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Pebble Bed Conductors

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Abstract

A new type of magnet design is proposed, where the conductor is composed of conducting pebbles in a low-melting temperature conducting matrix. The magnet should have high radiation tolerance. At the end-of-life of the conductor, the pebbles can be circulated out of the magnet after the conducting matrix is molten. Application of this approach to the centerpost in the Low Aspect Ratio Device are discussed.

I INTRODUCTION

There is a need for a magnet that can withstand large radiation fluxes, and can be easily replaced at the end of its life. In order to maximize the lifetime of the magnet, single turn magnets are preferable, with no requirement of insulation between turns. Insulation damage is the single largest case of failure for highly irradiated magnets.

This type of magnet is required for the central centerpost of Low Aspect Ratio [1, 2, 3] devices. The centerpost of this device is highly irradiated (since for all practical purposes, there is no shielding), and has a lifetime limited by an increase in the resistivity of the conductor, swelling of the conductor, or loss of ductility.

This paper addresses the design of single-turn magnets that can be replaced easily.

II PEBBLE-BED CONDUCTORS

Instead of a monolithic centerpost with cooling passages, as in the conventional single turn magnet design for the Low Aspect Ratio reactor design [4, 5], a centerpost with conducting pebbles in a conducting matrix is discussed in this paper. The advantages of this approach are that the swelling and loss-of-ductility limitations of the copper are avoided, and a practical method for quickly changing the conductor can be designed.

Figure 1 shows a schematic of the composite centerpost. The conductor in the centerpost is made of a large number of pebbles, in a packed-bed configuration. The pebbles are made of a highly conducting material, such as copper. To provide better contact between the pellets, a liquid or solid conducting matrix fills up the gap between the pellets. In this manner, the conductivity between pellets is dramatically improved over only contact-conductivity. The conductivity is also more predictable and homogeneous in the presence of this conducting matrix.

A Liquid vs solid matrix

As mentioned above, during operation the inter-pellet material can be either solid or liquid. If liquid, the inter-pellet could be used for cooling the magnet if it can be made to flow fast. With the LAR design, however, for the parameters of the reactor calculated by the Demo team [4], the maximum value of the toroidal field is about 16 T. This corresponds to an applied magnetic pressure of about 100 MPa (1000 bar). Not all of the pressure is applied to the liquid itself, since the liquid only carries a fraction of the current (the current prefers to travel through the substantially better conducting pellets. The pellets, of course, support this load through contact with other pellets, resulting in higher local stresses in the pellets, but partially removing the Lorenz loads from the liquid.

However, a substantial fraction of this pressure remains in the liquid itself, and it is hard to pump the liquid at the required pressures to cool the centerpost. In addition, since the liquid is electrically conducting, the pressure drop would be very large. Therefore, it was decided to analyze static inter-pellet material, with channels that cool the entire composite.

There is another reason for the making the inter-pellet material static. If the inter-pellet material is lithium (in order to improve the breeding), at the temperature where lithium melts (around 300 C), the conductivity of copper is about half of that at room temperature. The increase in power dissipation and thermal load in the centerpost is highly undesirable.

For these reasons, it was decided to design the composite centerpost so that inter-pellet matrix would be solid and at a low temperature during operation. To remove the copper

pellets at the end of their lifetime, the centerpost would simply be heated above the melting temperature of the inter-pellet material, and would then be drained and replaced with new material.

The arrangement of this composite conductor is not much different from gas-cooled pebble-bed blankets proposed for fusion [6]. The thermal conductivity of the pebble-bed blanket directly corresponds to the electrical conductivity of the composite conductor. However, thin surface coatings on the pellets do not substantially affect the thermal conductivity (due to the small dimensions of the coating, for example, an oxide layer), but would have profound consequences for the electrical conductivity. This is because the electrical conductivity of this layer can be many orders of magnitude different from that of the conducting pebbles, while the difference between thermal conductivities will not be as large.

