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SELF FIELD EFFECTS IN THE CRITICAL CURRENT MEASUREMENTS OF HERA CABLES

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INTRODUCTION

The measurement of critical current in superconducting cables of high current capacity can hardly be standardized. Indeed the cables themselves are produced in various shapes or even following different concepts to fit the special needs of a particular application.

Moreover the problems connected to cooling, mechanical forces and self-field are enhanced by the size of the cables and they need *ad hoc* solutions.

To avoid very high forces between the sample and the magnet, which supplies the bias field, the non-inductive configuration is usually preferred, and the magnetic field on the samples is accordingly modified. In the $5 \div 7$ Tesla field range the self field on a cable of large cross section and carrying large current density is not a neglecting fraction of the applied field and its exact value must be known to compare measurements made in different set-ups.

In this paper we compare the magnetic field effects in the critical current measuring rigs used at INFN-Genoa and at BNL for the Rutherford cables of the HERA dipoles.

THE MEASURING SYSTEMS

a) INFN-Genoa

The measurement set-up[1,2] that has been built in the I.N.F.N. laboratory in Genoa to perform the critical current measurements on the conductors for the HERA dipoles is based on the superconducting solenoid MA.R.I.S.A.. This solenoid can generate a maximum field of 6.4 Tesla at the center, and this field increases to 7.2 Tesla at the winding. The inner bore of the solenoid has a diameter of .5 m. To perform variable temperature measurements on S/C cables, a thin superinsulated cryostat has been inserted in the bore of the solenoid, reducing the useful diameter to .448 m.

Due to the field geometry the samples are arranged in turns of .41 m mean diameter. The sample lenght is 1.2 m, the distance between voltage taps is .8 m and the current junctions to the samples are .1 m long. Besides the strong radial force on the sample, we had to avoid a total force of 10^4 N between the sample and the magnet. By using pairs of samples, with the current flowing in opposite direction, we avoid this problem and at the same time reduce the effect of self field on the samples. This geometry is repeated by connecting in series the sample pairs, obtaining a modular sample-holder which allows to measure up to 12 samples simultaneously [Fig.1.a].

The HERA cables have a trapezoidal shape, with a height of 10. mm and the bases of 1.67 mm and 1.28 mm. The strands at the thinner side are strongly deformed and a deterioration of the critical current is expected to happen at this place. To expose this region to the maximum field, we arrange adjacent turns with the thinner side alternatively on the inside and on the outside of the turn itself.

The spread in the critical current of the produced cables is planned to be about 2 %, but we must be able to measure bad and very good cables too. A series connection of the samples can forbid this measurement. To overcame this effect, we shunt every cable with a S/C switch which is able to carry about 1000. A at 6 Tesla.

b) B.N.L.

The measuring system of B.N.L. is based on a superconducting dipole, with a maximum field of 5.9 Tesla and good homogeneity. The useful lenght is less than 1. m and the samples are arranged in straight sections. The distance between the voltage taps is more than .5 m and the current juctions are 12 cm long[3]. The requirement of avoiding strong forces between sample and magnet and of using a noninductive design are fulfilled in this case by using three samples togheter

, connected at one side and with three current leads at the other side [Fig.1.b]. The current flows in one sample and comes back through another or through the parallel connection of the other two samples. In such a way three samples can be measured in one run, even if their critical currents are quite different. The samples are separated along their lenght by a thin (.12 mm) layer of insulation and the thinner base is alternated from sample to sample.

SELF FIELD EFFECTS

On measuring the critical current of S/C conductors a great care must be taken in the evaluation of the real field at which the critical current is measured.

The field produced by the conductor must be added to the external magnetic field, almost uniform on the conductor width.

If a multiple sample-holder is used the influence of the neighbouring samples must be considered too.

This problem specially arises for the high current conductors. The simple analysis of a round conductor of radius r_0 with an uniform current density J in a magnetic field B shows clearly the importance of this effect:

The magnetic field on the cable radius is:

$$B_{circ} = \mu_0 J r_0 / 2 \tag{1}$$

At a temperature of 4.2 K and magnetic field of 5.5 Tesla the critical current density for the Nb-Ti is 2.3 10^9 A/m^2, so that a cable carrying 10 KA must have a S/C section of 4.35 10^{-6} m^2 . Assuming a value of 1.8 for the matrix/s.c. ratio the whole section is 1.21 10^{-5} m^2 corresponding to a radius of about 2 mm and the overall current density is 8.21 10^8 A/m^2; using this values in (1) we obtain B_{circ} = 1.0 Tesla

This field must be added to the external one ,so that inside the cable the transverse field ranges from 4.5 to 6.5 Tesla. Due to the twisting, all the filaments of the cable experience both the minimum and the maximum field.

The measured value of the critical current for this cable cannot be referred to 5.5 Tesla but to an higher field that, in principle, should be the maximum one (6.5 Tesla).

If the self field effect is not considered, a systematic error on the measurement is made. The error on the field, which is in this case 15%, gives a corresponding error on the critical current density, which depends on the J_c vs B curve. Because at 5.5 T and 4.2 K the field dependence of the critical current density is:

$$\Delta J_c(B) = 5.06 \cdot 10^8 A/m^2/Tesla \tag{2}$$

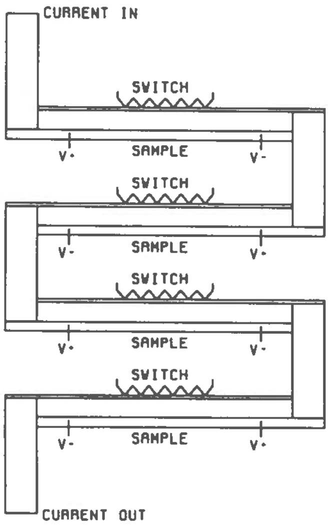


Fig.1.a -I.N.F.N. set-up

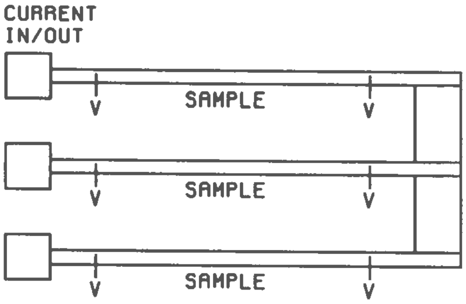


Fig.1.b - B.N.L. set-up

The net error is 22%

The cable for the HERA dipoles has a trapezoidal shape with dimensions of 1.67/1.28/10.0 mm; even using the same overall current density of the previously calculated round cable, due to this 'less compact' (than round one) geometry, the expected maximum self field is lower.

To make a comparison with a low current cable, the self field effect on a single strand of the HERA cable can be calculated.

Applying the relation (1) we find a maximum self field of 0.18 Tesla. Considering the same $J_c=J_c(B)$ function of (2) the net error is 4%.

