Undulator systems for the TESLA X-FEL

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Abstract

A large X-ray FEL lab is under consideration within the TESLA project and is supposed to be operated in parallel with the TESLA linear collider. There will be five SASE FELs and five conventional spontaneous undulators.

A conceptual design study has been made for the undulator systems for these X-FEL's. It includes segmentation into 6.1m long undulator 'cells'. Each consists of a 5m long undulator 'segment', a separate quadrupole, one horizontal and one vertical corrector, and a phase shifter. These items are presented and discussed.

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Introduction

Together with the TESLA linear collider a large X-FEL lab is planned which makes use of a part of the TESLA main linac. The whole project is described in detail in ref. /1/. The basic layout of the FEL lab is shown in Fig.1. This contribution only deals with the undulators, which for SASE FELs in the X-ray regime need total lengths exceeding 300m. Long undulators like these cannot be built in one piece: They have to be subdivided into 'undulator segments' of suitable length. Additional components for electron beam focusing, steering and detection and phase correction are needed as well. They are placed in between the segments. Together they form an 'undulator cell'. An 'undulator system' for the TESLA X-FEL is an array of up to 53 of such cells.

Together with Fig.1, Table 1 gives an overview over their parameters. Permanent magnet (PM) technology will be used exclusively. Five SASE FELs are planned in total. Four of them, SASE1 through SASE4 are primary FELs using the fresh TESLA electron beam. They produce linearly polarized light and operate primarily around the 0.1nm wavelength regime. There will be a secondary FEL, SASE5, which will be a helical one. It will reuse the beam with an somewhat increased energy spread after the passage through SASE3 and will operate in the soft X-ray regime at wavelengths up to 2.5nm. In addition, there will be five spontaneous radiators, U1 through U5, which will use the spent electron beam of the remaining three SASE FELs. As can be seen in table 1, there will be only four different types of devices, which reduces the magnetic design effort.

The most expensive part of an undulator is the magnetic structure. Fortunately there has been a tremendous development of PM based insertion device technology over the past 20 years when these devices came into use as intense sources of SR. An enormous progress has been made in their design, construction and optimization. There are now well established state of the art techniques to produce high quality insertion devices. With only a few exceptions, nowadays PM technology is used throughout. The undulator systems for the X-ray FEL will benefit from these developments a lot. Thus, the technology is available. The real innovative challenge is, however, the construction of the immense number of undulator segments in sufficient quality, in reasonable time and at reasonable cost.

Hardware Setup

Overview

Three cells of an undulator system are shown in Fig. 2. In between two neighboring undulator segments additional components are arranged: A phase shifter to adjust the proper interference condition between radiation emitted by adjacent segments, a quadrupole for electron beam focusing, horizontal and vertical correctors, and a beam position monitor. In total an intersection is 1.1m long. The quadrupoles are parts of the FODO lattice, i.e. a sequence of focusing and defocusing quadrupoles, which limit the beam size over whole length of the undulator. The distance between two of them is 6.1m. This allows for 5m long undulator segments. The β-function in the undulator sections is large enough so that the modulation caused by the FODO lattice is moderate /2/.

Wavelength tunability, i.e. gap tuning is required for three of the SASE undulators and the spontaneous radiators as well. This has two consequences: First, in the case of SASE undulators the saturation length is increased because the shortest wavelength at which the FEL is to operate is at the upper gap of the tunability range and thus determines the system length. Second, the phase matching of the photon beam between different segments becomes gap dependent. If the undulator gap and therefore the radiation wavelength is changed the interference condition is changed too. With the help of a suitably designed and excited small magnetic chicane called phase shifter the electron beam can be delayed in such a way that proper phasing is preserved.

