BESSY
Berliner Elektronenspeicherring-Gesellschaft
für Synchrotronstrahlung m.b.H.

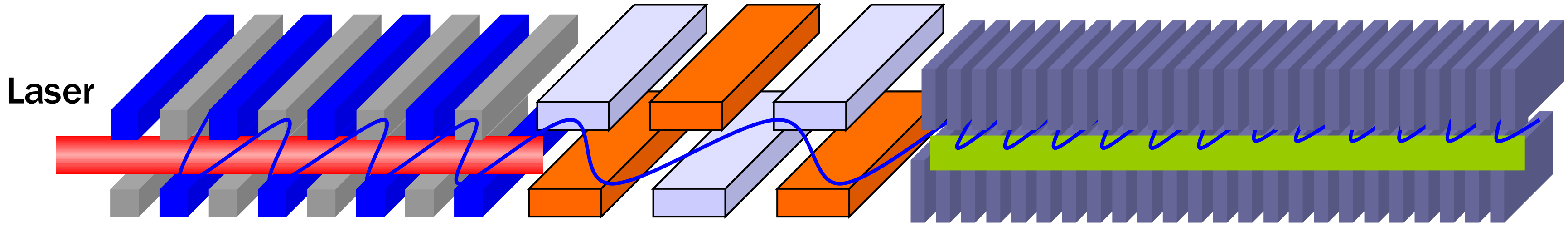
APPLE Undulators for HGHG FELs

Leibniz
Gemeinschaft

Outline

- HGHG Projects
- Cascaded HGHG, The BESSY Soft X-Ray FEL
- Undulator Magnet Design, APPLE III
- Magnetic Material and Field Optimization
- Support and Drive System, Motion Control
- Operation Issues, Focussing Effects
- Machine Protection

HGHG Projects



energy modulation of the electron beam (Modulator)

spatial bunching optimized for a particular harmonic

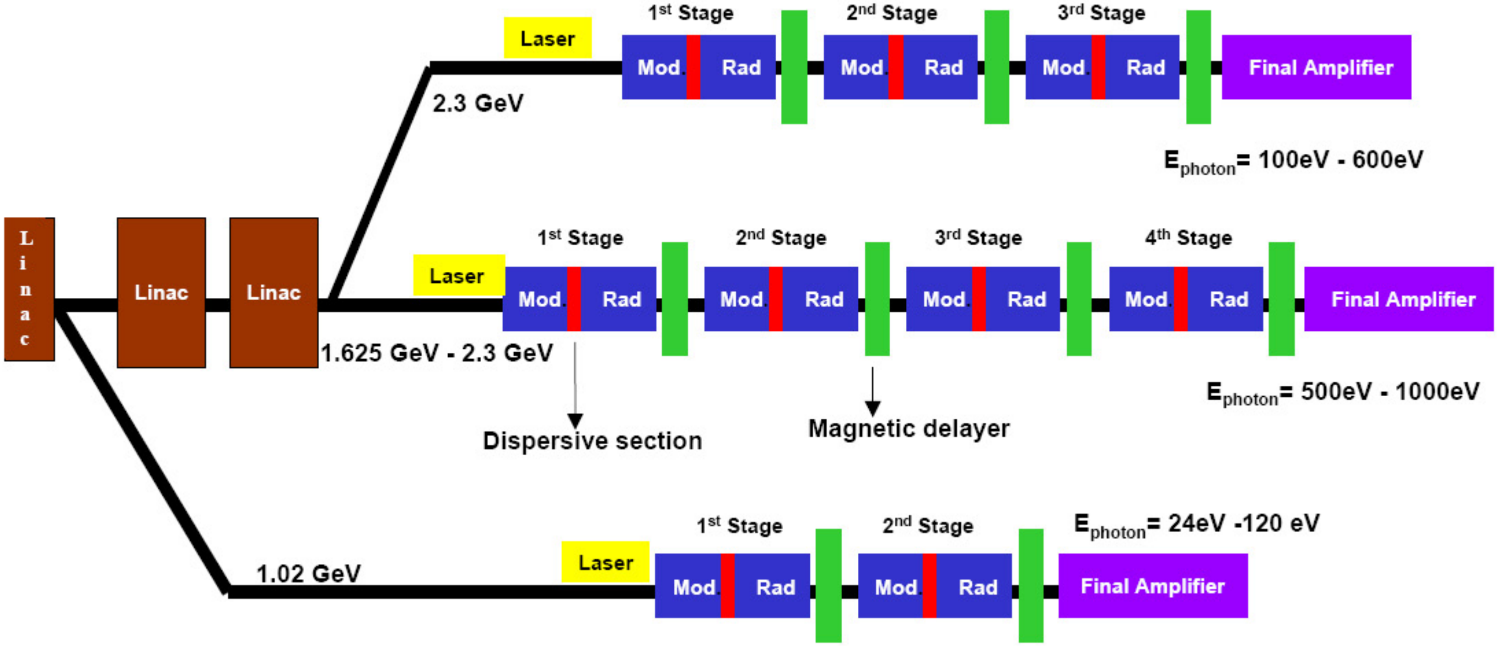
resonant to the harmonic (Radiator)

L.-H. Yu et al.,BNL
Phys. Rev. A44/8 (1991) 5178

	DUV	FERMI I / II	EUROFEL	BESSY	ARC-EN-CIEL I / II	SDUV
λ / nm	265 / 100	40 / 10	89 / 53	51 - 1	≤66 / 1	89
Electron energy / MeV	175 / 300	1200	450	1000 / 2300	220 / 1000	276
Stages	1	1 / 2	1	2 / 3 / 4	1 / 1	1
Status	operational / proposed	funded	construction	proposed	proposed	proposed

Cascaded HGHG FEL

The planned BESSY HGHG FEL facility consists of three HGHG lines to cover the energy range from 24eV to 1000eV



Undulator Parameters of the BESSY FEL

period length in mm and module length in m

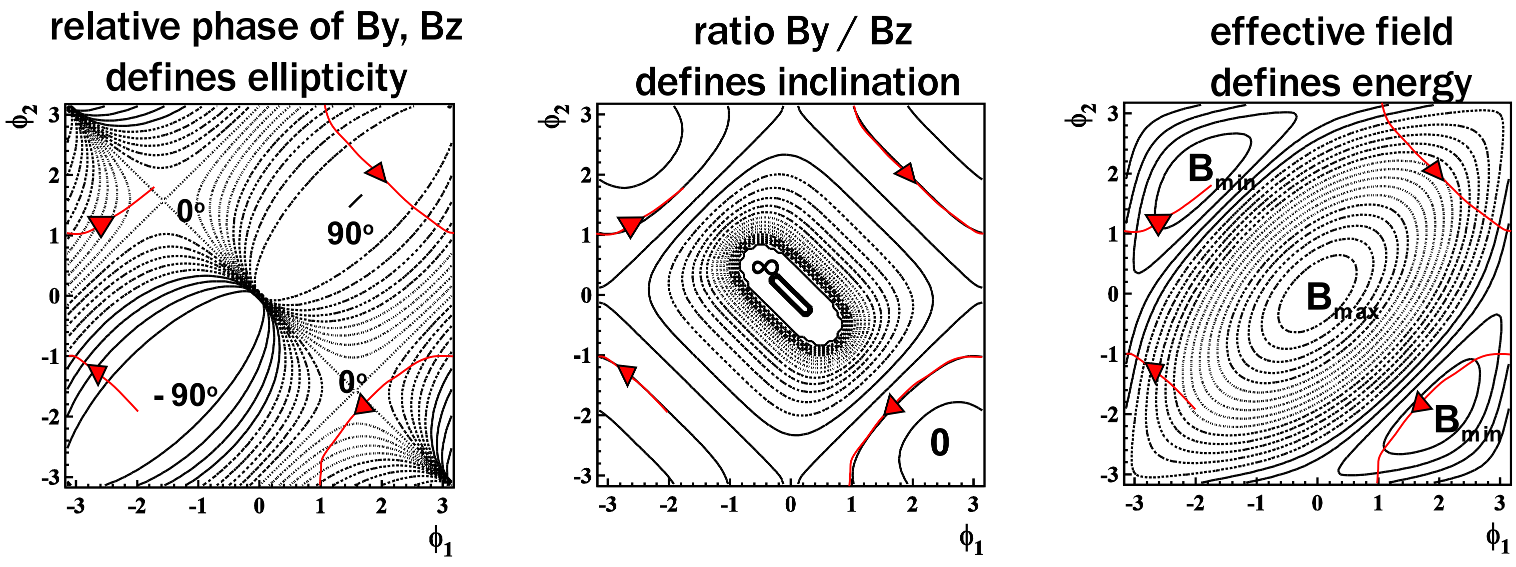
	LE-FEL		ME-FEL		HE-FEL	
Energy range	24 – 120 eV		100 – 600 eV		500 – 1000 eV	
	Modulator	Radiator	Modulator	Radiator	Modulator	Radiator
Stage 1	80 1,60	62 3,47	122 2,20	92 3,68	122 2,20	92 3,68
Stage 2	62 1,61	50 3,45	92 2,02	70 2x3,36	92 2,02	70 2x2,73
Stage 3			70 2,10	50 3x3,45	70 2,1	50 3x2,9
Stage 4					50 3,45	28,5 2x3,135
Final amplifier	50 3x3,45		50 5x3,45		28,5 5x3,135	
Total length	**20,48 m**		**44,88 m**		**49.555 m**	

APPLE for Full Polarization Control

Features of APPLE design:

- parallel motion : hor. / vert. linear und elliptical / helical polarization
- antiparallel motion: linear polarization with angles 0 - 90°
- 4 movable rows : linear polarization with angles 0 - 180°
- compensation of polarizing effects of the beamline optic with undulator

