those for the 100 kW dump.

Table 5-6 Neutron dose rates at the soil boundaries outside the north and west walls and the floor for the 10 kW dump and in the last row for the 100 kW dump (see Table 6-4)

| | Dose Rate (mSv/hr) | | | | | |
|---|---|---|---|---|---|---|
| | West Wall | | Floor Slab | | North Wall | |
| | Outside | Inside | Outside | Inside | Outside | Inside |
| Neutrons | 0.02 | 4.0E5 | <0.01 | 2.5E2 | <0.001 | 20 |
| Neutrons | 1.7 | 1.4E7 | -- | 6.9E3 | -- | 196 |

| | | | | | | |
| --- | --- | --- | --- | --- | --- | --- |
| @100kW | | | | | | |

**Requirement (RS 11)** The beam dump prompt radiation shielding in the vertical direction at a distance of 3 m outside the shielding shall attenuate neutrons to a dose rate of 50 mSv/hour and photons to a dose rate of 5 mSv/hr.

**Results**: The dose rate above the dump had to be kept lower than this requirement in order to also meet the requirement RS13 for dose rate limits in the Electron Hall for radiation-sensitive components. The total dose rate above the dump local shielding at 3 m is 1 mSv/hr.

**Requirement (RS 12)** The neutron dose rate outside the dump shielding shall be limited to 10 mSv/hour, in order to keep long-lived concrete activation below the CNSC regulatory Unconditional Clearance Level (UCL) of 0.1 Bq/g.

**Results:** The maximum dose rates at the inner boundary of the poured in place concrete in the Electron Hall are shown in Table 5-4. The 100 kW dump shielding design was not able to meet this requirement, and despite lower dose rates for the 10 kW dump shielding design, this requirement is again not satisfied. Therefore, the conclusion remains the same - ultimately, in the decommissioning of the Electron Hall, the poured-in-place concrete in the vicinity of the dump will be considered as activated material.

**Requirement (RS 13)** The beam dump prompt radiation shielding shall result in a combined neutron and gamma dose rate outside the dump shielding of less than 1 mSv/hr, at 3 m in the upstream direction from the outside of the beam dump shielding.

**Results**: This requirement does not affect personnel protection or the radiological environment for the hall. It is the requirement, however, that drives the size of the local shielding for the dump. Figure 5-7 and Figure 5-8 show that the dose rate on the south side and above the dump is at or below 1 mSv/hr at three meters.

In conclusion, the dump shielding requirements are better satisfied for the de-rated 10 kW dump than for the 100 kW.

N.B.: The simulations for the de-rated dump were conducted for 25 MeV since the lowest energy presents the most stringent requirements for power deposition in the incident plate of the dump, and these results were required for the thermal analysis. The operation of the dump at 10 kW with the licensed electron energy of 40 MeV would result in an increase in the dose rate in the forward direction from 6 to 12 × $10^3$ Gy·$m^2$/h·kW [TRS188 Fig.17]. The listed dose rates for the West Wall in Table 5-6 would increase correspondingly. Note, however, that the forward direction shielding (i.e. for the west wall) is the same for the 10 and 100 kW dumps. Therefore, since the design meets the shielding requirements for 75 MeV and 100 kW, it also meets the shielding requirements for 40 MeV and 10 kW.

### 5.1.5 Dismantling the 10 kW Beam Dump Shielding

Simulations were carried out to assess the activation of the de-rated beam dump and surrounding shielding. Operation with the de-rated dump is expected to last between one and two years, ramping up gradually to full power. The irradiation profile for calculation of residual fields assumed a worst case of 1 year operation on average 8 hours per day.

Dose rates were examined that will impact dismantling and disconnection of services from the service stand when the shielding is reconfigured from the 10 to 100 kW dump. With the upstream shielding removed, the dose rate from the beam dump inserts and surrounding shielding after one week of decay will be 10-20 µSv/hr at half a meter from the unshielded dump opening. Anticipated access would be for at most 4-5 hr with the aluminum insert in place. In addition, removing the aluminum insert would allow for placement of lead bricks at the opening of the lead shielding thereby reducing further the dose rate, should a more lengthy access be required.

The activation of the bulk concrete shielding blocks for the 10 kW dump was examined to determine the length of time required for radiation fields to decay to a level that allows the blocks to be used in other beam line applications. The simulations showed that after one year, the on-contact dose rate for the most exposed side of the concrete blocks (i.e., facing inward) is 10-15 µSv/hr. These few blocks will be used inside other shielded enclosures or stored to allow for self-shielding of the higher dose rate side. Sides of the blocks away from the dump insert have significantly lower activation, and outer blocks will be reusable with no restrictions within one month of dismantling the 10 kW dump shielding.

### 5.1.6 Shielding Verification using FLUKA

In addition to the point kernel method, the shielding was assessed with FLUKA simulations which are documented in TRI-DN-13-11. The simulations were completed for 50 MeV, 500 kW electron beam directed north with the e-Linac and for an eventual energy recovery ring that would have 500 kW electrons directed south around a ring. Attenuation of photons and neutrons for different configurations are shown in Figure 5-9 to Figure 5-18, and are discussed below. The locations (A – F) shown on the plan and elevation views of Figure 5-1 and Figure 5-3 are used for purposes of discussion. Results from the simulation correspond to ~ $1 \times 10^8$ 50 MeV electrons incident on a 10 cm long by 5 cm diameter iron target, an equivalent material and geometry for any of the magnets where the beam could be missteered. Standard concrete has been used for the shielding material and the beam loss position for assessing each area was taken to be at the location that would maximize the dose outside shielding. The simulation results are converted to an ambient dose equivalent using the AMB74[12] dose conversion coefficients. All projections displayed are shown averaged over a 40 cm slice to provide a conservative estimate of the dose rate. As well all projections are shown for a full beam loss and under these conditions the design dose rate outside shielding is ≤ 50 mSv/hr.

The conclusion from this shielding comparison is that generally dose rates calculated using the FLUKA model are comparable or less than those from the point-kernel method for shielding design presented above. This is consistent with earlier measurements made at TRIUMF along with comparisons of point-kernel method and FLUKA results for protons. Concurrence between these two methods provides confidence that FLUKA can be used to assess complex shielding configurations that do not lend themselves to the point-kernel method.

Location A (264' Elevation – Dogleg Shielding Void)

This location was initially assessed with a 12 ft thickness of concrete and a modest size hole bored through the north wall for the beam line transport from the e-Hall to the tunnel. The beam line optics necessitated a larger void in the concrete wall to accommodate the beamline components for the dogleg. In addition, the simulations carried out demonstrated that it would not be possible, with the tunnel section of the beamline built, to place sufficient shielding around the beamline components along the dogleg to attenuate the dose rates sufficiently to allow occupancy of the tunnel when operating in the e-Hall. Therefore, the tunnel will need to be defined as an access-controlled area when accelerating beam in the Electron Hall.

However, during the first phase of commissioning before the tunnel section of the electron beam line is installed, sufficient temporary shielding has been added to the north wall to allow occupancy in the tunnel. A "worst case" beam loss scenario postulating the failure of the first dipole (EHAT:MB4) immediately upstream of the north wall was simulated to determine the necessary amount of temporary shielding with a 100 kW, 75 MeV electron beam directed to the beam dump inside the Electron Hall (TRI-DN-13-11). Note that this is ~2 times higher in energy and 10 times higher in power than the present beam limits. The downstream end of the dipole vacuum vessel was assumed to be 0.31 cm thick stainless steel oriented perpendicular to the direction of the electron beam, 1.2 m from the nearest downstream point in the north shielding wall.

