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# PROPOSAL FOR MEASURING THE MAGNETS OF THE SLS

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PSI

This is a preliminary version of the proposal, and the time schedule is not attached. After all the magnets for the storagering and the booster have been ordered, the final version will be issued.

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# 1 Introduction

The **S**wiss **L**ight **S**ource (SLS) consists of the electron gun and three separate accelerators. The first accelerator in the row is a 100 to 150 MeV **L**inac (L), ordered as a “turn key” system. For the **B**ooster (B), which accelerates the electrons up to 2.4-GeV, the magnets have been offered and placing the order is imminent. For the correctors in the booster a separate tender will be issued. The beam, extracted from the booster will be injected into and stored in the **R**ing (R), from now on referred to as the storage ring. The tender request for the magnets and supporting girders has been issued and recently several offers received. The two transferlines – **L**inac/**B**ooster (LB) and **B**ooster/**R**ing (BR)– are only roughly drawn up, and therefore the procurement of their elements has not started.

The magnets – dipoles; multipoles; i.e. quadrupoles and sextupoles, and x- and y-correctors – will be fabricated by different firms. Magnet measurement is an essential part of component-tests for low emittance synchrotrons in order to ensure the required beam quality. For the magnets of both accelerators prototypes will be ordered to verify the magnet design, and to determine the end profile (chamfer) of the dipoles and the multipoles. The series magnets must be measured during production in order to spot promptly any deviation in their field quality, and to initiate the necessary corrective actions in the fabrication process. Further, these measurements must establish the relation between magnetic axes and planes of the magnet to its fiducial references for alignment in both synchrotrons and transferlines. Finally some sorting process, based on the results of the measurements, must be applied, to minimize unwanted effects on the beam.

# 2 The assignment

The different magnets — dipoles, multiples and correctors —foreseen to be installed in the two accelerators and in both transferlines are listed in Table 1.

| | | TLB | Booster | TBS | Storage ring | # |
|---|---|---|---|---|---|---|
| Dipoles | $n \neq 0$ | | 93 | | | 93 |
| | $n = 0$ | 2 | | 3 | 36 | 41 |
| All dipoles together | | | | | | **134** |
| Quadrupoles | | 11 | 18 | 7 | 174 | 210 |
| Sextupoles | | | 18 | | 120 | 138 |
| All multipoles together | | | | | | **348** |
| Combined | x and y | | 108 | | | 108 |
| Single | x or y | 5 | | 4 | | 9 |
| All dipoles together | | | | | | **117** |
| Total | | 18 | 237 | 14 | 330 | **599** |

Table 1: The production magnets for the SLS (March 1998).

However the total number of magnets to be measured is larger as given in Table 1. The grand total, as given in Table 2, includes the prototypes and the spare magnets too.

| | | TLB | Booster | TBS | Storage ring | # |
|---|---|---|---|---|---|---|
| Dipoles | Prototypes<br>In use<br>Spare | 2 | 2<br>93<br>2 | 3 | 1<br>36<br>2 | 3<br>134<br>4 |
| Quadrupoles | Prototypes<br>In use<br>Spare | 11<br>1 | 1<br>18<br>2 | 7 | 2<br>174<br>6 | 3<br>210<br>9 |
| Sextupoles | Prototypes<br>In use<br>Spare | | 1<br>18<br>1 | | 2<br>120<br>2 | 3<br>138<br>3 |
| Correctors | Prototypes<br>In use<br>Spare | 5 | 1<br>108<br>2 | 4 | | 1<br>117<br>2 |
| Grand total | | 19 | 249 | 14 | 345 | 627 |

Table 2: Magnets to be fabricated and measured.

The responsibility for the magnetic design rests for all magnets with PSI. Therefore the magnetic field measurement, the evaluation of the data and the shimming of all the prototypes should be performed under the leadership of PSI. Those prototype magnets which have been requested in the specifications are listed with their hardware name below in Table 3. It is at this time not known, whether any prototype magnet will be ordered for the transferlines.

| | TLB | Booster | TBS | Storage ring | Total |
|---|---|---|---|---|---|
| Dipoles | – | BD00, BF00 | – | BX00 | 3 |
| Quadrupoles | – | QS00 | – | QA00, QCW00 | 3 |
| Sextupoles | – | SB00 | – | SR00, SRW00 | 3 |
| Correctors | – | CH00 | – | - | 1 |

Table 3: The hardware name of the prototype magnets for booster and storage ring.

The tight reference time-schedule imposes severe conditions on the preparation of the measuring equipment and performing the required measurements. The lack of up to date magnet measuring devices at PSI led to this survey about the different possibilities to acquire the right tools to measure in time the prototype and series magnets of the SLS. This paper describe at first how the measurement of the 627 dipoles, multipoles, and correctors could be efficiently organized and carried out. Then it gives a survey of the available equipment, and gives an estimate of the manpower and in most cases the costs to perform the measurements. For the whole program a detailed and updated time schedule has been prepared and is presented here.

## 3 Measuring methods

The most popular methods of magnetic field measurement use the Hall effect and the principle of magnetic induction. At the moment PSI operates a well designed measuring bench, with a Hall probe movable in 3D on a precise coordinate table. The

outdated rotating-coil system is capable to measure the multipole content of quadrupoles only.
With Hall probes of quite small active area, e.g. $0.2\times0.2\ mm^2$, high accuracy can be reached; at low fields in the order of 0.5 Gauss, and at higher fields of at least $10^{-4}$. However each probe must be calibrated individually in a reference magnet e.g. against a NMR-probe, applying positive and negative field levels, because the non linearity is in the range of 0.2 to 2 %. Additionally the probe must be calibrated periodically to detect aging effects. The temperature sensitivity of probes is today in the range of 0.04 to 0.1 %/K, and therefore it must be compensated in the most cases by putting the sensor in a temperature stabilized casing. A less important role plays the planar Hall-effect arising from the difference of the magneto-resistance of the probe perpendicular and parallel to the magnetic field. Since this effect creates an additional voltage proportional to the square of the parallel magnetic field component, it can be compensated for by flipping the probe and repeating the measurement of the field map.
The principle of magnetic induction uses Faraday’s law; the change of the magnetic flux linked by a coil's winding induces a voltage in the coil. The voltage integrated between initial and final coil position gives directly the change of the average field over the surface area of the coil. The change of flux can be induced by translating, flipping, rotating or vibrating the coil in a static field or by changing the field over a static coil. The field in a point is measured with a search-coil, along a line with a thin, long coil shaped to the desired path. Gradients are measured with two thin coils separated by a fixed distance, and connected in series opposition. The moving wire technique, in which only one part of a winding is moved inside the field, is a variant of the moving coil method. A major use of this technique is the rotating coil method to measure the multipole content of magnetic fields. The measured quantity is either the induced voltage in function of time, and measured with a fast voltmeter or the integrated voltage using a digital integrator. A high-tech integrator, consisting of voltage-to-frequency converter and digital counter, has been developed by CERN and is commercially available for ca. 15 kFr.

