3)

Internal report
interpretation of Hall probe measurements

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Purpose:

To adjust and calibrate the experimental magnetic field measurements of the wiggler based on simulations with "elop".

1. Hall probe measurements

the magnetic field along the axis of the wiggler was measured at 9/4/97 and is recorded in file bplot1.xls the data was taken every 1mm starting from a point 76.5mm before the face of the first (correction) magnet.

2. Simulation

We operated elop with data of the wiggler as given in fig. 1 and tables 1 a-c.

2.1 the wiggler period is 44.44mm , and between the two half (correction) magnets there is a spacing of ~0.5mm (following Michael). This gives a total length of ~ $104\cdot 11.11+2\cdot 5.555+3\cdot 11.11+2\cdot 0.5=1200.88$mm ($\cong$ 1201mm) for the entire wiggler-end to end. This means that the zero point of the experimental measurements is in the simulation scale :

$Z(0)= -600.5-76.5=-677$mm.

Note: On 24/4/97 Jerzy measured the wiggler length with a caliper, and found it to be ~1199mm. This is 2mm smaller from our simulation assumption, and 3mm shorter if we also consider an observed 1 mm spacing between the 2nd and 3rd periods before the end to be rechecked)

2.2 The correction magnets spacing were determined so that there will be no betatron oscillation in the trajectories and the electron will get out on axis. They are **different** from the real spacing!

2.3 Only the magnetic field was calculated.

3. Comparison

3.1 The Hall probe measurement and the simulated data of magnetic field vs. axial coordinate (z) were drawn on the same scale (Fig.2a-d).It is observed that:

(a) While there is some variance in the magnitudes of the measured magnetic field maxima and minima, there is a definite average difference between the values of the measured and simulated magnetic fields (the measured field is about 10% lower than the simulated).

(b) A cumulative phase shift between the measured and simulated fields develops along the wiggler. At the end of the wiggler, the peaks of the measured field are 7mm further away

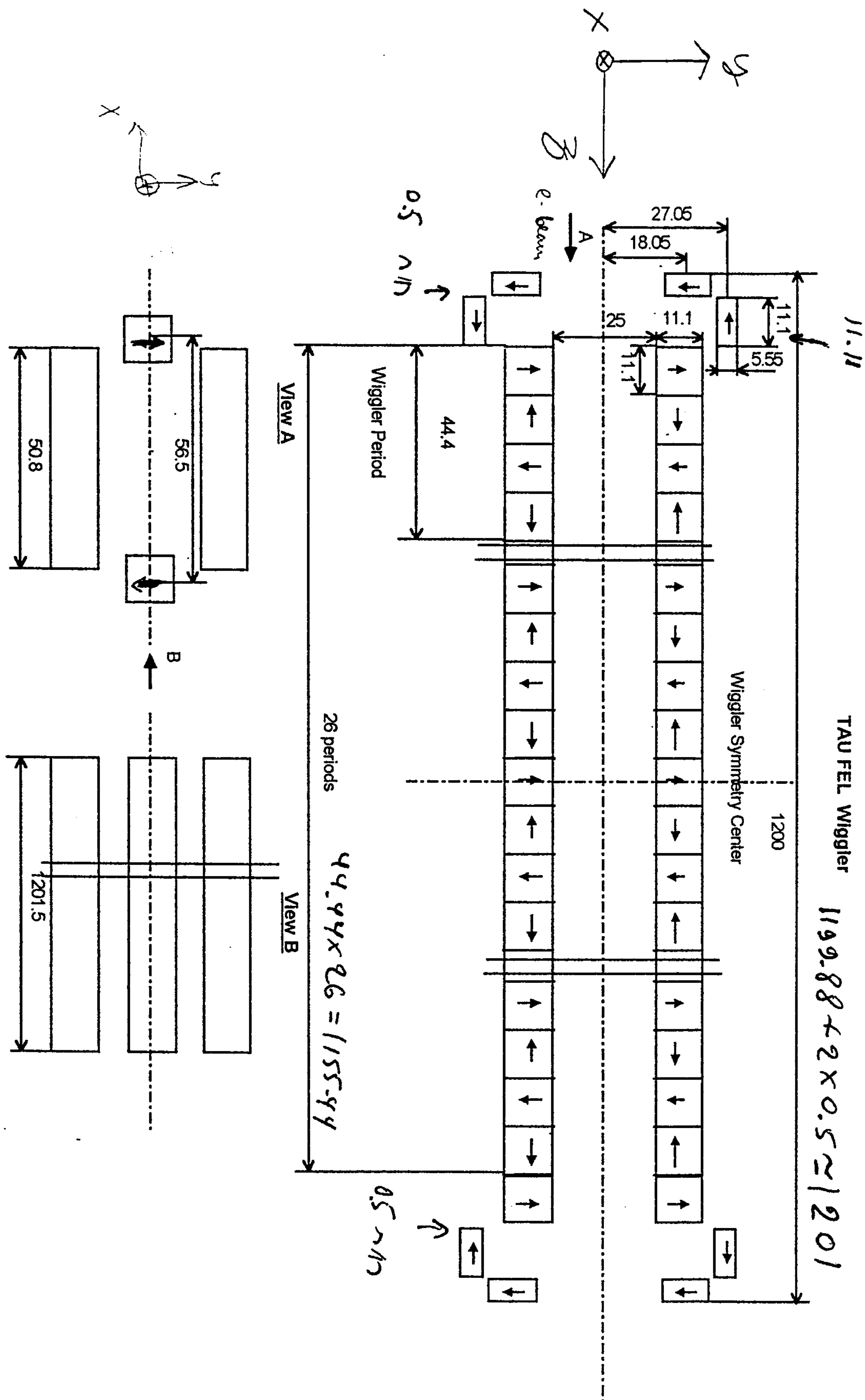
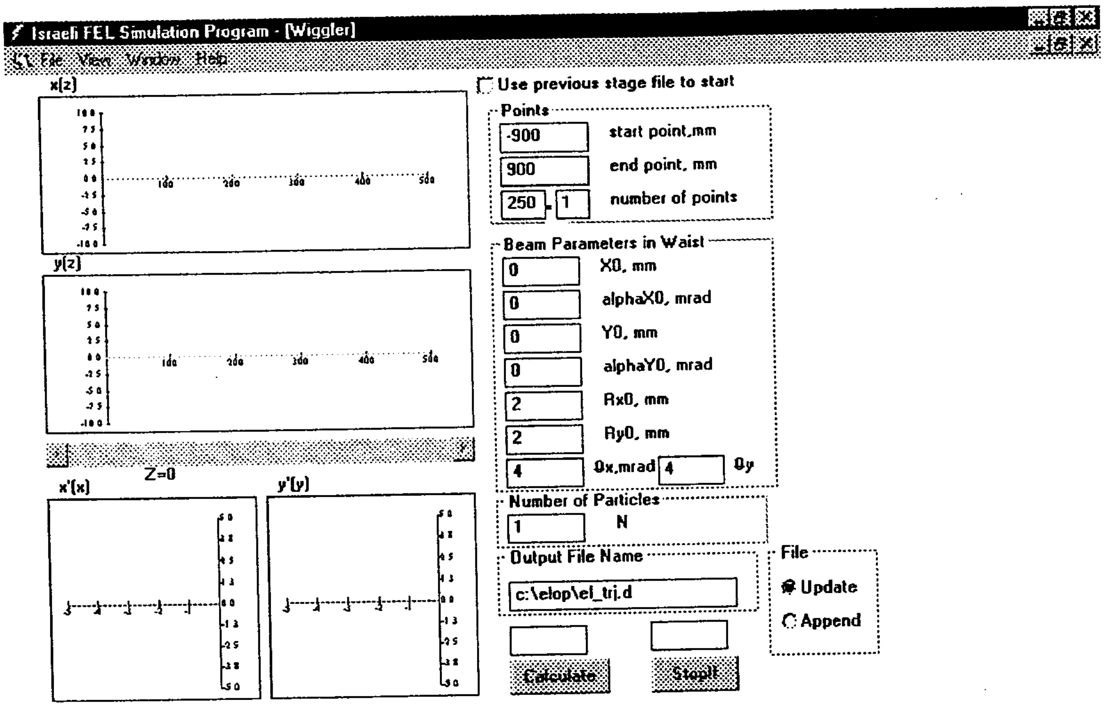


