SUPERBENDS FOR DIFFRACTION-LIMITED LIGHT SOURCES: REVIEW AND RECENT ADVANCES

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Abstract

All third-generation synchrotron radiation sources are currently planning upgrades toward diffraction-limited storage rings with brightness close to the theoretical limit and higher hard-x-ray production. In these new photon sources superconducting bending (superbend) magnets may play an important role to extend the useful photon energy range. The radiation produced by a superbend magnet is an order of magnitude higher in photon brightness and flux than that produced by a normal conducting bending magnet, making it a superior source of very hard x-rays. As an example, in the framework of the Elettra 2.0 project, a new superbend magnet is under development to provide photons up to 140 keV with an innovative compact design integrated with quadrupole side magnets. The 6T superbend will replace a B80 normal conducting with combined transverse and longitudinal gradient (1.4T central field) magnet. The magnetic design reflects the philosophy of the B80 design combined with innovative cryogenic solutions aimed at achieving a liquid helium-free system. This approach enables a simpler and more reliable design while avoiding the operational costs and uncertainties associated with liquid helium.

INTRODUCTION

The superbend, in the framework of the Elettra 2.0 project [1] will be conduction-cooled by two Sumitomo cryocoolers, ensuring stable operation without the use of liquid helium while maintaining a simple and robust system design [3].

The NbTi superconducting magnet will operate at approximately 3.5 K in conduction-cooled mode, using an integrated system of heat exchangers thermally coupled to the second cooling stage, thereby eliminating the need for a liquid helium bath [2, 4, 5].

A novel C-shaped configuration will allow the magnet to be easily installed and removed from its position on the storage ring vacuum chamber [7, 8, 9].

The procurement process has been completed, and according to the contract, the magnet will be delivered and fully tested by February 2028.

MAGNETIC DESIGN

The superbend design must comply with the constraints imposed by beam dynamics and the ring geometry, including a total bending angle of 6.5° and a magnetic length of 800 mm. Figure 1 presents the target magnetic field profile for the Elettra light source (blue line). This profile features a high-field central region extending over 80 mm with a non he superbend is cooled and maintained at cryogenic temperature using two Sumitomo 4 K cryocoolers operating in conduction -gradient bending angle of 3.44°. On either side, two lateral sections of 360 mm each provide an additional 1.53° per side, reaching a field level of 0.594 T with a nominal gradient (k) of −2.02, adjustable within ±20%.

The design requires a peak magnetic field of 6 T, while the gradient region must extend over at least 720 mm without exceeding 0.8 T at any point. To accurately reproduce the target field profile shown in Fig.1, the solution combines a dipole with two quadrupoles (Fig. 2), as reflected by the calculated magnetic field of the complete system (red curve). The quadrupole field is achieved by introducing a current imbalance between the left and right windings. In this configuration, the four windings are not connected in series; instead, the left and right sides are powered independently.

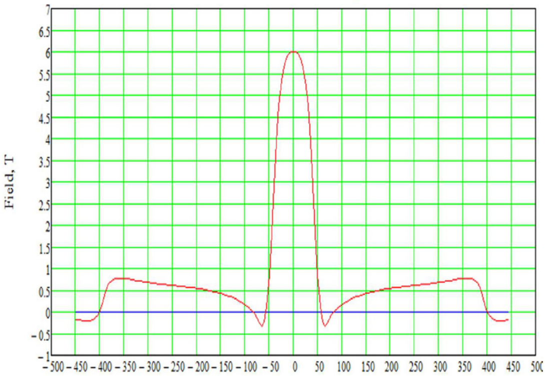

Figure 1: Superbend magnetic field profile.

This approach simplifies both the mechanical layout and the magnetic tuning, enabling remote optimization through adjustment of the power supply settings.

Simulation results indicate that a superbend with an increased total magnetic length of 880 mm induces only minor distortions in the linear beam optics.

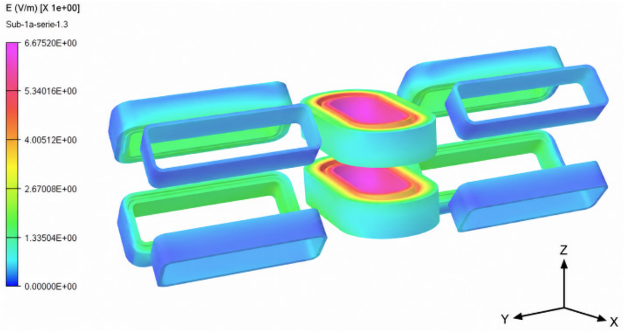

Figure 2: Magnetic field distribution on cold mass.

