Emerging Boom In Nano Magnetic Particle Incorporated High-Tc Superconducting Materials & Technologies - A South African Perspective

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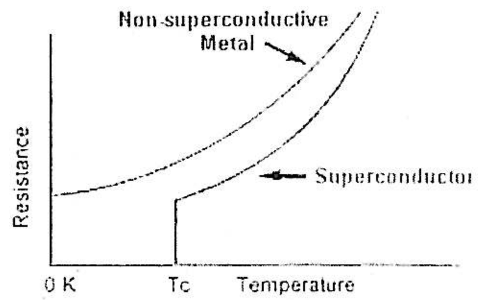
1. INTRODUCTION

With a strategy to establish and embrace the emerging nano particle incorporated Superconductivity Technology (based on the HTS materials and nano magnetic particles) in South Africa, the author has initiated the following research activity in South Africa, with the financial support by SANERI South Africa. This Superconductivity Technology has become a prime focus area of SANERI, South Africa.

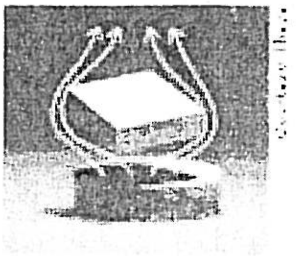
a. Superconducting Materials

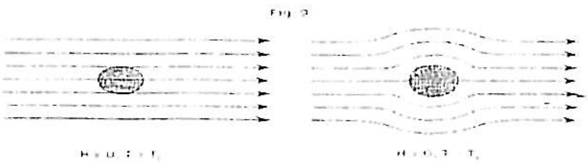
A material is said to be a superconductor when 1. DC electrical resistance becomes zero and 2. when it expels magnetic flux. These two properties are depicted in the following figures.



The resistance goes to zero as the superconductor is cooled below a characteristic temperature known as T_c Many of the old superconductors such as Mercury, Aluminium etc have their T_c's at extreme low temperatures of the order of few Kelvin. Therefore those materials are not very much useful for common man. However a great discovery by J.G. Bednorz and K.A. Muller has changed the scenario as the newly discovered cuprate or the "high temperature superconductors" (HTS) have broken the BCS limit. Superconductors such as YBCO which can superconduct above liquid nitrogen temperature have been discovered and it changed the technologies.

Flux expulsion as shown above is another important property of a superconductor, which actually is useful in levitation applications.





In the above figure we are showing an example of how superconducting levitation is possible. Conventional power transmission relies on wires made of metals such as aluminium or copper. Because metals have finite resistance, Ohmic losses takes place and usually about 10-15% power losses occur. However if one uses the superconducting cables [1,2], because superconductors have zero resistance, one can achieve zero power loss in power transmission. In prototype superconducting transmission lines at Brookhaven National Laboratory, USA, 1000 MW of power can be transported within an enclosure of diameter 40 cm. This amounts to transporting the entire output of a large power plant ōn one enclosed transmission line. This could be a fairly low voltage DC transmission compared to large transformer banks and multiple high voltage AC transmission lines on towers in the conventional systems. Several companies and the Governmental agencies in both Japan and USA are trying to advance this technology . An important parameter which tells us how much maximum lossless current can be sent through a superconducting wire is the so called critical current density (Jc). This Jc strongly depends upon the defects and impurities which acts as pinning centers in a superconductor. So by creating defects or adding impurities in a controlled way, one can improve the Jc [3]. Improvement of pinning in High-Tc superconductors (HTSC) by means of inclusions of pinning materials has long been an active subject area of research [4-7] Nano particle dispersions is the current trend [8-10]. *In the fundamental science aspect, it is a marriage of two potential fields namely Superconductivity and Nano science.* In this work, we focus on the nano magnetic particle effects in grain boundary structures in YBCO. YBCO when pelletized, shall have several variety of weak links and the grain boundary structure plays important role in the quality of superconducting properties, particularly the Jc [11].

