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SMALL SUPERCONDUCTING COILS AND APPLICATIONS TO PLASMA PHYSICS

by

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ABSTRACT

This paper discusses the problems and techniques of making superconducting coils of the type used in research laboratories. It includes the development of single strand Nb-Ti to multi-filament twisted composites, and narrow Nb_3Sn layer wound coils to 12·7 mm wide disc type coils. The paper concludes with a brief description of some superconducting applications to the field of plasma physics.

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1. SMALL SOLENOIDS

Small superconducting solenoids generating fields of up to 80 kG in bores of a few centimetres are now quite commonplace and reliable systems can be purchased from a number of manufacturers throughout the world. Early coils of this type used copper-plated Niobium-Zirconium but this has been superseded almost completely by Niobium-Titanium which is co-processed from the ingot to the final wire with the required amount of normal material, usually copper. This process of co-drawing is not only cheaper than electroplating but it enables the ratio of copper:superconductor to be varied over a wide range and the process produces a much better thermal, electrical and mechanical bond between the superconductor and the copper, thus improving the performance of the coils.

In small coils, degradation due to lack of sufficient stabilization has been a problem. Coil manufacturers have now learned to live with it and have learned by experience how much degradation is likely to occur and are able to allow sufficient margin between critical and operating current to cover it. A typical conductor would be a 0·25 mm diameter superconducting wire surrounded by copper such that the ratio of copper:superconductor lies within the range of 1:1 and 2:1. The coils are usually layer-wound with Mylar insulation between layers. In some cases copper foil is also inserted between the layers to reduce the thermal gradient between the wire and the liquid helium and to provide additional electromagnetic damping.

Several causes have been suggested for this degradation but with present-day conductors the most likely are flux jumping in the superconductor and wire movement due to magnetic forces. Flux jumping results from the collapse of the magnetisation energy in the superconductor. The magnitude of this energy is proportional to the square of both the diameter and the critical current density of the superconductor(1). For a constant diameter therefore, the conductor becomes more stable as the field increases (Fig.1). At lower fields the energy is sufficient to raise the temperature of the conductor above its critical value. Whether or not this resistive region spreads, causing the coil to quench, depends on the balance between heating due to the transport current flowing through the copper at this point and the rate of cooling from the conductor. Fig.1 shows these three regions under the critical current curve for a typical Nb-Ti conductor.

Sudden movement of wires under the influence of magnetic forces can create local heating which may result in the coil quenching prematurely. The forces increase with current density, magnitude of field and coil diameter so that this effect is more likely to cause degradation in larger coils. Fig.2 shows the performance of a coil of 20 mm mean diameter under a variety of conditions. The poorer cooling environment of gas results in lower quench currents than when the coil is immersed in liquid. After impregnation in Epoxy resin the performance improved very considerably suggesting that the earlier quenches were due to mechanical movement. After impregnation the quench current is still well below the critical value and is representative of a quench due to unstable flux jumps. The stable performance expected in the high field region is illustrated by the performance (Fig.3) of two smaller coils made from the same wire and shown in Fig.4.

Since the magnetisation energy reduces with diameter, if the conductor is made small enough it will be stable throughout the field range. For Nb-Ti this is about 0·05 mm which is too small for most practical purposes.

2. MULTI-FILAMENT, FINE WIRE COMPOSITES

The stability criterion for single conductors has now been extended by Smith(2) and Stekley(3) to cover a number of fine superconducting filaments embedded in a normal metal. In this case it is essential to twist the filaments to reduce the magnetisation of the conductor. Again, the individual filament size should not exceed about 0·05 mm. For coil systems generating high field gradients it may be necessary to fully transpose the filaments instead of simply twisting them and this will probably also be necessary for composites above a certain overall size.

A coil, 200 mm mean diameter, using this type of conductor has recently been tested. There were 61 Nb-Ti filaments in the 0·5 mm diameter conductor having a ratio of copper: superconductor of 1.1:1. After impregnation the coil was energised and quenched at 131 A in a maximum field of 45 kG. All subsequent quenches occurred at the critical value of 140 A. The current density in the winding was 5×10^4 A cm^{-2} at 140 A.

3. LAYER-WOUND NIOBIUM TIN COILS

Small solenoids for fields in excess of 75-80 kG have usually been made by layer winding 2·3 mm wide Nb_3Sn tape. The Nb_3Sn is obtained either by diffusion of tin into a niobium strip or by vapour deposition onto a Hastelloy strip. For protection and stabilization silver or copper can be electroplated onto the strip or larger amounts of copper in the form of thin foil can be soldered onto it.

