A Thin Quadrupole for the AGS

N. Tsoupas: 3D_Magnet Design

R. Alforque: Mechanical Design

A. Jain: Magnet measurements

W. MacKay: Discussions

I. Marneris Power Supply and
Power Loss Measurements

Why inserting a Thin Quadrupole in AGS?

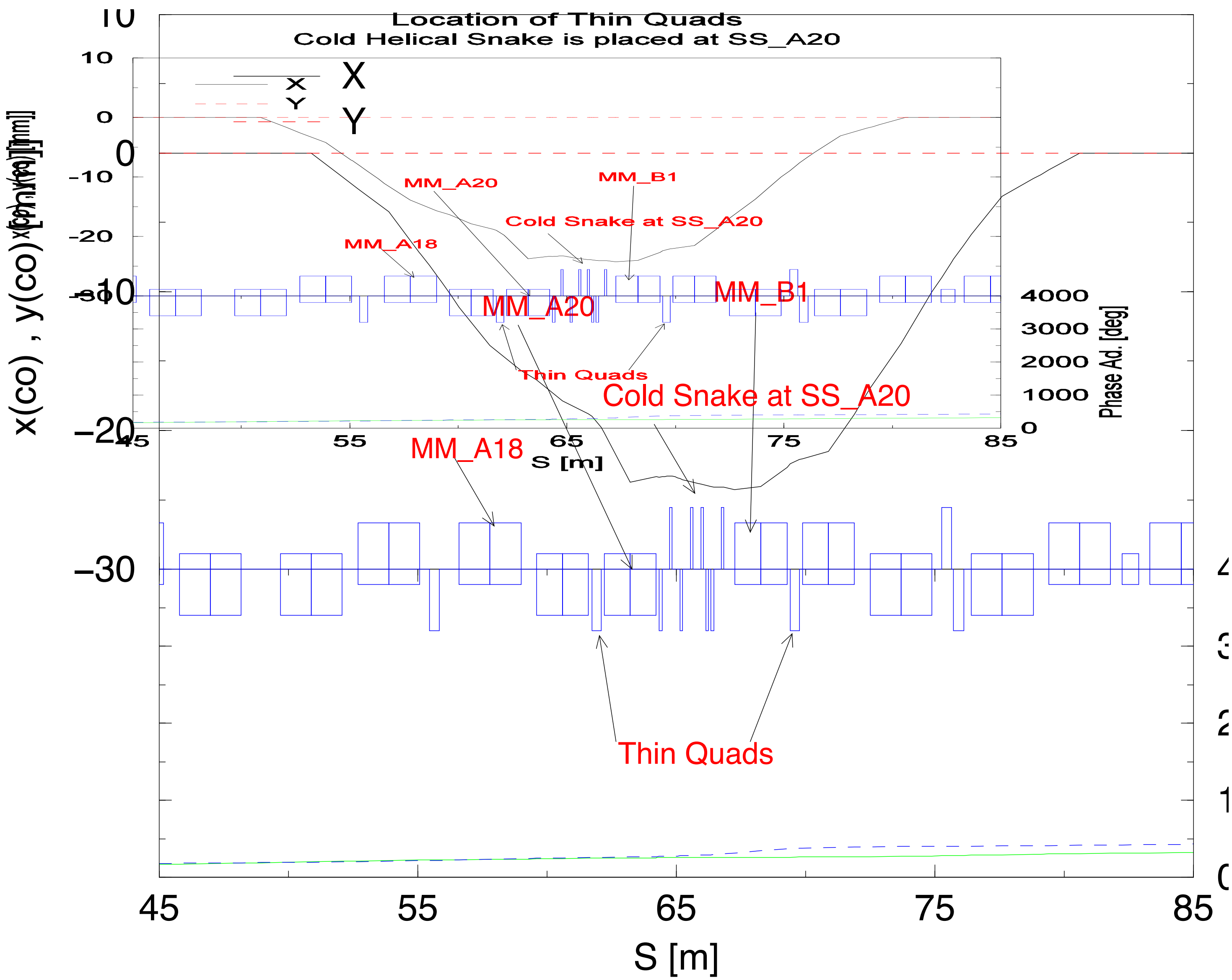
- One way to preserve the proton polarization in AGS during the acceleration, is to introduce Cold and Warm helical Snakes in AGS which:
  - Introduce artificial spin resonances for lossless polarization when crossing the imperfection spin resonances.
  - And also modify the spin tune to prevent many intrinsic spin resonances.
- The helical Snakes alter the beam optics of the AGS and the “Thin Quads” help restore the beam optics.

The strength of the “Thin Quadrupoles” is time varying therefore the iron core must be laminated.

So what's the "Big Deal"? Just another Quadrupole.

- Actually…I agree it is Not a "Big Deal".
- However….
  - During the stage of the transient-3D-calculations, among other quantities, the computer code was also providing power losses in the iron core of the magnet as a function of time.
  - The trend of some of the power losses as a function of time, as calculated by the code, appeared to me, initially, to be in error.
  - Soon I found an explanation, that the calculations are not in error.
  - I. Marneris confirmed also that the measured power losses, agree qualitatively with the theoretically calculated.

Where are the Thin Quadrupoles located in AGS?



Specifications of the Thin Quad

Required strength of the Thin Quadrupoles:

$\int G dl = K_1 \cdot L_{eff} \cdot (B\rho) = (0.3 m^{-2}) \cdot (0.35 m) \cdot (7.21 Tm) = 0.757$ [T]

For Radius of R_{quad}=8.3 [cm] and Iron length 9 [cm] an approximate value of the B_{pole_tip} is:

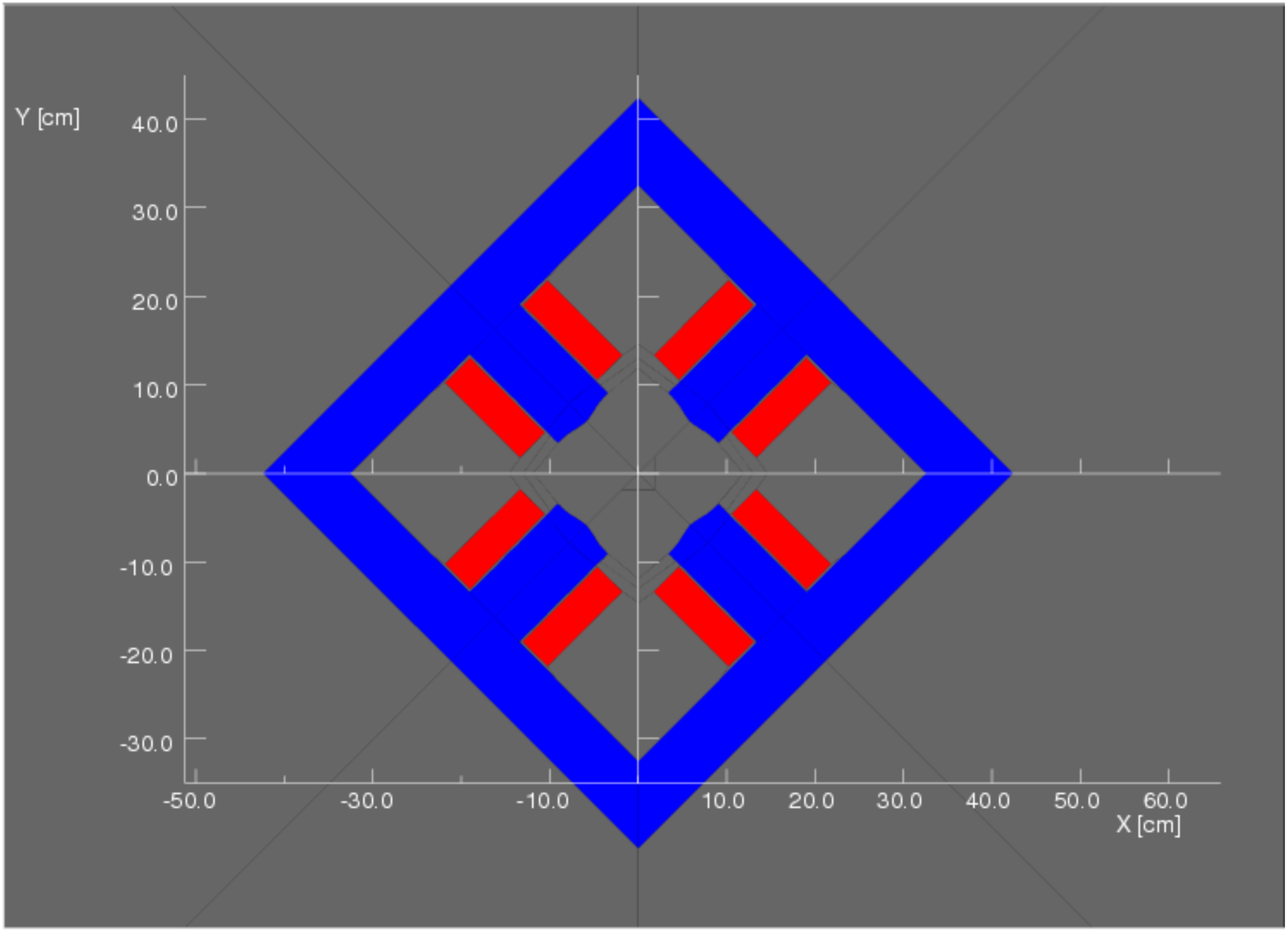
$B_{pole\_tip} = \{(\int G dl)/(L_{iron}+R_{quad})\} \cdot (R_{quad}) = 0.39$ [T]