III COMPOSITE CONDUCTIVITY

Very simple calculations of the performance of the conducting bed have been carried out using volume filling fractions. It was found that the pebble-resistivity is about twice the resistivity of the solid copper when a low melting material is used as the conducting metal. These calculations assume a two dimensional arrangement using cylinders instead of spheres.

Finite Element Method models will soon be used to perform more detailed calculations. The conductivity of the composite has been determined as a function of the resistivity of the pebbles and the surrounding fluid. The FEM model for the pebble bed conductor will include surface resistance, which is expected to be small if present at all. The model will analyze two spherical pebbles in contact with one another at one point, and with a filler material of a different electrical conductivity in the space surrounding the pellets.

It is possible to affect the filling fraction of the pebbles. If a uniform pellet size is used, the fraction filled with pebbles is approximately 60 – 70% by volume. The calculations performed above on the conductivity use this filling fraction. If, however, multiple pebble sizes are used, it is possible to increase the filling fraction and, therefore, the conductivity of the composite. If two optimal sizes are used, the filling fraction can be increased to about 85%. Using the simple estimate of the conductivity, the conductivity of the composite in this case is reduced by a factor of 1.6 from the conductivity of the monolithic conductor.

A Experimental Investigation

A small experiment was prepared to verify the calculations using brass and steel pellets. These one-fourth inch pellets were used to determine the effect of different resistivity of the pellets. Woods metal and conventional electrolyzers were used to vary the resistivity of the fluid.

The interpellet material was a low melting temperature alloy (similar to woods metal): a mixture of bismuth, indium, cadmium and lead, with a melting temperature of 50 C. The experiment was carried out in a glass jar filled with approximately 100 cm³ of pellets. There were two flat electrodes, one at the bottom of the pellets and one at the top. It is possible to mechanically apply pressure to the pellets through a solid rod.

To date, the experiments have produced negative results. The molten material has not wetted the pellets, and consequently none of the current flows through the pellets, only through the interpellet material. The electrical conductivity of the composite is lower than that of the interpellet material itself, by approximately the volume fraction of the liquid. Even after allowing the metal to freeze, the conductivity of the composite is low. After removing the

pellets from the molten bath and allowing them to cool, it is very easy to "peel" the frozen interpellet material from the pellets, indicating that very little metallurgy has occurred at the interface.

In an attempt to remove any oxide layer on the surface of the pellets, the pellets were placed in a hydrogen furnace for 10 minutes at 300 C, then the experiment was repeated. It is possible that the oxide layer reforms during transport to the glass jar or from oxygen dissolved in the molten metal. However, the results from this set of experiments were negative, indicating that it is not an oxide layer that causes the negative result, but that the inter-pellet material is not establishing a conducting path between pellets.

Experiments in the future will involve heating the composite to higher temperatures in order to provide thorough wetting of the pellets.

