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FAULT CONSIDERATIONS AND EFFECTS OF SHORTS IN THE ATLAS BARREL TOROID COIL SYSTEM

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Abstract

The ATLAS Barrel Toroid (BT) is a superconducting toroid made of 8 coils of 25 m length and 5 m width, providing the magnetic field for the muon spectrometer of the ATLAS detector, one of the experiments of the Large Hadron Collider, under construction at CERN. In addition to the BT the ATLAS magnetic structure foresees two End Cap Toroid (ECT) with the same 8 structure geometry of the BT, and a Central Solenoid (CS).

The evaluation of the forces arising in the Barrel Toroid coil system, when unbalanced current flows in different coils, has already been investigated when the LASA laboratory entered the ATLAS project.

Here the refinement of the calculations, with the definitive parameters and discharge circuit configuration is done.

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1 INTRODUCTION

The Barrel Toroid Magnet (BT)[1] is part of the Magnet System of the ATLAS Detector for the Large Hadron Collider (LHC). It provides the magnetic field required by the muon spectrometer. It consists of eight flat superconducting coil of 25 m length and 5 m width, radially assembled around the beam axis.

The field will extend over a length of about 26 meters with an inner bore of 9 meters and an outer diameter of about 20 meters.

In order to achieve a high reliability of the magnet system, an analysis of the fault considerations must be done. In addition the consequences and action needed to avoid damages in the system, must be analyzed.

2 FAULT SCENARIO

The main faults in the ATLAS Barrel Toroid system can occur in the following parts:

- Power supply
- Dump system : more precisely in the

  - Dump resistor (extreme case: no dump resistance or opening of all the resistance arms, intermediate case: some arms open or shorted).
    The effect of this fault is an unbalanced voltage at the diodes and at the coils.

  - Diodes (extreme case no diodes conducting; intermediate, some arms non conducting).

  The extreme case for these two faults situations described so far is that all the diodes/resistors branches are open, so a discharge occurs without dump resistor. These situations has already been described and analyzed elsewhere[2].

- Coil system : more precisely it can be an opening in the bus bar system

  - Main bus bar: the bus bar connecting the power supply to the coils,

  - Bus bar system: the part of the bus bar connecting the magnets, more precisely:
    - The connection among the BT
    - The connection among the ECT
    - The connection between the BT and the ECT

  During the charging of the magnet this opening can be detected and the ramp can be stopped.
  Depending on the value of the current (half charging, 80% charging) the right discharge procedure will apply.

- Short circuit among some part of the bus bar
  - Short to ground of the bus bar
  - Fault in the coil properly: i.e. fault in the heater system,
  - Short circuit in one or more coils.

The short can be detected at zero current but if, for any reason, the short occurs when the coil system is energized, the discharge procedure must be investigated and the forces, due to the current unbalancing, must be evaluated.

According to the previous work on force calculation[3)], the worst case is when 4 adjacent of the 8 coils are shorted.

In this paper the forces arising in case of unbalanced current configuration are evaluated, as in[3)], with the definitive configurations and values of the dump circuit.

The situation with a complete fault of the heater system with 1, 2, 3, and 4 coil shorted is reported, then the configuration of one coil shorted with the different situation of heater faults is evaluated.

The propagation velocity of the heater induced quench is variable with the current in the coils, and the values used are from the test of the B0 prototype.

3 EQUATIONS AND PARAMETERS

The section of the BT magnet layout is shown in Fig 1, while the circuit is shown in Fig 2.

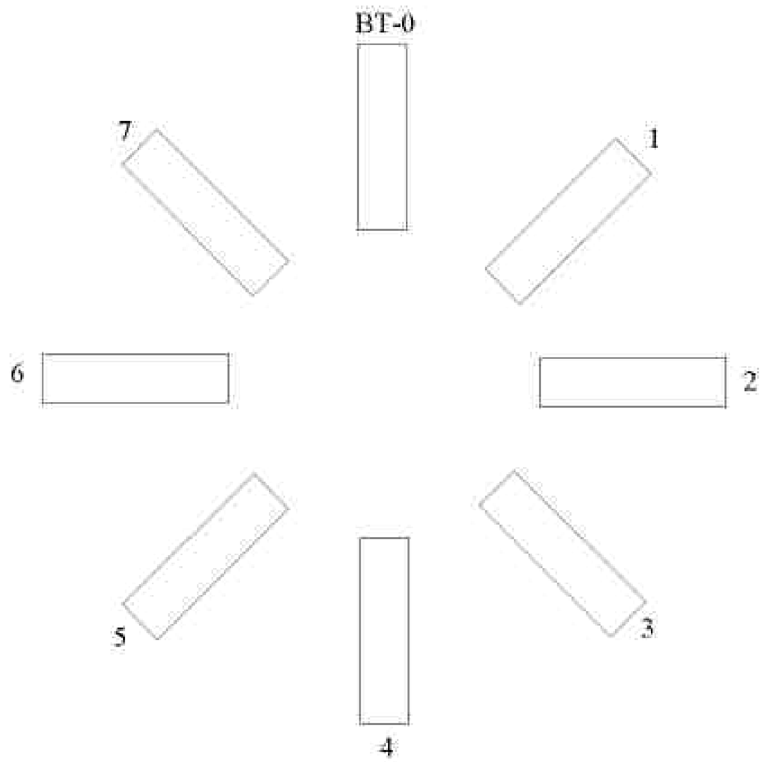

FIG. 1: Scheme of the BT coil system

At the top there is the electrical scheme of the coil system without any short, while at the bottom there is the scheme of the coil system with two BT coil shorted.

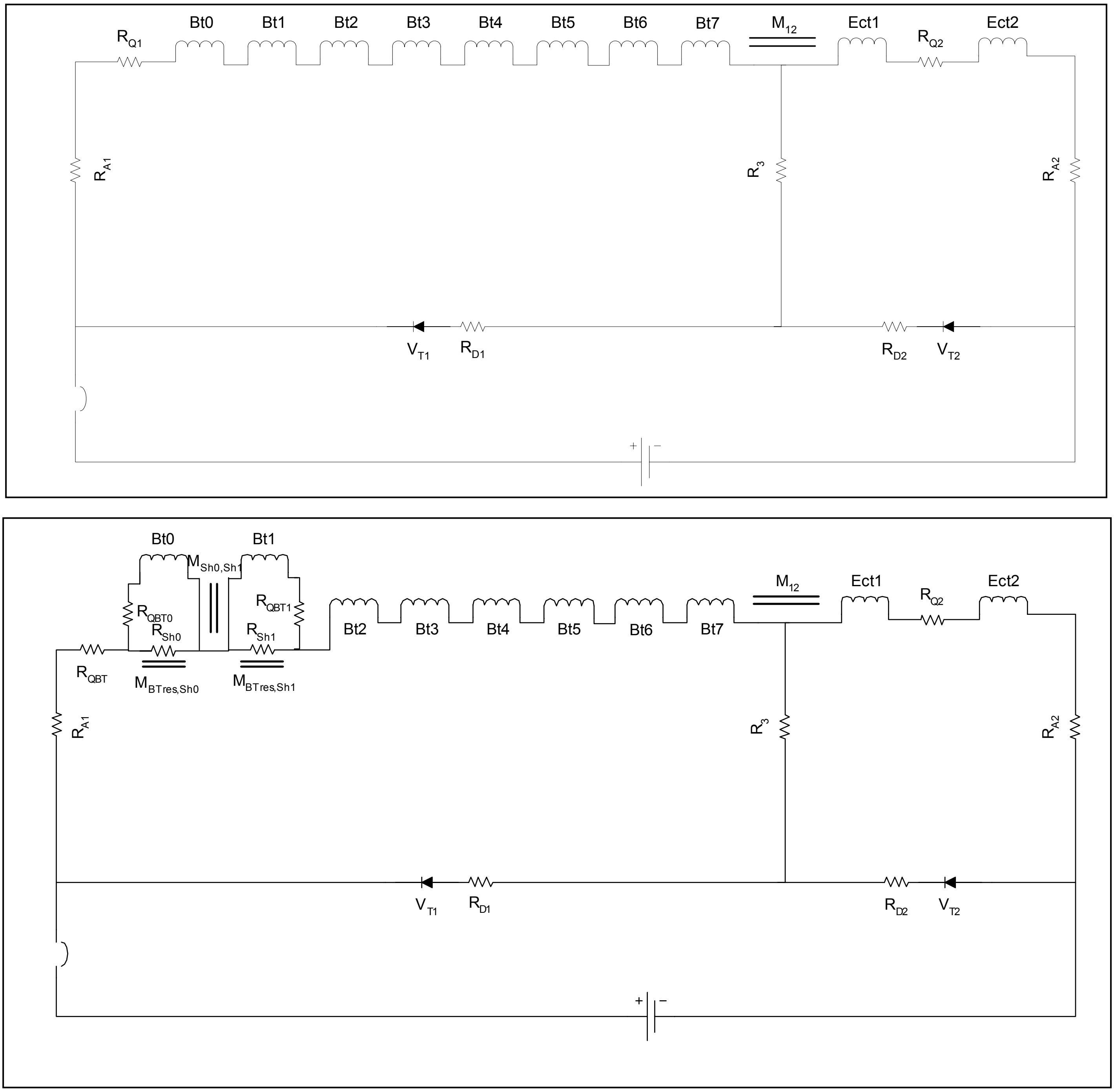

FIG. 2: Electrical scheme without any short (top) and with BT0 and BT1 shorted (bottom).

