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Thermal Optimization of Functional Insertion Components (FIC) for Cryogenic Applications

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Abstract. Various functional insertion components (FIC), directly connecting a cold mass and the ambient environment, are irreplaceable and play crucial technical roles in many superconducting cryogenic applications. However, such components also bring a huge heat leak to the cold mass. The heat leak is usually much greater than that through entire evacuated MLI insulation system and solid support structures combined. Therefore, this situation brings unimaginable challenges not only to the refrigeration loads to be met but also critical aspects of the FIC design in satisfaction of highly restrictive, even contradicting technical functions. The FIC must simultaneously minimize the heat leak provide a large amounts of DC current and RF power to/from the cold mass, as well as provide a reliable ultrahigh vacuum thermal isolation break with strong mechanical stability. Reviewed are the following commonly used FICs: 1) various RF input couplers for transmitting MW-RF power; 2) high DC power current leads for energizing various SC magnets; 3) various high order mode (HOM) couplers for damping unwanted RF energy; 4) instrumentation cable/wire to cold mass. Approaches to efficiently minimize the DC current heating, RF surface heating, heat leak through the solid body of FIC, efficient cooling approaches, while reliably providing the technical functions, are briefly summarized and compared for select applications from around the world.

1. Introduction

Superconducting (SC) magnets can provide the highest intensity and largest space of magnetic fields with zero resistance for DC current, and superconducting radio-frequency (SRF) cavities can deliver the quality value Q higher than copper (Cu) by $\sim 10^5$ and accelerating fields E_{acc} (e.g., up to 25 – 30 MV/m) higher than Cu by an order of magnitude in continuous wave (CW) mode. Huge cryogenic systems (multi-kW refrigerators both at 2 K and 4 K) have been operated successfully associated with the applications. About 2,000 m length of SRF cavities with RF input and HOM extract couplers have been in operation and development [1], and new projects of more than 20,000 m length of SRF systems have been proposed [2-4]. ITER in France [5] and EAST in China [6] both with greatest sizes of special shaped SC magnets have been tested for fusion projects. Recently CERN and Beijing have separately deliberated plans to develop future colliders much larger than existing LHC of 27 km [7]. MRI magnets [8] and SC power applications [9] have also employed many current leads.

There are irreplaceable functional insertion components (FIC), which are directly connected a cold mass and the ambient environment, and play crucial technical roles in above mentioned applications. Huge radio frequency (RF) power (megawatts) are transported to SRF cavities by RF input coupler (RFIC) from klystrons to generate strong electromagnetic accelerating fields. RFIC also provide tight vacuum breaks between ultra-high vacuum in accelerating space and ambient environment. High order



mode coupler (HOMC) are employed to extract or dissipate unwanted RF energy present in the cavity to protect particle beams from instability. High power current lead is also the irreplaceable device to provide DC power from ambient electrical ports to SC magnets with current up to 68,000 amps.

However, such components also bring a huge heat leak to the cold mass. The heat leak is usually much greater than that through entire evacuated MLI insulation system and solid support structures combined. It is also a critical challenge to reduce the solid thermal heat leak through the RFIC into the cryogen (LHe) and also to minimize the large heat load generated by high RF fields on the metal inner surface of the coupler [2-3]. There are about 3,000 leads carrying from 10 A to 13,000 A with total current of about 3 MA at LHC [7]. The heat load generated by each current lead to 4 K per kA per lead is around 4.5 W. Heat leaks through measuring wires are also crucial at below 1 K applications in space and/or on ground. Typical installations are shown in figure 1.

The situation brings unimaginable challenges not only to the refrigeration loads to be met, but also to critical aspects of the FIC design in satisfaction of highly restrictive, even contradicting technical functions. The FIC must simultaneously minimize the heat leak, provide a large amounts of DC current and RF power to/from the cold mass, as well as provide a reliable ultrahigh vacuum break with strong mechanical stability. The design and construction of FIC are complicated task related to many high technical challenges inherent in the engineering and physics. Comprehensive trade-offs and optimizations are required in the designs. The methodology to balance between technical functions demanded and minimization of heat load are discussed. Selected applications as demonstrations from around the world are also summarized.

