High Intensity Neutrino Source Test Facility at Meson System Overview of Hazards

Jim Steimel and Elmie Peoples-Evans

June 2, 2010

Version 3.0

1 Version Info

Refer to this section to view changes made between different versions of this document. Major version number changes will involve changes in the physical layout of the facility. More safety factors will be included as the facility is improved.

1.1 Version 1.0

This is the original version of the document, and it evaluates the safety hazards in the RF power sources and component test area. Some of the devices included in this version are the 2.5 MW klystron, 10 kV pulse modulator, waveguide switch, waveguide distribution, and waveguide shutter. This version also discusses the hazards and protections associated with installing test components to the waveguide coax transition for high power RF testing.

1.2 Version 1.1

This version adds the cavity test cave including the 250 kW and 25 kW coaxial RF distribution lines to the hazard analysis. This version will also act as the summary of hazards for times when the side of the waveguide switch opposite the test area RF (i.e. beam line RF) is terminated at the switch with a matched load.

1.3 Version 2.0

This version adds the operation of the 2.5 MeV beam line to the hazard analysis. This includes the new high power RF distribution required to get power to the beam line components. The waveguide switch no longer has a terminated end. This version also includes hazards associated with cryogenic distribution inside the cavity test cave.

1.4 Version 3.0

This version adds testing superconducting cavities in the cavity test cave to the hazard analysis. This version also explains the various combinations of modes of operations that are pertinent to the success of the HINS program.

2 Introduction

The purpose of the High Intensity Neutrino Source (HINS) program is to demonstrate the feasibility of a new design for a high energy, high intensity H- accelerator. There are two major aspects of this accelerator that make it different from any existing linear accelerator: multiple cavities are driven from a single high power source, and the transition from normal conducting to superconducting cavities occurs at a low particle velocity (β = 0.145). The first aspect implies that fine control of the phase and amplitude at individual cavities must be performed at high power levels. The second aspect implies that low velocity, superconducting cavity structures that have never been used to accelerate beam are necessary.

The test facility at Meson for the HINS program will consist of a linear accelerator up to 30 MeV of beam energy. The beam-line components for the facility will include an H- ion source, an RFQ, a section of room temperature cavities and superconducting solenoids, and a cryomodule with superconducting cavities and solenoids. The facility will also include all of the RF power and distribution, power supplies, a cavity test cave, a RF component test cage and controls necessary to accelerate the beam.

During this stage of the program, an H+ ion source will be used to test beam quality through the RFQ.

3 Scope

This document analyzes the potential hazards that exist from all the HINS activities in Meson Detector Building. This includes hazards from all currently installed equipment, testing in any test facility and 2.5MeV beam operations.

3.1 Physical Layout of System

The test facility is located in the southeast corner of the Meson building, just east of the Meson beam line. The klystron modulator components and the klystron all form a line just east of the cavity test enclosure (see figure 2). Klystron interlock, control, and power supply racks are located across from the pulse transformer. The waveguide and waveguide components around the klystron are located at least 12’ off the ground, with the exception of the bend just before the RF component test cage. Here the altitude of the waveguide drops to ground level before it enters the 10’ x 10’ shielded enclosure. The test area distribution system continues from a waveguide coupler to the west wall where it enters the coaxial switch before entering the cavity test cave.

The beam line is located about 23’ east of the klystron modulator components. A beam line enclosure is being constructed that will contain all foreseeable future expansions of the HINS beam line. The south end of the enclosure is a 16’ x 24’ area that contains the ion source and RFQ. The enclosure continues north for about 60’ with a width of 15’. There are labyrinth entrances to the enclosure at the north and south ends, and on the west side. The south end enclosure and labyrinth will not be completed before testing begins. The ion source and RFQ area is enclosed by a fence on three sides. The north side of the area leads to the rest of the beam line enclosure. The beam line RF distribution is located between the beam line enclosure and the klystron.

