Technical Specifications for MPEX Magnet Systems

MATERIAL PLASMA EXPOSURE EXPERIMENT (MPEX)

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Technical Specifications for MPEX Magnet Systems
for the
Material Plasma Exposure Experiment Project

MPEX-02-SPC-001, Rev. 0

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Change Log

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0	11/23/2020	Initial issue

Technical Specifications for MPEX Magnet Systems
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MPEX-02-ENG-002, Rev. 0

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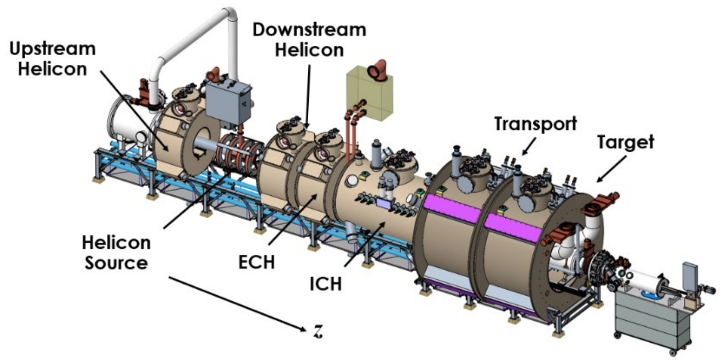
1 SCOPE

This technical specification is a performance specification that defines the requirements for the design, manufacture, inspection, testing, and packaging of the magnet systems for Material Plasma Exposure eXperiment (MPEX). The MPEX is a new linear plasma device to advance the understanding of plasma material interactions through the generation and delivery of plasmas as they are expected in future fusion reactor divertors (Figure 1-1). MPEX will be a steady-state device to study high fluence exposures of plasma facing materials and components.



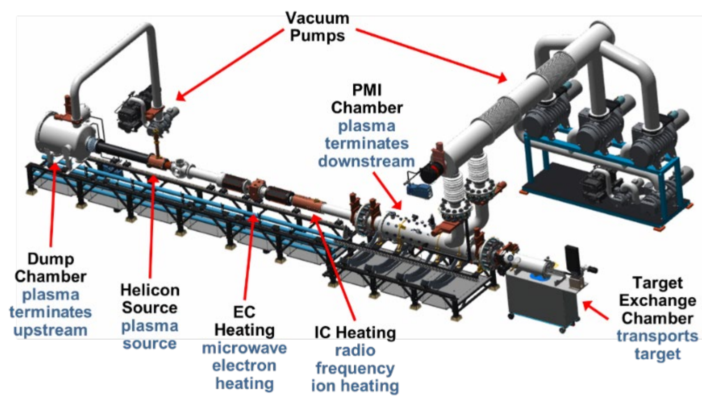


Figure 1-1: Current design for MPEX with (top) and without (bottom) the magnet system illustrated along with other MPEX system and components.

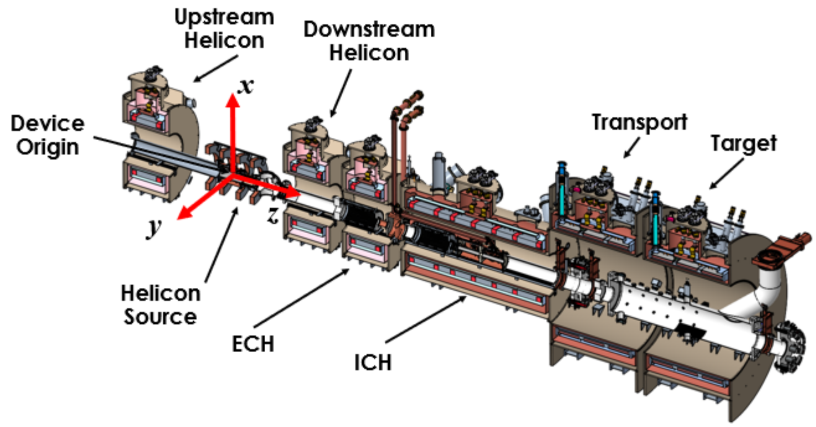


Figure 1-2: Illustration of device origin and reference axes relative to cross section of MPEX magnet systems.

The magnet system provides the necessary field profile along the length of MPEX in order to confine the plasma and enable plasma source and heating from generation to target at desired conditions. For the purpose of this technical specification, the MPEX magnet system is a solenoid geometry with seven sub-systems:

1.) *Upstream Helicon Magnet Sub-System* – provides necessary upstream mirror fields for helicon plasma source,
2.) *Helicon Source Magnet Sub-System* - provides fields along length of the helicon plasma source
3.) *Downstream Helicon Magnet Sub-System* – provides necessary downstream mirror fields for helicon plasma source,
4.) *ECH Magnet Sub-System* – provides the field profile to accommodate resonant zones for electron cyclotron heating (ECH) of the plasma
5.) *ICH Magnet Sub-System* – provides the field profile to accommodate ion cyclotron heating (ICH) at the 0.60-m long ICH antennae
6.) *Transport Magnet Sub-System* - provides the field profile to limit the expansion of the plasma from the ICH to the target and maintain the necessary distance between the ECH heating and target areas
7.) *Target Magnet Sub-System* – provides the field profile in the target area.

1.1 TERMINOLOGY

a. **Use of the words, "shall", "should", "may", and "will."** The words "shall", "should", "may", and "will" have the following specific meaning in the context of this document. "Shall" is used wherever a provision in mandatory. "Should" is used wherever it is necessary to express recommended provisions. "May" is used to express allowed provisions. "Will" is used to express a declaration of purpose. It may be necessary to use "will" in cases where the simple future tense is required.

b. **Units.** SI (Systems International) units and derived units are used throughout the MPEX design and procurement.

c. **Use of the word "system."** In this specification, the top-level entity, MPEX, is referred to in this document as the project or facility. The project or facility is comprised of systems, of which the magnet system is one of them.

d. **Use of the word "magnet sub-system."** In this specification, magnet sub-system refers to the grouping of components that provide the local variation of magnetic field required for specific region of MPEX. For example, a superconducting (SC) magnet sub-system is the group of vacuum cryostats, thermal shields, inner LHe vessels, coil windings, power supplies, and other internal structures and utilities that define the functional and physical boundaries for a specific sub-system. These sub-systems are defined in greater detail in section 2.2.

e. **Use of the word "component."** Component refers to the items that make up the sub-system. Like those mentioned in the "magnet sub-system" discussion (e) for the superconducting magnet sub-system, this can also include current leads, coil winding.

f. **Coordinate system**. The coordinate system utilized for the MPEX system is right-handed and uses x, y, z with the z-axis set along the local magnetic axis of the MPEX magnet system and the x-axis in the vertical direction. (Figure 1-2)

g. **Use of word "local magnetic axis."** This is the z-axis that is defined when the radial field is zero (Br=0) along the length of each MPEX magnet sub-system.

h. **Use of word "axial magnetic field."** This is the magnetic field generated by the MPEX magnet system along the z-axis or (0, 0, z).

i. **Use of word "physical center."** This is the axial midpoint between two outermost surfaces of a given MPEX magnet sub-system that are perpendicular to the local magnetic axis (see Figure 1-1).

j. **Use of word "device origin."** Device origin is the location at (0,0,0) that defines the reference location that is center of the helicon source antenna.

