A Permanent Magnet Wiggler Design for the TESLA Damping Ring

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Abstract

The TESLA Linear Collider requires damping rings equipped with long wigglers in order to reduce the beam emittance before the particles are injected into the main linac. We propose a compact permanent magnet wiggler which will be installed in the straight sections of the damping ring. The concept discusses the magnetic design and field distribution; a damping integral $I_D \sim 1.37\ T^2m$ per meter wiggler is reached which would correspond to a 475 m long device. Other aspects like characteristics of the synchrotron radiation power or possible radiation damage of the magnets are worked out to an extent that allows comparison to an alternative electromagnetic version of the damping wiggler which is investigated in parallel. Costs have been estimated for the mass production of the magnet structure.

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1 Introduction

The design emittance for the TESLA Linear Collider is by several orders of magnitude smaller than the beam emittance achieved by the positron source. A practicable way to reduce the emittance to the required value is to store the beam in a damping ring between two bunch trains. There, the actual damping process predominantly occurs in long wiggler sections whose parameters are based on the general layout and specification of the damping ring [1]. Several wiggler options have already been discussed previously [2] which are all based on permanent magnet technology. Also this report considers a permanent magnet device because of space limitation, overall cost arguments and ease of operation. In parallel however, a design proposal for a (room temperature) electromagnetic version of the damping wiggler is under investigation [3] which would imply lower manufacturing costs. Design issues of the permanent magnet wiggler proposed here are worked out to a level that enables a profound assessment of both designs.

Besides a presentation of the magnetic design of the permanent magnet hybrid structure we summarize the ongoing discussion about possible radiation damage which is a major concern for permanent magnets in radiative environment. The characteristics of the synchrotron radiation output have been calculated and can give some input to vacuum chamber design considerations. In the present concept, wiggler cells of about 5 m length are placed within an appropriate magnet lattice resulting in a total magnet length of more than 450 m. It is obvious that a device of that size has to be manufactured on industrial scale. A possible guideline for a mass production strategy is discussed which also has to include magnetic survey and complete mounting of the wiggler segments. Finally, costs have been estimated for production and assembly of the magnet structure including the supporting frame. These evaluations are made for a wiggler in the positron damping ring, the electron damping ring has to be equipped with a wiggler of at least half the length in order to achieve the lowest possible beam emittance for the collider operation.

2 Radiative Damping

In a damping ring the beam emittance is determined by the processes of radiation damping. Particles in the bunch emit synchrotron radiation and thus change their momentum opposite to their direction of flight. The momentum is restored by the RF accelerating force, which is in average parallel to the design orbit. The net effect of both processes is a reduction of the transverse beam emittance with the damping rate:

$$\frac{1}{\tau} \approx \frac{U_0}{2E_0T_0} \qquad (1)$$

Here, $U_0 \propto E_0^2 \oint B_z^2 dl$ is the average energy loss per turn, E_0 the beam energy and T_0 the revolution time.

Quantum fluctuations of the synchrotron radiation lead to a growth of the beam emittance. This quantum excitation and the radiation damping result in an equilibrium beam emittance. The influence of radiation is worst if it occurs in a place with large dispersion and betatron functions β. For a wiggler the approximate horizontal emittance contribution is, due to the so-called self-dispersion of the wiggler:

$$\gamma\varepsilon_x \propto B_0^3 \lambda_U^2 \beta_x \qquad (2)$$

where B_0 and λ_U are the wiggler peak field and its period length, respectively. The TESLA positron damping ring requires approximately seven damping times within 200 msec. The circumference of 17 km as well as the beam energy of 5 GeV is determined through other accelerator requirements. The energy loss per turn is thus adjusted by insertion of an appropriate number of damping wigglers. The energy loss contribution of the damping ring arcs is only a few percent. A higher contribution (i.e. a higher bending magnet field) is difficult to achieve with the simultaneous requirement of a small horizontal emittance. Table 1 summarizes the important damping ring parameters.

energy	5.0 GeV
current	160 mA
circumference	17 km
norm. injected emittance (vert., hor.)	1×10^{-2} m rad
norm. ejected vertical emittance	2×10^{-8} m rad
norm. ejected horizontal emittance	8×10^{-6} m rad
damping time	28 msec
energy loss in arc	1.1 MeV/turn
necessary wiggler field integral	605 T^2m

Tab. 1: TESLA damping ring parameters.

3 Magnetic Design

The wiggler consists of a modified permanent magnet hybrid structure with a period length λ_u = 400 mm and a fixed gap of 25 mm. The gap size arises from the required vertical space of about four times the injected beam size σ. With a transversal emittance of $\varepsilon \sim 1\ 10^{-2}$ m rad for the injected beam a beta function $\lesssim$ 10 m is needed to match the specified gap value which is close to the minimum value for the chosen beam optics in the damping ring [1].

Considering the total required wiggler length on the one and the overall available length on the other hand the magnet design has to remain simple in terms of efficient field generation. This means it should be dispensed with lots of additional (costs driving) magnet volume where it enhances the peak field only by little. As schematically displayed in Fig. 1 the wiggler poles are additionally powered by magnets from aside and from top to enhance the peak field further. The entire magnet structure is enclosed by an iron yoke. The antisymmetric configuration of the poles ensures the 1st field integral to be zero while the 2nd field integral can easily be tuned for any fixed gap device by appropriate end poles. In the present design a wiggler segment contains 12 full periods plus 2 half periods for the end poles resulting in an overall length of 5.26 m per segment. It should be mentioned that the segment length can be chosen without restraint according to the focussing lattice. However, it has to be considered that a shorter segment length enhances the overall length of the damping wiggler as each cell requires end poles contributing only partly to the damping integral. Furthermore, costs for magnetic survey, mounting or alignment do scale with the number of wiggler segments.

