A Prototype Phase Shifter for the Undulator Systems at the TESLA X-ray FEL

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Abstract

Five SASE FEL's and five spontaneous undulator systems are proposed for the FEL lab at TESLA. The SASE systems are the longest. Their total length can be in excess of 300m. In order to keep the beam size small over the whole system a strong focusing FODO lattice is needed. The parameters for the X-ray FEL's allow to separate between the undulators and the strong focusing. This has the advantage that the undulator system may be segmented into 5m long undulator segments and 1.1m long intersections, which include the FODO quadrupoles.

For most of the undulator systems the wavelength will be tunable. This is done by tuning the gap at a fixed energy. As a consequence the proper phasing of radiation emitted by individual segments becomes gap dependent too. In order to get the proper phase match, the electron beam has to be slightly delayed so that radiation emitted by the poles of one segment has a phase delay of multiples of 2π with respect to radiation emitted by the poles of any other segment. For TESLA a phase shifter for the SASE5 undulator system has the worst case requirements since this device has the highest period length, K parameter, operates at the longest wavelength and its wavelength is tunable by a factor of about 6.3. In this report a prototype design is proposed, which can be used at the SASE5 system and allows tuning over the full wavelength range. Properties are derived using analytical formulae. A design for a small electromagnet which can be used for the phase shifter and does not need water cooling is presented as well.

Introduction

For the TESLA project five SASE FEL's are planned in total /1/. A summary is also given in /2/ as well. In addition there will be five spontaneous radiators, which will use the spent electron beam of three of the SASE FEL's. From the standpoint of undulator design and the basic working principle there is no significant difference between SASE and spontaneous undulators. Therefore no special distinction is made. Table 1 gives an overview over the devices and their parameters which are planned for the TESLA FEL laboratory.

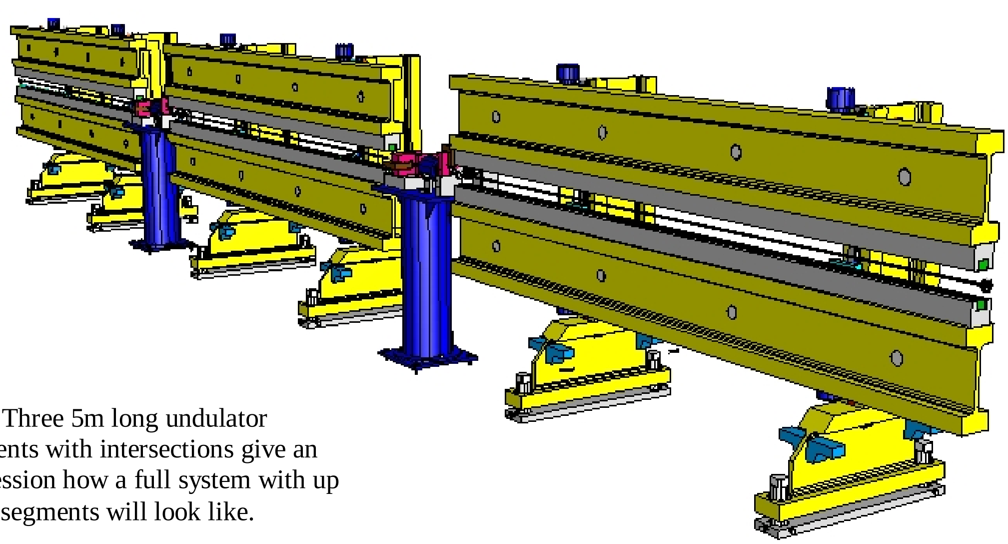

Fig1. Three 5m long undulator segments with intersections give an impression how a full system with up to 54 segments will look like.

Table 1 Parameters for the undulator systems in of the FEL lab at TESLA

Device	Type	E [GeV]	Wavelength Range [nm]	Photon Energy [KeV]	λ_0 [mm]	ρ * [10^{4-}]	K_{Min} / K_{Max}	B_{Min} / B_{Max} [T]	Gap_{Min}/Gap_{Max} [mm]	β [m]	Lsat + [m]	L_{Tot} ++ [m]	F_{Mag} ** [kN]	# of Seg-ments***
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**	**220 / 150 220 / 120 175 / 100**	**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	**50 30 15**	**0.003 -0.009 0.001 -0.003 0.0083-0.025 0.0028-0.0083 0.033 - 0.10 0.0123 - 0.033**	**420-140 1. Har 1260-520 3. Har 150-50 1. Har 450-150 3.Har 37 -12 1. Har 111-37 3. Har**	**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 ;