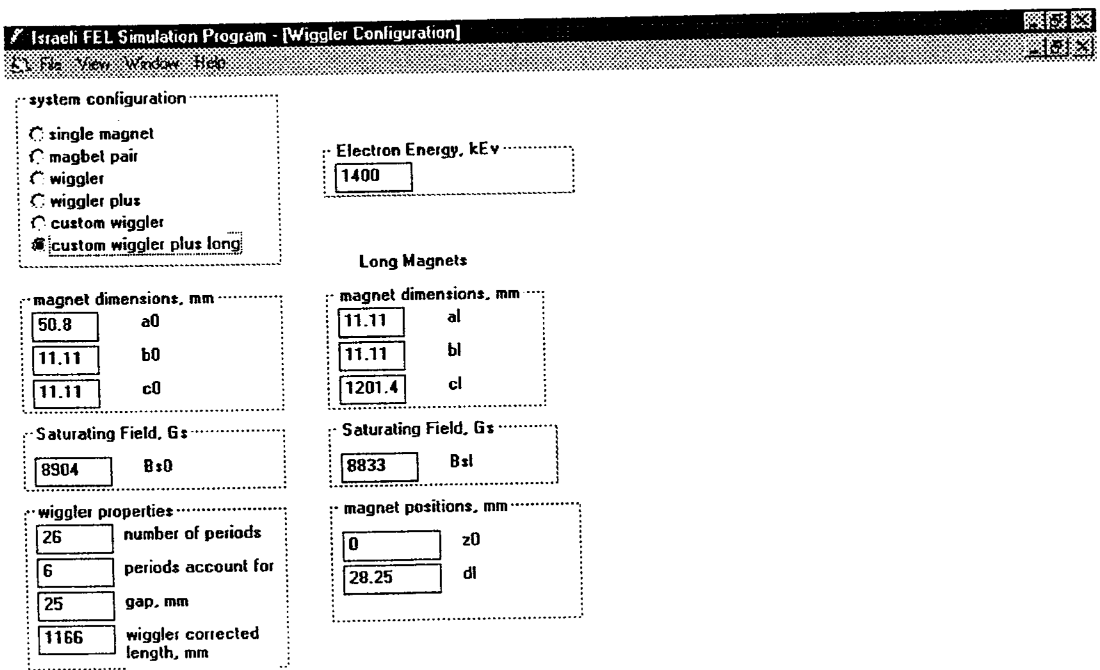
Fig. 1 TAU FEL Wiggler

Table 1

(a)


Israeli FEL Simulation Program - [Wiggler]
File View Window Help
x(z)
y(z)
Z=0
x'(x)
y'(y)
Use previous stage file to start
Points
-900 start point,mm
900 end point, mm
250 1 number of points
Beam Parameters in Waist
0 X0, mm
0 alphaX0, mrad
0 Y0, mm
0 alphaY0, mrad
2 Rx0, mm
2 Ry0, mm
4 0x,mrad 4 0y
Number of Particles
1 N
Output File Name
c:\elop\el_trj.d
File
Update
Append
Calculate
Stop!!

(b)


Israeli FEL Simulation Program - [Wiggler Configuration]
File View Window Help
system configuration
single magnet
magbet pair
wiggler
wiggler plus
custom wiggler
custom wiggler plus long
Electron Energy, kEv
1400
Long Magnets
magnet dimensions, mm
50.8 a0
11.11 b0
11.11 c0
magnet dimensions, mm
11.11 al
11.11 bl
1201.4 cl
Saturating Field, Gs
8904 Bs0
Saturating Field, Gs
8833 Bsl
wiggler properties
26 number of periods
6 periods account for
25 gap, mm
1166 wiggler corrected length, mm
magnet positions, mm
0 z0
28.25 dl

Israeli FEL Simulation Program - [Additional Magnets]

File View Window Help

Entrance magnets: 9

To edit values double-click on the cell:

	a	b	c	d	l	alpha	Bs
1	50.8	11.11	5.55	15.05	19.94	180	9082
2	50.8	11.11	5.55	31.05	11.11	-90	9082
3	13	11.11	5.55	68.5	-111.1	0	0
4	11	11.11	5.55	68.5	-433.	180	0
5	13	11.11	5.55	68.5	-511.	180	0
6	20	11.11	5.55	68.5	-577.	180	0
7	16	11.11	5.55	68.5	-599.	0	0
8	12	11.11	5.55	68.5	-955.	180	0
9	12.5	11.11	5.55	68.5	-1066	0	0

