Magnetic Measurements on the Undulator System for SASE FEL at the TESLA Test Facility

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Overview

Introduction :

Magnetic design considerations,
Combined function focusing, 4MFU structure
Parameters
Magnetic, Quadrupole Alignment specifications: Preservation of overlap

Magnetic measurements

Field optimization on ‚naked undulator'

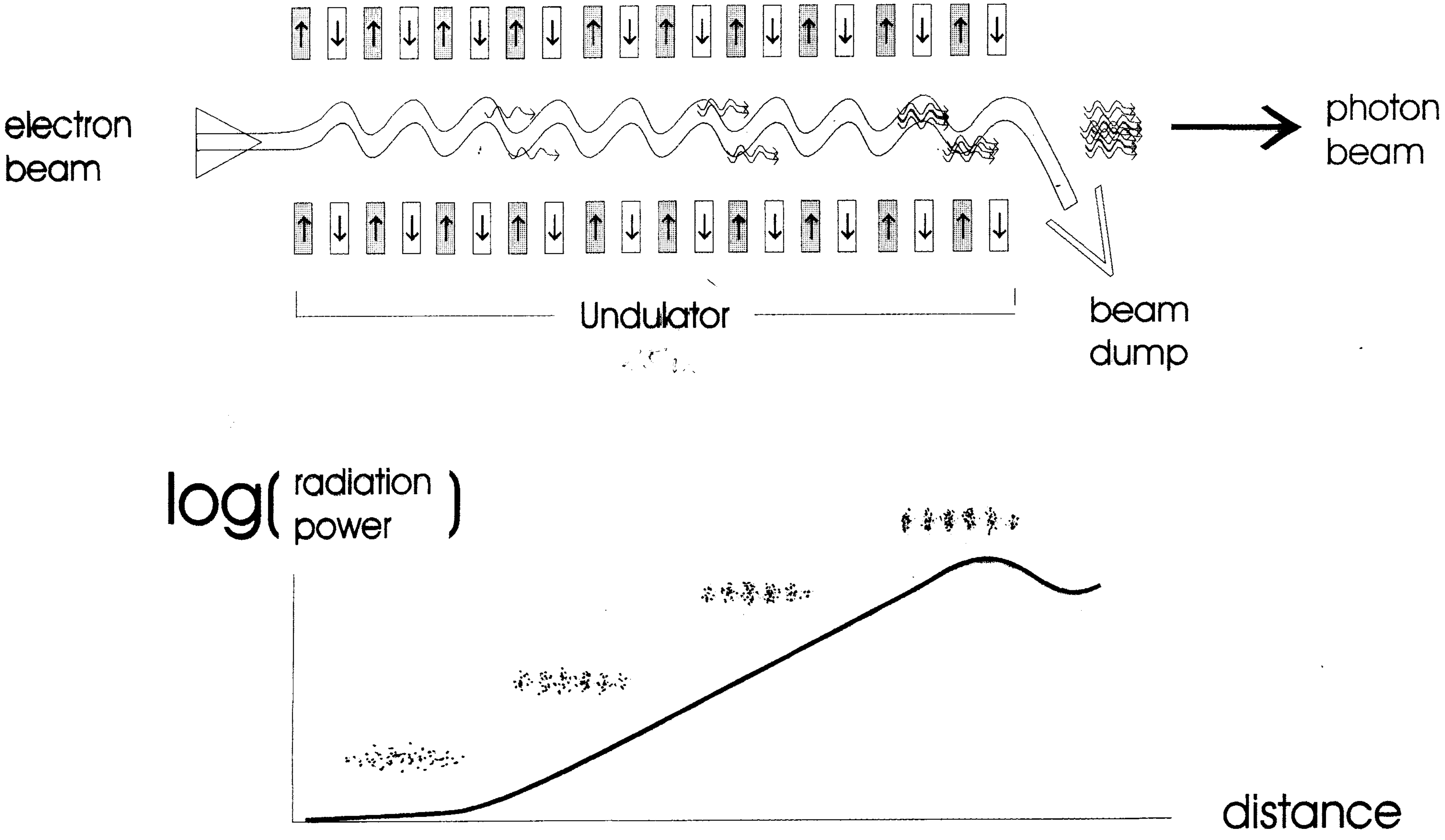
1.Horizontal field :– shiming
2 Vertical field : Field fine tuning by pole height adjustment
Results

Quadrupole alignment

Adjustment principle, linearized approach
Principle of measurement, Rectangular coil method, Fiducialization
Results

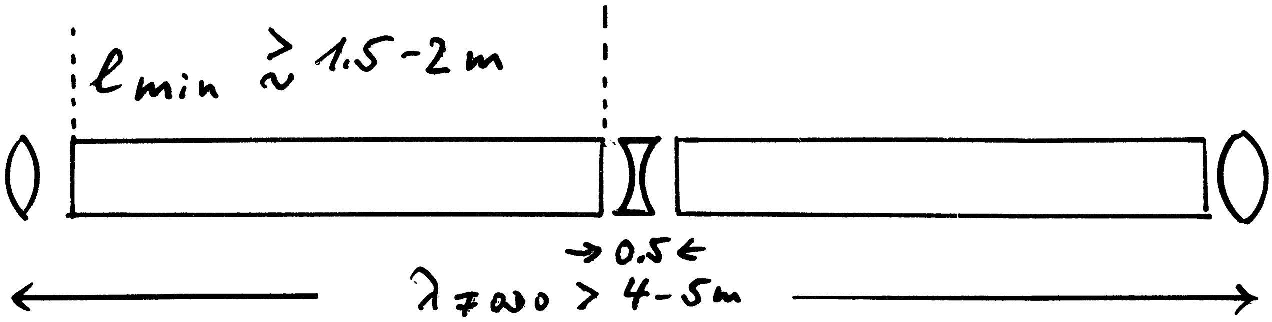
Outlook, Success of the DESY SASE FEL Project

First lasing 22.2.2000
Saturation 7.9.2001

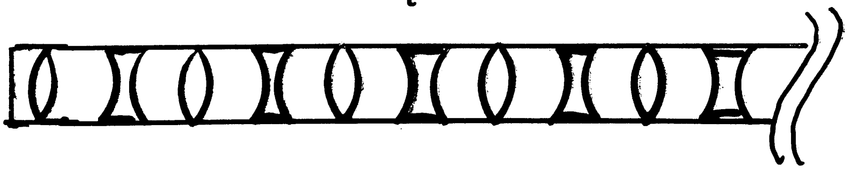


Free Electron Laser in the Self Amplified Spontaneous Emission (SASE) mode

Separate function



Combined function



and so on

FODO Lattice

$$\beta_{MAX/min} \cong 2 \cdot f \pm \frac{\lambda_{FODO}}{2}$$

Examples:

TTF-FEL Phase 1:

