STANFORD LINEAR ACCELERATOR CENTER

SPECIFICATION

STANFORD SYNCHROTRON RADIATION LABORATORY

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First Line:
SPEAR3

Second Line:
Magnet System

Title:
Gradient Dipole Magnet Measurements

145D & 109D

Magnet Measurement

Specification

145D和109D二极铁

磁铁测量

生产说明书

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1. GENERAL / 概述

This specification describes the magnetic measurements required to qualify the prototype and the individual dipole production magnets fabricated and measured at IHEP for delivery to SLAC and installation in SPEAR3. This document is presented in both English and Chinese text; in case of differences, the English version shall be used.

本说明概述了高能所为SLAC制造的SPEAR3二极铁样机和每一块生产铁的磁测要求。本说明有中、英文两种文字，如有不同，以英文为准。

1.1 Scope of the Specification / 说明书范围

This specification describes the minimum requirements for the magnetic measurement for the SPEAR3 prototype and production gradient dipole magnets. IHEP measurements shall include a sweeping compensated line integral coil measurement to determine the quality of the line integral field and a Hall probe measurement to characterize the saturation behavior of individual magnets. This specification outlines the good field region required for the magnets and the minimum line integral field linearity. Required production magnetic conditioning procedures and measurements for the full quantity of magnets are described. Suggested means of optimization of the pole end chamfer on the prototype magnet to achieve a minimum field integral linearity level are described in engineering note M307. The sweeping compensated line integral coil geometry, measurement system configuration and the suggested measurement and data reduction algorithms are described in engineering note M323.

本说明概述了SPEAR3梯度二极铁样机和生产铁磁测的基本要求。高能所应作的二极铁磁测为两项，第一项是横向平移补偿线积分线圈测量，通过这项测量可确定磁铁场的线积分质量；第二项是霍尔片测量，通过这项测量可判断每块铁的饱和特性。本说明书还提出了磁铁对场的线积分分布线性度有要求的好场区以及生产铁的标准化循环和实际测量规范。建议采用的为达积分场线性度最低要求在样机铁上进行优化端部削斜的方法和横向平移补偿线积分线圈的几何结构 、 测量系统构━煲━及建议采用的测量和数据处理的算法分别另纸在工程设计说明书M307和M323中做了详细介绍。

1.1.1 Applicable Document / 使用文件

Engineering Note M307 工程设计说━书M307	Gradient Dipole Magnet Chamfer Development Procedure 梯度二极铁端部削斜实验工艺
Engineering Note M323 工程设计说明书M323	Gradient Measurement Coil Design 梯度场测量线圈设计

1.1.2 Reference Document / 参考文件

Engineering Note M319 工程设计说明书M319	Gradient Dipole Magnet Design Summary 梯度二极铁设计总括

1.2 IHEP Scope of Work / 工作范围

IHEP shall measure the field integral distribution for the prototype magnet, collaborate with SLAC to develop an optimized chamfer which satisfies the field integral distribution requirements and perform final measurements of the prototype magnet for approval at SLAC prior to manufacturing the production quantities of gradient magnets. IHEP shall measure the field integral distribution for all production gradient magnets. IHEP shall also measure the saturation behavior of the central field (at 50mm gap) of the gradient magnet as a function of magnet current using a fixed Hall probe.

高能所在正式开始批量铁的生产之前应与SLAC合作，首先在━机铁上开发出符合场的线积分分布要求的端部削斜形状，对样机进行全面终检测量，将结果交SLAC核审。高能所应测量所有生产铁的积分场分布情况和用固定霍尔片测量梯度二极铁中心场（50毫米契隙处）相对于电流的饱和特性。

2. MEASUREMENTS TOOLING / 测量工具

2.1 Field Integral Measurement Tooling / 积分场的测量工具

SLAC shall design and fabricate two (2) sets of sweeping compensated line integral coils. The engineering design of this coil is described in engineering note M323. One set of coils shall be delivered to IHEP and the second shall be retained at SLAC. IHEP shall assemble a magnetic measurement system using the sweeping compensated integral coil to collect the raw output and reduce the measurement data. IHEP may use existing equipment if appropriate. If not already available, IHEP shall specify and purchase mechanical stages, motors, encoders, electronic devices, computers and interfaces, power supplies, current transformers or transducers and any other device(s) necessary to carry out the required measurements. The second set of compensated coils retained at SLAC will subsequently be used to verify prototype and production measurements on selected magnets. The coil configuration can measure gradient field integrals in the “uncompensated” mode and can measure the error field while rejecting the fundamental dipole and gradient field in the “compensated” mode.