## *3.1 Hall Probes*

The most common method to obtain detailed information about the field quality in a dipole is a measurement of the vertical field component in the mid-plane of the magnet with one or several Hall probes. Since this measuring method is very time consuming, the usual procedure is to measure only the prototype magnets in this way. From these data one may calculate the actual trajectories in the dipole and gain information on the field variation perpendicular to the particle’s trajectory. The access of the measuring arm into a C-frame magnet is easier accomplished than into a H-frame magnet. To elude the problem of access into H-frame magnets with large bending angles a mouse system can be used.
To measure the field distribution in a multipole the Hall probe is not convenient and less accurate than a harmonic coil. The main problem is, that calibration errors and the planar Hall-effect may introduce spurious harmonics. Therefor an overall gradient error is usually extracted instead of the multipole contents of the field. Usually in the horizontal mid plane a field map is measured, to check the field uniformity and to calculate the magnetic length of the multipole.

### 3.1.1 PSI's Dipole Measuring Bench

The PSI **D**ipole **M**easuring **B**ench (DMB) is installed in a shack of 5×8.6 $m^2$ area and 4.4 m height on the west side of the Aare in the building WMHA. The light weight top is removable and the magnet to be measured can be lifted into the shack with the 20 t overhead crane.
The walls and the roof of the shack are made of a thick plastic canvas, which is not a good thermal insulation. Therefore the temperature in the shack follows the rise and fall of the external diurnal temperature changes. The on/off air-conditioning system is not adequate either; because it blows only locally cold air into the shack. Therefore in the shack the temperature distribution is not isotropic and the ambient temperature is not stable.
The Hall probe is mounted on a telescopic arm, fixed to an axially movable tower. The telescopic arm and the tower can be rotated a full 360° around their axes However the probe can not be rotated or flipped precisely 180°. The moving range of the probe is horizontally 700, vertically 400 and axially 2200 mm. Flying measurements can be made by moving the probe in the axial direction forward and backward. However the driving belt, moving the tower in the axial direction, introduces a small (< 0.04 mm) positioning error. This error brings about that the sensitive point of the probe is shifted, depending on the direction of the movement, either to the right or to the left side of the direction of movement. It must be tested, whether the error can be eliminated, by measuring the field in both directions and taking the average value. Any point in the vertical plane can be accessed with an accuracy of 0.01 mm.

| **Ray-tracing programs:** | | |
|---|---|---|
| 1 | TRACK | 3D tracking through magnetic and/or electric fields |
| 2 | HEDGE | 3D tracking through “hard-edge” magnetic elements |

| **Utilities, plotting and analyzing programs:** | | |
|---|---|---|
| 3 | INTEGRATE | Fit of a “hard edge” magnetic element |
| 4 | FELDKARTE | Contour plot |
| 5 | PROFIL | Line plots |
| 6 | SMODAT | 2D data smoothing |
| 7 | COPYDAT | 2D data file handling |
| 8 | CONVERT | 2D<~>3D data file conversion |
| 9 | ERREGER | Excitation current, linear fit |
| 10 | KUBIK | Excitation current, cubic fit |
| 11 | DRUCK | Cooling water flow, logarithmic fit |

Table 4: At PSI available software.

There are two Hall probes available. The small SIEMENS (SBV 585-S1) probe has a active area of 0.15×0.15 $mm^2$, its temperature sensitivity is better than 0.01 %/K, and its accuracy is only about 1 Gauss at low fields. The high accuracy Hall probe (TMR-3B-10B25-02) from the SENTRON AG has an active area of 0.5×0.2 $mm^2$, and a very small temperature sensitivity of $3\times10^{-3}$ %/K. However its spatial extension is 250×12×10 $mm^3$ and therefore its utilization somewhat limited. To calibrate yearly the

probes a dipole made by Bruker GmbH and a NMR-probe of the Cyclotron Corporation (USA) are located in the shack of the DMB.
To energize the magnets three current stabilized power supplies are installed beside the shack. Two of them deliver a maximum current of 500 A at 160 V. The third one can be switched, to deliver 1000, 1700, 2000 and 3500 A at 120, 70, 60 and 35 V, respectively. To cool the magnet de-mineralized water is available at 30 °C inlet temperature and an inlet pressure of 0.1 MPa.
To design magnets and to evaluate calculated and measured data several programs have been written and acquired by the Magnet Section of PSI, which are listed above in Table 4.

### 3.1.2 Measuring Bench of BIMP

For BESSY II a Hall probe measuring system has been delivered by the Butker Institute of Nuclear Physics (BINP). The delivery time of the system is 6 months and it costs ca. 85 kFr. The main feature of the system is an array of 7 Hall probes, lined up perpendicular to the magnetic axis and located in a distance of 10 ± 0.02 mm from each other. The active area of the probes is $0.45\times0.15\ \mathrm{mm}^2$ and their temperature sensitivity is $10^{-3}$ %/K. The electronics includes the current supply (100 mA) for the Hall probes, high precision digital voltmeter and multiplexer, the step motor controller and a DAC. The system is connected to a PC, which runs the operating and analyzing programs.

