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

Development and Operation of APPLE Undulators at BESSY

Leibniz
Gemeinschaft

Outline

Operation of APPLE Undulators at BESSY, Preparing for Top-Up

Plans for New Insertion Devices at the BESSY SR

Developments for FEL-Undulators

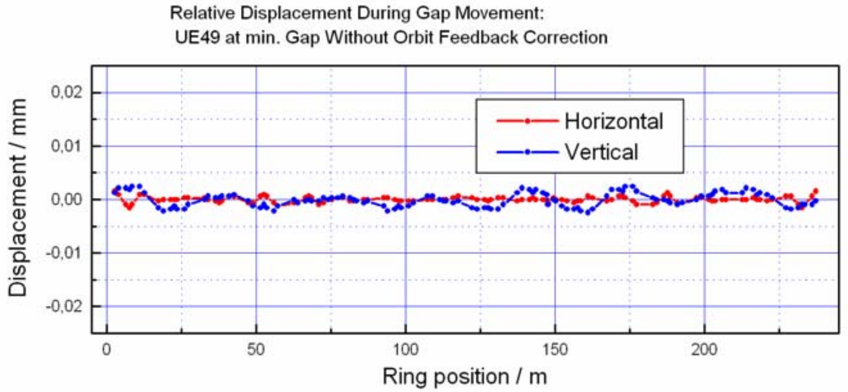
Undulators at BESSY

device	design	operational	λ_0 / mm	periods	Gap / mm	By / Bz / T
U49-1	Hybrid	1998 -	49,4	83	15	0,799
U49-2	Hybrid	2000 -	49,4	83	15	0,788
U125-1	Hybrid	1998 – 2005	125	31	20	1,162
U125-2	Hybrid QPU	2000 -	125	31	15	1,360
U41	Hybrid	1999 -	41,2	79	15	0,659
U139	Hybrid	2004 -	139	10	15	1,471
UE56-1	APPLE II	1999 - 2003	56	2 x 30	16	0,771 / 0,529
UE56k	APPLE II	2003 -	56	1 x 30	16	0,772 / 0,529
UE56-2	APPLE II	1999 -	56	2 x 30	16	0,772 / 0,529
UE46	APPLE II	2001 -	46,3	70	16	0,680 / 0,435
UE52	APPLE II	2002 -	52	77	16	0,742 / 0,505
UE49	APPLE II	2003 -	49	63	16	0,709 / 0,477
UE112	APPLE II	2006 -	112	32	20	0,994 / 0,765

Smooth Operation of BESSY Undulators

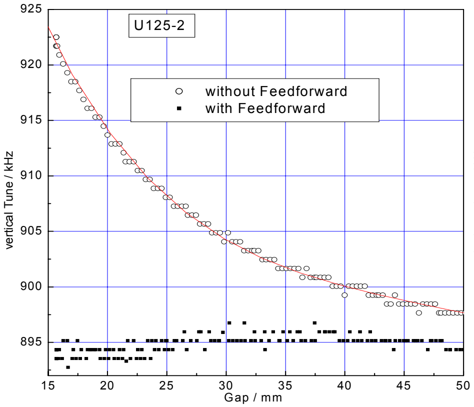
Undulators are coupled to monochromator and are operated under user control

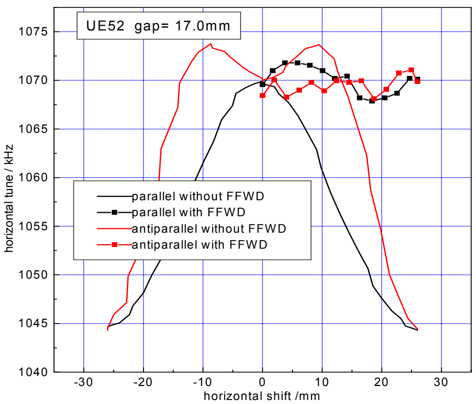
Feed forward correction of residual dipole errors



Feed forward correction of natural focussing

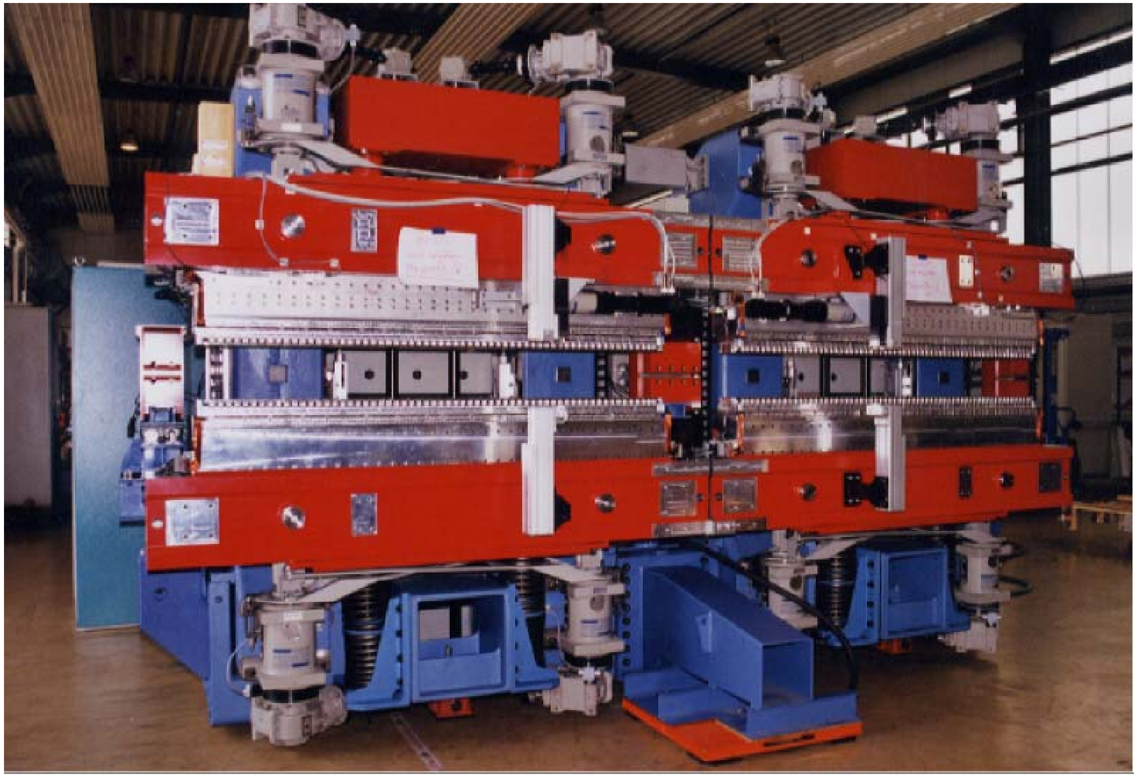
gap change





phase change

UE56 APPLE II Double Undulator

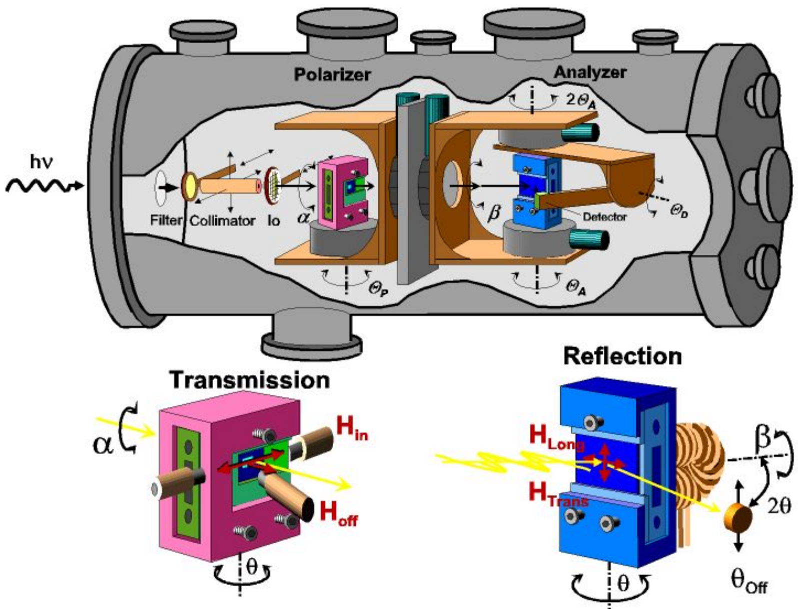


Upgrade of modulator:
Absolute encoders
Harmonic drive gear boxes
New motor controller
Pneumatic brakes

Rotatable permanent magnets pemit two operation modes:

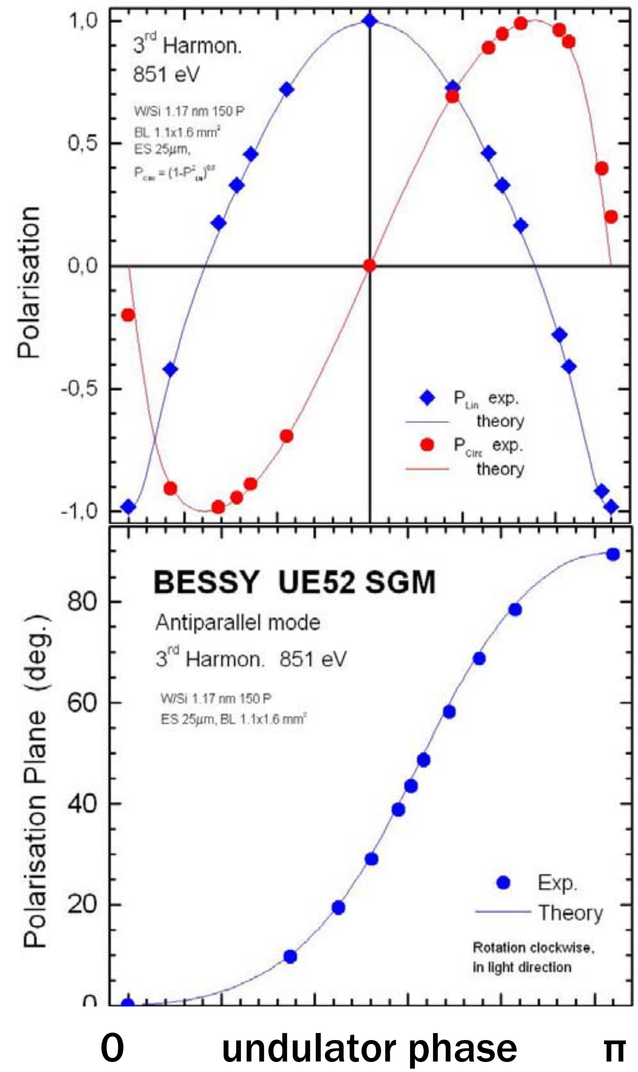
- Chicane mode for fast helicity switching
- Modulator mode couples two sections for higher brightness

Polarization Characterization



elliptical mode

inclined mode



The BESSY Soft X-ray polarimeter

Agreement between theory and measurement

Dynamic Multipoles

second order kicks, no straight line integrals (*Elleaume, EPAC 1992):*

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

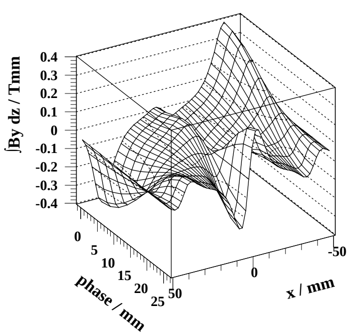
$$\theta_{x/y} = -\frac{L}{2(B\rho)^2}\frac{\lambda_u{}^2}{(2\pi)^2}\left\{B_x^0 \cdot \frac{\partial B_x^0}{\partial x/y} + B_y^0 \cdot \frac{\partial B_y^0}{\partial x/y}\right\}$$

APPLE, elliptical mode

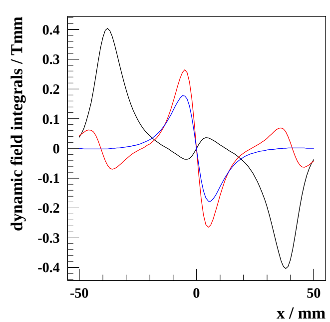
generic representation of second order kicks:

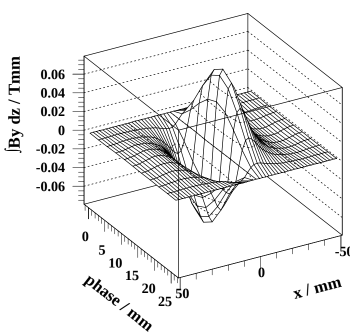
inclined mode

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



elliptical mode





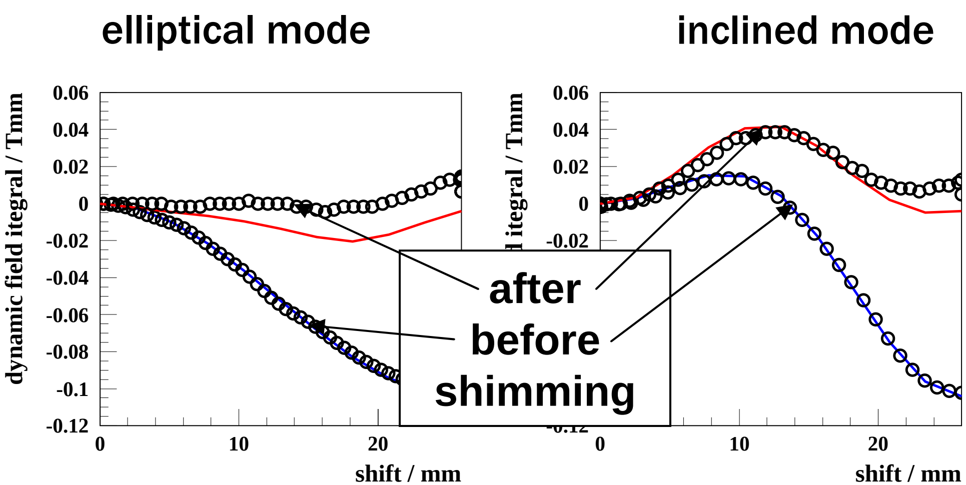
inclined mode

f_0
f_π
$f_{\pi/2}$

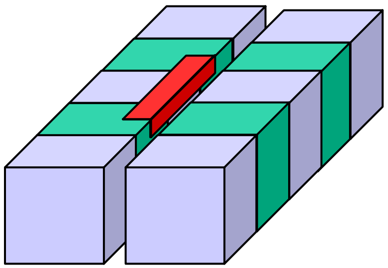
3 generic functions

Shimming of Dynamic Multipoles

BESSY UE52



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



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

reduced injection efficiency for high beta devices: UE52, UE56/2, UE56k
no effect for low beta devices: UE49, UE46

successful shimming of UE52, UE56-2 in situ

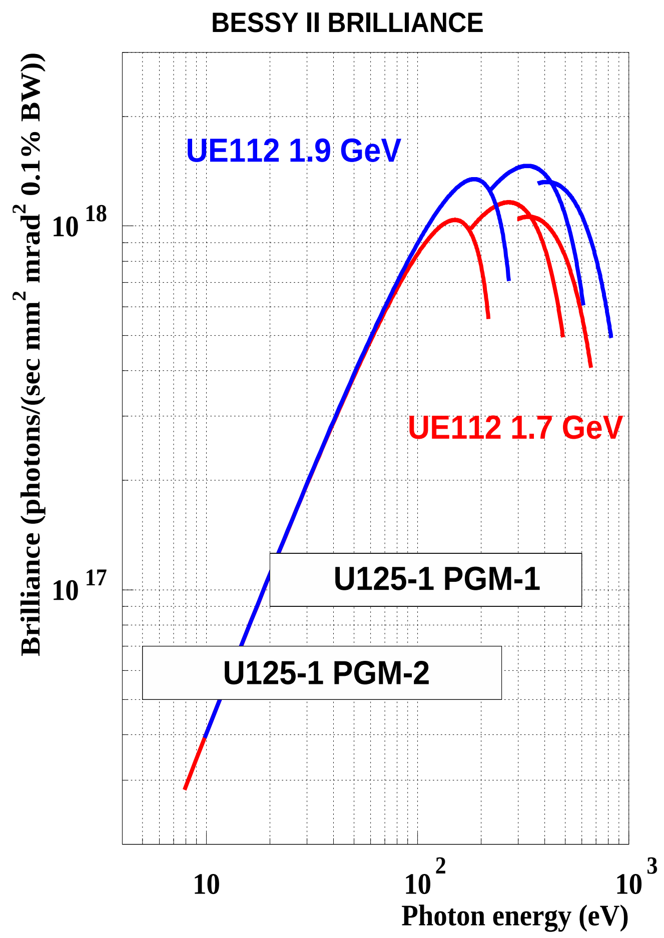
recovered: dynamic aperture,
injection efficiency
lifetime

APPLE II Undulator UE112

Full polarization control permits:
Compensation of polarizing effects of beamline components with appropriate undulator setting

Parameters at 1.7 GeV:

Circular polarization	: 6.5 – 660 eV
Linear horizontal polarization	: 5 – 660 eV
Linear vertical polarization	: 8 – 660 eV
Rotatable (linear) polarization	: 12 – 660 eV
Period length	: 12 mm
Number of periods	: 32
Minimum magnetic gap	: 20mm



APPLE II Undulator UE112
Need for Analytic and Symplectic Tracking

dynamic multipoles of UE112 are one order of magnitude larger
as compared to UE52 ⇨ tracking studies are required

symplectic tracking scheme based on generating function formalism

J. Bahrdt, M. Scheer, G. Wuestefeld, Wiggle 2005, Mini-Workshop, Frascati, 2005
J. Bahrdt, G. Wuestefeld, EPAC 2006

advantages: phase space conservation
very fast (several periods in one step)
uses analytic field description

application to APPLE Undulators:

representation of main field for variable gap,
shift and operation mode in a closed model

representation of Fe-shims (one data set per shift, gap)

Analytic Field Representation of APPLE II

Main field
scalar potential of four rows

$$V = \sum_{i=1}^{n} (V_{1i} + V_{2i} + V_{3i} + V_{4i})$$

$$V_{1i} = +((e^{+k_{yi}y} / k_{yi}) \cdot (B_{cyi}c_{xi-} + B_{syi}s_{xi-}) + B_0 e^{+k_z y} / nk_z) \cdot c_{z+}$$
$$V_{2i} = +((e^{+k_{yi}y} / k_{yi}) \cdot (B_{cyi}c_{xi+} + B_{syi}s_{xi+}) + B_0 e^{+k_z y} / nk_z) \cdot c_{z-}$$
$$V_{3i} = -((e^{-k_{yi}y} / k_{yi}) \cdot (B_{cyi}c_{xi+} + B_{syi}s_{xi+}) + B_0 e^{-k_z y} / nk_z) \cdot c_{z+}$$
$$V_{4i} = -((e^{-k_{yi}y} / k_{yi}) \cdot (B_{cyi}c_{xi-} + B_{syi}s_{xi-}) + B_0 e^{-k_z y} / nk_z) \cdot c_{z-}$$

$$c_{xi\pm} = \cos(k_{xi}(x \pm x_0))$$
$$s_{xi\pm} = \sin(k_{xi}(x \pm x_0))$$
$$c_{z\pm} = \cos(k_z z \pm \psi / 2)$$
$$k_{xi} = i \cdot k_{x0}$$
$$k_{yi} = \sqrt{k_{xi}^{\ 2} + k_z^2}$$

↓

$$\vec{B} = -\vec{\nabla}(V)$$

Shim field integral
scalar potential of two girders

$$\tilde{V} = \sum_{i=1}^{n} \tilde{V}_i$$

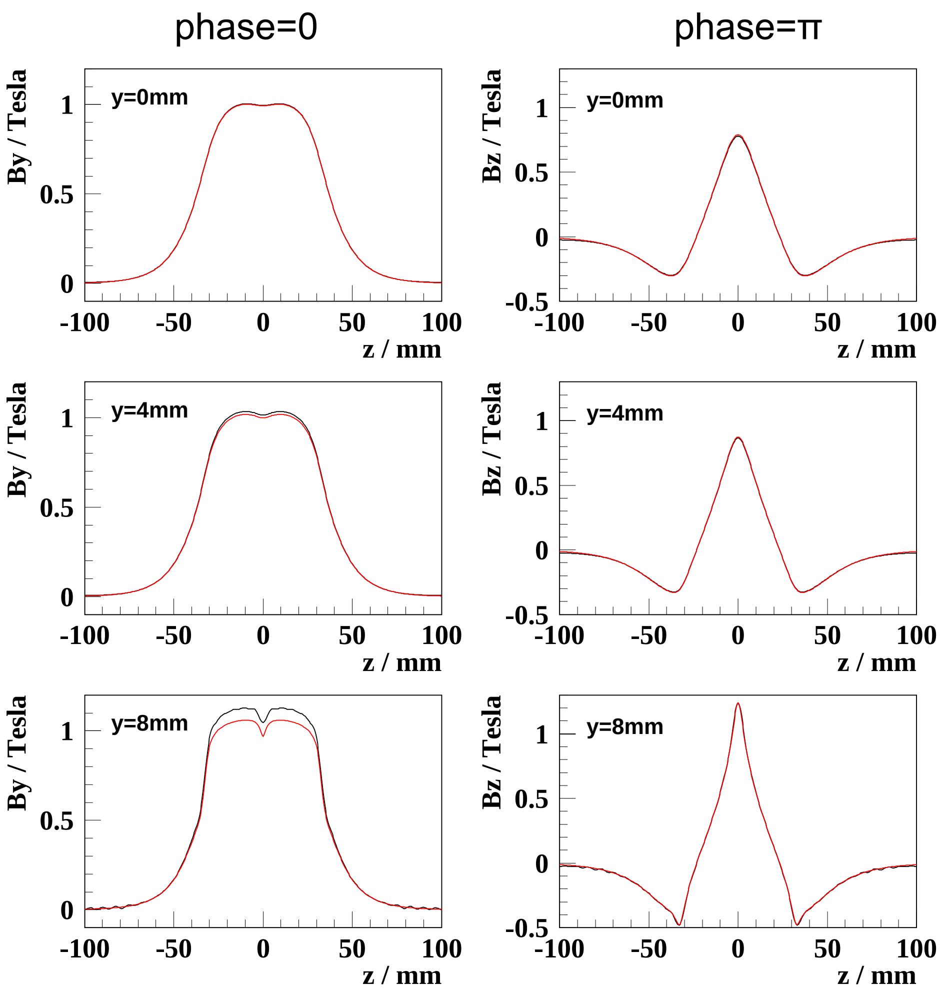
$$\tilde{V}_i = \frac{1}{k_{yi}}(\tilde{B}_{c1yi}\cos(k_{xi}x) + \tilde{B}_{s1yi}\sin(k_{xi}x)) \cdot e^{k_{yi}y} + \frac{1}{k_{yi}}(\tilde{B}_{c2yi}\cos(k_{xi}x) + \tilde{B}_{s2yi}\sin(k_{xi}x)) \cdot e^{-k_{yi}y}$$

↓

$$\tilde{B} = \int \vec{B} \cdot dx = -\vec{\nabla}(\tilde{V})$$

calculation of Fourier components i=1 to 30 of
- a single row (main field)
- a single girder (shim field integral)