Geometric Parameters of the Quads

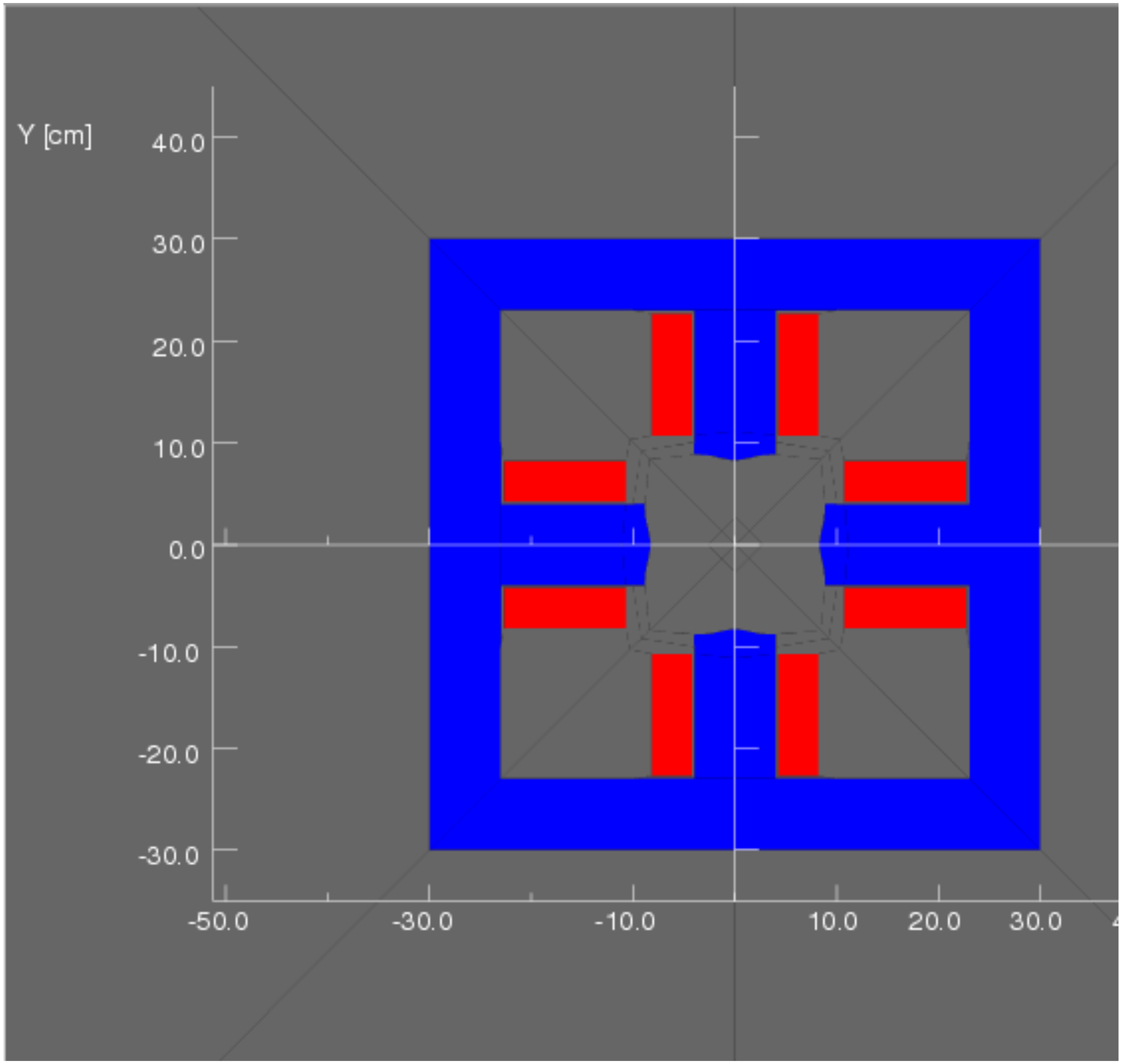
- L_{iron}=9 cm
- $L_{iron+coil}$=17.2 cm
- Aperture Radius=8.3 cm
- turns/coil=52 (Four layers x 13 turns)
- Conductor cross section=0.8cm x 0.8 cm

