KEK-75-9

PROTECTION OF LARGE-STORED-ENERGY SUPERCONDUCTING COILS

Francois KIRCHER

November 1975

NATIONAL LABORATORY FOR
HIGH ENERGY PHYSICS
OHO-MACHI, TSUKUBA-GUN
IBARAKI, JAPAN

KEK Reports are available from

Library
National Laboratory for High Energy Physics
Oho-machi, Tsukuba-gun
Ibaraki-ken, 300-32
JAPAN

Phone: 02986-4-1171
Telex: 3652-534 (Domestic)
(0)3652-534 (International)
Cable: KEKOHO

PROTECTION OF LARGE-STORED-ENERGY SUPERCONDUCTING COILS

Francois KIRCHER*

National Laboratory for High Energy Physics
Oho-machi, Tsukuba-gun, Ibaraki-ken, 300-32, Japan

Abstract

When the stored energy of superconducting magnets increases, the problem of the protection of the coil when a quench occurs becomes more and more important, especially if the sturcture of the coil is such that the energy can be dissipated only in a small part of the coil.

The aim of this paper is first to describe a program which enables to predict the increase of temperature inside the coil for several kinds of protection and to give results for KEK pulsed dipoles (under construction and planned for TRISTAN).

* On leave from Department du Synchrotron SATURNE, S.E.D.A.P., CEN/SACLAY

I. Generalities

Several kinds of protection are possible when a quench occurs in S.C. magnets. The problem is to extract as quickly as possible the stored energy from the magnet ; this can be done either by inductive coupling, or by an inverse voltage applied to the magnet in series with the power supply or by putting it in series with a protection resistance outside the cryostat. Usually, one or several of these kinds are used.

The important parameters for the protection device design are :

- the stored energy.
- the current when the quench occurs.
- the ratio of copper to superconductor in the S.C. wire or assembly used.
- the coil structure.

Other parameters are also important but cannot be defined so accurately due to their random aspect.

- place where the quench occurs (in relation with the structure).
- quench propagation velocities along the three directions.

Generally, the most critical value will be taken for these parameters.

It is difficult to make analytical calculations taking into account all the parameters. A computer program is needed : the one described now is very useful.

II. The "QUENCH" program[1]

This program calculates the increase of temperature after a quench occured in a S.C. magnet. The main assumptions are :

- the coil is developed in a parallelepiped shape. It is considered as a whole.
- there is no thermal exchange with the outside.
- the place where the quench occurs is chosen, after that, the quench propagates in the three directions.

The initial velocity along the wire can be imposed, or calculated, using the STEKLY's formula[2].

$$v = \frac{J}{C}\sqrt{\frac{LT_c}{T_c-T_o}} \qquad (1)$$

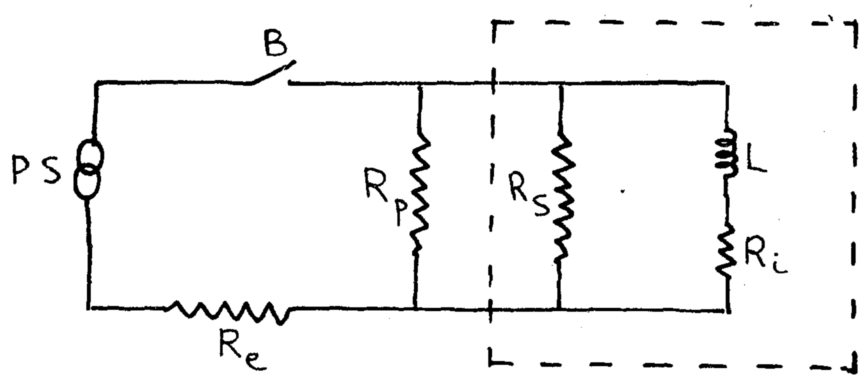
where

- J is the overall current density
- C the mean specific heat [at $(T_o + T_c)/2$]
- L the Lorentz number
- T_c the critical temperature of the composite (function of the applied magnetic field)
- T_o the operating temperature

A long the two other directions, the initial velocities are calculated taking into account the ratio of thermal conductivities along these directions and along the wire.

Then, the velocities are supposed to be proportional to the current.

- the electrical circuit is :



PS : power supply

B : current breaker

R_e : external resistance

R_p : protection resistance

R_s : switch resistance

L : self inductance of the coil

R_i : internal resistance of the coil (calculated by the program).

At every time, the current is calculated using :

$$L \frac{dI(t)}{dt} + \left(R_{ext} + R_i(t) \right) I(t) = V_{app} \qquad (2)$$

where

$$R_{ext} = \frac{R_e \cdot R_s}{R_e + R_s}$$ if the power supply is connected

or

$$R_{ext} = \frac{R_p \cdot R_s}{R_p + R_s}$$ if the breaker is opened

and $V_{app} = 0$

or $V_{app} = V_{inv}$ if an inverse voltage is applied

The program makes small increases of time ;
for each increase of time, the followings are calculated and written :

- increase of normal volume ΔV_i
- increase of internal resistance and of energy dissipated in each ΔV_i
- increase of temperature in each ΔV_i, taking into account the change of specific heat and of resistivity according to the temperature
- decrease of current, using eq. (2)

The program stops when the current is less than 1 % of the initial current or when the increase of maximum temperature is less than 0.01° K between two steps.

