RF Photoinjectors as Sources for Electron Bunches of Extremely Short Length and Small Emittance

Abstract

In collaboration with other HGF centers and a large number of international partners DESY plans an international institute for applied and fundamental research in Germany. This facility will offer unique research possibilities in areas such as elementary particle physics, solid state physics, chemistry, material sciences, medical diagnostics and molecular biology. The current research and development for TESLA will lead to an integrated system test for a superconducting linac and a SASE FEL in the VUV and the soft X-ray regime (TESLA Test Facility).

For the FEL and linac operation electron beams of highest beam quality are necessary. Therefore DESY runs a development program for rf electron sources for optimizing the beam quality and the operation parameters such as operation safety. In order to reach these goals it is indispensable that, besides further development of simulations and theoretical approaches, high quality measurements of the beam emittance are carried out. Experience shows that without an experimental program no significant progress can be expected.

An important challenge of this development is the need for powerful laser pulses with a pulse form, which is well defined on a sub-picosecond scale and synchronized to the time structure of the linac. The technology based on TiSa considered for this task by the MBI, has a potential for further developments and is of general interest in view of femtosecond lasers with high average power.

Contents

1. Introduction

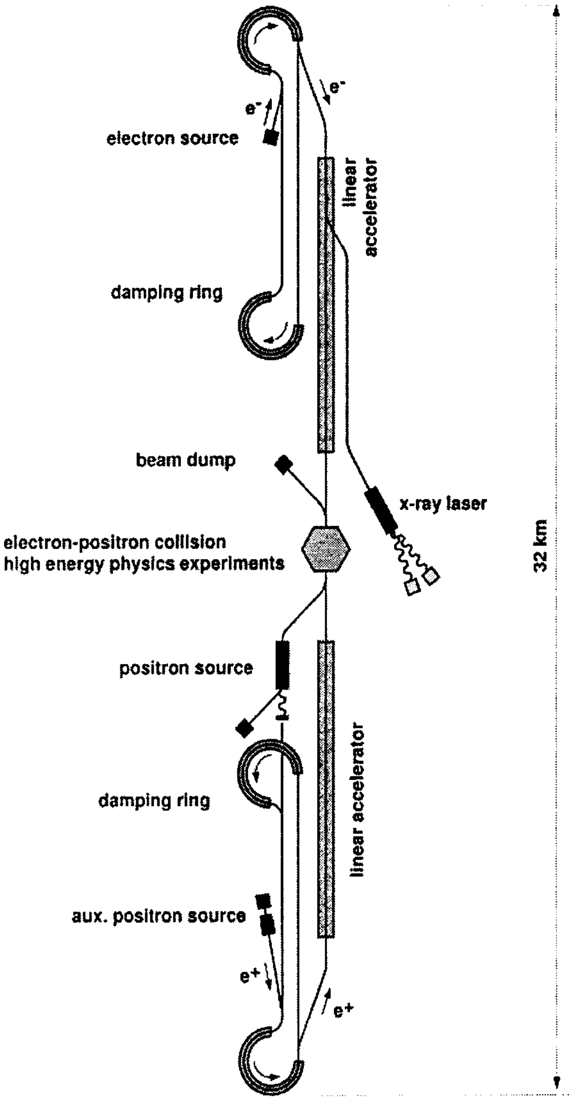

Fig. 1: Schematic overview of TESLA

DESY, in collaboration with other HGF centers and a large number of international partners, is planning an international institute for applied and fundamental research in Germany. This facility will offer unique research possibilities in areas such as elementary particle physics, solid state physics, chemistry, material sciences, medical diagnostics and molecular biology. Fig. 1 shows a schematic view of the planned facility. The central components are two superconducting linear accelerators for the collision of electrons and positrons ("Linear Collider") with very high kinetic energy (250 GeV per beam) and a X-ray facility that consists of several free electron lasers (FEL) and other radiation sources for the X-ray regime. The expected brilliance of this new type of sources is many orders of magnitude larger than the values that are reachable at current synchrotron radiation sources, see Fig. 2.

The conceptual outline of this facility was published in the two volumes of the "Conceptual Design Report" [1] in 1997.

The performance of both, the linear collider and of the X-ray laser depends vitally on extremely small beam dimensions. Because there is no mechanism that reduces the phase space volume (emittance) of the beam in a linear accelerator (in contrast to storage rings) the beam emittance at the source is of the highest importance.

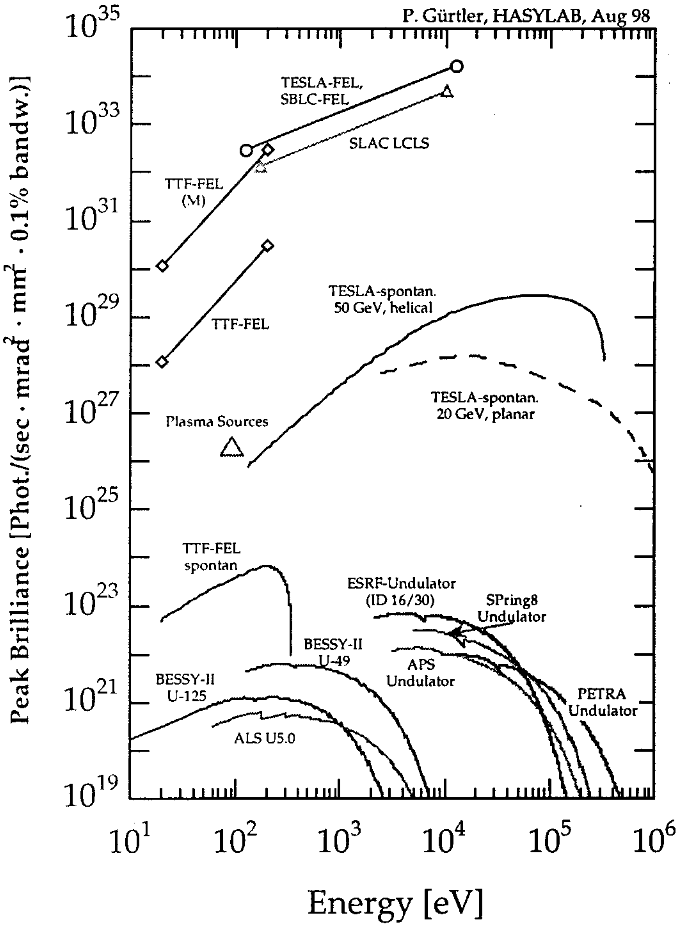

Fig. 2: Peak brilliance at the TESLA X-ray facility in comparison with synchrotron radiation sources of the third generation. Also the mean brilliance of TESLA (not shown here) is several orders of magnitude higher than at third generation sources.