Further, dispersion of nano magnetic particles in high-Tc superconducting materials shall lead to improved flux pinning and magnetic properties, and shall have direct influence on the magnetic levitation properties. The strong pinning allows the "freezing" of high magnetic fields. In contrast to classic magnetic bearings, superconducting magnetic bearings are self-stabilized due to flux pinning, which makes them good materials to be used in fly wheels [12] for energy storage. High-Tc superconductivity based magnetic levitation [13-16] has become a very fast growing field with the discovery by Murakami (ISTEC, Japan) etal [17] that the flux pinning is the key parameter that plays role in levitation. $YBa_2Cu_3O_{7-x}$ (YBCO) pellets are even under consideration as substitute for Liquid Helium-cooled NbTi-coils in the Japanese Maglev project [18]. Infact, the Railway Technical Research Institute, Tokyo, Japan is leading in the development of this technology[19]. In this context of growing impact of the utilization of High-Tc superconductors in the power transmission cables, magnetic levitation, energy storage flywheels, we propose to study the influence of magnetic nano and micron size particles dispersion in YBCO superconducting material for improving flux pinning, J_c and levitation efficiency and also RF properties for sensor applications. Our proposed studies will propel South Africa into this advanced level of international competition with groups from Japan and USA, who are the key players in this technology.

Statement of the research problem

We intend to take advantage of the recent advances in the synthesis of nano and micron size ferromagnetic particles such as Ni [20] and other materials. Micron size manganite particles [21] are also ferromagnetic and are very compatible with the HTSC material. We propose to disperse these ferromagnetic particles in the HTSC, in particular YBCO which will have superior flux pinning abilities as compared to traditional pinning inclusions such as Ag, and other materials. We shall study the impact of these ferromagnetic (FM) pinning centers on the improvement of both Jc and also the levitation performance of HTSC materials. The levitation performance shall be studied using a home built magnetic test-bed developed in our laboratory. The results shall have great experimental and production value for actual production of Magnetic particle dispersed HTSC for bulk applications like power transmission and magnetic levitation systems.

Aim of the research

The key research question that would be answered is the Percentage improvement of Jc and levitation efficiency as a function of percentage by Wt. dispersion of FM nano/micro particles in YBCO. And its comparison with the traditional pinning inclusions and dispersions. While this is an important information that we get from our studies, there is also another byproduct that shall come out of these experiments, namely the RF absorption properties (This is because we intend to measure Jc using a low field modulated rf absoption technique, as described in the methodology section) of the FM nano/micro particles dispersed YBCO. This is of great interest both for applications and fundamental issues because, recently there is a lot of interest in small particle electrodynamics at RF and microwave frequencies [20-21]. Small particle electrodynamics are totally different from that of bulk in both manganites, nano Nickel and YBCO [20-22] these studies can lead to a more detailed understanding of what is called the Gaint or Colossal magneto impedance properties which are very useful in sensor applications[21]. So FM Nano & micron size particle dispersed HTSC offers experimental ground for novel RF properties and sensor applications as well.

Methodology

1. **Sample Preparation**

YBCO Powders_Commercially available and purchased from USA.

Manganite Powders These powders are prepared by standard solid state route [21].

Nano Nickel Powders

For the synthesis of nano crystalline metallic particles two different methods are adopted. One technique is high-energy ball milling and other being a chemical reduction method [23,24]. In the former case planetary ball mill is used to synthesize Nickel fine particles with tungsten carbide milling media. Toluene is taken as wet milling medium, which is chemically inert and can be used to prevent heat that is generated during milling. Toluene also acts as a lubricant to prevent any damage to the balls during collision. The ball to powder ratio (BPR) is taken as 10:1 and the milling time is upto 40 hrs.