## *3.2 Rotating coils*

A mechanically stable cylinder holding the measuring coil(s) is rotated inside the bore of the multipole. The induced voltage is a function of rotational angle, its Fourier components give the multipole content of the field. The Fourier analyses is carried out in polar coordinates.

$$B(r,\theta) = (B_\theta+iB_r)\times e^{-i\theta} = \sum_n (B_n+iA_n)\times r\times e^{i\theta}$$

Here is $A_n$ the skew and $B_n$ the normal field component. The multipole order of the field component is given by the index n; n = 1 for the dipole, n = 2 for the quadrupole, n = 3 for the sextupole, and so forth. A multipole of order “n” has several allowed harmonics of the order $N = n\times(2k+1)$, here is k = 1,2, and so on. Therefore a quadrupole (n = 2) has 12 and 20 pole, and a sextupole (n = 3) has 18 and 30 pole harmonic contents.
As rotating coils two types of windings are used: the radial- and the tangential-coil. The bucking-coil is an additional set of windings mounted on the same frame as the main coil. The radial-coil is wound such that in one arm of the winding coincide with the rotational axis, and the other arm is on the surface of the winding frame as near as possible to the pole-tip of the multipole. The bucking-coils is wound in the same plane as the main coil, but with different outer and inner radius. Its signal can be added or subtracted from the signal of the main radial- or tangential-coil to eliminate a harmonic component of the field. For the tangential-coil the windings are located at a common radius on the surface of the winding frame, but with an angular separation $\phi$. Several different tangential-coils, all are wound on the same frame, e.g. the dipole-, the quadrupole-coil, and any higher order coil can be connected such, that the corresponding multipole terms are bucked out.

A sufficiently long coil, extending on both sides of the multipole into the field free region, delivers the integrated harmonic components of the multipole. Alternatively a short coil can be used to measure the harmonic components in the center of multipole. A disadvantage of this measuring technique is that the rotating coil must be designed and fabricated individually for each type of magnet to achieve maximum sensitivity.
There are several rotating coil systems in use at the laboratories all around world, but here only those machines are discussed which could be made available for measurements, and meet the requirements for the SLS multipoles.

### 3.2.1 ELETTRA's Rotating Coil

This **R**otating **C**oil **S**ystem (RCS) was designed at CERN to measure the relative amplitudes of harmonic components in quadrupoles and sextupoles with an accuracy of 0.01 %. The voltage induced during a complete rotation of 25.6 s duration is sampled 512 times using a HP 3852A voltmeter, synchronized to the coil rotation. To ensure constant angular velocity the stepping motor is driven by a high frequency (20 MHz) high precision quartz clock.
A measuring coil assembly contains 4 separate coils, each with 8 turns, divided into entry and exit coils and each of them has an outer ($R_{out}$) and inner ($R_{inn}$) coil. The ratio of the coil radii is $R_{out}/R_{inn} = 2$. For measurement coils can be selected separately or in pairs to obtain the sum or difference of the induced voltage. A longitudinally movable Hall probe is installed at 29.7 mm radius to determine the field strength in the center of the multipole to calculate its effective length.
If the signal of the two outer coils is summed, the offset of the magnetic axis with respect to the rotating coil axis can be calculated from the relative values of the (n-1)-th harmonics of the induced voltage. The roll angle can be calculated from the magnitude of the n-th harmonics of the induced voltage. The rotation around the x-axis (pitch) and around the y-axis (yaw) are determined by measuring with the entrance and exit coils separately and to null the offset of the magnetic axis at both ends of the multipole. The calculated corrections of the magnet axis are manually corrected.
The accuracy of the system is about 1 µV. corresponding to a sensitivity of $10^{-4}$ of the major component. The magnetic center can be determined with an accuracy of ca. 20 µm, and the roll angle to 0.02°. The alignment targets on the top of the multipole can be positioned with an accuracy of ca. 20 µm, by using a Taylor-Hobson telescope, whose axis is parallel to the rotating coil axis.

### 3.2.2 Danfysik's Rotating Coil

This sophisticated Model 692 RCS has been developed to measure the LEP magnets. It determines the strength, and the multipole content of the field as well as the magnetic axis for precise positioning of alignment targets on top of the multipoles.
The rotating coil, a reinforced Kevlar cylinder holding the main coil, is supported on air bearings and driven with a DC motor. Its angular position is measured with a 15 bit angular encoder, whose signal triggers the integrator. The induced voltage of the main coil is sampled and integrated over equally spaced angular intervals. This measurement provides the determination of the integrated field and the position of the magnet center. To increase the sensitivity for higher order harmonic components a bucking-coil, insensitive to the n-th and the (n-1)-th harmonics, is mounted on the kevlar cylinder. The multipole, while supported on air cushions, can be moved with regard to the rotating coil using five stepping motors. The resolution of the movement

is read out by linear potentiometer with ca. 1 µm resolution. For alignment a laser, a position sensitive light detector with 10 µm resolution, and two electronic inclinometers of 0.01 mrad sensitivity are provided together with a calibration device. The control system, consisting of a micro processor and a PC, monitors and supervises the pre-alignment, harmonic measurement and analysis, magnet centering and alignment, thereby minimizing the need of operator's intervention.
The Model 692 RCS has been acquired by the following laboratories: ESRF, APS, SSC, Frascati, BESSY II and SRRC.

3.2.3 Rotating Coil for LHC.

This very sensitive rotating harmonic coils system, has been invented at BNL, and it was used to measure the HERA magnets for DESY, then further improved at CERN. The measuring arm consists of a rigid shaft with one or more coils on it. This shaft can be rotated and moved axially by a stepping motor. An angular encoder is used to synchronize the rotational motion and the triggering of the integrator. To check the torsion and the bending of the shaft an ADC is employed. A PC applying VME controls the system combining labVIEW software with the control and measurement hardware. Since the aperture of the superconducting dipoles is round, they utilize a radial- and a tangential-coils to measure their magnetic field. For the multipoles they use a set of five coils, symmetrically arranged besides each other in the same diagonal plane of the rotating frame. The coils, each with 400 windings, are very precisely fabricated and their alignment is carefully controlled. There is a pair of outer-coils, a pair of intermediate-radius-coils, and a central-coil. The central-coil is sensitive to the dipole term and insensitive to the quadrupole term. The two intermediate-radius-coils have equal but opposite sensitivity for the quadrupole term and identical sensitivity to the dipole term. Only one of the outer-coils, which is twice as sensitive as the intermediate-radius-coils for the quadrupole term, is used for the harmonic measurement. The same set of coils can be used to buck out other harmonics if requested, however the signals of the coils must be added with weight factors different from ±1. The influence of the coil manufacturing accuracy, of the deviation between the rotating coil and magnet axis have been carefully studied and can be calculated.