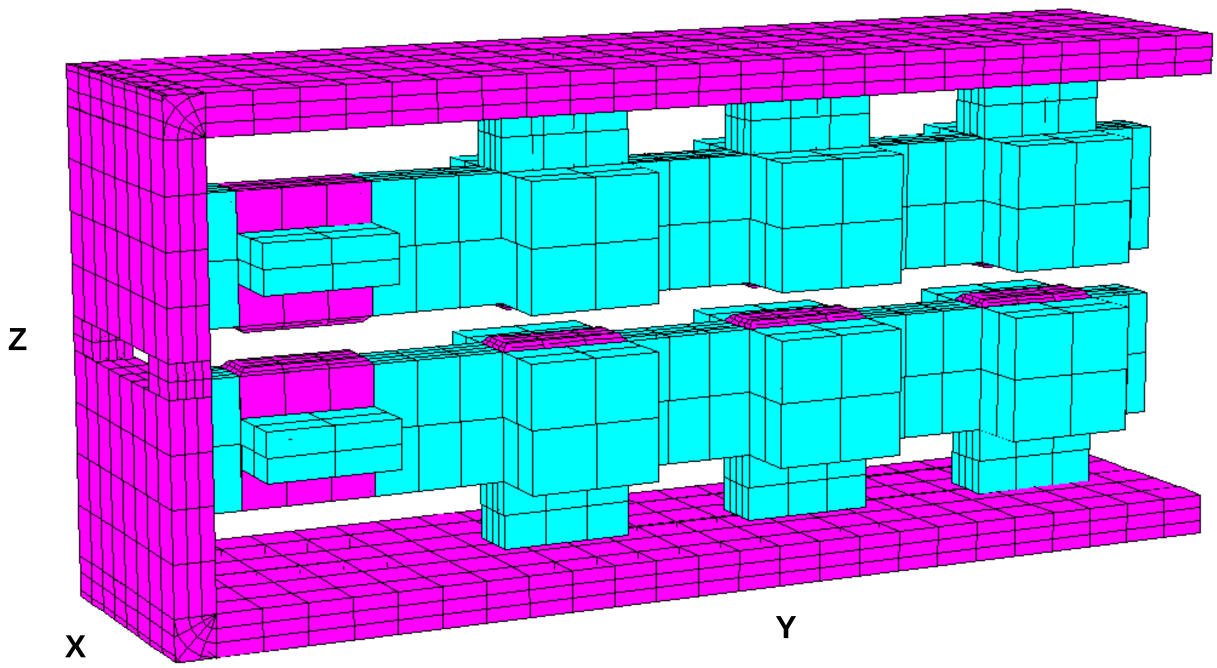

Fig. 1: Magnet structure of the TESLA damping wiggler. A short part of a full segment is displayed with dismantled iron yoke sides, the strength of the end poles is reduced.

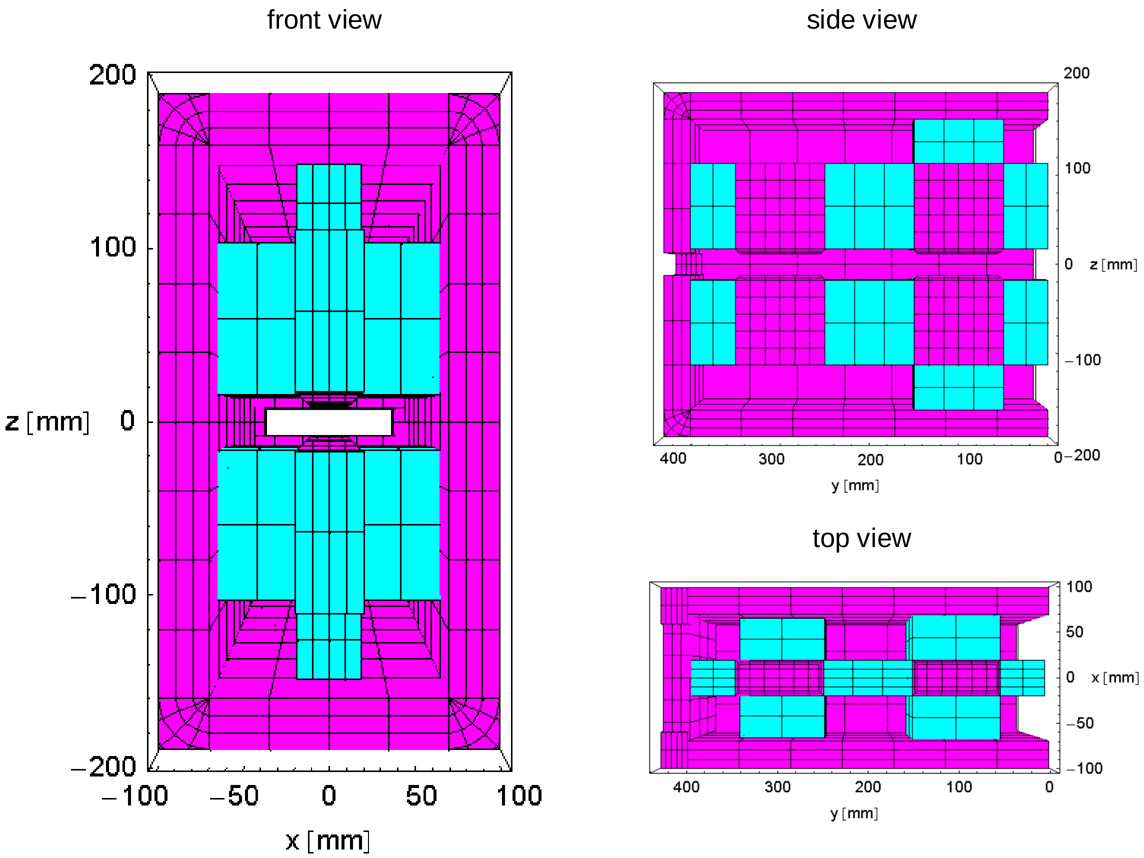

Fig. 2: Different cuts through the wiggler structure. Transversal dimensions of the compact device are ~200×400mm^2.

