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Comments on RHIC Beam Abort Sweeper Magnet

W. Q. Feng

June 1994

Collider Accelerator Department

Brookhaven National Laboratory

U.S. Department of Energy

USDOE Office of Science (SC)

DISCLAIMER

AD/RHIC/RD-68

RHIC PROJECT

Brookhaven National Laboratory

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Assumptions:

(1) Driving current: semisine $\tau = 40\ \mu S$ $I_{max} = 18$ kA (Fig. 3)

(2) Magnet core material: 4% silicon steel Lam. thickness, d = 0.002" - 0.008"

(3) No of turns, N,: 4

(4) Shape as shown in Fig. 1.

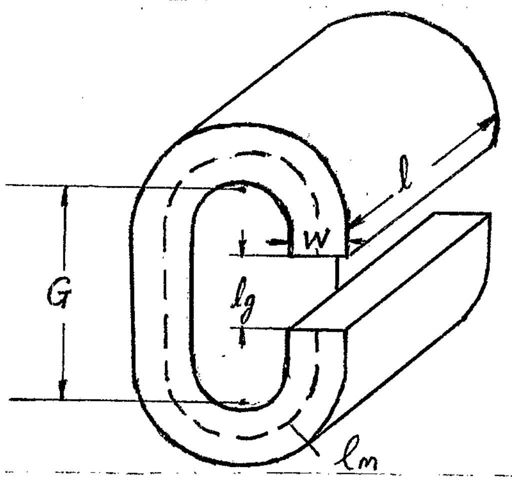
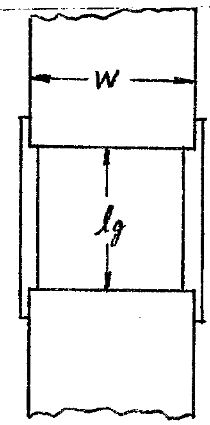


Fig. 1 a) Core



b) Gap

G	≈	13 cm
ℓ_m	≈	76 cm
ℓ	=	7.6 cm
ℓ_g	=	8.1 cm
w	=	8.9 cm

Results:

1. Magnetic Flux Density

Analytic calculation:

$$B = \frac{0.4\ \pi\ N\ I x 10^{-4}}{l_g + l_m/\mu_r} (T) [\textit{Generally } l_g >> l_m/\mu_r \textit{ because of } \mu_r \textit{ is in the range } 200-6000] \tag{1}$$

$= 1.0672$ (T)

Computer Simulation: (Fig. 2)

B (static) $= 0.979352$(T)

B_{max} (transient) $= 1.036275$(T) (Fig. 4)

The magnetic flux density, B, obtained by computer simulation is less than B from equation (1) because of fringing flux, which is a function of gap dimension, the shape of the pole faces and the shape, size and location of the winding and the shape and size of the window. Fringe flux is a larger percentage of the total for large gaps.

Note B_{max} (transient) is larger than B (static). This is because of the eddy current magnetic shielding effect of the copper plates which decreases the fringing flux.

2. <u>Inductance</u>

$$L = \frac{0.4\,\pi\,N^2\,w\,x\,10^{-6}}{l_g\,(1 + l_m/\mu_r)}\,F\,(H/m) \qquad (2)$$

where F is a fringing flux factor given by:

$$F = 1 + \frac{l_g}{\sqrt{A_c}}\ln\left(\frac{2G}{l_g}\right) \qquad (3)^*$$

where A_c is the cross sectional area.

Substituting the given values, we have

$L = 46.9\ \mu H/m\ (F = 2.12)$

*Colonel Wm. T. McLyman, Transformer and Inductor Design Handbook, 1988.

The computer simulation gives:

L (statics) = 44.2396 μH/m

L (Transient) = 41 ~ 65 μH/m (including calculation error) (Fig. 5)

Actually, when the core air gap length, l_g, is large compared to the ratio l_m/μ_r because of high relative permeability μ_r, variations in μ_r (200 - 6000) do not substantially affect the total effective magnetic path length or the inductance. A final determination of the air gap size requires consideration of the effect of fringing flux, which is a function of gap size, the shape of the pole faces and the shape, dimension and location of the winding and window. Its net effect is to decrease the total reluctance of the magnetic path and therefore increase the inductance by a factor F, as in Equation (2), (3).

Eddy currents, which lag the driving current and have different values and directions at different time, cause the inductances to vary during the pulse period compared to the static inductance.

3. Power Loss

Calculations show that the main part of the magnetic energy loss, which include two parts due to eddy currents and hysteresis, is eddy current loss.

The magnitude of eddy currents depends on the frequency and flux density imposed by the application and on the specific resistivity and thickness of the core material and conductive material in the magnetic field.

So in our situation, the eddy current loss in the copper plates are the most important part (~ 150 J/m for 0.1" thick copper plates). The loss in the coils is about 80 - 90 J/m (4 turns), and in the core the loss is less than 1 J/m (0.008" steel Lam.). Calculations show that the maximum stored energy amounts to more than 6700 J/m (I_{max} = 18 kA).

The eddy-current loss is reduced as the lamination thickness is reduced, this is also true of the copper plates.

4. Quality of the Magnetic Field in the Air-Gap

Although the eddy current loss in the two copper plates is large, the quality of the magnetic flux density in air-gap is much improved due to the eddy current fields of the copper plates, which increases the center flux density B_{yc}, make the homogeneity of B_y better and decreases the harmonics of B_y. The calculation results are shown in Table 1.

Table 1

	B_{yc} (T)	$\frac{\Delta B}{B_{yc}}(R=0.035m)$	ΔH (R =0.04m)
Statics	0.993953 (x = 0.01715, y = 0)	> 10%	~ 4%
Transient	1.036275 (x = 0.05715, y = 0)	< 1% (0.1% - 1%)	0.2 ~ 2%

where B_{yc} is the maximum value along y = 0 (x = 0.01715 - 0.09715), the center point in the coordinate system is located at x = 0.05715, y = 0 and

$$\frac{\Delta B}{B_{yc}} = \frac{B(x.y) - B_{yc}}{B_{yc}}, \ \Delta H = \frac{B_y\ (sextupole)}{B_y\ (dipole)}$$

(R is the radius of a circle with center at x = 0.05715, y = 0.) (Fig. 2)

More calculations are needed to quantitatively verify that the thinner copper plate will improve the quality of the field.

5. Voltage Between Core Laminations

Generally

$$v = \oint \vec{E}.\vec{dl} = -\int_s \frac{d\vec{B}}{dt} \cdot \vec{ds} \tag{4}$$

Because

$$\int_s \frac{d\vec{B}}{dt} \cdot \vec{ds} < \frac{d\phi}{dt} = \frac{SdB_{mod}}{dt} \tag{5}$$

and

$$\frac{dB_{mod}}{dt} \propto \frac{di}{dt} \tag{6}$$

for semi-sine waveform

$$(\frac{dB}{dt})_{max} = (\frac{dB}{dt})_{t=o} \tag{7}$$

And there are different

$$(\frac{dB}{dt})_{t=o}$$

at different points (x, y) in the core.

We obtain:

$$V_{max} = \frac{d\phi}{dt} = 0.01V\ (0.008''),\ 0.005V\ (0.004''),\ 0.0025V\ (0.002'')$$

6. Forces on Conductors

The quantitative relation for the force on a current element in a magnetic field is:

$$dF = IBdl \sin\phi$$

In our situation

$$F = \int_s \vec{J} \times \vec{B} ds$$

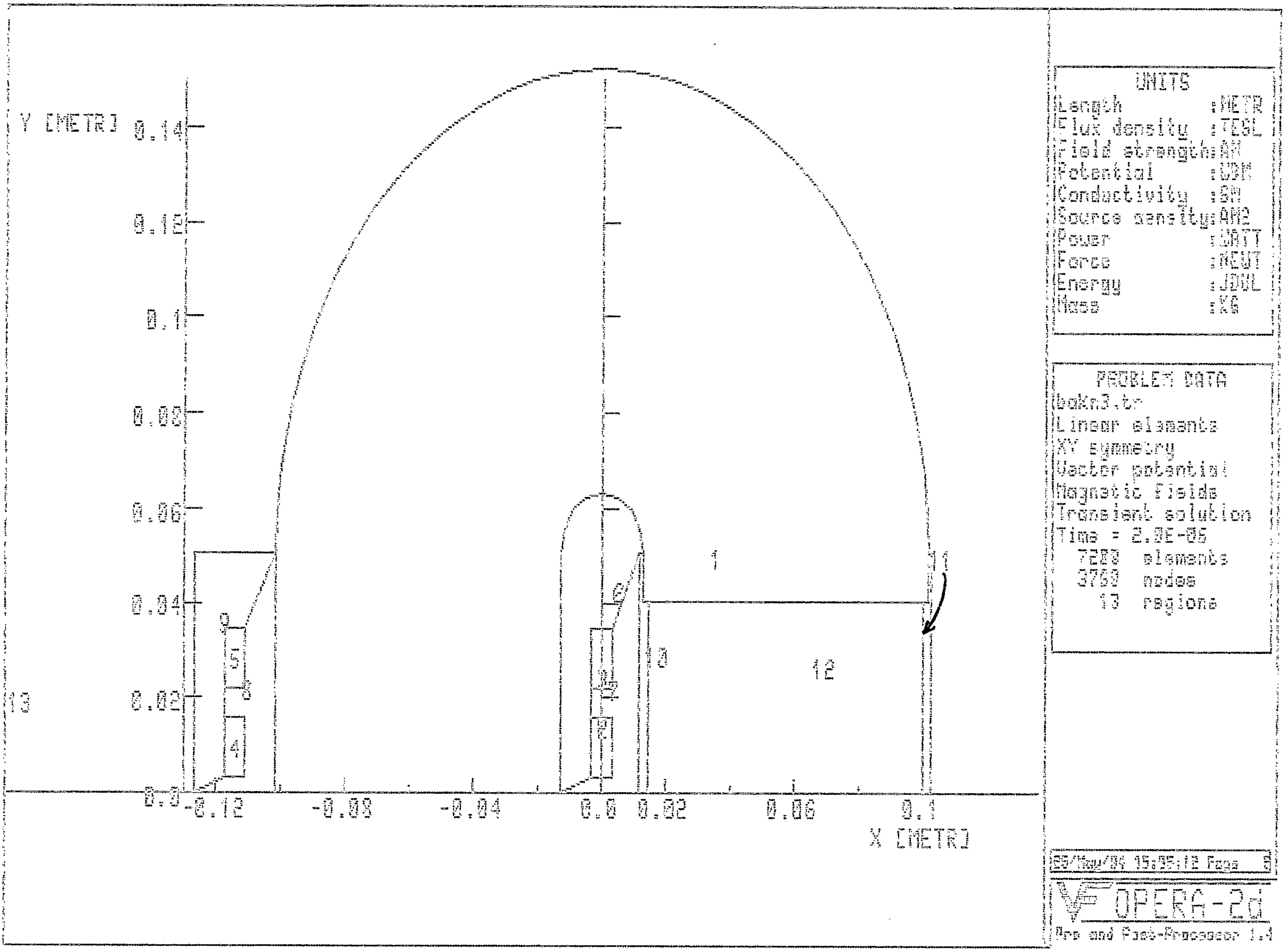
where F is the Force/unit length

and J is the current density.