The highest dose is along the axis that points through the thinnest shielding at the back of the north wall dogleg void. This is along the segment labelled K-L in Figure 5-10. The dose rate attenuation along this axis is shown below in Figure 5-9 and represents average dose

[12] The AMB74 dose conversion coefficients are based on the ICRP74 operational quantity, ambient dose equivalent, for photons and neutrons.

rates within ± 25 cm of the vertical plane for several vertical slices of 50 cm thickness.[13]

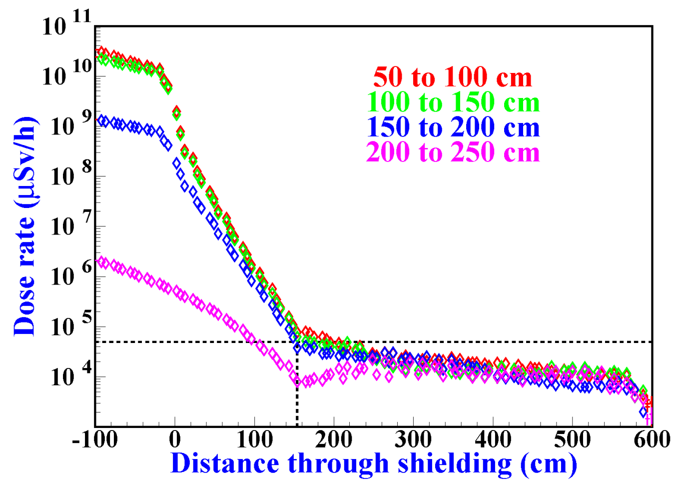


Figure 5-9 Attenuation through the dogleg shielding void in the North wall for different elevations. The horizontal dashed line is at 50 mSv/h and the vertical dashed line indicates the total thickness of concrete shielding used in the simulation.

The horizontal dashed line is at 50 mSv/h, the maximum allowed “worst case” dose rate outside shielding. The vertical dashed line indicates the total thickness of concrete (the existing wall plus 66 cm) shielding used in the simulation. Based on the attenuation profile, a total of over 120 cm of concrete blocks have been added to the existing wall to bring the maximum dose rate to less than half of the 50 mSv/h limit.

[13] Due to the symmetry of the 0-50 cm and 100-150 cm slices with respect to the 75 cm beam height, these attenuation profiles are essentially identical, and only the 100-150cm profile is shown.

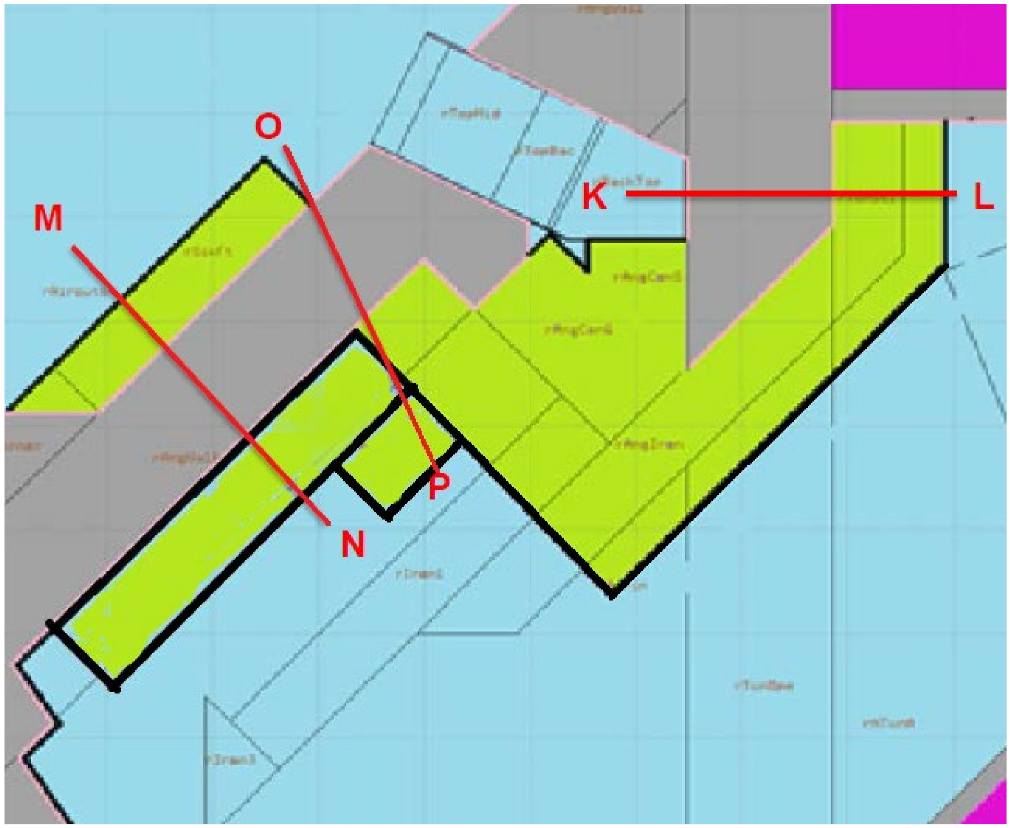


Figure 5-10 Specification for the BL4N/ARIEL tunnel shielding.

Figure 5-10 shows the specifications for shielding added to allow tunnel occupancy for operation of the e-linac at 100 kW into the electron hall beam dump. The original poured in place concrete is shown in grey, while added concrete is shown in green. Inside the hall, along the segment labelled M-N, a total thickness of 65 cm was poured in place. The total thickness of that wall along the M-N segment also includes 114.5 cm (ARIEL dwg #17662) poured concrete wall shown in gray, and temporary shielding blocks (30” = 76.2cm) shown in green with blue crosses, for a total concrete thickness perpendicular to the wall of 255.7 cm, or 8.4 feet. [N.b. The original specification was for 24” of temporary shielding, however only 30” blocks were able to be purchased.]

The adequacy of this shielding thickness for 100 kW operation is captured in Figure 5-11. This simulation did not include the dogleg void which has already been analyzed with a worst case loss above. The simulation covers a forward direction loss immediately out of the second cryomodule, showing the impact in the forward direction on the north west wall from a worst case loss. This is the most upstream location where 50 MeV electron beam is available.

The simulation was carried out for $4 \times 10^9$ primaries and shows a penetration for the total dose rate of 10 mSv/hr immediately outside the northwest wall on the left side looking downstream. The wall thickness in this region (Z = 2400 – 2800 cm) is 210 cm (≈ 7 feet). Figure 5-11 shows a significant reduction in dose for Z < 2500 cm owing to the attenuation inside the e-Hall from the north-south wall. As indicated above the wall thickness along segment MN in Figure 5-10 is 256 cm, and as such provides more than sufficient protection to ensure dose rates for an accidental full loss remain below 50 mSv/hr.

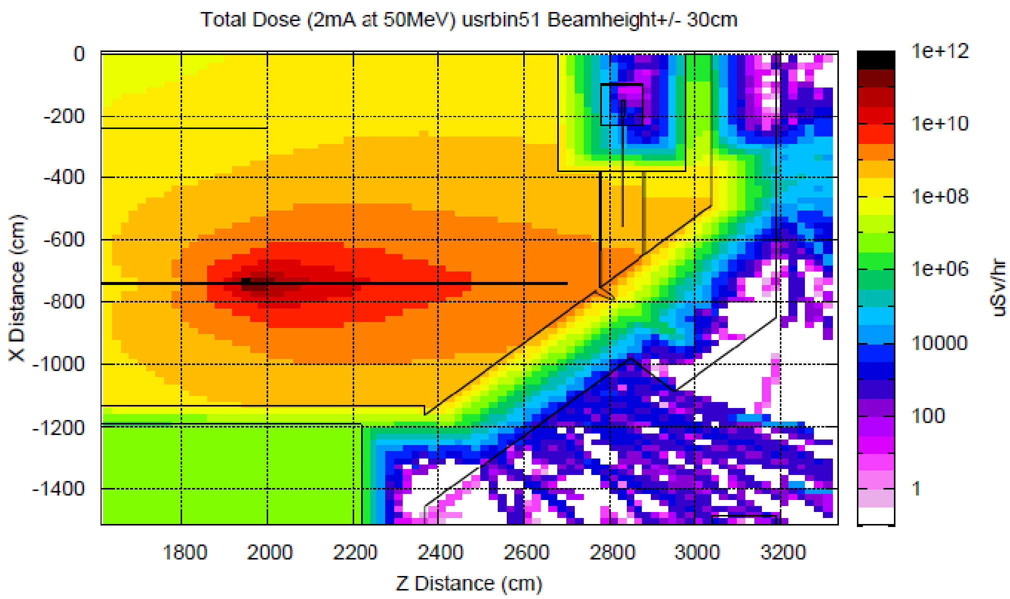


Figure 5-11 Total dose rate for a 50 MeV, 100 kW beam loss immediately downstream of the second cryomodule. [future state]

In comparing with the point kernel estimate of 12 feet of concrete for a forward direction loss, the 256 cm thickness scaled by 1/cos(45°), yields a total thickness of 362 cm, or 11.9 feet. Likewise, as indicated in Section 6.1.1 Shielding Requirements, the expected *worst case* chronic losses will result in a dose rate, scaled from the accidental full loss value, will be below 1 μSv/hr.

