Manufacturing Considerations of the Magnetic Structures for the Undulators for the X-FEL at TESLA

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Abstract

A study is presented to estimate the production effort of the magnetic structures for the undulator systems of the TESLA X-ray SASE FELs. The total magnetic length of the magnet structures is 1405m. It is proposed to produce these huge quantity 'turn key ready' on an industrial scale. This implies a resolute R&D effort. It should include the improvement and optimization of the material quality of NdFeB material, the development of robust magnetic measurement and fine tuning techniques, which can be used in an industrial environment and an extended prototyping phase. These developments are prerequisite for successful industrial production and are described in more detail. An estimate is made for production capacities which are required to produce 1405m of magnetic structure within five years.

1. Introduction

At DESY in Hamburg the Technical Design Report (TDR) for the TESLA project is presently being finalized /1/. It will be submitted by spring 2001. The TESLA project includes a 32km long linear collider with an integrated Free Electron Laser in the hard X-ray regime (X-FEL). A conceptual design of this project has already been published /2/. An overview over device parameters is given in table1. The X-FEL laboratory is shown schematically in Fig.1. It contains four primary FELs SASE1 through 4, at radiation wavelengths as low as 0.085 nm. SASE5 is working in the soft X-ray regime at 0.5-3.1nm using a helical undulator. It uses the spent beam of SASE3. There are five spontaneous radiators working in the hard to ultra hard X-ray regime down to 0.01nm. They are all planned as secondary devices.

All FELs use the principle of self amplified spontaneous radiation (SASE) /3,4/. For this principle a very long undulators are needed. The light emitted by electron bunches in the undulator interacts back with the electrons in the bunch resulting in microbunching of the electrons at the radiation wavelength. This in turn leads to an exponential increase of radiation intensity along the undulator which reaches saturation when complete microbunching of the electrons in a bunch is obtained. The saturation length of a SASE FEL strongly depends on the transverse and longitudinal emittance of the beam. For the parameters under discussion for the TESLA FEL the saturation length of a 0.1nm FEL can be as large as 220m, an undulator system can be as long as 323m (see table 1). The total system length has to take into account space for intersections for phase shifters, quadrupoles and correctors and some contingency for imperfect magnetic fields and misalignment. Only four different types devices are proposed. This limited variety of devices resembles the situation on small Synchrotron Radiation sources. The new dimension is, however, the sheer length, which is needed. For comparison, a 3rd generation synchrotron radiation source such as the ESRF has a total magnetic length of installed insertion devices of about 110m. Other facilities such as APS or Spring8 are similar. In contrast, as already mentioned, the total undulator length required for TESLA amounts to 1405m.