Exit magnets: 3

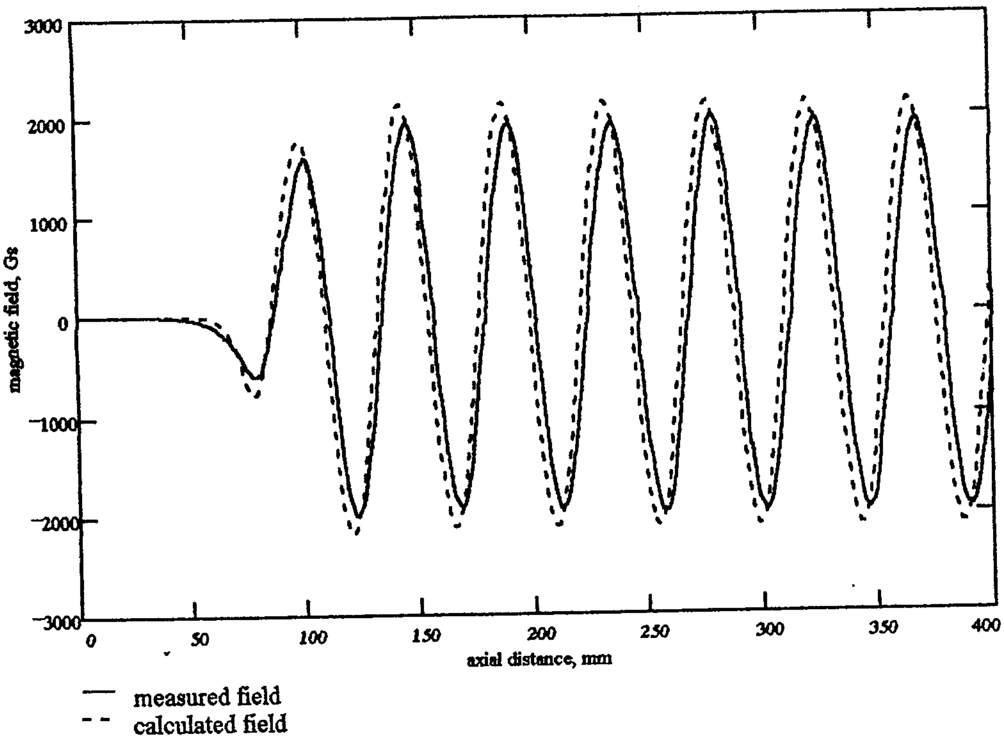
To edit values double-click on the cell:

	a	b	c	d	l	alpha	Bs
1	50.8	11.11	11.11	18.05	11.11	0	9082
2	50.8	11.11	5.55	31.05	22.22	90	9082
3	50.8	11.11	5.55	15.05	31.08	180	9082

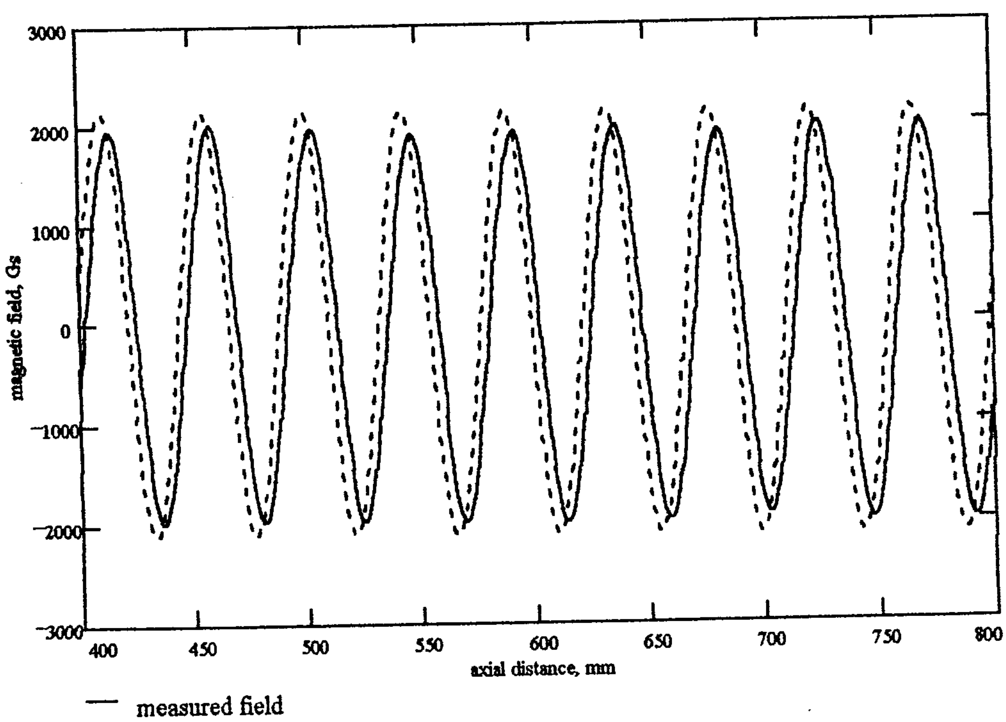
(c)

Fig. 2

TAU FEL wiggler measurement (Hall-Probe methode) and simulation (ELOP)

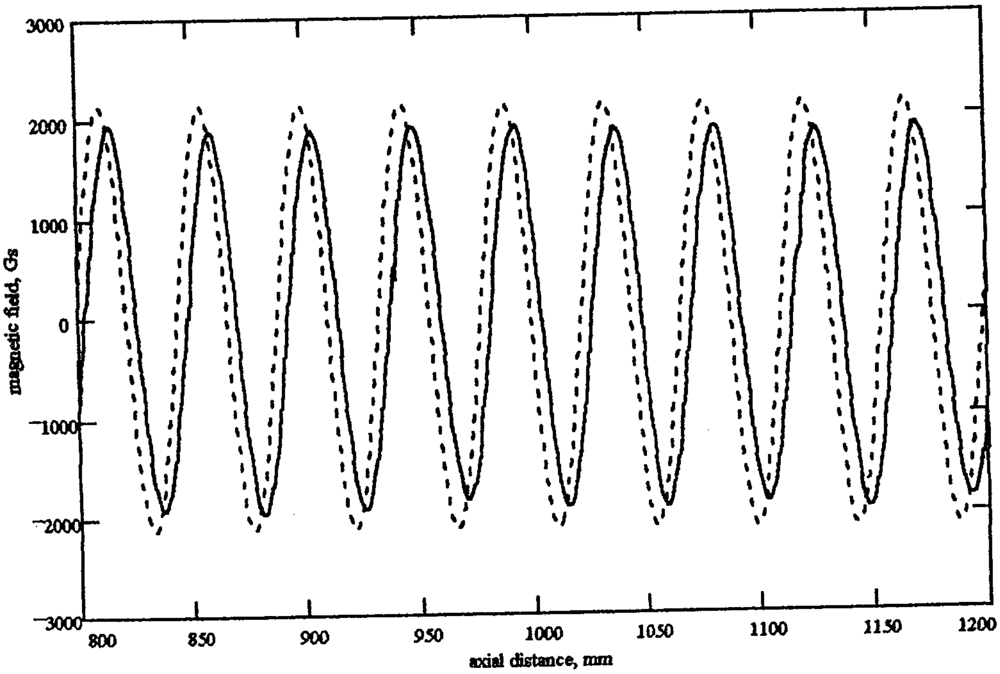


(a)



