PIP-II Vacuum Systems

Technical Requirements Specification

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**Document Approval**

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| --- | --- |
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| Stakeholder Reviews performed off-line using TRS Metadata sheets  | Dataset in TC |

Revision History

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| --- | 11/23/2021 | Initial Release  |
| A | 1/16/2024 | Changed pressure units from Torr to mbar. Updated references. Clarified Section 5.1.2. Updated system drawing in Section 5.1.3. Added material and magnetic permeability requirements in Section 5.2.2 and drawing note in Section 5.3. |
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# SCOPE

The PIP-II vacuum system shall include all vacuum environments for beam that covers regions from the Ion Source through the Booster Injection Girder and shall include the regions to the Beam Absorbers. The complete PIP-II vacuum system consists of four regions, Warm Front End (Ion source-LEBT-RFQ, MEBT), Superconducting Linac, Beam Transfer Line and Booster Injection Girder. Vacuum gate valves isolate each region when necessary for commissioning or operation. Additional valves are also installed inside the regions where it is required. This vacuum system design has been validated through the PIP2IT operations period and provided design guidance for PIP-II, especially the quantitative requirement of low particulate vacuum. The requirement must be sufficient to ensure the performance of CM in the course of its long run but practical and cost effective.

# ACRONYMS, TERMS, AND DEFINITIONS

|  |  |
| --- | --- |
| BAL | Beam Absorber Line |
| BTL | Beam Transfer Line |
| CM | Cryomodule |
| DPI | Differential Pumping Insert |
| EPDM | Engineering Process Document Management |
| FAV | Fast Acting Valve |
| FEM | Fermilab Engineering Manual |
| FESHM | Fermilab ES&H Manual |
| FRCM | Fermilab Radiological Control Manual |
| FRS | Functional Requirements Specification |
| HEBT | High Energy Beam Transport |
| HV | High Vacuum |
| HWR | Half Wave Resonator |
| IS | Ion Source |
| L2 | WBS Level 2 |
| L3 | WBS Level 3 |
| LEBT | Low Energy Beam Transport |
| MEBT | Medium Energy Beam Transport |
| PIP-II | Proton Improvement Plan II Project |
| SRF | Superconducting Radio Frequency |
| RFQ | Radio Frequency Quadrupole |
| TC | Teamcenter |
| UHV | Ultrahigh Vacuum |
| WBS | Work Breakdown Structure |
| WU | Warm Unit |

# REFERENCED DOCUMENTS

|  |  |  |
| --- | --- | --- |
| **#** | **Reference** | **Document #** |
| 1 | Interface Specification Document (ISD) | ED0016361 |
| 2 | PIP-II Linac Vacuum Analysis | ED00 |
| 3 | PIP-II Beam Transfer and Beam Absorber Lines Vacuum Analysis | ED00 |
| 4 | PIP-II Vacuum Systems Quality Control Plan  | PIP-II-Doc-5709 |

# ROLES AND RESPONSIBILITIES

## Author(s)

Responsible for TRS preparation, including layout, proper format, requirement identification, requirement verification expectations, requirement traceability, and additional descriptive detail, as appropriate. The author is expected to engage subject matter experts as needed to ensure technical content is appropriately assessed and captured. The author is also expected to identify all applicable stakeholders to their noted requirement(s). In some cases, the author can also have the role of the document Owner.

## Owner

Primary stakeholder and responsible for identifying the goals, objectives, and roles/responsibilities pertaining to that document and for assuring activities/expectations are performed as described. This is typically the Level 3 Manager of the sub-system to which this TRS belongs. The document owner is responsible for maintaining document content, revisions, and updates. An Owner is considered a “Checker” in Teamcenter workflow release when they are not the document Author.

## Reviewer

Technical Integration Office (TIO) reviewers are responsible for ensuring TRS format is consistent with project standards, the appropriate document owner/author/reviewer/approver have been identified, the appropriate review process was implemented, and the appropriate document release process is executed. The TIO reviewers are required to be aware that the TRS document exists and is maintained within the framework of the project Document Management and Control Procedure. A Reviewer is considered a “Checker” in the Teamcenter workflow release.