CRYOGENICS

The superbend is cooled and maintained at cryogenic temperature using two Sumitomo 4 K cryocoolers operating in conduction mode as shown in Fig 3. The first stages are dedicated to intercepting the thermal loads due to conduction and radiation and to keep cold the HTS current leads, stabilizing the temperatures below 40K. The second stages are directly coupled to the cold mass through high-conductivity copper straps, ensuring efficient heat transfer and stable low-temperature operation.

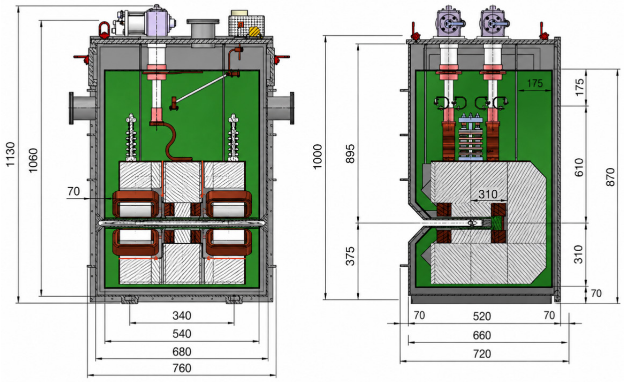

Figure 3: Cryostat and cooling system.

The cryocooler provides nominal cooling capacities of 60 W at 43 K on the first stage and 1.25 W at 4.2 K on the second stage; with two units installed, this corresponds to a total available cooling power of 120 W at 43 K on the first stage and 2.5 W at 4.2 K on the second stage (Fig.4).

Based on the thermal loads on stage 1 and stage 2 (Tables 1 and 2), together with the cryocooler capacity map shown in Figure 4, the expected operating temperatures at the cryocooler cold heads during ramp-up are approximately 33 K for the first stage and 2.6 K for the second stage.

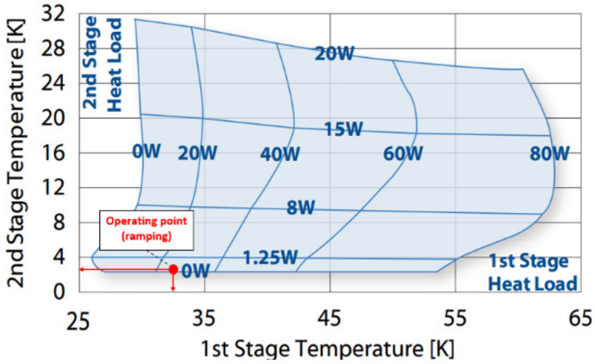

Figure 4: Cooling capacaty curve sumitomo cold head.

A temperature gradient of less than 0.5 K between the cryocooler cold head and the magnet is expected, as observed in similar systems. This leads to an estimated magnet temperature of about 3.1 K during ramp-up, consistent with conduction-cooled systems of comparable mass and cooling power. With the selected configuration of two cryocoolers, sufficient cooling capacity is available to maintain steady-state operation at temperatures below 3.1 K.

Table 1: Thermal Loads on First Stage

Item	**Load (W)**
Main dipole current leads(150A)	13.18
Quadrupole Plus current leads(150A)	13.18
Heaters	0.35
Suspension rod-magnet	1.61
Suspension rod-shield	1.39
Temperature sensors and voltage taps	1
Thermal shield	20.9
Total	**51.61**

Table 2: Second Stage Thermal Load

Item	**Load (mW)**
HTS current leads	150
Heaters	38
Suspension rod-magnet	20
Eddy losses	100
Ac losses	40
Temperature sensors and voltage taps	50
Thermal shield-magnet	18
Total	**416**

Two types of round NbTi multifilament superconducting wire are proposed for the coils of the superbend magnet, both characterized by a Cu/SC ratio of 1.3. The inner coils of the dipole will be wound using wire with a bare diameter of 0.85 mm, as this larger size provides the required load line margin and temperature stability (Fig.5). All remaining coils, including the dipole outer coils and the quadrupole coils, will instead be wound with wire of 0.7 mm bare diameter (Fig.6).

