# A 2.9 TESLA ROOM TEMPERATURE SUPERBEND MAGNET FOR THE SWISS LIGHT SOURCE AT PSI

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*Abstract*

The Swiss Light Source (SLS) at the Paul Scherrer Institute (PSI) in Villigen, Switzerland, is a 3rd generation synchrotron light source. With an energy of 2.4 GeV, it provides high brightness photon beams for research in materials science, biology and chemistry. The SLS storage ring contains 36 room temperature bending magnets, all of which produce light for experimental use; at the design energy of 2.4 GeV, they have a maximum magnetic field of 1.4 Tesla. Light is produced along the entire bending arc but can only be transferred to the external experimental facilities from selected short portions of the beam path. In cooperation with the Budker Institute for Nuclear Physics (BINP) in Novosibirsk, Russia, three of these magnets were replaced with new room temperature magnets with short regions of high magnetic field up to 2.9 Tesla. This enabled the production of intense light beams at shorter wavelengths than from the existing magnets. The critical energy of the 2.9 T magnet is 11.1 keV, compared to the 5.4 keV of the normal bend. This paper describes the design, including the multiple restraints, together with the measurement and commissioning of these so-called Superbends.

## INTRODUCTION

PSI is the largest research institute in Switzerland, active in many fields like nuclear energy, biology, general energy or particle physics. Within the large research facilities division (GFA), three accelerator complexes are in operation: The 1.2 Megawatt proton ring accelerator for experiments with protons, pions, muons and neutrons; the superconducting compact COMET cyclotron for the medical treatment of tumors with protons, and the Swiss Light Source (SLS), an electron booster and storage ring.

The SLS is a third-generation synchrotron light source. With an energy of 2.4 GeV and 400 mA stored beam current operating in top-up mode, it provides photon beams of high brightness for research in materials science, biology and chemistry. The storage ring contains 36 dipoles operating at 1.4 Tesla.

The beam lifetime is typically more than 7 hrs with an average availability of 96 to 98 %; the orbit stability is better than 1 micron. Fifteen beam lines and two lines for diagnostics are presently in operation.

## SUPERBEND CONCEPT

SLS users made a request for beam lines with more intense synchrotron light at shorter wavelengths. After some unfruitful attempts to design a superconducting magnet, the effort was transferred to the idea of building a high field resistive magnet by forcing the field beyond saturation in a central pole region. Three "standard" 1.4 Tesla dipoles (called BX), spaced symmetrically at 120°, would be replaced with three magnets having the same field integral but varying field strength along the beam axis. A short peak of 2.9 T in the central region of the magnet shifts the critical energy of the source from 5.4 keV up to 11.1 keV resulting in a considerable increase of flux for hard X-rays above 20 keV.

## DESIGN CONSTRAINTS

The three new magnets have to fit in the available space, with the same air gap and use the same vacuum chambers as the existing magnets. The space on the outer radius is limited by light beam lines exiting the storage ring tangentially from the previous magnet. The bottom (and top due to symmetry) yoke thickness is limited by the existing support system. The storage ring is built up using precisely positioned girders for the straight sections. The existing dipole magnets are supported on the ends of adjacent girders and there is a weight limitation to be taken into account. The existing BX magnet weighs 2.7 Tons.

A further constraint concerns the power supply. The existing 36 magnets are connected in series using a single power supply. Power supply variations are compensated through the high frequency cavities; therefore, a large part of the bending field integral should be obtained using the main ring power supply.

The SLS can also run at energies up to 2.7 GeV with relaxed parameters. We therefore tried to find a possibility to run the Superbends at this energy.

## MECHANICAL DESIGN

The basic magnetic design concept is shown in Fig. 1 as a cross section along the beam. It consists of a central highly tapered pole (1) surrounded by coil pancakes (2) which are reverse tapered to follow the pole shape. In the entrance and exit regions, conventional long flat poles (3) provide most of the bending power. These two poles and the central pole are surrounded by the main coil (4), which is connected electrically in series with the main storage ring power supply. In order to achieve the high central field with the tapered central coils, a second power supply, connected in series to the three Superbends, has to be used. In order to make a final precise symmetry between the three Superbends, individual wire wound correction coils are integrated into the main coils.

There are three side yokes, as shown in Fig. 2. The two on the outside radius are rather small due to the space limitations but are important for mechanical stability. The large inside yoke is also the heaviest part of the magnet. A central offset support was introduced under this yoke to take one third of the magnet weight (6.7 Tons). The thickness of the top and bottom yokes is restricted by the existing supports at each end but it was possible to add more iron in the central region.