Mechanical design

A standard gap separation drive and support system has been developed in a conceptual design study /3/. It considers the principles of economic manufacturing of large quantities, while tough requirements on mechanical accuracy have to be maintained. The 3D view in Fig. 3 shows how these ideas could be realized. In order to have a relative stability of the 1st harmonic better than the Pierce parameter ρ, girder deformation under changing load conditions (gap change) has to be limited to at most ±4μm. Consequently a voluminous I-beam profiles with dimensions 550 * 200 * 100 mm^3 are used. Using a four point support further limits girder deflection. The same profile is also used for the support columns and the floor stands. This is much simpler to build than a welded structure and has the same or even improved mechanical stability. In total 4700m with a weight of about 1900 tons are needed for the 281 support systems for the TESLA FELs. Only little machining is required on the columns. Standard guiding elements may be used. There are four individual gap drive motors which are electronically synchronized by a control unit. Motors and their motion control units are part of the control system /4/. In order to get absolute gap information with micrometer accuracy a separate frame is used to support absolute length encoders. In this way the exact girder position close to the corresponding drive motor can be measured without errors induced by deformation of the girder support or by the support structure. The gap adjustment accuracy is better than ±1-2μm. More details are found in ref. /4/.

Linear Magnetic structures

The FELs in the X-ray range will be equipped with planar devices based on NdFeB PM hybrid technology. Circularly polarized light can be produced using quarter wave plate X-ray optics, which now become quite common in the hard X-ray regime /5/. Thus, helical undulators are not required in this photon energy range. There will be three different planar types, with period lengths of 30, 45 and 60mm. A magnetic prototype has been designed for the SASE1 undulator /6/. At a gap of 12mm and a period length of 60mm the peak field is 1.33 T. At 25GeV and a gap of 22mm, this device would radiate at 0.1nm and at 12mm gap at 0.35nm. The width of poles and magnets was determined such that a transversal good-field-region of ±1 mm results in which the relative field variation is less than ρ, i.e. $4.2 \cdot 10^{-4}$ in the open gap position. In this way requirements on horizontal alignment of the undulator segments are reduced without affecting the FEL process. The maximum peak field is obtained for a pole dimension of 40×8×55 mm^3 (width × length × height) and 70×22×65 mm^3 for the magnet dimension. The field of an undulator segment has even symmetry so that the 2^{nd} field integral can be brought to zero with a simple half pole. The gap dependence of the 1^{st} field integral has bee reduced to below 0.05 Tmm by optimizing the length and vertical position of the last magnet, the height of the last pole as well as the width of the 2^{nd} last pole. The remaining dependence can be reduced further using appropriate shims or with the help of active correctors, which are available in the intersections anyhow.

Planar helical magnetic structure

For SASE 5 a helical structure is planned. In the soft X-ray range, above 0.4nm, no optical alternative to the generation of circularly polarized light exists. An APPLE II type undulator is proposed /7/, which is a planar structure thus allowing good lateral access for measurements and the insertion of vacuum chambers. Among all planar proposals for producing helical fields it offers the highest field and the largest variation of polarization properties. A prototype design for the SASE5 undulator system at TESLA including polarization characteristics was worked out based on extensive experience at BESSY /8,9/. Although the saturation length of a helical undulator in general is shorter than that of a planar device, helical undulators require considerably more mechanical effort than a planar ones.

Undulator Intersections

Fig 4 shows a 3D view of an undulator intersection embedded between two neighboring undulator segments. The phase shifter is seen to the left. A preliminary design is presented in ref /10/. It consists of three horizontal magnets. The length of the center one is doubled because it needs twice the strength. Horizontal correction may be integrated in one of these magnets. The vertical corrector, which is identical to the short phase shifter magnets but rotated by 90° is seen to the right. In between there is a quadrupole with a 15mm bore with a maximum gradient of 100T/m. Its magnetic length is 0.2m only, its total length is about 0.26m. With these quadrupoles a minimum β function of less than 15m at 25GeV can be obtained.

Although SASE2 and SASE3 are operated at a fixed gap, they should be gap adjustable too. There are good reasons to do so:

1. The radiation wavelengths of different segments have to be tuned with an accuracy better than ρ, which is in the order of $3.6\cdot10^{-4}$ (see table 1). As a consequence in different segments gap control with an accuracy of $\Delta g <\approx \pm 2\mu m$ or better is needed. This accuracy cannot be perpetuated in a truly fixed gap device. Although the field might be precisely adjusted in the lab it is hard to preserve on this level of accuracy. So, some fine adjustment has to be provided anyhow.
2. In order to compensate for the average energy loss of the electron beam along the undulator system, a taper has to be applied. It increases efficiency and maximizes the output intensity. Such a taper will be effectively a step taper, the gap will be changed in very fine steps from one undulator segment to the next: It is very advisable to have this taper adjustable in order to easily optimize output intensity.
3. A segment can effectively be switched off by fully opening its gap. In this way the effective length of the undulator system can be varied. For diagnostic reasons this option might become very important. In ref /11-13/ a ‘photon beam based’ alignment procedure is described. The electron beam orbit, the proper radiation wavelength of each segment and the phasing can be accurately controled in this way. Thus this diagnostic tools will play an important role in optimizing emission properties.
4. Experience at the TESLA Test Facility (TTF) has shown that high radiation levels inside the undulator region may be created if the beam is missteered, but very moderate doses can be

obtained during routine operation with a well adjusted beam. So most of the radiation exposure originates during setup and/or commissioning of the machine. By opening the gap this hazard to the magnet structures can be minimized.

In the fixed gap devices two of the three phase shifter magnets can be omitted. Only one magnet is needed for horizontal correction.

Summary and Outlook

The undulator systems for the TESLA X-FELs have been outlined. PM based magnet technology using NdFeB material will be used. Full use can be made from the achievements on PM based magnet technology for insertion devices for the 3rd generation SR sources. A new dimension is however the large number of segments, which requires new and efficient ways of production. The potential layout of a production plant for TESLA has recently been worked out in a study /14/. It also includes the project management structure, which is needed, to organize and synchronize the manufacturing and assembly of sub tasks, such as girders, support mechanics, motion control components etc. These issues will become very important for the production of the undulator systems of the TESLA X-FELs.

Acknowledgement

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Figure Captions

1 Schematic layout of the X-FEL laboratory at TESLA.

2 Three 5m long undulator segments with intersections give an impression how a full system with up to 54 segments will look like

