

Test stand for the characterization of superconducting magnets cooled with cryocoolers

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Abstract.

Superconducting magnets cooled with cryocoolers become more and more attractive due to an increasing cooling performance and decreasing costs. This cooling mode offers new perspectives to high field magnets like the possibility to be installed where space is limited and the use in rotating systems. At the Paul Scherrer Institute (PSI), two projects involving superconducting magnets cooled with cryocoolers are ongoing: a compact 6 T super-bend for the upgrade of the Swiss Light Source has been designed and a concept for a new generation of proton therapy gantries for cancer treatment was proposed last year. This contribution focuses on a dedicated compact and adjustable test stand in construction at PSI aiming at the thermal, mechanical and magnetic characterization of future superconducting magnets cooled with cryocoolers under operating conditions.

1. Introduction

With an increasing cooling performance and decreasing costs, cryocoolers become more and more attractive for the cooling of superconducting magnets, especially where space is limited and for rotating systems. At the Paul Scherrer Institut (PSI), several projects involving superconducting magnets cooled with cryocoolers are planned for the next years or under consideration, like the upgrade of the Swiss Light Source (SLS-2) and the development of a new generation of proton therapy gantries. The superconducting magnets needed for these projects have to be thermally, mechanically and magnetically characterized under operating conditions in a dedicated test stand, which will be presented in the following sections. The focus will be on the description of the experimental setup including the instrumentation and the magnetic measurement system. Furthermore, an overview on the status and outlook of the projects will be given.

1.1. Upgrade of the Swiss Light Source (SLS-2)

One of the main aims of PSI for the next years is the upgrade of the Swiss Light Source (SLS-2) in order to meet the demand of the users for higher photon flux and brilliance [1]. This involves the development of a new storage ring Multi Bend Achromat lattice reducing the emittance from 5 nm to 137 pm while maintaining the locations of the undulator based beam lines and the circumference of 287.25 m [1]. The preliminary design of the lattice foresees the use of longitudinal gradient bend magnets and three superconducting super-bends to produce hard X-rays. The super-bends have a hyperbolic longitudinal field variation with a narrow peak and



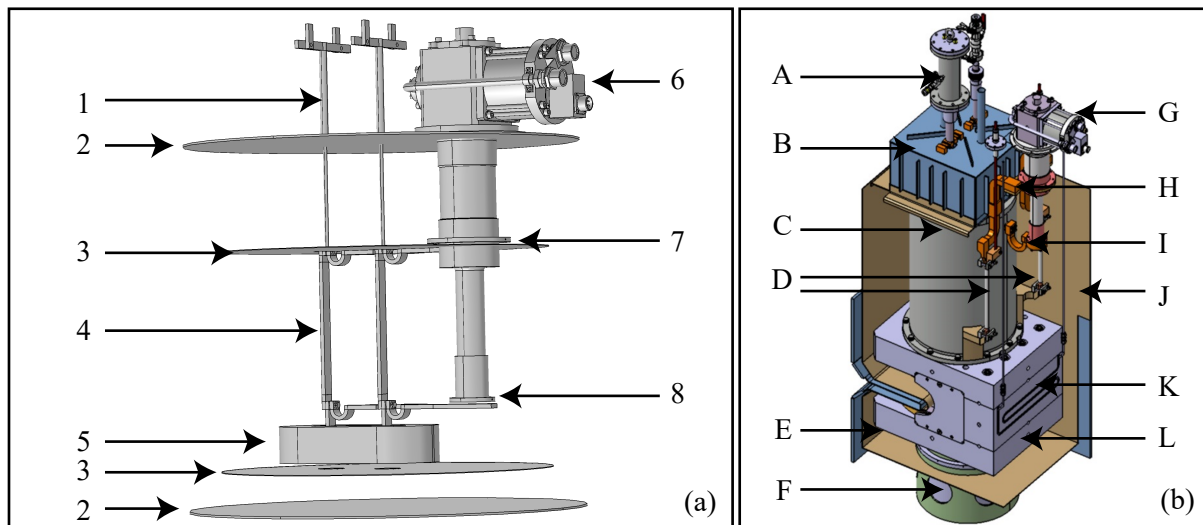


Figure 1. (a) Assembly for the pre-tests of the inner Nb₃Sn coil of the super-bend magnet for SLS-2 with 1: copper part of current leads 2: vacuum vessel, 3: thermal radiation shield, 4: HTS part of the current leads, 5: Nb₃Sn coil, 6: connection to helium flexlines, 7: cryocooler 1st stage and 8: 2nd stage and

