Fermi National Accelerator Laboratory

Fermilab

PIP-II Production SSR Focusing Lens

Technical Requirements Specification

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Document Approval

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

Revision History

Revision	Date of Release	Description of Change
-	11/02/2021	Initial Release
A		
B		
C		

Contents

1. Scope

This specification informs the cryomodule design, fabrication, assembly and defines technical requirements of the PIP-II pre-production SSR1 and SSR2 superconducting focusing lenses: magnet dimensions and electromagnetic parameters, heat loads and cryogenic system, vacuum system, instrumentation, transportation and key interfaces to interconnecting equipment..

2. Introduction

A total of two production SSR1 cryomodules and seven production SSR2 cryomodules will be employed in the PIP-II linac to accelerate H- ions from 35 MeV to 185 MeV. Each SSR1/2 cryomodule contains four/three superconducting focusing lenses, respectively.

The periodicity of the focusing elements is chosen to achieve sufficiently strong focusing to reduce beam loss on the walls of beam pipe. Besides to compensate for the transverse defocusing by the spoke-type accelerating cavities and for uncertainty in lens and cavity position, each lens is equipped with four dipole corrector windings that can be used in two modes: as steering coils and as skew quadrupole correctors. To monitor position of the beam at the location of the lenses, each magnet package will be equipped with a beam position monitor (BPM). Following a BCR proposal [1] it was decided that both SSR1 and SSR2 will share the same magnet design. Parameters are largely governed by SSR2 where operationally magnets need to be stronger. FRS for both magnets were revised in a single document [2].

This set of technical specifications was generated based on the PIP-II Functional Requirements Specification for focusing lenses of the SSR1 [3] and SSR2 [4] cryomodules and also the PRD [5]. Besides, additional requirements were specified that simplify integration of the lenses in the cryomodule.

The Technical Requirements Specification for the Cryomodule [6] and the Cavity, Coupler, and Tuner [7] are in separate documents.

The technical requirements for the SSR2 cryomodules presented in this document are based on the PIP-II GRD [9], PIP-II Physics Requirement Documents [10] [11] [12] [13] [15] [16] [17] [18], and PIP-II SSR2 Cryomodule FRS [19].

2.1. Roles and Responsibilities

2.1.1. 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.

2.1.2. 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.

2.1.3. 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.

2.1.4. 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.

2.1.5. 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).

2.2. Language style and formatting

In order to help the interpretation of the requirements, the language in requirements specifications was limited to:

- Requirements use "*shall*".
  Shall is used to indicate a requirement is binding, must be implemented, and its implementation verified.
- Goals and guidelines use "*should*".
  Should indicates a goal or a guideline that is recommended to be addressed but is not formally verified.
- Statements of fact use "*will*".
  Will statements are not subject to verification and used to provide description or communicate something that the system/device owner intends to provide.

3. General requirements

T-13800PSSR1and2FLCL-101	Each focusing lens will be conduction cooled.

T-13800PSSR1and2FLCL-102	The beam pipe shall be an integral part of the focusing lens assembly.
T-13800PSSR1and2FLCL-103	The BPM device shall be integrated with each focusing lens before it is installed in the cryomodule.
T-13800PSSR1and2FLCL-104	Each focusing lens shall be individually powered by power supplies located outside the cryomodule.
T-13800PSSR1and2FLCL-105	The main coils and the bucking coils of each lens shall be in series and in the same electrical circuit (one set of current leads).
T-13800PSSR1and2FLCL-106	Each corrector coil in each lens shall have its own separate electrical circuit, thus current leads set.
T-13800PSSR1and2FLCL-107	All the coils in the focusing lens shall be protected in case of a quench. Design of the coils and the quench protection system shall ensure that the temperature in any coil does not exceed 100 K.
T-13800PSSR1and2FLCL-108	All coils of each focusing lens shall be equipped with voltage taps to assure magnet safety during quenching. An appropriate detection scheme shall be developed.

4. Magnetic field requirements – main solenoid

T-13800PSSR1and2FLCL-109	When the focusing lenses are powered, the field should be less than 10 G at the outer surfaces of the adjacent cavity, or an imaginary circle which is centered on the beamline axis, having a diameter of 0.70m, 0.42m distance from the center of the magnet.

