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INTRODUCTION

The facility MA.RI.S.A., built up during 1986 at the I.N.F.N. laboratory in Genova, was used during last years to measure the critical current of several S/C cables (for HERA dipole magnets) up to 6.4T field at 4.2 K. Since the first measurements, a comparison was made with the results obtained at Brookhaven National Laboratory (BNL) on samples of the same cable. A difference of about 500-600 A was found (our measured critical currents were lower than the BNL ones). These results gave impulse to a research aiming to understand the influence of the several parameters involved in the Critical Current Measurement in order to compare results obtained in different sets-up. The experience made during two years of tests is reported.

THE CRITICAL CURRENT MEASUREMENT ON HERA CABLE

Standard criterium

Critical current measurement is made by applying a magnetic field B_{ext} normal to the wide face of a sample kept at temperature of boiling LHe. The electrical resistance is measured as function of the current; the critical current is defined as the current flowing through the conductor when an electrical resistivity of $10^{-14}\Omega$ m is measured. The critical field connected to the measured critical current is calculated by adding the maximum self field at the conductor ΔB_{sf}, (i.e. the field generated by the current flowing through the conductor), to the applied field B_{ext}.

The critical current is measured according the following steps:

I - I_c is measured using the aforementioned resistive criterium at applied field B_{ext} and at temperature T.

II - The field compensation is made by adding the maximum self field: $B = B_{ext} + I_c * \beta_s$ (where β_s is the slope of the maximum self field vs the current)

III -The measurements are referred to temperature T=4.6 K using the formulae found by Lubell[1].

IV -The results at three different fields are plotted and a best fit is performed, so that the critical currents at fields 5, 5.5, 6 Tesla are determinated.

Other informations are the quench current and the n-value. The quench current is the maximum current flowing through the cable without complete transition to the normal state. The n-value is the slope of the curve LogV vs. LogI(V is the measured voltage drop at the sample, I is the current through the sample).

INFN-Genoa Set-up [2]

The external magnetic field is given by a S/C solenoid (MARISA I) allowing measurements up to 6.4 T [3]. Several samples (from 2 to 6) are arranged inside the solenoid in turns of 0.41 m mean diameter. The sample length is about 1.2 m. To avoid destructive effects due to the magnetic forces the samples are connected in series not-inductively. The sample holder is composed by fiber-glass epoxy disks having suitable seats to host the samples and several holes allowing a good thermal exchange with the LHe bath. In the last version the disks are clamped together using stainless steel flanges and 16 bolts 20 mm diameter. This mechanical system allows to produce clamping forces up to 700 KN. Fig.1 shows an old version of the sample holder with mechanical clamping composed by stainless steel jaws and 9 bolts 16 mm diameter.

The temperature of the sample is assumed to be the temperature of the LHe bath. The temperature measurement is done by measuring both the vapour pression above the LHe bath and the electrical resistance of a Carbon Glass sensor placed into the bath.

The temperature measurement is affected by an error of 0.05 K.

The magnetic field is measured directely at the sample by a Hall effect probe.

The current is measured by using a Zero Flux Transformer, with accuracy of at least 10^{-4}.

The residual ripple of the controlled rectifier of the DC power supply is 20 A p-p at frequency greater than 300 Hz.

These considerations lead to evaluate the maximum error connected to the critical current measurement as about 200 A

BNL Set-up[4]

The magnetic field is generated by a short length S/C dipole magnet. Two samples are connected in series not-inductively and placed along the dipole axis. The maximum field available is 5.9 T.

COMPARISON OF THE TWO SETS-UP

There are some differences between INFN and BNL sets-up that can be the cause of different results. In order to compare the measurements obtained in the two systems, the following features must be taken into account:

-1- The samples geometry is strongly different (a loop for INFN set-up, straigth cable for BNL); it is not well understood the influence of the mechanical pressure applied to the samples to hold the magnetic forces in the two geometries. We observed in our set-up, applying the same pressure applied in BNL set-up (40 MPa), the occurrance of disturbances due to movements of the strands. As consequence more training quenches and generally premature quenching of the samples were observed well below the critical current values.

