STANFORD LINEAR ACCELERATOR CENTER

SPECIFICATION

STANFORD SYNCHROTRON RADIATION LABORATORY

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Title:
Quadrupole Magnetic Measurements

Quadrupole

Magnetic Measurements

Specification

四极铁

磁场测量

生产说明书

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SPEAR3 SPEC QUAD MAG MEAS

1. GENERAL/ 概述

The quadrupole magnetic measurement effort is divided among IHEP and SLAC. This document specifies the measurements required at IHEP and describes the complementary measurements that will be performed at SLAC. This document is presented in both English and Chinese text; in case of differences, the English version shall be used.

四极铁的磁测由高能所和SLAC共同承担。本说明概括了高能所需进行的磁测项目以及SLAC的辅助测量。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 quadrupole magnets. Required measurements at IHEP include a rotating compensated integral coil (thereafter call rotating coil) measurement to determine the quality of the line integral field and a magnet ramping measurement using a bucking magnet to determine the reproducibility of magnets. This specification outlines the good field region, minimum line integral field quality in this region, reproducibility and location of the magnet axis requirements. Required production magnetic conditioning procedures for the full quantity of magnets are described.

本说明书解释了SPEAR3四极铁样机和生产铁最基本的磁测要求，高能所应进行的测量包括用补偿积分旋测线圈（以後简称为旋测线圈）测量磁铁线积分场的质量和用斜坡电流测量方式通过一块反抵磁铁测量磁铁的一致性。本说明书对好场区，好场区内线积分场质量最低要求，铁的重复精度以及铁的磁中心偏差要求都做了说明。同时也阐述了生产铁测量的标准化循环要求。

1.1.2 Reference Document / 参考文件

Engineering Note M320	Quadrupole Engineering Design Summary
工程说明书M320	四极铁工程设计总括

1.2 Scope of Work / 工作范围

IHEP shall design and fabricate rotating coils for quadrupole measurements. IHEP shall measure the integrated multipole error spectrum of the prototype magnet and submit the results to SLAC for approval prior to manufacturing the production quantities of quadrupole magnets. IHEP shall measure the integrated multipole error distribution and determine the offset of the magnetic center from the rotational center of the measurement coil for all production quadrupole magnets. IHEP shall measure the reproducibility of production magnets using the magnet ramping technique and bucking magnet.

高能所应设计和制造四极铁测量用的旋测线圈。高能所应测量样机的多级分量积分值，将测量结果交SLAC，由SLAC审核批准生产铁的正式投产。高能所应测量所有生产铁多级分量的积分分布，确定磁中心相对于旋测线圈中心的偏离。高能所还应用斜坡电流和使用反抵磁铁的方式实施生产铁的一致性测量。

1.2.1 Field Integral Measurement Tooling / 场积分测量工具

IHEP shall design and fabricate two (2) sets of rotating coils. One coil shall be delivered to SLAC and the second shall be retained at IHEP. IHEP shall assemble a magnetic measurement system using the rotating 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 any device(s) necessary to carry out the required measurements. The second set of compensated coils delivered to SLAC will subsequently be used to verify prototype and production measurements on selected magnets. The coil shall be configured so that uncompensated as well as compensated measurements can be made.

高能所应设计和制造两（2）个旋测线圈。一个线圈发SLAC，一个线圈留高能所使用。高能所应建立与其匹配的相应测量系统，取数和处理数据。高能所可使用现有的适用设备。如无现成合用设备，高能所应采购所有测量工作所需仪器、设备。发至SLAC的线圈将用于复测样机和抽测生产磁铁。线圈的结构应可在补偿和非补偿两种模式间切换。

1.2.1.1 Measurement System and Procedure Tolerance / 测量系统自身和工作精度

The rotating coil shall be fabricated so that its axis is collinear with the housing axis within 0.100 mm. Measurements shall be made to identify the offset of the rotating coil axis with respect to the housing within 0.025mm. Installation of the rotating coil housing in the magnet shall be repeatable within 0.025 mm.