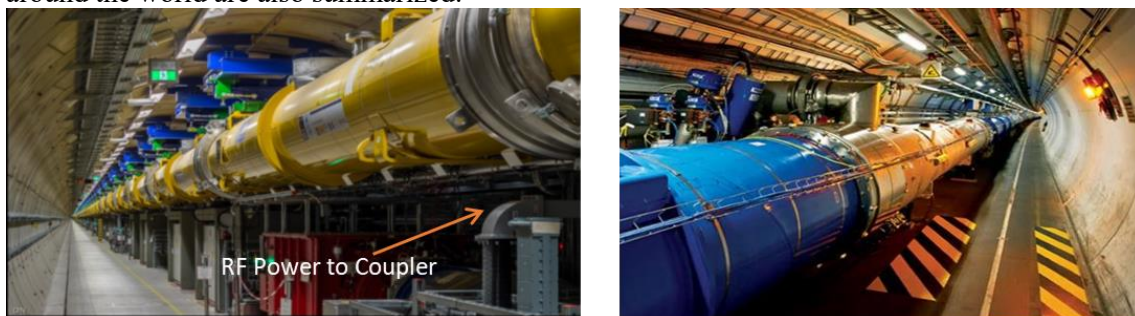


Figure 1. EU XFEL: Thousands of SRF cavities with RFIC & HOMC in cryostats in tunnel [2] (left); CERN LHC: SC magnets with thousands of current leads inside cryostats in tunnel, CERN photo (right).

2. Methodology: Function Demanded versus Minimizing Heating

The first point is to look at the balance between Heat Load and DC Current Delivering. The load of current leads on the refrigerator come both from conduction and joule heating. To reduce joule heating (up to 6.8 kA), lower electrical resistivity copper is chosen with short length and large cross section. On the contrary, to reduce thermal conductive load is in favor of a large ratio of length to cross section. The current leads are also designed as a heat exchange of cylindrical shape, which allow the returning cryogen vapor to flow through the leads from the cold end out of warm end, as shown in figure 2A. The parameters of the power leads, such as the lead diameters, lengths, shapes of exchange, and RRR values of lead materials must be optimized [10].

The second point is to examine the balance between Heat Load and RF Power Delivering. Huge RF power (up to megawatts) are transported by RFIC to SRF cavities of 2 – 4 K to generate strong electromagnetic accelerating fields as shown in figure 2B [11-12]. To reduce the conductive heat leak is in favor of a structure with thin walls of stainless steel for low electrical conductance, but to reduce the great amount of heat generated on the inner surfaces of RFIC by RF electromagnetic fields it is better to use copper walls. Due to the anomalous skin effects, RF fields can only penetrate a thin layer on inner surfaces of RFIC. Therefore, a solution is to coat a thin layer of copper on the stainless inner surfaces of RFIC. The thickness and RRR value of the copper layer are optimized to have minimum solid conductive heat leak and also have sufficient thickness to carry out the RF power. The vacuum-exposed window surface is coated with titanium nitride (TiN) to mostly eliminate the multi-pacting heating.