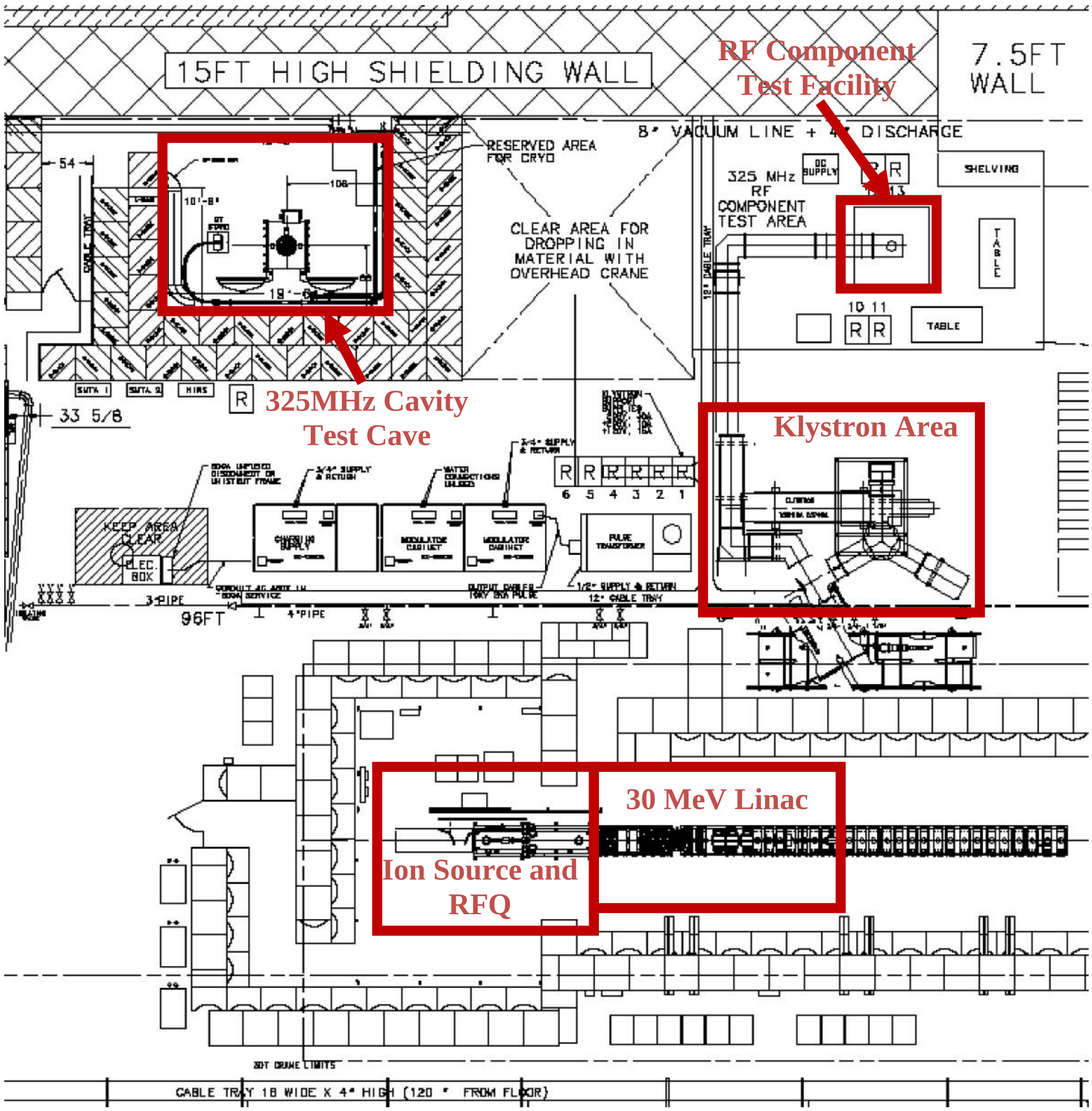

Figure 1: Planned layout of HINS facility at Meson.

3.2 Block Diagram of RF Power and Distribution System

The HINS test facility utilizes two RF power sources. A 2.5MW klystron for high power pulsed RF and 200W amplifiers for continuous wave (CW) RF. The 200W amplifiers are located in the relay racks outside of the 325MHz Cavity Test cave and the RF signal from the amplifiers are routed to the cavity test cave using ½" heliax. The high power RF system is centered around the 2.5 MW klystron and its support equipment. The pulsed bias of the klystron is provided by a charging supply, modulator, and pulse transformer combination capable of 100 kV pulses. Other power supplies control the filaments and solenoids of the klystron.

The 325 MHz RF reference signal is generated either with a remote controlled signal generator or a specialized LLRF system. The signal generator provides amplitude and frequency control, while the LLRF system provides amplitude and phase control at fixed frequency. For the CW system, the LLRF drives the CW amplifier directly. For the pulsed system, the signal goes through a gate switch to control rep-rate and act as an interlock control. The signal then goes through a variable attenuator to control amplitude and enters an 800W power amplifier followed by a 12dB attenuator, before going to the klystron. The output of the klystron enters WR-2300 waveguide which is connected to a circulator. The reverse output of the circulator is terminated with a water cooled, 45 kW(ave.) load, and the forward output is connected to an RF switch. The switch directs the RF power to either the RF test area or the beam line RF distribution.

