

# Safety Analysis for SNS Beam Test Facility



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Research Accelerator Division

**SAFETY ANALYSIS FOR BEAM TEST FACILITY**

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## 1. INTRODUCTION

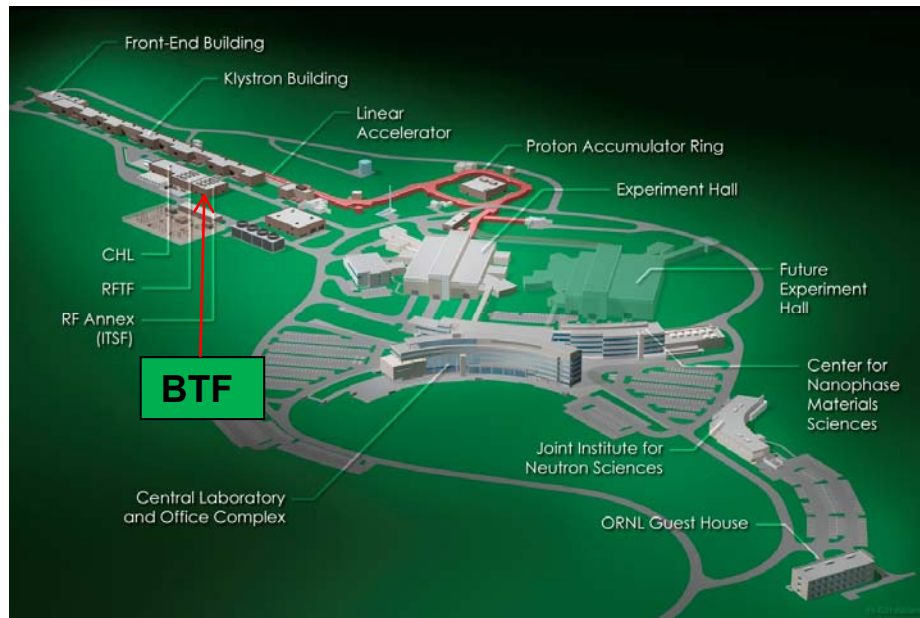
The Beam Test Stand, which is a major component of the Beam Test Facility (BTF), is a near replica of the operational SNS low energy Front End. In this document, we refer to the Beam Test Stand as the BTF. The long-term primary purpose of the BTF is to provide a test facility for research and development that will benefit general accelerator science and related applications, along with performance and reliability enhancements for SNS front-end systems. This work will be critical to sustaining routine 1.4 MW SNS operation and for increasing capability to 2.8 MW and beyond.

The BTF is located in a technical support building on Chestnut Ridge at Oak Ridge National Laboratory. The BTF is a room-sized accelerator with a single beam wholly contained within the beam transport vacuum envelope. The BTF has an active safety system, and has a single point of entry into the fenced enclosure that defines the BTF exclusion area. The BTF can be safely managed under the provisions of Title 10, Code of Federal Regulations (CFR) Parts 835 and 851. The BTF therefore generally meets the requirements for an exemption from the provisions of DOE O 420.2C, *Safety of Accelerator Facilities* consistent with paragraph 3.c.(1).(b). Accordingly, management proposes to request such an exemption for operation of the BTF.

However, SNS has established, robust processes and procedures for management of the SNS accelerator complex. It is prudent to leverage these processes and procedures to ensure effective management and oversight of the BTF even if it is operated under an authorized exemption from the requirements of DOE O 420.2C. To this end, SNS management has prepared a safety analysis to support a robust approach that will ensure safe operation of the BTF. The safety analysis that follows is performed in the spirit of and consistent with the approach prescribed in the Accelerator Safety Order (ASO) DOE O 420.2C and so contains language consistent with that found in formal safety assessment documents. Guidance from the ASO, DOE G 4201.C was also used in the preparation of this document. Management of the configuration of the BTF will be done consistent with the established SNS Configuration Management Procedures and the Radiation Safety (RS) Hold process, and proposed changes to the facility will be reviewed consistent with the established SNS Unreviewed Safety Issue process to ensure that the bounds of approved operations are properly maintained.

## 2. SITE, FACILITY, AND OPERATIONS DESCRIPTION

Section 3.1 of the Spallation Neutron Source Final Safety Assessment Document for Proton Facilities [Ref. 6] provides a detailed description of the SNS site and surrounding areas.



**Figure 1. Chestnut Ridge (SNS) Site Showing BTF Location.**

## **2.1 BTF LOCATION**

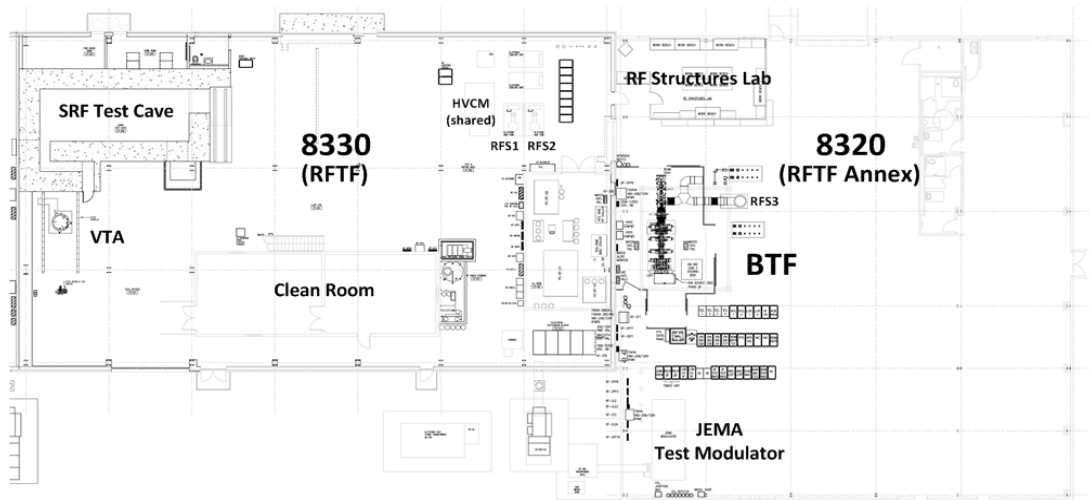
The BTF is housed on the SNS site in Building 8320, the RFTF Annex, as shown in Figure 1. Building 8320 is an annex to building 8330, the Radio-Frequency Test Facility (RFTF), and is used for Radio-Frequency (RF) and Superconducting RF (SRF) component and system testing and development. The buildings share a common wall. Personnel and equipment doors allow free travel of personnel and equipment between the two buildings. A standard exterior door ORNL Prox card system controls access to Buildings 8320 and 8330. No staff members are assigned occupancy in Building 8330. Three staff members of the Research Accelerator Division (RAD) Electrical and RF Systems (ERF) Group are assigned seats in Building 8320.

Building 8330, the RFTF, houses a number of test capabilities including the RF system test stand with a High Voltage Converter Modulator (HVCM), a SRF Test Cave, a Vertical Test Area (VTA) for superconducting cavity tests, a Clean Room area with SRF cavity processing capabilities, a Horizontal Test Assembly (HTA), a Cryomodule assembly area, and a surface science test facility for development of techniques that are intended to improve superconducting cavity performance. The HVCM in Building 8330 also supports the BTF. Building 8320, the RFTF Annex, houses the BTF, another HVCM modulator test unit (JEMA modulator), and an area for storage of processed RF windows. It also houses a RF structures laboratory, equipment storage, and personnel cubicles. The layout of the test facilities within Buildings 8320 and 8330 is shown in Figure 2.

Activities within buildings 8320 and 8330 will continue to evolve and that test facilities may be added or modified as needed to support the SNS mission. Current and future activities involve standard industrial and laboratory hazards that can be safely managed under the ORNL SBMS. Should future activities potentially impact accelerator safety of the BTF, such impacts would be evaluated with the established



SNS accelerator Unreviewed Safety Issue (USI) Evaluation Process as found in the SNS Operations Procedures Manual (OPM) OPM 2B-10 [Ref. 14].



**Figure 2. Location of Buildings 8320 (RF Annex) and 8330 (RFTF) on the SNS Site.**

The BTF is very similar to the SNS accelerator front end [Ref. 4]. It is composed of an H<sup>-</sup> ion source, low energy beam transport (LEBT), 402.5 MHz Radio-Frequency Quadrupole (RFQ), a medium energy beam transport (MEBT), a full-power shielded Beam Stop and low power R&D beam stops. In the SNS accelerator, the MEBT transports H<sup>-</sup> ions to the Drift Tube Linac (DTL) modules. In contrast, in the BTF, the MEBT transports H<sup>-</sup> ions to a dedicated beam stop.

The equipment above is enclosed within the BTF boundary that is a fenced area established within Building 8320. The concrete block wall between buildings 8320 and 8330 forms one side of the BTF while an approximately 21' wide by 31' long (8.3m x 12.2m) wire mesh fence forms the other three sides. The fence is approximately 10' (3 meter) tall.

The equipment and fence layout is shown in Figure 3. Five (5) entry gates/doors are available to move equipment in and out. The wall and fence serve as the primary radiological boundaries of the BTF. Gate2 is a Radiation swing gate which will not be locked or interlocked, as it is the normal entry point. Gates 1, 3, 4 and 5 are interlocked through the Personnel Protection System (PPS) during beam operation (see Section 2.10.2) but the interlock is not a Credited Control. Gate 4, though interlocked, is equipped with a timed interlock bypass to permit personnel and equipment access during operation provided administrative requirements are satisfied.

A number of equipment and support systems are located outside of the BTF enclosure, including:

- Ion source high voltage and plasma RF power supplies
- A 2.5 MW peak power, 402.5 MHz klystron, transmitter and water skid
- An 11 MW Peak Power HVCM (located in Building 8330)

- A structure water cooling system (located in Building 8330)
- Operator control and diagnostic stations
- Source, RF, and Instrumentation and Control equipment racks

The area outside and adjacent to the BTF enclosure is accessible space, which is not controlled for the purposes of radiological exposure. Three staff members are assigned to Building 8320, and other personnel work in Buildings 8320 and 8330 on a daily basis to support other activities not related to the BTF (e.g., associated with the co-located facilities within the buildings). Most personnel who work in these two buildings are trained and badged radiological workers, although it is not a requirement for access.

A 10' (3m) opening between the RFTF and Annex is located immediately outside the north end of the BTF fence. On the RFTF side of the BTF wall is an enclosed room containing water-conditioning equipment that is not normally occupied. Presently, the nearest routinely occupied space outside of the BTF fence is the RF Structures Laboratory shown in Figure 2.

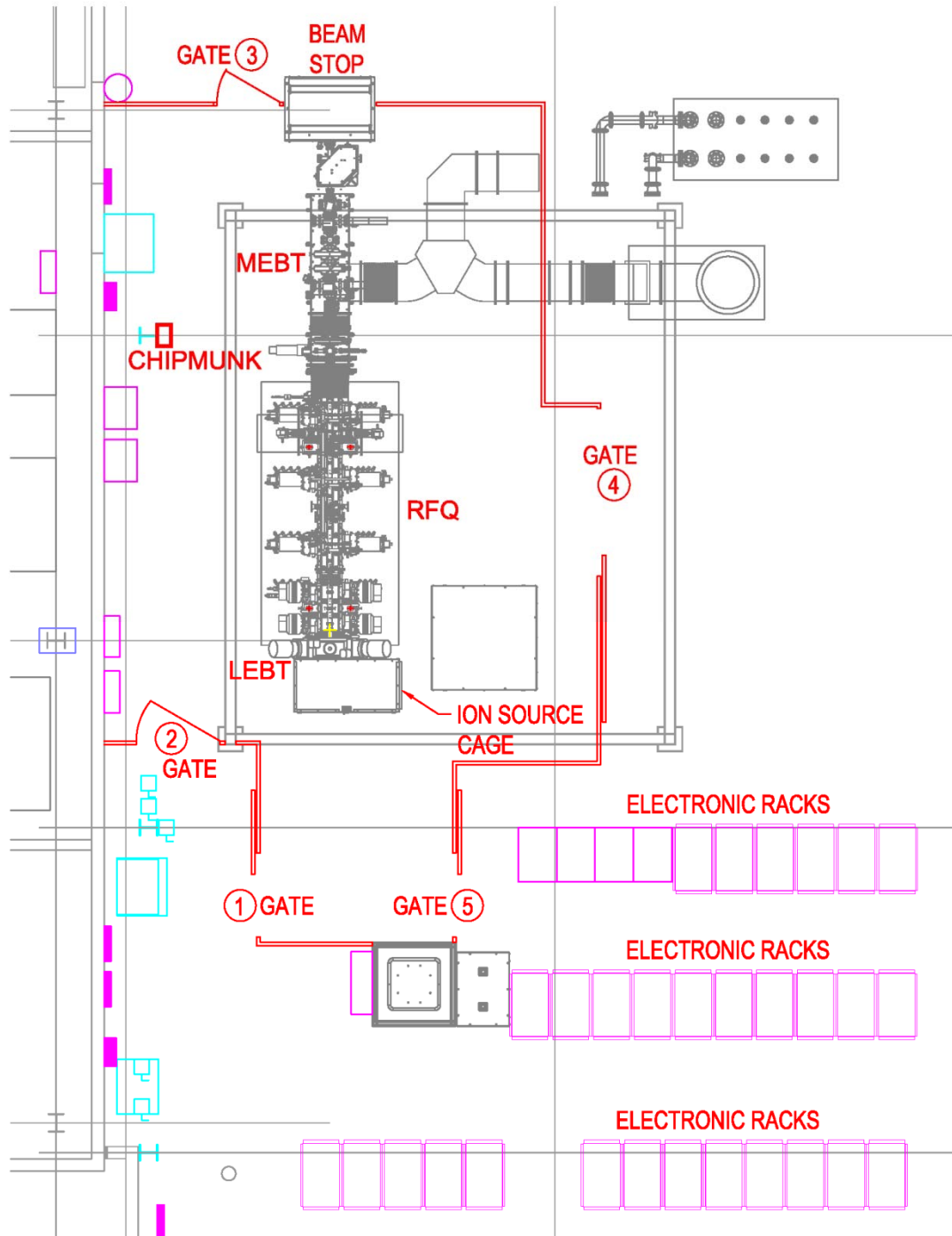


Figure 3. The BTF Fence Enclosure with numbered access gates (Red), equipment layout and adjacent area.

