Design and Measurement of the SLS Booster Combined Function Magnets

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***Abstract*–The booster bending magnets for the Swiss Light Source (SLS) at PSI include dipole, quadrupole and sextupole field components. The two types of magnet, focusing and defocusing, are laminated for operation at 3 Hz in the booster synchrotron. The 2D pole profile has been optimised with the smooth shimming method developed by the PSI Magnet Section. The 3D fringe field effects have also been computed. The prototype magnets were manufactured with removable pole ends to allow various end cuts to be measured. The prototypes were magnetically measured at the standard PSI measurement facility. The analysis, performed using the mid-plane field maps, confirmed the good field profile quality and helped determine the final pole end cuts for the magnet series.**

***Index Terms*–Combined function magnets.**

I. Design

For the booster synchrotron of the Swiss Light Source (SLS) at PSI two types of bending magnets are required: the focusing magnet BF and the defocusing magnet BD. Both magnets are combined function magnets containing dipole, quadrupole and sextupole field components [3].

One important requirement is to connect all magnets electrically in series.

The magnetic field on the axis in a 2D approximation is given by the following formula:

$$B(x) = B_0 + B_1 \cdot x + B_2 \cdot x^2$$

where: B_0 corresponds to a dipole
B_1 corresponds to a gradient or quadrupole
B_2 corresponds to a sextupole
the coordinate system has its origin in the center of the beam

The specified values for an energy of 2.4 GeV are given in Table 1.

The pole profile form includes dipole, quadrupole and sextupole components and has to be shimmed to compensate pole edge effects. The procedure for smooth shimming which makes use of the 2D computer code POISSON is described in Ref.[1].

For magnet BF the calculated magnetic field profile and the corresponding cross section of the magnet are shown in Fig. 1 and Fig. 2, respectively. For magnet BD see Fig. 3 and Fig. 4, respectively.

Both magnets are curved according to the bending radius of the beam.

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TABLE 1

	Magnet BF	Magnet BD	
B_0	0.1577	0.7138	Tesla
B_1	4.656	-3.088	Tesla/m
B_2	7.0	-10.0	Tesla/m^2
Radius R	50721.0	11208.0	mm
Bend.- Angle	1.130	6.441	∠deg.
$d_1 = B_0/B_1$	33.9	-231.2	mm
$d_2 = B_1/B_2$	665.1	308.8	mm
L_{eff}	1000.0	1260.0	mm

The pole ends have to be chamfered to take care of 3-dimensional end effects. During the design stage, we concluded that a single cut would be sufficient since the sextupole components are not critical. The chamfer also reduces eddy currents in the end laminations. Even a single cut has four parameters, two angles, the lateral position and depth of the cut. We therefore used 3D TOSCA [2] calculations to find a good starting point and chose neighboring configurations to independently see the affect of each parameter. We limited ourselves to three cases for each magnet type and asked the manufacturer to provide removable pole end pieces on the prototype magnets accordingly. This enabled us to measure and parameterise the various configurations in a short time and choose the final chamfer by interpolation. In practice, the sextupole components of the end fields were higher than assumed during the early design stage. This was not a problem for BF since, by varying the chamfer angle, we could react with the curved pole face and compensate. For BD we decided to add additional sextupole shims (see Fig. 5).

In operation the booster magnets will be excited using a sinusoidal current of 3 Hz overlayed by a direct current. To reduce eddy current effects the yokes are laminated with a lamination thickness of 0.5 mm. Furthermore, the material used is an (non grain oriented) electrical steel with low electrical conductivity.

Because the magnetic field in the magnet BF at the moment of beam injection is very low (only 7 mT), the material for the yoke has been specified with low coercivity: Hc<35 A/m.

The laminations are treated on both sides with a coating which serves as an electrical insulation and as an adhesive.

To obtain a solid yoke the laminations are stacked, put in a strong tool and glued together by compressing the laminations at approx. 200^o Celsius. In order to avoid internal stresses, no welding or bolting was used.

