Development of a Superconducting Electromagnet for Applied Field Arcjet Thrusters

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Within the framework of the research activity underway at CENTROSPAZIO on plasma propulsion and the research and development of Superconducting materials at Europa Metalli-LMI, a Superconducting magnetic coil was produced and characterized in order to investigate arcjet behaviour under strong magnetic fields. A Superconducting coil was required due to the need for strong magnetic fields with small electric power sources. The aim of this work was to study the laboratory application of Superconducting magnets on the arcjet thruster currently under testing at CENTROSPAZIO.

Introduction

Since 1988, CENTROSPAZIO has been involved in the research and development of plasma engines such as MPD, FEEP and arcjets [1]. Activities on low power arcjets, in particular, have involved both computational and experimental studies. For the computational activity, fluid-dynamic models were realized to describe arcjet operation and to analyze the influence of typical parameters on performance; moreover, thermochemical models were developed and arcjet system studies and mission optimization have been performed. Experimental activity concerned the parametric characterization of a 1-kW Arcjet in the framework of an Advanced Space Technology Program (ASTP) contract awarded to BPD Difesa e Spazio by ESA, with CENTROSPAZIO acting as subcontractor [2]. This project represented the most important electric propulsion programme carried out in Italy and received the largest allocation of funds from both ESA and ASI (Italian Space Agency); a follow-on programme, concerning the development of 1-kW advanced engineering model arcjet for flight pre-qualification is planned to start in autumn 1993, with CENTROSPAZIO responsible for the technology development and the application of diagnostic equipment. As a part of its basic research programme, CENTROSPAZIO is currently pursuing the development of an applied-field low power arcjet with a Superconducting coil; this work is aimed at investigating the capability of an applied field to increase performance and extend the operating range of the present arcjets.

Current interest in Superconducting technology is promoted by the feasibility of its possible application in the new flight-qualified generation of applied-field arcjet; Superconducting magnets offer strong magnetic fields with low ohmic losses and use electric power sources compatible with those on board the present type satellites; moreover, the weight of a Superconducting magnet coil is quite low, compared to resistive or permanent magnets capable to produce the same field strength.

To this purpose CENTROSPAZIO started a collaboration with Europa Metalli-LMI, a large Italian company involved for a long time in the development of both low and high transition temperature Superconducting wires, [3] to carry out a feasibility study of a Superconducting magnet capable of producing at least 1000 G for 1 hour of continuous operation. From this collaboration a low transition temperature Superconducting coil was produced and tested.

Physical and Technological Background

In Superconducting (SC) technology a distinction can be made between low and high transition temperature Superconductors. A Superconductor is characterized by its peculiar behaviour in electrical conductivity, which vanishes below a certain temperature. Actually, there is not just one temperature which separates the SC behaviour from the ohmic conduction, but a transition zone defined by an "onset" transition temperature (Tc), which occurs when the conductor starts to drop its ohmic resistivity, and an "offset" transition temperature (Tc'), which occurs when the complete SC phase is reached. In addition, a medium transition temperature (Tc), limited by the preceding ones, can be defined. In this study the "onset" transition temperature was adopted as the critical one. Superconducting properties were first discovered by H.K. Onnes in 1911 when he noticed how Mercury dropped off its resistivity when cooled under 4.15 K; since then, great
improvements have been made on the limits of the transition temperature of SC materials. However, a wide application of SC conductors is still limited by the low operating temperatures needed. Superconductors are defined as "Low Transition Temperature SC", if their critical temperature is below that of the liquid Helium (4.2K) or as "High Transition Temperature SC" if their critical temperature is greater than that of liquid Helium but less than that of liquid Nitrogen (77 K). An explanation for the drop in electrical conductivity is given by the BCS theory (Bardeen, Cooper and Schrieffer) theory which supposes that the conduction electrons move in couples ("Cooper couples") due to the interaction with the mechanical vibrations of the crystal lattice of the matter. These vibrations tend to neutralize the repulsive force that the electrons usually exchange and in fact a small attractive force is produced between them. This interaction depends strongly on the temperature.

For temperatures above the transition, the thermal fluctuations destroy the Cooper couples and then the Superconducting phase. The coupling interaction determines two important microscopic length scales, the first one being the distance between the electrons of a Cooper couple, known as the "coherence distance", and the second relative to the force of the "Meissner effect", that is the ability of the Superconductor to push out the intruding, externally-applied magnetic field. This effect results from the induced currents which create a magnetic field opposite to the one that generated them. The intensity of these induced currents drops exponentially from the SC surface, and the distance on which this drop occurs is known as the "penetration length".