Details of the magnetic design are illustrated in Fig. 2. The whole structure has a rather compact size with a cross section of only ~200×400 mm^2. The poles have a dimension of 100×40×100 mm^3 (L×W×H) with a symmetric chamfer of 5 mm corresponding to the pole overhang in the gap region and are made from low carbon steel. NdFeB with a remanence of M_r ~1.15 T is used for the axial, side and top magnets with dimensions of 100×40×95 mm^3, 100×50×95 mm^3, 100×40×50 mm^3, respectively. An iron plate with a thickness of 30 mm encloses the whole and acts as magnetic yoke. It is on zero magnetic potential and shields the inside of the wiggler magnetically. In particular, the shield acts as a field clamp which terminates the magnetic field sharply at the ends avoiding extensive fringe fields in the focussing section adjacent to a segment. This design is very compact and mechanically stable as the yoke also serves as support to carry the magnetic assembly. There is an opening in the yoke face for the vacuum pipe of 25×120 mm^2.

The magnetic design has been calculated using the Radia code [4]. Only a representative sub-unit with several periods of a complete wiggler segment has been computed for the determination of the magnetic properties. Sufficient segmentation of the single elements of the magnetic structure was proven in order to assure convergence and reliable results of the calculation. A maximum value of B_0 = 1.67 T was found for the vertical peak field in this geometry which corresponds to a K value of 62.5. Figure 3 illustrates a 2-dimensional field

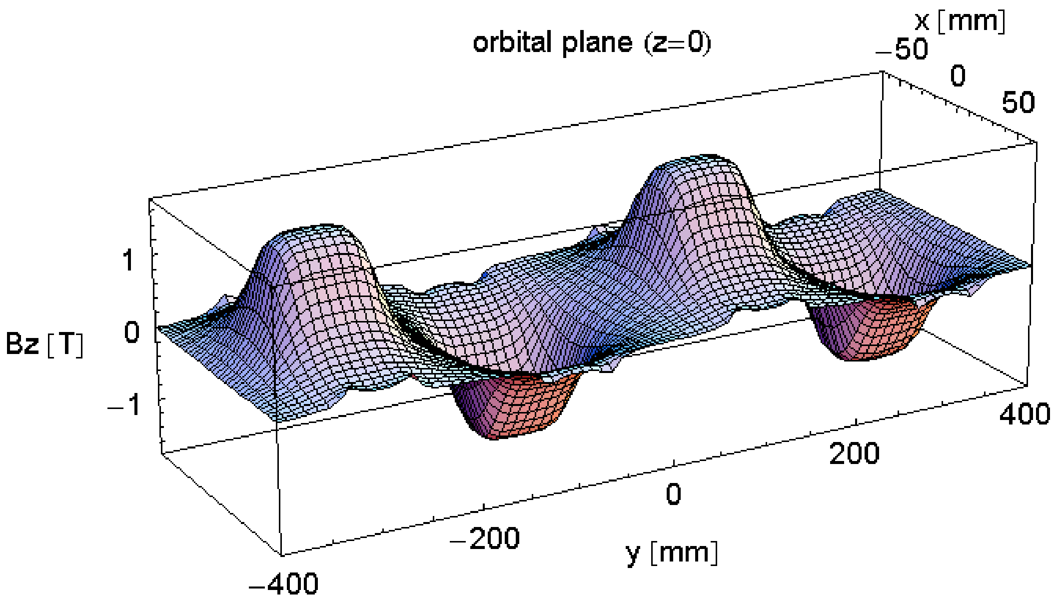

Fig. 3: 2-dimensional field map within the orbital plane z = 0.

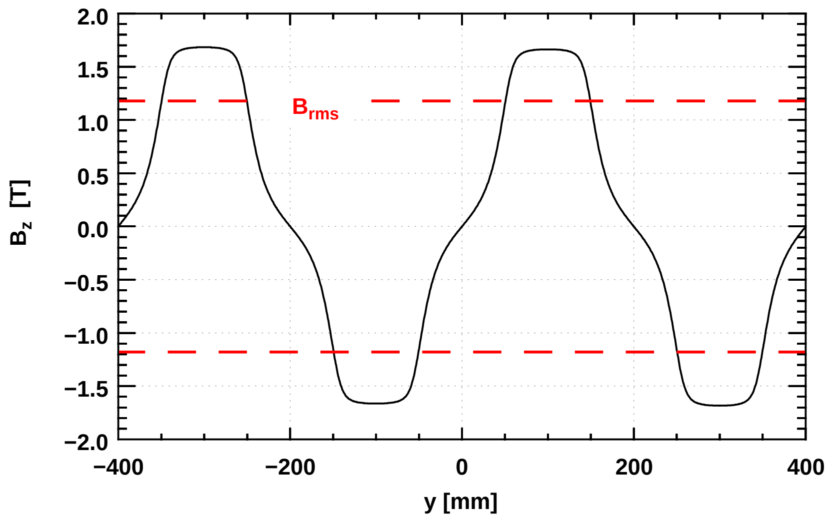

Fig. 4: Vertical field along the wiggler axis. A peak field B_0 = 1.67 T is obtained with a corresponding rms value B_0^{rms} = 1.17 T.

map of B_z within the horizontal plane. The on-axis field dependence $B_z(y)$ shown in Fig. 4 exhibits broad plateau-like maxima and a pronounced deviation from a sinusoidal field distribution. The corresponding rms values are B_0^{rms} = 1.17 T and K^{rms} = 43.8. A good field region of ±10 mm is needed in the transversal direction for the injected positron beam. It has been shown [5] that only moderate transversal field homogeneity is required for periodic structures. The transversal field dependence $B_z(x)$ in Fig. 5 shows a broad maximum plateau with a value

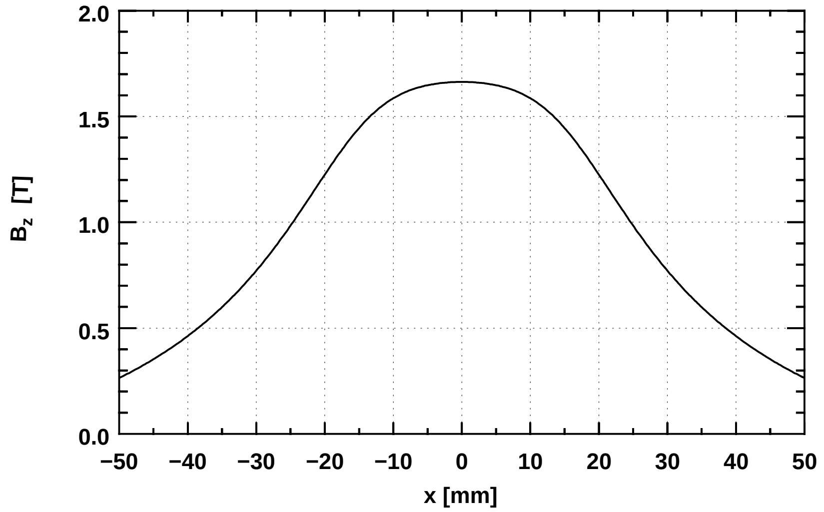

Fig. 5: Transversal field dependence $B_z(x)$ in the orbital plane z = 0.