Because the excitation is not direct current, eddy currents in each conductor lead to the forces on them. The forces on coils depend on both the excitation current and eddy currents, but the excitation current is primary cause. The maximum magnitude of the forces on coils occur when the value of the excitation current comes up to the maximum, as shown in Figs. 10 through 17.

The forces on two copper plates and on the steel-core depend on eddy currents, but the force on the core is very small (less than 1 N/m).

It is important to treat carefully the two copper plates because of their special location, thinness and the large forces on them, see Figs. 2 and 6 through 9.

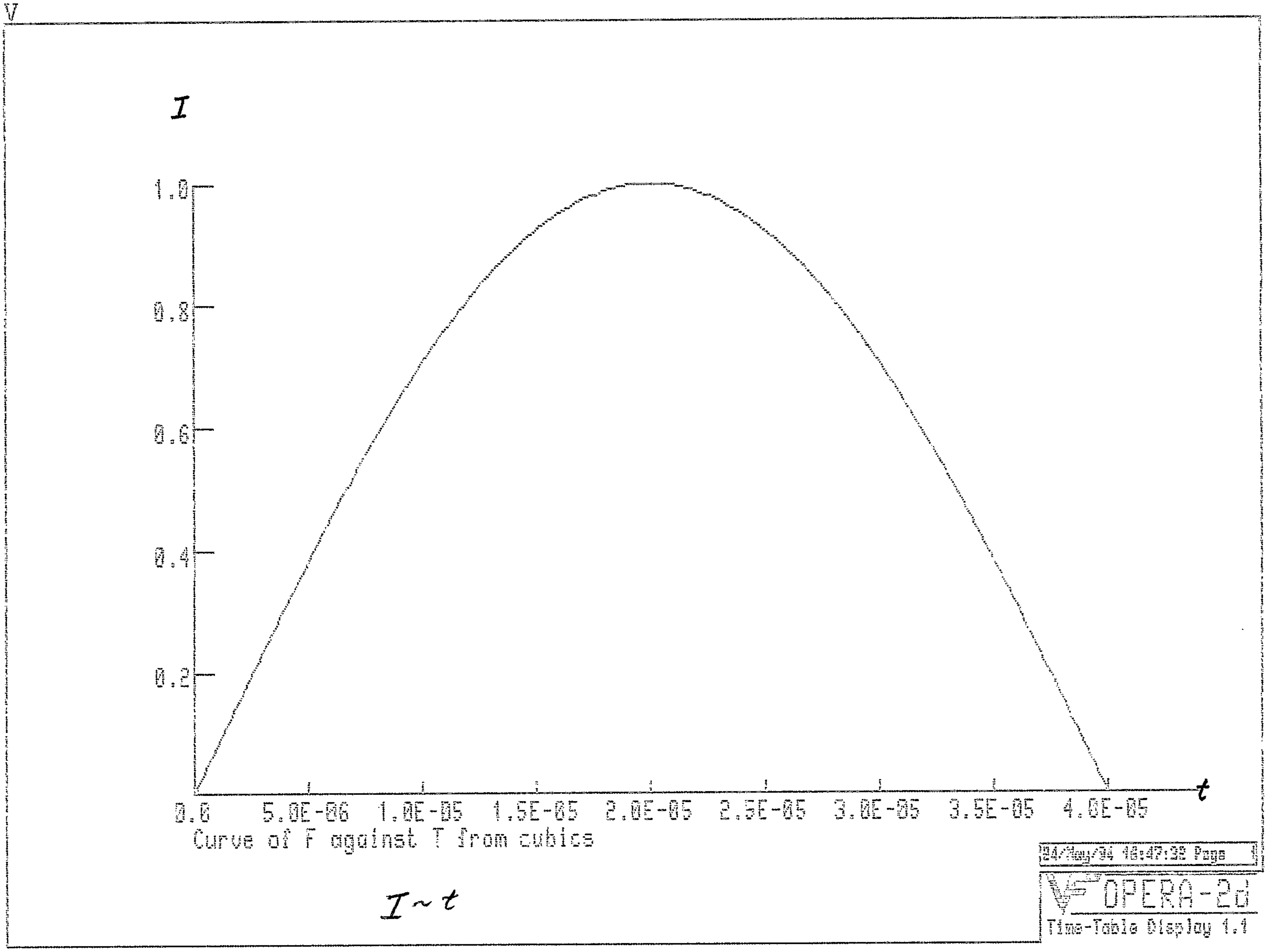


Region 1 — silicon-steel core (0.002"–0.008")

Region 2.3.4.5 — coils

Region 10, 11 — copper plates (d=2.54 mm)