Table 1 main coil parameters

	Parameter	Value	Unit
T-13800PSSR1and2FLCL-110	Focusing strength	>4.5	T^2m
T-13800PSSR1and2FLCL-111	Max. Current in the solenoid	75	A

T-13800PSSR1and2FLCL-164	Solenoid operating range	5-100	%
T-13800PSSR1and2FLCL-165	Solenoid ramp time to max. current	<300	s
T-13800PSSR1and2FLCL-112	Effective length of the solenoid field	185 ± 30	mm

Table 2 dipole correctors parameters

	Parameter	**Value**	**Unit**
T-13800PSSR1and2FLCL-113	Integral of the dipole field	>6	mT-m
T-13800PSSR1and2FLCL-114	Current in the corrector	< 12	A
T-13800PSSR1and2FLCL-166	Filed quality of corrector coils	+/-5	%
T-13800PSSR1and2FLCL-167	Corrector field good field region (diameter)	24	mm
T-13800PSSR1and2FLCL-168	Corrector field operating range	-100-+100	%
T-13800PSSR1and2FLCL-169	Corrector ramp time to max. current	<30	s

5. Mechanical and geometrical requirements

T-13800PSSR1and2FLCL-115	The beampipe aperture shall be 40 mm.
T-13800PSSR1and2FLCL-116	The production of the focusing lens shall strictly follow the coils position, and dimensions stated in the design documentation.
T-13800PSSR1and2FLCL-117	The space envelope for the lens and the required mechanical interfaces shall follow the indications provided in F10158044 and F10156092.

T-13800PSSR1and2FLCL-118	The magnet yoke shall be fabricated out of 316L and the yoke, including all the hardware, shall have a permeability of less than 1.02.
T-13800PSSR1and2FLCL-119	Insulation material with appropriate thickness must be used to form the ground and interlayer insulation. The insulation voltage requirements must be generated using results of a quench analysis of a chosen quench protection scheme.
T-13800PSSR1and2FLCL-120	Winding of the main and the bucking coils shall be made using wire tension that generates prestress in the body of the coils to prevent them from separating from the yoke at the maximum (quench) current. In a case when this pre-stress cannot be generated by tensioning, additional pre-stress shall be applied using auxiliary measures.
T-13800PSSR1and2FLCL-121	All coils shall be epoxy impregnated.
T-13800PSSR1and2FLCL-122	To allow adjustment in the beamline, the lens will be connected to the cavities by means of bellows.

6. Alignment requirements

T-13800PSSR1and2FLCL-124	Uncertainty of the location of the effective magnetic axis relative to reference points on the outer surface of the unit shall be better than +/- 0.1 mm rms.
T-13800PSSR1and2FLCL-125	Uncertainty of the angular location of the effective magnetic axis relative to reference points on the surface of the unit shall be better than +/- 0.5 mrad rms.
T-13800PSSR1and2FLCL-126	Each magnet shall be mounted perpendicular to the longitudinal (Z) axis within +/- 0.2 mrad rms in both transverse planes.
T-13800PSSR1and2FLCL-127	Each magnet shall integrate a minimum of two survey fiducials, one placed on the top surface and one on the side. The fiducials

	shall be positioned such that they are on the same plane and shall be visible for survey after the string is assembled.

7. Cryomodule integration requirements

During the design phase, attention shall be paid to details on how the focusing lens will be installed in the cryomodule:

T-13800PSSR1and2FLCL-128	Each focusing lens shall be installed on an individual support post.
T-13800PSSR1and2FLCL-129	The location of the cold diodes shall not interfere with other components of the beamline.
T-13800PSSR1and2FLCL-130	The focusing lens shall be compatible with clean room assembly.

8. Labeling and numbering requirements

T-13800PSSR1and2FLCL-131	Each magnet shall be labeled as P2-SSR-X-BARC-YYY where “X’ represents drawing revision no. and YYY denotes three-digit serial number.
T-13800PSSR1and2FLCL-132	The standard coordinate system is right-handed. Its origin is at the end of RFQ (downstream end of RFQ veins +2 cm). Axis Z is directed along accelerator. Axis Y is directed up. Axis X is directed left to the beam direction. The base flange (on the side of the beam entrance point) must be chosen and marked for each lens to simplify the installation, adjustment, and tuning process during the assembly and commissioning of the cryomodule.
T-13800PSSR1and2FLCL-133	The leads of each coil shall be labeled as flows:
a	For the main coil: MC_Start and MC_End.
b	For the bucking coils: BC1_Start, BC1_End, BC2_Start, and BC2_End. Only the first and the last labels are needed if the internal splicing is used.
c	For the steering coils the labeling must reflect the position of the coil relative to the vertical plane.