$E = 0.3\,GeV$

$\bar{\beta} = 1\,m$

$\beta_{MAX}/\beta_{Min} \approx 3$

$\beta_{max} = 1.5\,m$

$\beta_{min} = 0.5\,m$

$\frac{\lambda_{FODO}}{2} = 0.478\,m \simeq 0.5$

$\rightarrow$ combined function

X-FEL @ DESY

$E = 10\,GeV$

$\bar{\beta} = 8\,m$

$\beta_{MAX}/\beta_{Min} = 2$

$\beta_{MAX} = 10.66\,m$

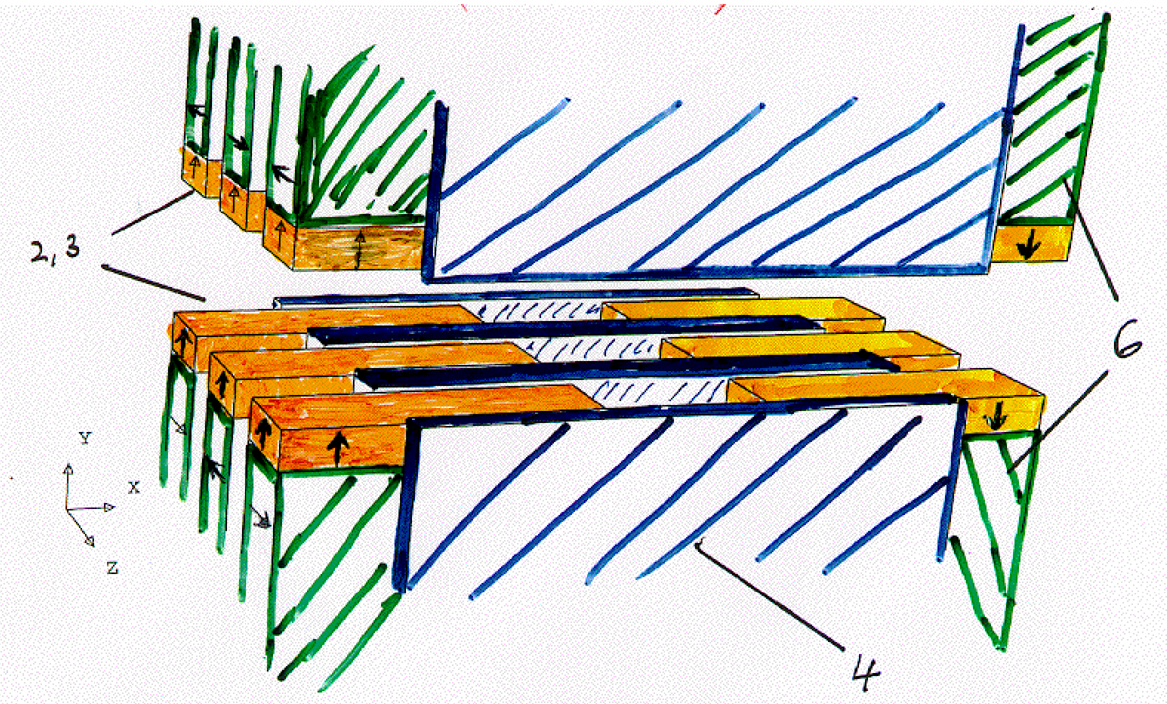
$\beta_{min} = 7.33\,m$

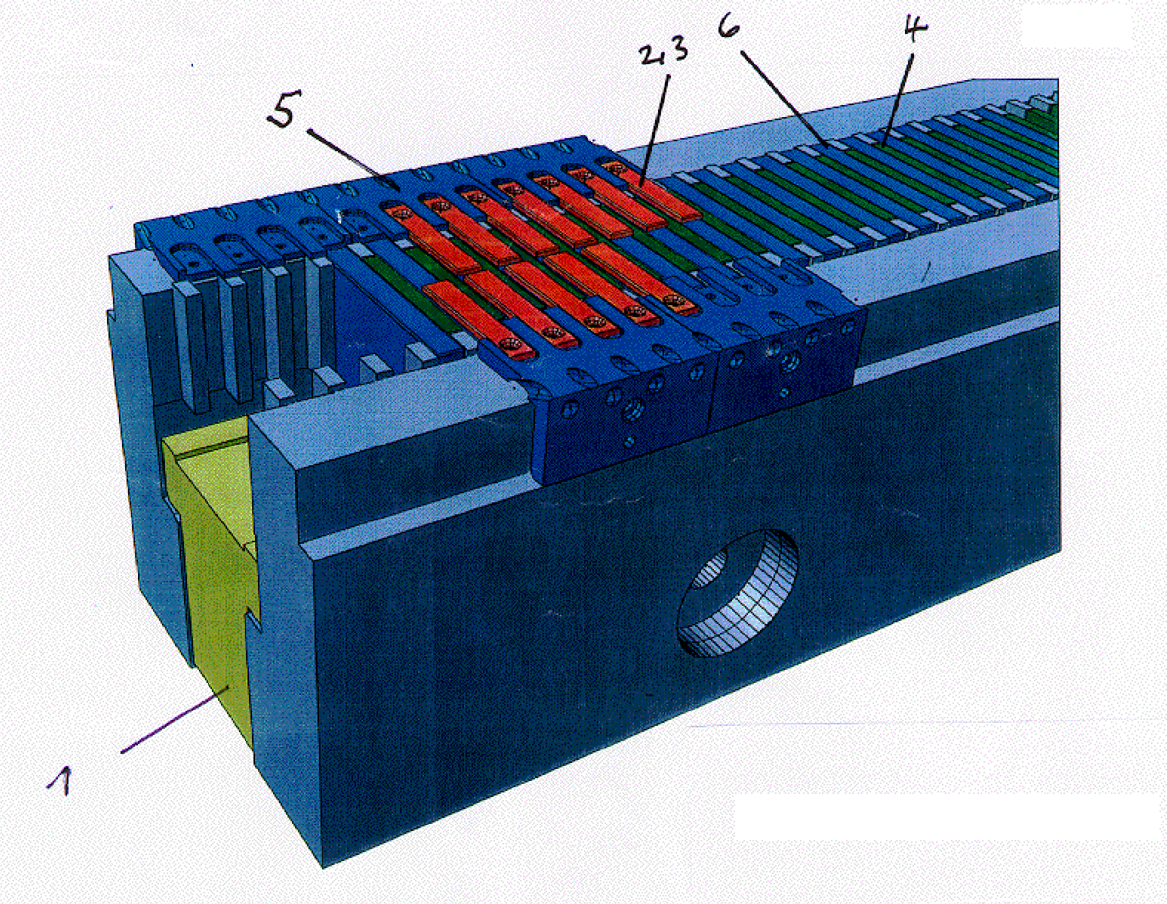
$\frac{\lambda_{FODO}}{2} \lesssim 2.66\,m$

$\rightarrow$ separate function

$L_{und} \simeq 2.2\,m$

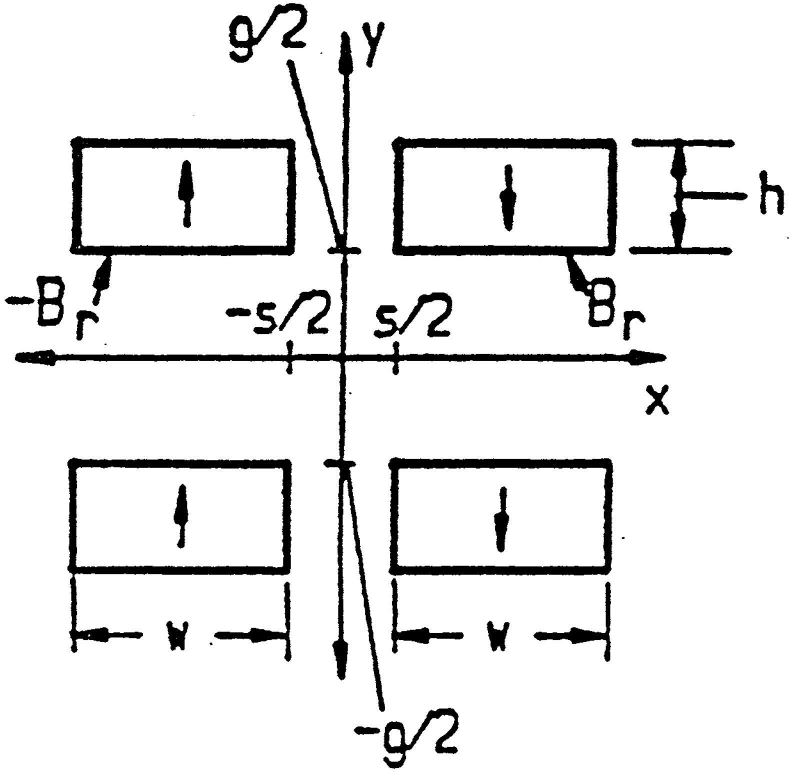
$L_{Quad} \simeq 0.5\,m$





Aluminium Support Structure	1
Focusing Magnets (NdFeB)	2,3
Soft Iron Pole	4
Keeper for focusing Magnets	5
Permanent Magnets (NdFeB)	6