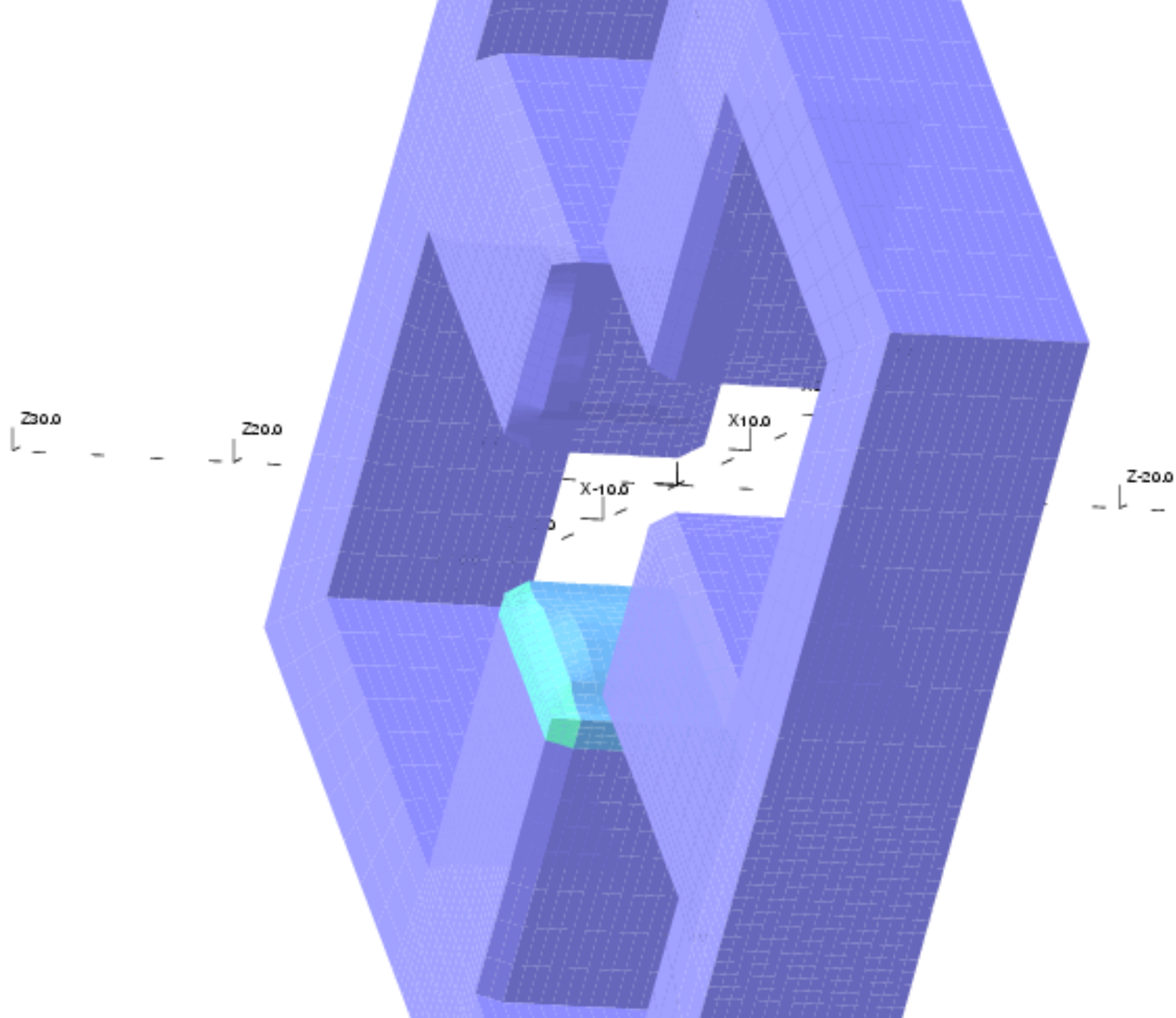
Procedure of the Calculations

- Design of a 2D-model (Static Calculations)
  - Provides good approximation of the pole shape
- Design of a 3D-model (Static Calculations)
  - Helps minimize the higher order magnetic multipoles by shaping the ends of the pole pieces
- Use of 3D-Transient calculations:
  - Optimize lamination thickness
  - Optimize vacuum chamber thickness
  - Minimize losses due to Eddy currents

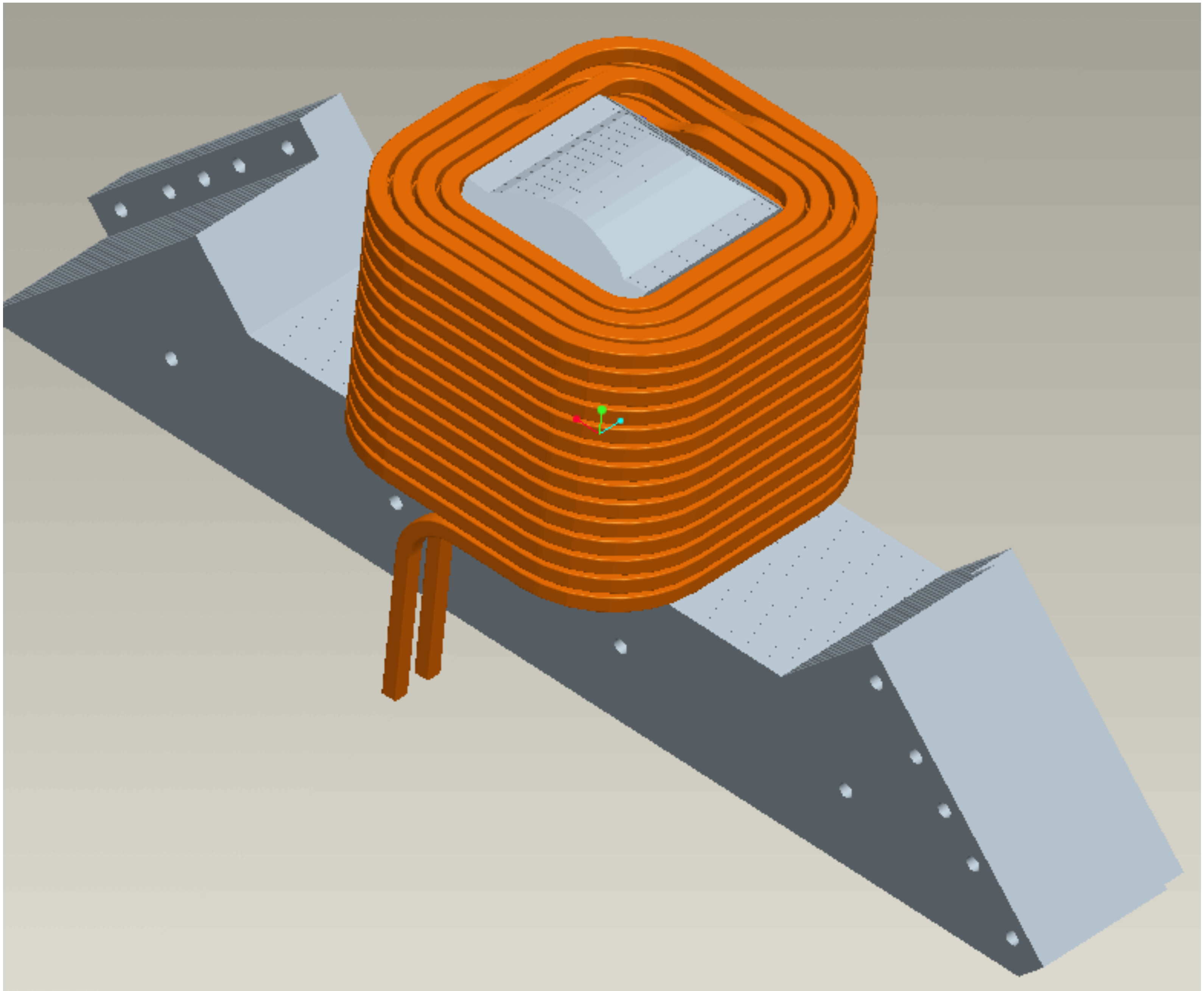


Y [cm]
40.0
30.0
20.0
10.0
0.0
-10.0
-20.0
-30.0
-50.0
-30.0
-10.0
10.0
20.0
30.0
40.0
50.0
60.0
X [cm]


Y [cm]
40.0
30.0
20.0
10.0
0.0
-10.0
-20.0
-30.0
-50.0
-30.0
-10.0
10.0
20.0
30.0



Z30.0
Z20.0
X10.0
X-10.0
Z-20.0



Results from 3D Static Calculations

- I=350 A
- J=804 A/cm^2
- B_{pole_tip}=0.5062 [T] at R=8.2 cm
- $\int B_{quad} dz = 6.015 \cdot 10^{-2}$ [Tm] at R=7.0 cm ($\int B_{quad} dz$)/R=0.86 [T] required 0.8 [T]

- $\int B_{12pole} dz = +1.07 \cdot 10^{-4}$ [Tm] at R=7.0 cm +17 units
- $\int B_{20pole} dz = -2.8 \cdot 10^{-4}$ [Tm] at R=7.0 cm -48 units
- $\int B_{28pole} dz = -0.54 \cdot 10^{-4}$ [Tm] at R=7.0 cm -9 units
- L=0.0094 H
- $V = V_L + V_R = L \bullet dI/dt + IR$ =0.0094[H]*(350[A]/0.2sec) + 350[A]*R
  =16.5 [V] ± 11.5 [V]

- L_{cond}=85 [m] A_{cond}=0.0000435 m^2 $\rho_{Cu} = 1.673 \cdot 10^{-8}$ [Ωm] R=0.033 [Ω]

Allowed Harmonics:

$$B_r(z,r) = B_{quad}(z,r)\sin(2\theta) + B_{12pole}(z,r)\cdot\sin(6\theta) + B_{20pole}(z,r)\cdot\sin(10\theta) + \ldots$$

Transient Calculations:
Time varying current in the Quad

- To determine the maximum iron lamination thickness which will not affect dramatically the quality of the field as compared to that of the static field.
- To calculate
  - the Ohmic losses in the iron laminations
  - Conductor coils

  due to the eddy currents

Maxwell Equation are Approximated at “low frequency” and λ>>model size

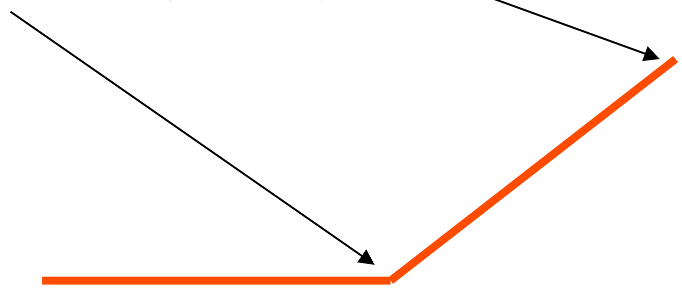
∇x$H = J + \cancel{\partial D/\partial t}$