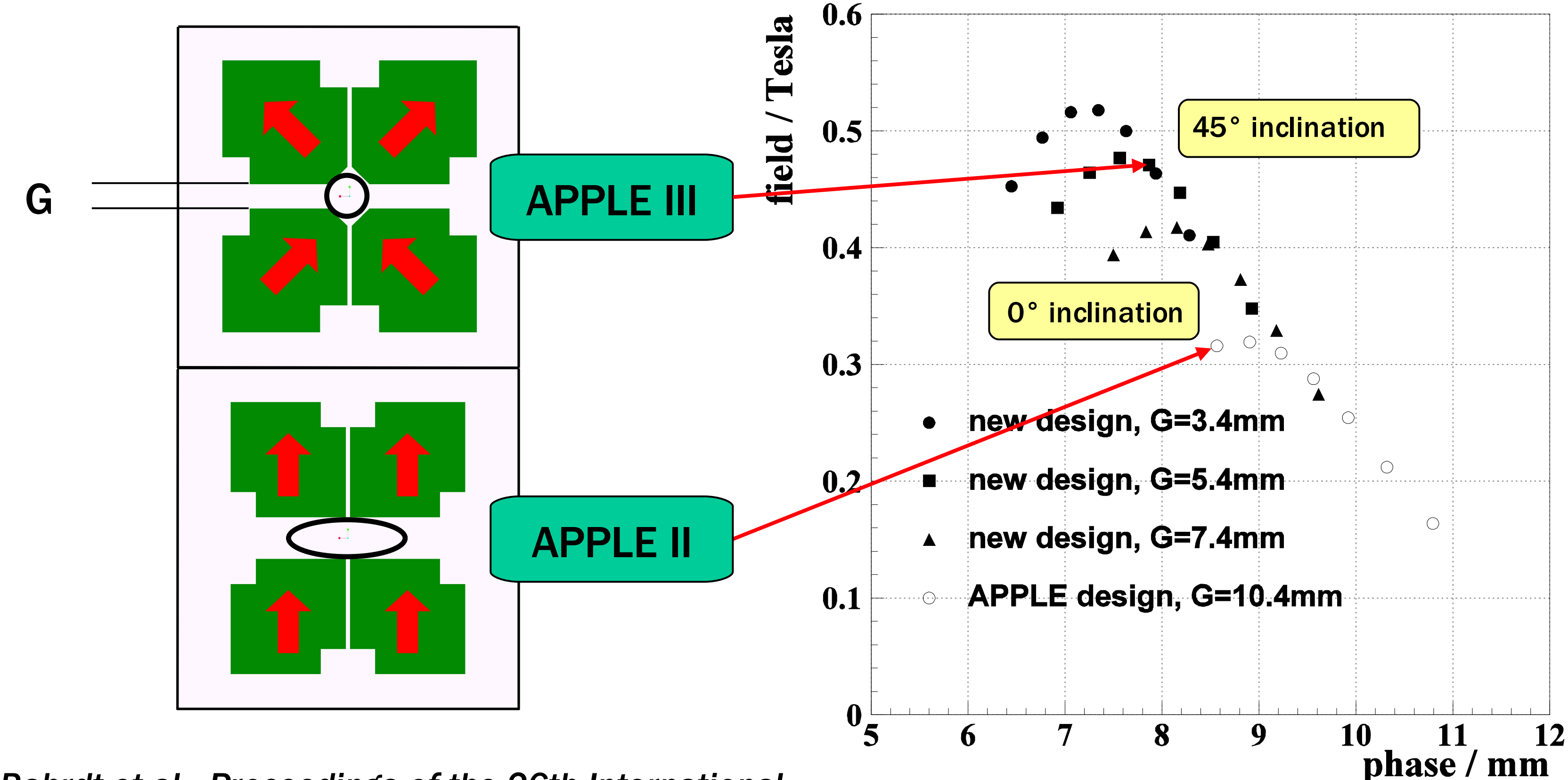
any arbitrary polarization ellipse can be produced:



The APPLE III Design

last Radiator and final amplifier have a new design

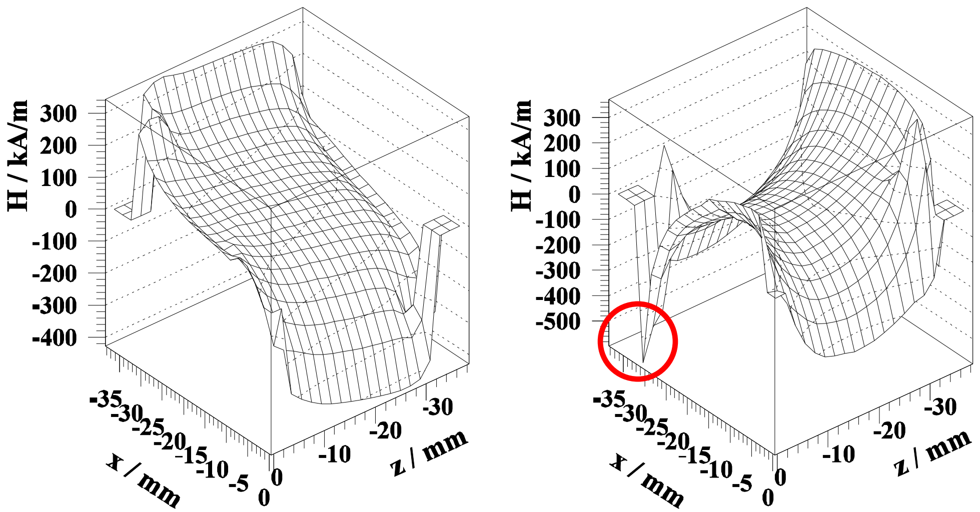
APPLE III design: factor 1.4 higher field as compared to APPLE II



J. Bahrdt et al., Proceedings of the 26th International FEL Conference, Trieste, Italy, 2004, pp610-613

Reverse Fields in A-Magnets of UE50

APPLE III - APPLE II



A-magnet

B-magnet

plotted are the strongest reverse fields among all combinations within

- entire gap range
- entire shift range
- various operation modes
- entire z range within magnet

choosing slightly different magnet grade for APPLE III recovers magnet stability:

typical values

grade	Br / Tesla	Hcj / kA/m
655 TP	1.26	1910
677 TP	1.18	2465

Tolerances

Trajectory errors

$\int\int B\, dl\, dl' < 0.1\sigma$ of photon / electron beam ≈ 5-10µm

$\int\int B\, dl\, dl' <$ 17 Tmm**2 @ 1.0 GeV achievable with state

< 38 Tmm**2 @ 2.3 GeV of the art techniques

Phase errors

phase errors due to energy spread dominate over field errors if

$\Delta\Phi_{rms} < \sigma / \gamma\rho 1.73 \approx 6.6°$ for the HE-FEL, achievable with sorting

Multipole errors

less critical for single pass devices

Systematic field errors

$\Delta K / K \approx 5 \times 10^{-4}$ ⇒ energy shift < 0.16 of bandwidth

⇒ gap positioning accuracy < 2µm ⇒ $\Delta K / K = 2 \times 10^{-4}$ demonstrated

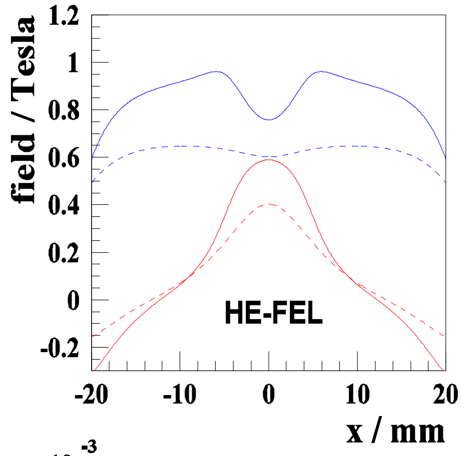
⇒ temperature stability of magnets: $\Delta K / K = 2 \times 10^{-4}$ for ΔT=0.2°C

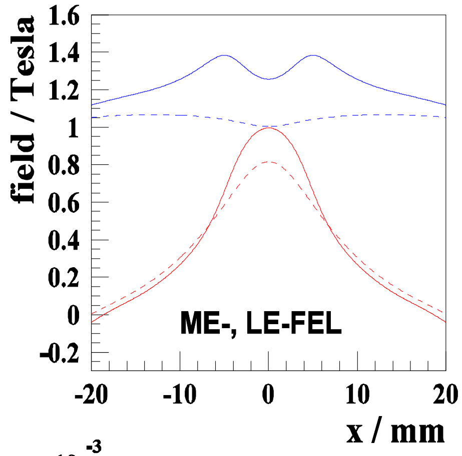
temperature control of tunnel

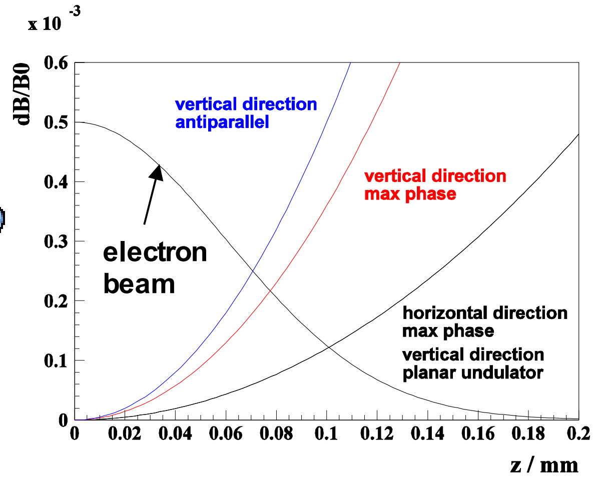
⇒ transverse alignment tolerance < 40µm ⇒ $\Delta K / K = 2 \times 10^{-4}$

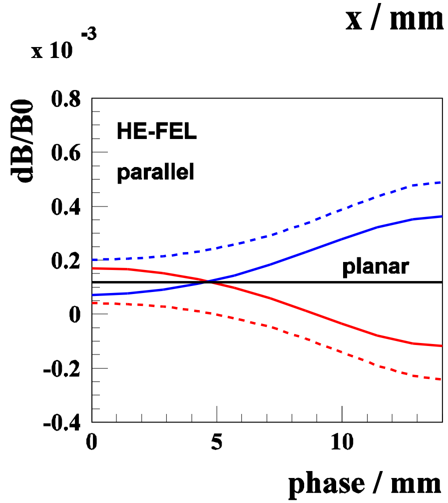
stiff structures for antiparallel motion, movable stages