MAGNETIC FIELD CALCULATION

To evaluate the self field effects on the critical current measurement, several magnetic field calculations were performed for different configurations of HERA samples, using MAFCO code. In all cases the current flowing in the sample is 8.000 A. To take into account the different compaction of the cable at the narrow and at the large side we assumed a graded current density varying from 625 A/mm^2 on the narrow side to 479 A/mm^2 on the larger one.

The external field was applied normal to the wide face with an intensity of 5. Tesla.

The reference data for the cables are shown in Table I. These characteristics were derived from data by B.N.L.[3] and D.E.S.Y.[4].

TABLE I: Critical current values [A]

B_{app} [Tesla]	T=4.3 K	T=4.6 K
5.0	10470	9470
5.5	9474	8500
6.0	8480	7480

single straigth sample

In Fig.2.a and 2.b the field configurations for a single straight sample are shown (fixed field and opposite current in the two cases).

The field varies from a minimum of 44.7÷45.0 KGauss to a maximum of 55.0÷55.3 KGauss with a whole variation of 10.3 KGauss (for the round case, before considered, the whole variation was 20. KGauss).

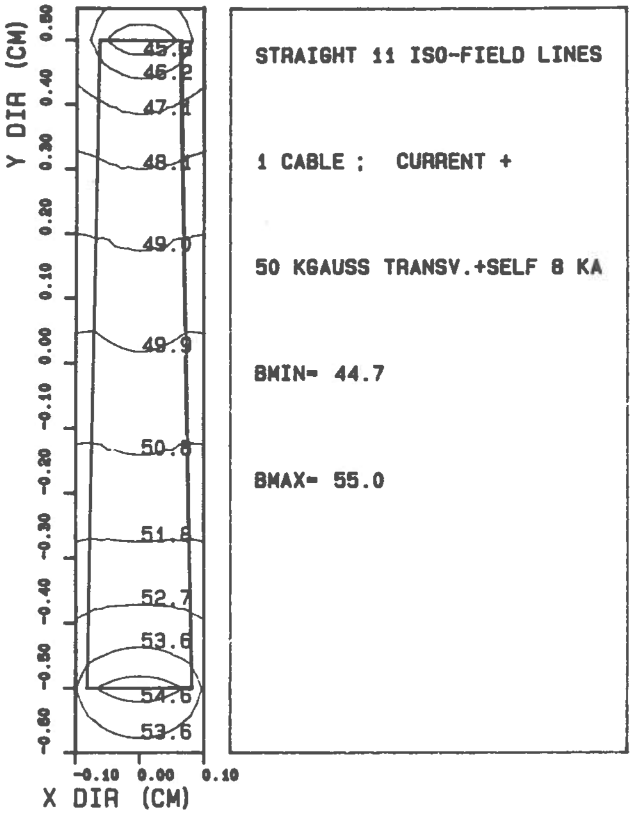


Fig.2.a - Single straight (Cur +)

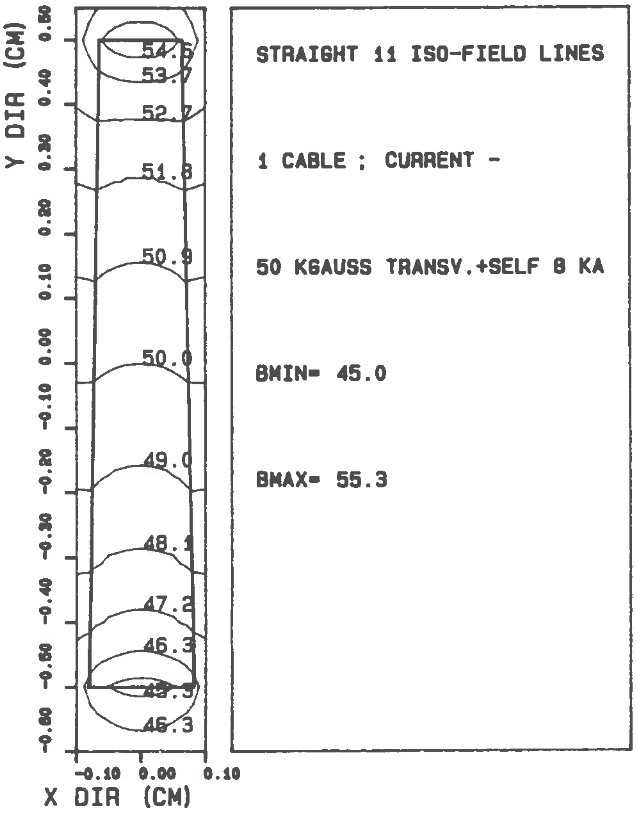


Fig.2.b - Single straight (Cur -)

If the load line for the current in the sample versus the total field (applied + self) is reported on a plot togheter with the critical current curves of Table I, as shown in Fig.3. ,it is possible to verify that a critical current of 8380 A is measured at a total field of 55.7 KGauss and a temperature of 4.6 K. If only the applied field is considered the same critical current is referred to a field of 50 KGauss, where instead the critical current is 9470 A ,with an error of 13% on the measured value.

The same error can be seen at 4.3 K where a critical current of 9270 A is measured because the total field is 56.3 KGauss. Should the self field not considered, the measured critical current would be referred again to a field of 50 KGauss at which the real critical current is 10470 A.

The error is really a constant ,as shown by the following arguments:

In the region from 50 to 70 KGauss the critical current is well described by a linear dependance on the magnetic field:

$$I_c(B_{tot}) = a_1 B_{tot} + a_2(T) \tag{3}$$

where the total field B_{tot} is given from two factor

$$B_{tot} = B_{appl} + B_{self-field} \tag{4}$$

In (3) a_1 is the angular coefficient ,independent on the temperature.

The maximum self-field on the conductor with a transport current It is:

$$B_{sfm} = I_t/a_3 \tag{5}$$

From (3) and (4)

$$I_t = a_3 \cdot (B_{tot} - B_{appl}) \tag{6}$$

Substituting (6) in (3) the measured critical current is found:

$$I_{cm} = (a_1 B_{appl} + a_2)/(1 - a_1 a_3) \tag{7}$$

The error done neglecting the self field is:

$$\varepsilon = (I_c(B_{appl}) - I_{cm})/I_c(B_{appl}) \tag{8}$$

Substituting (3) and (7) in (8) it is found:

$$\varepsilon = -a_3/a_1 \tag{8}$$

The error does not depend on a_2, i.e. on the absolute value of I_c. Using the values shown in Table I, a_1 is - 5.02 10^{-3} KGauss/A. Being the calculated maximum self field of 5.3 Kgauss at a current of 8000 A, a_3=6.62 10^{-4} KGauss/A it results ε =.13 as found graphically before (see Fig.3).