PLANAR PM QUADRUPOLE



PLANAR PM SEXTUPOLE

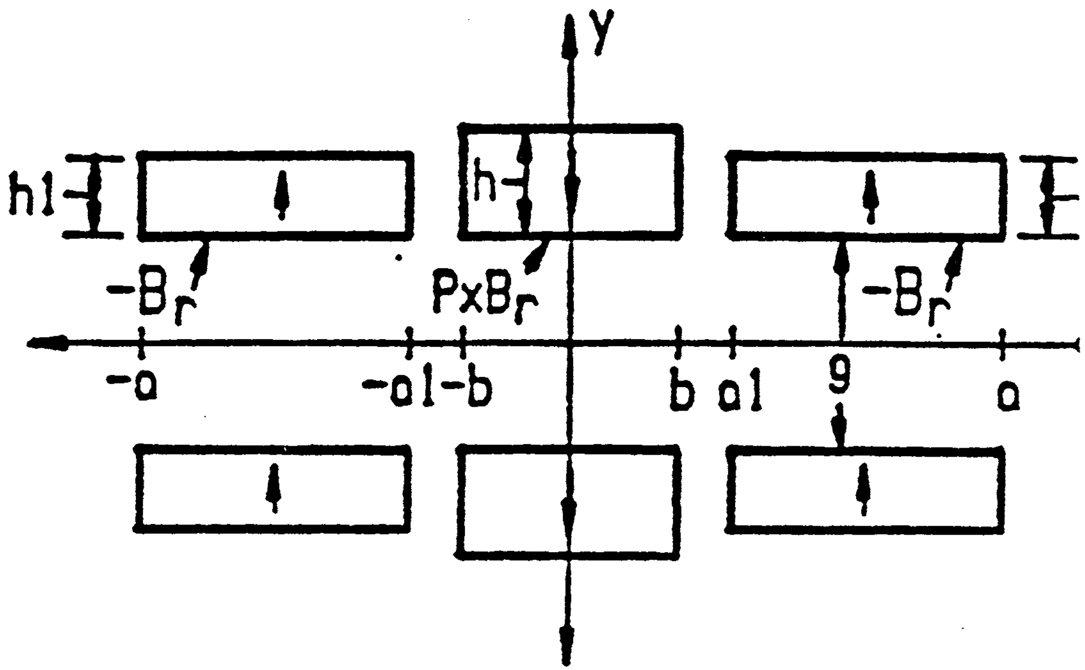
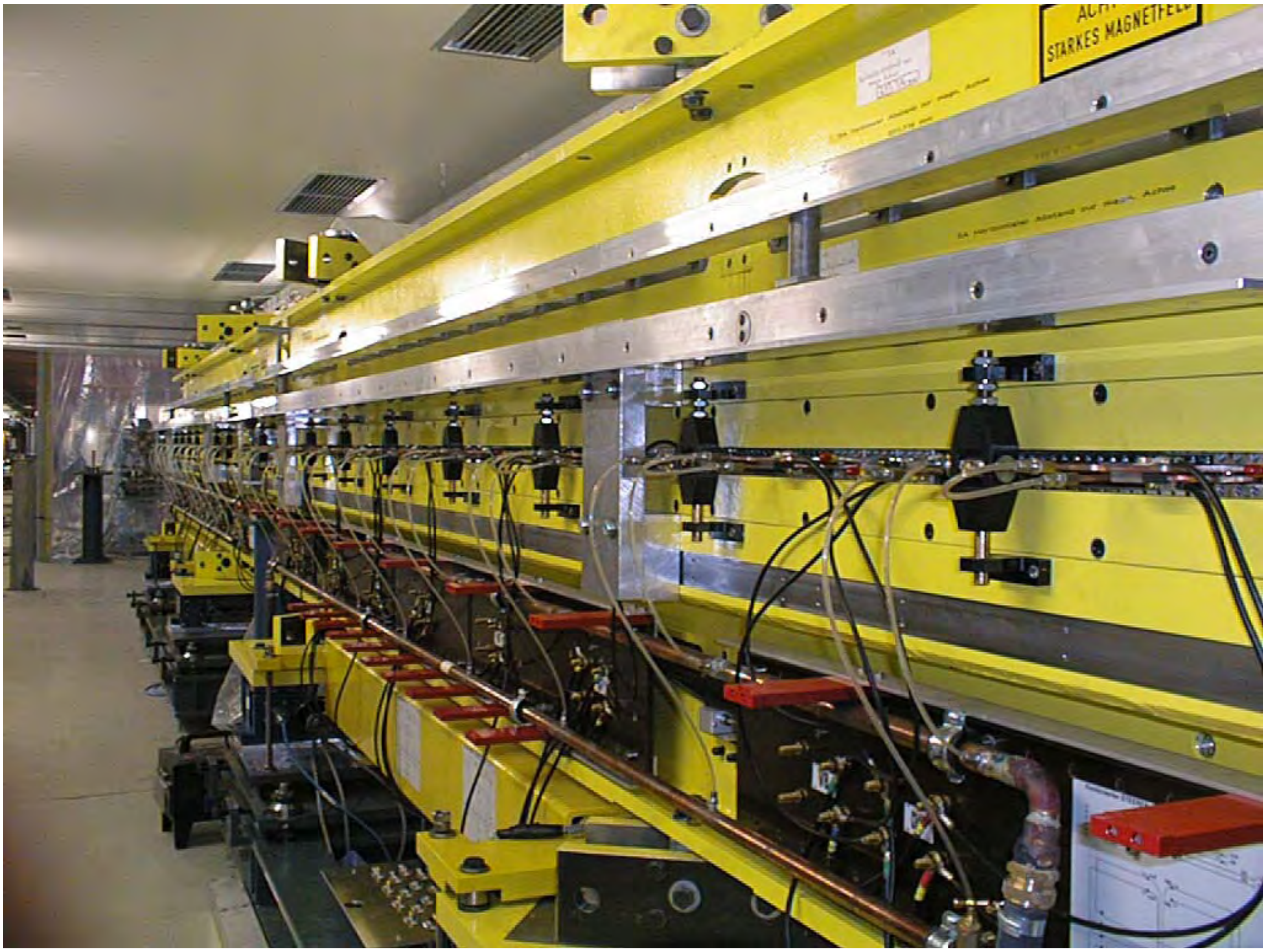


Table 1: Undulator parameters for the undulator for the VUV - FEL at the TESLA Test Facility

Gap (fixed)	[mm]	12
Period Length	[mm]	27.3
Undulator Peak Field	[T]	0.5
K - Parameter		1.27
Design Gradient	[T/m]	18.3
Number of poles per undulator module		327
Total length per module	[mm]	4492.2
Length of FODO quad section	[mm]	136.5
FODO Period Length	[m]	0.9555
Number of FODO periods per module		5
Separation between undulator modules	[m]	0.2853


STARKES MAGNETFELD

Magnetic measurements

Optimization goal: Straight trajectory with I2 <= 10 Tmm^2 @ 300 MeV
Quadrupole Adjustment : ±50µm

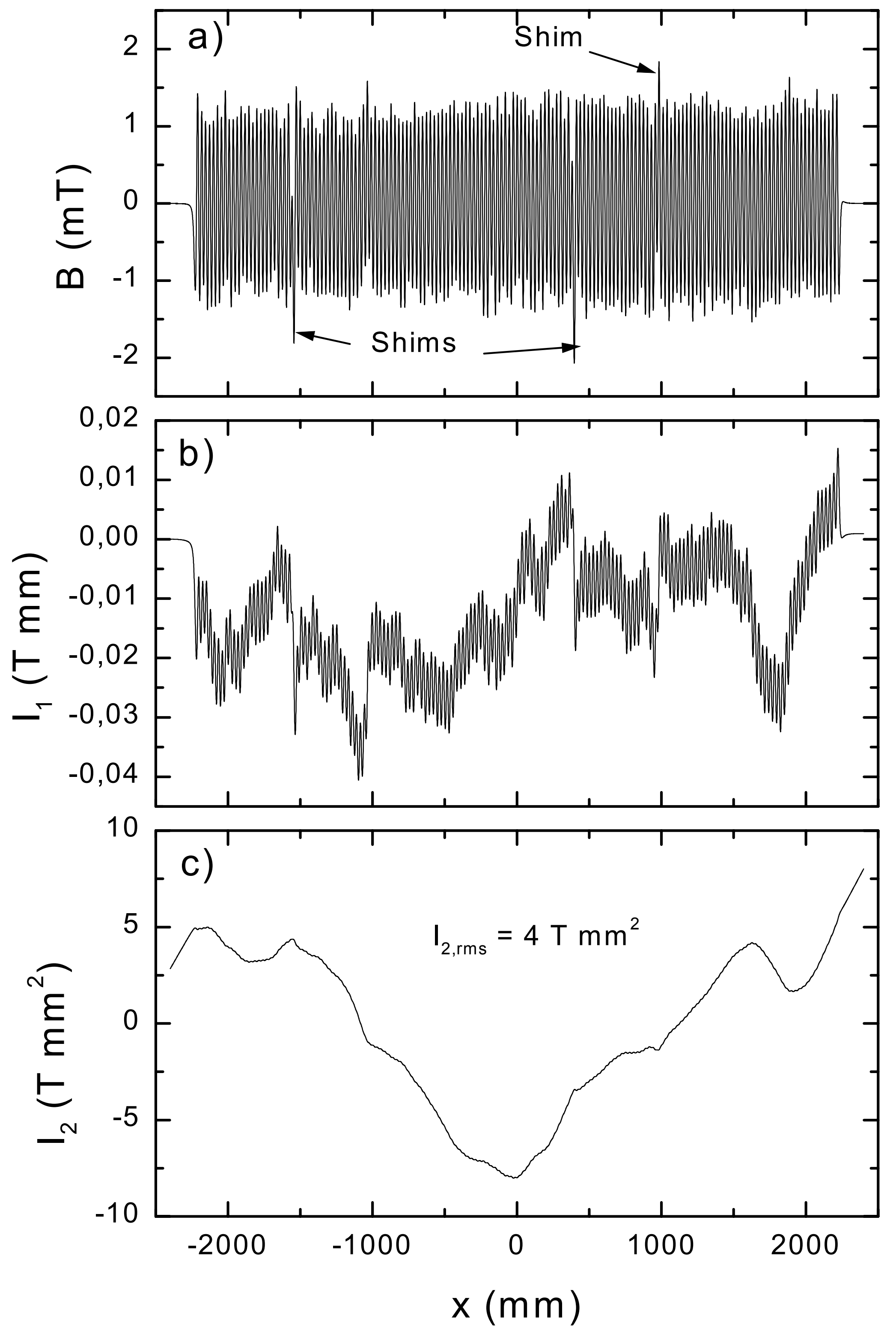
1.) Optimization of Undulator field

a) B_z Measurement with coil N=3400; 5x10mm^2 , analog integrator, Shims
b) B_y calibrated Hallprobe "Field fine tuning by pole height adjustment"
c) define center axis with respect to fiducial surfaces