Fine particles of nickel are prepared by reducing the transition metal salt $NiCl_2.6H_2O$ by a reductor of sodium borohydride ($NaBH_4$), in aqueous solution, at room temperature and in ambient atmosphere. The $NaBH_4$ is added drop-wise over a period of 1 hour to a $NiCl_2.6H_2O$ solution in a beaker, with constant magnetic stirring. An instantaneous exothermic reaction takes place with the formation of black slurries of fine particles and evolution of H_2 gas. Further details on synthesis and reaction mechanism are given elsewhere [23,24].

Transmission electron microscopy (TEM) measurements yield particle sizes of about 50-60 nm and in the case of chemically prepared samples. The structure of the sample was studied with Philip's X-Ray diffractometer of (Model 1710) using Cu K_α radiation of wavelength λ = 0.15418 nm. Also TEM micrographs and selected area diffraction (SAD) patterns are used for detailed structural analysis [20]. The RF measurements were done with an HP 4191A Impedance Analyzer. The instrument is well calibrated and the measurements are done at 1MHz. No binder or any dilution matrix material is used. In other words, the powder is taken as is in a quartz tube sealed with a Teflon tape. The sample is subjected to the RF magnetic field inside a coil. The response is thus purely magnetic in nature. The background due to the quartz tube and Teflon tape, along with the empty coil, is subtracted from the original data so that a pure sample response is obtained. The impedance measurements are carried out in the temperature range from 77K to room temperature.

Then the ferromagnetic nano size nickel powders are dispersed in YBCO at various %wt proportions (from 0.1% to 10%). However in all the cases, we haven taken care that the dispersion doesn't exceed the percolation threshold, so that dispersed particle magnetic behaviour doesn't dominate the YBCO superconducting properties. Here the intention is only to use these dispersions as pinning centers. Then one must be operating below the percolation threshold. The micro & Nano magnetic dispersed YBCO(mag-YBCO) powders are then pelletised into disc shaped pellets of various radius.

Magnetic levitation

A home built magnetic bed shall be used for this purpose, shown in Fig.1. The mag-YBCO pellets shall be suspended in their superconducting state on this magnetic bed. Loads of various values shall be applied on the pellet and then the height of suspension from the bed surface shall be monitered as a function of load.

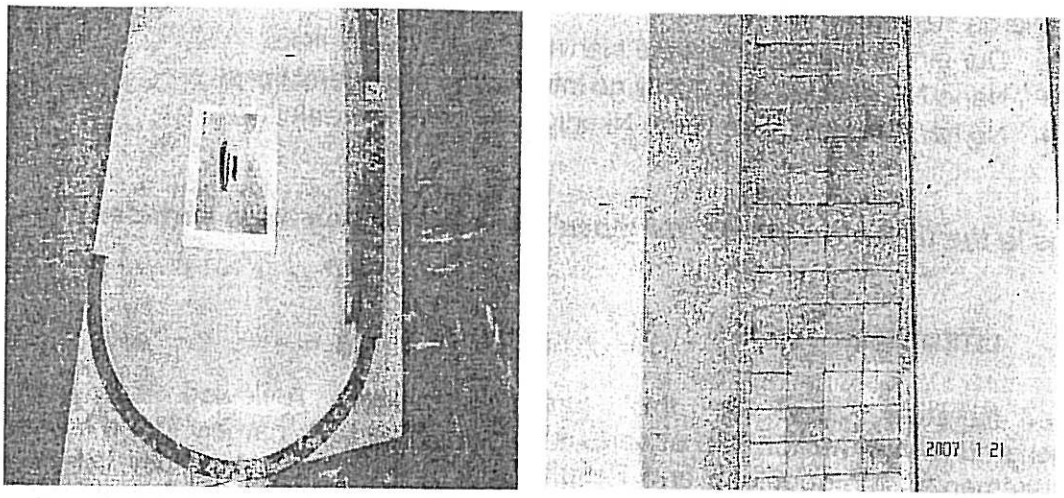


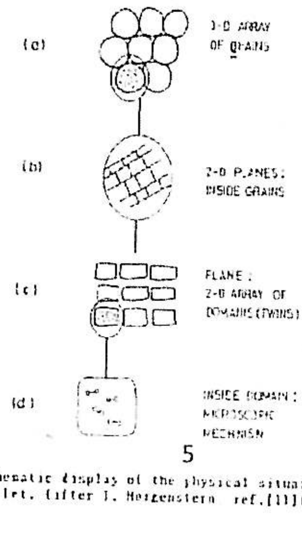
Fig.1 (a) Home built magnetic test bed. (b) Detailed view of the arrangement of magnets