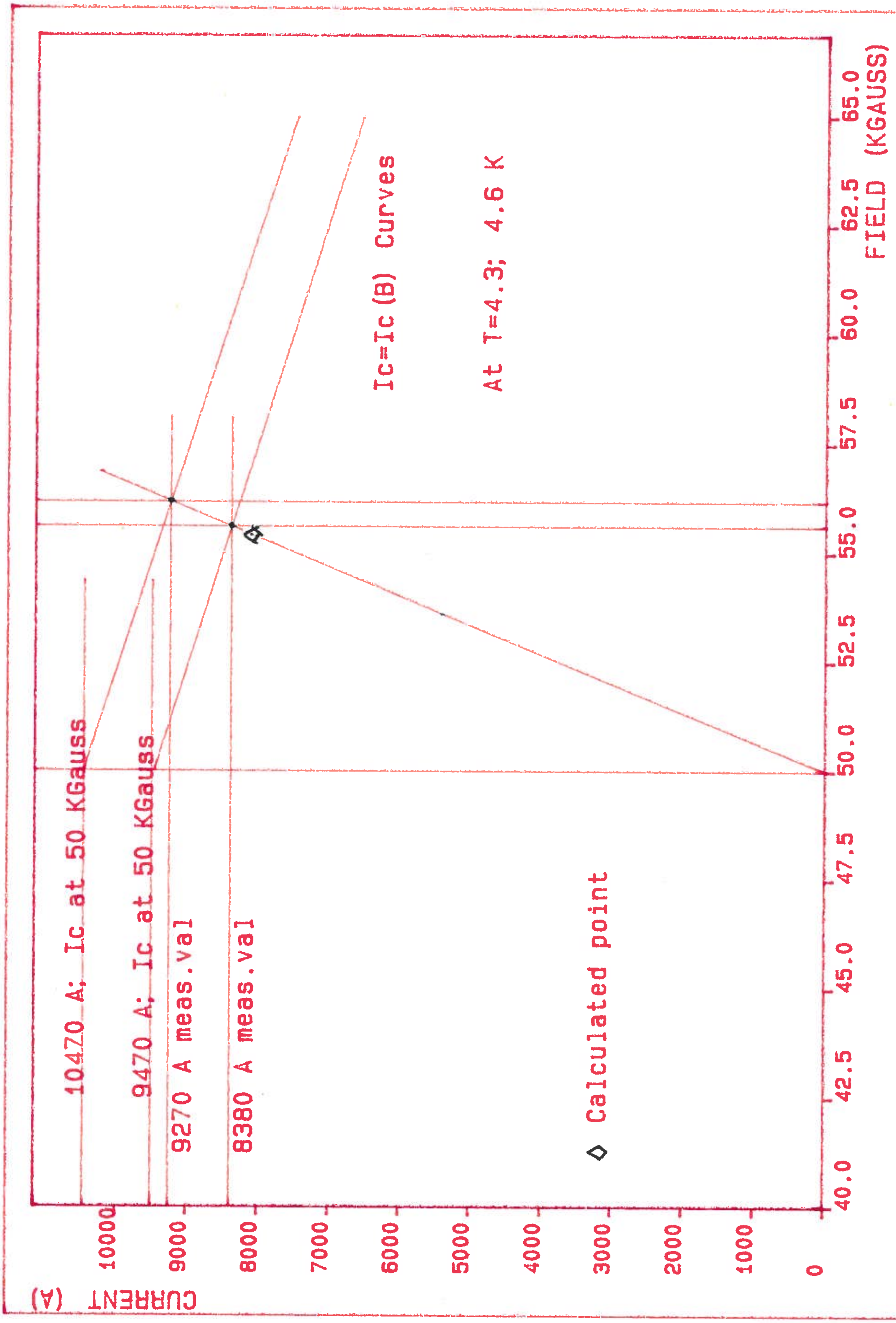


Fig.3 - Self field load line

Fig.2. shows the non-symmetry of self-fields respect to current reversal in the sample. The worse situation is that in which the maximum field is on the narrow side; this case has just been considered before.

Reversing the current the maximum field is 55 KGauss; the error whitout self-field compensation is 12%.

In the two cases the measured critical currents are different by about 70 A.

single sample in round configuration

In Fig. 4.a and 4.b, the field distribution for a single sample arranged in the round configuration is shown. In 4.a the narrow side is placed on the internal radius, in 4.b it is placed on the external one.

The difference from the previous straight case is due to the 'coil effect', so that at the internal radius the field is greater by about 100 Gauss.

The maximum field is found in the case in which the narrow side of the sample stays on the inside of the turn (4a); this maximum field is 55.4 KGauss

In the two cases the errors are 13.4% (a) and 12.2%. The real external field generated by MA.RI.S.A. and applied to the sample is indeed sligtly not-uniform. It is increasing from 4.9839 Tesla at the internal radius (r=20.0 cm) up to 5.0174 Tesla at the outer radius (r=21.0 cm), with a whole variation of 335 Gauss corresponding to a relative variation of .67 %.

The real field configurations are shown in Fig.5.a and 5.b; the respective errors are 13.1% and 12.7%. In the next calculations of the 'round configurations' the effect of the real field will be neglected .

2 straight samples

This configuration, toghether with the following one, represents the geometry which is used at B.N.L. as described before. The two straight samples are non-inductively arranged, as shown in Fig.6, and their self field is strongly reduced from that of a single sample.

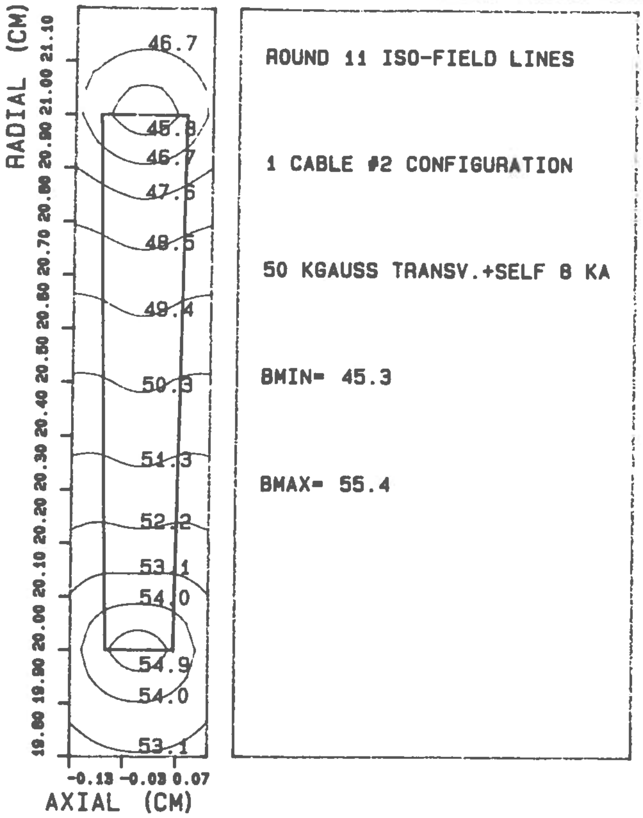
The maximum field is 52.7 KGauss on the narrow side. The measured critical current is 8890 A at 4.6 K; if referred to 50 KGauss the error is 6.7%.