3 Standard undulator segment for the TESLA undulator systems

4 Components in the intersection between undulator segments

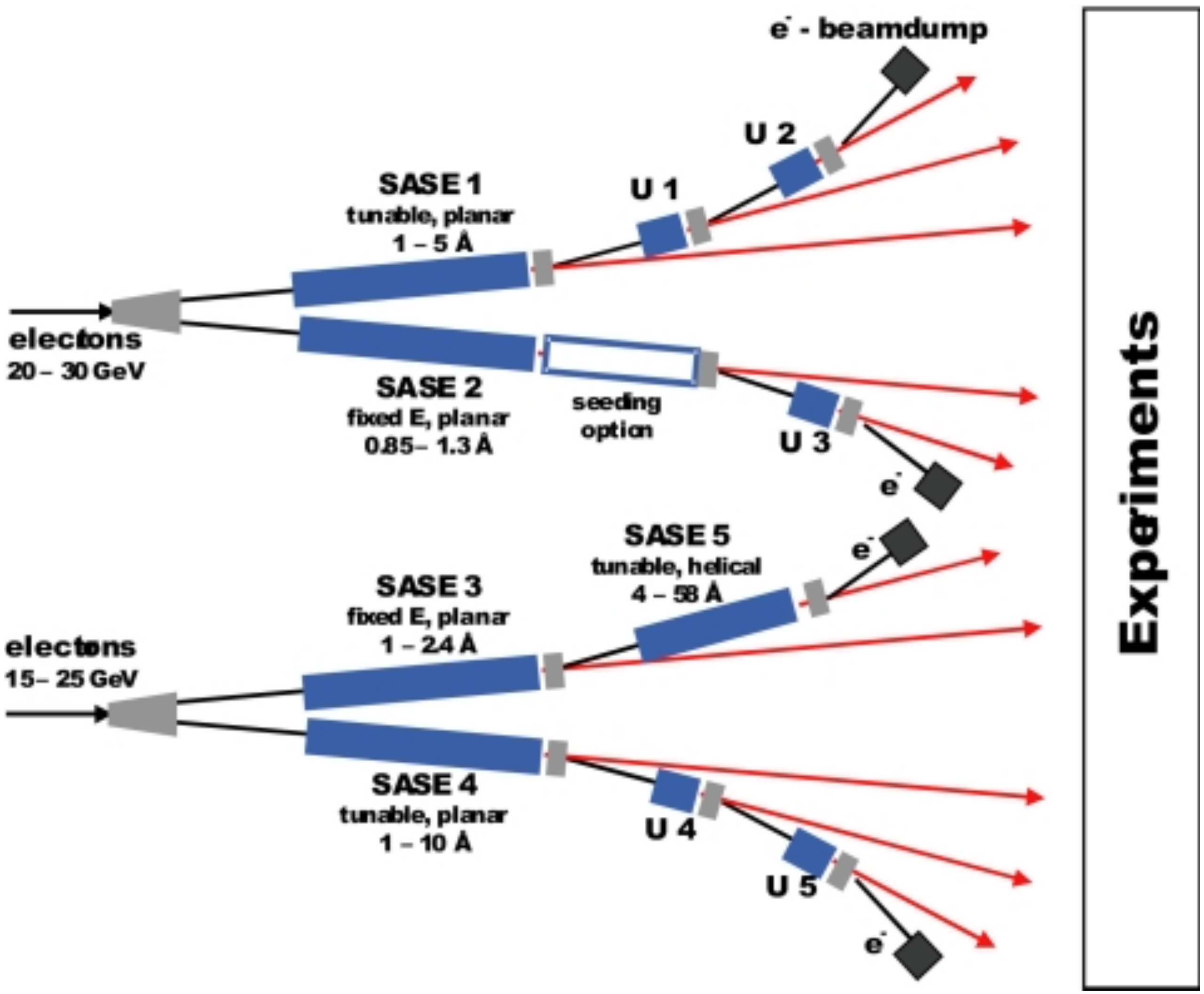
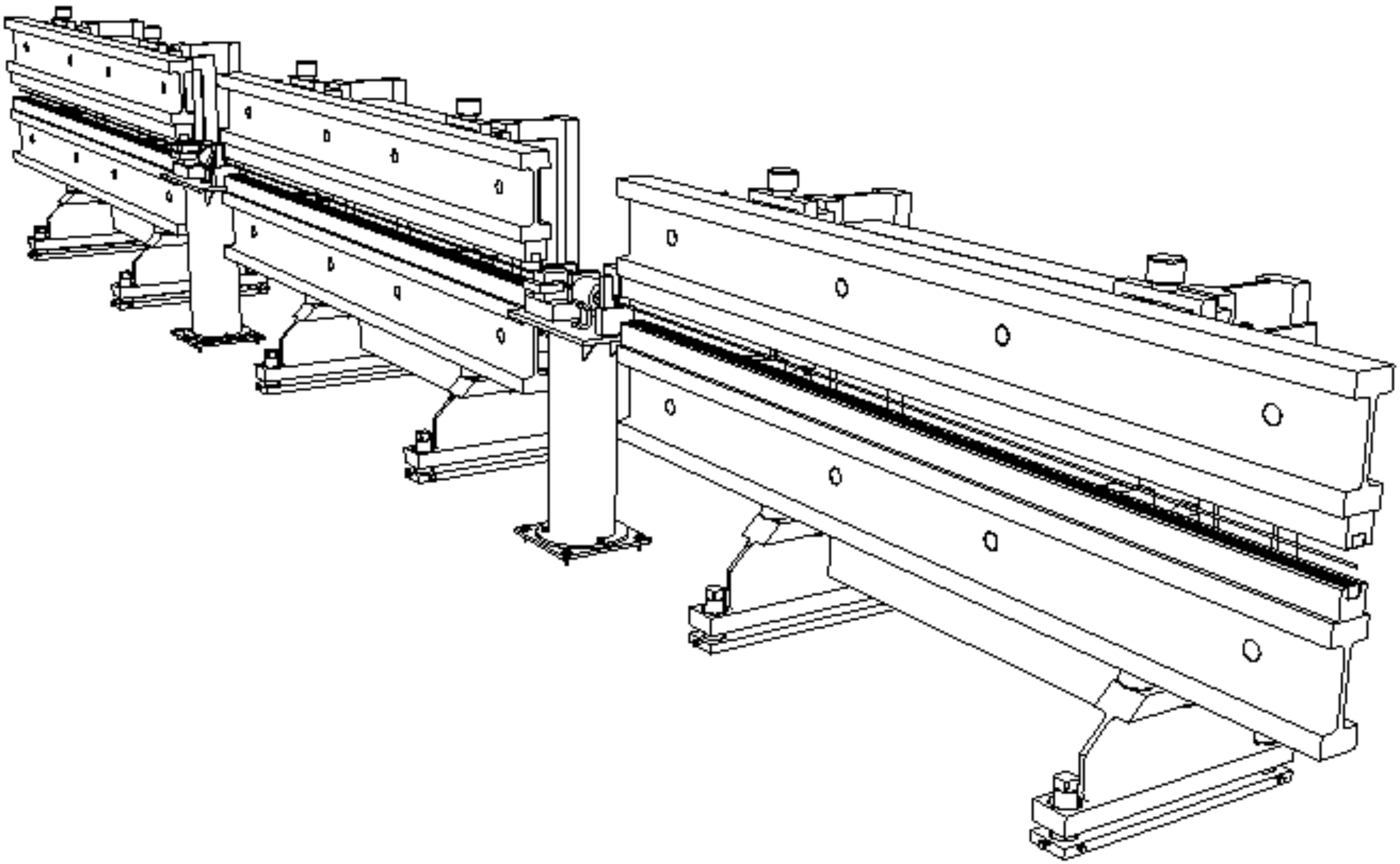