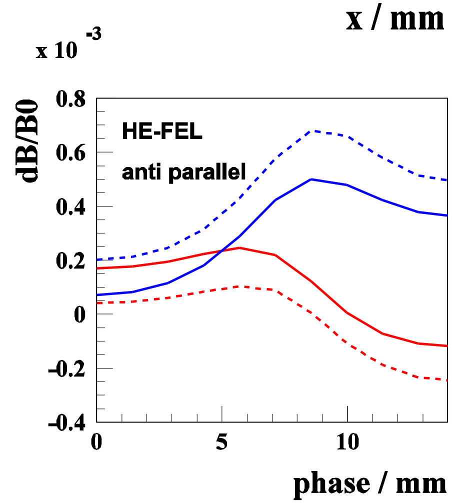
Good Field Region of APPLE IDs









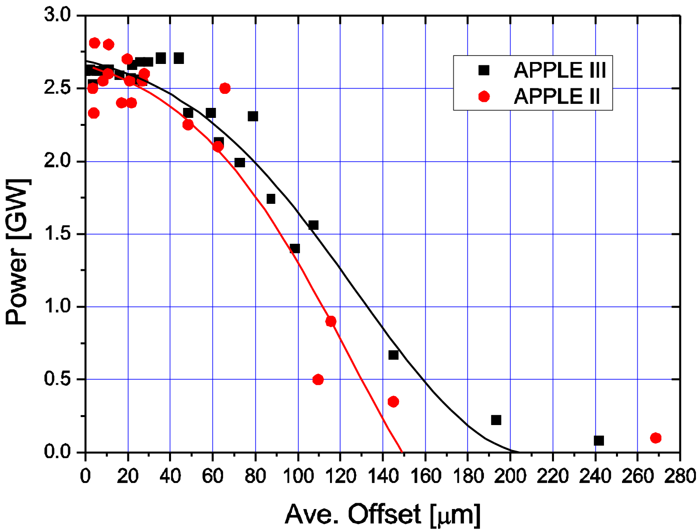


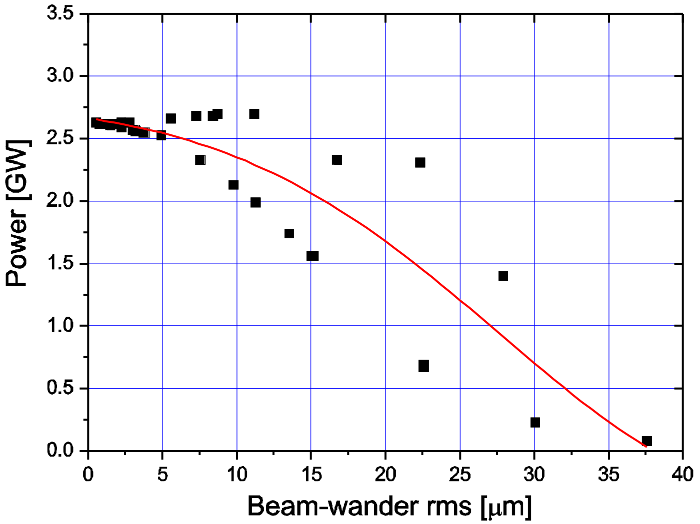
blue: vertical field
red: horizontal field
solid: APPLE III
dashed: APPLE II

tight alignment tolerances in both transverse directions → support structure

APPLE III (solid) slightly relaxed as compared to APPLE II (dotted)

Transverse Alignment Accuracy





tolerance studies on the transverse positioning accuracy for APPLE III undulator (BESSY HE-FEL)

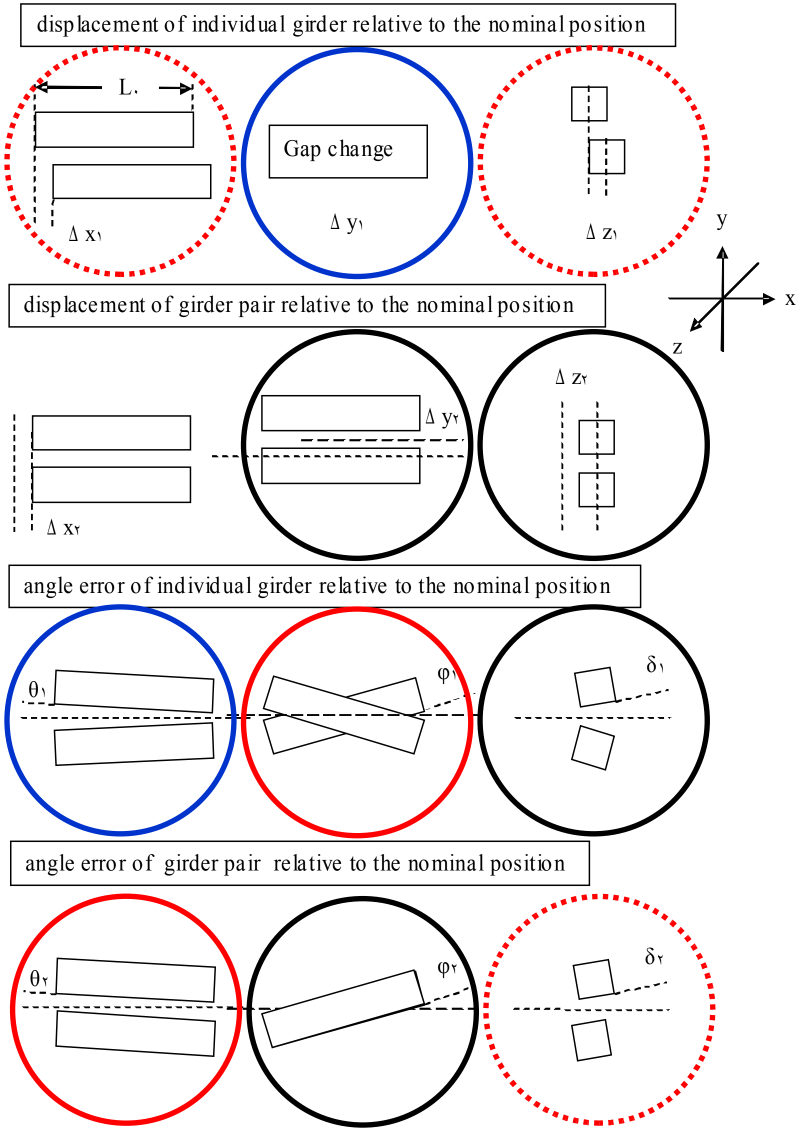
random transverse displacement of final amplifier undulator modules

simulation of trajectory wander and power degradation using GENESIS

40µm displacement is acceptable.

A. Meseck, J. Bahrdt, 27th, International FELConference, Stanford, Ca, 2005, pp47-50

Classification of Geometrical Tolerances



Colour	Solution
black:	independent on forces accuracy and stiffness of of support structure
blue:	closed loop servo systems
red, dotted:	dependent on forces appears in inclined mode produces K-shift stiff support structure
red, solid:	dependent on forces appears in inclined mode produces ΔK/K-shift feed forward / back compensation using 4 motors

Dynamic Multipoles I

dynamic multipoles: second order effect

no straight line integrals, not measurable with moving wire

$$\theta_{x/y} = -\frac{1}{(B\rho)^2}\int \left\{ \int B_x dz' \cdot \int \frac{\partial B_x}{\partial x/y} dz' + \int B_y dz' \cdot \int \frac{\partial B_y}{\partial x/y} dz' \right\} dz$$

$$\int B dl \propto B \cdot \frac{\partial B}{\partial z} \cdot \frac{\lambda_u^2}{E^2}$$

P. Elleaume, Proceedings of the EPAC 1992, pp 661-663

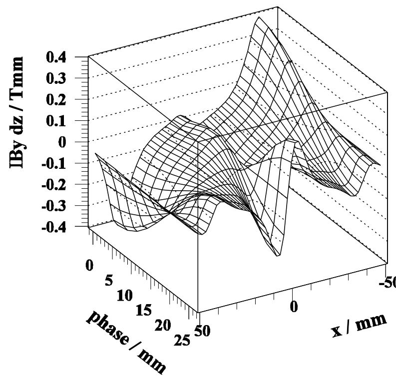
have to be regarded at:

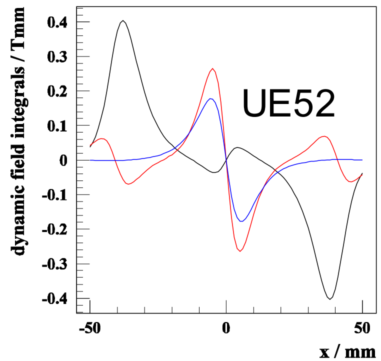
- **low and medium electron energies (less critical for X-FEL)**
- **long period lengths**
- **high fields, large transverse gradients (e.g. high field wiggler, APPLE)**

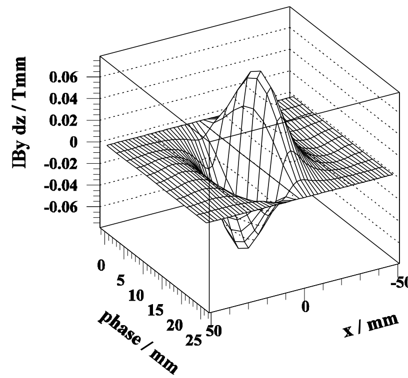
responsible for:

- **natural vertical focussing, horizontal defocussing (APPLE)**
- **impact on dynamic aperture via higher order terms (less important for single pass devices)**

Dynamic Multipoles II







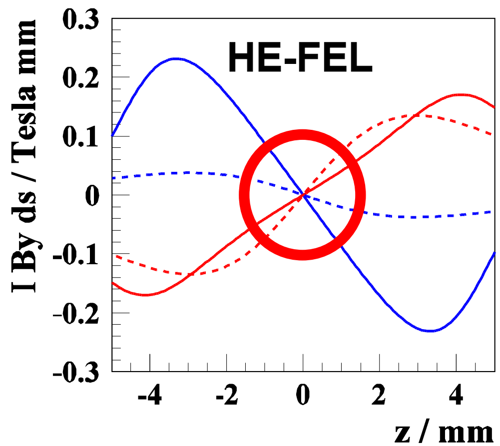
f_0

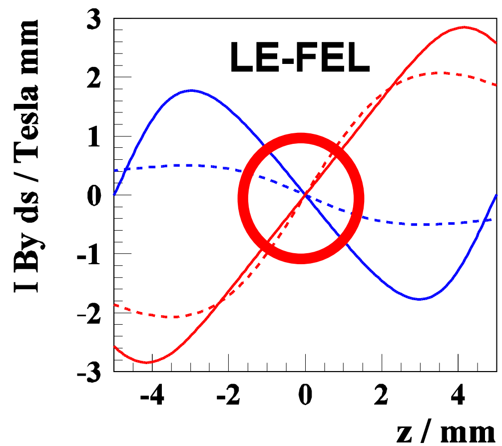
f_π

$f_{\pi/2}$

3 generic functions

$$\theta_x(x) = f_0(x)\cdot\cos^2(\varphi/2) + f_\pi(x)\cdot\sin^2(\varphi/2) + f_{\pi/2}(x)\cdot\sin^2(\varphi)$$