The development and the system test of suitable electron sources therefore has been a central part of the TESLA Test Facility (TTF) from the very beginning. At this facility at DESY the technical fundamentals for the build up of TESLA should be worked out in international cooperation. However in the mean time it has become evident that sufficient progress is not possible without a separate test stand. This is especially true in case of the VUV FEL, which is due to deliver an VUV beam to the first users by the year 2003. This operation which involves the extension of the test facility should not be hindered by the extensive tests which the source will require.

2. The FEL Principle and the Dependence on the Quality of the Electron Beam

In about 1970 J. M. J. Madey recognized that coherent electromagnetic radiation can be amplified by stimulated emission of bremsstrahlung if the relativistic electrons travel collinearly with the radiation field through a periodic magnetic field structure [2]. The operational principle with an electron beam, a monochromatic electromagnetic wave and an undulator, which produces the magnetic field, is shown schematically in Fig. 3.

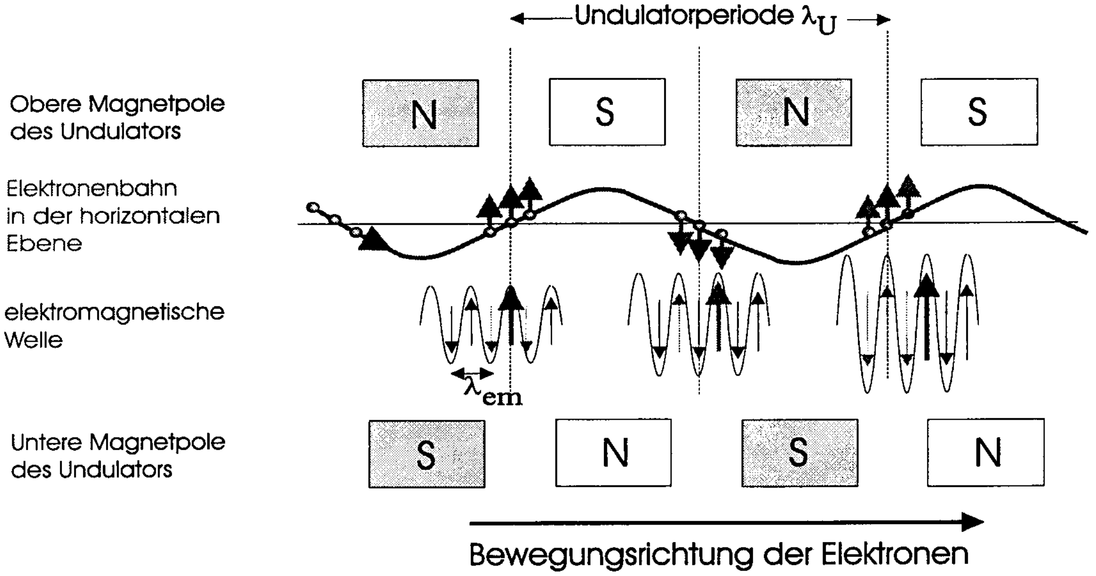

Fig. 3: Resonant phase relation between electromagnetic radiation and transverse electron motion in a periodic magnetic field.

For clarity the electron trajectory is shown separate from the wave. If the radiation is in resonance with the first harmonics of the undulator radiation an electron falls back by one photon wave length per undulator period so that the relation between the wave phase and the transverse electron motion is stationary. Therefore some electrons gain energy while others lose energy. This leads to a modulation of the charge density of the electron beam that corresponds to the photon wavelength. This process, called micro-bunching, finally leads to an enhanced emission and to an exponential growth. By changing the magnetic field strength B_u of the undulator as well as the undulator wave length λ_U and the electron beam energy the photon wave length λ can be varied over a large range according to the relation

$$\lambda = \frac{\lambda_U}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

Here γ is the electron beam energy in units of the electron rest mass and $K=0.934 \cdot B_U[T] \cdot \lambda_U[cm]$ is the undulator parameter.

Hereby a process was found that could be used for amplifiers and oscillators and which covers a wide frequency range from the infrared to the X-ray regime. Based on optical cavities a number of such Free Electron Lasers have been built in the infrared and the visible regime. Nevertheless, an extension to wavelengths in the UV or in the

X-ray regime failed as optical components of high reflectivity and strong, tunable and coherent sources for the start of the FEL process were not available.
It became clear that the FEL process would also work in a single pass arrangement by the amplification of spontaneous radiation, if undulators of sufficient length were available [3, 4]. In this case the partially coherent undulator radiation that is radiated in the first part of the undulator interacts with the electron beam over a large distance which finally leads to a density modulation and an exponential amplification to the saturation level (Fig. 4). This so-called self-amplification of spontaneous undulator radiation (Self-Amplified Spontaneous Emission, SASE) thus presents an attractive possibility for the production of intense, tunable and coherent radiation at short wave lengths.