e- - beamdump
U 2
U 1
SASE 1
tunable, planar
1 – 5 Å
electons
20 – 30 GeV
SASE 2
fixed E, planar
0.85 – 1.3 Å
seeding
option
U 3
e-
SASE 5
tunable, helical
4 – 58 Å
e-
SASE 3
fixed E, planar
1 – 2.4 Å
electons
15 – 25 GeV
SASE 4
tunable, planar
1 – 10 Å
U 4
U 5
e-
Experiments

Fig 1

2



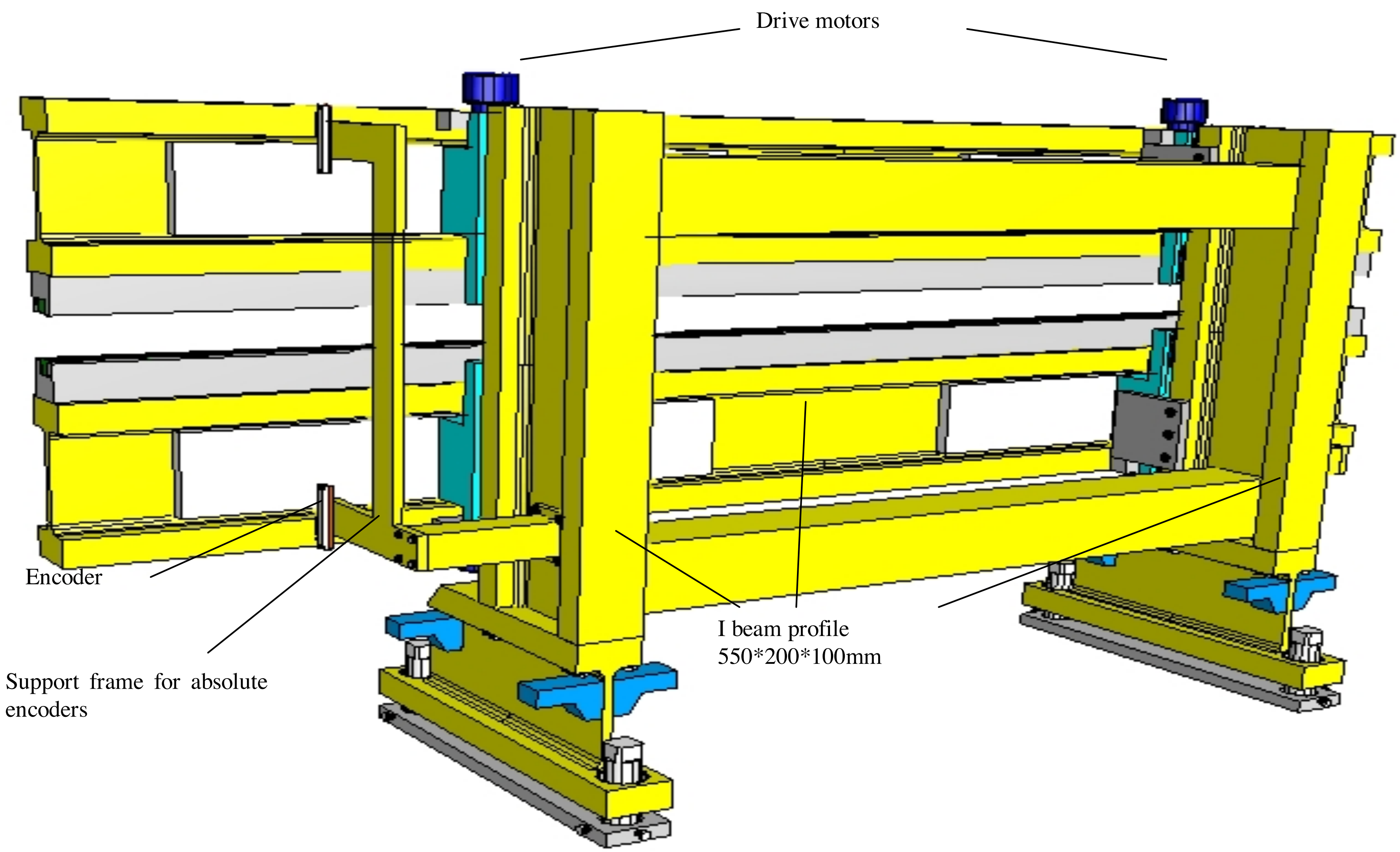

Drive motors
Encoder
Support frame for absolute encoders
I beam profile 550*200*100mm

