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CRITICAL CURRENT MEASUREMENTS OF HIGH T_c SUPERCONDUCTORS IN A SCANNING LOW TEMPERATURE CRYOSTAT

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INTRODUCTION

Maintaining uniformity of properties over long distances is one of the fabrication problems encountered with the new high T_c superconductors. Uniform properties are crucial in long tapes or wires with high critical current since local nonuniformities can limit the current carrying capacity of the whole piece. Transport critical currents in high T_c superconductors are conventionally measured with the contact 4-point probe DC current-voltage technique [1]. This technique requires contact with the sample and spatially averages over the region between the two voltage contacts. Two techniques have been used to infer the critical current using the Bean critical state model. The first uses the net magnetization of a suitably shaped sample in an external magnetic field [1,2]. The second combines a DC magnetic field with AC induced currents to infer spatial flux profiles [3]. The AC magnetization technique offers an advantage in that it is noncontacting; however, it also averages the measurement over a large area and requires that the sample be shaped and positioned such that it exhibits zero demagnetizing factor.

This paper describes a measurement technique and a scanning cryostat assembly that are capable of determining local critical current in a tape or wire with high resolution and without any direct sample electrical contact. A small compensated coil was used to induce AC currents in slab-shaped samples. The coil was situated near the surface on one side of the slab. With this method, the AC probe can be used as a noncontacting dissipation probe, replacing the voltage probe in the 4-point contact method, when an externally driven transport current is used, or by itself as a local critical state generator and dissipation detector. The results are shown to be meaningful even when the internal magnetic field is not uniform due to shape demagnetizing effects.

MEASUREMENT TECHNIQUE

One of the samples measured was a slab, 0.69 mm thick by 6.53 mm wide by 14.9 mm long, of solid state reaction sintered $YBa_2Cu_3O_{7-x}$ that exhibited a zero resistance transition temperature near 90 K. The probe was a small solenoidal coil, with a radius of 1.6 mm and height of 2.4 mm, wound with 21 turns of #38 wire (Figure 1). The coil induced a circular AC current in the sample. The calculated peak magnetic field intensity parallel to and at the sample surface ranges from about 80 A/m, in the absence of a sample, to 190 A/m with a fully superconducting sample for an excitation current of 100 mA. The response of the induced current was recorded by two balanced pickup coils wound coaxially with the drive coil and a lockin amplifier at frequencies of 1 to 10 kHz. This coil arrangement is similar to that used for measurement of the London penetration depth in thin films [4] and recently described for conductance measurements [5] in general. For the results reported here, the coil position was fixed at approximately the center of the sample surface with 0.7 mm between the sample and the lowest winding.

The AC probe produces a small induced current in the material that is dependent on the sample material's magnetic state. This induced current undergoes dissipation and reduction of diamagnetism when the transport current reaches the critical value. These measurements are similar to those of the conventional AC susceptibility method except that here the internal DC field is produced by the transport current and the AC field penetrates from one side and adds to or subtracts from this DC field. Recently published results [6-9] have shown that the low field AC susceptibility behavior of $YBa_2Cu_3O_{7-x}$ can be described with the critical state model by incorporating the magnetic field dependence of the local