III. Application to the protection of the pulsed dipole now under construction at KEK

III. 1 General parameters

A cosΘ type pulsed dipole is now under construction at KEK. The design is made of several current blocks separated by epoxy wedges. Consequently the thermal conduction between blocks is very bad and for the protection design, it is necessary to consider a fictive coil, of which dimensions are :

- thickness : thickness of the block where the quench occurs.
- length : length of one developed block times the number of blocks

The first assumption does not take into account the difference of thickness for all the blocks but thermal propagation along the wire and lack of thermal propagation between blocks can so be simulated.

General parameters of the magnet are :

Coil composition	Niobium Titanium	18.1 %
	Copper	24.5 %
	Insulation and resin	57.3 %

Maximum field on conductor : 45 kG

Braid dimensions : $2.55 \times 0.05\ cm^2$

Coil width : 2.55 cm

thickness : 0.05 cm times the number of layers in the block

length : 106 cm times the number of blocks

Maximum current : 3000 A

Self inductance : 7 mH

Stored energy : 32 kJ

III.2 Influence of the random parameters

As said before, among the important parameters, two at least are random :

a) Place where the quench occurs : according to the block, the dimensions of the fictive coil will be changed. Fig. 1 shows the influence of this parameter on the maximum increase of temperature, assuming no protection. Following assumptions are made :

1 block per pole for N = 60 layers

4 blocks per pole for N = 15 or 11 layers

6 blocks per pole for N = 6 layers

7 blocks per pole for N = 3 or 2 layers

In this case, the quench velocity is calculated in the worst case where B = 0 kG.

For further calculations, two designs will be chosen[3].

- four-block design : smallest block : 7 layers
  largest blcok : 20 layers
- seven-block design : smallest block : 2 layers
  largest block : 13 layers

b) quench velocity along the wire : according to the place in the block, the magnetic field can have all the values between 0 kG and B_{max} :

the quench velocity given by (1) can vary as follows : from 5.6 m/sec for 0 kG to 10.4 m/sec for B_{max} = 45 kG. The influence of this parameter or the maximum increase of temperature is given on Fig. 2 and 3, for the two extreme block of each design.

For further calculations, the quench will be assumed to begin in a place where B = 0 kG, which is the worst case.

It is interesting to notice that these two random parameters have not influence at the beginning of the phenomenon ($t \leq 200$ msec).

III. 3 Influence of the kind of protection

For the two designs, several kinds of possible protection have been studied.

- inverse voltage of 10, 20 or 30 V applied 50 msec after the detection of a quench.
- protection resistance of 0.1 Ω put in series with the coil 150 msec after detection of a quench (the value of the resistance is quite conservative, giving V_{pr} = 300 V).
- inverse voltage of 20 V applied 50 msec after detection then protection resistance of 0.1 Ω, 150 msec after detection.

The results are summed up in Fig. 4 for the four-block design and in Fig. 5 for the seven-block design.

If one assumes that the maximum increase of temperature admissible is 140° K, the followings can be carried out :

- if only an inverse voltage is applied, a value of at least 30 V is needed.
- if only a 0.1 Ω protection is put in series, this must be done in less than 250 msec.
- if the two kinds of protection are used, there is no problem. This kind of protection has two advantages : it doubles the number of protection devices, and applying an inverse voltage can generate other normal areas in the coil, which is good to dissipate the energy in several places inside the coil.

III. 4 Summary

The followings protection device is suggested :

- at least : a protection resistance of 0.1 Ω put in series with the coil in less than 250 msec.

- better : first apply an inverse voltage of 20 V around 50 msec after detection of the quench and then put the resistance of 0.1 Ω in less than 250 msec after detection.

If the protection device works well, the increase of temperature will be almost the same for the two designs.

If the protection device dose not work, the probability to burn the coil is much larger with the seven-block design. (See Fig. 2 and 3).

IV. Towards TRISTAN

Some calculations are presented now about the protection of the future dipoles for TRISTAN. The main changes with respect to the prototype now under construction are :

- four-block design with 11 layers in the smallest block
- ratio copper / SC = 2 in the assembly
- packing factor of 75 % in the assembly

These two last assumptions give almost the same dimension for a 3000 A conductor.

The basic protection device assumed is an inverse voltage of 15 V applied 50 msec after detection then a protection resistance (such as to have an external voltage of 500 V) put in series 150 msec after detection.

Random parameters are as above, that is to say quench occurs in the smallest block in a place where B = 0 kG.

Magnet length effect

As the length of the magnet increases so does the stored energy. Fig. 6 shows the increase of temperature versus the length of the magnet, assuming a current of 3000 A. There is no problem even with a 4 m long magnet. It is interesting to notice that for a 0.5 m long magnet, the maximum temperature is 45° K.