There will be only four different types of devices. This is a situation commonly found on small XUV synchrotron radiation (SR) sources. The difference is however the sheer length required by the SASE process. The length of a single X-FEL is about twice the total length of the total undulator length in a 3rd generation X-ray machine such as ESRF, APS or Spring8. Fig. 1 shows three undulator segments out of a much larger system as it is proposed for the TESLA X-ray FEL's. The whole undulator is composed out of 5m long so called undulator segments followed by 1.1m long intersections. For gap adjustable systems an intersection contains a quadrupole, a beam position monitor, corrector magnets and a phase shifter. See also appendix A.
There are different ways to design a phase shifter. A chicane using rotatable permanent magnets has been used for phase matching two segments of a helical unduator system for BESSY /3/. Because no iron is used this system has no hysteresis. It nevertheless produces stray fields and requires control of six rotational axes. A more conventional and economic way is a three magnet chicane using electromagnets. Phase matching is obtained by properly changing the excitation of the coils. This report deals with the properties of such a chicane as needed for the SASE5 undulator system at TESLA.

Basic formulae

In an undulator the radiation wavelength is given by:

$$(1) \quad \lambda_R = \frac{\lambda_u \cdot \left(1 + K_{RMS}{}^2\right)}{2\gamma^2}$$

Here λ_0 is the period length, γ is the kinetic energy of the electrons measured in units of its rest mass. The K parameter is most universally defined via the RMS value of the magnetic field.

$$(2) \quad K_{RMS} = \frac{e \cdot B_{RMS} \cdot \lambda_u}{2\pi \cdot m_e \cdot c}$$

For planar periodic fields with purely sinusoidal variation it is

$$(3) \quad (B,K)_{RMS} = \frac{1}{\sqrt{2}} \cdot (B,K)_{Max} \ . \qquad \text{and for helical fields} \qquad (B,K)_{RMS} = (B,K)_{Max}$$

Here e is the electron charge, m_e its mass and c is the speed of light.
In an ideal device the radiation emitted by different periods always has a phase difference, which is a multiple of 2π. In reality, however, the field is not purely periodic in addition there might be beam wander resulting from residual field errors. A more general treatment is required, based on the radiation integral, which is derived in ref /4/. Based on ref. /4/ a comprehensive treatment of emission properties of insertion devices has been done by Walker /5/. He demonstrated the importance of the optical phase, which is the exponent of the radiation integral.

$$(4) \quad \varphi(t) = \omega \cdot t - \frac{\vec{n} \cdot \vec{r}(t)}{c}$$

Here ω is the frequency of the emitted light, $\vec{n}$ is a unit vector describing the observation direction and $\vec{r}(t)$ describes the electron trajectory in the magnetic field. In the forward direction, along the symmetry axis of the undulator the optical phase can be expressed as /5/:

$$(5) \quad \varphi(z) = \frac{2\pi}{\lambda_R} \left\{ \frac{z}{2\gamma^2} + \frac{\int_{-\infty}^{z} x'^2(z')dz'}{2} \right\}$$

Here $z = ct$; λ_R is the radiation wavelength and x' is the electron's deflection angle. The two terms in the bracket have some descriptive meaning: The first gives the contribution to the phase if the electron travels just a distance z in free space. The second represents the additional contribution of a magnetic field to the phase delay. x' can be derived from $B_y(z)$ by:

$$(6) \quad x'(z) = \frac{e}{\gamma m_e c} \int_{-\infty}^{z} B_y(z')dz'$$

By means of eqs 5 and 6 the optical phase can also be evaluated from measured magnetic field data. In ref /5/ a detailed description on the phase analysis of insertion devices is given. Eqs (5) and (6) can also be used for treating the phasing problem between individual undulator segments (see below). Another application of eq 5 is the phase adjustment between undulator segments by means of an active phase shifter. The trajectory in a symmetric three magnet chicane is sketched in Fig. 2 a). A magnet creating a bend α is followed by a second in a distance Δl with a bend -2α. The third of strength α, the same distance apart, bends the beam back to the axis. The center magnet which requires double strength is most easily made with twice the iron length. The