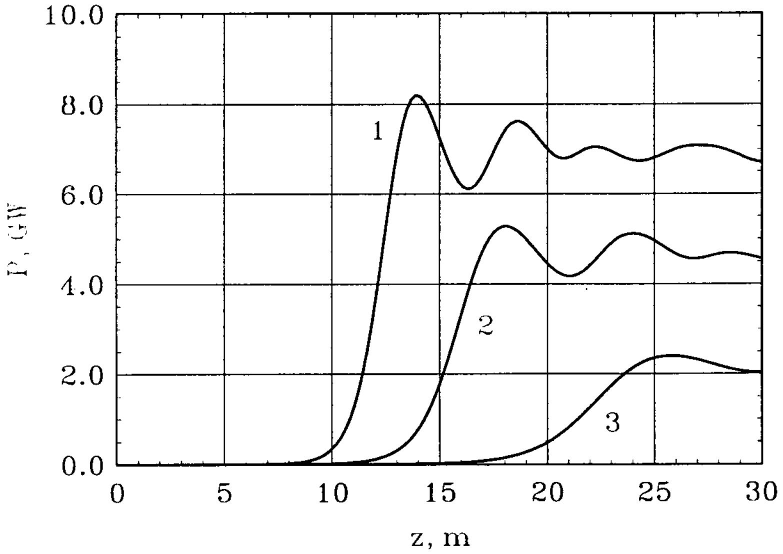

Fig. 4: Dependence of the output power of a FEL on the normalized beam emittance in example of the TTF FEL at 6.4 nm. Energy width of the electron beam: 0.1%; transverse beam emittance: (1) $\varepsilon_n=10^{-6}$ m, (2) $\varepsilon_n=2\cdot10^{-6}$ m, (3) $\varepsilon_n=4\cdot10^{-6}$ m.

The fundamental properties of SASE can be expressed in terms of the so-called ρ-parameter [4], which in one-dimensional theory is defined as:

$$\rho=\left(\frac{1}{64\pi}\left(\frac{K\lambda_U f_B}{\gamma\sqrt{2}}\right)^2\frac{I_p}{I_A\beta\varepsilon_n}\right)^{1/3}$$

Here, f_B is the decoupling factor, I_p is the peak electron current, I_A is the Alfven current (~17kA), β is the beta function of the electron beam in the undulator and ε is the normalized beam emittance. Typical values of the ρ-parameter are in the range of 10^{-3}. The ρ-parameter determines the gain length $l_g = \lambda_U/4\pi\rho$ and the maximum power at saturation $P_{sat} = \rho\cdot P_{beam}$ (P_{beam} is the electron beam power) (Fig. 4). ρ depends strongly on the electron beam parameters. A high space charge density with simultaneous adjustment of the electron beam diameter and the electron beam divergence in the undulator are necessary to maximize the interaction of the radiation field with the electron beam. Only in this way a high amplification and saturation can be realized within a reasonable undulator length. Additionally, the energy width ΔE/E within the electron bunch must be small enough (<ρ) so that all electrons fulfill the resonance condition. The experimental growth saturates after ~1/ρ undulator periods because of the enlarged energy width of the electron beam that is caused by the FEL process.

Also the smallest wave length that is achievable with the FEL directly depends on parameters that are determined by the electron source [5]:

$$\lambda_{\min} / \text{Å} \approx 4\pi \frac{\varepsilon_n / \text{mrad mm}}{\sqrt{I_p / \text{kA} \cdot L_U / \text{m}}}$$

Here, L_U is the undulator length.

These relations demonstrate how dependent the development in the field of free electron lasers of short wave length is on the production of electron beams of highest beam quality and hence on the development of electron sources. Since the development of rf electron sources 1986 in the USA [6] the required beam qualities can be reached. Despite the continuous further development that has taken place worldwide since then, this type of injector has not yet become a problem-free standard component. So, besides further optimization of the beam emittance, questions concerning stability, reliability and the production of flexible pulse train patterns have to be answered.

In addition, recent very promising developments at DESY indicate new possibilities for the use of rf electron sources. The production of high brilliance beams for the electron cooling of protons in PETRA and the production of flat beams for linear colliders have to be mentioned here. In this context flat means a beam with small vertical and larger horizontal emittance.

For the production of flat beams a solenoid field is used at the cathode. The correlated emittance growth that normally occurs at the exit of the solenoid can be completely transformed into the horizontal plane by a suitable arrangement of skew quadrupoles as suggested by Ya. Derbenev. In simulations emittances of $2 \cdot 10^{-7}$m in the vertical plane and $1 \cdot 10^{-5}$m in the horizontal plane could be reached with a charge of 1.6 nC. This development is of high importance in connection with the planning of the construction of the linear collider TESLA because it can provide a significant contribution to the cost reduction and to a simplification of the commissioning.

3. Operational Principle of RF Electron Source

Conventional electron sources which consist of a thermal cathode and a static acceleration unit are not suitable for the production of electron bunches of high phase space density such as necessary for the operation of a short wavelength free electron laser. After the development of rf electron sources by J. Fraser and R. Sheffield [6] in the mid-eighties a new type of electron source is available which makes the required phase space densities a distinct possibility.

While in a static source an extraction voltage of only 100-300kV is supplied over the short range between anode and cathode, the cathode in a rf gun is located within the cavity resonator. The emitted electrons are extremely quickly accelerated to relativistic energies by the rf field and leave the resonator with energies in the MeV range. Due to the fast acceleration acting over a long distance the influence of the space charge force on the beam emittance is kept small. The focusing forces which act on the electrons in the rf field also lead to a correlated emittance growth. In order to keep this effect small it is necessary to keep the beam dimensions within the resonator small.