Accuracy of APPLE Main Field Description

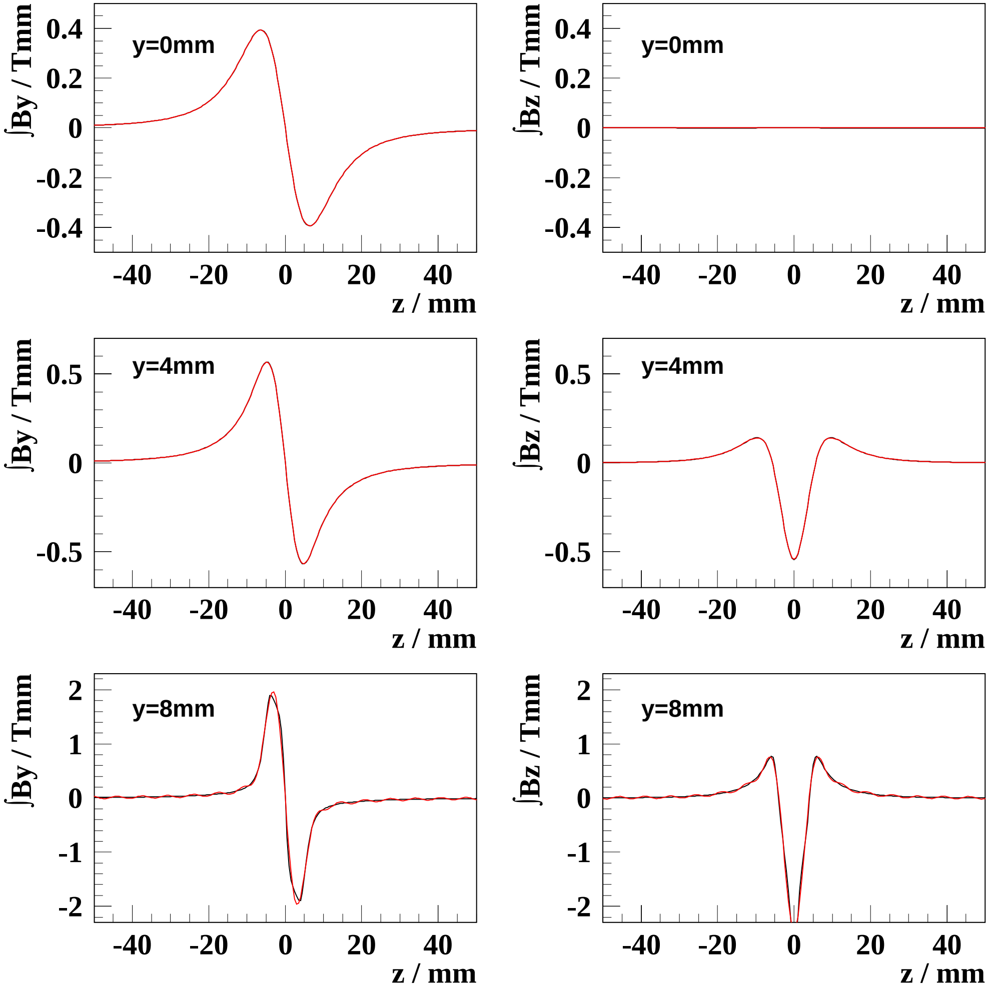


analytical representation (black)
simulation with RADIA (red)

parametrization of 3D-field
using only a few coefficients
provides a very good field description

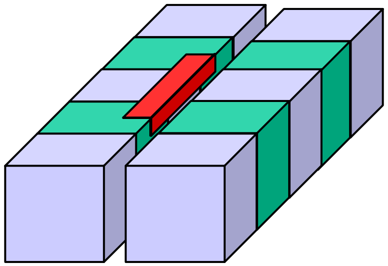
- for various gaps
- various shifts
- large vertical offsets

Accuracy of Shim Description



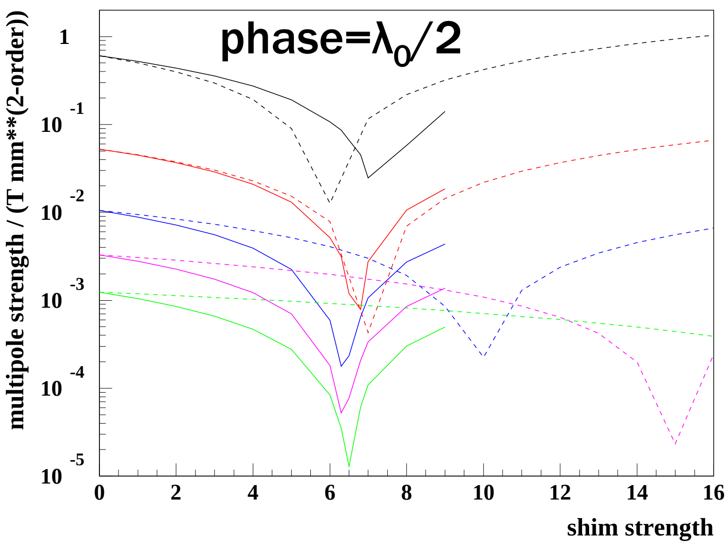
field integrals of L-Shim

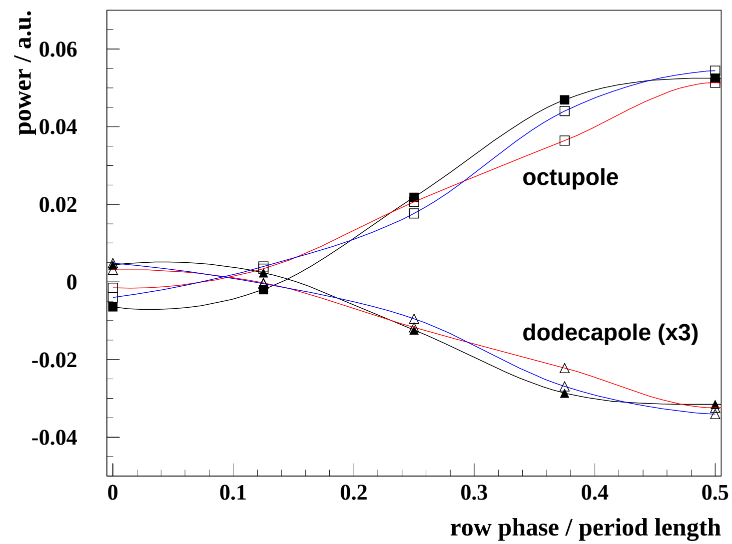
analytical representation (black)
simulation with RADIA (red)



L-Shims as proposed by Chavanne et al., EPAC 2000

Shim Optimization for UE112, Elliptical Mode



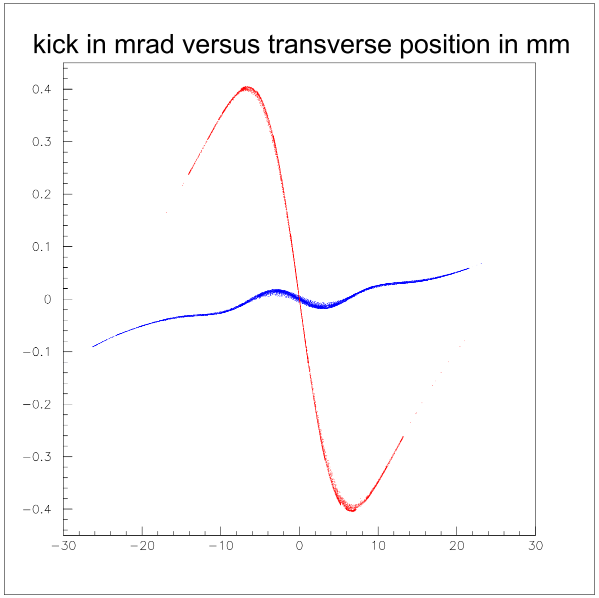


quadrupole
octupole
dodecapole
hexadecapole
ikosapole

two shim widths:
solid: 2mm
dashed: 4mm

black: Dynamic multipole
red: negative shim strength
blue: combination of shims
with different lengths

Tracking Studies for the UE112



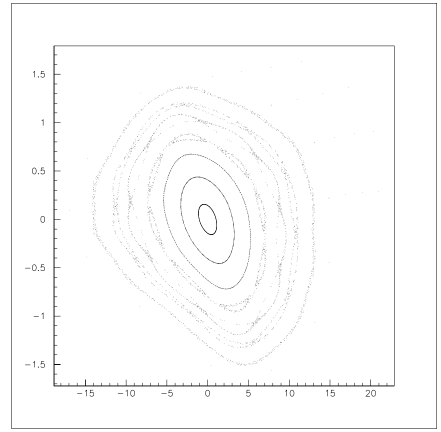
horizontal kick of the electrons passing the UE112

red: without L-shims

blue: with 32 L-shims

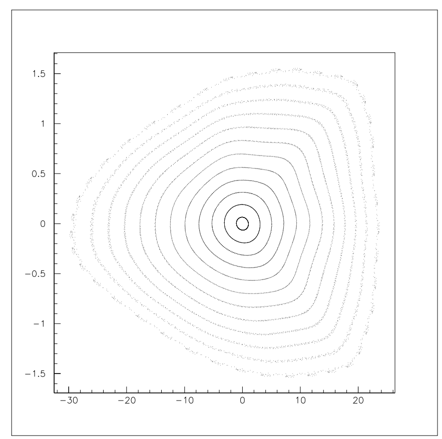
G. Wüstefeld

phase space plot



1000 turns
amplitudes: 1-30mm hor.
1mm vertical

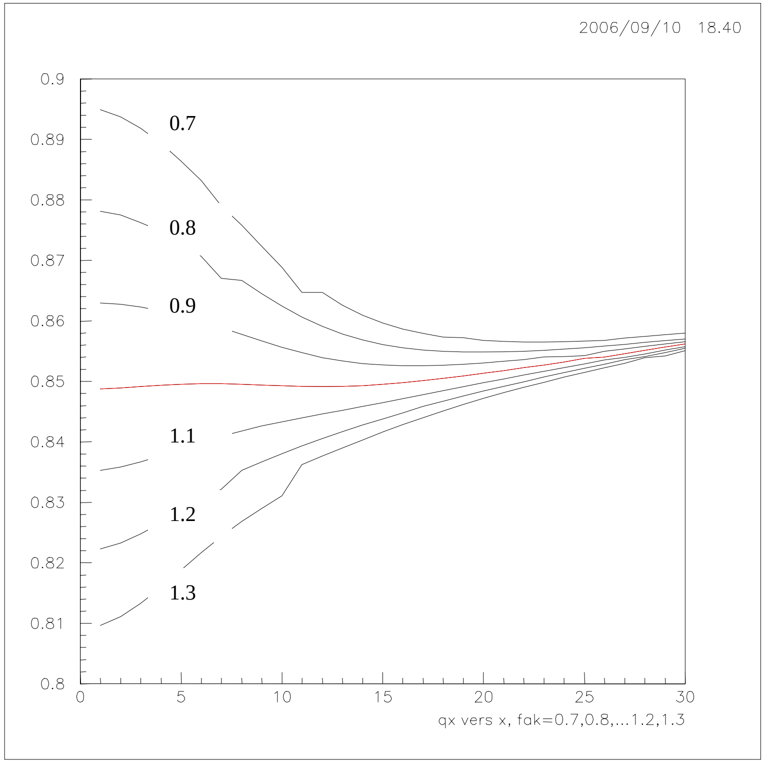
without shims
trajectories stable for z < 15mm



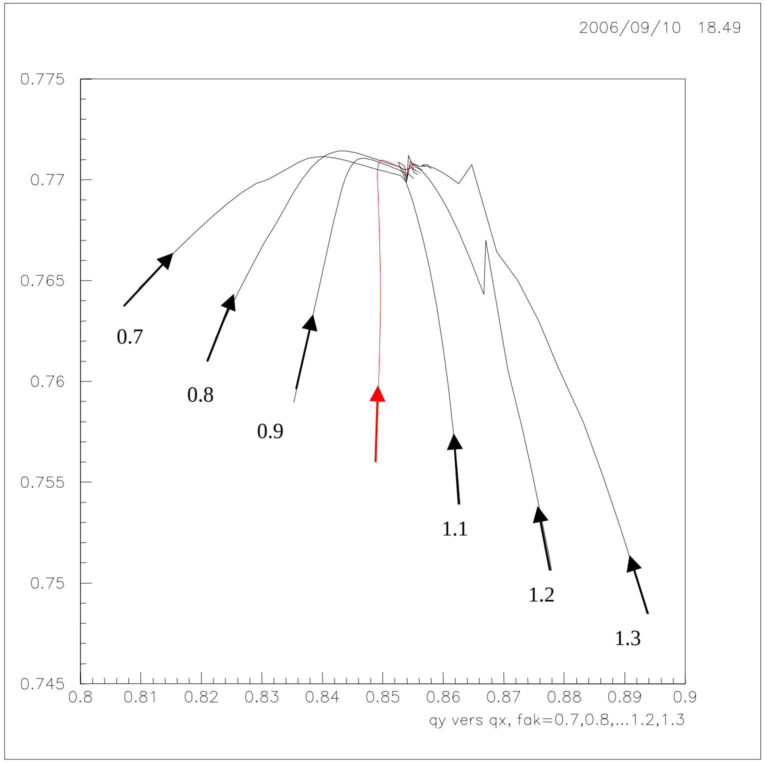
with shims
trajectories stable for z < 30mm