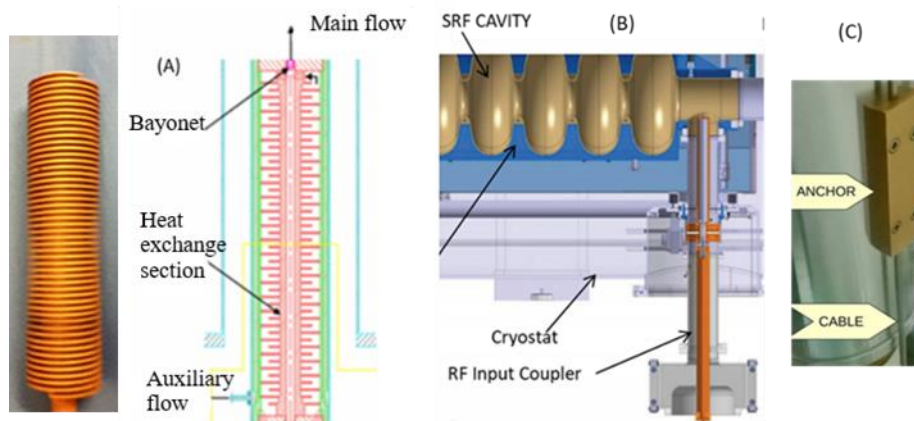


Figure 2. (A) Flow Pass for LHC13 kA current leads in vacuum and a spiral fin heat exchanger center conductor used at SSC [10]; (B) ESNS RFIC associated with the cryostat and RF cavity [12]; and (C) thermal anchor for measuring cable.

Advanced materials for thermal management include the use of high T_c superconductors (HTS). The cold end of current lead is about 2 K to 4.5 K in most SC magnets. This design allows for the current lead to have a conventional portion that starts at room temperature and interfaces with a high temperature superconductor (HTS) section at around 80 K. This HTS section will span the remaining range to low T_c superconductors (LTS). The HTS portion greatly eliminates the joule heating and also reduces solid conductive heat leak.

LTS materials are used to take away unwanted RF power from SRF cavities where HOMC is utilized. To avoid significant RF dissipative losses, these HOMC pickup probes can be made of LTS (Nb) and remain superconducting during operation. However, LTS has low thermal conductivity. To overcome the problem, a direct thermal path is provided from the niobium probe through single-crystal sapphire thermally anchored to bulk copper.

Use of advanced absorber materials is another idea to make all HOM fields propagating into the beam tubes and dissipate the energy at higher or room temperature out of cold cavity (outside the cryomodule in some cases). Several labs have utilized ferrite beam-line absorbers to dissipate several kilowatts of the HOM power. Other institutes also used low temperature absorbers. Broad-band absorbing materials such as Ferrite, SiC, and AlN are among the choices.

Highly efficient cooling by convective means is another method. FIC can be designed as part of a heat exchange system, which is cooled convectively by cryogen. In order to increase the heat-exchange surface, the cryogen flowing channels can be braided leads, strips collected packet, wires and tubes, spiral-fin, and porous materials. Vapor cooled FIC rely on the heat conduction down the lead to boil a liquid cryogen which generates vapor used to cool the lead. Forced-flow cooling designs are used in large scale applications to control cryogen flow.

Conductive cooling and thermal anchors can also be designed. For reducing the heat leak through the walls of the FIC (RFIC, HOMC coupler, current lead, and instrument wires) into liquid helium or cold mass, the heat interception anchors are applied to FIC at certain temperatures. The thermal anchors are normally made of braided copper straps.

3. RF Input Coupler (RFIC)

Coaxial RFIC is the most popular design used for SRF cavities in accelerator applications. The development of the TESLA RF input coupler (RFIC) is a successful demonstration of international collaboration, which has adapted into many other SRF projects. Moeller [13], Shu [14], Peterson [15] reported the design, construction and testing results of a RFIC for TESLA-ILC, by AMAC in collaboration with DESY Germany, LNL France, and CPI USA, as shown in figure 3. The main operating parameters are: 1.3 GHz 1110 kW, pulse length 1.3 ms, cryogenic losses of 12 W at 70K, 1 W at 4K, and 0.12 W at 2K. Figure 3 A is a photo of the RFIC, which shows a 300 K flange for mounting

to cryostat, 70 K and 4 K flanges designed for anchored cooling by cryogenics, and a 2 K flange sealed to the beam tube of the SRF cavity [11,13]. Finally, figure 3C shows the anchors.