-2- INFN set-up allows measurement at higher field level; this opportunity was taken in order to perform the measurements. In fact due to the disturbances no results were obtained at fields lower than 5.8 T (where Ic $\simeq$9000 A). Measurements were made in the range of applied field 5.8 T - 6.4 T at currents of 9000-6000 A.

-3- The magnetic field profile at the sample is strongly different in the two sets-up. This is mainly due to the spacing between nearest neighbour samples (10 mm for INFN , 0.25 mm for BNL). The field at the samples is shown in fig.2 for the BNL set-up and fig.3 for INFN one in a configuration of a pair of samples; for both cases the external field is 5 T and the current flowing through the conductors 8000 A. It is remarkable that in INFN set-up the Peak Field region is wider than in BNL one; this can be better seen in fig. 4, where the field at the sample (both for INFN and BNL set up) normalized at the maximum field is shown as function of the position moving around the cable . That occurrance gave us the starting idea that the self field has more effect in our set-up compared to the BNL one. We developed a theory in order to correctely consider the self field effect[5]; the main feature of this theory is that the Critical Field does not correspond with the Peak Field but with an Effective Field, depending on several parameters (The maximum self field, the twist pitch of the strands, the sample geometry, the n-value, etc.) .

EXPERIMENTAL RESULTS

Description

Table I shows the results of measurements on 24 different samples, performed using the facility MA.RI.S.A. in the 1987-1988 period. For each sample they are shown : 1) Identification, 2) Date of measurement, 3) Critical Current using the "Peak Field Correction" for INFN and BNL sets-up at 6 Tesla and 4.6 K, 4) Critical Current using the "Effective Field Correction" at the same conditions than (3) for every INFN measurements and some BNL measuremements, the measurement parameters of which were known. 5) The differences between the measured critical currents in the two sets-up.

Before discussing the results, we want to add some historical notes to the data reported.

- Samples 1-2 were placed in a sample holder designed for a pair of samples.

- Samples 3-6 were arranged into an improved sample holder, allowing the measurement of 4 samples.

- Samples from 7 to 24 were hosted in a sample holder designed for 6 samples. Performing the measurements 1-12 a lot of training quenches was observed and the maximum voltage per unit length measured before the quench was 20 μV/m (some times 50 μV/m). In order to reduce the training and to perform measurements up to the real quench current, foreseen at higher voltage level, a new sample holder was designed allowing us to apply higher mechanical pressure.

- Samples 13-24 were measured using the new sample holder. Some problems occurred for the samples 13-18 when we were getting experience in adjustments of the sample holder.

- Because the mechanical disturbances did not disappear, limiting the measurement capacity of the apparatus (some times it was impossible to measure the critical current), samples 19-24 were impregnated with Woods-metal, so that movements of the strands were forbidden.

Discussion

From the results of the measurements a simple consideration can be done:

In spite of some experimental parameters (mechanical pressure, sample holder configuration and cable cooling) were changed our measured values of critical current are always lower than BNL ones for amount of 500-600 A (mean value). This difference is slightly reduced if the more correct in our opinion "Effective Field" is considered.

From the analisys of the self field in both the sets-up it results that for the INFN measurements the Effective Field Correction leads to increase the field of about 1000-1200 Gauss at 7000 A and for BNL measurements, at the same current, of 300-400 Gauss. These values are strongly different from the Peak Field ones (4000 Gauss for INFN, 2800 Gauss for BNL), however this consideration does not change very much the difference of measured critical currents.

From this analisys it came out the idea that the difference between INFN and BNL measurements could be due to some physical effects connected to the different sets-up. Our attention was devoted again to the magnetic field; the analisys of the field at the samples in the two sets-up (already reported in fig.2 and 3) first suggested the Effective Field concept and then the idea of a Degradation effect.