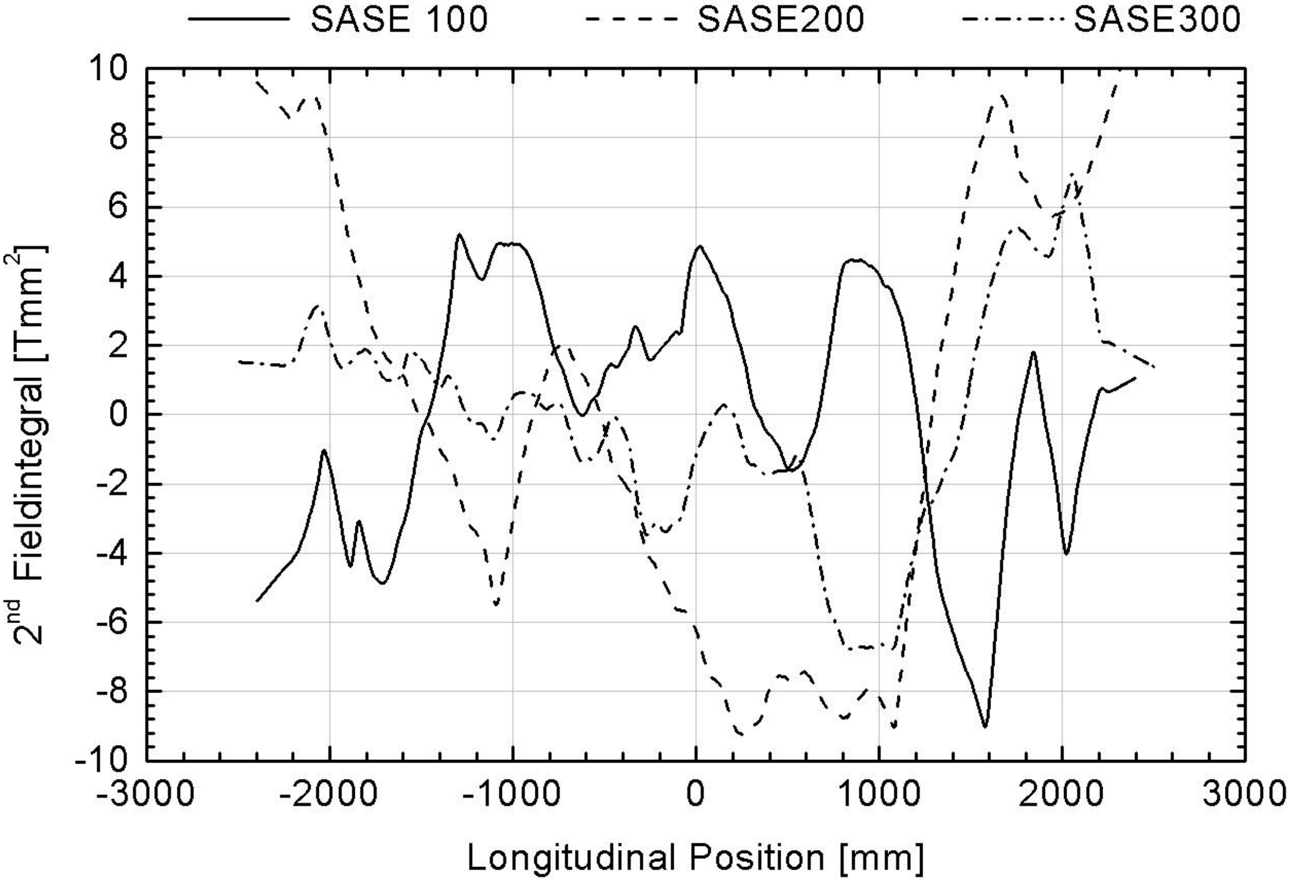
2.) Attach Quadrupole sections

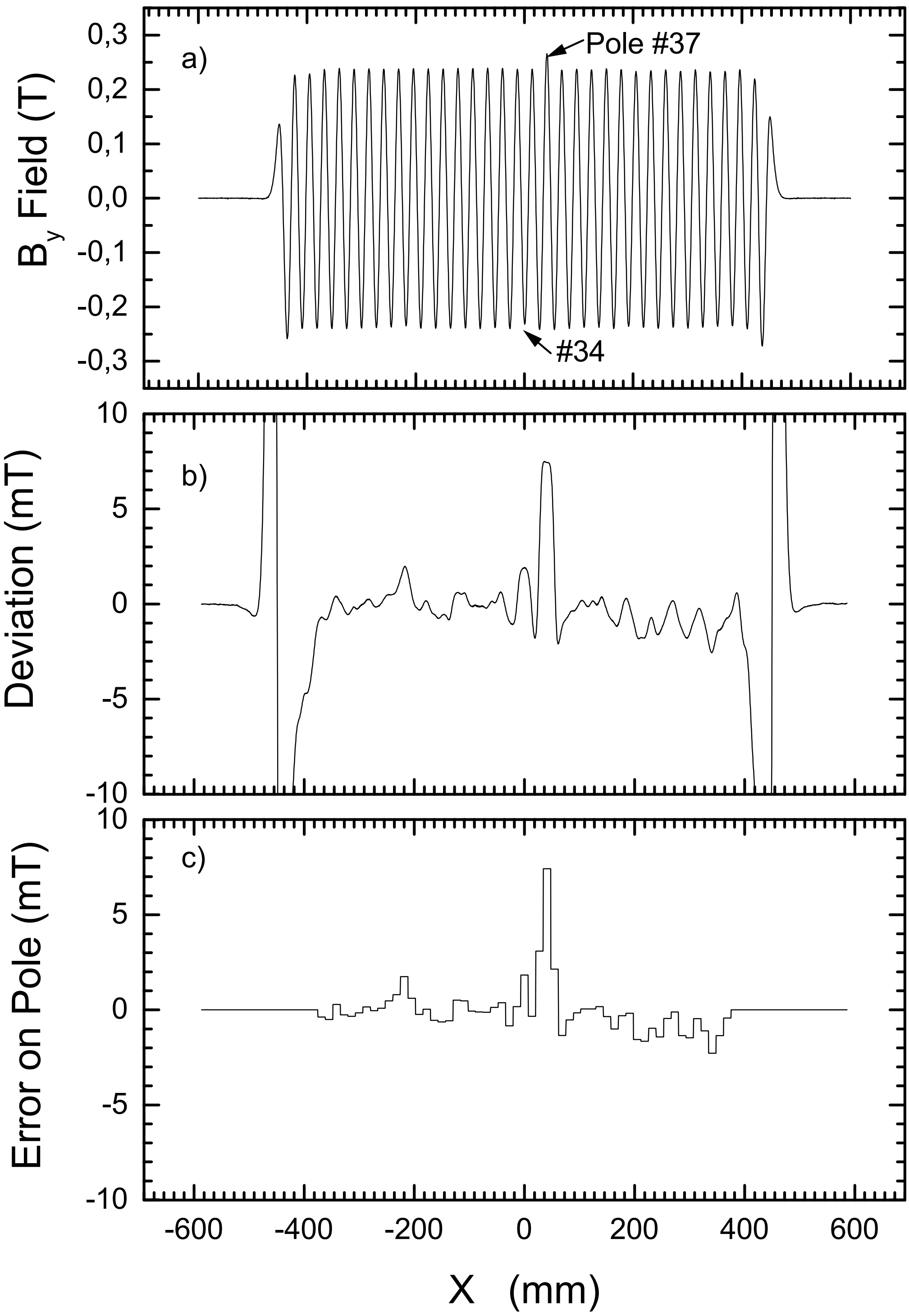
a) apply Rectangular Coil Method for measurement of
- Quadrupole strength
– Hor. center position
– Ver center position
in the presence of the undulator field

b) adjust quads using a linearized approach to the device axis
c) remeasure, iterate