(b) full assembly of the 6 T super-bend magnet for SLS-2 [2] with A: liquid helium (LHe) supply, B: liquid nitrogen (LN₂) reservoir, C: LHe reservoir, D: High temperature superconductor (HTS) current leads, E: 316 L stainless steel cryostat, F: support, G: Gifford-McMahon (GM) cryocooler, H: connection to cryocooler 1st stage, I: connection to cryocooler 2nd stage, J: copper thermal shield, K: tube for precooling, L: ARMCO yoke.

a full width at half maximum of about 70 mm to limit the energy spread and the radiated power. The peak field values at the beam position are ranging from 2 T to 6 T, with a 3 mm wide peak flat top along the beam trajectory and a field homogeneity of 1 % with an operating current of 400 A [2].

The superconducting coils made of Nb₃Sn (inner coils as shown in Figure 1(a)) and Nb-Ti (outer coils) will be conduction cooled through the iron yoke and the support structure as can be seen in Figure 1(b) in order to place the coils as close to the electron beam as possible [2]. A 40 l cylindrical liquid helium (LHe) reservoir is connected on top of the yoke using a Gifford-McMahon (GM) cryocooler as helium re-condensing unit. An additional vessel containing liquid nitrogen (LN₂) is foreseen to intercept the heat input caused by radiation and conduction. The cryogenic liquids will also serve as cold buffer during short downtime and for the exchange of the cryocooler during maintenance.

1.2. Compact and light magnets for a new generation of proton therapy gantries

Proton therapy is an increasingly used technique for the treatment of cancer because of the maximized radiation dose to the tumor and the minimized dose to the surrounding healthy tissue [3,4]. PSI has a long standing record in proton therapy cancer treatment. Presently three gantries are in operation using the spot scanning technique developed at PSI [3,5]. To irradiate the tumor from any direction, a rotating system called gantry as a last bending and focusing section of a proton therapy facility can be used. Superconducting magnets allow reducing the weight and the footprint of the machine and enable new treatment techniques by having a large momentum acceptance [6].

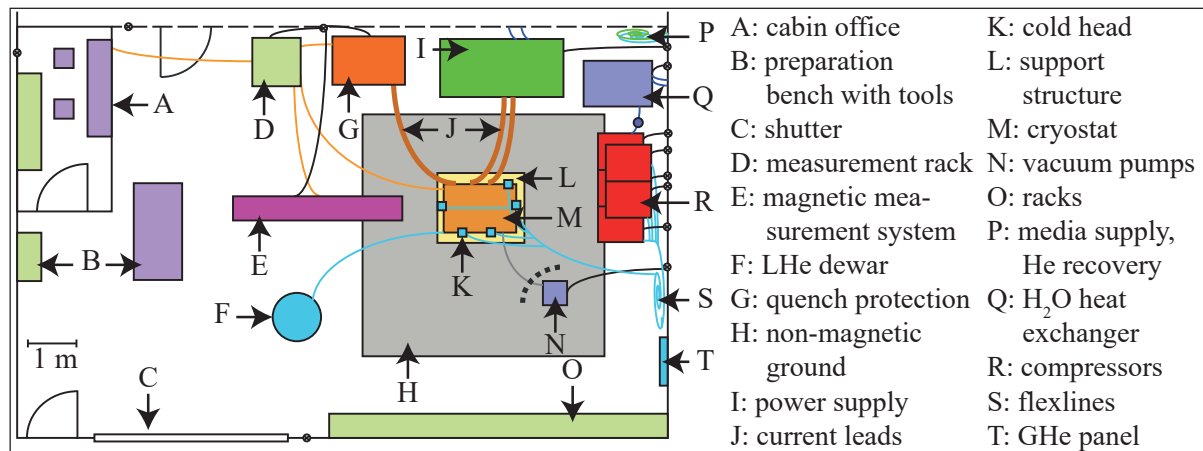


Figure 2. Schematic overview of the new PSI lab for the superconducting magnet test stand.

At PSI, a concept for the last bending section of a proton therapy gantry using superconducting Nb₃Sn combined function magnets with a curved warm bore has been developed involving combined function superconducting magnets [7]. Due to the need of a rotating magnet system, helium bath or forced flow cooling is extremely challenging for gantries. Therefore, GM cryocoolers are foreseen for a two-stage cryogen-free cooling of the magnets in the conceptual design.