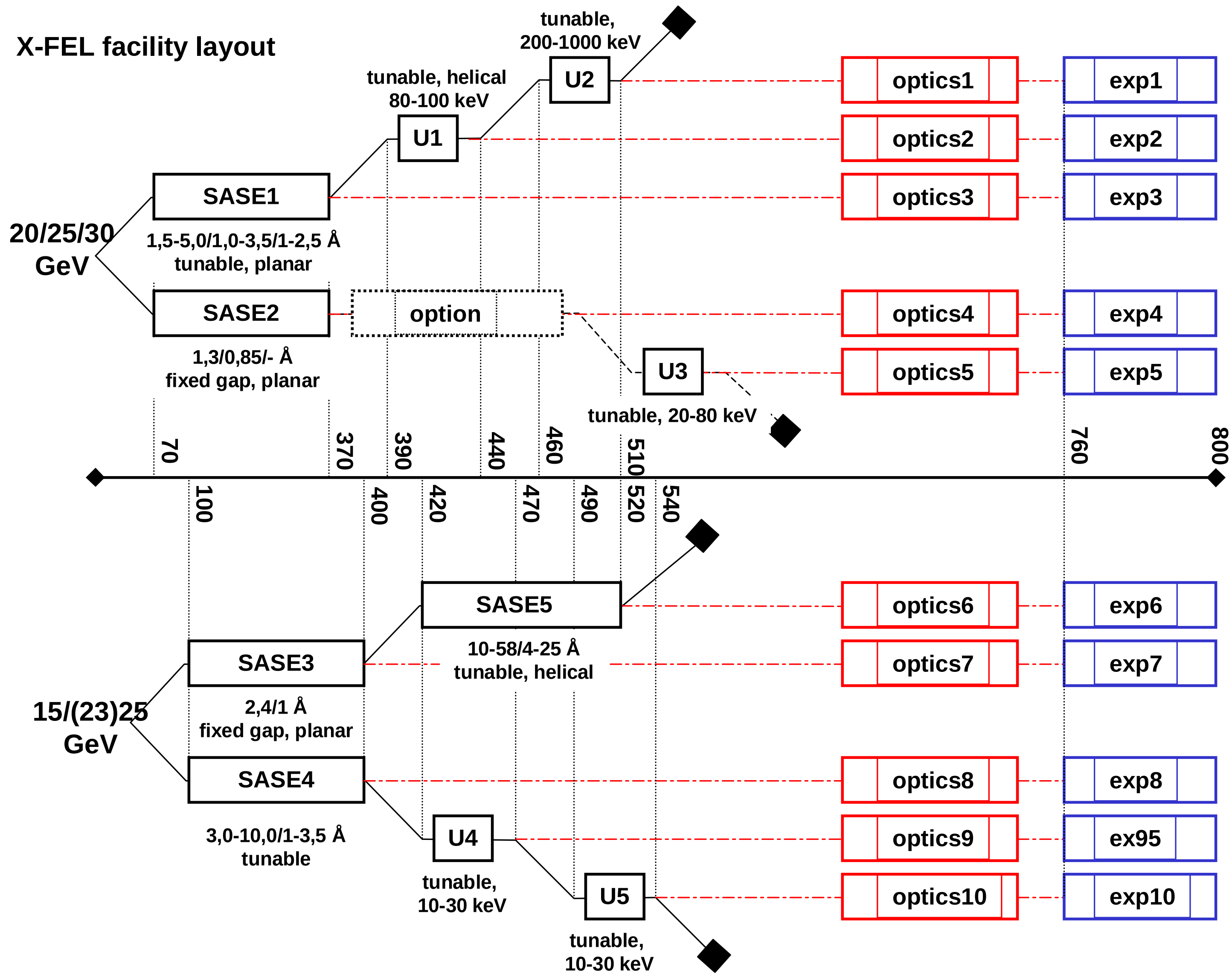

Fig. 1: Schematic arrangement of the undulator systems in the TESLA X-ray FEL lab

ice	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-4ments***
E1	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**
E2	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**
E3	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**
E4	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**
E5	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**
5	planar	**30 15**	**0.0083-0.025 0.0028-0.0083 0.033 - 0.10 0.0123 - 0.033**	**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 ;

Table 1 Parameters for the undulator systems for the X-ray FEL Lab at TESLA taken from Ref. 1

The TESLA undulator setup will benefit a lot from developments and progress made in the design and construction of undulators and wigglers built during the past 20 years at 3rd generation sources. The technology to build, measure and tune insertion devices is meanwhile well developed. Magnetic shimming and tuning techniques are now available so that devices can be produced with a magnetic performance very close to perfect /5,6/.
The key components of the undulator system are the magnetic structures. They are the most demanding and by far the most expensive components. Permanent magnet (PM) technology will be used, which is the only reasonable choice. This has been discussed extensively in /2,7/.Consequently this report concentrates on questions relevant to the mass production of magnetic structures for the insertion devices for TESLA.

This report focuses on the production effort and the logistics needed to produce the magnetic structures in industry. The ultimate goal is to have undulator segments produced, which are assembled, measured and fine trimmed to magnetic specifications so that they are ready for use. It is one of the big challenges for the TESLA project to get the magnetic structures for the undulator systems produced in reasonable time with reasonable quality and at reasonable cost.

This report is the fourth in a series on issues on the undulator systems for the TESLA FELs. The mechanical support system was treated in /8/, the control system in /9/ and the phase shifter in the intersection in /10/. A fifth on magnetic design of a prototype structure is in preparation /11/.

2. Description of an undulator systems for TESLA

For the TDR a detailed concept of the undulator systems has been worked out. Although this concept is not directly related to the subject of this report, it nevertheless sets the boundary conditions. Therefore a short description of this system is given below.

2.1. General layout of an undulator system

The undulator system will be segmented into 5m long undulator segments followed by an 1.1m long intersection, which contains a quadrupole for the strong focusing FODO lattice, a phase shifter, beam correctors, beam position monitors and a vacuum pump. One undulator segment and the adjacent intersection form an undulator cell. A small fraction of an undulator system consisting of three undulator segments and two intersection is shown in Fig. 2.

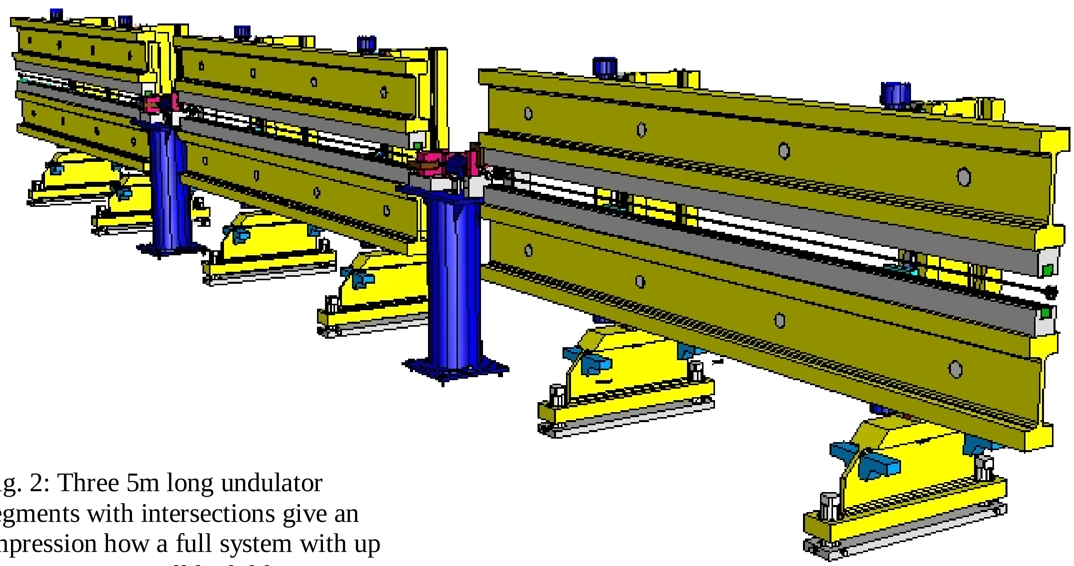

Fig. 2: Three 5m long undulator segments with intersections give an impression how a full system with up to 54 segments will look like