旋测线圈的制造应能保证其旋转中心与外筒的偏心度小于0.100毫米。偏心度的测量误差应在0.025毫米内。旋测线圈外筒在磁铁内的重复定位精度应小于0.025毫米。

1.2.1.2 Data Correction / 数据修正

Means for correcting or compensating for the "drift" due to small DC voltages during the measurements shall be developed and described by IHEP. If adequate power supply stability cannot be maintained during measurements, means to correct for any power supply variation during the measurements shall be developed by IHEP.

由于测量产生的是微直流电压信号，故其会出现“漂移”现象，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。

1.2.2 Magnet to Magnet Reproducibility Measurement Tooling / 铁间一致性测量工具

Paired coils used to determine magnet to magnet reproducibility shall be either fabricated by IHEP or assembled using existing coils.

高能所负责或用现有线圈改造，或制造对儿线圈用以测量铁间一致性。

2. REQUIREMENTS / 场质量要求

2.1 Tolerance of the Field Integral Distribution / 场线积分分布误差

The field quality requirements for prototype and production magnets are defined in terms of multipole errors evaluated at the good field radius. The integrated allowed and unallowed multipole error field normalized to the fundamental field at 32 mm radius shall be less than $5x10^{-4}$ and $3x10^{-4}$ when main coils are excited at the magnet operating current, respectively. Measurements shall also be made at the magnet design current to determine if there are any changes in the field quality. The same multipole field quality requirements shall be satisfied when the modulation system coils (QMS coil) are excited at their design currents.

样机和生产铁的场的质量以好场区范围内多级分量误差值为衡量标准。在主线圈为磁铁运行激磁电流值时，32毫米半径处场的系统和随机多级分量积分值与四极分量之比应分别不大于$5x10^{-4}$和$3x10^{-4}$。按磁铁设计电流激磁时的场的质量也应进行测量，以确认场的质量是否会有变化。调制(QMS)线圈在设计电流激磁时，磁铁应能达到同样的场质量。

2.1.1 Magnet Currents / 磁铁电流

The quadrupoles are divided among four groups 15Q, 34Q, 50Q and 60Q. They are designed for higher excitation in order to provide for possible future upgrade. The operating and design currents for various length quadrupole magnets are:

四极铁分为四组，分别为15Q，34Q，50Q和60Q。考虑到将来加速器可能的升级，它们的设计电流都高于运行电流。各组四极铁的运行和设计电流如下表：

Quadrupole Type **磁铁名**	**Operating Currents** 运行电流	**Design Currents** 设计电流
15Q, 34Q & 50Q	81 Amps	89 Amps
60Q	68 Amps	75 Amps

2.1.2 Modulation System Design Currents / 调制系统设计电流

The modulation system design current for 15Q, 34Q, 50Q and 60Q magnet is:

15Q，34Q，50Q和60Q调制系统设计电流为:

Quadrupole Type	**15Q**	**34Q**	**50Q**	**60Q**
Design Currents (DC)	17 Amps	12 Amps	7 Amps	4 Amps

2.1.3 Polarities / 极性

The power connection for all magnets should be connected using the appropriate magnet polarities prior to conditioning and exciting for measurements. Modulation system power supply connections should be made with the same polarities as the main coils for individual magnets. The polarities of quadrupoles among 4 groups are:

磁铁标准化循环和通电测量之前，电源的连接要符合被测铁的极性要求。调制线圈的电源也应按被测磁铁主线圈的极性连接。各组四极铁的极性如下：

磁铁名	15Q	34Q	50Q	60Q
Focussing 聚焦铁数量		33	20	6
Defocussing 散焦铁数量	30	13		

2.2 Magnet to Magnet Reproducibility Tolerance / 铁间一致性误差

The integrated quadrupole field shall not vary by more than $1x10^{-3}$ (+/- $5x10^{-4}$ variation from the mean) among all the magnets of a given length at the operating current.

运行场强下，每组内四极铁之间积分四极场的不一致性不应大于$1X10^{-3}$（平均值的$\pm 5X10^{-4}$）。

2.3 Magnet Center / 磁中心

The measured offset of magnetic center of all production quadrupole magnets shall be within a radius of 0.05mm.