On this kind of conductor (Rutherford of trapezoidal cross section) the cabling affects the critical current. A degradation occurs specially in the region of thin edge. On measuring the critical current in both the sets up, the systems are adjusted in such a way that the Peak Field is at the thin edge. We made the hypothesys that in our set-up, due to the wider extension of the Peak Field region at the sample, the degradation effect becomes more evident (see fig.4)

In order to prove this assumption three experiments were planned:

-1- Some samples were measured again reversing the field so that the Peak Field is applied at the thick edge. The difference of measured critical current gives informations about the degradation. The results are shown in Table II; difference from 500 to about 900 A were measured. This large gap in critical current reversing the field was the first indication proving strong degradation effect.

-2- A sample measured in our set up was removed from the sample holder and measured again by BNL. The sample was LMI214; a critical current of about 600 A higher than our measurement was observed. This result gave the information that our set up did not cause degradation of the sample (due for istance to the mechanical stress)

-3- The last experiment we are performing at the present time is to reproduce in our set up the sample magnetic condition of BNL one. This require strong modifications of the sample holder now under progress.

CONCLUSIONS

Two years of experimental work on critical current measurements of large cables for High Energy Physics applications, showed that the critical current for this kind of cables has quite complex implications; it is not possible to transfer the concepts developed for small wires to these cable. We had experienced the importance of the field inhomogeneity at the sample. Both the "Effective Field" and the "Field Effect on the Degradation" are two important parameters to be taken into account.

The several measurements performed gave us the further indication that measurements on large cables using Round Simmetries (like in a solenoidal magnet) requires a carefull and critical operations in the sample holder preparation. For HERA cables the time for set up arrangement was about two weeks.

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TABLE I

MEASUREMENT RESULTS OF CRITICAL CURRENT AT B=6T, T=4.6 K

N.	Ident.	Date	(I_c INFN-Ge)		(I_c BNL)		Difference	
			Max	Eff	Max	Eff	Max	Eff
1	LMI32	Oct87	7700	7400	8350	*	-650	*
2	LMI38	Oct87	7780	7470	8330	*	-550	*
3	LMI173	Feb88	7330	6800	7920	*	-590	*
4	LMI118	Feb88	6900	6450	7560	6900	-660	-450
5	LMI181	Feb88	7330	6770	7960	7300	-630	-520
6	LMI177	Feb88	7630	7050	8050	*	-420	*
7	LMI189	Mar88	7300	6740	7950	7280	-650	-540
8	LMI190	Mar88	7600	7040	7800	7150	-200	-110
9	LMI194	Mar88	7800	7220	7950	*	-150	*
10	LMI214	Mar88	6900	6400	7430	*	-530	*
11	LMI216	Mar88	6730	6270	7460	6830	-690	-560
12	LMI199	Mar88	7830	7170	7850	7170	-20	0
13	LMI224	Apr88	7040	6400	8180	*	-1140	*
14	LMI225	Apr88	7080	6500	8110	*	-1020	*
15	LMI226	Apr88	6770	6150	7600	*	-830	*
16	LMI243	Jul88	7600	7050	8190	*	-590	*
17	LMI263	Jul88	7590	7010	8110	*	-520	*
18	LMI267	Jul88	7800	7150	8120	*	-320	*
19	LMI223	Dec88	6900	6350	8270	*	-1370	*
20	BBC33	Dec88	7200	6600	7840	7200	-640	-600
21	LMI222	Dec88	7000	6420	8230	*	-1230	*
22	BBC70	Dec88	8200	7540	8650	*	-450	*
23	LMI227	Dec88	7000	6430	7580	*	-580	*
24	LMI59	Dec88	7300	6700	8380	*	-680	*

TABLE II

DIFFERENCE OF CRITICAL CURRENT VALUE REVERSING THE FIELD

Id.	Date	Difference
LMI223	Jan-89	500
LMI222	Jan-89	500
BBC33	Jan-89	770
LMI227	Jan-89	700
LMI59	Jan-89	870