3 straight samples

For 3 samples in the straight configuration, there are two possibilities:

1) Full current (input) in the central sample ; half current in each lateral sample (output) . [Fig 7]

2) Full current in one of the side sample, half current in the central one and in the second lateral sample. [Fig.8]



ROUND 11 ISO-FIELD LINES

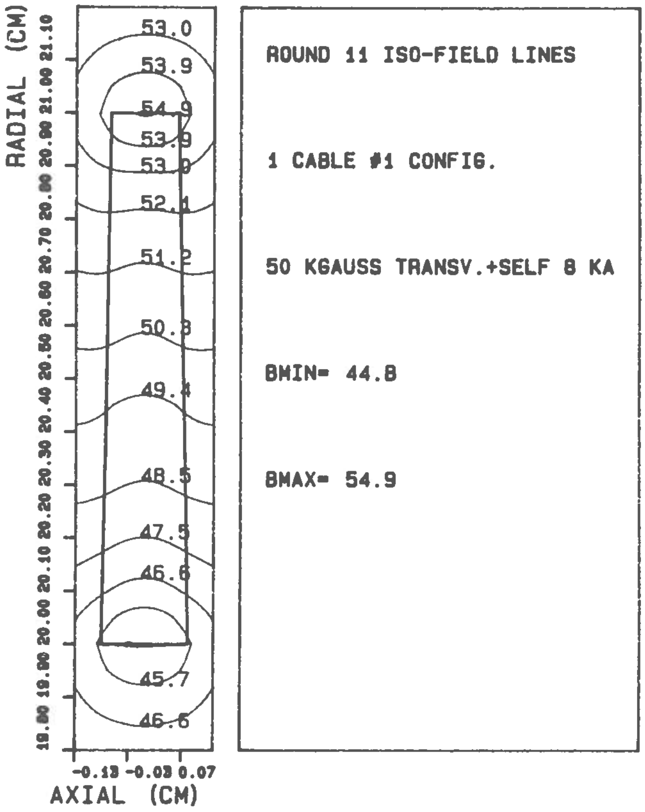
1 CABLE #2 CONFIGURATION

50 KGAUSS TRANSV.+SELF 8 KA

BMIN= 45.3

BMAX= 55.4

Fig.4.a - Single round # 2



ROUND 11 ISO-FIELD LINES

1 CABLE #1 CONFIG.

50 KGAUSS TRANSV.+SELF 8 KA

BMIN= 44.8

BMAX= 54.9

Fig.4.b - Single round # 1

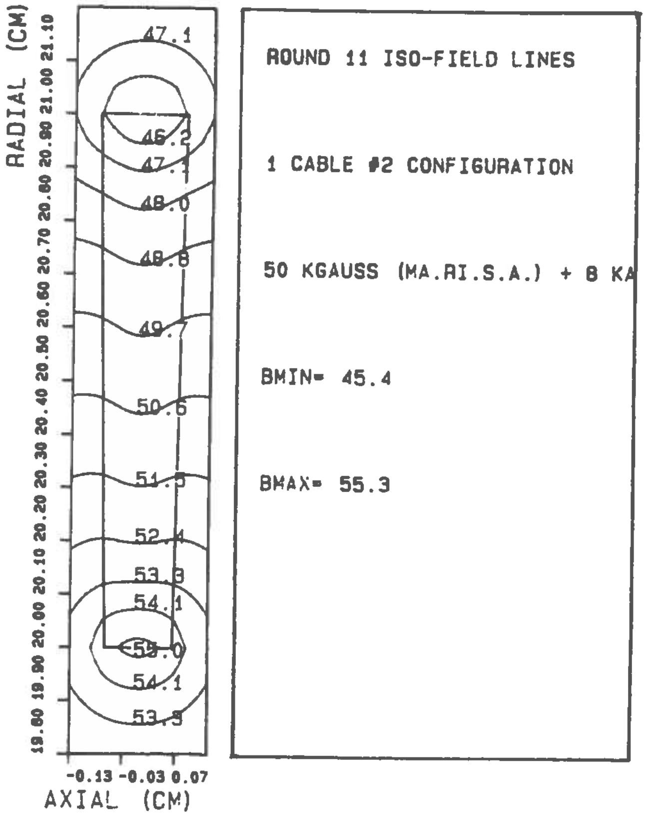


Fig.5.a - Single #2 in MA.RI.S.A.