It is expected that for the magnet sub-systems, the MPEX Magnet System will use a combination of superconducting and resistive magnet technologies in order to provide the necessary magnetic fields to the requirements in section 3.0. For the base preliminary design, all magnets are superconducting except for the Helicon Source Magnet Sub-System magnet which consists of four room-temperature (RT) coils.. A magnet sub-system refers to the necessary components required to generate the specific magnetic field for each sub-system. For a SC-based magnet sub-system, this includes but is not limited to the insulated SC coil windings, an inner LHe vessel, thermal shield, internal support structures for these structures, cryogenic supply system, vacuum cryostat, power supplies, and other necessary components. For resistive-based magnet sub-systems, this includes but is not limited to insulated copper windings, connections for water cooling, support structures to maintain the field profile, power supplies, and other necessary components.

1.2 ACRONYMS

ACGIH	American Conference of Governmental Industrial Hygienists
ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
BPVC	Boiler & Pressure Vessel Code
CMP	Configuration Management Plan
DCM	Document Control Matrix
DOE	Department of Energy
ECH	Electron Cyclotron Heating
EM	Electromagnetic
ENG	Engineeirng
ES&H	Environmental, Safety, & Health
GPM	Gallons per Minute
I&C	Instrumentation & Controls
ICD	Interface Control Document
ICH	Ion Cyclotron Heating
ISM	Integrated Safety Management
LHe	Liquid Helium
LTV	Lock, Tag, Verify
MPEX	Material Plasma Exposure eXperiment
NIST	National Institute of Standards and Technology
NQA	National Quality Assurance
ODH	Oxygen Deficiency Hazard
ORNL	Oak Ridge National Laboratory
QA	Quality Assurance
QAP	Quality Assurance Program
P&ID	Piping and Instrumentation Diagrams
PPE	Personal Protection Equipment
PR	Project Requirements
RF	Radio Frequency
RT	Room Temperature
SBMS	Standard Based Management System
SC	Superconducting
SOW	Statement of Work

Su	Ultimate Strength
Sy	Yield Strength
TLV	Threshold Limit Values
VAC	AC voltages

2 APPLICABLE DOCUMENTS

This section lists the documents that are referenced by the technical specifications. Documentation will be made upon request for reference. However, the Statement of Work [1] and this Technical Specification should utilize to develop the preliminary design and final design of the MPEX magnet subsystems and support their successful manufacture.

[1] Statement of Work for MPEX Magnet System, MPEX-02-ENG-001
[2] Structural Design Criteria for MPEX Magnet System, MPEX-02-ENG-007
[3] MPEX Design Analyses and Calculations Procedure, MPEX-01-ENG-006
[4] 2013 AMSE Boiler and Pressure Vessel Code, Sec VIII: Rules for Construction of Pressure Vessels, Division 2: Alternative Rules
[5] MPEX Vacuum Handbook, MPEX-00-ENG-002
[6] Magnet System Test Plan for MPEX, MPEX-02-ENG-003

3 TECHNICAL REQUIREMENTS

This section outlines the performance requirements and acceptance criteria for the magnet sub-systems that comprise the MPEX magnet system.

3.1 MAGNETIC FIELD REQUIREMENTS

As stated previously, the MPEX Magnet System provides the magnetic field along the length of the device that confines the plasma and enables the generation of plasma and its heating from source to target. In order to achieve the performance goals for MPEX, the MPEX Magnet System has be to able to generate the on-axis field profiles shown in Figure 3-1. The options shown in the helicon and ECH sub-systems will be explained in greater detail in sections 3.2.3 through 3.2.6. An appendix, Section 7, has been provided that outlines the axial magnetic field for the highest field case along the length of MPEX and corresponding coil windings locations, dimensions, and current densities that were utilized to generate the field profiles in Figure 3-1 and Section 6.

This information is from the reference design that was developed by ORNL. This reference design DOES NOT represent a final approved design for the magnet system but was utilized to assess technical feasibility of the magnet system, manage key interfaces between the magnet system and the other MPEX systems, and the requirements listed in this Technical Specification. The seller is responsible for providing preliminary and final design packages for the magnet

sub-systems as stated in section 7.3 of the Statement of Work [1]. Documentation related to the reference design is available upon request.

3.2 STEADY STATE OPERATION

Each magnet sub-system shall be able to be operated for a minimum of eight hours continuously. This eight hours shall be measured after the sub-system has reached thermal equilibrium as measured by a change in temperature less than 0.5 K over a 1 hour period. Operating current shall be stable to less than 0.01% over the eight-hour period.

3.3 ALIGNMENT AND FIDUCIALS

The center of the solenoid field axis shall be determined by the results of field measurements with respect to alignment fiducials The supplier is free to choose the location of the fiducials (e.g. flanges, vacuum vessel, etc.); however, they must clearly define the field center at each end of the magnet and must be approved by ORNL. The solenoid field center axis measurement with respect to the fiducials shall be accurate within 0.3 mm in total. The supplier shall document the exact locations, dimensions, and accuracies of the fiducials in the final design report as well as the fiducialization procedure. The fiducials shall be machined or welded on the vacuum vessel in order to allow its precise alignment. The supplier shall document how to transfer the field mapping to fiducials in the final design report.

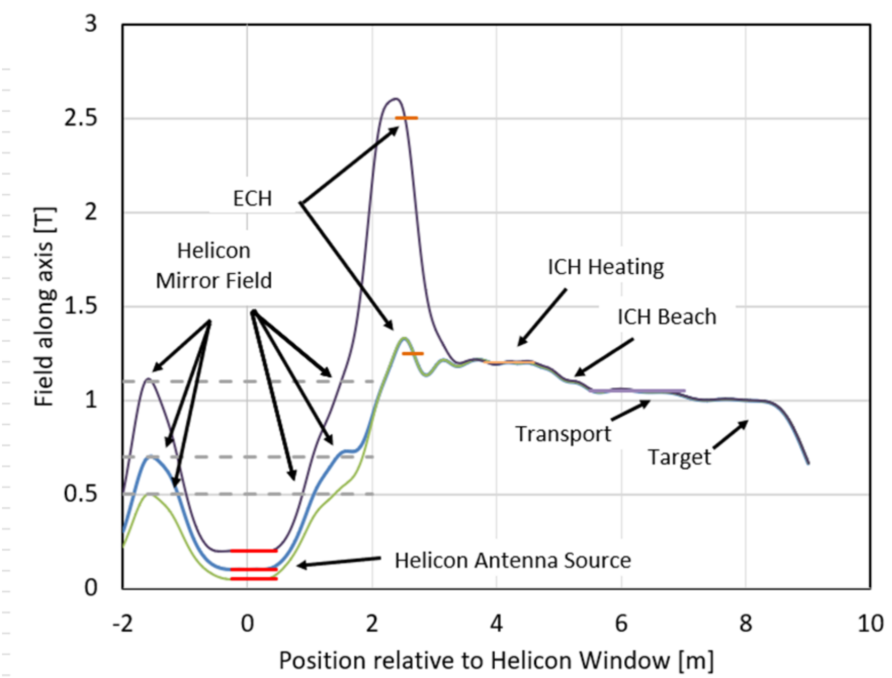


Figure 3-1. MPEX magnetic field profiles for different Helicon and ECH operating modes for 70 GHz baseline configuration.

3.4 ERROR FIELD

The error field for each magnet sub-system shall be assessed relative to its contribution to the total field profile shown in Figure 3-1. With respect to axial magnetic field along the sub-system length, the variation in field at a given z location shall be $\Delta B_z < 0.01\ B(r=0)$. With respect to the radial field, the $\Delta B_r < 0.01\ B_r(r=r_0)$ with r_0 no greater than 0.10 m from the axial center of the solenoid field axis.