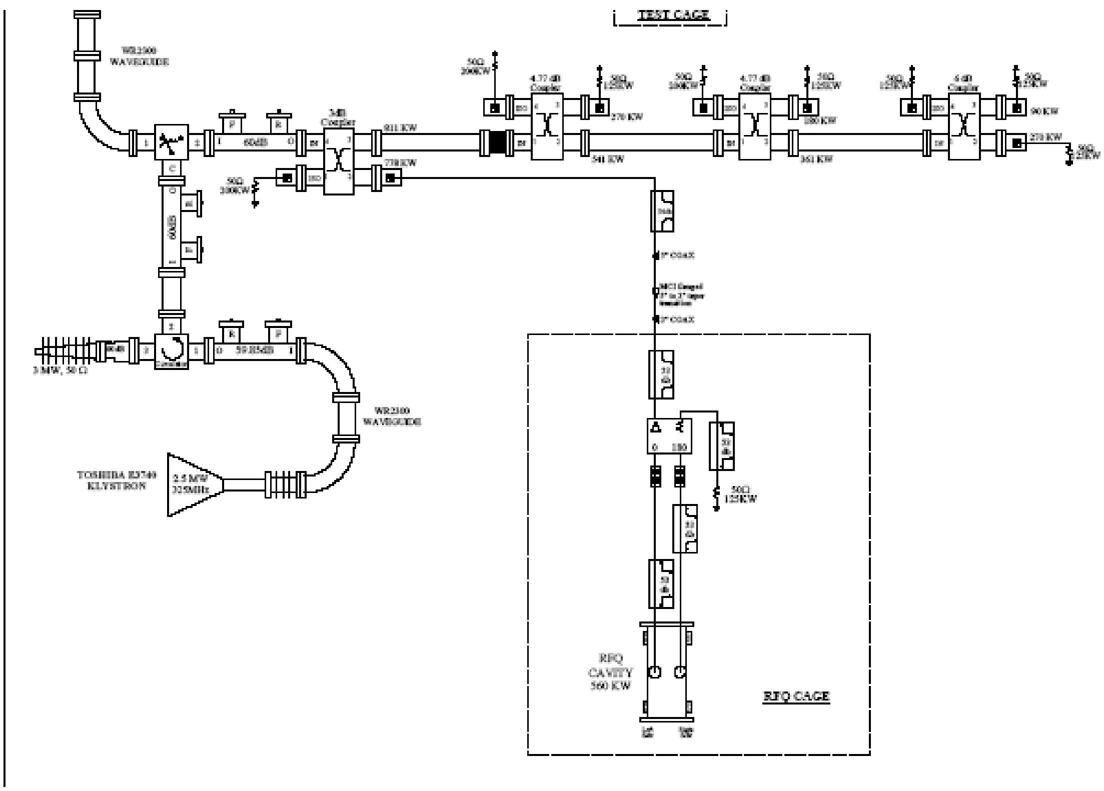

Figure 2: Block diagram of HINS RF distribution showing klystron and beam line distribution.

The RF test area output of the waveguide switch is connected to a waveguide to coax coupler. The waveguide output of this coupler goes to the cavity test cave, through the waveguide shutter followed by a waveguide to coax transition. The coupled port (10dB) of the coupler is terminated with a water cooled load. The reflected-coupled port of the coupler drives a 3” coaxial RF line that is connected to a set of RF switches. These switches route power either to another water cooled load or the continuation of the coaxial line. The line enters another coupler (10dB) that splits the signal into a 250 kW line and a 25 kW line. These two lines are then routed into the cavity test cave. The 25 kW line is used as the RF source for testing the room temperature test cavity, and the 250 kW line is used to test the superconducting cavity.

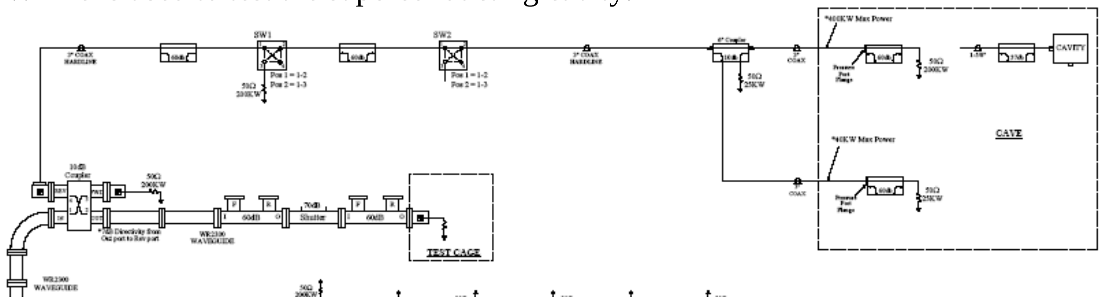

Figure 3: Block diagram of HINS RF distribution showing test area distribution.