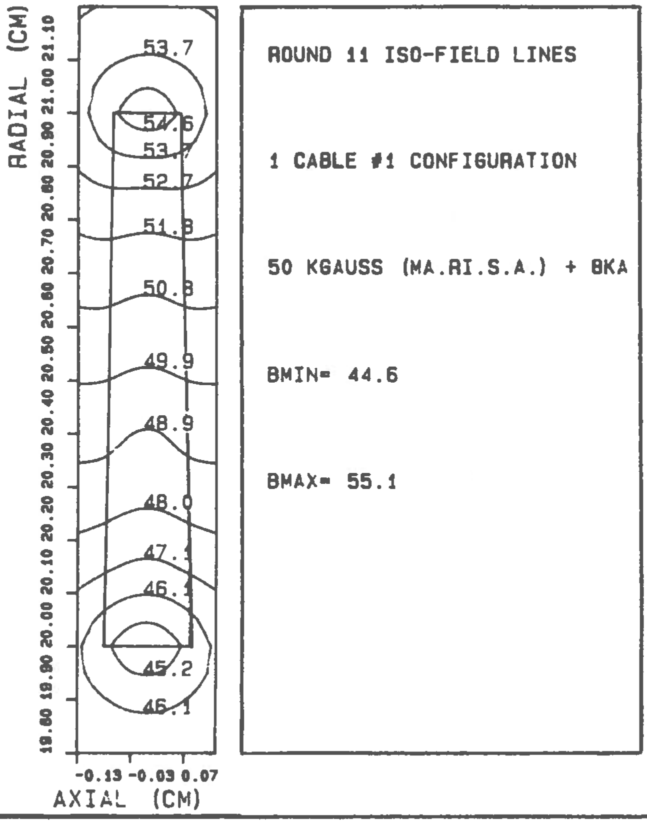
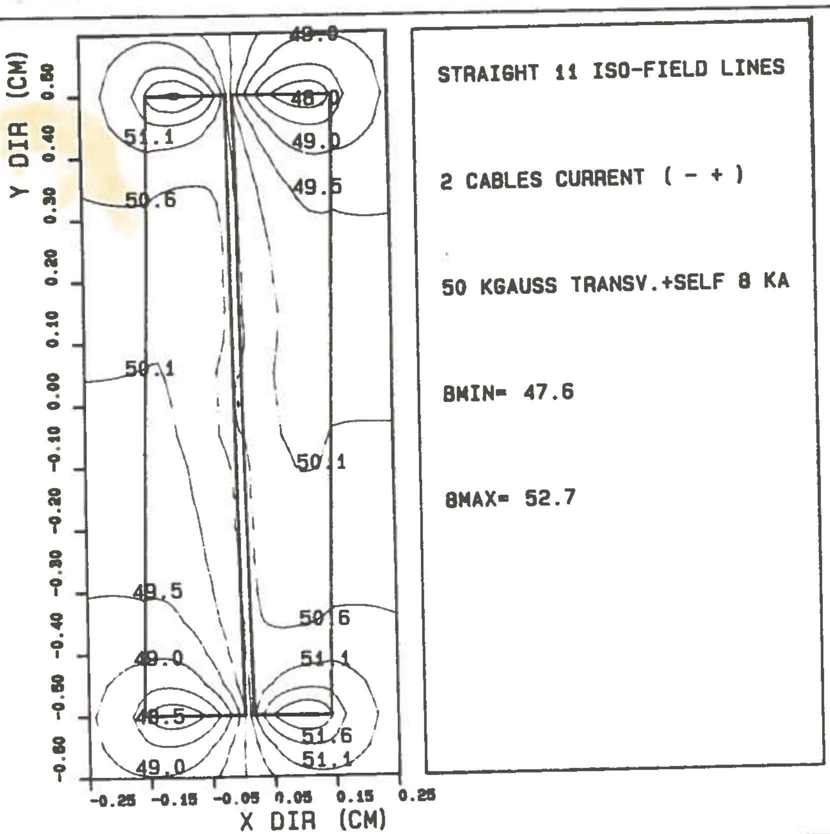


Fig.5.b - Single #1 in MA.RI.S.A.



STRAIGHT 11 ISO-FIELD LINES

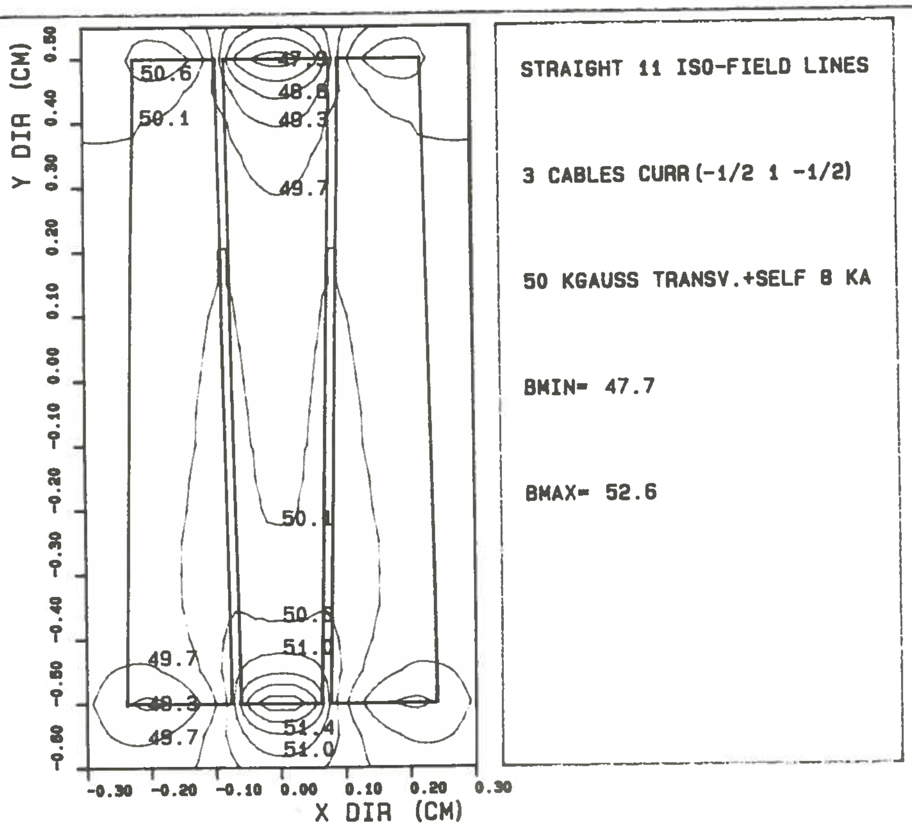
2 CABLES CURRENT (- +)

50 KGAUSS TRANSV.+SELF 8 KA

BMIN= 47.6

BMAX= 52.7

Fig.6 - Pair of straight samples (B.N.L)



STRAIGHT 11 ISO-FIELD LINES

3 CABLES CURR(-1/2 1 -1/2)

50 KGAUSS TRANSV.+SELF 8 KA

BMIN= 47.7

BMAX= 52.6

Fig.7 - 3 Samples #1 (B.N.L.)