In the direction of the thinnest shielding, along segment OP in Figure 5-10, the total distance is slightly larger than the sum of the perpendicular thickness of the gray and temporary shielding, (114.5 + 76.2 + 60) cm = 250.7 cm. The only shine from this direction would be from a lateral loss so 90° has been used and the attenuation calculated and shown in the last row of Table 6-2, bringing the dose rate down to 1.5 μSv/hr.

Location B (284’ Elevation)

Figure 5-12 is an elevation view for a loss at a northern most point along the beamline (Z = 2650 cm) normalized for a loss of 500 kW, as location B will have occupancy with e-Linac operation at full power. The beam is directed to the right onto an iron target. In the lateral direction, directly above the beam loss point, photons shown in the left plot are seen to be more penetrating than neutrons shown in the right plot.

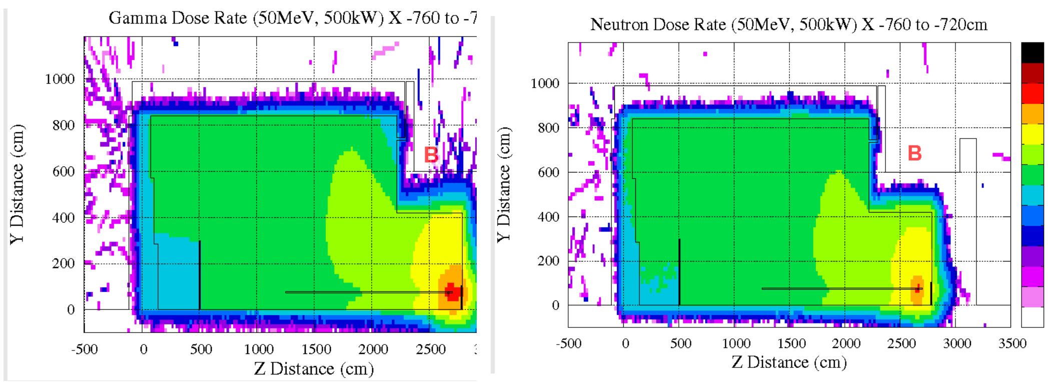


Figure 5-12 Elevation view showing the photon & neutron ambient dose rate at Location B for a 50 MeV, 500 kW electron beam loss just inside the north shielding wall. Location B above the slab is indicated.

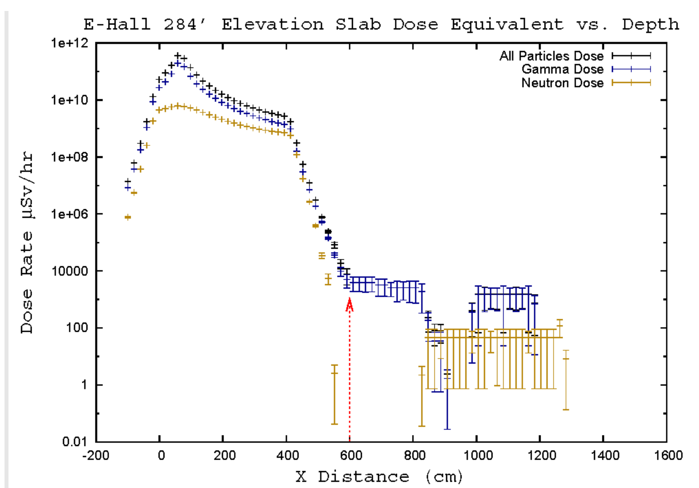


Figure 5-13 Attenuation of the dose equivalent through the six foot thick slab at the 284' elevation. The red arrow marks the top of the slab.

The attenuation profile of the dose equivalent through the six foot thick slab is shown in Figure 5-13 for the different radiation components. Given the close proximity to the beam loss an area of ± 50 cm in the highest dose rate region has been used to extract the one-dimensional projection. The dose rate immediately above the slab for this catastrophic loss is 6.8 mSv/hr, and is well within the 50 mSv/hr limit.

Location C (297' Elevation)

The full point loss at the end of the last cryomodule was used to evaluate the dose directly overhead atop the Electron Hall roof beams (Location C). This point was chosen as this is the earliest point at which the electron beam is at its full beam power. Figure 5-14 is a projection looking South, with the cyclotron vault located to the left in the figure.

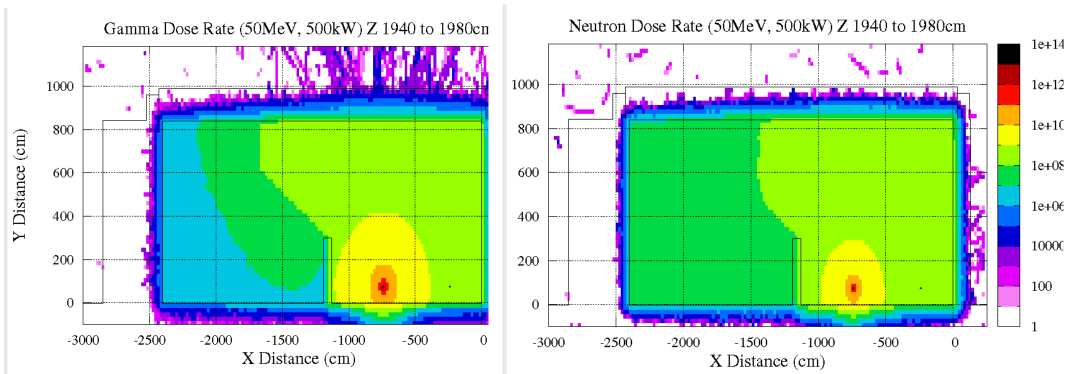


Figure 5-14 Elevation view looking South showing the penetration of photons and neutrons for the roof beams for a 50 MeV, 500 kW electron beam loss. The region right of the West shielding wall (X > 1.2 m) is normally filled with soil below grade (Y < 7.6 m)

Figure 5-15 is an elevation view, a projection looking West, with the beam directed to the right. Locations B and C are marked in the figure to orient the reader.

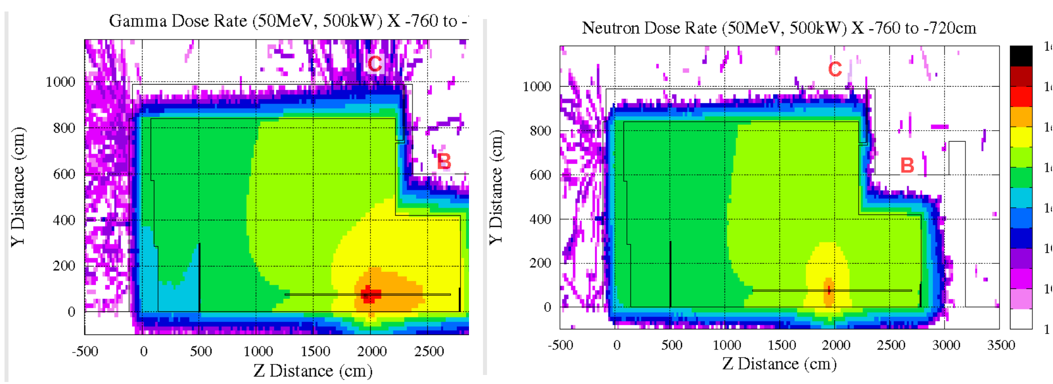


Figure 5-15 Elevation view looking West showing the photon and neutron penetration for the roof beams for a 50 MeV, 500 kW electron beam loss. Locations B and C are also indicated.

Figure 5-16 shows the extracted dose rate through the thickness of the roof beam, showing for a 2 m × 2 m area in X and Z. The photons are the dominant contribution to dose and for the 75 MeV, 500 kW beam result in a dose rate of 19 mSv/hr immediately above the roof beam. This is within the 50 mSv/hr dose rate limit for an accidental full beam loss.

