Integrating UHV (Ultra High Vacuum) and HTS (High Temperature Superconducting) magnets for x-ray synchrotron based experiments

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Abstract. Integrating UHV (ultra high vacuum) and superconducting magnets poses special challenges to the magnet designer. A range of HTS (High Temperature Superconducting) magnets have been developed for UHV synchrotron beamline applications providing users with compact powerful cryogen-free solutions. Recent examples include HTS magnets for LARIAT (Large Area Rapid Imaging Analytical Tool) [8.5 T with 110 mm warm bore], x-ray scattering experiments at BESSY and LNLS [5-6 T with 110 degrees scattering angle aperture], x-ray magnetic circular dichroism, and resonant scattering experiments at ALBA. This paper will focus on the in-UHV HTS magnet installed at ALBA.

1. Introduction

Achieving desired field and field uniformity while conforming to geometrical constraints and then building a system to meet stringent UHV requirements, represented the main challenges of this system. 2D and 3D magnetic and mechanical stress FEA (finite element analysis) was used to optimize the magnet layout. Novel magnetic yoke shape and coil geometry was necessary to deliver the specific magnetic field requirements. Designing for UHV integrity was a significant constraint for the mechanical design which also required careful material selection. The success of this magnet system provides a ‘springboard’ for further development in UHV x-ray scattering imaging technologies. The combination of large incidence angle variation, optical access, and available sample manipulation provides a very flexible system. Additional room temperature (copper) coils are also integrated, providing superimposing DC and AC fields.
2. **Key requirements**
General specifications are shown in the Table 1.

| Description                              | Value | Units |
|-------------------------------------------|-------|-------|
| Physical gap (min.)                       | 50    | mm    |
| Maximum incidence angle – Axial           | ± 46  | °     |
| Maximum incidence angle – Radial          | ±10   | °     |
| Central field (Max.)                      | 2     | T     |
| Field homogeneity in 10x10x10 [mm] central volume | 2    | %     |
| Stability (10sec.)                        | 1     | %     |
| Repeatability (>10 loops)                | 1     | %     |

Additional requirements are:
- The magnet is mounted inside UHV chamber, therefore must be UHV compatible and must be able to withstand bake-out temperatures of up to 100°C;
- The magnet system must be able to present the field in longitudinal (along the beam) and perpendicular (normal to the beam) orientation;
- The magnet system must be able to rotate ± 46° around its vertical axis in longitudinal and ± 10° in perpendicular field orientation;
- Magnetic stray field must be minimized.

Teams at ICMAB and ALBA performed a feasibility study for various magnet configurations, resulting in the current layout, shown in Figure 1. The main challenges revolved around assembly within tight space constraints, thermal isolation of HTS coils from bake-out temperature and obtaining required field and uniformity within the limited space. Using conduction cooled HTS coils enabled the 2[T] specification to be met within set requirements.
The coils were manufactured using first generation, BSCCO wire. Maintaining UHV compatibility of the system was achieved by using vented Viton O-ring seals on all magnet-to-UHV boundaries and a metal seal CF flange on UHV-to-atmosphere interface.

3. Modelled performance
Magnetic and thermal design of the system is performed using Opera TOSCA® software. Figure 2 shows the 3D FEA model and the system central volume.

The magnet system performance (magnetic and thermal) is modeled to achieve the specifications, while respecting design limits of HTS technology. The FEA showed that the requirements can be met. Additional (ambient temperature) field coils have been designed to provide superimposing DC and AC (up to 50kHz) field over the sample area. Modeled performance of the superimposing coils is shown in Figure 3.
4. Conclusion
The magnet was assembled and tested as per testing procedure agreed on with ALBA – ICMAB team. The testing took place at the HTS-110 factory and at ALBA BOREAS beamline. The system achieved required field (2T) and high homogeneity. An additional requirement for sweeping performance (cycling the field from +2 to -2T in succession of up to 10 cycles) was also satisfied. The superimposing coils were tested in DC and AC mode. In AC mode, the coils were run at up to 50kH sinusoidal AC, 0.55[A] RMS for horizontal and 0.4[A] RMS for vertical

Figure 4. Field plot of 10 x 10 [mm] plane at z = 0

Obtaining required field with limited space for HTS coils, design of the superimposing coils, and manufacturing the system that is UHV compatible proved difficult and complex, but achievable applying HTS-110 methodology. Table 2, shows the summary of tested magnet system.

| Description                                | Value   | Units   |
|--------------------------------------------|---------|---------|
| Cool-down time                             | 28      | Hours   |
| Maximum operating current                  | 150     | A       |
| Maximum sweeping rate                      | 1.6     | T/min.  |
| Operating temperature at steady 2[T]       | 21      | K       |
| Operating temperature in full field sweeping regime | 25     | K       |
| Homogeneity of 10x10x10mm GFR              | 0.5     | %       |
| Repeatability (>10 loops)                 | 1       | %       |