## *3.3 Integral measurements*

This type of measurement is made for dipoles and multipoles with long coils, which cover the central, and both fringe field regions of the magnet. This technique although it provides less information than a complete mapping of the field is adequate to measure large series of magnets, because its speed, reproducibility and sensitivity. For magnets used in synchrotron radiation sources it is customary to measure the field integral along the nominal electron trajectory.
The measurement is most easily performed by integrating the induced voltage while increasing the excitation current from zero to the desired value. To take into account the remanent field the coil must be placed, before the current is turned on, into a zero field chamber, and then moved into the magnetic field. To measure the homogeneity in the central region the coil is moved radial in the horizontal plane. The coil is very sensitive to higher order harmonics, since the dipole component of the field stays constant.
The Integral Null-method delivers the most accurate results, a relative accuracy of $10^{-4}$ has been achieved at APS and at ESRF in Grenoble. In this case the differences of induction is measured, either between two identical coils or between a reference

magnet and a series magnet powered in series. The construction and fabrication of suitable long curved coils requires special care, however the gain in time schedule makes the effort worth while.

## *3.4 Alignment of the magnetic axis*

The precise alignment of quadrupoles and sextupoles in particle accelerators is an important issue. Special stretched wire techniques were recently developed, tested and are widely used to align superconducting multipoles. To achieve the requirements for the alignment of the multipoles in the storage ring one of the following methods should be utilized.

### 3.4.1 Pulsed wire

This method is based on the fact that a pulse of current, passing along a stretched wire, excites proportional to the local transverse magnetic field a transverse Lorentz–force. The motion of the wire evolves to a wave that propagates along the wire to a position sensor. By measuring the amplitude of the motion versus time it is possible to calculate the magnetic field distribution along the wire. To avoid interference between the waves containing the information and the waves reflected at the wire's ends, the length of the wire must be at least 50 % longer than the measured region. Further it is required that a short, high voltage pulse is generated to detect small wire motions. This method was developed and used at LANL to test a wiggler of several meters length. The accuracy achieved with this method is about ±0.1 mm. For long magnets (5-10 m) the wire sag (~ 0.01 mm/m) becomes significant and levitation coils were used to support the wire.

### 3.4.2 Vibrating wire

A stretched wire has fundamental and higher harmonic vibrational modes, thereby the length of the wire is equal to the half wave length of the fundamental mode. If the wire is in a transverse magnetic field, and the frequency of the current in the wire is an Eigenfrequenz of the wire vibration the corresponding harmonic will be excited. The strength and phase of the vibrations depends on the field distribution along the wire. Applying various frequencies one can extract information about the field distribution, i.e. about the misalignment of the magnets. The wire length is equal to the length of the test region, and since the method is very sensitive no high voltage is needed. The experimental set up consists of a position sensitive detector, a PC and a high frequency current generator of ca. 1 A.

At Cornell University a 3 m long wire was used and 30 harmonics were applied to align a 300 mm long quadrupole. The misalignment between geometrical and magnetic axes has been determined to be larger than 125 µ, The tests implied that this method is capable to measure alignment errors of less than 1 µ.

At SLAC a special measuring bench has been developed to determine the magnetic center of a quadrupole and the electric center of the attached **B**eam **P**osition **M**onitor (BPM). The wire was vibrated and the induced voltage monitored with a spectrum analyzer, the accuracy achieved was a few micron.

### 3.4.3 Moving wire

At DESY a stretched, single CuBe wire, with return loop outside the magnet, was used to measure the integrated strength and to determine the magnetic axis of the superconducting HERA quadrupoles. The induction loop was connected through a low noise amplifier to a **V**oltage-to-**F**requency **C**onverter (VFC). The wire could be moved with micrometer precision in the horizontal and vertical direction. The sagging of the wire and diamagnetic force on the wire were eliminated by taking data at different mechanical tension in the wire and extrapolating to infinite tension. This method was used at SLAC to determine the magnetic axis of multipoles with an accuracy of ca. 1 µm.

# 4 Proposal for measurements.

This proposal has been worked out after a series of visits to several research centers to collect information about the merits of the different measuring methods and on the capability and availability of their measuring equipment.

## *4.1 Scope of the measurements*

Here is only a general frame of the magnetic measurements given, details can be found in the Specifications for the magnets. Foreseen are the measurements outlined below for the booster and storage ring magnets. The data obtained will be used to get the information, listed in this paragraph, and to perform the indispensable beam dynamics calculations.

### 4.1.1 Dipoles

1) For all dipoles the excitation curve; measured by increasing the current to its maximum value and reducing it to zero.
2) For the prototype dipoles:
   - The form of the chamfer must determined, such that the shape of the end-field and its multipole content are according to specifications.
   - A field-map of $B_y(z,x)$ in the mid-plane (y = 0) at three excitations. The size of the field map must be chosen such, that outside the magnet it reaches the region where $B_y(z,x)$ is smaller than 1 Gauss.
3) For each series magnet:
   - Either an integral measurements along five radii and at three excitations, to proves that the field integral does not deviate from the field in the prototype by more than the specified value,
   - Or a field map $B_y(z,x)$ in the mid-plane (y = 0) at three excitations. Either five trajectories or the effective length along five radii must be calculated to prove that the field does not deviate from the field in the prototype by more than the specified value.

The measured field map must be evaluated in order to extract the following information:

1. The effective length at different radii.
2. The multipole content of the field, especially of the end-fields,
3. The transverse field homogeneity for dipoles with parallel poles,
4. The field-index (n = $(\rho/B)\times G$) for combined function dipoles,
5. The real electron trajectories, calculating them with a tracking algorithm,
6. A fit of the excitation curve to check how much is the yoke saturated.