Care must be taken in winding the material so that a small space is left between turns to prevent inter-turn shorting (Fig.5). A reasonable tension must be maintained so that the turns will not move axially under the influence of the radial fields. It is common practice to wipe each layer with narrow strips of vacuum grease every few centimetres round the circumference. At the operating temperature this freezes and helps to prevent movement of the tape. Thin strips of copper foil about 5 mm wide are also laid directly on top of the tape, thus resistively shorting the turns in each layer to prevent large voltages developing when the coil quenches and also to help stabilize it. The insulation between layers is a sandwich of Mylar-copper-Mylar. A disadvantage of the shorting strips is that they cause the solenoid to have a long charging time constant and it is necessary to measure the field to ensure that it is stable. It follows that if such a coil is used for determining the critical current characteristic of a super-conducting wire the requirement to stabilize at each value of field will result in a time-consuming process. The exact adjustment to some pre-determined field value will also be difficult.

4. WIDE NIOBIUM-TIN TAPE COILS

Wider tape is now readily available and is considerably cheaper per amp-foot. It cannot be layer wound so easily because the change of direction at the side plates would cause the tape to buckle. It can be wound into disc coils which can then be stacked together to give a coil arrangement capable of withstanding large axial forces.

For solenoids, the usual method of construction is to wind the coils in pairs on a former, with the joint between the two coils being supported by the former. The joint can be made by soldering two or more pieces of the tape across the starts of the two coils. The coils are then wound in opposite directions until the required outside diameter is reached. Joints, similar to those on the inside, are then made on the outside between pairs of coils.

The width of the finished tape, which is probably a composite including solder, copper foil and possibly stainless steel re-inforcing strip, must be constant to a high degree of accuracy throughout the coil. The radial component of the magnetic field interacts with the coil current to produce axial forces which are cumulative along the stack of coils. These forces are transmitted from coil to coil through the radial spacers which provide cooling channels. Unless the tape has a uniform width these forces will be applied to high splots on the coil instead of being spread evenly over the whole surface and the eges of the tape will be damaged. Shorts between turns are likely to follow which will eventually lead to failure of the coil.

A good winding tension is essential to obtain a solid winding which will not compress and ripple under the influence of the inward radial forces on the outer turns.

The turns require insulating from each other, particularly if it is required to extract the energy from the coil when it quenches. It is an advantage if this is applied to the tape by the manufacturer since it is difficult to interleave the insulation during winding with sufficient accuracy of aligment.

Copper foil can be soldered on one or both sides of the superconducting tape. This improves the diffusion of heat from a point of instability in the Nb_3Sn and also provides magnetic damping. Both these effects increase the stability of the coil. The low resistance of the copper foil also reduces the temperature of the hot spot developed when the coil quenches and in large coils this may determine the thickness required. Stainless steel strips can also be added, or in the case of vapour deposited Nb_3Sn the Hastelloy substrate thickness may be increased, to give the tape additional mechanical strength.

During charging, magnetisation energy is dissipated in the form of heat which must be removed to prevent permature quenching. Radial cooling channels are usually provided for this purpose by inserting spacers of insulating material between coils.

The stability of tape wound coils is associated with the orientation of the magnetic field to the tape and to the magnitude of the field. A single pair of 12·7 mm wide coils will usually operate close to short sample performance. As further coils are added the performance degrades and the initial quench now occurs in one of the end coils rather than in the centre where the field is greatest. This is because the flux jump energy is related to the dimension of the conductor perpendicular to the field lines and for the radial component of field in the end coil, this is the width of the tape, whereas in the centre coils the field is wholely axial so that the dimension in this case is only the thickness of the tape. The radial field component must therefore be limited by some means, such as by increasing the coil spacing at the ends, by reducing the current density at the ends or by the use of Nb-Ti windings where necessary.

Fig.6 shows a 90 kG coil of this type which is capable of being energised to full field in 3 minutes.

5. APPLICATIONS TO PLASMA PHYSICS

The use of superconductors for plasma physics experiments has been slow to develop. The main reasons for this are that plasma physics laboratories are now equipped with large power sources, and it has therefore been possible to meet the requirements with conventional means. Ports for particle injection and diagnostics complicate the cryogenics required for superconductors and large forces must be transmitted from the coils to the room temperature case.

Superconductors are being considered more seriously now, however, either because the power requirements are becoming excessive for conventional equipment or because of the particular advantages which can be gained from the use of superconductors. Fig.7 shows the magnetic 'well' generated by a current flowing in the wire shaped like the seam of a baseball. Fig.8 shows the outline of a superconducting winding to provide such a confining field being constructed at Livermore(4). Quarter inch square Nb-Ti/copper composite running at 2,400 A will be used to generate 20 kG in the well. The maximum field at the conductor will be 75 kG. The forces are extremely high and the tie bars shown must be capable of withstanding a load of 450,000 kg.