3.5 MAGNETIC FIELD DIRECTION

Positive polarity of the coils is defined as a field pointing in the +z-direction with positive current in the coils. Positive polarity is achieved when the current direction relative to the axis of the MPEX coil windings is clockwise while looking downstream.

3.6 MAXIMUM RAMP RATE TO MAXIMUM FIELD & NORMAL SYSTEM SHUT DOWN

Each MPEX superconducting-based magnet sub-system shall be able to reach the maximum design field or be ramped from maximum field during a normal shut down in less than 30 minutes without quenching of the superconducting coil windings within the sub-system.

Each MPEX RT magnet sub-system shall be able to reach the maximum design field no faster than two minutes and no less than 5 minutes.

3.7 MAGNET ASSET PROTECTION – EMERGENCY SHUT DOWN

Each MPEX superconducting magnet sub-system shall be equipped with a control system that works with the power supply for each coil to remove stored energy externally from each system during an emergency shut down that is either triggered by operator or from loss of electrical power. The control system should be sized with respect to the coil windings in the superconducting magnet sub-system to limit the voltage generated to less than 1 kV and a shut down duration no greater than 30 seconds.

Each MPEX RT magnet sub-system shall be equipped with a control system including emergency backup power that could result in the quench of nearby superconducting magnet sub-systems due to induced voltages and currents. This control system should have the ability for the current to be ramped down at a constant rate over a minimum period of time of 30 seconds during an emergency shut down that is either triggered by operator or from loss of electrical power.

3.8 SUPERCONDUCTING-BASED MAGNET SUB-SYSTEM THERMAL CYCLES

Each MPEX superconducting-based magnet sub-system shall be able to reach operating temperature within 7 days and be able to return to room temperature within 7 days.

The superconducting coils magnet sub-systems shall be designed for at least 20 cool-down and warm-up cycles over its operating lifetime.

3.9 VACUUM REQUIREMENTS – MAXIMUM LEAK RATE

Maximum leak rate for the vacuum jacket utilized in MPEX superconducting magnet sub-system shall not exceed 1.0 x 10^{-9} Torr-L/s.

3.10 VOLTAGE REQUIREMENTS

a. Each coil winding within a given magnet sub-system shall be able to withstand 1 kV at room temperature and 2 kV at coil winding temperature operating temperature with respect to coil winding support structure.

b. Turn-to-turn insulation shall be designed to withstand 2 kV at operating temperature.

4 DESIGN AND CONSTRUCTION REQUIREMENTS

4.1 DESIGN

Figure 4-1 show a three-dimensional rendering of the equipment as developed under the reference design. An electronic copy of this reference design that was used in this technical specification will be sent to the sellers upon receipt of award. This model is to be used as engineering guidance of critical dimensions of the final design and compatibility with the configuration that is shown. The magnet sub-systems to be described in this section include:

1.) *Upstream Helicon Magnet Sub-System*
2.) *Helicon Source Magnet Sub-System*
3.) *Downstream Helicon Magnet Sub-System*
4.) *ECH Magnet Sub-System*
5.) *ICH Magnet Sub-System*
6.) *Transport Magnet Sub-System*
7.) *Target Magnet Sub-System*

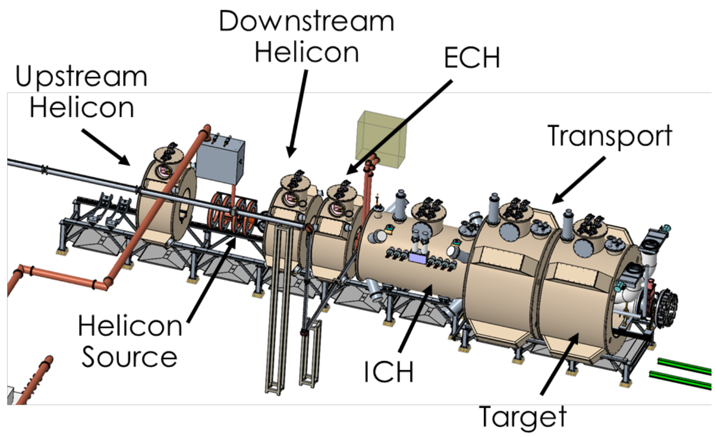


Figure 4-1. Rendering of MPEX magnet system based on reference design [2].

4.2 LOAD CONDITIONS

Each magnet sub-system shall be constructed to handle loads that are applied during shipping, installation, steady state operation, and off-normal events.

Structural elements including the cold mass assembly bolts, cryostat suspension rods, and structural supports between magnet sub-systems shall be built to the guidance provided by Structural Design Criteria for the MPEX Magnet System [2]. This document provides the criteria and conditions for structural element evaluation with respect to design margin relative to the minimum specified Yield Strength (Sy) or the Ultimate Strength (Su) and with respect to the analysis, supporting information, and relevant simulation that is consistent with the MPEX Design Analysis and Calculation Procedure [3] or equivalent.

4.2.1 Shipping Loads

Each magnet sub-system shall be constructed with mechanical supports to maintain its alignment to handle shipping loads (loading/unloading, transportation, etc.) from the manufacturer to ORNL.

A separate, removeable shipping restraint system is permitted for supporting the cold mass during Transportation if the additional refrigeration heat loads from shipping related supports prevent the refrigeration margins from being reached or the cold mass suspension components can not be used to support the shipping and handling loads.

4.2.2 Gravitational Loads

Each magnet sub-system shall be constructed with mechanical supports to maintain its alignment due to gravitational loading of the internal structures and sub-components. An additional safety factor of 2 will be included in calculation of the gravity loads on the cold mass suspension components.

4.2.3 Steady State Operation – EM Loading

Each magnet sub-system shall be equipped with mechanical supports and reinforcement to maintain its alignment due to mechanical loading from magnetic fields generated during steady state operation at the maximum field profile given in Figure 3-1.

The reference design that is provided in the appendix in section 7.0 provides approximate locations of coil windings and can be utilized to generate the background magnetic field from other magnet sub-systems.

4.2.4 Off-Normal Events – EM Loading

Each magnet sub-system shall be equipped with mechanical supports and reinforcement to maintain its alignment due to mechanical loading from loss of field due to the quench of the superconducting magnet coil windings.

The maximum upstream and downstream mechanical loading can be represented by the loss of magnetic field from nearest downstream and upstream magnet sub-system respectively. Like the steady state field operation loading, the reference design that is provided in the appendix in section 7.0 provides approximate locations of coil windings and can be utilized to generate the background magnetic field from other magnet sub-systems.

4.2.5 Shield Environments

Each magnet sub-system shall be constructed to withstand the mechanical forces imparted on it from two shielding walls being utilized to protect equipment from elevated and/or stray magnetic field. (Figure 4-2). Currently, the shield wall for the vacuum systems and compressors is currently to be made of low carbon steel with a nominal thickness of 0.0127 m (½”) and a height of 2.44 m (8’) and total length of 6.10 m (20’). It is parallel and a distance of 3 m from the local magnetic axis. The second shield wall of Alloy 49 is located parallel and a distance of 5-m from the local magnetic axis. It has a nominal thickness of 0.0127 m (½”) and a height of 2.44 m (8’) and total length of 13.7 m (45’).

An updated configuration on the shield wall locations and compositions will be provided by ORNL to the Seller during the final design process for the MPEX magnet system.