The transition from SC behaviour to the common ohmic conduction is also affected by another parameter, that is, the externally-applied magnetic field investing the SC materials. In fact, a SC is characterized by its response to the penetration of the magnetic flux in the matter, that tends to destroy the SC phase. Depending on the larger or the smaller penetration of magnetic field into the conductor, we regard a SC as "Superconductor of type I" or as "Superconductor of type II", respectively.

In a SC of type I, there is a threshold for the magnetic field intensity, and its limit value (Hc) approaches zero when the temperature reaches the SC transition (also defined as the "critical") temperature; this is due to the fact that the coherence distance is greater than the penetration length.

In a SC of type II, there are two critical values for the external magnetic field; the lower value (Hc1) of the critical external field affects the SC phase but doesn't destroy it completely; increasing the intensity of the magnetic flux, there is the reduction of the SC behaviour until this disappears at the higher value of the critical external magnetic field (Hc2); this is due to the larger penetration length with respect to the coherence distance. These SC materials remain in the Superconducting phase even if pierced by a magnetic field.

Low transition temperature SC (LTSC) are mainly Nb-Ti or Nb-Sn alloys, with various stoichiometric ratios; in general, these compounds are merged in pure copper and extruded, resulting in multi-fibre wires.

High transition temperature SC (HTSC) are made of Bi-Sr-Ca-Cu-O (BSCCO) or Y-Ba-Cu-O (YBCO) powders in various stoichiometric ratios, mixed together and forced through several thermal cycles until the correct crystallographic phase is obtained; this heterogeneous compound is then inserted in a silver clad and machined.

Prototype SC Electromagnets

The first phase in the realization of the SC electromagnet was to determine a set of possible SC wires to be used. This work was carried out at Europa Metalli-LMI Research Center Laboratories and the results were achieved for several types of SC materials. The specifications imposed the electrical feeding with a common laboratory 50V DC power supply (the same voltage of the power bus on board of spacecrafts), capable to provide currents ranging from 20 to 300 A. The characterization of the wires was carried out with liquid Helium for LTSC (also defined as "conventional Superconductors") and with liquid Nitrogen for HTSC (also defined as "ceramic Superconductors").

Tests were performed both with and without externally applied magnetic fields, and both the transition temperature as well as the critical current density (limit of the current in SC phase divided by the real SC cross-section) were measured.

On completion of this work, two types of SC wires were selected for possible application in the electromagnet coil, one of the LTSC type and one of the HTSC type.

Firstly a SC magnetic coil using a LTSC wire realized in the LMI laboratories (a 0.84 mm diameter Nb-Ti type I Superconductor [Fig. 1]) was realized; this selection was due to the possibility to obtain a single layer of turns due to the high currents transported by this wire [Fig. 2], resulting in a strong magnetic field; in addition, the Nb-Ti wire is easily machinable.

The SC was then wounded onto a cryogenic, insulating, cylindrical support with machined trecks into its external surface in which to insert the wire, to counter the magnetodynamic attractive forces arising when a current flows to a conductor; the resulting coil was made of 19,5 turns [Fig. 3].

The connections to the power supply were obtained by welding the two ends of the SC to two pure copper tubes, which had been drilled previously on their external surface to allow the liquid Helium to circulate inside, thus avoiding overheating in the junctions (that represent the more resistive points) that could destroy the Superconducting phase. The whole system (an SC electromagnet linked to the copper connections) was placed in a Dewar container made of two insulating jackets: one is vacuum insulated and the other is filled with thermally insulating, expanded foam.

A map of the magnetic field along the axis of the coil was then performed in boiling, liquid Helium, and the value of the field intensity was checked by a Hall effect
probe, mounted on a moving support. The results of this mapping showed that the maximum field strength was along the magnet axis, in correspondence to its midpoint and its value was 1210 G with a 500 A current (below the maximum current sustainable by the wire); the plot of the magnetic field strength along the axis revealed the typical bell-shape [Fig. 4].

A 1 hour endurance test was performed with a current level of 400 A. This level was imposed by the heat produced at the connections of the copper tubes to the SC coil, which could force the liquid Helium to evaporate rapidly.

The very low operational temperature of this kind of SC wires, and thus the need for liquid Helium, was considered as the major constraint for the applicability of Nb-Ti Superconductors. To allow a simpler experimental apparatus and to reduce the costs of the refrigerating system, a second, HTSC electromagnet was made.