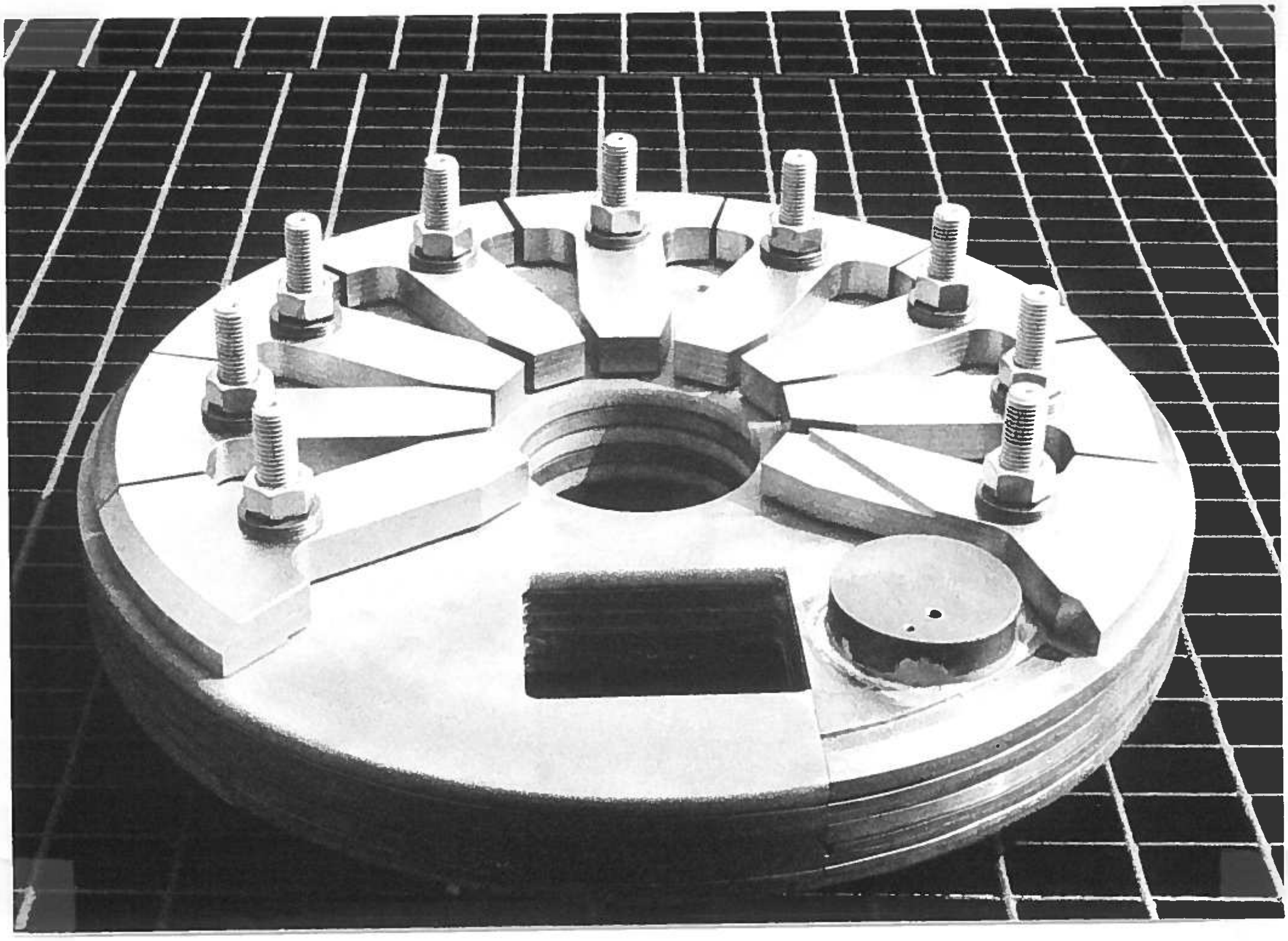

FIG.1 SAMPLE HOLDER OF INFN SET-UP