Protection kind effect

For a 4 m long magnet with a current of 3000 A. Fig. 7 shows the influence of the kind of protection. One can notice :

- it is not interesting to reduce the time when the inverse voltage is applied.
- it is more usefull (but more dangerous also) to increase the protection resistance.
- the best way to do is to reduce the time when the protection resistance is put in series.

Current effect

It is interesting to reduce the current of a S.C. magnet for an economical point of view (losses in current leads) and also because the wire can be simpler.

Fig. 8 shows the effect to reduce the current for a 4 m long magnet. The following assumptions are made :

- conductor size and coil components adjusted to the current.
- same stored energy
- protection device as described above with protection resistance adjusted to have an external voltage of 500 V.

One can see that it is possible to reduce the present current of a factor two at least without trouble.

V. Conclusions

A program enabling to calculate the increase of temperature during a quench has been described. Application to the dipole now under construction at KEK has permitted to define a protection device and also to show the interest to increase the number of layers in the smallest block if something is wrong with the protection device.

Application to dipoles for TRISTAN shows that these dipoles can be 4 m long with a current of 1500 A and well protected with a quite simple device.

References

[1] The "QUENCH" program was first written by M.N. WILSON (Rutherford High Energy Laboratory).
"Computer simulation of the quenching of a superconducting coil" RHEL M151 (1968).
Several improvements were made by M.J. NEWMAN. The version available at KEK was kindly supplied to the author by M.N. WILSON ; some improvements to take into account an inverse voltage were made afterwards.

[2] Z.L. STEKLY and E. HOAG : J. Appl. Phys. 34 (1963), 1376

[3] K. MORIMOTO : private communication

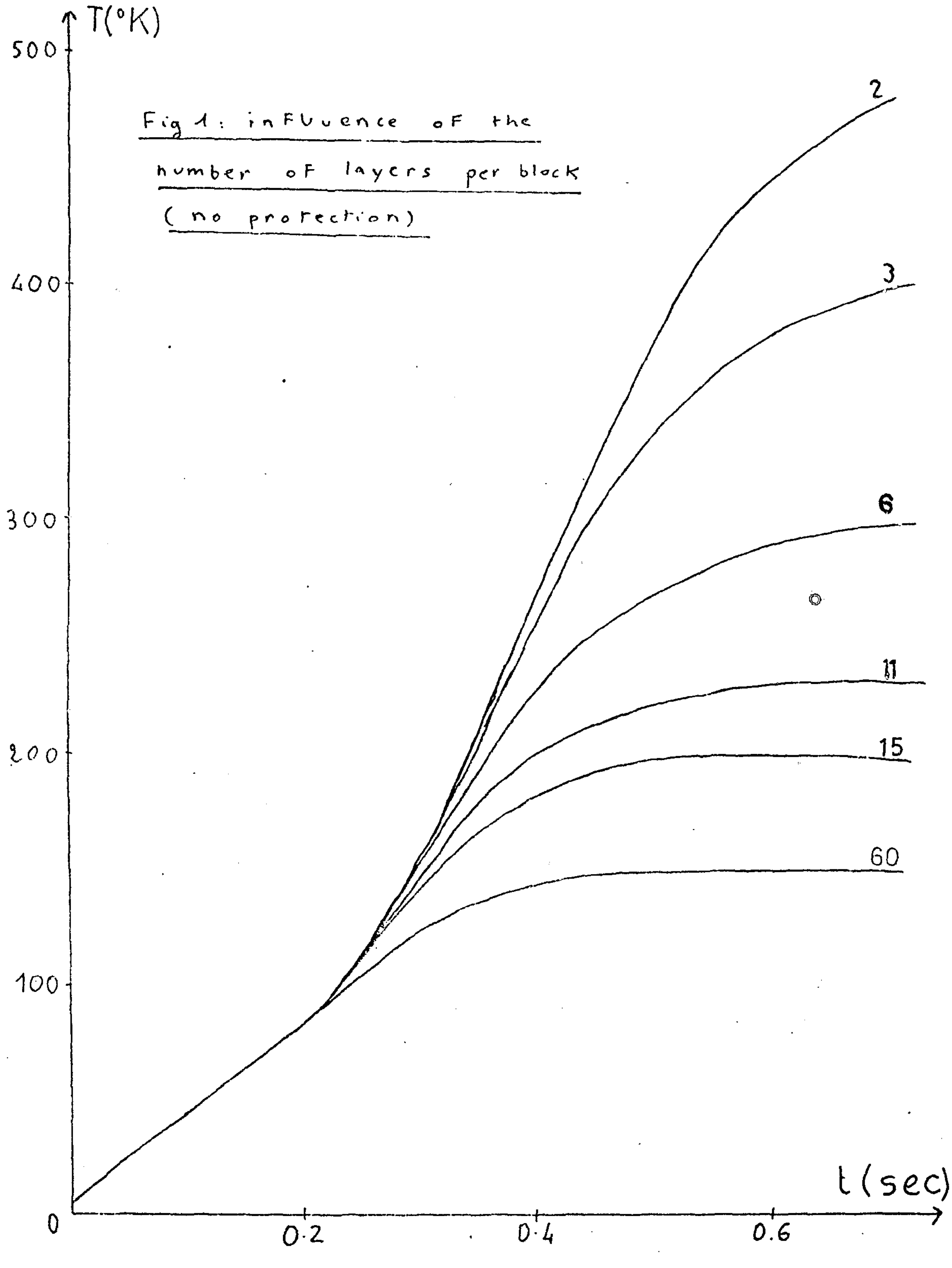


Fig 1: influence of the number of layers per block (no protection)