2.2 Mechanical design of an undulator segment

A standard gap separation drive and support system has been developed in a conceptual design study /8/. It considers principles of economic manufacturing of large quantities, while tough requirements on mechanical accuracy have to be maintained. The 3D view in Fig. 3 shows how these ideas could be realized. For the girders a voluminous I-beam profile with dimensions 550 x 200 x 100 mm is used. In order to limit girder deformation under changing load conditions, which occur during gap change, to values smaller than ±4µm such a large girder profile is needed with a corresponding large moment of inertia and a four point support is needed. More details are found in /8/. The same profile is also used for the support columns and the floor stands. This is much simpler than to build a welded box type structure and has the same or even improved stability. This large profile cannot be ordered off the shelf. It has to be produced on special request by a steel mill. This is unproblematic since more than 4700m of this profile with a total weight of about 1900 tons will be needed for the 281 support

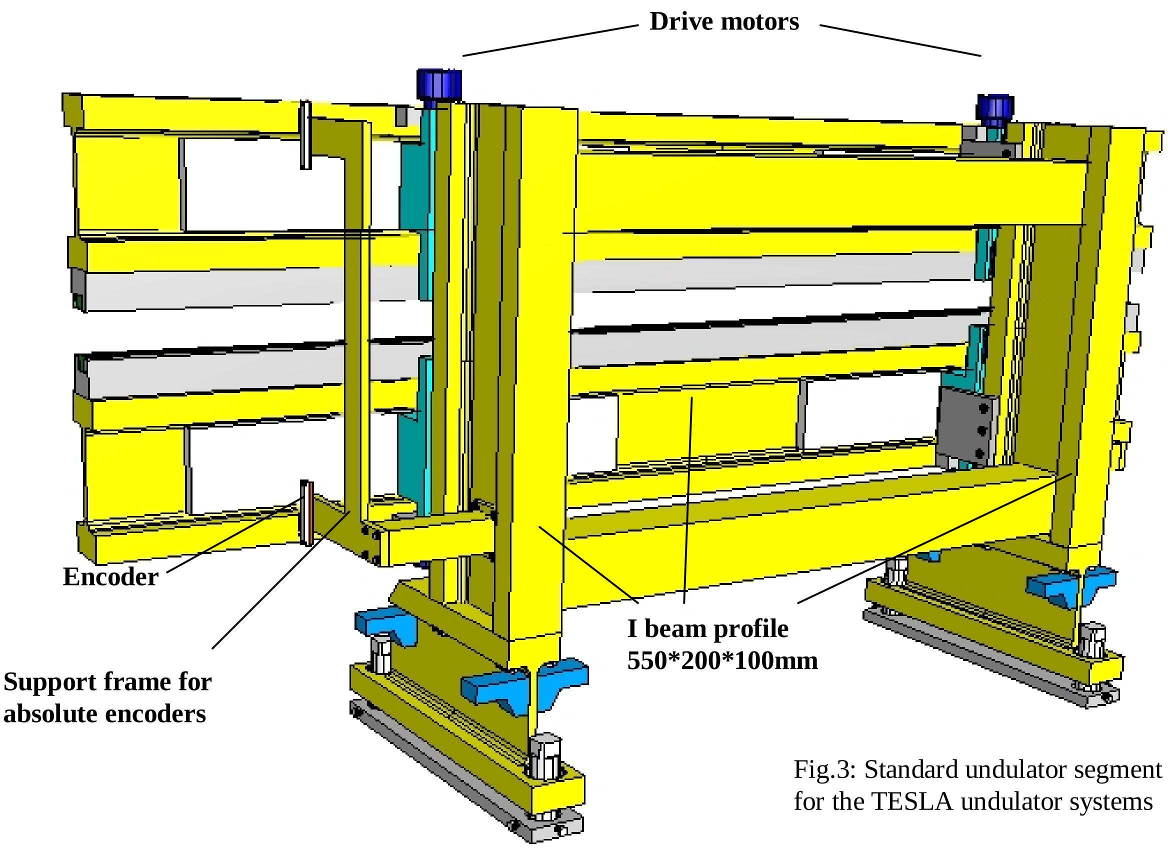

Fig.3: Standard undulator segment for the TESLA undulator systems

systems. The price is about 900 Euro/ton. Only little machining is required on the columns. Standard guiding elements are used. There are four individual motors which are appropriately synchronized by a control unit. Motors and their motion control units are part of the control system /9/. In order to get gap information with micrometer accuracy separate frames are used to support absolute length encoders. In this way the exact girder position close to the motor can be measured without errors induced by deformation of the girder support or the support structure. Gap adjustment accuracy is better than ±2µm.

2.3 Linear Magnetic structure

Three different planar magnetic structures with λ_0=30, 45 and 60mm are needed for TESLA. Representative for the other structures a planar magnet design for λ_0=60mm based on NdFeB PM hybrid technology has been developed for a prototype structure for the SASE1 undulator /11/. Its parameters are consistent with those given in table 1. At a gap of 12mm and a period length of 60mm the peak field is 1.33 T. At 25GeV and a gap of 22mm this device would radiate at 0.1nm and at 12mm gap at 0.35nm.The width of poles and magnets were determined such that a transversal good-field-region of ±1 mm results in which the relative field variation is less than the ρ-parameter, i.e. $4.2\ 10^{-4}$ in the open gap position. This is the most restricting case. In this way horizontal alignment requirements on the undulator segments are reduced and the FEL process is not affected by poor field homogeneity. Thus the proportions of magnets and poles have been optimized in terms of a sufficiently wide good-field-region and simultaneously, the required magnet volume has been minimized. The maximum peak field is obtained for a pole length of about 8 mm. The iterative optimization results in a pole geometry of $40\times 8\times 55\ mm^3$ (width × length × height) and $70\times 22\times 65\ mm^3$ for magnets. This corresponds to a magnet volume of 400 cm^3 per period or a demand for 13.3 tons magnet material for the 53 segments of 5m length.