## 2.2 BTF FUNCTION

The functions of the BTF are:

- Verify design performance of the new Research Instruments (RI) Radio-Frequency Quadrupole (RFQ) structure with beam. Note that full RF conditioning of this device has been performed.
- Provide a platform for testing new equipment to improve SNS's availability, reliability, beam quality, and power capabilities.
- Provide a platform for R&D for novel hadron beam physics and technology.

The BTF can operate with several combinations of ion source peak current and RFQ duty factor (repetition rate and pulse width). Details are provided in subsequent sections.

## 2.3 SIMILARITIES AND DIFFERENCES BETWEEN BTF AND THE SNS FRONT END

The SNS Front End consists of a Cesium-enhanced, volume RF-discharge Ion Source with a nominal  $-65$  kV potential to ground.  $H^-$  ions produced in the ion source are extracted at the  $-65$  kV potential difference. The short Low Energy Beam Transport (LEBT) section contains two electrostatic lenses that focus the beam into the Radio Frequency Quadrupole (RFQ). The 402.5 MHz RFQ bunches the  $H^-$  beam and accelerates it to about 2.5 MeV, while simultaneously refocusing it in both transverse planes. The SNS Front End also contains a Medium Energy Beam Transport (MEBT) section with four RF Rebunchers to maintain the longitudinal bunch length of the beam following the RFQ and a low power beam stop. The BTF has two major differences: the BTF MEBT has no RF Rebunchers and includes a full power beam stop.

The SNS LEBT has glass windows that provide a leak path for X-rays that creates low radiation levels in localized areas that are shielding by temporary shielding as needed. The BTF LEBT has no glass windows.

The BTF Personnel Protection System (PPS) architecture uses a single Safety PLC instead of two industrial PLCs as described in Section 2.10.2.

## 2.4 SHARED EQUIPMENT AND INFRASTRUCTURE

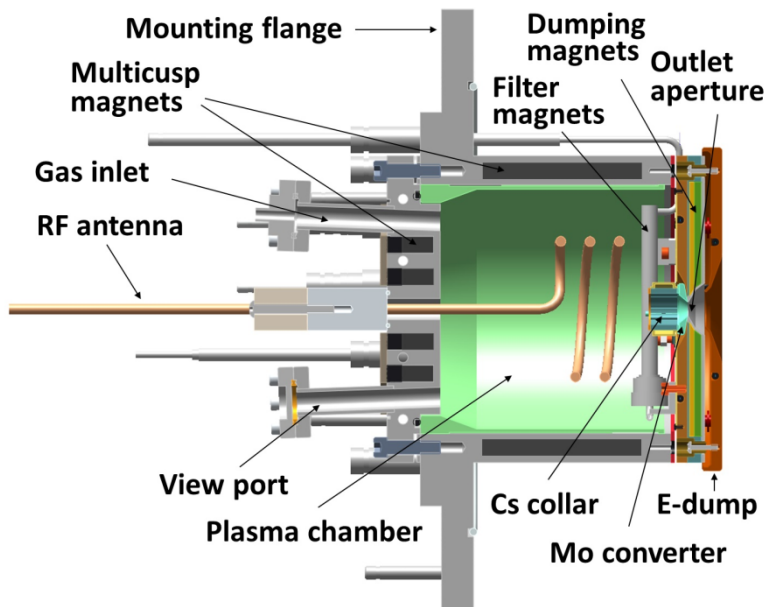
The BTF RFQ 402.5 MHz transmitter shares the high voltage converter-modulator (HVCM) shown in Figure 2 with two other RF systems in the RFTF. Only one of the three loads can be driven at any time. The three loads are:

- RFS1 805 MHz RF Transmitter located in 8330 used for RF testing and conditioning, SRF Test Cave operations, and Vertical Test Area operations
- RFS2 402.5 MHz RF transmitter located in 8330 used for RF testing and conditioning for multiple components
- RFS3 402.5 MHz RF transmitter located in 8320 used for powering the BTF RFQ

The present converter-modulator in Building 8330 can support either one 805 MHz transmitter, one 402.5 MHz transmitter, or simultaneous operation of two 402.5 MHz transmitters. Therefore, the BTF RFQ cannot operate at the same time as the RF Test Stand 805 MHz klystron. Plans are underway to develop and commission a second converter-modulator. This additional modulator could allow fully independent operation of the BTF and RF test facilities. Configuration of the HVCM load is done administratively.

## **2.5 BTF ION SOURCE AND LEBT**

The BTF employs an RF-driven, Cesium-enhanced, volume-type H<sup>-</sup> ion source that is nominally held at a voltage of -65 kV with respect to ground. A schematic representation of the ion source is shown in Figure 4. The ion source system consists of a plasma chamber, extraction electrode and a short Low Energy Beam Transport (LEBT). Both the ion source and LEBT electrodes are identical to and interchangeable with those employed on the SNS production Front-End systems and the Ion Source test stand located in Building 8100. Plasma is produced by the pulsed application of radio frequency energy to an antenna either immersed in or surrounding the plasma chamber (2 MHz, ~50 kW, 1 ms, 60 Hz). Plasma is sustained between pulses by the continuous application of ~300 W of 13.7 MHz power. Most H<sup>-</sup> ions are generated from the interaction of the plasma with a heated, cesiated surface near the plasma chamber extraction opening. H<sup>-</sup> ions are then extracted from the plasma chamber by an electrode nominally biased to -59 kV with respect to ground by the e-dump supply, and ions are then accelerated to 65 KeV after entering the LEBT. The LEBT contains two electrostatic lenses with the second lens being split in four segments to allow precise steering of the beam into the RFQ (see next section). Each lens is nominally held at -40 to -45 kV with respect to ground. The ion source is electrically coupled to a -65 kV high voltage platform containing the 13 MHz, e-dump and Cs-heater power supplies as well as associate diagnostics. The second lens of the LEBT is also electrically connected to a steering deck containing four steering power supplies. The rest of the LEBT power supplies are held in a grounded rack with high voltage coupled to the LEBT tank through shielded cables and feedthroughs.



**Figure 4. Schematic representation of the BTF Ion Source.**

Hazards presented by the Ion Source and LEBT systems include: electrical (AC distribution and DC high voltage), ionizing X-ray radiation from co-extracted electrons, non-ionizing RF radiation, mechanical energy (compressed gas cylinders, weight loads associated installation/removal of ion sources), thermal energy from the Cs heater and fire from the use of hydrogen gas.

The approach to mitigating these industrial hazards at the BTF is to adopt the same safety procedures in use for the SNS front end system, including the approved version of the applicable Research Safety Summary (RSS) 8010.x, task specific Job Hazard Analyses (JHA) and trained Front End staff. Specific hazards and controls are identified in the work control documents. In general, electrical hazards are mitigated by employing finger-safe enclosures surrounding the high voltage platform, steering deck and ion source, with access door interlocks that shut off high voltage and RF power supplies when the doors are opened. Hazardous energy control is done in accordance with prescribed SBMS procedures is performed in conjunction with routine source installations, maintenance, and repair work where manual contact with previously energized components is possible. The performance of any 'hot' work is forbidden. The ion source operates at 65 kV. Beams produced at this energy cannot induce radiological activation of materials but can produce small quantities of X-rays from the co-extracted electron beam. For normal BTF operation the ion source is within the fenced area and will be subject to the overall facility radiological postings, typically radioactive materials area and possibly up to a radiation area for external radiation. When operating in source-only mode with the RFQ not energized, the source will be surveyed at each startup and posted according to the measured radiation levels by an RCT. For non-ionizing RF radiation, NARDA meter surveys will be conducted at nominal 2 and 13 MHz power levels to ensure RF emissions are within limits and shielding applied as necessary. Compressed gas bottles are secured in accordance with laboratory policy. The hydrogen feed system is tested for leaks according to established procedures to mitigate potential fire hazards. Established SNS Front End source

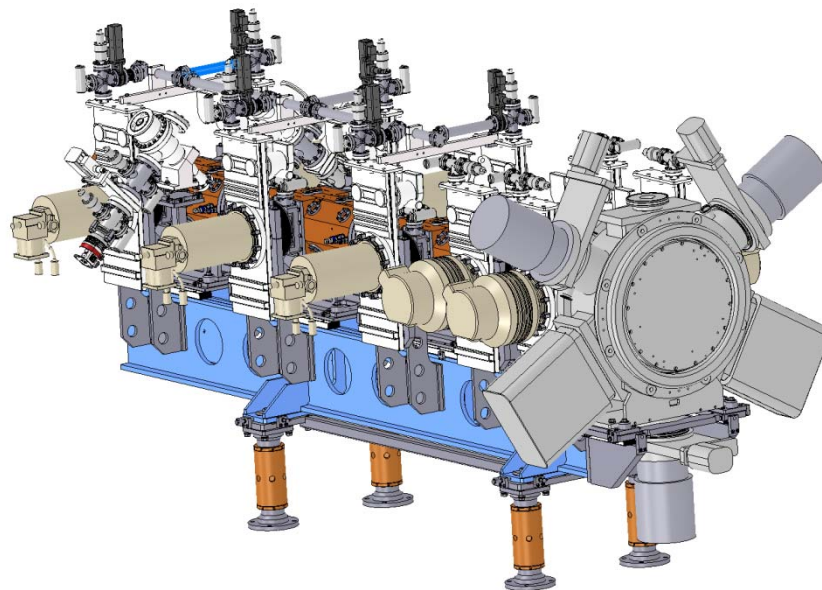
installation/removal procedures shall be followed to mitigate material handling hazards when handling the ion source.

## 2.6 THE BTF RFQ

### 2.6.1 RFQ Design and Fabrication

The Research Instruments (RI) RFQ is fabricated from oxygen-free high thermal conductivity (OFHC) copper. The walls of the structure are thick enough so that the structure is self-supported without the need for a strong back. The structure thickness renders the RFQ largely self-shielded from electromagnetic radiation produced by the accelerating RF as described below.

The BTF RFQ is designed to accelerate the H<sup>-</sup> beam from 65 keV to 2.5 MeV. RFQ acceleration can involve up to 30 percent transmission loss, so an average input current of, for example 4.3 mA could be required to deliver a desired output average current of 3 mA. The design peak RF voltage between the RFQ electrodes is 83 kV and the highest design electric field gradient is 1.85 kilpatrick, or approximately 36 MV/m for a frequency of 402.5 MHz. This voltage is generated by pulsed RF at 402.5 MHz with a duty factor of up to 6 percent at a maximum repetition rate of 60 Hz. The dark current from the high voltage electrodes in vacuum will be a source of X-ray radiation. The copper walls of the RFQ effectively shield this X-ray radiation. An engineering rendition of the LEBT and RFQ structure with pumps is shown in Figure 5.



**Figure 5. The RFQ and LEBT.**

The H<sup>-</sup> beam accelerated to 2.5 MeV is above the threshold for neutron production in both copper (2.17 MeV) and stainless steel (1 MeV). Experience with the SNS RFQ, which has an identical physics design

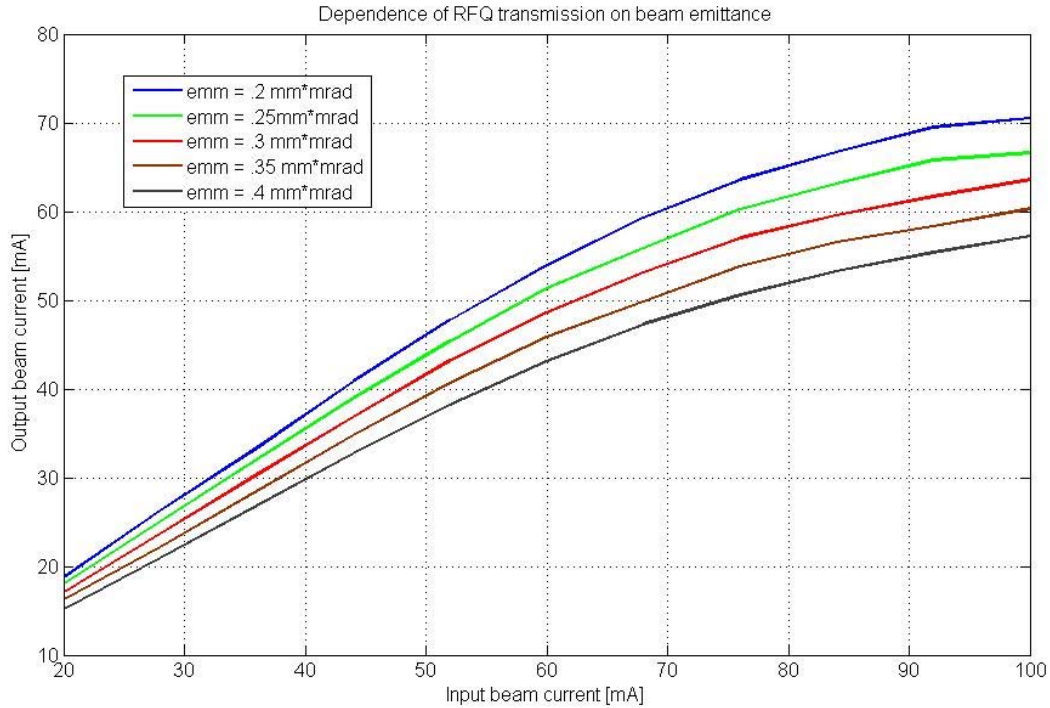
(length, gradient, frequency), shows that neutron production in the RFQ is negligible under normal operating conditions. The  $H^-$  beam loss occurs in the low energy part of the RFQ where the beam energy is substantially below the neutron production threshold of 2.164 MeV for  $^{65}\text{Cu}$ , which has a natural abundance of 30.8 percent. No measurable neutron radiation has ever been observed originating from the Berkeley RFQ currently in use on the SNS accelerator and, given the equivalence of the physics design the same is expected of the RI RFQ installed in the BTF.

The RFQ generates X-rays as an incidental byproduct of the RF fields used to accelerate the beam. Field emission from the RFQ surfaces generates electrons that are accelerated by the RF and then strike surfaces to produce X-rays with end-point energy of 83 keV, the maximum electrode voltage relative to ground. Most of the resulting X-rays are low energy, but some can penetrate the RFQ structural components, and low-z blank-off flanges provide especially easy penetration paths for the X-rays. Radiological surveys conducted during commissioning, testing, and conditioning of the BTF RFQ did detect some radiation from the BTF RFQ. During one early RF acceptance test (July 29, 2014, Survey SNS-384030) up to 40 mrem/h on contact, 5 mrem/h at 30 cm was measured at aluminum blank-off flanges with the cavity RF operating at nominal peak power of 550 kW but at about one-third of the nominal duty factor (30 Hz, 600  $\mu\text{s}$ ). Those flanges were replaced with the vacuum pumps intended for those locations, and no measurable radiation was found during the next several tests. However, radiation levels up to 1 mrem/h at 30 cm were found with the RFQ operating at nominal peak power and full duty factor (550 kW peak, 60 Hz, 1 ms with 33 kW of average power) on September 15, 2015 (Survey SNS-413321). It is not anticipated that the BTF RFQ will generate X-rays capable of harming a person, but fields above the Radiation Area threshold might be produced at times. When the BTF RFQ operates as part of the BTF accelerator, the caged area will be posted appropriately based on operating conditions.