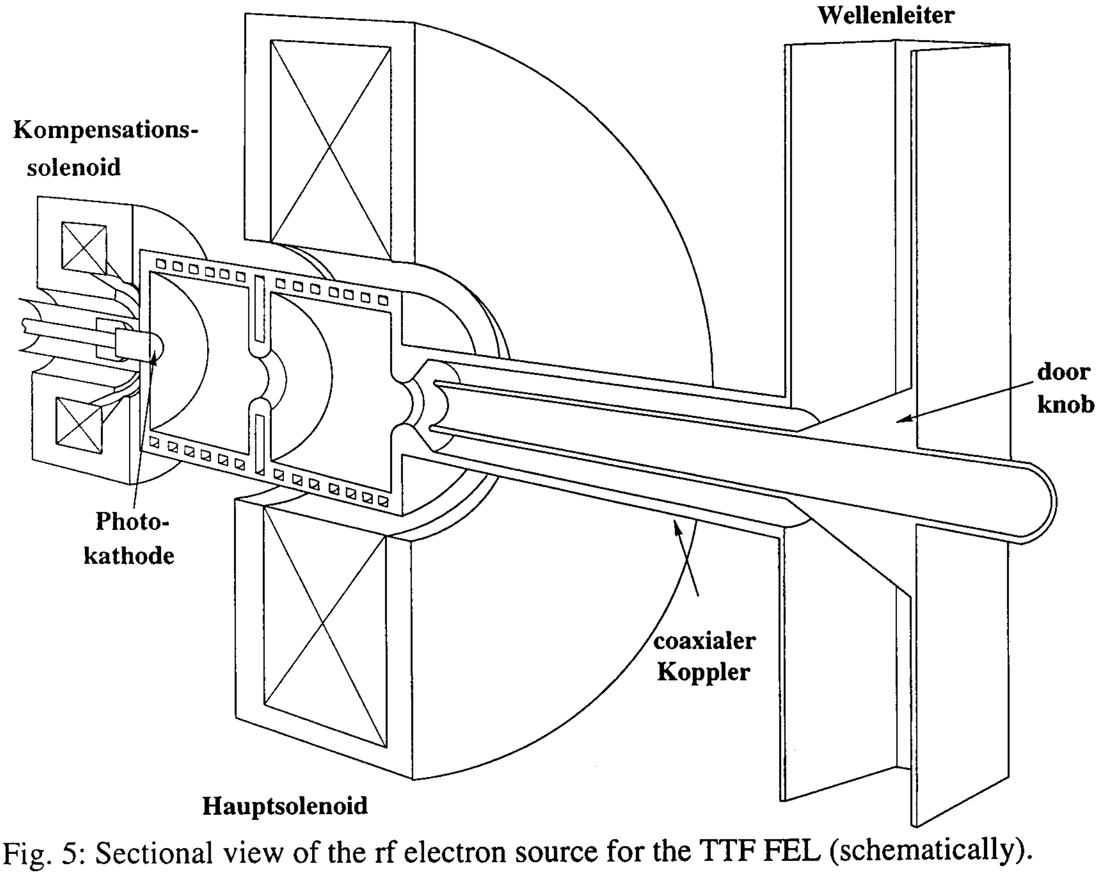

Fig. 5: Sectional view of the rf electron source for the TTF FEL (schematically).

The enhanced particle density leads to increased space charge forces which are not entirely outweighed by the positive properties of rf guns. On the other hand, the necessarily short bunch length reduces the effort for further compression of the beam after the resonator and is therefore very welcome in the case of free electron lasers. Fig. 5 schematically shows a cut through the source built at DESY with the newly developed axial-symmetric input coupler. This input coupler prevents field asymmetries, which were identified as sources of emittance growth.

A further complication of rf electron sources is that the current density which the cathode must deliver exceeds the limit (~100A/cm^2) which a thermal cathode can provide. Typical parameters of high brilliance rf guns (e.g. 1nC charge, 10ps pulse length and 7mm^2 emission area) lead to current densities of 1000-2000A/cm^2. Therefore, photo cathodes are used which not only deliver the necessary high current densities but also allow the length and form of the pulse to be controlled on a picosecond time scale by means of the laser. The demands of laser power and laser stability are high; moreover the pulse train structure which is required by the linac operation or by the users is not standard for conventional laser systems. However, the demands on the laser system can be relaxed if photo cathodes with high quantum efficiency are used. The search for suitable cathode materials which reach a high quantum efficiency and a sufficient lifetime under the conditions present in an rf resonator led to the development of Cesium Telluride (Cs_2Te) cathodes at CERN [7]. With a quantum efficiency of 2% and a lifetime of several months Cesium Telluride is the most suitable material for the operation of rf electron sources with high average current.

The space charge induced emittance growth is partially caused by a correlation between phase space distribution and longitudinal position in the bunch. This can be corrected by a simple focusing scheme provided the electron source is operated in a certain parameter range. The scheme was developed by B. Carlsten [8]; Fig. 6 shows schematically the evolution of the phase space along different positions of the beam trajectory. An electron bunch of vanishing emittance is started in Fig. 6a. The space charge force acts in first order as a defocusing lens whose strength varies over the length of the bunch. In the longitudinal direction the transverse force is strongest at the center of the bunch and decreases towards the ends. Therefore a double-fan-like structure opens up in phase space (Fig. 6b). After a focusing kick (Fig. 6c) the space charge acts against the beam divergence which leads to a partial closure of the double-fan structure. At the position where the fan is closed (Fig. 6d) the process needs to be stopped in order to prevent the fan to open again. This is achieved by placing an additional accelerating resonator at a suitable position.