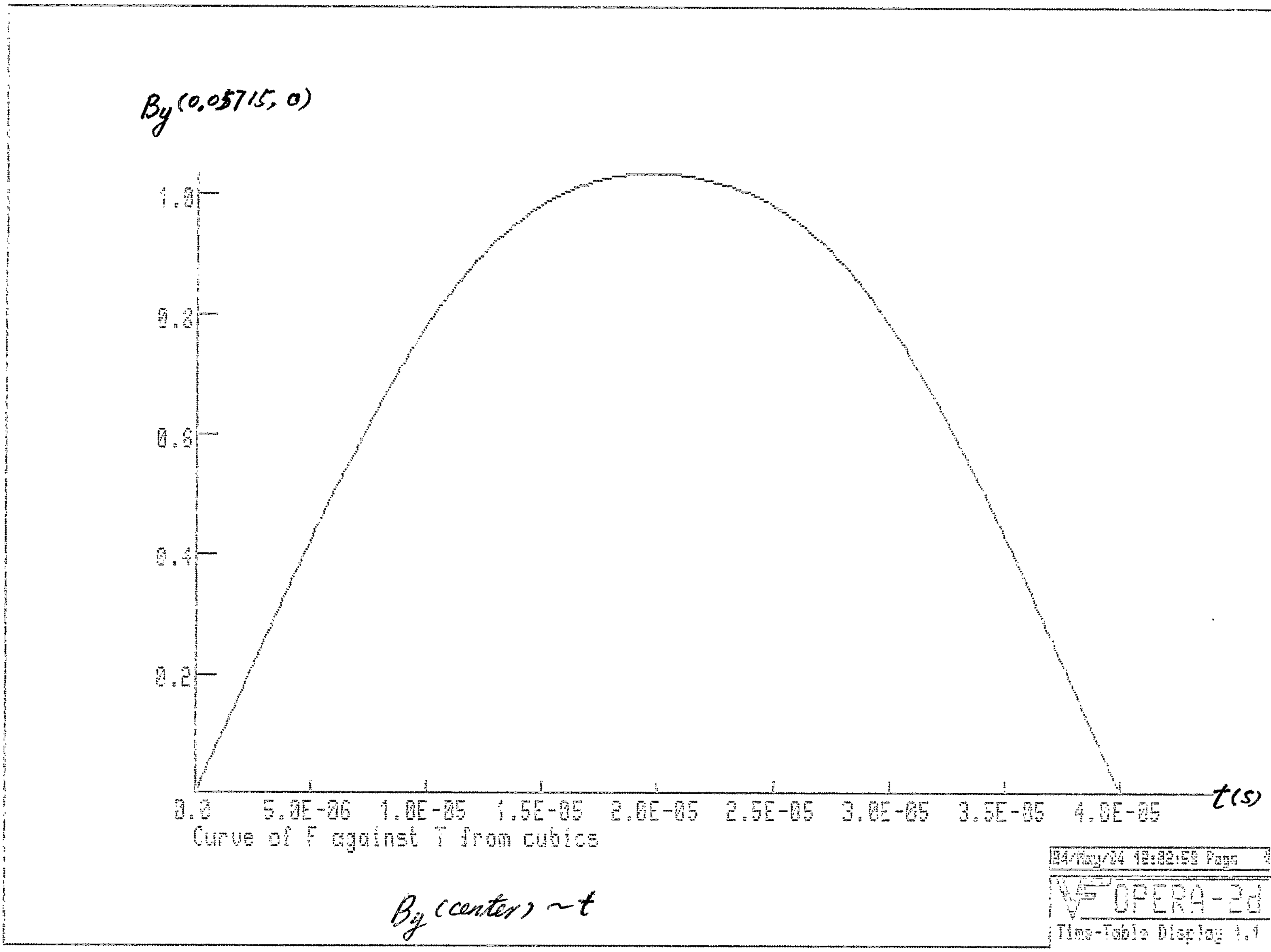
Fig. 2



I —— driving current

$I_{max} = 18KA.$

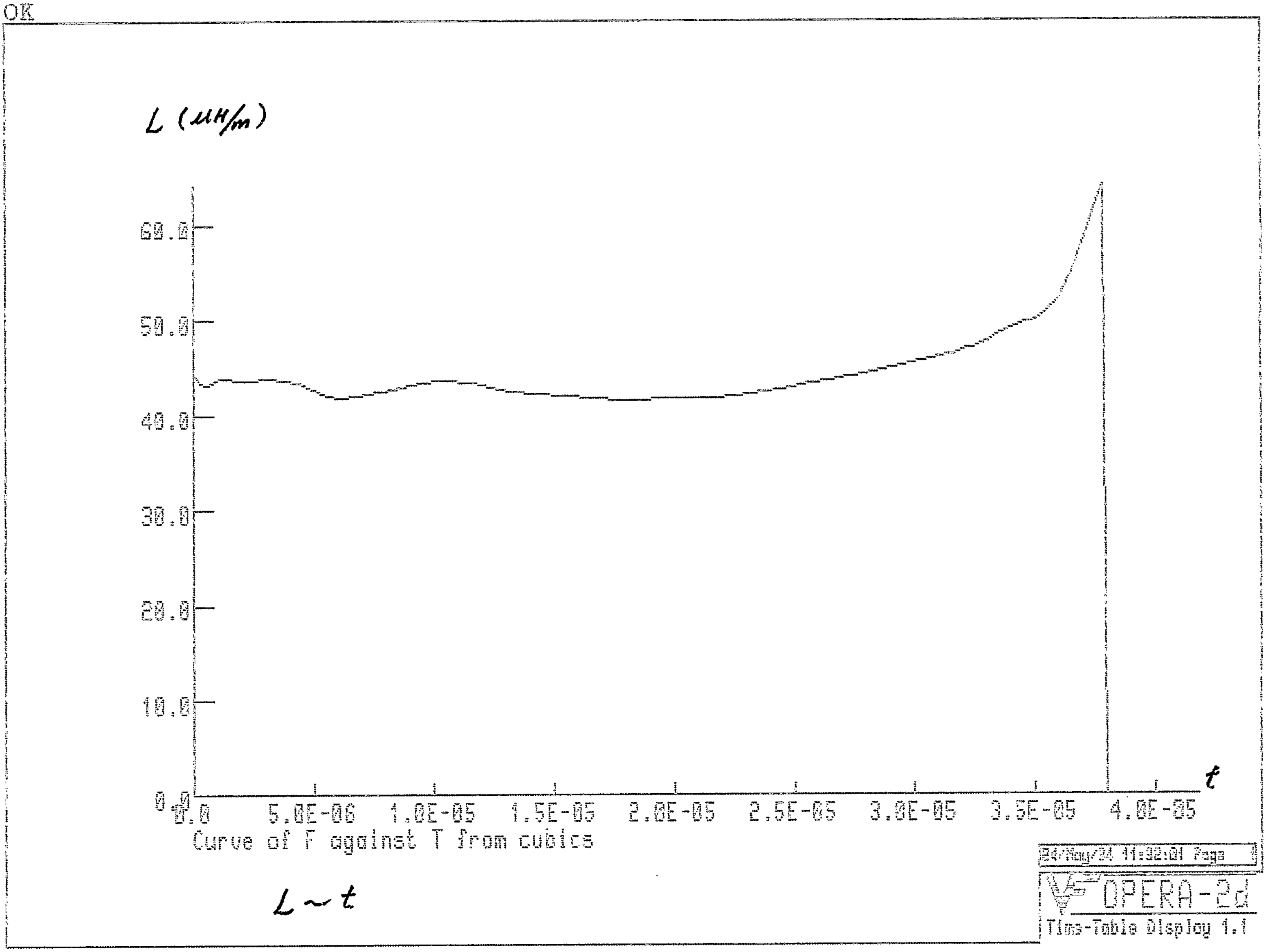
Fig.3



t	By (T)
0.00000	0.00000
1.000E-6	0.087548
2.000E-6	0.174562
4.000E-6	0.344814
6.000E-6	0.506463
8.000E-6	0.655311
1.000E-5	0.785215
1.200E-5	0.885715
1.400e-5	0.958679
1.600E-5	1.005591
1.800E-5	1.029565
2.000E-5	1.036275
2.200E-5	1.024528
2.400E-5	1.000826
2.600E-5	0.954861
2.800E-5	0.882499
3.000E-5	0.783429
3.200E-5	0.655069
3.400E-5	0.506361
3.600E-5	0.344736
3.800E-5	0.174499
4.000e-5	0.000053

