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Conceptual design of the gap separation drives for the undulators for the TESLA X-FEL

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Abstract

A conceptual design study of the mechanical drive and support systems of the undulator segments for the X-ray FEL has been performed. 281 of these systems will be needed for the undulator systems. Each will support a 5m long magnetic structure. Their total length will be about 1714m.
An attempt has been made to combine the contradicting requirements of high mechanical stability, rigidity and reproducible gap motion with economical manufacturing of a large number of segments. One standard girder profile is used. Welding and machining minimized. Standard off the self items are used wherever it is possible.
In the appendix tolerances for girder deformation, gap adjustment accuracy , horizontal and vertical alignment tolerances as well as requirements on temperature stability are given. Results of finite element calculations on the mechanical deformation of girders and support systems are presented. A design concept is outlined in detail.

1. Introduction

An integral part of the TESLA Project (TESLA= **T**era **E**lectronvolt **S**uperconducting **L**inear **A**ccelerator) will be a Free Electron Laser (FEL) facility in the X-ray range (X-FEL) /1/, which is presently in a conceptual design stage. There will be five FEL's using the so called principle of self amplified spontaneous radiation (SASE). Four of them will be optimized for minimum wavelengths around 0.1 nm. The fifth will use the spent beam of one of the short wavelength devices and will be optimized for 2.5 nm
In addition five spontaneous radiators are planned. The magnetic length of these devices ranges from 50m for the spontaneous radiators, about 120m for the 2nm SASE FEL to ultimately 220m for the 0.1nm X-FEL's. The total magnetic length of all undulators is about 1405m. Table 1 gives an overview over the undulators presently (November 2000) under discussion for the X-FEL and the total required lengths.
The magnetic parameters of the devices differ according to their spectral requirements they are optimized for. One helical planar structure is planned for the 2.5nm SASE FEL. As seen in table 1 the variety of different devices is small. During the last 20 years the magnetic design as well as the construction of insertion devices (ID's) has been developed to a high degree of perfection for the use in 3rd generation synchrotron radiation (SR) sources but also for the first SASE FEL's. The technology how to built, measure and tune these device is well established and has become state of the art. The real challenge and the real innovative aspect for the TESLA X-ray FEL Laboratory is the organization of the manufacturing of the large quantities in a reasonable time at reasonable costs. Just for illustration: The magnetic length of each of the TESLA SASE X-FEL's (≈200m) exceeds that of all insertion devices in a typical 3rd generation X-ray SR source such as the APS in Argonne, the ESRF in Grenoble or Spring8 in Nishi Harima. The total undulator length needed for the TESLA X-FEL lab exceeds most likely that of all undulators presently in use world wide.
Cost and time effective "Mass production" of insertion devices will therefore be an important issue for the TESLA undulators.
Only four different undulator designs are needed. This limits the magnetic design effort tremendously, but also calls for a standardized mechanical design. Economic production also implies the simplification and streamlining of mechanic as well as magnetic components as well as the definition of standard components.
This report describes conceptual design considerations for a standard mechanical gap separation drive system for the undulators of the X-FEL's.

2. Standardization of gap separation drives (GSD's)

281 GSD's will be needed (see table1). Any cost economic approach calls for a small as possible number of different GSD's. One being the ultimate optimum. Nevertheless considerations for standardization also hold if more than one standard GSD will be needed.

Table 1: Overview over the devices planned for the TESLA X-FEL (October 2000)

Device	Type	E [GeV]	Wavelength Range [nm]	Photon Energy [KeV]	l_0 [mm]	r * [10^{4-}]	K_{Min} / K_{Max}	B_{Min}/ B_{Max} [T]	Gap_{Min}/Gap_{Max} [mm]	b [m]	Lsat + [m]	$L_{Tot\ ++}$ [m]	F_{Mag} ** [kN]	# of Seg-4ments***
SASE1	planar	**30 25 20**	**0.1-0.25 0.1-0.35 0.15-0.50**	**12.4 - 4.9 12.4 -3.5 8.25 -2.5**	**60**	**4.3/5.9 4.2 / 6.3 5.1 / 7.7**	**4.6 - 7.5 3.7 - 7.5 3.7 - 7.0**	**0.82 - 1.33 0.66 - 1.33 0.66 - 1,25**	**19 – 12 22- 12 22-13**	**45**	**175 / 100 220 / 120 220 / 150**	**323.3**	**26.7 / 70.2**	**53**
SASE2	planar	** 25 20**	** 0.085 0.13**	**- 14.6 9.3**	**45**	** 3.6 4.1**	** 4.0 4.0**	** 0.95 0.95**	**- 12 12**	**- 45**	**-- 210 155**	**311.1**	**35.8**	**51**
SASE3	planar	**23 15**	**0.10 0.24**	**12.4 5.2**	**45**	**3.8 4.1**	**4.0 4.0**	**0.95 0.95**	**12 12**	**45**	**185 115**	**274.5**	**35.8**	**45**
SASE4	planar	**25 15**	**0.1-0.35 0.3-1.0**	**12.4 – 3.5 4.1 - 1.24**	**60**	**4.2 / 6.3 7.1 / 10.3**	**3.7 - 7.5 3.9 - 7.5**	**0.66 - 1.33 0.70 – 1.33**	**22-12 21-12**	**45**	**220 / 120 125 / 80**	**323.3**	**26.7 / 70.2**	**53**
SASE5	helical	**23 15**	**0.4-2.5 1.0-5.8**	**3.1 - 0.5 1.25 - 0.21**	**107**	**14.5 / 26.8 19.2 / 35.7**	**3.8-9.6 3.9-9.6**	**0.38 - 0.96 0.39 – 0.96**	**35-12 35-12**	**15**	**120 / 60 95 / 50**	**176.9**	**11.5 / 73.2**	**29**
U1-U5	planar	**30 15**	**0.0083-0.025 0.0028-0.0083 0.033 - 0.10 0.0123 - 0.033**	**150-50 1. Harm 450-150 3.Harm 37 -12 1. Harm 111-37 3. Harm**	** 30**	**----**	** 0.--3.1**	** 0. -1.10**	** up-(13)-6**	** 45**	**50.0+++ 250 total**	**61.0 305 total**	**51.6 max**	**10 50 total**
										Sum	**1405**	**1714.1**		**281**

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

++ The total length of an undulator system includes the saturation length plus1.1m 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 “saturation length” represents the assumed magnetic length of each 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. For SASE5 due to the spent beam an energy spread of 6.0 MeV is used.

** A pole width of 40mm and a undulator segment length of 5.0m is assumed. Load values for max. / min gaps are given. The total magnetic length including 20% contingency is 1405 m, the total undulator length, intersection inclusive is 1714.1 m

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

Standard devices should be designed for worst case assumptions on mechanical loads, mechanical deformation and accuracy. The magnetic parameters shown in table 1 are not too different, the magnetic loads only differ bfactor of 2 (see table 1). Furthermore mechanical over designing always has benefits in terms of accuracy, deformation and mechanical stability and might in the end more economic than having two or three different designs instead of one.