SLAC负责设计和制造两套横向平移补偿线积分测量线圈。该线圈的工程设计在工程设计说明书M323中有详细解释。一套线圈留SLAC使用，另一套送高能所。高能所应建立一套与该线圈相匹配的测量系统，以收取测量数据和进行数据处理。如果高能所现有系统能够满足要求，也可不必另建新系统。如无可适用系统，高能所则应提出技术要求，并采购机械移动平台、电动机、编码器、电器设备和配套的计算机系统和接口软、硬━，电源、电流互感器或传感器以及其他所有完成磁测所必需的仪器、设备。留在SLAC的线圈将用于随後的样机鉴定测量和批量铁抽验。SLAC所设计的线圈可在“非补偿”和“补偿”两种模式间切换。“非补偿”模式用于测量梯度积分场；“补偿”模式用于消除二极基波和梯度场（四极场），测量高阶误差场。

2.1.1 Data Correction / 数据修正

Means for correcting or compensating for the “drift” due to small DC voltages during the sweeping coil measurements shall be developed and described by IHEP. Means to correct for any power supply variation during the measurements shall be developed and described by IHEP.

由于微直流电压的影响，横向移动线圈测量过程中信号会产生“漂移”，高能所应在系统中加入修正或补偿“漂移”的手段。对于电源不稳定造成的数据偏差，高能所也应有相应的修正措施。高能所选取的该两项修正方法，都应━文字说明。

2.2 Hall Probe Measurement Tooling / 霍尔片测量工具

A second set of measurements will require a static Hall probe, mounted in a repeatable location in production magnets, in order to characterize the saturation behavior of each production magnet. Required tooling will include the Hall probe, its power supply and means of placing the Hall probe in a repeatable location in each of the production magnets.

第二项测量需使用一个非移动式（固定）霍尔片，在批量铁的某一固定位置测量、鉴定每块生产铁的饱和特性曲线。所需工具除霍尔片外，还包括它的电源装置和将霍尔片在磁铁内定位于某一固定位置的机械装置。

3 MAGNET FIELD REQUIREMENTS / 磁场质量要求

3.1 Field Quality / 场的质量

The nonlinear deviation of the line integral field from the linear field distribution (linearized via least square fit based on measurement data) at 630 Amps shall be less than ¡À 5x10^{-4} at the measurement location in the good field region. The good field region is -47 mm $\leq$ x $\leq$ 47 mm for 145D gradient dipole magnets and -42 mm $\leq$ x $\leq$ 42 mm for the 109D gradient dipole magnets from the 50mm aperture position. If it simplifies procedures, IHEP may choose the larger required good field region for both the 145D and 109D magnets.

激磁电流为630安培时，好场区范围内场的线积分的非线性部分与线性部分（测量数据经最小二乘法拟和所得直线）的偏差在每一测量点应小于5x 10^{-4}。145D铁的好场区宽是±47毫米，109D铁的好场区宽是±42毫米，契隙50毫米处为0点。如高能所为测量方便，两种铁采用统一测量宽度，则145D铁的好场区应被选作测量场宽。

3. 2 Deviations from Ideal Field Integral Distribution / 与理想场积分分布的误差

The fringe field length of the dipole field is generally longer than the fringe field length of the quadrupole field. The two dimensional design assumes that the effective lengths for both field components are equal. The prototype optimization process will attempt to define a chamfer for which the effective lengths are equal. However, limitations in the available thickness of the prototype inserts may not permit equal effective lengths. In that case, the optimization process will linearize the distribution of the field integral and attempt to reduce the integral of the nonlinear terms. The resulting dipole (at 50mm gap) effective length and quadrupole effective length may be slightly different from the design values specified in the design engineering note M319. This is not crucial to the operation of SPEAR3 since the lattice includes adjacent defocusing quadrupoles which can be tuned to compensate for any difference from the nominal tune resulting from different gradient magnet parameters. It is more important that the transverse distribution of the field integral is linear.