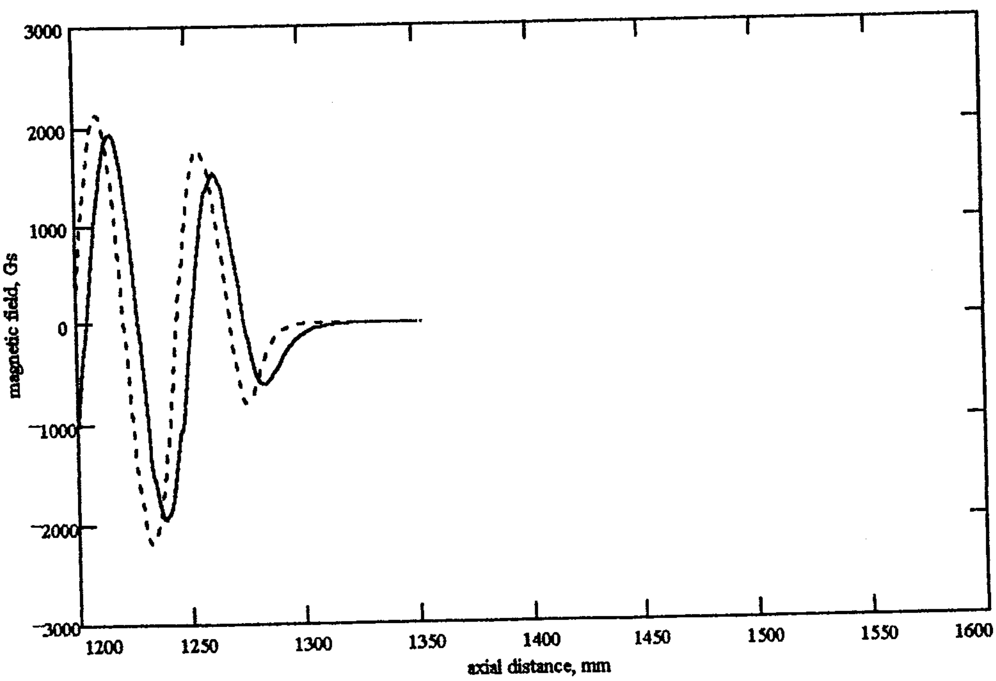
(b)

- - calculated field



(c)

— measured field
- - calculated field



(d)

— measured field

relative to the measured data. Considering that the simulation was done for a 1201mm wiggler, the Hall probe data suggests a wiggler of length 1201+7=1208 mm (0.6% longer).
(c) The measured maxima and minima values of the magnetic field are approximately equal, suggesting that the probe was placed well on axis, and no bias due to the longitudinal magnets was picked up. This, however, may not be an accurate conclusion and will be reexamined later.

3.2 It is hard to judge the quality of the periodic magnetic field from observation of the magnetic field only. A better measure is the second integral function:

$$\tilde{x}(z) = C\int_0^z\int_0^{z'} B_y(z'')\,dz'dz'' \qquad (1)$$

$$\text{where } C = -\frac{e}{\gamma\beta mc} = +163(\text{Tesla}-\text{m})^{-1} \qquad (2)$$

(for γ=3.73, β=0.963)
Note that this function gives the electron trajectory only if β is constant along the wiggler and if B_y does not vary as a function of x. The correct expression for the trajectory is:

$$x(z)=C\int_0^z(\beta/\beta(z'))\int_0^{z'} B_y(z'')dz''dz' \qquad (3)$$

$$\text{where } \beta_z(z)=\sqrt{\beta^2-\beta_x{}^2}=\beta\sqrt{1-\left(\frac{\beta_x}{\beta}\right)^2} \quad \text{and} \quad \frac{\beta_x}{\beta}=C\int_0^z B_y(z')dz' \qquad (4)$$

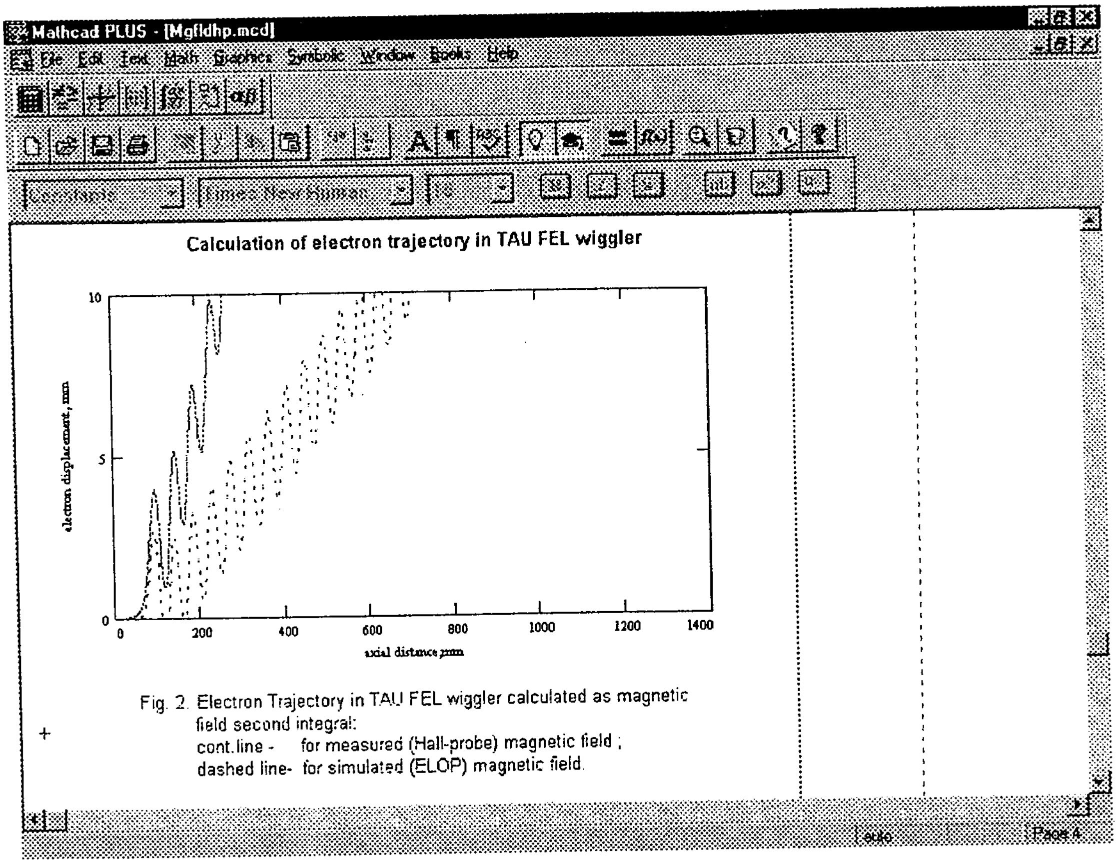
If also the assumption that B_y does not vary with x does not hold, then the trajectory must be carried out properly by integration along the electron trajectory (and not on axis) as is automatically done by ELOP.

Because the Hall probe measurements were made only on axis, we cannot calculate the exact trajectories. Though we can still use Eq. 3 for estimating the trajectories, we prefer to use Eq. 1 (the second integral) as a measure of quality (also we should bear in mind that in the long-pulse pulsed-wire technique this is the function that is measured). For this reason, in order to compare measurements and simulations we will use at this point only the second integral function (Eq.1). At the end, after good agreement is obtained between the measurements and simulations, we will have to apply Eq. 3, and the full simulation of elop, to verify a good trajectory.