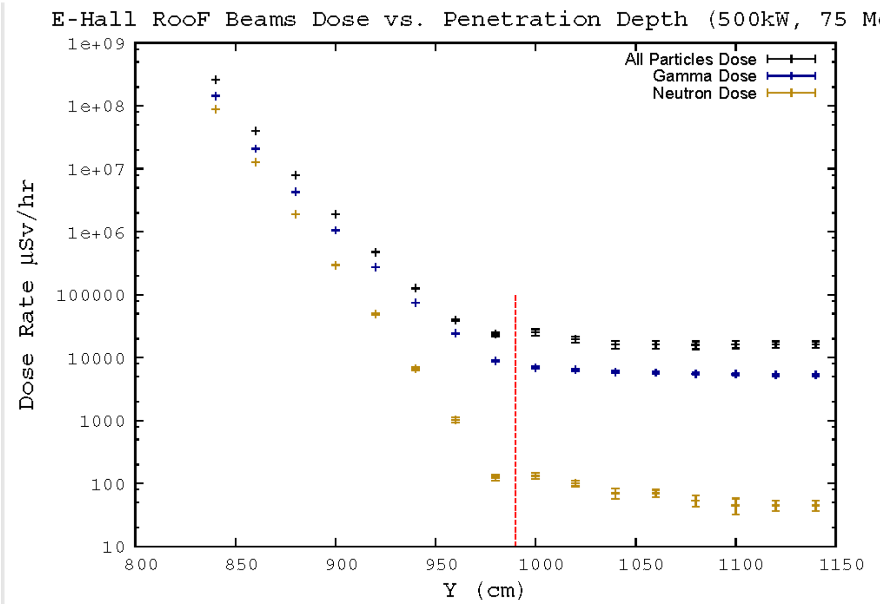


Figure 5-16 Dose equivalent attenuation through the roof beams for an accidental full loss of 75 MeV, 500 kW electrons in the e-Hall. The red line indicates the outside of the roof beam.

Location D (289’ Elevation), E (301’ Elevation) and F (264’ Elevation)

A projection taken east of the e-Linac to include locations D, E and F on the South side of the Electron Hall is shown in Figure 5-17. The beam loss location, energy and power are the same as for Figure 5-14 and Figure 5-15. Both locations F and D on the south side of the Electron Hall (Z ≤ 0) at the B2 level (Y = 0 cm) and at grade (Y = 760 cm) respectively have dose rates below 10 mSv/hr for a full 500 kW loss. Location E where offices are located at (Y = 1160 cm) has a dose rate of less than 1 mSv/hr. Both these dose rates are well within the requirements for the respective low and high occupancy areas.

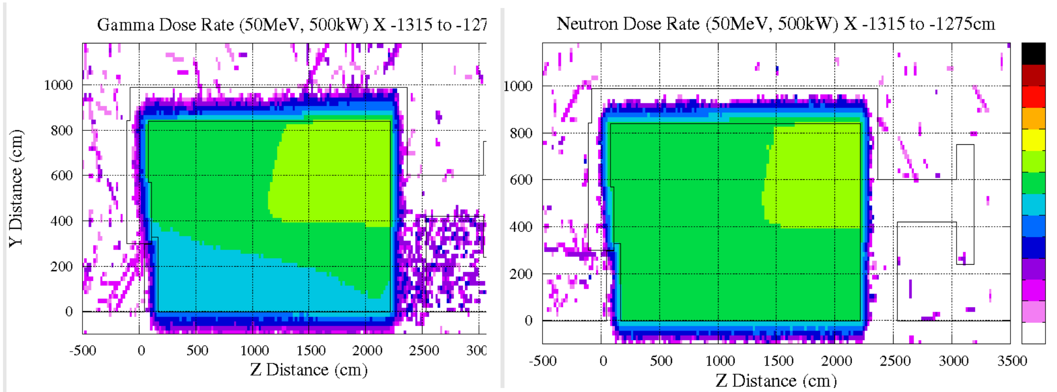


Figure 5-17 Elevation view looking West showing the photon and neutron dose rate on the South side at different elevations

Electron Hall Access Mazes

FLUKA is a useful tool for assessing the design for penetrations and mazes in the shielding walls. The simulation shows that at the mid-point along the length of the southeast maze the neutron dose rate is an order of magnitude higher than the gamma dose rate. Therefore, unlike the bulk shielding, in the case of the maze the neutrons are more penetrating and therefore drive the shielding design. Figure 5-18 shows the neutron dose rate for a 500 kW point loss immediately after the cryomodule EACB (future state) for both the southeast maze at the B2 level and the northeast maze at the 284' elevation. The B2 level projection also shows the dose rate at the cyclotron vault maze entrance, where the e-Maze vault-side access control door is located that forms part of the lock-up chain for the Electron Hall. This door is located at X = 2700 where the simulation shows dose rates well below 50 mSv/hr.

The e-Maze e-Hall-side access door remains in much the same location as it was in the former Proton Hall. An additional bend to the vault maze on the vault side was added during the 2014 shutdown in order to reduce the dose rate at the e-Maze, e-Hall-side door which arises from proton beam losses in the 500 MeV cyclotron. This additional shielding has reduced the chronic dose rate in the e-Hall maze to less than 10 μSv/hr.

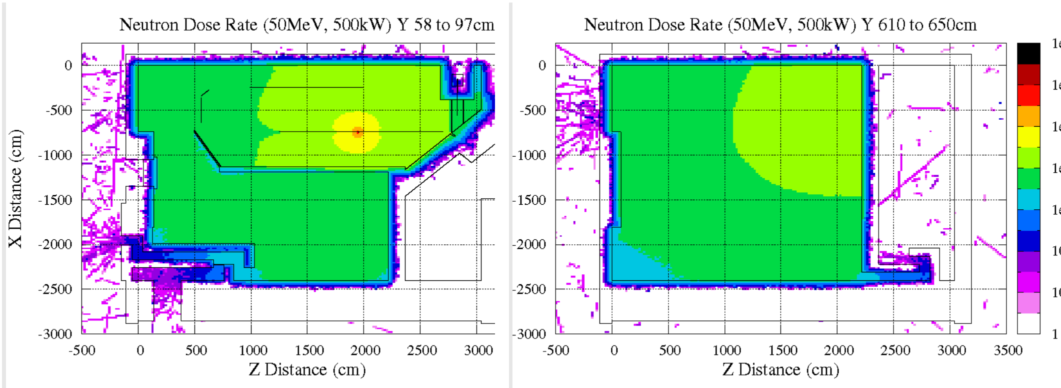


Figure 5-18 Neutron dose rates at the B2 level (264'elevation) and the 284' elevation showing the attenuation along each of the access mazes for the Electron Hall.

### 5.1.7 Summary of shielding simulations

The fixed shielding in the e-hall has been shown to meet TRIUMF safety requirements for chronic losses of $1x10^{-4}$ and catastrophic full beam losses assuming either a 50 MeV 100 kW beam or a 50 MeV 500 kW beam and with both the point-kernel method and FLUKA simulations. This is 1.25 times higher in energy and at least 10 times higher in beam power than the present commissioning limits. Moreover, beam dump activation and associated radiation dose analysis was done assuming beams ranging from 25MeV and 75 MeV with beam power up to 100kW. Finally extra shielding has been added to the north end of the e-hall to allow occupancy of the e-tunnel while the e-Linac is being commissioned.

## 5.2 Access Control and Radiation Monitoring System

### 5.2.1 Interlocked Access Control System

Hazardous levels of prompt radiation are present in some areas of the ARIEL project due to the operation of the electron accelerator. The Access Control System (ACS) protects people from this hazard by maintaining safe configurations that keep people out of these areas when the hazard is potentially present, and by turning off the accelerators and clearing any unsafe configurations should they occur as the result of a failure or intervention. In the parlance of radiation safety systems these areas are known as `exclusion areas'.

The requirements for the e-Linac Access Control System have been described elsewhere (Document-43329). The system consists of e-Linac beam inhibit devices and Area Safety Units, both interfaced to a central logic controller backed up by relays and hardware disconnects. It performs two complementary interlock functions that together maintain safe configurations:

It enforces standard beam delivery procedures and ensures that a safety beam inhibit device cannot be used to turn a beam on unless all exclusion areas that might receive beams are locked and secured;

It enforces standard area access procedures and ensures that a locked and secured exclusion area cannot be unlocked unless beams to the area are off. Once a locked and secured area has been unlocked and opened the system prevents beams from being turned on.

It also turns off the accelerator (an `access trip') and restores a safe configuration if a safe configuration is lost due to a beam inhibiting device failure or area intervention.

As described in Section 3, the areas to be designated as exclusion areas have been determined by the application of existing TRIUMF policy TSN_1.8.0. Policy for Maximum Allowable Dose Rates in Accessible Areas at TRIUMF taking into account shielding effectiveness and both normal and abnormal accelerator operation.