This second magnet consisted of a multi-fibre BSCCO 2212 wire [Fig. 5 and 6], wound onto a cylindrical support and then subjected to a thermal cycle in order to obtain the proper crystallographic structure [Fig. 7]. During the characterization test, it was discovered that the Superconducting phase was not obtained in the whole wire, thus suggesting that the mixture of compounds in the central portion of the wire was not oxygenated properly during the thermal cycle [Fig. 8].

This preliminary work showed that it is impossible to produce an HTSC electromagnet at the present state of the art.

An SC Electromagnet for application

Test carried out on the two SC electromagnet prototypes revealed how, with current technology, only LTSC conductors could be employed to meet the specifications. In order to produce a 1000 G magnetic field, it was clear that a greater number of turns were needed with respect to the prototype, as the current limit was fixed at 300 A. A multi-layered coil was chosen and manufactured and the current level necessary for a 1000 G field was lowered below the imposed limit of 300 A, considering the modest electric supply available on board spacecraft.

A 0.55 mm diameter Nb-Ti wire was chosen [Fig. 9] for the coil as a greater number of turns could be obtained; the reduced current density tolerated by this wire with respect to the 0.84 mm one was not considered a problem, because of the reduced operational current. The 35% decrease in the wire diameter, for a given size and at a constant current, produced a theoretical 33% increase in the magnetic field for each layer of turns. With an 8 layer coil, the resulting field was 12 times greater than that for a single layer, that is the same magnetic field could be reached with a 12 times lower current (about 40 A).

For the insulation of the turns on the same layer, the SC wire was coated with nitrocellulose paint. In order to insulate one layer of turns from the other an epoxy resin was chosen because of its good insulation, cryogenic and mechanical properties.

The layers of turns were deployed in the following sequence: first of all the SC wire is wound onto the support, then covered with a layer of epoxy resin, fiberglass, and again epoxy resin, and so on.

With this configuration it was possible to transmit the Helium bath temperature (4.2 K) to the whole system, so as to avoid quenching the SC wire. The maximum clearance of the coil was imposed by the specifications, thus an 8 layer coil was produced.

Finally, a 300 turns coil was manufactured and characterized in the same way as the other magnets. The coil was mounted on its cryogenic, cylindrical support and the two ends of the coil wire were brazed to two copper tubes acting as an interface with the test chamber (Dewar) [Fig. 10]. As in the previous test the tubes were drilled to allow the internal circulation of liquid Helium. The copper tubes, acting as electrical fittings, were externally connected to a power supply (0-1000 A max. at 10 V) set for these tests at 30 A current and self-regulated in voltage.

The mapping of the magnetic field inside the coil was still made with a Hall effect probe, that could be transversed both axially than radially; the typical bell-shape profiles were obtained for the field intensity, with its maximum value on the axis at the midpoint of the coil. This value was found to be of 1618 G at a 30 A current (Fig.11). These results indicated that the specifications on the maximum magnetic field could have been met at a 17,85 A current.

A test was made in order to investigate the maximum field that the SC coil could generate; during the wire characterization it was found that the Nb-Ti wire could be able to sustain 169 A, even when subjected to an external magnetic field of 6 T. However a non-destructive measurement was required, and the limit current was not reached.

The induced magnetic field on the turns was assumed not to exceed 4 T and, from the simple laws of dependence of the limit current on the external magnetic field, it was found that this limit current was 253 A. A reduction factor of 0.7225, accounting for the quality of the insulation and the separation distance of the turns, was used for the limit current, that resulted 185 A.

This current was used to evaluate the maximum magnetic field safely generated by the coil: a 20 sec. test was carried out (the minimum required for the equilibrium of the system) and, at the end of this period, a magnetic field of 9970 G, a value very close to 1 T, was measured (Fig.11). If the magnetic field on the coil could be limited to 2 T, with a 300 A maximum current a 16187 G magnetic field could be reached.

The 6.3% discrepancy between the measured and the predicted magnetic field indicated proper coil manufacturing.

The one hour endurance test was carried out at a current level ranging from 80 to 120 A, in order to avoid rapid evaporation of the refrigerating liquid Helium. The test comprised three consecutive phases: 25 min. at a 80 A current, 15 min. at 100 A, and 20 min. at 120 A. The maximum field intensity was found to be 6463 G at 120 A, without any change in coil operation.
Feasibility Study for the Application of a SC Magnet on the Arcjet

A feasibility study on the SC coil manufactured by Europa Metalli-LMI laboratories has been carried out at CENTROSPAZIO for the application of the magnet to the low power arcjet used in the parametric test [Fig. 12]. The performance and the start-up behaviour of the arcjet with axially applied magnetic field by means of a resistive coil had been evaluated in previous tests [4]. Here the magnet was supplied either by a dedicated electric power generator or directly by the arcjet main power supply. The operational characteristics resulting from this configuration were considered very interesting.