2.4 Planar helical magnetic structure

For SASE 5 a helical structure is planned. There are two criteria which have to be fulfilled:

1. The structure should be planar thus allowing lateral access for high precision magnetic characterization and the insertion of vacuum systems.
2. Polarization properties should be adjustable.

A Sasaki-type undulator is proposed, which fulfills these requirements in an ideal way /12/. In addition, for a planar helical structure, it offers the highest fields and largest variation of polarization characteristics found in literature.

At BESSY II several of these devices are either in operation or under construction. They are up to 3.2m long. A design study of a helical undulator system for SASE5 has been made by the BESSY group, who is involved in these activities /13/. There, the polarization properties are explained in detail.

A Sasaki type undulator with adjustable properties requires considerable more mechanical effort than a planar one. For changing the polarization properties one half of the structure needs to be shifted and has to be equipped with suitable drives. This has to be done on all segments of the system with a magnetic length of 120m. It is a pure permanent magnet structure. No soft iron must be used for the girders. So its magnetic field quality depends completely on the quality of the permanent magnet material only. Great care is therefore needed in the characterization and selection of the magnets. The experience at BESSYII with this type of device is very encouraging.

2.5 Gap tunability, Phase matching, Beam Correctors

For three of the SASE undulators and the spontaneous radiators tunable wavelengths by means of gap tuning is required. This has three consequences:

1. In the case of the SASE undulators the saturation length is increased because the shortest wavelength at which the FEL is to operate is at the upper gap and determines the system length.

2. The phase matching of the photons originating from different segments becomes gap dependent. This relates likewise to the SASE and the spontaneous devices as well. A phase shifter consisting of a three magnet chicane is needed. A phase shifter with sufficient strength has been designed for the for the TESLA undulators. It is described in more detail in ref. /10/.

3. The third complication relates to field errors in the undulator which may become gap dependent and require suitable compensation.

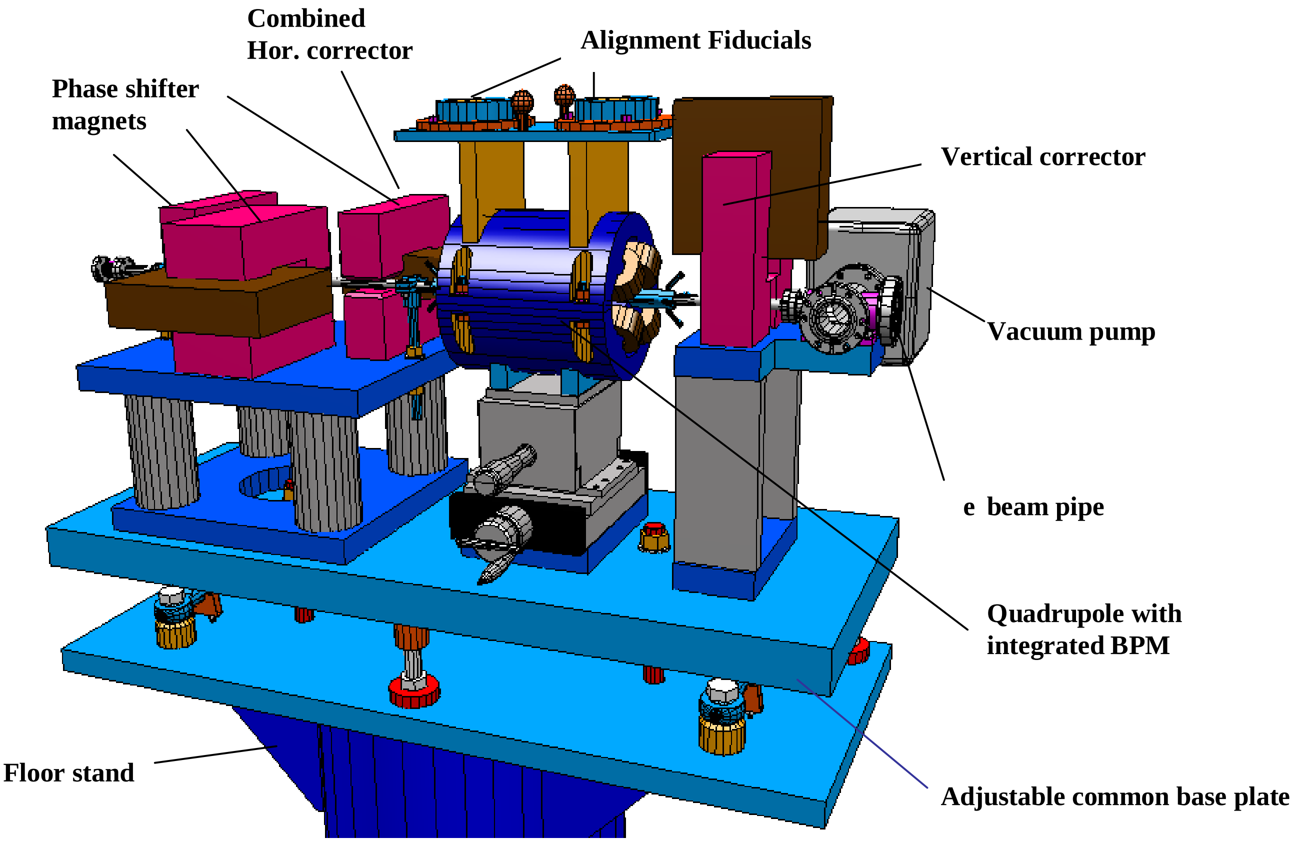

Fig. 4: Components in the intersection between undulator segments

Fig 4 shows a 3D view of an undulator intersection embedded between two neighboring undulator segments. The phase shifter is seen to the left. It consists of three horizontal magnets. The length of the center one is doubled because it needs twice the bending strength. The vertical corrector is seen to the right. In between there is a quadrupole with a 15mm bore which is capable of producing a maximum gradient of 100T/m. Its magnetic length is 0.2m only, the total length is about 0.26m. With these quadrupoles a minimum β function of less then 15m at 25GeV can be obtained without problems.