There is a large economic advantage in producing large quantities. The design can be fully tested in prototypes and will be very well documented. Eventually several generations of improved versions can be built before mass production really starts. Finally this will result in an almost perfect design, which is well documented and almost free of errors. During mass production problems are very much reduced since they have already been solved many times. Also after installation maintenance, operation and spare part storage and supply is much more simplified, more efficient and economic.

Experience on the BW5 wiggler for DORIS III which is an enforced version of the BW2 X-ray wigglers has shown that a factor of 2 in mechanical load does not at all increase cost significantly /4-6/.

3 Design description

This chapter will cover the boundary conditions set by the FEL process, the accelerator and the buildings. Estimates for mechanical accuracy based on FEL properties will be given.

3.1 Segmentation

Long undulators for FEL's with a total length of 200m or more have to be segmented for two reasons. One is for pure practical reasons: It is very difficult to machine very long items such as the girders to support the magnetic structure with lengths exceeding 4-8m. Above manufacturing of these long items becomes very expensive. The deformation under magnetic loads increases with the fourth power of the support distance (see appendix B). Thus by increasing the undulator length one has to either tolerate more deformation or use more support points. The second argument has physical reasons. The β function inside an undulator is typically between 20 and 45m (see table 1) and is therefore much smaller than the saturation length which is in the order of 120-220m. In order to keep the variation of the β function acceptably small additional external strong focusing is required. For X-FEL's a separated function FODO lattice is a good choice/7,8/. Here undulator segments and quadrupoles alternate. For the X-FEL's a length of an undulator segment of was choosen to 5.0m followed by an intersection of 1.1m for the quadrupole, beam correctors and beam diagnostic equipment.

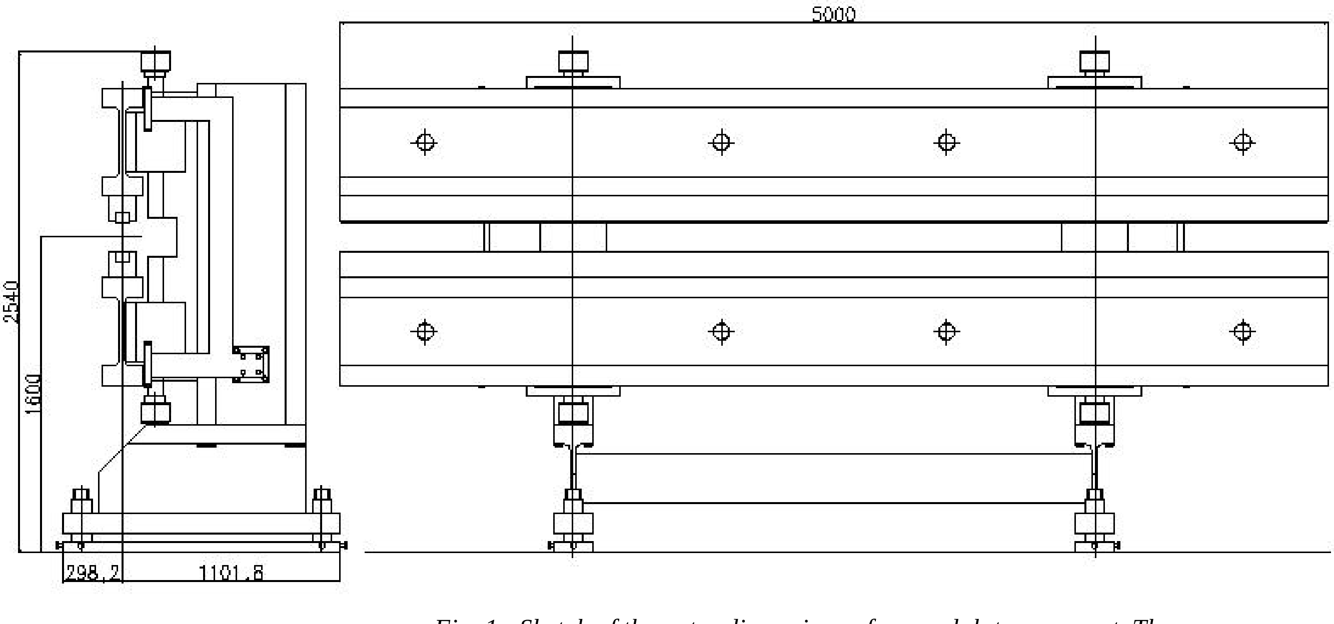

Fig. 1 : Sketch of the outer dimensions of an undulator segment. The view is against the e^- beam direction.

3.2 Outer dimensions

Table 2 contains important outer geometric dimensions of a GSD. They were determined by the boundary conditions set by the buildings. The segmentation length is based on considerations of the allowed β-function variation as shown above. The beam height is the same as for the insertion devices in HASYLAB. Fig. 1 shows a front and side view of the conceptual design of a standard GSD for the TESLA undulator segments... Some dimensions are given in table 2.

Table 2 : Mechanical boundary condition set by the accelerator environment

Girder (segment) length	mm	5000
Beam floor height	mm	1600
Total device height	mm	2540
Transversal width to right side of beam	mm	298.2
Transversal width to left side of beam	mm	1101.8
Total transverse width	mm	1400.0

3.3 Accuracy requirements

The mechanic support system has to be designed in such a way, that the FEL process is not deteriorated. Table 3 gives the key numbers which have a large impact on the mechanical design.

All SASE undulators will use a minimum gap of 12mm. This value is a reasonable compromise between wake fields in the vacuum chamber which require a large gap and a high field strength, which requires a gap as small as possible. The spontaneous radiators use a smaller gap as can be seen in table 1.

One of the key parameters for the mechanical design is the maximum load by magnetic forces, which is assumed to 73.2kN (see table1). The Girder deformation as well as the control of the gap on either end has to be better than ± 2 µm in order not to perturb the FEL effect.

The FEL effect may be effected by mechanical and temperature stability in the following way:

- Elastic girder deformation leads to different peak field variations as a function of the gap. As a result the undulator may be locally tuned out of resonance. The requirement is that the resonance frequency stays tuned within $\Delta E/E \leq \rho$ where ρ is the Pierce parameter (see table 1). ρ is smallest for the 0.1nm FEL's.
- All segments have to be adjusted in such a way that they have the same resonance frequency within ρ.
- NdFeB material has a reversible temperature coefficient of the remanent field of 0.11%/°C. Appropriate temperature stabilization along the 300m long undulator system is therefore mandatory.

Table 3 gives an overview over the requirements. They are derived in more detail in Appendix A and B.

Table 3: Mechanical requirements and specification. Given are worst case parameters

Min. / Max. Gap*	mm	6/12 - 200
Design (worst case) magnetic force load	kN	73.2
Max. girder deformation under changing magnetic load	µm	≤± 2
Gap adjustment accuracy	µm	≤ 2
Taper control	µm	≤± 2
Temperature stability	°C	±0.25
Vertical alignment accuracy	µm	≤±1 60
Horizontal alignment accuracy	µm	≤± 500

* For SASE undulators the gap is 12mm, for spontaneous radiators it is 6mm

3.4 Design overview

Fig 2 shows a 3-D view of the proposed GSD, which includes all the details to be discussed below. The same type of profile is used for the girders and the support columns. This minimizes welding and requires only little machining. and simplifies the whole manufacturing.