blue: phase = 0

red: phase = π

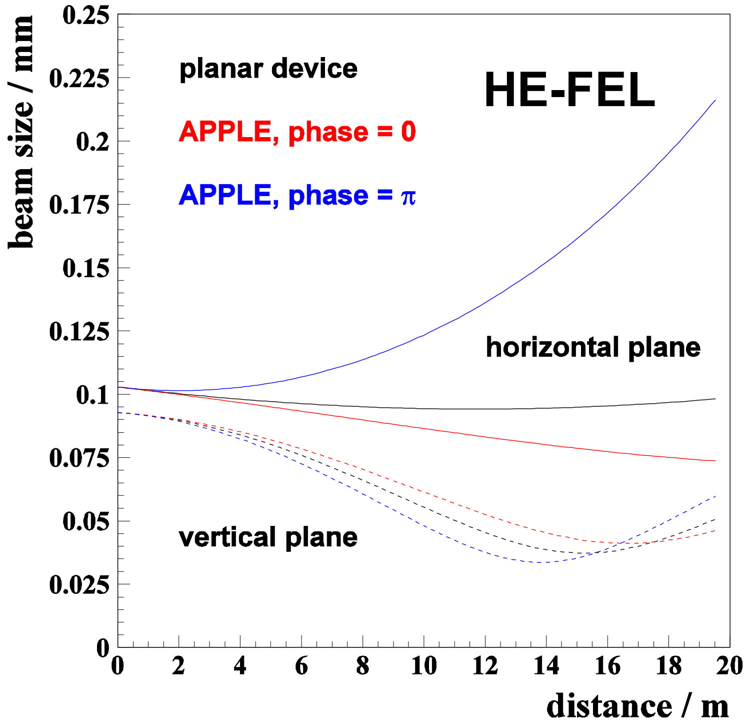
solid: APPLE III

dashed: APPLE II (field scaled to APPLE III value)

module length: 3m

Beam Size Variation

dynamic quadrupole modifies the electron beam size



$$K_x = \frac{2 \cdot e^2}{(\gamma m c)^2} k_{x-eff}^2 \cdot k^2 \cdot \left(\sum_{n=1}^{\infty} (B_{xn}^2 + B_{yn}^2)\right)$$

$$k_{x-eff}^2 = \sum_{n=1}^{\infty} \frac{B_{xn}^2 \cdot k_{xxn}^2 / n! + B_{yn}^2 \cdot k_{xyn}^2 / n!}{B_{xn}^2 / n! + B_{yn}^2 / n!}$$

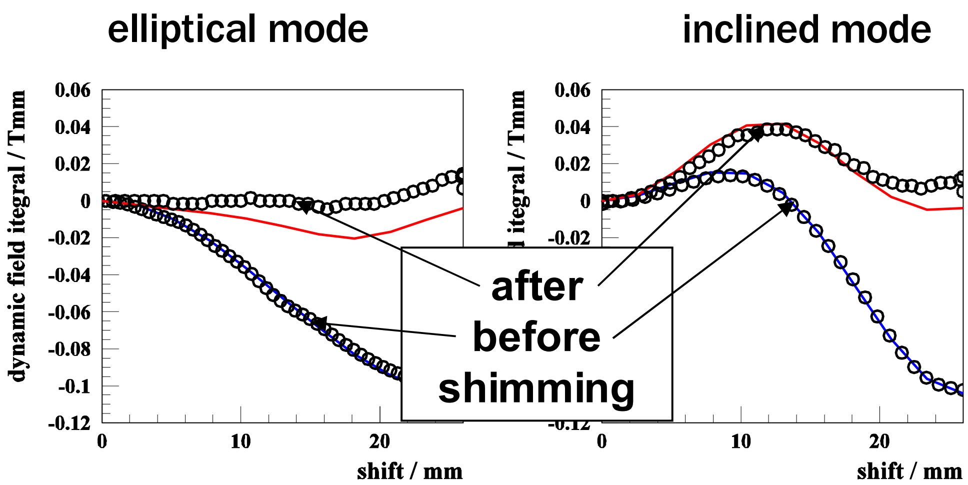
focussing is stronger for the other FELs by a factor of:

9	ME-FEL
45	LE-FEL

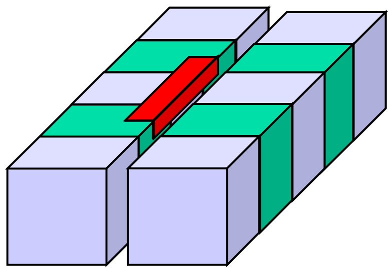
adaptive focussing is essential for optimum
overlap of electron beam and photon beam
effects can partly be compensated with Fe shims

Reduction of Dynamic Quadrupole

BESSY UE52



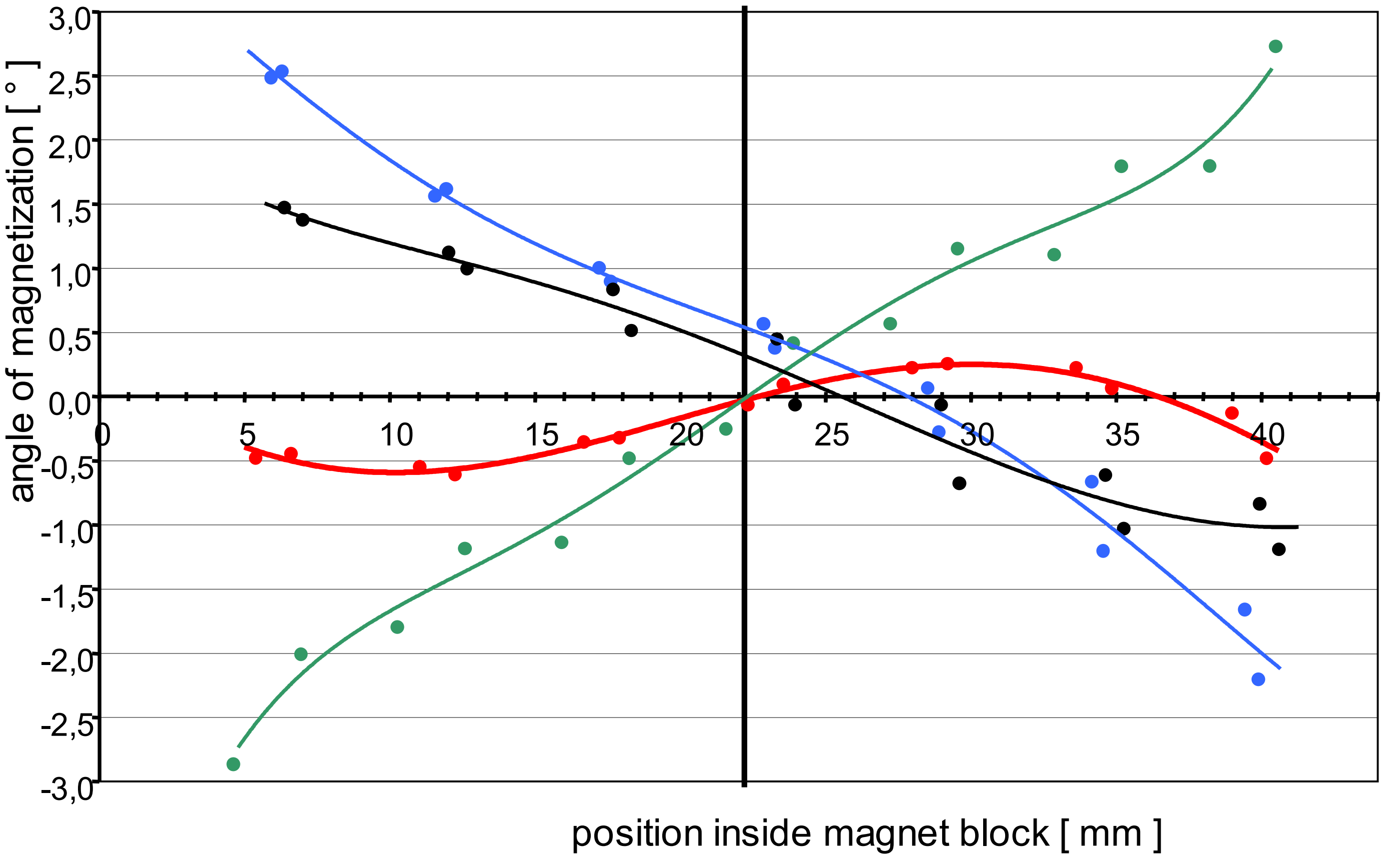
J. Bahrdt et. al., SRI 2006, Daegu, Korea

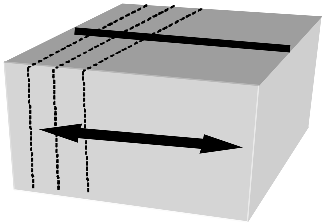


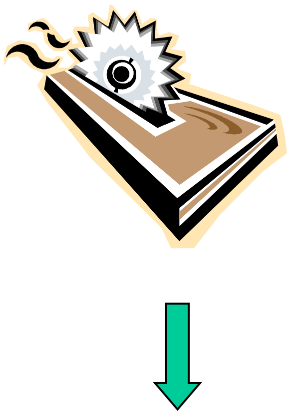
J. Chavanne et al., Proceedings of the EPAC 2000, Vienna, Austria, pp 2346-2348

scheme works fine for parallel mode for APPLE II devices
additional (active) schemes are necessary in inclined mode
applicability to APPLE III design has to be checked

Magnet Block Inhomogeneities







Helmholtz coil

Courtesy of Vacuumschmelze, Hanau

Improvement of Magnetic Material

BMBF-Verbundprojekt:

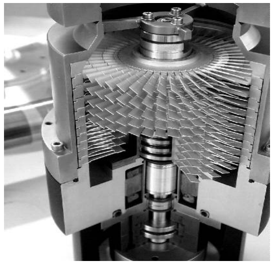
Optimierung der Homogenität von Nd-Fe-B Magneten

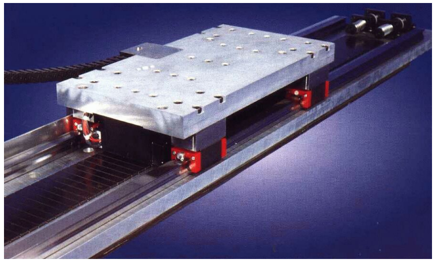
Förderkennzeichen: 03X4501A

VAC, BESSY, Associated partners: DESY, SIEMENS, Applied Films

Improved magnet quality will assure:

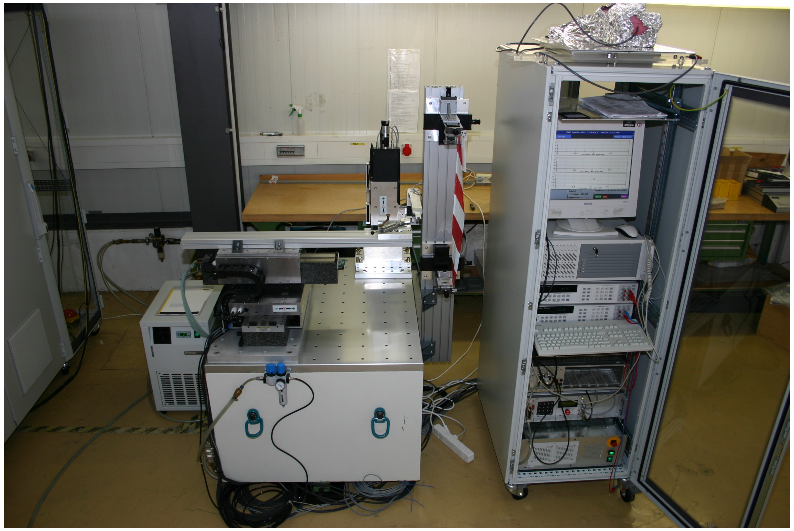
- reduced time required for block characterization, sorting, shimming
- reduced production cost





Magnet Block Characterization

Today, block characterization is essential for an effective sorting
improved magnetic material will reduce production cost

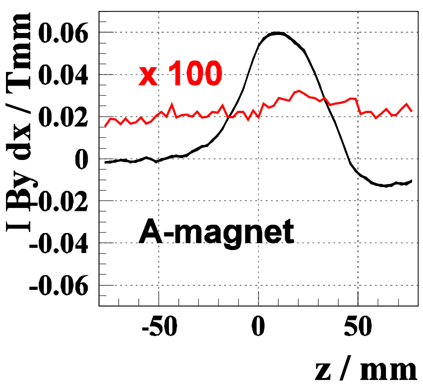


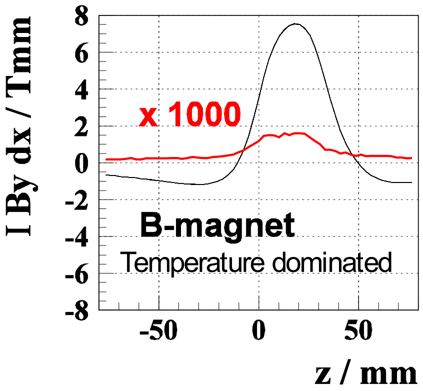
automated Helmholtz coil system for measurement of dipole moment

stretched wire system for characterization of inhomogeneities

new measuremenmt setup:
reproducibility:

A-magnets:	2.0 x 10^{-4} Tmm
	3.0 x 10^{-4} rel.
B-magnets:	1.5 x 10^{-3} Tmm
	2.1 x 10^{-4} rel.





Field Optimization I

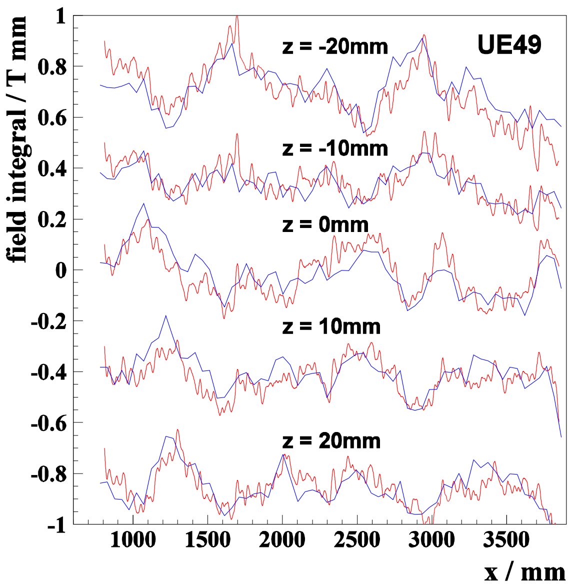
How to meet the FEL-field tolerances

A) single block characterization and initial sorting and in-situ sorting

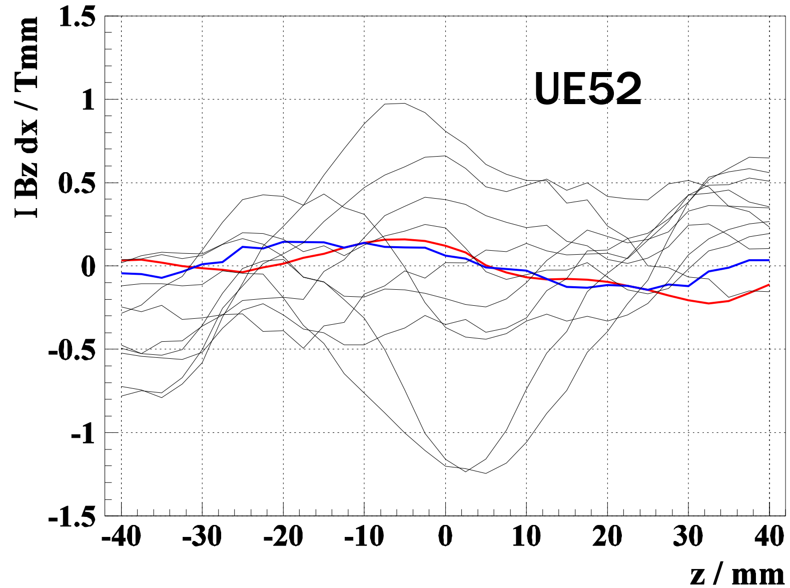
B) shimming

A) excellent agreement between predicted and measured fields integrals
for BESSY undulators UE52, UE49, UE112
efficient sorting procedure

longitudinal distribution



transverse distribution



blue: prediction from single block measurements
red: hall probe measurements

Field Optimization II

B) Special shimming techniques for APPLE devices

- trajectory and phase shimming by virtual shimming (transverse block movement)
- shimming of shift dependent field integrals with Fe shims
- shimming of shift independent field integrals with magic fingers
- shimming of dynamic multipoles with FE shims

adjustable permanent magnet arrays at both ends of the device

J. Bahrdt, W. Frentrup, A. Gaupp, M. Scheer, U. Englisch, Nucl. Instr. and Meth. 516 (2004) 575-585.

Specifications of Support and Drive System

handling of strong forces
- in all three directions (APPLE),
- forces change sign with shift!