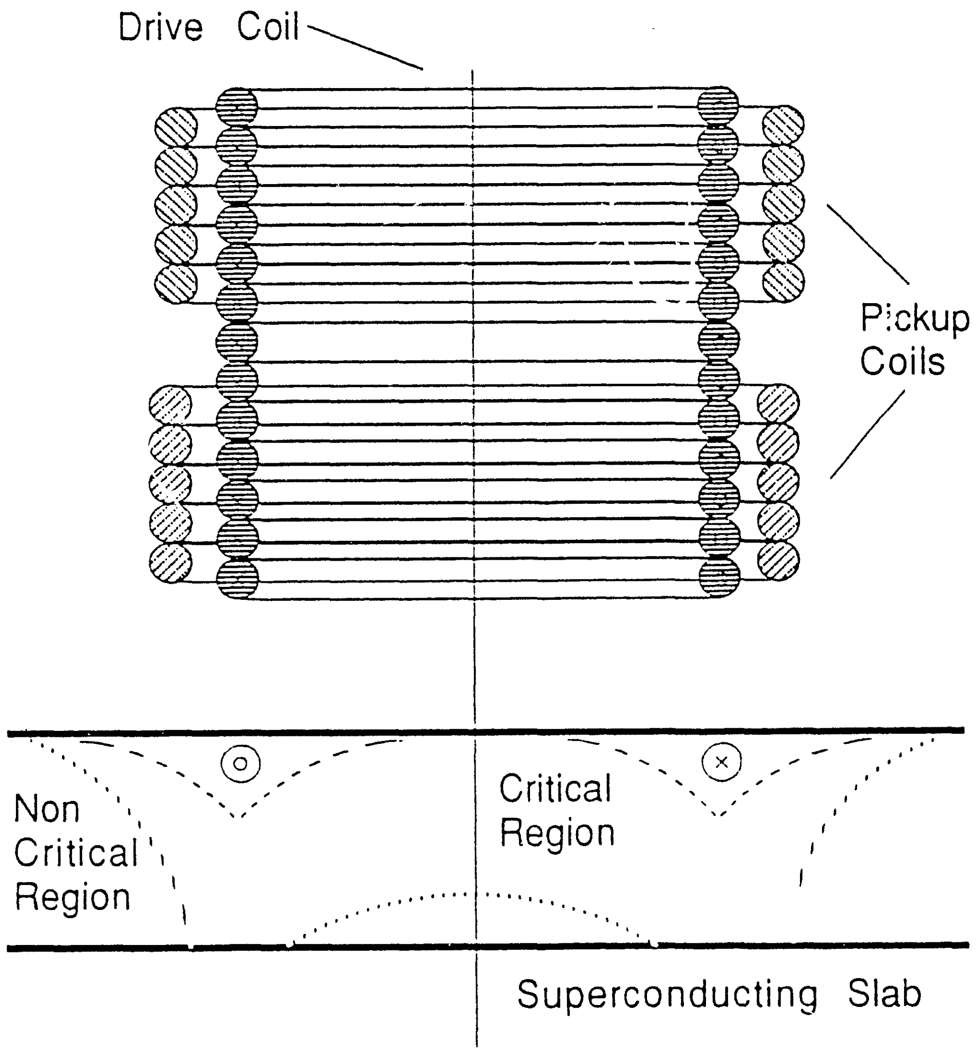

Fig. 1. AC coil and sample geometry. Also shown are the expected critical state region boundaries for two different external field values.

critical current density. Good agreement with experimental measurement was found for several harmonic components of the AC susceptibility, indicating that the low field behavior is dominated by the establishment of the critical state in the intergrain junctions. The same conclusions can be made about the results reported here. Since the sample was always in the earth's magnetic field, it can be assumed that the sample was always in the critical state. However, the slab and coil geometry produce a demagnetizing field inside the sample that is not uniform and complicates the interpretation.

The probe was used by increasing the AC excitation field until full penetration of the critical state region through the slab was achieved locally under the coil, see Figure 1 and reference [10]. Figure 2, which gives the AC signal amplitudes as a function of the excitation coil current, shows that as the applied field is increased, the dissipation signal, V(in), increases nonlinearly to a maximum and then levels off. The diamagnetic signal, V(out), increases roughly linearly with applied field and levels off also. The general behavior of this response is similar to that expected, assuming that the critical state is established in the sample. Figure 3 shows a comparison of the measured signals to the calculations using the critical state model of reference [8]. The calculations are for a slab geometry in a parallel field where the demagnetizing factor is zero and assume a $1/|H_{local}|$ dependence on the local critical current density. The overlap seen in Figure 3 was obtained by using a single normalization factor for the ratio V(in)/V(out) for all three data sets and the indicated full penetration fields { H* }.