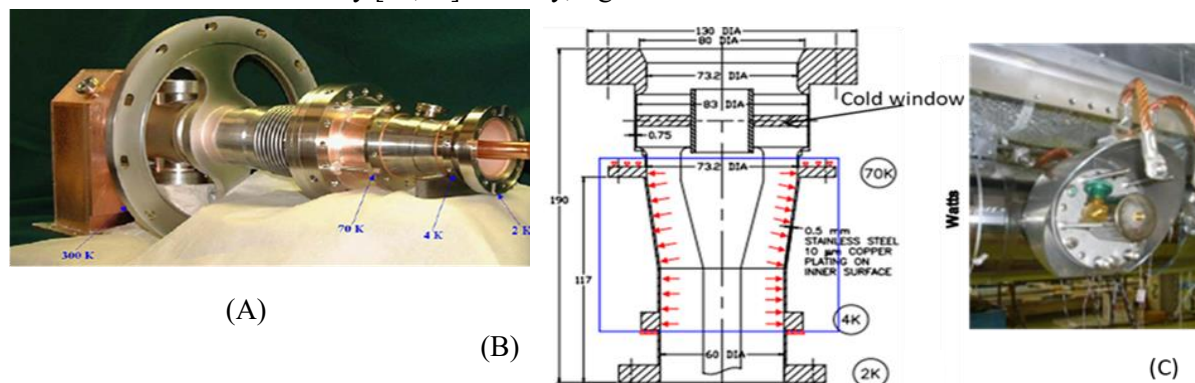


Figure 3. (A) TESLA style RFIC, Shu & Moeller; (B) Geometry and thermal loads for small model analysis, arrows stand for RF dissipation, Shu; and (C) 4 K and 80 K cooling anchors from RFIC.

The thermal calculations were performed with ANSYS and take into account the temperature, the respective thermal conductivity and RF electrical losses at each mesh point. Although thermal simulation has been performed for entire RFIC, figure 3B shows only a small model geometry and thermal loads of the outer conductor portion from 4 K flange to 70 K flange [14-15]. During RF heating evaluation, the anomalous skin effect on surface resistance was in our thermal model and the coating of 10 μm copper is enough on 0.5 mm stainless steel wall. A copper RRR value of 3 – 5 is preferred in practice. In pure metals, the thermal conduction in the normal state is dominated by the electronic conduction term and the lattice conduction term (phonon conductivity) can be neglected. As the metal becomes superconductive, its thermal conductance K_s falls below the value of the normal phase K_n . This decrease in thermal conductance is caused by the gradual disappearance from the thermal distribution of the free electrons. Therefore, the ratio the electronic thermal conductivity in the normal state to the phonon thermal conductivity in the superconducting state can be larger than 10^5 .

The waveguide RFIC is also attractive for applications with very high power (larger than 100 kW), and very high beam current (several hundred mA), since its cooling is simpler, only the outer waveguide wall needs cooled. However, the waveguide coupler associated with cryostat is more complicated in mechanical structures than the coaxial RFIC. There are also significant numbers of waveguide RFICs in use at Cornell, Jefferson Lab (Jlab), KEK, and other laboratories [16-17].

Figure 4 (left) shows the highest power waveguide coupler in operation at CESR-B, having reached close to 300 kW CW in operation with beam current of 550 mA in two beams [16]. The waveguide wall is cooled by cold helium gas flowing through the tracing welded to the waveguide walls. Next followed is the waveguide double E-bend elbow, which is cooled by liquid nitrogen. The inner surfaces of the waveguide are also coated by copper layers. The minimum 2 K heat load from 50 K (static and dynamic) induced by the waveguide RFIC as function of the intercept location and properties of material (S.S. and Cu coating) was calculated as shown in figure 4 (right) [17]. The letter designations in figure 4 (right) are defined as follows: (A) SS 0.8 mm and Cu 6 μm – RRR 30; (D) SS 0.4mm and Cu 15 μm – RRR 15; and complete details are given in the publication [17].