Tune Shift vs. Amplitude for Different Shim Strengths

Horizontal tune shift vs. hor. amplitude

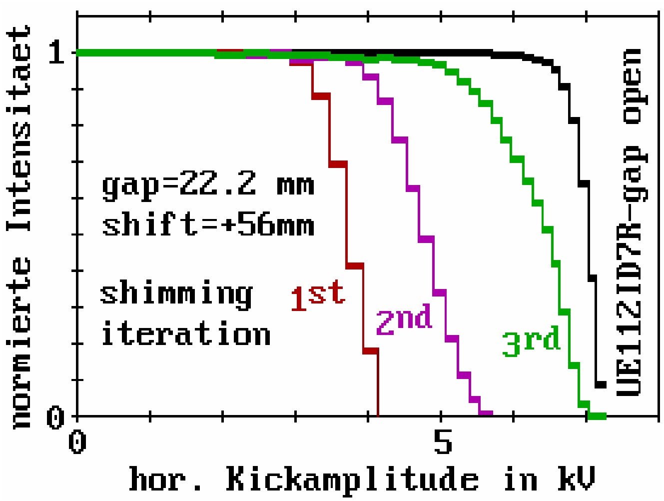


Hor. and vert. tune shift vs. amplitude



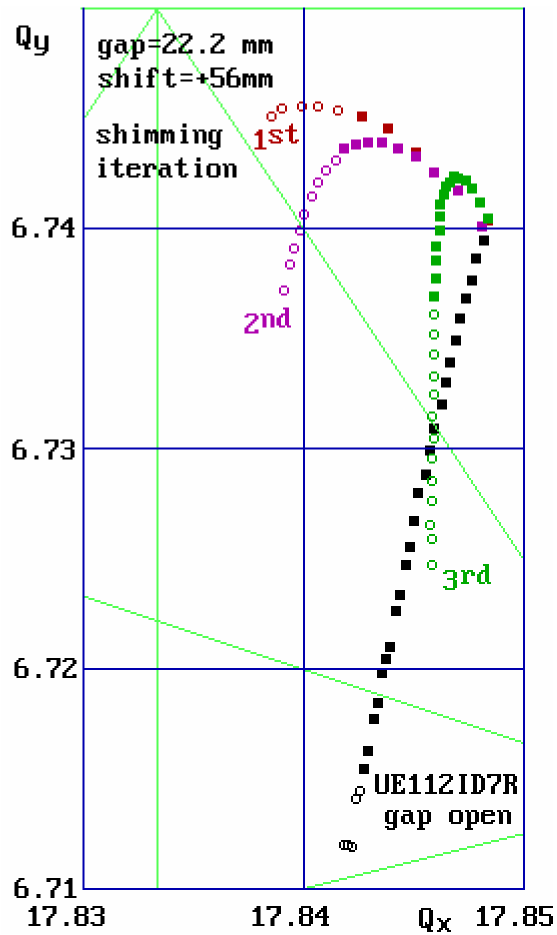
minimum tune variation for chosen shim strength (1.0)

UE112 Final Shimming



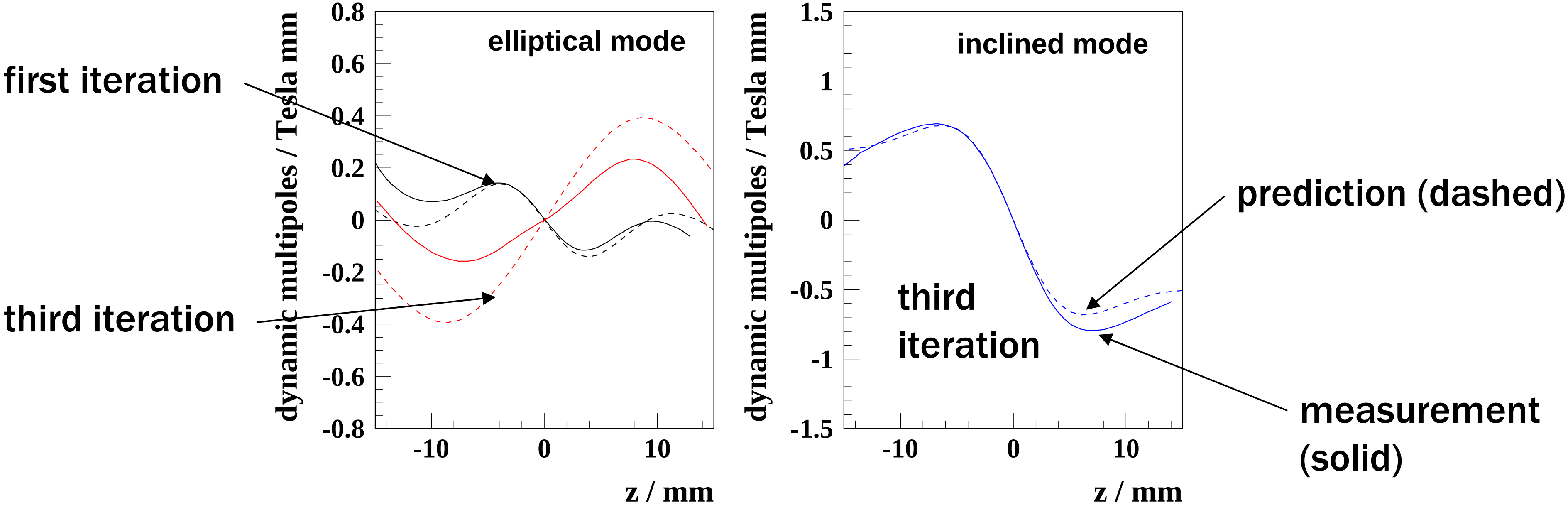
Increase of horizontal aperture by shimming the UE112 with L-shims

P. Kuske



Amplitude dependent detuning for different shimming iterations – open symbols indicate beam loss of more than 2%

Predicted and Measured Dynamic Multipoles



Black : first iteration
red / blue: third iteration

Passive shimming in elliptical mode is sufficient
Active shimming in inclined mode is required
This will be realized with rotatable permanent magnets

Ideas for the BESSY Storage Ring

New operation modes

- Top-up operation within the next year
- Energy enhancement from 1.7 GeV to 1.9 GeV

New Insertion Devices

All straight sections are filled!

- Replacement of UE56-1 double undulator with
  femto second slicing facility (2004)
- Replacement of planar devices with variably polarizing devices
  e.g. U125-1 ⟺ UE112
- Smaller period length devices dedicated to special user requirements:
  1: elliptically polarizing in-vacuum devices
  to cover LII/III edges of Fe, Co, Ni with first harmonic
  and rare earth MIV/V edges with third harmonic
  2: planar SC-undulators for protein crystallography

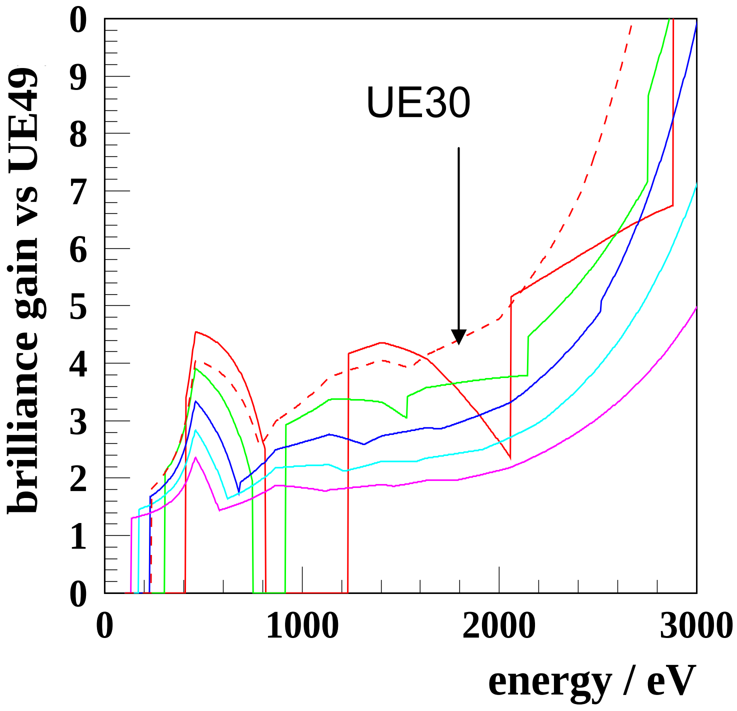
UE30: In-Vacuum Elliptical Undulator

elliptical

Design goal:
Smallest period compatible with overlap between 1st and 3rd harmonic

Parameters:

Photon energy range	: 250eV – 2500eV
Polarization	: hor. / vert. linear, elliptical
Period length	: 30mm
Number of periods	: 98
Minimum gap	: 6mm



Challenges for an APPLE Design:
linear bearing in ultra high vacuum
drive system and encoder in UHV
Cu coated Ni foil for image currents
flexible taper

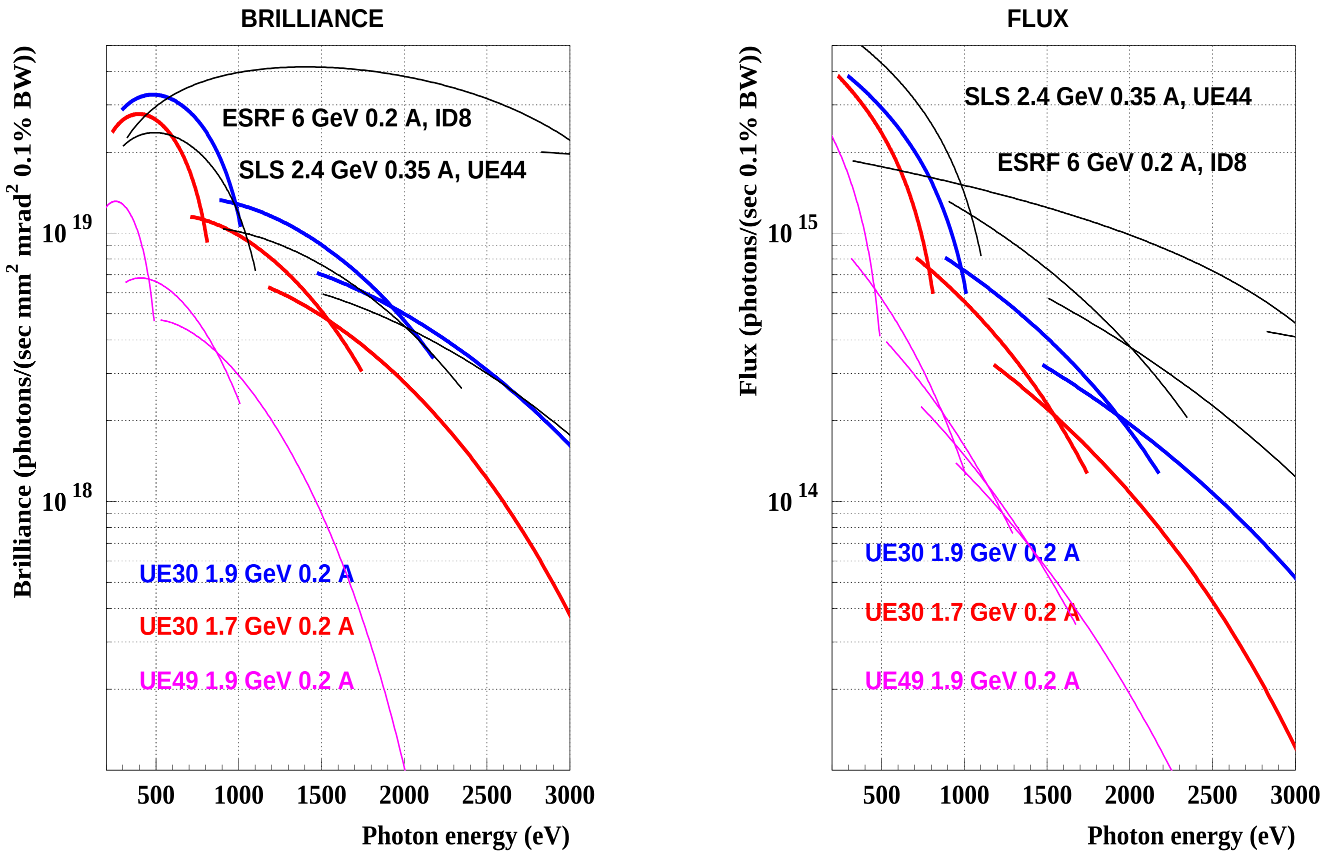
ANKA design
ALS design

Comparison of various ID parameters:
period lengths: red: 30mm,
light blue: 32.5mm, blue: 35mm,
green: 37.5mm, magenta: 40mm

solid: out of vacuum, 10mm gap;
dashed: in-vacuum, 6mm gap

Other options: SC variably polarizing device: NbTI, 4K
SC variably polarizing device: Nb_3Sn
SC variably polarizing device: NbTi, 1.8K

