OVERVIEW ON MAGNETIC FIELD MANAGEMENT AND SHIELDING IN HIGH Q MODULES*

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Abstract

Maintaining very high cavity Q_0 in linac applications creates new challenges for cryomodule design. Magnetic shielding from both external fields and internal fields is required and its importance to thermal gradients during Tc transition is now emerging. This paper will describe the design challenges and possible mitigation strategies with examples from various applications or laboratories including DESY/TTF, FRIB, LCLS-II, Cornell University and KEK.

INTRODUCTION

Superconducting RF (SRF) accelerators have been increasingly adopted in various applications from nuclear physics, high energy physics, basic energy sciences and medical physics, etc. Maintaining high performance while reducing the construction and operational costs have been the forefront of the SRF science and technology. Pushing the limits of high operating quality factor (Q) of SRF cavities results in significant cost savings by reducing cryogenic costs. This is especially significant when considering the fact that continuous wave (CW) SRF accelerators require several tens of million dollar cryogenic plant.

Latest developments of nitrogen doping brings the usable niobium cavity Q_0 to be 5 times higher than previously specified [1]. The residual surface resistance of a nitrogen doped cavity, however, is slightly more sensitive to trapped magnetic flux [2,3]. As the cavity operational Q and BCS resistance are inversely proportional, it is important to reduce the residual resistance.

Many factors contribute to the residual surface resistance of a niobium cavity. Surface contamination, oxides are improved by careful chemical and clean room processes while hydrides are minimized using high temperature hydrogen degassing, low temperature baking, and relatively fast cool down through 100K. Magnetic flux trapping, on the other hand, requires optimal design and operational control to minimize its effect on residual resistance.

Ambient magnetic fields arise from several sources. Environmental magnetic fields consist the combined field of earth's magnetic field, buildings, utility infrastructures, and instrumentation equipment. Cryomodule enclosure shells such as vacuum vessels and end caps, as well as components inside the cryomodule are also potential sources that contribute to the ambient magnetic field at the SRF cavities.

A review of the magnetic field effect on cavity Q shows the importance of the magnetic field management in an actual cryomodule. Many types of materials and engineering solutions are available to reduce the ambient magnetic field in the cavity. Earlier systematic studies have been very thorough during the Tesla Test Facility cryomodule development [4]. The magnetic shield design studies have been spotty since then.

The operational control can further reduce the magnetic flux trapping using high thermal gradient during superconducting transition that can overcome the flux pinning force [5].

Design and practices will be showcased in this paper using LCLS-II prototype cryomodule as an example.

MAGNETIC SHIELDING MATERIALS

There are many types of magnetic shielding materials that provides various levels of magnetic shielding at different temperatures and under different ambient magnetic field. Permeability and the saturation are the two main parameters to consider which material to choose, in addition to the cost of the material. There have been many characterization studies related to the magnetic shielding materials [6,7].

There are two major shielding materials typically used in a cryomodule, depending on the shielding design. Traditional mu-metal has very good permeability at room temperature, but decreases dramatically at cryogenic temperature. Cryogenic magnetic shield has high permeability at cryogenic temperature but cost much more than mu-metal. Cryogenic magnetic shield material is very vulnerable to stress and impact vibration. While stress can be relieved by high temperature annealing, handling can introduce stress to the material again. Potential impact of the material is usually unavoidable during an actual assembly. These practical limitations suggest that the design has to consider the worst case permeability for the cryogenic magnetic shields. Based on past experience, a relative permeability of 7,000 for mu-metal and 12,000 for cryogenic magnetic shield are typically used in designing magnetic shield at cryogenic temperatures [4]. Magnetic design in cERL cryomodule at KEK uses a flat sheet format to minimize the fabrication and assembly stress in order to retain the highest permeability [8].

Both A4K and annealed mu-metal have been considered for the cryomodules of Facility for Rare Isotope Accelerator (FRIB) [9]. Cornell ERL linac cryomodule utilized A4K. Both XFEL linac cryomodule and cERL cryomodule chose Cryophy, a material similar

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to A4K. LCLS-II plans to use Cryoperm 10 as the magnetic shield material.

Traditional mu-metal if annealed may have higher permeability even at cold temperature. Experiment at Michigan State University showed annealed mu-metal has relative permeability greater than 10,000 at 4K [10].

Cryogenic material typically changes permeability with temperature. Experimental data [6, 7] indicated the permeability is lower in the temperature range of 20K-40K. Most magnetic shields will be around that temperature range when the SRF cavities transition to superconducting state in the cryomodules. Having one layer of cryogenic magnetic shield that is in a higher temperature range takes advantage of better shielding during the superconducting transition. The outer layer of magnetic shield in Cornell University's ERL main linac cryomodule is in close contact with the cryomodule's 40K/80K thermal shield. Cryogenic shielding material has experiences higher relative permeability as its temperature approaches 4K. This is another advantage that one can take during the design of the magnetic shielding.