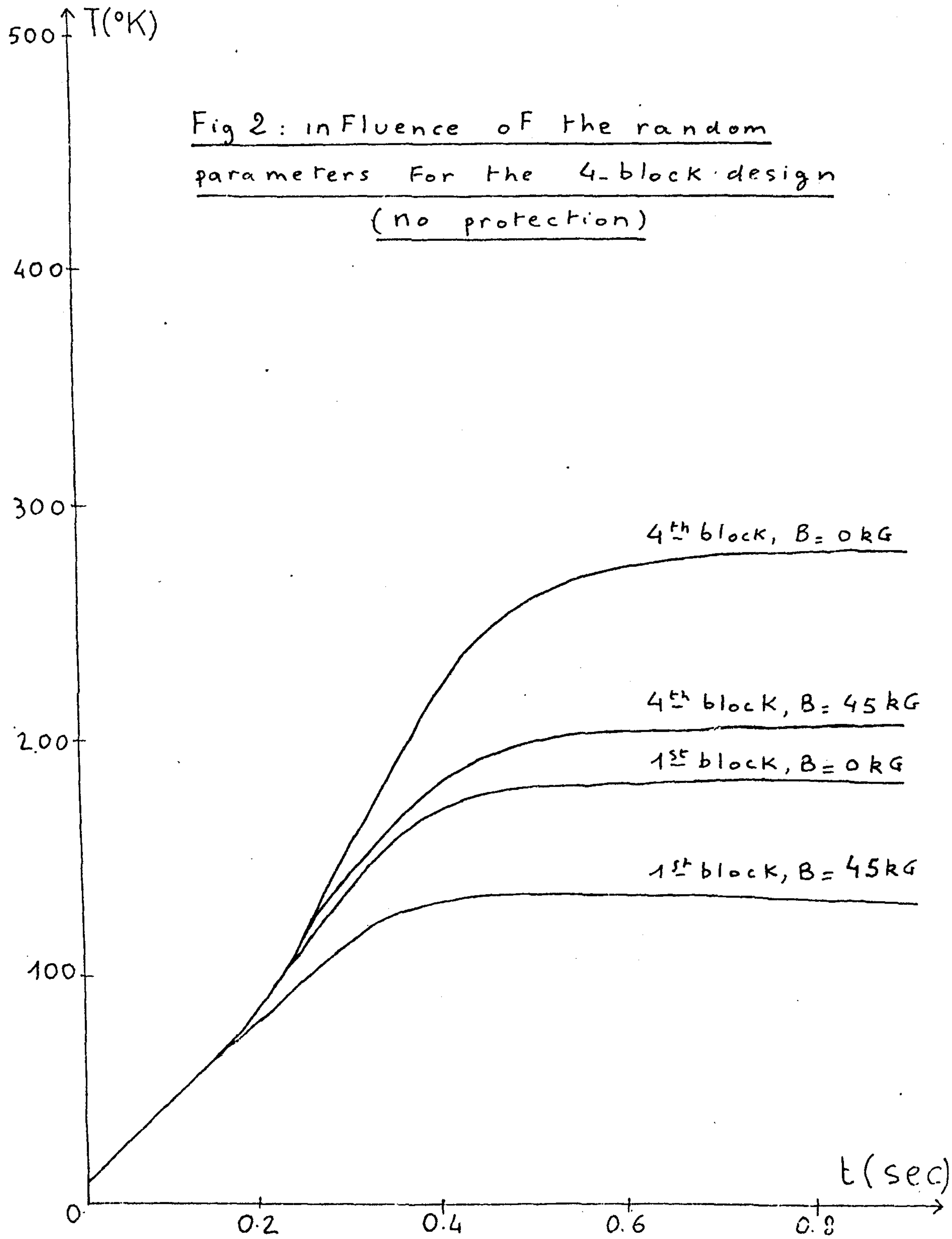


Fig 2: influence of the random parameters for the 4-block design (no protection)