The beam line RF output of the waveguide switch is connected to a 3dB waveguide coupler. This coupler splits the klystron power between the beam line RFQ and the beam line cavities. There will be no other beam line cavities other than the RFQ for this stage of the study. The beam line cavities output of the coupler connects to a series of other waveguide hybrids (4.77dB, 4.77dB, and 6dB) in preparation for a multi-cavity beam line. All of the outputs and isolated ports of these couplers are terminated with 125kW or 200kW coaxial loads.

The RFQ output of the hybrid has four possible configurations during this stage of the study. During the initial beam tests with the RFQ, the output of the waveguide coupler connects to a 5” flexible, coaxial cable that transitions to 3” hard-line coaxial cable. This cable connects to a 3dB hybrid that splits the RF power into the two RFQ, RF inputs. The third output of the hybrid is terminated with a 125kW load and absorbs any imbalance in reflected power coming back from the RFQ. In a second configuration, part of the 5” flexible line will be replaced with a 10’ long, waveguide, variable coupler. In a third configuration, part of the 5” flexible line will be replaced with a high power ferrite vector modulator, consisting of two smaller coaxial hybrids, two ferrite stub tuners, and a large circulator. The fourth configuration uses both the variable coupler and ferrite vector modulator. The isolated port of the coupler, and the reflected power port of the circulator will be terminated with 200kW loads.

3.3 Beam Line Block Diagram

The beam line begins with a 50kV ion source. The power supplies for the source are located immediately east of the source itself. Hydrogen ions are generated with a source of hydrogen gas located underneath the ion source. Immediately after the 50kV source is a toroid and vacuum port. This is followed by a focusing solenoid and a two-plane steering magnet. The beam stop follows the steering magnet, and a second steering magnet and focusing solenoid finish out the low energy beam transport (LEBT). The beam stop contains two paddles with independent control for stopping the beam. One paddle is pneumatically driven, and one paddle is driven mechanically.

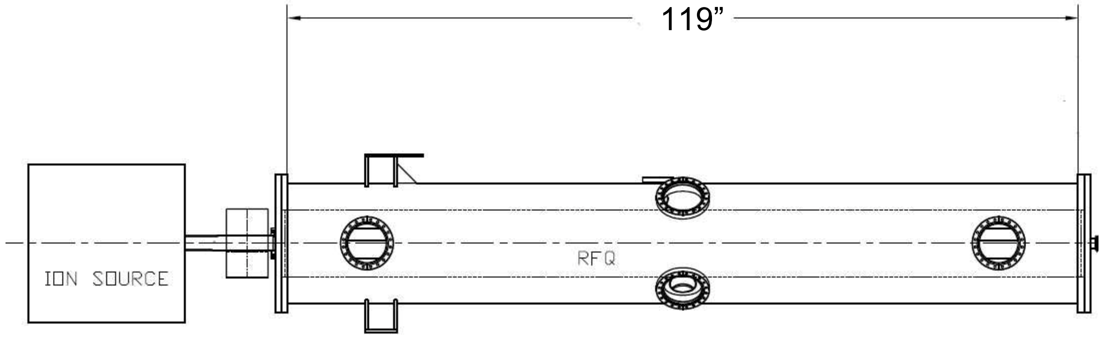

Figure 4: Diagram of Ion Source and RFQ.

The 50keV beam leaves the LEBT and enters the RFQ. The RFQ is a long, resonant, RF structure designed to accelerate and focus the beam simultaneously as the beam travels its distance (~3m). The resonant structure itself is all water-cooled copper, and the beam travels through a small aperture at the center of the structure. This resonant structure is enclosed in a steel vacuum enclosure. With the RF drive at the proper level, the RFQ should accelerate beam up to 2.5 MeV at its exit.

The RFQ is followed by a 2.5MeV beam diagnostic and dump line. There is a beam current monitor at the end of the RFQ which is followed by a BPM. This is followed by two wire scanners, another current monitor, and another BPM. The beam line vacuum port comes after the BPM and is followed by a third wire scanner and the final beam absorber.