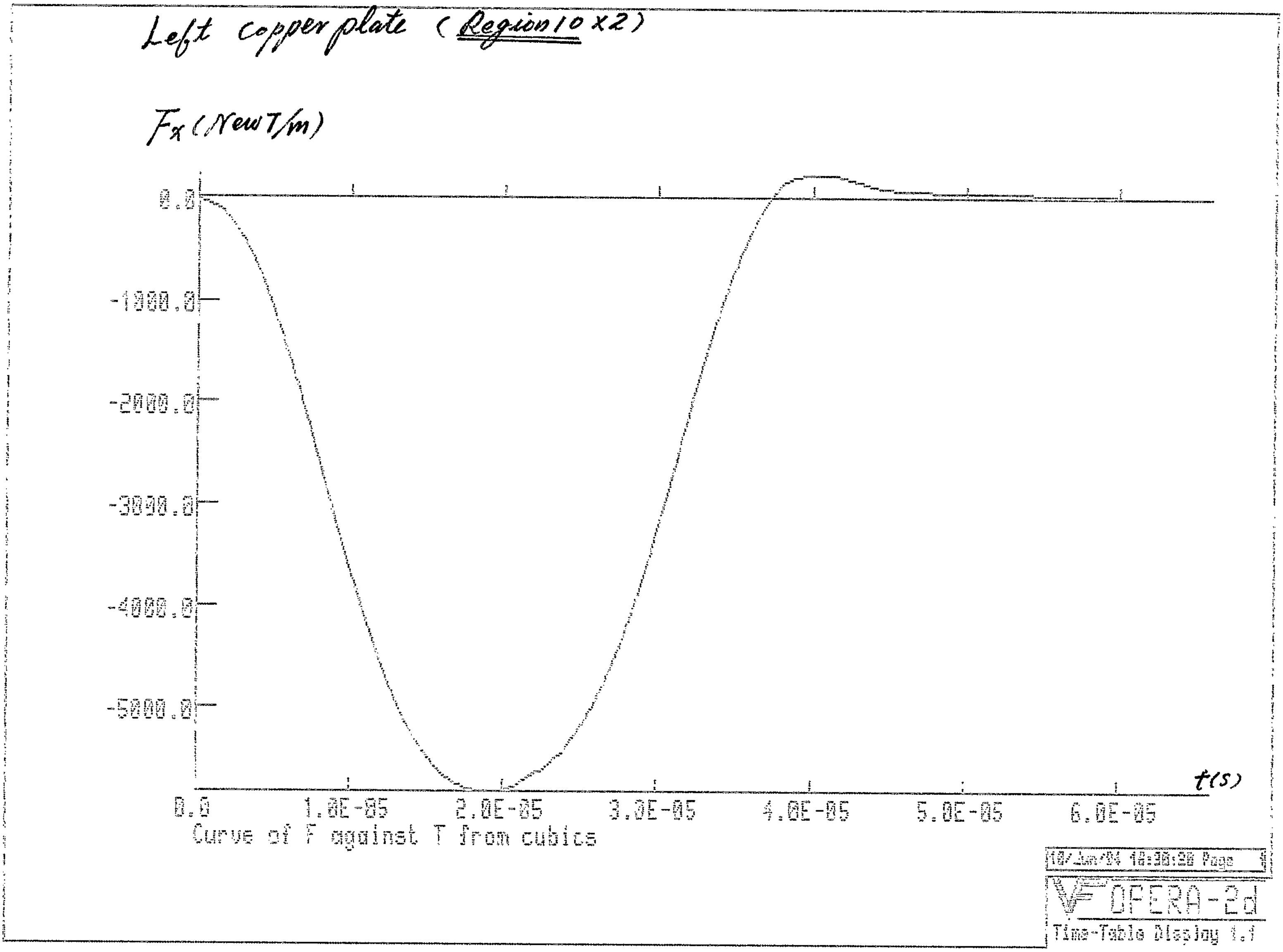
Fig. 4

OK



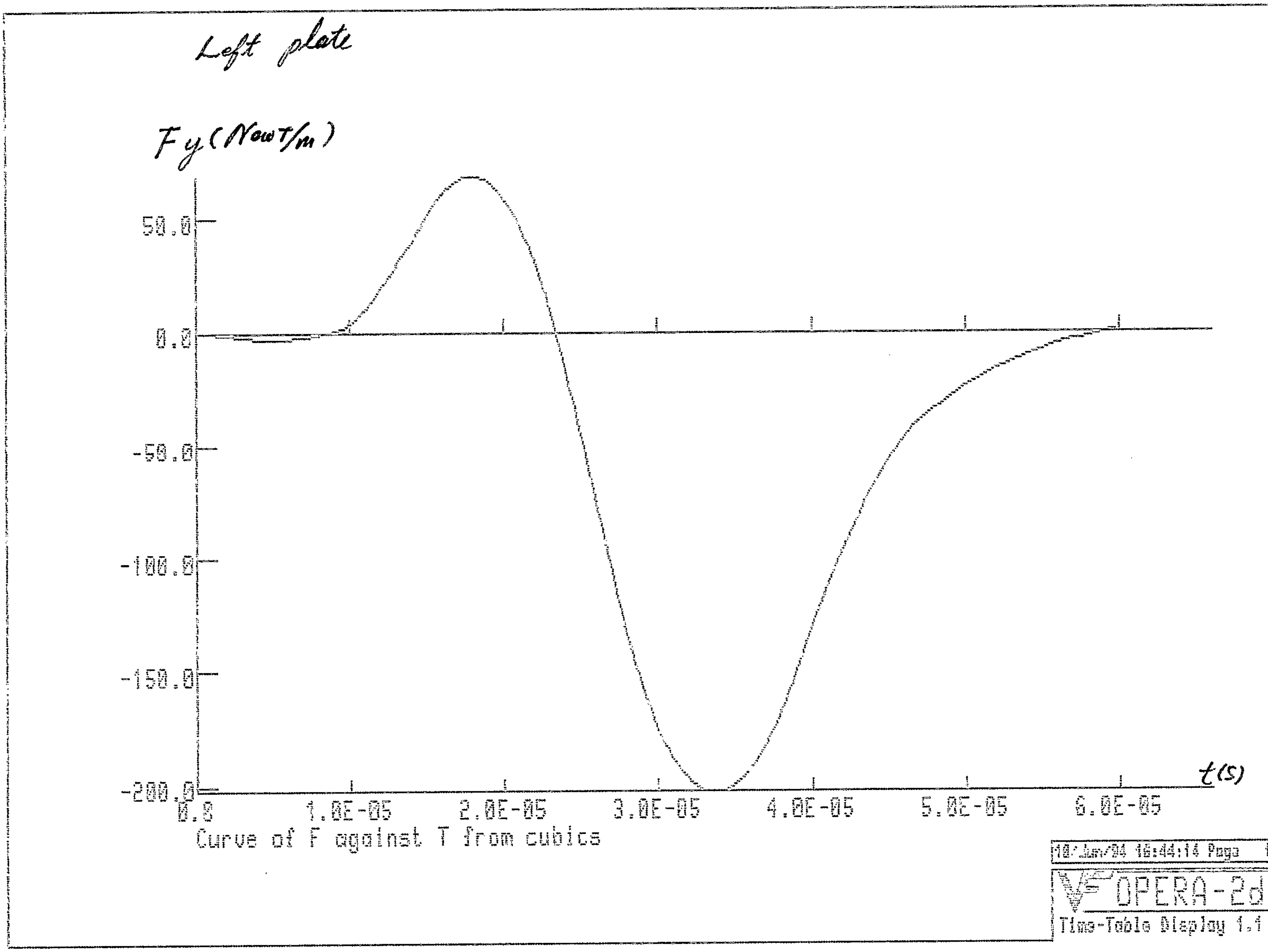
t (s)	L (μH/m)
Static	44.2396
5.000E-7	43.201
1.000E-6	43.7158
2.000E-6	43.723
4.000E-6	43.641
6.000E-6	41.9201
8.000E-6	42.5839
1.000E-5	43.5577
1.400E-5	42.3398
1.600E-5	41.9393
1.800E-5	41.6494
2.000E-5	41.8097
2.200E-5	41.9275
2.400E-5	42.6011
2.600E-5	43.4813
2.800E-5	44.4262
3.000E-5	45.5149
3.200E-5	46.8286
3.400E-5	49.1766
3.600E-5	52.4965
3.800E-5	65.5913

Fig. 5



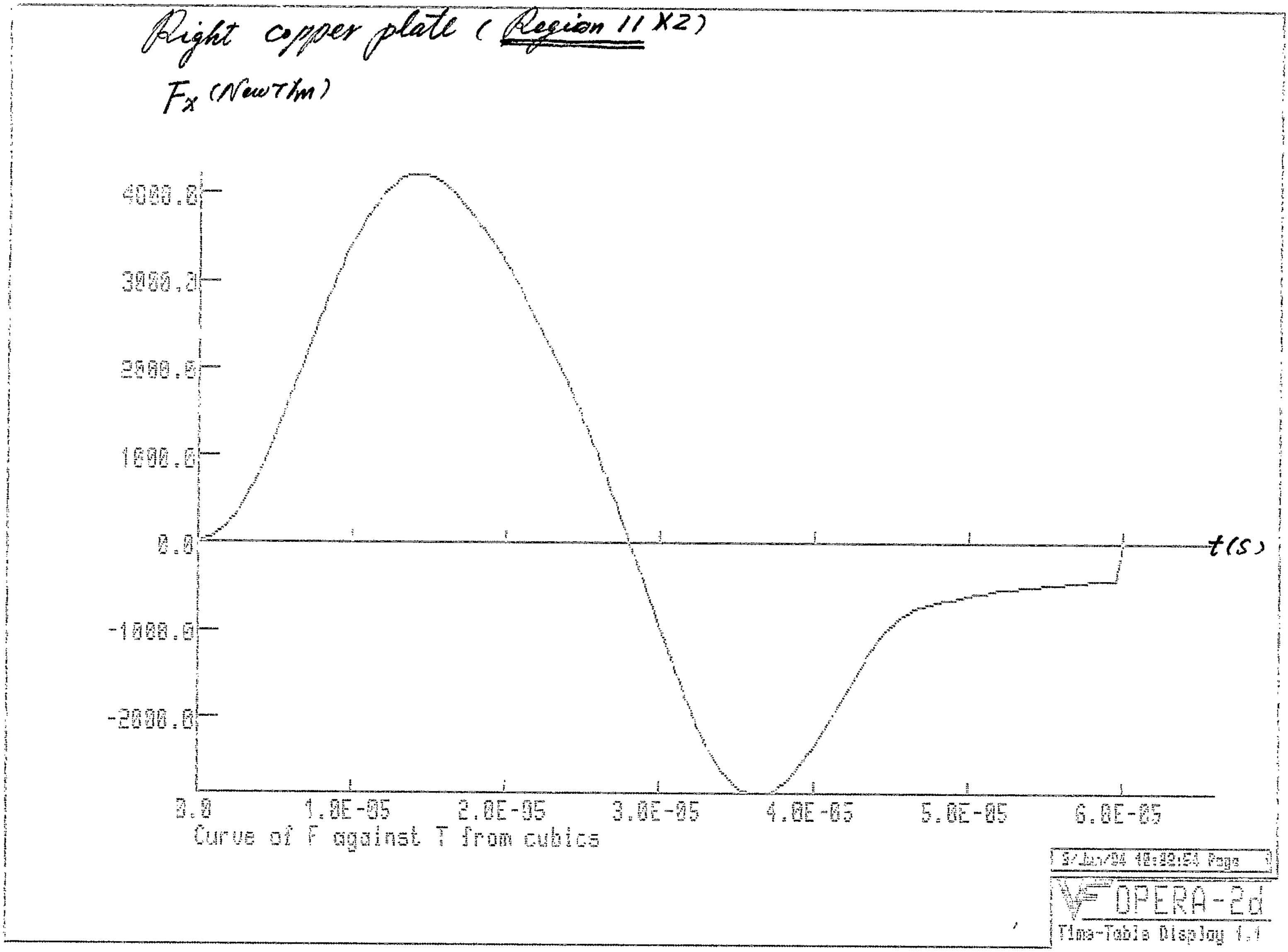
t(s)	Fx (Left plate)
0.00000	0.00000
2.000E-6	-185.6136
4.000E-6	-717.558
6.000E-6	-1573.668
8.000E-6	-2596.66
1.000E-5	-3654.90
1.400E-5	-5249.56
1.600E-5	-5641.22
1.800E-5	-5803.98
2.000E-5	-5813.82
2.200E-5	-5652.16
2.400E-5	-5403.88
2.600E-5	-4923.94
2.800E-5	-4194.96
3.000E-5	-3231.62
3.200E-5	-2125.42
3.400E-5	-1098.354
3.600E-5	-329.556
3.800E-5	129.0794
4.000E-5	227.7940
4.500e-5	92.5614
5.000e-5	56.1708