IV STRESS CALCULATIONS

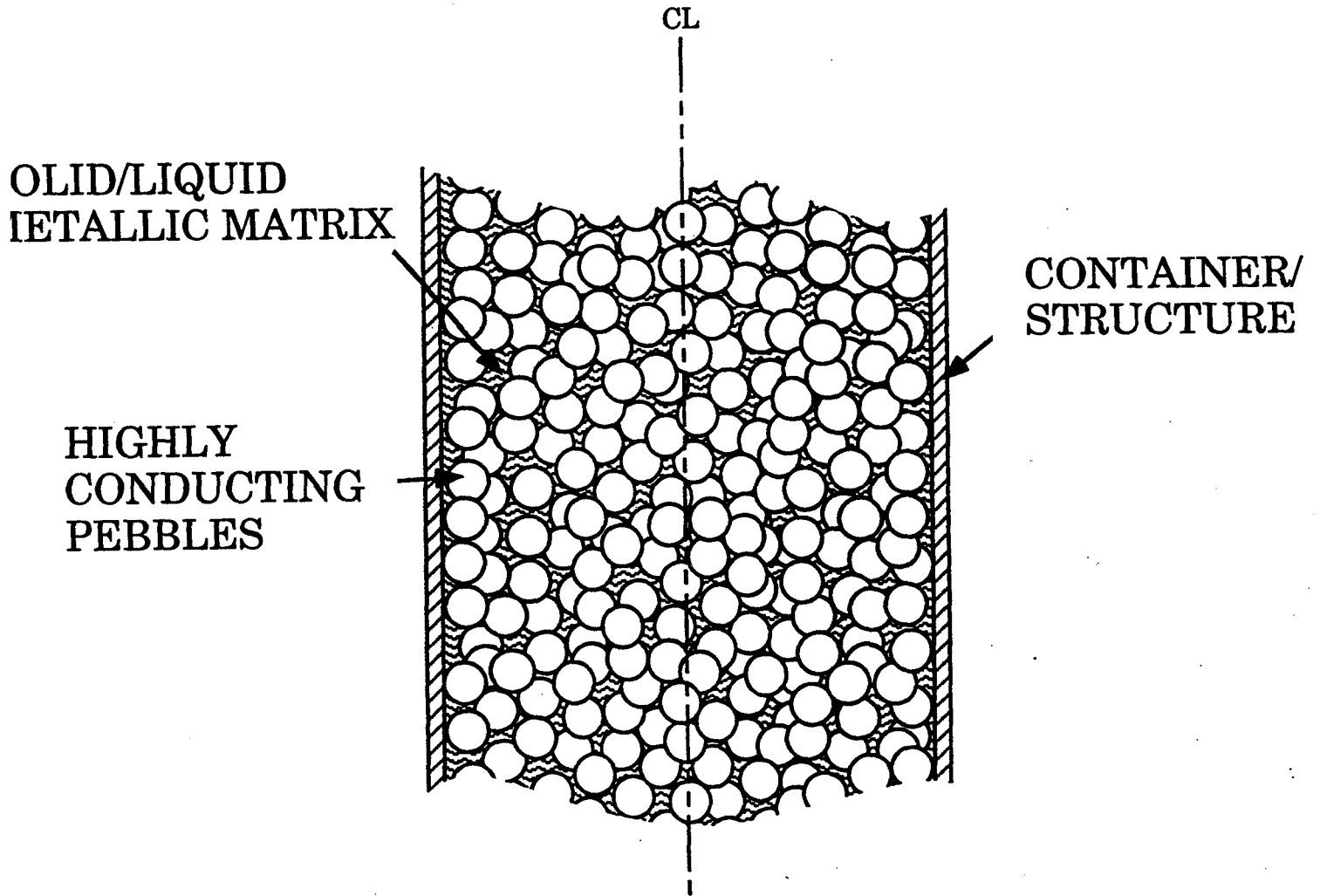
The stress condition in the composite material has been calculated. The current flowing in the composite imposes large Lorenz loads in the interpellet material. If the interpellet material is liquid, large hydrostatic pressure builds up in the liquid, on the order of $B^2/2\mu_0$. The pressure at the top and bottom of the column would be hard to support. Consequently, the possibility of having a solid (but low melting temperature) interpellet material has been investigated. There are several advantages including the fact that the temperature of the central column can be decreased, since the interpellet material does not have to be liquid, hence increasing the material choice. For example, to use liquid lithium, the temperature of the central column would have to be over 300 C, with a substantial increase in resistivity of the copper or pellet material. When it is necessary to change the pellet due to the radiation damage of the copper, the interpellet material is melted and the center column is drained.

V CONCLUSIONS

Progress has been made in developing magnets that are easy to replace once they have been irradiated to the point of no longer being usable. Additional effort is required to calculate and measure the effective electrical conductivity of the composite.

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**Packed bed of conducting beads
immersed in a liquid metal**

Figure 1: Schematic diagram of a packed-bed pebble centerpost, with either solid or liquid inter-pellet material. Cooling channels are not shown.