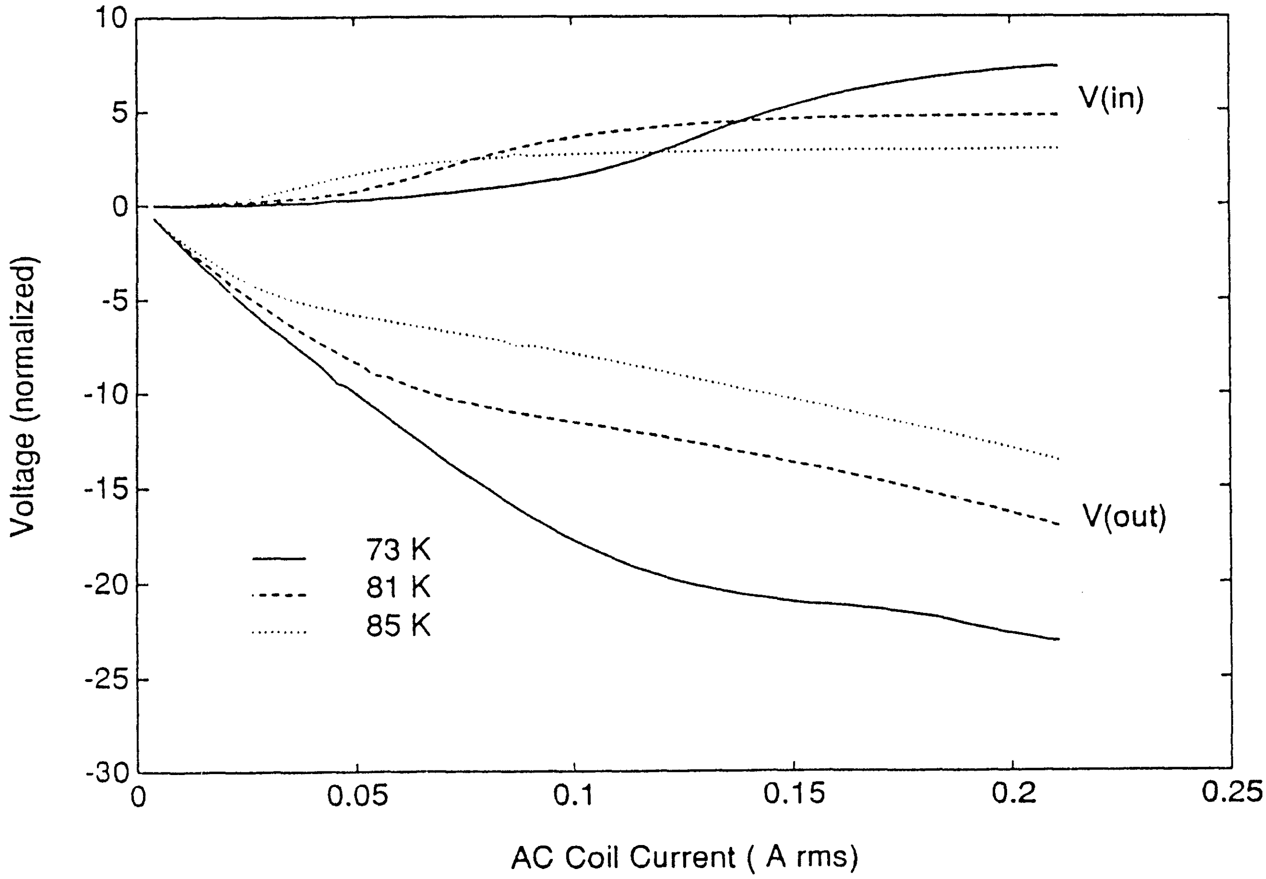

Fig. 2. AC probe response at 10 kHz on a slab sample as a function of the excitation coil current magnitude and different temperatures.