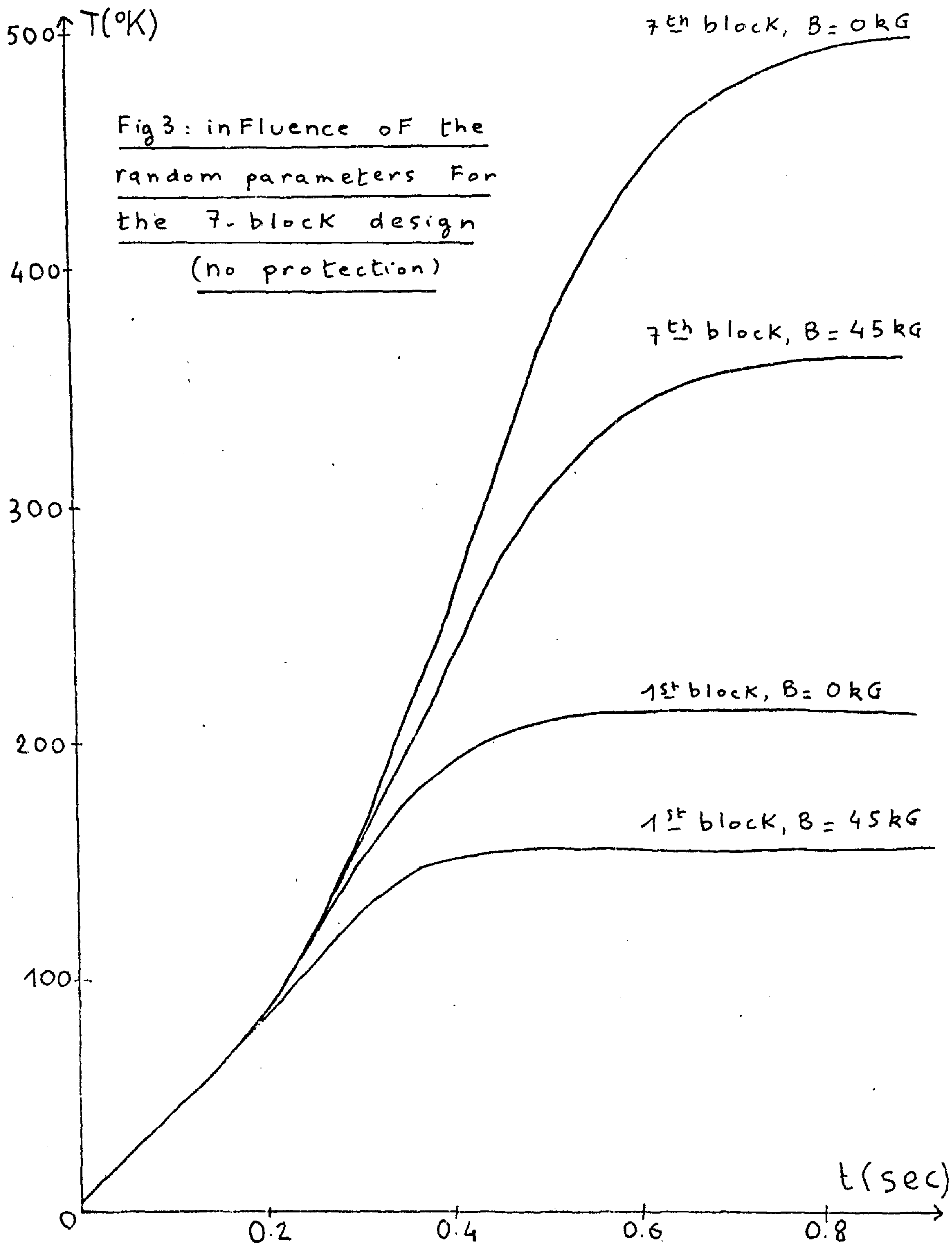


Fig 3 : influence of the random parameters for the 7-block design (no protection)
T(°K)
500
400
300
200
100
0
7th block, B = 0 kG
7th block, B = 45 kG
1st block, B = 0 kG
1st block, B = 45 kG
t (sec)
0.2
0.4
0.6
0.8