Methodological assumptions

1. It is assumed that the nano Ni particles only goes into the grain boundaries of YBCO and not into the grains.
2. Thorough grinding of many cycles, shall give us a very uniform Ni dispersion in the YBCO powder.

Concept clarification

We used nano Ni particles as pinning centers in a YBCO superconductor . YBCO superconductor is highly granular and has a hierarchy of weaklinks including grain boundaries. As the nano Ni particles are throroughly dispersed in the YBCO powders by grinding only and as we did not give any heat treatment, we believe that the nano Ni only enters the grain boundaries of the YBCO powders, when pelletized. These nano Ni particles can kill superconductivity locally in the grain boundaries and act as strong pinning centers. However in a dilute dispersion, nano Ni being magnetic can also reduce the grain boundary Josephson junction critical current density, which should actually reduce the levitation efficiency. However as the %wt of nano Ni is increased progressively at some stage, pinning effects shall dominate and levitation efficiency should increase.



Schematic display of the physical situation in a ceramic pellet. (after I. Morgenstern ref.[11]).

Micron size weak links

- Our aim is to strengthen the pinning at these weak links
- Nano Ni particles can easily go into micron size weak links!
- No heat treatment so Nano Ni only gets into the weak links.

This is the first attempt to strengthen Weak links using nano particles.

2. LITERATURE REVIEW

The literature used in this work has been reviewed as parts of Background/Introduction and at various stages of the text, namely in the sections of Experimental, Methodology and Results and Discussion and is fully listed in the Bibliography. However in the following we review some of the general ideas that revolve around the Superconducting Maglev concepts:

Advantages of Superconducting Maglev

Superconducting maglevs use linear motor concept and not rotary [25]. The motor does not rotate; instead, it exerts a kinetic force in a straight line, or guideway. One part of the motor is mounted on the train, the other on the guideway. The train shall have light but powerful superconducting magnets, and the guideway shall have energized coils along the sides. Therefore the train does not carry transformers and inverters. That's why the train is very light and slim, but still capable of harnessing a large propulsive force. Other advantages are [25]:

1. No current collectors
2. Electromagnetic force levitates the vehicles, so there are no wheels or rail adhesion problems.
3. Superconducting magnets create a strong magnetic force to propel the vehicle and they also levitate the vehicles and guide them within the bounds of the guide way.
4. Natural stabilizing effect provided by electromagnet induction. No controlling devices whatsoever are needed to keep the train on its guide way, and there is no risk of the train 'derailing.' The magnetic levitation force is ideal for supporting a train at very high speeds.

Advantages of Superconducting magnets used in the Japanese and M-2000 Maglev systems [26]:

- "Superconducting magnets enable Maglev vehicles to operate with much greater clearances above the guide way, than are possible with room temperature magnets. With superconducting magnets, the gap between the Maglev vehicle and the guide way can be 6 inches. With room temperature electromagnets or permanent magnets, the gap is only about 3/8 of an inch. Large gaps improve safety, allow greater construction tolerances, decrease construction costs, and reduce sensitivity to ground settling and earthquakes.
- Superconducting magnets enable the levitated vehicle to be inherently and passively strongly stable against external forces (winds, grades, curves, etc.)

that act to displace the vehicle from its normal suspension point. Attractive force suspensions based on room temperature electromagnets are inherently unstable, and require constant, fast response servo control of the magnet current to operate safely.