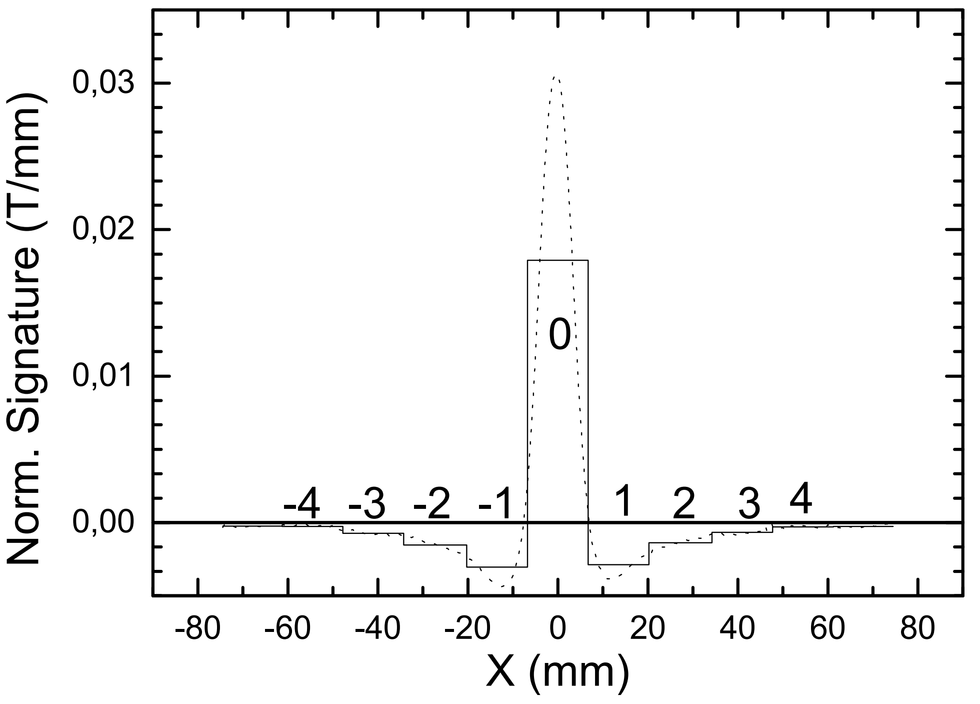


a)
Shim
Shims
B (mT)
b)
I_1 (T mm)
c)
$I_{2,rms}$ = 4 T mm^2
I_2 (T mm^2)
x (mm)


SASE 100
SASE200
SASE300
10
8
6
4
2
0
-2
-4
-6
-8
-10
-3000
-2000
-1000
0
1000
2000
3000
2nd Fieldintegral [Tmm2]
Longitudinal Position [mm]

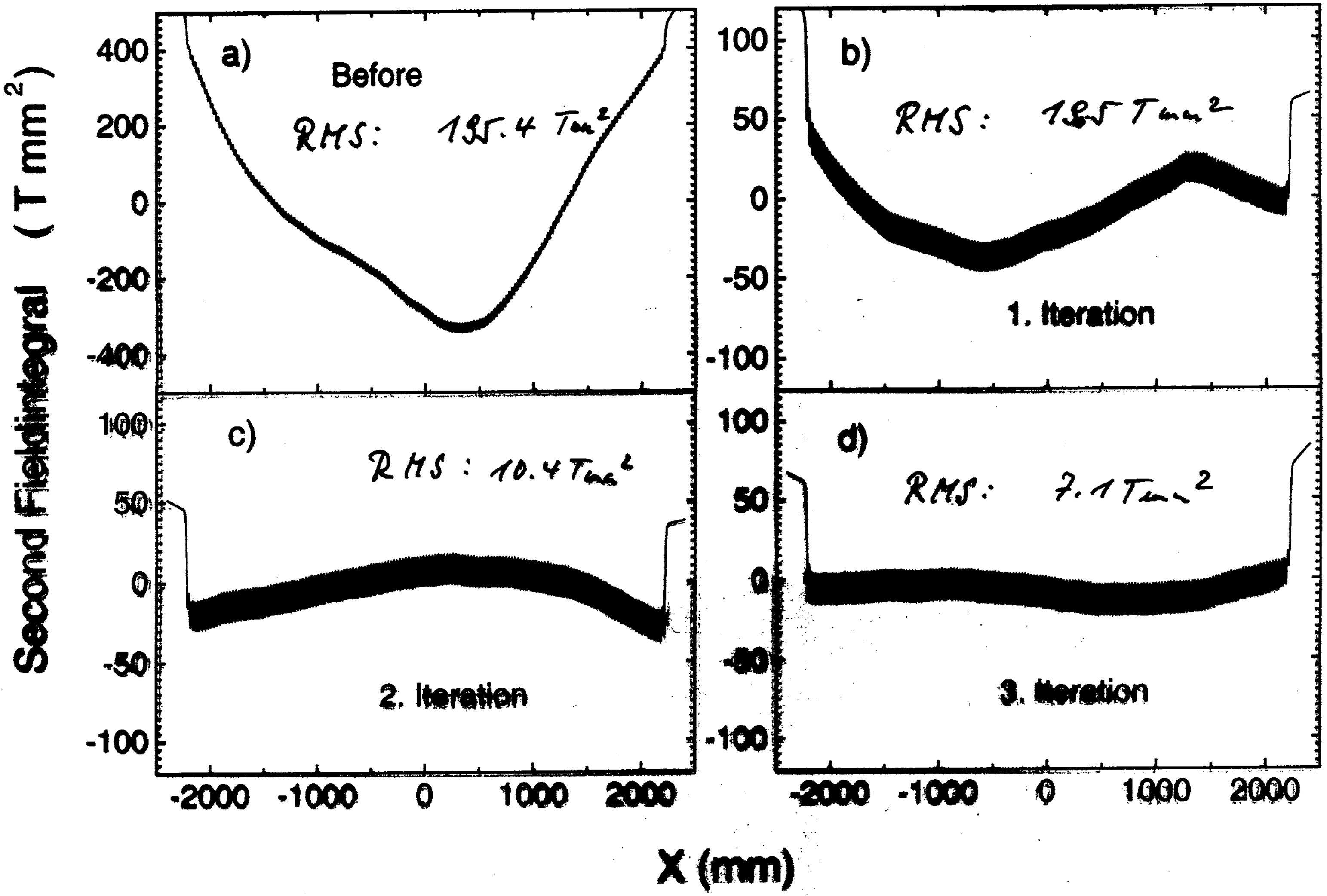


a)
Pole #37
#34
B_y Field (T)
0,3
0,2
0,1
0,0
-0,1
-0,2
-0,3
b)
Deviation (mT)
10
5
0
-5
-10
c)
Error on Pole (mT)
10
5
0
-5
-10
-600
-400
-200
0
200
400
600
X (mm)



S_j : Field on j^{th} pole [T]
p_i : Shift of i^{th} pole [mm]
$a_{i,j}$: Norm. field change on pole j due to shift of pole i

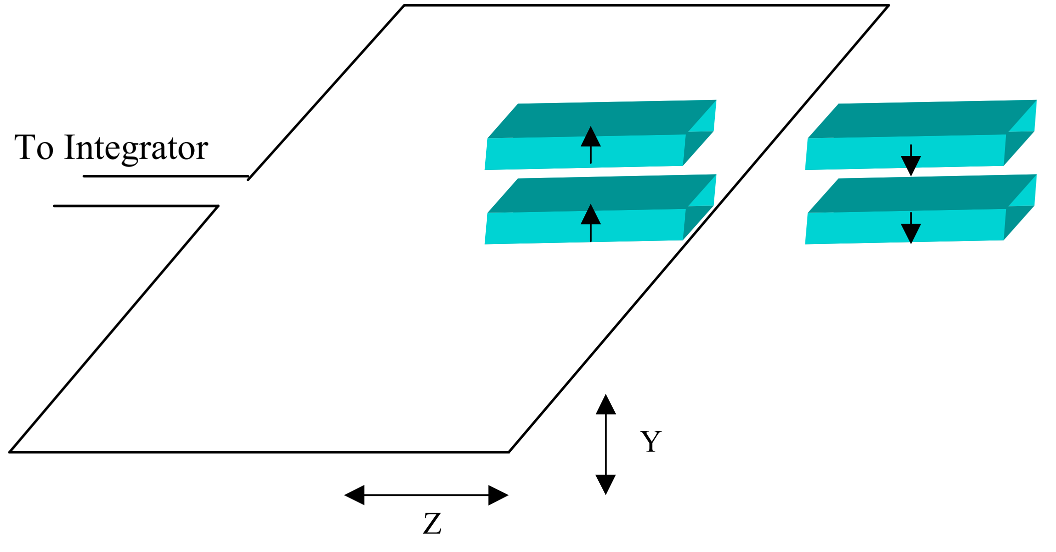
$$
\begin{array}{lcl}
S_1 & = & a_0 \cdot p_1 + a_1 \cdot p_2 + a_2 \cdot p_3 + \ldots + a_{i-1} \cdot p_i + \ldots + a_{N-1} \cdot p_N \\
S_2 & = & a_{-1} \cdot p_1 + a_0 \cdot p_2 + a_1 \cdot p_3 + \ldots + a_{i-2} \cdot p_i + \ldots + a_{N-2} \cdot p_N \\
S_3 & = & a_{-2} \cdot p_1 + a_{-1} \cdot p_2 + a_0 \cdot p_3 + \ldots + a_{i-3} \cdot p_i + \ldots + a_{N-3} \cdot p_N \\
\cdot & = & \qquad\qquad \cdot \qquad\qquad \cdot \\
\cdot & = & \qquad\qquad \cdot \qquad\qquad \cdot \\
S_j & = & a_{1-j} \cdot p_1 + a_{2-j} \cdot p_2 + a_{3-j} \cdot p_3 + \ldots + a_{i-j} \cdot p_i + \ldots + a_{N-j} \cdot p_N \\
\cdot & = & \qquad\qquad \cdot \qquad\qquad \cdot \\
\cdot & = & \qquad\qquad \cdot \qquad\qquad \cdot \\
S_N & = & a_{1-N} \cdot p_1 + a_{2-N} \cdot p_2 + a_{3-N} \cdot p_3 + \ldots + a_{i-N} \cdot p_i + \ldots + a_0 \cdot p_N
\end{array}
$$



$$I2_{RMS} = \frac{1}{\sqrt{2}} \cdot \left(\frac{\lambda_u}{2\pi} \right)^2 \cdot B_{Max}$$