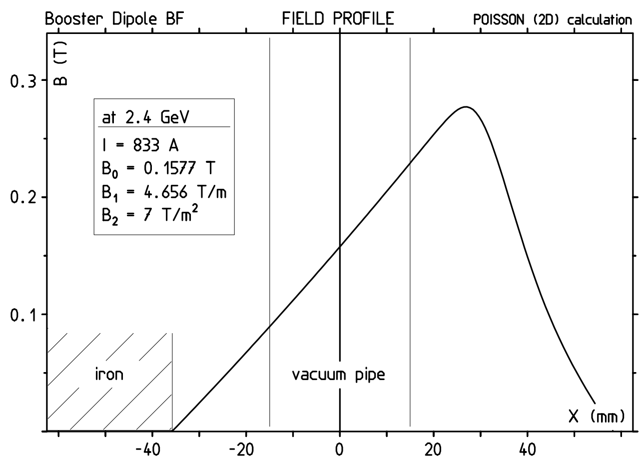

Fig. 1. Field profile for magnet BF

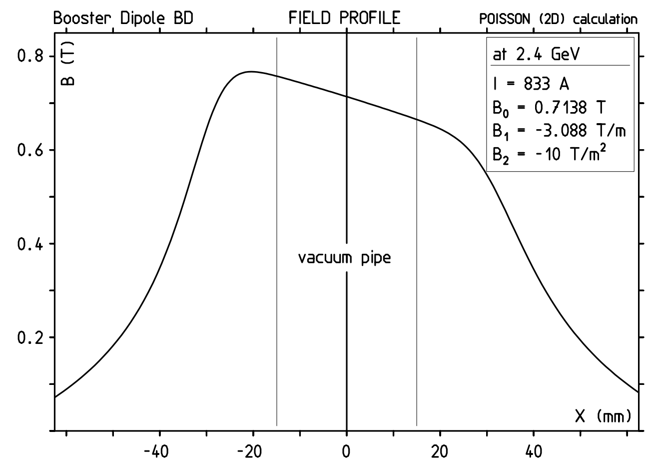

Fig. 3. Field profile of magnet BD

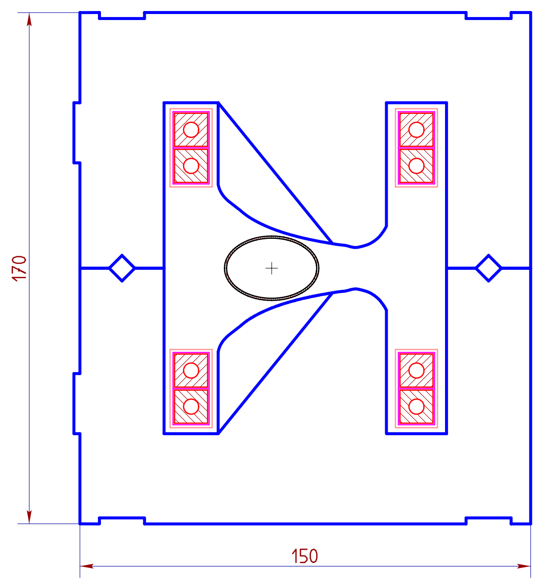

Fig. 2. Cross section of magnet BF

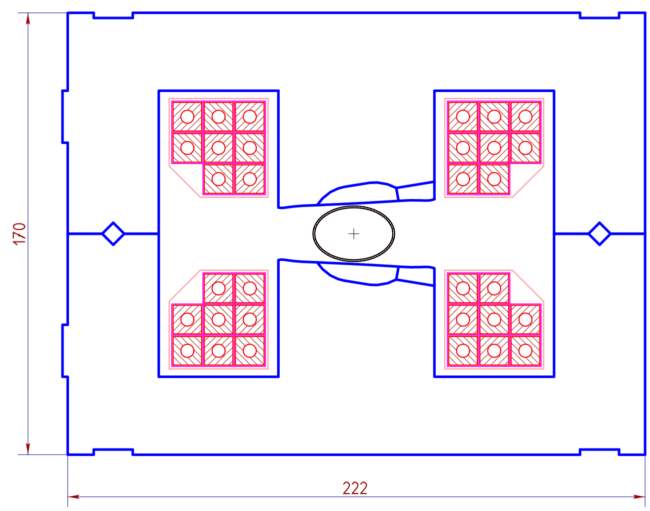

Fig. 4. Cross section of magnet BD

All magnets for the booster synchrotron, 45 BF magnets and 48 BD magnets, will be electrically connected in series. Hence we chose a coarse conductor cross section of 11 x 11 mm with a cooling channel of 5 mm diameter. To be able to adjust small differences in the excitation behavior between BF magnets and BD magnets a correction turn for a current of 7 A (1.4 mm enamel wire) is integrated into each BF coil.