2.6 Control system

Each undulator system needs its own control system. It has to do the following tasks:

- synchronize the motors for gap motion
- provide gap dependent current settings for phase shifters and corrector magnets
- provide full computer control of the undulator system
- provide great flexibility to allow for numerous special operation modes

Most efficiently the control system is also organized in a cellular way in analogy to the mechanical setup. In this way it can be easily extended in a modular fashion. The control system of each cell consists of the four drive motors for the gap separation system and related components such as encoders, switches etc. which are needed in each undulator segment. The corrector coils of that segment which in general need current settings depending on the actual gap value of that segment also belong to that cell. Each cell is an individual unit and an undulator system is a repetitive array of up to 53 cells. A study for the realization of such a control system using industrial SIMATIC components has been made /9/. It complies with the above requirements.

3. Production strategy for TESLA

3.1 Past experience of Insertion Device manufacturing

Since the early 1980's insertion devices based on PM technology are used as sources of intense synchrotron radiation. The first was a wiggler to be used at SPEAR /14-16/. At DESY/ HASYLAB the first two insertion devices were the W1 and W2 wigglers /17,18/, which became operational at 1984 and 1987, respectively. These devices were all laboratory made. The mechanical design was made in house, magnets were purchased as single pieces, were magnetically characterized, sorted and subsequently glued and assembled to a magnetic structure. These steps were always very manpower demanding.

Production strategy changed as larger quantities were needed. The organization of the manufacturing of the ID s for DORIS III with a magnetic length of 32.7m /19-21/ and more recently the undulator for the VUV-FEL at the TESLA Test Facility /22/ with a total length of 15m was consequently very much different.

As before the mechanic and magnetic design was made in house. Standardized gap separation drives and girder profiles were designed for economic reasons. The manufacturing process was organized and supervised by DESY: The mechanical part was manufactured in suitable mechanical engineering companies found around Hamburg. The magnetic structures were built by magnet manufacturers such as Krupp-Widia, (Essen), Vacuumschmelze, (Hanau) or UGIMAC, (France). These companies took over responsibility for state of the art production of the 'magnetic systems': They produced the permanent magnets, poles, non-magnetic support parts etc., and also assembled the magnetic structures and mounted them onto girders which were supplied externally. Only fully assembled magnetic structures were then supplied to DESY, where they were mounted onto the drive and support system. The last step, the magnetic measurement and tuning of the structures was then made at DESY. On one hand this division of labor helped to keep DESY staff directly involved into ID activities as low as only 2-4 people and on the other hand still allowed good control over the magnetic performance of the devices. Excellent experience was made with this production strategy.

3.2 Plans for TESLA

3.2.1 General strategy

The insertion devices for TESLA a highly repetitive. Large numbers of identical items will be needed. This holds for all components involved in the undulator systems. Standardized components will be used wherever it is possible. This will be done for the mechanical support systems /8/ , the control systems/9/ and for the components needed in the intersections /10/. To a large extent this also holds for the magnetic structures. There will be only four different types of magnetic structures for ten beam lines, corresponding to 106 segments with λ=60mm, 96 with λ=45mm, 50 with λ=30mm and 29 helical ones. Moreover, except for the helical structure, their mechanical design will be very similar.

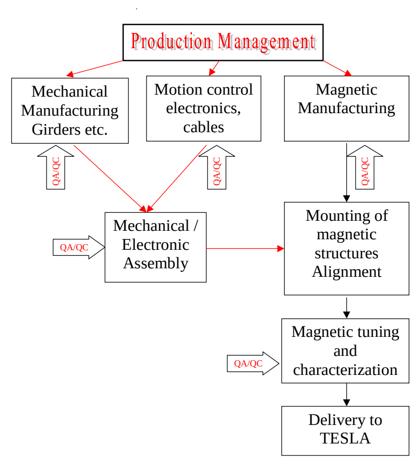

Fig. 5: Production management structure for the undulator segments

With the good experience on industrial manufacturing in mind it is evident to further extend the manufacturing process to ultimately deliver complete 'turn key ready' systems. For the manufacturing of the magnetic structures this implies, that magnetic measurements and fine tuning have to be within the volume of work, which will be commissioned out.

The production of undulator segments could be organized as shown in Fig 5. It is based on existing experience that it is difficult to find a supplier for all activities such as mechanic machining, motion control engineering and magnetic manufacturing. Usually magnet manufacturer don't want to deal too much with heavy mechanical engineering or electronic equipment. Mechanic workshops on the other side are afraid of dealing with magnetic structures. It is more advantageous to have these activities done at different well specialized companies.

It is essential that there is an efficient production management to organize the activities. It could either be done by TESLA staff or by an external contractor. The production management takes responsibility for the whole undulator manufacturing. Its duties and responsibilities are: Control of cost, quality, timeliness, coordination and synchronization of activities, coordination of sub delivery of components, quality assurance and quality control, documentation etc.. A possible flow chart how the production of undulator segments could be organized is sketched in Fig. 5. The assumption is made that there are three sub contractors, one for mechanics like support systems, girders etc, one for electronics such as servo drive systems, controls, data communication etc. and finally one for the magnetic structures. After production of the mechanics they have to be equipped with motors, encoders, limit switches etc., the electronics have to be made operational. This is made in a first step, which has to be organized. supervised and quality has to be warranted.The girders have to be delivered to the magnet manufacturer so that the magnetic structures can be assembled. After delivery the drive systems have to get combined with the magnetic structures to make the undulator segment operational. Then it has to be magnetically measured and fine tuned. In all these steps, quality assurance and quality control plays an important role, so that the performance of the individual production steps and the final product are warranted and well documented.