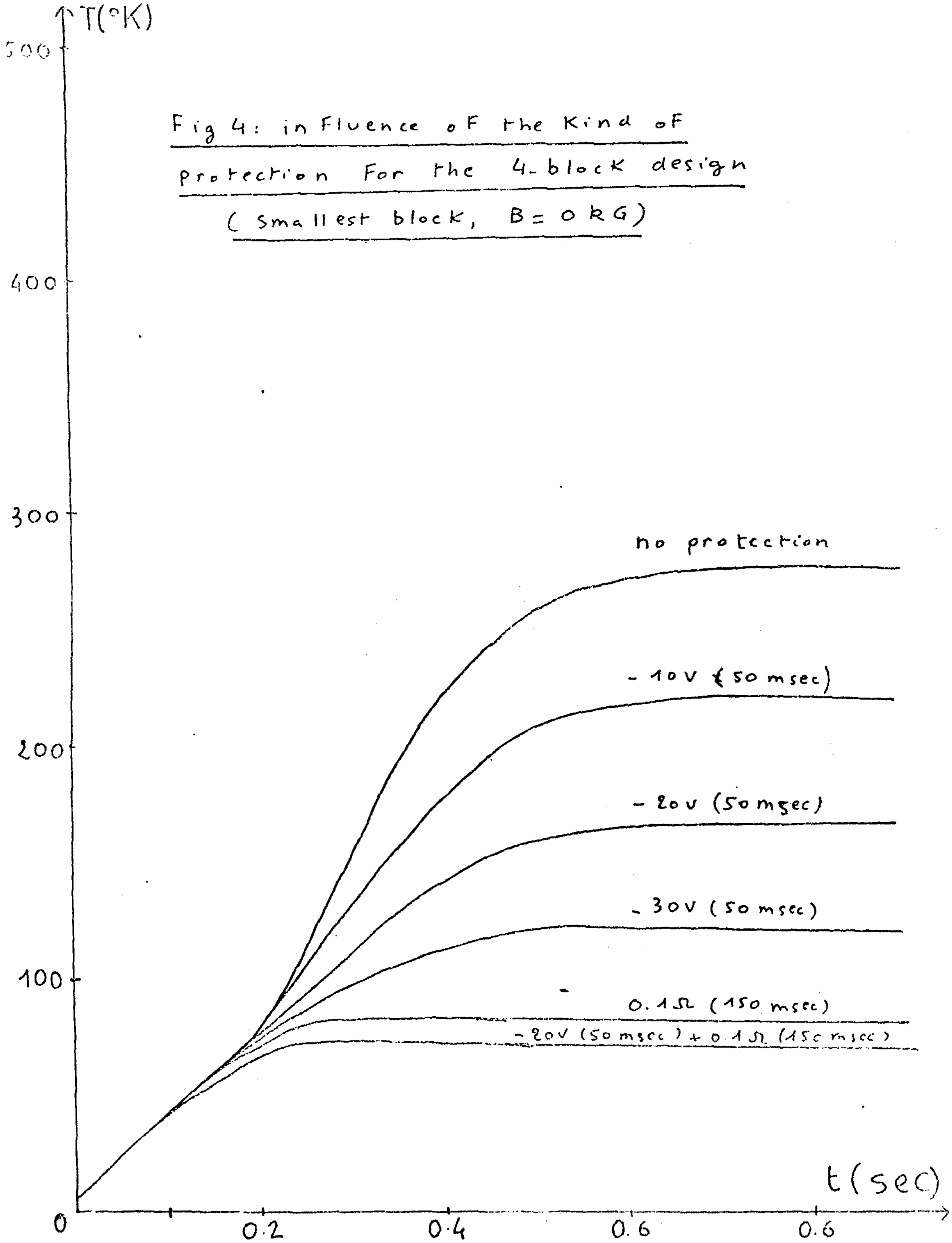
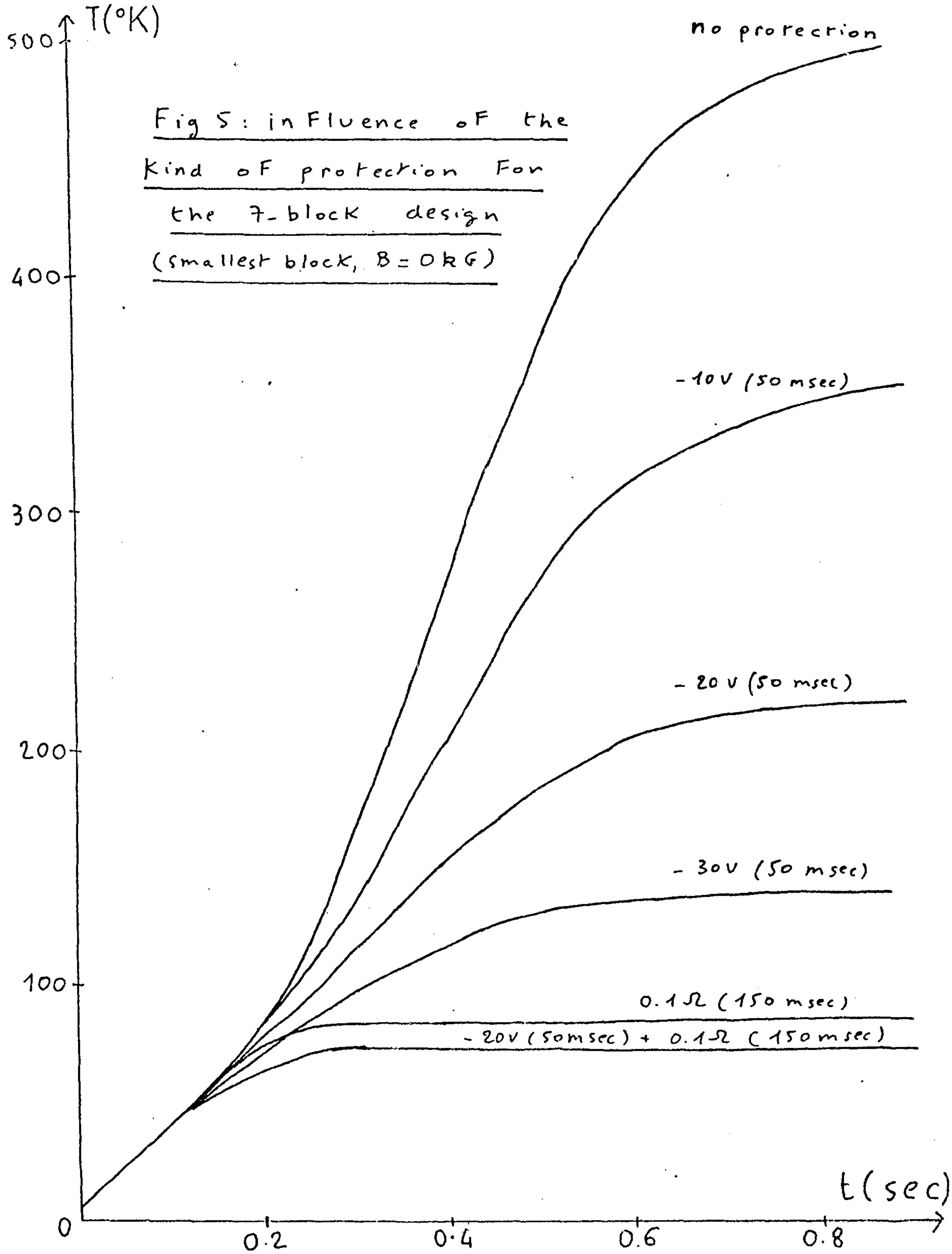