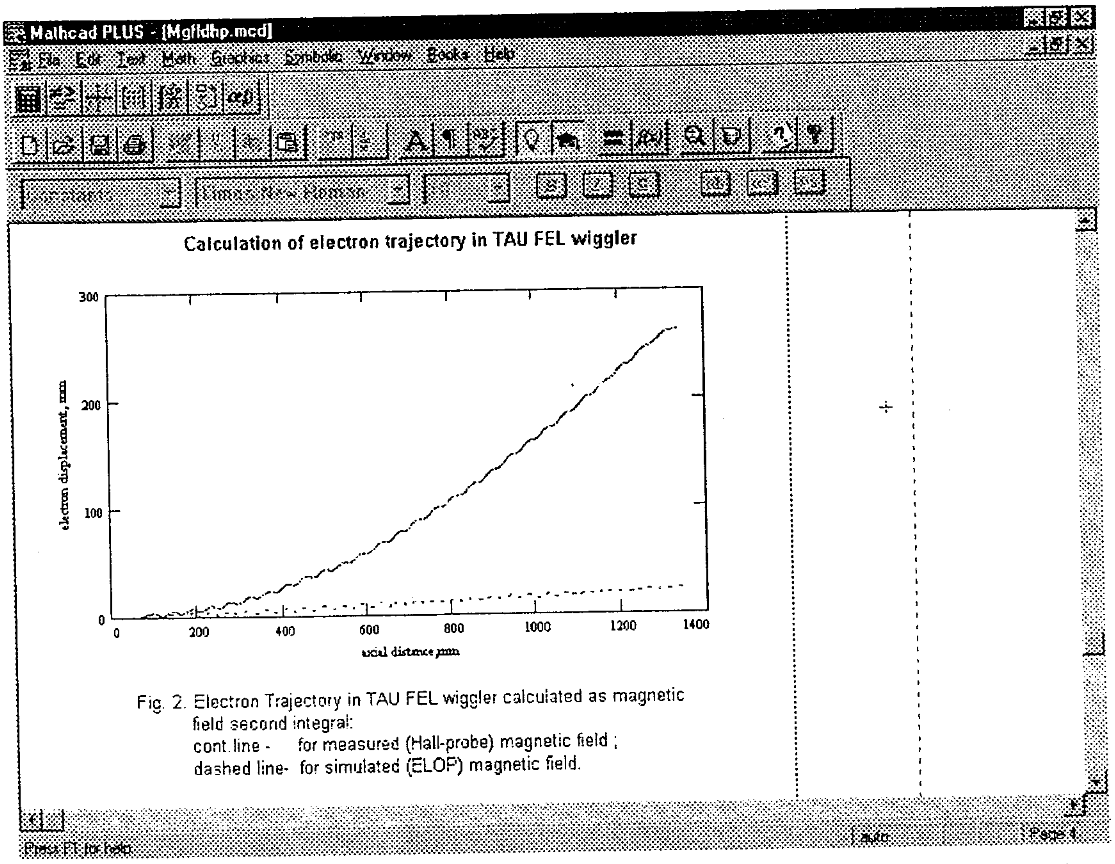
3.3 Fig. 3 a,b show the double integral function (Eq.1) of both the measured and simulated magnetic fields. One may note that:
(a) The wiggling amplitude seems to be correct in both curves (about 3mm peak to peak).
(b) The measured data suggests a much bigger drift of the electrons than the simulated data. This is not surprising, because the simulation was done with optimal correction parameters (**it should be repeated** with the actual correcting magnets according to the design).

3.4 In order to remove the discrepancy between the amplitudes and phases of the measured and simulated magnetic fields, we made the following assumptions:
(a) The **measurement** of the magnetic field by a Hall probe should be very accurate. The reasonable assumption is, that the Br value taken in the simulation for the remnant field of the individual magnets (B_{s0} = 8904Gs) is too big (either the magnets became weaker or the

Fig. 3


Mathcad PLUS - [Mgfldhp.mcd]
File Edit Text Math Graphics Symbolic Window Books Help
Calculation of electron trajectory in TAU FEL wiggler
electron displacement, mm
0
5
10
0
200
400
600
800
1000
1200
1400
axial distance, mm
Fig. 2. Electron Trajectory in TAU FEL wiggler calculated as magnetic field second integral:
cont.line - for measured (Hall-probe) magnetic field ;
dashed line- for simulated (ELOP) magnetic field.
auto
Page 4

(a)


Mathcad PLUS - [Mgfldhp.mcd]
File Edit Text Math Graphics Symbolic Window Books Help
Calculation of electron trajectory in TAU FEL wiggler
electron displacement, mm
0
100
200
300
0
200
400
600
800
1000
1200
1400
axial distance, mm
Fig. 2. Electron Trajectory in TAU FEL wiggler calculated as magnetic field second integral:
cont.line - for measured (Hall-probe) magnetic field ;
dashed line- for simulated (ELOP) magnetic field.
Press F1 for help
auto
Page 4

(b)

initial measurement model was not correct). To correct this we multiplied the simulated field data by a factor x0.9.

(b) The wiggler length inferred from the Hall probe measurement data (1208 mm) seems to be too long. We suspect that the mm paper used for the position measurement is not accurate. To adjust to the more reliable **simulation** data of length, we multiply the measured coordinate (z) by a reduction factor x1201/1208.

These two assumptions should be still more carefully checked. However, their use gives very good agreement between the measured and simulated magnetic field along the entire wiggler Fig.4a-d).

4. Correction

4.1 The big deflection of the electron trajectory in the positive x direction (see Fig 3c), can be reduced to a large extent by adjusting the first correction magnets, and bedding the initial slope of the trajectory to the negative direction, until the electron exits the wiggler on axis. We simulated this operation by deducting from the second integral function of the modified measured magnetic field data (x(z)) a linear function given by: $\tilde{x}(L)(z-76.5)/(L-76.5)$.

This results in the desirable zero double integral condition $-\tilde{x}(L)=0$. The result is shown in Fig. 5: Instead of a total deflection at the end of the wiggler of ~270mm (Fig.3b), we get only 50mm deflection in the middle of the wiggler (Fig.5).

4.2 To improve the trajectory along the wiggler, evidently additional magnets must be added along the wiggler to correct the "bow". The first test is to see if the additional magnets, that are already glued, do the right thing. To do this we calculated the second integral function of the simulated field of these additional magnets (Fig. 6 Table 2). The result seems to suggest that these additional magnets cause part of the bow (if there is no sign mistake). If the initial correction magnets will be readjusted to keep the zero double integral condition, the additional magnets contribute to a ~8mm bow out of the 50mm measured.

4.3 A different conclusion can be drawn from observation that the average trajectory of the second integral function is nearly a smooth parabola. From Eq. 1 we can conclude that such a trajectory can be formed by a constant magnetic field (along the wiggler). The average trajectory is approximately $\bar{x}(z)=0.14z^{**}2$. Hence Bo=[$\bar{x}$ (z)]"/C=0.14x2/163=.0017Tesla=17 Gauss.

Consequently, a fixed magnetic field of 17 gauss can fix the "bow". This can be done by adjustment of the longitudinal magnets or displacement of the wiggler axis.