The radiation hazard associated with e-Linac operation derives from both X-rays that are present when RF power is applied to the accelerating cavities, and from bremsstrahlung and neutrons with beam present. The areas designated exclusion areas during e-Linac operation are:

- the Electron Hall (including the West Tunnel); and
- the e-Hall/Cyc Maze that connects the e-Hall and 500 MeV Vault.

As described in Section 5.1.6, during the first phase of operation of the e-Linac in the e-Hall, sufficient temporary shielding has been added to the angled north wall to allow ARIEL Tunnel occupancy while operating with 100 kW beam to the dump. For the second phase of operation when the temporary shielding is removed to allow completion of the beamline, the ARIEL Tunnel will be added to the exclusion areas for e-Linac operation.

Area Safety Units (ASUs) are subsystems that interface beam exclusion areas within an ACS.

Each ASU shall:

- House mechanical hardware that provides a signal indicating that all doors to an exclusion area are `locked';
- Use Watchman Stations to enforce timed physical searches that ensure an area is unoccupied before access doors are closed;
- Initiate audible and visual start-up alarm cycles including a final warning after doors are closed and provide a `secured' signal at the end of the final alarm cycle;
- Act as the central termination point for all area Emergency Trip pushbuttons.

The exclusion area locks are designed so that a locked area cannot be unlocked from the outside unless the Area Safety Unit is receiving a key release control signal, therefore Area Safety Unit locked and secured signals and central logic can reliably ensure areas are unoccupied and are inaccessible.

The ASU for the Electron Hall is located at the southeast maze entrance at the 264’ elevation. The ASU for the e-Hall/Cyc Maze exclusion area connecting the Electron Hall and the 500 MeV Vault is also located adjacent to the e-Hall ASU.

The beam inhibit devices are capable of assuming states that:

- prevent beam from being created in the accelerator, or
- prevent beam from being accelerated within the accelerator, or
- effectively block beam to a given area, or
- prevent beam from being directed into an area.

The beam inhibit devices are designed so that they cannot deliver accelerated beams to areas unless they are receiving enable control signals. Therefore, approved combinations of electron accelerator safety beam inhibit device safe status signals and central logic backed up by hardware disconnects can reliably ensure beams are off and are prevented from coming on. The beam inhibit devices for the e-Linac are:

- e-gun HV power supply (350 kV);
- Injector (EINJ) klystron power supply (65 kV); and
- Accelerator module EACA klystron supply (65 kV).

In addition, there are beam inhibit devices for confining the electron beam to the e-Hall and directing it to the dump. These depend on the settings for a combination of two benders; EHAT:MB4 which directs beam to the dump and the bender EHBT:MB0 downstream of MB4 that directs beam to the tunnel. The beam inhibit devices are:

- EHAT:MB4 bender polarity switch and reed switch; and EHBT:MB0 power supply.

The status of all beam inhibit devices and exclusion areas are displayed in the e-Linac Control Room on a dedicated ACS console.

The Access Control System incorporates an independent Emergency Trip system that unconditionally turns off the electron accelerator should any Emergency Trip pushbutton be activated.

A schematic of the e-Linac Access Control System showing the different elements described above and the interface to the e-Linac Radiation Monitoring System is shown in Figure 5-19.

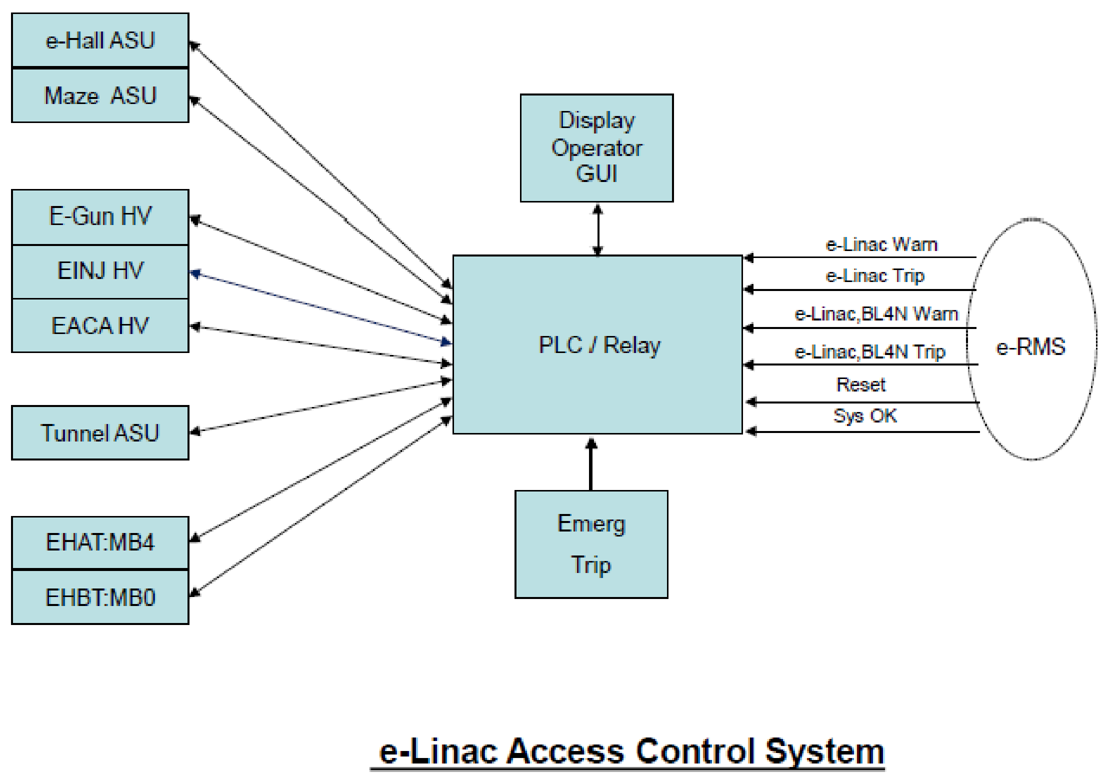


Figure 5-19 Schematic of the e-Linac Access Control Systems and the interface to the different components and the e-Linac Radiation Monitoring System

Eight watchman stations are in place in the e-Hall. The present configuration is captured in the e-Linac Access Control System requirements (Document-43329). Configuration changes of the accelerator trigger a design review of the access control system. Training is implemented for Locking Up and Accessing the e-Hall and is captured in Section 6.6.

### 5.2.2 E-Linac Radiation Monitoring System

The e-Linac Radiation Monitoring System (eRMS) uses both gamma and neutron detectors to directly measure dose rates outside shielding, with particular attention being paid to maze openings where neutron levels are expected to be higher.

Each detector has associated warn and trip setpoints of 10 µSv/h and 20 µSv/h respectively. Local and Control Room audible, and visual alarms are energized when any warning setpoint is exceeded. The electron accelerator is turned off when any trip setpoint is exceeded.

The speed of the trip is such that the maximum dose per beam loss incident is less than 100 μSv.

The status of all radiation detectors is displayed in the e-Linac Control Room on a dedicated RMS console.

The design of the eRMS is described elsewhere (Document-43329). The locations of gamma monitors mounted on the roof of the e-Hall at two elevations are shown in Figure 5-20. The locations of gamma/neutron detector pairs mounted at the two access mazes to the e-Hall are shown in Figure 5-21.