## Approver

The L2 Manager will evaluate the basis for requirements definition, ensure that requirements are properly articulated, and ensure that they align with higher level requirements specifications, as applicable. The L2M will ensure that CAMs, associated engineering staff, and other Systems Managers are properly engaged and notified of the document’s technical implications. Only the System Manager responsible for the work product addressed in the specification is expected to provide approval. The Approver is an “Approver” in the Teamcenter workflow release.

## Stakeholder

Each TRS includes a metadata sheet which lists each TRS requirement individually and assigns stakeholders to each. A stakeholder is a subject matter expert pertaining to the given requirement and/or has a direct stake in the requirement.

Identified stakeholders are expected to be reviewers, ensuring accuracy and completeness, of requirements and content applicable to them and their associated scope of work. Stakeholder reviewers ensure a record of decision is made offline for accepting, rejecting, or modifying the requirement statement assigned to them within the TRS metadata sheet (included as a dataset in Teamcenter).

# REQUIREMENTS

## System Definition

### Background

This TRS addresses the technical requirements of the vacuum systems for the Warm Front End (including Ion Source), superconducting Linac, Beam Transport Line to the Booster and the Beam Absorber. Vacuum gate valves isolate each region as necessary for commissioning or operation. Environments adjacent to the cryomodules must be designed to preclude a significant particle influx in the event of an unexpected loss of vacuum.

The vacuum system shall be designed to minimize the influx of gases due to atmospheric leaks, outgassing from either the vacuum surfaces or the matrix of the vacuum enclosures.

### High Level Operations Concepts/Scenarios

Vacuum gate valves are located at the ends of each region to segment the accelerator and facilitate partial Linac commissioning, operation, or repair. The vacuum system focuses on the following:

* Managing large gas loads from ion source and beam absorber
* Minimizing particulate migration in vacuum region transition from HV to UHV at last downstream section next to cryomodule
* Protecting cryomodules from vacuum failures in the WFE and BTL

### System Diagram

The following schematic highlights each unique vacuum space in the PIP-II Accelerator.



Figure 1: Vacuum system sections for the PIP-II accelerator

### Interface Definition

Vacuum interfaces exist between both other hardware systems as well as systems which facilitate communication and beam control. Major interfaces include:

* SRF/Cryogenics
* LLRF/RFPI: Vacuum status is provided to the RF protection interlocks to allow/inhibit RF drives depending on the vacuum state.
* Control System: The status of gate valves throughout the accelerator system is communicated via the Control system. When residual pressures rise above preset limits, the gate valves close to protect accelerator vacuum in adjacent areas. Overall vacuum status is reported to machine operators.
* MPS: Fast acting valves that prevent contaminating gas flow into the cryomodule region are activated based on their own closed loop control scheme for fast action. MPS is notified to inhibit beam.
* Instrumentation

The Interface Specification Document for Vacuum [1] describes the complete set of interfaces.