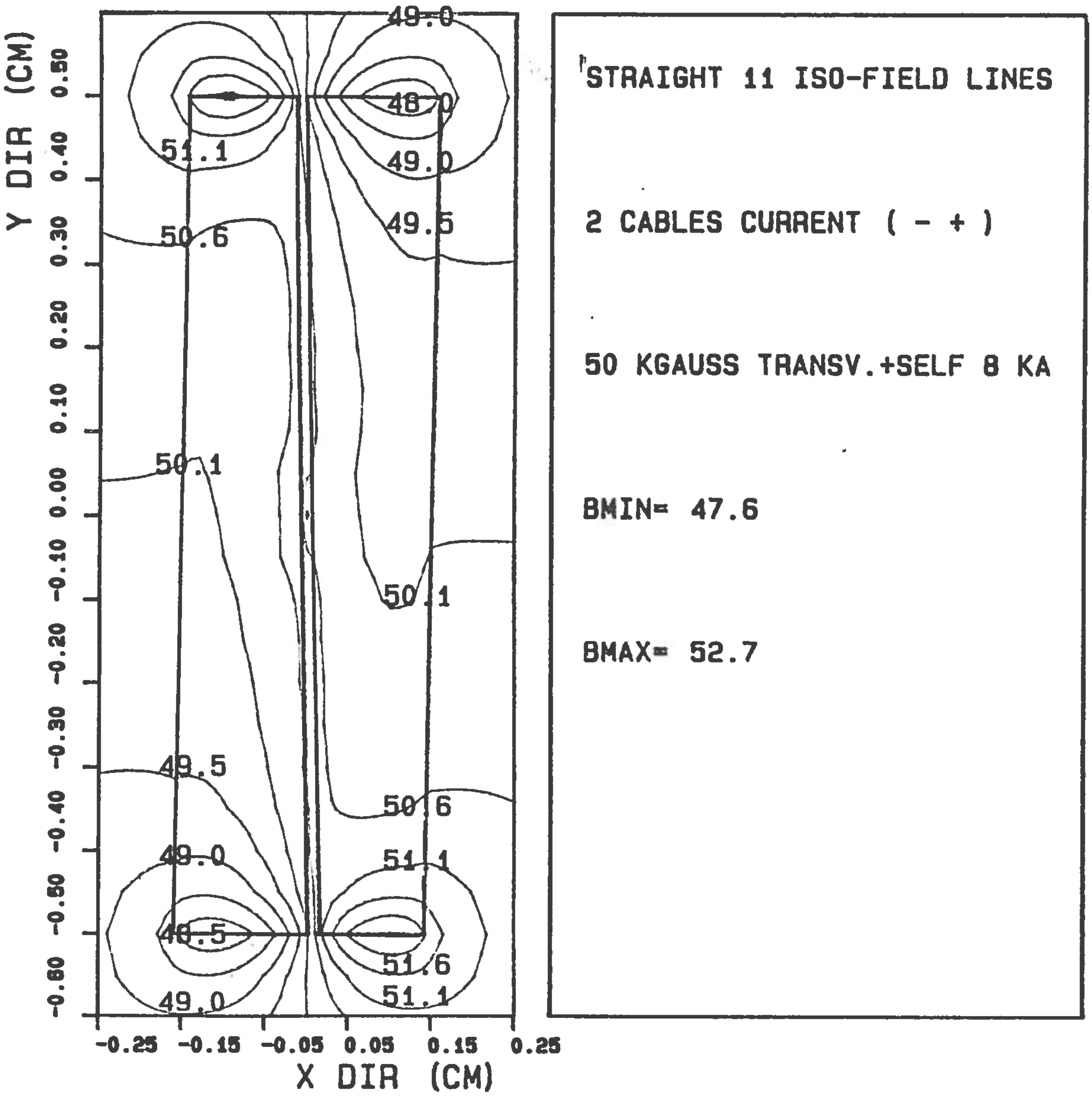

FIG.2 FIELD MAP AT THE SAMPLE (BNL)