- Superconducting magnets let Maglev vehicles levitate much heavier loads than are possible with room temperature electromagnets or permanent magnets. Heavier load capacity lets Maglev vehicles carry freight, water, mining ores, etc., to generate large revenues.
- Superconducting magnets have much lower power requirements than conventional room temperature electromagnets.

Some of the questions and doubts about 'refrigeration, 'safety', 'cost of operation', 'environment issues' were clearly answered by MAGLEV-2000 and are given below.

REFRIFGERATION

The only disadvantage of superconducting magnets is their need for refrigeration. However, the power for the refrigerator is small compared to the power to overcome air drag on the vehicle. Accordingly, operating cost for superconductors is a minor perturbation.

FABRICATION DIFFICULTIES

The superconducting magnets on Maglev vehicles are not complicated to construct or operate. Thousands of superconducting magnets now operate routinely and reliably around the world in MRI devices, high-energy accelerators, and other applications

SAFETY AND FAILURE PROBABILITY

The M-2000 Maglev vehicles are designed with multiple (typically 16) superconducting magnets that operate separately and independently of each other. The M-2000 vehicle will remain levitated and operate safely even if several of its magnets were to fail. Because the failure rate of superconducting magnets is very low, the probability of two magnets failing in a period of few minutes, the time needed to reach a stopping point, would be less than once in a million years of operation.
Such a failure rate is much smaller than the engine failure rate in jet aircraft. Furthermore, the Maglev vehicle would continue to operate, while the jet aircraft would not. In fact, it would take the simultaneous failure of at least 6 independent magnets to compromise levitation capability -a probability that is infinitesimally small compared to other modes of transport.

ELECTRICAL POWER FAILURE

The M-2000 vehicles are automatically and passively stably levitated as long as they move along the guide way. The electric power fed to the guide way magnetically propels the M-2000 vehicles and maintains their speed. If the guide way power were cut off, the vehicles would coast for several miles, gradually slowing down due to air drag. When they reach 30 mph, they settle down on auxiliary wheels and brake to a stop on the guide way. When power is restored to the guide way propulsion windings, the vehicles can magnetically accelerate back up to their cruising speed.

Because the vehicles are automatically levitated and stabilized for speeds greater than 30 mph, there is no chance of a crash if guide way power is cut off.

Cost to travel by Maglev compared to airplanes?

M-2000 Maglev operational costs for vehicles, energy, and labour total about 4 cents per passenger mile, not including the amortization cost for the guide way. Projecting guide way amortization cost is difficult since it depends on ridership and whether the guide way carries freight as well as passengers. For a M-2000 guide way cost of 10 million dollars per 2-way mile, that carries only passengers, amortization cost is about 10 cents per passenger mile, assuming a 30-year payback period and 10,000 passengers daily. If the guide way carries 1000 trailers daily and allocates 3 cents per ton mile (30 tons per trailer} of revenue to guide way amortization, the passenger share for guide way amortization is zero cents per passenger mile. Total cost for passengers is then only 4 cents per passenger mile, about 1/3 of that for air travel. If M-2000 guide ways carry both passengers and truck type freight, Maglev will be much cheaper than air travel.

Maglev vehicles are much cheaper than airliners -a few million dollars per vehicle, compared to a 100 million dollars or more for an airliner - and because their operating cost is very low, Maglev travel will be much more comfortable than air travel. There is no need to pack riders in like sardines to save money -passengers will travel in first class style, for lower cost than economy air. Moreover, the vibration and noise experienced on airliners are completely absent on Maglev vehicles.