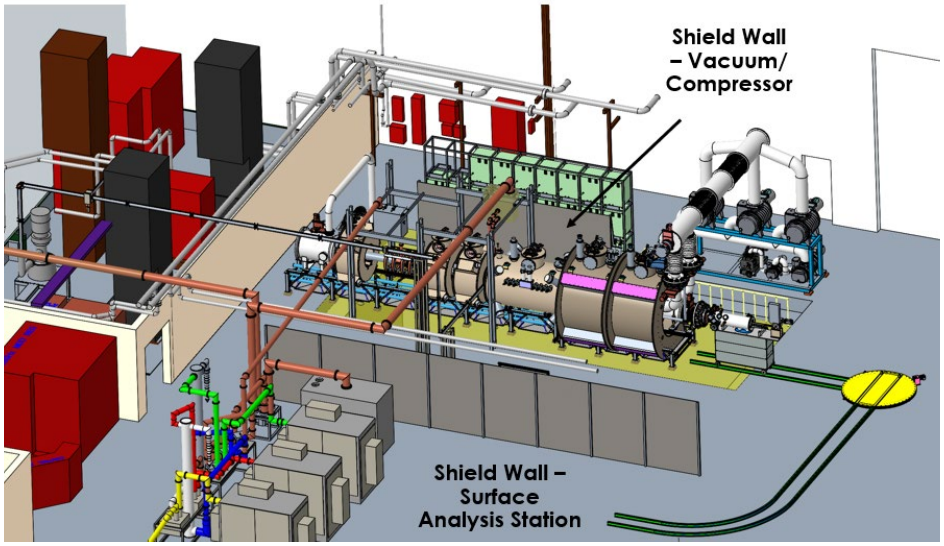


Figure 4-2. Current layout of shield walls relative to MPEX system.

4.2.6 External Vacuum System Bakeout

The vacuum system that is placed within the inner diameter of the MPEX magnet sub-system during installation has to be baked out in order for the vacuum system to meet their system requirements for MPEX. This bakeout will be carried out by heating the vacuum system surface to a maximum temperature of 150°C.

Each magnet sub-system shall be designed from materials and/or equipped with insulation to be able to operate at their steady state operating temperatures without electrical load while vacuum surfaces external to their inner diameters operate at 150°C. Nominal diameters of the vacuum sufraces are 0.3 m in the Upstream Helicon, Helicon Source, Downstream Helicon, ECH, and ICH Magnet Sub-Systems and 0.7 m in the Transport and Target Magnet Sub-System.

4.3 SUPERCONDUCTING MAGNET SUB-SYSTEM REQUIREMENTS

4.3.1 SC Coil Winding

a. Maximum operating current in SC coil windings shall be no greater than 400 A.
b. Maximum operation voltage of the power supply for the SC coil windings shall be no greater than 20 V.
c. SC coil windings shall be insulated from support structures in order to withstand a 1 kV at operation temperature.
d. Commercially available superconducting wires shall be utilized for the SC coil windings.

e. The SC wire is to be fully insulated with Formvar or Polyesterimid/ Kapton such that the superconducting wire is fully covered by at least 0.08 mm (0.003") of insulation in diameter or insulation builds typical of "NEMA-MW 1000 Section 15-C Heavy".

f. The magnet shall be designed to have a critical current margin such that the current stays below 70% of the short sample critical current at the maximum field within the coil winding.

g. The SC wire shall be multifilamentary and the filamentary composition so that the AC loss that is generated from the ramp from zero operating current to full operating current at maximum field over a period of thirty minutes is the lesser of 50% of the steady state design refrigeration margin or 2.5 W per magnet sub-system.

h. SC coil windings utilized for the Helicon/ECH/ICH Magnet Sub-Systems shall have common inner diameters and should have common outer diameters and coil heights in order to simply winding construction for these systems.

i. SC coil windings utilized for the Transport and Target magnet sub-systems shall have common inner diameters and should have common outer diameters and coil heights in order to simply winding construction for these systems.

j. Each coil winding shall be powered individually by a dedicated power supply even for those coil windings that share a common cryogenic environment.

4.3.2 Cryogenic Refrigeration

a. Each SC magnet sub-system shall be equipped with stand-alone helium-based cryogenic refrigeration systems that maintain the liquid helium level or coil temperature at the desired operating conditions.

b. Each SC magnet sub-system-shall be equipped with stand-alone helium-based cryogenic refrigeration systems that maintain thermal shield temperatures at a maximum temperature of 50 K. While this can be accommodated with a two-stage helium cryocooler, additional single stage cryocoolers for the thermal shield are highly likely.

c. When single stage or two stage cryocoolers are utilized, the maximum peak to peak vibrational magnitude impact from the cold head operation to the SC magnet sub-system shall be less than 0.1 mm.

d. A minimum margin of a factor of two shall be provided for the refrigeration systems providing cooling power to maintain the coil operating temperature. The final design estimate for the heat load to the coil windings and supporting vessels and structures shall serve as the baseline and the effective cooling power of the helium refrigeration system at 4.2 K shall be at least 50% higher than this value. This margin will be confirmed as part of the performance test for the magnet sub-system.

e. A minimum margin of 50% shall be provided for the refrigeration systems providing cooling power to maintain the thermal shield temperature. The final design estimate for the heat load to the thermal shield and supporting structures shall serve as the baseline and the effective cooling power of the helium refrigeration system at 50 K shall be at least 25% higher than this value. This margin will be confirmed as part of the performance test for the magnet sub-system.

f. Multi-layer insulation suitable for use with superconducting magnets shall be used at a minimum density of 20-30 layers/cm with a minimum clearance of 6.35 mm between surfaces to radiation heat loads to the thermal shield and inner LHe vessel.

4.3.3 System Instrumentation Requirements

Given the nature of superconducting magnet sub-systems, instrumentation provides the ability to monitor the system performance and be able to determine potential changes in the operating environment that could impact MPEX operations.

a. Each liquid helium (LHe) vessel utilized in a SC magnet sub-system shall be equipped with two independent liquid helium level sensors and monitor systems.

b. Each LHe vessel shall have at least four cryogenic sensors suitable for use in high magnetic field.

c. Each LHe vessel shall be equipped with pressure sensors to track vessel pressure during filling and operation

d. Each thermal shield shall have at least six cryogenic sensors suitable for use in high magnetic field environments to track the temperature profile of the thermal shield.

e. Each coil winding shall be equipped with at least two pairs of voltage taps in order to monitor for the appearance of a quench in order to safely shut down the other MPEX systems.

f. A minimum of four strain gages shall be affixed to mechanical support structures between the vacuum cryostat and the coil winding structures to measure the mechanical loading of the SC magnet sub-systems during cooldown, steady state, and off-normal operations

g. Thermal contraction shall be taken into account in the routing and fastening of the pipe and of the wires in order to not overstretch and damage the equipment.

h. Wires and leads shall be made with sufficient length to allow serviceability from the outside of the cryostat.

4.3.4 Liquid Helium Vessel Requirements

a. The coil/coils shall be mounted inside the liquid helium (LHe) vessel. The LHe vessel shall be made of 316L stainless steel. Welding should be done in a way to minimize remanent field. The LHe vessel shall comply with the parameters listed in Table 4-1.

b. The coils and all other components mounted inside the LHe vessel shall be designed to withstand the pressure testing required for the assessment of the LHe vessel.

c. Any components mounted in the LHe vessel shall not become loose during handling or thermal cycling (e.g. mechanical shocks, cool down, etc.). For example, use of point welding or STYCAST for bolts and/or nuts is suggested. The supplier must report method(s) to be used.

d. External LHe fill and vent lines will be provide to the vessel to facilitate the usage of external LHe dewars to cooldown the SC magnet sub-systems.

e. LHe vessels shall be equipped with necessary relief valves in order to handle the sudden release of helium gas in the event of a coil winding quench and/or sudden loss of vacuum.