2. Objective and setup of the superconducting magnet test stand

For the thermal, mechanical and magnetic characterization of future superconducting magnets cooled with cryocoolers under operating conditions, a dedicated test stand is currently under construction at PSI. The scope of the characterization is the verification of the effectiveness and reliability of the cooling method, of the electrical performance, of the instrumentation, of the quench performance and of the field strength and quality.

Figure 2 shows the schematic overview of the new PSI lab with the room dimensions $13.45 \times 8.5 \times 4.7 \text{ m}^3$. The superconducting magnets to be tested will be integrated within their cryostats and fastened on the non-magnetic ground of $5.0 \times 5.0 \text{ m}^2$ size. A vacuum pumping station consisting of a prepump and a turbopump will be flanged to the cryostat and protected from the magnetic stray field by a dedicated shield. Up to five cryocoolers can be attached to the superconducting magnet. Their compressors need to be water cooled, using a closed cooling water circuit with a heat exchanger and an ion exchanger. Optionally, LHe from a dewar or LN₂ from the ring line can be used for the pre-cooling of the magnet. A 500 A power supply is used for the first tests and can be upgraded in future for the tests of superconducting gantry magnets. Dump resistors are used for the quench protection. The measurement equipment is installed in a rack. From a cabin for noise insulation, the measurements are monitored and controlled.

3. Instrumentation

Figure 3(a) shows an exemplary Piping and Instrumentation Diagram (P&ID) for pre-tests of superconducting components at the magnet test stand. Up to five cryocoolers, consisting each of a water-cooled compressor, a cold head with two stages and helium flexlines as connection, can be used for the cooling of the assembly. For first tests, one GM cryocooler of type SRDK-415D-F50H from *Sumitomo* and a pair of 500 A HTS current leads of type CS-0500-305 from *HTS-110* will be installed. The first stage of the cryocooler will be connected to the thermal

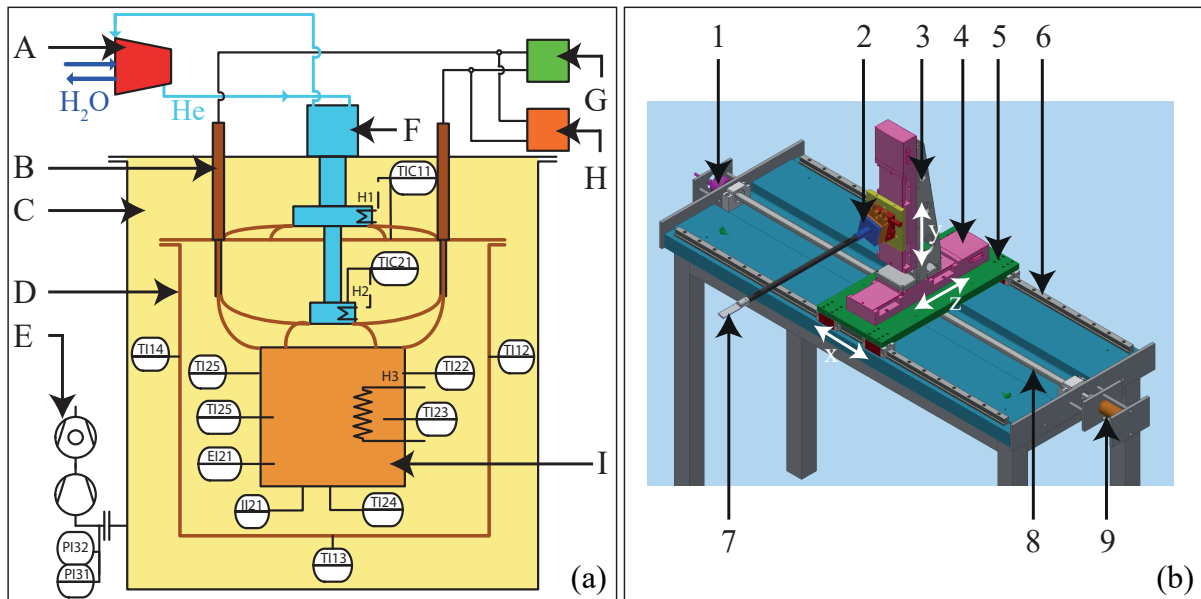


Figure 3. (a) Exemplary P&ID of the test stand for pre-tests of the SLS-2 super-bends with A: up to five compressors, B: current leads, C: vacuum vessel, D: radiation shield, E: vacuum pumps, F: up to five cold heads, G: power supply, H: quench protection, I: sample or coil to be tested and (b) drawing of the exemplary magnetic measurement bench for SLS-2 with 1: rotary encoder, 2: rotation and tilt stages, 3: support structure, 4: linear stages, 5: slide, 6: linear guideways, 7: Hall probe support, 8: ball screw, 9: DC motor.