The production is based on assumptions on magnet material quality and tuning techniques, which have to be available and ready for use. They have a large impact on production times and cost. A resolute R&D effort is needed to make these techniques available prior to production. This is described in more detail in section 3.2.2. below

3.2.2 The three phases of the undulator project

The design, construction, installation and commissioning of the undulator systems is a huge activity. In order to get an overview over open questions, the R&D effort mentioned above as well as other activities, three phases have been defined, which will be described below. An overview is given in Table 2.

3.2.2.1 Project Definition Phase

Project definition means that the whole effort is outlined so that a realistic estimate on cost and manpower is possible. This covers all the activities needed to define undulator systems on the basis of requirements as defined by the future scientific needs. Thus the whole effort is determined by
a) by the intended future scientific use and
b) the requirements of FEL physics.
The scientific use determines the wavelength range and kind of device (number, SASE FEL or spontaneous radiator, wave length and tunability range, helical or planar structure). The total device length , i.e. the saturation length depends on anticipated machine parameters (normalized emittance, bunch length, bunch charge) and have to be determined by the underlying FEL physics. It is not the scope of this report to discuss these issues.

The TDR which is due in spring 2001 makes this definition and with its completion the definition phase is finished. The results presented in the TDR are also the basis for this report. Its quintessence in as much as undulator systems are concerned is reproduced in table1. It includes the results of numerous workshops and discussions on future scientific use, which were the basis for the undulator parameters. It also includes a thorough analysis of achievable machine parameters, which have a big impact on the total lengths of the undulator systems. Only parameters which correspond to present state of the art technology are taken into account.

Project phases for TESLA Undulators

Definition Phase ***TDR / 2001***

Definition of devices parameters by :

a) intended scientific use

b) machine parameters, FEL- Physics, Tolerances , Error Analysis

Prototype Phase ***5 years***

R&D efforts

Optimization of Insertion Device Technology

Optimization of magnet material production

- Powder metallurgical process optimization for more homogeneity
- Improve magnet orientation process

Development of magnetic measurement techniques for industrial use. (Test stands, Software etc.)

Design efforts

Mechanical design optimized for mass production

Motion control engineering

Magnetic design

Phase shifter design optimization

Prototyping

Heavy prototyping (>2-4 segments - mechanic + magnetic+ phase shifter)

Logistics

Define project management structure

planing of production capacities, manufacturing sites etc.

Goal: Everything ready for production start

Production Phase ***5 years***

Setup manufacturing plant / production capacities (1 year)

Production of≈ 280 segments at a rate of≈ 1.5 segment / week (4 years)

Goal: Completion of 281 segments within≈ 5 years

Table 2. Overview over the phases and activities of the TESLA undulator project

3.2.2.2 Prototype Phase

During the Prototype phase all questions regarding design and manufacturing of the undulators have to be addressed. The success of this work has a big impact on the on the whole project. The following points were localized

1. R&D efforts

a) Improvement and optimization of permanent magnet quality

This problem relates to the manufacturing process of the permanent magnet material and the magnetic structures, which are the most expensive and delicate items in the whole setup. Permanent magnets made from NdFeB with a high energy product will be used. This magnet material combines high field strength with high stability against demagnetization and is therefore ideally suited for insertion device applications like wigglers and undulators.
The magnets are produced using powder metallurgical methods. The powder is oriented crystallographically by applying a strong magnetic field while it is pressed in a die. The die determines the geometric shape of the magnet. Then it is sintered to reach full density. Magnetic homogeneity is determined to a large extent by the quality of the orienting field. Other properties strongly depend on alloy composition as well as on pressing and sintering parameters. The production steps of these materials are well established today. Main applications of NdFeB- magnets with quantities of many thousand tons per year worldwide are magnets for all kinds of electro motors, voice coil systems for hard disk drives and magnets for linear motors. For these applications the variation of magnetic properties and mechanical tolerances in the range of a few percent are typical and can be tolerated. For undulator applications the variation of properties should be at least one order of magnitude lower to be tolerated without further action. Today magnetic structures need therefore extensive measurements on all single magnet blocks prior to assembly and subsequent block sorting using mathematical methods such as ‘Simulated annealing’ /23,24/. Assembling a ‘sorted’ magnet structure therefore implies ‘single block addressing’. A block has to be numbered, measured, well packed in a suitable, labeled container and stored for later use. After sorting it has to be found again, unpacked and inserted into the magnet structure at the proper position in proper orientation as determined by the sorting procedure. Today this technique is state of the art and quite cost driving. For the undulator for the TTF about 25% of costs for the magnet structure were due to these steps. For a small number of insertion devices it might be still acceptable. For a 200-300 m long undulator structures of this project more than 30000 individual magnet blocks will be needed. Single block addressing of such large ensembles will require large storage room and will be very time consuming. Single block handling could be omitted if the magnets could be produced in a more homogeneous quality with considerably smaller errors than presently available. By optimizing the manufacturing process of the magnets the quality of the material can be improved significantly and reliably so that single block measurement and sorting become superfluous. Clearly these problems can only be addressed in close collaboration with a manufacturer of permanent magnet material. An analysis of the production process has shown, that there are at least two steps, which could be improved:

1) By a better control of the chemical composition of the magnet powder, the magnetic properties can be controlled with higher precision. The typical lot size for the powder production is about 1 -2 tons. For one FEL undulator system about 12 - 14 tons of powder will be needed. To reach more identical properties for larger lot sizes special blending procedures for fine grained powders have to be developed and the influence of storage time of the powders on magnetic properties has to be examined.