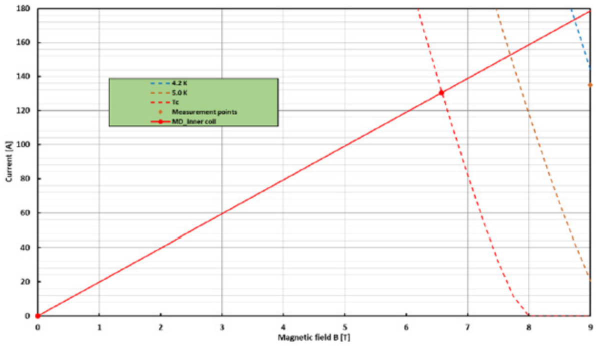

Figure 5: Inner dipole load line.

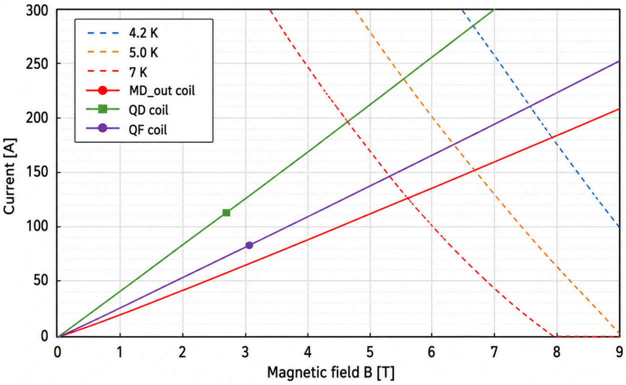

Figure 6: Outer dipole and quadrupole load lines.

Table 3 summarizes the main characteristics of the superconducting design of the superbend. By comparing these values with the load lines shown in Figures 5 and 6, it can be observed that the operating margin is sufficient to ensure safe and stable magnet operation, with a minimum operating margin of 24.8% on the main dipole and a minimum temperature margin of 1.4 K.

Table 3: Superconductive Properties

Parameter	**Unit**	**MD In.**	**MD Out.**	**QD**	**QP**
Operation current	A	130.5	130.5	116.0	86.5
B_{max}	T	6.57	5.63	2.73	3.08
Critical current @4.2 K I_c	A	173.6	184.4	286	212.7
Loadline fraction		75.2%	70.8%	40.6%	40.7%
Temperature margin	K	1.6	1.4	2.6	2.7

CONCLUSION

The cryogenic and magnetic design of the superbend for the Elettra 2.0 light source has been finalized and frozen, the mechanical design is currently being finalized. Installation in the storage ring is scheduled by early 2028. The presented cryogenic analysis and magnetic design demonstrate that the superconducting magnet operates with a large margin, ensuring robust and reliable performance. The adoption of a conduction-cooled, helium-free solution further enhances system reliability and significantly reduces operational costs. Overall, the proposed design with the use of NbTi, a well-established and highly reliable LTS superconductor represents a well-balanced solution in terms of performance, simplicity, and long-term operability.

REFERENCES

[1] E. Karantzoulis, *et al*., “Design strategies and technology of Elettra 2.0 for a versatile offer to the user community”, *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 1060 (2024), pp 1-35. doi:10.1016/j.nima.2023.169007

[2] M. Wilson, *Superconducitng Magnets*, USA: Clarendon Press, 1987.

[3] R. Conte, *Éléments de Cryogénie*, Masson & Cie, 1970.

[4] C. E. Taylor and S. Caspi, “A 6.3 T Bend Magnet for the Advanced Light Source”, *IEEE Trans. Magnetics,* vol. 32, No. 4, 1996, pp. 2175-2178. doi:10.1109/20.508596

[5] J. Zbasnik, *et al*., “ALS Superbend Magnet System*,” IEEE Trans. App. Supercond.*, vol. 11, no. 1, March 2001, pp. 2531-2534.

[6] Advanced Light Source Division, “Superbend Magnet System Conceptual Design Report”, Lawrence Berkeley National Laboratory Publication, PUB-5457, Apr. 2000.

[7] D. S. Robin *et al.*, “Superbend Project at the Advanced Light Source”, in *Proc. PAC'01*, Chicago, IL, USA, Jun. 2001, paper WPPH077, pp. 2632-2634.

[8] E. Karantzoulis, *et al.,* “Elettra 2.0 Technical Design Report”, Elettra – Sincrotrone Trieste, ST/M-21/01, 2021.

[9] M. Modica, A. Fabris, D. Castronovo, D. Caiazza, E. Karantzoulis, and S. Di Mitri, “Superconducting dipole for Elettra 2.0”, in *Proc. IPAC'24*, Nashville, TN, USA, May 2024, pp. 2840-2842. doi:10.18429/JACoW-IPAC2024-WEPS62