An example of a machine which can satisfy all the physics requirements only if it incorporates superconductors is the Levitron or Spherator in which one or two current-carrying rings are supported on the magnetic field and are surrounded by plasma. If the ring is supported by mechanical supports, or if it is energised through leads, the plasma will be lost to them. If the ring is of high conductivity normal material it can be supported by a pulse field which induces eddy currents in the ring. The field in this case will diffuse into the ring taking the plasma with it. A superconducting ring in which a DC current is induced in the only way in which all the required conditions can be met. Fig.9 is a diagrammatic representation of such a system; the ring is supported by the field produced by the vertical field coils; the stabilizing coils are necessary to control the position of the ring since it is in a state of unstable equilibrium. Machines of this type are being planned or are already under construction at Princeton, Livermore, Culham and Garching. The Princeton machine is well underway(5) and is designed to operate either with a single ring at 1520 mm diameter, 375 kA or with 2 rings at 1020 and 2040 mm diameter and currents of 500 kA and 250 kA. In this machine, only the floating rings are made of superconducting material which is 2·3 mm wide Nb_3Sn. The ring is complete with its own room temperature cryostat and can be filled with liquid helium at atmospheric pressure. After filling, or partial filling, the winding is sealed and the temperature takes several hours to rise to 12 °K. Increased operating time can be obtained by the introduction of a lead shield to increase the thermal mass of the ring.

The surface of the Livermore and Culham rings will be cold. The windings will be sealed inside a pressure vessel which will be filled with helium gas at room temperature to a pressure of 100 to 200 atmospheres. Cold clamps will cool the ring to about 4·2 °K when the gas pressure will be 1-2 atmospheres. The Livermore ring is 800 mm diameter, 90 mm minor diameter and will operate at currents up to 600 kA. The corresponding figures for the Culham ring are 600 mm, 90 mm and 500 kA. In both cases the surface of the ring will be below 20 °K in contrast to the room temperature surface at Princeton.

A high overall current density is required in the floating rings. The Livermore one uses 5 mm wide Nb_3Sn tape and therefore has the advantage of a high critical temperature. This, however, is at the expense of field uniformity which should be better with the Culham design which uses 'intrinsically stable' fine filament Nb-Ti conductor impregnated in epoxy resin. In these two experiments Nb-Ti superconductors will be used for the vertical field coils.

6. REFERENCES

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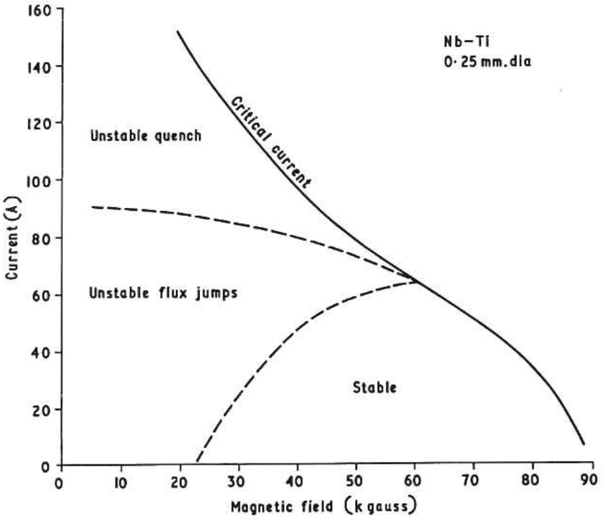

Fig. 1 (CLM-P 211)
Typical stability diagram for 0.25 mm diameter Nb-Ti conductor