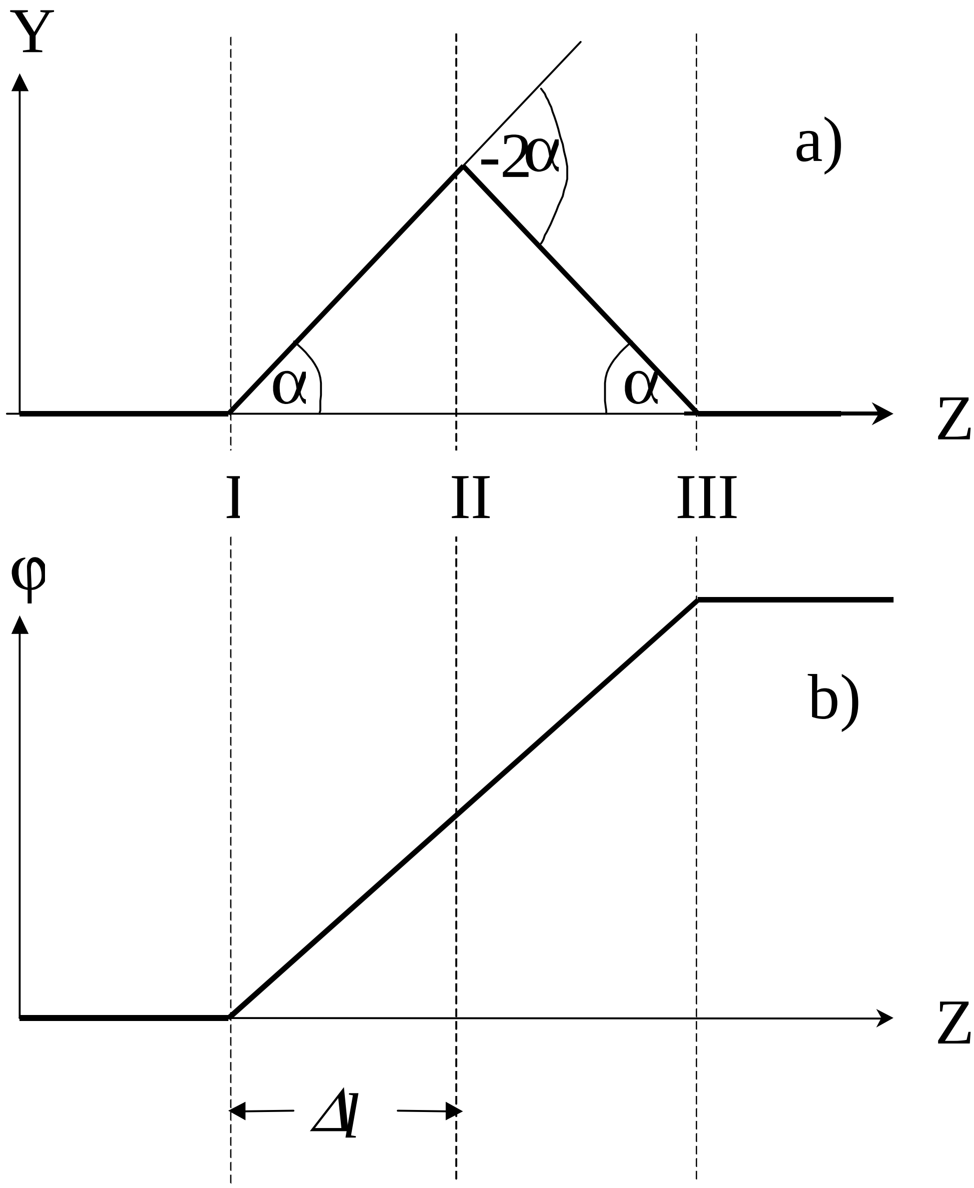

Fig. 2:
a) Electron trajectory in a symmetric three magnet phase shifter. in the short magnet approximation.
b) Phase advance in the phase shifter.

design of a suitable chicane magnet is described in Appendix A. Using eq 6 the bend angle α might be calculated:

(7) $$\alpha = \frac{e}{m_e c \gamma} B_0 l_m = \frac{0.586}{\gamma} B_0 l_m [Tmm]$$ for α in rad

Here B_0 is the field in the magnet and l_m its magnetic length, which differs from its mechanic length. For simplicity the short magnet approximation is used. It means that l_m is small as compared with the length of the system and a real trajectory can be approximated by the polygon in Fig 2a). In a realistic system l_m is in the order of a few centimeter and the overall length is about 0.3m.
By using eq 5 the phase change after the third magnet due to switching on the magnetic field may be calculated:

(8) $$\Delta\varphi = \varphi - \varphi_0 = \frac{2\pi}{\lambda_R}\Delta l\left(\frac{e}{mc\gamma}\right)^2 (l_m B_0)^2 = \frac{2.158\cdot 10^9\,\Delta l[m]}{\lambda_R[nm]}\left(\frac{B_o l_m[Tmm]}{\gamma}\right)^2 \quad \text{for } \Delta\varphi \text{ in [rad]}$$

To give an impression on the magnitude, the phase delay with parameters similar to those needed for the SASE5 system at TESLA is calculated: $\Delta\varphi=2\pi$ results for $\lambda_R=2.5nm$, $\Delta l=0.1m$, $l_m=50mm$, $\gamma=46000$ and a field of 0.248T.