The equations of the BT circuit in the various cases of short of one ore more full short of the coils composing the BT systems are the followings:

No shorts

$$\begin{cases} \overline{R}_1 I_{BT} + L_{BT}\dfrac{dI_{BT}}{dt} + R_3(I_{BT} - I_{ECT}) + V_{T1} + M_{BT,ECT}\dfrac{dI_{ECT}}{dt} = 0 \\ \overline{R}_2 I_{ECT} + L_{ECT}\dfrac{dI_{ECT}}{dt} + R_3(I_{ECT} - I_{BT}) + V_{T2} + M_{ECT,BT}\dfrac{dI_{BT}}{dt} = 0 \end{cases}$$

Four shorts

$$\begin{cases} \overline{R}_1 I_{BT} + L_{BTres}\dfrac{dI_{BT}}{dt} + R_3(I_{BT} - I_{ECT}) + V_{T1} + M_{BT,ECT}\dfrac{dI_{ECT}}{dt} + \\ + R_{Sh0}(I_{BT} - I_{Sh0}) + R_{Sh1}(I_{BT} - I_{Sh1}) + R_{Sh2}(I_{BT} - I_{Sh2}) + R_{Sh3}(I_{BT} - I_{Sh3}) + \\ + M_{BTres,Sh0}\dfrac{dI_{Sh0}}{dt} + M_{BTres,Sh1}\dfrac{dI_{Sh1}}{dt} + M_{Btres,Sh2}\dfrac{dI_{Sh2}}{dt} + M_{BTres,Sh3}\dfrac{dI_{Sh3}}{dt} = 0 \\ \\ \overline{R}_2 I_{ECT} + L_{ECT}\dfrac{dI_{ECT}}{dt} + R_3(I_{ECT} - I_{BT}) + V_{T2} + M_{ECT,BT}\dfrac{dI_{BT}}{dt} = 0 \\ \\ R_{Sh0}(I_{Sh0} - I_{BT}) + R_{q0} I_{Sh0} + L_{Sh0}\dfrac{dI_{Sh0}}{dt} + M_{Sh0,Btres}\dfrac{dI_{BT}}{dt} + \\ + M_{Sh0,Sh1}\dfrac{dI_{Sh1}}{dt} + M_{Sh0,Sh2}\dfrac{dI_{Sh2}}{dt} + M_{Sh0,Sh3}\dfrac{dI_{Sh3}}{dt} = 0 \\ \\ R_{Sh1}(I_{Sh1} - I_{BT}) + R_{q1} I_{Sh1} + L_{Sh1}\dfrac{dI_{Sh1}}{dt} + M_{Sh1,Btres}\dfrac{dI_{BT}}{dt} + \\ + M_{Sh1,Sh0}\dfrac{dI_{Sh0}}{dt} + M_{Sh1,Sh2}\dfrac{dI_{Sh2}}{dt} + M_{Sh1,Sh3}\dfrac{dI_{Sh3}}{dt} = 0 \\ \\ R_{Sh2}(I_{Sh2} - I_{BT}) + R_{q2} I_{Sh2} + L_{Sh2}\dfrac{dI_{Sh2}}{dt} + M_{Sh2,BTres}\dfrac{dI_{BT}}{dt} + \\ + M_{Sh2,Sh0}\dfrac{dI_{Sh0}}{dt} + M_{Sh2,Sh1}\dfrac{dI_{Sh1}}{dt} + M_{Sh2,Sh3}\dfrac{dI_{Sh3}}{dt} = 0 \\ \\ R_{Sh3}(I_{Sh3} - I_{BT}) + R_{q3} I_{Sh3} + L_{Sh3}\dfrac{dI_{Sh3}}{dt} + M_{Sh3,BTres}\dfrac{dI_{BT}}{dt} + \\ + M_{Sh3,Sh1}\dfrac{dI_{Sh0}}{dt} + M_{Sh3,Sh1}\dfrac{dI_{Sh1}}{dt} + M_{Sh3,Sh2}\dfrac{dI_{Sh2}}{dt} = 0 \end{cases}$$

Where :
$\overline{R}_1 = R_{A1} + R_{Q1} + R_{D1}$ is the resistance in the Barrel Toroid circuit
R_{A1} is the resistance of the bus bar from the power supply to the BT coil
R_{Q1} is the resistance of the transited part of the BT coil
R_{D1} is the BT dump circuit resistance
I_{BT}, is the current in the BT circuit
L_{BT} is the inductance of the whole BT coil system
L_{BTres} is the inductance of the not shorted BT circuit
R_3 is the resistance of the common (BT-ECT) arm of the circuit
V_{T1} is the BT dump circuit diode voltage
$M_{BT,ECT}$ is the mutual inductance between the BT and ECT coil system
$\overline{R}_2 = R_{A2} + R_{Q2} + R_{D2}$ is the resistance in the End Cap Toroid circuit
R_{A2} is the resistance of the bus bar from the power supply to the ECT coil
R_{Q2} is the resistance of the transited part of the ECT coil
R_{D2} is the ECT dump circuit resistance
I_{ECT}, is the current in the ECT circuit
L_{ECT} is the inductance of the ECT coil system
V_{T2} is the ECT dump circuit diode voltage
$M_{Btres,Shn}$ is the mutual inductance between the unshorted BT coils and the n^{th} BT shorted coil
I_{Shn} is the current in the n^{th} shorted coil
$M_{SHn,Shm}$ is the mutual inductance between the n^{th} and the m^{th} BT shorted coils
R_{Shn} is the short resistance of the n^{th} shorted coil
R_{qn} is the resistance of the transited part of the n^{th} shorted coil

The first equation refers to the BT circuit, its second and third line contain the shorting terms; if only one short is present the last three term of the second and third line are null, if two shorts are present the last two are null and so on.

The second equation is the equation of the ECT circuit.

The BT ECT circuits are coupled through the common current lead with resistance R_3 and the mutual inductance M_{12}.

The other equations refer to the shorted coil; if only one short is present there will be only the third; if two coils are shorted there will be the third and the fourth and so on.

The shorted coils and the BT coil system are coupled through the short resistance R_{Shn} and the mutual inductance[4)].

The parameters used are listed in Table 1.

TABLE 1: Parameters used in the calculation

Parameter	BT	ECT
Current (A)	20500	20500
Inductance (H)	5.14	2.2
Inductance of a single coil (H)	0.525	=
Mutual inductance of a single coil with the remaining (H)	0.1108	=
N° of diodes/resistance branches	20	20
N° of diodes in each branch	7	3
Diode voltage (V)	0.74	0.74
Equivalent diode voltage (V)	5.18	2.22
Equivalent dump resistance (Ω)	6.28×10^{-4}	1.58×10^{-4}
Bus bar length (m)	200	300
Common bus bar length (m)	200	

The self and mutual inductance have been calculated in[4)].

The study has been carried out both by neglecting the heater action and considering the action of the heaters with some fault in their firing.

For the case of one short, the full operativity and the full fault of the heater system, taking into account the effect of the shorting resistance R_{Sh0} has been examined.

When the heater is switched on, the transition to the resistive state starts; the velocity of propagation of the quench is variable with the current in the coil as from the B0 coil test.

The longitudinal propagation velocity vs. the magnet current is plotted in Fig. 3.

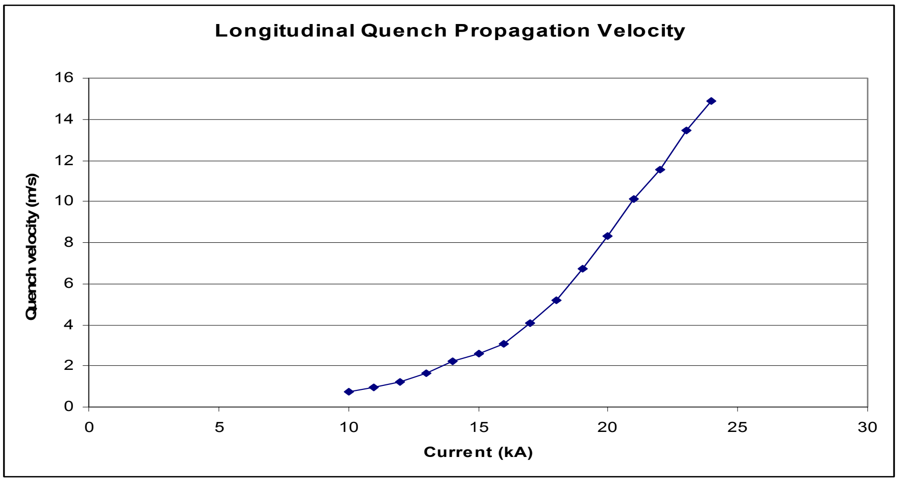

FIG. 3: Longitudinal quench propagation velocity as from B0 tests.