$\Delta B/B_0 \lessapprox 4\ 10^{-2}$ for -10 mm $\leq x \leq 10$ mm which is sufficiently small. A total amount of 6120 cm^3 magnet material per period is necessary to achieve these field properties.

An antisymmetric field configuration has been chosen for this device. In this case the 1st field integral is zero by definition while the 2nd field integral has to be brought to zero by means of appropriate trimming of the end poles which is easy and straight forward to realize for a planar fixed gap device. The shortest ends can be attained by simply weakening the field of the last pole. A possible solution is to skip the top magnet and to reduce the height of the side magnets (Fig. 1). Then, vertical adjustment of the side magnets serves as a sensitive tune of 2nd field integral as illustrated in Fig. 6. This procedure results in a tiny trajectory slope of about 0.3 mrad across the wiggler which is negligible compared to the ~13 mrad opening

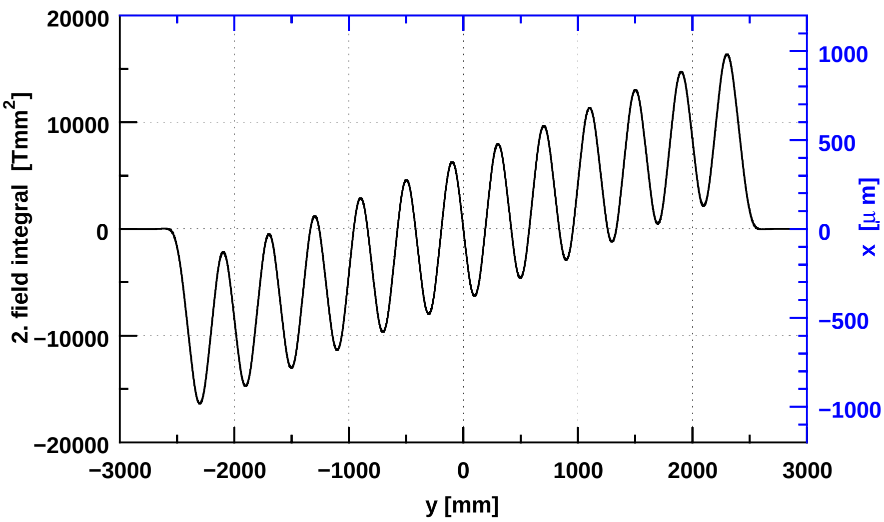

Fig. 6: Reducing the strength of the end magnets is an efficient way to trim the 2nd field integral and resembles the shortest possible end configuration. The resulting trajectory slope of ~0.3 mrad is negligible compared to the 13 mrad opening angle of the synchrotron radiation cone.

angle of the radiation cone (Sect. 5). The maximum trajectory excursion is about 990 µm and has to be compared with the regular periodic deflection by ±400 µm in case of an on-axis trajectory. The impact of the tilted trajectory on the field roll-off is negligible: The central part of the beam experiences a $\Delta B/B_0 = 4{\cdot}10^{-4}$ compared to $1{\cdot}10^{-4}$ for an on-axis trajectory, for the outer parts at x = ±10 mm these values are $6{\cdot}10^{-2}$ and $5{\cdot}10^{-2}$, respectively. Therefore, the tilted trajectory should not entail noticeable drawbacks but makes the segments even more compact. A more thorough investigation of the influence on beam dynamics will follow.

In an antisymmetric field configuration there are no multipole components for an ideal structure. Multipole fields can only occur due to field imperfections. A coarse estimation of field errors to be expected is possible by comparison to similar devices, e.g. the 2 T wiggler BW5 at the DORIS III storage ring. This wiggler was not at all trimmed towards a low multipole content and nevertheless reached multipole coefficients of 1.1 T/m, 9.8 T/m^2, and –1050 T/m^3 for the sextupole, octupole, and decapole component, respectively. The skew components had been in the same order. These values would match the damping ring requirements. Furthermore, small residual multipole components of individual wiggler segments can be compensated to a large extent from cell to cell by appropriate orientation of successive modules making use of their three-fold rotational symmetry.

A key quantity of a damping wiggler is the value of the damping integral $I_D = \int B_z^2 dl$ per period which determines the total length of the wiggler. Due to the strong deviation from a sinusoidal field distribution analytical approximations of the field integrals will hardly lead to reliable results. The numerical determination of the I_D is presented in Fig. 7 and shows a step-like behavior with a remarkable growth value of 0.55 T^{2}m per wiggler period, i.e. 1.37 T^{2}m per meter. The TESLA layout [1] requires an overall damping integral I_D ~ 645 T^{2}m while the arcs in the ring will only contribute with ~40 T^{2}m. Hence, a damping integral of I_D ~ 605 T^{2}m has to be achieved in the wiggler section which corresponds to a wiggler length (including end poles) of about 475 m equivalent to 90 modules à ~5 m length. The modular construction of the wiggler segments also allows to place the wiggler in several shorter series according to the needs of the machine.