radiation shield and the current leads, while the second stage will be attached to the sample or coil, depending on the type of test. The test stand will be equipped with up to four *Lake Shore Cernox*[®] temperature sensors of type CX-1050-CU-HT (TIC21, TI22, TI23 and TI24) for the measurement of the shield temperature and up to six *Lake Shore Cernox*[®] temperature sensors (TIC11, TI12 to TI16) of type CX-1050-SD-HT for the measurement of the sample or coil. A *Lake Shore Model 218* temperature monitor will be used for the read-out of eight of the temperature sensors. The other two temperature sensors (TIC11 and TIC22) can be used to monitor and control temperatures with the help of two heaters (H1 with a heating power of 35 W and H2 of 1.5 W) with an *Oxford Instruments Mercury iTC* temperature controller. The vacuum pressure will be measured by a transmitter of type PKR 251 from *Pfeiffer Vacuum*. For the pre-tests, the electric current of a superconducting Nb₃Sn wire will be measured (II21) during a quench triggered by a heater (H3). The quench detection will be based on voltage taps (EI21). Once the measured voltage exceeds a certain threshold during a quench, the electrical circuit will be opened and the energy will be dissipated at an external air-cooled dump resistor. The data acquisition system and quench detection will be based on *National Instruments* cards and *LabVIEW*[®] programming. A later upgrade to a *Beckhoff TwinCAT 2* system is foreseen.

4. Magnetic measurement system

Before the installation in the beam line, the field quality of the magnets has to be checked. The proposed magnetic measurement system aims at a field accuracy in the range of 0.1...0.5 % and at a reproducibility as good as 0.01 %. For this purpose, a magnetic measurement bench adjustable to different geometries and accessible regions will be included in the test stand to complete the magnets' characterization. A 3D Hall probe with a spatial measurement resolutions

of 150 μm will be used to map the three components of the magnetic field inside the limited dimensions of the gaps [8].

The Hall probe will be moved inside the good field region and its position during the scan will be measured with a bench assembly. The exemplary bench for the magnetic characterization of the SLS-2 super-bends shown in Figure 3(b) is currently under construction, an extension for strongly bend magnets is foreseen. The motion system is a three-coordinates cartesian robot able to position the sensor in the measurement volume and composed by three orthogonally stacked linear stages. To avoid and limit electromagnetic disturbances on motors, sensors and electronic parts, the Hall probe is mounted on a cantilever arm fixed on the top stage with two rotational stages to manually adjust the orientation of the sensor in space. Displacements in y and z direction are carried out by two high precision commercial stages mounted on a slide plate moving along the x-direction thanks to a precision ball-screw and two linear guideways driven by a DC motor. All the axes are equipped with rotary encoders to ensure a positioning uncertainty of $\pm 0.2\text{ mm}$ and a resolution of 0.5 mm obtained through simulation of the measurement process.

The overall working volume is $1000 \times 150 \times 150\text{ mm}^3$, which is compatible with the good field region size of $400 \times 8 \times 6\text{ mm}^3$. The dimensions of the carbon fiber tube have been obtained by minimizing the static deflection of the arm, limiting the effect of the stray field on motors and avoiding vibrations during scanning. The motion control and the data acquisition will be performed on a single machine through a *LabVIEW*[®] interface, which communicates with the stages and with the Hall probe electronics. By defining the volume to scan and the required number of points, Hall probe data acquisition is triggered by evenly spaced encoder pulses along the three directions. For other magnet geometries, the measurement bench will be adapted while the control and acquisition system will be the same. For example, an externally actuated measurement robot that will be driven inside the aperture along curved guidelines inside the curved warm bore will be developed at a later stage to qualify the superconducting gantry magnets.

5. Status and Outlook

A magnet test stand is under development at PSI, which will allow the thermal, mechanical, quench performance and magnetic characterization of superconducting magnets cooled with cryocoolers under operating conditions. Therefore, a measurement system including Cernox[®] temperature sensors and voltage tabs will be installed and a test bench for magnetic measurements using a Hall probe will be installed. The new building for this test stand will be completed in October 2018, the commissioning with Nb₃Sn model coils is foreseen for the beginning of 2019. The first magnetic measurement system will be operational in 2020.

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