As from[3)] when there is an unbalanced current is one of the BT coil an azimuthal force between the unbalanced coil and the remaining BT coils arise.

In addition there is a radial force between the ECT coils and the unbalanced BT coil.

4 RESULTS

The behaviour of the BT system in case of various configuration and operation condition when a short occurs is investigated.

The cases studied are the followings:

1. Short of one coil, no heater action in any coil.
   - 1.a Zero short resistance
   - 1.b High short resistance (10 mΩ)
   - 1.c Low short resistance (10 μΩ)
2. Short of one, two, three, four adjacent coils, no heater action, low short resistance.
3. Short of one coil and all heaters action.
   - 3.a Zero short resistance
   - 3.b High short resistance (10 mΩ)
   - 3.c Low short resistance (10 μΩ)
4. Short of one coil, BT heaters action, ECT heaters action, NO heaters on the shorted coil
5. Short of one coil, BT heaters action, NO ECT heaters action, heaters on the shorted coil.
6. Short of one coil, BT heaters action, NO ECT heaters action, NO heaters on the shorted coil.
7. Short of one coil, NO BT heaters action, ECT heaters action, heaters on the shorted coil.
8. Short of one coil, NO BT heaters action, NO ECT heaters action, heaters on the shorted coil.
9. Short of one coil, NO BT heaters action, ECT heaters action, NO heaters on the shorted coil.

The heater action starts after 60 s from the beginning of the discharge.

4.1 No Heater Actions (in any coil), One Coil Shorted, Various Short Resistance (cases 1a, 1b and 1c)

In fig. 4 the currents in the BT coils, in the ECT and in the shorted coil is plotted, in case of different shorting resistance (0 Ω, 10 μΩ and 10 mΩ).

The discharge occurs across the dump system, without any action from the coil heaters

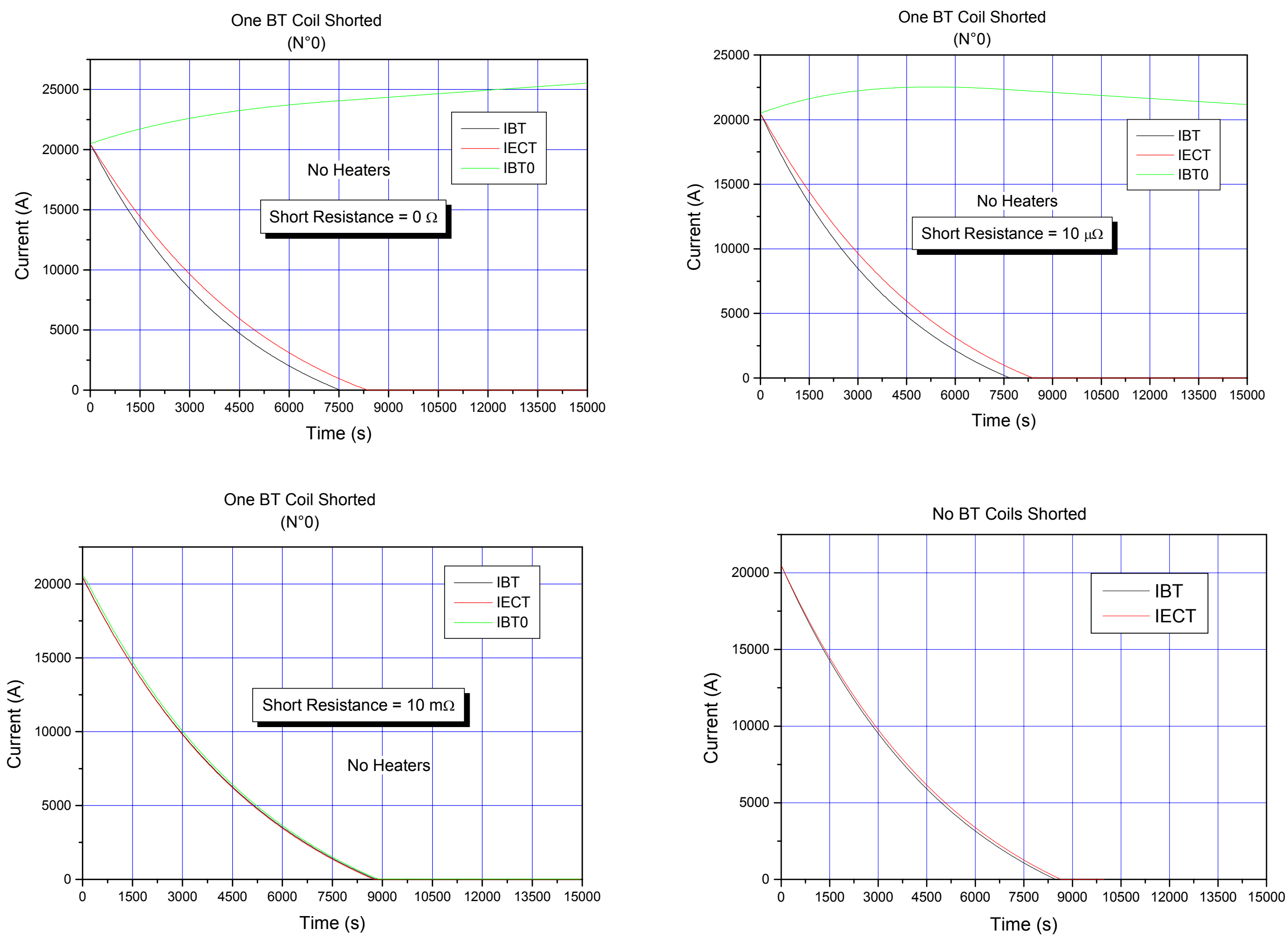

FIG. 4: Current in the BT, ECT and in the shorted coil, when only one coil is shorted, for different values of the short resistance.
The bottom right graph shows the current without any shorts.

In fig. 5 the force corresponding to the situation of fig. 4 are shown (the case without shorts is omitted).

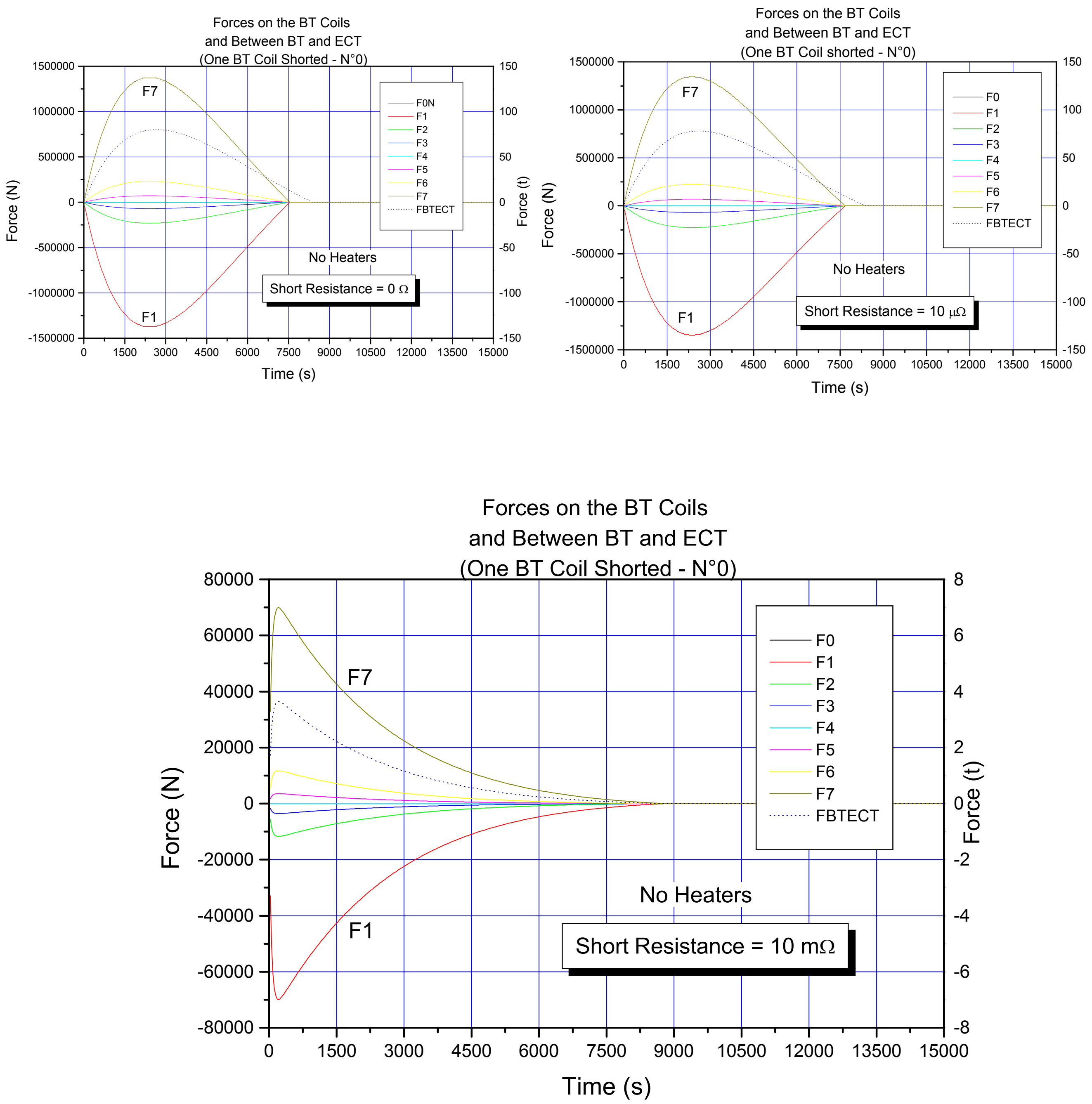

FIG. 5: Forces in the BT coil system and between BT and ECT when only one coil is shorted, for different values of the short resistance.