所有生产四极铁所测磁中心偏离值都应不超出0.05毫米半径范围。

3. MEASUREMENTS / 测量

3.1 Supporting Documentation / 支持文件

3.1.1 Field Uniformity / 场均匀性文件

Supporting documentation for the field uniformity measurements shall include details of the measurement coil engineering design, including the positions of the various coil bundles and the number of turns in each bundle. The computed dipole and quadrupole absolute sensitivity (using theoretical dimensions) and the relative sensitivities to the error multipoles in the bucked configuration shall be tabulated. Means for correcting the "drift" and any power supply variation during the measurements shall be described. Sketches shall be included which describe the orientation of the coil drive axis, identify the coordinate axes of the measurements with respect to the magnet features (i.e. the location of the power busses) and the rotation direction of the measurement coil.

场均匀性测量的支持文件应包括测量线圈物理和机械设计的详细说明，其中包括线圈各扎的位置和每扎的匝数。二、四极分量的计算绝对敏感度（用线圈的理论尺寸）和反抵模式时多级分量的相对敏感度应列表说明。测量中所采用的修正"漂移"和电源不稳定造成的数据偏差的手段。同时还应附有示意图，说明线圈转轴的方位，所取的相对于磁铁某一部件（如电源母板）建立的测量坐标轴以及测量线圈的旋转方向。

3.1.1.2 Rotating Coil Positioning / 旋测线圈的定位说明

The measurement coil housing shall be indexed to the top poles of the magnet using a pair of sleeves located at repeatable longitudinal positions at each end of the magnet. A second pair of sleeves shall be fabricated and delivered to SLAC. The offset of the rotating coil axis using the two pairs of sleeves shall be measured. The offset and the

longitudinal position of each sleeve information shall be sent to SLAC.

测量线圈的外筒应通过放置在磁铁前后两端重复位置的一对半瓦片座靠在四极铁的上极头上。高能所应生产两套瓦片，其中一套作为旋测线圈的附件发SLAC使用。高能所应测量旋测线圈使用两套瓦片的定位偏差度，偏差度数据和瓦片在磁铁内的纵向位置都应提供给SLAC。

3.1.2 Reproducibility / 一致性

Supporting documentation for the reproducibility measurements shall include details of the measurement coil engineering design, including the positions of the various coil bundles, the number of turns in each bundle and the computed quadrupole absolute sensitivity (using theoretical dimensions). The identification number of the bucking magnet and standard magnet shall be identified.

场一致性测量的支持文件应包括测量线圈物理和机械设计的详细说明，其中包括线圈各扎的位置和每扎的匝数、四极分量的计算绝对敏感度（用线圈的理论尺寸）。所用反抵磁铁和标准磁铁的身份号。

3.2 Field Uniformity and Magnetic Center Measurements / 场均匀性和磁中心测量

Each magnet shall be conditioned prior to the measurements. The magnets need not be reconditioned before measurements at each current level. Uncompensated mode of the rotating coil shall be used to measure the quadrupole and dipole components of the magnet field. The result of real and skew components of the dipole field shall be used to compute the offset of the magnetic center of the tested magnet from the rotational center of the measurement coil. Compensated mode of the rotating coil shall be used to measure the multipole errors.

测量之前，磁铁应做标准化循环。磁铁在各场平测量前，不需再做标准化循环。旋测线圈的非反抵模式用来测量磁铁的四、二极场；所得二极场的正、斜极矩用来计算被测铁相对于旋测线圈旋转中心的偏离。反抵模式用来测量多极分量误差。

3.2.1 Conditioning Cycle / 标准化循环

Prior to measurements, each magnet shall be conditioned by raising its current to 110% of its design current three times and returning to zero. The current rate of rise and return to zero shall be approximately linear (avoid step functions) and shall take no less than 10 seconds per cycle. The maximum conditioning current (110% of design current) shall be:

每块磁铁测量前，须经标准化循环。其激磁电流应升至设计电流的110%而後回零，如此反复三次。电流的提升和回零应相对呈直线（避免阶梯作用），各循环不应低于10秒。各铁标准化循环最大电流（110%于设计电流）为：

Quadrupole Type **磁铁名**	**Max. Conditioning Currents** 最大标准化循环电流
15Q, 34Q & 50Q	98 Amps
60Q	83 Amps

3.2.2 Measurement Currents for Main Coil /主线圈的测量电流

Uncompensated and compensated measurements shall be made at main coil currents at:

反抵和非反抵测量模式主线圈的测量电流如下：

Group	15Q	34Q	50Q	60Q
Main Coil (Amps)	61, 71, 81 and 89			50, 60, 68 and 75

3.2.3 Measurement Currents for Modulation System Coil/ 调制系统线圈的测量电流

Uncompensated and compensated measurements shall be made at modulation system coil current at:

反抵和非反抵测量模式调制线圈的测量电流如下：

Group	15Q	34Q	50Q	60Q
QMS Coil (DC Amps)	17	12	7	4

3.2.4 Measurement Results / 测量结果

The raw unbucked and bucked integrator output before performing Fourier analysis shall be stored in magnetic media and kept at IHEP. The raw data should include identifying information (magnet serial number, date, time, ambient temperature and operator).

在做傅利叶分析之前积分器输出的原始非反抵和反抵数据应由高能所磁盘存档。原始数据应包括鉴别资料（磁铁身份号，日期，时间，环境温度和测量人员）。

3.2.5 Tabulated Results / 表格数据

The tabulated results for each measurement shall include, at minimum, the data described in section 3.2.5.1 and 3.2.5.2 along with identifying information (magnet serial number, date, time, ambient temperature and operator).

每项测量的表格数据除去鉴别资料（磁铁身份号，日期，时间，环境温度和测量人员）外，至少应包括条款3. 2. 5. 1和3. 2. 5. 2所述数据：

3.2.5.1 Results of Uncompensated Measurements / 非反抵测量数据

Measurement current, drift counts, dipole and quadrupole integrator counts, integrated fields (using computed coil sensitivities), their absolute phases with respect to coil horizontal axis at start of rotation. X, Y and magnitude of the offset of magnetic axis from the coil axis.

测量电流，漂移计数，二、四极分量积分器计数，场积分（使用线圈敏感度计算值），它们相对于线圈在起始位置时水平轴的绝对相角，磁中心相对于线圈旋转轴的X，Y位移。

3.2.5.2 Results of Compensated Measurements / 反抵测量数据

Measurement current, drift counts, quadrupole bucking ratio, normalizing radius, integrator counts, computed multipole normalized to the fundamental quadrupole and

phases relative to the quadrupole zero phase on the positive magnet x-axis for all multipole error terms from n=3 to n=18.

测量电流，漂移计数，四极反抵比，归一化半径，积分器计数，多极分量相对于基础四极分量的计算比值，和所有n=3至n=18极分量相对正接磁铁X轴四极分量0相位的相角。

3.3 Reproducibility Measurements / 一致性测量

Each magnet shall be conditioned using the conditioning cycle described in Sec. 3.2.1 prior to making the reproducibility measurements. Magnet to magnet reproducibility measurements shall be made with a bucking magnet using the magnet ramping method for each production magnet at the currents specified in section 3.2.2 for each group of magnet. These measurements shall be compared to the same measurements made with a "standard" magnet in series with the same bucking magnet.

每块铁在一致性测量前，都应按3.2.1款所述进行标准化循环。每块生产铁都要做铁间一致性测量。测量应使用一个反抵磁铁，用加斜坡电流方式进行。各组铁应加的斜坡电流见条款3.2.2。各场平所得测量数据应与一块与反抵磁铁串接的"标准"铁所做同样测量得到的数据进行比照处理。

4. PROTOTYPE MAGNET / 样机

An end chamfer has been developed at SLAC using a three dimensional magnet code. This chamfer is specified in the core assembly drawing and is expected to result in a three dimensional fringe field distribution that will satisfy the line integral field quality requirements for all the length variations of the SPEAR3 quadrupoles. It is planned that the prototype magnet will be a 34Q quadrupole. The measurement described in Section 3.2 of this specification shall be performed on the prototype.

SLAC用三维程序计算出了四极铁的端部削斜几何尺寸。铁芯图纸中给出的既是这一计算图形，预计其能对边缘场的分布起到补偿作用，满足SPEAR3所有长度的四极铁的线积分场质量要求。计划样机为34Q铁，完成后，应按本说明3.2款的测量要求进行测量、检验。

4.1 Prototype Chamfer Design Acceptance / 样机端部削斜设计确认

The results of the prototype measurements shall be analyzed at IHEP and forwarded to SLAC for approval. Chamfer machining of the production magnets shall not proceed until SLAC acceptance of the prototype performance has been obtained.