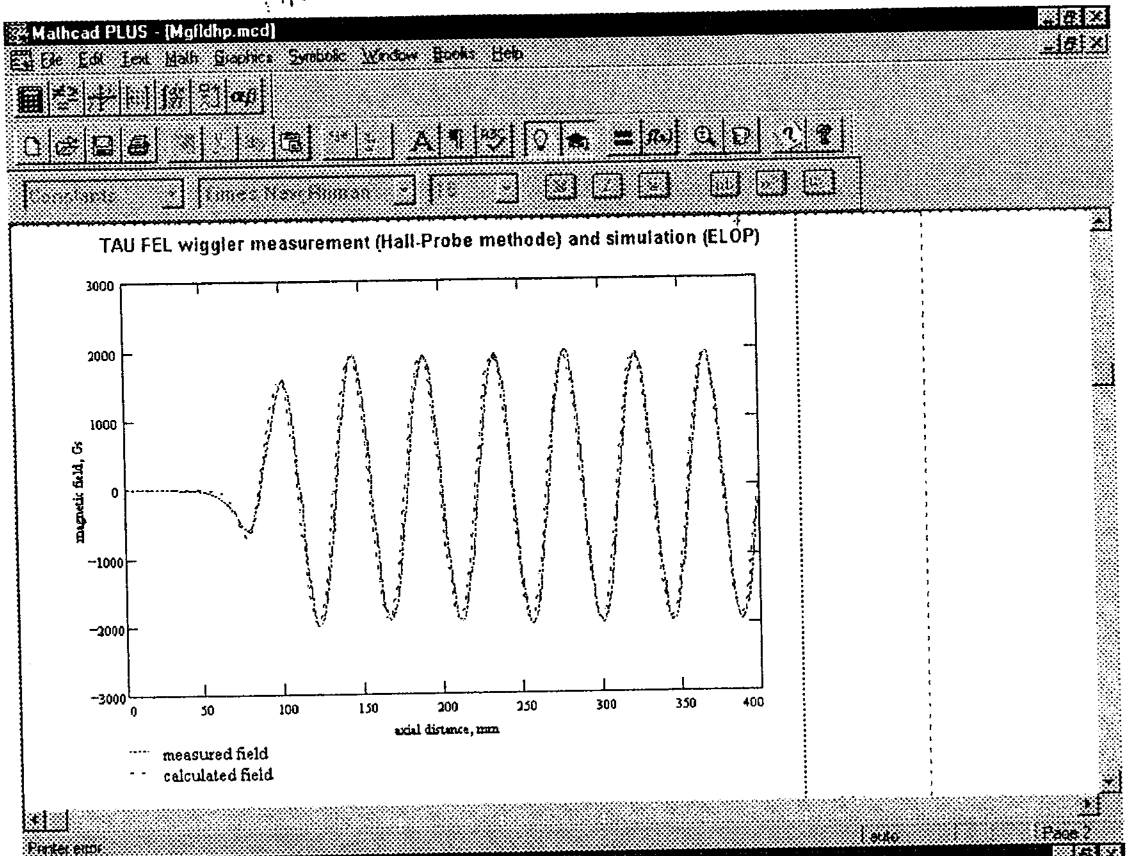
4.4 According to calculations made by Amir and Yosi (on July,4,96) the magnetic field gradient produced by the longitudinal magnets is α_r = 34.6 Gs/mm (following M. Cohen's Ph.D. thesis, page 59). This result agrees with the betatron period $\lambda_{\beta x}=2\pi\sqrt{\frac{\gamma\beta mc}{e\alpha_r}}=26.6\text{cm}$ that was also obtained in ELOP simulations. According to this, a deviation of 0.5 mm of the measurement axis from the zero-focusing-field axis is sufficient to produce a constant magnetic field of 17 Gauss.

