<table>
<thead>
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<th>Position</th>
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1 INTRODUCTION

1.1 Purpose
This Engineering Specification Document (ESD), in conjunction with the Linac Coherent Light Source (LCLS) Physics Requirements Document #1.4-001 “General Undulator System Requirements,” defines the requirements for a quadrupole magnet that is to be used in the LCLS undulator system at Stanford Linear Accelerator Center (SLAC). The Advanced Photon Source (APS) will be the primary technical contact for development of this magnet.

1.2 Scope
This document describes the technical details of a proposed fabrication order for 38 quadrupole magnets for use in the LCLS undulator beamline at SLAC. These magnets have laminated steel cores with three epoxy-impregnated air-cooled coil segments around each pole. These magnets can provide a large quadrupole gradient of both polarities and a small bipolar horizontal corrector dipole field and a small bipolar vertical corrector dipole field.

1.3 Deliverables
This specification is for complete magnet assemblies including a magnet physics design, a mechanical design, fabrication, and testing as described below. The magnet assembly includes the following main components (refer to Figure 1):

- Laminated core with end plates
- Four (4) quadrupole coil segments
- Four (4) dipole vertical corrector coil segments
- Four (4) dipole horizontal corrector coil segments
- Thermal switches
- Two (2) magnetic shields (one at each end)
- Electrical power connectors and thermal interlock wiring
- Mechanical fiducial mounts
- Base plate
- Identification plate
2 MAGNET REQUIRED DESIGN PARAMETERS

The required parameters of the LCLS undulator quadrupole magnet are listed in Table 1.

Table 1: LCLS undulator quadrupole magnet required parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum quadrupole integral field gradient at maximum quadrupole supply current</td>
<td>4</td>
<td>T</td>
</tr>
<tr>
<td>Minimum corrector integral field (vertical and horizontal) at maximum corrector supply current (vertical and horizontal)</td>
<td>0.3</td>
<td>T-mm</td>
</tr>
<tr>
<td>Maximum allowable deflection at the pole tips, relative to the bottom of the base plate, when a 22 kg load is applied to any exterior face of the magnet</td>
<td>0.004</td>
<td>mm</td>
</tr>
<tr>
<td>Maximum quadrupole supply current</td>
<td>6</td>
<td>A</td>
</tr>
<tr>
<td>Maximum dipole corrector supply current (horizontal or vertical)</td>
<td>1</td>
<td>A</td>
</tr>
<tr>
<td>Minimum pole gap diameter</td>
<td>11</td>
<td>mm</td>
</tr>
<tr>
<td>Maximum temperature rise of the core at 20°C ambient temp at maximum current</td>
<td>9</td>
<td>°C</td>
</tr>
<tr>
<td>Maximum total field at 1 mm beyond the magnetic shields (2)</td>
<td>0.0015</td>
<td>T</td>
</tr>
<tr>
<td>Maximum length</td>
<td>127</td>
<td>mm</td>
</tr>
<tr>
<td>Gap centerline height from the bottom surface of the base plate</td>
<td>131.9</td>
<td>mm</td>
</tr>
<tr>
<td>Maximum total mass</td>
<td>40</td>
<td>kg</td>
</tr>
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</table>
3 MAGNET DESIGN AND FABRICATION REQUIREMENTS

3.1 Coils

3.1.1 Design
There are four poles on each magnet and three coil segments per pole. Each pole shall contain one quadrupole coil segment, one vertical corrector coil segment, and one horizontal corrector coil segment. On each magnet there shall be four quadrupole coil segments connected in series, four vertical corrector coil segments connected in series, and four horizontal corrector coil segments connected in series allowing the quadrupole field, vertical dipole corrector field, and/or horizontal dipole corrector field to be produced independently with separate power supplies. The coil packs on each pole shall be identical starting with the horizontal dipole corrector coil segment on the inner and the quadrupole coil segment on the outer.

All coils for these magnets shall have solid copper conductor, epoxy-impregnated, and air-cooled designs. The conductor in each coil segment on each pole shall be continuous with no internal joints. Any fiberglass tape used for wrapping must be of a type wettable by epoxy and must not inhibit heat transfer. Coils shall not have any opaque coating applied after curing. Coils must not show any significant bubbles or cracks after impregnation, curing, and burn-in.

For each coil type, on the upper half of the magnet, the coil ends of each segment shall be suitably brazed in series and the two free ends shall be brought to a single terminal block mounted on one side of the upper magnet half. Similar connections shall be made on the lower magnet half. All braze joints shall be properly insulated. Jumpers shall connect the top magnet half coil types to the corresponding bottom magnet half coil types in series. These connections shall be made in such a way that they produce no perturbing fields.

3.1.2 Materials

3.1.2.1 Conductor
The conductor shall be certified ASTM C 10200 or equivalent copper insulated with double poly-glass over Kapton or equivalent.