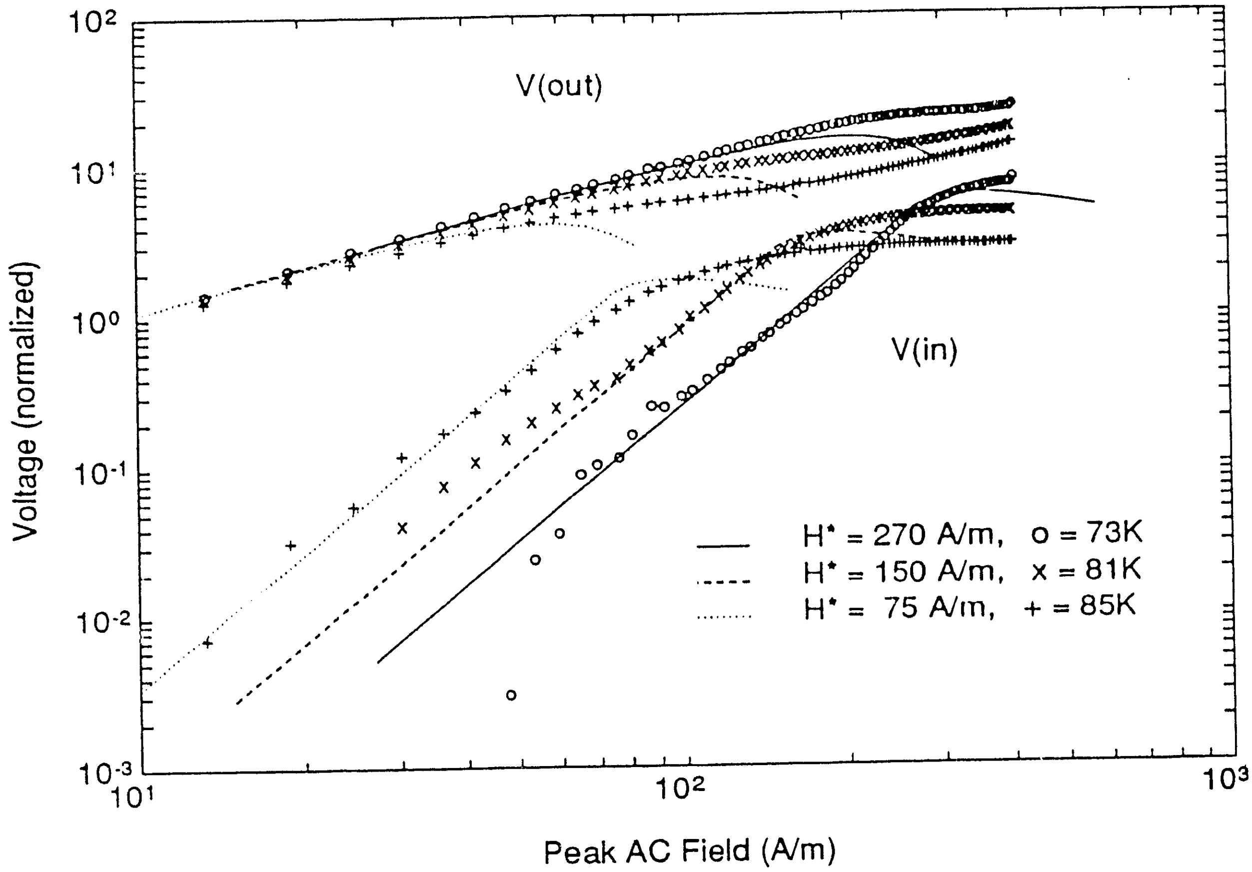

Fig. 3. Comparison of the data from Figure 2 and the first harmonic signal calculated for a slab sample in a parallel field using the critical state model of reference [8]. A single normalization factor for the ratio of the two signals was used as well as the full field penetration values indicated.

RESULTS

The data reproduce the theoretical dependence of the signals on applied field strength with V(out) being proportional to H and V(in) proportional to H^3. Furthermore, the values for H* obtained from the data are in the same proportion to those obtained from DC measurements, although with different magnitude (H* at 73 K is 81 A/m DC and 270 A/m AC). The agreement is rather good considering that there are significant differences between the geometry used here and the slab in a parallel field assumed for the calculation. The most important differences are that here the flux lines in the sample will be curved and the demagnetizing coefficient is not uniform. For this reason it is not surprising that the agreement is lost at higher applied fields as the critical region saturates in the sample. The more detailed calculation needed to explain this behavior is the subject of further work. Given the above uncertainty, the results show that the AC probe can be used to determine the local value of the full penetration field, and therefore the critical current through the critical state model, and may be used to obtain the same information as the DC critical current measurement without electrical contact.

SCANNING CRYOSTAT

Figure 4 shows the experimental geometry of the scanning cryostat. Samples were placed on a copper plate thermally connected to a 40 pin integrated circuit socket assembly, which allowed easy insertion and removal. The socket was thermally connected to a closed cycle helium refrigerator installed at the bottom of a high vacuum chamber. The vacuum was required for proper operation of the refrigerator and allowed a minimum temperature of about 15 K. The probe coil assembly was mounted above the sample on a vacuum-tight manipulator, which allowed motion in any direction with 5 μm resolution. The probe assembly and upper radiation shield were cooled to liquid nitrogen temperatures by contact to a reservoir within the manipulator assembly. This cryostat pumped down and cooled the sample to 70 K from 300 K in about 100 minutes with about ±0.5 degree long term stability. Typical measurements took 15 to 20 min at one temperature. This cryostat configuration allows for rapid sample exchange and extended measurement times if needed.