tapering

↓

cast iron structures
flexible joints

reproducibility of gap and phase on 1µm level

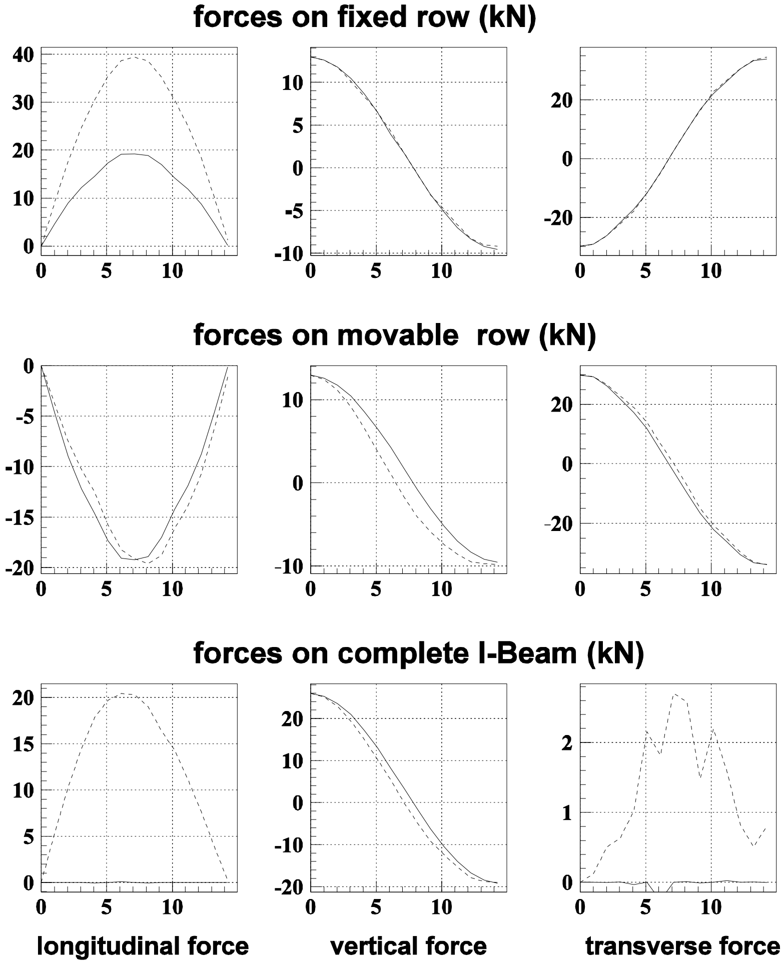
↓

servo motors, feed back loop
advanced measurement concept

optimization of magnet girder

↓

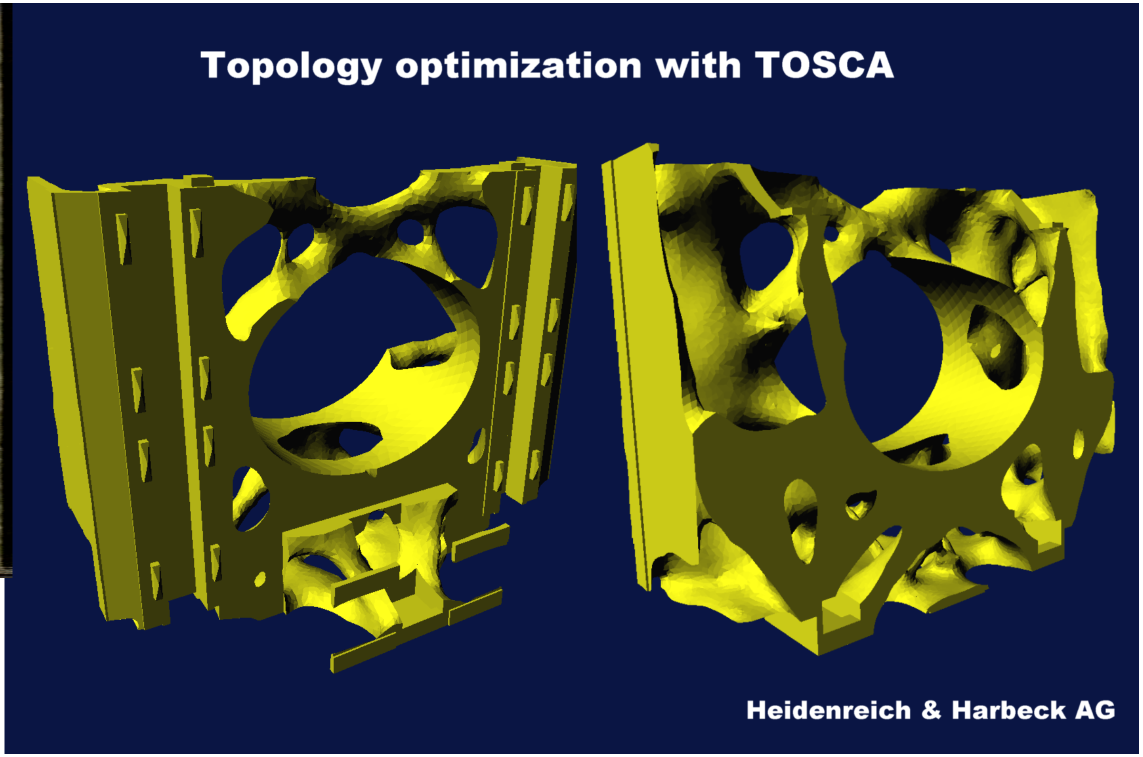
detailed FEM studies



forces of HE-FEL in parallel (solid) antiparallel (dashed) mode
forces of ME- and LE-FEL are roughly a factor of two larger

Bionic Optimization

learning from nature



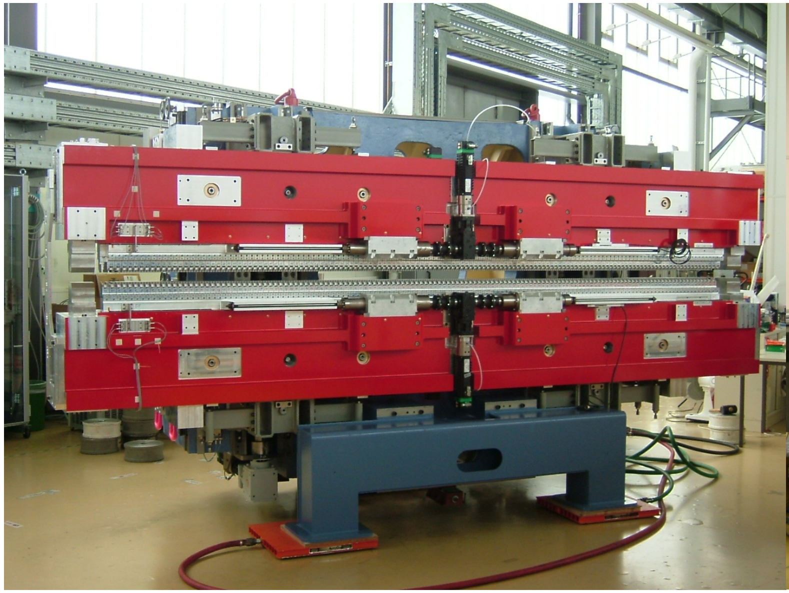
mass reduction at location with low stress
addition of mass at locations with high stress

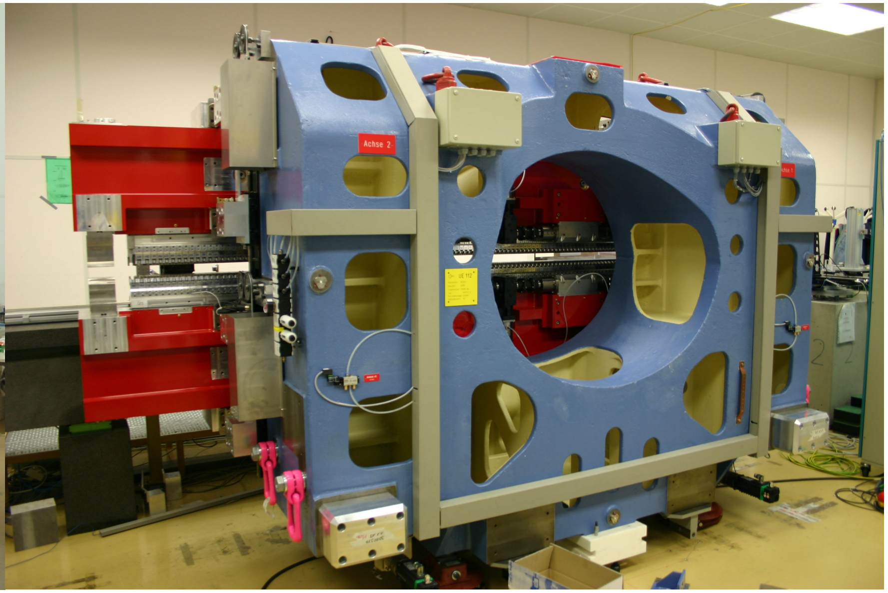
transformation of optimized structure into structures compatible with existing fabrication techniques is not yet automated

New Support System for the UE112

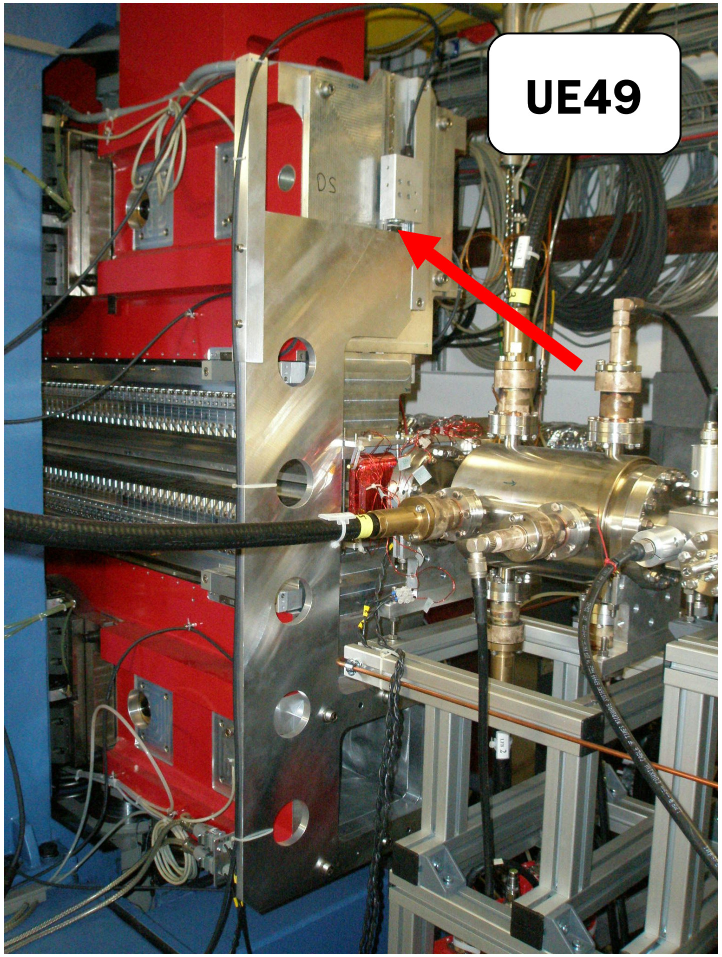
model options for cast iron structures

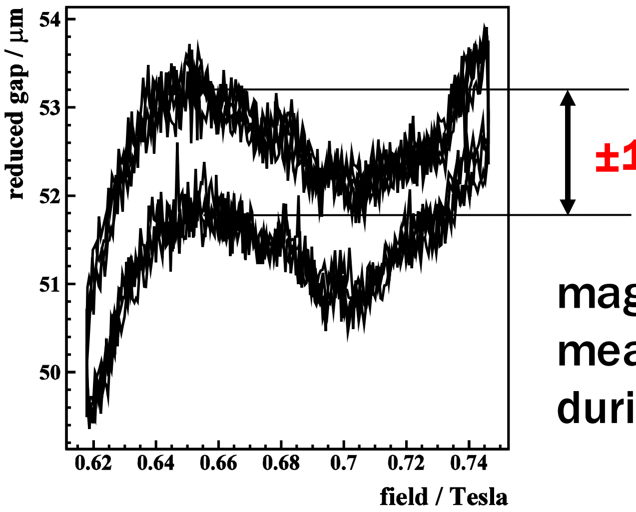
wooden models: many casts possible, cost effective for series production
polystrene models: reduced costs for prototype fabrication
only core model: reduced costs for prototype fabrication (new technology)