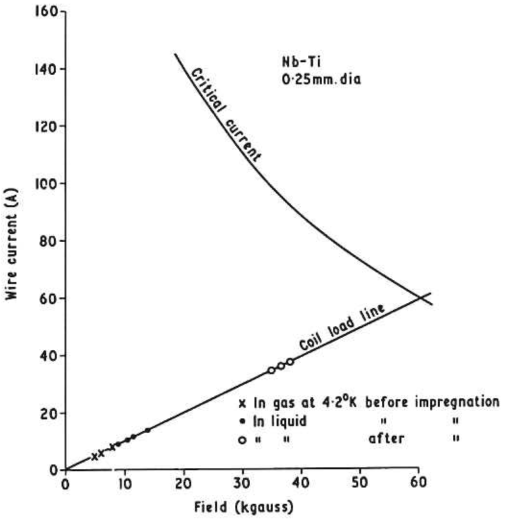

Fig. 2 (CLM-P 211)
Quenching performance of 200 mm mean diameter Nb-Ti coil

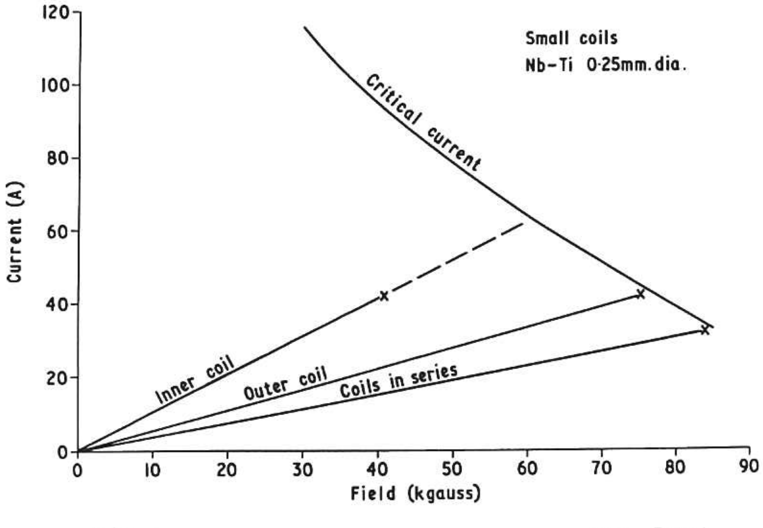

Fig. 3 (CLM-P 211)
Quenching performance of two concentric Nb-Ti coils

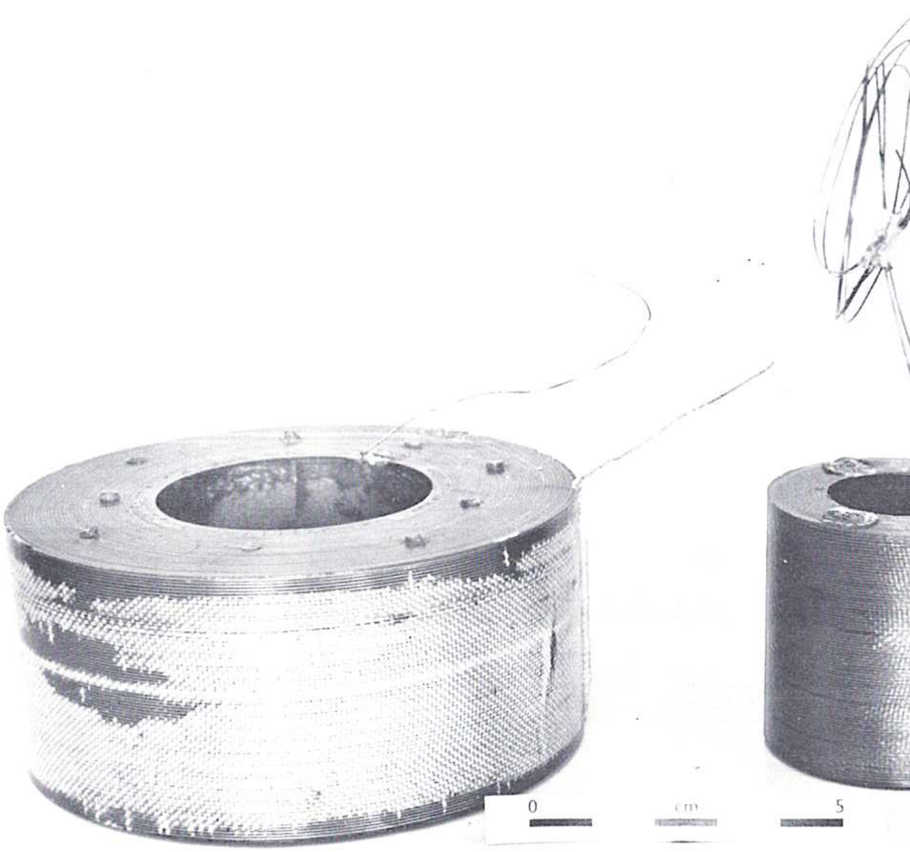

Fig. 4 (CLM-P 211)
Nb-Ti coils 44.5 mm long. Inner coil: 25 mm bore, 50 mm outside diameter. Outer coil: 50 mm bore, 100 mm outside diameter