The following points have been treated in more detail:

- *Girder deformation*
  The girders need a very large moment on inertia in order to minimize deformation under changing magnetic loads. Their cross section therefore has the dimensions are 550*200*100mm. Profiles of this size are non standard items. They have to be produced by a steel mill on special request. It has been investigated that this is no problem for the quantity needed for TESLA. The weight of a girder is about 400kg/m. A total length of roughly 4500m corresponding to 1800 tons is needed for the 281 GSD's . Appendix B deals with the calculation of girder deformation and the selection of the girder profile.
- *Girder support*
  Girder deformation is reduced significantly by a four point instead on a conventional two point support. An intermediate auxiliary girder system is needed for this purpose. This four point support is described in appendix B as well

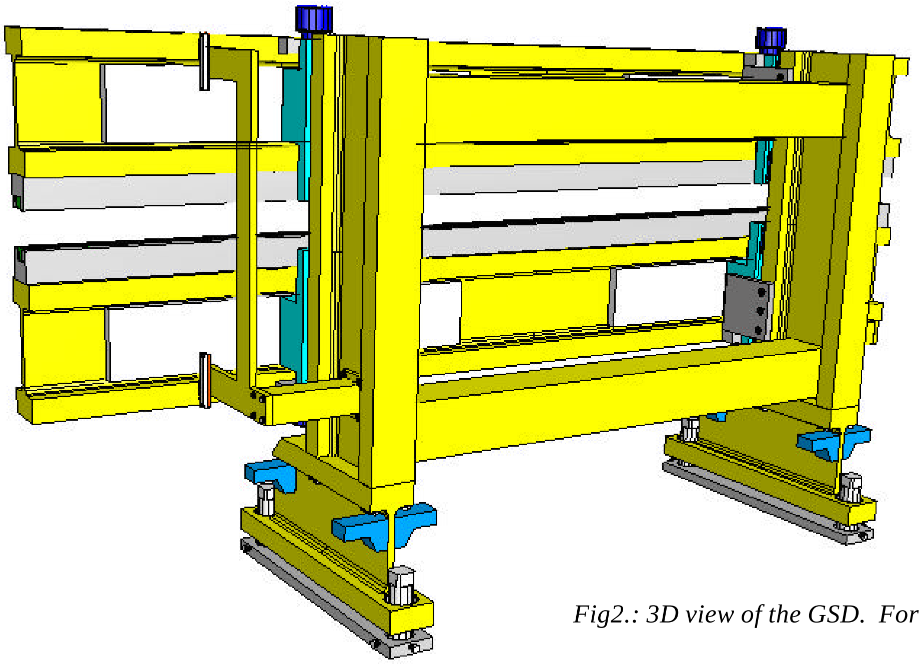

Fig2.: 3D view of the GSD. For details see text.

- *Guiding systems*
  There are heavy guiding systems to support the girders. They are made in a similar fashion than those used in heavy machine beds and are as closed to the girders as possible in order to reduce moments. (see Appendix D). No high performance spindles are needed because of the servo motor system and its position feedback. (see below).
- *Drive Motors*
  There are four servo motors to move the girders. These four motors represent four degrees of freedom, which can be used to:
  1. adjust the gap on either end, or, equivalently adjust a taper. This requires two degrees of freedom
  2. adjust the magnetic center on either side, which requires another two degrees of freedom.
  The four motors may also be used for precision alignment purposes of the vertical magnetic center.
  In any case a motion control system must be capable of safely synchronizing the motors for girder movements. A study has been made how the motion control of an undulator system for one of the TESLA FEL's can be made./ 12/.
- *Encoder systems*
  Each of these motors has its own absolute linear encoder system for position feedback . They are mounted on C-shaped 'Measurement frames' which are separately supported. The purpose of these frames is to provide base or reference system, which does not move even if there is distortion under mechanical load. Relative to this base the girder movement can be measured with high accuracy. Changes resulting from elastic deformation of the main or auxiliary girders, errors in the spindle and the guiding systems are completely eliminated in this way. In this way no highly accurate spindles are needed. The support points of the C-frames have been chosen such, that these points are free of deformation due to magnetic forces. Finite element calculations have shown that the bottom of the support column is a good place (see Appendix C).
- *Support frame*
  There is a simple but stiff support frame: The vertical columns, which have to withstand the magnetic forces are most easily made from the same girder profiles than used for the girders for the magnetic structures. They result in a slightly increased stiffness than a welded box or a cast iron frame. The horizontal spacer connections are of secondary importance in this context. In Appendix C a comparison between a welded box profile and the girder profile is made.
- *Alignment tolerances*
  They are moderate. There is a four point vertical support and adjustment system. These supports use base plates bolted on the floor, which also contain a simple longitudinal and transverse alignment. These adjustments allow for alignment in all degrees of freedom (see Fig. 3). In appendix A alignment tolerances

are given.. If needed vertical precision alignment is also possible using the four axis motor control as described above.

- *Transport system*
  There is also a transport system for moving the device over long distances (several hundred meters) to their insertion location. It is based on castors and hydraulics, which are used to lift an undulator segment for transport so that it can be placed in its final position.

4 Summary and outlook

The mechanical design presented here is a feasibility study. A study for a cost effective design of a large number of GSD's was made, which complies with the accuracy criteria needed for FEL operation.
Although 281 units are to be built, manufacturing is not believed to be a big issue, provided that a good and well documented design exists. It has however to be tested and improved in several prototypes.
The bottle neck for the mass production of undulator segments is the manufacturing of the magnetic structures which is planned to take a total of five years after thorough prototyping /13/. Logistically the production of the mechanical parts is closely interconnected with the manufacturing of the magnetic structure and the subsequent magnetic measurements and tuning. Therefore mechanical and magnetic manufacturing has to be done at the same time but maybe done at different companies.
Experience with the Insertion Devices built at HASYLAB so far has shown, that there are a few, however not very many, mechanical workshops, which have the appropriate equipment and sufficient capacity. Futhermore a large order might always be split up among several suppliers. Thus the manufacturing of the GSD's may be done right in time in any case.