Fig 3

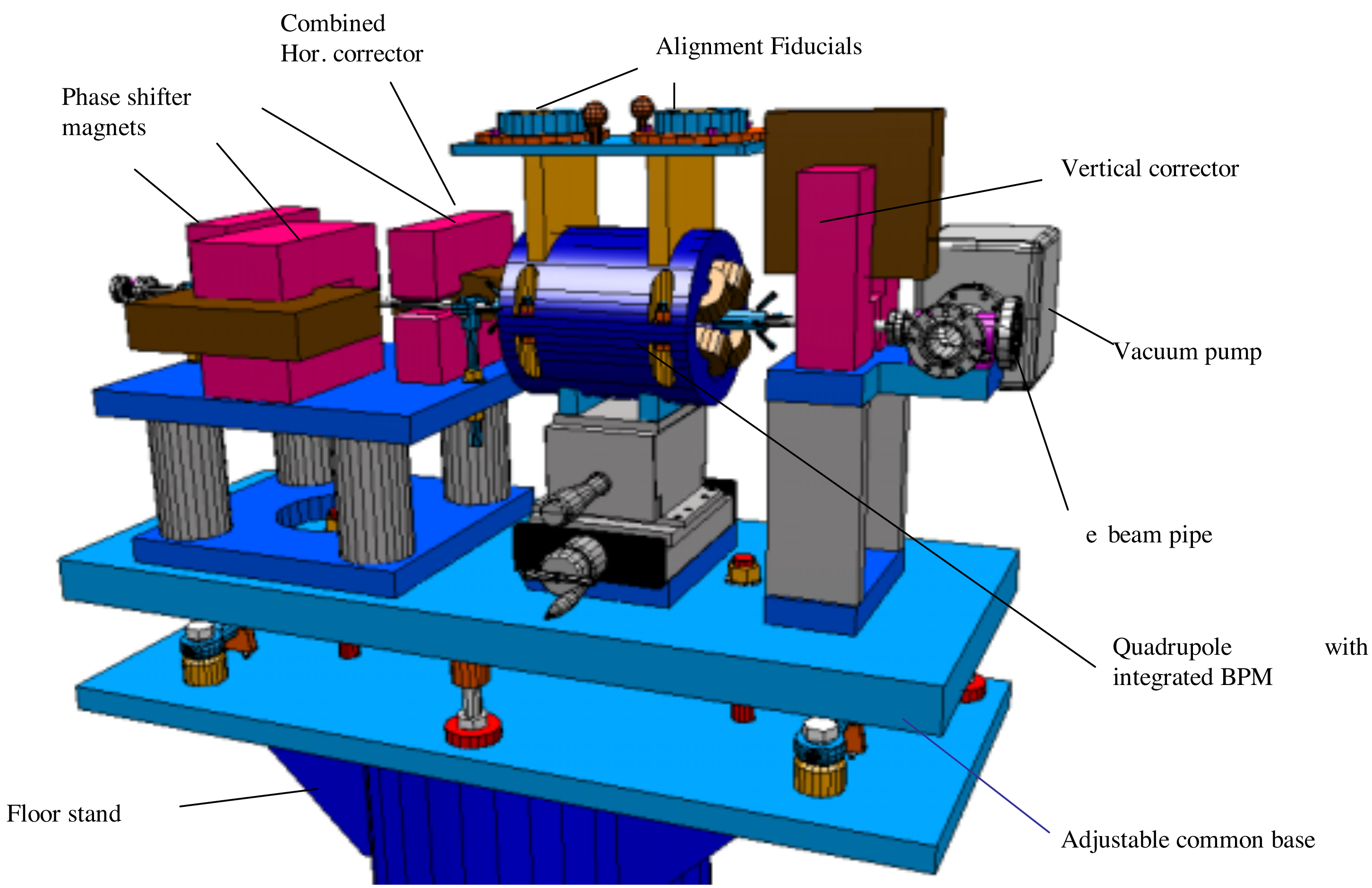

Combined
Hor. corrector
Alignment Fiducials
Phase shifter
magnets
Vertical corrector
Vacuum pump
e beam pipe
Quadrupole with
integrated BPM
Floor stand
Adjustable common base

Fig 4

Device	**Type**	**E [GeV]**	**Wavelength Range [nm]**	**λ_0 [mm]**	**ρ* [10^{4-}]**	**K_{Max}**	**B_{Max} [T]**	**Gap_{Min} [mm]**	**β [m]**	**L_{sat} + [m]**	**L_{Tot} ++ [m]**	**# of Segments****
SASE1	**planar**	**25**	**0.1-0.35**	**60**	**4.2**	**7.5**	**1.33**	**12**	**45**	**220**	**323.3**	**53**
SASE2	**planar**	**25**	**0.085**	**45**	**3.6**	**4.0**	**0.95**	**12**	**45**	**210**	**311.1**	**51**
SASE3	**planar**	**23**	**0.10**	**45**	**3.8**	**4.0**	**0.95**	**12**	**45**	**185**	**274.5**	**45**
SASE4	**planar**	**25**	**0.3-1.0**	**60**	**4.2**	**7.5**	**1.33**	**12**	**45**	**220**	**323.3**	**53**
SASE5	**helical**	**23**	**0.4-2.5**	**107**	**14.5**	**9.6**	**0.96**	**12**	**15**	**120**	**176.9**	**29**
U1-U5 +++	**planar**	**30**	**0.0083-0.025 0.0028-0.0083**	**30**	**----**	**3.1**	**1.10**	**6**	**45**	**50.0 250 total**	**61.0 305 total**	**10 50 total**
									Sum	*1405*	*1714.1*	*281*

+ The saturation length L_{sat} is taken as the required net magnetic length of the undulator

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

+++ For the spontaneous radiators U1-U5 the wavelength range given is for the1st and 3rd. harmonic. Here L_{Sat} represents the magnetic length of a device. The summation in the bottom line includes 5 devices.

* For SASE1-4 a normalized emittance ε_n of $1.6*10^{-6}$m, an energy spread of 2.5MeV and a peak current of 5000A is used. An energy spread of 6.0 MeV is assumed for SASE5, which takes into account the energy spread caused by SASE3. ρ is always calculated for the shortest wavelength, i.e. the largest possible gap.

** Length assumptions: Undulator segment : 5.0m ; Intersection : 1.1m ; resulting cell length : 6.1m ;

Table 1 : Parameters for the 10 undulator systems planned for the TESLA X-FEL Laboratory. λ_0 denotes the undulator period length, ρ the Pierce parameter, B_{Max}, K_{Max} the maximum peak field and undulator deflection parameter at the minimum gap position, Gap_{Min}, respectively, β the average β function in the undulator region. See also the footnotes.