## Requirements

### Performance

|  |  |
| --- | --- |
| T-ED0013681-A001 | Vacuum shall provide appropriate pumping such that the Ion Source achieves a vacuum level of <1x10-2 mbar at the low vacuum region of its vacuum chamber and <1x10-6 mbar at the downstream high vacuum part of the chamber. |
| T-ED0013681-A002 | Vacuum shall provide appropriate pumping such that the LEBT shall operate at a vacuum level of <5x10-7 mbar. |
| T-ED0013681-A003 | Vacuum shall provide appropriate pumping such that the RFQ shall operate at a vacuum level of <5x10-7 mbar. |
| T-ED0013681-A004 | Vacuum shall provide appropriate pumping such that the MEBT upstream of the DPI shall operate at a vacuum level of <5x10-7 mbar. |
| T-ED0013681-A005 | Vacuum shall provide appropriate pumping such that the region of the MEBT between the DPI and the HWR shall operate at a vacuum level of <1x10-9 mbar when cold and shall be particle free. |
| T-ED0013681-A006 | Vacuum shall provide appropriate pumping such that the cryomodule shall operate at a vacuum level of <1x10-9 mbar when cold. |
| T-ED0013681-A007 | Vacuum shall provide appropriate pumping such that the SRF Linac shall be designed to achieve a vacuum of <5x10-7 mbar range before cool-down at the Ion Pump located in the warm insert unit (WU) and <1x10-9 when the cryomodule is cold. |
| T-ED0013681-A008 | Vacuum shall provide appropriate pumping such that the transition region from the Linac to the BTL shall operate at a vacuum level of <1x10-9 mbar when cold and shall be particle free. |
| T-EDRS0013681-A009 | Vacuum shall provide appropriate pumping such that the BTL/BAL shall operate at a vacuum level of <5x10-8 mbar, be compatible with the SRF Linac at the upstream end (<1x10-9 mbar), and the Booster vacuum system at the downstream connection (<5x10-8 mbar). |
| T-ED0013681-A010 | The vacuum system design of injection girder shall be compatible to Booster vacuum requirements, <5x10-8 mbar. |
| T-ED0013681-A011 | The fast-acting valve shall close in 10ms or better. |
| T-ED0013681-A012 | Plating or coating of vacuum components shall not be allowed in areas that require low particulate vacuum. |
| T-ED0013681-A013 | Beam vacuum shall be <0.1 mbar during cryomodule warm up. |
| T-ED0013681-A014 | A special slow pumping cart with mass flow controllers shall be used while at pressure larger than 0.1 mbar. |
| T-ED0013681-A015 | A regular portable turbo cart will be used for pumping down of the BTL/BAL, and upstream of WFE. |
| T-ED0013681-A016 | Data shall be logged at 1Hz for gauges, pump status, and gate valve position. |
| T-ED0013681-A017 | Gate valve positions shall be integrated into MPS. |
| T-ED0013681-A019 | The insulating vacuum interface with cryomodules shall be a 6" ConFlat flange.  |
| T-ED0013681-A020 | Insulating vacuum shall achieve <5x10-5 mbar or better before cooldown. |
| T-ED0013681-A021 | The certification process for all vacuum subassemblies shall follow the certification standard defined in the Vacuum Systems Quality Control Plan [4]. |
| T-ED0013681-A022 | Warm unit vacuum assemblies shall be assembled in an ISO 4 (Class 10) cleanroom. PIP-II vacuum assembly standards as defined in the Vacuum Systems Quality Control Plan [4] shall be followed. |
| T-ED0013681-A023 | Damping pads shall be used for roughing pumps near cryomodules to reduce vibration.  |

### Physical Characteristics

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| --- | --- |
| T-ED0013681-B001 | Vacuum assembly hardware (bolts, studs, etc.) shall be made of 316L plated or unplated stainless steel. Alternatively 651 silicon bronze or titanium 6Al-4V may be used for studs or flange nuts. Stainless on stainless connections are prohibited. In special cases, other materials are acceptable with prior approval by Vacuum Systems. |
| T-ED0013681-B002 | In low particulate areas, vacuum assembly hardware (bolts, studs, etc.) shall be made of 316L unplated stainless steel. Flange nuts shall be made of 651 silicon bronze and studs for blind holes shall be made of 651 silicon bronze or titanium 6Al-4V. All hardware shall be electropolished and external threads must be rolled threads. Stainless on stainless connections are prohibited. In special cases, other materials are acceptable with prior approval by Vacuum Systems. |
| T-ED0013681-B003 | All vacuum components shall be cleaned according to the standard procedure specified in the Vacuum Systems Quality Control Plan [4]. |
| T-ED0013681-B004 | No elastomer seals shall be used for beamline UHV downstream of the DPI. Vacuum grease shall not be used in any section of the beamline. |
| T-ED0013681-B005 | Vacuum Systems shall be consulted with regards to specifications and outgassing rates for in-vacuum materials other than stainless steel. |
| T-ED0013681-B006 | Soldering shall be avoided in any components inside vacuum space. For special cases, Vacuum Systems shall review and approve the use of soldering. |
| T-ED0013681-B007 | Materials with lowest outgassing rate shall be selected for UHV areas. Outgassing in the vacuum space shall be minimized for vacuum component design. Vacuum Systems shall review all vacuum component designs. |
| T-ED0013681-B008 | In UHV areas, manual valves shall be all-metal. |
| T-ED0013681-B009 | Warm units’ axial length shall be so that they shall fit between cryomodules as defined by Linac Installation. |
| T-ED0013681-B010 | Vacuum shall use standard 19-inch rack mountable equipment. |
| T-ED0013681-B011 | Every cable needs to be identified and entered into the cable database. This should include cable type, connectors, and cable lengths. |
| T-ED0013681-B012 | Vacuum shall use PIP-II agreed upon standard cables, connectors, and feedthroughs. |
| T-ED0013681-B013 | FAVs shall be placed upstream of HWR, downstream of the last cryomodule, and downstream of the RF Separator.  |
| T-ED0013681-B014 | No in-situ baking is planned, but warm units and other devices that may require baking in the future shall be designed to withstand bakeout to 150°C.  Lower baking temperature limit requirements must be approved by Vacuum Systems. Baking will be implemented for accessible parts if necessary.  |
| T-ED0013681-B015 | Each warm unit shall have one port for vacuum pumping. The exact location of the vacuum port within the beam instrumentation fiducial volume shall be defined by Beam Instrumentation Systems. |
| T-ED0013681-B016 | Critical components such as warm units shall be vacuum certified by Vacuum Systems prior to installation. |
| T-ED0013681-B017 | All vacuum equipment used on insulating vacuums shall not be reused for beam vacuum, and all vacuum equipment shall be clearly labeled as such. |
| T-ED0013681-B018 | All mechanical pumps shall be oil-free (dry). |
| T-ED0013681-B019 | Components and subassemblies provided by Vacuum must be designed to facilitate installation and maintenance of the accelerator. |
| T-ED0013681-B020 | Relative magnetic permeability of beam tube, fittings, flanges, and other components in vicinity of the beam must be <1.05. Welding of these components shall minimize the heat affected zone and use no filler, or filler with low magnetic permeability if filler must be used. Other materials or locally higher magnetic permeability may be acceptable with approval from the Project Scientist or their designee. |