3.1.2.2 Impregnation
The coils shall be laid up with wet epoxy and vacuum-impregnated with an epoxy whose formulation and cure process shall be approved by APS.
3.1.3 Coil Tests after Impregnation

- Resistance of each coil segment shall be measured and recorded along with the ambient temperature. Resistance measurements shall not vary by more than 10% from the average value of each coil segment type.
- A coil null measurement test shall be performed to verify that the coils have the same number of turns and no dead turn-to-turn shorts.
- An impulse ("ring") test shall be performed on each coil segment and recorded to verify that there are no turn-to-turn shorts.
- A ground insulation (hi-pot) test at 1000V shall be performed and recorded. The test shall be done between each coil segment and ground by wrapping aluminum foil around the coil and grounding the foil. If coil segments are potted together, then a test shall be done by wrapping aluminum foil around the coil pack and a hi-pot test shall be done between each coil segment in the coil pack and the foil and also a hi-pot test shall be done between each coil segment in the coil pack. There shall be no leakage current of more than 5 μA on all tests.
- A dimensional inspection shall be performed and recorded for each coil segment.

3.2 Core

3.2.1 Pole Design

The shape of the quadrupole pole tips shall be made to minimize the 12-pole relative harmonic of the quadrupole body field to less than 10^{-4}. There shall be 1.4 mm minimum wide flats at each corner of a pole face such that they provide a minimum measurable gap between adjacent poles of 3.98 mm after the cores are assembled. End bevels shall be provided at the pole tips to minimize the 12-pole harmonic in the integral quadrupole field. Side bevels shall be provided on the poles to avoid sharp corners near the coils (refer to Figure 2).

3.2.2 Construction

Each core segment shall be a wet-lay-up laminated construction. Lamination lots shall be sorted and equally distributed throughout all magnet core sections to ensure that all core segments of all magnets have reproducible systematic errors and BH properties. The laminations shall be shuffled and flipped to minimize any inaccuracies created from thickness variation across the face of the laminations or other geometric anomalies.
3.2.3 Lamination Die
The laminations shall be stamped with a 2-stage die such that the first stage produces a rough cut lamination that stress-relieves the steel before the second stage produces the high-precision finished part. The lamination die sections, if required, shall not have any joints in any corner or on any pole face or abutting surfaces.

3.2.4 Lamination Material
The laminations shall be stamped out of M-22 silicon steel that is 0.64 mm thick with C5 coating. The grain direction of the silicon steel shall be oriented parallel with the pole axis.

3.2.5 Mechanical Integrity
The mechanical strength of the core shall be such that when it is rigidly mounted to its base plate, a 22-kg load applied to any external face of the core shall not cause the pole tip to deflect more than 4 μm relative to the bottom of the base plate.

3.2.6 Painting
The core shall be painted Rustoleum Industrial Choice DTM5200 water-based acrylic enamel “safety red.” The pole tips, the bottom area where the base plate attaches, and the top area where the fiducial base mounts shall not be painted.

3.3 Magnet Assembly

3.3.1 Aisle Side
When facing downstream, the aisle side of the magnet is the left side.

3.3.2 Beam Direction
The beam direction shall be identified by an arrow visible from the aisle side of the magnet.

3.3.3 Assembly and Keying
Each magnet assembly shall be easily split into a lower half and an upper half for installation around a vacuum chamber through the gap. After reassembly, the geometric symmetry shall be maintained. This will require parts to be pinned or keyed with clearances of no more than 12.7 μm and torque specifications to be implemented.

3.3.4 Magnetic Shields
Figure 1a shows a suggested quadrupole focusing magnet design with magnetic shields. Magnetic shields shall be provided to reduce the leakage field beyond the ends of the magnet to less than the value given in Table 1. Magnetic shields
do not need to be magnetically connected to the core. Magnetic shields shall not make the magnet longer than the maximum length specified in Table 1.

A second set of optional magnetic shields shall be supplied along with the first article. The optional magnetic shields are shown in Figure 3. The optional magnetic shields shall be designed to use the same mounting hardware as the original magnetic shields such that the original magnetic shields can easily be replaced by the optional magnetic shields. These optional magnetic shields allow better air flow through the magnet to enhance heat transfer but will not shield the magnetic field as well as the original magnetic shields shown in Figure 1a. The optional magnetic shields are not expected to meet the leakage field requirement given in Table 1. The optional magnetic shields will be evaluated after receiving the first article, when it will be determined what shield configuration to use.

In both cases the magnetic shields shall split in order to separate the top magnet half from the bottom magnet half. The magnetic shields shall have a hole in the center to accept an 11-mm outside diameter vacuum pipe. Bright nickel finish plating (0.0002/0.0004) thick shall be applied to at least the outside surface of the magnet shields. The shiny nickel plating is to reduce the radiation heat transfer to devices near the magnet.