Fig. 6



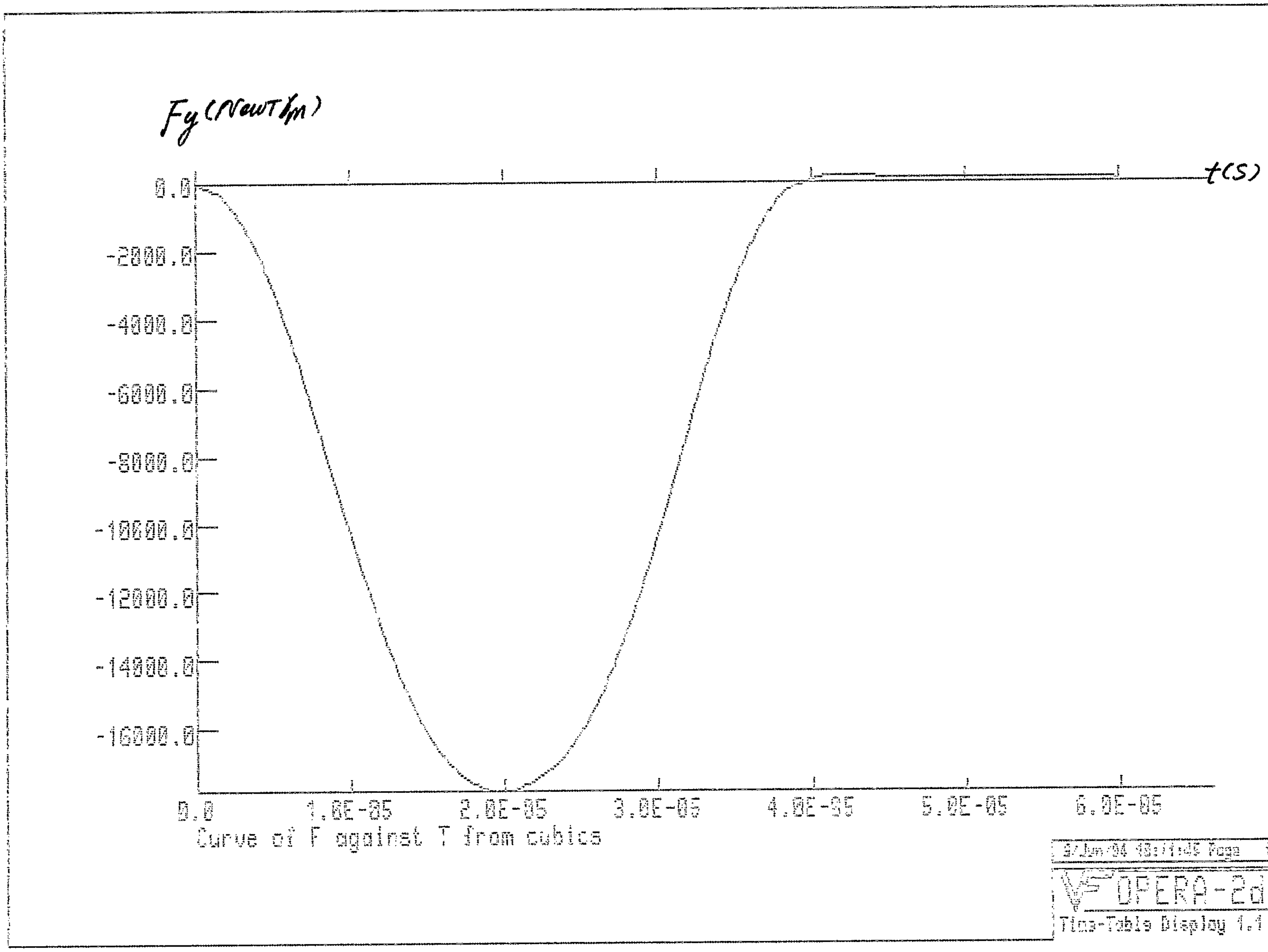
t(s)	Fy(Left plate)
0.00000	0.00000
2.000E-6	-1.4251
4.000E-6	-3.0133
6.000E-6	-3.0337
8.000E-6	-1.1179
1.000E-5	3.2139
1.400E-5	39.7854
1.600E-5	61.4048
1.800E-5	69.1808
2.000E-5	59.4148
2.200E-5	31.2760
2.400E-5	-17.0181
2.600E-5	-75.0904
2.800E-5	-133.8962
3.000E-5	-175.7502
3.200E-5	-197.1042
3.400E-5	-202.64
3.600E-5	-192.4376
3.800E-5	-167.556
4.000E-5	-129.506
4.500e-5	-55.908
5.000e-5	-24.2338

Fig. 7



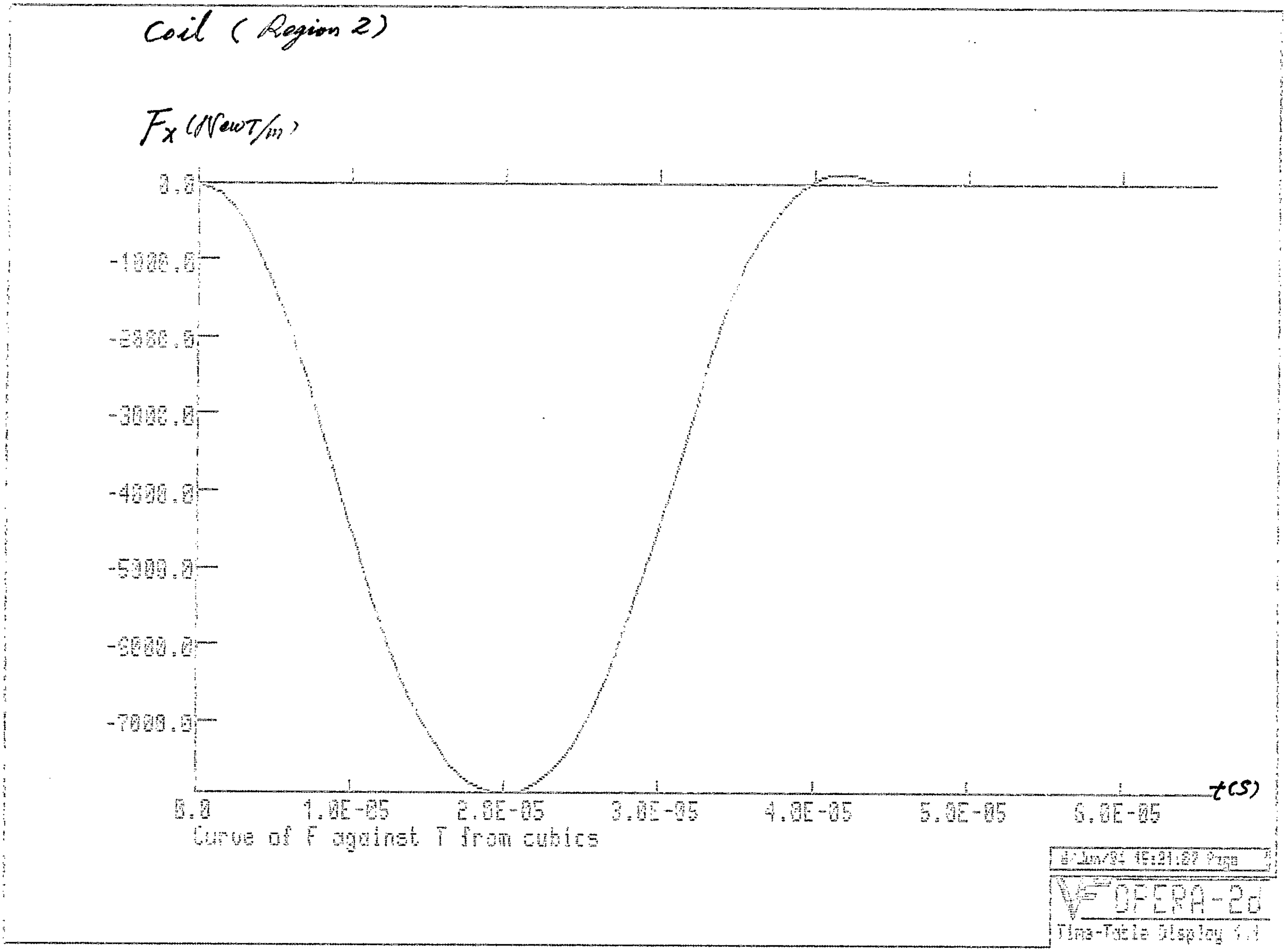
t(s)	Fx (Right plate)
0.00000	0.00000
2.000E-6	229.484
4.000E-6	828.628
6.000E-6	1703.436
8.000E-6	2633.36
1.000E-5	3454.0
1.400E-5	4216.84
1.600E-5	4082.66
1.800E-5	3683.58
2.000E-5	3169.78
2.200E-5	2488.58
2.400E-5	1791.6
2.600E-5	952.878
2.800E-5	-6.764
3.000E-5	-991.582
3.200E-5	-1928.97
3.400E-5	-2595.02
3.600E-5	-2865.22
3.800E-5	-2766.94
4.000E-5	-2316.1
4.500e-5	-941.622
5.000e-5	-598.168

Fig. 8



t(S)	Fy (Right plate)
0.00000	0.00000
2.000E-6	-539.728
4.000E-6	-2044.30
6.000E-6	-4433.06
8.000E-6	-7307.02
1.000E-5	-10319.24
1.400E-5	-15297.40
1.600E-5	-16782.98
1.800E-5	-17565.98
2.000E-5	-17821.28
2.200E-5	-17458.98
2.400E-5	-16702.06
2.600E-5	-15240.74
2.800E-5	-13053.0
3.000E-5	-10307.36
3.200E-5	-7179.2
3.400E-5	-4215.6
3.600E-5	-1926.28
3.800E-5	-443.09
4.000E-5	42.92
4.500e-5	124.678
5.000e-5	112.3794