Table 4-1. LHe Vessel Parameters.

Maximum allowable working pressure [atm]	1013 kPa (10 atm) differential pressure
Applicable design standard and directives	ASME BPVC [4]
Required minimum conformity assessment procedure	Supplier Proposal, ORNL approval

4.3.5 Vacuum Cryostat Requirements

a. All vacuum spaces for the MPEX magnet sub-systems shall be designed, constructed, and operated in accordance with the requirements specified in the MPEX Vacuum Handbook [5].

b. All vacuum spaces shall be equipped with a penetration that includes an isolation valve & vacuum gauges to monitor pressures within each cryostat. The penetration should also be equipped with hardware to permit maintenance through the use of dry nitrogen and external vacuum systems as required.

c. All vacuum spaces shall be equipped with relief devices sized according to applicable standards (or the MPEX vacuum handbook) to handle the sudden introduction of helium gas from the inner LHe vessel via leaks.

4.3.6 Quench Protection

a. Each superconducting magnet sub-system shall be equipped with a passive quench protection system that prevents the coil temperature from rising above 150 K. The system shall be designed such that the magnet can safely quench at maximum operating current with no damage to the coils or cryostat.

b. This quench protection should be designed in order to accommodate the emergency shut down requirement in section 3.7 through the use of voltage taps on the coil winding specified in requirement section 4.3.3e.

4.3.7 Power Supply Requirements

Per 4.3.1j, each coil winding shall be powered separately and continuously by a dedicated dc power supply. To meet the design requirements, each power supply shall meet the following requirements:

a. The long term (24-hour) stability of the current from the power supply shall be no greater than 0.01% of full-scale current.

b. Ripple of the current from the power supply shall be no greater than 0.01% of full-scale current.

c. Cabling from the power supply to the coil windings shall be sized with respect to length and cross-sectional area such that the total voltage drop from this cabling is less than 1 V.

4.4 ROOM TEMPERATURE MAGNET SUB-SYSTEM REQUIREMENTS

4.4.1 Coil Winding Requirements

a. Each RT coil winding shall be powered by separate power supplies

b. Each RT coil winding power supply shall have bi-polar capability

c. Maximum current of RT coil winding power supply shall not exceed 500 A.

d. Maximum voltage of RT coil winding power supply shall not exceed

e. RT coil turn to turn insulation shall be able to withstand 1 kV.

4.4.2 Cooling Water Requirements

a. A minimum supply flow rate per coil winding shall be no less than 3.8 L/min (1 GPM).

b. Maximum supply temperature per coil winding shall be no greater than 30°C (85°F).

c. Maximum supply pressure per coil winding shall be no greater than 551 kPa (80 psig).

4.4.3 Power Supply Requirements

Per 4.4.1a, each coil winding shall be powered separately and continuously by a dedicated dc power supply. To meet the design requirements, each power supply shall meet the following requirements:

a. The long term (24-hour) stability of the current from the power supply shall be no greater than 0.01% of full-scale current.

b. Ripple of the current from the power supply shall be no greater than 0.01% of full-scale current.

c. Cabling from the power supply to the coil windings shall be sized with respect to length and cross-sectional area such that the total voltage drop from this cabling is less than 1 V.

4.5 UPSTREAM HELICON MAGNET SUB-SYSTEM DESCRIPTION / REQUIREMENTS

The Upstream Helicon Magnet Sub-System provides the upstream mirror field for the helicon source generation.

a. The Upstream Helicon Magnet Sub-Systems shall be composed of superconducting-based magnet sub-system.

b. The minimum axial magnetic field shall be no less than 0.5 T.

c. The maximum axial magnetic field shall be no greater than 1.1 T.

d. The minimum inner diameter shall be no less than 0.647 m (25.5”).

e. The physical center of the magnet sub-system shall be located at 1.429 m (56.25”) upstream of device origin, or (0, 0, -1.429 m).

f. The maximum axial length occupied by the magnet sub-system shall be no greater than 0.85 m.

g. The field profiles within the Upstream Helicon Magnet Sub-System shall be maintained when the ECH Magnet Sub-System is operating between 1.25 T and 2.5 T.

4.6 HELICON SOURCE MAGNET SUB-SYSTEM DESCRIPTION / REQUIREMENTS

The Helicon Source Magnet Sub-System provides uniform axial magnetic field that allows the coupling to the helicon antenna to the plasma for the helicon source.

a. The Helicon Source Magnet Sub-System shall be a RT-based magnet sub-system located between the superconducting-based magnet sub-system and its physical center shall be located at the device origin. (Figure 1-2)

b. The inner diameter of the Helicon Source Magnet Sub-System shall be no less than 0.482 m (18.5”).

c. The maximum outer diameter of the Helicon Source Magnet Sub-System is 0.75 m (29.5”).

d. The axial clearance at the center of the Helicon Source Magnet Sub-System shall be no less than 0.203 m (8”) to accommodate the rf waveguide for the helicon source (see Figure 4-3).

e. The maximum axial length occupied by the Helicon Source Magnet Sub-System system shall be no greater than 0.914 m (36”).

f. For steady state operation, the minimum axial magnetic field shall be no less than 0.05 T.

g. For steady state operation, the maximum axial magnetic field shall be no less than 0.20 T.

h. For steady state operation, the uniformity of the axial magnetic field peak-to-peak over the length of 0.55 m from (0,0, -0.20 m) to (0,0, +0.35 m) shall be no greater than 3%.
i. During start-up operation of helicon source, an axial magnetic field peak-to-peak of 0.02 T is required from Helicon Magnet Sub-System along the length mentioned in d of the helicon window and downstream limiter with a non-uniformity of this length of less than 7.5%.
j. The transition from the axial magnetic field of 0.02 T to steady state operation shall be no less than two minutes and no greater than five minutes.

4.7 DOWNSTREAM HELICON MAGNET SUB-SYSTEM DESCRIPTION / REQUIREMENTS

The Downstream Helicon Magnet Sub-System provides the downstream mirror field for the helicon source generation.

a. The Downstream Helicon Magnet Sub-Systems shall be composed of superconducting-based magnet sub-system.
b. The minimum axial magnetic field shall be no less than 0.5 T.
c. The maximum axial magnetic field shall be no greater than 1.1 T.
d. The minimum inner diameter shall be no less than 0.647 m (25.5”).
e. The maximum axial length occupied by the magnet sub-system shall be no greater than 0.85 m.
f. The physical center of the Downstream Helicon Magnet Sub-System shall be located at +1.314 m (+51.75”) downstream of device origin, which is (0, 0, +1.314 m).
g. The field profiles within the Downstream Helicon Magnet Sub-System shall be maintained when the ECH Magnet Sub-System is operating between 1.25 T and 2.5 T.

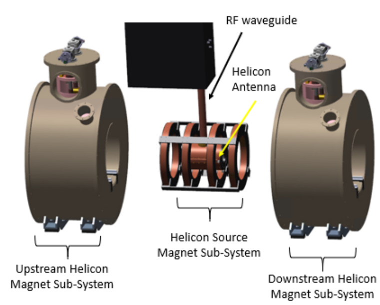


Figure 4-3. Layout of Helicon Magnet Sub-systems with an emphasis of the axial clearance needed for the Helicon Source Magnet Sub-System relative to the RF waveguide.