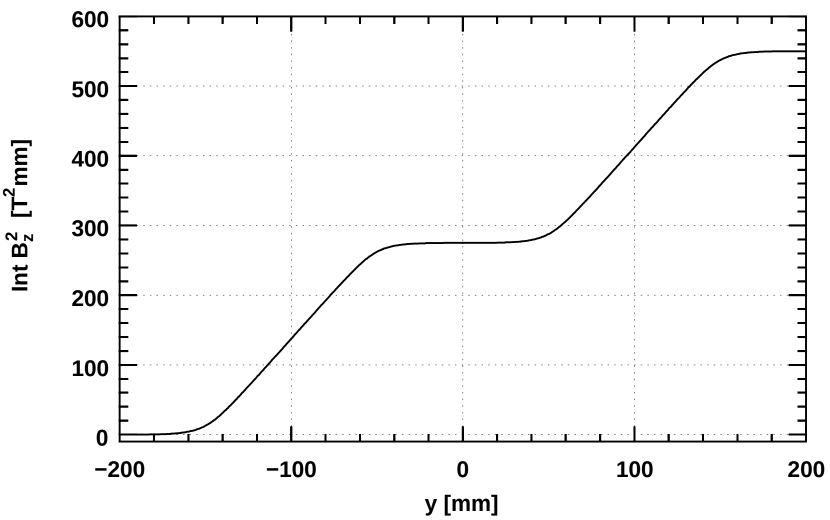

Fig. 7: The damping integral $I_D = \int B_z^2$ dl has a growth rate of 0.55 T^{2}m/period corresponding to 1.37 T^{2}m per meter.

4 Parameter optimization

At present, the magnetic design has been pushed to a level which allows a thorough discussion and comparison to other damping wiggler ideas like an electromagnetic device [3]. Advantages and drawbacks of both solutions can be carefully compared on the basis of this report. In case of a future go-ahead for a permanent magnet wiggler concept the present design has to be completed in some aspects and should be refined in others.

It is estimated that, retaining all specified parameters dependent on the beam optics, further optimization can yield a performance improvement, i.e. peak field B_0 and damping integral I_D, in the order of a few percent. This mainly covers modifications of the magnet proportions while keeping constant their total volume. Figure 8 demonstrates that the peak field B_0 can be slightly enhanced further by increasing the pole length to 110 mm. Although even improvements in the per mille range are fruitful because of mass production arguments it must be considered whether higher uniformity of the magnet blocks for the manufacturing might be even more economical in total. The endpole design has to be refined and a field error analysis should be performed to estimate multipole components and to consider a suitable compensation scheme. Finally, tolerances for magnet quality, assembling and alignment accuracy have to be determined.

If it would be possible, a slight release of some machine restrictions as the minimum beta function or the required good field region would imply considerable potential for savings and optimization of the damping wiggler. In these cases the pole width and the gap could be reduced, both leading to a higher damping integral and, hence, to a shorter device. For example, a magnetic gap of only 20 mm with the same magnetic arrangement as discussed above would result in a damping integral $I_D = 1.74\ T^2m$ per one meter wiggler structure, i.e. an increase of 27% which directly translates to a shortening of the device by 19 segments or 100 m.

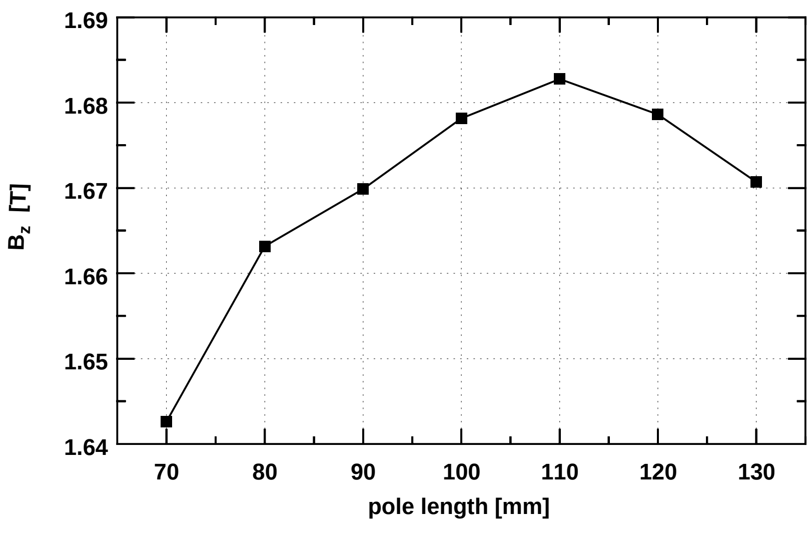

Fig. 8: The optimization of the pole versus the magnet length (λ_u = 400 mm = const.) exhibits a shallow maximum around 110 mm pole length.

5 Radiation Damage

Radiation resistance is one of the concerns about long term reliability of permanent magnet insertion devices. In the past, many studies have been performed to investigate the damage mechanism and to quantify the performance degrade [6-9] but these observations can hardly be transferred one-to-one to the situation at TESLA. Incontinent exposure to radiation will result in a demagnetization of the permanent magnets. While there is not yet a microscopic understanding of the damage mechanism it is obvious that degradation of the magnetization occurs by a breaking up of mono-domains within the magnet. Due to that material with high coercive force has to be used.

The synchrotron radiation created by the wiggler itself is not harmful to the magnets. Several studies [10] summarized by Ref. [7] have reported that irradiation of various magnet material by gamma radiation of a ^{60}Co source does not lead to any measurable demagnetization up to dose level of ~14 MGy. However, the produced synchrotron radiation might immediately destroy the vacuum pipe if it is dumped somewhere in an uncontrolled way due to a miss-steered beam. Precautions have to be taken analogous to the routinely working safety system at the PETRA undulators [11].

Any particle loss causes hard bremsstrahlung and a decaying secondary particle shower. For simplicity, only two processes are distinguished here: i) A miss-steered beam which accidentally hits parts of the wiggler will dump all its energy in a rather small volume, and ii) marginal loss of fractions of the beam continuously happening during normal operation causes a low level, however, permanent radiation background which leads to a long-term demagnetization of the magnets. Dark current, a third possible process, cannot exist in storage rings and will be of no concern.