The ability of these measurements to provide spatial information is illustrated in Figure 5, which shows the maximum diamagnetic signal as a function of position for another sample of $YBa_2Cu_3O_{7-x}$ scanned in the cryostat at 72 K. The mean variation was about 6% over the entire area,

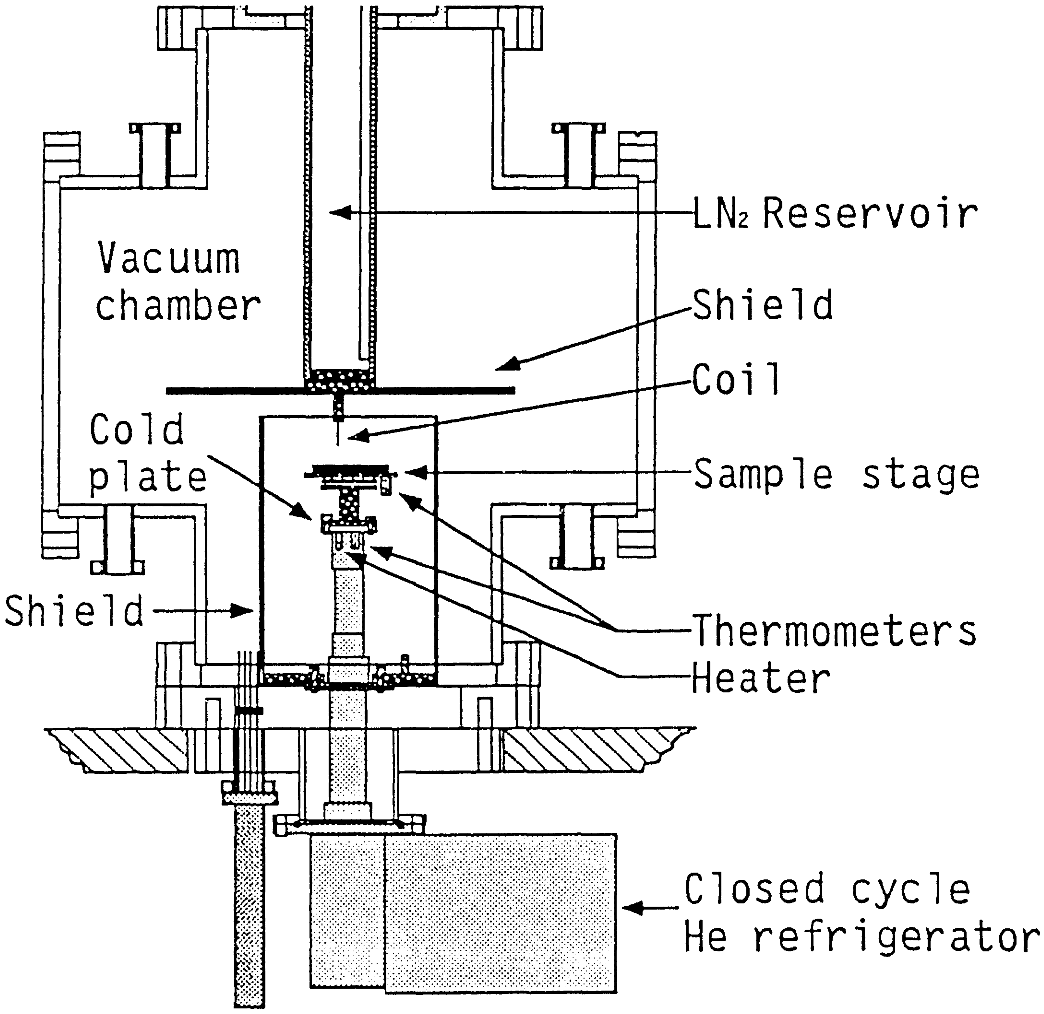

Fig. 4. Scanning low temperature cryostat including closed cycle refrigerator, vacuum chamber, and high vacuum manipulator. The sample is bonded to a copper plate mounted to a removable socket and thermally connected to the low temperature refrigerator.