4. High power current leads

In the field of high energy physics, their accelerators have hundred-thousands of SC magnets located around the magnet ring, such as, the Fermilab Tevatron 6.86 km and the CERN LHC 27 km. There are about 3000 current leads, which carry currents from 100 to 13,000 amps at LHC [7]. About 60 current leads with current ranged from 10,000 to 68000 amps are employed for fusion magnets at ITER [5]. Most MRI magnets use LTS that operate at 2 K to 5 K with current leads of 1000 – 2000 A. On the other hand, most of the current leads for SC power applications are operated between 70 K to ambient. The current leads can be category two basic types: conventional current leads (current carriers made of copper or brass) and hybrid HTS current leads (current carriers are mixed: normal metal and HTS).

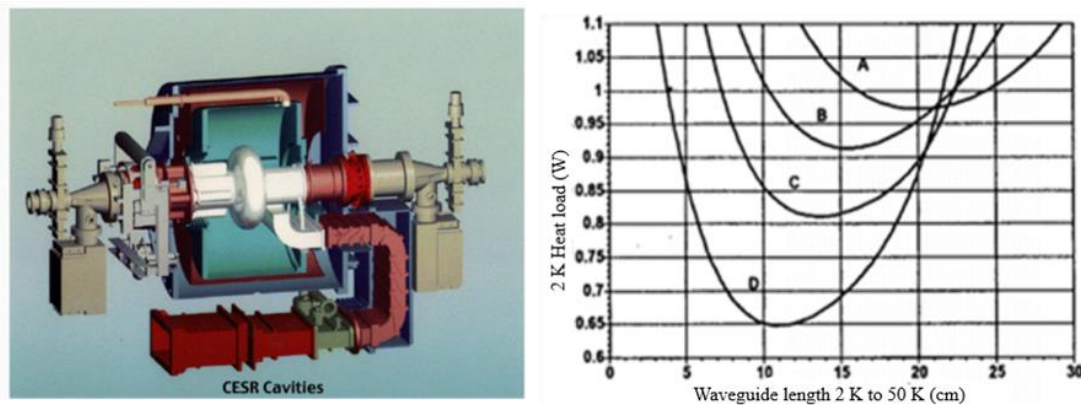


Figure 4. Cornell B waveguide coupler with SRF cavity in cryomodule for CESR luminosity upgrade; cavity also uses a fluted beam tube as an HOM coupler to deliver higher order power to lossy ferrite loads [16]; the 2 K heat load from 50 K (static and dynamic) induced by the waveguide RFIC [17].

Conventional metal current leads are first examined. The SSC laboratory collaborated with Fermilab and BNL developed 6.6 kA leads for the accelerator dipoles and 10 kA for MTL [18]. These were all copper construction with a helical fin heat exchanger design. The vapor-cooled current lead consists of a finned copper conductor assembly that has a copper power head brazed onto its warm end and superconducting cable soldered into its cold end. This assembly fits inside of a “folded” G-10 insulating tube assembly, which in turn fits into the feed can mounting assembly. The helical fin pitch was selected such that there was sufficient surface area for helium vapor to remove the heat generation along the lead. The single helical flow path assures that the cooling will be distributed uniformly along the lead. An extensive thermal optimization was accomplished to meet the constraints: maximum heat flux of 7.9 W and maximum single-phase He flow rate of 0.07 g/s per 1,000 A. The assembly structure of the 10-kA vapor cooled current lead (SSC/Fermilab design) and the spiral fin or helical flow path heat exchanger is shown in figure 5.