Another material worth to mention is METGLAS® magnetic foil. It is a special alloy that has a relative permeability of 45,000 un-annealed at room temperature. It has relatively comparable permeability at cryogenic temperature [11]. The material is flexible and may be utilized to augment the otherwise rigid cryogenic magnetic shield.

DESIGN OF MAGNETIC SHIELDING

Design of the magnetic shield takes into account the temperature, location, geometric factor and right balance among material cost, assembly cost and operational cost in case of active cancellation.

Global Shield and Local Shield

Global shield refers to large enclosures close to cryomodule's vacuum vessel and is typically at room temperature. Global shield can also take a form of smaller sized enclosure and be located at cryogenic temperature such as that in the main linac cryomodule of Cornell University's Energy Recovery Linac (ERL) [12]. Global magnetic shield reduces the earth magnetic field. Due to large sizes in a typical cryomodule, the material cost is higher even considering the lower cost of mu-metal. In addition, global shield alone will not help in case of potential magnetic components within the magnetic shield. Many components indeed have high remnant magnetic field such as welded stainless steel pipes, tuner motors, support structures, etc.

Many cryomodule designs, particularly high Q cryomodules, are using local magnetic shield such as cERL cryomodule, LCLS-II cryomodules. Cornell University's ERL main linac cryomodule uses both global and local magnetic shields. XFEL cryomodules use local magnetic shield which provide better ambient magnetic field reduction and can benefit the potential CW operation [13]. FRIB cryomodules also employ the local magnetic shields.

Multilayer Shields

Depending on the design requirement, multiple layers can be used to achieve high attenuation of the external magnetic field. High Q cryomodules such as those in ERL main linac and LCLS-II linac use two layers of the magnetic shields. ERL main linac uses one layer of magnetic shield, laid directly on the cavity helium vessel. Second layer is laid on the 40K/80K thermal shield. The vacuum vessel in Cornell University's ERL cryomodule is carbon steel and provides additional shielding to the environmental magnetic field. Full cryomodule test is planned in near future to test the design. Nevertheless, concept has been demonstrated in commissioned main injector cryomodule and horizontal test bed.

LCLS-II design uses two layers of magnetic shield outside of the helium vessel. Internal layer of the shield includes the end group shields that is congruent to the cavity end group structures such as HOM couplers, field probe, power coupler port and beam pipes. Second layer is simply a cylinder that is spaced one inch from the first layer. A supplemental METGLAS® foil is planned to be used to extend the port covering and minimizes all openings on the magnetic shields.

Shields Internal and External to Helium Vessel

As mentioned earlier, the cryogenic shielding material typically has much higher relative permeability below 10K. Installation of a layer of magnetic shielding inside the helium vessel takes full advantage of the high relative permeability and also minimizes the openings that is for power couplers, HOM couplers, tuners, support structures and instrumentations. Such practice was adopted in several cryomodule designs [14,15].

Active Cancellation

Previous studies indicated that the longitudinal attenuation factor is much lower in a long cylinder shaped magnetic shield [4] due to the demagnetization factor of a cylinder. For a local shield that encloses a long string of cavities of a cryomodule, this is particularly challenging as one would need to break off the long cylinder structure to decouple the influence between the neighbouring shields. At the same time one has to make sure the end effect is not causing the field leaking into the end cells of the cavities.

Adding material thickness and layers of the shields is not favourable in terms of cost benefit balance. Active cancellation may be more effective in certain circumstances. Prototype cryomodules of LCLS-II plan to use the active cancellation solution to minimize the longitudinal fields to below specification of 5 mG. The use of active cancelation for the production LCLS-II cryomodule will be decided after the test of the prototype cryomodules.

Other Factors

Other things that may be applicable to the design include the orientation of the linac in relative to the earth magnetic field direction and strength, as well as local building designs.

Depending on the application, the accelerator orientation may require stronger magnetic shield attenuation. For a linac such as XFEL, the shielding cylinder is nearly perpendicular to the earth magnetic field. The longitudinal attenuation factor of the local magnetic shield is less demanding compared to a north-south orientation. The LCLS-II linac orientation is not perpendicular to earth magnetic field. The earth magnetic field is in an approximate 21-degree declination angle relative to the linac orientation [16]. This certainly will not be a deciding factor in accelerator design as the civil construction is more complex in planning and implementation.