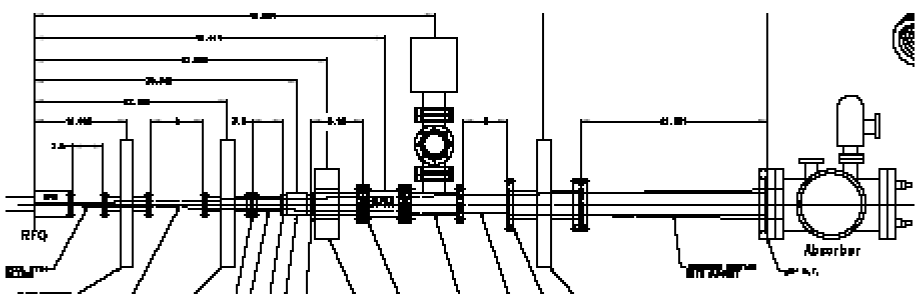

Figure 5: Scale drawing of 2.5 MeV dump line.

3.4 Superconducting Cavity Testing Block Diagram

One or possibly two 200W amplifiers will serve as the RF power source for cavity CW tests using a high Qext drive antenna. The RF power cable from the 200W amplifiers may be left open when not connected to a cavity under test. The RF power source for high power pulsed cavity tests is the 250 kW line from the klystron. When the high power transmission line from the klystron is not connected to a cavity under test, it will be terminated with an appropriately rated RF load. The Cavity Test Cave safety interlocks prevent introduction of RF power to the Cave from either the 200W amplifiers or the klystron during personnel access to the Cave. The RF switch provides an additional interlock to prevent local application of RF power to a cold cavity and thereby minimizes the possibility of exposure to resultant X-rays.

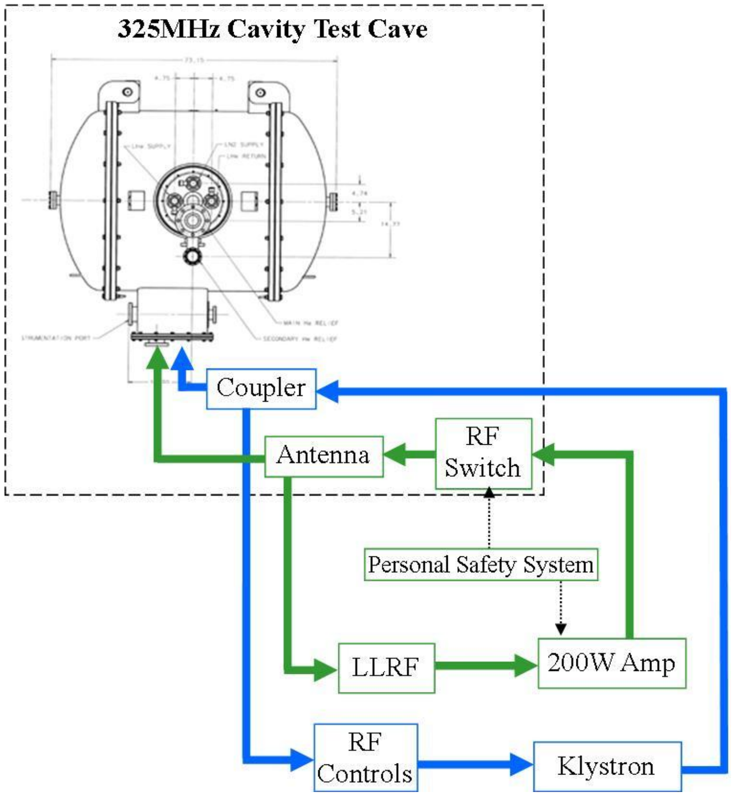

Figure 6: Block diagram of the SC cavity test setup.

3.5 Operational Specifications

This section contains a summary of the pertinent operational specifications used to gauge personnel safety.

	Max
Operating Frequency	325 MHz
Klystron Peak Power	2.5 MW
Klystron Average Power	78 kW
Electromagnet Current	20 A
Electromagnet Voltage	375 V
Klystron Peak Beam Voltage	100 kV
Modulator Peak Voltage	10 kV
Ion Pump Voltage	3.9 kV
RF Driver Amp	800 W
SC Cavity Line Peak Power	400 kW
RT Cavity Line Peak Power	40 kW
RFQ Peak Drive Power	500 kW
RFQ Peak Field	25 MV/m
Ion Source Peak Voltage	50 kV
Ion Source Peak Current	50 mA
Amplifier Peak Power	200 W
SC Cavity Peak Field	61MV/m

Table 1: Absolute maximum ratings for key operational specifications.

3.6 Modes of Operation

3.6.1 Cavity Test Cave Operational Modes

The operational modes inside the cavity test cave include cavity testing and conditioning for RT and SC cavities. The test stand for RT cavities is located near the south wall of the cave and the horizontal test stand (cryomodule) for the SC cavity is in the center of the room, near the east wall (see Figure 1.) The klystron is used during RT cavity testing and conditioning for all types of RT cavities. The SC cavities can be conditioned and tested using the klystron or 200W amplifiers. There will be times when the klystron and the 200W amplifiers will be operated in parallel. The klystron will still function as a power source for one device at a time and therefore will not be used to power SC and RT cavities at the same time.