### **2.6.2 Calculated RFQ Transmission**

The dependence of the RFQ output current on the input current for various input beam emittances is shown in Figure 6. The output beam current increases proportionally to the input beam current at low input current but saturates at higher beam current. The saturation level is inversely proportional to the input beam emittance. A typical measured beam emittance out of the ion source is .3 mm\*mrad at 50 mA. The maximum current the source can produce is about 80mA. Assuming 100mA ion source current and .2 mm\*mrad emittance, which are both very conservative numbers never demonstrated by this type of ion source, the maximum output beam current is about 70 mA. The maximum beam current experimentally achieved out of the SNS RFQ during 10 years of operation was 50 mA.





**Figure 6. RFQ output beam current vs. input beam current for different beam emittances.**

## 2.7 The BTF MEBT

The BTF MEBT is designed to transport the 2.5 MeV H<sup>-</sup> beam that exits the RFQ to the BTF MEBT beam stop through an evacuated stainless steel beam pipe that contains transverse beam focusing elements (quadrupole electromagnets), beam diagnostic devices (beam position monitors, wire scanners, current transformers), vacuum pumps and other necessary equipment. Note that the range (maximum penetration depth) of 2.5 MeV H<sup>-</sup> ions in stainless steel is approximately 26  $\mu\text{m}$ .

The bounding conditions for duty factor of the RFQ are:

- Maximum 60 Hz, 1 ms (6%)
- Minimum 1 Hz, 50  $\mu\text{s}$  (0.005%)

Operation for accelerator physics R&D will typically take place at 10 Hz, 50  $\mu\text{s}$  (0.05%).

At full duty factor, a maximum accelerated peak current of 50 mA yields an average maximum accelerated average current of 3 mA (effective beam power of 7.5 kW), directed only at the high power shielded beam stop designed to shield the neutrons and gamma radiation generated in the beam stop. Such conditions will only exist during the commissioning phase with beam of the RFQ structure itself, and will last no more than approximately 30 days. The vast majority of beam operation through the MEBT for physics purposes will be at 10 Hz or less and 50  $\mu\text{s}$  or less. The typical average beam current

for these systems will be a maximum of 25 $\mu$ A (for 50 mA peak accelerated beam) that is 0.8% of the typical maximum beam current capability.

During routine operations a very small fraction of beam may be lost in the MEBT. This small beam loss will very produce low levels of neutron and gamma radiation. Higher levels of radiation could be generated if a large fraction of the H<sup>-</sup> ion beam is inadvertently directed (or “lost”) in the MEBT structure material between the exit of the RFQ and the high power shielded beam stop.

In contrast to the SNS MEBT, there are no RF rebuncher cavities in the BTF MEBT; therefore, X-rays that can be generated by the high RF voltages in the RF rebuncher cavities are not of concern for the BTF MEBT.

## **2.8 THE BTF BEAM STOP AND BEAM STOP SHIELDING ASSEMBLY**

During planned high power BTF RFQ commissioning operation the H<sup>-</sup> ion beam (3 mA, 2.5 MeV, 7.5 kW) is directed onto a water-cooled beam stop designed to absorb the radiation generated when the H<sup>-</sup> ion beam stops within the beam stop material. The beam stop design is shown in Figure 7. This device was used for the SNS Front End commissioning in 2003, subsequently removed, and retained for future use. Water-cooled plates made of Titanium-Zirconium-Molybdenum (TZM) alloy stop the beam and remove the heat. This material minimizes but does not eliminate neutron and gamma radiation generated by the beam interaction. The beam impinges on the plates at a shallow angle to distribute beam power over larger area given the very short range in the material. The beam stop plates are enclosed in a vacuum chamber made of aluminum. The plates are electrically insulated from ground (high resistivity water) and connected to an electrical vacuum feed through to allow measurement of the absorbed charge and beam pulse temporal structure. The beam stop material has a melting point of 4753 °F (Ref. MTI Metal Technology); therefore, it will not melt or evaporate in case of an ordinary external fire.

Dose rates associated with running 7.5 kW of 2.5 MeV H<sup>-</sup> beam in to the unshielded BTF MEBT beam stop are calculated to be ~300 mrem/hr at a distance of 30 cm. Supplemental shielding has been designed and installed as shown in Figure 8. The beam stop / supplemental shielding assembly extends through the access control fence such that the rear and sides of the beam stop are accessible to personnel not associated with the BTF and are not accessed controlled (see Figures 3 and 8). The green section is composed of borated polyethylene, surrounded by fire suppression sheets of aluminum. Support plates of carbon steel, shown in yellow in Figure 8, surround this shielding. As an ALARA measure, a cage-type (e.g., steel mesh fencing) boundary has been installed around the lower portion of the supplemental shielding assembly because slightly elevated dose rates may exist underneath the shielding assembly due to service penetrations and the presence of a vacuum pump assembly. If necessary, access within the caged area underneath the beam stop during operation will be authorized under the provisions of ORNL SBMS for Radiological Protection and would require controls such as an RWP.

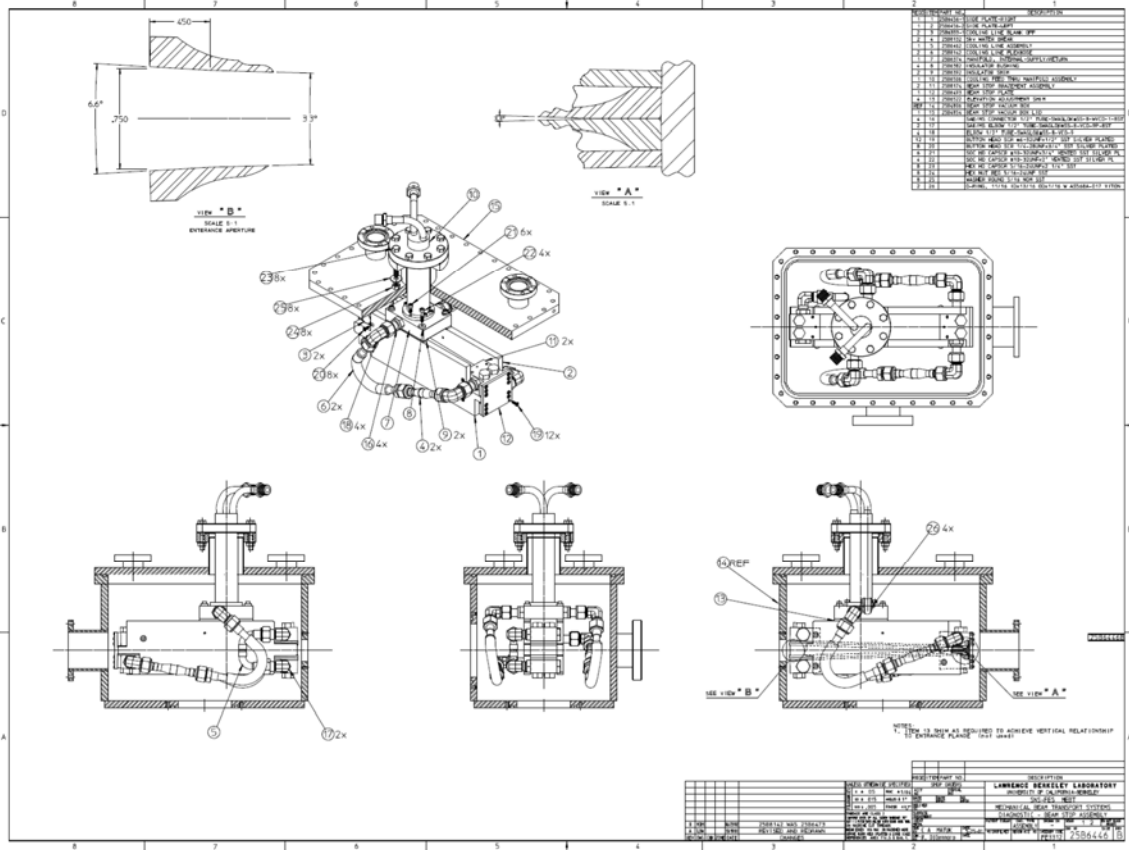


Figure 7. The BTF Beam Stop Detail.



Figure 8. The BTF Beam Stop and Shielding.

## 2.9 BTF EXPERIMENTS

The MEFT between the exit of the RFQ and the high power beam stop contains a portion of the beam diagnostic devices required to support complex 6 dimension beam phase space measurements that are necessary to support planned accelerator physics R&D. The other diagnostic, a Beam Shape Monitor (BSM) requires a magnetic field to analyze the beam energy.

A 90° bending magnet (dipole) upstream of the high power beam stop will bend the beam to beam-right. From there the beam can be directed straight ahead into a BSM thereby completing the 6-dimension beam phase space apparatus. A schematic layout of the physics configuration is shown in Figure 9. All beam operation in the physics configuration (dipole energized) will be limited to a maximum duty factor of 10 Hz or less and 50  $\mu$ s or less. The typical beam current for these systems will be  $\leq 25\mu$ A that is equivalent to a maximum of 62.5 W of beam power. The beam duty cycle will be controlled as described in Section 2.10.1. The beam stop for the 6D phase space measurement system is made of carbon, which works well at low beam power. There is no neutron production from (p,n) on Carbon at 2.5 MeV and the gamma production cross sections are very low. The predicted radiation dose [Ref. 2] from 25 $\mu$ A of 2.5 MeV H<sup>-</sup> ion beam that impinges on carbon is 8 mrem/hr at 30 cm. Consequently this beam stop requires no shielding.

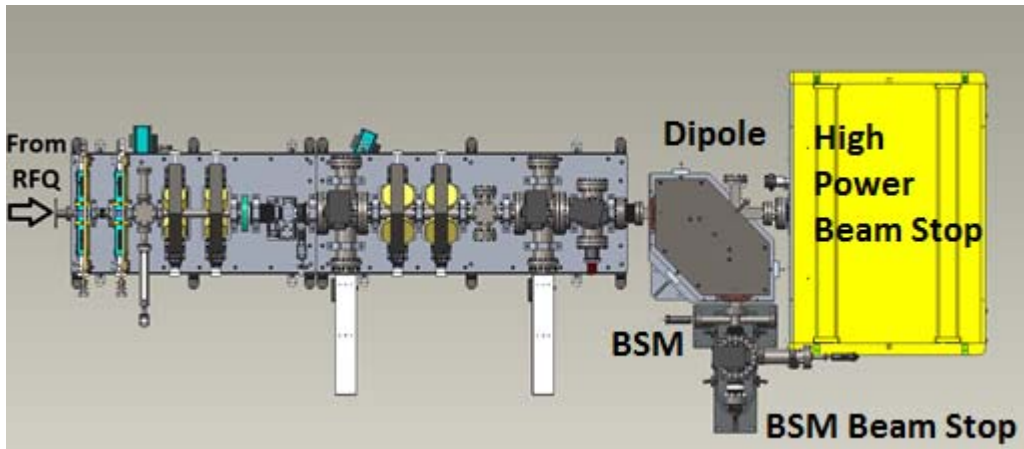


Figure 9. Physics configuration layout including MEFT and high power beam stop.

## **2.10 PROTECTION SYSTEMS AND TIMING SYSTEM**

The Integrated Control Systems (ICS) subsystems are structured in a manner that provides layered protection (defense-in-depth) against threats to both equipment and personnel. The PPS is a credited system that ensures protection of workers against prompt radiation but, as discussed below, other controls provide layers of protection against potential operational problems before they require PPS actuation.

The supervisory control system provides the first layer of defense by enforcing system configuration rules, annunciating abnormal conditions, and responding when conditions approach unacceptable boundaries. While the supervisory control system acts to prevent challenges to other ICS systems, it is not credited to protect workers from permanent harm or death.

The Machine Protection System (MPS) is the second layer of defense, responding to out-of-bound operating conditions by shutting off the beam. The MPS is a high reliability system but is not a Credited system for personnel protection. However, it does contribute to layered protection (defense in depth) by preventing challenges to the PPS radiation monitoring function by terminating beam operation quickly when beam losses occur.

Thus, both the Experimental Physics and Industrial Control System (EPICS)-based supervisory control system and the MPS contribute to overall assurance of safety by limiting challenges to the PPS, which is described below in Section 2.10. Control, protection, and safety functions are layered so that as the consequences of a failure increase so, too, does the quality level of the responsible system.

### **2.10.1 Machine Protection and Timing Systems**

The MPS is designed to protect the BTF equipment from beam-related damage by terminating beam operation within 20  $\mu$ s of receiving notification of a fault condition. Fault condition indications are transmitted from sensors on High Power RF (HPRF), Vacuum, Beam Diagnostic Devices and Cooling systems. The BTF MPS configuration utilizes a combination of components that are representative of the MPS hardware found on the SNS accelerator. This configuration consists of two standard SNS field nodes, a Trigger Control Chassis (TCC), an MPS Programmable Logic Controller (PLC) and a Human Machine Interface (HMI). An Input-Output Controller (IOC) interface is also provided to show system status via EPICS and configure mask settings.

The field nodes provide the interface for sensors to communicate a faulted condition to the MPS. The field nodes propagate the fault to the TCC to terminate an active beam operation sequence and prevent further beam cycles until the fault condition is cleared.

The MPS PLC and HMI provide the user(s) with an interface to set the desired machine modes. The HMI displays five different machine modes that can be configured for the BTF. This is referred to as the "Mode Selector." The MPS Operating Modes are:

1. MPS Off
2. MPS Standby mode “source-shifted operations only”
3. 10 Hz, 50  $\mu$ s pulse width
4. 60 Hz, 1 ms pulse width

These timing modes are “hard-coded” into the Field Programmable Gate Array (FPGA) of the TCC. The TCC enforces restrictions on which operating modes are available depending on the beam destination selection. When the high power beam stop is selected, the system will permit operations under any of machine modes listed above. When the BSM beam stop is selected, the system will restrict operations to Modes 1 through 3 only. Mode 3 limits the RFQ and beam duty factor components separately to a 50  $\mu$ s pulse width and a 10 Hz repetition rate. Mode 4 will permit full duty RFQ and beam operation up to a 1ms pulse width and 60 Hz repetition rate and will only be used for RFQ full power testing to the MEBT beam stop. All other research and development operation will be limited in duty factor by using Mode 3. An engineered system is used to establish which beam stop destination is active at any given time and the RAD Accelerator Operations Manager will control this capability. The system that permits operation in Modes 1-4 may be authorized for use if and only if the MEBT 90° bending magnet is configured to prevent being energized through means of an RS-Hold in accordance with established SNS RS-Hold procedures. An RS-Hold will be applied to the power supply for the 90° dipole bending magnet. In the absence of such a power supply the RS-Hold will be applied to a short across the magnet leads. This protocol ensures that operation beyond Mode 3 cannot occur if the 90° bending magnet is capable of being energized for mode operation.