**3.3.5 Terminal Blocks**

Molex 38770-0110 (or equivalent) terminal blocks shall be provided for connecting the input power to each set of windings and connecting the thermal switches. A thermocouple barrier strip (Omega #BS4 or equivalent) shall be provided for connecting the thermocouple wire. Power supply terminal blocks shall be located on the non-aisle side of the magnet. Sensor terminal blocks and the thermocouple barrier strip shall be located on the aisle side of the magnet.
3.3.6 Terminal Block Markings

- Polarity markings (positive (+) and negative (-)) along with winding identification (quadrupole (Q), vertical (V), or horizontal (H) corrector) shall be listed on the terminal blocks for each set of windings as follows for an electron beam:
  - Quadrupole-horizontal focusing
  - Horizontal corrector-steer to the right (non-aisle side)
  - Vertical corrector-steer up

- Markings identifying the thermal switches shall be listed on the terminal blocks.
- A barrier strip jacket (Omega #BSJ-E or equivalent) shall be supplied on the thermocouple barrier strip to identify the thermocouple polarity.

3.3.7 Terminal Covers

Terminal covers shall be provided to cover the terminal strips and jumpers to prevent accidental or inadvertent contact with exposed live electrical parts. The terminal covers shall be made in accordance with SLAC Magnet Terminal Cover Guidelines #SLAC-I-730-0A11S-003-R000.

3.3.8 Thermal Switches

One Honeywell #3100U-3-1446 thermal protection switch shall be mounted to each coil pack with thermal epoxy (4 switches per magnet). The switches shall be connected in series at a terminal block.

3.3.9 Temperature Sensing

One “cement-on” thermocouple (Omega #C01-E) shall be attached to the core and terminated at the thermocouple barrier strip with spade lugs (Omega #SLCH-20 and SLCO-20 or equivalent).

3.3.10 Fasteners

Fasteners must be either non-ferromagnetic or, if they are ferromagnetic, they must not contribute to field errors in the gap field or remanent fields. They must be satisfactorily corrosion resistant. This includes fasteners used to bolt the magnet core segments together, terminal block fasteners, terminal cover fasteners, and magnetic shield fasteners.

3.3.11 Fiducials

A stainless steel fiducial plate that mounts on the top of the external yoke of the magnet with four fiducial holes shall be provided to facilitate survey and alignment (see Figure 1). A stainless steel fiducial plate that mounts on the aisle side of the magnet with one fiducial hole shall be provided to facilitate survey and alignment (see Figure 1). All fiducial holes shall be made from SLAC tooling ball sockets #PF-444-316-376 tack welded to the plate.
3.3.12 Mounting
An aluminum base plate as shown in Figure 1 shall be supplied as support for the magnet. It will extend beyond the magnet to allow mounting holes for bolts that will attach the magnet to an APS-supplied positioning system installed under the magnet. The geometry in Figure 1 is not meant to be prescriptive but all magnets shall incorporate such a horizontal base plate. APS will provide a centerline height, footprint dimensions, and bolt hole pattern for the base plate.

3.3.13 Identification
Each magnet assembly shall have affixed to the outer surface of an upper part of the yoke a metal identification plate stating:
- Title: "LCLS Undulator Quadrupole Magnet"
- Magnet serial number (UNDQUAD-001, UNDQUAD-002, ...)
- Name of vendor, country of origin, and date of completion
- Magnet drawing number
- Total weight of the magnet in pounds

3.3.14 Burn-in
After complete assembly, each magnet shall be operated with each coil type connected to the maximum operating current for a period of not less than 4 hours continuously, and the temperature rise at the outer surface of the core shall be measured and shown to stay below the asymptotic value specified in Table 1. This test shall be done at 20±2°C ambient air temperature.

3.3.15 Material Certification
Material certifications shall be supplied for the materials used for the core laminations and the copper coils.
3.4 Tests and Measurements of Magnet Assembly

3.4.1 Electrical Measurements

- Resistance (R) of each coil type on the magnet assembly shall be measured and recorded along with the ambient temperature.
- Inductance (L) and Quality factor (Q) measurements shall be done at 1 kHz and recorded for all three coil types.
- Measurements of R, L, and Q of each coil type shall not vary by more than 10% from the average value of each coil type on all magnets.
- A ground insulation (hi-pot) test at 1000V shall be performed and recorded. The test shall be done between each coil type (3 tests). The test shall be done between each coil type and the core (3 more tests). There shall be no leakage current of more than 5 µA on all tests.

3.4.2 Magnetic Measurements

Magnet measurements shall be done on the quadrupole field and both the horizontal and vertical dipole fields.

3.5 Test Equipment Calibration

All measurement equipment used to test parts of this magnet shall have up-to-date calibration.