Required tuning range

Fig. 3 shows a schematic field distribution of two undulator segments, which are separated by a 'separation distance' *L*. *L* in this example is measured by the distance from the end pole in one segment to the end pole in the next segment. The field is cos like, the end poles in Fig 3 are have full strength but half length only. This simplification makes the formulae more manageable. In a real structure the full poles inside the structure are taken as reference and for constructive interference the phase shift is increased by a suitable multiple of 2π. In the simplified case below only radiation of both end poles must interfere constructively. This can be described by the phase condition:

(9) $$\frac{L}{2\gamma^2\lambda_R} = \frac{L}{\lambda_0\left(1+K_{RMS}^2\right)} = \eta \;; \qquad \Delta\varphi[rad]=2\pi\ \eta$$

for proper phase matching η must be an integer. Eq(9) shows, that the phase match changes if the field strength and therefore λ_R or equivalently K_{RMS} is changed. For SASE5 (see table 1) with L=1.1m, γ=46000 and $\lambda_R = 2.5nm$ one obtains η=0.104 or a phase delay of the radiation between the two end poles of 0.653 rad or

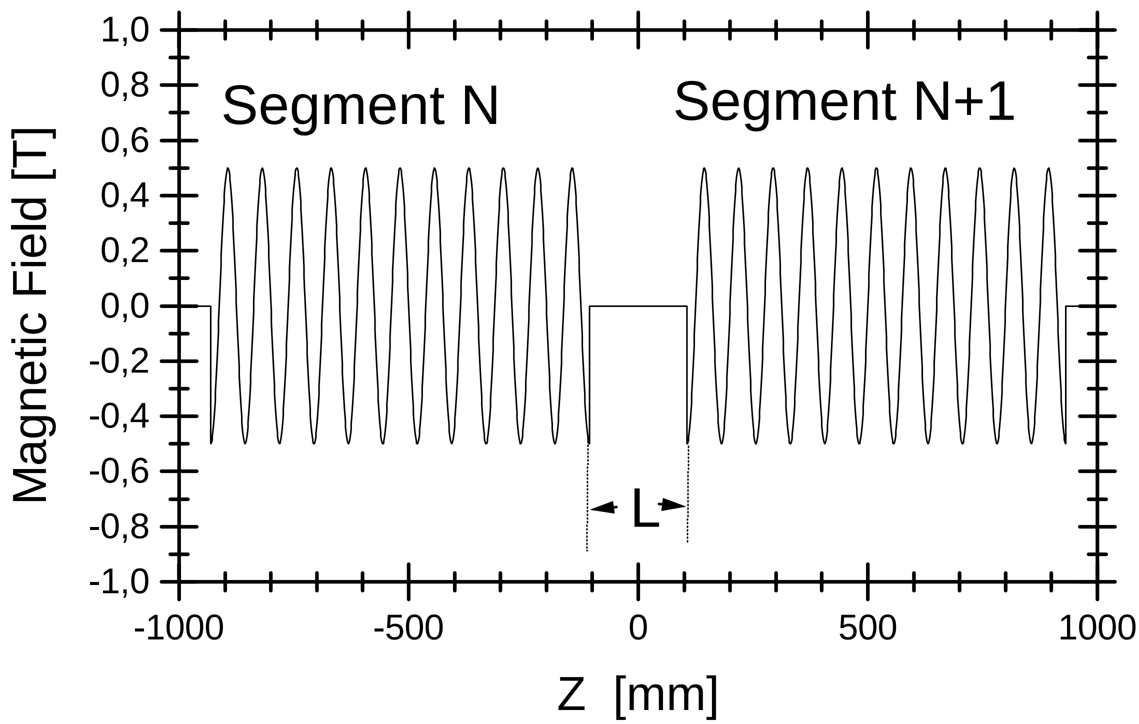

Fig. 3: Schematic field distribution of two undulator segments separated by a distance *L*

37.4°. In order to reestablish proper phasing the electron beam has to be further delayed by an amount :