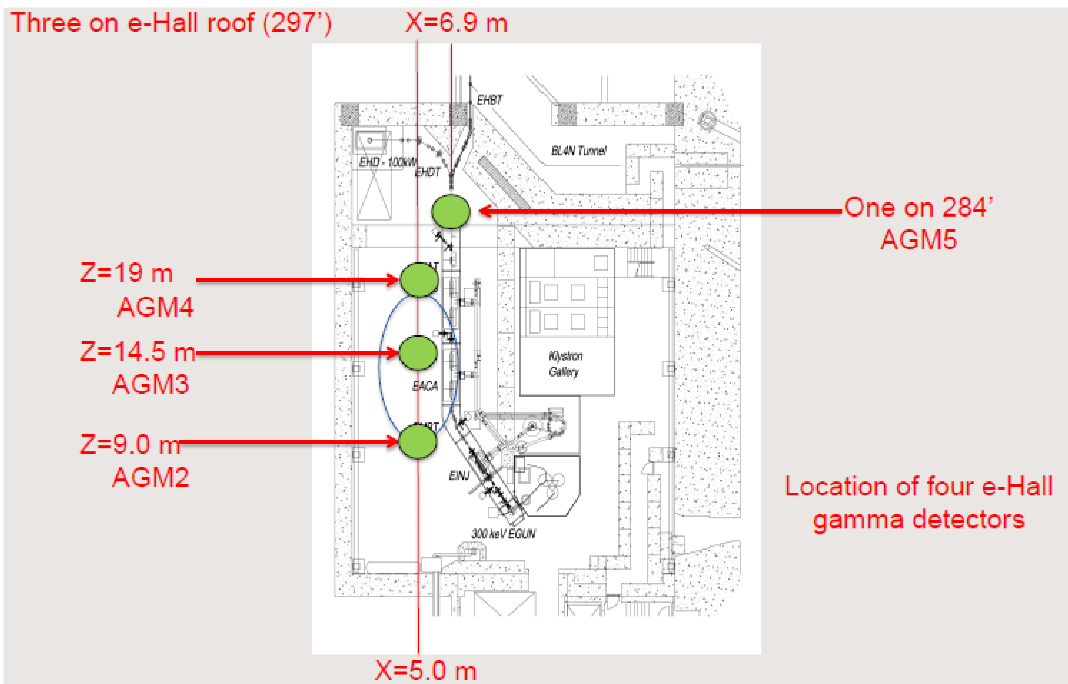


Figure 5-20 Schematic showing the location of e-Hall gamma monitors. These are located on the roof at elevation 297' and one is on the lower elevation roof (284') at the north end of the e-Hall. [N.b. The gap in the south wall is where the 4-foot thick shielding door is located.]

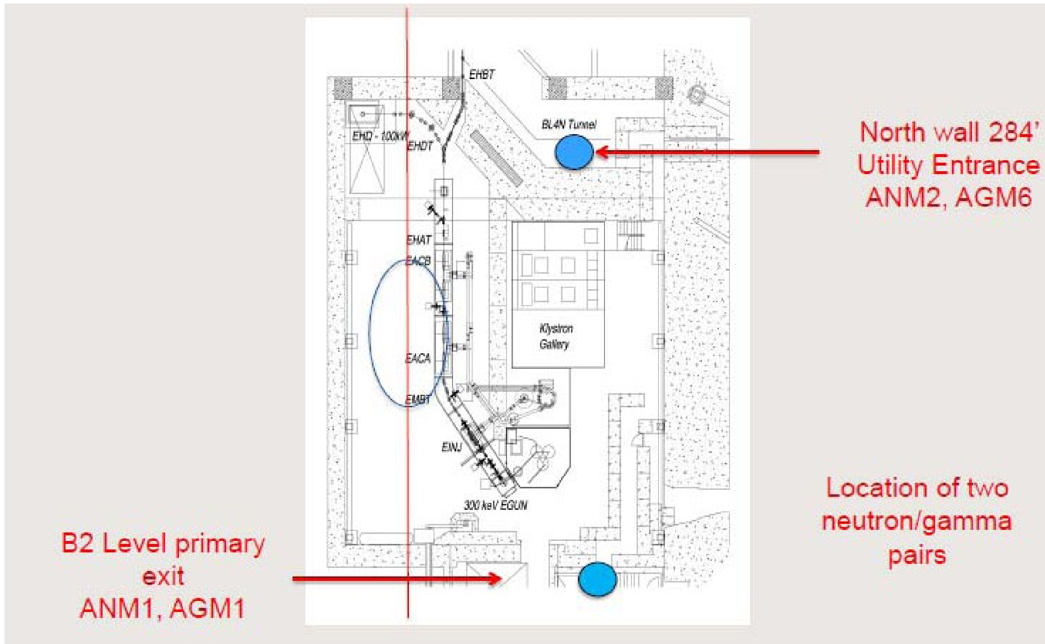


Figure 5-21 Schematic showing the location of the neutron/gamma monitor pairs. One is located at the 264' elevation south exit maze, and the other is located at the 284' elevation north exit maze from the Electron Hall. [N.b. The gap in the south wall has been closed by a 4-foot thick shielding block.]

### 5.2.3 Emergency Power

The Access Control System, the Radiation Monitoring System, the Oxygen Deficiency Monitoring System are powered by an uninterruptible power supply (UPS) backed up by the diesel generator.

## 5.3 Operating Mode Definitions

The only mechanism for Operators to configure the e-linac operating conditions is through the Operating Modes interface of the EPICS controls. The terminology "beam property" and "beam path" were introduced at the ISAC facility, but the usage at e-linac is not identical. Permitted combinations of property and path result in an Operating Mode. The beam property is a prescribed range of in-pulse current and duty factor (up to C.W) leading to a maximum power at a prescribed beam energy. The "beam path" is a start-through-end list of in-beamline elements starting at the gun and terminating on a prescribed beam dump. The property and modes are tabulated in the ARIEL e-linac MPS Requirements, Document-85636. The EPICS control rejects Operator requests for non-permitted combinations of property and path. Using the control system to define modes to ensure delivery of beam at or below the rated power level for all consistent beam paths provides an extra level of redundancy for machine protection.

## 5.4 Electron Hall Air Monitoring

As described in Section 4.1.3, 4.1.4, and 4.2.4 only modest levels of air activation and emissions from beam operation to the high energy beam dump are expected. Activated air from the e-Hall or the top of the surge tank from the water package, as well as vacuum exhaust from the section of the beam line in proximity to the beam dump is directed to a dedicated HEPA filtered exhaust stack on the roof of the Main Accelerator Building. A sampling manifold has been installed in the duct and is used to draw a sample to a new air monitor that has been added to the bank of air monitors on the 500 MeV Vault roof.

Emissions from the water package are directed to the nuclear exhaust by ventilation fan EHDT:HVAC:EF01. Machine Protection System slow interlocks are in place to inhibit beam operation if either this local fan or the e-Hall main ventilation fan are off. A hydrogen sensor is located at the top of the water package surge tank. An MPS slow interlock trips the beam if the hydrogen concentration exceeds half of the explosive limit (≥ 2%) Radioactive emissions are monitored and additional mitigation measures put in place if these represent a measurable fraction of current site emissions.

A separate bank of air monitors, located in the ARIEL building penthouse is prepared for the Target Hall and associated activities in the ARIEL building.

## 5.5 Radiation Surveys and Area Dosimeters

A radiation survey is required prior to beginning work in all ARIEL high radiation areas. This is controlled by the work permitting process described in *TSN 3.7 Work Permit System*. The radiation survey consists of both field and removable contamination measurements throughout the area to be entered. If there is potential for airborne contaminants than air sampling is performed as well.

'OSL Area dosimeters' are deployed in areas of high occupancy to provide an integrated dose for the area and to verify that dose rates remain ALARA.

## 5.6 Personnel Dose Monitoring

Dose monitoring for personnel follows the established dose monitoring program at TRIUMF as described in *TSN 1.2 TRIUMF Policy on Radiation Exposure*. OSL[14] dosimeters are issued for all staff and personnel with regular access inside the security fence. Short-term

[14] OSL dosimeters are the Landauer badges that use the optically stimulated luminescence technology.

visitors are issued a direct reading dosimeter and escorted on site by the TRIUMF contact.

# 5.7 Mitigation of Other Hazards

## 5.7.1 Ozone Monitoring

As shown in Section 5.2.3, with an air exchange rate of approximately once per hour, ozone equilibrium concentration levels in the Electron Hall during machine operation are just below the Threshold Limit Value (TLV) for which remediation measures are recommended. In the early stages of operation, a hand-held ozone monitor will be used to confirm levels in the Hall immediately after accelerator operation. Depending on these findings, procedures and hall exhaust will be adjusted to ensure that ozone levels are well below the TLV before the hall is opened for occupancy.

## 5.7.2 Hydrogen Monitoring for the Beam Dump

Emissions from the water package are directed to the nuclear exhaust. A hydrogen sensor is located at the top of the water package surge tank. The control system for the beam dump services ensures that this air volume is flushed as required to keep hydrogen levels below half of the explosive limit in air (< 2%). Radioactive emissions are monitored and additional mitigation measures put in place if these represent a measurable fraction of current site emissions.