24/4/97

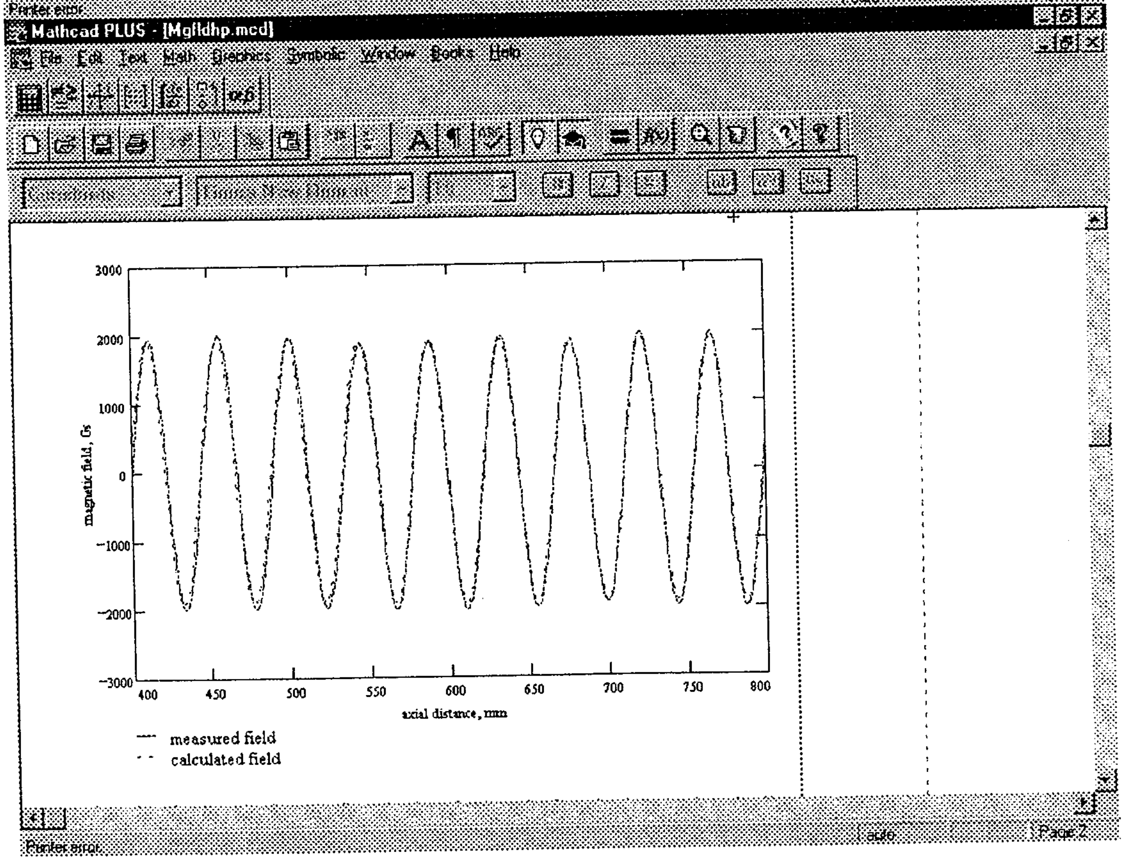
$Z = Z \cdot \frac{1201}{1208}$

$B = B \cdot 0.9$

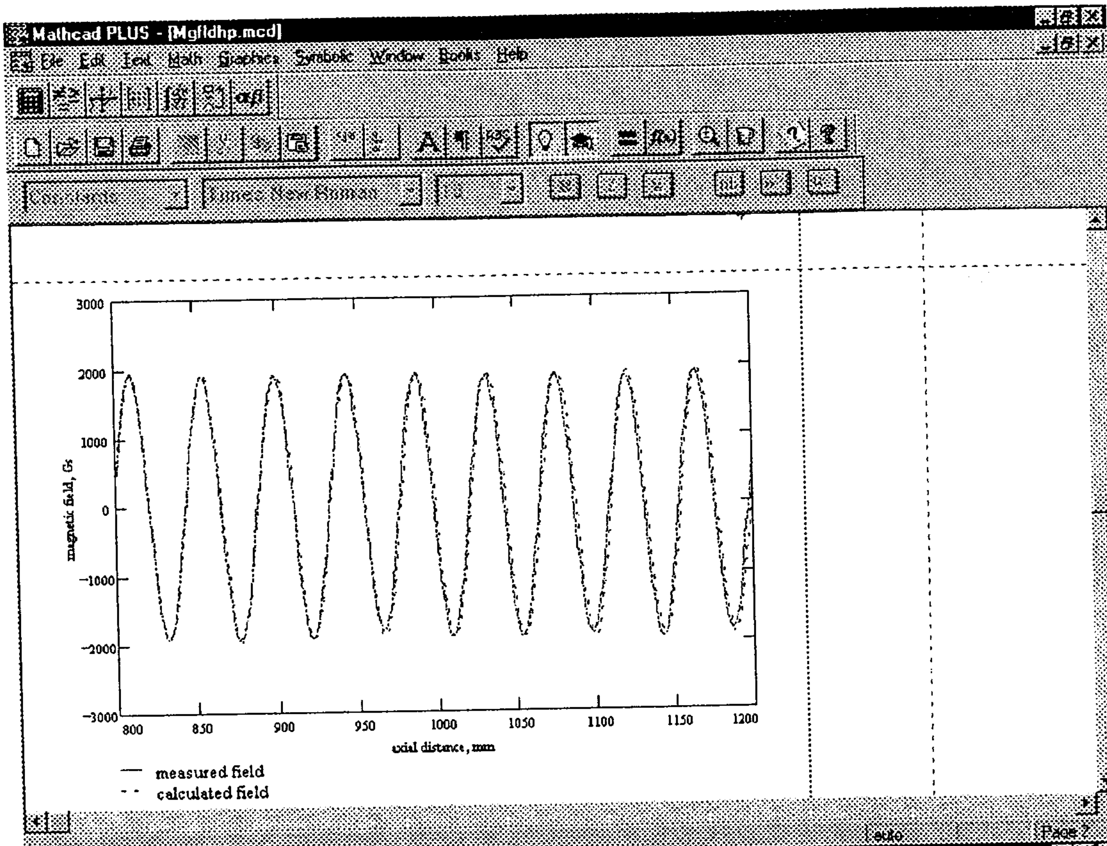
fig. 4



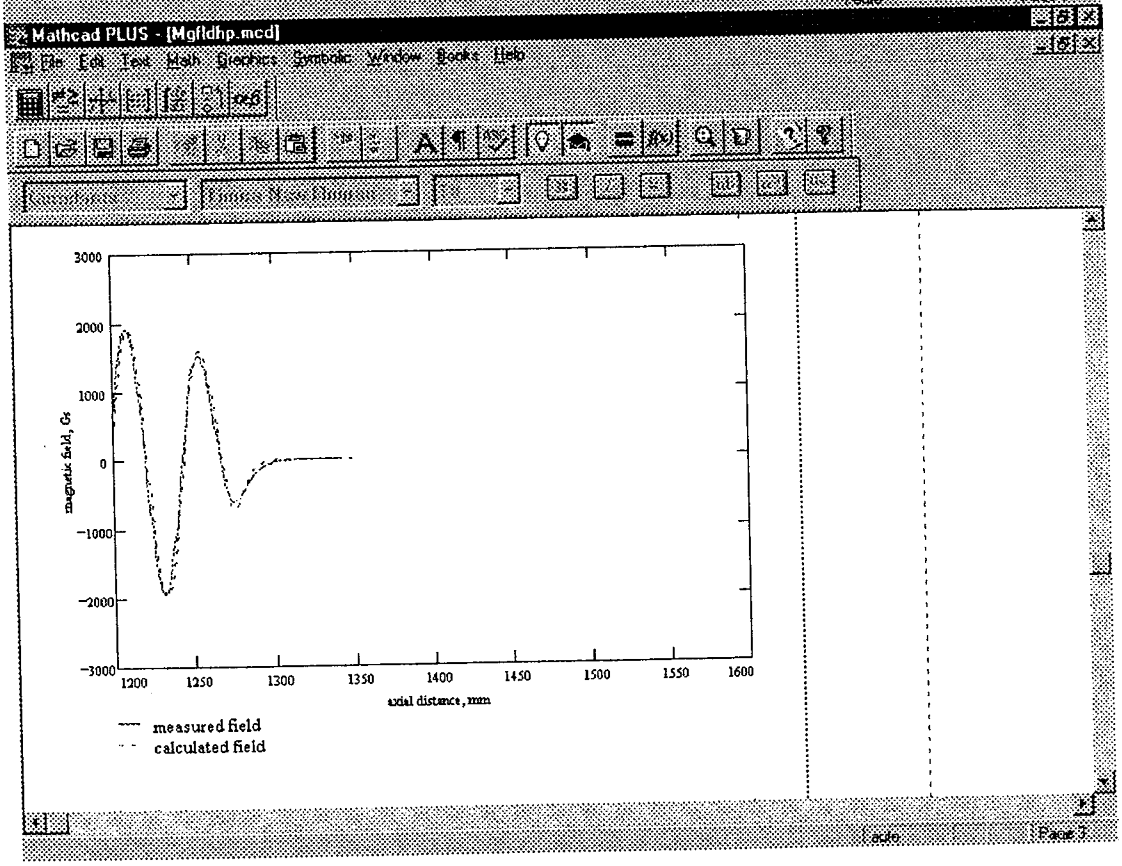
a



b


Mathcad PLUS - [Mgfldhp.mcd]
File Edit Text Math Graphics Symbolic Window Books Help
magnetic field, Gs
3000
2000
1000
0
−1000
−2000
−3000
800 850 900 950 1000 1050 1100 1150 1200
axial distance, mm
measured field
calculated field
auto
Page 2

c


Mathcad PLUS - [Mgfldhp.mcd]
File Edit Text Math Graphics Symbolic Window Books Help
magnetic field, Gs
3000
2000
1000
0
−1000
−2000
−3000
1200 1250 1300 1350 1400 1450 1500 1550 1600
axial distance, mm
measured field
calculated field
auto
Page 3