UE30: In-vacuum Elliptical Undulator



Performance comparable to out-of-vac. APPLE at 2.4 GeV machine

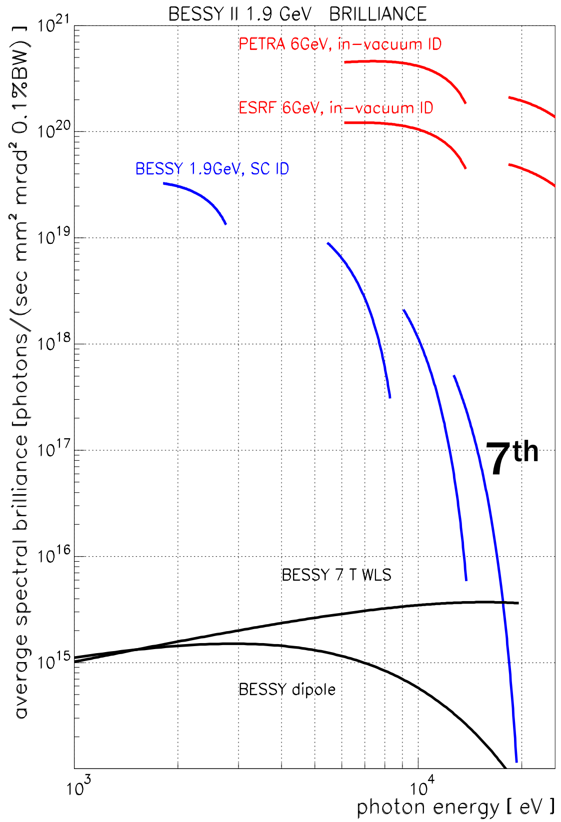
SC-ID for Protein Structure Crystallography

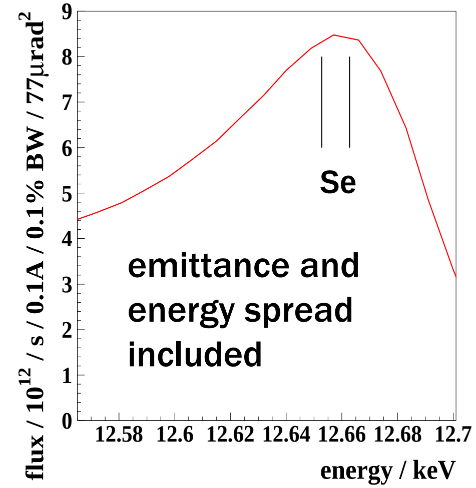
Parameters at 1.9 GeV:

SC-wire	: NbTi (80%)
Usable harmonics	: 1, 3, 5, 7
Energy range	: 2 - 12,65 keV
Fixed polarization	: hor. linear
Period length	: 11,0mm
Number of periods	: 100
Kmax	: 1,2
Fixed gap	: 4,5mm

Detailed studies required on:

Image current heating
Thermal load of upstream dipole
Reproducibilty, hysteresis
Scanning capabilities





Width of 7th harmonic permits MAD-experiments at min. f‘ and max. f‘‘ without undulator scanning

New materials like Nb_3Sn material or 1.8K technology may provide even higher fields in the future

Developments for FEL-Undulators
partly tested at BESSY SR

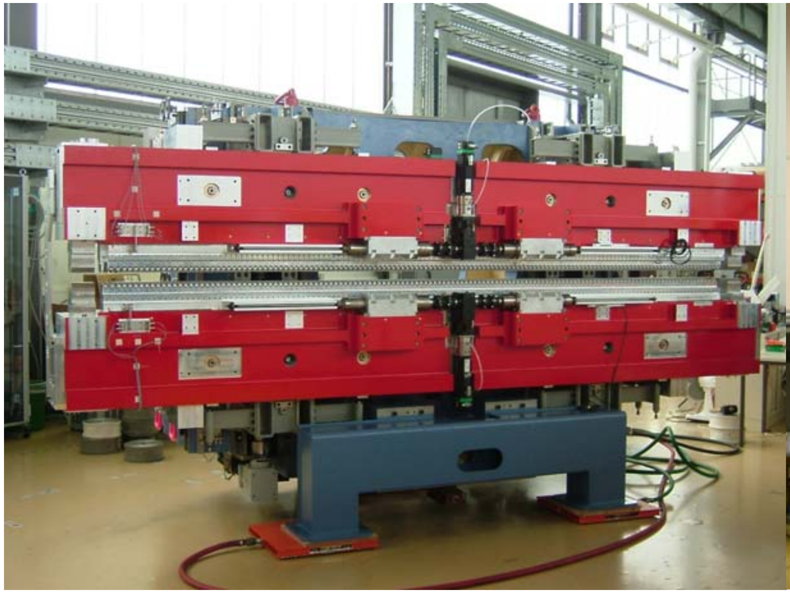
- Support and drive system prototypes: UE112, PETRA III APPLE
- Prototype structure for APPLE III, development of shimming strategies
- Mover for transverse alignment of APPLE devices
- Permanent magnet phase adapter
- Mashine protection: beam loss simulation
  collimator, radiation monitors (Cherenkov and powermeter)
- Control system for complex facility in analogy to BESSY ID control system
- Industrial aspects of undulator fabrication:
  support and drive system
  magnet structure
- Software development: Wavefront propagation with PHASE

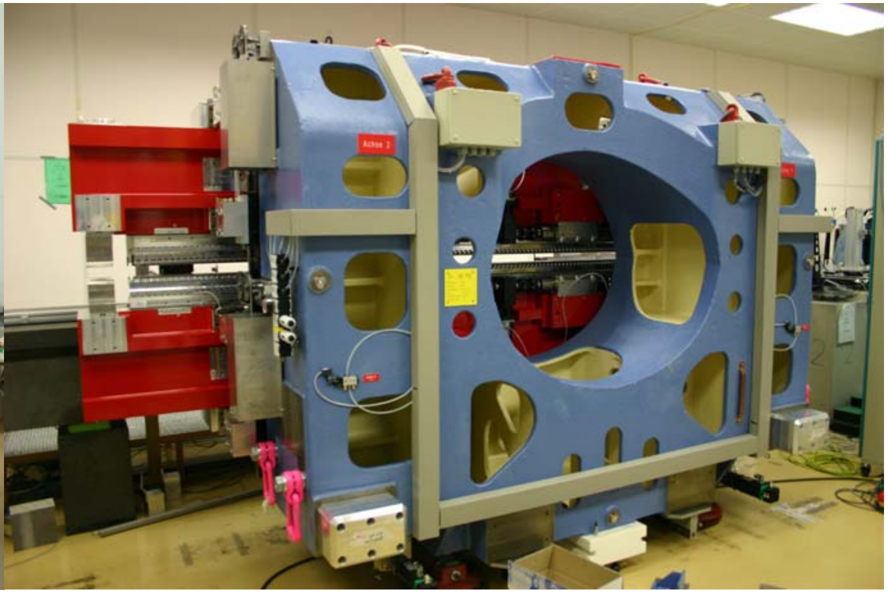
New Support and Drive System for the UE112

UE112: 4.2m APPLE structure

only one piece of cast iron

bionic optimization

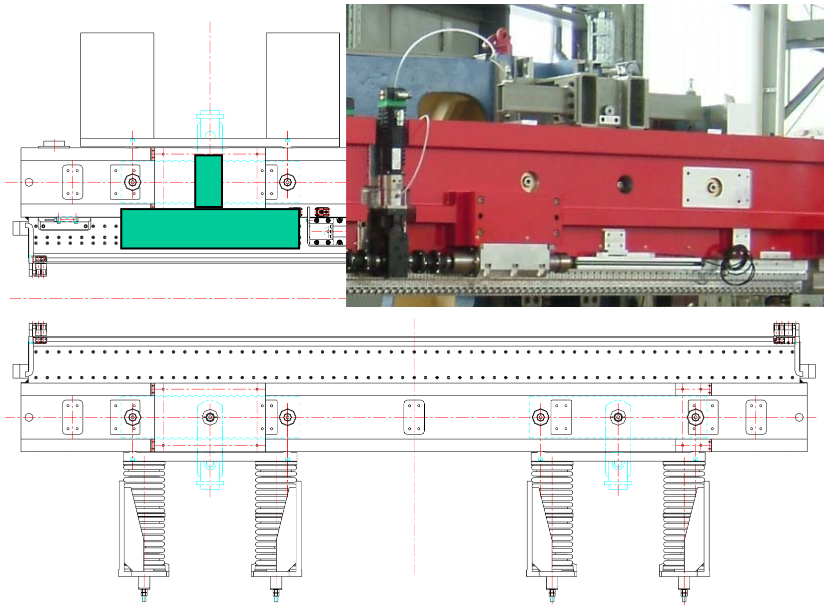


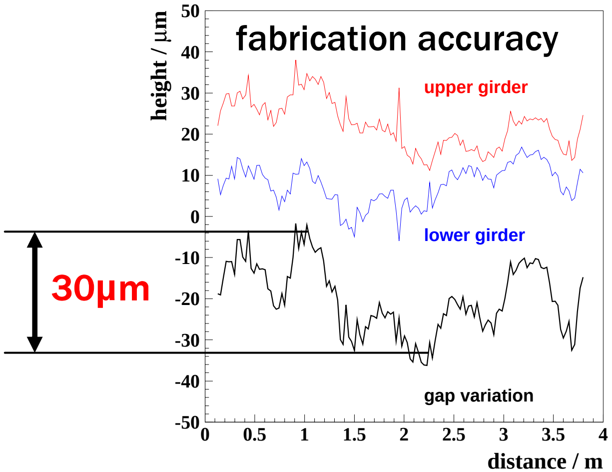


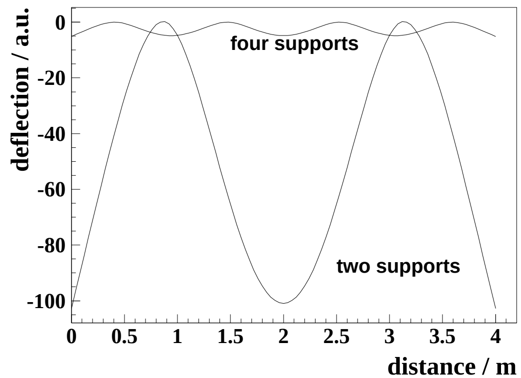
model options for cast iron structures

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)