高能所应对样机测量数据进行分析，将结果呈SLAC审核。生产铁的削斜在SLAC确认设计无误之前不可进行。

4.2 Alternate Chamfer Shape / 削斜替换方案

If, for any reason, the SLAC suggested chamfer results systematic error multipoles that fail to satisfy the field quality requirements for the quadrupoles, SLAC shall provide an alternate chamfer shape that can be machined on the same prototype. This chamfer shape will remove

more material than the suggested prototype chamfer shape. This alternate shape is scaled from the ALS and PEPII quadrupoles and its performance (though not as good as the SLAC suggested chamfer) has been measured for the production quantities of these magnets and will satisfy SPEAR3 requirements. Chamfer machining of the production magnets shall not proceed until SLAC has accepted the final prototype performance.

万一SLAC建议采用的端部削斜方案没能满足四极铁高阶系统误差的要求，SLAC将提供另一可在同一样机上继续往深里加工的削斜方案。这一替补方案放样于PEPII和ALS四极铁的设计，并且经过批量铁的测量，应能满足SPEAR3铁的要求（尽管不如SLAC所建议的方案理想）。在SLAC最後确定削斜方案之前，生产铁不可开始加工端部削斜。

5 PRODUCTION MAGNETS / 生产铁

Acceptance of the chamfer shape is based on the performance of 34Q prototype magnet. It is expected that this same chamfer, used for all quadrupole lengths, will result in acceptable performance for all magnets. However, there may be some small differences in the performance of the three remaining different length quadrupole magnets. Because of this, measurements of the first article of 15Q, 50Q and 60Q quadrupoles should be made by IHEP prior to machining the chamfers on the remaining production magnets of these lengths.

根据34Q样机铁测量结果所确定的端部削斜设计将用于所有其他长度的四极铁，预计场的质量应能满足要求。不过三种其他长度的四极铁的表现会有些许的不同。因此，高能所只有在对15Q，50Q和60Q的第一块生产铁测量后，方可开始该种铁批量削斜生产。

5.1 Production Magnet Acceptance / 生产铁验收

In order to promptly correct any fabrication or assembly problems, magnetic measurements of quadrupole magnets shall proceed as soon as a production magnet has been assembled. The backlog of assembled but unmeasured quadrupole 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，每块四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。

5.1.1 Corrections / 返工

In case the field quality or reproducibility measurement for any magnet does not satisfy the requirements outlined in sections 2.1, 2.2 and 2.3 and their subsections 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 and assembly tolerance satisfied requirements. The 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 that accompanies each magnet.

如果任何一块磁铁的场的质量获重复精度不符合本说明书款2.1, 2.2, 2.3及其子条款的要求，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和总装精度。在实施相应的改进措施后，需对该铁进行复测。如仍未达到要求，需再修、再测，直至合格。所有返修过程都应在该铁的跟踪卡上做记录。

5.2 Rejections / 报废

If corrections described in section 5.1.1 do not result in magnets which satisfy the magnetic quality or reproducibility 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5.1.1款所述返工不能使铁达到场质量或重复精度要求，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；或暂时搁置一旁，直至找出补救方法。

5.3 Data Archiving, Storage and Transfer / 取数、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。

6. SLAC Measurements / SLAC测量项目

6.1 Field Quality / 场质量

SLAC shall measure and verify the field quality of approximately 20% of the production magnets delivered from IHEP using the IHEP supplied rotating compensated line integral coil.

用高能所提供的旋测线圈，SLAC对大约20%的生产铁抽检场质量。

6.2 Transfer Function / 传递函数测量

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

SLAC应测量积分四极场传递函数。

6.3 Magnet to Magnet Transfer Function Reproducibility / 铁间传递函数一致性

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

SLAC实施铁间四极场传递函数一致性测量。

6.4 Fiducial Locations / 定标位置

SLAC shall measure the location of the fiducial balls using the mechanical axis of the quadrupole as the datum. If there are significant differences among the magnetic center offsets of production quadrupoles, the fiducial coordinates shall be adjusted.

利用四极铁的机械中心为基准，测量准直测量球靶的位置。如果生产四极铁磁中心的离散度太大，每块铁的准直坐标都应予以调整。