4.2 No Heater Actions, More Coil Shorted, Low Short Resistance (10 μΩ)

Here the behaviour of the coil system (current and forces) is shown in case of shorting of different numbers of adjacent coils (n° 0,1,2,3). The discharge occurs across the dump system with a complete fault of the heaters.

The short resistance considered is 10 μΩ.

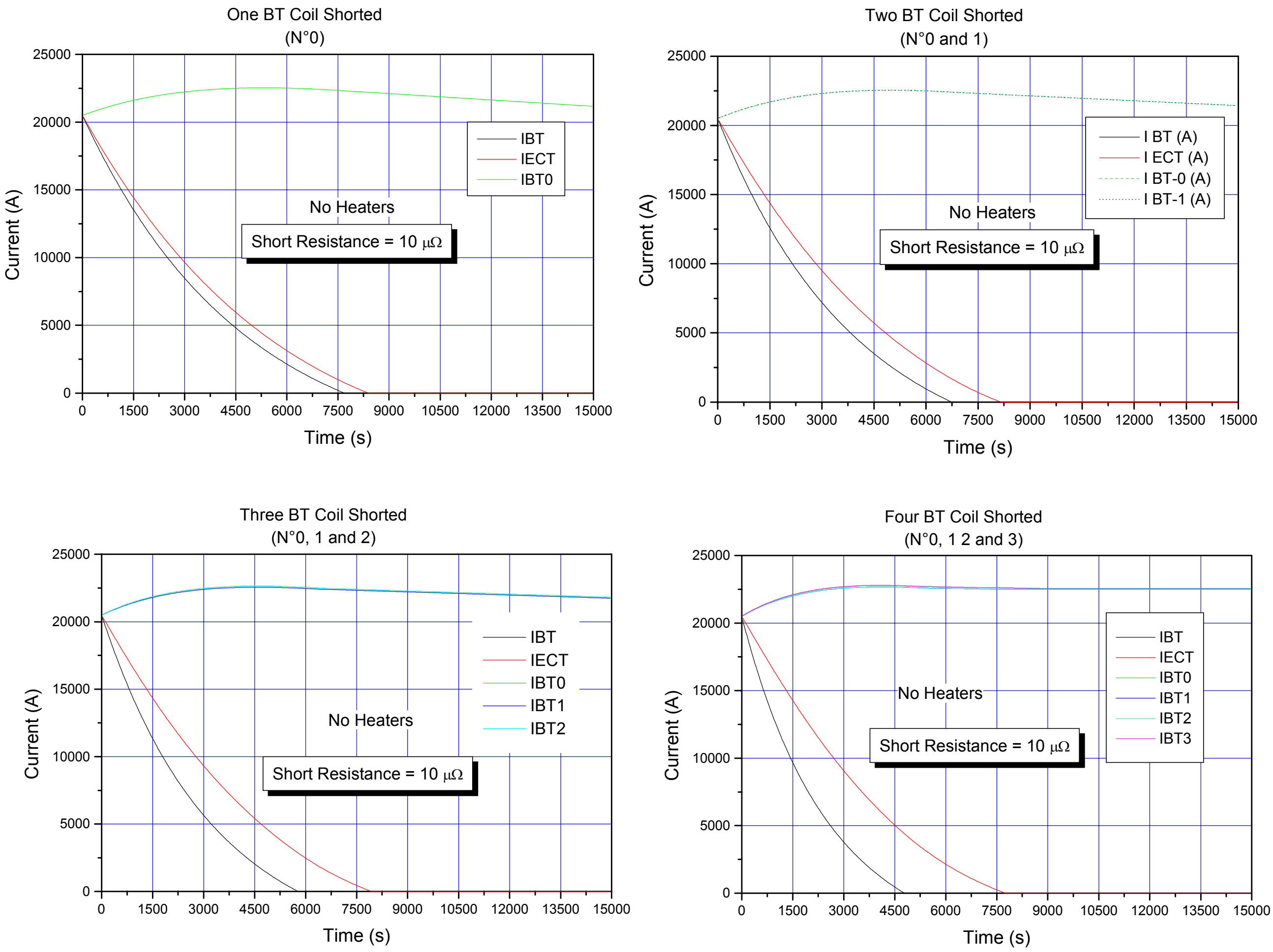

FIG. 6: Current in the BT, ECT and in the shorted coil, when one, two, three or four coils are shorted.

In Fig. 7 the forces between the BT coils and among the BT and ECT coil systems are plotted in case of one or more short in the BT coils.

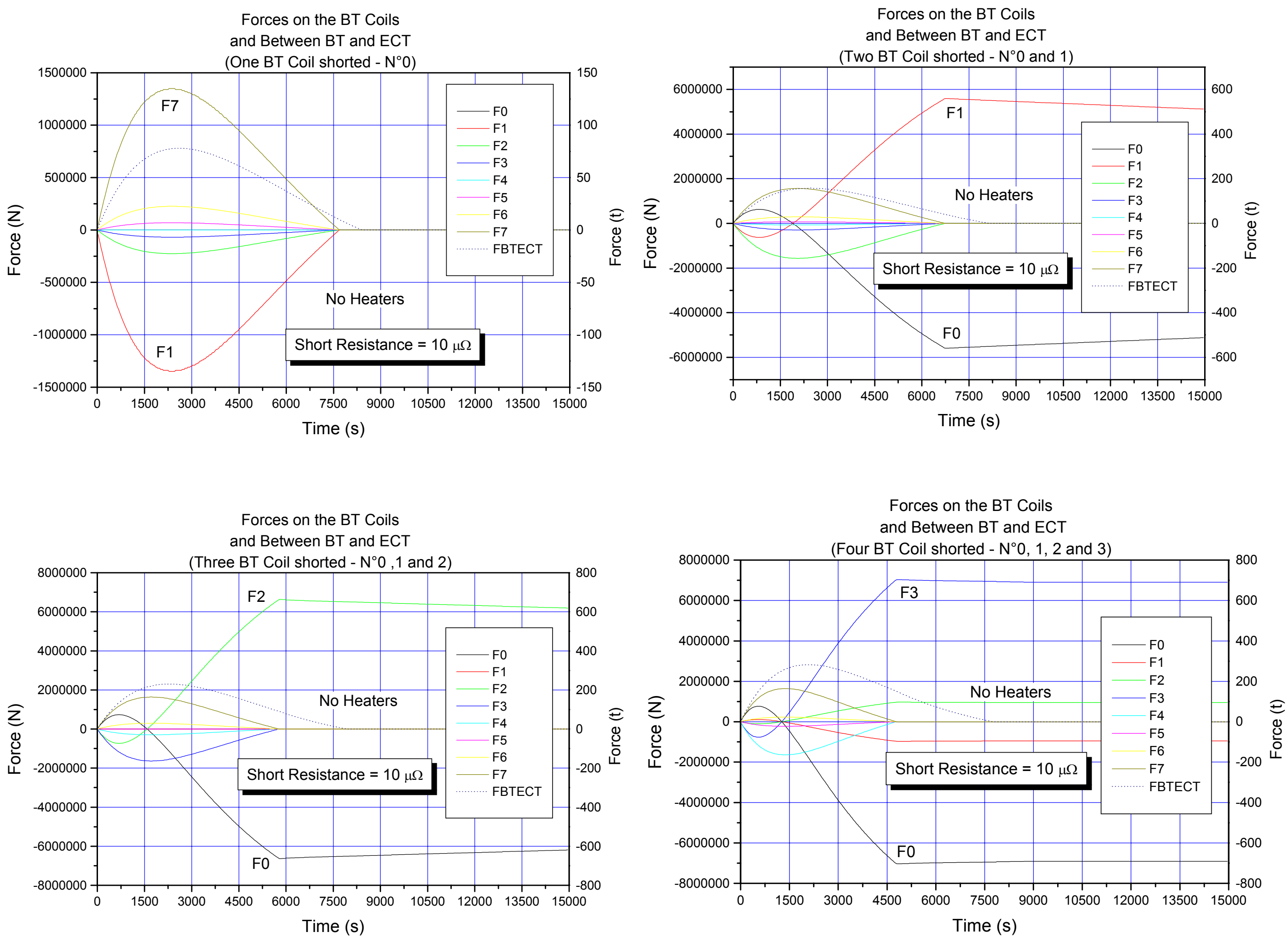

FIG. 7: Forces in the BT coil system and between BT and ECT whit different number of BT coils shorted.