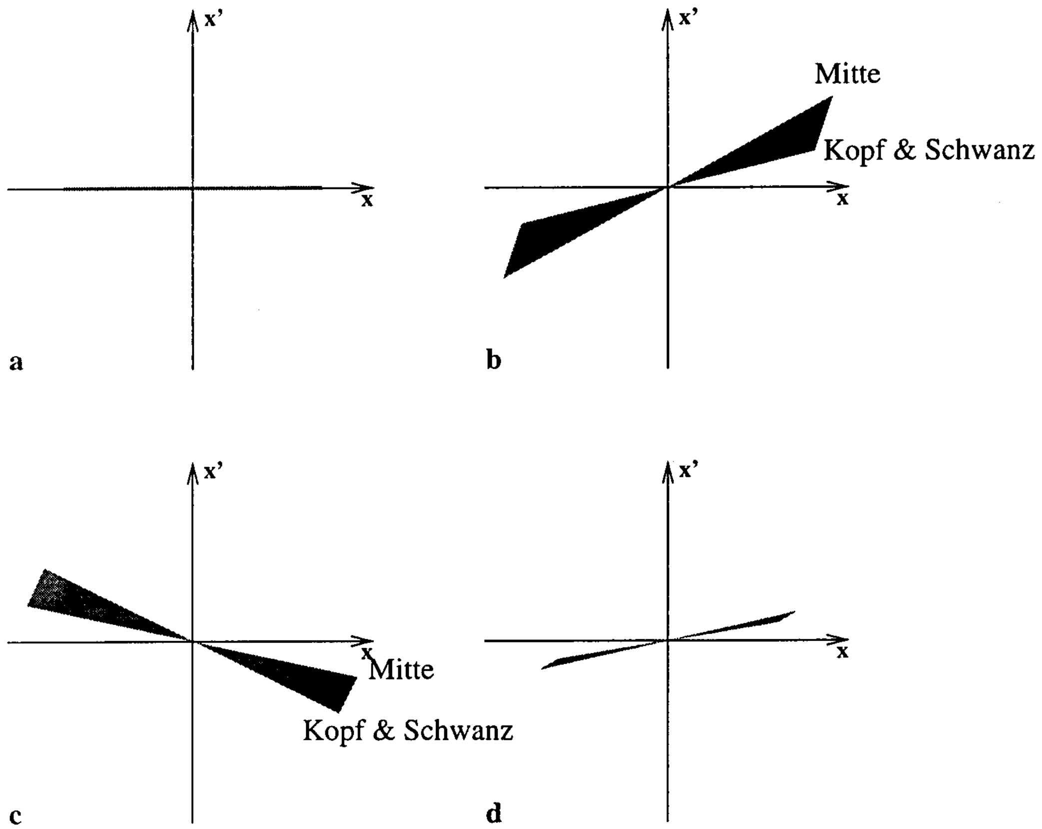

Fig. 6: Schematic development of the transverse phase space with compensation process for space charge induced correlated emittance growth.

In practice the correction principle is limited by a process, which is called phase space bifurcation. The problem can be illustrated by a comparison: The attempt to focus the electron bunch against the space charge force is comparable to the attempt to kick balls onto a mountain crest against the force of gravity. If the supplied impulse is too high or the mountain is too low the balls roll over the crest of the mountain and down on the other side. Exactly this happens with the electrons in the ends of the electron bunch because of the locally smaller space charge force. While the main part of the electrons moves in phase space back from the fourth quadrant (Fig. 6c) to the first quadrant (Fig. 6d), a small part of the electrons from the head and the tail moves from the fourth quadrant into the third and leads to the development of a beam halo. Apart from the focusing strength the development of the halo depends strongly on the longitudinal density variation of the charge in the bunch and can therefore be influenced by the form of the laser pulse.

That correction of space charge induces emittance growth can be shown in simulations and has largely also been demonstrated in experiments. In simulations transverse emittances of 1 π mrad mm and longitudinal emittances of 20 keV mm have been reached. Measurements generally result in larger emittances than the simulations. Besides the possibility of faulty or incomplete simulations, measurement problems have also been quoted as a reason. The measurement of small emittances is very difficult especially at low energies where the space charge cannot be fully neglected and it is only possible by using newly developed components.

4. The International State of Development

The increasing interest on rf electron sources is reflected in an increasing number of theoretical and experimental developments. In the experimental area the Brookhaven National Laboratory (BNL) is especially important where a working group has been active in that area since the late eighties. Besides the development of fundamental concepts for the design of a rf electron source, valuable measurements have also been carried out concerning both, the beam dynamics and the behavior of metallic photo cathodes. In cooperation with BNL an rf gun was designed also for the Stanford Linear Accelerator Center (SLAC), which has now been built at SLAC in a test stand. This development is connected to the LCLS FEL project that is planned at SLAC and follows similar goals to the planned investigations at DESY. Within the framework of a collaboration for the TESLA project an rf gun and a test stand was built and put into operation at the Fermi National Accelerator Laboratory (FNAL). A copy of this source is in operation at the TTF linac. It will presumably reach the required beam parameters for the first operation phase of TTF and is designed for long pulse trains i.e. high thermal load. However, it is not optimized with respect to the smallest emittance. Developments for the production of highest beam bunch charges were done mainly at CERN in connection with the CLIC Linear Collider project.

Theoretical research has been performed predominantly at the INFN in Milan and at the university of Los Angeles in recent years. Important studies concerning the behavior of photo cathodes have also been done at the INFN in Milan as well as at CERN. The INFN will also deliver the photo cathodes for the TESLA test facility.

Laser developments have been mainly ‘in-house’ developments at the different laboratories. However, the operation of a superconducting linac with its specific pulse structure as well as the reliability and stability needed for a user facility require cooperation with laser institutes. Therefore, besides the development of the MBI for DESY, the laser in operation at FNAL was designed and built by the university of Rochester. The laser development at MBI is thus of central importance for TESLA and for the worldwide FEL and photo injector development.

5. Research and Development Program

Besides the above-mentioned completely new applications and their associated problems, there are two questions concerning the development of rf electron sources for free electron lasers which are of central importance: what is the smallest attainable emittance and which process determines that value. In order to work on these questions it is not only necessary to develop new analytical approaches, new computer programs for the simulation of electron sources will also be needed because in spite of recent improvements the available programs do not meet the increased demands. A program that was written at DESY last year (ASTRA) is now available in a first version and will be the basis of future developments. Furthermore, in cooperation with the technical university of Darmstadt and the university of Rostock a set of different programs will be combined and extended to simulate operation from the injector area through the linear accelerator and the bunch compressors to the undulator (*Track).