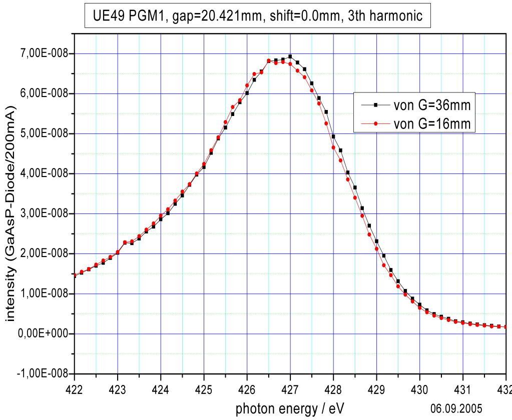


Gap Positioning Accuracy



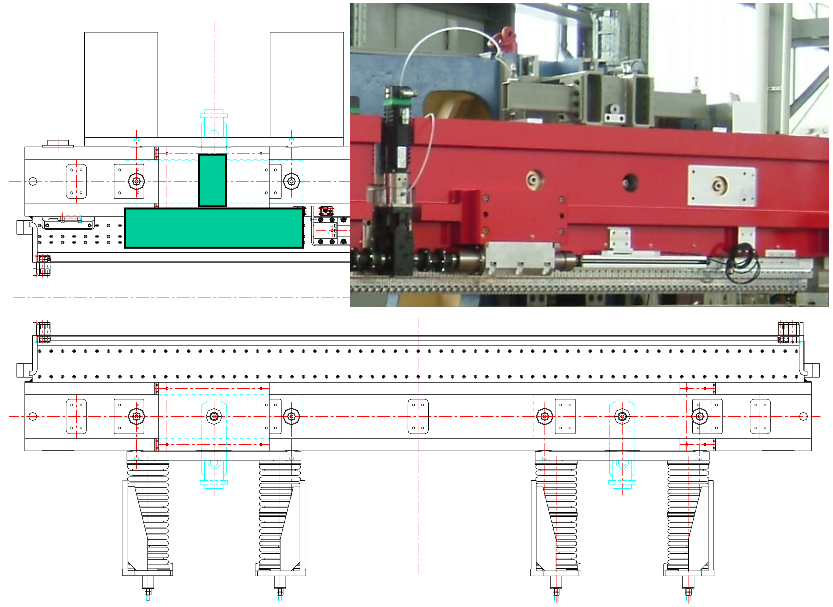


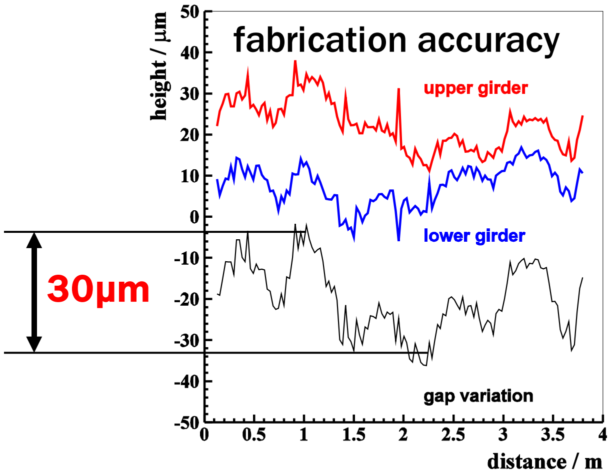
magnetic field measurement during gap drive



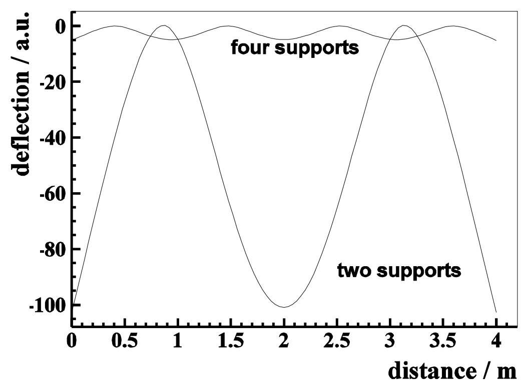
spectra measured for different directions of gap drive

Magnet Girder



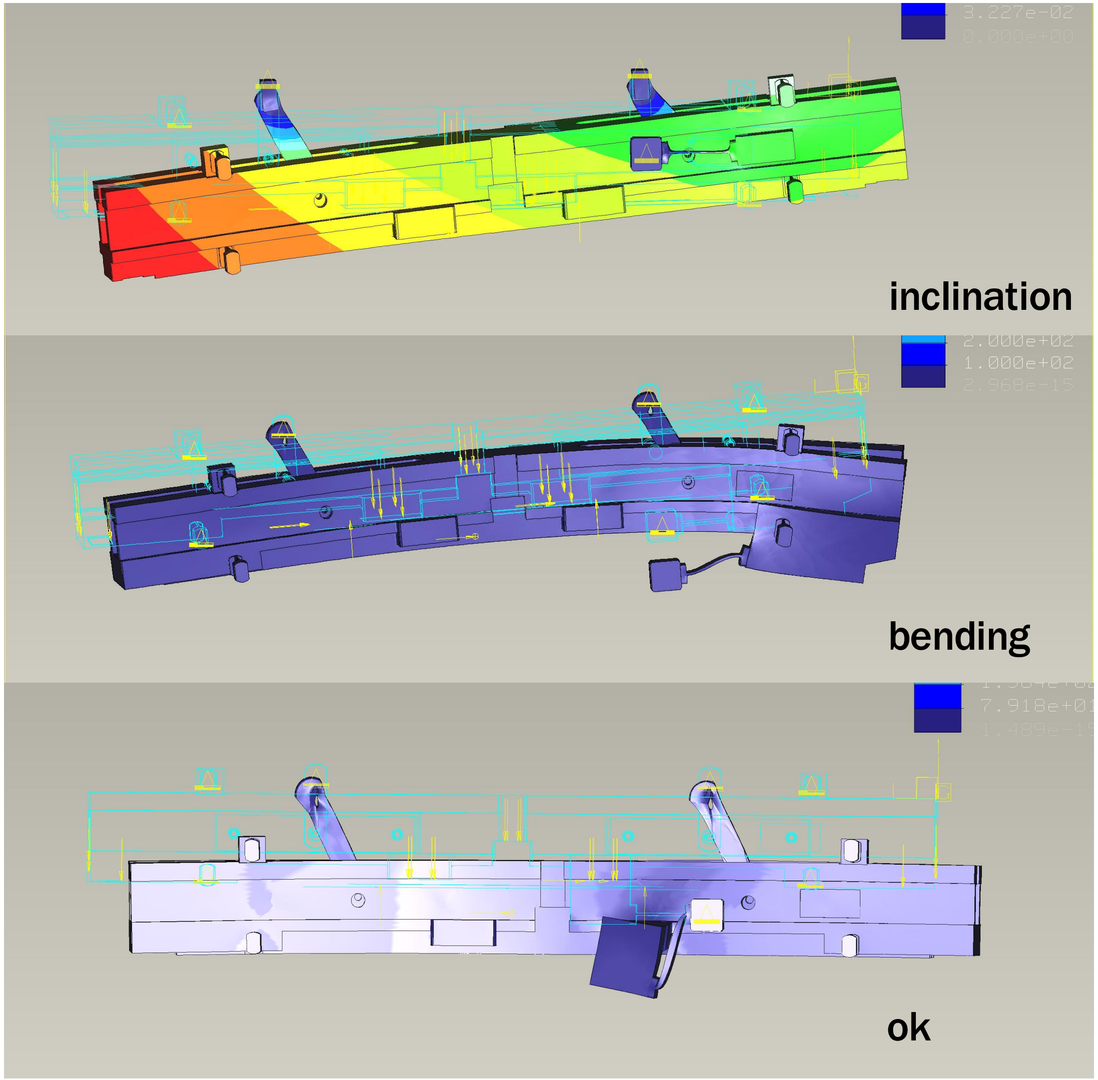


residual fluctuations can be compensated with spacers



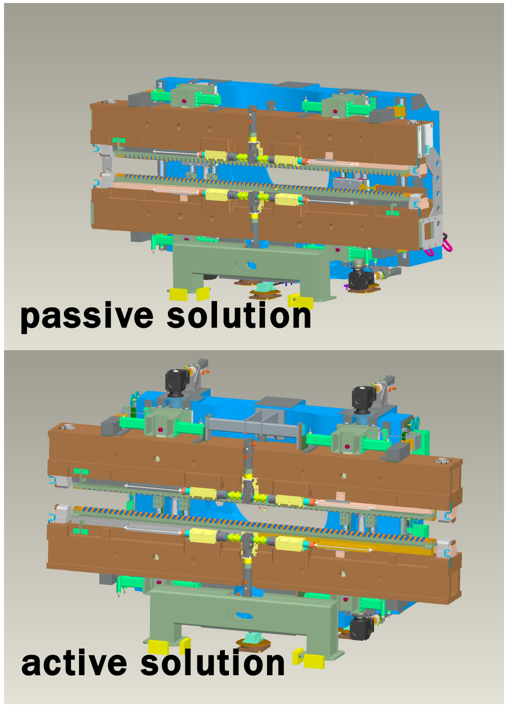
support at four locations for bending minimization (realized at BESSY IDs UE49, UE46, UE112)

Girder Optimization



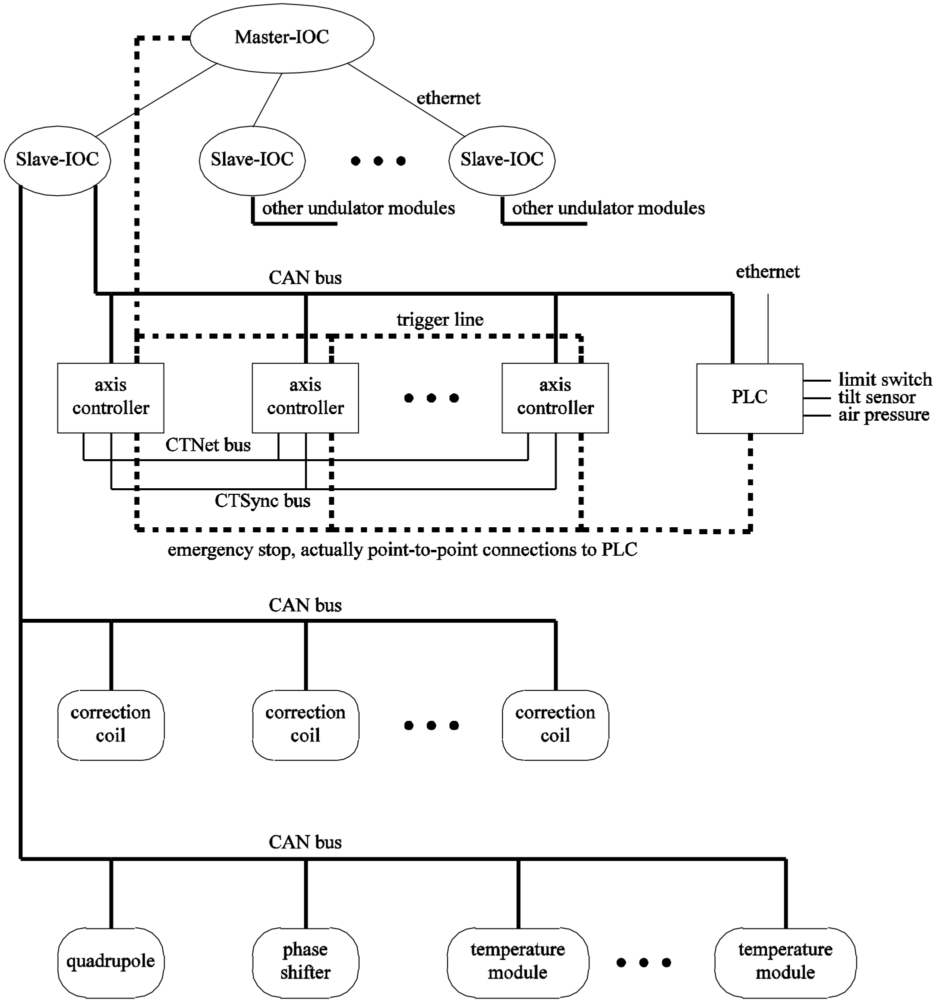
Passive solution:
The correct positioning of the longitudinal fixed bearing is essential to avoid:

5. **girder inclination**
6. **girder bending**



Motion Control, Operation

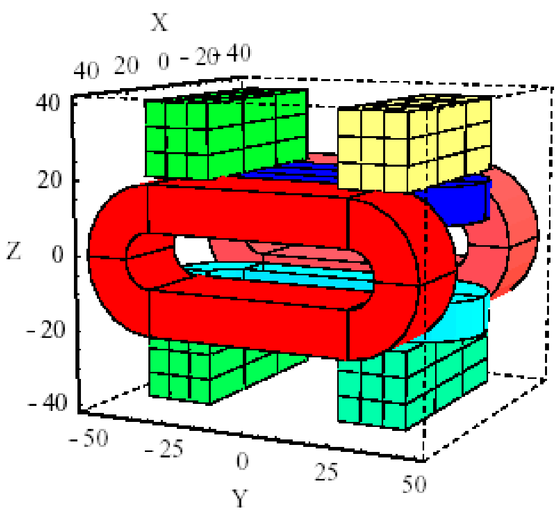
Control System for one module



Reproducibility is required:

- air coils (no iron)
- permanent magnet quadrupoles
- permanent magnet phase shifter

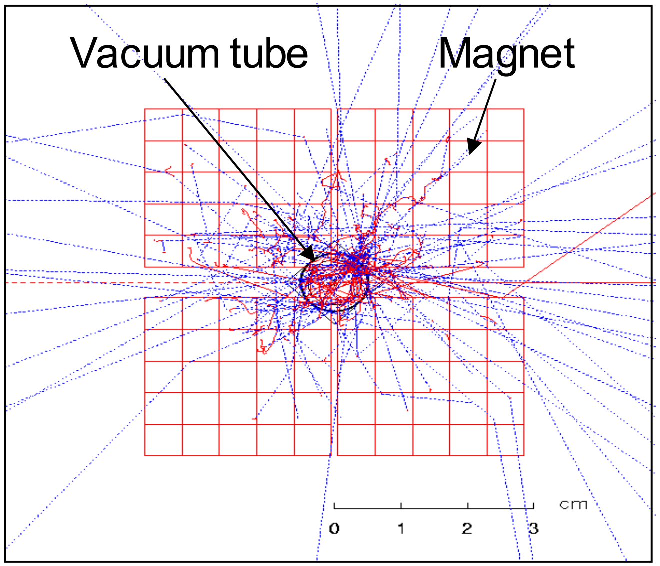
phase shifter + air coil unit



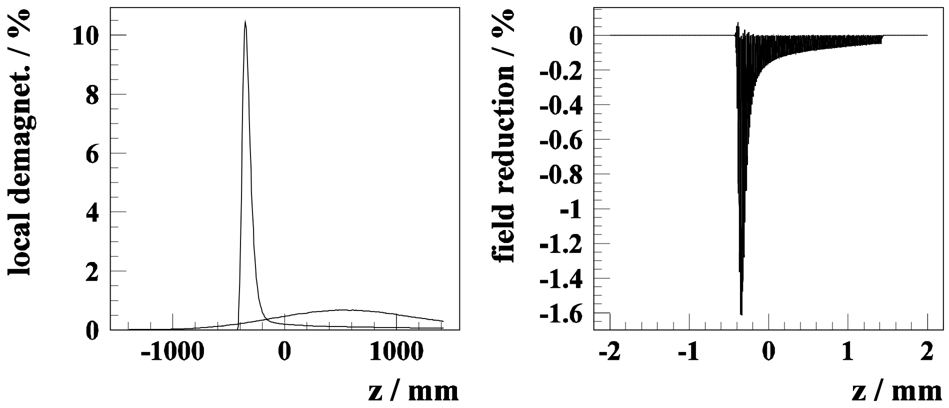
Beam Loss Simulations with GEANT

Model for simulations

- APPLE III geometry
- circular vacuum pipe
- electron beam hits one magnet row at
  i) 1 mrad
  ii) 0.1mrad
- 70kGray (red. Dose) for 1% remanence loss
- segmentation of magnets:
  i) 5 x 5 (1mrad)
  ii) 7x7 (0.1mrad)



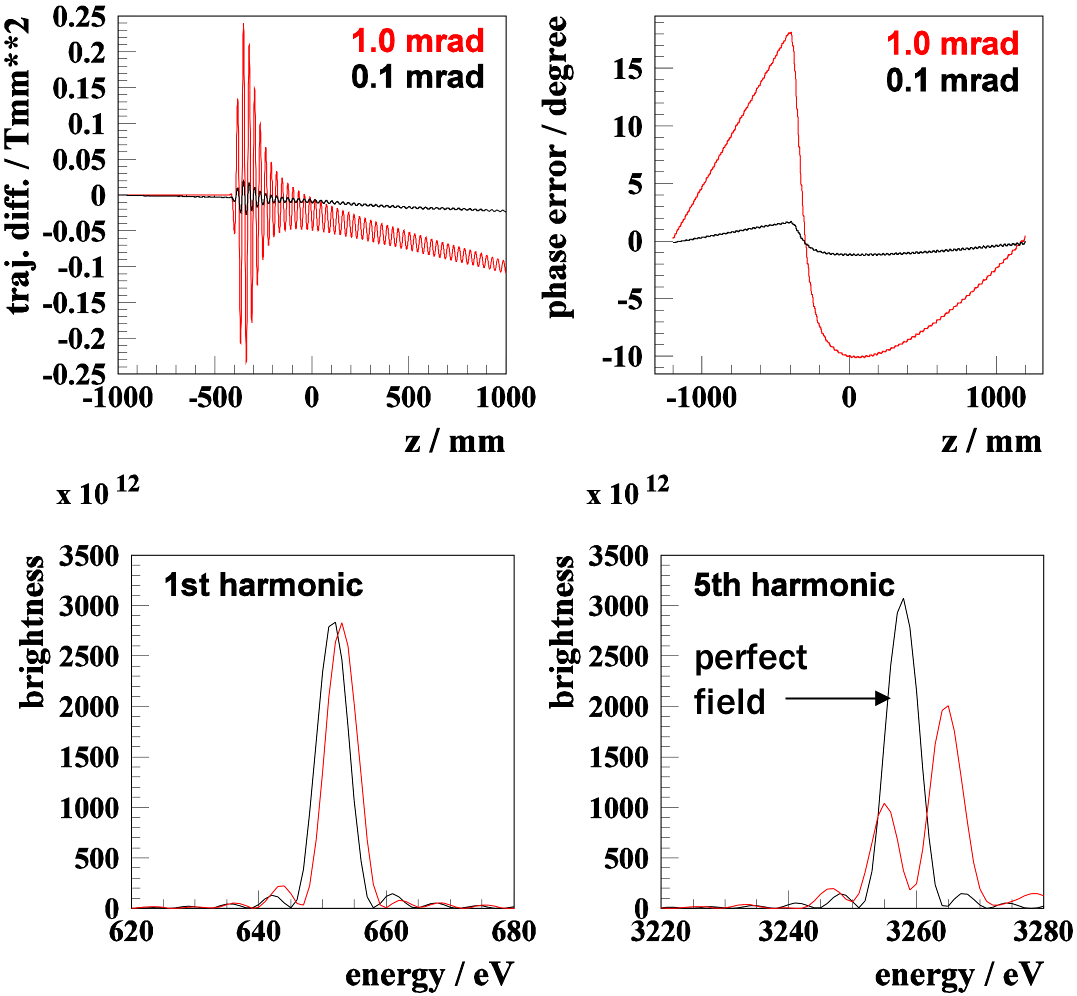
Results



Procedure

- dump 300.000nC into the vacuum pipe at one location
- get doses inside magnet segments
- derive local demagnetization
- get spectra from modified magnets

Analysis of Field Data



Results

maximum doses:
- 0.73 MGy @ 1mrad
- 0.049 MGy @ 0.1mrad

field reduction on axis:
- <= 1.6% @ 1mrad

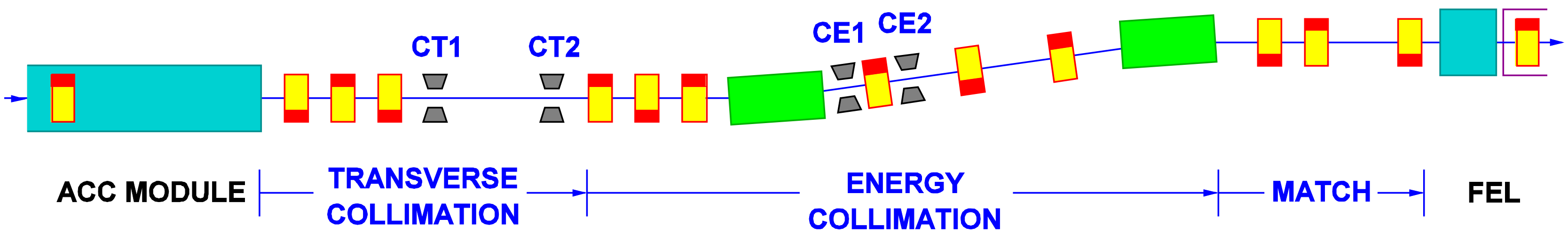
only minimum trajectory error

phase error of $\Delta\Phi=7°$ @ 1mrad

spontaneous spectrum:
- energy shift of 1st harm.
- spoilt 5th harm.
- phase jump

Collimation System for BESSY FEL

transverse: ± 30 σ
longitudinal: 5%



Experience at FLASH Phase I (with transverse collimator):
maximum detected dose over 3 years = 12 kGy
remeasuring undulator: $\Delta B / B < 2 \times 10^{-4}$
(no changes within measuring accuracy)

PHASE II (dogleg collimator)
a few ten Gy per week for aligned e-beam

Conclusion

- Magnetic field tolerances can be achieved with specific techniques
- Stiff structures can handle 3D-forces
- Closed loop servo systems for gap, phase provide 1µm accuracy
- Alignment is challenging due to small good field region of APPLE
- Complex control system, compensation of undulator focussing
- Machine protection system for undulator magnets is required

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