4.8 ECH MAGNET SUB-SYSTEM DESCRIPTION / REQUIREMENTS

The ECH Magnet Sub-System provides the resonant zone for the electron cyclotron heating downstream of the helicon source generation.

a. The ECH Magnet Sub-System shall be composed of a superconducting-based magnet system located downstream of the Helicon Magnet Sub-System.

b. The minimum axial magnetic field shall be no less than 1.25 T.

c. The maximum axial magnetic field shall be no greater than 2.5 T.

d. The physical axial center of the ECH Magnet Sub-System shall be located 2.318 m downstream from the Device Origin, or (0,0, +2.318 m).

e. The baseline axial location for the 1.25 T ECH resonant heating zone shall be located at 0.30 ± 0.03 m downstream from physical axial center of the ECH Magnet Sub-System.

f. Axial movement of the 1.25 T ECH resonant heating zone by a minimum of +/- 0.05 m from the baseline axial location shall be possible by adjustment of currents within the ECH and ICH Magnet Sub-Systems.

g. The resonant heating zone shall be located in a gradient region where axial field is higher upstream of the resonant zone.

h. The baseline axial location for the 2.5 T resonant heating mode shall be located 0.20 ± 0.02 m downstream from the axial center of the ECH Magnet Sub-System.

i. Axial movement of the 2.5 T ECH resonant heating zone by a minimum of +/- 0.05 m from the baseline axial location shall be possible by adjustment of currents within the ECH and ICH Magnet Sub-Systems.

j. The minimum inner diameter of the ECH Magnet Sub-System shall be no less than 0.647 m (25.5”).

k. The maximum outer diameter of the ECH Magnet Sub-System as measured by the outer diameter of the sub-system cryostat shall be no greater than 1.60 m (63.0”).

l. The maximum axial length of the ECH Magnet Sub-System as measured from the upstream axial boundary of the outer cryostat to the downstream boundary of the outer cryostat shall be no greater than 0.85 m.

m. LHe fill, vent, & relief lines should be located on upstream half of cryostat of ECH Magnet Subsystem.

4.9 ICH MAGNET SUBSYSTEM DESCRIPTION/REQUIREMENTS

The ICH Magnet Subsystem provides the axial magnetic field in order to facilitate ion cyclotron heating downstream of the ECH Magnet Subsystems

a. The ICH Magnet Subsystem shall be composed of a superconducting-based magnet system located downstream of the ECH Magnet Subsystem.
b. The physical center of the ICH Magnet Subsystem shall be located 4.178 m (164.5”) downstream from the Device Origin, or (0,0, +4.178 m).
c. The 0.60-m long ICH resonant heating zone with an axial magnetic field of 1.2 T shall be located from -0.20 m (0,0,+3.978 m) to +0.40 m (0,0,+4.578 m) upstream/downstream of the physical center of the ICH Magnet Subsystem.
d. The variation of the axial magnetic field peak-to-peak along the 0.60 m long length of the ICH resonant heating zone shall be 5% or less.
e. The beach normalization region of 1.1 T shall be 0.05 m in length with a variation along this length of less than 5%. It is preferable if the 5% variation slopes downstream, i.e. does not have a peak.
f. The start of this beach normalization region shall be downstream 1.00 m ± 0.05 m (0,0, +5.10 m) of the ICH resonant heating zone.
g. Axial movement of the 1.2 T ICH resonant heating zone by a minimum of 0.0254 m in either axial direction shall be possible through adjustment of currents within the ICH Magnet Subsystem.
h. Axial movement of the 1.1 T ICH beach normalization region zone by a minimum of 0.0254 m in either axial direction shall be possible through adjustment of currents within the ICH Magnet Subsystem.
i. The minimum inner diameter of the ICH Magnet Subsystem shall be no less than 0.647 m (25.5”).
j. The maximum outer diameter of the ICH Magnet Subsystem as measured by the outer diameter of the cryostat shall be no greater than 1.60 m (63.0”).
k. The maximum axial length of the ICH Magnet Subsystem shall be no greater than 2.5 m.

4.10 TRANSPORT MAGNET SUBSYSTEM DESCRIPTION / REQUIREMENTS

The Transport Magnet Subsystem serves as a functional bridge between the ICH and Target Magnet Subsystem to prevent plasma expansion through maintaining axial field between them and provide the necessary 5-m length that is needed between the ECH resonant heating and the target location.

a. The Transport Magnet Subsystem shall be composed of a superconducting-based magnet system located downstream of the ICH Magnet Sub-System.
b. The minimum axial magnetic field along the Transport Magnet Subsystem along its length shall not be less than 1.0 T.
c. The maximum axial magnetic field along the Transport Magnet Subsystem along its length shall not be greater than 1.1 T.

d. The axial center of the Transport Magnet Subsystem shall be located 6.224 m downstream from the Device Origin (center of the Helicon Subsystem).

e. The minimum inner diameter of the Transport Magnet Subsystem shall be no less than 1.5 m.

f. The maximum outer diameter of the Transport Magnet Subsystem as measured by the outer diameter of the subsystem cryostat shall be no greater than 2.5 m.

g. The maximum axial length of the Transport Magnet Subsystem shall be no greater than 1.5 m.

4.11 TARGET MAGNET SUBSYSTEM DESCRIPTION/REQUIREMENTS

a. The Target Magnet Subsystem shall be composed of a superconducting-based magnet system located downstream of the Transport Magnet Subsystem and shall have the ability to provide confinement fields with axial magnetic fields at or near 1.0 T.

b. The physical center of the Target Magnet Subsystem shall be located 7.827 m downstream from the device origin, or (0,0, +7.827 m).

c. The Target Magnet Subsystem shall have a region of uniform axial magnetic field of 1.0 T over a length of 0.40 m with maximum peak-to-peak variation less than 1.0%. This region of 0.40 m shall be centered -0.20 m relative to the axial center of the Target Magnet Subsystem.

d. The minimum inner diameter of the Target Magnet Subsystem shall be no less than 1.5-m.

e. The maximum outer diameter of the Target Magnet Subsystem as shall be no greater than 2.5 m.

f. The maximum axial length of the Target Magnet Subsystem shall be no greater than 1.5 m.

4.12 MANUFACTURING TOLERANCES

Dimensions and tolerances for the manufacturing of the MPEX magnet subsystems and components shall be interpreted per ASME Y14.5M-2018. Unless otherwise specified, the default tolerances shall be ±1 mm for dimensions expressed to the nearest mm (XXX mm), ±0.3 mm for dimensions expressed to the tenth of mm (XXX.X), and ±0.03 mm for dimensions expressed to the hundredth of mm (XXX.XX).

4.13 CLEANLINESS

a. The equipment exterior surfaces shall be cleaned of all debris, followed by washing, swabbing and rinsing with any non-halogenated general-purpose solvent.

b. The equipment interior surfaces shall be cleaned to a condition suitable for connection to a ultra-high vacuum system. Halogenated solvents are not permitted.

4.14 TEST AND INSPECTION

4.14.1 Manufacturing Inspection Plans

As stated in the Statement of Work sections 7.4 and 7.5, the Seller shall provide a manufacturing inspection plan that outlines the resource loaded schedule for the assembly and fabrication of each MPEX magnet system including key dimensional inspections and hold points.

4.14.2 Vendor Magnet Subsystem Test Plan

A magnet test plan that is specific to the MPEX magnet subsystems shall be developed by the Seller to assure that the magnet performance can meet the technical specifications. This test plan should include insulation integrity monitoring, periodic coil winding insulation testing both at room temperature and at magnet operating temperatures, LHe performance check including quench test of the coil windings, and full performance test of the final assembly. The MPEX Magnet Test Plan [6] can be utilized as guidance in its development, but the final test plan from the Seller will be reviewed and approved prior to the start of manufacturing. This testing shall be consistent with the magnet test plan that will cover the essential testing.