The new program provides not only a precise and fast simulation of the beam transport but also a more detailed analysis of the evolution of the phase space, than was possible up to now so that a better understanding of the beam dynamics is expected. The first tasks will be:

- large area parameter scans.

- investigation of the evolution of the space charge field and the emittance growth during the emission process of the electrons from the cathode.
- investigation of the influence of the rf field shape on the beam dynamics and optimization of the field shape and the resonator geometry, respectively.
- investigation of the influence of the longitudinal laser pulse form on the beam emittance and the halo formation.
- investigation of the beam dynamics of dark current.

Parallel to this theoretical work an experimental verification of the results obtained is absolutely essential for confirmation and further developments.

An important but not very precisely known contribution to the beam emittance is the so-called thermal emittance, which describes the intrinsic emittance of the electrons when they escape from the cathode surface [9]. It depends on the cathode material, the energy of the laser photons and probably on the coverage of the cathode surface with adsorbate layers. Measurements of the thermal emittance under varying conditions are under preparation at the INFN in Milan. Besides measurement and control of thermal emittance, a further extension of the cathode lifetime and tolerance of bad vacuum conditions is desirable.

In view of the operation of a free electron laser at a superconducting linear accelerator and the acceleration of long pulse trains with high average current, a number of technological questions have to be studied. Of special concern are the thermal and rf technological problems that are connected with the coupling of a long rf pulse of high power into a normal conducting resonator. Because a further enhancement of the rf power is desirable from the beam dynamics point of view these problems will become even more critical in the future.

In the area of beam diagnostics numerous developments and new concepts have been suggested and partially realized in the recent years, which in part are also applicable for the low energies in the injector. Bunch length measurements based on Josephson junctions, new high resolution beam screens on the basis of Nd:YAG powder and improvements in the design of slit masks (so-called pepper pots) come under this heading.

The development of a laser for an rf gun with the pulse structure of the TESLA accelerator is determined primarily by the following parameters:

the *micro pulse length* in the range of ps or sub-ps which follows from the required emittance of the accelerator; the *macro pulse length* of about 1 ms; the two *clock frequencies* of the micro and macro pulses (1MHz and 10Hz respectively); the *wave length* of the photons (250 nm) which is given by the work function of the cathode material as well as the *pulse energy* of the micro pulses given by the product of the quantum efficiency of the photo cathode and the desired bunch charge of the accelerator.

Secondary parameters (although just as important for the application) are the *ability to synchronize* the laser to the external rf frequency with ps precision, the *amplitude stability* in the range of a few percent and a comparably high *long term stability* and *reliability* of the complete system.

From the present state of the art the individual parameters can be relatively easily fulfilled, however, their combination requires a new and extremely demanding laser development at the limit of the available technologies.

With the limitation of a minimal pulse length (or rise time, respectively) of only a few ps, a TTF photo cathode laser was recently developed at the Max-Born-Institute in Berlin which fulfills the above mentioned specifications completely as the worldwide first and only system. Besides the careful choice of the active material (Neodymium doted Yttrium-Lithium-Fluoride, Nd:YLF) the development of new design elements was necessary, such as a pulse train oscillator of the required time structure, active electronic regulation of the flash lamp current for the pumping of the material, adaptive optics and a new synchronization electronic. The laser has now been successfully in operation at the TTF accelerator for several months.

With the project of a test stand for rf electron sources of extremely short bunch length and small emittance in hand a new challenge for the laser development arises. While practically all other specifications stay the same only the requirement for a pulse duration or rise time in the sub-ps regime cannot be provided by the active medium Nd:YLF. A simple substitution of a different medium of higher bandwidth as e.g. Titanium doted Sapphire (Ti:Sa), Neoddymium doted glass or Chrome doted Fluoride crystals is not possible. Whether this is due to the lower optical storage capacity of Ti:Sa, the lower heat conductivity of glass or the difficulty to produce large volume Fluoride crystals of suitable quality: in any case it is doubtful whether the necessary average power together with the shortest pulse duration in the micro pulse is attainable. Theoretical estimates show that, with the available Nd:YLF laser, the possibilities of a conventional oscillator amplification arrangement are largely exhausted if one needs to fulfill all TESLA specifications at the same time.

On the other hand the demand for shorter pulses or shorter rise times is indispensable for this kind of test stand. The optimum laser pulse length and pulse form can only be determined experimentally so that future accelerators are not unnecessarily limited in their emittance by the laser.

For the project in hand it is therefore suggested to develop a new photo cathode laser with the TESLA time structure which produces substantially shorter pulses (<1ps) and has a variable pulse form. This goal can only be reached with the use of the most modern techniques and innovative amplifier concepts. The complete laser system is presented in one of the following chapters.

This laser development although originally for the specific needs of the photo cathode development contains new elements, which can be of interest and use in a substantially wider environment. The most important aspect is that the positive properties of the most modern active laser material Ti:Sapphire are connected with the requirements of very high average power.

The average power of 200 W is reached during the whole macro pulse, i.e. for a time that is very long compared to the optical storage time of the medium. Therefore, at least during that time, the average power of usual ultra short pulse lasers (1-10W) is surpassed by at least one order of magnitude.

This is remarkable in so far as ultra-short pulse techniques in the femtosecond regime have many potential fields of application. (E.g. material treatment including ultra precise treatment of surfaces, production of incoherent X-ray pulses from plasma sources, femto chemistry, non-linear processes in measurement techniques, chemical analysis, medical diagnostic and therapy.) However, they have so far found only little application mainly because of the insufficient average power of the lasers. Furthermore, new possibilities of flexible pulse form production and of optical parametric amplification will be tested which can immediately be transferred to a great number of other applications.