4.3 Full Heater Actions, One Coil Shorted, Various Resistance (cases 3a, 3b and 3c)

Here the discharge with the action of the heaters in case of one short in the BT coil system is examined for different short resistances.

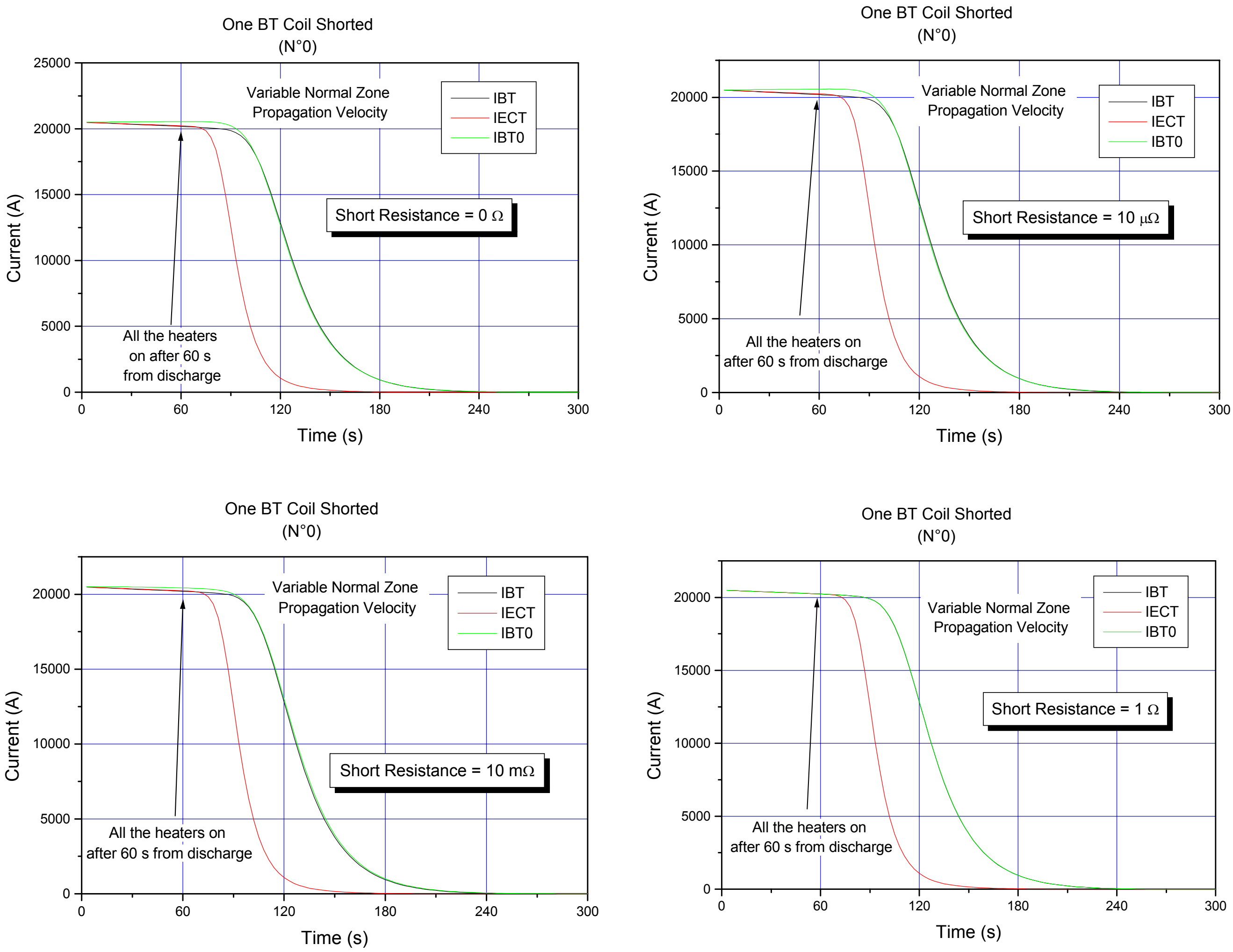

FIG. 8: Current in the BT, ECT and in the shorted coil, when one coil (BT0) is shorted, for various shorting resistance.

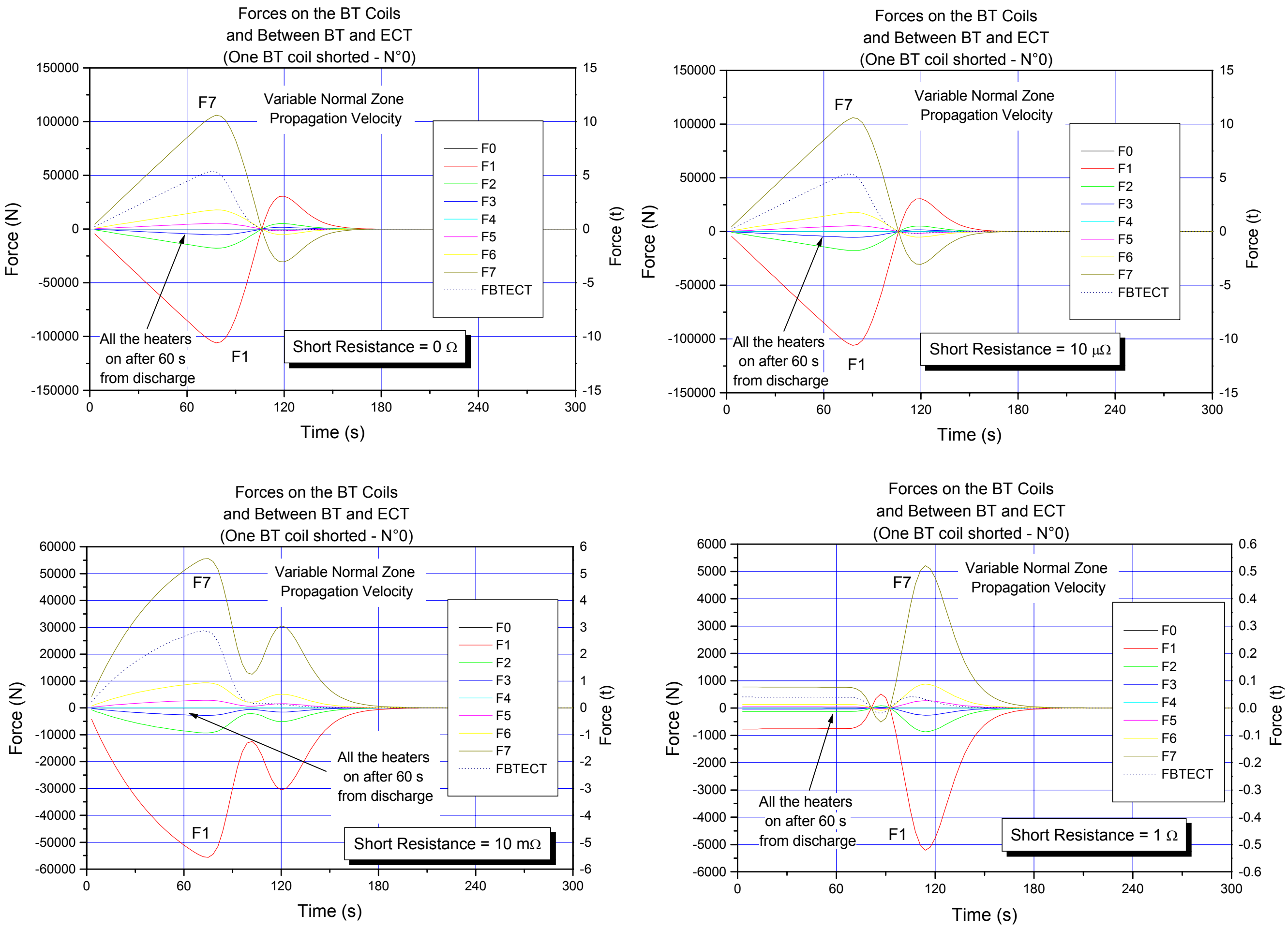

FIG. 9: Forces among the BT coils and between the BT and ECT coils when one coil (BT0) is shorted, for various shorting resistance.

It is worth noting that the forces and the current evolution depends, as obvious, on the value of the short resistance. The behaviour is quite similar when the resistance is relatively small (10 μΩ) or nul.