5 References

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Appendix A : Accuracy requirements

Girder deformation, taper control

It is required that the change of the resonance wavelength be smaller than the Pierce parameter ρ, which for TESLA typically is about $5*10^{-4}$. In this case the FEL process is not affected. The tolerable detuning of the harmonic is therefore given by:

(A1) $$\frac{\Delta E}{E} = \frac{\Delta l}{l} = \frac{K \cdot \Delta K}{1.+0.5 \cdot K^2} \leq r$$

which leads to a K-parameter uncertainty of

(A2) $$\frac{\Delta K}{K} = \frac{\Delta B}{B} \leq \frac{r \cdot (1.+0.5K^2)}{K^2}$$

The worst case of Eq (2) results in for K=10 (SASE5):

$$\boldsymbol{DK/K = \pm 0.51 r = 2.5*10^{-4}}$$

The peak magnetic field of a NdFeB Hybrid structure of period length λ as a function of the gap *g* can be described as:

(A3) $$B(g/l) = a \cdot \exp\left[b \cdot (g/l) + c \cdot (g/l)^2\right]$$

where in the case of a planar hybrid undulator a= 3.44; b=-5.08; c=1.54. For the helical device SASE5 a=1.614; b=-4.67; c=0.620. These values are taken from ref /***/

The derivative of eq (2) is given by

(A4) $$\frac{\partial B}{\partial (g/l)} = B(g/l) \cdot \left[b + 2 \cdot c \cdot \left(\frac{g}{l}\right)\right]$$

so that by combining eq(2) and (4) the result

(A5) $$\Delta g \cong \pm \frac{l \cdot \Delta B}{B(g/l) \cdot [b + 2 \cdot c(g/l)]} = \pm \frac{l \cdot r \cdot (1.+0.5K^2)}{[b + 2 \cdot c(g/l)] \cdot K^2}$$

For the above example, λ=45mm, gap=12mm and *DB/ B= 2.5*10^-4^:*

$$\boldsymbol{Dg » \pm 2mm}$$

which for larger values is quite independent of *K*

This derivation does not differ between gap changes due to girder deformation or taper. In other words about *2mm* can be tolerated either as deformation or as unwanted taper due to imperfect gap control.

Temperature control

NdFeB material has a reversible temperature coefficient of the remanent field of Tk_{Br} of 0.11% / °C . With eq(2) one obtains:

(A6) $$\frac{\Delta B}{B} \leq \pm \frac{r \cdot (1.+0.5K^2)}{K^2} = \pm Tk_{Br} \cdot \Delta T$$

For and *DB/B=* $2.5*10^{-4}$ the resulting acceptable temperature variation is:

DT = ±0.25°C

Alignment Tolerances

Here alignment tolerance means the precision required to align an undulator to its symmetry axis. The field of an undulator is not homogeneous. Due to Maxwell's equations the sinusoidal variation along the electron beam axis (Z) result in a cosh like behavior in the vertical (Y) direction. For a magnet structure sufficiently wide in the horizontal (X) direction, the dependence of the magnetic field on X is negligible. Then the field components of a planar undulator are given by:

$$B_x = 0$$

(A7) $$B_y = B_{Peak} \cdot \cosh(2 \cdot p \cdot y / l) \cdot \cos(2 \cdot p \cdot y / z)$$

$$B_z = -B_{Peak} \cdot \sinh(2 \cdot p \cdot y / l) \cdot \sin(2 \cdot p \cdot y / z)$$

For small y the B_y component can be expanded as

(7) $$B_y \approx B_{Peak} \cdot \left(1 + \frac{1}{2}\left(\frac{2p}{l}\right)^2 \cdot y^2 + ...\right) \cdot \cos(2 \cdot p \cdot y / z)$$

A worst case assumption for *DB/ B is DB/ B_{Peak}* An allowable Y value therefore is:

(A8) $$y = \pm\sqrt{\frac{\Delta B}{B_{Peak}} \cdot 2 \cdot \left(\frac{l}{2p}\right)^2}$$

For *DB/ B= 2.5*10^{-4}* and *l=45mm* one obtains*:*

y= ± 0.16 mm

This value is within the capability of optical alignment techniques and does not require specialized equipment such as laser interferometers.
In the horizontal, the x direction the tolerance depends on the horizontal width of the poles of the structure only. The poles of the X-FEL structures are wide enough so that *DB/ B£ 2.5*10^{-4}* over a range *of ±0.5 mm.* Therefore

x=± *0.5 mm*

Appendix B : Calculation of girder deformation

Principle

It is required that the girder deformation under magnetic forces is below a given limit, which is in the micrometer range. The maximum deformation of a girder which is constrained on both sides in such a way that the tangents are kept horizontal is given by:/9/

(B1) $$f = \frac{q \cdot l^4}{384 \cdot E \cdot I}$$

f is the deformation, *q* is the load per unit length , *E* is the modulus of elasticity and *I* is the moment of inertia. The deformation is proportional to l^4 therefore the distance of the supports plays an important role. It is therefore beneficial from the point of view of girder deformation to have more than two support points.

A comparison between a conventional two point and a four point support is schematically shown in Fig B1 and B2 for identical load and girder conditions. The difference is impressive. For the example shown below the deformation is reduced from 14µm for the two point support to 0.6µm for the four point case. It is essential to properly choose the distances of the supports in order to have a homogeneous deformation line.

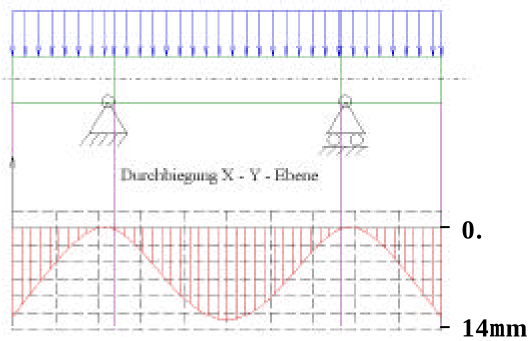

Fig. B1: 2 Point support. The lower curve is the deformation line. The maximum corresponds to 14 mm

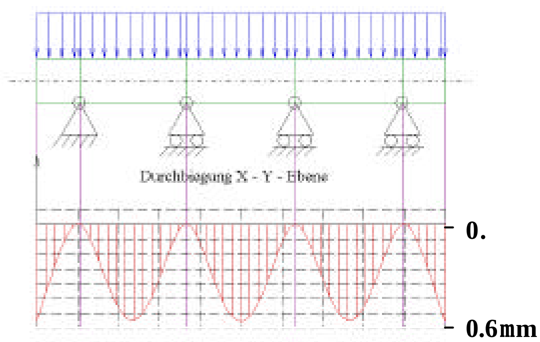

Fig. B2: 4 Point support. with identical load conditions as in Fig B1. The maximum deformation corresponds to 0.6 mm

A concept for a mechanical solution of a four point support with proper choice of distances is shown in Fig B3 For each girder there are now two auxiliary intermediate ones. On each of these there are two pivots which support the girder. The distances between the supports are again optimized for a 5m long device length. The support of the pivots has to be free of mechanical play. The operational range of the FEL undulators is below 22mm for SASE 1-4 and below 35mm for SASE5 (see table 1). In this gap range the magnetic force always exceeds the girder weight so that no change of load occurs.