6. Contribution of TU Darmstadt: Self Consistent Simulation of Photo Injectors

The standard programs for the calculation of electron sources are EGUN for static sources and PARMELA for the calculation of rf electron sources. Both programs have been available for a long time but do not make usenew developments in the computer and software area. Increased requirements of the program users are also not accounted for. The program ASTRA, newly developed at DESY, is based on a similar principle as PARMELA. An alternative approach to ASTRA and PARMELA is pursued by the particle in cell (PIC) codes in the time domain such as the programs TS2/TS3 of the MAFIA program package [10]. This method allows, in principle, a completely three-dimensional and self-consistent treatment of space charge dominated beam trajectories. Global stability criteria define a maximum time step on the discrete time axis for each explicit and completely self-consistent analysis in the time domain. However, this leads to considerable problems during the particle emission because the start velocity of the electrons is very small which leads to an unacceptably long simulation time [11]. These problems can be avoided by the use of simplified models. In a preparatory step the models are supposed to be realized for the simpler case of static sources before the calculation is extended to the case of rf guns.

Another field of research is the secondary emission and the closely connected subject of dark currents. Although a number of papers have already been published, a realistic method for a three dimensional simulation is still missing. Such a tool can be realized by the extension of available PIC modules.

For both fields of application mentioned here, experimental comparisons are indispensable. The calculation of the electromagnetic fields is obtained by the direct solution of the Maxwell equations and is only limited by numerical accuracy. The same is true for the solution of the equations of motion. However, the mechanisms of emission at the source as well as those of secondary emission is characterized by strongly simplified models and needs extensive validation. Reliable analysis and optimization of electron sources by computer simulation can only be achieved by such a method.

The extension of the existing simulations to provide fully three-dimensional modeling at the cathode area as well as the analysis of dark currents, in conjunction with other codes such as ASTRA, will complete the simulation requirements. This also fits perfectly into the *Track initiative which aims to provide the complete simulation of all stages of a linear accelerator.

7. Contribution of the MBI: The Photocathode Laser for the Test Stand

7.1. The design concept for the photocathode laser

Recently, a photocathode laser was developed at the Max-Born-Institute and successfully tested at the Tesla Test Facility. This laser is now routinely used to generate electron bunches for the TTF. This photocathode laser fulfills most parameters required for the test stand.

However, the shorter rising and falling edges of the micropulses required for the test stand cannot be achieved with the present TTF photocathode laser. Therefore the photocathode laser for the test stand requires another design concept which is outlined in Fig. 7.

The new concept plans to produce approximately 0.3 ps long laser pulses by a cavity-switched Titanium Sapphire oscillator. Subsequently, the pulses will be chirped to 20 ps FWHM and than amplified in an optical parametric amplifier (OPA). Two non-linear optical crystals will be used to transfer the wavelength to 260 nm. The pulses will be shaped and the suitable rising and falling edges will be formed in the last stage of the laser system. An extended version of the TTF photocathode laser with an output power increased by about one order of magnitude will be required to pump the parametric amplifier.

pulse length	6-20 ps FWHM
shape of the micropulses	rectangular, with short rising and falling edges
new demand on the rising edge of the micropulses	<1 ps
wavelength (ultraviolet)	$\lambda = 260$ nm
energy per micropulse in the ultraviolet	20 μJ (at 1 MHz)
energy per macropulse train in the ultraviolet	160 mJ
length of the macropulse train	800 μs maximum
repetition rate of the micropulses	1 MHz and 9 MHz
repetition rate of the makropulse trains	5...10 Hz