4.14.3 Test Equipment

Measuring and Test Equipment (M&TE) calibration status shall be current with calibration certification that is traceable to National Institute of Standards and Technology.

4.15 MATERIALS

Material certifications shall be provided for those materials utilized in the fabrication of the MPEX magnet subsystem as it relates to vacuum and pressure vessels. Outside of these instances, supporting documentation on materials that are utilized for components such as thermal shield structural support elements, & the superconducting wire where the material properties represent an important parameter shall also be provided.

4.15.1 Magnetic Material Usage

a. Magnetic materials with a relative permeability that is greater than 1.03 shall not be used within the cryostat and the vacuum chamber without formal project approval.

b. Radially outside of the cryostats, the use of magnetic materials is allowed for the MPEX structural elements.

4.15.2 Permitted Materials

The following materials are permissible with correct handling and cleaning:

- Stainless Steel 304 & 316 series, nitronic 50 or 60 series.
- Copper OFHC (Phosphorous De-oxidized grade should not be used)
- Copper Chromium Zirconium

- Aluminum and its alloys (Do not use cast components)
- Gold
- Silver
- Titanium
- Ceramic >94% (Aluminum Oxide Al_2O_3, Silicon Nitride Si_3N_4)
- Machineable glass (Macor)

4.15.3 Prohibited Materials

The following materials shall not be used or come in to contact with components in the form of jigs, fixtures, tools, packing etc.:

- Brass
- Soft Solder, Standard Hard Solder, or Electrical Solder
- All Plastics
- All Glues
- Grease
- Do not use silicon or sulfur based machining lubricants when machining any components (Use water soluble machining lubricants only)
- GE Varnish
- Anodized surfaces
- Any material containing:
  - Zinc, Cadmium, Phosphorus, Sodium, Selenium, Potassium or Magnesium
- Dirt and other contaminants

Note: The above lists are not exhaustive. Exceptions or additional limitations may apply if specified in approved drawings and specifications with supporting documentation and analysis consistent with MPEX DAC [3] or equivalent.

5 MAGNET SYSTEM INTERFACE CONTROL REQUIREMENTS

Given that the MPEX magnet system has to function with other MPEX system such as rf heating and vacuum, there are interfaces between these systems that are managed through the development of interface control documents. While the majority of the interfaces and their consequences have been captured in the requirements listed in section 4, there are a few specific interfaces where additional information is needed.

5.1 ECH-ICH MAGNET SUBSYSTEM INTERFACE REQUIREMENTS

a. The minimum axial space between the ECH and ICH Magnet Subsystem shall be 0.152 m (6”).

b. Penetrations into this minimum axial space from either the ECH or ICH Magnet Subsystems are permitted with ORNL review and approval.

c. The drop in the axial magnetic field within the axial space between the ECH and ICH Magnet Subsystems shall not drop below 1.15 T for both ECH resonant heating modes at either 1.25 T or 2.5 T (Figure 5-1 for clarification).

d. The ripple field in the axial magnetic field within the axial space between the ECH and ICH Magnet Subsystems shall be no greater than 1.2 T for the 1.25 T ECH resonant heating mode.

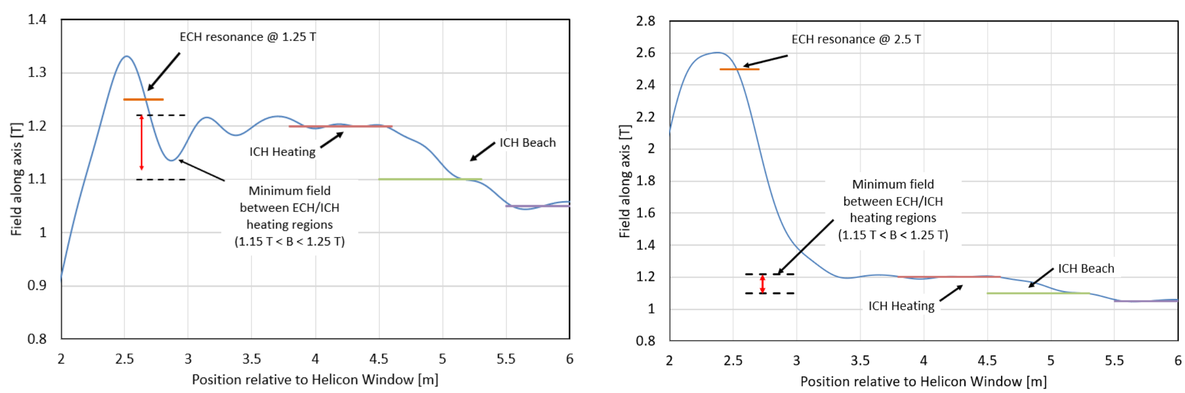


Figure 3-1: Illustration of magnetic field ripple requirement with respect to the transition between the ECH and ICH magnet subsystems.

6 PREPARATION FOR DELIVERY

Each magnet shall be thoroughly cleaned to remove any oils, grease, dirt, chips, etc. that may have accumulated on the equipment during testing. Each magnet shall be packaged individually in wooden shipping containers with proper bracing and placed on wooden platforms to avoid any damage during handling and shipping. Potential contact points between the magnet and the crate shall be padded to prevent damage during shipping. The exterior of the container shall provide access for moving the container by forklift.

7 APPENDIX – MPEX FIELD PROFILE AND REFERENCE COIL GEOMETRY

Table 7-1 provides the axial magnetic field profile that meets the requirements outlined in section 3 and Table 7-2 provides the coil winding locations, sizes, and current densities that were utilized to generate the field profile in Table 1 and in Figure 3-1. Like the renderings shown in Figures 1-1 and 3-2, the coil winding information should be only utilized to determine the specifc field contribution and the impact of neighboring magnet sub-systems on each specific magnet sub-system design and fabrication.

Table 7-1. Minimum, maximum, and nominal axial field for the MPEX magnet system that reflects reference design to meet the requirements spelled out in section 3.

Position [m]	Nom. Axial Field [T]	Min. Axial Field [T]	Max. Axial Field [T]	Notes
-2.00	0.30	0.22	0.49	
-1.90	0.41	0.30	0.67	
-1.80	0.53	0.39	0.87	
-1.70	0.64	0.46	1.04	
-1.60	0.70	0.50	1.11	
-1.50	0.70	0.50	1.08	
-1.40	0.67	0.47	1.00	
-1.30	0.63	0.44	0.91	
-1.20	0.57	0.39	0.80	
-1.10	0.48	0.33	0.67	
-1.00	0.38	0.26	0.53	
-0.90	0.29	0.20	0.40	
-0.80	0.22	0.15	0.31	
-0.70	0.17	0.11	0.25	
-0.60	0.13	0.09	0.21	
-0.50	0.11	0.07	0.20	
-0.40	0.10	0.06	0.20	
-0.30	0.10	0.05	0.20	
-0.20	0.10	0.05	0.20	
-0.10	0.10	0.05	0.20	
0.00	0.10	0.05	0.20	
0.10	0.10	0.05	0.20	
0.20	0.10	0.05	0.20	
0.30	0.10	0.05	0.20	
0.40	0.11	0.06	0.20	
0.50	0.13	0.08	0.22	
0.60	0.16	0.11	0.26	
0.70	0.21	0.14	0.33	