3.6.2 RF Component Test Cage Operational Mode

The only operational mode inside the RF test cage is RF component testing. The klystron is the normal power source used to test components inside the test cage. Occasionally, test cage operations and SC cavity operations with the 200W amplifiers will occur simultaneously.

3.6.3 Beam Line Enclosure Operational Modes

The three modes of operation within the beam line enclosure include ion source testing, RFQ testing and conditioning, and beam operations. During ion source testing, the klystron is free to function as a power source for any RF mode of operation, including RFQ testing and conditioning. Regardless of the mode of operation within the beam line enclosure, CW testing and conditioning of SC cavities in the Cavity Test Cave is possible.

The following table describes the different modes of operation for the current stage of the HINS program:

Mode Name	Waveguide Switch Pos	Coaxial Switch Position	Waveguide Shutter	Ion Source Beam Stop	Description
Klystron Testing	TA	LD	Closed	X	For testing klystron operations up to the klystron operating limits.
RF Component Testing	TA	LD	Open	X	For testing RF power components in the RF component test cage. Requires an approved procedure for all tests.
RT Cavity Testing	TA	Cave	Closed	X	For testing and conditioning room temperature test cavities in the cavity test cave. An approved conditioning procedure is required for each type of cavity tested. An approved procedure is required for each experimental test regardless of cavity type.

SC Cavity CW Testing	TA	Cave	Closed	X	For testing and conditioning superconducting cavities in the cavity test cave. A conditioning procedure will be written and approved for CW RF testing. An approved procedure for experimental tests will be required.
SC Cavity Pulsed Testing	TA	Cave	Closed	X	For testing and conditioning superconducting cavities in the cavity test cave. A conditioning procedure will be written and approved for CW RF testing. An approved procedure for experimental tests will be required.
RFQ Testing	BL	X	Closed	Closed	For testing and conditioning the RFQ without beam. All conditioning work must follow an approved conditioning plan.
Ion Source Testing	X	X	X	Closed	For testing, conditioning, and operating the ion source into the beam stops up to the ion source operating limits.
Beam Operation	BL	X	Closed	Open	For 2.5 MeV beam operation into the beam absorber, within the operating limits of the beam absorber.

Table 2: HINS modes of operation. BL - Beam Line, TA - Test Area, LD – Coaxial Load, X - Doesn't Matter, CW – Continuous Wave

4 Hazard Analysis

4.1 Environmental

The Meson facility has issues with environmental control of the building. Hopefully, some of the major issues will be dealt with when the roof is repaired. Until then, measures need to be taken to prevent damage to equipment.

4.1.1 Precipitation

The Meson facility roof leaks when it rains or snow begins to melt. This precipitation can short out electrical equipment it comes into contact with. To remedy the problem, the RF power source, component test areas, and ion source area of the HINS facility at Meson are covered with corrugated aluminum roofing to shed the water from the ceiling of the building.

4.1.2 Extreme Temperatures

There is no temperature regulation in the northeast corner of the Meson building. The temperatures can be quite extreme compared to a normal office environment. To keep from damaging the klystron, the air temperature in the room must be maintained between

0 - 40°C. This temperature range is easily attainable with the temperature control equipment in the building when the building has power.

4.2 Mechanical

The only exposed moving parts in the Meson/HINS facility are the overhead cranes, wire chambers and variable tuners.   Wire chambers and tuners are controlled by slow moving stepper motors and do not pose any hazard to bystanders. The only other hazards are static.

4.2.1 Large Suspended Objects

There are massive waveguides and waveguide components resting 12' above the ground. In order to operate and perform regular maintenance on the system, people will need to walk and work under the components. The waveguides and components are mounted on Unistrut, and the entire support system has been inspected and approved by Accelerator Division and Technical Division structural experts. No RF system operation or maintenance will be permitted while changes are being made to overhead components or the support structure.

4.2.2 High Elevation Access

Enclosures for wiring, water utility monitors, and some controls of the waveguide switch and circulator are located on top of each of the components at a height of about 15'. Maintenance of these circuits may be required. Care must be taken to use proper ladders or hoist equipment when accessing the enclosures. Also, if the work is to take place within the travel boundary of an overhead crane, the crane will need to be locked off.

4.3 Electrical Contact

The only exposed high voltage electrical contacts or components on the HINS system are the overhead crane bus lines. All other exposed contacts are enclosed in power supply chassis or cabinets with interlocked access doors. There will be occasions where internal components of high voltage supplies will need maintenance. Protections and procedures need to be in place for safe access into these supplies.

