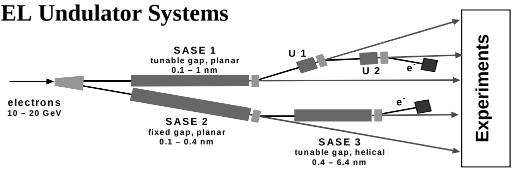
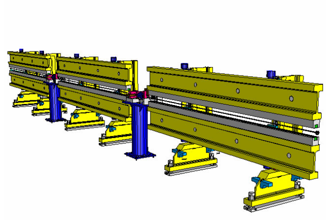
Parameters and Realization of FEL Undulators

R&D challenges towards the X-FEL Undulator systems

FEL Undulator Systems



Schematic of X-FEL Laboratory



String of 3 out of 41 Segments

Parameter Overview

Device	Type	E [GeV]	Wavelength Range [nm]	Photon Energy [KeV]	λ_0 [mm]	K_{Min} / K_{Max}	B_{Min} / B_{Max} [T]	g_{Max} / g_{Min} [mm]	β [m]	Lsat + [m]	L_{Tot} ++ [m]	# of Segments**
SASE1	planar	10 20	0.4 - 1.24 0.1 - 0.31	3.1 - 1.0 12.4 - 4.0	48	3.3 - 6.2	0.82 - 1.33	17 - 10	35	90 - 55 175 - 90	250.1	41
SASE2	planar	10 20	0.4 0.1	3.1 12.4	38	3.8	1.06	10	35	75 145	213.5	35
SASE3	helical	10 20	1.6 - 6.4 0.4 - 1.6	0.8 - 0.2 3.1 - 0.8	86	3.6 - 7.5	0.45 - 0.93	24 - 10	15	65 - 40 95 - 55	140.3	23
U1-U2	planar	10 20	0.01 - 0.1 0.0025 - 0.025	100 - 12.4 49.2 - 400	23	0.5 - 2.18	0.23 - 1.015	15.1 - 6	35	50.0+++ 100 total	61.0 102 total	10 20 total
								Sum		510	705.9	119

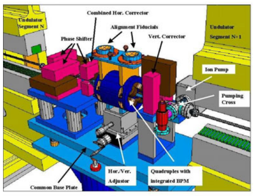
\+ The saturation length is taken as the net magnetic length of the undulator.

++ The total length of an undulator system includes the saturation length plus 1.1m for intersections (Quadrupoles, phase shifters, correctors, diagnostics, pumps etc. plus 20% contingency for field errors, misalignment etc. For the spontaneous radiators no contingency for the device length is considered.

+++ For the spontaneous radiators U1 and U2, the "saturation length" represents the assumed magnetic length of 50m for each device. No contingency is considered.

* For SASE1 and 2 a normalized emittance ε_n of $1.4 \cdot 10^{-6}$m, an energy spread of 2.5MeV and a peak current of 5000A is assumed. For SASE3 the energy spread is increased due to the passage through SASE2. Here an increased energy spread of 14.0 MeV is used.

** Length assumptions: Undulator segment : 5.0m ; Intersection : 1.1m ; resulting cell length : 6.1m, contingency is included.



Intersection

System characteristics

- Segmentation: 5m Undulator, 1.1m Intersection, FODO lattice for electron beam, all undulators are gap tunable
- Standardization wherever possible:
  - * Standardized mechanical system $\lambda_{FODO} = 12.2\,m$
    - massive, heavy, stable, ARMCO steel
    - Gap tunable
    - High precision
    - 4-axis drive system
    - optimized for mass production
  - * Standardized Intersection: Phase shifter, Quadrupole, BPMs, Correctors
  - * Standardized control sytem
- One Photon Diagnostic station per system

Gap Tunability

\+ Allows for independent tuning of photon energy

\+ Variable step taper from segment to segment possible

\+ Fine adjustment needed anyhow. $\Delta g <\approx \pm 1\text{-}2\mu m$ compatible with ≤ ρ (≈ $2 \cdot 10^{-4}$)

\+ New ways for photon diagnostics

\+ Segments can be switched off, variation of effective length

\+ Minimization of radiation damage by opening the gap

- Increases System length, short wavelength limit is at large gap
- Wavelength (Gap) dependent control of optical phase required
- Control of gap dependent field errors
- Needs challenging control system