二极场的边缘长度通常比四极场的边缘长度要长。磁铁的二维设计假设这两种分量的有效长度相等。样机的优化端部削斜过程，也企图找出能使有效长度相等的端部削斜几何尺寸。然而，样机活极头的厚度可能会限制有效长度最终达到完全一致。如果出现这种情况，优化实验的目标可订为以达到积分场的分布呈线性为准，尽量消除非线性分量。最终的结果可能会是二极场(50mm契隙处）的有效长度和四极场的有效场度与工程设计说明书M319的设计指标有所不同。如果出现了这一情━也不要

紧，因为SPEAR3的拉梯斯计算在二极铁旁设了散焦四极铁，利用二极铁旁的这些四极铁可对二极铁性能数据进行调整。总之，相对予有效长度的绝对准确，积分场横向分布是否呈线性，更为重要。

3. 3 Saturation Characteristics / 磁铁的饱和特性

The magnet to magnet reproducibility of the production magnets depends on two characteristics of the magnets, their relative mechanical lengths and the saturation characteristics of the iron. Mechanical length tolerances are specified in the fabrication drawings for the magnet cores. The saturation characteristics are determined by the uniformity of the iron used in the cores for each magnet and the degree that the laminations are compressed (the packing factor). Lamination sorting and core fabrication specification of the packing factor are used as means for controlling the saturation characteristics of the magnet. Measurements of the saturation characteristics of the magnet using a Hall probe through the full range of excitation is required.

生产铁的一致性主要取决于两个因素：铁的相对机械长度和铁芯的饱和度。铁的机械长度的公差在铁芯图纸中作了规定。铁芯的饱和度取决于每块铁铁芯所用冲片钢板材料磁性能的一致性以及叠装时的叠装压力（叠装系数）。正因为如此，冲片的掺合和叠装系数都有明确要求。磁铁在各激磁强度下的饱和特性需用霍尔片测量检验。

3. 3.1 Saturation Tolerance / 饱和度误差

A Hall probe shall be carefully located in the same relative position in each magnet. Since the field distribution of a gradient magnet is not constant, it is understood that small variations in the location or the direction of the axis of the probe relative to the magnet coordinate axis will result in differences in the absolute field measured by the probe. Therefore, the results of the Hall probe measurements will be interpreted only to compare the deviation from linearity of the measurements from each magnet. The field from the measurement of each magnet will be normalized by a factor which makes the unsaturated (low field) characteristics of the magnets identical. For this normalized behavior, the saturation field for each magnet must not vary by more than $1x10^{-3}$ at 690 Amps (the approximate current for operation at 3.3 GeV).

霍尔片在每块被测铁中的定位应十分仔细，尽量保证相对重复。由于梯度二极铁的场不是恒定场，因而霍尔片微小的定位误差或其轴与磁铁坐标的相对方位偏离都会使场的绝对测量出现偏差。故铁与铁间，只对霍尔片测出的每块铁的饱和曲线的线性度作比较。也就是将每块铁所得场的测量结果乘以一个系数作标准化处理，使每块铁的饱和曲线在未饱和时（低场强）测得的特性值起始于同一坐标点。在励磁电流为690安培（3.3Gev时的大约电流强度）时，铁与铁间经标准化处理后的饱和度值的差别不一大于$1x10^{-3}$。

4. MEASUREMENT At IHEP/ 高能所应作测量

IHEP shall perform the following measurements on all production magnets.

生产铁在高能所应作的测量项目如下。

4.1 Field Linearity Measurements / 场线性度测量

Each magnet shall be conditioned by raising the current to 110% of the nominal design current (690x1.1=760 Amps) three times and returning the current to zero prior to adjusting the current to the measurement levels. The uncompensated and the compensated measurements shall be performed by sweeping the line integral coil transversely along the magnet central plane ±50 mm from the nominal center of the 145D magnet and ±45 mm from the nominal center of the 109D magnet (the transverse range is slightly larger than the required good field region width for each magnet) to measure gradient field integrals and the error field, respectively. These measurements will be performed at 630 Amps and 690 Amps.

每块磁铁在调整到测量电流进行测量前，都应经三次从零电流升至760安培（110％于690安培设计电流）再回零的标准化循环。测量电流为630安培和690安培两个电流强度，测量模式为横向平移线积分线圈的非补偿和补偿两种，分别测量梯度场积分和高阶误差━。测量线圈应从磁铁的标称中心开始沿145D或109D磁铁的水平中心面横向做±50毫米或±45毫米移动（移动范围比好场区稍大）。

4.2 Saturation Behavior Measurements / 饱和特性测量

A Hall probe will be approximately placed at the longitudinal center of each magnet within 0.5 mm transversely and vertically of a fixed position for each magnet. Each magnet shall be conditioned by raising the current to 110% of the nominal design current (690x1.1=760 Amps) three times and returning the current to zero prior to adjusting the current to the measurement levels. Hall probe measurements shall be made at 10 evenly spaced current levels between zero and 630 Amps (approximately 63 Amp increments). Six more measurements shall be made at evenly spaced current increments between 630 and 690 Amps (10 Amp increments). The settings may be approximate, but the current measurements should be made to five significant figures (0.01 Amps).