The main limitations for the application of the SC magnet and its refrigerating jacket to the arcjet mostly consisted of the small space available around the thruster and the absence of appropriate mounting flanges in the vacuum chamber.

The thermal load radiated outside the arcjet nozzle was too high to be directly transmitted to the cooling jacket of the coil, which, for a proper operation, had to be centered on the restricted region of the arcjet nozzle (constrictor).

The heat flux radiated from the external nozzle surface represents about 15 to 20% of the arc power, depending on the mass flow rate (the greater the mass flow rate, the smaller the radiated energy). At 1-kW operation, the energy radiated by the external surface of the nozzle does not exceed 200 W.

To ensure the stability of the SC phase, the Nb-Ti wire must be kept at an almost constant temperature of 4.2 °K, and therefore in a liquid Helium bath. Forced refrigeration cannot be considered because, if the limit temperature is reached, even locally, the SC phase would be destroyed, and the subsequent temperature rise due to ohmic dissipation would lead to rapid propagation of the SC transition and possibly to violent boiling of the refrigerating fluid. It was therefore decided to enclose the magnet insulating container in boiling liquid Nitrogen bath, in order to maintain a constant temperature [Fig. 13].

In addition, a specially-designed nozzle was used for this application. The external diameter was reduced and a front radiator was added [Fig. 14] to drain the radiated energy from the external surface of the nozzle. Moreover, the nozzle was lengthened in order to place the constrictor at the point of maximum field intensity (coil midpoint), for maximum benefit. Coatings were considered both to reduce the emissivity of the surfaces below the magnet cooling jackets and to increase the effectiveness of the front radiator. Assuming an average radiated power of 180 W from the external surface of the nozzle, during a 2 hour test the heat load on the outer refrigerating system is 1296 kJ, corresponding to 0.928 gr/s liquid Nitrogen flux at 77°K.

Conclusions
The investigation of arcjet performance with strong externally applied magnetic fields and the development of a laboratory model SC magnet represent an important step towards improving arcjet operational characteristics with advanced technology devices. The strong magnetic fields obtained with the SC coils were considered a good incentive to investigate arcjet behavior under these conditions. Given the present state of the art, only LTSC coils are suitable for laboratory experimentation. Flight applications is not foreseeable, at least in the short term, due to the very low operating temperatures of this kind of coils. From the work carried out at CENTROSPAZIO, the application of SC technology to laboratory models of future-generation applied field arcjet thrusters seems possible. In view of ongoing research and development, an increase in the transition temperatures of next-generation SC materials can be foreseen, thus widening their field of application. If this trend is confirmed, the scheduled presence of liquid Nitrogen on board future scientific satellites could make HTSC magnets suitable for application to arcjet thrusters.

Acknowledgements
The authors wish to express their gratitude to Mr. P. Ricotti for his work on the characterization of SC wires, as well as for the design and manufacturing of the SC magnets at Europa Metalli-LMI Research Laboratories. His contribution was fundamental for the completion of the present activity.

References
Fig. 1 Multiwire Nb-Ti LTSC Superconductor (Ø = 0.84 mm)

Fig. 2 Plot of $I_c$ for a Nb-Ti wire sample (Ø = 0.84 mm, $B = 6$ T).
Fig. 3 First prototype of LTSC electromagnet (19.5 turns, Ø = 0.84 mm).

Fig. 4 Plot of B as a function of the current (19.5 turns, Ø = 0.84 mm).
Fig. 5 HTSC BSCCO 2212 wire (Ø 0.95 mm)

Fig. 6 3000 X photo at SEM of HTSC BSCCO 2212 wire.
Fig. 7 The HTSC prototype BSCCO coil.

Fig. 8 Plot of $I_c$ vs. distance from the edge of the BSCCO wire.
Fig. 9 Plot of $I_c$ for a Nb-Ti wire sample (Ø = 0.55 mm, B = 6 T).

Fig. 10 Final electromagnet with multiwire Nb-Ti LTSC (300 turns, Ø = 0.55 mm).
Fig. 11 Plot of $B$ as a function of the current (300 turns, $\varnothing = 0.55\, \text{mm}$).

Fig. 12 The low power arcjet thruster tested at CENTROSPAZIO (1-kW).
Fig. 13 Modified arcjet nozzle design.

Fig. 14 Double refrigerating containers system design.