4.1.2 Multipoles

1) For all multipoles the excitation curve; measured by increasing the current to its maximum value and reducing it to zero.
2) For the prototypes:
   - The form of the chamfer must determined, such that the shape of the end-field and its multipole contents are according to specifications.
   - An integral measurement of the harmonic contents of the field must be made.
   - Either the harmonic contents or the field in the central, homogeneous region of the magnet must be measured.
3) For each series multipole:
   - An integral measurement of the harmonic contents of the field must be made.
   - Either the harmonic contents or the field in the central, homogeneous region of the magnet must be measured.

The measured data must be evaluated in order to extract the following information:

1. The effective magnetic length.
2. The normalized multipole content of the field.
3. A fit of the excitation curve, to check how much is the yoke saturated.

## *4.2 Tolerances*

It will be distinguished between the accuracy of the magnetic field measurement and of the spatial positioning of the measuring probe. The requirements are more stringent for the multipoles on the girders than for all magnets in the transferlines and in the booster as well as for the dipoles in the storage ring. The Table 5 summarizes the tolerances for the magnet measurements as known up to now.

| Dipoles | TLB | Booster | TBR | Storage ring | |
|---|---|---|---|---|---|
| Field: dB/B | | | | $< 2\times10^{-4}$ | |
| Roll angle | | | | | mrad |
| Sensor Positioning: $\pm \Delta x$, $\pm \Delta y$ | | $\pm$ 0.075 | | $\pm$ 0.075 | mm |

| Multipoles | TLB | Booster | TBR | Storage ring | |
|---|---|---|---|---|---|
| Gradient in Quadrupoles: dB/dr | | $< 10^{-3}$ | $< 10^{-3}$ | $< 2\times10^{-4}$ | |
| Gradient in Sextupoles $d^2B/dr^2$ | | $< 10^{-3}$ | $< 10^{-3}$ | $< 5\times10^{-4}$ | |
| Magnetic axis Position: $\Delta x$, $\Delta y$ | | $\pm$ 0.1 | $\pm$ 0.1 | $\pm$ 0.015 | mm |
| Roll angle | | | | | mrad |
| Pitch and jaw angles | | | | | mrad |

Table 5: Tolerances for the magnet measurements
(The values for the empty fields have yet to be defined!)

## *4.3 Performing the measurements*

Up to now no final decision has been made, who will fabricate the magnets of the accelerators. Therefore a scenario is described, which seems to be to most economic, and straight forward to get the magnets measured in time. The distinctive feature of the suggested procedure is that only small crews are employed, they perform the quality assurance during production and supervises the magnetic field measurements too. This is conceivable, because neither task will occupy fully the capacity of the crews. It is explained below that three separate crews should be formed to perform the tasks.

#### 4.3.1 Booster

Including the prototypes 249 magnets will be ordered for the booster and 7 quadrupoles for the BR transferline. There are 97 combined dipoles – 50 BD and 47 BF –, 48 multipoles – 15 QS and 13 QL quadrupoles, 20 SC sextupoles – which will be procured either by one or by two different manufacturers. Additionally 111 single correctors, including one prototype, will be ordered at a further supplier. As long as the multipoles are produced at the same site, the following procedure should be followed:

##### 4.3.1.1 Dipoles

For both prototypes –BD00 and BF00 – all measurements should be performed with the DMB at PSI. The time of two months, stipulated in the specifications, should suffice also in the case, that some unforeseen difficulties arise.
For the measurements of the series magnets at the supplier the following terms must hold:

1. The magnets are measured under the supervision of PSI representative(s). The minimum scope of the measurements is given in paragraph B.5 of the specification [1].
2. All the necessary facilities including the temperature stabilized test area, measuring equipment and the manpower necessary to perform the measurements should be provided by the manufacturer.
3. The high current stabilized power supply required to energize the combined BD and BF dipoles can be provided by PSI. The main data of the transportable PS are given in Table 6 below.

| **Electric data** | | |
|---|---|---|
| Max. Current | 1800 | A |
| Max. Voltage | 40 | V |
| Long time stability | $<10^{-4}$ | |
| **Cooling water** | | |
| Max. Inlet pressure | 1.0 | MPa |
| Max. pressure drop | **….?** | MPa |
| Mass-flow | 10 | l/h |

Table 6: Power supply for the combined dipoles BD and BF.

##### 4.3.1.2 Multipoles

For both prototype quadrupoles – QS00 and QL00 – as well as for the prototype sextupole – SB00 –the necessary measurements should be performed in Triest with ELETTRA's rotating coils system. This will be the sole opportunity to train a PSI crew, which must later train and supervises the staff of the supplier. The rotating coil

inclusive a rotating Hall probe or short flip-coil should be ordered and manufactured at CERN.
For the measurements of the series multipoles at the supplier the following terms must hold:

1. The measurements should be carried out by the manufacturer's staff and on its site under the guidance and the supervision of PSI representative(s).
2. The scope of the measurements is given in paragraph C.5 for quadrupoles and in D.5. for sextupoles in the specifications [1].
3. All the necessary facilities including the temperature stabilized test area, power supplies and the manpower needed to perform the measurements should be provided by the manufacturer.

### 4.3.2 Storage ring

The deadline to offer the magnets for the storage ring has just expired, therefore at this time no final statement can be made about a potential manufacturer or about the procedure for the magnetic measurements. A total of 345 elements must be ordered, and it is assumed that in order to reduce the risk of delayed delivery, the package will be split. Several scenes can be imagined how the order could be split, however this report deals only with that scene which is the most economical to perform the required measurements. It is opined that the package split in the same way as foreseen for the booster magnets, i.e. order, including the prototypes, at one firm 39 dipoles – 14 BX and 25 BE –, and at another one 306 multipoles - 182 quadrupoles (44 QA, 13 QAW, 43 QB, 13 QBW, 55 QC, 14 QCW), and 124 sextupoles (110 SR, 14 SRW). After delivery the multipoles must be mounted with high precession on 48 girders. To achieve the requested accuracy they must be mounted directly on their actual girder and then the position of their magnetic axis measured, and if needed the multipoles will be aligned.