∇x$E = -\partial B/\partial t$

$J = \sigma E$

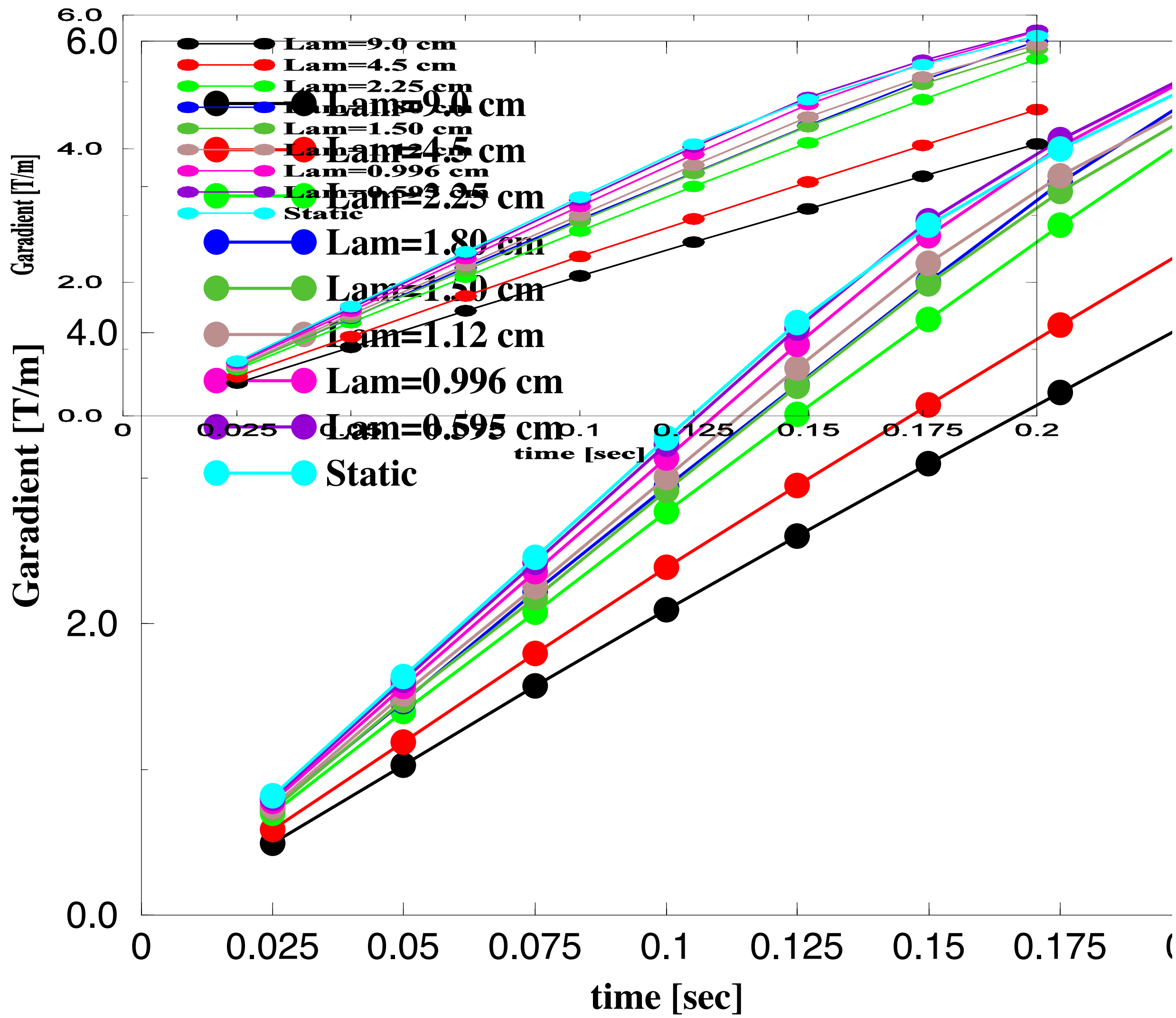
Data for the time varying calculations

- The current as a function of time is a linear ramp (t=0sec,I=0A) to (t=0.2 , I=340 [A])



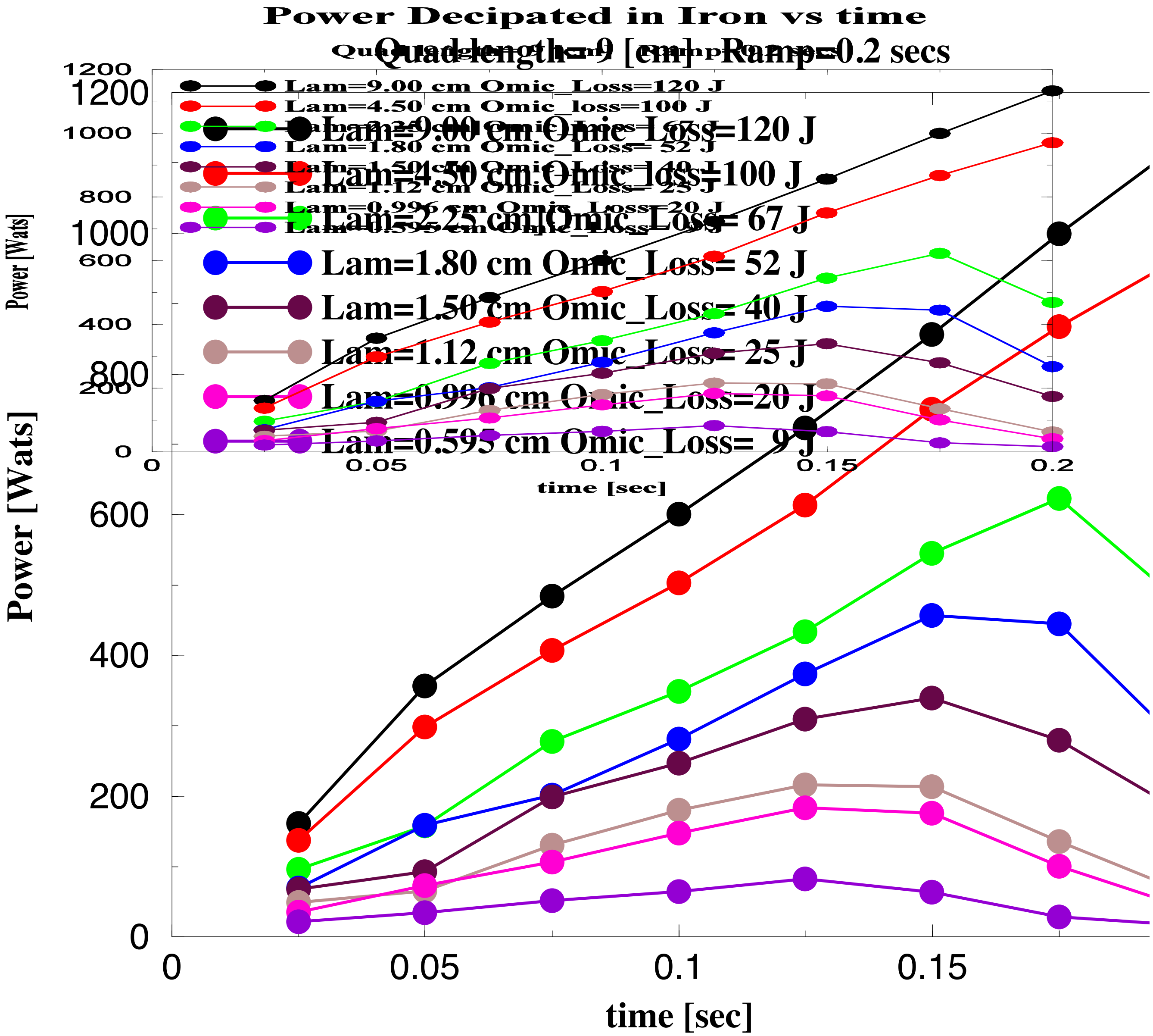
- Iron plates of thickness {9, 4.5, 2.25, 1.80, 1.50, 1.106, 1.12, 0.996, 0.553} [cm] are use to make the 9 cm thick quadrupole
- The assumed conductivity of the iron was $1 \cdot 10^{7}$ $[\Omega m]^{-1}$
- The usual conductivity of magnetic iron is $0.77 \cdot 10^{7}$ $[\Omega m]^{-1}$

Gradiend vs time for Various Lam Thicknesses



Some Results from the measurements: I=300A, R=7 [cm]