When the short resistance is relatively high (10 mΩ) the forces among the BT coils lowers, while increase the force between the BT and the ECT.

In the limiting case of very high short resistance (1 Ω), the current in the shorted and in the not shorted coils are about the same, so the forces in the BT system are very small, but the current unbalancing of the BT respect to the ECT are very high, leading to very high radial forces between the BT and the ECT.

For the detailed analysis of the forces in the BT coil system the following analysis, about the fault of the heater system when one BT coil is shorted, will be carried out for the "conservative" case of low short resistance (10μΩ).

4.4 BT Heaters Action, ECT Heaters Action, NO Heaters on the Shorted Coil

In this case the currents and forces are plotted in Fig. 10 and 11 respectively.

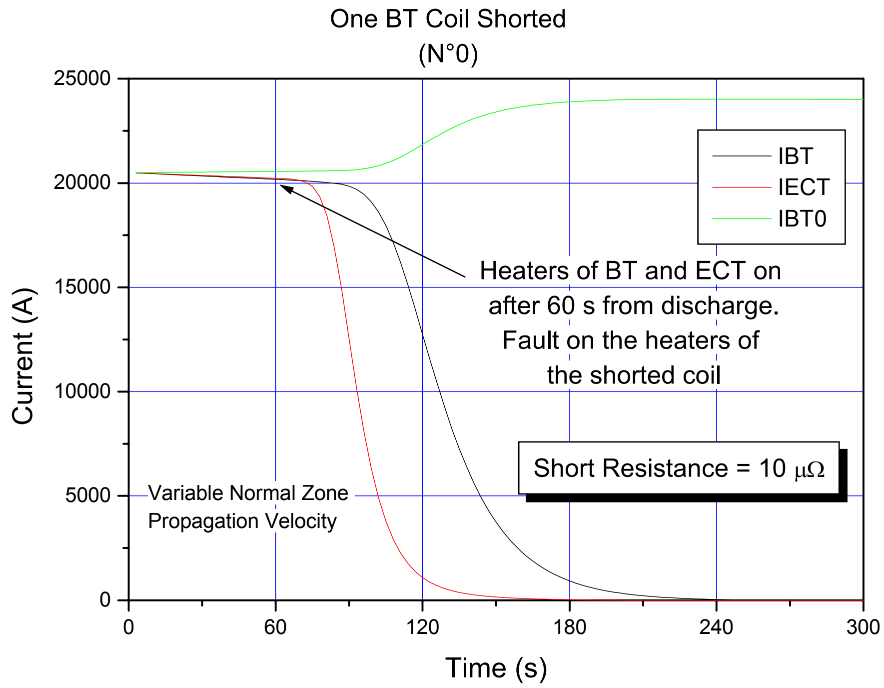

FIG. 10: Current in the BT, ECT and shorted BT coil. Firing of the heaters 60 s after the beginning of the magnet discharge. The shorted coil heater fault.

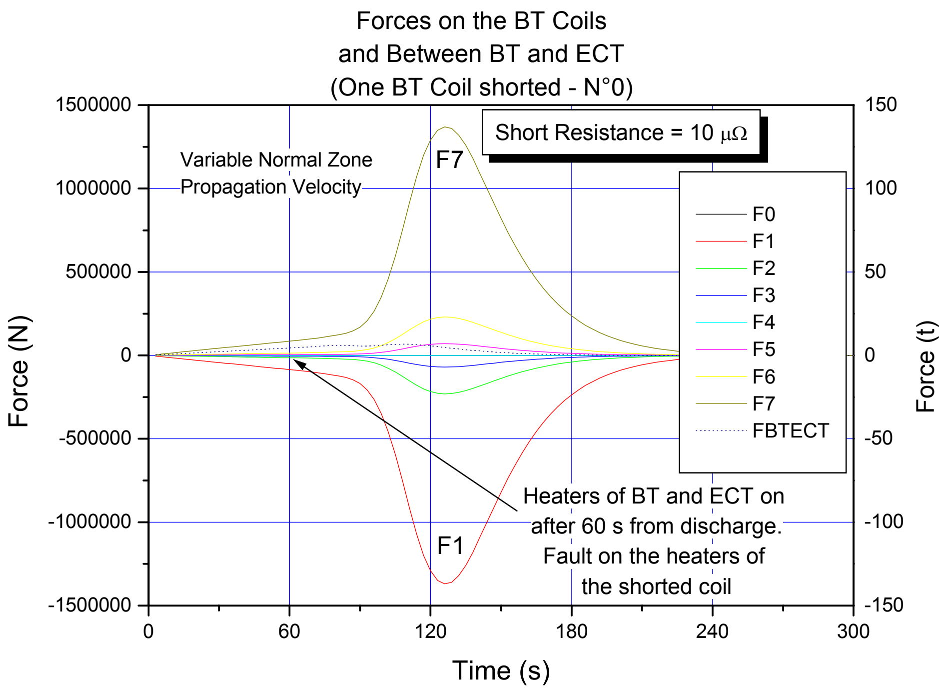

FIG. 11: Forces among the BT coils and between BT and ECT. The shorted coil heater fault.

4.5 BT Heaters Action, NO ECT Heaters Action, Heaters on the Shorted Coil

In this case the currents and forces are plotted in Fig. 12 and 13 respectively.

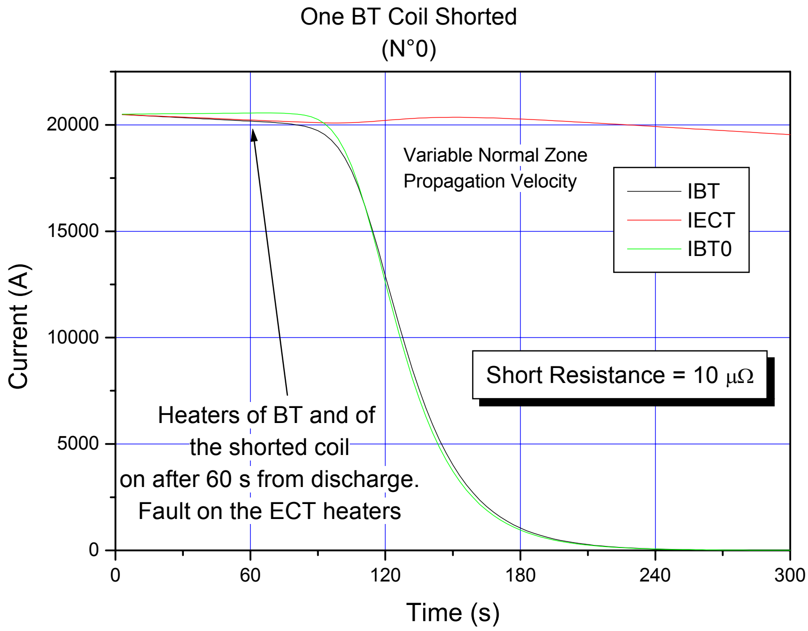

FIG. 12: Current in the BT, ECT and shorted BT coil. Firing of the heaters 60 s after the beginning of the magnet discharge. The ECT coil heater fault.

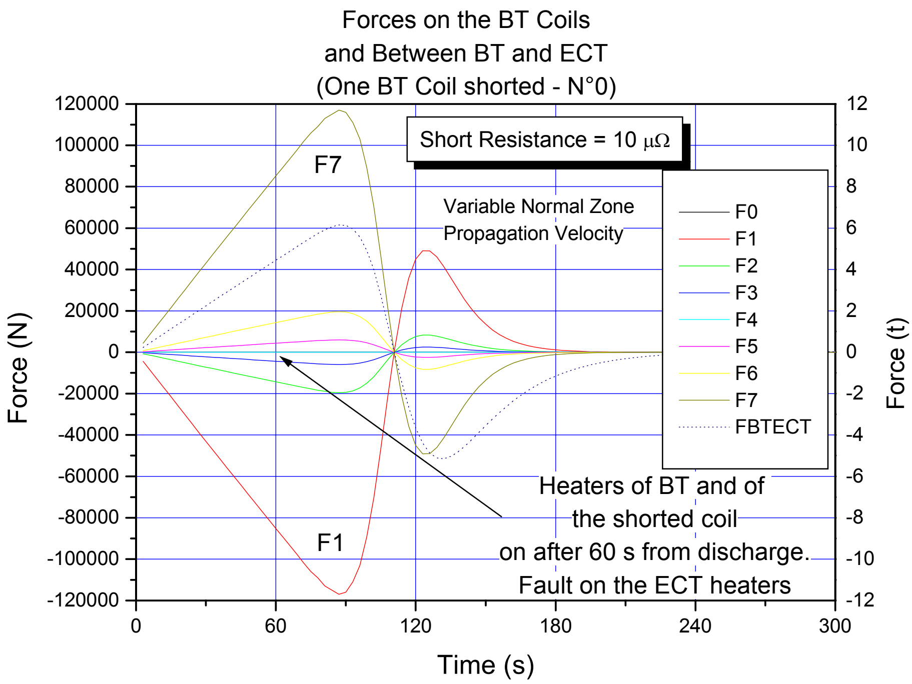

FIG. 13: Forces among the BT coils and between BT and ECT.
The ECT coil heater fault.