(10) $$\Delta\varphi_{Corr}[^\circ] = 360\cdot\nu - \Delta\varphi = (\nu - \frac{L}{2\gamma^2\lambda_R})\cdot 360 > 0\,; \qquad \nu = 1,2,.....$$

which is 322.6° plus a multiple of 360°. The inequality on the right side has to be fulfilled, since electrons can only be further delayed. In principle the phase could also be matched by increasing *L*, but for the above example $2\gamma^2\lambda_R=10.6m$, which is a too large number. A special situation might occur for short wave lengths when η>1. In this case the phase delay between end poles is already larger than 360° and the delay has to be ν* 360° with ν=2 or even larger. For a wavelength tunable device η might be < 1 for the long wavelength but > 1 for the short wavelength. This means that at the long wavelength λ_{R1} the phase angle (1-η_1)*360° is missing for full constructive interference. For the short wave length at λ_{R2} with, for example, $1 < \eta_2 < 2$ a correction phase of (2-η_2)*360°is needed. Thus one can in principle correct for 360° at λ_{R1} and for 720° at λ_{R2} . But then a discontinuity in the excitation of the chicane has to occur at:

(11) $$\lambda_R = \frac{L}{2\gamma^2}$$

Due to hysteresis in the coils discontinuous excitation should be avoided. This can be done by designing the chicane for a suitable larger tuning range. The number ν has to be chosen, so that for the whole range for $\lambda_{R1} \le \lambda_R \le \lambda_{R2}$ the phase shift to be corrected for $\Delta\varphi_{Corr} > 0$.
If $\nu > 1$ the phase delay of the chicane needs to be larger. The required magnet strength of the chicane can be calculated by using eq (8)

(12) $$B_0 l_m = \frac{mc}{e}\gamma\sqrt{\frac{\Delta\varphi_{Corr}\lambda_R}{2\pi\Delta l}} = 2.844\cdot 10^{-6}\gamma\sqrt{\frac{\Delta\varphi_{Corr}[°]\lambda_R[nm]}{\Delta l[m]}}$$ for Bl_m in [Tmm]

Table 2: Phase shifter requirements for the SASE5 undulator at TESLA which is the worst case. γ=46000, L=1.1m. The coil excitation NI versus Bl_m are calculated for the magnet design described in Appendix A. The wavelength range correspond to the tunability range of SASE5

		ν= 1			ν=2			ν=3		
λ_λ [nm]	Δφ [°]	$\Delta\varphi_{Corr}$ [°]	Bl_m [Tmm]	NI [kA]	$\Delta\varphi_{Corr}$ [°]	B_m [Tmm]	NI [kA]	$\Delta\varphi_{Corr}$ [°]	Bl_m [Tmm]	NI [kA]
3.0	31.2	328.8	13.0	1.69	688.8	18.8	2.45	1048.8	23.2	3.02
2.5	37.4	322	11.7	1.52	682	17.1	2.23	1042-0	21.1	2.75
2.0	64.7	313.3	10.4	1.35	673.3	15.2	1.98	1033.3	18.8	2.45
1.5	62.4	297.6	8.7	1.13	657.6	13.0	1.69	1017.6	16.2	2.11
1.0	93.6	266.4	6.8	0.886	626.4	10.4	1.35	986.4	13.0	1.69
0.5	187.1	172.9	3.85	0.502	532.9	6.75	0.88	892.9	8.74	1.14
0.4	223.9	136.1	3.05	0.397	496.1	5.83	0.76	856.1	7.65	1.00
0.3	311.9	48.1	1.57	0.205	408.1	4.58	0.60	768.1	6.28	0.82
0.2	467.9	-	-	-	252.1	2.94	0.38	612.1	4.58	0.60
0.1	935.7	-	-	-	-	-	-	252.1	2.94	0.38

For the undulator systems for TESLA, SASE5 has the toughest requirements on the phase shifter.
Table 2 gives an overview over required magnet strengths and corrector coil excitations as a function of λ_R.
Three cases for ν=1,2,3 are calculated. Fig 4 shows graphs of these relations. In Appendix A a magnet design for the magnets of the phase shifter is presented. It is the basis for the relationship between the required magnet strength and coil excitation, which is assumed in Table 2 / Fig. 4. It is seen in Fig 4 that the higher ν the higher the tuning range and the higher the magnet strength required for the chicane magnet. However the tuning range for SASE5 from 0.4 to 2.5 nm can still be covered with ν=1.
The formulae given above give good estimates. However, one should be aware of the limitations. First, in order to estimate the required tuning range of a given magnet structure eq(11), (12) give a good estimate. However the field distribution of real end poles does not look like the one in Fig. 3 and might even be more complicated if the gap dependence is taken into account. For a truly quantitative estimation the phase delay between two undulator segments has to be calculated using eq(5). Then the full poles in the structure have to be taken as reference for an undulator segment with a real end pole configuration. Second by using the short magnet approximation for the chicane magnets some errors are introduced as well by applying eqs (8), (12). For designing the chicane the results presented in this report are fully sufficient. For the proper phase matching however one has to rely on measured magnetic field data anyhow.