4.3.1 Modulator LOTO

The klystron modulator consists of three separate components: the charging supply, the pulse modulator, and the pulse transformer. Both the charging supply and pulse transformer are enclosed in chassis or containers that are screwed/bolted shut. The modulator has maintenance access panels and a door, but these accesses are interlocked to cut power to the modulator and short out any stored charge. Because of the large amount of stored energy in the klystron modulator, a special LOTO procedure describes the proper shutdown process for accessing the modulator and its components for maintenance. All maintenance of the modulator must be performed by personnel trained in the LOTO procedure ADDP-EE-9923 by a modulator expert.

4.3.2 Klystron LOTO

The klystron itself has no exposed wiring, with all power entering the klystron through standard insulated cables and connectors. The only access area of the klystron that is interlocked is the lead shield door, and this is for protection against ionizing radiation (see section on ionizing radiation hazards). Shutting down the klystron for maintenance requires disabling multiple power supplies in the proper sequence. Therefore, a special LOTO procedure describes the proper shutdown sequence for the klystron. All maintenance of the klystron and its supplies must be performed by personnel trained in the LOTO procedure ADDP-RF-7903 by a klystron expert.

4.3.3 Ion Source LOTO

There is no exposed wiring on the ion source. All wires and high voltage contacts are protected by Plexiglas or grounded cages. One of the power supply racks floats up to 50kV, so the rack is contained in a large rack enclosure. This enclosure is locked shut and interlocked. In order to perform maintenance on the ion source or its power supplies, multiple power supplies must be powered down and locked off in the proper sequence. Any stored charge must be bled off with a grounding stick before work can commence. Because of the complex power down procedure and stored energy in the power supplies, a special LOTO procedure for ion source maintenance was created. All maintenance of the ion source and its supplies must be performed by personnel trained in the LOTO procedure ADDP-EE-9927.

4.3.4 Standard LOTO for Other Supplies

All other energized components and power supplies in the system are self contained, have a single, lockable power source, and have little or no stored energy. Maintenance of these components require standard LOTO training. This includes the LOTO for the overhead crane to avoid exposure to the live bus lines.

4.4 Non-ionizing Radiation

One of the main hazards of the HINS RF distribution system is accidental personnel exposure to high power RF waves traveling through the air. The system must be designed to keep the 78 kW of potential average power from the klystron from reaching people with a density of more that $1mW/cm^2$. The possible sources of exposure are: leaks in the waveguide distribution system, open connections in the component test cage, or broken components connected in the component test cage. Details of the specifications and remedies for the RF exposure hazards are in a separate document, but a summary is contained here.

4.4.1 Certification of Fixed Waveguide

All permanent beam line RF components, RF distribution components, and waveguides must pass an inspection and low power test before being used to distribute high power RF. The inspection will look for visible openings in the waveguide connections and reliability of the support structure. The waveguides will be filled with low power RF signals, and an antenna will be used to check for any leakage in the area.

4.4.2 LOTO of Waveguide Components

This LOTO procedure defines the steps required to safely work on the waveguide distribution system. Any activities that will or may affect the mechanical integrity of the waveguide distribution system fall under the scope of this procedure. This includes any cables that connect klystron power to cavities but does not include cables that connect CW power to cavities. The procedure itself, ADDP-RF-7902, is a subset of the klystron modulator LOTO procedure, without the need to access the modulator cabinet. Without modulator power, no RF power can be transmitted down the waveguides.

4.4.3 Waveguide Leak Detectors

A number of RF detectors will be placed at waveguide junctions to insure that leaks do not develop over time. These detectors are interlocked to disable the drive to the klystron if they sense RF levels much greater than the ambient surroundings.

4.4.4 Enclosed/Shielded Component Test Cage

To protect the area around the component test cage from stray RF due to open connections and component malfunction, a 10’ x 10’ gated, interlocked, fenced enclosure surrounds the test area. The fenced enclosure serves two purposes: it keeps passersby away from any components under tests, and it acts as an RF shield and distance barrier to workers and passersby in case of RF leakage within the enclosure. No RF is permitted to run to the component test cage unless the fenced enclosure is clear, closed, and locked.

4.4.5 LOTO of Component Test Area

No one will be allowed to enter the component test cage while there is a possibility of generating high power RF with the klystron. The component test area LOTO falls under the jurisdiction of the waveguide distribution LOTO procedure, ADDP-RF-7902.

4.4.6 Component Test Cage Leak Detectors

As a backup to the LOTO procedures and interlocked enclosure, RF leak detectors are located within the enclosed component test cage. If these leak detectors sense RF above the safe levels in the enclosure, they will disable the klystron RF.