Consequently, i) collimators and other protection systems have to be installed in front of the damping wiggler to avoid a full beam loss within the wiggler section of the damping ring. Tesla Test Facility (TTF) experience demonstrates the success of a phase space collimator which will protect the device adequately during regular routine operation [12]. Beam position and current monitors as well as a fast interlock system will ensure wiggler protection in case of system failures. ii) The current stored in the damping ring (160 mA) is similar to that of a 3rd generation light source and, hence, the operating conditions of the damping ring have to be comparably or more stable to keep the permanent radiation background sufficiently small. The typical average exposure in a synchrotron storage ring is in the order of 100 Gy/Ah [13] to 500 Gy/Ah [6]. It has been shown [6,7] that the magnet lifetime of synchrotron storage ring insertion devices easily exceeds several thousand Ampere hours normal operation without significant demagnetization.

In case of the TESLA damping ring additional radiation background will be caused by the main linac, however, doses will be rather small as electronics will be placed within the tunnel. Present calculations for TESLA operation [14] estimate a linac-based radiation dose of about 10-100 mGy/h at the damping wiggler location in the tunnel which might add up to ~5000 Gy after 10 years of operation. A 1 MeV neutron displacement damage of ~10^6 1/cm^{2}h has to be expected in the tunnel for a 250 GeV electron beam; again requirements for electronics are more critical than for permanent magnet material. To some extent the wiggler itself also resembles a shield for its inner parts which contribute most to the magnetic field generation.

Recently, a detailed study [9] has investigated the damage of ID magnets by 2 GeV electron bombardment. It reveals that the demagnetization profile across a magnet block strongly depends, besides others, on various things like magnet shape, magnetization direction, magnet stacking order or the material of the primary electron target. As long as an adequate theoretical model is missing, these observations point out that a precise prediction of potential demagnetization and a sound radiation resistance estimation is impossible today.

Nevertheless, a coarse life time estimation is attempted on the basis of literature values: Ref. [15] reviews various studies on damage effects which scatter by more than two orders of magnitude, however, those which were found to be applicable to conditions at the APS storage ring gather at a value of roughly 0.3 MGy radiation dose per 1% demagnetization of the magnet material [16]. We adapt these pessimistic values to the situation at TESLA and furthermore assume a mean exposure of ~300 Gy/Ah which corresponds to the average of values mentioned above although doses should be significantly lowered due to the collimator. Considering an annual operation time of 5000 h and a stored current of 160 mA, a 10% magnetization loss would be observed after twelve years of operation. It should be emphasized that such a crude estimation has an immense error bar; it only serves to indicate that magnet lifetime is in a feasible order of magnitude and radiation damage problems can be handled in the future. The recipe to circumvent demagnetization problems beyond the safety measures pointed out above is to choose magnet material with an ample reserve in terms of coercive field H_c instead of leering at highest remanent field B_r.

6 Radiation Output

The synchrotron radiation created in the damping wiggler has large power and puts a high thermal load onto the vacuum chamber. The radiated power has been calculated using the "bend source approximation" for the present machine parameters E = 5 GeV, I = 160 mA. The wiggler field has been approximated by a sinusoidal field with an amplitude of 1.67 T, i.e. a rms value corresponding to that of the determined wiggler field B_0^{rms} = 1.17 T. The spectral distribution of the radiated power has been calculated for one wiggler segment containing 12 full periods and is depicted in Fig. 9 together with the integral power. The peak power occurs around 5 keV while the averaged critical energy is E_c ~ 28 keV. The integral power adds up to 33.9 kW per segment, about 90% of it is generated in a window between 2.5 keV and 90 keV. The on-axis power (1×1 mrad^2) has been determined for comparison and results in an integral value of 3.4 kW per segment.

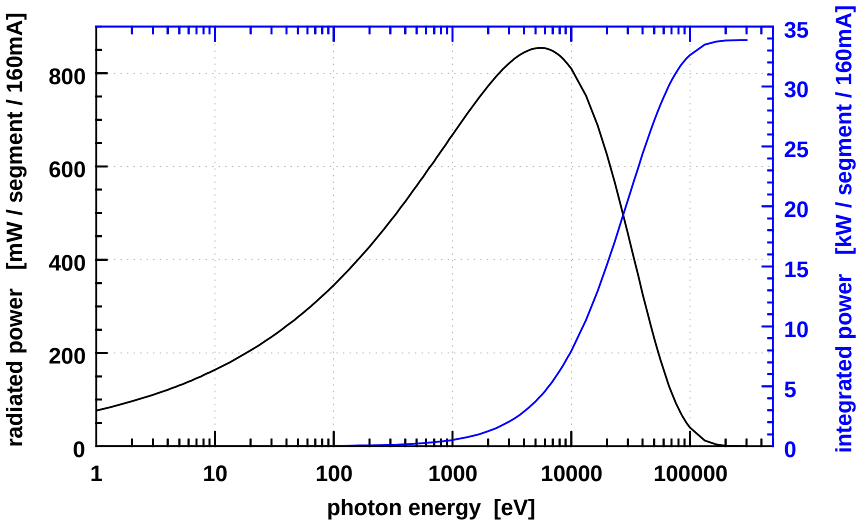

Fig. 9: Radiated power of a 12 periods wiggler segment together with the integral value. The power is radiated in a fan of 13 mrad opening angle, the integrated (1×1 $mrad^2$) on-axis power is in the order of ~3 kW.

Most of the power is of course radiated into forward direction with a horizontal opening of $\alpha \sim 2K/\gamma \sim \pm 6.4$ mrad. Hence, a vacuum chamber width of at least ~100 mm is necessary to avoid that light created at the entrance of a ~5 m long segment hits the chamber wall of the *same* module. It is planned to place absorbers from all sides in the drift space between two wiggler segments which shadow the intersection components and the successive segment against the radiation of the previous upstream module. A vacuum chamber design for the damping wiggler has been proposed previously [17] and a refined concept is currently developed within a study for the electromagnetic damping wiggler alternative [3]. There is almost no difference in the vacuum chamber for both wiggler options.