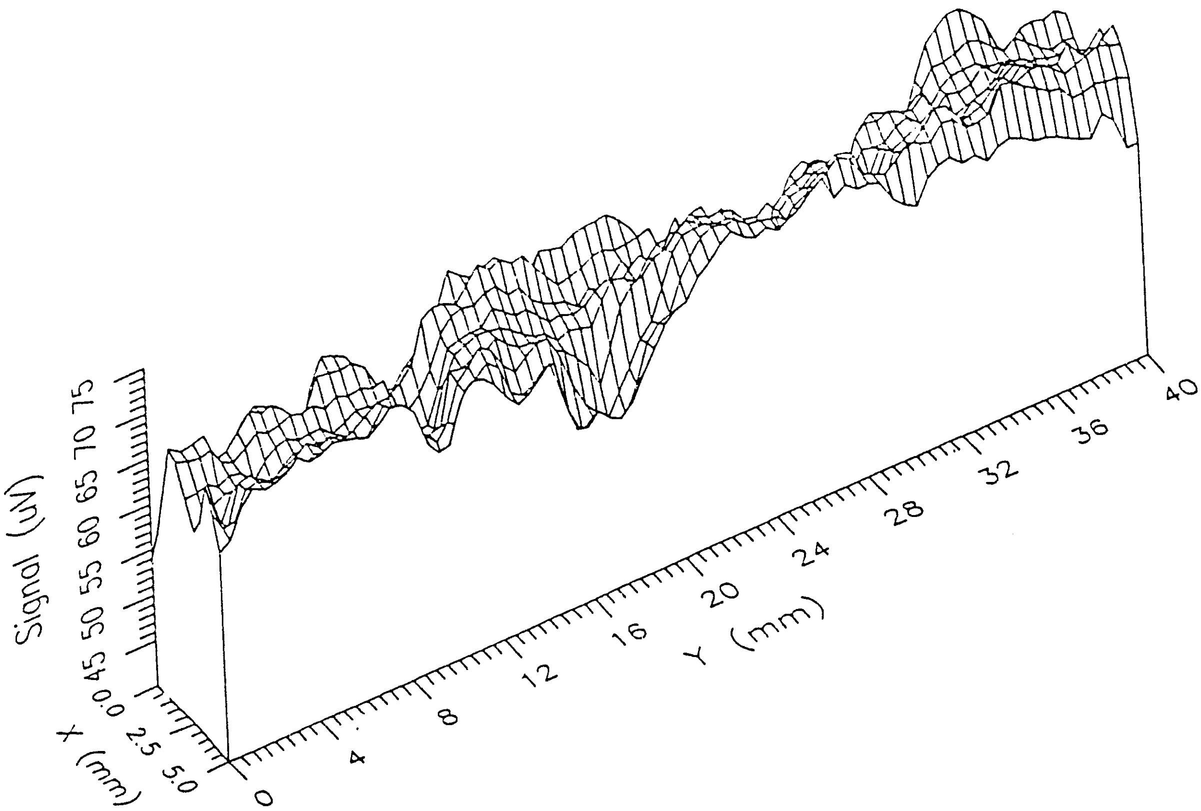

Fig. 5. Scanned response over a $YBa_2Cu_3O_{7-x}$ sample showing nonuniformity by changes in the total signal response at a temperature (72 K) well below the transition temperature.

indicating a nonuniformity of that amount. The coil used for these measurements was similar to that described earlier except that it had a radius of 0.3 mm, which provided a resolution of about 1 mm for locating nonuniformities and defects. Repeating the measurements of Figure 2 at each coil position can yield spatial determination of critical current values.

CONCLUSIONS

This paper described the application of an AC surface probe, similar to presently used eddy current probes, to the measurement of DC transport critical currents and critical state dissipation in high T_c superconductors. It has been shown that the probe can detect the onset of full field penetration in superconducting samples by measuring the response of AC induced screening currents. In this manner the AC probe can be used to replace the contact DC probe for determining critical currents in a noncontacting and local manner suitable for scanning over or along the sample.

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