The hybrid HTS current leads are generally assembled from three main components (from cold to warm): the HTS shunt / LTS-linker and joint assembly, the resistive heat exchanger (HEX), and the room temperature (RT) terminal block. The LHC 13,000 A current lead is a typical hybrid HTS current leads design for accelerators as shown in figure 6 [19]. The resistive part (HEX) was cooled by helium gas supplied at around 20 K and 1.3 bar. The HTS part was self-cooled by vaporization of helium at 4.2 K. The 20 K helium flow was controlled using a warm valve that was controlled off of the interface temperature of the warm end of the HTS section. The flow was regulated to maintain the warm end of the HTS element at around 50 K. Each lead has two temperature sensors at the warm end of the HTS section, one at the room temperature terminal, eight voltage taps along the lead for monitoring the resistive, HTS, and Nb-Ti sections of the lead. For the resistive section a 100 mV threshold is set and a 3 mV threshold is set to trigger a power abort of a circuit if these are reached. An upgrade concept that uses an auxiliary flow of helium which will keep the superconductor cold but allow the upper conventional portion to warm up and prevent frost build up when there is no current applied.

Hybrid leads for a fusion magnet include the ITER tokamak, the world’s largest fusion machine that is planned to harness the energy of fusion. There are great number of huge magnets: 18 toroidal field coils, 6 central solenoid modules, 6 poloidal field coils, and 18 correction coils [20–22]. The currents used range from very large (68 kA for the toroidal-field coil) to medium (10 kA for the correction-coil), transferring up to 2.6 MA currents into and out of the cryogenic environment of the machine.

The current leads for ITER must have minimal heat load to the cold end and minimal helium flow through the optimization of the length and current carrying cross section of the lead. The leads must have a sufficient heat capacity to withstand a thermal runaway from a loss of flow accident (LOFA). The leads are forced flow cooled so the heat exchanger design must have a minimal pressure drop. Finally, a low resistance connection to the warm bus and LTS must be provided. For example, when the TFC leads are at 68 kA, a joint resistance of 0.1 nΩ would result in a heat load of 0.46W per lead which

must be removed at the low end operating temperature of between 2 K to 5 K to prevent from quenching the SC magnets.

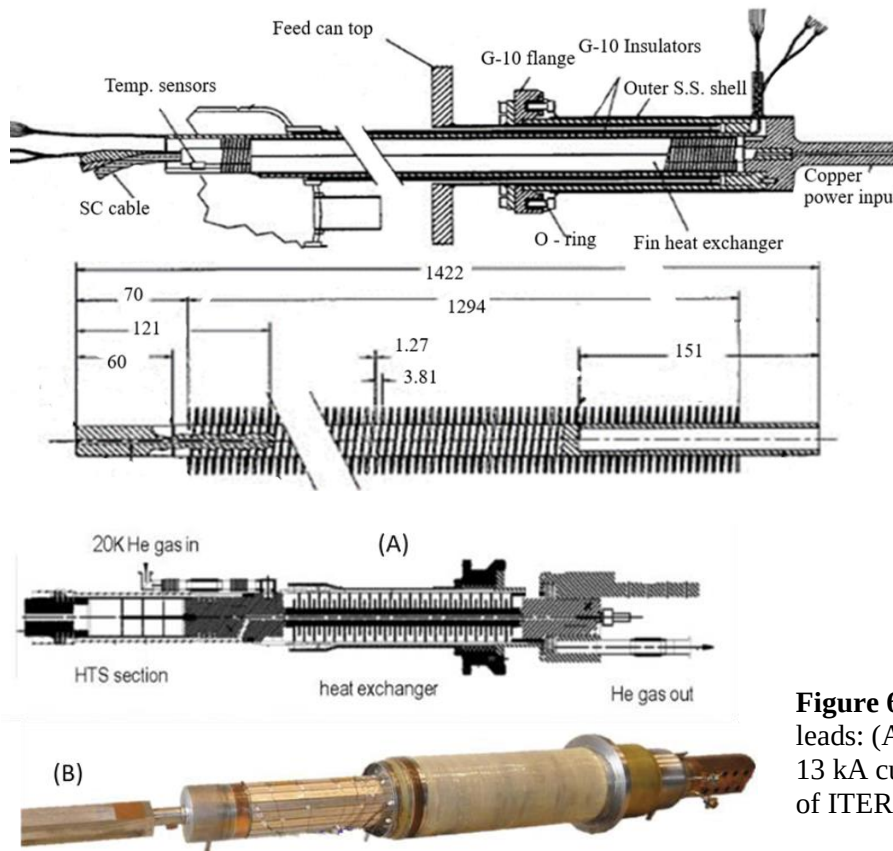


Figure 5. Assembly structure of the 10-kA VCPL & Structure of the spiral-fin copper core [18].