II. Magnetic Measurements

A. *Magnet measuring machine*

The PSI measuring machine has the following range: horizontal 2100 x 645 mm, vertical displacement 360 mm. The accuracy of the position is about 0.02 mm.

The magnetic field will be measured using a single Hall probe calibrated in a laboratory magnet against a NMR probe.

The measurement is done in so called "flying mode", which drastically reduces the time needed for a field map.

In order to minimize thermal effects especially of the Hall probe the measuring facility is in a controlled temperature environment.

B. *Adjustment of magnet and Hall probe*

For this purpose we use a magnetic active tip mounted into reference holes in the magnet yoke. Small field maps measured close to the magnetic active tip are used to relate the Hall probe magnetic center to the yoke position.

For pure dipole magnets the precision of adjustment is not so important, but for magnets containing gradient fields a high precision is required.

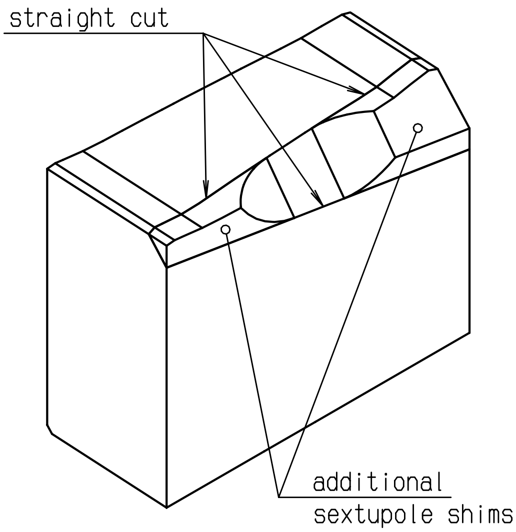

Fig. 5. Pole end piece for magnet BD

C. Field maps

Field maps with a rectangular mesh have been measured in the magnetic mid plane only. It was not possible to measure above or below the mid plane due to the limited space. The probe holder has a length of 2 m to allow the measurement of the field maps with a length of 1800 mm. We used a carbon fibre tube with 12 mm diameter. To reduce transversal oscillations we mounted two tubes in parallel. The minimal gap height for magnet BF is 13.8 mm, for magnet BD it is 19.9 mm.

Most of the field maps were measured with a step size of 2 mm in the transverse direction. In the longitudinal direction the step size was 2 or 4 mm.

D. Excitation

During operation of the booster the magnets are excited by a 3 Hz sinusoidal current of $I_{pp} \approx 800$ A ($\hat{I} \approx 400$ A) overlayed by a direct current of $I_{DC} \approx 430$ A. For all our measurements we used a direct current, ranging from 35 A up to 950 A corresponding to an injection energy of the electron beam of 100 MeV and an extraction energy of 2.7 GeV. The design energy of the booster is 2.4 GeV.

E. Excitation procedure

Ferro magnetic material shows a hysteresis behavior: the magnetic field depends on the history of excitation. For the booster the acceleration of the beam will take place during rising magnetic field, and the current will never be smaller than 10 A (the latter is given by the power supply). We therefore chose the excitation procedure shown in Fig. 6 where the correct point of the excitation curve is reached on the ascending part.

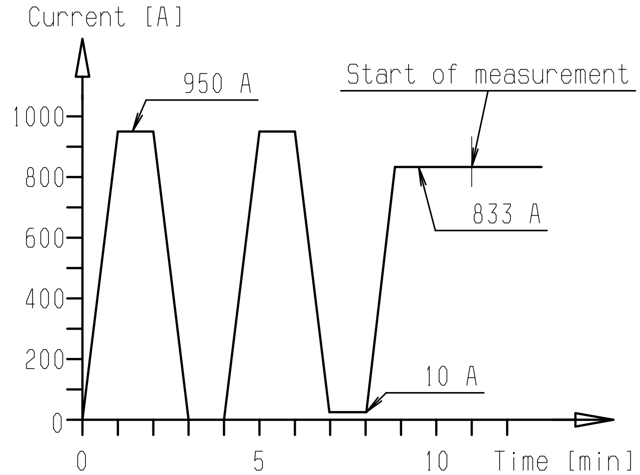

Fig. 6. Excitation procedure for magnet BF and BD

The max. current of 950 A used in this procedure is higher than any current needed for operation of the booster at an energy of 2.4 GeV.