将霍尔片放入磁铁大约纵轴中━的位置，其在每块铁中的放置位置X和Y方向应基本重复在0.5毫米内。每块磁铁在调整到测量电流进行测量前，都应经三次从零电流升至760安培（110％于690安培设计电流）再回零的标准化循环。霍━片测量电流为0到630安培间10个均分点（大约为每63安培一个梯度）。在630至690安培间再测6个均分点（约10安培一个梯度）。电流的设置可能每次都有少许出入，但电流的读数应为5个有效数字（0.01安培）。

5. PROTOTYPE MAGNET / 样机铁

A prototype magnet shall be built with a sufficient number of pole inserts in order to iterate and optimize a pole end contour which will satisfy the field linearity requirements for the family of gradient magnets.

在制造样机的同时，应加工出足够数量的活极头供反复实验、修改端部削斜方案,直至获得梯度二极铁所要求的场线性度。

5.1 Prototype Chamfer Development / 样机端部削斜实验

The measurement described in section 4.1 of this shall be performed to characterize the field quality for the unchamfered prototype (at 630 Amp only) and the prototype with the optimized chamfer. The optimization current is 630 Amps (the approximate current for operation at 3.0GeV) and measurement region shall be ¡À 55mm from the nominal center of prototype magnet. Engineering Note M307 and Section 5.1 of the specification PS 444-400-02 describe suggested means for determining the geometry of the chamfer which will satisfy the field integral distribution desired for the prototype.

样机在使用未经削斜的活极头时（只测630安培时的性能）和最後装入按削斜终方案加工的活极头后都应实施本说明款4.1所述测量。优化按630安培电流测量所得值进行（3.0Gev运行能量时的电流），测量范围为样机铁标称中心±55mm。工程设计说明书M307和生产说明书PS444-400-02款5.1详细解释了建议采用的确定样机最终符合积分场分布要求的端部削斜几何形状的实验过程。

5.2 Prototype Chamfer Design Acceptance / 样机端部削斜方案确定

Upon satisfaction of the line integral field linearity requirements outlined in section 3.1 of this specification, a second and third line integral field linearity measurement shall be made on the prototype magnet excited to 690 Amps and 550 Amps. A tabulation of the final chamfer shape dimensions and a hardcopy and an electronic copy stored on a floppy disk of the measured data at 550, 630 and 690 Amps shall be delivered to SLAC for evaluation and approval. Fabrication of the production magnet cores shall not proceed until the chamfer development process has been completed and the final chamfer shape and prototype performance has been evaluated and approved by SLAC.

在样机获得符合本说明款3.1所要求的场线积分线性度后，再加测其在690安培和550安培励磁电流时的场线积分分布的线性度。高能所需提供最後确定的极头形状的点坐标值表以及存有550, 630和690安培三个场强下的测量数据的磁盘和文本复印件供SLAC审核、批准。在SLAC没有批准最后削斜方案之前，生产铁的铁芯制造不可开始。

6. PRODUCTION MAGNETS / 生产铁

6.1 First Production Magnet / 第一块生产铁

Production magnets may exhibit small differences from the prototype magnet since they will be constructed using sorted laminations and will not have solid steel inserts but will have the chamfer shape cut directly on the two glued end packs. Although the field linearity performance is expected to closely reproduce the performance of the prototype, SLAC will want to verify the performance of the first production magnet as soon as possible. As soon as the first production 145D and 109D magnet assemblies are completed, IHEP shall conduct the measurement called out in section 4.1 of this specification and immediately forward the results of the measurement to SLAC for evaluation.

生产铁的铁芯是用经掺合的芯片叠装的，极头是用粘接芯片加工而成，而不是如样机为实心铁块活极头，故生产铁的磁性能可能会与样机有微小差别，但是预期场的线性度与样机不会有大的出入。尽管如此，SLAC还是希望能尽快得到第一块生产铁的磁测数据。高能所第一块145D和109D磁铁的机械制造完工之后，应立即按本说明书款4.1要求测磁，并将测量数据尽快发SLAC评估。

6.2 Production Magnet Acceptance / 生产铁验收

In order to promptly correct any fabrication or assembly problems, magnetic measurements of gradient dipole magnets shall proceed as soon as a production magnet has been assembled. The backlog of assembled but unmeasured dipole magnets shall be no more than five (5) magnets. Satisfaction of the requirements shall be indicated on the magnet assembly traveler by a dated signature of the magnetic measurement engineer in charge.