Fig 4: influence of the kind of protection for the 4-block design (smallest block, B = 0 kG)


T(°K)
500
400
300
200
100
0
Fig 5: influence of the kind of protection for the 7-block design (smallest block, B = 0 kG)
no protection
- 10 V (50 msec)
- 20 V (50 msec)
- 30 V (50 msec)
0.1 Ω (150 msec)
- 20 V (50 msec) + 0.1 Ω (150 msec)
t (sec)
0.2
0.4
0.6
0.8

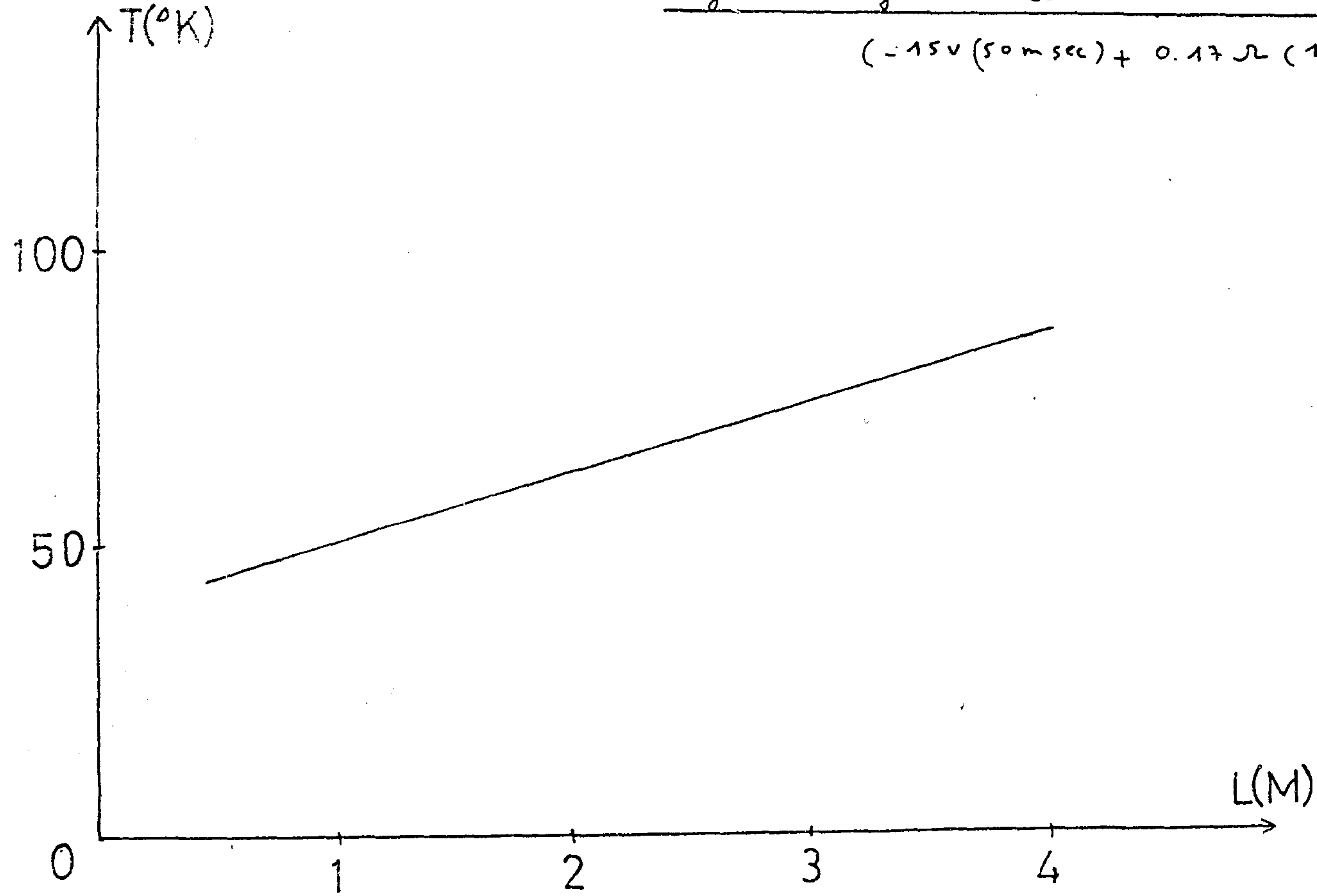


Fig 6: length effect for KEK Future dipole

(-15V (50 msec) + 0.17 Ω (150 msec), 3000 A)

Fig 7: effect of the kind of protection

For KEK future dipole

(L = 4m, I = 3000A)

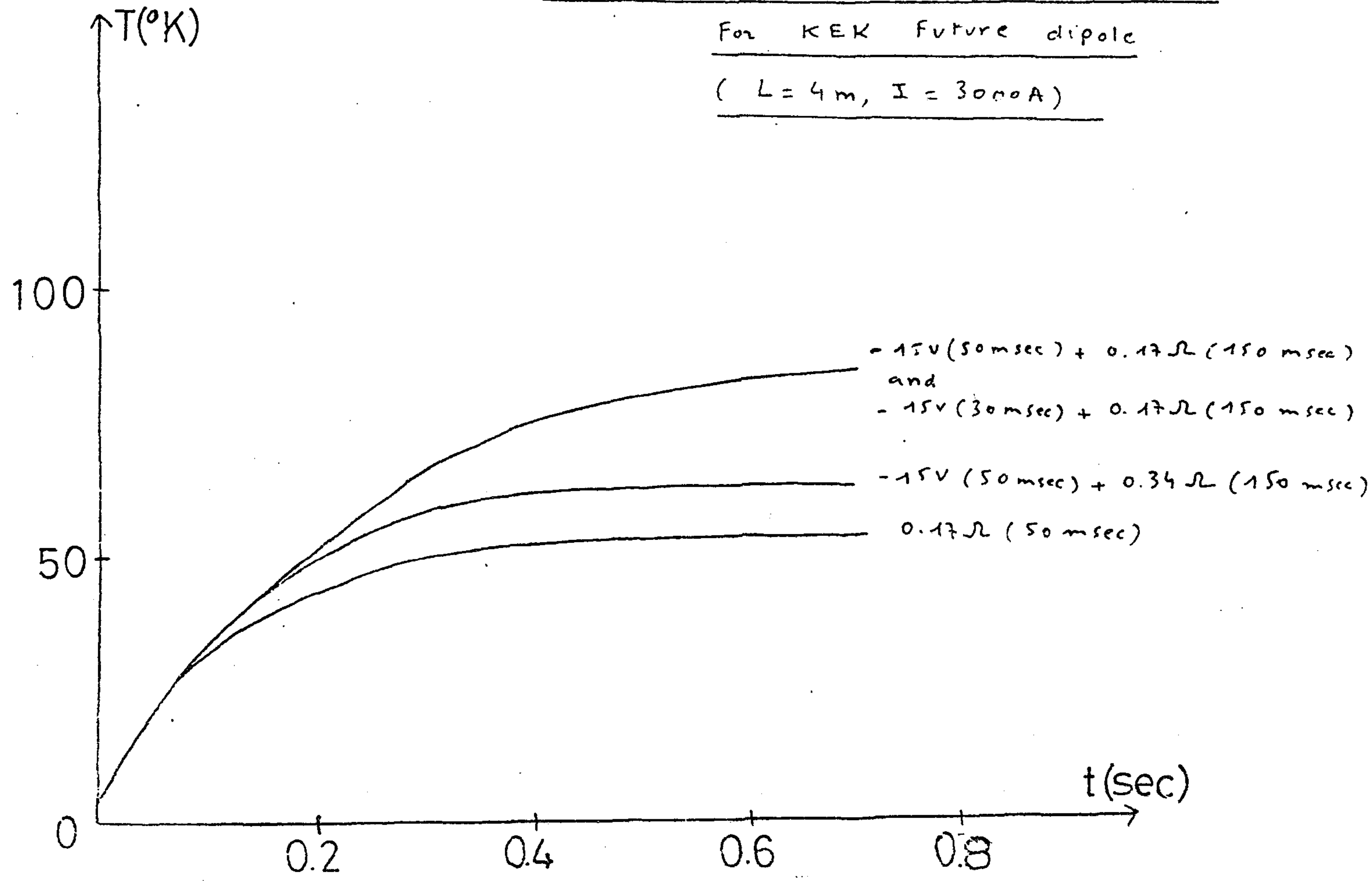


Fig 8: current effect for KEK Future dipole

(-15v (50msec)+ 0.17Ω (150 msec), I = 4m)