	$\int Gdz$ [T]	$\int(\text{Oct})dz/\int Gdz$ 10^{-4}	$\int(12p)dz/\int Gdz$ 10^{-4}	$\int(20p)dz/\int Gdz$ 10^{-4}	$\int(28p)dz/\int Gdz$ 10^{-4}
Trans.C alcul.	0.85	0	-20	-210	-35
Measur Quad#1	0.87	-7	+55	-45	-13
Static Calc.	0.86	0	+17	-48	-9

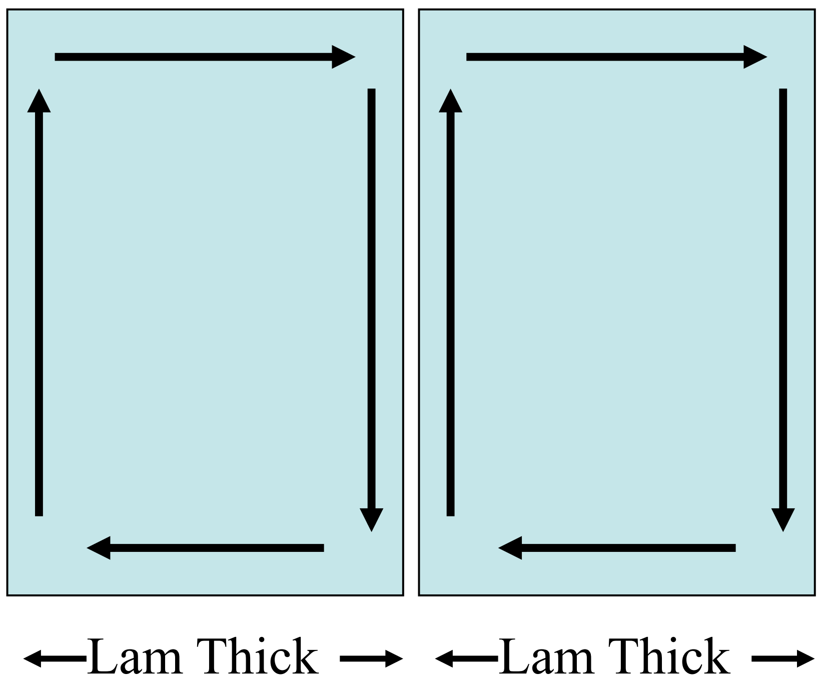

Power Decipated in Iron vs time
Quad-length=9 [cm] Ramp=0.2 secs
Lam=9.00 cm Omic_Loss=120 J
Lam=4.50 cm Omic_loss=100 J
Lam=2.25 cm Omic_Loss= 67 J
Lam=1.80 cm Omic_Loss= 52 J
Lam=1.50 cm Omic_Loss= 40 J
Lam=1.12 cm Omic_Loss= 25 J
Lam=0.996 cm Omic_Loss=20 J
Lam=0.595 cm Omic_Loss= 9 J
Power [Wats]
time [sec]
0
200
400
600
800
1000
1200
0.05
0.1
0.15
0.2

Skin Depth $\delta=(2/\omega\mu_0\mu\sigma)^{1/2}$

Magnetic Flux Parallel to Lamination or Normal to plane

$f=1.25\ \mathrm{sec}^{-1}$ $\mu_0=4\pi 10^{-7}$ [Hen/m]

$\mu=6000$ $\sigma=1.0\mathrm{x}10^{7}$ [$\mathrm{Ohm}^{-1}\ \mathrm{m}^{-1}$]