Position [m]	Nom. Axial Field [T]	Min. Axial Field [T]	Max. Axial Field [T]	Notes
0.80	0.28	0.18	0.43	
0.90	0.36	0.23	0.56	
1.00	0.45	0.28	0.70	
1.10	0.53	0.34	0.82	
1.20	0.59	0.39	0.92	
1.30	0.63	0.45	1.00	
1.40	0.68	0.50	1.07	
1.50	0.72	0.54	1.11	
1.60	0.73	0.56	1.19	
1.70	0.73	0.59	1.32	
1.80	0.75	0.66	1.52	
1.90	0.82	0.76	1.82	
2.00	0.92	0.89	2.16	
2.10	1.02	1.01	2.42	
2.20	1.11	1.11	2.55	
2.30	1.20	1.19	2.60	
2.40	1.28	1.28	2.61	
2.50	1.33	1.33	2.54	
2.60	1.30	1.30	2.34	
2.70	1.22	1.22	2.03	
2.80	1.15	1.15	1.73	
2.90	1.14	1.14	1.51	
3.00	1.18	1.17	1.39	
3.10	1.21	1.21	1.32	
3.20	1.21	1.21	1.26	
3.30	1.19	1.19	1.21	
3.40	1.18	1.18	1.20	
3.50	1.20	1.20	1.21	

Position [m]	Nom. Axial Field [T]	Min. Axial Field [T]	Max. Axial Field [T]	Notes
3.60	1.21	1.21	1.22	
3.70	1.22	1.21	1.22	
3.80	1.21	1.20	1.22	
3.90	1.20	1.19	1.20	
4.00	1.20	1.19	1.20	
4.10	1.20	1.20	1.20	
4.20	1.20	1.20	1.21	
4.30	1.20	1.20	1.21	
4.40	1.20	1.20	1.21	
4.50	1.20	1.20	1.21	
4.60	1.19	1.19	1.20	
4.70	1.18	1.18	1.19	
4.80	1.17	1.17	1.18	
4.90	1.15	1.15	1.16	
5.00	1.13	1.13	1.13	
5.10	1.11	1.11	1.11	
5.20	1.10	1.10	1.10	
5.30	1.09	1.09	1.10	
5.40	1.08	1.08	1.08	
5.50	1.06	1.06	1.06	
5.60	1.05	1.04	1.05	
5.70	1.05	1.04	1.05	
5.80	1.05	1.05	1.05	
5.90	1.06	1.06	1.06	
6.00	1.06	1.06	1.06	
6.10	1.06	1.06	1.06	
6.20	1.05	1.05	1.05	
6.30	1.05	1.05	1.05	
6.40	1.05	1.04	1.05	
6.50	1.04	1.04	1.05	

Position [m]	Nom. Axial Field [T]	Min. Axial Field [T]	Max. Axial Field [T]	Notes
6.60	1.05	1.05	1.05	
6.70	1.04	1.04	1.05	
6.80	1.04	1.04	1.04	
6.90	1.03	1.03	1.04	
7.00	1.02	1.02	1.03	
7.10	1.01	1.01	1.01	
7.20	1.01	1.01	1.01	
7.30	1.00	1.00	1.00	
7.40	1.00	1.00	1.00	
7.50	1.00	1.00	1.00	
7.60	1.01	1.01	1.01	
7.70	1.01	1.01	1.01	
7.80	1.01	1.01	1.01	
7.90	1.00	1.00	1.00	
8.00	1.00	1.00	1.00	
8.10	1.00	1.00	1.00	
8.20	1.00	1.00	1.00	
8.30	0.99	0.99	1.00	
8.40	0.99	0.99	0.99	
8.50	0.97	0.97	0.97	
8.60	0.94	0.94	0.94	
8.70	0.89	0.89	0.89	
8.80	0.82	0.82	0.82	
8.90	0.75	0.75	0.75	
9.00	0.66	0.66	0.67	

Table 7-2. Magnet axial field for the MPEX magnet system that reflects reference design to meet the requirements spelled out in section 3.

Coil Winding and Conductor Specfications considered for MPEX Magnet System Reference Design

								Maximum Field Cases		
Coil	Wire Dia (in)	Cu:SC	Inner Diameter (cm)	Outer Diameter (cm)	Width (cm)	z_center (cm)	# of turns	Current (A)	Current Density (A/cm^2)	Current Density (A/m^2)
1	0.045	3:1	82.2	97.0	7.62	-163.83	4050	160.0	11525.0	1.152E+08
2	0.045	3:1	82.2	97.0	7.6	-121.9	4050	80	5762.5	5.762E+07
3	**0.4**	**N/A**	**48.3**	**71.7**	**6.4**	**-14.0**	**66**	**441.0**	**387.5**	**3.875E+06**
4	**0.4**	**N/A**	**48.3**	**71.7**	**6.4**	**14.0**	**66**	**452.0**	**397.2**	**3.972E+06**
5	**0.4**	**N/A**	**48.3**	**71.7**	**6.4**	**-38.0**	**66**	**305.0**	**268.0**	**2.680E+06**
6	**0.4**	**N/A**	**48.3**	**71.7**	**6.4**	**38.0**	**66**	**466.0**	**409.5**	**4.095E+06**
7	0.045	3:1	82.2	97.0	7.6	110.5	4050	80	5762.5	5.762E+07
8	0.045	3:1	82.2	97.0	7.6	152.4	4050	130	9364.0	9.364E+07
9	0.045	3:1	82.2	97.0	7.6	210.8	4050	294	21177.2	2.118E+08
10	0.045	3:1	82.2	97.0	7.6	252.7	4050	290	20889.0	2.089E+08
11	0.045	3:1	82.2	97.0	7.6	311.2	4050	116	8355.6	8.356E+07
12	0.045	3:1	82.2	97.0	7.6	353.1	4050	75	5402.3	5.402E+07
13	0.045	3:1	82.2	97.0	7.6	381.0	4050	73.5	5294.3	5.294E+07
14	0.045	3:1	82.2	97.0	7.6	416.6	4050	81.5	5870.5	5.871E+07
15	0.045	3:1	82.2	97.0	7.6	452.1	4050	80	5762.5	5.762E+07
16	0.045	3:1	82.2	97.0	7.6	487.7	4050	74	5330.3	5.330E+07
17	0.045	3:1	82.2	97.0	7.6	528.3	4050	53	3817.6	3.818E+07
18	0.045	7:1	170.2	177.1	34.8	580.0	8672	92	6627.4	6.627E+07
19	0.045	7:1	170.2	177.1	34.8	622.4	8672	17	1224.6	1.225E+07
20	0.045	7:1	170.2	177.1	34.8	664.8	8672	73	5258.7	5.259E+07
21	0.045	7:1	170.2	177.1	34.8	740.3	8672	66	4754.4	4.754E+07
22	0.045	7:1	170.2	177.1	34.8	782.7	8672	18	1296.7	1.297E+07
23	0.045	7:1	170.2	177.1	34.8	825.1	8672	94	6771.5	6.771E+07

Coils	1,2 7 through 17			**Coils 3 through 6**			Coils	18 thru 23		
Conductor	Supercon 42S25			**Conductor**	Luvata #7068		Conducto	Supercon MR24		
	NbTi			**Copper**				NbTi		
	0.045" diameter wire			**0.4" x 0.4" square**				0.045" diameter wire		
	Cu:Sc		3 to 1	**0.176" cooling channel**				Cu:Sc		7 to 1
	Diameter of wire		0.045	**0.42" x 0.42" with insulation**				Diameter of wire		0.045
	Number of Fil.		42					Number of Fil.		24