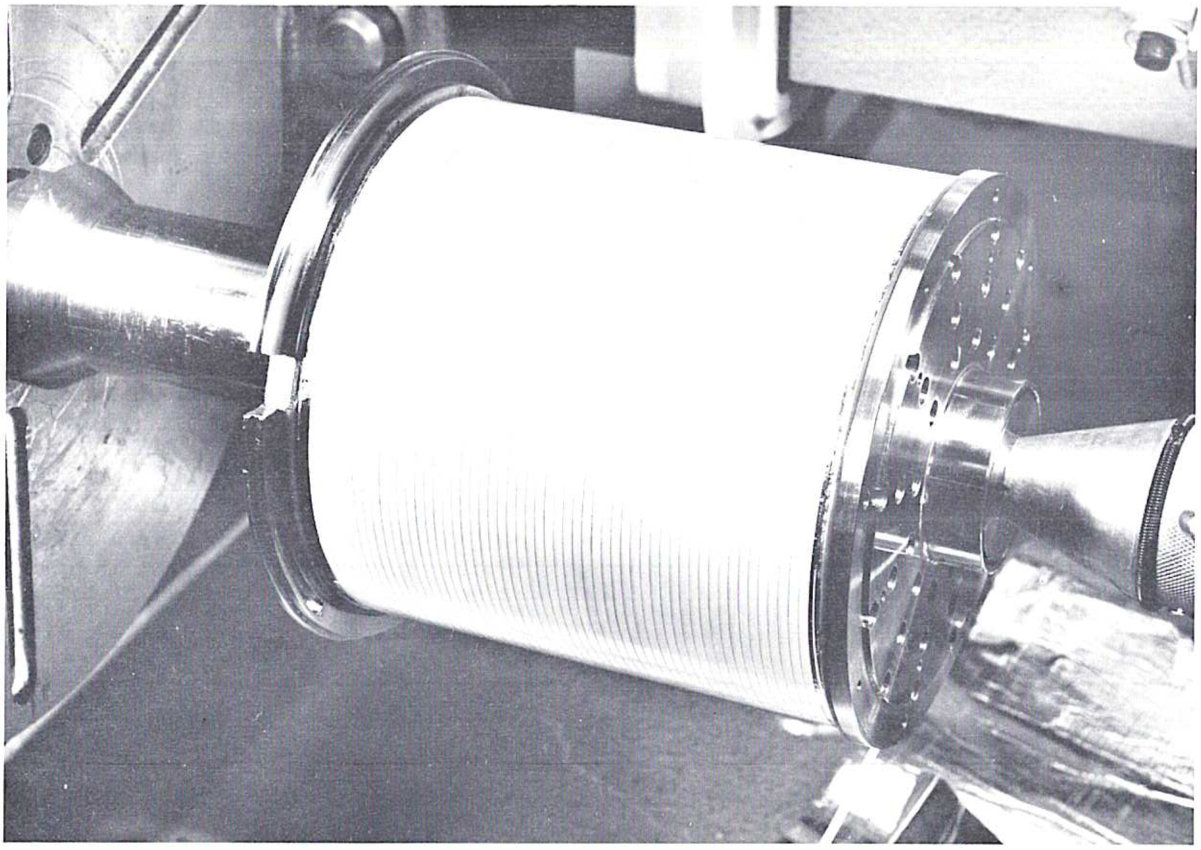

Fig. 5 (CLM-P 211)
Winding 108 kG Nb_3Sn ribbon magnet. (By permission Oxford Instrument Co. Ltd)