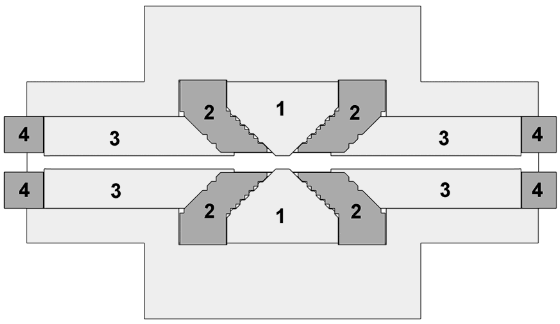


Figure 1: Longitudinal cross section of the Superbend bending magnet.

Contrary to the design of the BX dipoles, which are laminated for stability reasons, the Superbend was built using solid low carbon steel to achieve the maximum filling factor. Saturated iron is intrinsically stable.

During the initial measurement phase, we found that the two small yokes were highly saturated. This opened up the possibility of installing a third back-leg coil around the large side yoke to provide extra field for the 2.7 GeV operation mode. This is planned for some convenient time in the future.

## MAGNETIC DESIGN

The magnetic design was performed by the Budker Institute of Nuclear Physics using the Mermaid Code [1]; they also performed the mechanical design and manufacture.

## MAGNETIC MEASUREMENT PROCEDURE

The magnetic measurements were performed at the PSI magnetic measurement facility in Switzerland by measuring rectangular field maps in the mid-plane using a Hall Probe [2].

The measuring machine moves on air cushions over a precision polished granite block with a positional accuracy of 10 microns. A rectangular map consists of a number of lines measured on the fly, without stopping at each measurement point, and in both directions to cancel out any induced voltages. At each point, the Hall voltage, the position, the supply current and the time are recorded. The Hall voltage is converted to field values off-line.

In order to physically relate the position of a field map to the magnet geometry, small precise holes are machined at strategic points during magnet manufacture.

Removable precise magnetic pins or double pins placed in these holes can be localized by using the Hall probe to find the filed maximum at the pin centre. The same holes would later be used by the PSI Survey Group to align the magnet in the beam line.

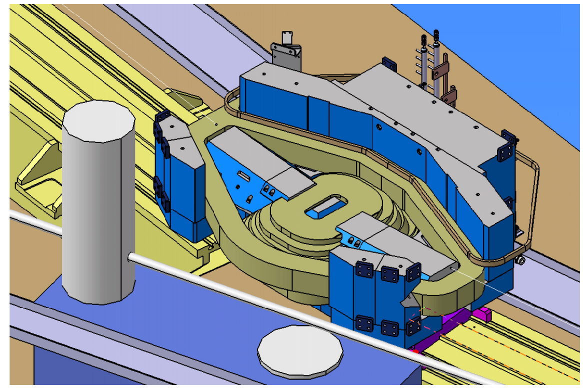

Figure 2: 3D model of the lower part of the Superbend bending magnet. The central pole and coils, the main coil, the three return yokes and the back-leg coil can be clearly seen.

Prior to measuring the first Superbend, a Hall Probe calibration up to 3 Tesla was performed at the LHC dipole test facility at CERN. Since the absolute field integral was not as important as the comparison with the existing magnets, we then re-measured the spare standard BX storage ring dipole at its operating currents. The field integrals are determined by the PSI ray tracing code TRACK [3]. It was also possible to determine the exact beam position at the magnet centre, which is the source of the extracted light. The lateral difference in the light source position between the Superbend and the existing standard magnets was calculated to be 4.1 mm.

## MAGNETIC MEASUREMENT RESULTS

The initial measurements gave a field integral which was 1% too strong for the 2.4 GeV mode but about 3% too weak for 2.7 GeV. This is to be expected, since the central coils are always set at full current to achieve the maximum possible field for the extracted light. When the main power supply current is raised for the 2.7 GeV mode, only the field in the two long poles, which accounts for about 76% of the field integral, is affected. Before weakening the magnet by removing material, which would have made the task of reaching 2.7 GeV even more difficult, we put two reversed back-leg turns around the large yoke, connected in series with the central coils. This turned out to make a nearly perfect match and the method was adopted with a permanent coil. At a later stage, this coil will be replaced by a 42 turn coil connected to a separate bi-polar power supply. This will enable operation of the storage ring at any energy up to 2.7 GeV. Measurements were also made at higher main coil currents to simulate the 2.7 GeV operation mode.

Figure 3 shows the measured fields along the beam path for the storage ring operation for the Superbend and for the BX dipole.

Table 1 gives the main magnet parameters.

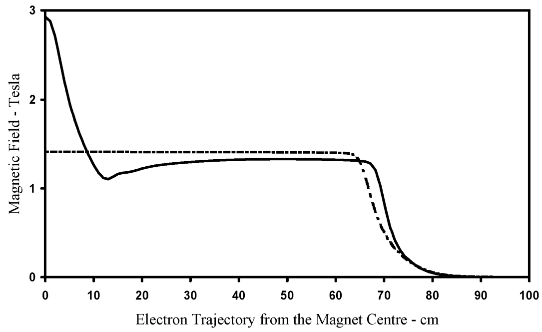


Figure 3: Magnetic field along the electron trajectories for the BX magnet (dashed) and for a Superbend at 2.4 GeV, obtained from TRACK using rectangular field maps measured by a Hall probe.