R&D Needs

Challenges

- Long distributed undulator systems (see table above)
- Magnet technology:
  - Material improvement
  - Optimized passive magnet structures
- Low hysteresis material for phase shifter magnets
- High precision mechanical drive system
  - 1µm reproducibility
  - No distortion under load changes
  - Thermal stability
- Large scale production issues
  - Build 120 Segments of total length ≈ 500m in 3-5 years
  - Project logistics, QA / QC
- System control
  - Advanced multi-axes Motion Control
  - Synchronization with Phase shifters, correctors etc.
  - Integration with optical diagnostic system

Basic R&D

- Magnet material improvement by ≈ factor 10 = simplified and more economic production, improves quality
- Magnet technology:
  - Undulator end design (passive, phase neutal)
  - Low hysteresis soft magnetic material (Phase shifter, correctors, quadrupole)
- Undulator control system
  - High precision / dynamic motion control
  - Synchronize control multi axis system
  - Undulator system ⟺ Photon diagnostic
- Photon diagnostic : Photon Beam based Alignment, test of prototype system
- Vacuum system: Ultra smooth , high conductivity vacuum chambers for the undulator segments

Production oriented R&D

- Design of "Standard drive system"
  - streamlined for large number production
  - Documentation
  - Heavy prototyping
- Magnetics
  - Development of measurement techniques for use in industrial environment
- Control system
  Modular, high reliability, long term availability
- Project management and control
  - Logistics : Manufacturing, External competence, Liability
  - QA/QC
- Planing of production site

Resulting R&D Activities

1 Improvement of magnet material quality (Vacuumschmelze Hanau, BESSY, DESY)

Typical PM Material quality

State of the art:

RMS magnetization errors	**± 1.5 %**
Angular misorientation	**± 1.5 °**
North South effect	**± 5 %**
Geometric tolerances	**± 50 µm**

Target properties

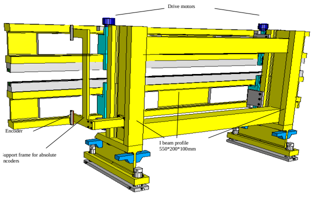
RMS magnetization errors	**± 0.1-0.2 %**
Angular misorientation	**± 0.1-0.2 °**
North South Effects	**± 0.5 %**
Geometric tolerances	**± 10-20 µm**

⇨ Simplified production

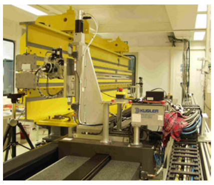
- **No sorting needed**
- **Simplifies logistics**
- **Reduced costs**

2 High precision support

M. Rüter, J. Pflüger "Conceptual Design of the Gap Separation Drives for the Undulators for the TESLA X-FEL ", **TESLA-FEL 2000-07**



3 Magnetic Measurement techniques (SLAC/LCLS, APS, IFPAN, DESY)



New measurement techniques
- 2-D, 3-D sensors, (planar Hall probes, Coil-Hallprobe sensors)
- 2-D, 3-D sensor calibration
- simultaneous 2-D, 3-D measurements

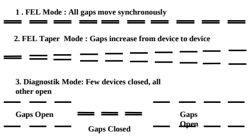
Development of fast alignment techniques
- Survey, fiducials etc.
- Automated fine alignment (adjustable platform)

Measurement and tuning techniques for use in industrial environment
- Procedures for mass production (shimming, pole height tuning etc.)
- Development of suitable benches, test stands
- Adoption of control and data processing software

4 Control system study (Siemens, DESY)

H. H. Radszuweit, J. Krunkowski, J. Pflüger, M. Tischer " Ein SIMATIC basiertes Kontrollsystem für die Undulatoren des TESLA Röntgenlasers" **TESLA-FEL 2000-09** in german

Undulator modes of operation



1 . FEL Mode : All gaps move synchronously

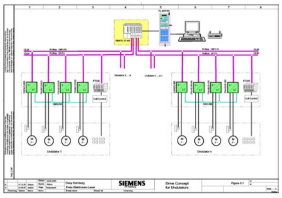
2. FEL Taper Mode : Gaps increase from device to device

3. Diagnostik Mode: Few devices closed, all other open

4. Vertical Gap alignment Mode : The center plane of each undulator segment is aligned

5. Local Mode : The gap of each undulator segment is adjusted locally with pushbotton control

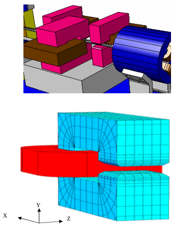
6. More modes: Control of power supplies without gaps, gaps without power supplies, operate only a part of the undulator . . . .