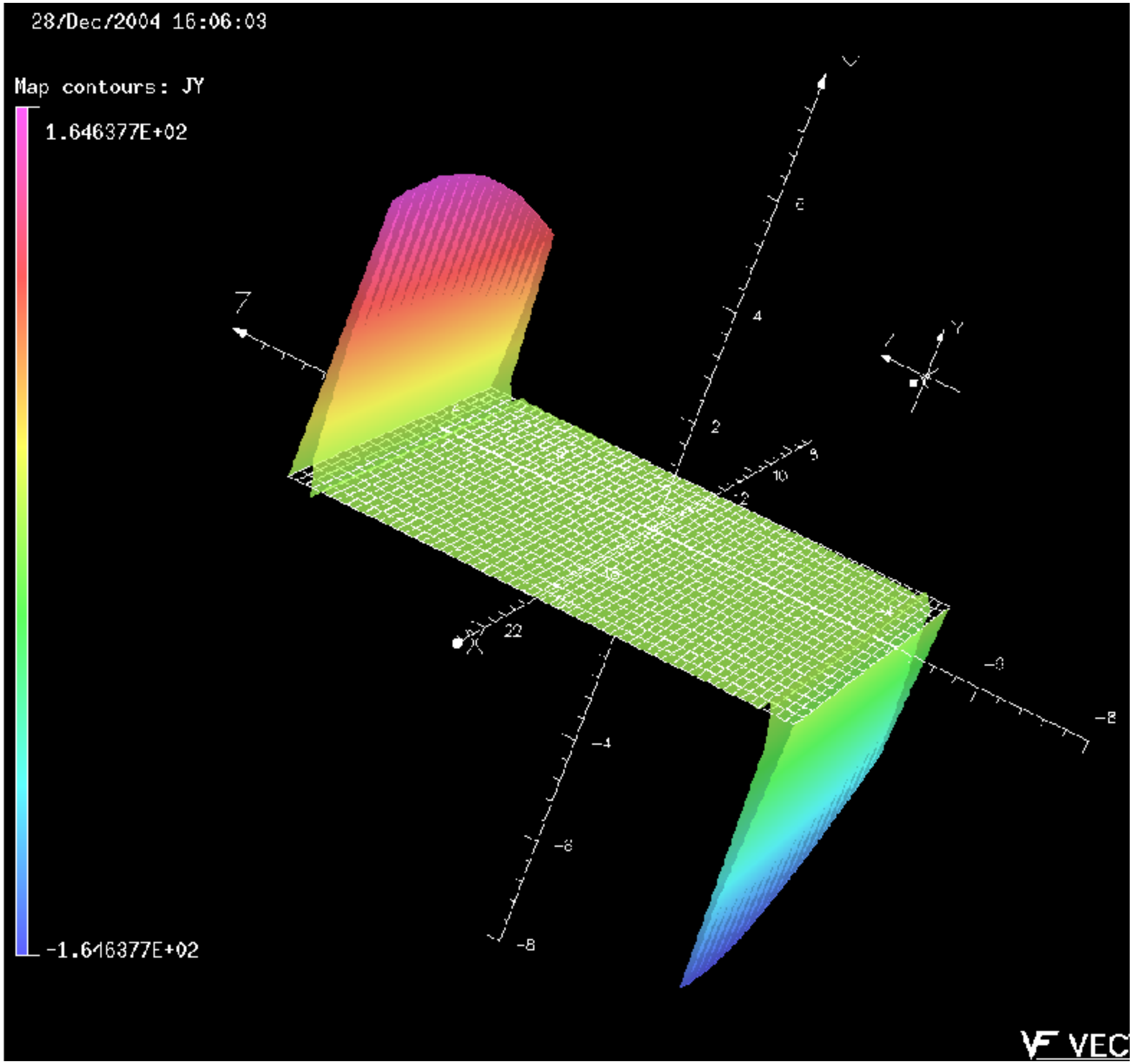


$\delta=1.8$ [mm] at $\mu=6000$

$\delta=5.8$ [mm] at $\mu=600$

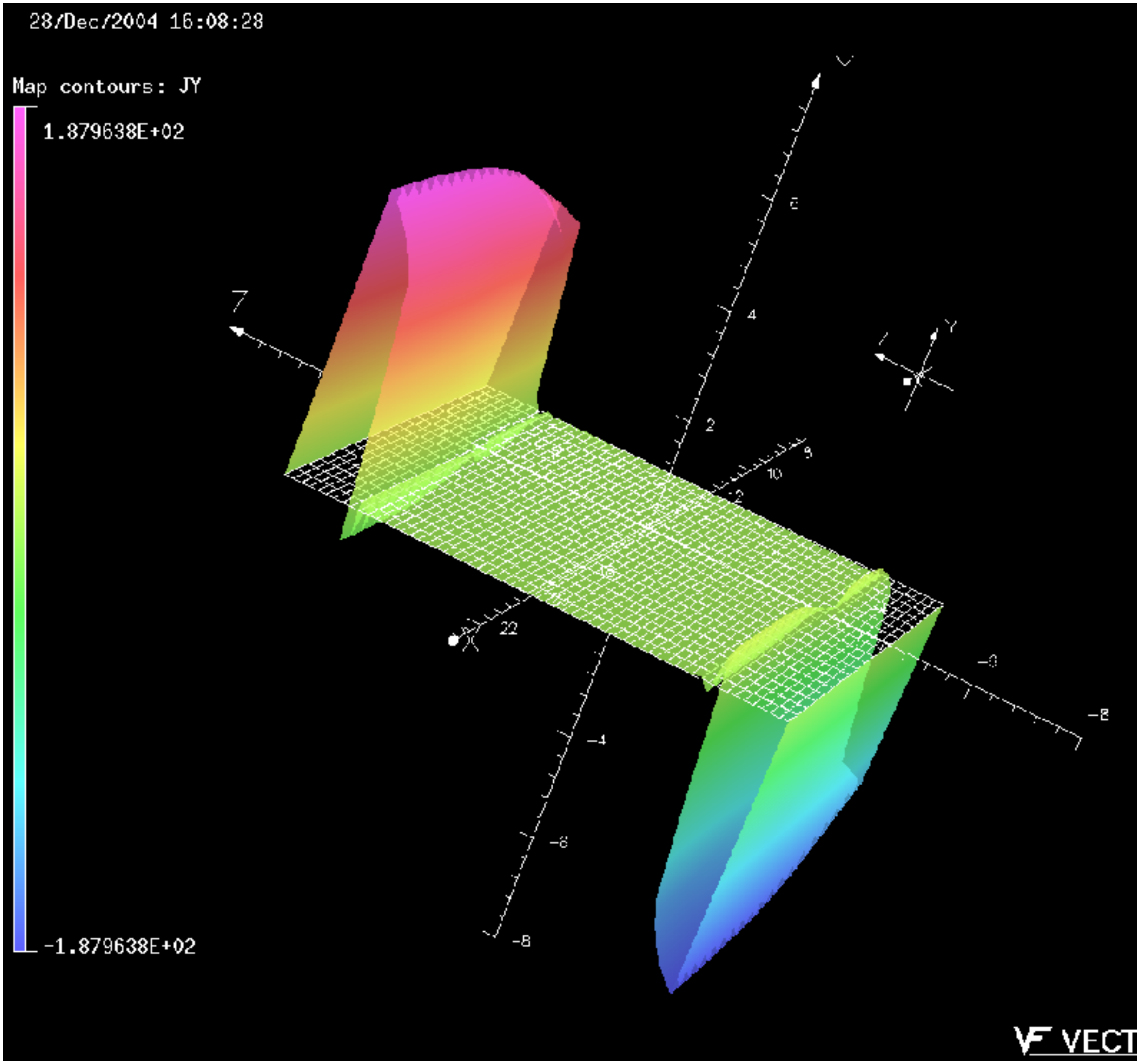
Thick Lamination

Time=t1



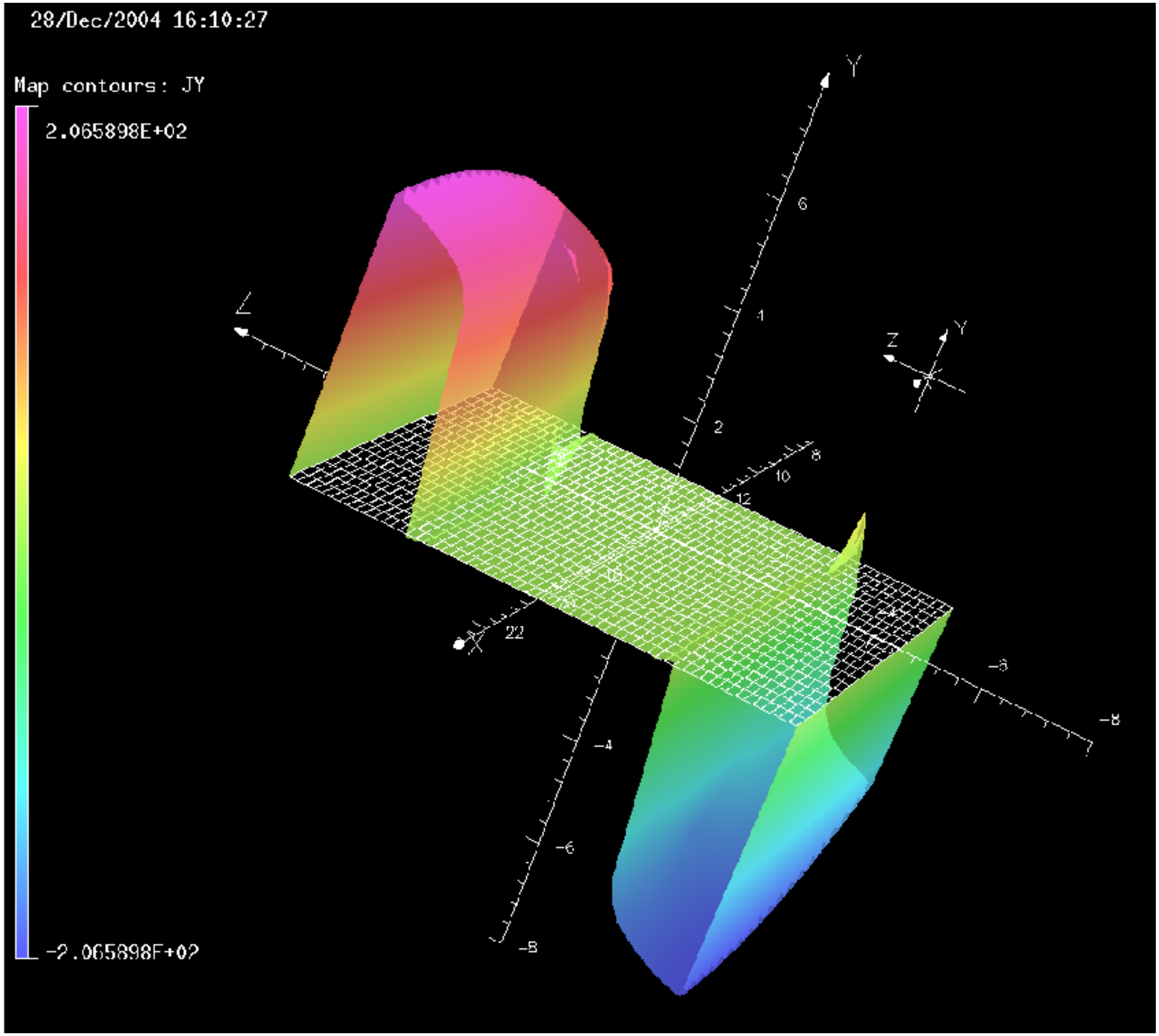
Thick Lamination

Time=t2



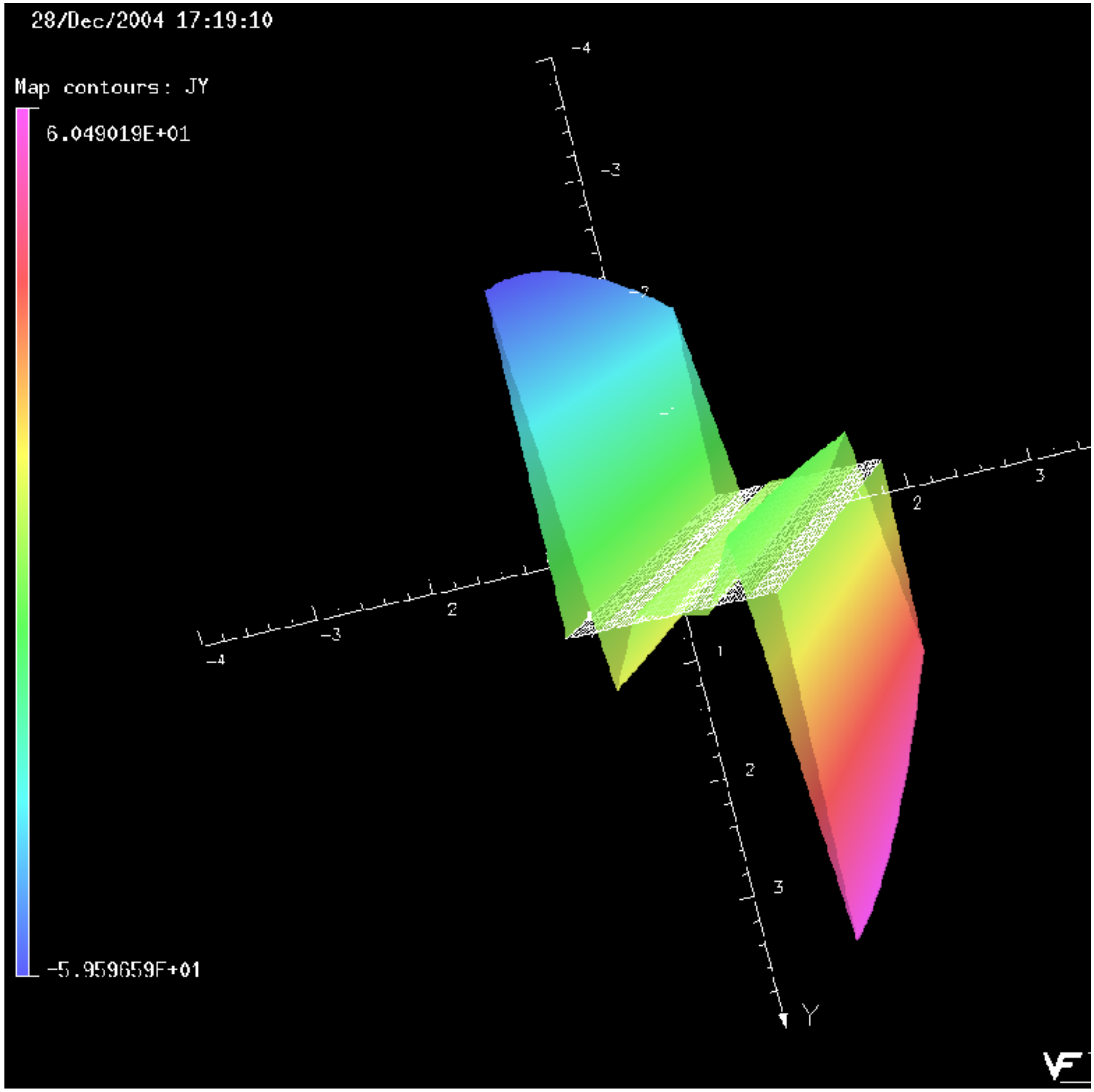
Thick Lamination

Time=t3



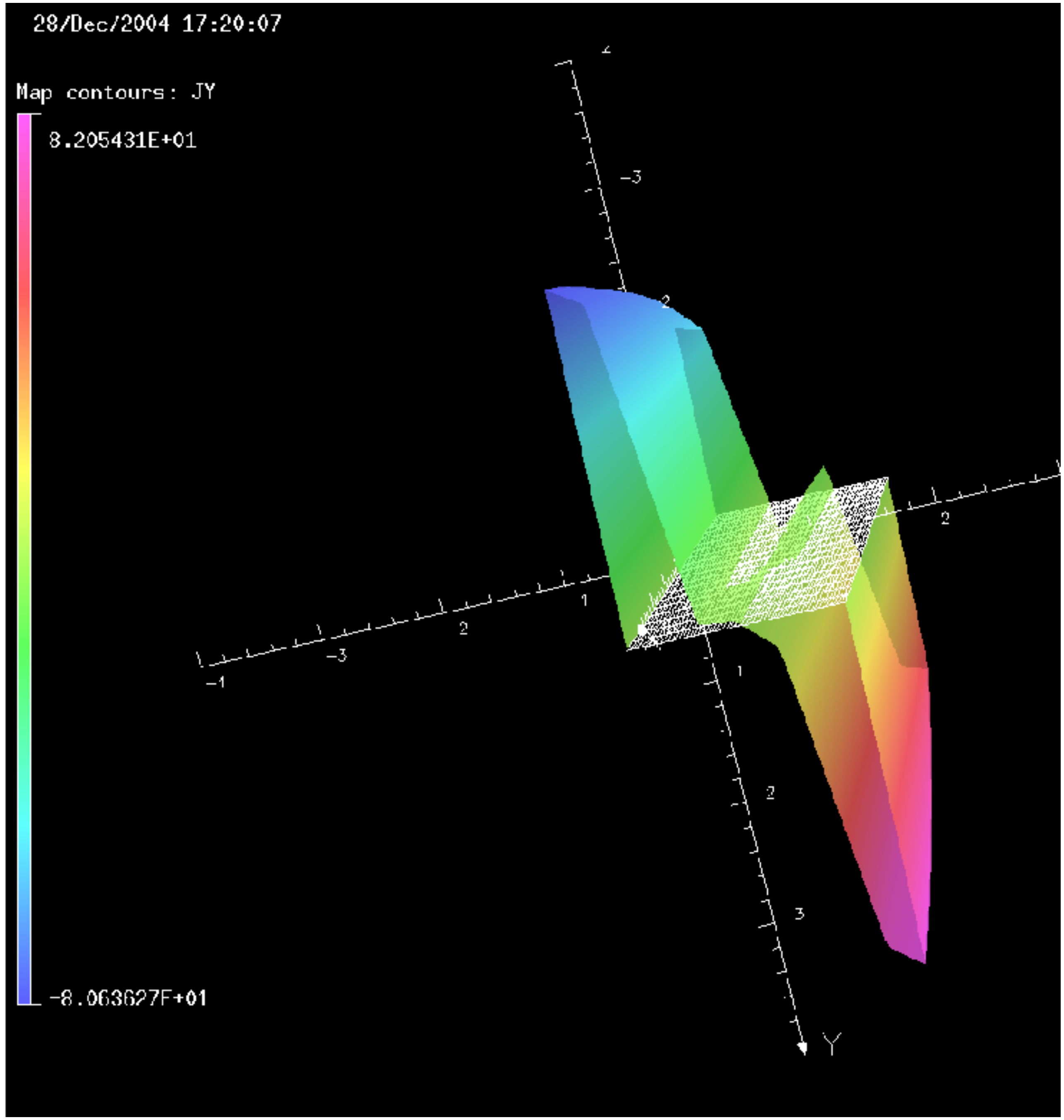
Thin Lamination

Time=t1