Al-Magnet Girder



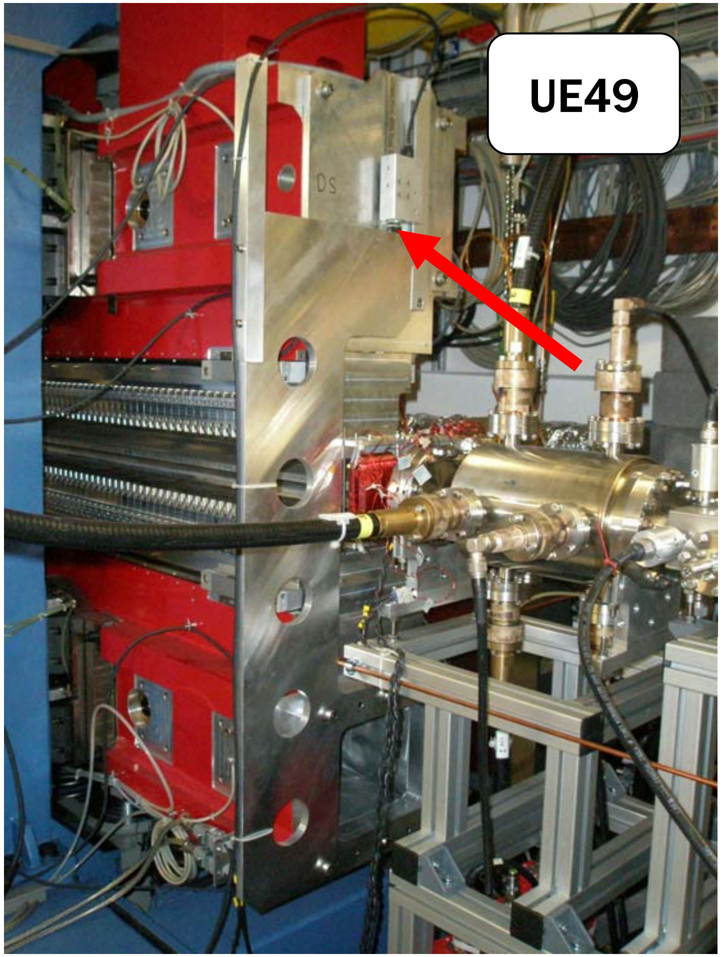


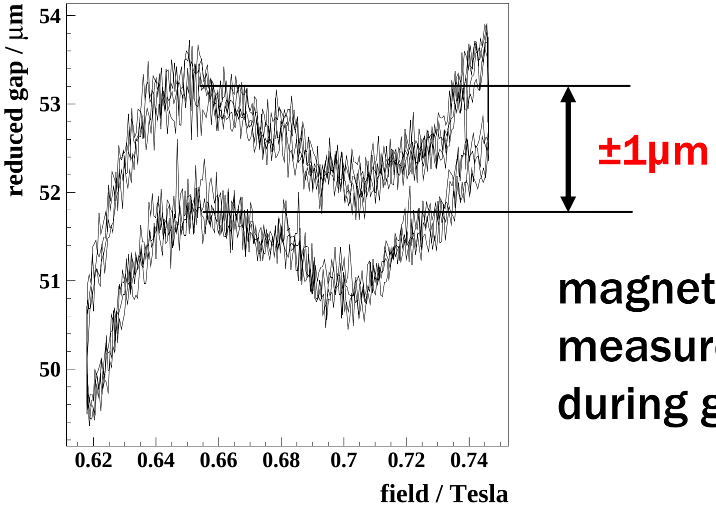


residual fluctuations can be compensated with spacers

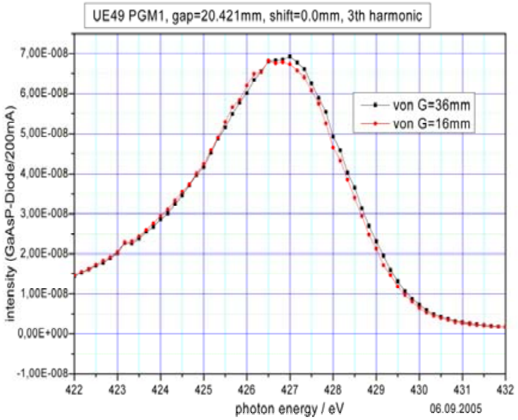
support at four locations for bending minimization (realized at BESSY IDs UE49, UE46, UE112)

Gap Positioning Accuracy





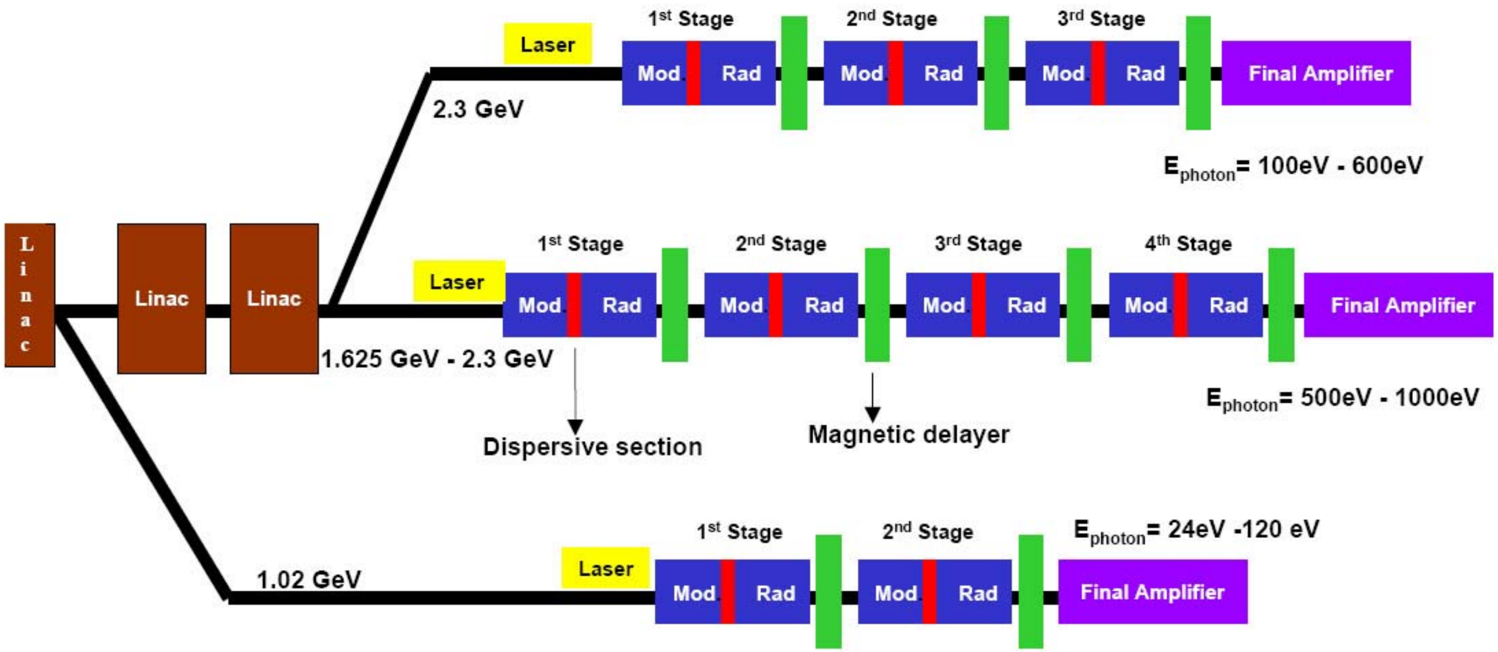
magnetic field measurement during gap drive



spectra measured for different directions of gap drive

Cascaded HGHG FEL

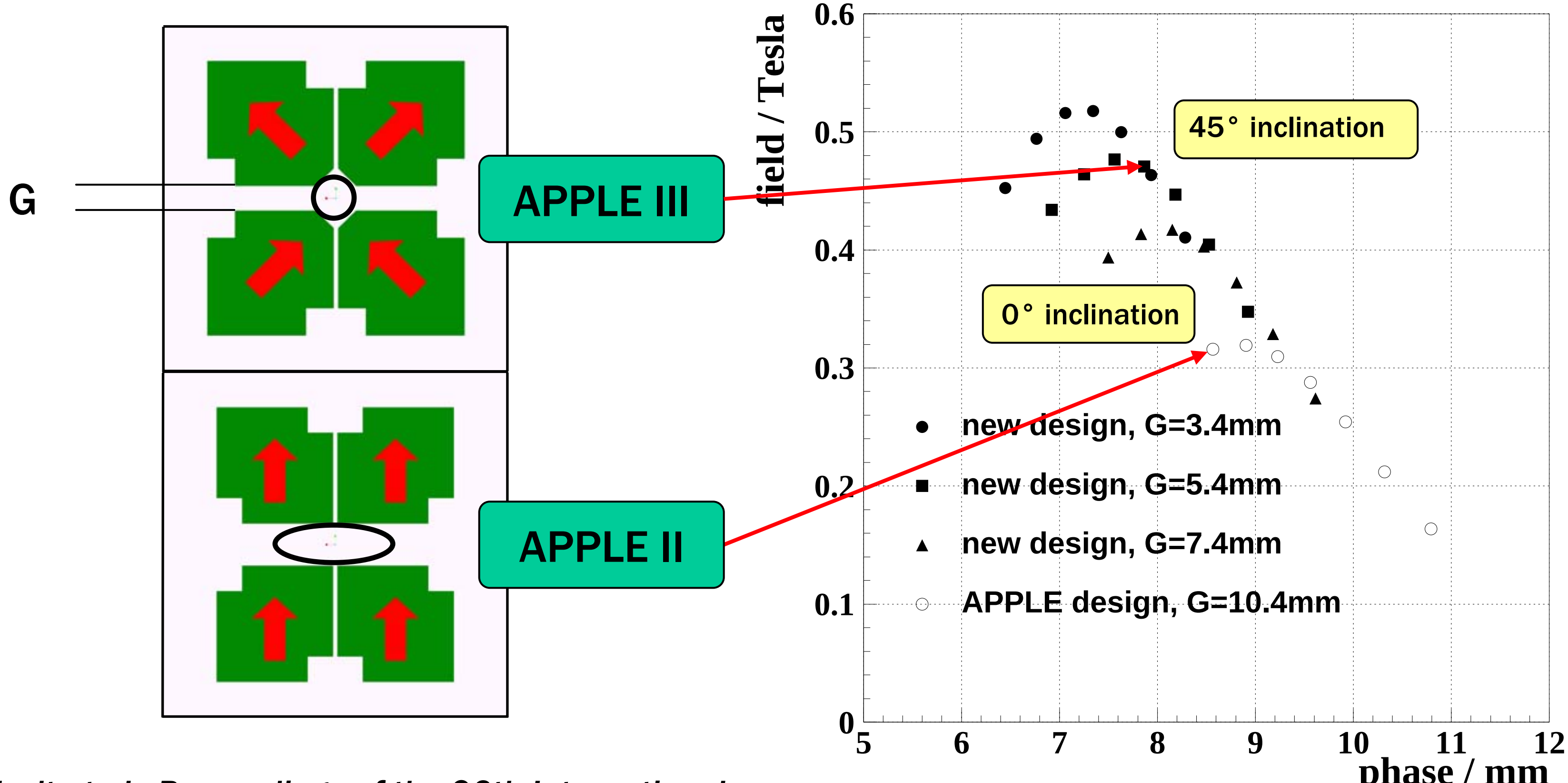
The planned BESSY HGHG FEL facility consists of three HGHG lines to cover the energy range from 24eV to 1000eV



Last radiators and final amplifiers are of the APPLE III type

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

22mm APPLE III prototype under construction

Magnet Block Characterization

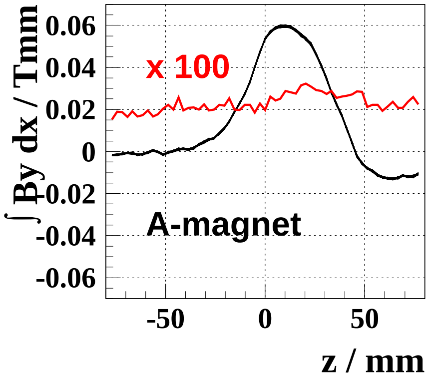
Today, block characterization is essential for an effective sorting improved magnetic material will reduce production cost

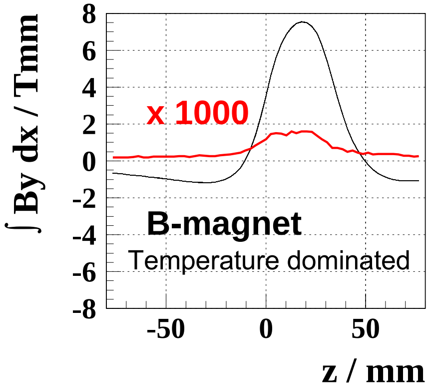
automated Helmholtz coil system for measurement of dipole moment

stretched wire system for characterization of inhomogeneities

new measuremenmt setup:
reproducibility:

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





Field Optimization

How to meet the FEL-field tolerances

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

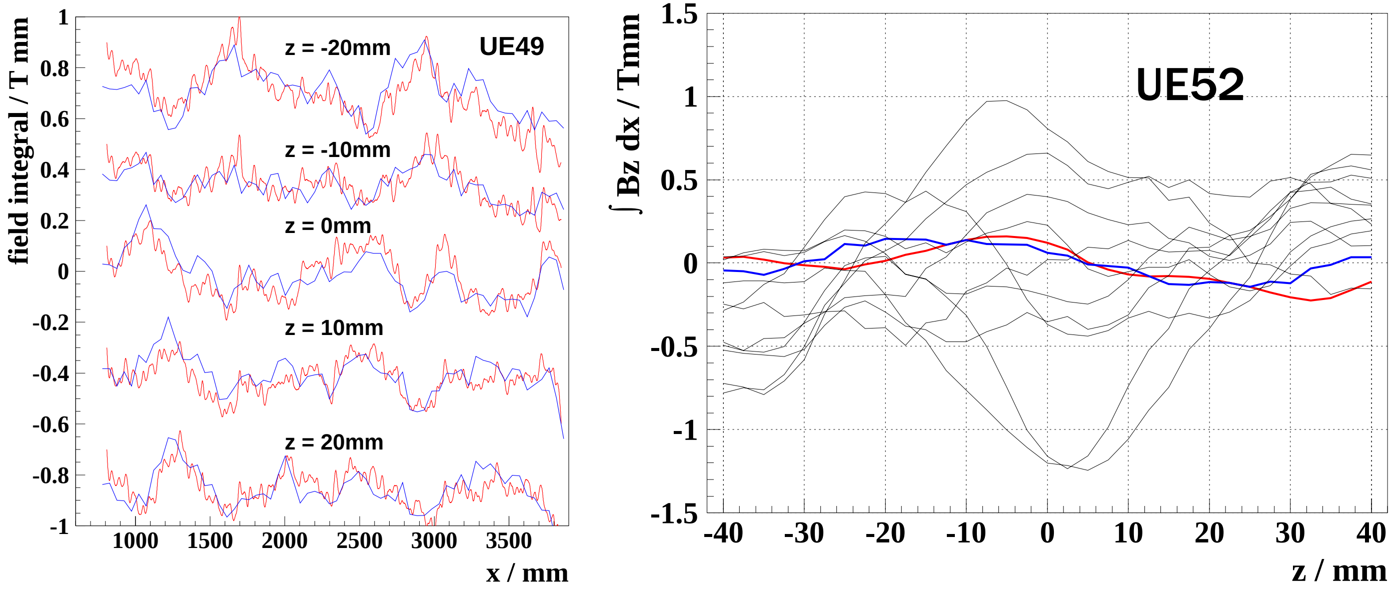
B) virtual shimming, Fe-shimming, end correctors