The TCC receives machine mode settings from the MPS PLC and fault status information from the field nodes. The machine modes instruct the TCC which series of pulse widths and repetition rate combinations are permitted for a given machine cycle. A new machine cycle is initiated every 16.67 ms (60 Hz). These limits are monitored and enforced by the internal system electronics. During non-beam machine cycles, the system generates a source-shifted mode. This mode separates, in time, the RFQ and ion source gate pulses. This permits the ion source and RFQ to operate and maintain thermal stability but prevents beam injection into the RFQ when the RFQ field is present. When the TCC receives a faulted condition during a beam production cycle from a field node, it terminates beam by truncating the RFQ and ion source gate pulses. Additional machine cycles operate under the source-shifted mode until the fault condition is cleared.

### **2.10.2 Personnel Protection System**

The BTF Personnel Protection System (PPS) architecture is similar to the SNS PPS that is described in Section 3.2.4 of the Spallation Neutron Source Final Safety Assessment Document for Proton Facilities [Ref. 6]. The primary function of the PPS is to protect workers from potentially injurious prompt radiation produced by accelerator operations. The BTF fence enclosure shown in Figure 3 defines a restricted access boundary that requires authorized workers to sign in on an active Radiological Work Permit (RWP) and obtain an Electronic Pocket Dosimeter (EPD) for access during BTF operation. Workers

are protected by an active, credited radiation monitor (Chipmunk) that is monitored by a Safety PLC which shuts off the beam in a credited manner if the detected radiation limits listed in Table 1 are exceeded.

The PPS system was developed in accordance with the requirements for Quality Level 1 equipment specified in the Spallation Neutron Source Quality Manual [Ref. 14]. These requirements include the following: (1) independent design reviews; (2) thorough documentation; (3) vendor qualifications; (4) configuration control; (5) formally trained operations and maintenance workers, and; (6) formal testing and certifications. The SNS Radiation Safety Committee provides independent review of proposed substantive changes to the PPS as appropriate.

### **BTF PPS Safety Functions**

The PPS provides the following primary safety function:

- Terminate beam if radiation levels increase over acceptable levels in potentially occupied monitored areas

### **BTF Critical Devices and Safety Functions**

The BTF Critical Devices are:

1. Ion Source: Contains Permits to:
  - 65 kV power supply: The PPS safety function will inhibit the main power to the 65 kV power supply through the 65 kV Safety Contactor
  - 13 MHz amplifier: The PPS safety function will inhibit the main power to the 13 MHz amplifier
  - 2 MHz amplifier: The PPS safety function will inhibit the main power to the 2 MHz
2. RFQ/Klystron RF: Contains Permits to:
  - Transmitter RF 402.5 MHz to Klystron: The PPS safety function will activate the RF transfer switches to shut off RF to the klystron but will NOT inhibit operation of the LLRF transmitter or the HVCM under normal operations
3. RFTF HVCM (ESTOP Only): Combines Permits with HVCM Permit from RFTF PPS:
  - The PPS safety function will shut off the HVCM on activation of an ESTOP

The BTF PPS Safety Functions are consistent with those defined in Section 5.2.1 of the Spallation Neutron Source Final Safety Assessment Document for Proton Facilities [Ref. 6].

### **System Architecture**

The BTF Personnel Protection System (PPS) architecture uses a single Safety PLC instead of two industrial PLCs. This is the standard practice now implemented for the Instrument PPS of the SNS

Instrument beam lines. The manufacturer is phasing out the Industrial PLC model used in the original design that used two Industrial PLCs. The single Safety PLC also affords better diagnostics and the use of certified safety functions. The two-programs/two programmer model requires independent programming of the safety logic for each of the redundant safety channels in the Safety PLC is also retained. Only one interlocked Safety Radiation Monitor (Chipmunk) is required because of the small facility footprint. The system has been designed to accommodate two additional inputs should the footprint of the BTF expand in the future resulting in a requirement for additional inputs.

### **Chipmunk Radiation Monitors**

As used in this document, the term “Chipmunk” refers to devices that have been shown through design reviews and testing to have radiation detection and fail-safe capabilities equivalent to Fermi Chipmunks. The primary remote output of the Chipmunk consists nominally of one pulse for each 0.0025 mrem detected. These pulses form the principal input from the instrument to the PPS. Since there is only one detector for gammas and neutrons, the quality factor of the instrument is adjusted for neutron energy, gamma/neutron dose ratio, pulse width and timing, and field magnitude, as needed, to ensure that the intended degree of protection is provided. The SNS Radiation Safety Officer is responsible for specifying the location and number of Chipmunks.

Chipmunks produce several outputs that are used by the PPS. Dose rates are indicated by a pulsed output as described above. The PPS totals the number of pulses over time to determine dose rate. Adjustable dose rate limits are used to activate area alarms and stop beam production. These limits are based on a rolling average to prevent spurious trips (e.g., activate an area alarm if the average dose over a 1-minute (min.) period exceeds 5 mrem/h, and stop beam operation if the average dose rate over a 15-min. period exceeds 5 mrem/h). Chipmunks have a keep-alive gamma source that causes an output pulse to be generated periodically regardless of radiation level. The PPS monitors the pulse output and stops beam operation if no pulses are detected after a defined time delay (i.e. from 120 seconds for a QF=1 to 20 seconds for QF=10).

The radiation monitors produce two digital outputs used by the PPS. A 20 mrem/h fixed alarm output is used to stop beam operation immediately by generating a PPS trip signal. Chipmunk internal diagnostics monitor for a lack of pulse outputs and out of tolerance critical parameters (such as ionization chamber high voltage). If these diagnostics detect an internal failure of the Chipmunk, a digital output is produced that stops beam operation by generating a PPS trip if it persists continuously for more than a nominal 30 s. The same internal failure signal is sent to the MPS for immediate beam suspension via the Fast Protect—Auto Reset feature of the MPS. The main control system archive engine records the radiation levels. This allows for trending of radiation levels in monitored areas and retrieval of historical data.



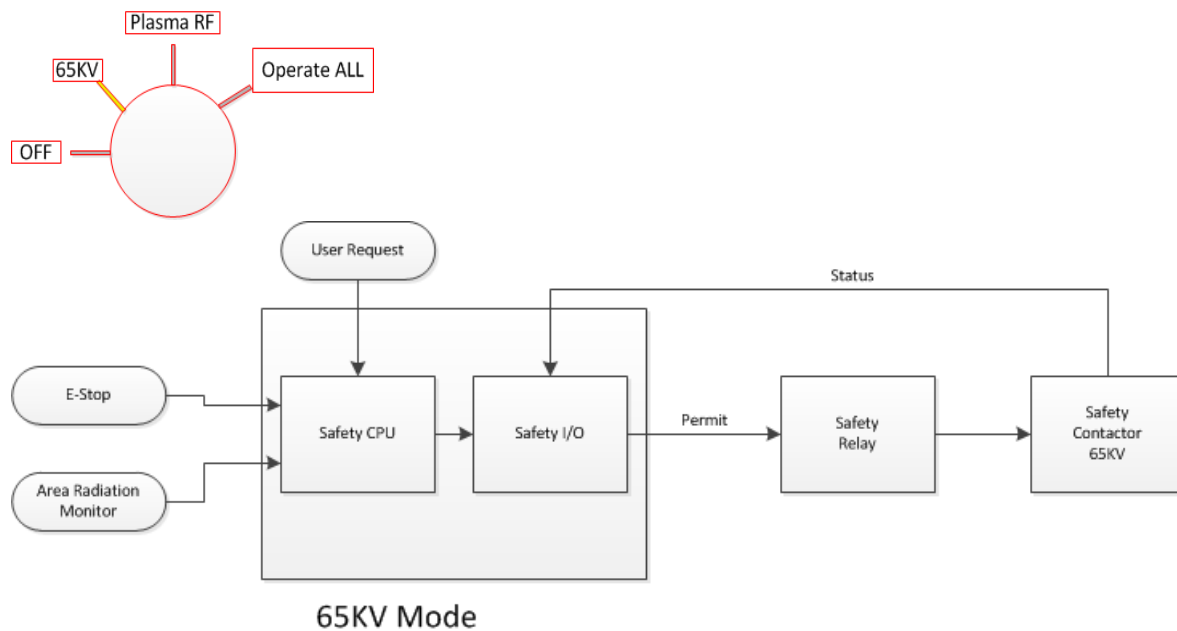
## BTF PPS Operating Modes

The BTF PPS Operating Modes are:

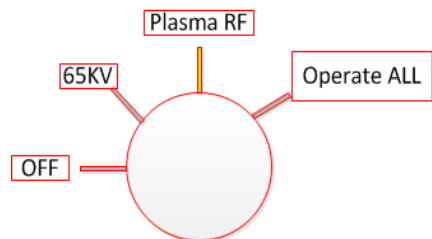
- **OFF Mode** (Inhibit all PPS controlled systems)
- **65 KV Mode** (Permit to operate Only the 65 KV system)
- **Plasma RF Mode** (Permit to operate Only the 13 MHz, and 2 MHz systems)
- **Operate All Mode** (Permit to all PPS controlled systems)

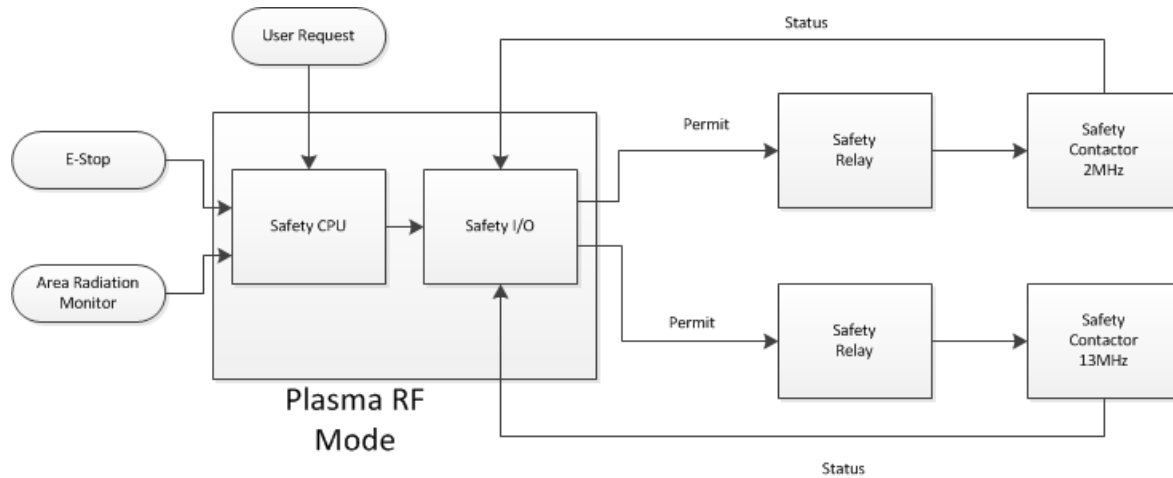
The following are BTF PPS Operating Modes with functional block diagrams:

### 65KV Mode (Permit to operate only the 65 KV systems)

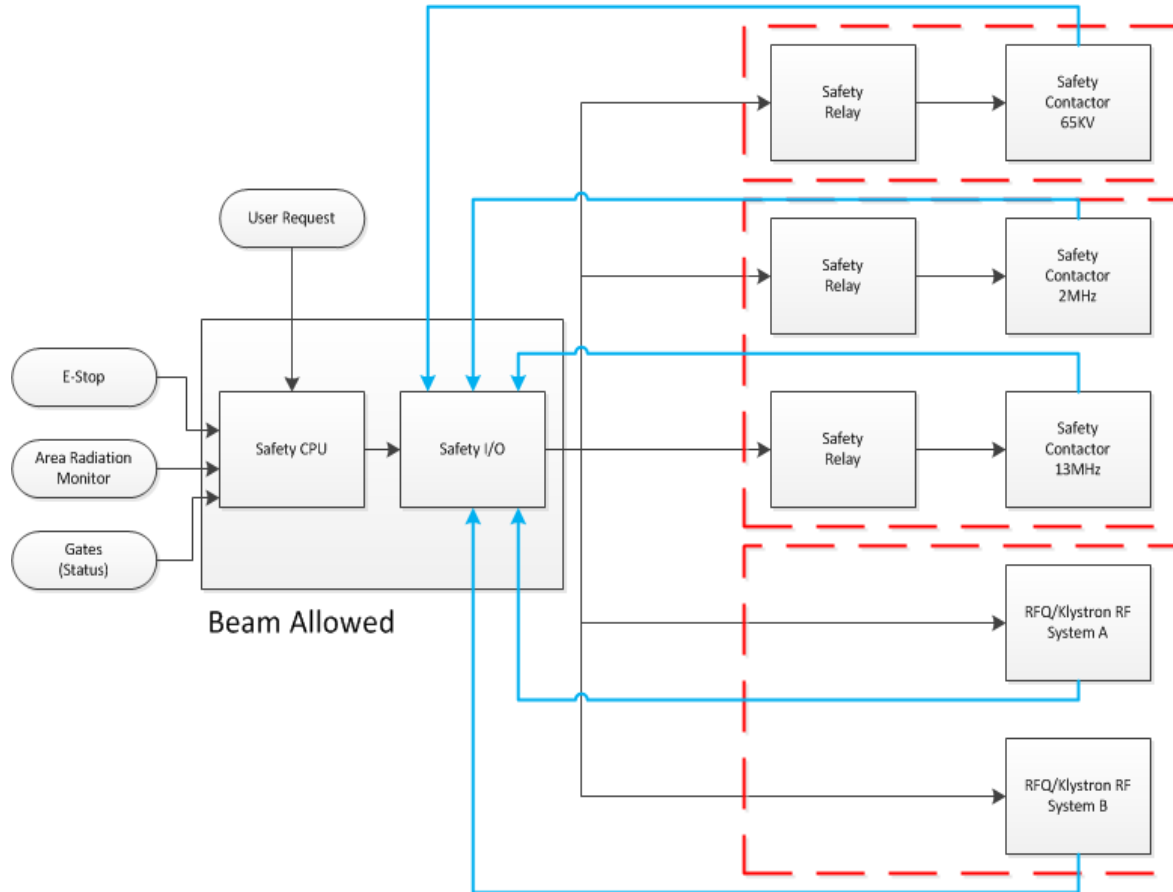


### Plasma RF Mode (Permit to operate only the 13 MHz, and 2 MHz systems)



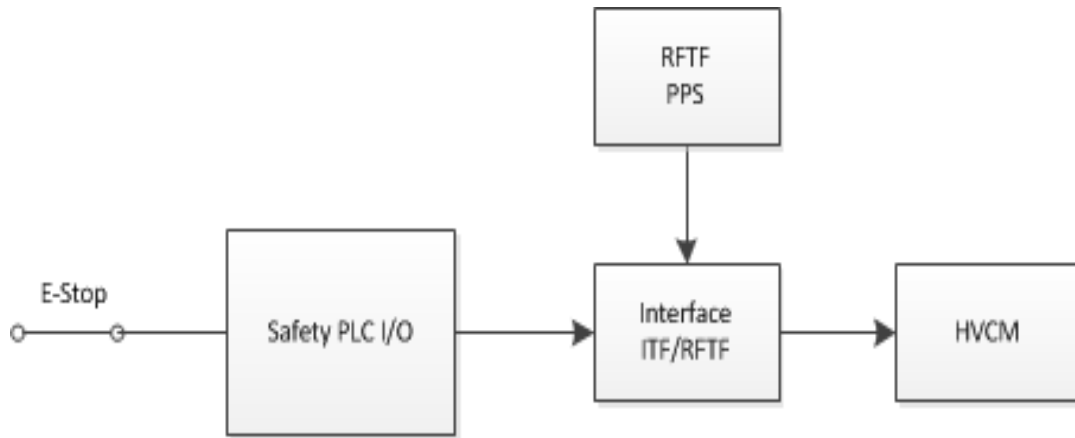


**Operate All Mode (Permit to all PPS controlled systems)**



**ESTOP in All Modes**

Each E-Stop will be wired with a Failsafe configuration  
 Each E-Stop will be wired with 1 out of 2 (1oo2) configuration



The fence/boundary for the BTF is shown in Figure 3 and means of access along with administrative controls have been described previously.

### 2.10.3 Emergency Power and/or UPS

No UPS or emergency power is available for BTF equipment.

## 2.11 OPERATIONS

### 2.11.1 Operational Assumptions

The hazard analysis presented in this document is based largely on the list of conservative assumptions provided in Table 1.

Parameter	Value	Unit
<b>Primary Beam</b>	H <sup>-</sup>	
<b>Ion source potential to ground</b>	-65	kV
<b>Ion Source RF1 plasma frequency</b>	2	MHz
<b>Ion Source RF1 power</b>	70	kW
<b>Ion Source RF2 plasma frequency</b>	13.7	MHz
<b>Ion Source RF2 power</b>	300	W
<b>Typical Instantaneous peak H<sup>-</sup> beam current to the high power beam stop</b>	50	mA
<b>Typical Maximum Average beam current to high power beam stop (50mA*1msec*60Hz = 3 mA)</b>	3	mA
<b>Typical Maximum Peak beam power to high power beam stop</b>	125	kW
<b>Typical Maximum Average beam power to high power beam stop</b>	7.5	kW
<b>Maximum pulse duration</b>	10 <sup>-3</sup>	s
<b>Maximum pulse repetition rate</b>	60	pps
<b>H<sup>-</sup> kinetic energy out of RFQ</b>	2.5	MeV
<b>RFQ RF Frequency</b>	402.5	MHz
<b>Typical RFQ Peak RF Power (No Beam)</b>	550	kW

Parameter	Value	Unit
Typical RFQ Average RF Power (Beam ON, 10% DF)	68	kW
Typical RFQ Average RF Power (No Beam, 10 % DF)	55	kW
RF HV Converter-Modulator Peak Voltage	120	kV
High power beam stop composition	TZM	
Beamline Vacuum	<10 <sup>-6</sup>	Torr
RFQ Composition	OFHC (Cu)	
MEBT Structural Composition	300 Series Stainless Steel	
Length of MEBT	11'-11"	
Dose rate associated with typical maximum beam spill (50 mA*1msec*60Hz = 3 mA) on Stainless Steel, point source [Ref. 2]	8.54	rem/hr@ 30cm
Dose rate associated with typical maximum beam spill (50 mA*1msec*60Hz = 3 mA) on Copper, point source [Ref. 2]	15.4	rem/hr @ 30cm
In-beam proton dose rate [Ref. 2]	1.9x10 <sup>15</sup>	R/hr
Dose rate associated with unshielded TZM beam stop with typical maximum beam (50 mA*1msec*60Hz = 3 mA) [Ref. 2]	330	mrem/hr @ 30cm
Max dose rate associated with shielded beam stop (underneath beam stop) with typical maximum beam (50 mA*1msec*60Hz = 3 mA) [Ref. 2]	30	mrem/hr @ 30cm
Dose rate associated with shielded beam stop (top and sides) with typical maximum beam (50 mA*1msec*60Hz = 3 mA) [Ref. 2]	0.14	mrem/hr @ 30cm
Dose rate at ~3-ft distance from typical full power point beam loss in stainless steel [Ref. 2]	769	mrem/hr @ 100cm
Maximum Restricted Area Boundary dose rate associated with typical full power beam spill on stainless steel [Ref. 2]	338	mrem/hr
MEBT to Fence Distance (nearest approach)	5'	
Chipmunk to MEBT distance (nearest approach)	2'9"	
Chipmunk to Beam Stop distance	5'8"	
Typical maximum BSM Average Current	25	μA
Typical maximum 6D Phase Space Raft Average Current	25	μA
Chipmunk 15 min rolling avg beam trip set point	5	mrem/h as specified by RSO
Chipmunk instantaneous trip set point	20	mrem/h
Chipmunk/PPS instantaneous trip response time	2	seconds
Facility Lifetime	40	years

Table 1: Key BTF Parameters

## 2.11.2 Administrative

### 2.11.2.1 BTF Organizational Chart

Personnel in the Research Accelerator Division (RAD) who have similar or identical roles in the Operation and Maintenance of the SNS Accelerator Systems will largely fill the Roles and Responsibilities for the BTF. A recent representative RAD Organizational Chart is shown below in Figure 10.

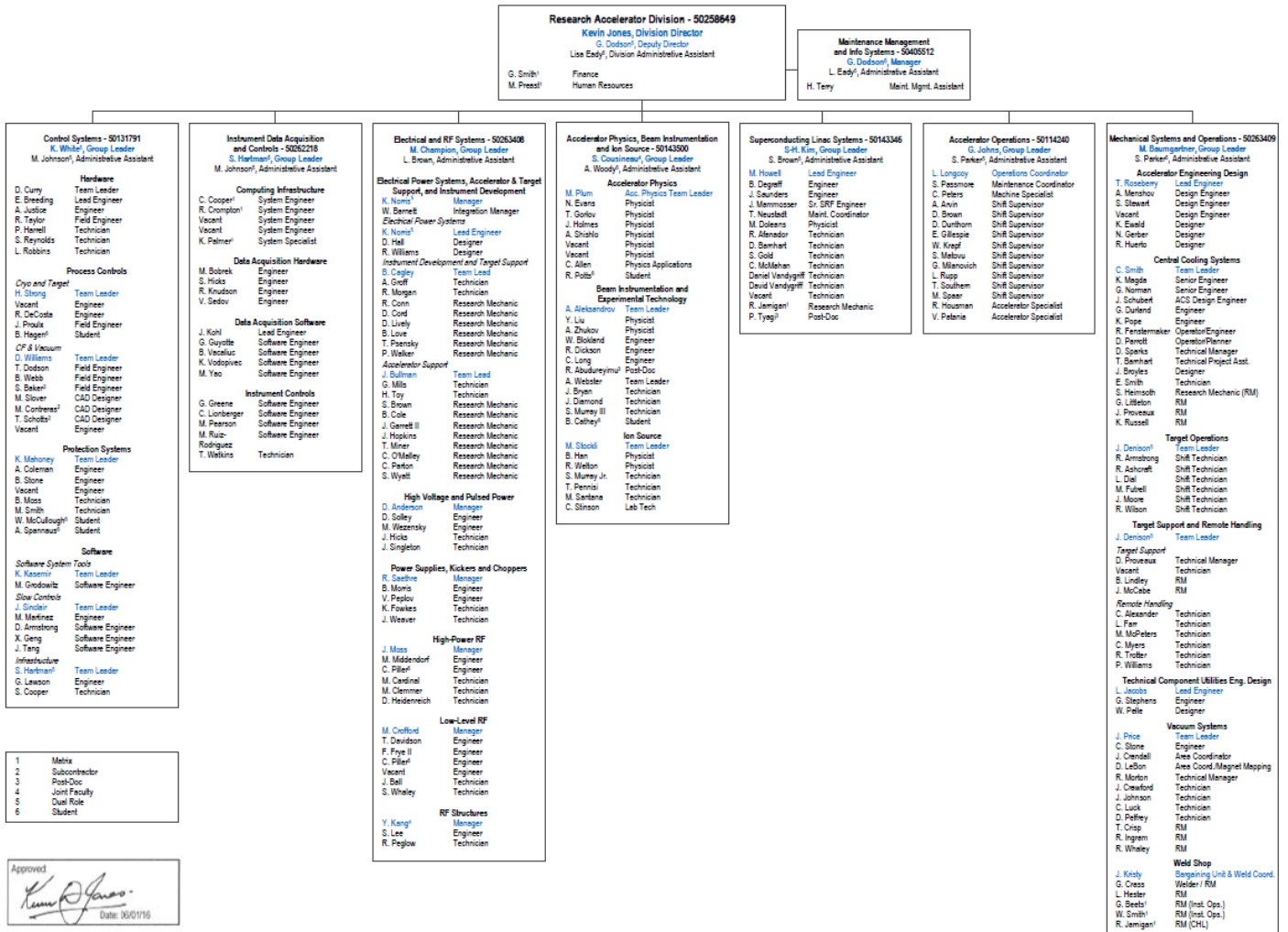


Figure 10. Representative RAD Organization Chart.

Key roles and responsibilities related to BTF operations include:

- The BTF Manager, who is appointed by the RAD Director and reports to the Accelerator Physics, Beam Instrumentation and Ion Source Group Leader.
- BTF Operators, who will initially be drawn from the Accelerator Operations group to be supplemented when appropriate by personnel from the Accelerator Physics, Beam Instrumentation and Ion Source Group.

#### **2.11.2.2 Procedures**

Operations and maintenance will be performed in accordance with approved procedures. The procedures for operations of the BTF will reside in the SNS OPM. They will be managed in accordance with OPM 1.A-2. Initial operations will be performed locally. This will require one qualified operator to be in Building 8320 near the BTF or in the Central Control Room where remote monitoring and control is available during all beam operations.

#### **2.11.2.3 Configuration Control of safety related items**

Configuration management of the credited engineering controls will be handled in accordance with the principles and process defined in SNS OPM 3.A-8.1. This same configuration control process is used for active credited controls for the SNS accelerator facility. Radiation protection is governed by SBMS requirements and is implemented in the OPM in section 2.H. This includes radiation protection, monitoring, and shielding. The Radiation Safety Committee will provide the same advisory function to management for the BTF as it does for the SNS accelerator facility. The existing RS Hold system defined in the SNS OPM will be used for administrative control of systems for the purposes of radiation protection.

### **2.12 ENVIRONMENTAL AND WASTE MANAGEMENT**

Environmental Hazards, including Waste Management at the BTF will be handled in accordance with Section 4.5 of the SNS FSAD for Proton Facilities [Ref. 6]

### **2.13 WORK CONTROL**

SNS Work Control will be used for maintenance and related activities at the BTF.

## **3. HAZARD AND ACCIDENT ANALYSIS**

### **3.1 METHODOLOGY**

Although NScD management does not proposed to operate the BTF as an accelerator, this chapter nevertheless evaluates hazards posed by operation of the BTF in a manner consistent with that prescribed by DOE O420.2C and its related Guide. Controls have been identified as necessary to ensure that hazards are safely and adequately controlled/mitigated. The principal hazard is radiological, and standard industrial

and laboratory hazards are also identified. Hazards associated with routine operations as well as accident conditions are evaluated. The approach is consistent with that presented in the SNS Safety Assessment Document for the Proton Facility (FSAD-PF) [Ref. 6]. Controls that provide an essential safety function are designated as Credited Controls. Other controls that contribute to the layers of overall safety assurance are not designated as credited controls.

Standard industrial and laboratory hazards are safely managed as part of ORNL's established institutional safety programs. ORNL implements institutional safety through the ORNL Standards Based Management System (SBMS). Promulgation of the SBMS is a key part of ORNL application of the principles of integrated safety management.

Hazard analysis includes the following steps: (1) hazard identification and screening; (2) assessment of the frequency and potential consequences of unmitigated risk; (3) identification of relevant and effective mitigation/preventive measures; and (4) assessment of mitigated risk.

In the hazard analysis, the unmitigated risk is evaluated in terms of frequency and consequence. This places it on the risk matrix, illustrated in Figure 11. The following assumptions govern the determinations of unmitigated risk:

- The unmitigated risk does not include active safety or control systems or administrative controls.
- Assigned frequencies (labeled "Probability Level" on the figure) are qualitative and are typically based on engineering judgment. For the unmitigated evaluation, the frequency is that of the unmitigated initiating event.
- Assigned consequence can be qualitative but must be conservative. Consequences are summarized in Table 2.
- The hazard analysis is not carried further if the unmitigated risk is extremely low.

Controls to mitigate risks are identified as appropriate. Risk is reevaluated assuming the mitigating features are in place that would either reduce the consequence or make the challenge less frequent. This should move the location on the risk matrix to an "acceptable" or "desirable" category.

A credited control is one determined through hazard evaluation to be essential for safe operation directly related to the protection of personnel or the environment from significant injury. Consistent with DOE Guide 420.2-1A [Ref. 10] the number of credited controls is a limited subset of the total number of controls employed for overall facility operation. Credited controls are assigned a higher degree of operational assurance than other controls.