4.6 BT Heaters Action, NO ECT Heaters Action, NO Heaters on the Shorted Coil

In this case the currents and forces are plotted in Fig. 14 and 15 respectively.

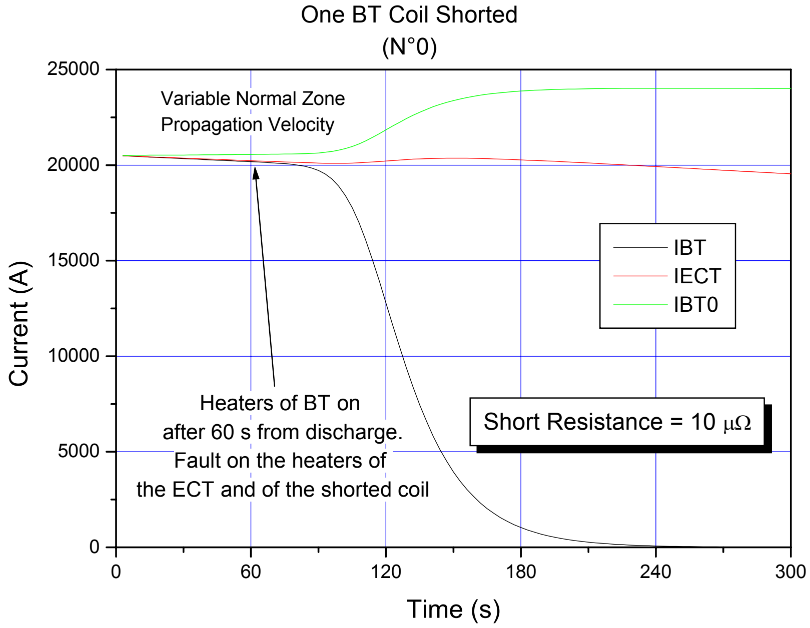

FIG. 14: Current in the BT, ECT and shorted BT coil. Firing of the heaters 60 s after the beginning of the magnet discharge. The ECT and the shorted coil heater fault.

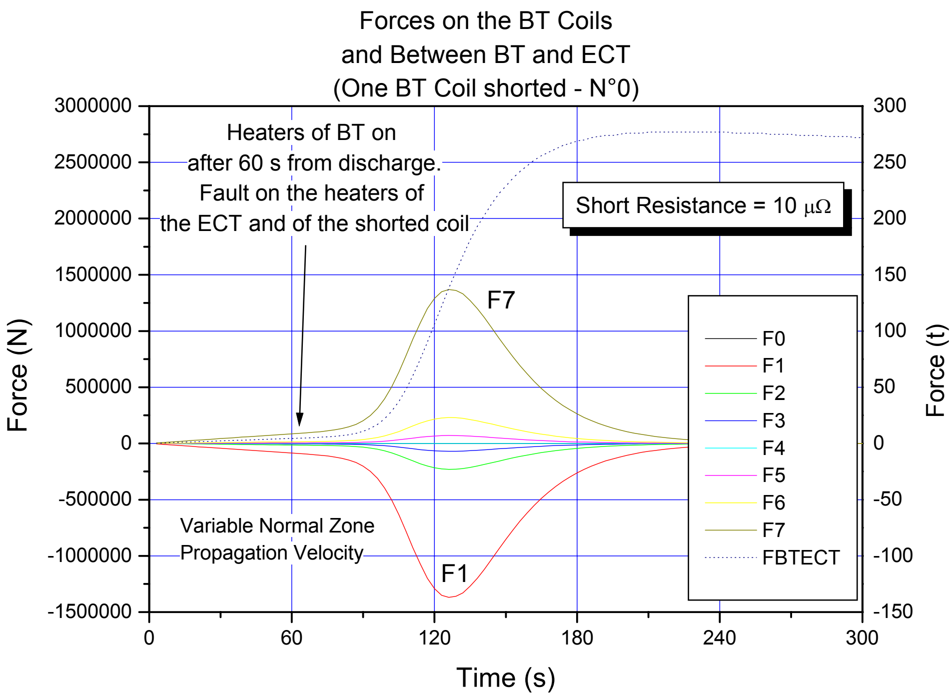

FIG. 15: Forces among the BT coils and between BT and ECT. The ECT and the shorted coil heater fault.

4.7 NO BT Heaters Action, ECT Heaters Action, Heaters on the Shorted Coil

In this case the currents and forces are plotted in Fig. 16 and 17 respectively.

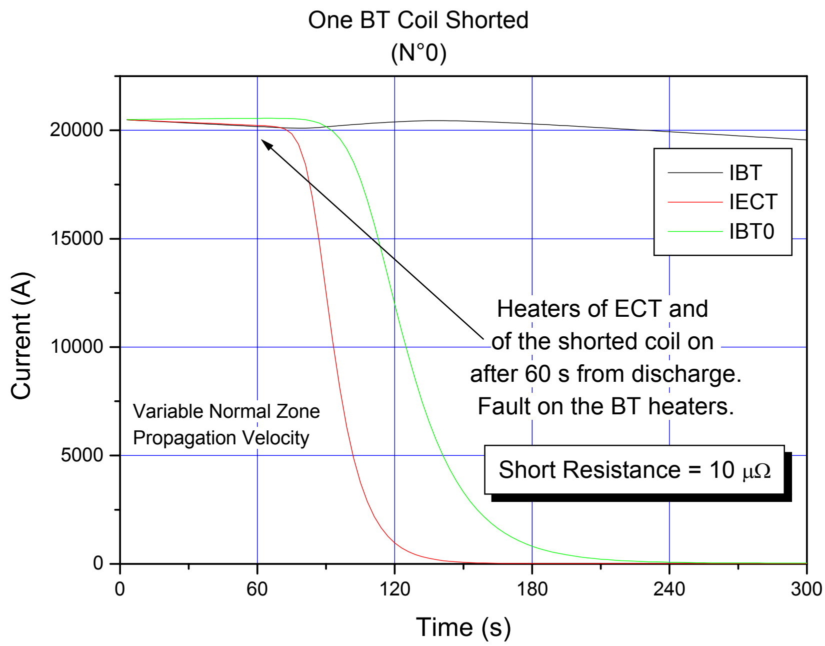

FIG. 16: Current in the BT, ECT and shorted BT coil. Firing of the heaters 60 s after the beginning of the magnet discharge. The BT coil heater fault.

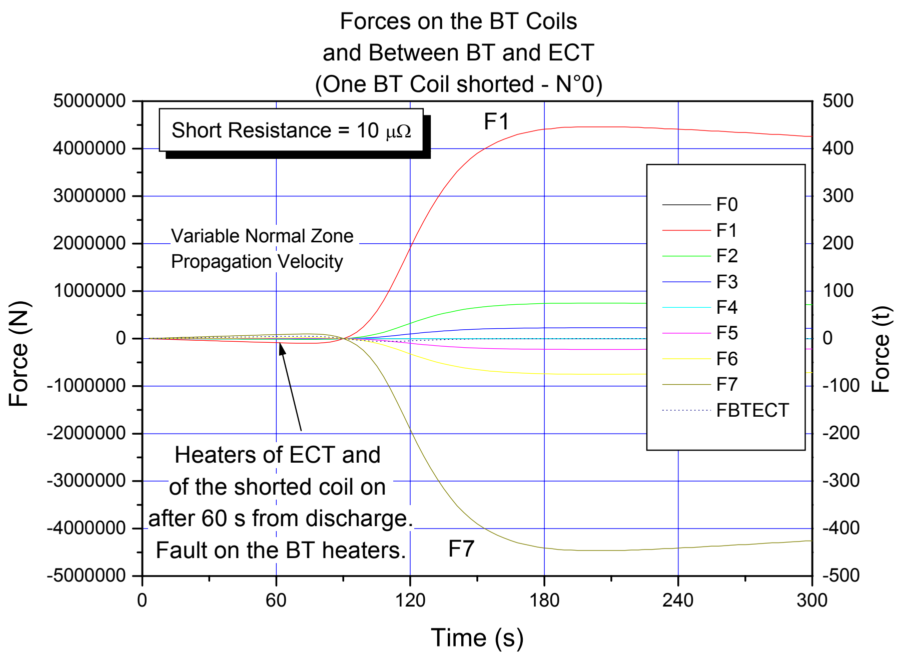

FIG. 17: Forces among the BT coils and between BT and ECT. The BT coil heater fault.

4.8 NO BT Heaters Action, NO ECT Heaters Action, Heaters on the Shorted Coil

In this case the currents and forces are plotted in Fig. 18 and 19 respectively.