## 5.7.3 Oxygen Deficiency Monitoring System & Cryogen Safeguards

The Electron Hall and the Compressor Building are equipped with an Oxygen Deficiency Monitoring System that consists of the same model sensors as those used in the upgraded system at ISAC with an electro-chemical cell sensor with a full membrane. Two sensors have been positioned in the Electron Hall on the east and west side of the north-south shielding wall and one sensor is located in the west service tunnel at the B3 level immediately below the e-Hall. Because of the high neutron radiation fields anticipated on the west side of the shielding wall in the Electron Hall and in the service tunnel, these sensors are positioned immediately outside the e-Hall, and a pump is used to draw a sample from each of these locations. The pumps as well as the sensors and monitoring system are on emergency power. A local alarm and beacon is located in the respective areas and a green/red indicator light at the entrance to the area in order to inform staff that it is safe/unsafe to proceed into the area.

The ODM system requirements are that upon a drop in the oxygen level below 19.5%

- a local audible alarm in the area and a remote alarm in the Main Control Room is generated;
- the green status indicator changes to red at the entrances to the area;
- air exhaust for the area is driven to the maximum flow rate; and
- the enable signal for the control valves on the distribution line for LN2 to the Electron Hall is removed forcing the valve to close.

The Compressor building is also equipped with a sensor mounted at 1.4 m above the floor with a local alarm beacon and a red/green status indicator is mounted at the entrance to the building.

### 5.7.4 $SF_6$ Mitigation Measures

The 3 $m^3$-atm of $SF_6$ is not sufficient to cause an asphyxiation hazard in the service tunnel which has a volume below a 1.4 m height of 67 $m^3$. Nevertheless, this area has oxygen deficiency monitoring and personnel will be alerted should an $SF_6$ leak result in a local *alarm.*

### 5.7.5 Fire Suppression Systems

A fire hazard analysis has been completed for the ARIEL project by an outside consultant to meet the requirements of NFPA-801 in addition to the NBBC and NFCC. In addition, the modifications to the Electron Hall and the construction of the new ARIEL building and tunnel have had a code design analysis completed by the code specialist retained by the A&E firm for the project.

A revision to the fire hazard analysis for the former proton hall is being completed. To first order the fire hazard is comparable in nature and magnitude for the Electron Hall as it was when the space was the Proton Hall. Both spaces include beam line components and associated services. The one difference, regarding the added combustible inventory for the insulating oil (500 l) used in the e-Linac klystrons, is being reviewed by a fire protection engineer.

There is no sprinkler system for the Electron Hall. Two smoke detectors mounted in the exhaust air ducts for the hall are displayed and will annunciate as part of the Fire Alarm System in the Main Control Room.

### 5.7.6 Communication Systems

Communication between the Control Room and the Electron Hall is via a public address system. In addition, telephones in a few locations in and around the Electron Hall have been installed.

## 5.8 Excursions from Normal Operation

### 5.8.1 Radiation Monitoring System Failure

The Radiation monitoring System is designed to detect excursions of beam losses that can result in high radiation fields and to terminate beam operation within 0.2 s. A failure of the RMS simultaneous with an accidental full loss of the 500 kW beam could result in dose rates up to 50 mSv/hr in areas outside shielding. It is unlikely that such catastrophic beam losses would remain undetected by the machine protect system for very long. Nevertheless, if undetected for an hour it would result in a dose of 50 mSv to TRIUMF personnel.

### 5.8.2 Oxygen Deficiency Monitoring System Failure

Failure of an oxygen deficiency monitor could result in an undetected asphyxiation hazard for personnel particularly in the areas below grade such as the Electron Hall and the West Service Tunnel. The ODM system is on emergency power and has been designed to alarm should any system component fail. Cryogenic system procedures that have an associated increased risk for release of cryogenic liquids shall require personnel to wear personnel $O_2$ monitors and may also require a buddy system.

### 5.8.3 Cooling Water Failure

Interlocks in all water circuits provide for the shutdown of the appropriate accelerator system in the event that flow rates or pressures in that system deviate from nominal values.

A leak in the high active cooling water package for the high power beam dump is detected either with sensors in the catch tray or a level monitor on the ballast tank. Either indicator results in shut down of the accelerated beam to the dump. All drains in the Electron Hall are directed to the Main Accelerator Building radioactive sump. This water is assayed by the TRIUMF Radiation Protection Group (RPG) as part of the Emissions Monitoring Program before release to the sanitary sewer.

In the worst case, should a leak of tritiated water into the hall occur, access would be restricted and require Personal Protective Equipment (PPE) specified by the RPG to limit the exposure from both inhalation (air-supplied respirator) and skin absorption (TYVEK suit).

### 5.8.4 Electrical Power Failure

The accelerator installation has been designed so that an electrical power failure leads to safe shutdown of the accelerator and the cryogenic system.

### 5.8.5 Fire

The *TRIUMF Fire Protection Program* includes a pre-incident plan that provides emergency responders, Vancouver Fire & Rescue Services, with a summary of ignition sources, fire loads and other hazards in each area of the laboratory.

The procedures in the event of a fire are described in the *TRIUMF Emergency Response Plan*.

A fire hazard analysis has been completed to address the modifications being made for the Electron Hall. The added combustible load from the volume of stored insulating oil in the klystron and e-gun RF systems is mitigated by safeguards for containing the oil and a minimization of ignition sources in the Hall. In addition, there is no significant inventory of radioactivity present in the Electron Hall that could be released from the facility in the event of fire.

### 5.8.6 Explosion

There is no explosion hazard directly associated with this facility. All vessels containing cryogenics or compressed gas have pressure relief valves in the event of over pressure. In addition, the cryogenic modules include a burst disc to mitigate against a sudden warm up of the LHe in the cavity.

### 5.8.7 Design Level Earthquake

The BCBC 2006 and NBCC 2005 define the design level earthquake as the seismic ground motion at a given site having a 2% probability of exceedance in 50 years at a median confidence level. This is statistically equivalent to a 0.04% annual probability of exceedance. This probability level was chosen because it is in line with the accepted reliability level for the seismic performance of building structures in Canada, and it allows this reliability level to be achieved uniformly across the varying seismotechtonic environments in the country. The design ground motion does not correspond to a single value of earthquake magnitude. Rather, it results from a probabilistic evaluation of the many possible seismic events of varying magnitudes, types, distances, and likelihoods that all contribute to the total seismic hazard at a given site.

Seismic design of new Normal Importance buildings according to the provisions of the BCBC 2006 and NBCC 2005 are intended to provide the following outcomes:

- Protect the life and safety of building occupants and the general public as the building responds to strong ground shaking (i.e., the design ground motion).
- Limit building damage during low to moderate levels of ground shaking.

The Code acknowledges that the building and its contents may suffer damage during the design level earthquake which may require significant repair before occupancy and functioning of the building can be resumed, but that structural collapse will be prevented and that the lives of its occupants will be safeguarded.

# 6 Commissioning

## 6.1 E-Linac Commissioning

A commissioning plan (Document-108335) outlines all the activities and their correspondence with the relevant TSOP processes to ensure compliance with TRIUMF's Quality Management System. Principal among the processes are those for Commissioning TSOP-13, Operations Management TSOP-11, and Training TSOP-04. The plan identifies roles and responsibilities, engineered and administrative controls for safe operation, readiness requirements for equipment commissioning without and with beam, the acceptance criteria and deliverables for each stage of commissioning.

The commissioning of the E-linac to 30 MeV and 10 kW is being accomplished in several stages. Figure 6-1 includes a layout of the different beam transport sections and the beam dumps associated with each of these sections. These are referenced in the following list of commissioning stages.

1. Injector Commissioning – beam energy up to 10 MeV with the average e-beam power increased up to 1 kW delivered to the analyzing station EMBD.
2. Accelerator Commissioning – beam energy of about 30 MeV (but no greater than 40 MeV) with average e-beam power up to 10 kW delivered to EHD, the high-power beam dump.

Stage 1 has been completed. Stage 2 is nearly completed. The first demonstration of a 10 kW beam at 30 MeV took place on September 13, 2021.

For each stage of commissioning equipment readiness of the relevant systems has been verified prior to the start of commissioning.