Thick Lamination

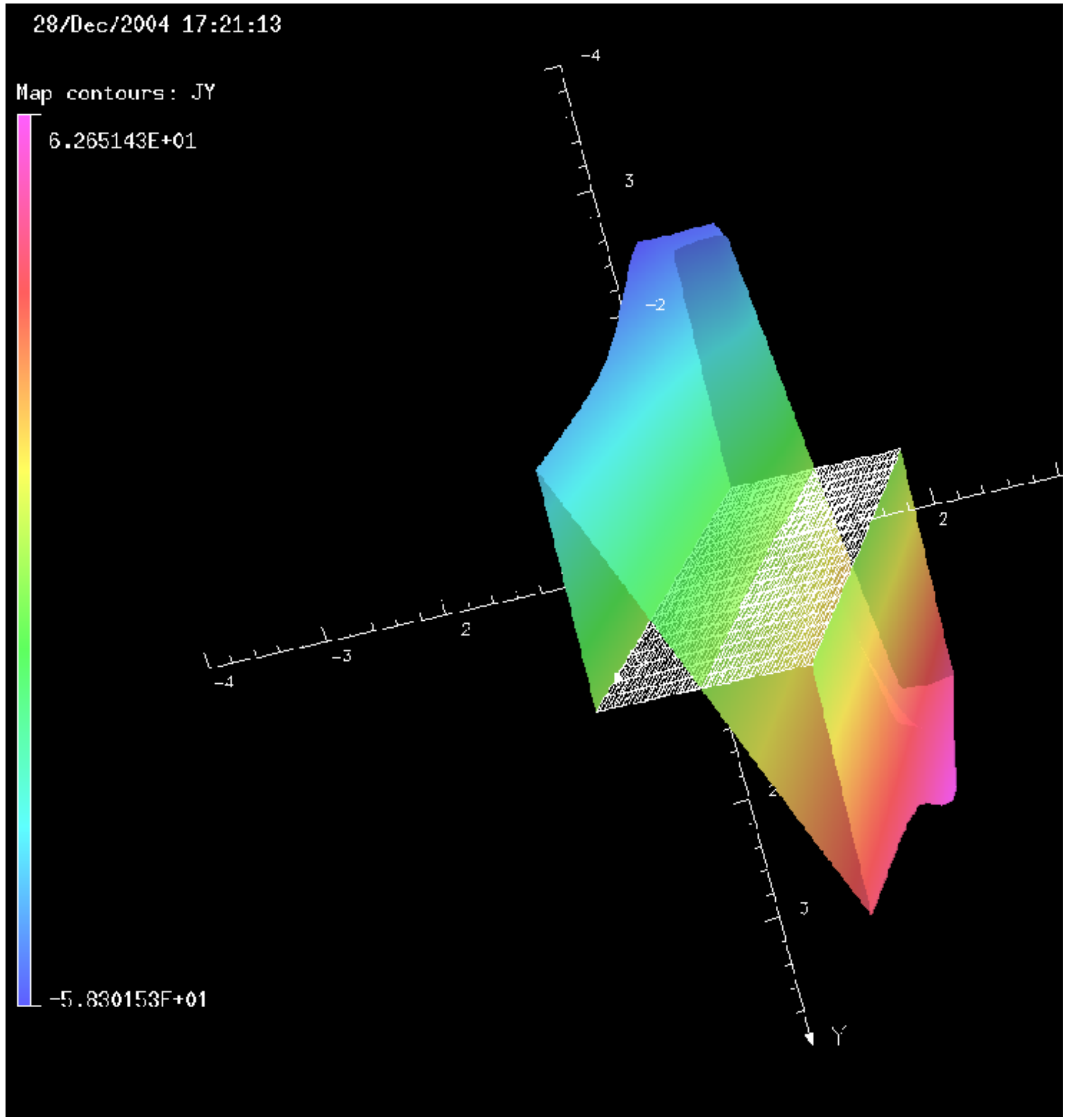
Time=t2

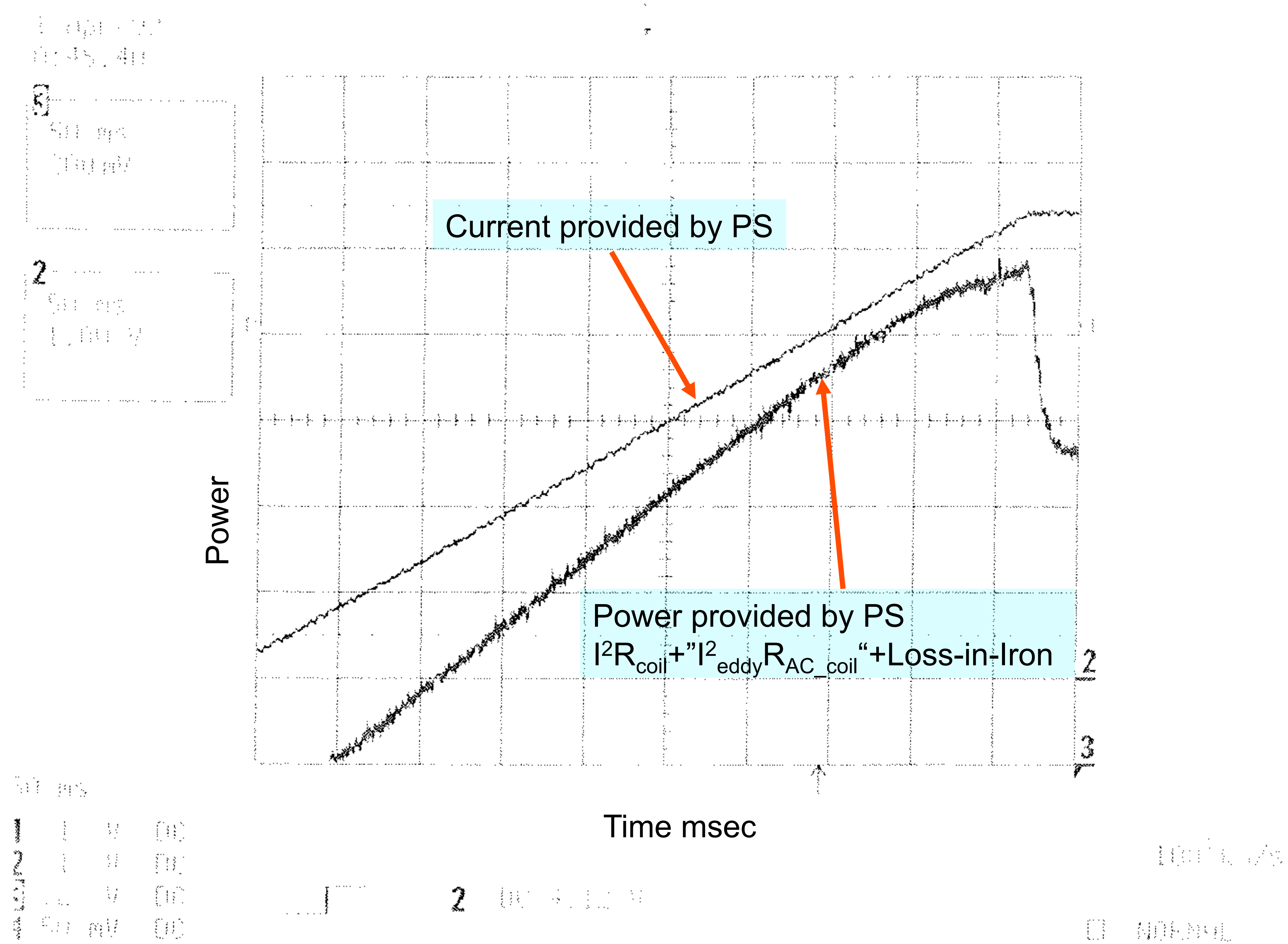


Thick Lamination

Time=t3

Eddy Currents Cancel

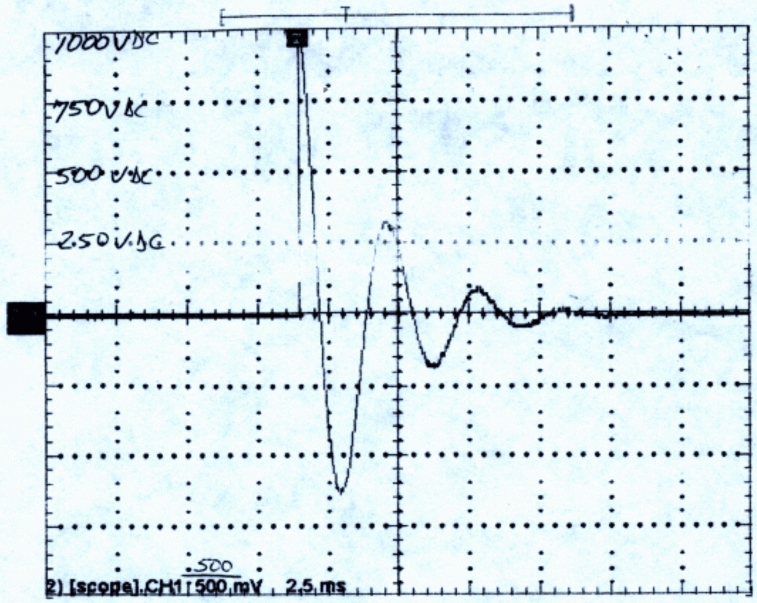



Current provided by PS
Power provided by PS
I^2R_{coil}+"$I^2_{eddy}R_{AC\_coil}$"+Loss-in-Iron
Power
Time msec

The End

What is the ratio $\int B_{sex} dz / \int B_{quad} dz$ for an AGS main magnet at the Radius R=5 cm?

- K_1 (of AGS at 1 to 2 GeV/c) ~0.0485 m^{-2} (MAD)
- K_2 (of AGS at 1 to 2 GeV/c) ~0.0111 m^{-3} (MAD)
- $K_2/K_1=\{2B_{sex}/(B\rho)R^2\}/\{B_{quad}/(B\rho)R\}$
- $B_{sex}/B_{quad}=60\times10^{-4}$ at R=5 cm



1000 VDC
IMPULSE

25 MICRO FARET

AGS QUAD S/N 01
FINAL RING ALL COILS
FULLY ASSEMBLED.

TOT RES. 39.77 mΩ SE

HYPOT OK SE 2000 VDC