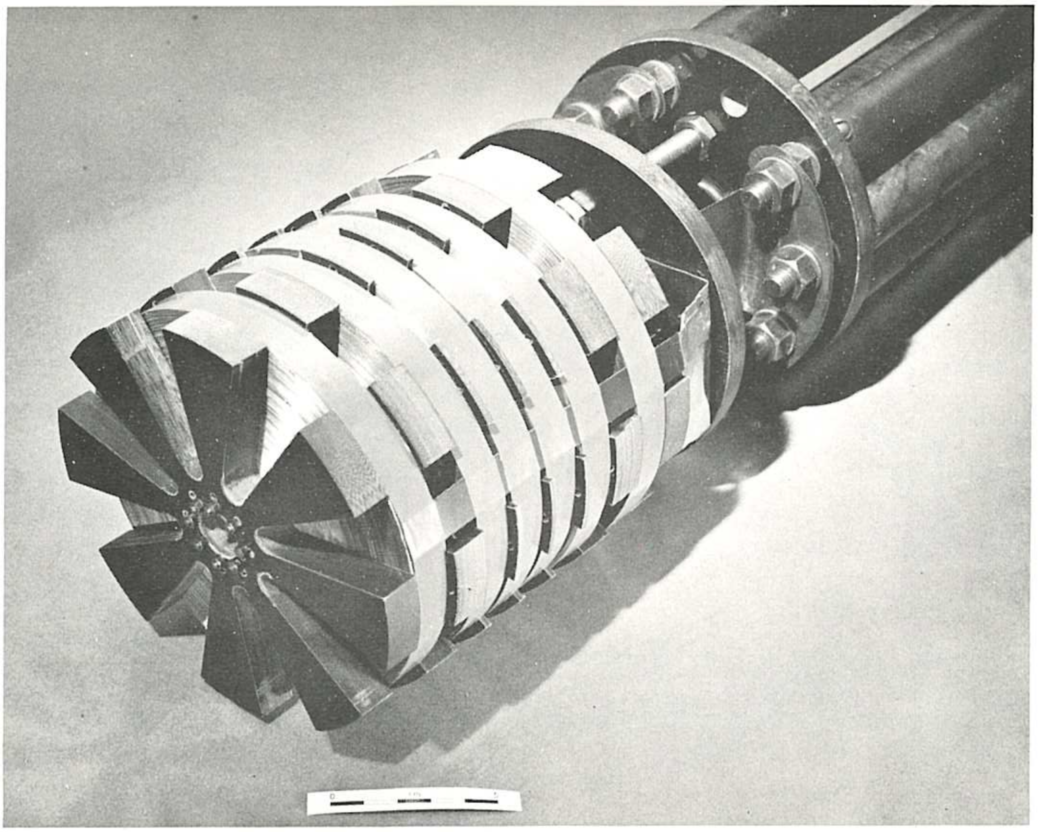

Fig. 6 (CLM-P 211)
12.7 mm wide Nb_3Sn tape coil. Bore = 2.5 mm. I = 330 A. B = 90 kG. Current density in coils = 2.4×10^4 A cm^{-2}