为了尽快发现可能的制造或装配问题，每块梯度二极铁的测量应在总装完成后立即进行。完工待测铁的库存量不应超过5块。磁测合格的铁，应在磁铁总装跟踪卡上注明，并由磁测执行人签名和日期。

6.2.1 Identification / 磁铁身份号

Measurement data from all magnets shall be referenced to the identification serial number for each magnet. The date that measurements were performed, the ambient temperature during measurements, and names of key personnel performing the measurements shall be listed with the data for each magnet. For magnets approved for shipment, the assembly traveler shall be signed and dated by the magnetic measurements supervising engineer.

每块铁的磁测数据应以该铁的身份号牵头。测量时的环境温度和主要操作人员的姓名和日期，需与数据同时列入测一记录表。检验合格准备发运的磁铁，其总装跟踪卡应有磁测负责人的签名和日期。

6.2.2 Corrections / 返工

In case the field linearity or the saturation characteristics for any magnet does not satisfy the requirements outlined in sections 3.1 and 3.3 in this specification, IHEP shall perform a careful mechanical inspection of the core to determine whether the chamfer satisfied mechanical tolerances and/or the core stacking factor satisfied requirements. The indicated corrections shall be made and the magnetic measurements shall be repeated. This procedure shall be repeated until the magnet satisfies the requirements. All corrections made on the magnet shall be noted in the magnet assembly traveler which accompanies each magnet.

如果任何一块磁铁的场分布或饱和性能不符合本说明书款3.1和3.3的要求，高能所应对铁芯的机械质量进行认真复查，看削斜尺寸是否符合公差要求，或者是否达到了要求的叠装系数。在一施相应的改进措施后，需对该铁进行复测。这一过程需反复，直至铁的质量达到要求。所有返工措施和过程都应在该铁的跟踪卡内留有记录。

6.2.3 Rejections / 报废

If corrections described in section 6.2.2 do not result in magnets which satisfy the linearity or saturation characteristic requirements, SLAC shall be notified promptly, and plans and procedures for necessary correction of production procedures shall be mutually negotiated between technical personnel at IHEP and SLAC. Problems which are not easily corrected may require rejection of the magnet in question or some of its components and/or temporary suspension of a portion of the production effort until satisfactory corrective plans are developed.

如果6. 2. 2款所述返工不能使铁达到场分布或饱和特性要求，应立即通知SLAC，高能所和SLAC的技术代表需立即磋商，共同找出解决问题的方法。如该铁实在无法修补，应予整体或部分报废；或暂时━置一旁，直至找出补救方法。

6.3 Data Achieving, Storage and Transfer / 数据获取、留存和转交

All measurement results shall be filed in hardcopy and on magnetic media and archived at IHEP in duplicate. One set of measurements on hardcopy and an electronic copy of measurements on magnetic media shall be shipped to SLAC along with delivered magnets. More frequent data transfer is encouraged.

所有测量数据应有文本拷贝和磁盘拷贝两种文本，在高能所复制存档。一套两种文本的复制件应随磁铁的发运交SLAC。如果磁测数据能不按批量、先于磁铁发货交递则更为理想。

7. MEASUREMENTS at SLAC/ SLAC测量项目

7.1 Prototype Measurement / 样机测量

7.1.1 Prototype Field Integral Linearity / 样机积分场线性度

The deviation of the prototype field line integral distribution from the ideal field integral distribution shall be verified by sweeping a single wire transversely along the magnet central plane ±50 mm from the nominal center of the prototype at SLAC using wire system.

SLAC负责用单导线测量系统测量样机场的线积分分布与理想设计分布的偏移值。测量时单导线沿样机水平中心面在±50毫米范围内横向平移。

7.1.2 Prototype Verification / 样机复检

A sweeping compensated coil measurement shall be repeated at SLAC to verify prototype magnetic field quality described in section 3.1 in this specification.

SLAC按本说明书款3. 1用横移补偿线圈复检样机磁场质量。

7.2 Production Measurement / 生产铁测量

7.2.1 Transfer Function / 传导函数

The integrated dipole field transfer function shall be measured at SLAC.

SLAC应测量积分二极场传递函数。

7.2.2 Magnet to Magnet Transfer Function Reproducibility (SLAC)

Magnet to magnet dipole field transfer function reproducibility measurements shall be performed at SLAC.

SLAC负责二极场传导函数铁间一致性测量。

7.2.3Verification / 复检测量

Verify production magnet magnetic field quality using sweeping compensated coils retained at SLAC.

用留在SLAC的横移补偿线圈对生产铁磁场质量进行抽检。

7.3 Fiducial Locations / 定标测量基准

The measurement of the transfer function at SLAC shall be used to adjust the fiducials used for final magnet alignment.

SLAC的传导函数测量值将用来确定磁铁准直基准。