Building structures and radiation shield blocks may have strong magnetic field due to the magnetized steel rebar and iron in some fortified concrete materials. Utility pipes including HVAC, water pipes and cryogenic distribution systems all can have magnetic field that can be superimposed to the environmental magnetic field source.

MAGNETIC HYGIENE

To achieve the remnant field as low as possible, a good shield design is always accompanied by a successful magnetic hygiene implementation.

Magnetization of Components

It is a common knowledge that non-magnetic stainless steel 316L can lose their austenitic state after exposure to high temperatures, such as during welding and machining. Once its permeability becomes higher, the affected part or area can easily become magnetized. Austenitic cooling treatment is not practical for many of the affected parts. There have been cases where a stainless steel bolt with a relative permeability of 1.05 can be magnetized up to 1 Gauss and create a high remnant magnetic field near a niobium cavity. As such, magnetic hygiene becomes necessary during the assembly of a cryomodule even for a design that meticulously takes into account of all high magnetic component near a niobium cavity.

Both simulation and experimental analysis has shown the remnant field of a magnetized component depends on the permeability, mass of the high permeability region and its shape aspect ratio [17,18]. A very thing wall of welded bellows can have a strong remnant field on the contact, but due to its small mass, the field attenuates quickly away from the weld seam. A one-inch-thick tuner bar that has a similar field on the contact will have its remnant field decay slower than the welded bellow.

Many stainless steel tools are highly magnetic. Many of them exceed 10 gauss remnant field on contact. It is shown that magnetic component such as stainless steel studs or RF connectors can become highly magnetized by wrenches that touch them during assembly.

In LCLS-II cryomodule design, there are many openings in the magnetic shield. Surrounding magnetized components have potential to increase the magnetic field in the cavity location to be higher than specification [18]. Figure 1 illustrates magnetic tuner support that increased the magnetic field in the end cell of a cavity.

Vacuum vessel is another source of remnant magnetic field other than the environmental magnetic field. For the cost benefit, vacuum vessel commonly uses carbon steel. Carbon steel provides additional magnetic shield provided it is not magnetized itself. Magnetized carbon steel vacuum vessel is a subject in the quality control of magnetic hygiene.

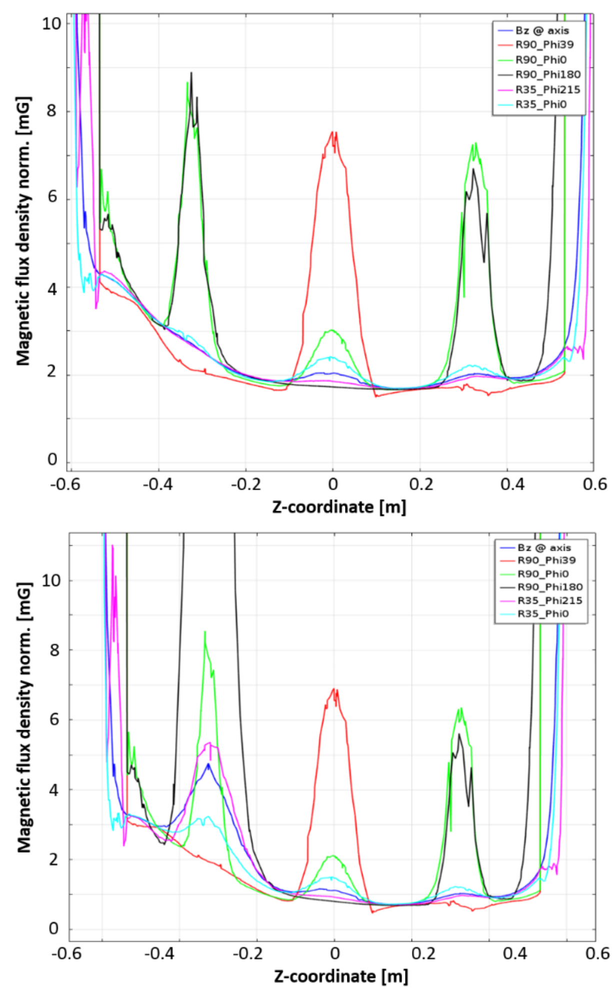

Figure 1: Effect of the magnetic tuner support bearing. Upper figure represents a nonmagnetic tuner bars. Lower figure represents a magnetic tuner bars [18] (Courtesy of I. Terechkine).