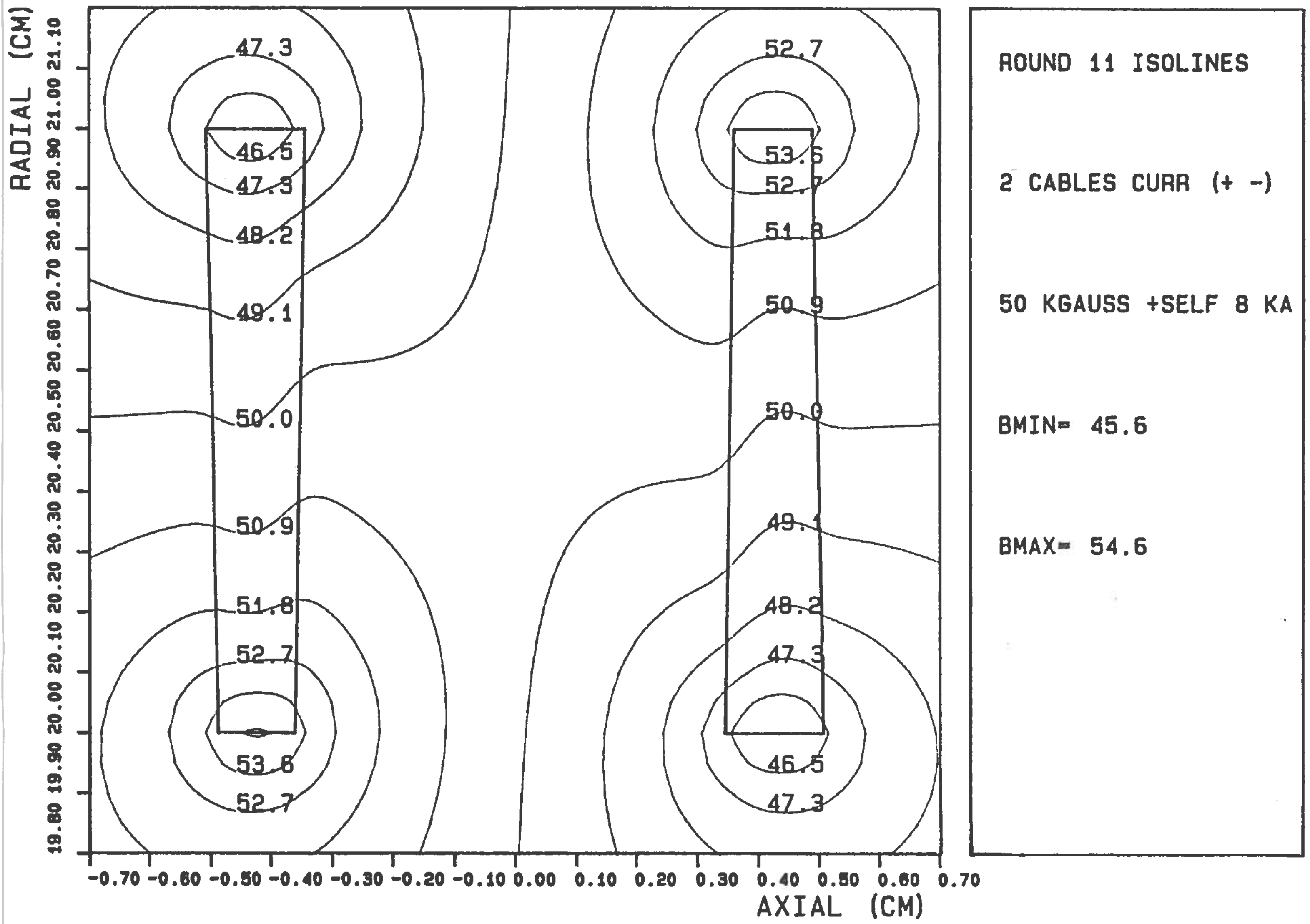

FIG.3 FIELD MAP AT THE SAMPLE (INFN)