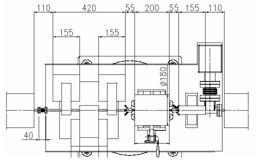


- Synchronized gap movement
- Synchronization with phase shifter, correctors etc.
- Interaction with Photon Diagnostics essential
- Extendable in a modular way
- High reliability
- Long term availability of components

5 Phase shifter study

J. Pflüger, M. Tischer "A prototype phase shifter for the undulator systems at the TESLA X-ray FEL", **TESLA-FEL2000-08**

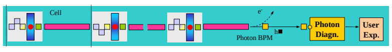




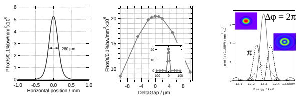
- Low Hysteresis soft magnet material
- Synchronisation with gap movement

6 Photon Beam based Alignment (APS, DESY)

M. Tischer, P. Illinski, U. Hahn, J. Pflüger, H. Schulte-Schrepping, Nucl. Instr. & Meth A483 (2002) 418, **TESLA-FEL 2000-13**



Alignment of Trajectory, Gap, Phase



• precision ~0.2µrad • 5^{th} harm. ~ 62 keV • detuning above peak ⇒ narrowing of cone • cms independent of detuning 0.2µrad resolution ⇔ ~7% cms accuracy	• precision ~3µm • fixed MC energy • 5^{th} harm. ~ 62 keV (ref. gap = 23mm, open) 3µm deviation ⇔ ~8% intensity drop	• Measurement at const. energy E_{fund} •⇒ flux variation ~400 for φ advance π→2π

For more detail see poster by M. Tischer

7 Magnet design (Lebedev, DESY)

M. Tischer, J. Pflüger "Magnet Design of a Prototype Structure for the X-ray FEL's at TESLA" **TESLA-FEL 2000-12**

Magnet design

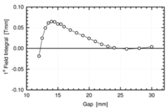
→ end field termination (gap-independent field integrals)

→ residual field integrals: $I2_2 \leq 80$ Tmm²

→ angular kick within single cell ≤ 0.2µrad

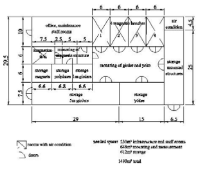
→ good field region $\Delta B_z(x)/B_z(x=0) < \rho \sim 4 \cdot 10^{-4}$ over ±1mm

→ shimming strategies



8 Design of Production site (Vacuumschmelze Hanau, DESY)

R. Cremer, F. J. Börgermann, J. Pflüger, M. Tischer," Manufacturing Considerations of the magnetic Structures for the Undulators for the X-FEL at TESLA", **TESLA-FEL 2000-10**



Further Reading

1. Technical Design Report, Part V, March 2001, Editors: G. Materlik, T. Tschentscher, Chapter 4 **DESY 2001-011, ECFA 2001-209, TESLA Report 2001-23, TESLA-FEL 2001-05**

2 .Technical Design Report, Supplement, October 2002 **DESY 2002-167, TESLA-FEL 2002-09**

See also: **http://tesla.desy.de**

3. B. Faatz "Influence of different focusing solutions for the TESLA X-ray FEL's on debunching of the electron beam" **TESLA-FEL 2000-15**

4. B. Faatz, J. Pflüger "Field accuracy requirements for the undulator systems of the X-ray FEL's at TESLA" **TESLA-FEL 2000-14**

5. P. Elleaume, J. Chavanne, Bart Faatz "Design considerations for a 1 Angstroem SASE undulator", **TESLA-FEL 2000-16**

6. J. Bahrdt, A. Gaupp, U. Englisch, W. Frentrup, M. Scheer, "Conceptual Design of a helical undulator for a TESLA SASE FEL", **TESLA-FEL 2000-11**

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