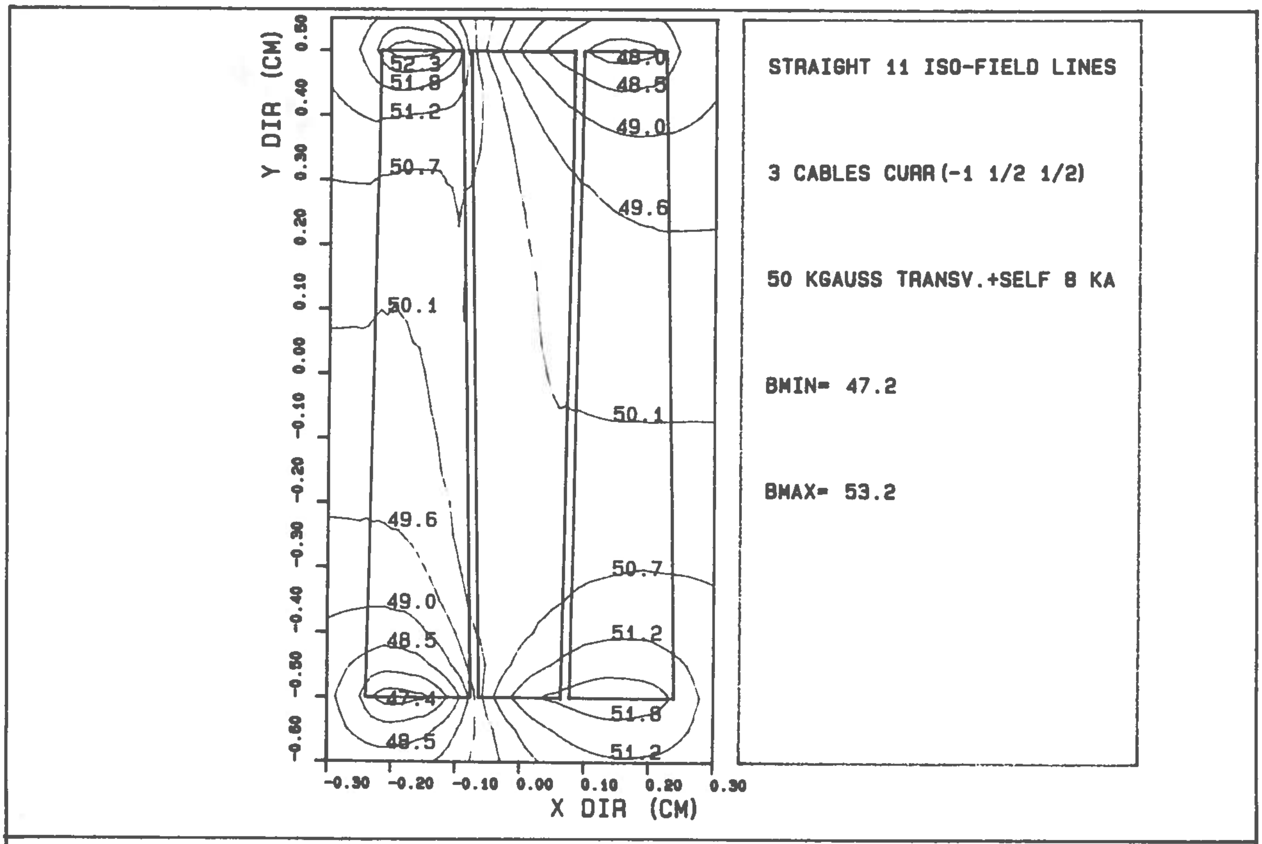


Fig.8 - 3 Samples #2 (B.N.L.)

The errors are 6.5% and 8% in case 1 and 2 respectively.

In some cases at B.N.L. only the two lateral samples are used. The field map for this case is shown in Fig 9. The maximum self field is 53.7 KGauss and the error is 9.0 %.

1 pair of samples: round configuration

The field map for 2 samples in the round configuration is shown in Fig.10. Apart from the previously described straigth samples, the measured critical currents on the two cables are not equal; indeed the maximum fields (on the narrow side) are on the internal radius for one sample and on the external radius for the other one; they are different because of the 'coil effect'.

The error is 11.5% for the cable having the maximum field on the internal radius (#1). For the other cable (#2) the error is 11.2%.

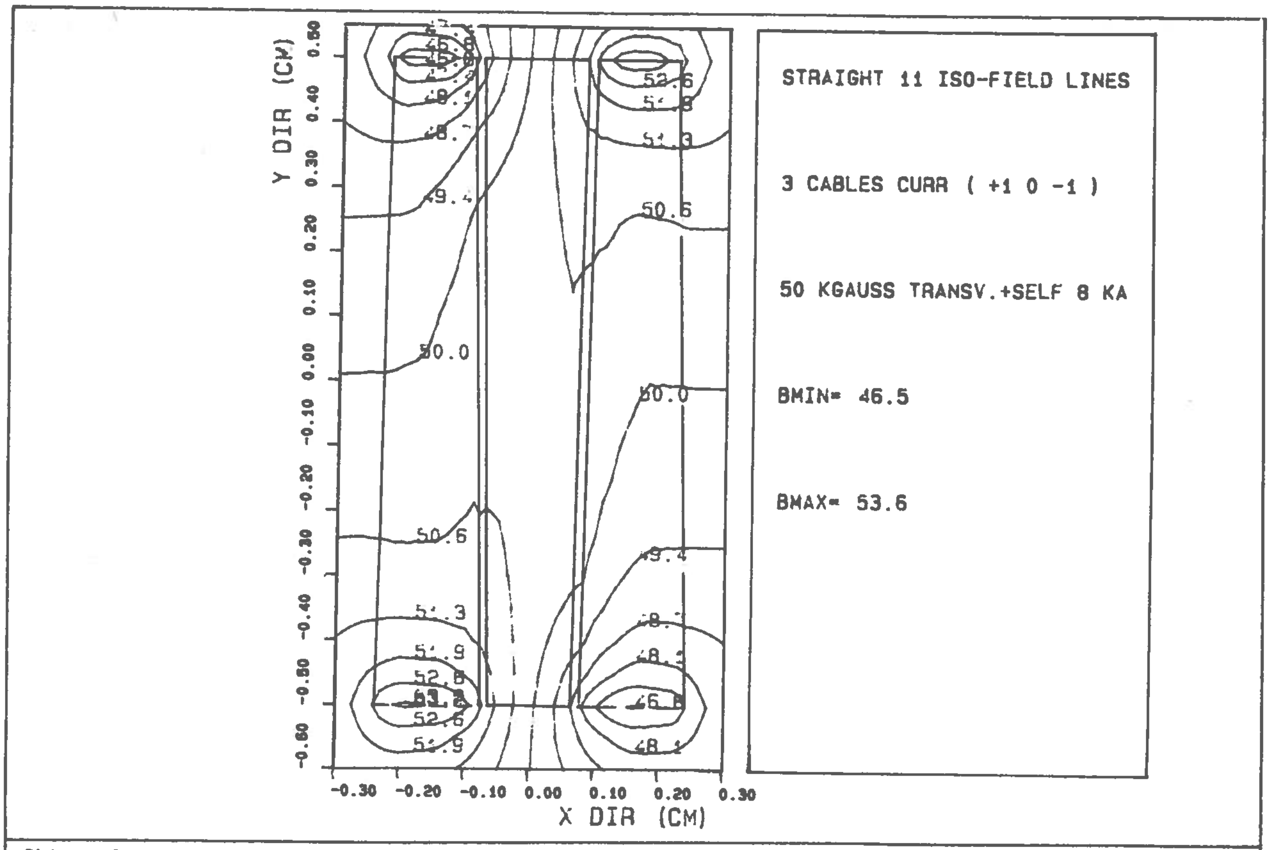


Fig.9 - 3 Samples #3 (B.N.L.)