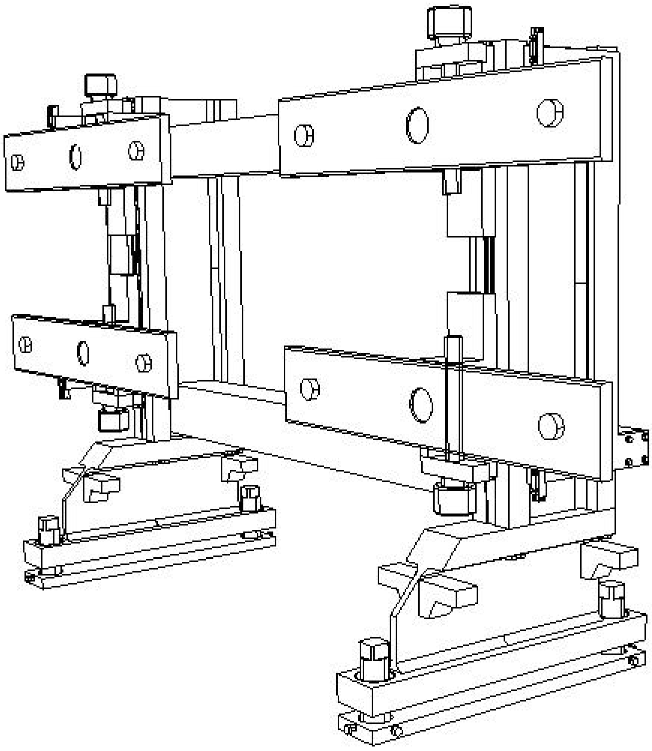

Fig B3: The four point support of the magnetic girders needs intermediate auxiliary girder, which are supported by the gap separation units.

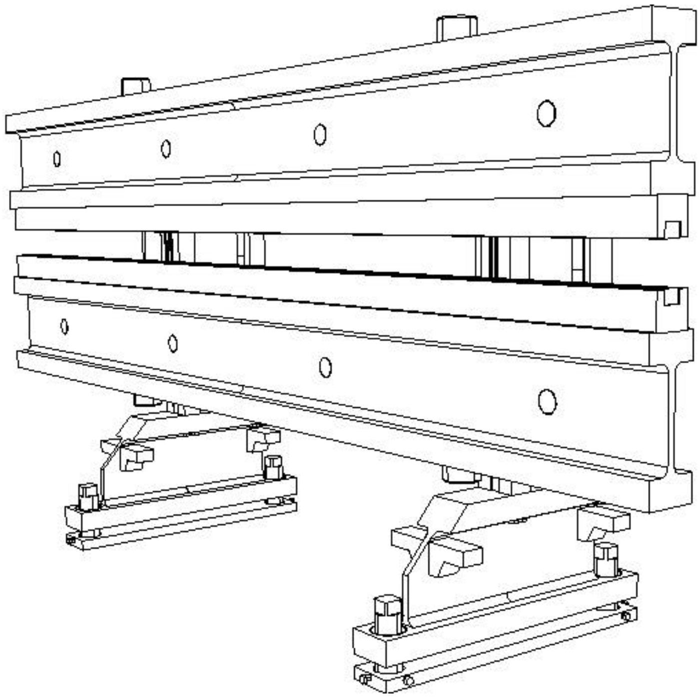

Fig B4 : GSD with attached four point supported girders.

Finite element calculations

The exact girder deformation was calculated using finite elements. By making use of symmetry properties only ¼ of a girder has to be used for the calculations. The weight of the girders , 19.2 kN, was taken into account. Therefore two separate calculations were made. The green / light part of Fig B5 shows this ¼ of the girder.
The magnitude of the magnetic forces and the requirements on maximum deformation require a girder with a large moment of inertia. Therefore after some iteration the profile shown in Fig B6 was proposed.
Table B1 gives an overview over the parameters used for the calculations.

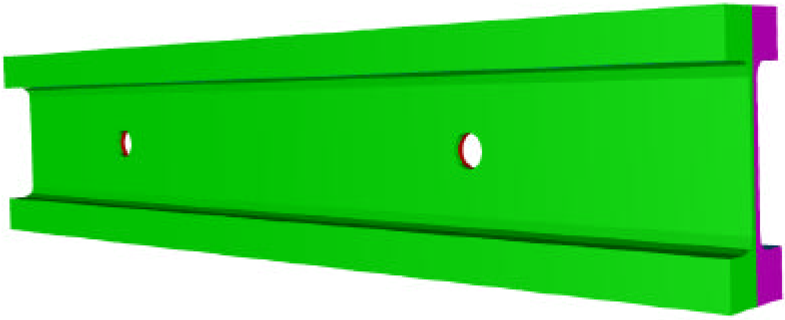

Fig.B5: ¼ of the girder (light / green) used for the finite element deformation analysis

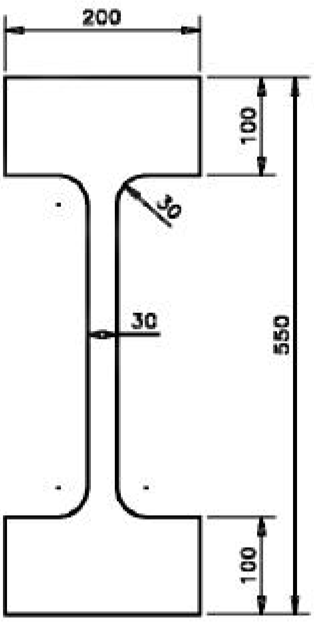

Fig B6: Proposed girder profile

Table B1: Input parameters used for the calculations

Material		St 37
Weight	kN	19.82
Total length	mm	5000
Magnetic Force	kN	
Tensile Strength	N/mm^2	340
Yield Strength	N/mm^2	235
Moment of Inertia	N/mm^4	$2.32*10^9$
Section Modulus	N/mm^3	$8.44*10^6$
Young's Modulus	N/mm^2	$2.15*10^5$
Density	kg/dm^3	7.85
Operating Temperature	°C	20
Girder cross section	mm^2	50500
Unit weight	kg/m	396

Results

Fig. B7 shows the deformation of the girders. The weight force is included and compensates a part of the magnetic forces on the bottom girder and consequently increase the load on the top one. The deformation profile is consequently slightly asymmetric. The right half of the girder pair is shown..

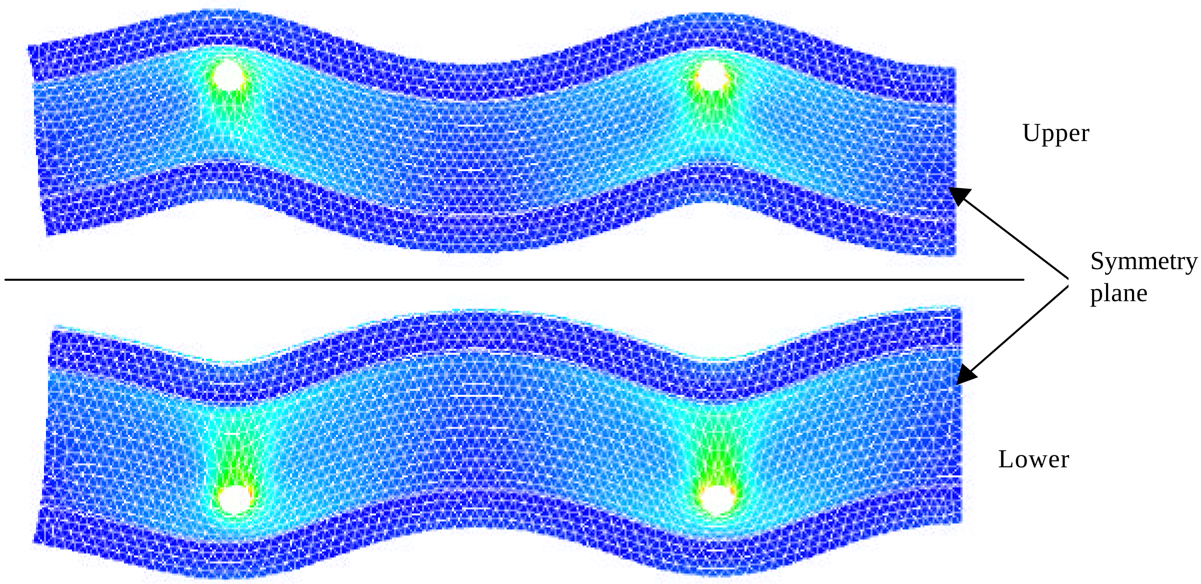

Fig. B7 Deformation profile of girders. only the left half is shown for symmetry reasons.