#### 4.3.2.1 Dipoles

The prototype dipole – BX00 – should be measured at PSI with the DMB. Because the 38 series magnets are all long, parallel pole dipoles, their measurement can be with confidence entrusted to the supplier. For the measurements of the series magnets the following terms should hold:

1. The dipoles should be measured under the supervision of as PSI representative(s). The minimum scope of the measurements is given in paragraph B.7.2 of the specifications [2].
2. The Integral Null-method is the favored measuring technique, because it is simple and fast, if five coils along the actual path of the electrons are used. The measuring equipment should be designed at PSI, however the fabrication may be performed by the supplier.
3. The prototype dipoles should be used as reference magnets.
4. All the necessary facilities including the temperature stabilized test area, power supply, and the manpower necessary to perform the measurements should be provided by the manufacturer.

#### 4.3.2.2 Multipoles

As previously mentioned the 306 multipoles may be ordered by two different suppliers in order to ensure timely delivery. In any case these magnets must be measured very carefully to achieve good beam quality and not to loose unnecessarily

beam intensity in the storage ring. It is therefore recommended to procure an ELETTRA type RCS to measure the multipoles. This equipment, if ready in time, it could be used to measure the quadrupoles of the LB transferline, and subsequently the prototype multipoles of the storage ring. Later on it should be used to measure the series multipoles. The rotating coils including the rotating Hall probes or short flipping coils should be ordered and manufactured at CERN.
The four prototype magnets 2 quadrupole – QA00 and QCW00 –, and 2 sextupoles – SR00 and SRW00 –, should be measured at PSI with the mentioned RCS. If the order for the multipoles is split between two suppliers then one manufacturer must have its own RCS device or a RCS must be acquired on loan. Besides BESSY II in Berlin the research center ENEA in Frascati (Italy) could be asked to borrow for this purpose their Danfysik Model 692 RCS,. In any case the measurement of the 306 series multipoles should be carried out at the premises of the suppliers.
For the measurement of the series multipoles the following terms must hold:

1. The measurement should be carried out by the manufacturer's staff and on its site under the guidance and the supervision of PSI representative(s).
2. The scope of the measurements is given in paragraph C.5 for quadrupoles and in D.5. for sextupoles in the specifications [2].
3. All the necessary facilities including the temperature stabilized test area, power supplies and the manpower needed to perform the measurements should be provided by the manufacturer.

## *4.4 Alignment of multipoles on the girder*

To enforce the stringent tolerance requirements for the multipoles of the storage ring it is inevitable to align them on their actual girder. The storage ring comprises 48 girders. From the 30 long (l = 4.5 m) girders (GL) 24 carry 7 and 6 only 6 multipoles. Each of the 18 short (l = 3.7 m) girders (GS) carries 5 multipoles. It is assumed that the alignment of the magnets on the girders will take place outside the ring-tunnel, in the Technical gallery of WSLA. It takes at least 6 working days to align the multipoles on one girder. To perform the alignment of the multipoles on the 48 girders efficiently and in time two girders will be aligned simultaneously. This procedure increases the chance to finish the alignment of the multipoles in accordance with the SLS time schedule.

### 4.4.1 Preparation of equipment

There are three distinct methods to align multipoles with high precision, however neither of them has been utilized at PSI. Therefore at first the right method must be chosen, then the whole equipment designed, fabricated, installed and finally tested. It is desirable to perform this test as early as possible in order to have time to improve the setup and to fabricate in time the second equipment. For testing the equipment either a prototype or possibly a dummy long girder, and the four prototype multipoles – QA00, QCW00, SR00 and SRW00 – must be used, to simulate the alignment procedure. Since the multipoles have to be energized a power supply, and cooling water must be available in the test area. To have stable temperature in the test area it should have an air-conditioning system, which can be used for one of the two shacks erected later in WSLA. The design, fabrication of the equipment and the tests should be performed by PSI staff.

#### 4.4.2 Performing the measurements

The alignment of the multipoles on the 48 girders will be performed in the Technical Gallery of the SLS building. There must be two test areas (8.5 × 4.5 m), each with an air-conditioned shack (3.5 m height). Both shack must be accessible with the overhead crane to bring in girders, the multipoles and remove the assembled girders after the elements have been aligned. Additionally each shack must have his own power supply and cooling water connections.
At first the elements of the girder will be mounted. The mechanical axis of each multipole will be aligned to the nominal position of the girder's axis. The stretched wire measurement will provide the relative position of the mechanical and magnetic axes for each multipole. If the deviation between the two axes for an element is larger than the tolerance value the multipole will be removed. Next shims, prepared beforehand, will be machined to the requested size and subsequently the multipole will be newly mounted. In the meantime another multipole can be measured. After all multipoles have been measured and aligned a final test should be made. At this time all elements will be energized to check and measure the resulting alignment. Finally the girder will be removed and put onto its final location in the ring-tunnel.

### *4.5 Correctors and transferlines' magnets*

Correctors will be used in the booster and in both transferlines. For the storage ring the coils of 72 correctors are integrated into the corresponding number of sextupoles, and will not be discussed separately.

#### 4.5.1 Correctors for the Booster

There is one prototype – CH00 –, 54 horizontal – CH –, and 54 vertical – CY – so called single function series correctors. The magnets have been designed at PSI and the specification is in preparation and will be issued soon. The prototype should be measured with the DMB of PSI. The series magnets should be also measured at PSI, using the Integral Null-method. The equipment for such a measurement is simple, since one needs only a set of three straight coils. To perform the measurement the set of coils is moved along a straight path, from the reference into the test corrector, while both are connected in series and energized. The set of the three coils must be designed such that it can be used in both types of correctors.

#### 4.5.2 The Linac-Booster transferline

The final specification of the magnets for the LB transferline are still not issued. At the moment 2 dipoles, – BY and BI –, 12 quadrupoles, – QT –, and 5 combined function correctors – CT – are earmarked for this transferline. The design of all elements could be made at PSI. The measurement of the dipoles and of the correctors could be carried out with the DMB of PSI. The quadrupoles must be measured with a RCS device. It is suggested, if the time schedule permits, to use the equipment which will be procured for the measurement of the multipoles for the storage ring.