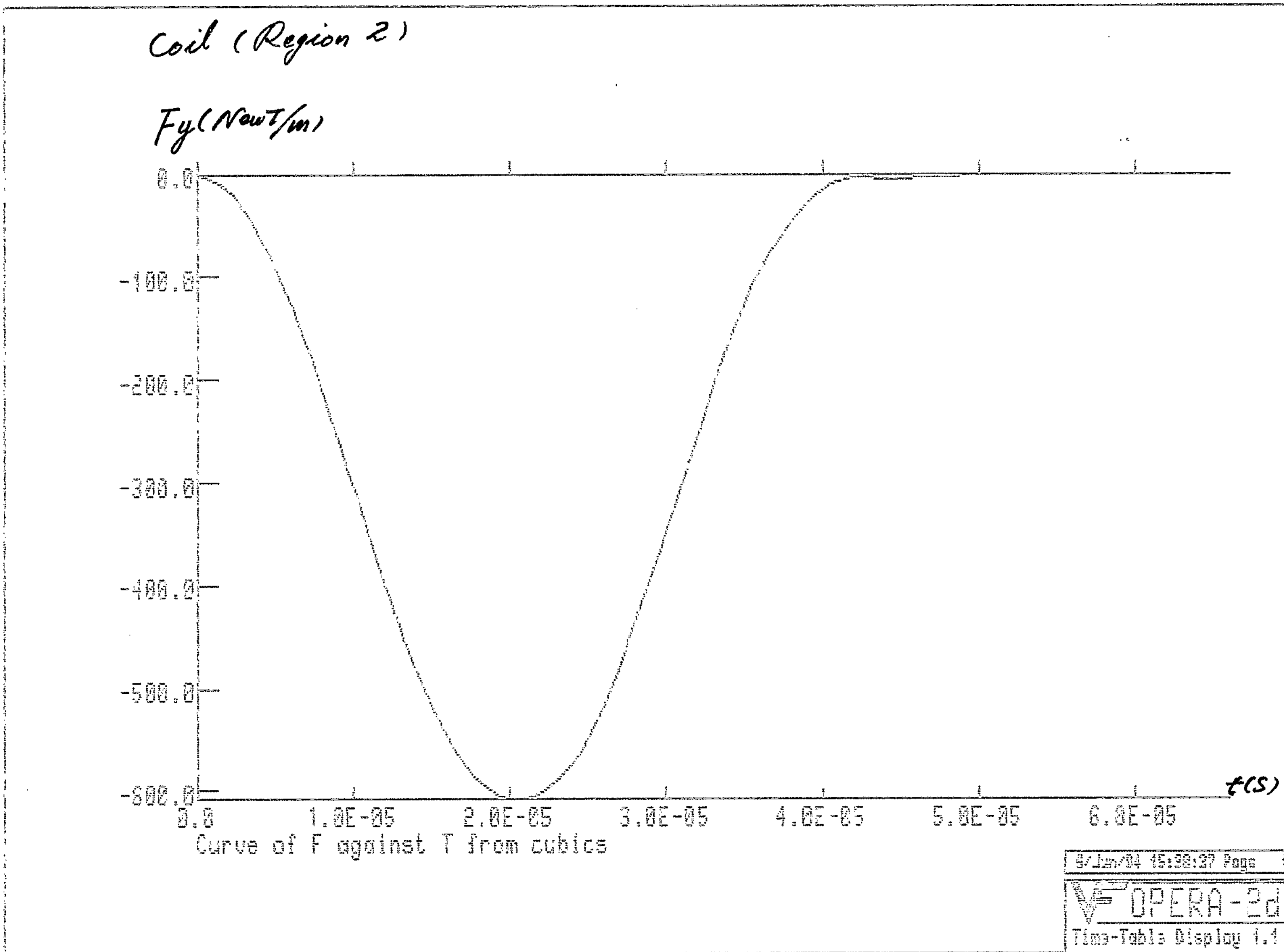
Fig. 9



t(S)	Fx(Coil 2)
0.00000	0.00000
2.000E-6	-239.709
6.000E-6	-1911.7
1.000E-5	-4515.97
1.200e-5	-5795.12
1.400E-5	-6776.31
2.000E-5	-7947.36
2.500E-5	-7125.41
3.000E-5	-4482.53
3.500E-5	-1304.54
4.000E-5	24.3964
4.500e-5	5.465981
5.000e-5	5.966064
5.500e-5	3.782824
6.000e-5	3.66415
6.000e-5	3.66415

[EOB]

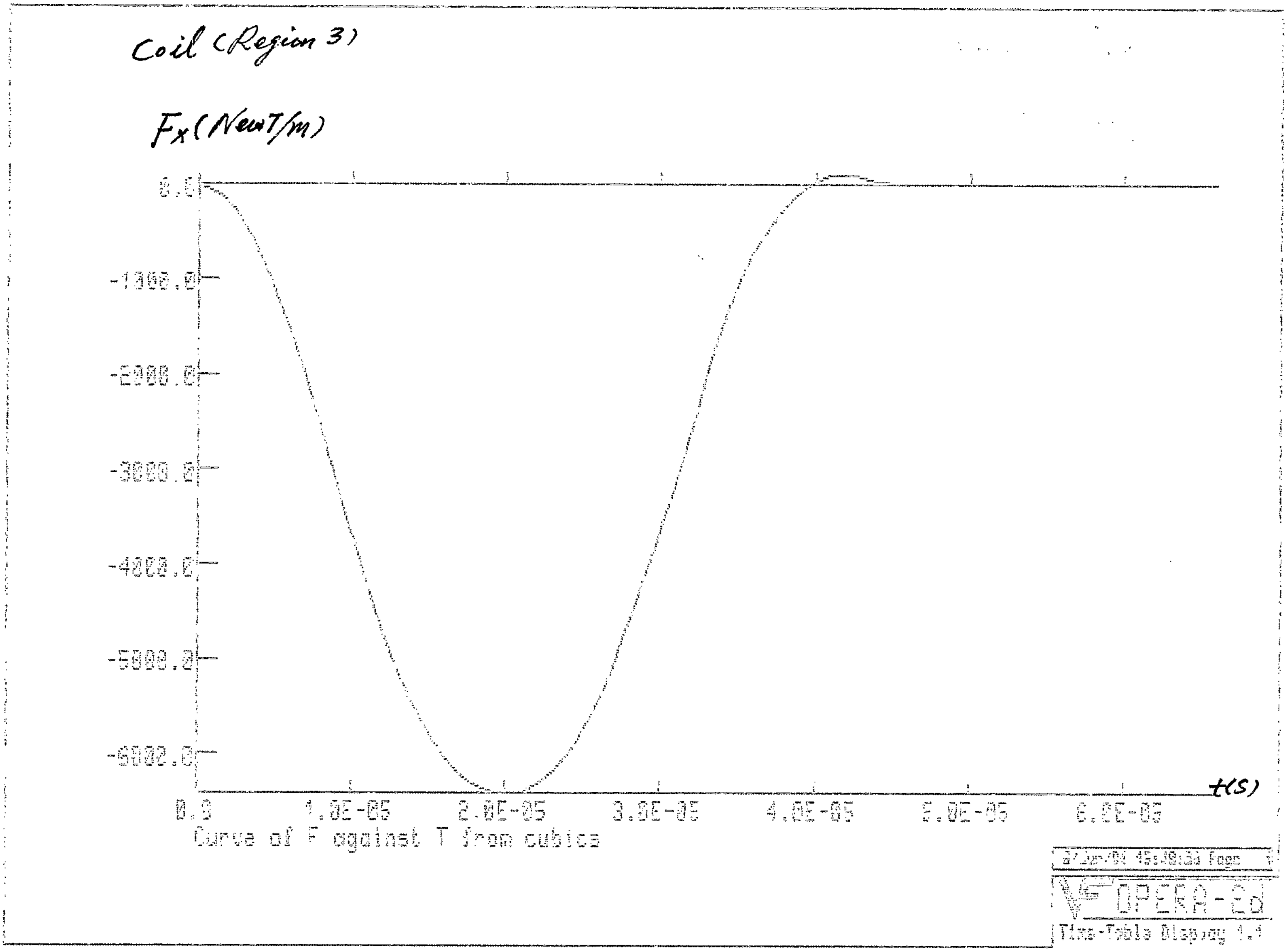
Fig. 10



t(s)	Fy(Coil 2)
0.00000	0.00000
2.000E-6	-16.0522
6.000E-6	-128.386
1.000E-5	-305.503
1.200e-5	-400.93
1.400E-5	-484.003
2.000E-5	-608.446
2.500E-5	-548.926
3.000E-5	-347.14
3.500E-5	-124.473
4.000E-5	-14.9544
4.500e-5	-5.2116
5.000e-5	-1.108977
5.500e-5	-0.0346226
6.000e-5	0.19824
6.000e-5	0.19824

[EOB]

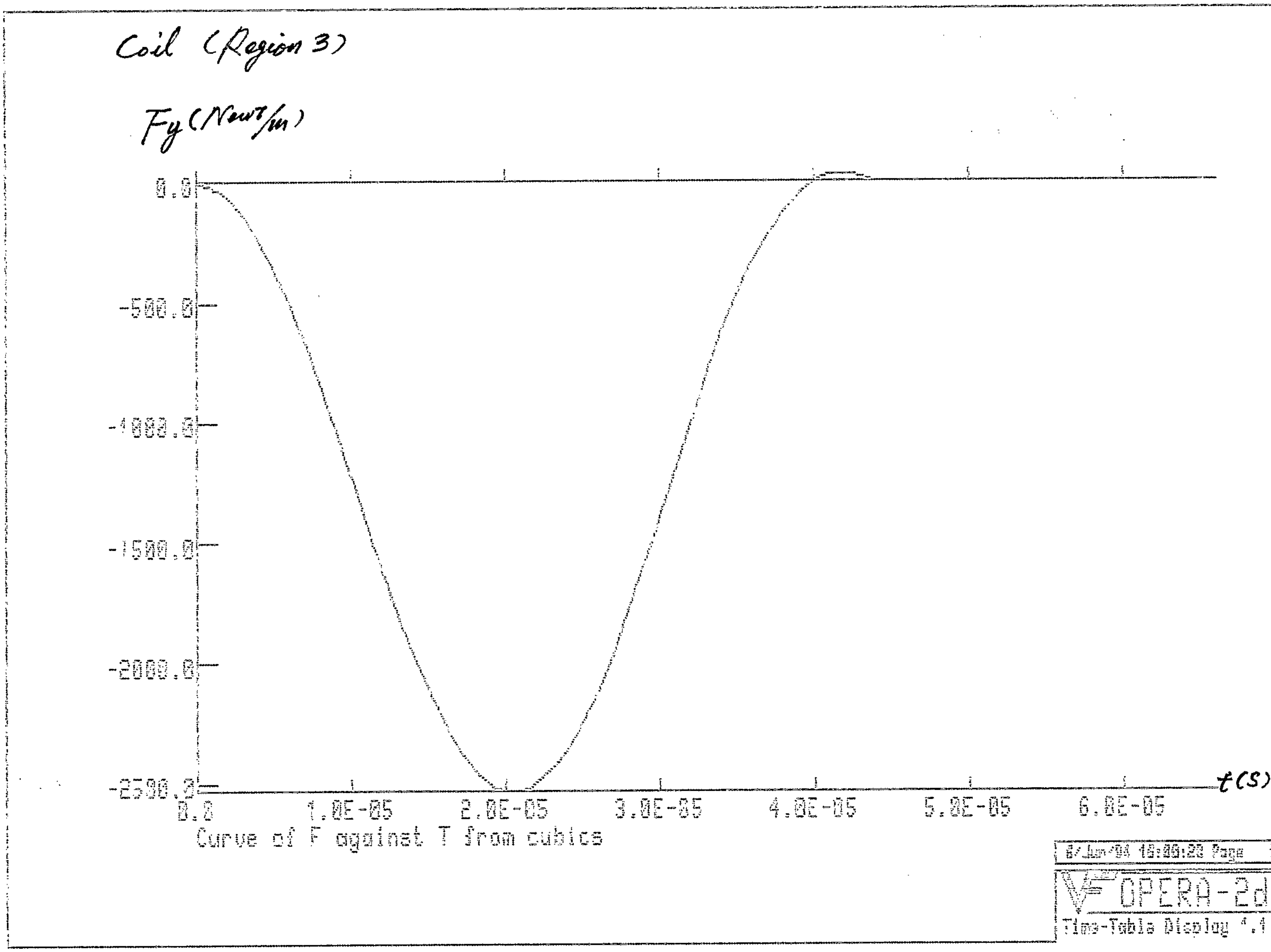
Fig. 11



t (s)	Fx (Coil 3)
0.00000	0.00000
2.000E-6	-195.895
6.000E-6	-1562.07
1.000E-5	-3688.12
1.200e-5	-4721.12
1.400E-5	-5489.31
2.000E-5	-6423.14
2.500E-5	-5762.3
3.000E-5	-3651.53
3.500E-5	-1054.61
4.000E-5	31.917
4.500e-5	12.9951
5.000e-5	10.8124
5.500e-5	7.07913
6.000e-5	5.52778
6.000e-5	5.52778