d

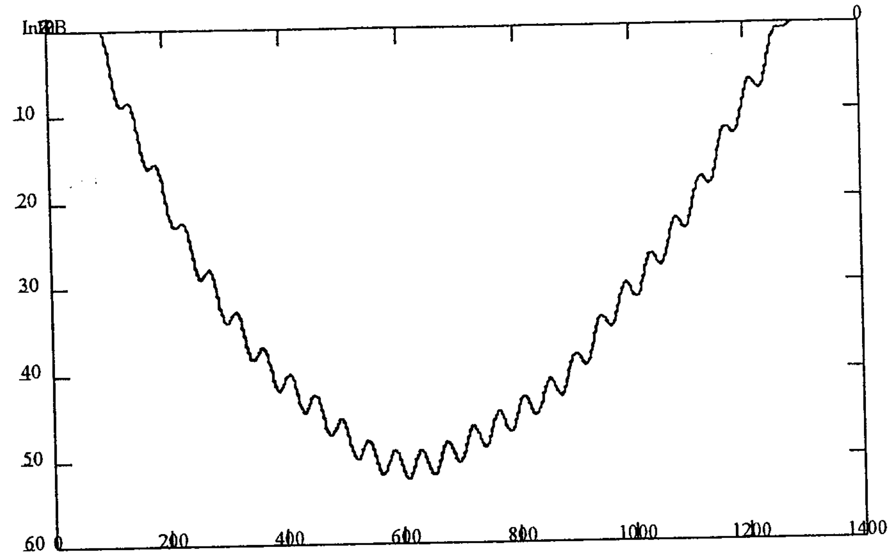
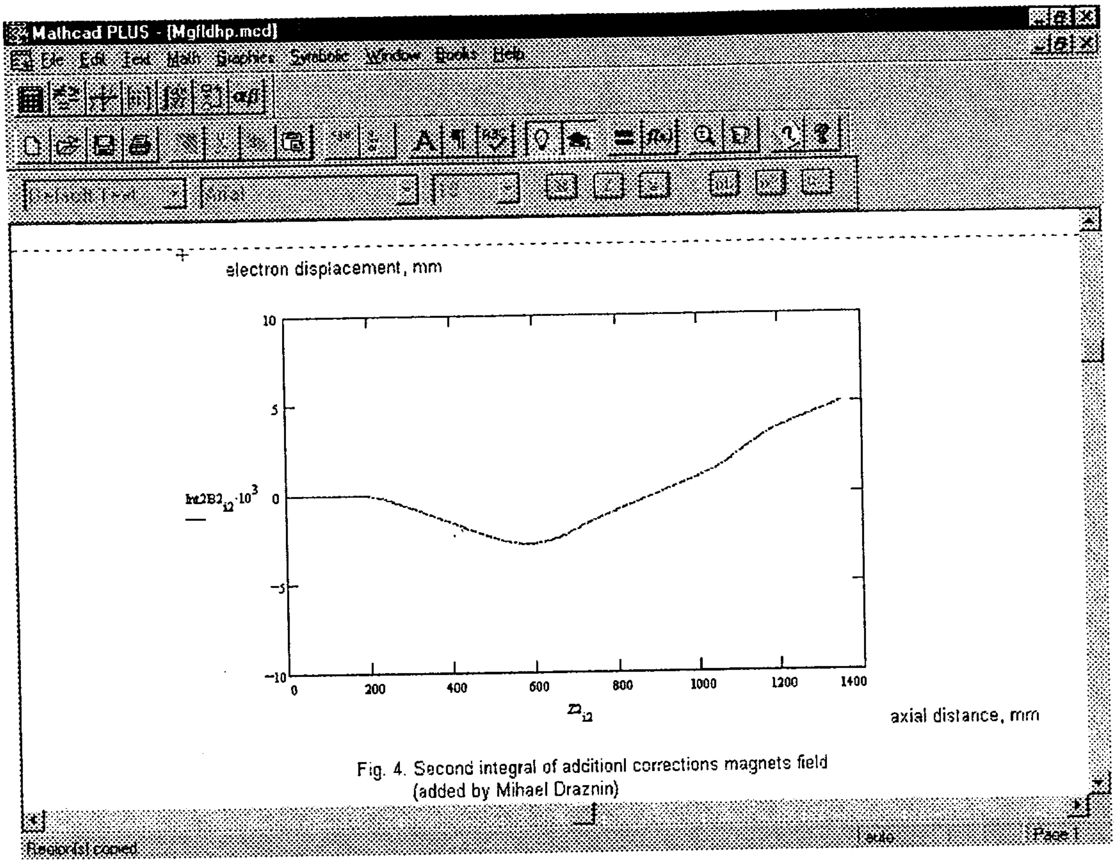


Fig. 3. Measured magnetic field second integral (electron trajectory)
after correction by:
B -> B-B(L)*(L-76.5)*(Z-76.5)
which simulates readjustment of the first correcting magnet so that field second integral eliminates at the end of the wiggler.

Fig. 6



Mathcad PLUS - [Mgfldhp.mcd]
File Edit Text Math Graphics Symbolic Window Books Help
electron displacement, mm
10
5
0
−5
−10
0
200
400
600
800
1000
1200
1400
axial distance, mm
Fig. 4. Second integral of additionl corrections magnets field
(added by Mihael Draznin)
Region(s) copied
auto
Page 1

Table 2

Israeli FEL Simulation Program - [Additional Magnets]

File View Window Help

Entrance magnets: 9

To edit values double-click on the cell:

	a	b	c	d	β	alpha	Bs
1	50.8	11.11	5.55	15.05	19.94	180	0
2	50.8	11.11	5.55	31.05	11.11	-90	0
3	13	11.11	5.55	68.5	-111.1	0	9082
4	11	11.11	5.55	68.5	-433.3	180	9082
5	13	11.11	5.55	68.5	-511.0	180	9082
6	20	11.11	5.55	68.5	-577.7	180	9082
7	16	11.11	5.55	68.5	-599.9	0	9082
8	12	11.11	5.55	68.5	-955.5	180	9082
9	12.5	11.11	5.55	68.5	-1066.	0	9082

Exit magnets: 3

To edit values double-click on the cell:

	a	b	c	d	β	alpha	Bs
1	50.8	11.11	11.11	18.05	11.11	0	0
2	50.8	11.11	5.55	31.05	22.22	90	0
3	50.8	11.11	5.55	15.05	31.08	180	0

Table 4. Additional correction magnets

Conclusions:

It may be necessary to adjust the wiggler relative to the pulsed wire with a micrometer!

5. Actions

5.1 Check the calculations and complete the simulations.

5.2 In the pulsed wire experiment adjust the entrance correcting magnet and the wire position until the "bow" disappears.

5.3 By simulations determine the optimal spacing of the first correcting magnets. Decide if and how much to machine the metal.

5.4 By simulations determine the effects of Michael's additional magnets on the "Straight" rojectories and where should additional magnets be placed optimally.

5.5 Check Eq. 4 and full simulation.

5.6 Mark the coordinates on the wiggler:

+ x = up
+ z = downstream
+ y = right-facing downstream