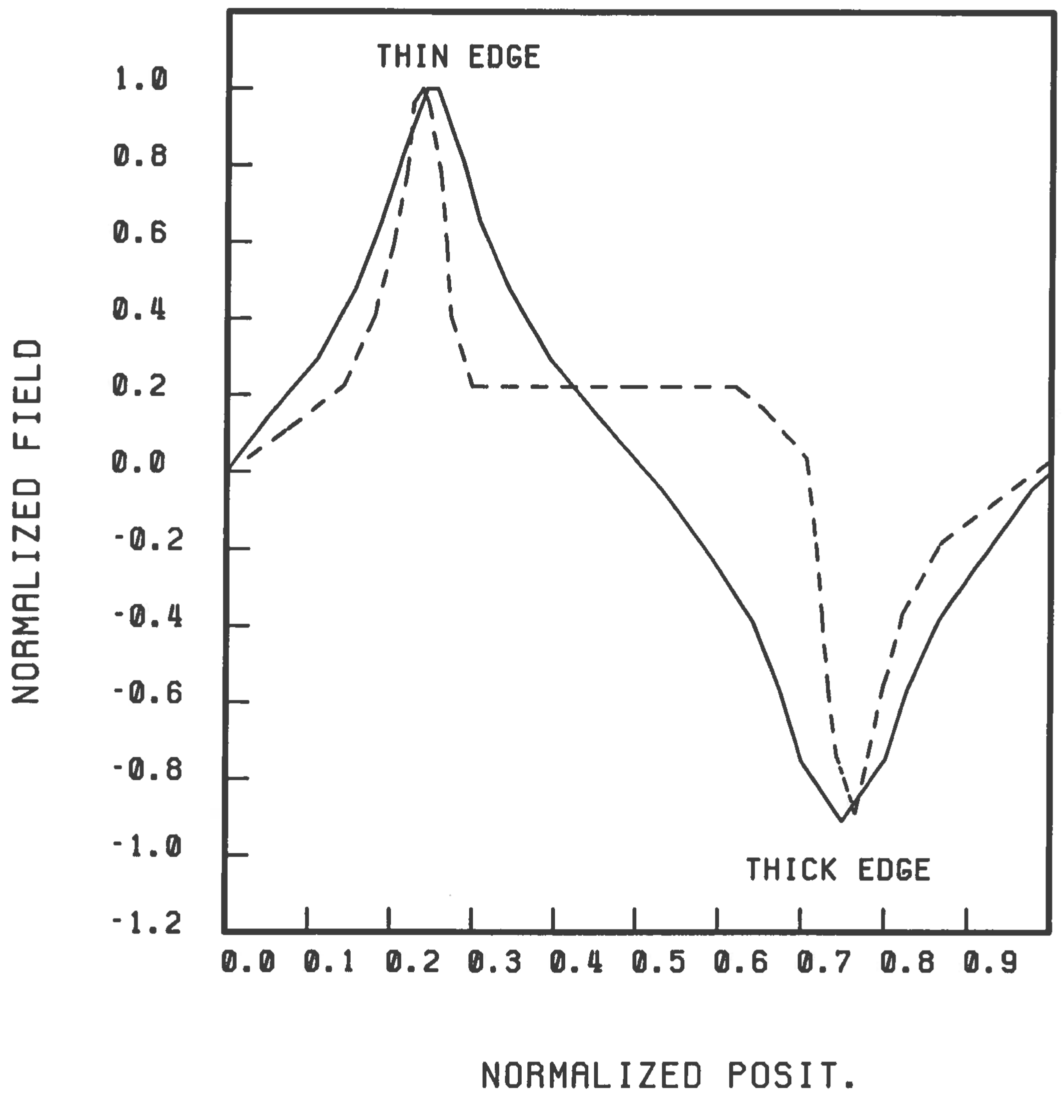

FIG.4 BNL (---) AND INFN (—) FIELD PROFILE AT THE SAMPLE