λ_u : 27.3 mm
B_0 : 0.57
$I2_{RMS}$: 6.7 Tmm²

Measurement of the Quadrupole Centers using the Rectangular Coil Method (RCM)



Flux through rectangular coil moving along *y* :

$$\Delta\Phi(y) = N \cdot L \cdot \int_{y_a}^{y} B_z(y') \cdot dy' \cdot = N \cdot L \cdot g \cdot \tfrac{1}{2}\left((y-y_0)^2 - (y_a - y_0)^2\right)$$

$$B_z(y) = -g \cdot (y - y_0)$$

same coil moving along z :

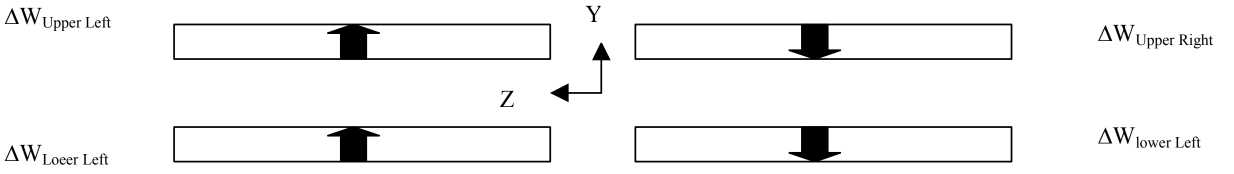
$$\Delta\Phi(z) = N \cdot L \cdot \int_{Z_a}^{Z} B_y(z') \cdot dz' \cdot = N \cdot L \cdot g \cdot \tfrac{1}{2}\left((z-z_0)^2 - (z_a - z_0)^2\right)$$

$$B_y(z) = g \cdot (z - z_0)$$

Polynomial Fit: $\Phi_{y,z} = a \cdot (y,z)^2 + b \cdot (y,z) + c \implies (y_0, z_0) = -b/2 \cdot a \quad ; \quad g = 2 \cdot a / L \cdot N$

g	field gradient
L	effective quad length
y_a , z_a	Start point
y_0, z_0	quad center
N	Number of turns (49)
L_{Coil}	Coil length (327.6 mm)
w_{Coil}	width of coil (330 mm)

Linearized Quadrupole fine tuning



$$\Delta Q = \frac{s \cdot c_q}{2}\left\{\Delta w_{UR} + \Delta w_{UL} + \Delta w_{LL} + \Delta w_{LR}\right\}$$

$$\Delta y = \frac{s \cdot c_v}{2}\left\{\Delta w_{UR} + \Delta w_{UL} - \Delta w_{LL} - \Delta w_{LR}\right\}$$

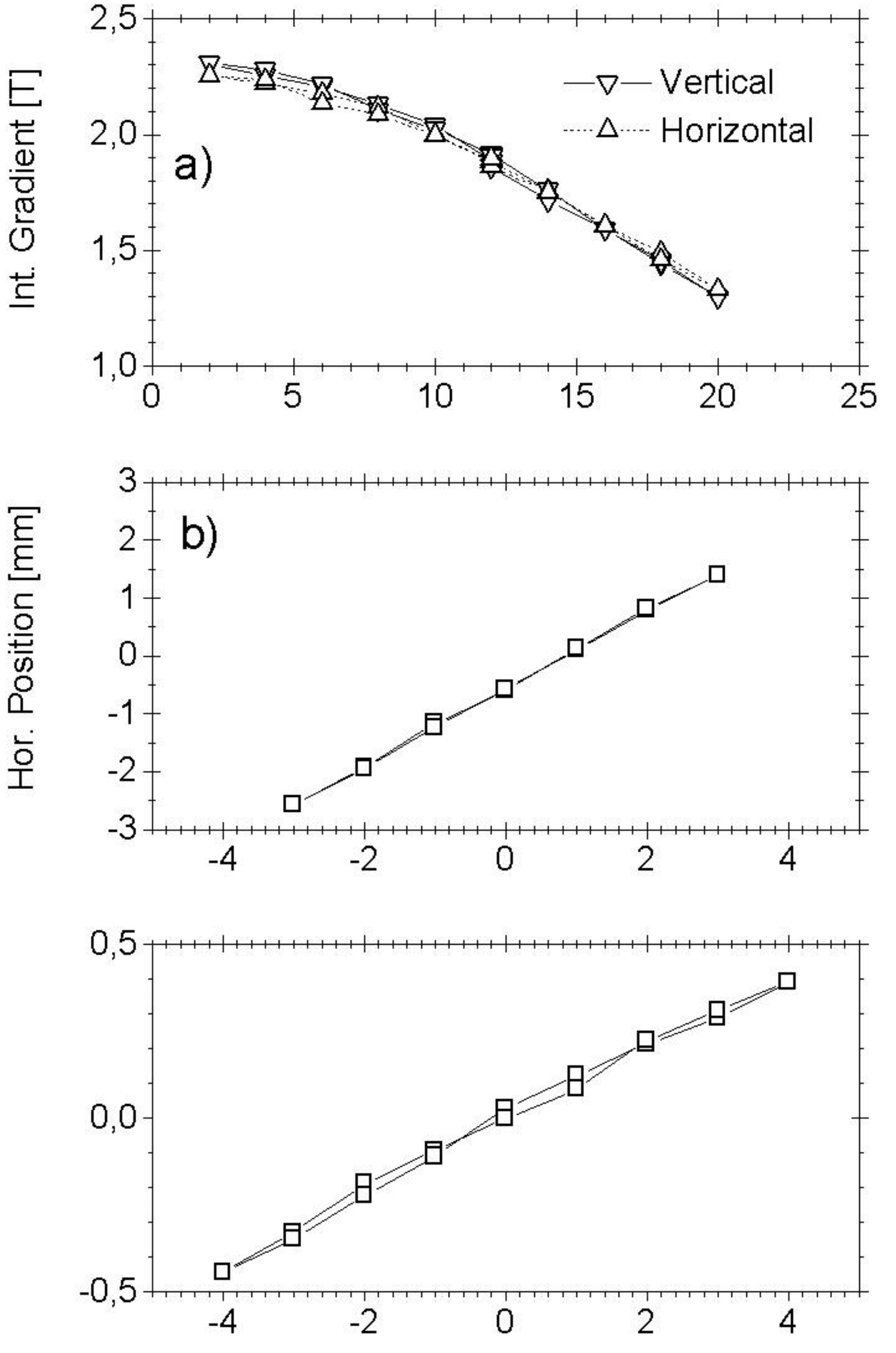
$$\Delta z = \frac{s}{4}\left\{- \Delta w_{UR} + \Delta w_{UL} + \Delta w_{LL} - \Delta w_{LR}\right\}$$

$$\Delta w_{UL} = \frac{\Delta\widetilde{Q} + \Delta\widetilde{y} + \Delta\widetilde{z}}{4}; \quad \Delta w_{UR} = \frac{\Delta\widetilde{Q} + \Delta\widetilde{y} - \Delta\widetilde{z}}{4}$$