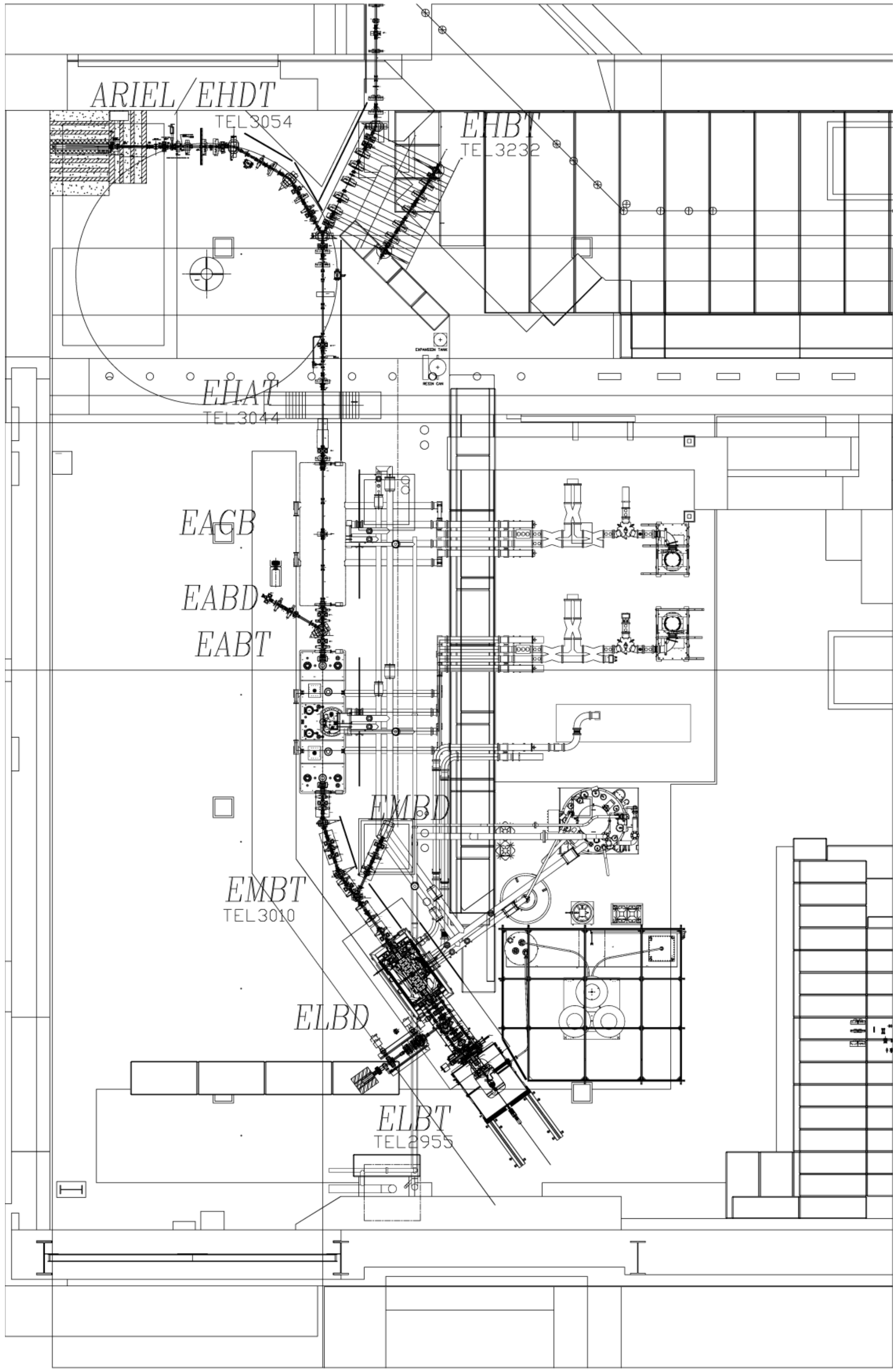


Figure 6-1 Electron Hall beam line component layout January 2014

## 6.2 Administrative Procedures

The commissioning plan (CP) describes roles and responsibilities for the commissioning team to ensure that operation for the purposes of commissioning adheres to the processes in TSOP-11 for the two basic activities at commissioned facilities - beam delivery and equipment maintenance. A commissioning schedule overseen by the head of commissioning is followed that captures both beam commissioning and maintenance activities. Communication of the schedule is via a web accessible calendar and a digest of the work completed is captured in the TRIUMF site maintenance list. An electronic log is used for capturing the day's activities, and the seconded operator on day shifts assists with these administrative operational tasks.

A process for transitioning from maintenance to commissioning activities has been defined and is consistent with TSOP-08 Calibration, Inspection and Recurring Maintenance process for scheduled maintenance work. The CP outlines the process for configuration control during the installation and operations phases. Once equipment is commissioned, all maintenance work on the e-Linac is controlled work. Fault reports are used for managing repairs to equipment. These generate work permits for controlled work on all commissioned systems. TSN 1.5 Policy and Procedures for Defeat of Interlocks and for Device Disables are followed.

## 6.3 E-Linac Radiation Safety System Commissioning

The commissioning plan (Document-108174) for the E-linac Radiation Safety Systems was used to carry out the system tests and a commissioning report completed by the Safety Systems Group prior to accelerating beam in the Electron Hall (Document-109675). The tests include: a check of all safety system device functionality; testing the Access Control System area safety unit functionality; verification of all signal inputs and outputs for the safety system PLC and relays; and a PLC simulator test for a variety of input signal states and confirming the correct output signal state. An addendum to these tests was completed once the eight watchman stations were installed and the record is Document-114067.

In addition, a verification exercise was designed to ensure that the search path defined by the eight watchman stations does provide good coverage of the E-Hall exclusion area. The verification plan (Document-114264) also captures a performance requirement of 100%. A record of successful completion of the exercises is Document-114067.

## 6.4 Oxygen Deficiency Monitoring System Commissioning

The Oxygen Deficiency Monitoring System commissioning plan was released (Document-110698) and includes a full testing of the functionality of the system for each sensor; checks of all interior and exterior status indicator lights and alarms; checks of the remote-controlled shut-off valves; with the above testing done with both a 19% and 17% $O_2$ gas mixture as well as a complete failure of the sensor. The commissioning report is Document-113818.

## 6.5 Shielding and Radiological Assessment

A Shielding and Radiological Assessment Plan (Document-108545) describes the radiological measurements to be completed at each stage of commissioning. These include prompt radiation dose rates outside shielding; measurements where possible inside shielding to verify the radiation field source term; residual activation dose rates for beam line components, beam line services systems; and lastly activity concentration for exhausted Electron Hall air and dump cooling water.

## 6.6 Training Implementation

Training plans have been developed consistent with the Systematic Approach to Training (TSOP-04). The e-Linac training coordinator and the seconded operator have completed the training outlined in Training Plan - E-LINAC Monitoring and Prerequisites for Beam Tuning (Document-118072). The framework for the program is a task analysis which draws on existing facility operations training plans and has been tailored for e-Linac systems and commissioning. Specifically, the plan captures the different skill set of an operator versus an accelerator physicist, both of whom will carry out operational tasks at different times in the control room during commissioning. The broad category of tasks in the training plan include personnel safety alarm response, major equipment alarm response, access control system procedures for the e-Hall exclusion area, performance of administrative tasks, use of EPICS for monitoring the e-Linac control system, and operation and monitoring of all e-Linac systems. The plan does not include any operator training for beam tuning and delivery as those tasks are performed by system experts during the commissioning phases.

In addition training has been implemented for all who access the e-Hall exclusion area.

- Working in Exclusion Areas Training - Document-114192 – This training is required for all who access the e-Hall, which is an exclusion area. It includes training for Personnel Safety Alarm, Lock-out/Tagout as well as some on-the-job training.

Training needs analysis will be completed and training plans adjusted as new procedures are brought online and/or added to the e-Linac Operations Manual. The training needs will capture additional training requirements as we transition from operation by system experts to operation by non-experts in order to ensure that the accelerator is operated safely.

# Appendix A:

This Appendix contains an up to date beam line layout for the Electron Hall, and Electron Hall architectural drawings from the as-built drawing package.

Electron Hall e-Linac beam line layout, Jan 2014 (as shown in Figure 6-1)

TRIUMF dwg# 17660 Electron Hall Site Summary

TRIUMF dwg# 17661 Electron Hall B3 plan

TRIUMF dwg# 17662 Electron Hall B2 plan

TRIUMF dwg# 17663 Electron Hall Grade plan

TRIUMF dwg# 17664 Electron Hall Roof plan

TRIUMF dwg# 17665 Electron Hall Sections

A complete set of architectural drawings including the ones attached here will be available on the TRIUMF document server.