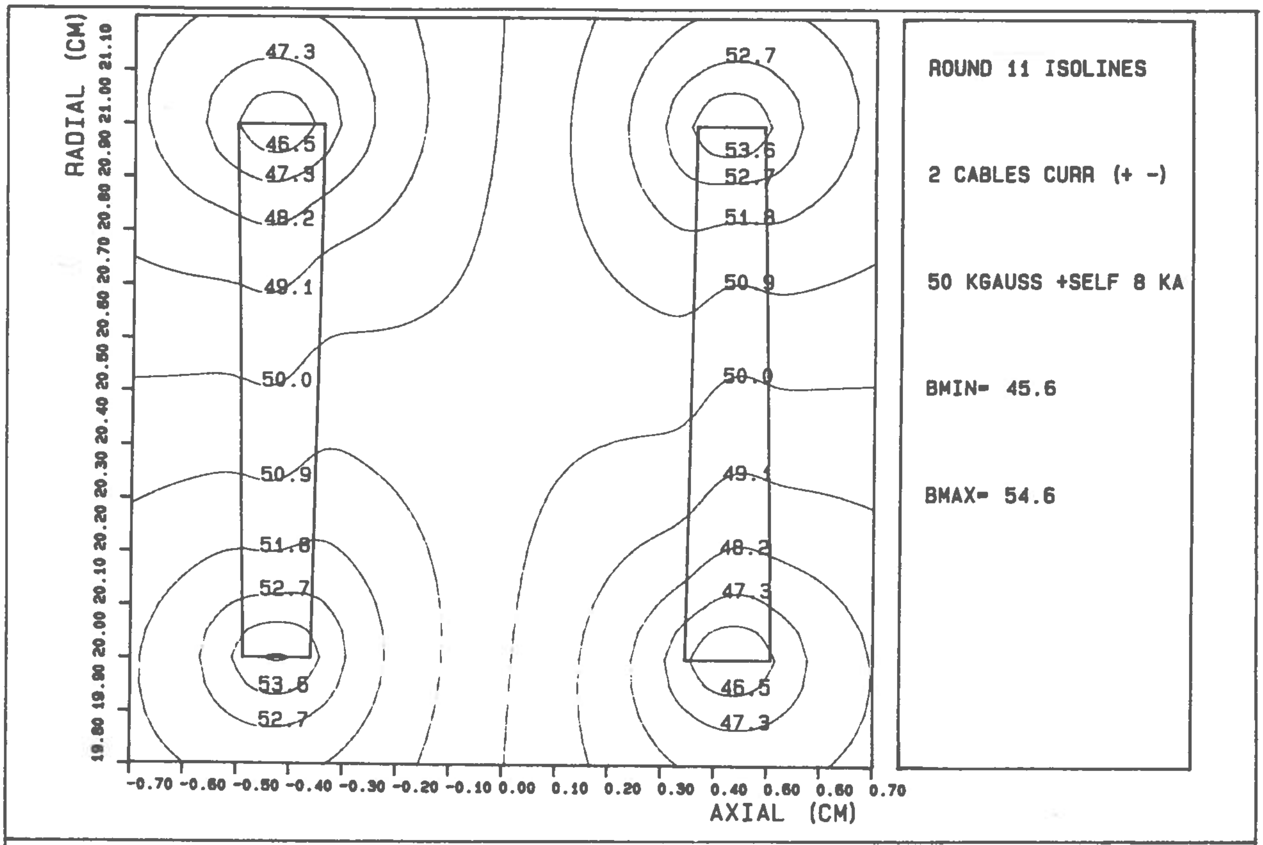


Fig.10 - Pair of round samples

2 pairs of samples: round configuration

The configuration with four cables is shown in Fig.11 and 12 (Axial negative middle-plane and positive respectively).

In this case the situation is furtherly complex, because each cable experiences a field different from the other ones.

The maximum absolute field is found at the internal radius of the extreme left (negative) cable (B=5.47 Tesla); the second 'maximum' field is found at the outer radius of the extreme right cable . where B=5.45 Tesla. At the two middle cables the maximum field has lower values , being 5.40 Tesla at the internal radius of the middle right cable and 5.38 Tesla at the outer radius of the middle left one.

Moving from extreme left cable, the four errors are : 11.7%, 9.5%, 10.0%, 11.2%.

In Table II the self field data given before are sumarized, togheter with the errors introduced in the data analysis by neglecting the self field effect.

In the first column of the table the configuration is defined; the numbers in brackets are those of figures and the signs are connected to the current direction; the convention used is: current positive-maximum field on the bottom of the figure.

In the second columnn the maximum self field is reported.