SNS Policy [Ref. 5,6] establishes criteria for the selection of credited controls. Selection criteria relevant to credible hazards associated with the BTF are aligned with those associated with the SNS Proton Facilities [Ref. 6] and are listed below:

1. If the unmitigated radiation dose to a worker can exceed 25rem, a credited level of control shall be identified.
2. If the unmitigated radiation dose to a worker outside the building exceeds 25 rem and occurs at an estimated frequency exceeding  $10^{-4}$ /year, at least two separate credited levels of control shall be identified.

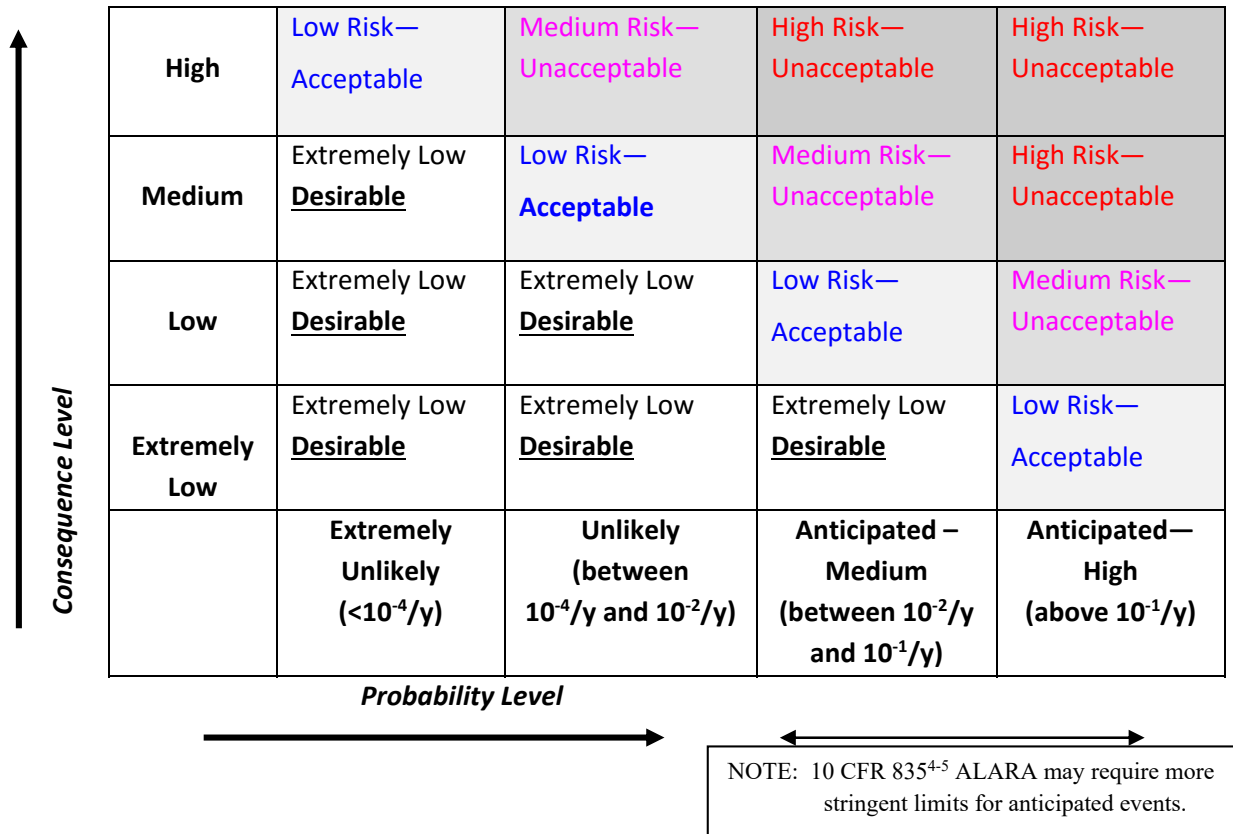


Figure 11. Risk Matrix

Definition of Consequence Levels	
Level	Definition
Extremely Low	Will not result in a significant injury or occupational illness or provide a significant impact on the environment. For occupational exposures, assumes dose below 5 rem.
Low	Minor on-site with negligible off-site impact. May cause minor injury or minor occupational illness or minor impact on the environment. For occupational exposures, assumes dose between 5 rem and 25 rem
Medium	Major impact on site or off site. May cause severe injuries or occupational illness to personnel, a single accidental death, or major damage to a facility or operation or minor impact on the environment. For occupational exposures, assumes dose between 25 rem and 100 rem.
High	Serious impact on site or off site. May cause deaths or loss of the facility/operation. Possible significant impact on the environment. For occupational exposures, assumes dose greater than 100 rem.

Table 2. Definition of Consequence Levels



As used above, the term “level of control” refers to one or more Credited Controls that are sufficient to mitigate the identified accelerator hazard. The criteria for designating credited controls are described in more detail in Section 4 of the FSAD for Neutron Facilities [Ref. 5].

### **3.2 STANDARD INDUSTRIAL HAZARDS**

Standard industrial hazards associated with the BTF are safely managed by compliance with applicable subject areas within the ORNL Standards Based Management System (SBMS). Standard industrial hazards are documented in the BTF Research Safety Summary (RSS) and managed in accordance within the corresponding ORNL SBMS topical areas.

Significant standard industrial hazards associated with BTF include:

- Electrical hazards (e.g., -70 kV Ion Source High Voltage)
- Non-ionizing radiation Radio Frequency (RF) Hazards
- Vacuum Hazards
- Mechanical hazards

### **3.3 RADIOLOGICAL HAZARDS – ROUTINE OPERATIONS**

#### **3.3.1 Prompt Radiation Hazards associated with Routine Operations**

Prompt radiation hazards associated with routine operations of the BTF may arise from:

1. X-ray leakage from the Ion Source and LEBT
2. X-ray leakage from the RFQ,
3. MEBT and diagnostic assembly beam losses, and
4. Radiation leakage from the beam stop/beam stop shielding assembly.

Each potential source is described below.

##### **3.3.1.1 Ion Source and LEBT x-rays**

The BTF Ion Source and LEBT electrodes are maintained under negative DC potential of up to – 65 kV. The dark current from the high voltage electrodes in vacuum will be a source of X-ray radiation. The stainless steel vacuum chamber has sufficiently thick walls to shield the radiation to negligible levels. However, there may be some leakage of radiation through ceramic feed-throughs. X-ray leakage at the feed-throughs will be identified through RCT radiation surveys conducted during initial operations and routine periodic surveys and mitigated by temporary local shielding under RCT control as needed. Radiation surveys conducted during initial operations of the BTF Ion Source found 1.0 mrem/Hr on contact and 0.5mrem/hr at 30 cm radiation from the Ion Source/LEBT assembly when operating at full capacity, 50 mA, 1mS and 60 Hz (ORNL Radiological Survey SNS-426566 03-10-2016 0). Experience with the SNS front-end shows that only low-level localized pencil beams of X-rays are expected and these are easily identified and

blocked by simple local shielding. Such local shielding is controlled under OPM 2.H-5.1 the SNS Radiation Shielding Policy.

### 3.3.1.2 RFQ Beam Loss and X-rays

Significant radiation fields are not anticipated for RFQ operations. Radiation fields may arise from beam loss. The expected transmission of the RFQ is ~85% and the losses (~15%) occur in the low energy end of the RFQ where the beam is bunched and synchronized to the RF frequency. The beam energy in the low energy sections of the RFQ is well below the (p,n) threshold for protons incident on natural copper, thus neutron production is not possible in the low energy section.

The RFQ generates X-rays as an incidental byproduct of the RF electric fields used to focus and accelerate the beam. The dark current arising from field emission of electrons from the high voltage electrodes in vacuum may be a source of X-ray radiation. The structural copper walls of the RFQ shield the emitted X-ray radiation resulting in very low external radiation levels. Radiological surveys conducted during commissioning, testing, and conditioning of the BTF RI RFQ detected some X-ray radiation. During one early test (July 29, 2014, Survey SNS-384030) up to 40 mrem/h on contact, 5 mrem/h at 30 cm was measured at aluminum blank-off flanges over vacuum pump penetrations that were not shielded with the full copper structural thickness. These measurements were made with RF operating at 550 kW (nominal peak power) and a duty factor of 30 Hz, 600  $\mu$ s, which is 30% of, the nominal duty factor of the RFQ. These flanges were replaced when the pumps intended for those locations were installed, and no measurable radiation was found during the next several tests. However, on September 15, 2015 the RFQ was operated at its nominal power and duty cycle of 550 kW, 60 Hz, 1 ms (33k W of average power) and dose rates up to about 1 mrem/hr were measured at a distance of 30 cm (Survey SNS-413321). Consequently, a dose rate of ~ 1mrem/hr at 30 cm is a considered an approximate representative dose rate for well-conditioned operation of the RI RFQ structure. The nearest unrestricted area to the RFQ is a distance of about 10 feet to the fence. Dose rates at the fence can be approximated as:

$$1 \frac{mrem}{hr} \cdot \frac{(1ft)^2}{(10ft)^2} = 0.01 mrem/hr$$

During beam operations the fenced area surrounding the BTF will be appropriately posted for the expected operating conditions.

### 3.3.1.3 MEBT Beam Losses

Beam losses may occur in the MEBT during routine operation even though the MEBT is designed to transport beam from the RFQ exit to the beam stop without significant loss. Such losses are normally a very small fraction of the transported beam and typically occur as distributed losses over some length of the MEBT structure, rather than as point losses. Routine operation of the SNS front end has demonstrated that beam losses are maintained well below 0.1% in the MEBT. Radiation sensitive Beam Loss Monitor (BLM) ion chambers are positioned near the MEBT to provide non-safety related, non-credited defense-in-depth radiation field measurements that truncate beam operation through the MPS.

Beam losses in the MEBT can produce neutrons because the H<sup>-</sup> beam energy of 2.5 MeV is above the threshold for neutron production in the MEBT stainless steel structure. Gamma radiation is also generated but the neutron component strongly dominates potential dose rates [Ref. 2].

The magnitude of routine beam losses can be estimated from the dose fields calculated for a point loss of the full beam power. A dose rate of 8.54 rem/hr at 30 cm is predicted from a point loss of the full beam at full power (7.5 kW, 3mA at 2.5 MeV) in stainless steel [Ref. 2]. This value represents the bounding unmitigated dose rate arising from a beam spill in the stainless steel structure of the MEBT. Operational beam losses would only involve a fractional beam loss and would be distributed rather than occurring at a discrete point; therefore, expected dose rates would be significantly lower ( $\leq 10^{-3}$  fractional loss) than for a full power point loss.

The bounding dose rate associated with a beam loss of 0.1 % of full power can be estimated by assuming a point beam loss in the MEBT. The bounding beam loss dose rate 30 cm from the MEBT based on over 10 years of SNS front end operating experience for 0.1 % of a full power beam loss is 8.54 mrem/hr (0.1% x 8.54 rem/hr at 30 cm).

Bounding dose rates for routine beam losses in the MEBT at the BTF fence line can be inferred assuming a point loss  $\sim 1/r^2$  dependence. The nearest distance between the MEBT and fence-line is about 5 feet. The expected dose rate at 5 feet from a point  $10^{-3}$  fractional beam loss would be about:

$$8.54 \frac{mrem}{hr} \cdot \frac{(1ft)^2}{(5ft)^2} = 0.34 mrem/hr$$

Direct exposure to the H<sup>-</sup> ion beam is inherently precluded because H<sup>-</sup> ions interact strongly with matter through Coulomb interactions. The beam can only be transported in a high vacuum of  $\sim 10^{-7}$  Torr. The range of the 2.5 MeV H<sup>-</sup> ion is very short and cannot penetrate structures required to maintain the vacuum required to transport beam. For example, the maximum stopping length of 2.5 MeV protons in steel, copper or aluminum is  $\sim 26 \mu\text{m}$  [Ref. 12]. Beam pipe structures designed to hold the necessary vacuum to support beam transport are significantly thicker and therefore inherently stop the H<sup>-</sup> beam. Neutron and gamma radiation produced when the beam is stopped in such materials can readily penetrate materials and therefore is of primary concern, as discussed above.

#### **3.3.1.4 Leakage from Beam Stop/Beam Stop Shielding Assembly**

High power beam may be directed into the high power beam stop assembly located at the end of the MEBT as described in Section 2.8. The incident H<sup>-</sup> beam creates penetrating neutron and gamma radiation when it strikes the beam stop material. Unmitigated dose fields associated with stopping maximum beam power (7.5 kW, 3 mA average current, 2.5 MeV) into the beam stop are predicted to be  $\sim 325$  mrem/hr at 30 cm from the beam stop surface [Ref. 2]. A supplemental shield was designed and installed to reduce dose fields around the beam stop,.

The rear and sides of the beam stop are accessible to personnel not associated with the BTF and is not accessed controlled (see figure 2). Calculated dose rates for the maximum beam power with the beam stop supplemental shielding installed are expected to be less than 0.2 mrem/hr at a distance of 30 cm with the exception of the floor area directly beneath the beam stop, which is expected to be as high as 30 mrem/hr [Ref. 2]. A turbo-molecular vacuum pump, shown in Figure 8, located directly below the beam stop complicates shielding beneath the beam stop. A cage-type steel mesh fencing boundary has been installed around the bottom of the beam stop shielding to preclude personnel access to the area beneath the beam stop from outside the fenced area. The mesh cage underneath the beam stop is under configuration control as an installed item and requires a special tool for removal. Access to this cage is administratively controlled and requires a Radiological Work Permit.

### **3.3.1.5 Dose from typical beam loss in the BSM Beam Line**

The expected dose for typical beam in the MEBT and BSM beam line is directly scalable from the estimates for the MEBT beam line under maximum beam loss conditions. For physics applications the duty factor is controlled as described in Section 2.10.1, and the maximum current in the MEBT and BSM beam lines is 0.83% of the bounding maximum current in the MEBT. Therefore the bounding dose rate at 30 cm for full point loss of the physics beam is scaled by this amount to yield  $0.0083 \times 8.54$  rem/hr or 71 mrem/hr. During normal operation, as discussed in Section 3.3.1.3, beam losses are typically  $\leq 0.1\%$  of the maximum available beam, so the operational dose rate arising from normal beam loss of the physics beam would be  $\leq 0.071$  mrem/hr.

### **3.3.1.6 Dose from the BSM Carbon Beam Stop**

The BSM beam stop is made from carbon, which is very suitable for low beam power physics operation. The threshold for neutron production from (p,n) reactions on Carbon is well above the maximum RFQ energy of 2.5 MeV and the gamma production cross sections are low. The predicted radiation from the typical physics operation beam current of  $25\mu\text{A}$  incident on a carbon is 5 mrem/hr at 30 cm [Ref. 9]. The BSM beam stop consequently requires no additional shielding.