Due to its weight the top girder has 1.11µm more deformation than the bottom one. There is no effect on the gap. The girder deformation under magnetic forces follows a Hook's law.

(B2) $$f = S \cdot q$$

The notation is the same as in eq B1. The 'spring' constant S was derived from the above calculations to

S=0.093mm/kN

It connects a given uniformly distributed magnetic load to a girder deformation .
This result deserves some comment. In Appendix A the effect on undulator performance due to gap deformation was investigated. It was implicitly assumed that these are changing load conditions. A fixed gap device has static conditions and local gap changes can always be adjusted by means of shimming or tuning techniques. The method of field fine tuning by pole height adjustment /11/, which was very successfully applied for the undulator for the TTF is an excellent example for this. A gap tunable undulator has a gap range which is used for FEL operation. The deformation due to load changes has to be kept below a limit in this gap range only. Therefore only the load different between the minimum and maximum gap load has to be taken into account..
Table B1 gives an overview over the five SASE devices.
Typical values for the 0.1nm FEL's are $\leq \pm$ 3µm. Because of the larger ρ parameter for SASE5 the mechanical requirements are looser, although here the total mechanical load is largest.

Table B1 : List of tolerances on gap deformation of SASE undulators

	B_{Min} / B_{Max} [T]	**r*10^{-4} ***	**Total Magnetic Load [kN]**	**Load change ** [kN]**	**Total deformation [mm]**	**deformation change [mm]**	**Required Tolerance + [mm]**
SASE1 planar	0.65 / 1.33	4.3	26.7 / 70.2	43.5	±3.25	±2	≤ ± 3
SASE2 planar	0.95	3.6	35.8	0 fixed gap	±1.7	0	≤ ±2
SASE3 planar	0.95	3.6	35.8	0 fixed gap	±1.7	0	≤ ±2
SASE4 planar	0.67 / 1.31	4.2	16.7 / 70.2	53.5	±3.25	±2.5	≤ ±3
SASE5 helical	0.38 / 0.96	14.5	11.5 / 73.2	61.7	±3.5	±3	≤ ± 17

* worst case assumed (smallest ρ)
** load change calculated between minimum and maximum gap
*** deformation change under changing magnetic load
\+ required tolerance using eq A5

Appendix C: Deformation of the support stands

Box shaped support column

For a first impression of the mechanical stability and rigidity of the support column it was modeled as box of rectangular shape which gets somewhat conical to the top. Fig C1 shows the CSD using the box column, Fig C2 shows the finite element model used. Steel plates of type ST37 are used. The material thickness and the dimensions are indicated in Fig. C2. For the front surface a thickness of 70mm is assumed, to simulated the contribution from the guiding elements as well. Experience with box structure exist from the DORISIII GSD's They could be manufactured by welding individual steel plates together. The example and dimension shown here show some limit what could be obtained with a reasonable technical effort.

The resulting deformation when magnetic forces are applied are shown in Fig. C3. In complete analogy to eq. B2 one can calculate 'spring' constants for the deformation and the tilt angle

For the deformation at the girder position one obtains: S_D=6.9*10^{-4} mm/kN resulting in a 50μm deformation for the worst case load conditions (72kN). In a similar fashion for the tilt angle S_D= 9.2*10^{-8}rad/kN resulting in a tilt angle of 6.7μrad.

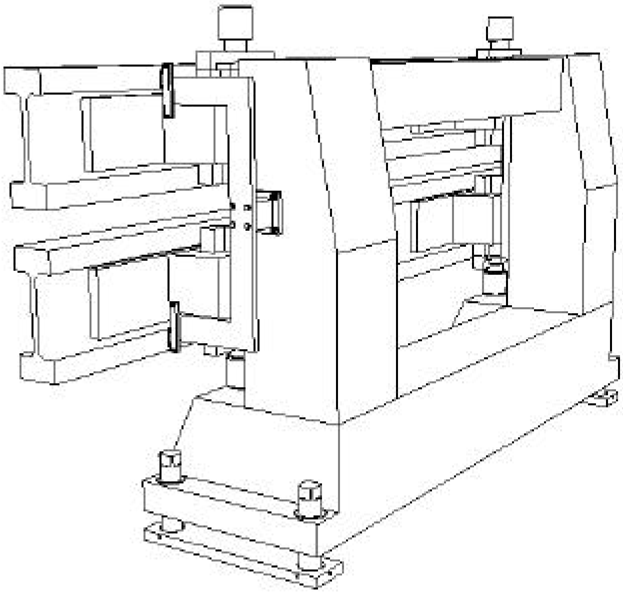

Fig C1: Box type support

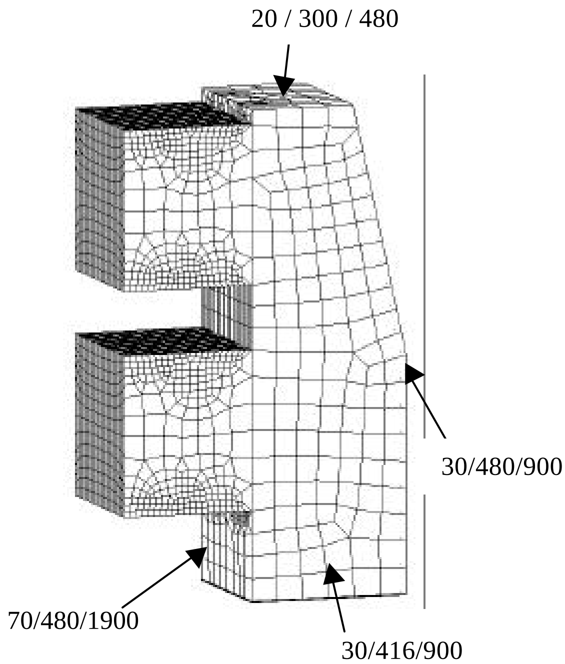

Fig. C2: Finite element model of the box support column. The numbers indicate the material thickness/ the dimensions.