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

efficient sorting procedure

longitudinal distribution

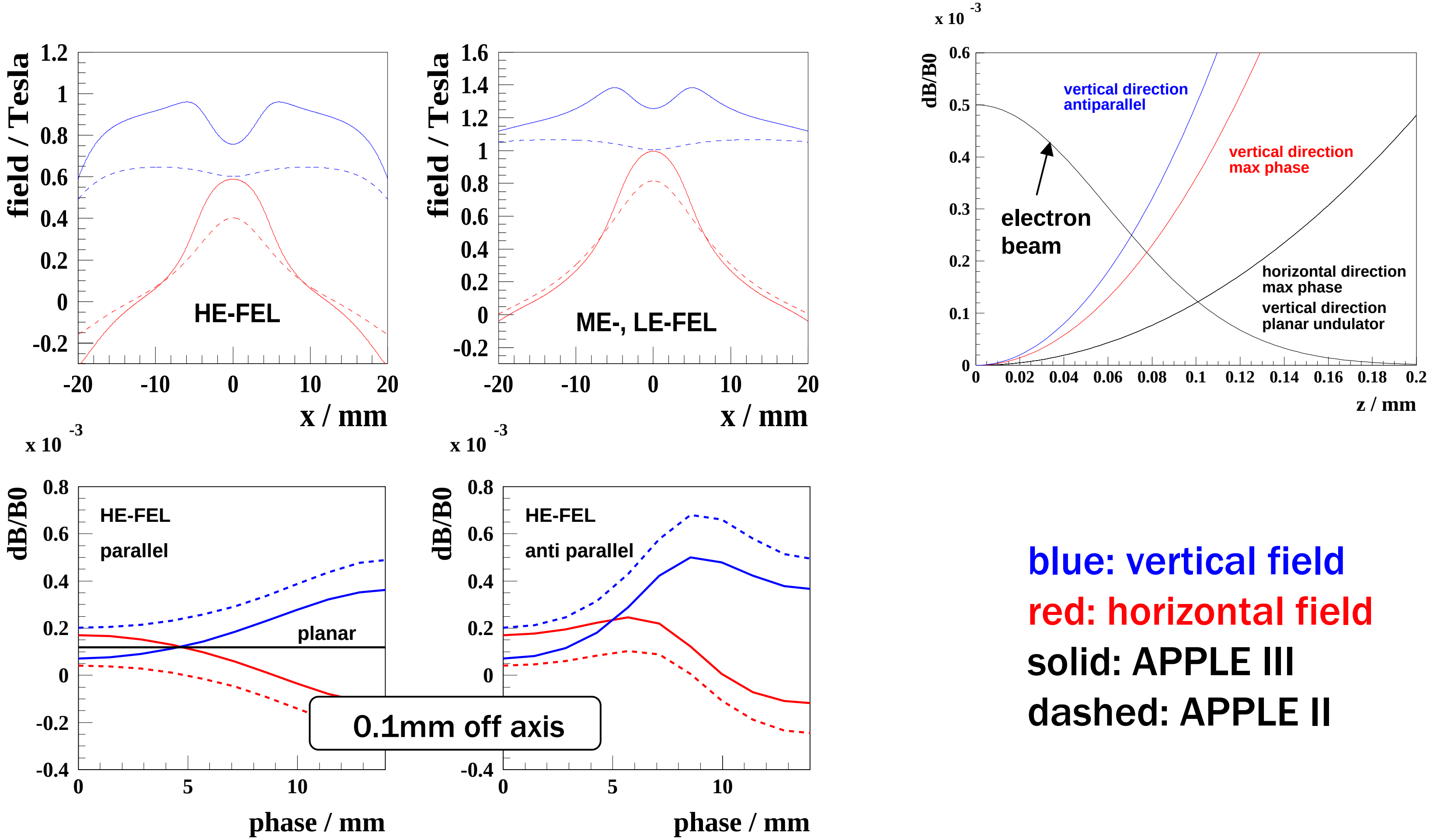
transverse distribution



blue: prediction from single block measurements

red: hall probe measurements

Good Field Region of APPLE IDs

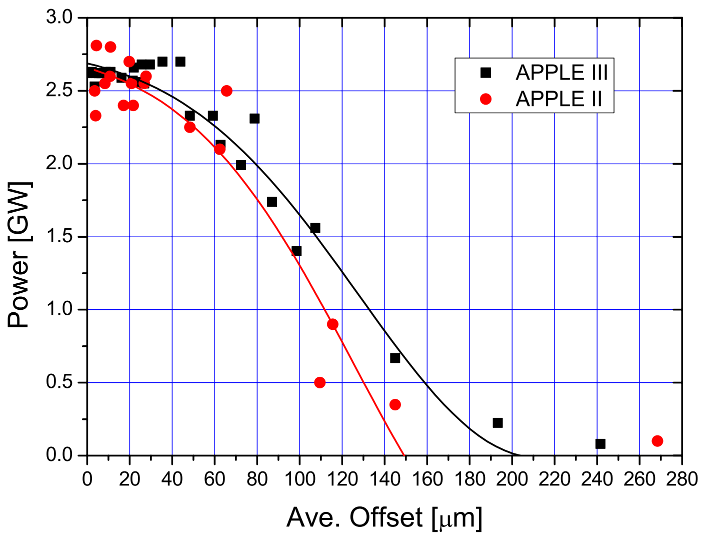


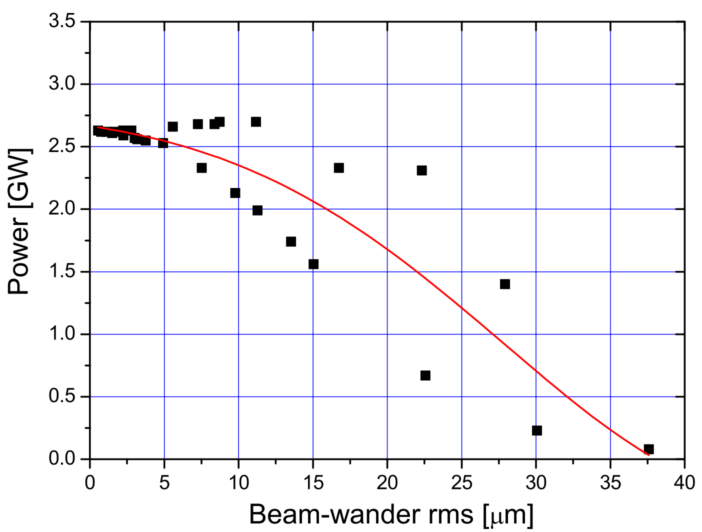
blue: vertical field
red: horizontal field
solid: APPLE III
dashed: APPLE II

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

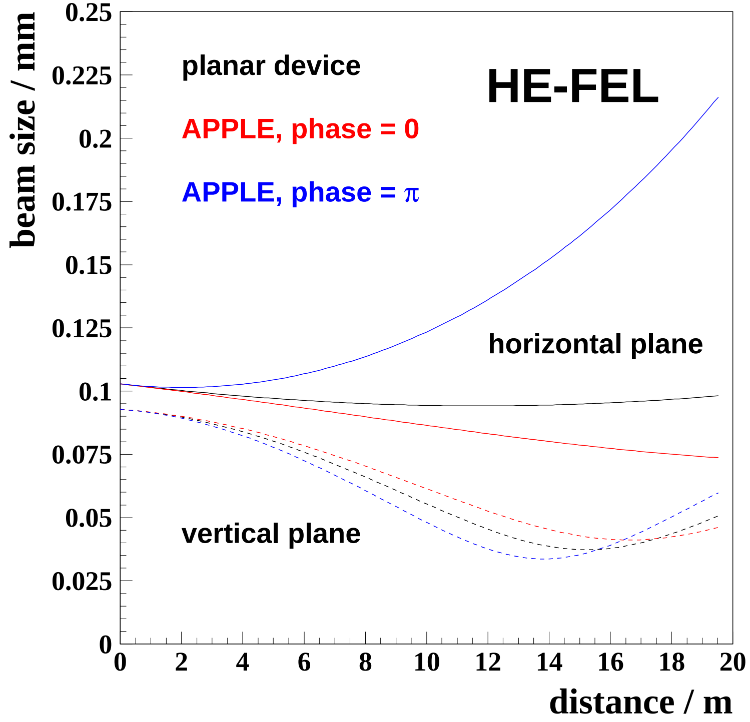
simulation of trajectory wander and power degradation using GENESIS

40μm displacement is acceptable.

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

Natural focussing / defocussing

Dynamic quadrupole modifies the electron beam size dependent on gap and phase position!



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

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

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

9 ME-FEL

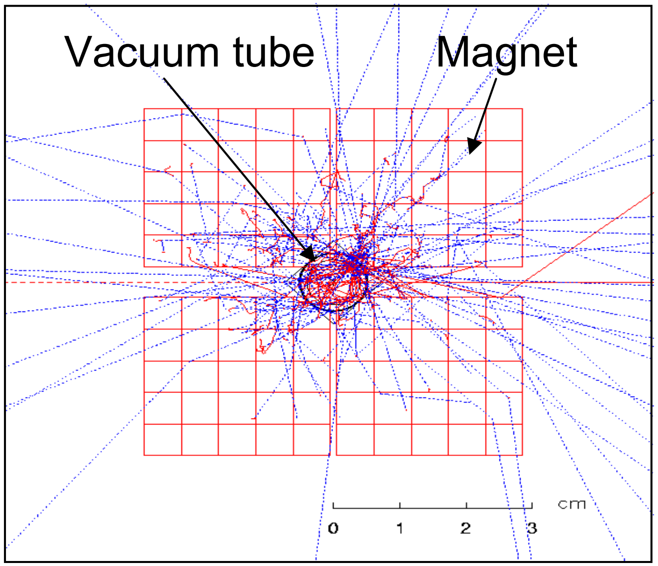
45 LE-FEL

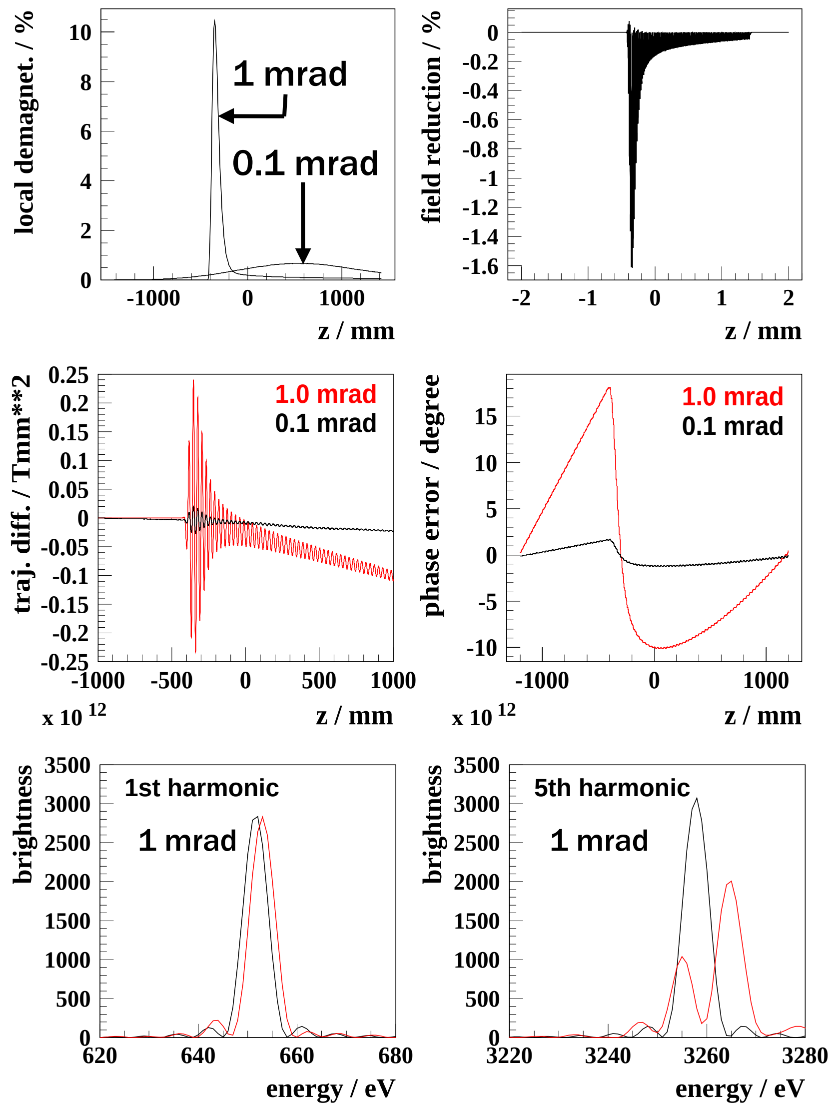
adaptive focussing is essential for optimum
overlap of electron beam and photon beam
Compensation with Fe shims has to be tested for APPLE III