d	SC-0_Start and SC0_End for the leads of the coil that creates the vertical field and is located at the azimuth 0º (that is at the top of the device).
e	SC-270_Start and SC-270_End for the leads of the coil that creates the horizontal field and is located at the azimuth 270º (that is at one of the sides of the device).
T-13800PSSR1and2FLCL-134	The type and size of spherical survey target used at each location shall be noted in measurement documentation.
T-13800PSSR1and2FLCL-135	Each fiducial location shall be identified by magnet or assembly serial number and a 1-letter fiducial identifier. Fiducial lettering shall be marked on the magnets.

9. Cryogenics requirements

T-13800PSSR1and2FLCL-136	Cooling is provided to the focusing lens by means of a direct connection to the 2K helium line using high thermal conductivity copper flexible straps.
T-13800PSSR1and2FLCL-137	The focusing lenses shall be designed to tolerate a 1W continuous heat load from the beam without quenching.
T-13800PSSR1and2FLCL-138	The beam pipe shall be independently connected to the 2K helium line to provide a direct cooling path for the beam heat load.

10. Vacuum requirements

The beampipe volume shall comply with the following requirements:

T-13800PSSR1and2FLCL-139	The vacuum level at room temperature shall be better than 1E-6 mbar.

T-13800PSSR1and2FLCL-140	The vacuum level at cryogenic temperature shall be better than 1E-9 mbar.
T-13800PSSR1and2FLCL-141	The leakage rate shall be better than 2E-10 mbar*l/s.
T-13800PSSR1and2FLCL-142	During pump downs, a Residual Gas Analyzer shall be used to sample the gas coming out of the beampipe volume to ensure that no contaminant is present. When the beampipe pressure is less than 1·10-6 mbar, the ratio between the sum of partial pressures from atomic mass unit (amu) 45 to 100 and the total pressure should be less than 1/300.
T-13800PSSR1and2FLCL-143	The beampipe volume shall be protected from the migration or movements of particle contamination during pump down and backfill. Thus, evacuation and backfill of the beampipe volume shall be performed in a controlled manner with a mass flow controller set to 3 lN/min (50 mbar·l/s) using filtered Nitrogen gas.

11. Instrumentation requirements

T-13800PSSR1and2FLCL-144	All sensors should be mounted to provide a means to strain relieve the wires.
T-13800PSSR1and2FLCL-145	The instrumentation wiring shall be of radiation resistant materials and meet the radiation damage requirements. In addition it should be of a material and size that minimizes heat load to the internal systems.

11.1. Temperature Sensors

T-13800PSSR1and2FLCL-146	Temperature sensors shall be 4-wire and shall be mounted in a way to thermalize the wires.
T-13800PSSR1and2FLCL-147	For temperature measurements at 30K or higher, the following temperature sensors shall be used: Si Diode Lakeshore DT-670 Band A-1.
T-13800PSSR1and2FLCL-148	For temperature measurements below 30K, the following temperature sensors shall be used: Cernox CX-1030 series

T-13800PSSR1and2FLCL-149	Temperature sensors operating in the range of 2.0 to 15K shall be calibrated with an accuracy of 50mK.
T-13800PSSR1and2FLCL-150	Temperature sensors operating in the range of 15K to 30K shall be calibrated with an accuracy of 250mK.
T-13800PSSR1and2FLCL-151	Temperature sensors operating in the range of 30K to 300K shall have an accuracy of 1K.
T-13800PSSR1and2FLCL-152	At least one temperature sensor shall be installed on the magnet and one on the current leads.

12. Interfaces

Interfaces are described in the PIP-II Master Interface Control Document (MICD) [13] where each interface is defined by a unique identifier at the L3 level while cross-linking with requirements documents and interface specification documents (ISD) for each identifier in order to ensure traceability.

T-13800PSSR1and2FLCL-153	Interface Specification Document (ISD) specifying all external interfaces of the focusing lens shall be created.