In the thirth and fourth ones the relative errors on the field and the critical

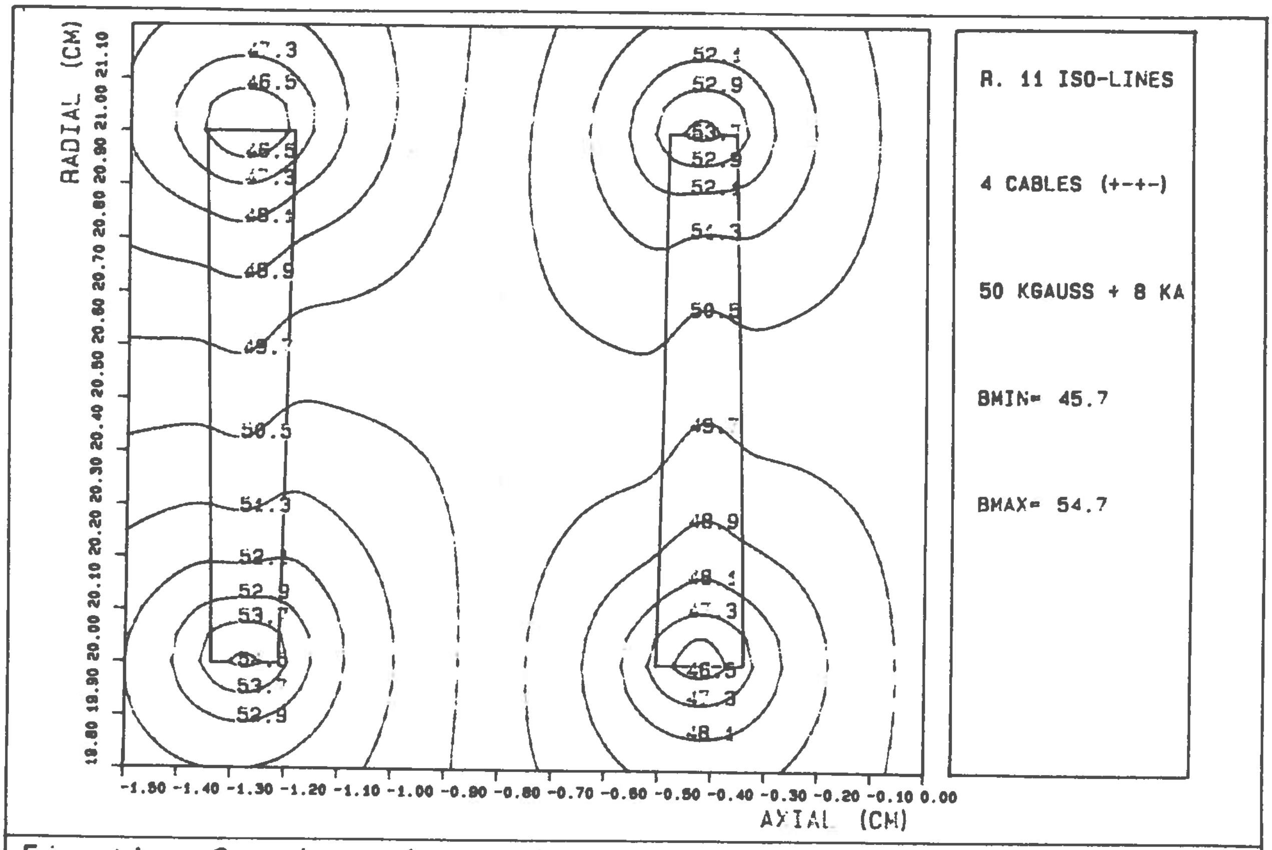


Fig.11 - 2 pairs of round samples (axial -)

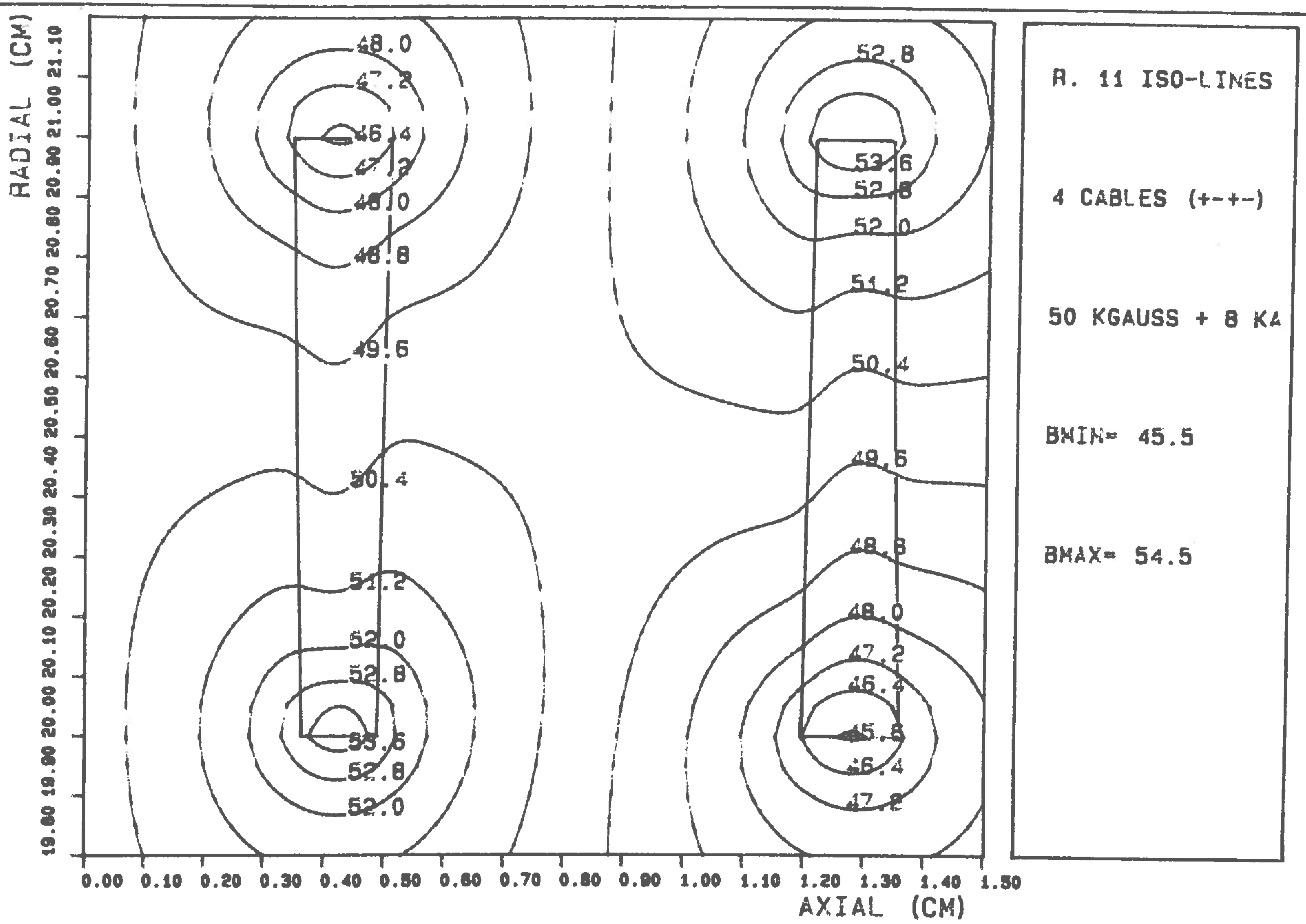


Fig.12 - 2 pairs of round samples (axial +)

current density.

For some configurations as the pair of round samples,there are different errors for each sample; in the last column these errors are reported.

TABLE II: Sistematic errors

Configuration	self field [KGauss]	B error %	J_c error max %	J_c errors others %
1 straight (2a) +	5000	10	12.4	
1 straight (2b) -	5300	10.6	13.1	
1 round (4a) +	5400	10.8	13.4	
1 round (4a) -	4700	9.4	11.7	
1 round (4b) +	4900	9.8	12.2	
1 round (4b) -	5200	10.4	13.0	
2 straight (6)	2700	5.4	6.7	
3 straight (7) +	2600	5.2	6.5	
3 straight (7) -	2300	4.6	5.7	
3 straight (8) +	3200	6.4	8.0	
3 straight (8) -	2800	5.6	7.0	
3 straight 9 +	3600	7.2	9.0	8.7
2 round (10) +	4600	9.2	11.5	11.2
2 round (10) -	4400	8.8	11.0	10.7
4 round (11-12) +	4700	9.4	11.7	9.5 10.0 11.2
4 round (11-12) -	4500	9.0	11.2	10.5 9.7 9.2

CONCLUSIONS

The self field effects on the cables for HERA dipoles, in the configurations used for critical current measurements, were studied in detail.

We have shown that the relative error introduced by neglecting the self field depends mainly on the geometrical arrangment of samples and on their shape. It is independent from the field level and from the critical current value, changing with temperature or cable quality, till the J_c vs B slope does not change.

The self field effects are considerable both in the BNL and INFN set-ups and a comparison of the results must take them into account

In the multi-sample system as used in both laboratories, the self field depends on the position of the samples and on the current distribution between them. A 1% accuracy in the critical current data requires a complete field map and a complete recording of the experimental conditions.

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