### Reliability, Maintainability, and Availability

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| --- | --- |
| T-ED0013681-C001 | Vacuum shall provide systems capable of continuous operation with at least 95% availability. |
| T-ED0013681-C002 | Vacuum shall provide systems capable of continuous operation (24 hours/7 days per week). |
| T-ED0013681-C003 | Vacuum design and component selection shall be driven by PIP-II's machine lifetime requirement. |
| T-ED0013681-C004 | Vacuum systems shall have sufficient redundancy to meet the availability requirement. |
| T-ED0013681-C005 | Vacuum systems shall have sufficient redundancy to provide more than 99% beam operation uptime. |
| T-ED0013681-C006 | Components must be selected and used to maximize lifetime (ex., cycle valves and degas ion gauges only when necessary, choose ion gauges with extra filaments, etc.) |
| T-ED0013681-C007 | Redundant gauges shall be used at warm units and near beam absorbers. |

### Environmental Conditions

|  |  |
| --- | --- |
| T-ED0013681-D001 | Vacuum components shall be selected so that they perform well and survive in high radiation areas. When service is required, the vacuum systems must be designed for safety and to achieve ALARA. |
| T-ED0013681-D002 | Temperature and humidity shall be sufficient to keep vacuum systems inside the PIP-II tunnel within their operating range. |
| T-ED0013681-D003 | The exhaust of scroll pumps at the Ion Source shall vent to outside the enclosure and meet all hydrogen safety regulations as outlined in FESHM 6020.3. |
| T-ED0013681-D004 | Accelerator Controls shall provide datalogged temperature and humidity readings.  |

### Transportability

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| --- | --- |
| T-ED0013681-E001 | Warm units and all other vacuum subassemblies shall be backfilled with dry nitrogen for transportation and installation. |
| T-ED0013681-E002 | Warm units and all other vacuum subassemblies shall be designed to ensure that they don't experience damage, including due to vibration, during transportation. |
| T-ED0013681-E003 | Vacuum shall provide transportation requirements including backfill or crating, as applicable, to instrumentation devices that are part of the warm units. |

### Safety

The system shall abide by all Fermilab ES&H (FESHM) and all Fermilab Radiological Control Manual (FRCM) requirements including but not limited to:

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| --- |
| Pressure and Cryogenic Safety |
| * FESHM Chapter 5031 Pressure Vessels
 |
| * FESHM Chapter 5031.1 Piping Systems
 |
| * FESHM Chapter 5031.5 Low Pressure Vessels and Fluid Containment
 |
| * FESHM Chapter 5031.6 Dressed Niobium SRF Cavity Pressure Safety
 |
| * FESHM Chapter 5032 Cryogenic System Review
 |
| * FESHM Chapter 5033 Vacuum Vessel Safety
 |
| Electrical Safety |
| * FESHM Chapter 9110 Electrical Utilization Equipment Safety
 |
| * FESHM Chapter 9160 Low Voltage, High Current Power Distribution Systems
 |
| * FESHM Chapter 9190 Grounding Requirements for Electrical Distribution and Utilization Equipment
 |
| Radiation Safety ANSI ASC A14.3-2000, Safety Requirements for Fixed Ladders  |
| * FRCM Chapter 8 ALARA Management of Accelerator Radiation Shielding
 |
| * FRCM Chapter 10 Radiation Safety Interlock Systems
 |
| * FRCM Chapter 11 Environmental Radiation Monitoring and Control
 |
| General Safety |
| * FESHM Chapter 2000 Planning for Safe Operations
 |

Any changes in the applicability or adherence to these standards and requirements require the approval and authorization of the PIP-II Technical Director or designee.

In addition, the following codes and standards in their latest edition shall be applied to the engineering, design, fabrication, assembly and tests of the given system:

|  |
| --- |
| ASME B31.3 Process Piping  |
| ASME Boiler and Pressure Vessel Code (BPVC) |
| CGA S-1.3 Pressure Relief Standards |
| NFPA 70 – National Electrical Code |
| IEC Standards for Electrical Components |

In cases where International Codes and Standards are used the system shall follow FESHM Chapter 2110 Ensuring Equivalent Safety Performance when Using International Codes and Standards and requires the approval and authorization of the PIP-II Technical Director or designee.

Additional Safety Requirements that are not listed above are included in Table 5.2.

## Design and Construction Standards

Standard Fermilab ultra-high vacuum (UHV) drawings notes apply. Some examples are listed below:

* ASSEMBLY TO BE VACUUM TIGHT. NO LEAK SHALL BE DETECTABLE ON THE MOST SENSITIVE SCALE OF A HELIUM MASS SPECTROMETER LEAK DETECTOR WITH A MINIMUM SENSITIVITY OF 2 X 10-10 ATM-CC/SEC FOR HELIUM.
* ASSEMBLY TO BE ASSEMBLED AND PACKAGED SO AS TO ASSURE NO CONTAMINATION FROM FOREIGN MATERIALS, METAL CHIPS OR OTHER CONTAMINANTS. CLEANING PROCEDURE TO BE APPROVED BY FERMILAB.
* ALL DESIGN, ASSEMBLY, AND HANDLING IS TO CONFORM TO STANDARD ULTRA HIGH VACUUM PRACTICE.
* (INSERT DEGASSING NOTES HERE, IF APPLICABLE). DEGASSING PROCEDURE MUST BE APPROVED BY FERMILAB.
* ALL VACUUM WELDS TO BE MINIMUM PENETRATION FUSION WELDS, USING A MINIMUM OF FILLER ROD IF REQUIRED TO ASSURE LEAK TIGHTNESS

# VERIFICATION

Vacuum analyses were performed using Molflow software [2,3] and verified in the PIP2IT test accelerator.

Commercial items like pumps, valves, fittings, and instrumentation will be inspected and tested for cleanliness, functionality, leak tightness, and performance before acceptance and integration into PIP-II. Manufactured devices will be inspected, cleaned, leak checked, and packaged before delivery for installation. Some specialty items, like welded metal bellows, are critical to the reliability of the accelerator and require additional inspection steps from experience developed during the PIP2IT program. Acceptance criteria for these items align with the requirements.

Vacuum system assemblies will be cleaned, assembled, and leak checked using UHV procedures where required. Warm units between cryomodules will also follow particle-free cleaning practices required by the SRF Linac vacuum region.

Final acceptance as an integrated vacuum subsystem system will be determined when the system meets all technical requirements before hand-off to installation.

# QUALITY ASSURANCE PROVISIONS

The PIP-II Vacuum Systems Quality Control Plan [4] outlines the quality aspects of the design, acceptance, assembly, qualification testing, and transportation of the vacuum systems.

# APPENDIX A – *(NOTES, BACKGROUND, DIAGRAMS, CALCULATIONS, ETC.)*

 None