Figure 6. Hybrid HTS current leads: (A) Schematic of the LHC 13 kA current lead [19]; (B) Photo of ITER 68 kA current lead [20].

A complete 68 kA hybrid lead is shown in figure 6B. The conventional or upper portion (300 – 65 K) of the lead is forced flow cooled using helium vapor supplied at 50 K and 0.4 MPa. The heat exchanger design for the copper portion is a fin type with a zig-zag flow configuration [21]. The HTS material is a Bi-2223 superconductor tape with a gold-doped silver matrix. The HTS section is conduction cooled by a helium heat exchanger at the cold end, as show in figure 7A. Between the THS block and LTC magnet cable is the LTS linker as shown in Figure 7B and the model of helium cool termination for 68 kA in figure 7C.

5. RF HOM Coupler (HOMC)

The HOM fields excited by electrical bunches at accelerator also increases the cryogenic losses due to the additional power dissipation in the cavity wall at LHe temperature. The cryogenic losses can be very serious when the beam currents become greater. For example, the CEBAF 12 GeV project beam current is 0.2 mA with an HOM power per cavity of 0.05 W; the KEK-CERL current is 100 mA with an HOM power per cavity of 185 W [23].

The HOMC (damper) is a device which subtracts and removes the HOM wave energies from the cavity space at 2 – 4 K in order to avoid resonant build-up of beam induced voltage and beam instabilities. The HOMC must transmit the HOM power efficiently out to higher temperature level to reduce unwanted cryogenic load, and also have effective cooling and compact structure to fit in the cryostat. There are three types of HOM couplers: 1) coaxial HOM coupler, 2) waveguide HOM coupler, and 3) beam tube HOM damper. Figure 8A shows the main parts of a TESLA-style coaxial-type HOM coupler. To reduce the RF heating on the tip surface, the HOM pick up probe is made of superconductor (Nb). Figure 8B is Cornell Style waveguide HOM coupler's absorber graphite loaded SiC mounted onto the HOM end flange with extended copper cooling. Figure 8C shows a Ferrite beam line absorber for large beam current application [24].

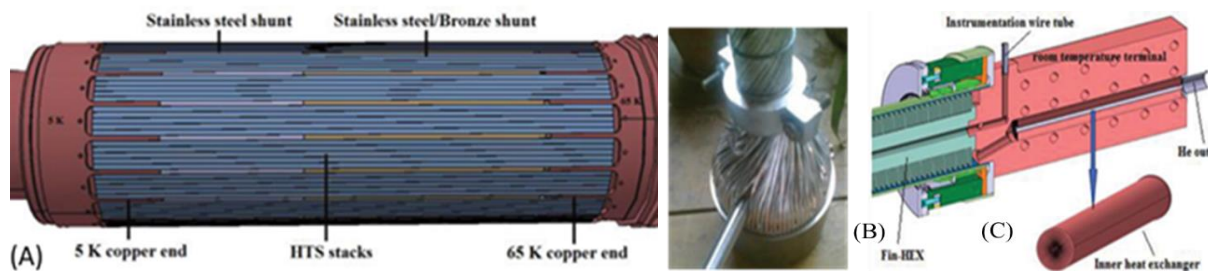


Figure 7. (A) Overview of HTS module of the ITER 65 kA current lead, (B) Picture of The LTS linker for 68/52 kA trial leads, (C) model of helium cool termination for 68 kA prototype [20].