[EOB]

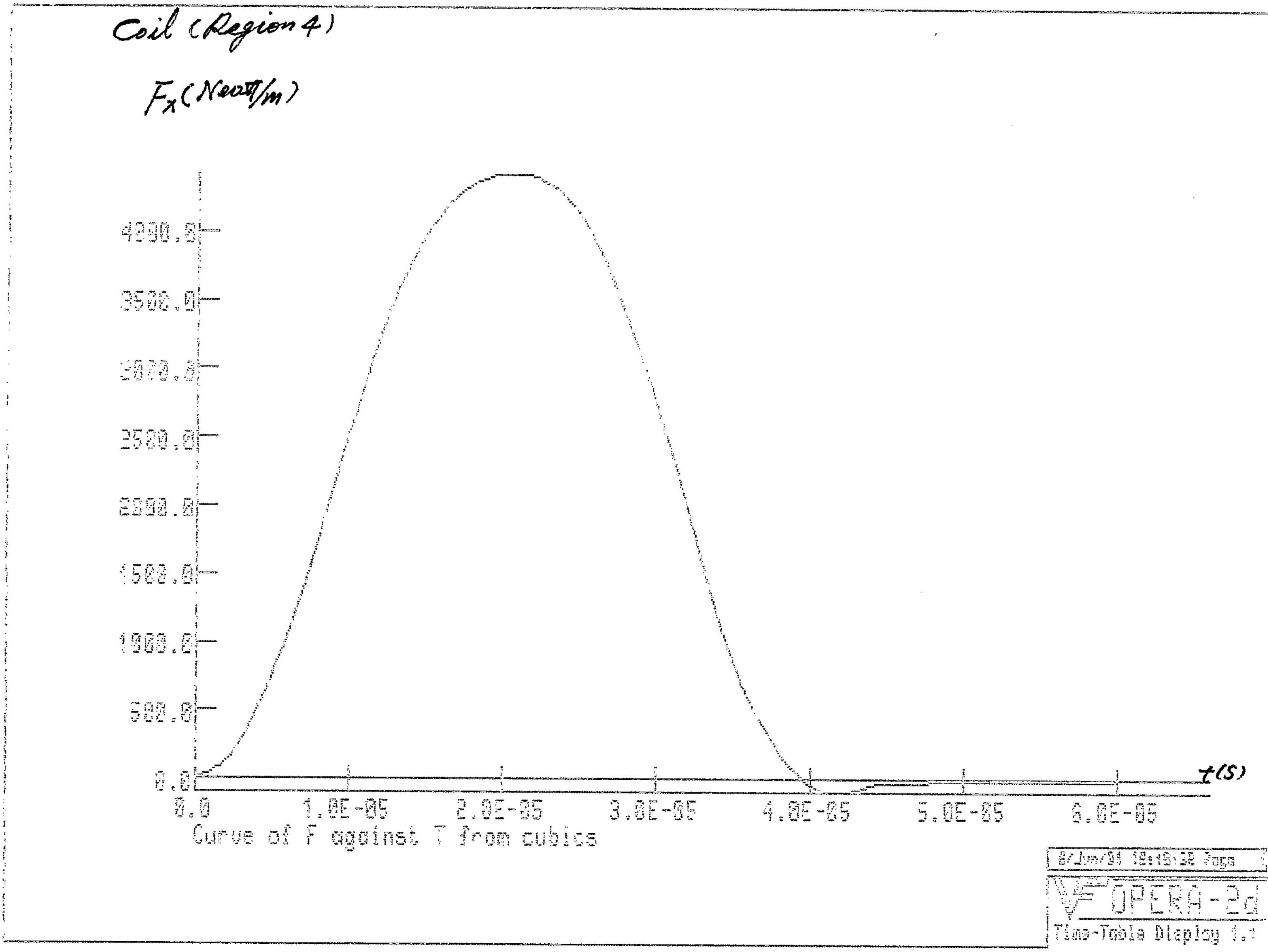
Fig. 12



t (s)	Fy (Coil 3)
0.00000	0.00000
2.000E-6	-62.423
6.000E-6	-506.308
1.000E-5	-1223.45
1.200e-5	-1620.2
1.400E-5	-1966.44
2.000E-5	-2533.91
2.500E-5	-2248.59
3.000E-5	-1385.0
3.500E-5	-457.449
4.000E-5	0.71632
4.500e-5	-1.072736
5.000e-5	0.594392
5.500e-5	-0.115242
6.000e-5	-0.545673
6.000e-5	-0.545673

[EOB]

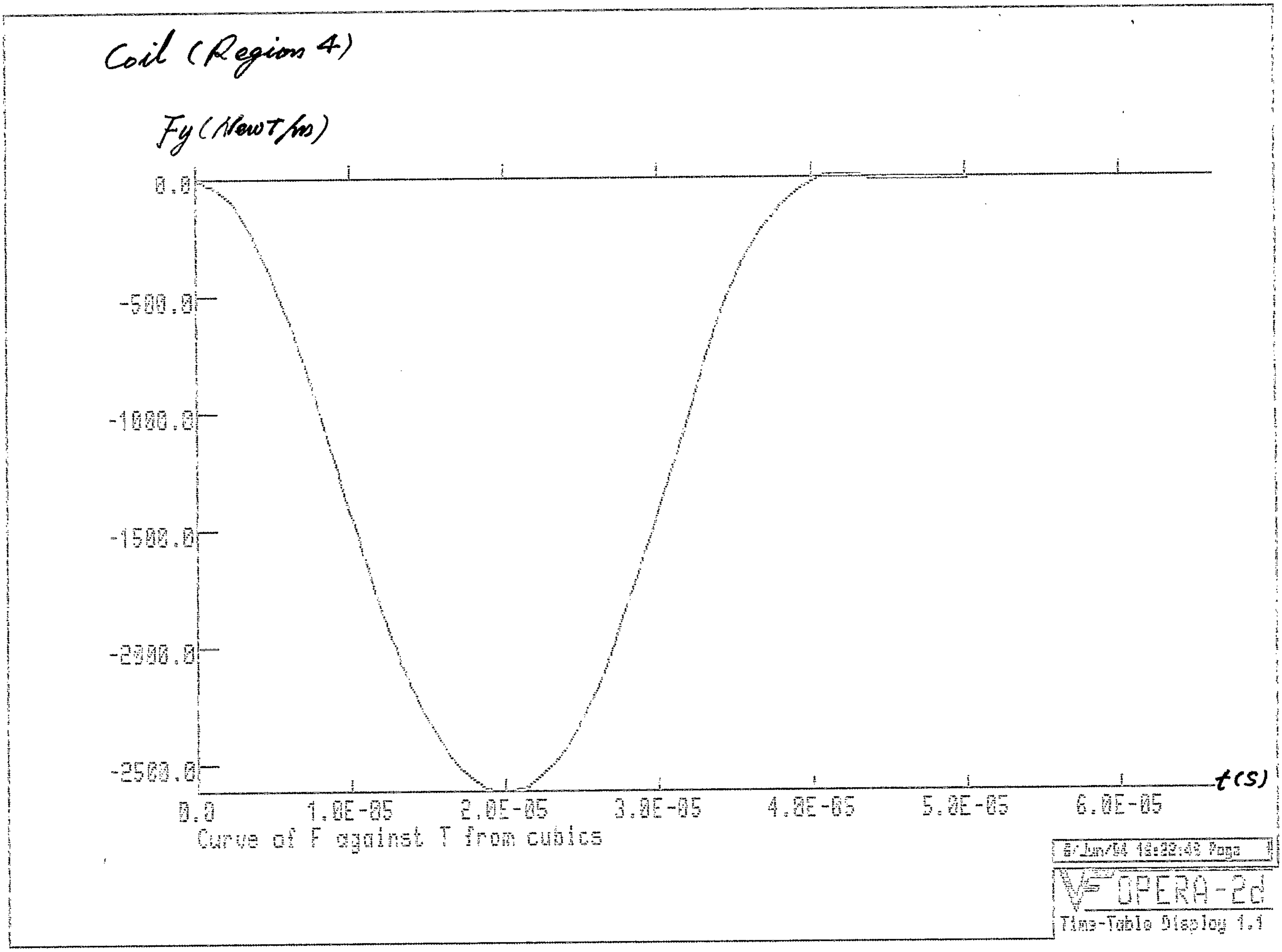
Fig. 13



t(S)	Fx(Coil 4)
0.00000	0.00000
2.000E-6	132.836
6.000E-6	1072.53
1.000E-5	2553.84
1.200e-5	3265.55
1.400E-5	3801.66
2.000E-5	4418.32
2.500E-5	4099.98
3.000E-5	2712.99
3.500E-5	840.369
4.000E-5	-42.0955
4.500e-5	-23.0143
5.000e-5	-18.1666
5.500e-5	-12.9875
6.000e-5	-10.0849
6.000e-5	-10.0849