### **3.3.1.7 Summary of Prompt Radiation Hazards Associated with Routine Operations**

The contributions from the sources identified above can be summed to determine bounding dose rate estimates for routine operations at full power (7.5 kW, 3 mA average at 2.5 MeV), but summing the dose contributions is somewhat unrealistic because it assumes an individual is in multiple locations at the same time. Table 2 below summarizes dose fields associated with nominal routine full power operations for the worker at a distance of 30 cm from the radiation source within the restricted area defined by the fence boundary in Figure 3, and for individuals that might be standing outside the restricted area at the fence line.

As shown in the table below, the maximum 30-cm dose rates within the restricted area during routine full power or BSM operation are expected to be  $\sim 9$  mrem/hr and the maximum fence-line boundary dose rates are expected to be  $\sim 2$  mrem/hr. Both the restricted and unrestricted areas will be surveyed periodically and posted in accordance with operational surveys.

Source	Restricted Area Dose Rate @ 30 cm	Unrestricted Area Dose Rate @ Boundary
RFQ X-ray leakage	~ 1 mrem/hr	~ 0.01 mrem/hr
Routine MEBT beam loss (full beam power)	~ 8 mrem/hr	~ 0.3 mrem/hr
Routine BSM System (low beam power)	~ .08 mrem/hr**	~ 0.003 mrem/hr
Full Power Beam Stop/Beam Stop Shield leakage*	~ 0.2 mrem/hr	~ 0.2 mrem/hr
BSM Beam Stop	8 mrem/hr	~ 2 mrem/hr
<b>Totals – Full Power</b>	<b>~9.2 mrem/hr</b>	<b>~0.5 mrem/hr</b>
<b>Totals – BSM</b>	<b>~8.0 mrem/hr</b>	<b>~2.0 mrem/hr</b>

\* Dose rates on the floor underneath the shielding are calculated to be about 30 mrem/hr.

\*\* If the BSM system is being operated at low power, the MEBT dose rate in the Restricted Area is reduced from 8 mrem/hr to 0.08 mrem/hr and the dose in the Unrestricted area is <0.01 mrem/hr .

**Table 3. Area Dose Rate Summary For Various Conditions**

Dose rates of this magnitude do not pose an acute health risk and are safely managed under the provision of the ORNL Radiological Protection Program to ensure compliance with 10 CFR 835 and to ensure personnel doses are maintained ALARA. Controls required by SBMS for restricted areas with dose fields of this magnitude typically include items such as:

- Radiation Area postings
- RWP required for entry into radiation areas
- Self-alarming personal dosimeters
- Routine radiological surveys

### 3.3.2 Residual Radiation Hazards and Radionuclide Inventory

Proton beam bombardment will induce residual radioactivity in the TZM beam stop. The majority of the radionuclide inventory associated with BTF will be in the TZM beam stop. The predicted end of life radionuclide inventory has been evaluated by the SNS Neutronics Group [Ref. 11]. As described in Section 2, operations at full power are expected to be rare, with the majority of operations taking place with power on the order of 1/120<sup>th</sup> of full power (~25  $\mu$ A average). Activation calculations [Ref. 8] assumed full power operation (7.5 kW, 3 mA average at 2.5 MeV) for a total of 100 hours spread over 8 years (25 hour campaigns at full power with 730 days between campaigns). With a final 1-day cool down period following the final beam campaign, the beam stop isotope inventory would total only 19  $\mu$ Ci. Conservatively estimating the associated dose rate using the “6CE” relationship [Ref. 11] yields 0.114  $\mu$ rem/hr at a distance of 30 cm.

The SNS Neutronics Group also performed an analysis of beam stop activation using assumptions for a bounding operational history. Operations were assumed to be continuous throughout the standard work year, giving 2000 operational hours per year. 90% of these operations were assumed to occur at 1/120th of full power and the remaining 10% at full power. To simplify calculations, this was conservatively considered equivalent to 290 hours of continuous full power operation per year for 10 years, yielding a total operational history of 2900 effective full power hours. After a 1-day cool down, the estimated beam stop inventory would be 334  $\mu\text{Ci}$ , which can be similarly estimated as above to produce a 2 mrem/hr field at 30 cm. Additionally, the dose rates estimated represent unshielded conditions, but the beam stop is housed within a substantial shield to protect against prompt radiation from beam operation. Thus radiation from the beam stop would only be measurable if the beam stop is dismantled. The levels of activity anticipated do not present a direct radiation hazard to personnel and safe handling would be well within the scope of the ORNL SBMS radiation protection program.

### **3.4 RADIOLOGICAL HAZARD - ACCIDENT ANALYSIS**

#### **3.4.1 Beam Spill Accidents**

##### **3.4.1.1 Unmitigated Beam Spill Event**

This section evaluates conservative unmitigated beam spill events to determine the need for a Credited Engineered Control to mitigate the effects of uncontrolled beam spill.

The underpinning documents that govern the possible consequences of beam spill events are References 2 and 9 and all subsequent discussions are founded on these two documents. During the preparation of this document, and subsequent to the preparation and approval of Reference 9, a scaling error was discovered in Revision 0 of Reference 2. This error resulted in underestimate of the dose rates for a full power beam spill (2.5 MeV, 3 ma, 7.5 kW). This incorrect value was used to develop the dose rate estimates in Reference 9. Reference 2 was corrected and reissued as Revision 1, and the revised dose rate estimates in Revision 1 are used in this document. Reference 9 has not been reissued since this error was identified, and so dose values in this analysis that are derived from Reference 9 have been scaled for consistency where applicable.

As described in Section 3.3, the BTF is designed to transport beam through the MEBT with minimal beam loss. Beam losses (also referred to as beam spills) that do occur are typically distributed over some distance and are controlled by the BTF control system as described in Section 2.10. Beam losses within the structure of the MEBT create neutron and gamma radiation fields. A point beam loss, where all of the beam energy is deposited at a discrete point in the MEBT structure, would create peak radiation fields given the very short stopping length of the 2.5 MeV  $\text{H}^-$  beam.

The unmitigated beam spill event evaluated here very conservatively assumes that a full power point beam loss persists for 8 hours with staff concurrently occupying certain areas near the beam spill. Several features would preclude such an event:

- Beam will rarely be run at full 3 mA average current (7.5 kW power). Beam studies will normally be conducted at about 1/120<sup>th</sup> or less of this power (maximum of 62.5 W power).
- The postulated event would have to be coincident with complete failure of the defense-in-depth beam loss monitors and the machine protection system to terminate the beam.
- Such a significant beam spill (7.5 kW) would cause localized heating and subsequent outgassing or cause a structural failure from overheating that would spoil the vacuum and prevent beam transport. A 2.5 MeV negative hydrogen ion or proton beam cannot propagate in air.
- Operator procedures and practices make it unlikely that an operator could allow such an extreme condition to persist for hours without intervention.

The probability of operation with a full or near full beam loss persisting for hours is highly unlikely. In the SNS front end no significant beam loss event has occurred in over 10 years of operational experience. Regardless, a persistent full power beam loss is assumed in this analysis. The event is conservatively considered to occur perhaps once every 10 to 100 years (*Anticipated-Medium* event as defined in Section 3.1).

A detailed analysis of the unmitigated beam spill accident is provided in Reference 9. Note: the analysis presented in Reference 9 lists 13.7 rem/hr as the exposure at 30 cm for an unmitigated beam spill accident with a 3mA beam in Cu. The actual exposure is 15.4 rem/hr. A summary of the analysis from Reference 9 is provided below but the exposures from beam spill have been corrected by the appropriate ratio. Additionally, the 90° dipole bending magnet return yoke is 4 cm of carbon steel. In a worst-case geometry, this steel attenuates the radiation from a spill accident by 18% [Ref. 13]. As in the previous case, exposures from beam spill have been corrected by the appropriate ratio in section 3.4.1.2 Mitigated Beam Spill Event, Scenarios 1 and 2.

A full power beam spill into copper is assumed which produces a field of 15.4 rem/hr at 30 cm from the spill [Ref. 2]. This condition is assumed to persist for 8 hours with no mitigating response. Even though the MEBT is constructed primarily of stainless steel, copper was assumed as bounding because beam interaction with copper produces a dose rate 1.8 times greater than stainless steel [Ref. 2] and copper is a material commonly used in accelerators. Two exposures are evaluated to address personnel working either within the restricted fenced area or personnel located outside of the fenced area (See Figure 3). This distinction is beneficial since personnel outside of the restricted area may not be familiar with work control requirements for the BTF.

Although there are no time or location restrictions for personnel inside the restricted area, the times presented are considered bounding for potential operational activities. Normally, 1 ft dose rates are assessed when evaluating the nearest approach for individuals assumed to be located directly adjacent at a piece of equipment. The design of the MEBT is such that the structure extends about 12 inches away from the MEBT beam path. Normally, the nearest approach for personnel working directly on or adjacent to the MEBT can be assumed to be 1 ft away from the structure, which would be 2 ft away from the MEBT beam path where a beam spill could occur. However, in certain locations a worker could feasibly position themselves within 1 ft of the MEBT, though it is unlikely that they would occupy that position for extended

periods. For the purposes of this analysis, it is assumed that the worker is within 1 ft of the MEBT for 1 hour. The exposure for a full power (7.5 kW, 2.5 MeV, 3 mA average current) beam spill calculated in Reference 9 is 15.4 rem/Hr at 1 ft. (30 cm).

The fence line surrounding the BTF defines the closest approach for personnel in the unrestricted area relative to the MEBT beam path. The nearest fence line to MEBT distance was measured at 4 ft 11 in [Ref. 9] and is the distance between the potential beam spill location near the end of the MEBT and the fence line that just misses the beam stop structure. This location is chosen since it would provide the highest dose rate at the fence. Using a simple  $1/r^2$  assumption, the dose rate for a full power point beam loss (in copper) at the fence line would be  $\sim 616$  mrem/hr. Since the area north of the fence line (the fence section with the beam stop) is a building thoroughfare, it is unlikely that an individual would remain in this unrestricted area for an extended time. Nevertheless, it is conservatively assumed that personnel in this area are exposed to the beam spill that occurs at the nearest MEBT to fence line distance for 8 hours. The results of this unmitigated accident scenario are presented in Table 4 below.

Staff working in Restricted Area for 1 hour	Personnel working in Unrestricted Area for 8 hours
15.4 rem	4.9 rem

**Table 4. Unmitigated Beam Spill Dose Evaluation**

The maximum average power assumed in the analysis above was 7.5 kW (2.5 MeV and 3 mA average current) based on a maximum peak current from the RFQ of 50 mA. As shown in Section 2.6, the theoretical maximum possible peak output current from the RFQ is about 70 mA that could produce an average maximum power of 4.2 mA. Dose rates associated with an increase in maximum average power scale linearly with power. Doses for a 1 hour exposure at 1 ft. (30 cm), associated with a maximum average power of 4.2 mA in the unrestricted area would be  $15.4 \text{ rem} \times (4.2 \text{ mA}/3 \text{ mA}) = 21.5 \text{ rem}$ . As discussed in Section 4, an ASE maximum average power limit of 5.1 mA has been established, well above what the machine is capable of producing. Unmitigated doses associated with a maximum average beam power of 5.1 mA would be  $15.4 \text{ rem} \times (5.1 \text{ mA}/3 \text{ mA}) = 26.1 \text{ rem}$  [9]. Unmitigated doses in the unrestricted area have also been linearly scaled with the results shown in Table 5 below.

Postulated unmitigated consequences approach or exceed the 25 rem threshold described in Section 3.1, which triggers categorization as a “Medium” consequence and the necessity to designate of a Credited Control to mitigate the consequences of such an event.



Maximum Average Beam Power (mA)	Staff Working In Restricted Area, 1 ft. (30cm) for 1 hour (rem)	Personnel working for 8 hours at the fence in the Unrestricted Area (rem)
3.0	15.4	4.9
4.2	21.5	6.9
5.1	26.1	8.3

**Table 5. Unmitigated Doses, Associated with Various Maximum Average Beam Power Assumptions**

The Credited Engineered Control identified for this accident scenario is a PPS interlocked radiation monitor (Chipmunk) that terminates beam upon detection of elevated dose rates. The credited safety function of the PPS will be to terminate beam upon elevated radiation fields at the PPS Chipmunk as follows:

- Terminate beam within 2 seconds (“prompt”) of dose rates greater than 20 mrem/hr at the Chipmunk
- Terminate beam upon a 15 min rolling average dose rate greater than 5 mrem/hr at the Chipmunk

The PPS additionally provides features such as interlocking gates, E-stop button, and audio-visual alarms that are not credited.

### 3.4.1.2 Mitigated Beam Spill Event

Personnel doses associated with the beam spill event as mitigated by the credited function of the PPS are evaluated below and are based on the analysis provided in Reference 9

Mitigated doses were evaluated for three scenarios:

- Scenario 1: Beam loss creates radiation levels at the Chipmunk that are just below the 15-minute rolling average PPS beam trip set point of 5 mrem/hr. For this scenario, the same exposure times and personnel-to-beam spill distances are assumed as for the unmitigated case discussed above.
- Scenario 2: Beam loss creates radiation levels above the 5 mrem/hr rolling average set point but just below the prompt PPS beam trip set point of 20 mrem/hr. For this scenario the individual in the restricted area is assumed to be located at a distance of 2 feet from the spill. The individual in the unrestricted area is assumed to at the same location as for the unmitigated beam spill discussed above.
- Scenario 3: Beam loss creates radiation levels above the prompt PPS beam trip set point of 20 mrem/hr. For this scenario, the maximum dose field possible is assumed to occur. Because of the short 2-second duration of the accident the individual in the restricted area is assumed to be located at a distance of 1 foot from the spill. The individual in the unrestricted area is assumed to at the same location as for the unmitigated beam spill discussed above.

Because an individual may be closer to the location of a postulated MEBT beam spill than the Chipmunk, workers may be exposed to higher dose fields than those at the Chipmunk. The extreme case would be if the point beam spill occurred near the entrance of the MEBT (at that RFQ-MEBT interface) which is about 8 feet 7 inches line-of-sight distance [Ref. 9] from the Chipmunk detector. An individual standing adjacent to the MEBT at the location of such a beam spill could be exposed to radiation levels on the order of 70 times higher than that at the Chipmunk assuming the  $1/r^2$  radiation field dependence for a point loss.