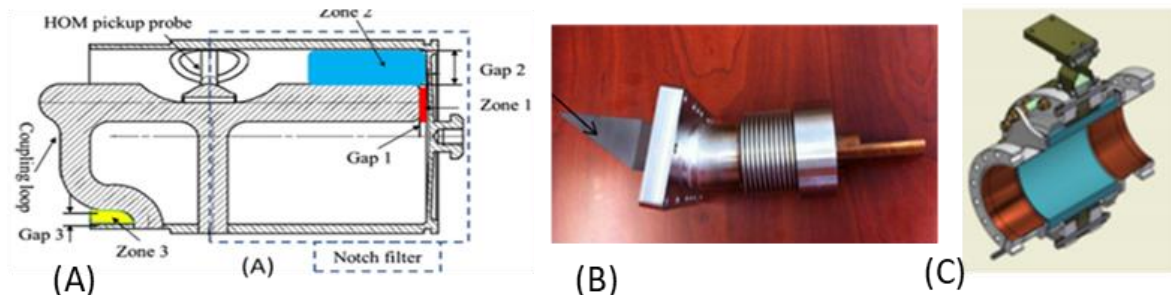


Figure 8. (A) TESLA-style coaxial HOM coupler [23]; (B) Original waveguide HOM coupler at 2 K; and (C) Ferrite beam line absorber for large beam current application [24].

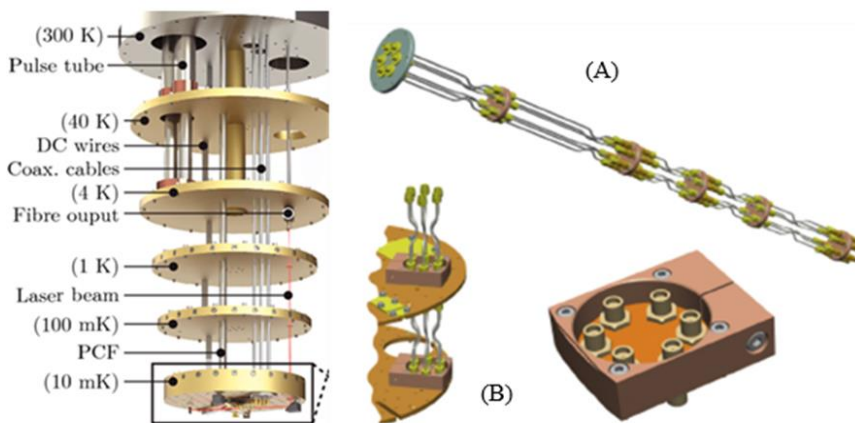


Figure 9. Framework of a dilution refrigerator: (A) RF wiring cartridge with hermetic feedthroughs from 300 K to 10 mK; (B) Split clamps to thermal anchor the cartridge [25].

6. Cryogenic anchor for functional wires

Cryogenic anchoring of instrumentation lead wires is another crucial design detail. Batey in [25] and Pagano [26] separately reported new developments in advance anchor designs in details. Figure 9 shows how a RF wiring cartridge will be anchored on multi cold stages [25]. Measuring wires from ambient to working cold mass cause additional heat leak. It is particularly serious when the cooling capacity is very small at ultralow temperatures and/or cooling power is difficult to supply in aerospace applications. Thermal anchoring of wires to heat sinks in cryogenic equipment is required at each intermediate stage [25-26]. Special attention is needed if coax cables are used. Thermal anchoring in large scale applications is quite different compared to ultralow temperature small apparatus. Effective and precise thermal anchoring of wires is mandatory to measure temperature in milli-kelvin accuracy and to avoid unnecessary cooling power due to additional heat conduction. Besides mechanical clamp and solder, special cryogenic epoxies are used with electrically conductive, thermally conductive/electrically insulative, low outgassing approved.

7. Conclusion

Development of various functional insertion components have enabled successes in projects for large scale SC magnets and SRF cavities as well as projects in space and at ultralow temperatures. The

methodologies and thermal optimization discussed here can also be utilized in other cryogenic applications. Sincere thanks are given to colleagues for their discussions and information for the paper.

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