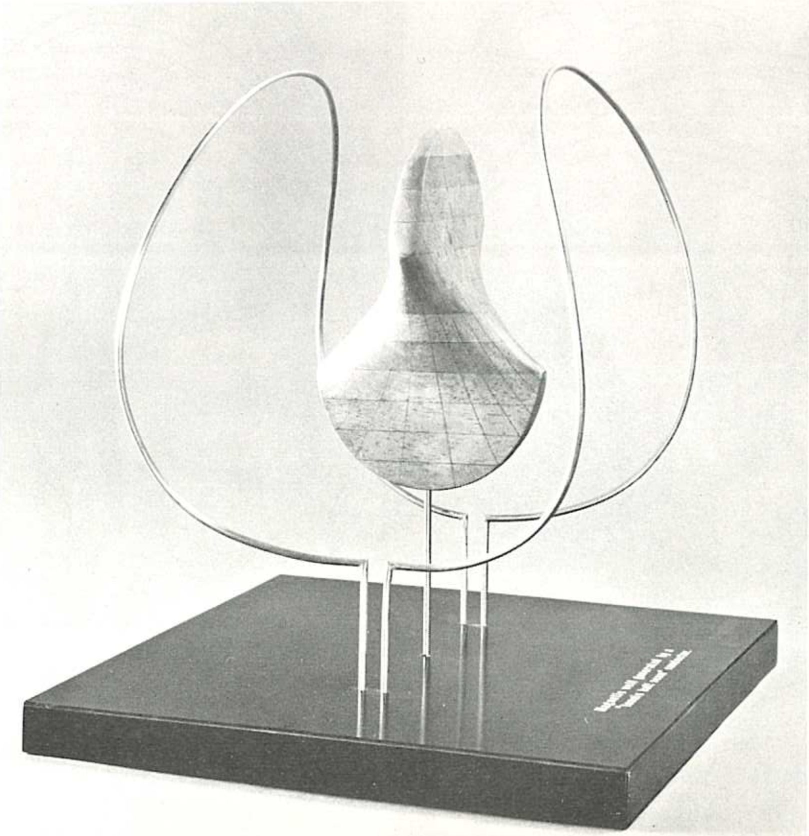

Fig. 7 (CLM-P 211)
Magnetic well generated by baseball seam conductor

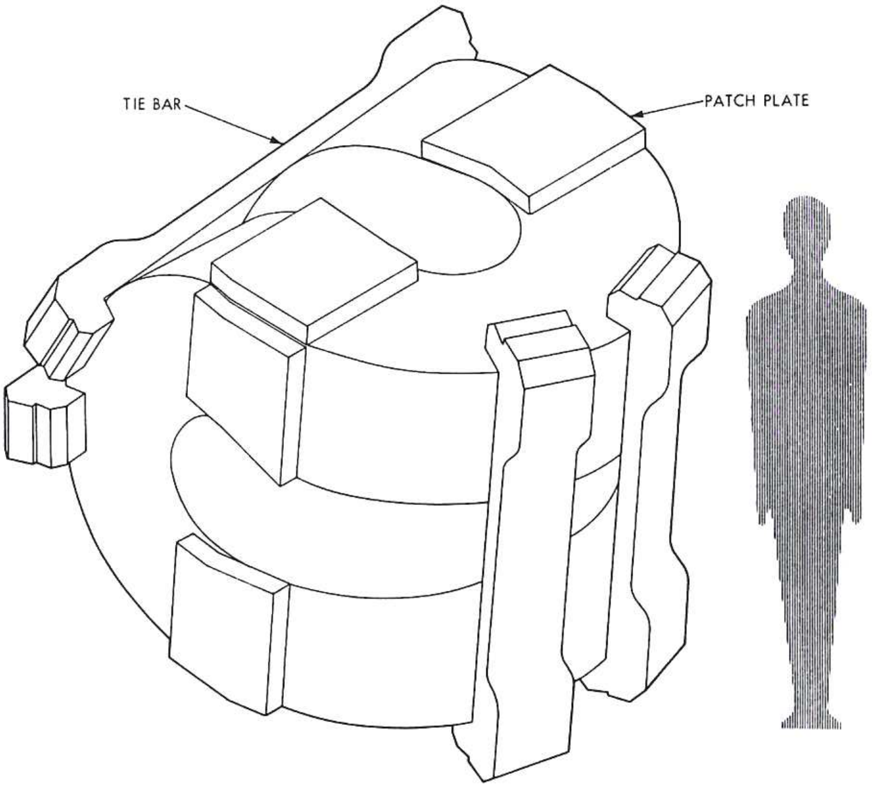

Fig. 8 (CLM-P 211)
Structural shell for superconducting baseball magnet