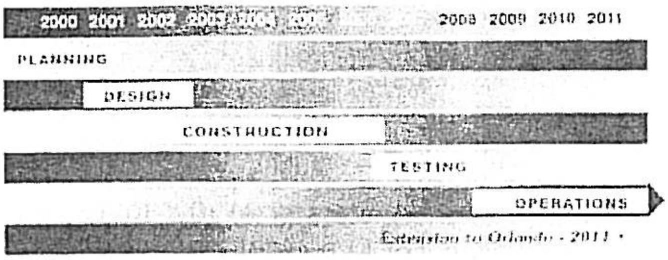
Health or environmental hazards from the magnetic fields of a Maglev vehicle

There are no health and environmental hazards from the magnetic fields around the M-2000 Maglev vehicle. The magnetic fringe fields from the quad rumple magnets on the M-2000 vehicles drop off much faster with distance than do the fringe fields from dipole magnets. This rapid decrease in fringe fields allows the magnetic fields in the passenger compartment to be at Earth ambient level, ~ 0.5 Gauss. All humans live constantly in Earth's magnetic field and are adapted to it.

Global Players

Japan, USA, Germany.

MAGLEV 2000 expects to have its 20-mile Minimum Operating Segment up and running by the beginning of 2009. This makes allowances for about two years of environmental work and engineering development, four years of construction, plus another two years for certification and testing of the initial segment. Extensions to Orlando or other parts of Central Florida could follow soon after.



(Figure from NASA report, executive summary Maglev Deployment Program of the Federal Railroad Administration in June, 2000)

Looking at the above programme schedule of MAGLEV one can see how fast are the competing players in the global scene.

Other Levitation applications: **Maglev space Propulsion**

A Maglev launch system would use magnetic fields to levitate and accelerate a vehicle along a track at speeds up to 600 mph. The vehicle would shift to rocket engines for launch to orbit. Maglev systems could dramatically reduce the cost of getting to space because they're powered by electricity, an inexpensive energy source that stays on the ground — unlike rocket fuel that adds weight and cost to a launch vehicle. "Each launch using a full-scale Maglev track would consume only about $75 worth of electricity."

Major Players in Space Propulsion

1. PRT, Inc of Chicago
2. Lawrence Livermore National Labs
3. Foster Miller, Inc. of Boston
4. Boeing, Rockwell.
5. NASA Centres

3. ETHICAL CONSIDERATIONS

High academic ethics are followed with due credit to everybody involved. This research initiative is beneficial to the South Africa and the world as a whole. The 'Superconducting Magnetic Levitation' is a eco-friendly concept which has high human ethics.

4. RESULTS AND DISCUSSION (DATA ANALYSIS)

Levitation

Well characterized nano nickel particles (50 nano meters size) (0.1 to 10%wt) are mixed with the high-Tc cuprate superconducting YBCO powders in a controlled way and then pelletized into thick pellets.

Nano nickel particle being magnetic should kill superconducting order locally and thus act as a 'pinning center'.Further the size of the chosen nickel particles are roughly 3 orders smaller than the micron size grain boundaries of the YBCO. We did not do any heat treatment after mixing so that the added nickel only gets into the grain boundaries. This means we are able to tailor the grainboundary pinning by nano nickel.

Nickel being magnetic should kill superconductivity locally. This would first reduce the Jc of the grain boundary junctions but as the concentration is increased further then at some point the added nickel acts as a strong pinning center. Strong pinning shall lead to a better levitation.

This is what exactly happened. We saw negligible levitation for 1% and 5%wt of addition of nickel into YBCO. However we observed excellent levitation for 10% wt nickel addition into YBCO. The levitation results are shown in Figs.2-5