#### 4.5.3 The Booster-Storage ring transferline

The magnets in the BR transferline have been defined and the design of 3 dipoles – BG – has been initiated. The 7 quadrupoles– 1 QS and 6 QL –, are of the same type as utilized in the booster. They will be ordered and measured together with the latter. For the 4 combined function correctors – CG – only rough information exists, however they could be ordered and measured together with the single function correctors of the booster.

# 5 Means and Ways of realization

The realization of this demanding program in the tight time schedule is only then possible if the support of the project's leadership is unanimous and steady during the processing of the tasks. In the following paragraphs an attempt is made to list the means to perform the work outlined in paragraph 4. The enumeration of the required support is not taking in account any obstacle, which could necessitate the request of additional resources.

## *5.1 Required Support*

To perform the magnet measurements as proposed above several gadgets must be designed, fabricated and/or procured by a supplier. This paragraph gives a compilation of the support needed from different sources.

1) From the PSI departments B8 and B9:
   - Refurbishment of the DMB-shack; Install a new air-conditioning system and replace the walls made of canvas with isolating boards. An offer to overhaul the shack has been submitted by H. Blaser from the Gruppe Gebäudetechnik (ORG 9240) from the Sektion Gebäude– und Anlageningenieurwesen (ORG 9200) of PSI.
   - Design and manufacture coils to perform the measurements of series magnets with the integral Null-method, for the;
     - ⇒ 95 dipoles (BX and BE) of the storage ring,
     - ⇒ 110 correctors (CH and CV) of the booster.
   - Reproducing ELETTRA's RCS to measure the multipoles of the storage ring;
     - ⇒ the 4 prototype quadrupole (QA00 and QCW00) and sextupoles (SR00 and SRW00) of the storage ring,
     - ⇒ the 180 series quadrupoles (43 QA, 13 QAW, 43 QB, 13 QBW, 55 QC, and 13 QCW) and perhaps the 122 sextupoles (110 SR, 14 SRW) a too,
   - Design and manufacture the stretched wire measuring equipment, install in the girder test area an air-conditioned shack, the necessary infrastructure (cooling water connections, power supply, and so forth).
   - Move the shack in which the tests were performed into the Technical Gallery of WSLA, and build there a second air-conditioned shack. Install the necessary infrastructure (girder support, cooling water connections, power supply, and so forth)for both shacks.
   - Send to and put into operation at the site of the supplier of the booster (BD and BF) dipoles the current stabilized power supply of PSI.
2) From the PSI Magnet Section (ORG 1230);
   - The experience, know how and the software support of the Gruppe Magnetentwicklung (ORG 1231) to determine the shape of the chamfers for the dipoles and multipoles of both accelerators.
   - The Gruppe Messtechnik (ORG 1232) to carry out the required magnetic field measurements on 3 prototype dipoles (BD, BF, BX), on 1 corrector (CB00), and on 110 series correctors.

- Provide replacement, while the persons supervising production and measurement of the booster and storage ring magnets are on their holidays, at military service, or sick.

3) From the CERN group CM-Electronics in the Experimental Physics division, under the supervision of R. Grabit (EP/CME), the design and fabrication of three rotating coils for multipole measurements.
   - One rotating coil of ca. 35 mm outer diameter to measure 28 quadrupoles (15 QS and 13 QL) and 20 sextupoles (SB) for the booster and for the BR transferline.
   - A second rotating coil of ca. 59 mm outer diameter to measure 180 quadrupoles (44 QA, 13 QAW, 43 QB, 13 QBW, 55 QC, 14 QCW) for the storage ring.
   - A third rotating coil of ca. 67 mm outer diameter to measure 124 sextupoles (110 SR, 14 SRW) for the storage ring.

   The third coil is only needed in the event that all multipoles of the storage ring are measured with the same ELETTRA type RCS.
4) From the CERN Surface and Material group in the Engineering Support and Technologies division (EST/SU) know how and technical advise from M. Mayoud. This group makes use of the stretched wire method to measure LHC magnets.
5) From R. Walker and his collaborator D. Zangrando of ELETTRA:
   - Instruction and support for the PSI crew, which should go to Triest and measure 2 prototype booster multipoles (QS00 and SB00) there.
   - The documentation and support to reproduce ELETTRA's RCS in order to measure the 182 quadrupoles and 124 sextupoles of the storage ring.
6) If sextupoles and quadrupoles for the storage ring are not procured at the same supplier then;
   - Borrow from BESSY II in Berlin or ENEA in Frascati a Danfysik’s Model 692 RCS device.
   - Order from Danfysik a rotating coil, with ca. 67 mm outer diameter.

## *5.2 Manpower*

The estimate is based on the following assumptions:

1) The 97 dipoles and the 41 multipoles (28 quadrupoles and 20 sextupoles) for the booster and 7 quadrupoles for the LB transferline will be procured at two different suppliers.
2) The 39 dipoles and the 306 multipoles (182 quadrupoles and 124 sextupoles) of the storage ring will be procured at two different suppliers.
3) The magnetic field of the 3 prototype dipoles (BD00, BF00 and BX00) as well as of all the 111 correctors (CH and CV) will be measured with the DMB of PSI.
4) The same PSI crews which are responsible for the quality control of the booster and storage ring magnets, respectively, will also perform the measurements of the prototype multipole, and serve as instructors as well as supervisors for the magnetic field measurement of the series dipoles and multipoles.
5) The manpower for the requested support of B8 (engineers, drafts man, workshop, electricians, installation crew, transport service) and B9 (cooling, overhauling) is not taken in account.

The minimum estimated manpower to perform the work described in this report is:

1) Two crews each consisting of two persons:
   - For the booster 2 people;
     - ⇒ A HTL engineer, and
     - ⇒ an electrical technician TS.
   - For the storage ring another 2 people:
     - ⇒ An electrical HTL engineer, and
     - ⇒ a mechanical technician TS.
2) The crew operating the DMB of PSI must consist of at least 2 people. It must be foreseen, that an external consultant, with experience in magnet measurement methods, should be hired to support the group's efforts.
3) If not all multipoles of the storage ring are procured at the same supplier an additional electric HTL engineer must be hired.