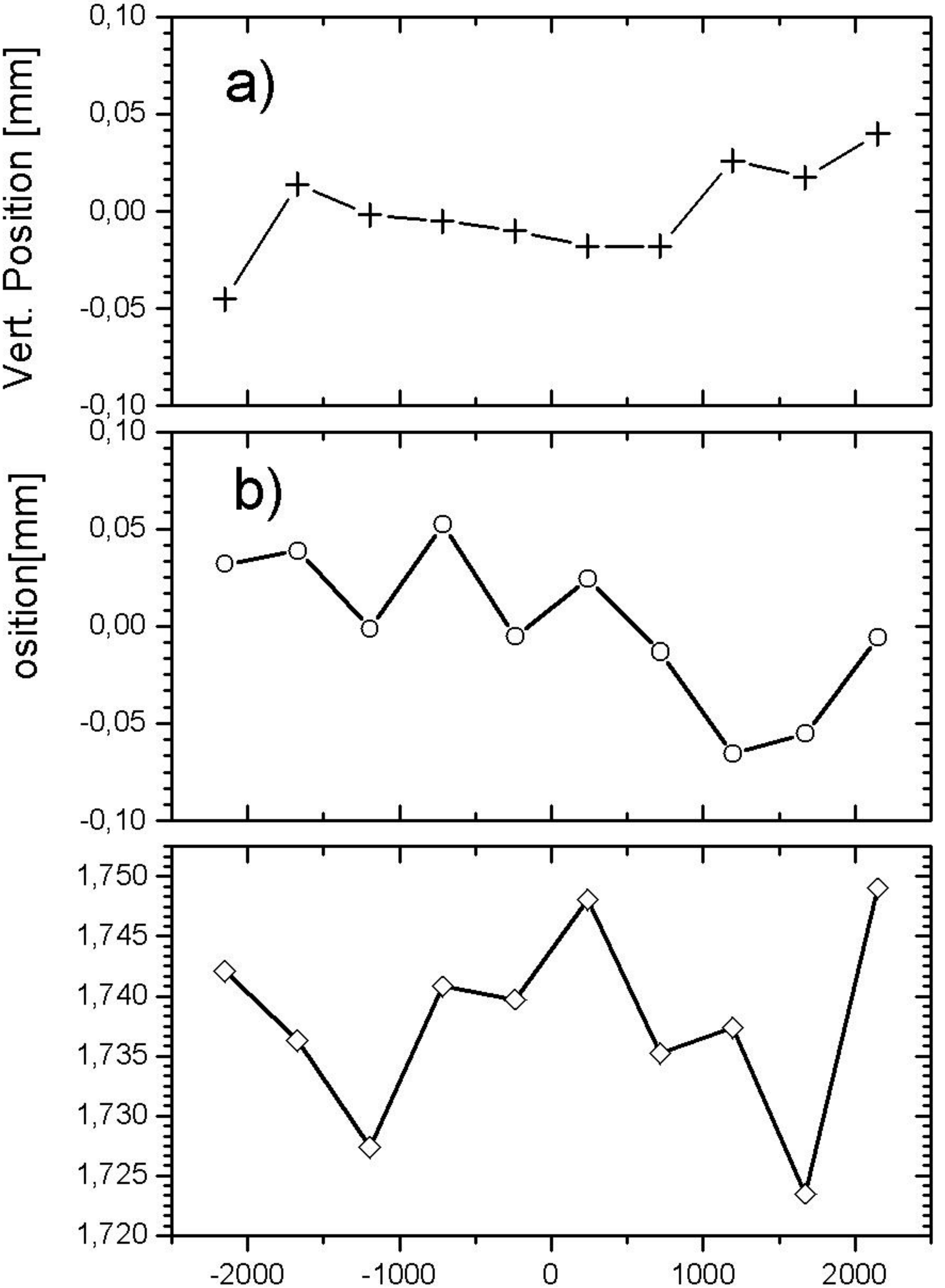
$$\Delta w_{LL} = \frac{\Delta\widetilde{Q} - \Delta\widetilde{y} + \Delta\widetilde{z}}{4}; \quad \Delta w_{LR} = \frac{\Delta\widetilde{Q} - \Delta\widetilde{y} - \Delta\widetilde{z}}{4}$$

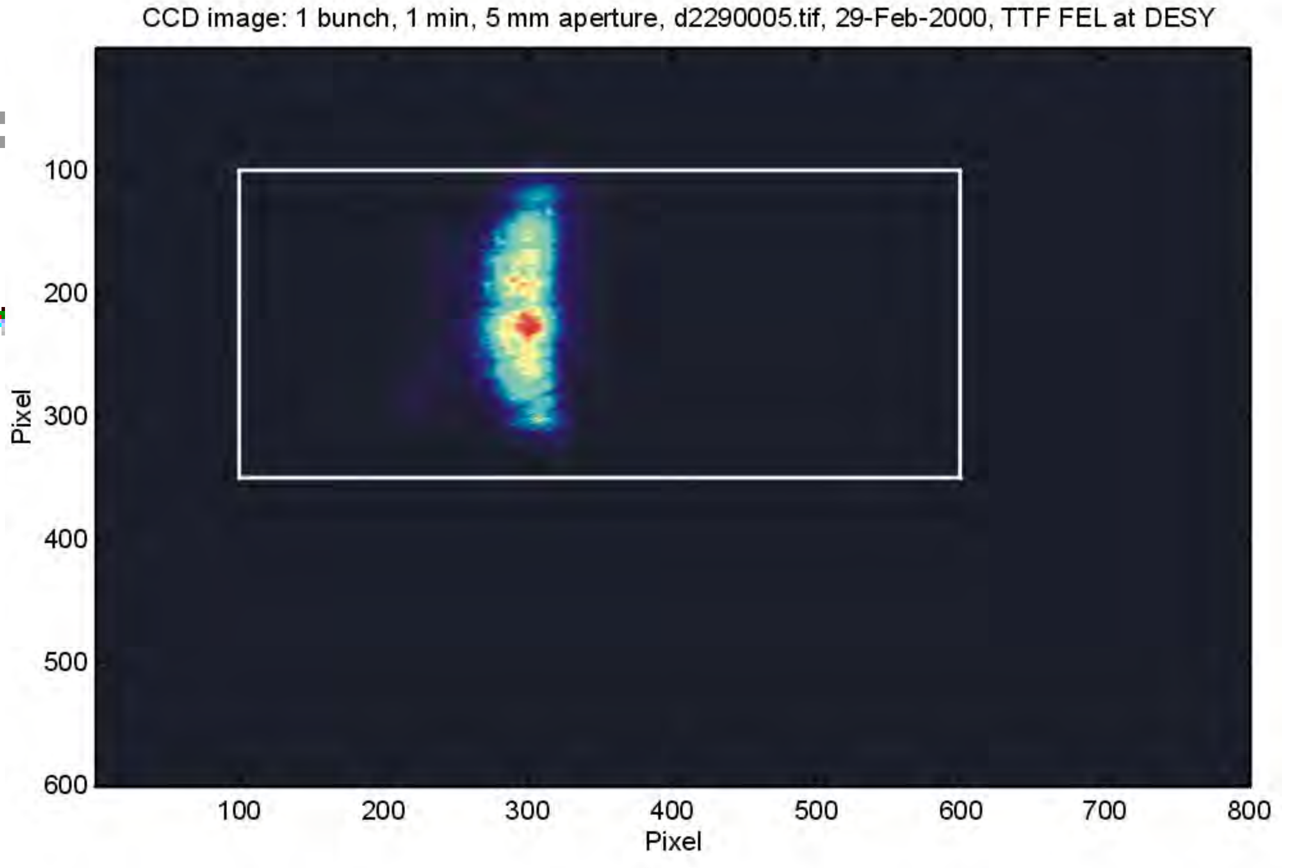
$$\Delta\widetilde{Q} = \frac{2 \cdot \Delta Q}{s \cdot c_q}; \quad \Delta\widetilde{y} = \frac{2 \cdot \Delta y}{s \cdot c_v}; \quad \Delta\widetilde{z} = \frac{4 \cdot \Delta z}{s};$$