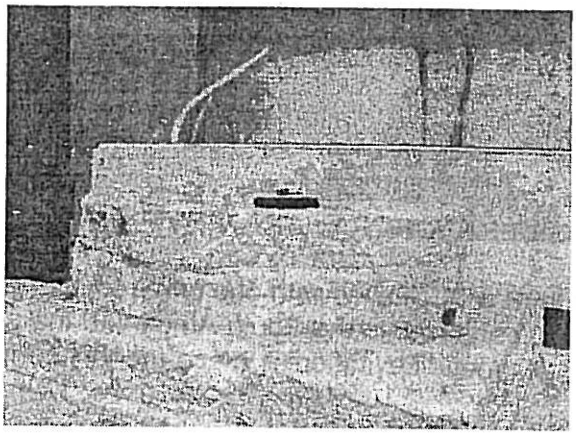


Fig.2 Levitation in pure YBCO superconducting pellet

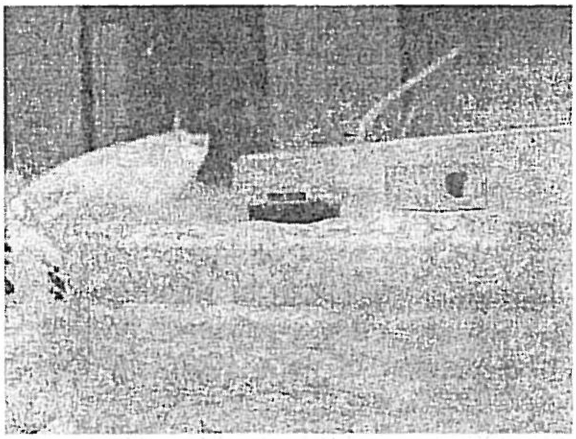


Fig.3 Almost negligible levitation in 1% wt nickel added YBCO superconducting pellet.

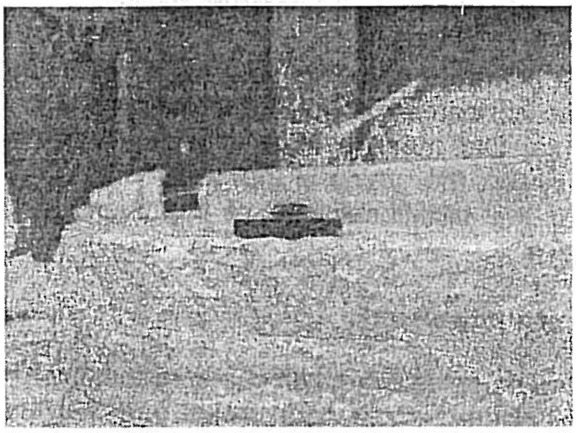


Fig.4 Excellent levitation in 10%wt nano nickel added YBCO superconducting pellet.

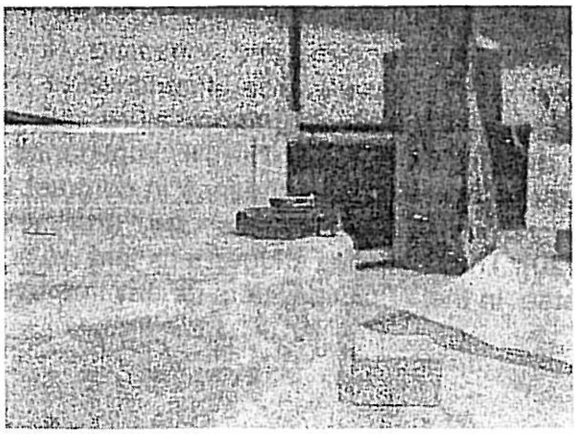


Fig.5 Same as Fig.6 but in different angle.

Pinning also has direct influence on Jc namely to increase this parameter of a given superconducting material. This means, a parallel measurement of Jc as function of Ni addition should show an increase of Jc from 0.1% to 10% wt Nickel addition in YBCO. Measurements of Jc are yet to be finished therefore we could not report here our Jc data.

EMPIRICAL FINDINGS

1. We found that dilute dispersion of Nano Nickel in YBCO superconducting powders does not show any significance levitation. However around 10%wt addition and dispersion of nano Nickel in YBCO is producing significant levitation.
2. The RF-impedance of pure nano Nickel powder has considerable temperature dependence where as the nano Nickel with NiO shell has no appreciable temperature dependence of the impedance.