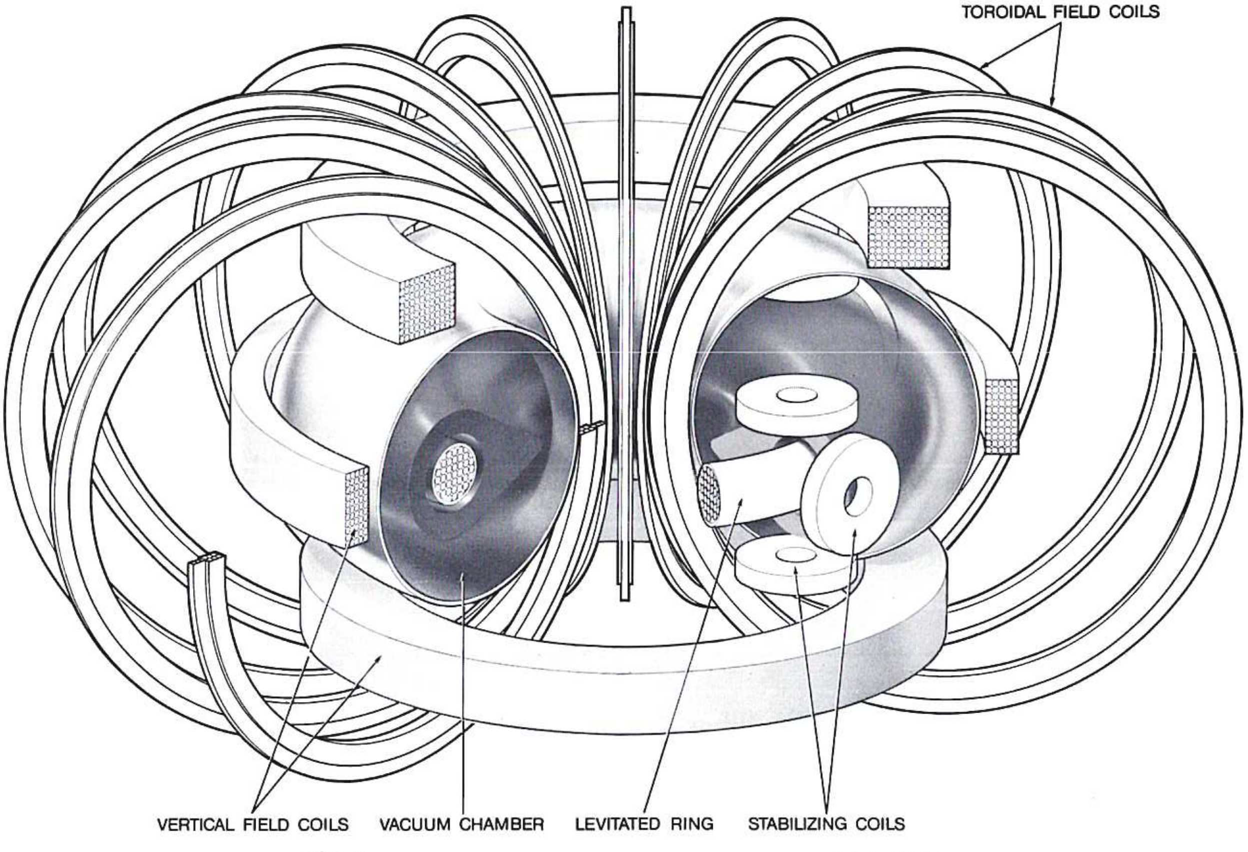

Fig. 9 (CLM-P 211)
Diagrammatic representation of superconducting Levitron

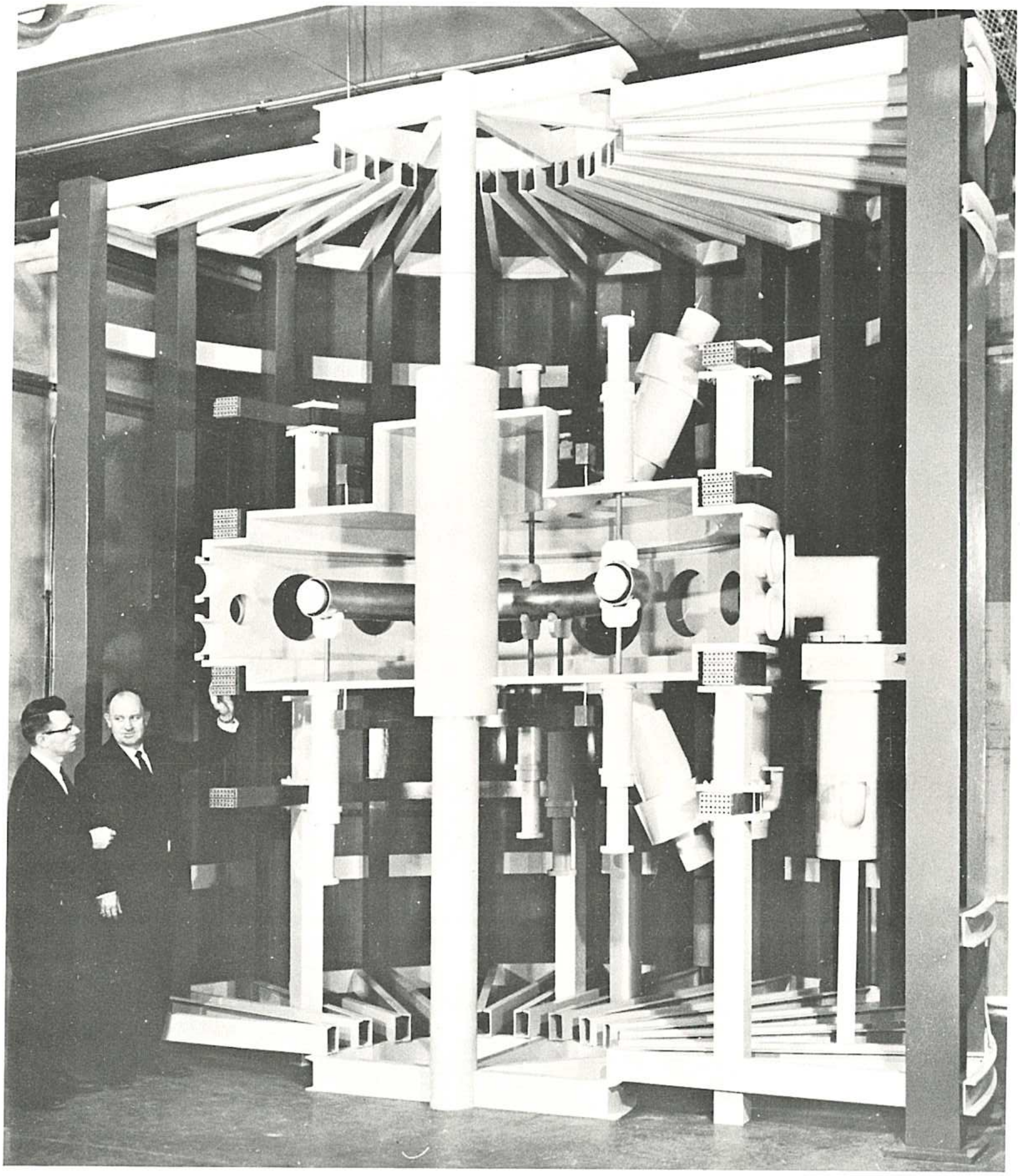

Fig. 10 (CLM-P 211)
Cross-sectional model of Princeton spherator