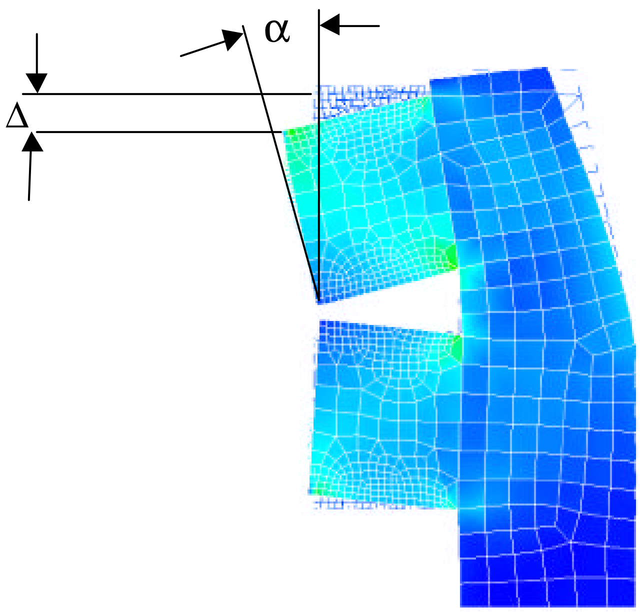

Fig. C3: Deformation under load conditions :The maximum deformation, D at the outermost part of the girder is 0.05 mm, the deformation angle a is .067mrad.

Girder support column
A modified support column was modelled by using the same profile than for the girders. It turned out that both alternatives have very similar properties. A comparison between these two alternatives are made in table C1. It is seem that both have almost the same properties. The girder alternative has even slight advantages. Using girders for the support columns means a large simplification in terms of manufacturing. No welding is needed. The girders jsut have to be cut to the appropriate length and need only little machining. Consequently this alternative is preferreable for the sake of simpler manufacturing.

Table C1: Comparison of box and girder type columns

	Units	Girder	Box shaped
Material		ST 37	ST 37
Moment of Inertia	N/mm^4	$2.32*10^9$	$2.27*10^9$
Section Modulus	N/mm^3	$8.4*10^6$	$7.87*10^6$

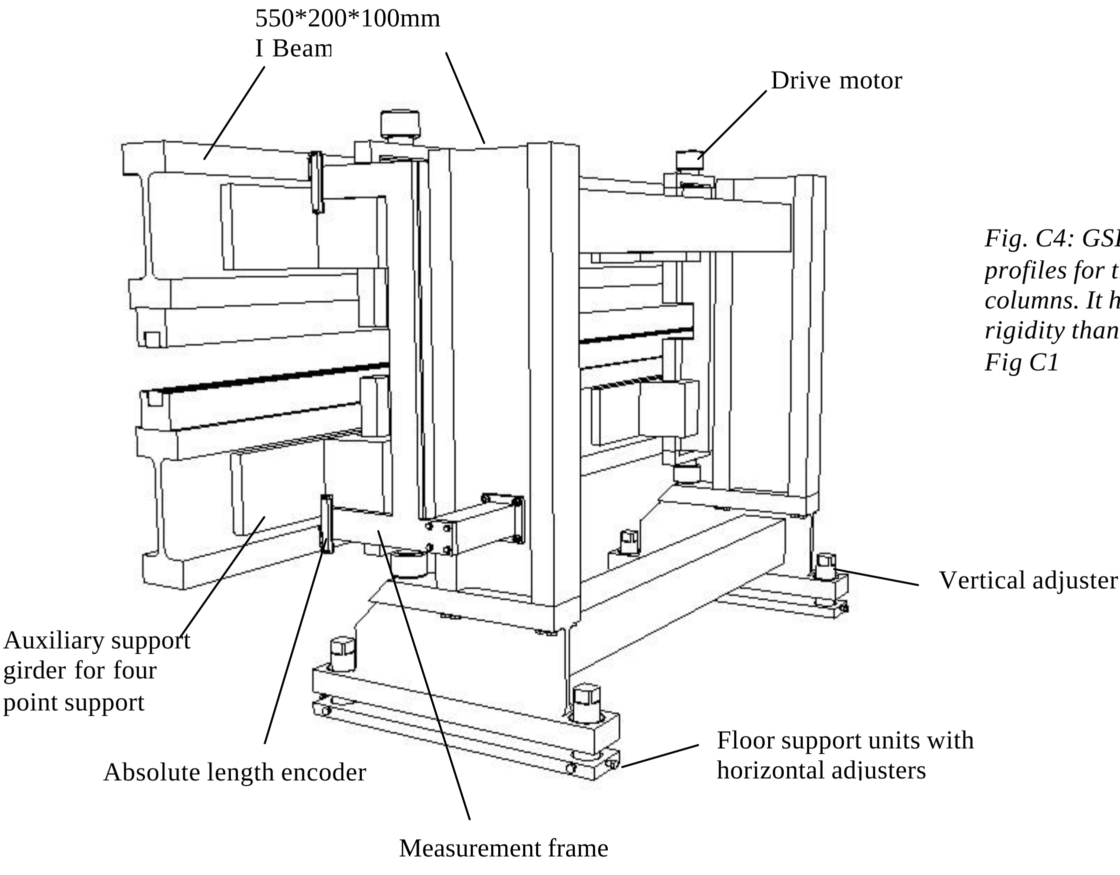

Fig. C4: GSD using girder profiles for the support columns. It has the same rigidity than the one shown in Fig C1

Measurement Frame
The discussion of the deformation of the support columns has shown the necessity of a separate frame for an length encoder system if the true girder movement is to be measured. This measurement frame should be attached at the support column where there is minimum or no deformation at all. In Fig C4 shows an location which satisfies this requirement.

Appendix D: Guiding system for gap change

There are four drive motors, one for each girder support. They are electronically synchronized. Each motor acts on a low cost spindle, which is integrated into the guiding system. Standard guiding elements with rectangular guide rails are used. They can be used in a very space saving way., requiring only a minimum of overall height. Large moments can be absorbed by these rectangular profiles. The length of a carriage is 155.5mm, the static/dynamic load capacity is 121/98 kN. To demonstrate the principle Fig D1 shows a view from top onto one drive units and guiding system. The motor is seen in the left. To the right there is the girder of the support column. Only minimum machining of the support column is required in order to provide a flat enough surface for the guide rail. The overall distance from the guide rail center to the center of the magnetic structure, the lever arm, is 350mm, the spindle support is at half that distance.

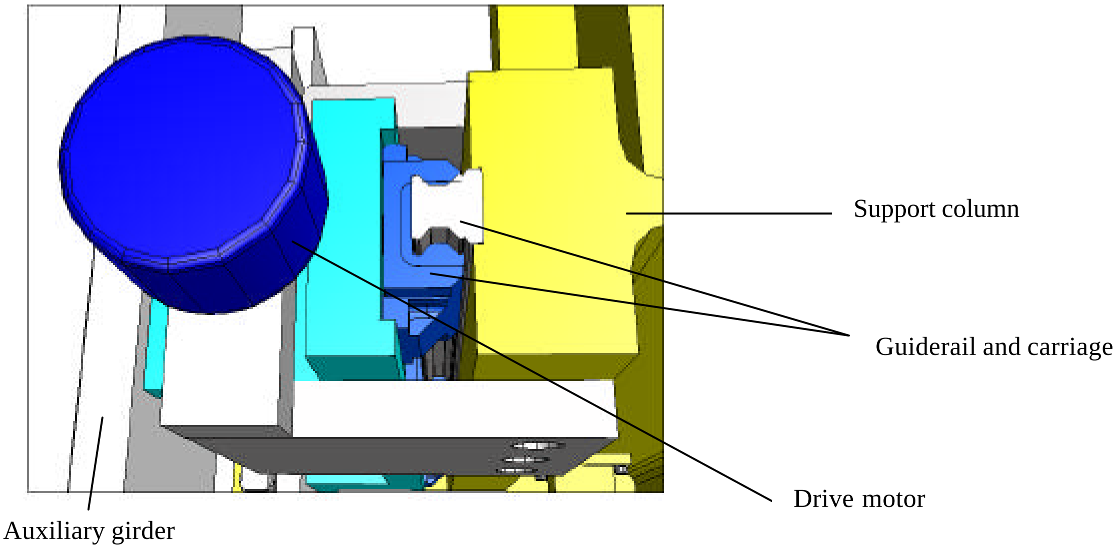

Fig D1: Top view on one support unit. The drive motor is seen to the left, the vertical support columns are seen to the right. In between there is the guide system using rectangular guiding rails