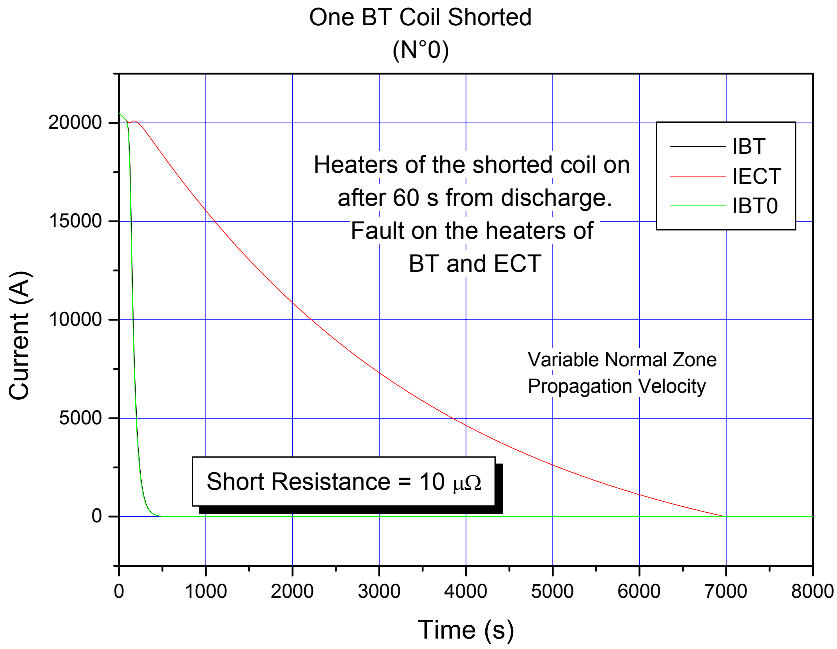

FIG. 18: Current in the BT, ECT and shorted BT coil. Firing of the heaters 60 s after the beginning of the magnet discharge. The BT and ECT coil heater fault.

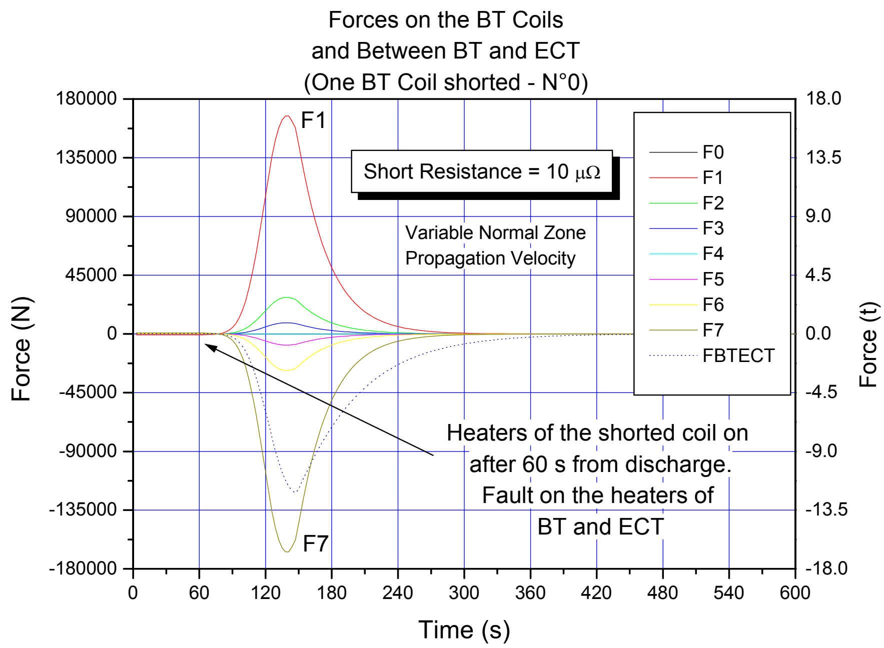

FIG. 19: Forces among the BT coils and between BT and ECT.
The BT and ECT coil heater fault.

4.9 NO BT Heaters Action, ECT Heaters Action, NO Heaters on the Shorted Coil

In this case the currents and forces are plotted in Fig. 20 and 21 respectively.

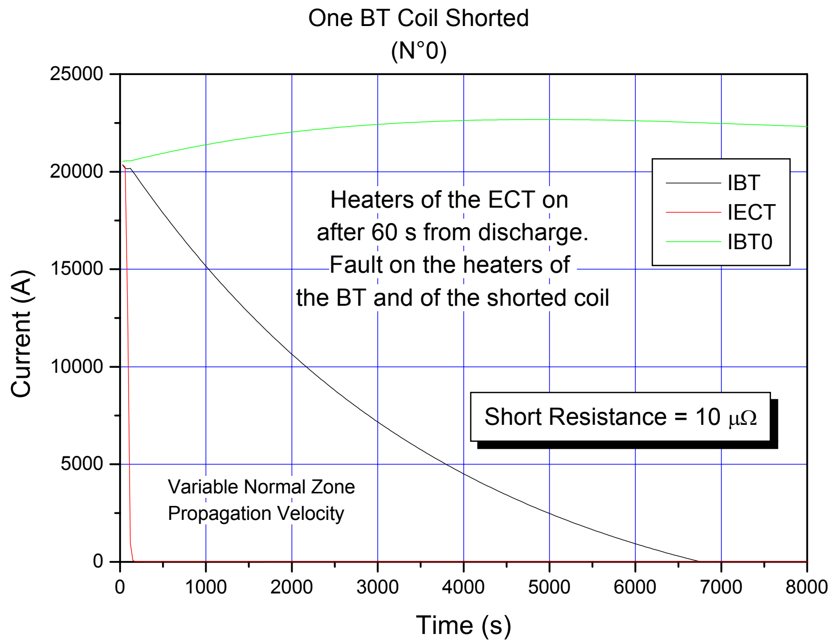

FIG. 20: Current in the BT, ECT and shorted BT coil. Firing of the heaters 60 s after the beginning of the magnet discharge. The BT and shorted coil heater fault.

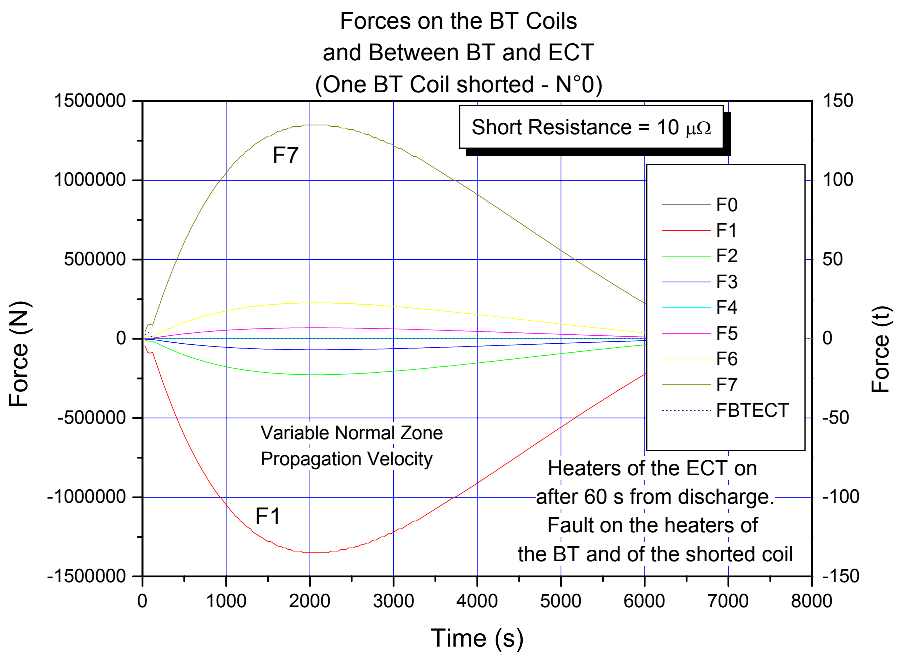

FIG. 21: Forces among the BT coils and between BT and ECT. The BT and shorted coil heater fault.

5 CONCLUSIONS

The forces arising from an unbalancing in the BT coil current has been calculated, as already done in[3]. The definitive configuration of the power circuit, does not lead to significative differences respect to what already known.

Azimuthal forces, up to 450 tons, between two adjacent BT coil can arise; radial forces up to about 270 tons can arise between the BT and ECT coils, depending on the case.

The value of the shorting resistance deeply affects the current behaviour and consequently the forces acting in the magnet system; unfortunately the value of the shorting resistance is unpredictable, the calculation are done with a low value of resistance, in a conservative situation, i.e. leading to the highest forces.

These intense forces arise, of course, when the current unbalancing is high; this case happens when a fault in the heater system occurs, by which one or two coil systems are not dumped.

For this reason a high reliability in the dump and protection system is mandatory.

6 ACKNOWLEDGEMENTS

The author wish to thanks Mr. G.Baccaglioni and G. Cartegni for the fruitful discussion during the development of this work.

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