Worst-case beam spill and personnel locations were evaluated in Reference 9. The results are summarized in Table 6 below.

Accident Scenario	Staff Working in Restricted Area (mrem)	Personnel in Unrestricted Area (mrem)
Scenario 1	710	63
Scenario 2	109	7.8
Scenario 3	8.5	0.34

**Table 6. Mitigated Beam Spill Doses**

As shown in Table 6, the highest mitigated doses are associated with Scenario 1, a beam spill that creates dose fields at the chipmunk that are just under the beam trip set point of 5 mrem/hr. Reference 9 further evaluated doses assuming chipmunk to beam spill distances as large as 10 feet that lead to a potential dose in the restricted area of 964 mrem.

A sensitivity analysis was performed to assess the impacts of variations on maximum beam power and chipmunk and receptor locations. The results (Ref. 9) are summarized below.

**Increase in Maximum Beam Power Assumption**

As discussed in Section 3.4.1.1 above, dose rate is proportional to the maximum average beam power and the maximum average beam power the machine is thought to be capable of producing is 3 mA. However, Section 2.7 showed a theoretical maximum of 4.2 mA based on the RFQ’s theoretical ability to transmit beam. Further, a maximum average beam power limit of 5.1 mA has been established that is well above what the RFQ can possibly transmit. Unmitigated doses associated with the higher maximum average beam powers are presented in Section 3.4.1.1 above.

Mitigated doses associated with the maximum average power of 5.1 mA are evaluated in Reference 9. The only mitigated dose scenario impacted by assuming higher power levels is Scenario 3, the maximum beam spill event, because the peak dose rate is proportional to power. Mitigated doses associated with Scenarios 1 and 2 would be unaffected. The peak dose rate associated with a full power point beam spill in copper would be  $15.4 \text{ rem/hr} \times (5.1 \text{ mA}/3\text{mA}) = 26.2 \text{ rem/hr}$ . Such a beam spill would exceed the 20 mrem/hr prompt beam trip set point and shut the beam down within 2 seconds leading to a dose for individual in the restricted area of 14.5 mrem and 0.58 mrem for the individual in the unrestricted area.

**Increased Chipmunk-to-Beam Spill Distance (e.g. relocation of Chipmunk)**

The analysis above is based on the measured line-of-sight Chipmunk to MEBT/RFQ interface distance of 8 feet 7 inches [Ref. 9], assumed to represent the maximum possible point beam spill to Chipmunk distance. Reference 9 also evaluates a beam spill to Chipmunk distance of 10 feet. Again, the maximum consequence is found with Scenario 1 where dose fields are just below the PPS set point of 5 mrem/hr. Increasing the beam spill to Chipmunk distance reduces the dose rate at the Chipmunk for a given beam spill leading to a maximum dose to the worker in the restricted area of 964 mrem.

#### **Increase in time spent very near beam spill**

Reference 9 provides an analysis of mitigated dose associated with increasing the time spent at a distance of 1 foot from one hour to two hours. The maximum mitigated dose is associated with Scenario 1 where dose fields are just below the PPS set point of 5 mrem/hr. The resulting mitigated dose to the individual in the restricted area was calculated to be 872 mrem [9].

#### **3.4.1.3 Beam Spill Event Summary**

The beam spill event is summarized in the qualitative risk assessment shown in Table 7 with the standard format used in Reference 6. As identified in Section 3.4.1.1, the unmitigated risk consequences could approach or exceed 25 rem (“medium” consequence) and therefore a credited control is required. The PPS mitigation is sufficient to reduce the consequence should such an event occur, to the “extremely low” category (i.e. less than 5 rem).

**Qualitative Risk Assessment for  
Prompt Radiation inside the Proton Beam Enclosures**

FACILITY NAME: Beam Test Facility

NUMBER: BTF-1

SYSTEM: Beam Test Facility

SUB-SYSTEM: Not Applicable

HAZARD: Prompt Radiation (Proton Beam) Inside Beam Enclosures

Event	Person inside enclosure during inadvertent full or near full power beam loss for extended period of time.
Possible Consequences, Hazards	Personal injury due to prompt radiation associated with the proton beam. Worker dose could potentially approach or exceed 25 rem.
Potential Initiators	Loss of beam control while persons working in vicinity, loss of configuration control.

**Risk Assessment Prior to Mitigation**

Note: Refer to Figure 4.1.1-1 for an explanation of consequence, frequency, and risk levels. "Low" and "Extremely Low" risk levels are considered acceptable.

Consequence:	<input type="checkbox"/> High	<input checked="" type="checkbox"/> Medium	<input type="checkbox"/> Low	<input type="checkbox"/> Extremely low
Probability w/o mitigation:	<input type="checkbox"/> Anticipated High	<input checked="" type="checkbox"/> Anticipated Medium	<input type="checkbox"/> Unlikely	<input type="checkbox"/> Extremely Unlikely
Risk Category:	<input type="checkbox"/> High Risk	<input checked="" type="checkbox"/> <b>Medium</b>	<input type="checkbox"/> Low Risk	<input type="checkbox"/> Extremely Low

Does the hazard require a Credited Control? Y/N Yes

Hazard Mitigation	<ol style="list-style-type: none"> <li>1. PPS automatic beam cut off on excessive radiation detected by the interlocked Chipmunk Radiation Detector (CREDITED).</li> <li>2. Accelerator operations procedures.</li> <li>3. RWP required for entry ensure personnel are wearing alarming self reading dosimeters when accessing the enclosure with beam on.</li> <li>4. BTF control system designed to minimize losses, interlocked with Beam Loss Monitor radiation detectors designed to terminate beam on excessive radiation levels.</li> </ol>
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**Risk Assessment Following Mitigation**

Consequence	<input type="checkbox"/> High	<input type="checkbox"/> Medium	<input type="checkbox"/> Low	<input checked="" type="checkbox"/> <b>Extremely low</b>
Probability	<input type="checkbox"/> Anticipated High	<input type="checkbox"/> Anticipated Medium	<input checked="" type="checkbox"/> <b>Unlikely</b>	<input type="checkbox"/> Extremely Unlikely
Risk Category	<input type="checkbox"/> High Risk	<input type="checkbox"/> Medium	<input type="checkbox"/> Low Risk	<input checked="" type="checkbox"/> <b>Extremely Low</b>

**Table 7. Risk Assessment for BTF Beam Spills**

### **3.4.2 Airborne Radioactive Material Events**

The amount of residual radioactivity associated with the BTF is small and is concentrated in the TZM beam stop. Neutronics analysis [Ref. 11] shows the expected activity at 1 minute following a 25 hour full power run is  $\sim 62 \mu\text{Ci}$ . Should some mechanism be identified such that a fraction could credibly become airborne, the large building volume would dilute it quickly. Two potential mechanisms are evaluated that might allow some of the beam stop material to potentially become airborne: a loss of beam stop cooling that leads to overheating of the beam stop during beam operations and a facility fire

#### **Beam Stop Cooling Loss**

The Beam Stop is cooled by water. The Beam Stop cooling flow meter provides an interlock to the MPS that will shut off the beam if there is insufficient water flow. However, the water flow MPS interlock is not credited. In case of loss of cooling water flow during operations at high beam power, the absorbing surface of the plates will heat up and start outgassing. Most likely, the outgassing would sufficiently spoil the high vacuum and terminate the beam without breaching the beam tube barrier to air. In this case, any radioactive material released due to overheating would be contained within the MEBT beam tube. Should the beam continue to operate, the beam stop material being heated could melt or otherwise fail leading to a breach of the beam tube barrier to air with the corresponding loss of vacuum that would terminate the beam. This scenario would result in the immediate loss of vacuum in all BTF vacuum enclosure, including the MEBT, RFQ and Ion Source. This in turn will cause immediate shutdown of the ion source and the RFQ. Because the beam tube is under high vacuum, any gases associated with the overheating would be sucked into the structure at the instant of a breach to air failure where they would cool and condense. A loss of cooling water flow event is not deemed a credible mechanism for releasing a significant portion of the activated beam stop material.

#### **Building Fire**

The supplemental shielding assembly provides protection of the inner beam stop from heat that might be associated with a building fire. There is an automatic fire suppression system in the building. The building is protected by a standard NFPA-13 sprinkler system that would act to minimize the chances of a significant fire that might impact the beam stop. A building fire is not deemed a credible mechanism for vaporizing a significant portion of the activated beam stop material.

### **3.4.3 Offsite and Environmental Hazards**

The worst-case accident associated with the BTF is the beam spill accident evaluated above. The associated dose fields are too low to create a significant hazard outside of the building. Because the ORNL site boundary is far removed, direct radiation hazards at the site boundary would not be detectable, even in the worst-case event. Residual radioactivity associated with the BTF is concentrated in the beam stop, is not readily dispersible, and is below levels that could potentially impact the environment or offsite personnel.

### **3.5 Loss of Configuration Control**

#### **Loss of Configuration Control – Beam Stop Shielding**

This accident scenario postulates a loss of beam stop shielding configuration control. It is postulated that the BTF is operated at full power with the beam stop shielding out of place while the beam impinges on the unshielded beam stop, which is an integral part of the MEBT vacuum system. As described in Section 3.2.1 above, dose fields associated with running maximum beam power (3 mA average) into the beam stop without the shielding in place are predicted to be about 325 mrem/hr at 30 cm from the beam stop surface [2]. Potential unmitigated personnel doses associated with spending time in close proximity could be simply bounded by assuming an individual spends a full 8 hours at a distance of 1 ft. from the unshielded beam stop resulting in a dose on the order of  $8 \text{ hr} \times 325 \text{ mrem/hr} = 2,600 \text{ mrem}$ . Such doses do not rise to the level of requiring a credited control but would raise ALARA concerns and highlight the importance of maintaining configuration control of the supplemental beam stop shielding. In this scenario, both the PPS and the MPS would turn the beam off as described earlier, mitigating the consequences of the accident scenario.

The configuration of the beam stop shielding will be controlled under the SNS Radiation Shielding Policy and Procedures, OPM 2.H-7. Should the Beam Stop Shielding need to be moved, an appropriate Radiation Safety Hold will be applied to prevent operation with beam.

#### **Loss of Configuration Control – System Hardware**

Loss of configuration control of system hardware can impact radiological safety. The configuration of the BTF will be configuration controlled as described in Section 2.10 consistent with SNS configuration control policies.

### **3.6 Hazard and Accident Analysis Summary**

The only significant accelerator specific hazards identified are the direct radiation hazards potentially created by a beam spill. Potential personnel doses for an unmitigated beam spill scale with power with the highest power evaluated being equal to a maximum average beam current of 5.1 mA at 2.5 MeV (established well above the machine capability). The PPS function of terminating beam upon elevated radiation levels at the interlocked chipmunk detector have been credited and determined to safely mitigate any beam spill accident.

## **4. CREDITED CONTROLS AND THE BTF OPERATING ENVELOPE**

### **4.1 INTRODUCTION**

This section explains physical and administrative bounding conditions and controls to ensure safe operations of the BTF, including both engineered and administrative controls.

#### **4.1.1 Safety Basis**

The hazard analyses in Chapter 3 have demonstrated for the BTF prompt radiation hazard that the following systems should be designated as Credited Engineered Controls:

- The PPS including chipmunk radiation detectors. These systems are essential to ensure safety of workers in and near the BTF.

#### **4.1.2 BTF Operations Envelope**

Strict adherence to the approved bounding conditions of BTF operation is expected during all commissioning and operations activities. Similarly to Safety and Operating envelopes for accelerator Facilities, it may be advisable to establish a BTF "operations envelope" (OE). Other limitations, controls, and restrictions not directly based on the Safety Analysis could be addressed in the OE. The parameters in the BTF OE represent the normal operating parameters. Operation outside the parameters of the OE is permissible with appropriate authorization. The SNS OPM procedures support the concept of an OE.

### **4.2 CREDITED CONTROLS**

Credited controls are identified in accordance with the SNS Policy for Selection of Safety Related Credited Controls for the accident events analyzed in Chapter 3 of this document. This section addresses development of requirements for maintaining operability of the credited engineered controls. It is sometimes necessary, for maintenance or other purposes, to take a credited control out of service. The ASE defines the compensatory measures that must be put into place if a CEC is taken out of service for any reason. Existing SNS procedures such as Hold for Radiation Safety (RS Hold) and Configuration Management are utilized to ensure proper application of the compensatory measures.

#### **4.2.1 Personnel Protection System (PPS)**

##### **4.2.1.1 Safety Function**

The overall safety function of the PPS is protection of workers against prompt radiation. The credited function of the PPS is to shut off beam if some failure causes radiation levels to increase above acceptable levels in occupied areas. Typical radiation levels near the BTF do not present a hazard to the worker. Under certain accident conditions, as shown in the hazard analysis, there are cases when

unacceptable radiation levels could occur in occupied areas. Based on these cases, the PPS chipmunk radiation detectors are credited to shut off beam transport.

#### **4.2.1.2 System Description**

The BTF PPS is described in Section 2.10.2 of this document.

#### **4.2.1.3 Functional Requirements**

To ensure that radiation levels in occupied areas do not result in excessive dose, the PPS monitors radiation using sensors (chipmunks) designed for detection of pulsed radiation sources. If any chipmunk indicates radiation levels exceeding the lower threshold for a high radiation area, the PPS trips off devices in the BTF that interrupt beam acceleration.

#### **4.2.1.4 System Evaluation**

The standards, SIL levels, hardware and architecture utilized in the development of the BTF PPS are shown in Section 2.10.2 of this document.

#### **4.2.1.5 Assurance of Continued Operability**

The ORNL SBMS and SNS policies and procedures require that credited safety functions of the PPS be operable as necessary to support beam delivery. Annual certification (not to exceed 15 months) is performed in accordance to the procedures outlined in SNS OPM Chapter 3.

## **5. CREDITED MANAGEMENT SYSTEMS AND SAFETY PROGRAMS**

There are no credited administrative Controls needed to ensure safety for the BTF. There are several non-credited administrative processes that play an important role in supporting efficient safe operations.

- RWP required for entry into the fenced area, RWP requires direct reading personnel dosimetry.
- Procedures and training to evacuate upon Chipmunk audio/visual alarm.
- Configuration Management – no operation without beam stop and shielding in place.
- Procedures – RCT surveys any time the configuration is changed.
- Operating procedures.

## **6. SUMMARY AND CONCLUSIONS**

A single Credited Engineered Control that terminates beam operations based on measured elevated radiation has been identified as necessary to ensure safety.

- One Credited control: a PPS chipmunk beam interlock is required.



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