[EOB]

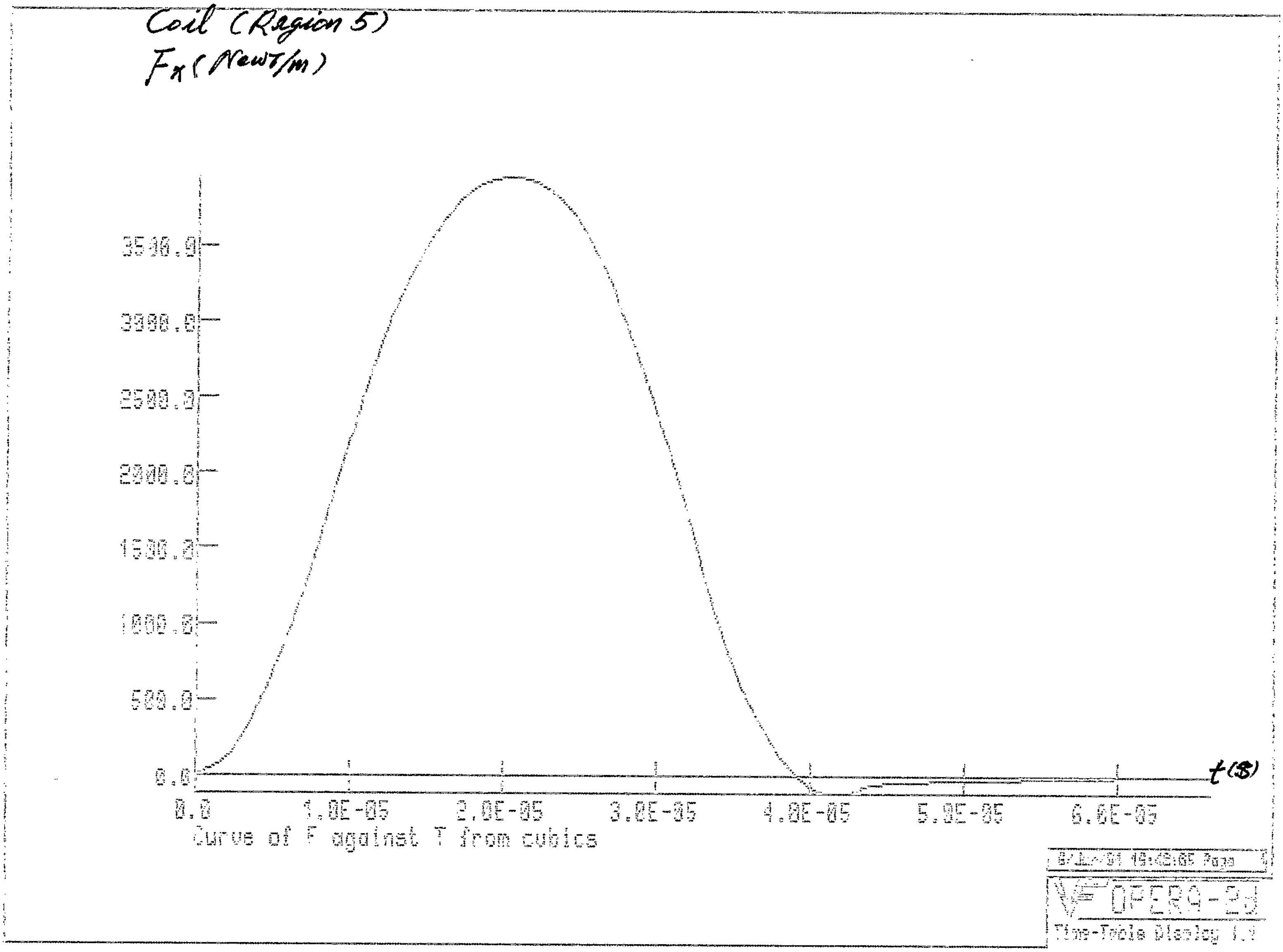
Fig. 14



t (s)	Fy (coil 4)
0.00000	0.00000
2.000E-6	-76.2061
6.000E-6	-605.245
1.000E-5	-1428.04
1.200e-5	-1846.11
1.400E-5	-2182.36
2.000E-5	-2612.61
2.500E-5	-2308.99
3.000E-5	-1418.55
3.500E-5	-425.82
4.000E-5	-20.1949
4.500e-5	-12.201
5.000e-5	-6.32126
5.500e-5	-4.60763
6.000e-5	-3.52614
6.000e-5	-3.52614

[EOB]

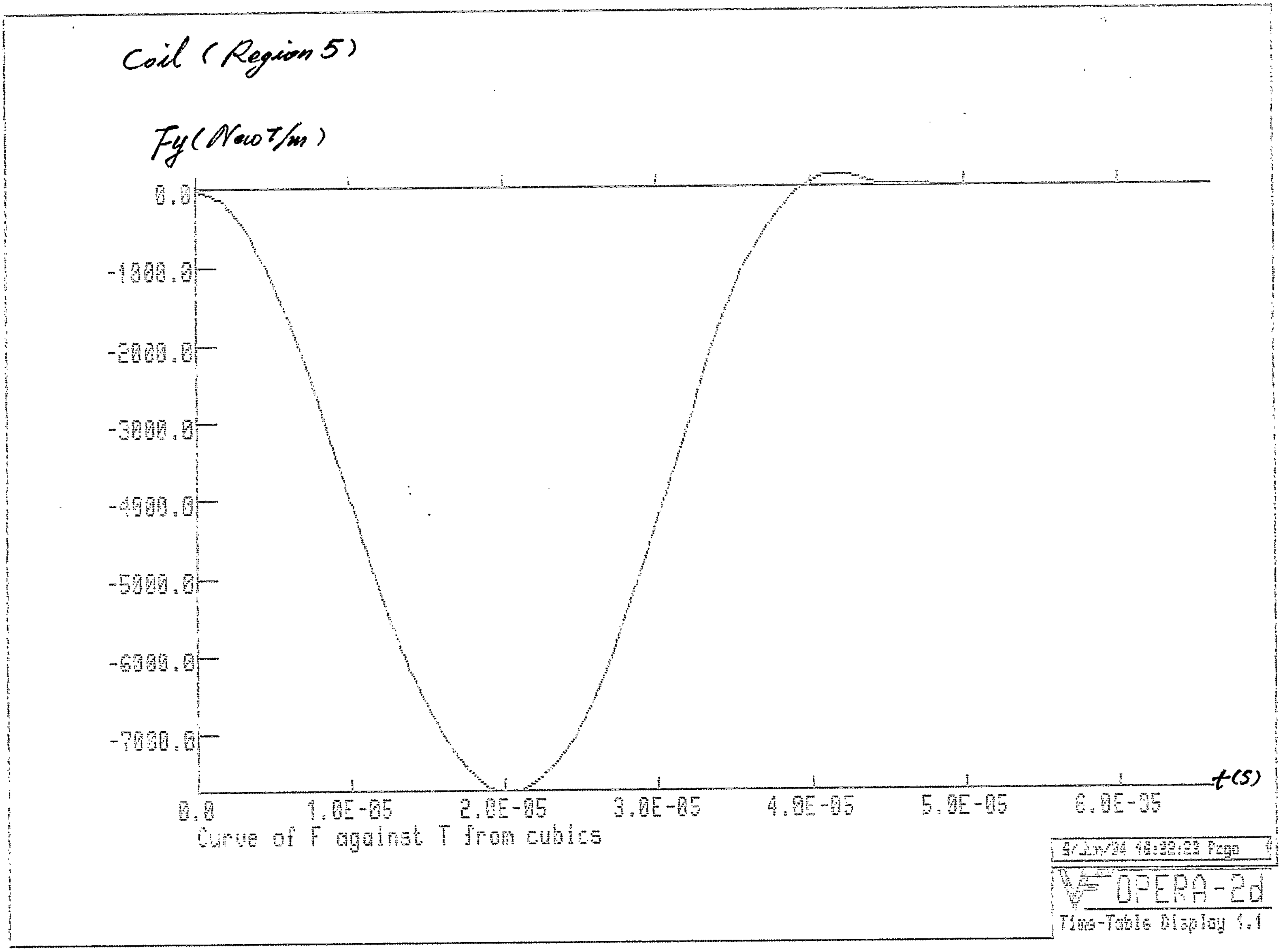
Fig. 15



t(S)	Fx(Coil 5)
0.00000	0.00000
2.000E-6	116.147
6.000E-6	937.07
1.000E-5	2236.54
1.200e-5	2867.06
1.400E-5	3333.79
2.000E-5	3952.54
2.500E-5	3625.01
3.000E-5	2372.33
3.500E-5	706.304
4.000E-5	-75.8696
4.500e-5	-46.9591
5.000e-5	-32.634
5.500e-5	-20.9111
6.000e-5	-13.8873
6.000e-5	-13.8873

[EOB]

Fig. 16



t(S)	Fy(Coil5)
0.00000	0.00000
2.000E-6	-202.822
6.000E-6	-1672.24
1.000E-5	-4010.71
1.200e-5	-5241.64
1.400E-5	-6249.65
2.000E-5	-7746.83
2.500E-5	-6871.59
3.000E-5	-4248.95
3.500E-5	-1285.67
4.000E-5	77.2071
4.500e-5	34.0948
5.000e-5	23.7171
5.500e-5	13.9725
6.000e-5	8.50909
6.000e-5	8.50909

[EOB]

Fig.1b