4.4.7 Pressurized Coaxial Lines

The 3” coaxial waveguide inside the cavity test cave is pressurized with dry air. Pressure switches that detect the pressure within the coaxial waveguides are connected to the safety interlock system. A pressure drop implies some air gap in the coaxial waveguide connections that could be leaking high levels of RF power. An airtight system implies nowhere for the RF to leak out.

4.5 Cryogenics and Other Gasses

The HINS cavity test cave is already equipped with some cryogenic distribution components in anticipation of commissioning a super conducting horizontal test cryostat and cavity. There are ODH hazards in this cave. Also, the ion source uses hydrogen as a source of protons. The coaxial RF distribution up to the RFQ, including the hybrid, is filled with sulfur-hexafluoride to reduce high field sparking in the hybrid.

4.5.1 Cavity Test Cave ODH

The HINS cavity test cave has been designated an ODH 1 hazard. All people entering the cave must carry a personal oxygen monitor. Also, fixed oxygen monitors have been installed in the cave and are monitored by the safety system.

4.5.2 Hydrogen Supply

The ion source hydrogen supply is located in a small bottle underneath the ion source. This bottle supplies the ion source gas regulation system. The gas is contained and vented to the outside of the ion source enclosure. The system has been inspected and approved by fire safety. Analysis of the safety issues for the bottle and distribution can be found in "Hydrogen Safety Considerations for HINS Proton Source in Meson Building", Beams-doc-3505.

4.5.3 SF6

SF6 is an inert, non-toxic gas used to keep high field RF distribution components from sparking during operation. The process for dealing with venting gas for beam line maintenance can be found in "HINS Sulfur Hexafluoride System Policies and Procedures" Beams-doc-3093.

4.6 Ionizing Radiation

There are two processes that generate ionizing radiation in the HINS facility. The first process is accelerating electrons in a vacuum, which can produce substantial x-rays. This process occurs whenever the klystron or the amplifier is used. The klystron accelerates electrons to a relatively high voltage to amplify RF signals carried by the electrons. The amplifier also accelerates electrons to amplify RF signals carried by the electrons, but at lower voltage than the klystron. The maximum average power available for x-ray production in the cavities is as follows: 375 watts for RT cavities using the 25 kW line of the klystron and 500 watts for SC cavities using the 250 kW line. The maximum power of the amplifiers is 200 watts, thus the maximum available power for x-ray production in the CW regime is considerably less than that of the pulsed power regime. Also, stray electrons accelerated in a cavity could generate x-rays as well. Proper precautions must be taken to insure that personnel are not exposed to harmful x-rays during klystron operation and cavity testing.

The second process is the activation of beam line components due to the impact of high energy particles. This has the potential to produce x-rays and stray neutrons. Proper precautions must be made to insure personnel are not exposed to this activation.

4.6.1 Klystron Lead Shield

The klystron as shipped from Toshiba Corp. includes a lead shield around the electron collector. This shield should sufficiently protect any personnel around the klystron during its operation. The shield contains a latched door for maintenance access to the collector of the klystron. This door is interlocked to disable the modulator power supply if the door is opened. The klystron collector area will be inspected and certified by monitoring x-rays as the power level of the klystron is increased.

4.6.2 Cavity Test Cave Shielding and Security

The cave walls are designed to shield personnel outside the cave from any harmful x-rays that may be generated in the process of testing cavities for the HINS test facility. Access to the cave is interlocked to the klystron modulator. The klystron modulator will not operate without the cave being properly cleared, secured, and locked.

The RF switch and amplifier used for CW testing and conditioning of SC cavities inside the cavity test cave will be interlocked to the safety system. The status of the safety system will dictate the position of the RF switch, open or closed, as well as the state of the amplifier, on or off. The safety system can inhibit RF by opening up the RF switch and cutting power to the amplifier.

4.6.3 RFQ Shielding

The high RF fields required to accelerate beam in the RFQ can produce x-rays. The RFQ copper structure is contained within an aluminum vacuum chamber. This vacuum chamber effectively shields the x-rays generated within the RFQ structure. The RFQ has been successfully conditioned to its full peak power rating and twice the planned average power operation. The x-ray levels around the structure were measured during the commissioning process, and the levels were not significant relative to the precision of the instruments.

4.6.4 Beam Line Radiation

The 2.5 MeV beam does not penetrate the beam line and dump material far enough to create hazardous reaction products outside the vacuum enclosure. A detailed analysis of this hazard can be found in the document, “Fermilab HINS Program 2.5 MeV Beam Design, Operations, and Safety Assessment”.