2) The homogeneity of a die-pressed magnet block, that means angular miss orientation of the magnetization and asymmetric field strength (North /South effect) is critically influenced by the geometry of the field coil used for the magnetic orientation of the powder and the direction of the field with respect to pressing direction (axial or transversal to pressing direction) during the pressing process of the magnet. These influences have to be examined in more detail and the geometry of the orientation coil has to be optimized for the magnet sizes used at TESLA. A better position control of the pressing die with respect to the field coil has to be developed. Eventually larger orientation coils with a different geometry than the presently used flat ones

and a lager press are needed. To study these effects an increased resolution of the measurement techniques with an accuracy of about 10^{-5} is needed and has to be developed. The influence of the different parameters on the performance of the system has to be analyzed by numerical calculations and experimental methods.
A successful research and development on these two points would result in magnets with much better control of magnetization, angular miss orientation of the magnetization vector and homogeneity. Single block handling could be omitted completely. This simplifies and cheapens the production process of the magnetic structures significantly.

b) Development of magnetic measurements and fine tuning technology which can be used in an industrial environment.
Magnetic measurement and trimming techniques are needed in every lab dealing with insertion devices. They are well developed and ready for use, but they are made for experts by experts. The goal of this development is to make suitable magnetic measurement and fine tuning techniques available in an industrial environment. This relates to the techniques and the software control as well. Measurement and alignment techniques of the undulator segments must be both simple and straight forward to use. Clear instructions should be given by the software, so that the system can be operated by trained technicians. At least one prototype measurement system has to be set up which then could be copied later on. The goal should be that one magnet structure could be trimmed by two skilled technicans in not more than three working weeks.

2. Design activities.
Extended Design work is needed for:
a) Mechanical support and drive system
b) Motion control system
c) Magnetic design
d) Phase shifter, intersection

All design issues have to be treated in this point. There will be one universal mechanical drive and support system which can be used for all magnet structures/8/.It will be designed for worst case requirements. 281 of these support systems will be needed. Consequently optimization and streamlining the designs for mass manufacturing will be very important for economic reasons.
The control of the undulator cells which form one undulator is another R&D project. It is by no way straight forward to design a system which is capable to move the gaps of all undulator segments simultaneously and synchronously controlling correctors, which are needed to keep the beam straight. However there is a first concept how such a system can be implemented using industrial components /9/.
The magnetic design of the insertion devices is the third design task. It includes the FEL devices and the spontaneous radiators as well. There will be only four different types of undulators. A first prototype design, which could serve as an example for magnetic design is given in ref. /11/. The helical undulator system for SASE5 will certainly require much more design effort than the planar ones.
Phase shifters are needed to properly adjust the phase of the light emitted by different undulator segments, especially when the gap is changed. Based on the prototype design of ref. /11/ magnet geometry and core material has to be chosen. A low cost solution, which nevertheless meets all requirements, has to be developed, since a total of 1134 individual magnets have to be manufactured for the phase shifter and the intersections. There are more components in the intersections which need design work as well.

3. Prototyping
Heavy prototyping of all components which are produced in large quantities is mandatory. This holds for the mechanical support structures, the control system and the phase shifters. For the magnetic structures it is most important. Most likely several generations of prototypes have to be built. One generation being the source of improvement and refinement for the next. The aim should be that all questions related to the design, construction, optimization and mass

manufacturing of undulator segments are solved and well prepared plans, drawings, specifications and other documentation for the production of these items exist.

4. Logistics

a) Production management structure

It is inevitable that the different components which are used for the undulator segments will be produced at different companies. For example, the support mechanics will be built most economically at suitable engineering companies. The girders eventually have to be built at other locations because they need larger machine tools. The motors, control systems and wiring has to be organized and finally the complete support mechanics have to be sub-delivered to the magnet manufacturer who will equip it with a magnetic structure and do the tuning and measuring. These are just some examples which need organization, supervision and control by an effective production management.
It also takes responsibility for quality assurance and quality control and is ultimately responsible for the whole setup.
A working production management structure has to be established. There exist several options: The production management could be made by DESY / TESLA personnel or alternatively contracted out to a suitable company. As a third alternative a prime contractor may be found, who will take over all responsibilities for working devices, which comply with previously defined quality standards, upon delivery to TESLA. The installation of a working structure is of great importance for an efficient production process.
Certainly several years are required until such a structure is established and operational when production starts.

b) Planing manufacturing capacities

The capacities needed for the manufacturing of the devices have to be planned
Mechanical manufacturing and control systems are not considered problematic. Experience shows that even in the Hamburg region there are several suppliers with adequate skills and sufficient capacity. Eventually there could be more than just one supplier of these systems. In contrast the production of the magnetic structures is more delicate and demanding, since there are only a very few suppliers worldwide, who are capable and there might be even less who might be interested as new production facilities have to be setup.