- **Implications of our results & Literature review**

  Most of the literature on using YBCO and other superconductors for levitation purposes is concerned about the improvement of pinning inside the grain . For example, Our main result is to improve pinning in the grain boundaries that actually link the grains in the superconducting material. This is totally in contrast to the traditional way of improvement of pinning and adds new knowledge.

- **Summary of study results**

  Nano Nickel particles were well characterized by XRD, TEM and RF methods. These well characterized nano nickel particles are dispersed from dilute to moderately high (0.1% to 10%wt) in in YBCO powders.

RF IMPEDANCE

RF impedance measurements at 1 MHz as a function of temperature and are carried over pure Ni and Ni encapsulated in a NiO shell nano crystalline powders. Pure Ni particles are obtained by ball milling and annealing. Ni encapsulated NiO particles are obtained by the chemical route. The impedance of Ni encapsulated NiO core-shell system is almost independent of temperature and an order of magnitude less than the pure Ni nano powders [20]. The RF impedance of pure Ni nano powders show a clear linear temperature dependence in contrast to that of the Ni-NiO core-shell particulate powders. The results are analysed in terms of classical electrodynamics[20]. These studies suggests us that we should use the pure Ni nano powders to disperse in the YBCO powders for any improvement of pinning effects to be observed.

LEVITATION

The dispersed nickel particles being nano size, are expected to go into the grain boudaries of the micron size YBCO grains when just pelletized and not heat treated. These nano nickel particles shall kill the superconductivity locally and should decrease the grain boundary supercurrent density at dilute additions of nickel. However the nickel addition is increased to a moderately high %wt (in our case 10%wt). the nano nickel particle being magnetic should act as a good pinning center and the pinning effects should dominate. Exactly this is what happened. We see no appreciable levitation at dilute addition of nano nickel but as the nickel addition is increased, an appreciable levitation is being observed.

SIGNIFICANCE OF THE STUDY

1. We have initiated the ' Superconducting Magnetic Levitation' studies in South Africa.
2. We are able to utilise the advanced nano methods to artificially create defects and improve pinning and levitation in the YBCO superconducting material.
3. This initiative of Superconducting Magnetic Levitation is a big field and shall eventually get converted into a field where commercial benefits for the Superconducting Maglev train and transport sector.
4. This is a highly advanced research activity, merging Nano and Superconductivity technologies. This will lead to skills transfer to students and staff in these fascinating fields.

5. FUTURE WORK

Though we have shown positive levitation results in Part-I, technically it is important to measure Jc, the critical current density. This is the most important superconductivity parameter that dictates the efficiency of most of the applications like Levitation, usage of Superconductors in power appliances like electric motors, generators, magnetic energy storage systems etc. Therefore the objective of our Part-II extension of the project is to systematically measure Jc in this nano nickel dispersed YBCO superconducting materials and correlate it with. the Levitation results.

Further more varieties of nano particles of higher (stronger) magnetization as compared to that of nano Ni particles, shall be dispersed in YBCO to study the improvement. Levitation experiments shall be carried out and with parallel measurements of Jc.

Nomenclature

Nano	: 10^{-9}
HTS	: High temperature superconductors
Critical Temperature (T_c)	: The temperature below which a material becomes superconducting
Critical Current Density (J_c)	: The maximum current a superconducting material can carry without any resistance.
First Critical Field (H_{c1})	: The field at which first time flux enters into the superconducting sample.
Second Critical field (H_{c2})	: The field at which a superconducting material turns normal
Coherence Length (ξ)	: The length scale overwhich the superconducting order decays
London's Penetration depth (λ)	: The depth of penetration of the magnetic flux from the surface of a superconductor or the screening length.
Fluxon (φ_o)	: The smallest unit of quantized magnetic flux
Surface Resistance (R_s)	: The resistance for AC currents
YBCO	: $YBa_2Cu_3O_{7-x}$
H^*	: Bean's Critical field
NRMA	: Non-Resonant Microwave Absorption

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