In the space between two wiggler segments components like cooled absorbers, vacuum pumps, quadrupoles, monitors and steering coils will be placed. There are no crucial mutual restrictions between these components on the one and the wiggler modules on the other hand, and therefore, these devices are not discussed in this report.

7 Production and Survey

The length of the damping wiggler is in the order of all insertion devices installed at the latest 3rd generation synchrotron storage rings worldwide. It is obvious that a device like that has to be manufactured on an industrial scale. Although the production of about 50 tons of magnets for one of possibly two wigglers is in the order of ~10% of the annual production of a large manufacturer of this material, the actual challenge is not the fabrication of the raw material but the further processing to a complete wiggler segment. The production concept implies that a company delivers completely mounted, shimmed and characterized segments which are ready for installation in the linac tunnel.

The synchrotron radiation produced by a damping wiggler is not of interest and in this context the wiggler is not a precision device in terms of field quality. Therefore, it is fortunately not necessary to apply individual characterization and sorting of more than 18.000 single magnets needed for one damping wiggler system. Nevertheless, the performance of the wiggler will benefit from future improvements of the magnet fabrication process [18].

A mechanical design for magnet and pole keepers and their attachment to the iron yoke has not been worked out yet but considering the simple geometry of the device the construction work of these parts should not be too difficult. The size of the center and side magnets is too big that they could be made out of a single piece. Instead, pairs of magnets have to be glued to one block which is an established standard technique. Individual manufacturing tools are required, e.g. dies and forms to press the three different sorts of magnets, several fixtures for gluing them, special auxiliary assembling tools or a hydraulic mounting device. These things will be developed by or in conjunction with the magnet supplier.

After assembly each structure is magnetically surveyed and tuned. As the wiggler is completely enclosed by the iron yoke it is not possible to access the gap region by conventional hall probes. However, the optical properties of the wiggler are not important and, hence, it is sufficient to determine the integral properties of the device. The 1st and 2nd field integral and also multipole components can be measured by means of a moving wire system [19]. A pulsed wire system can be used to determine the electron trajectory through the wiggler module. A standard moving wire system has to be suitably modified to these needs. Detailed and complete survey and shimming recipes have to be elaborated in the prototype phase which can then be handed to the company so that a trained person will be able to characterize and tune a device without being an expert. A vertical field correction can be realized by adjusting the vertical position of one of the side magnets. Residual horizontal field integrals need to be corrected by placing shims. If it is not applicable to place shims through the ends of the magnet structure small windows in the yoke side parts should be considered to access the gap region. Relevant multipole components have to be logged and will be taken into account by appropriate order and orientation of the segments in order to compensate multipole errors as good as possible.

The insertion of the vacuum chamber probably needs some more effort than usually. Due to nonexistence of any lateral opening in a wiggler segment the bare vacuum chamber has to be inserted from one end before welding the second vacuum flange to the chamber. After that the vacuum chamber cannot be removed anymore out of the wiggler. The welding may not at all affect the adjacent magnets thermally. Alternatively, a mechanical design could be considered where the upper and lower part of a segment can be separated for an easy insertion of the vacuum chamber; in this case a precise snug fit has to guarantee absolutely reproducible mounting positions.

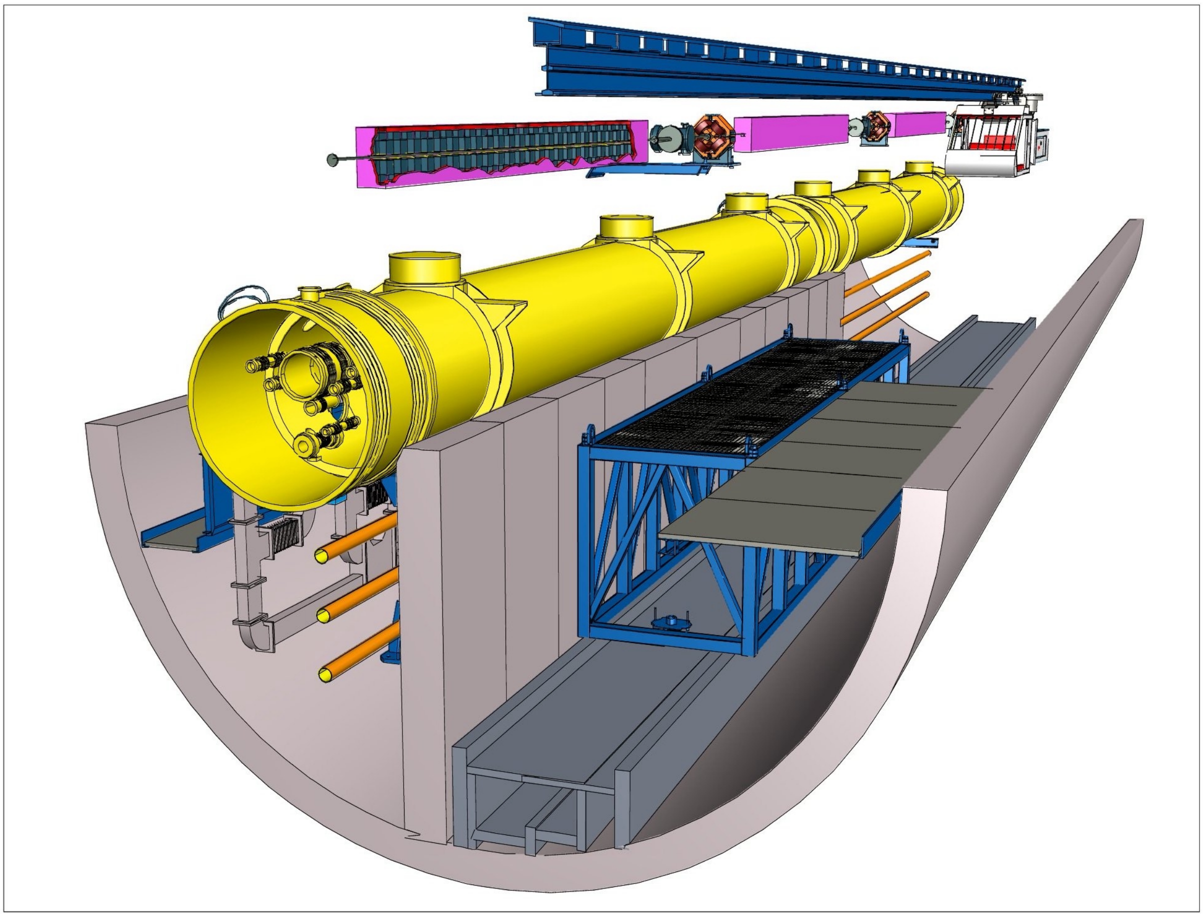

Fig. 10: TESLA tunnel cross section [20]. The compact damping wiggler will be installed below the ceiling; each wiggler cell consists of a magnet structure, an absorber and a quadrupole.