The created Interface Specification Document should address (but is not limited to) the following interfaces:

Interface Areas	Physical Interfaces
Vacuum/Cryogenic	• Flanges of the beam pipe • Position and dimensions of the connection to the 2-phase helium pipe
Structural	• Support post
Alignment	• Alignment fiducials
Instrumentation/Power	• Instrumentation connectors to the vacuum vessel feedthroughs • Current leads

13. Engineering and Safety Standards

The focusing lenses, including its subassemblies, parts and tooling, shall be designed, manufactured, documented and tested to comply with the Department of Energy directive 10 C.F.R. 851 [25], the appropriate chapters of the Fermilab Engineering Manual [26], the Fermilab Environment Safety and Health Manual (FESHM) [27], including but not limited to:

- FESHM 9000: Electrical Safety
- FESHM 10110: Below-The-Hook Lifting Devices

14. Quality Control

T-13800PSSR1and2FLCL-154	A Quality Control (QC) plan shall be developed to cover the design, procurement, assembly, and qualification testing of the focusing lens.
T-13800PSSR1and2FLCL-155	Quality in the design shall be assured through a thorough series of planned reviews.
T-13800PSSR1and2FLCL-156	Electronic travelers shall be developed to document quality control efforts at all stages of production. This includes incoming materials inspection, subcomponent fabrication, winding, impregnation, assembly, and testing.

Electronic travelers should contain inspections and tests which will verify the technical requirement specifications defined in this document. Non-conformances should be rectified during the design or fabrication phases. Any non-conformances are to be entered into the discrepancy report system.

15. Verification

The acceptance criteria set forth in this section lists the higher level requirements from this Technical Requirements Specification that shall be checked or tested before the focusing lenses are accepted.

15.1. Magnetic field

T-13800PSSR1and2FLCL-157	The focusing lens shall meet the requirements set in Tables 1 and 2.

15.2. Geometry

T-13800PSSR1and2FLCL-158	The focusing lens shall meet the requirements set in Section 5.

15.3. Alignment

T-13800PSSR1and2FLCL-159	The focusing lens shall meet the requirements set in Section 6.

15.4. Vacuum

T-13800PSSR1and2FLCL-160	The focusing lens shall meet the vacuum requirements set in section 10

15.5. Cooling

T-13800PSSR1and2FLCL-161	The focusing lens shall tolerate 1W heat load from the beam without quenching.

15.6. Interfaces

T-13800PSSR1and2FLCL-162	All external interfaces shall be verified to meet the specified position, type and configuration.

15.7. Quality Controls and Documentation

T-13800PSSR1and2FLCL-163	Design reports, engineering notes, operating procedure, travelers and other relevant documents shall be revised and approved before the subsequent activities start.

16. Appendix A: Materials

16.1. Beamline Materials

Materials used for the design of the beam line shall be selected from the approved list of materials. It is important to ensure that the correct fabrication techniques (e.g. only the use of water-soluble machining lubricants for manufacture) handling and cleaning procedures are used so as not to compromise the vacuum performance of the selected material.

Approved Materials List:

- 316L Stainless Steel according to ASTM A240 (or equivalent)
- Titanium Grade 2 according to ASTM B265/ASTM B348
- Titanium Grade 5 according to ASTM B265/ASTM B348
- Niobium RRR Grade according to ASTM B393
- Oxygen Free Copper (phosphorous de-oxidized grade should not be used) and high RRR copper (RRR greater than 50)
- Aluminum and its alloys. Do not use cast components and anodized aluminum.
- Nb55Ti45
- Gold
- Silver
- Molybdenum
- Platinum
- Beryllium Copper
- Ceramic (as Al2O3) > 90%
- Machinable glass (Macor)

Prohibited Materials List:

- Brass
- Soft Solder
- Standard Hard Solder
- Electrical Solder
- All Plastics
- ASTM type 303, free cutting stainless steel
- All Glues
- Greases
- Silicon or Sulphur based machining lubricants when machining any components (only water-soluble machining lubricants are permitted)
- GE Varnish
- All organic and petroleum-based materials
- Anodized surfaces or any mechanically polished components
- Any material containing: Zinc, Cadmium, Phosphorus, Sodium, Selenium, Potassium or Magnesium

16.2. Materials of components in Insulating Vacuum

Materials approved for the beam line are also suitable for components in insulating vacuum. In addition, some of the materials specifically prohibited from use for the beam line may be suitable for components in insulating vacuum:

Approved Materials List:

- Brass
- Phosphor bronze (the current leads of the solenoids and correctors)
- Sapphire (for insulation of current leads)
- Kapton
- Aluminum tape
- Soft Solder (cryogenic compatible)
- Standard Hard Solder
- Electrical Solder
- G10 & G11
- Indium
- Loctite 243 - Used for single torques application when Indium is NOT required - Non Wicking type
- Loctite 290 - Used for multiple torque applications - Wicking type
- Stycast 2850FT Black with Catalyst 24LV CL (mixture 20 grams of stycast and 1.4 grams of catalyst)
- GE Varnish
- Peek
- Teflon
- For hardware: Stainless Steel 316 or 316L, Silicon bronze, Aluminum. The use of Stainless steel 304L is acceptable for very small hardware such as pem nuts if they are located at least 200 mm from the cavity surface
- The material of the main tube of the vacuum vessel should be determined based on magnetic and mechanical simulations

Prohibited materials list:

- Greases (except for Apiezon and Dow-Corning vacuum greases)
- All Glues except those listed in the approved materials
- All Plastics except those listed in the approved materials
- ASTM type 303, free cutting stainless steel
- Silicon or Sulphur based machining lubricants when machining any components (only water-soluble machining lubricants are permitted)

17. References

[1] "SSR solenoid design/validation test, PIP-II BCR#," 2019.

[2] "Focusing lens SSR1 SSR2 - Functional Requirements Specifications (FRS), ED0011213 Rev A".

[3] "Focusing lens for SSR1 cryomodule FRS, ED0001315".

[4] "Focusing lens for SSR2 cryomodule FRS, ED0003642".

[5] "PIP-II Magnets - Physics Requirements Document PRD, ED0010226".
[6] *PIP-II SSR2 Cryomodule TRS, ED0009651.*
[7] "PIP-II Cavity, Coupler and Tuner TRS, ED0009784".
[8] "PIP-II SSR Focusing Lens TRS, ED0011214".
[9] "PIP-II Global Requirements Document, ED0001222".
[10] "PIP-II Parameters PRD, ED0010216".
[11] "PIP-II RF System PRD, ED0010220".
[12] "PIP-II SRF Cavity Parameters PRD, ED0010221".
[13] "PIP-II Beam Loss PRD, ED0010243".
[14] "PIP-II Magnets PRD, ED0010226".
[15] "PIP-II Controls PRD, ED0010225".
[16] "PIP-II Vacuum PRD, ED0010228".
[17] "PIP-II Misalignment Tolerances PRD, ED0010231".
[18] "PIP-II Cryo Heat Loads PRD, ED0008200".
[19] "PIP-II SSR2 Cryomodule Functional Requirements Specification , ED0001829".
[20] "PIP-II Cryomodules Transverse Envelope, F10127878".
[21] "Fermilab Engineering Manual".
[22] "Fermilab ES&H Manual".
[23] "Low-particulate UHV cleaning and assembly procedure, ED0003571".
[24] "PIP-II Master ICD, ED0010433".
[25] "Worker Safety and Health Program, 10 CFR Part 851, February 9, 2006," [Online].
[26] "Fermilab Engineering Manual (FEM)," [Online]. Available: https://directorate-docdb.fnal.gov/cgi-bin/RetrieveFile?docid=34.
[27] "Fermilab Environmental Safety and Health Manual (FESHM)," [Online]. Available: https://eshq.fnal.gov/manuals/feshm/.
[28] "Fermilab Radiological Control Manual (FRCM)," [Online].
[29] I. OSI: Open Source Insruments, http://www.bndhep.net/Devices/BCAM/.
[30] C. Boffo, *SSR solenoid design/validation test, PIP-II BCR#.*

18. Acronyms

BPM	Beam Position Monitor
CM	Cryomodule
EPDM	Engineering Process Document Management
FEM	Fermilab Engineering Manual
FESHM	Fermilab ES&H Manual
FRCM	Fermilab Radiological Control Manual

FRS	Functional Requirements Specification
GRD	Global Requirements Document
HTTS	High Temperature Thermal Shield and Intercepts
LTTS	Low Temperature Thermal Shield and Intercepts
MAWP	Maximum Allowable Working Pressure
MLI	Multi-Layer Insulation
PIP-II	Proton Improvement Plan II Project
PRD	PIP-II Physics Requirement Document
SCD	System Configuration Document
SRF	Superconducting Radio Frequency
SSR1	Single Spoke Resonator Type 1
SSR2	Single Spoke Resonator Type 2
SW	Standing Wave
TC	Teamcenter
UHV	Ultra-High Vacuum