Magnetic Hygiene Quality Control

For LCLS-II prototype cryomodule, a tentative magnetic hygiene plan was developed as listed in following bullets and will be explained in details:

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- Magnetic hygiene scope definition
- Material specification and certification
- Incoming inspection and demagnetization
- Tooling inspection and demagnetization
- Pre-assembly inspection and demagnetization
- Assembly check points in production traveller

Based on the simulation of the field attenuation of the magnetic components [17], a limited magnetic hygiene scope is proposed. For any component that is within 3-inches from niobium cavity including beam pipes is considered in the magnetic hygiene scope.

Material specification should be clearly identified in mechanical drawings and procurement document. Material certifications are requested to ensure that only non-magnetic materials are used. When an exception is used, low remnant magnetic field should be specified as measured on contact and 1-in distance field magnitude.

Incoming inspection utilizes spot checking of components with a permeability reader. Permeability reader always magnetizes the components that has relative permeability greater than unity. Complete measurement of all components using permeability reader is not recommended. All components will be subject to remnant magnetic field inspection. Any component that shows high remnant magnetic field will be set aside for demagnetization, depending on cost of the component.

Tools are regularly checked for remnant magnetic field. A wrench that has strong remnant magnetic field (>10 gauss) has shown to magnetize a RF connector that is made of steel. Tools that have strong magnetic field can be demagnetized to below 10 gauss and becomes incapable of magnetizing the other components.

A pre-assembly magnetic field inspection is optional if the components are kept in a relatively magnetic field clean environment. If a component's history is unknown, inspection is a must, especially when the components are part of a vacuum assembly.

Magnetic field check points are listed in production traveller. For example, a magnetic field check is conducted after tuner is installed.

Magnetic field check also prevents potential flare-up of a high remnant field component that is beyond the magnetic hygiene scope. High remnant magnetic field component can be wrapped in a magnetic foil or removed to be demagnetized.

Figure 2 illustrates a prototype demagnetization coil set for vacuum vessel demagnetization. Figure three compares the magnetic field measured before and after the demagnetization.

Figure 2: A prototype demagnetization coil wrapped around a LCLS-2 type vacuum vessel [19].

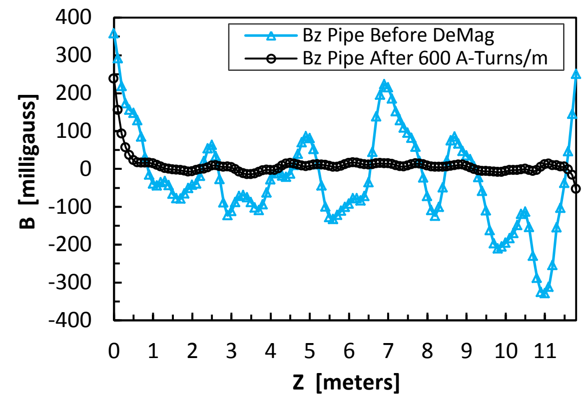

Figure 3: Field measured before and after demagnetization of the carbon steel vacuum vessel (Courtesy of A.C. Crawford).

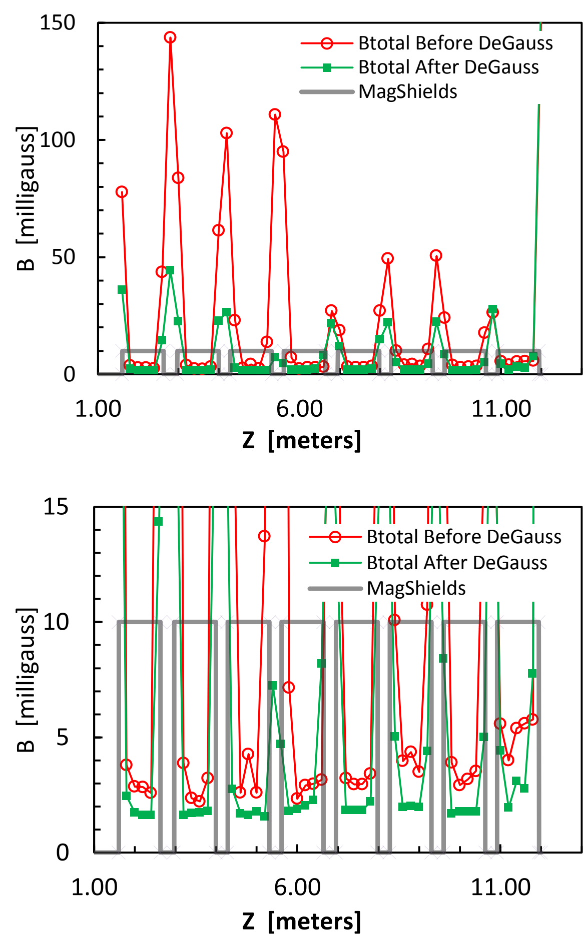

Figure 4: The Magnetic field at the shielding center showing the reduction of the cavity edge field (upper plot) and zoomed plot (lower plot) showing the reduction of the cavity center field after the in-situ demagnetization of a mock-up cryomodule (Courtesy of A.C. Crawford).