8 Supporting Construction

The damping wiggler will be located in the straight sections of the damping ring and will be mounted below the ceiling of the main linac tunnel (Fig. 10). Due to its compact size only moderate construction effort is necessary to carry the wiggler. At present, there does not exist a mechanical concept yet, however, it would be quite reasonable to use an adapted quadrupole magnet support as a wiggler segment needs the same mechanical adjustment features for alignment as a quadrupole does. A wiggler segment could be carried by two of these supports mounted at both ends of a module.

The weight of the pure wiggler structure –including the iron yoke but without any mechanical support– has been calculated to 381 kg per 1 meter wiggler structure corresponding to a weight of ~2 tons per wiggler segment. The idea of the present concept is that a wiggler segment is self-supporting, i.e. that the iron yoke also acts as support girder for the magnet structure. The magnetic force between the two wiggler halves has been estimated to ~110 kN.

A wiggler of this type is a comparatively robust device which gives no reason for any transport problems within the tunnel. By the time of installation of a wiggler segment in the tunnel the vacuum chamber must already be inserted into the bore-like opening of the wiggler.

9 Costs

Several points will contribute to the total costs of the discussed device, e.g. final developments, mechanical engineering and preparation of drawings, the hardware material, man power effort for manufacturing the complete device or later operational expenses.

An amount of 115 kg NdFeB magnets as well as 266 kg low carbon steel for the poles and the yoke is required per meter wiggler structure. Special manufacturing and mounting tools have to be developed and built. Assembling of these parts to a wiggler segment, magnetic survey and tuning is also covered in this estimation. Only usual random tests during magnet fabrication and no individual magnetic and geometric characterization of the magnets are considered in this assessment. Expenses for the suspension frame of each segment and overall contingencies have been added to this cost evaluation. Altogether, this results in a value of 31.200 €/m wiggler length which corresponds to 24.500 € per 1 T^2m damping integral.

Permanent magnet insertion devices generally distinguish by the absence of operational costs. Long lasting experience with permanent magnet wigglers has shown that these devices demand almost no maintenance. For the fixed gap wiggler like this it is limited to occasional inspection of mechanical joints as strong forces permanently act within the device.

10 Summary

The presented concept demonstrates that permanent magnet technology is feasible for a long high field wiggler device. Table 2 summarizes the parameters of the damping wiggler. The design excels in a compact size which allows to install the wiggler at the ceiling of the TESLA main tunnel so that no further straight sections in the arcs of the damping ring tunnel are necessary. The length of a wiggler segment can easily be adapted to the value most appropriate for the focussing lattice.

The design criterion is based on the following aspects: i) The wiggler does not require a high field quality, ii) the antisymmetric field design assures a 1^{st} field integral equals zero, iii) a zero 2^{nd} field integral is obtained by trimming the end poles, and iv) a low multipole content is preserved by the antisymmetric configuration.

The wiggler produces a radiation power of ~34 kW per segment of 5.26 m length which has to be absorbed by the vacuum chamber and additional absorbers. A safety system might be necessary to prevent vacuum components from immediate destruction by an accidentally miss-steered beam. For a permanent magnet device, experience and calculations have to prove a sufficiently low radiation exposure for stable long-term operation. A radiation background of 10-100 mGy/h has been estimated for the dose induced by the main linac which is smaller than the radiation dose generated by the damping ring itself considering normal operation conditions comparable to other storage rings. This points out that radiation damage problems can be handled. However, uncontrolled beam loss has to be circumvented by a reliable collimator system in front of the wiggler section.

Further refinement of the design may optimize the device by several percent in terms of peak field, damping integral or magnet volume, i.e. production costs. Any release of machine based wiggler specifications will have more considerable impact on savings. A prototype phase has to prepare the later production on industrial scale. For this purpose appropriate procedures and treatments for assembling, magnetic survey and installation have to be elaborated. Despite higher initial costs of a permanent magnet wiggler a passive device like this is advantageous because of missing operational costs and negligible maintenance.

Wiggler Parameters		
wiggler period λ_U	40 cm	
magnetic gap g	25 mm	
pole dimensions (L×W×H)	100×40×100 mm^3	low carbon iron
axial magnets	100×40×95 mm^3	NdFeB
side magnets	100×50×95 mm^3	
top magnets	100×40×50 mm^3	
yoke thickness	30 mm	low carbon iron
cross section	200×385 mm^2	
peak field B_0	1.67 T	B_0^{rms} = 1.17 T
wiggler parameter K	62.5	K^{rms} = 43.8
trans. homogeneity $\Delta B/B_0$	~4 10^{-2}	for x=±10 mm
damping integral I_D	1.37 T^2m per meter	0.55 T^2m per wiggler period
damping integral I_D	6.73 T^2m per module	inclusive end poles
required damping integral I_D	605 T^2m	for the wiggler section
# of (full) periods/segment	13 (12)	
segment length	5.26 m	
# of modules	90	
total magnetic length	473.4 m	
# of magnets	~18.000	
total magnet volume	~6.8 m^3	≅ 51 tons
weight per segment	2.0 tons	(without support)
magnetic force	~110 kN	
critical energy E_c	28 keV	
radiated power per segment	33.9 kW	
on-axis power per segment	3.4 kW	(1×1 $mrad^2$)
horizontal opening α	± 6.4 mrad	

Tab. 2: Summary of relevant parameters of the permanent magnet damping wiggler.

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