The booster and storage ring crews should participate in the design and tests of the stretched wire measuring device and must later perform the alignment of the multipoles on the girder.

A drawback of this proposal is that for illness, holidays and military service of the crew members skilled replacement is needed, which can only be drawn from the Magnet Section (ORG 1230) of PSI, which may be at that tine heavily loaded with other duties and is unable to provide the requested manpower.

## *5.3 Cost estimates*

The following cost estimates do not include the wages of PSI staff, and additionally the traveling expenses to the suppliers. The cost estimate to measure the dipoles and multipoles of the booster is given in Table 7. The refurbished DMB shack should be used to measure the prototype dipoles of the storage ring and both transferlines.

In Table 8 are shown the estimated costs to measure the magnets of the storage ring. The expenditure for a PSI's own RCS inflates considerably the estimated costs for the measuring equipment of the storage ring magnets.

The cost estimate for the stretched wire measurements, compiled in Table 9, has an uncertainty of about ±20 %. The expenditures for the magnet measurements are more reliable and the error is ca. ±10 %.

| **Booster:** | | | |
|---|---|---|---|
| | **Item** | **Cost kFr.** | **Source of estimate** |
| | **Prototype magnets:** | | |
| 1 | Refurbish DMB-shack in WMHA | 70 | H. Blaser (PSI) |
| 2 | Rot.coil for booster multipoles | 25 | R. Grabit (VERN) |
| | **Series magnets:** | | |
| 1 | Transport & install PS for BD & BF | 15 | Estimate J.A. Zichy |
| 2 | Integral Null-method setup for CB | 25 | ditto |
| 3 | Transport & install ELETTRA's RCS | 25 | ditto |
| | **Total of estimated costs:** | **160** | |

Table 7: Estimated costs for booster magnet measuring equipment.

| Storage ring: | | | |
|---|---|---|---|
| | **Item** | **Cost SFr.** | **Source of estimate** |
| | **Prototype magnets:** | | |
| 1 | Reproduce ELETTRA’s RCS for PSI | 200 | Estimate J.A. Zichy |
| 2 | Rot.coil for quadrupoles | 25 | R. Grabit (CERN) |
| 3 | Rot.coil for sextupoles | 25 | ditto |
| | **Series magnets:** | | |
| 1 | Integral Null-method coils for BX & BE | 55 | Estimate J.A. Zichy |
| 2 | Transport & install PSI's RCS | 25 | |
| | Transport & install a borrowed RCS | 30 | ditto |
| | **Total of estimated costs:** | **360** | |

Table 8:Estimated costs for storage ring magnet measuring equipment.

| Stretched Wire measurements: | | | |
|---|---|---|---|
| | **Item** | **Cost SFr.** | **Source of estimate** |
| 1 | Equipment to test method | 100 | Estimate J.A. Zichy |
| 2 | Shack and air-condition for test area | 80 | Extrapol. H. Blaser |
| 3 | Move test area into WSLA | 10 | Estimate J.A. Zichy |
| 4 | Second measuring equipment | 40 | ditto |
| 5 | Second test area in WSLA | 90 | Extrapol. H. Blaser |
| | **Total of estimated costs:** | **320** | |

Table 9: Cost estimate for alignment the multipoles on the girders.

The two crews, which will control the production, perform the quality control, and supervise the series magnets measurements must be equipped with laptop computers in order to write reports and evaluate the measured data efficiently and in short time at the suppliers site.

## *5.4 Time schedule*

A new time schedule was made, because the previous had to be revised in view of the planing described above. The summary of the schedule "SLS Magnet Measurement" is Page 1 of the Appendix. It is subdivided in three blocks, each of them is shown in greater details on successive pages.
The tasks concerning the booster at the two production sites, see Page 2, are in such a succession, that the responsible crew members have to act simultaneously at two sites. The correctors must be delivered in two lots, if the supplier does not measure them at its site.
The time schedule of the storage ring, see Page 3, shows that a PSI's RCS, a copy of ELETTRA's Rotating Coil System, is not ready in time if no precautions are taken. It is possible either to start construction of PSI's RCS and ordering the two rotating coils

immediately or to borrow a Danfysik type RCS and order at once simple rotating coils at the Danish firm. The delivery of the multipoles will take place in three lots. After delivery the elements will be mounted and aligned simultaneously in two test areas. This requires that each lot contains the proper 98 elements belonging to one segment of the storage ring.
On Page 4 is shown the time schedule for testing, fabricating, and delivering the girders in three lots. Further the preparations to select and build the measuring equipment to align the multipoles using stretched wire measuring method. Finally it contains also the time schedule to align the elements on the 48 girders working simultaneously in two test areas.
Page 5 of the schedule shows, how is the delivery of the multipoles, girders, the completion of the two test stands in the technical gallery of the WSLA linked with the alignment of the elements for the three lots.
The feasibility of the time schedule is endangered right now by the lack of skilled collaborators, and by the fact that to hire new staff usually takes several month.

## 6 Conclusions

The scheme of the procurement and measurement of the elements for the booster seems to be realistic. To make a concluding statement about the procurement and measurement of the components for the storage ring is at the moment to early. The reason is the uncertainty whether the suppliers perform the magnetic measurements at the production site, and whether the supplier or PSI has to provide the measuring equipment.

## 7 References

1. Joho, J.A. Zichy: Specifications for the SLS Booster Magnets, SLS report: TME-TAN-1997-0204,(December 1997)
2. L. Rivkin: Specifications for the SLS Storage Ring Magnetic Elements and Girders, SLS report: TME-TA-1998-0301, (February 1998).
3. W. Joho, J.A. Zichy, D. George: Specifications for the SLS Booster Correction Magnets, SLS report: TME-TA-1998-00017 (April 1998).

## 8 Appendix

Time schedule for " SLS Magnet Measurement" :

1) Summary, an page 1.
2) Booster, on page 2.
3) Storage ring, on page3.
4) Girder's test, fabrication, and alignment of multipoles, on page 4.
5) Links for assembling the girders, on page 5.