Fig. 6 shows a preliminary floor plan of a production plant. It is designed such, that the magnetic structures for 281 undulator segments could be produced, measured and trimmed in about four years of continuous operation. About $1500m^2$ of floor space are needed. Existing experience on the assembly and measurement of the 15m long undulator for the TTF was taken as a basis. There is an area were the new unmagnetized magnets are magnetized and measured. These measurements are primarily for quality control reasons. No further single block treatment is done. Next is the assembling area for magnetic sub units, which then are mounted onto girders. There is a central area in which the girders and support systems are combined so that an undulator segment as the one shown in Fig. 3 results. There are four magnetic benches, which need temperature stabilization. Their throughput determines the production time. Three weeks/segment are taken as a basis. 210 week of continuous single shift operation or about four years are needed. Magnetic measurements and trimming will be the bottleneck of the production. Eventually one has to extend capacities by temporarily adding a second shift.
Storage areas for receiving new magnets, non-magnetic holder parts, girders and support systems are needed. Also a shipping area for completed segments has to be foreseen. At the end of the prototype phase everything should be prepared to start the large scale production of undulator segments.

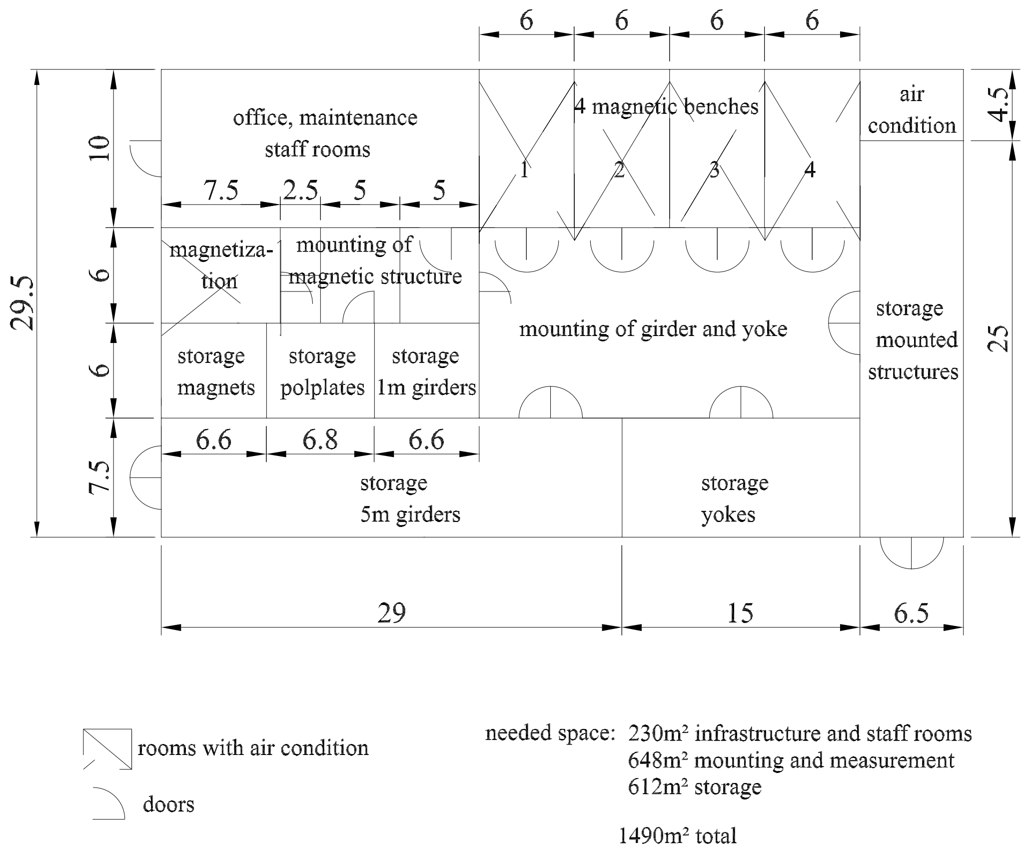

Fig. 6: Preliminary design of a production facility, which could produce about 280 magnetic structures within four years. The layout is based on experience made with undulator for the TTF.

3.2.2.3 Production Phase

Here the production of≈ 281 undulator segments within a reasonable time has to be organized. About 281 undulator segments have to be built within reasonable time.

It is assumed that the production of undulator segments may follow the schematic shown in Fig 5. Heavy items such as girders and support units are supplied externally. Only storage and assembly area is provided. Magnets are delivered non magnetized. Together with the poles and nonmagnetic keeper parts they have been manufactured externally. There is no machining in this facility. Everything is concentrated on assembly of the magnetic structures. For clarity the assumptions made on the assembly process are briefly summarized:

- Magnet material can be produced with sufficient quality to allow for economic manufacturing, i.e. no single block handling is needed
- Industrial measurement techniques are ready for use
- All items are well designed, they are well tested in prototypes and well documented drawings exist.
- An effective production management structure has been established
- The layout of the production facility has been thoroughly planned.

- The supplier of the magnetic structures acts as a subcontractor within the whole project. There will be a project management organizing the supply and delivery of components
- Mechanic support systems and girders will be supplied externally
- For the magnetic measurements the girders have to be mounted onto support systems which also will be supplied externally.
- The magnetic measurements and the fine tuning should be doable within three working weeks and require two skilled technicians / engineers.
- After these steps a 'turnkey ready' undulator segment is available for installation and will be delivered to TESLA

After the production phase has been started about one year is needed until the facility has been set up and is fully operational. To do so a suitable location has to be found and be equipped as shown in Fig 6. No potential supplier known today has about $1500m^2$ of floor space readily available. From this standpoint one year is optimistic. Assuming that everything is well tested on prototypes, the production may start right after the factory is set up. The average production rate is about 1 1/2 segments per week.

4. Time estimates

Both the prototype activities and production requires about 5 years each, so that a total of 10 years is needed. This is longer than the official TESLA construction time of 8 years. In order to solve this conflict some of the R&D activities should be taken out of the TESLA construction scheme and started well before an official project start. The superconducting cavity technology for TESLA has been and still is developed in a similar way.
In this way the undulator systems can be completed in time.

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