Beam Loss Simulations with GEANT

Model for simulations

- 70kGray (red. Dose) for 1% loss of B_r
- dump 300.000nC into the vacuum pipe at one location
- get doses inside magnet segments
- derive local demagnetization
- get spectra from modified magnets

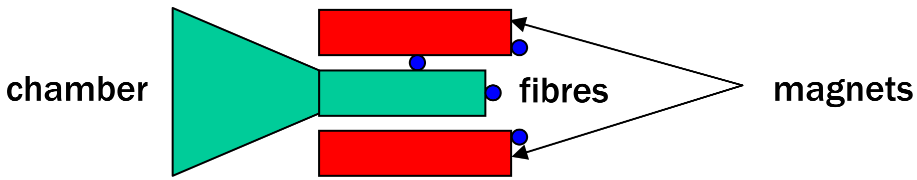


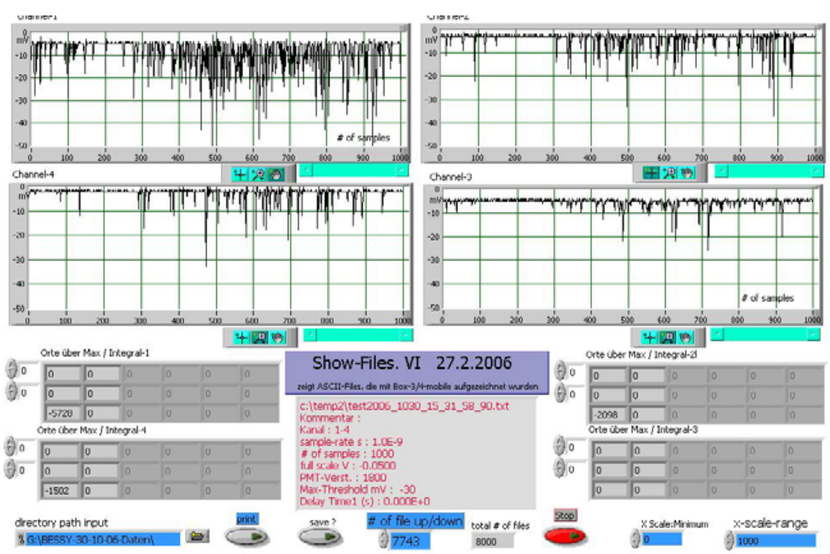


Radiation Monitoring

Cherenkov monitors

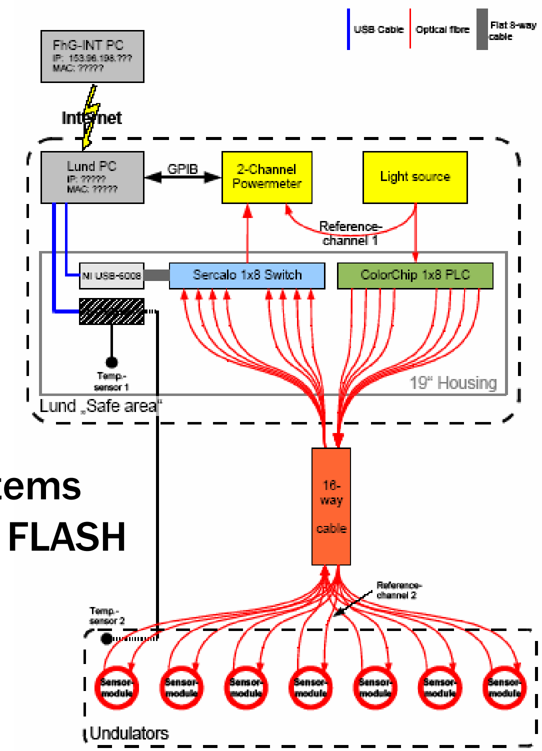
To be used for fast trigger
Collaboration with HMI, Berlin
First experiments at BESSY
Time resolution ⟷ sensitivity





Powermeter monitors

To be used for
absolute dose measurements
Collaboration with Fraunhofer Institut
Euskirchen



Similar systems
are used at FLASH

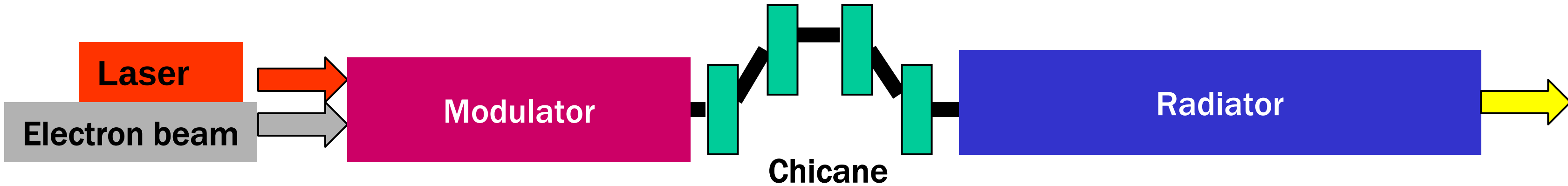
Johannes Bahrdt, BESSY, New Frontiers in Insertion Devices, ELETTRA, Trieste, Italy November 20th-21st, 2006

HGHG-FEL at MAX-lab (EUROFEL)

Laser
λs = 266.66 nm
FLAT TOP shape
peak power: 300 MW
pulse duration: 300 fs fwhm

Modulator
λu = 0.048m
30 periods
λs

Radiator
λu = 0.056m
30 periods
$\lambda s/3$ - $\lambda s/5$



Electron beam
$\varepsilon_{nx}=\varepsilon_{ny}$= 3 mm.mrad
I_{peak}= 500 A
100μm (rms) bunch length
E_{beam} = 420 MeV
rel. e-spread = 0.1%
$\sigma_x = \sigma_y$ = 300 μm

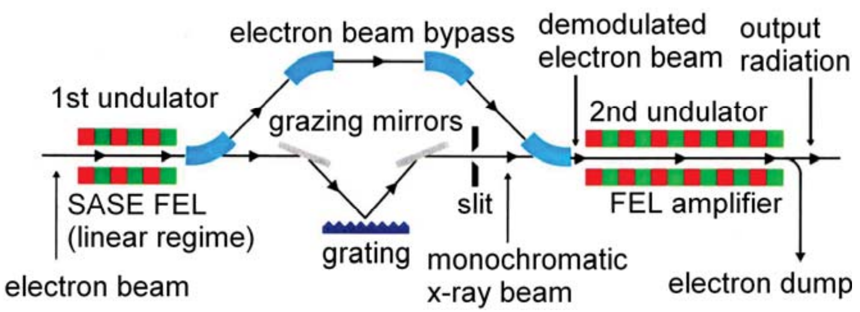
Chicane
4x dipol magnets:
length: 0.12 m
field: ~0.15 T
separation:
distance: 0.4 m

Undulators as delivered by BESSY

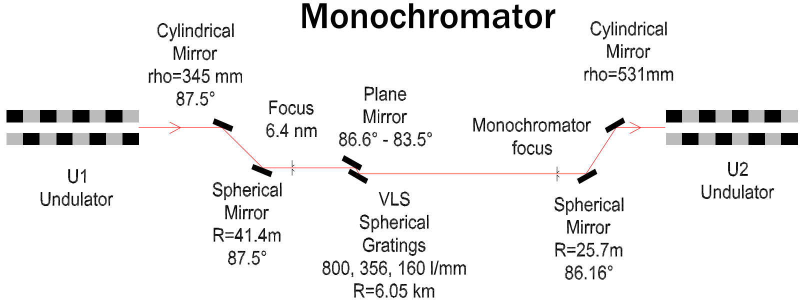
	Modulator	Radiator
Beam height:	500mm	
Period length:	48mm	56mm
Number of periods:	30	30
Remanence:	1.15 T	1.15
Magnetic gap:	9,5mm	12

Wavefront Propagation with PHASE

Self seeding option at FLASH

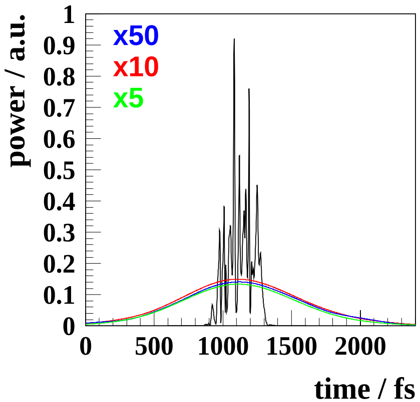


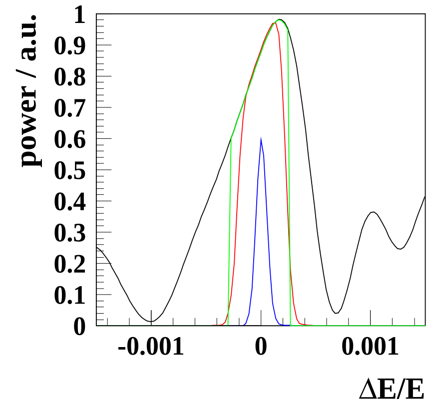
Monochromator

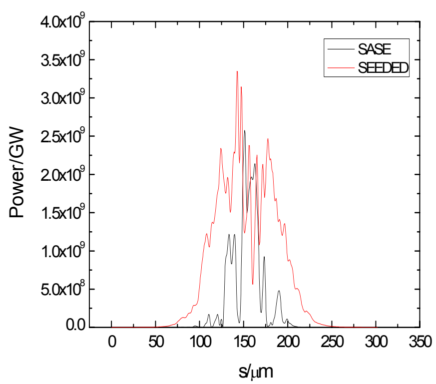


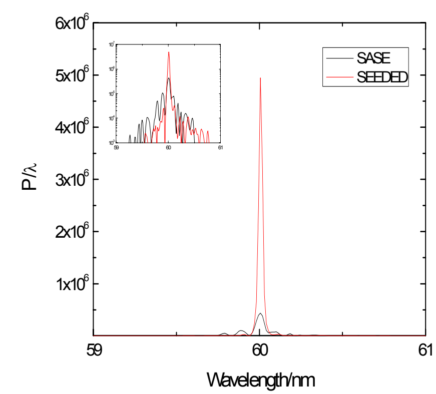
GENESIS ➡ PHASE ➡ GENESIS

Wavelength selection with monochromator









red: seeded

black: unseeded

Summary

- APPLE devices in low and medium energy rings
  have to be shimmed for the dynamic multipoles
  to be compatible with top-up operation
- A detailed analytic representation of the main field and the shim field
  permits an accurate and fast symplectic tracking
- Tracking studies and experiments show that the dynamic multipoles
  of long period APPLE devices still can be compensated:
  Fe-shims in elliptical mode
  Active compensation in inclined mode
- Upgrade plans: topping up
  energy enhencement to 1.9 GeV
  small period devices, elliptical and planar
- Design studies and hardware development for HGHG FEL:
  Test of components at BESSY SR and MAX-lab (EUROFEL)
  BESSY Soft X-Ray FEL demonstrator