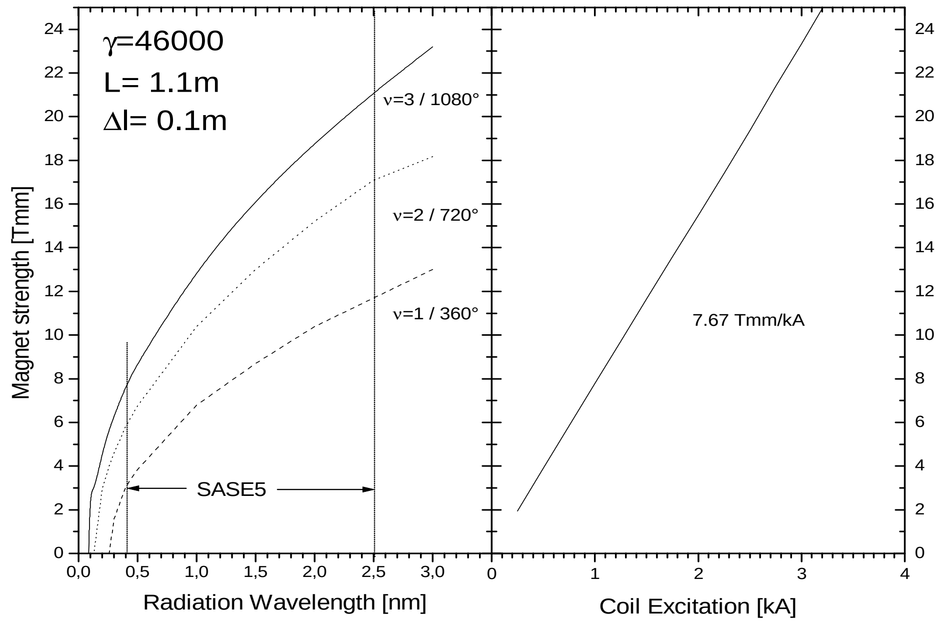

Fig.4: Required magnet strength and coil excitation as a function of the radiation wavelength for the SASE5 undulator system for TESLA

References

1. Undulator chapter in the Technical Design Report (TDR) Editors: R. Brinkmann, G. Materlik, J. Rossbach, A. Wagner, in preparation
2. HASYLAB annual report 2000 in preparation
3. J. Bahrdt, W. Frentrup, A. Gaupp, M. Scheer, W. Gudat, G. Ingold, S. Sasaki "Elliptically polarizing insertion devices at BESSYII" Proceedings of the SRI2000, Aug 21-25, 2000, Berlin, Germany
4. J.D. Jackson, 'Classical Electrodynamics', 2nd Edition, John Wiley, New York, 1975
5. R. P. Walker "Interference effects in undulator and wiggler radiation sources" Nucl. Instr. and Methods A335, (1993) 328

Appendix A : Design of a phase shifter magnet using RADIA

A prototype magnet for the chicane of a phase shifter has been designed. The core is made ARMCO iron with a cross section of 55 by 55mm. The gap is 12mm, which is the same as used in the SASE undulators. The coil around the yoke has a cross section of 2500 mm^2. Fig A1 shows a 3D view of this magnet. It is one of the single strength magnets of the chicane, which are used at the begin and end. The center one, which needs twice the strength, can be made by doubling the iron length. To prevent saturation on the edges there is a 5mm chamfer. Fig A2 shows a technical drawing of the magnet. The properties of this magnet have been calculated using RADIA. Fig. A3 shows the excitation curves for the magnetic flux density and the total field integral, which is called magnet strength. A comparison with the required magnet strength in table 2 shows that the magnet will be operated in the linear regime with a maximum excitation of about 3 kA. The linearity in this regime is very good, the slope is 7.67 Tmm / kA. The magnetic length has been determined by comparing the two curves in Fig A3. Its value is 77.9 mm. In

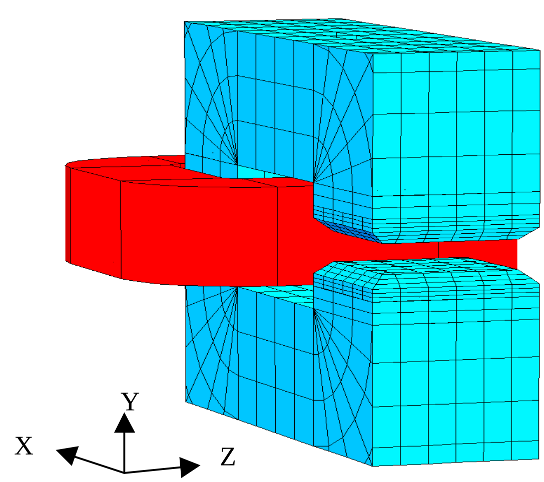

Fig. A1 3D view of the phase shifter magnet. The gap is 12mm the iron has square cross section of 55mm by 55mm the linear regime the magnetic flux density in the gap can be estimated by the field integral along a field line:

A1) $$\oint \vec{H} \cdot d\vec{s} = \int_{Iron} \frac{Bdl}{\mu_0 \mu_r} + \int_{Gap} \frac{Bdl}{\mu_0} = \frac{g \cdot B}{\mu_0} = N \cdot I$$

μ_0=4π*10^{-7} Vs/Am, B is the magnetic flux density and g is the gap. The iron integral can be neglected as long as the μ_r is very large, which is the case in the linear regime. Solving for B one obtains:

(A2) $$B = \frac{\mu_0}{g} \cdot NI = 0.105 \cdot NI[kA] \quad \text{for } B \text{ in Tesla}$$

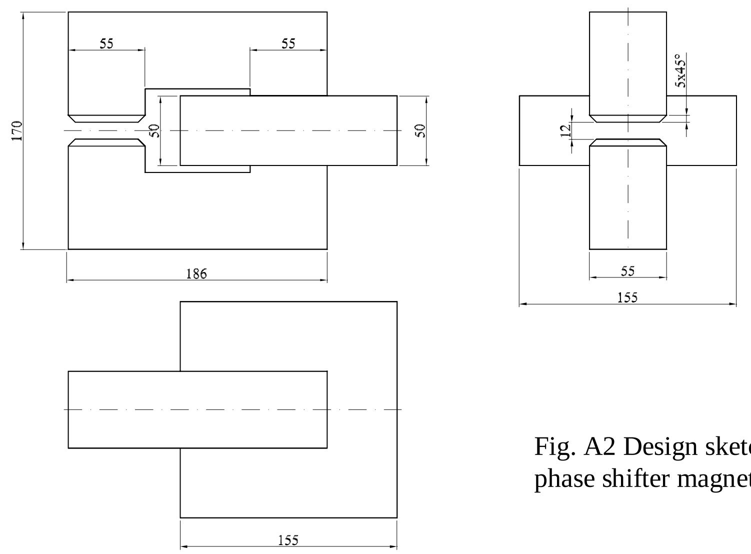

Fig. A2 Design sketch of the prototype phase shifter magnet

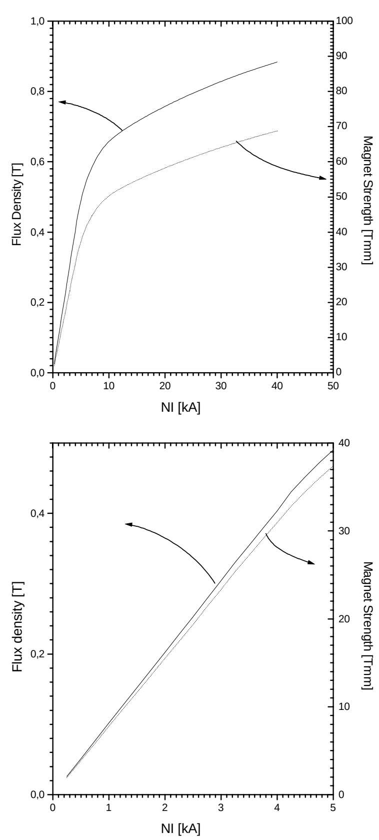

Fig. A3 Excitation properties of the prototype magnet. Peak field in Tesla (left scale) and total magnet strength in Tmm (right scale) are plotted as a function of the excitation current. From these two curves the magnetic length has been determined as 77.9 mm. It is independent of the excitation current. The lower figure shows a ten times enlarged view of the linear regime up to 5 kA, which is important for the operation of this magnet.

Using the slope in the linear region up to 4kA as determined in FigA3

(A3) $B = 0.102 \cdot NI[kA]$ again for *B* in Tesla

This is a surprisingly good agreement within a few percent. For the tuning range of SASE5 ($0.4 \leq \lambda_R \leq 2.5$nm) the chicane needs to be operated at even lower excitation levels between 0.4 and 1.52 kA only. Since the coil cross section is 2500mm^2 (see Fig A2) and the current density in this case is 0.6A/mm^2. The dissipated power in the coil is given by :

(A4) $P = \rho \cdot V \cdot j^2$

V is the volume of the coil which is 0.00105 m^3 (see Fig A2). For copper the specific resistance is ρ=1.8*10^{-8} Ωm. The resulting ohmic power loss for *j*=0.6 A/mm^2 (6x10^5 A/m^2) in one magnet only about 7Watts. So water cooling is not needed.