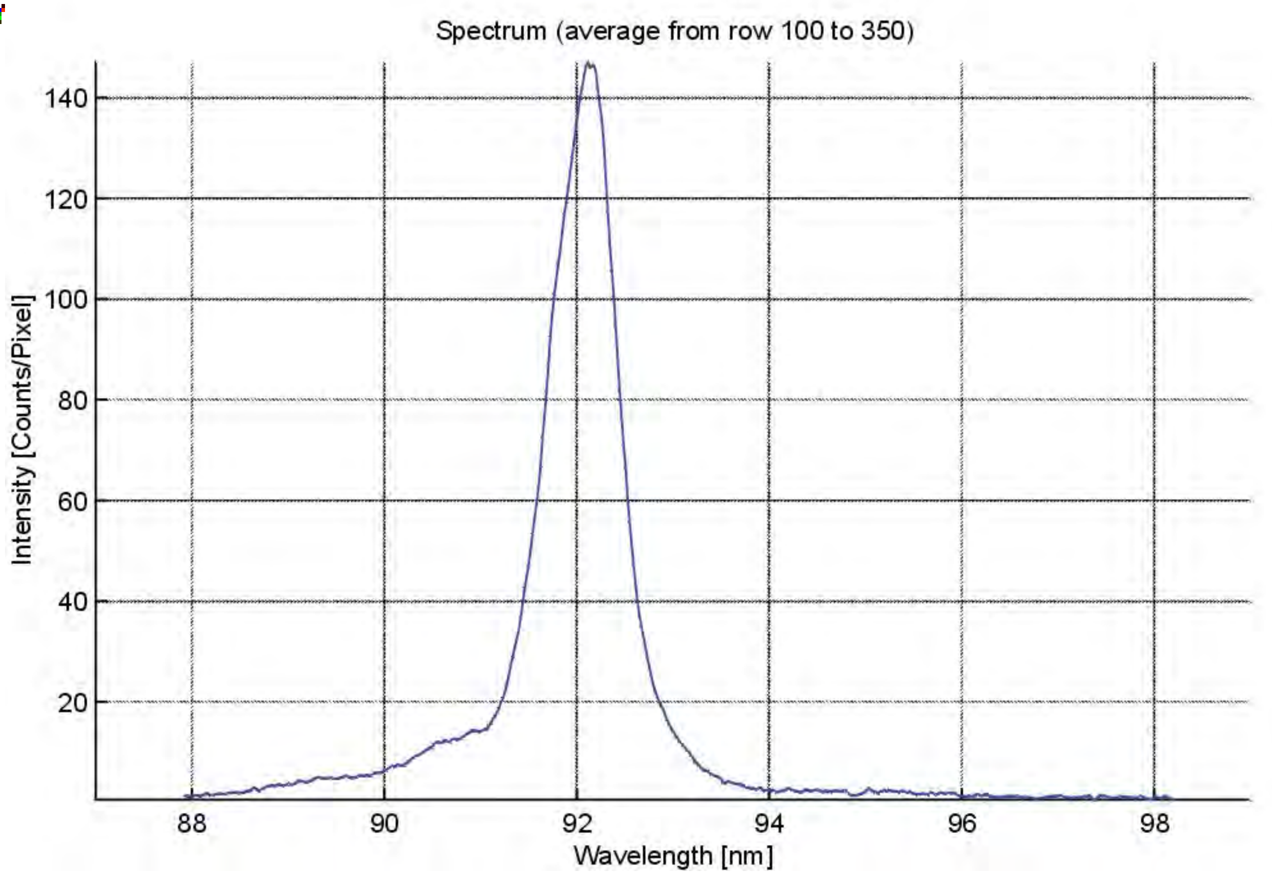
Δw's : Turn angle of set screw on magnet arrays Upper/Lower Right / Left
+ clockwise - counterclockwise
C_Q : Coupling constant: quadrupole strength / per unit magnet shift
C_v : Coupling constant vertical center shift per unit magnet shift
s : Set screw pitch

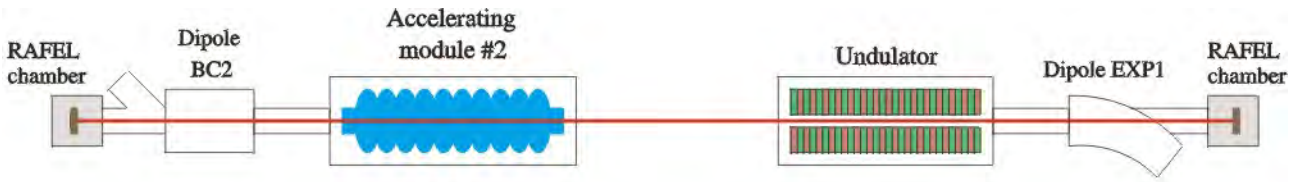


2,5
2,0
1,5
1,0
Int. Gradient [T]
a)
Vertical
Horizontal
0
5
10
15
20
25
3
2
1
0
-1
-2
-3
Hor. Position [mm]
b)
-4
-2
0
2
4
0,5
0,0
-0,5
-4
-2
0
2
4

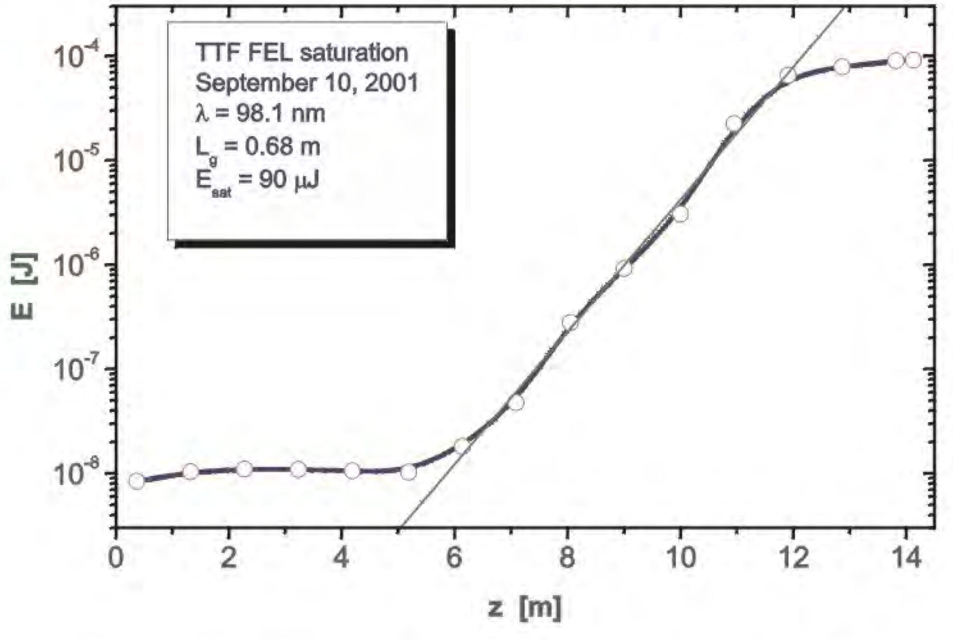

a)
b)
Vert. Position [mm]
osition[mm]
0,10
0,05
0,00
-0,05
-0,10
1,750
1,745
1,740
1,735
1,730
1,725
1,720
-2000
-1000
0
1000
2000


CCD image: 1 bunch, 1 min, 5 mm aperture, d2290005.tif, 29-Feb-2000, TTF FEL at DESY
Pixel
100
200
300
400
500
600
100
200
300
400
500
600
700
800
Pixel

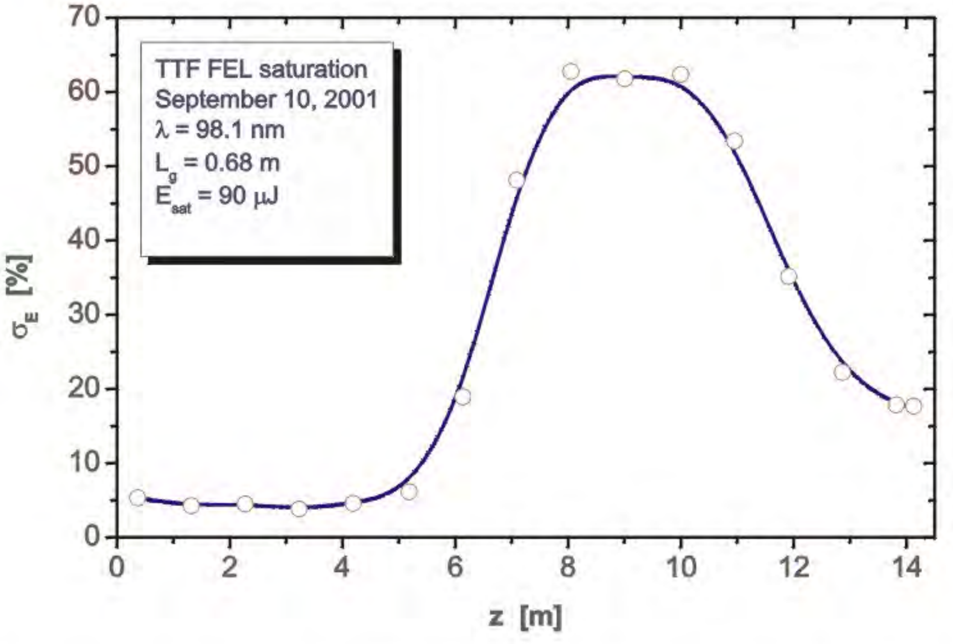

Spectrum (average from row 100 to 350)
Intensity [Counts/Pixel]
140
120
100
80
60
40
20
88
90
92
94
96
98
Wavelength [nm]



Layout of TTF FEL



Average energy in the radiation pulse versus undulator length



Normalized rms deviation of the fluctuations of the energy in the radiation pulse versus undulator length, $\sigma_E^2 = \langle (E - \langle E \rangle)^2 \rangle / \langle \mathcal{E} \rangle^2$

Status of the TTF FEL

September 2001

Wavelength	*80-180 nm*
Mode of operation	*Saturation*
Spectrum bandwidth (FWHM)	*0.6%*
FEL radiation pulse energy	*80-120 μJ*
FEL radiation pulse length	*0.5-1 ps*
FEL radiation peak power	*100-150 MW*
# bunches in a train	*24*
Repetition rate	*1 pps*
FEL radiation average power	*2-3 mW*
FEL radiation peak brilliance	6×10^{27} *phot./sec/mrad²/mm²/(0.1% BW.)*
FEL radiation average brilliance	3×10^{17} *phot./sec/mrad²/mm²/(0.1% BW.)*