Demagnetization of Cryomodule

As the design and magnetic hygiene insure the final cryomodule has low remnant magnetic at the cavities, cryomodule may still be subject to unknown magnetization forces during the shipping and installation.

An in-situ demagnetization of the assembled cryomodule is proposed. A mock-up test with an ILC vacuum vessel and major pipe components is conducted. A demagnetization coil set shown in the Figure 2 was used to demonstrate the concept [20].

The magnetized invar rod and magnetic shield was successfully demagnetized as shown in Figure 4.

MAGNETIC FLUX EXPULSION DURING FAST COOL DOWN

As the cavity remnant field approach low value, any remaining magnetic flux such as those in the end cells of the cavities can be further reduced by flux expulsion when a cryomodule goes through fast cool down during superconducting transition of the niobium cavities [21].In a horizontal integrated test of a 9-cell LCLS-II cavity, it was demonstrated that the high thermal gradient between top of the cavity and bottom of cavity can be achieved to effectively expel magnetic flux that is still in the end cell.

Table 1 listed the temperature difference during the transition of the niobium cavity. Temperature difference was measured as the cavity upper temperature minus the cavity bottom temperature as the cavity bottom crosses the transition temperature. Figure 5 shows the temperature and magnetic field evolution during a fast cryogenic cool down that is very similar to cryomodule environment.

Table 1: Cavity Temperature Difference

Cell #	ΔT [K]
Cavity Cell #1	8
Cavity Cell #5	20
Cavity Cell #9	15

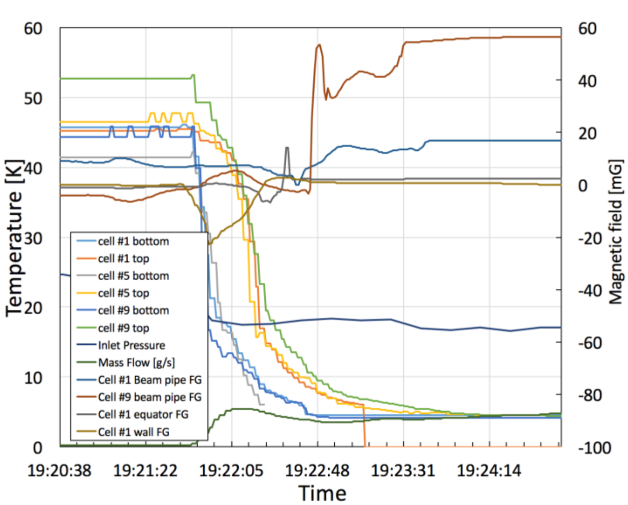

Figure 5: A small thermal current and high thermal gradient between the top and bottom of the cavity successfully expelled the remaining magnetic flux in the cavity during a fast cryogenic cool down [22].

The Q_0 of 3.1×10^{10} at 16 MV/m measured during the horizontal test, shown in Figure 6, matched closely to the bare cavity vertical test result that indicated the residual resistance was very low and the magnetic management during the horizontal test was very successful.

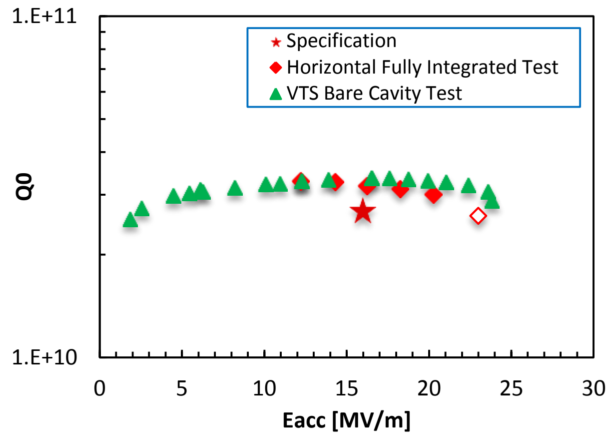

Figure 6: The Q_0 of a horizontally tested fully integrated cavity is compared to its Q_0 measured in vertical test. The empty diamond represents an estimated Q_0 value at 23 MV/m when cavity is operated below quench field [22].

CONCLUSION

The magnetic field management is very important in high Q cryomodules. The careful design, vigilant magnetic hygiene practice and quality control, as well as proper cryogenic cool down can yield successful lower residual surface resistance due to trapped magnetic flux.

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