Fig. A4 gives an impression how the phase shifter is integrated into intersection between two undulator segments. There is a common adjustable base plate supported by a stable floor stand. The three magnets of the phase shifter are seen on the left, the quadrupole mounted on precision adjusters is in the center. It is equipped with alignment fiducials. One of the phase shifter magnets is simultaneously used for horizontal correction.. For vertical correction an additional but identical magnet is rotated by 90°. The vacuum system with the beam pipe, an noble ion pump and the pumping cross is also seen.

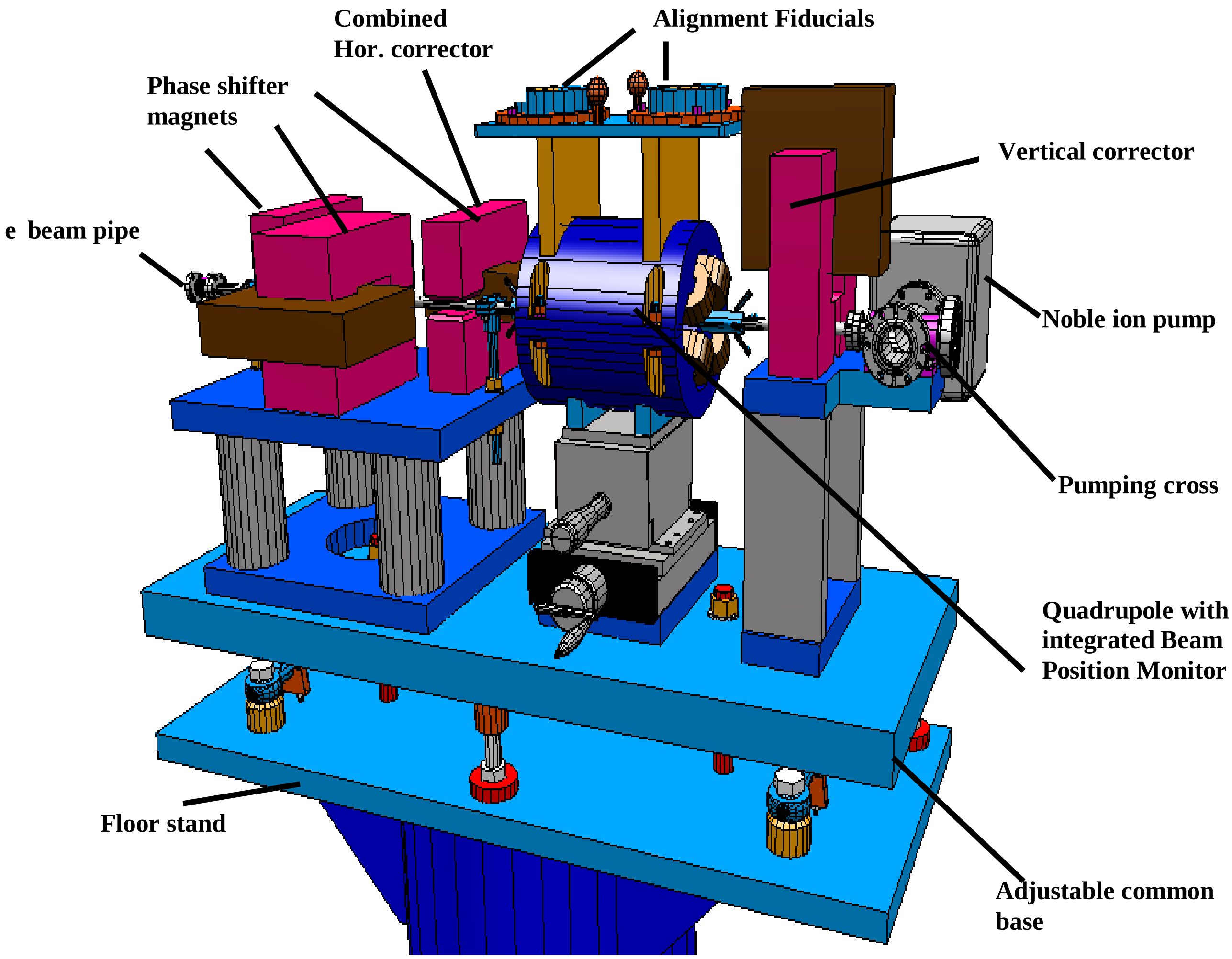

Fig. A4 Total view of components in the intersection between undulator segments