## INSTALLATION AND COMMISSIONING

Installation of each of the three magnets was performed during three separate routine shutdowns. The top half of the existing magnet was removed to allow removal of the vacuum chamber and to seal the open vacuum ports. The top half was remounted to allow removal of the whole magnet. The new support geometry was prepared and the Superbend installed, and surveyed and leveled after a further removal of the top half. The new vacuum chamber could then be installed and tested for 24 hours. On the following day, the top yoke was installed and internal connections completed.

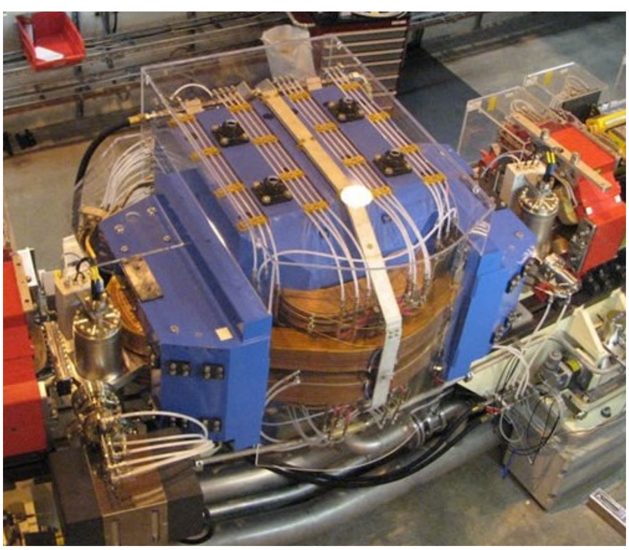

Figure 4: One of the three Superbends mounted in the SLS storage ring. The main coils and the separate central coils can be clearly seen.

Following basic testing, the electrical and water connections could be completed and a full power test performed. The electron beam could be found and successfully stored within one shift; the users were also in operation very quickly and were very satisfied with the performance. The completed magnet can be seen in Fig. 4.

## CONCLUSIONS

By using a special geometry and additional coils, it was possible to create a room temperature magnet that has a peak field of 2.9 T in the centre. This Superbend magnet was designed to have the same field integral than the existing BX magnets present in the SLS storage ring, also using the existing power supply for its main coils. The geometry had to be adapted to allow the installation of the Superbend magnet in the restricted space of the storage ring. Careful designing and planning greatly facilitated installation and commissioning. The critical energy of the Superbend magnet is 11.1 keV, compared to the 5.4 keV of the BX magnet.

Table 1: Superbend Magnet Data

| Operating conditions | Main coils | Central coils |
|---|---|---|
| Air gap [mm] | 40 | |
| Magnetic field at 2.4/2.7 GeV [T] | 1.33/1.50 | 2.91/2.95 |
| Current 2.4/2.7 GeV [A] | 412.8/481 | 500 |
| Voltage 2.4/2.7 GeV [V] | 26.4/31.1 | 53 |
| Power 2.4/2.7 GeV [kW] | 10.9/15 | 26.5 |
| Resistance at 20°C [mΩ] | 60.5 | 50.0 |
| OFHC Copper Conductor OD [mm] | 13x11xR1 | 11x11xR1 |
| Cooling passage ID [mm] | 6 | 5 |
| Cooling water flow [l/min] | 24 | 42 |
| Pressure drop [bar] | 4.5 | 8 |
| Water inlet temperature [°C] | 25 | |
| Temperature rise [°C] | 6.6/9.0 | 9.3 |
| Turns | 108 | 352 |
| Number of cooling circuits | 8 | 14 |
| Approx. coil weight [kg] | 570 | 500 |
| Approx. total magnet weight [kg] | 6700 | |

## REFERENCES

[1] A. Dubrovin, “Mermaid code for 3D magnetic field calculations in accelerator design”, Proceedings of the International Computational Accelerator Physics Conference 2004, St. Petersburg, 2004, p. 47.
[2] S. Sanfilippo, “Hall probes: physics and application to magnetometry”, Proceedings of the CAS-CERN Accelerator School: Magnets, Bruges, Belgium, 16-25 June 2009, edited by D. Brandt, CERN 2010-004, pp.423-462
[3] V.Vrankovic, D.C.George, J.M.Schippers, “Ray tracing with the program TRACK (from beam transport magnets to cyclotrons)”, Proceedings of the XXXIII European Cyclotron Progress Meeting, Warsaw/Kraków, Poland, September 18-21, 2002