Appendix E Transport of undulator segments

The total lengths of undulator systems shown in table 1 are in excess of 300m. The systems will be installed into tunnels with a diameter of about 4m. It is large enough so that a segments can pass by already installed ones. For heavy equipment such as undulators there will be only one central access. This has the consequence that undulator segments have to be transported over distances of several hundred meters. Fig. E1 and E2 show a concept how this problem could be solved. Transport castors are used. They have an U-shaped slit, which can be moved around the base as shown in detail in Fig. E2. They use heavy load rolls equipped with brakes, which are

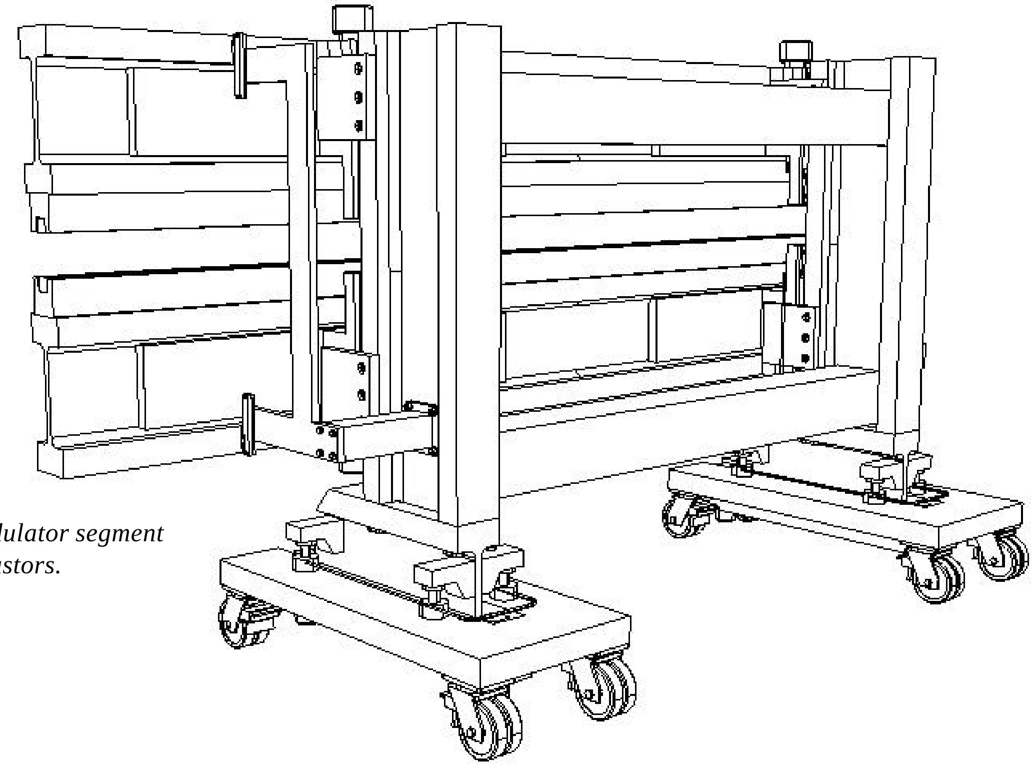

Fig E1: An undulator segment on transport castors.

available off the shelf. For transport four rectangular brackets are mounted on each of the floor stands. If actuated four hydraulic cylinders act on these brackets to lift the segment by a few centimeter. If lifted up it can be pulled using a tractor. A simple guide rail mounted on the outside wall of the tunnel similar to a handrail may be used to guide the segment over longer distances and to avoid damaging other equipment. This problem is easy to solve and will not be treated further in this report. If a segment is on place the segment is lowered and the transport rollers are removed.

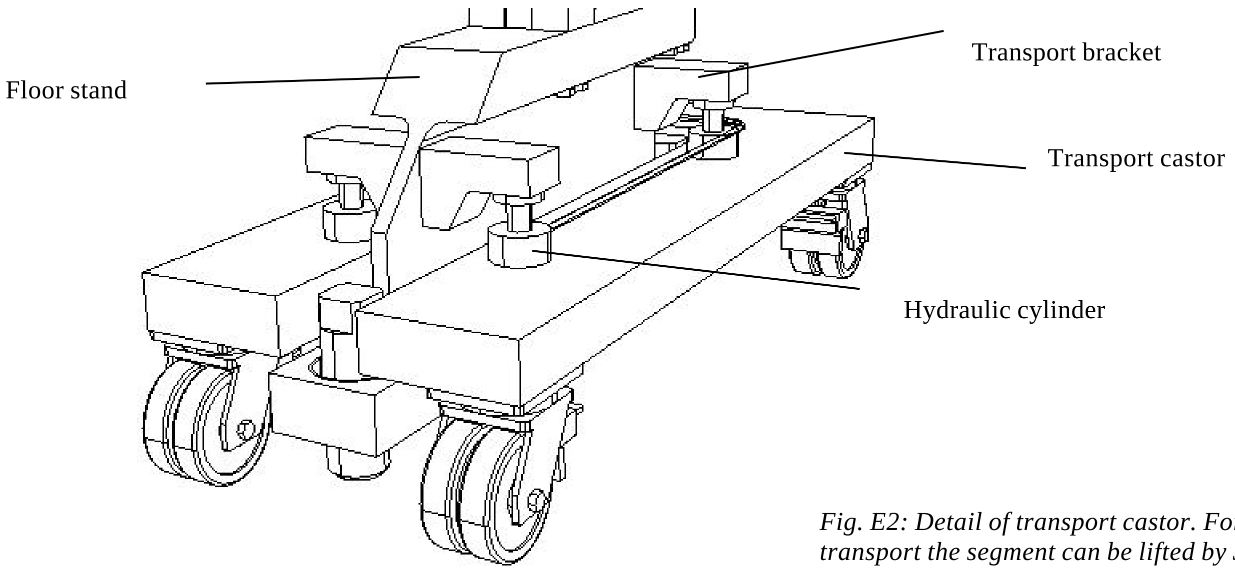

Fig. E2: Detail of transport castor. For transport the segment can be lifted by 3-4cm using four hydraulic cylinders .