III. MEASUREMENT RESULTS

A. Field maps

We measured field maps with all types of pole end pieces at various currents.

After measuring the field maps we had to evaluate the above mentioned field components. Here we distinguished between "local" values and "integrated" values:

- "local" values refer to the magnet without pole end effects. We used these values to decide whether the pole profile could be accepted and the stamping of the laminations for the series magnets could be started.
- "integrated" values refer to the whole magnet including its pole end effects. According to these values we decided whether the pole end pieces had the correct chamfer and the length of the yokes was correct. The field values for the integration along the theoretical beam path, which is taken as a circular arc and two straight lines at the entrance and exit (hard edge model), are found by linear interpolation within the measured rectangular mesh. The integration was also done on several lines "parallel" to the theoretical beam path.

In the following Tables 2 and 3 the specified values and the values calculated according to our field measurements are listed and compared for a current of I= 833.0 A. This current value is required for the electron beam at an energy of 2.4 GeV.

Thanks to the careful preparation including the 3D pole end calculations it was possible to achieve the design goal, to produce six connected parameters (dipole, quadrupole, sextupole) from a single current, within a reasonable time.

TABLE 2. Magnet BF

	SPECIFIED E= 2.4 GeV	Measurement, I= 833.0 A local (Profile)	Integral	
L_{eff}	1000.0	---	1003.4	mm
B_0	0.1577	0.1574	0.1574	T
B_1	4.656	4.646	4.648	T/m
B_2	7.0	6.2	7.2	T/m^2
d_1	33.9	33.9	33.9	mm
d_2	665.1	751.1	643.4	mm

TABLE 3. Magnet BD

	SPECIFIED E= 2.4 GeV	Measurement, I= 833.0 A local (Profile)	Integral	
L_{eff}	1260.0	---	1262.3	mm
B_0	0.7138	0.7108	0.7108	T
B_1	-3.088	-3.071	-3.091	T/m
B_2	-10.0	-9.9	-9.1	T/m^2
d_1	-231.2	-231.4	-230.0	mm
d_2	308.8	311.8	339.4	mm

B. Excitation curve

The excitation curve has been measured to quantify the saturation effect. In Fig. 7 the deviation from a linear excitation curve is shown for both magnets, BF and BD:

$$\Delta B = B(I) - G \cdot I$$

where ***G*** is the gradient ***G= B(I)/I*** for the linear part of the excitation curve.

For magnet BF the saturation effect is nearly zero as was expected due to the low magnetic induction in the iron parts. For magnet BD, due to the higher magnetic induction in the iron parts, a small saturation effect exists. The difference in the magnetic behavior can be compensated by exciting the correction turns, which are integrated in the coils of magnet BF, in an appropriate way.

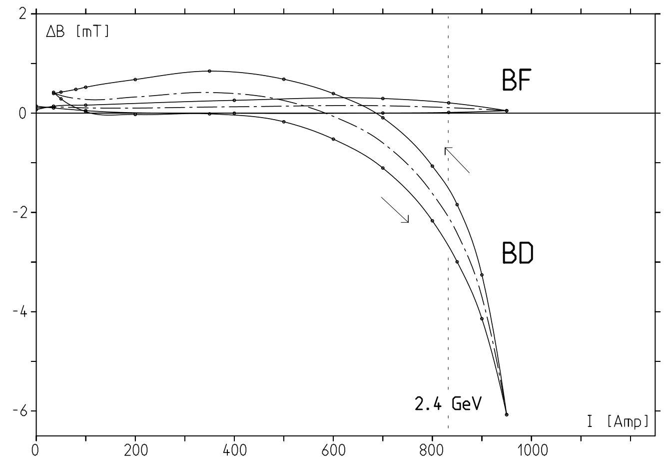

Fig. 7. Excitation curve of magnet BF and BD

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