Table 1: Design parameters of the photocathode laser

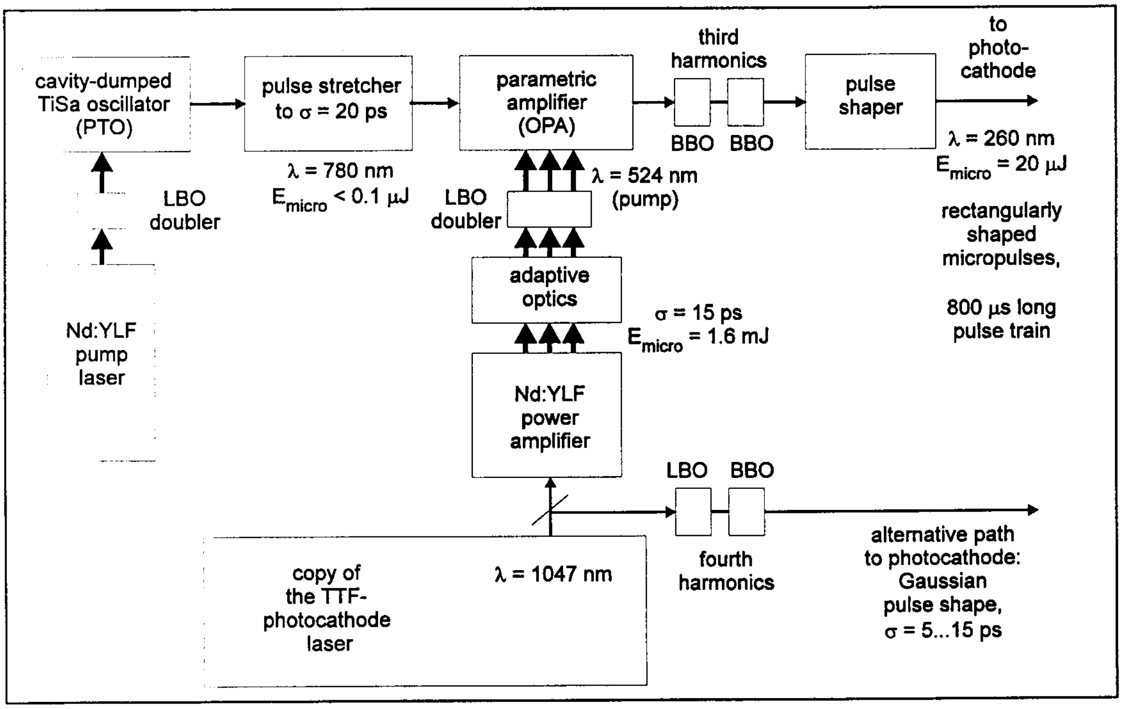

Fig. 7: Principle scheme of the photocathode laser for the test stand

7.2. Amplification process in the laser

Compared to the photocathode laser of the Tesla Test Facility, the planned photocathode laser should generate pulses with rising and falling edges significantly shorter than 1 ps. The photocathode laser of TTF uses Nd:YLF as the lasing material. Nd:YLF has a long lifetime at the upper laser level (τ = 480 µs), a sufficiently large cross section for stimulated emission ($\sigma = 1.8\mathrm{x}10^{-19}$ cm^2) as well as weak thermal lensing. However, it has only a fluorescence bandwidth of 2 nm. Therefore rising and falling edges shorter than 1 ps cannot to be achieved with Nd:YLF. Other materials with larger fluorescence life time, as Cr:TiSa, Alexandrite, Neodymium doped glasses were examined for suitability to produce 800 µsec long pulse trains. Compared to Nd:YLF, all these materials have either a shorter lifetime at the upper laser level (e.g. Cr:TiSa with τ = 3.2 µsec) or a smaller cross-section for stimulated emission (such as Neodymium-doped glasses with $\sigma = 0.4\mathrm{x}10^{-19}$ cm^2). Therefore all these materials would have to be pumped much more intense than Nd:YLF. Since an average laser power of about 200 W should be maintained during an 800 µsec long pulse train, a pump power between 3 kilowatt and several 100 kilowatts would be required depending on the efficiency of the pump system.

This high pump power makes it extremely difficult to develop a photocathode laser, which can generate 800 µsec long trains at 10 Hz repetition rate using the laser materials mentioned above. The development effort would significantly exceed the effort for the existing TTF photocathode laser.

The problems resulting from the high pump power can be partially avoided if the amplification channel of the photocathode laser would not be based on the usual laser principle of stimulated emission but on the so-called parametric amplification which can be achieved in special non-linear crystals. The advantage of this parametric amplification is that the thermal heat of the amplifying medium is very.week.

Optical Parametric Amplifiers (OPA) have been described in the literature for several years. Recently, an energy for the output pulses of 400 Joule at 21 fsec pulse length has been theoretically discussed. However, the experimental realization of such amplifiers remained restricted to pulse energies in the microjoule and millijoule range at an average power below 1 W. The theoretical studies show clearly that an average laser power of 200 W at pulse length of 0.1 ps should be attainable during an 800 µs long pulse train provided that a sufficiently strong pump laser can be set up.

7.3. The pump laser for the OPA with 1.6 kilowatt laser power during the pulse train

Reaching the necessary parameters of the pump laser of the optical-parametric amplifier (OPA) will require a severe technological effort. This pump laser must work in the TEM-00 mode and generate a nearly diffraction-limited optical wave field. Since the OPA unlike laser media has no energy storing capability, the pump laser must provide the radiation energy with the same pulse structure as the desired output pulse but with longer micropulses.

A suitable pump laser for the OPA is not commercially available. However, an extended version of the present TTF photocathode laser would be a suitable pump source. Consequently, we have integrated a copy of this TTF photocathode laser into that new laser design. This has the additional advantage that the pump laser can also be used independently of the OPA for direct illumination of the photocathode, when short pulses or pulses with short edges are not required for a particular experiment.

In order to use the TTF photocathode laser to pump the OPA, its pulse energy must be increased by one order of magnitude. This is due to the following facts:

- The parametric amplification will achieve an efficiency of about 15%.
- Generation of the desired shape of the micropulses requires an appropriate system at the output of the laser. This pulse shaping system introduces losses of about 50%.
- A slight energy gain of about 1.5 is expected in comparison to the TTF photocathode laser, since the radiation at the laser output needs to be converted only to the third (and not to the forth) harmonics.

The increase in power of the pump laser will attained by an additional Nd:YLF booster amplifier with 12 mm rod diameter. This booster should raise the average laser power to 2.0 Kilowatt during the pulse train .

Wave front deformations due to temperature gradients in the laser rods have already been observed at a much lower average power at the TTF photocathode laser. At present, two moveable cylindrical lenses compensate these wave front deformations. In the pump laser for the OPA those wave front deformations will have to be corrected with higher spatial resolution. Otherwise, the pump beam would transmit its deformations to the signal wave, which would lead to unacceptable spatial inhomogenieties of the output pulse produced by the photocathode laser.

7.4. Generation of the desired shape of the micropulses

Two different procedures for the generation of variable shapes of picosecond pulses are described in the literature:

1. Synthesis of a pulse from several short pulses ("pulse stacking"). The individual pulses are separated from the main laser beam by using semitransparent mirrors. The energy of each individual pulse can be tuned depending on the required shape of the finally stacked pulse by applying appropriate filters.

   Simplicity and sufficient flexibility are the advantages of the pulse-stacking method. The main disadvantage lies in the ripples which remain in the shape of the output pulse.
2. Optical pulse shaping by spectral masking. This method is based on spatial splitting of the individual spectral components of the laser pulse by means of gratings. Subsequently, the spectrum in the Fourier plane is modified with the aid of masks and transmission filters. This procedure results in micropulses of the desired shape after recombination of the individual spectral components.

We intend to test both procedures within the framework of the project in order to select the more suitable one.

In addition, the optimum position of the pulse shaper has to be determined. In order to make the decision one has to take into account nonlinearities of processes exploited in the amplification channel, e.g. saturation of the OPA and the frequency conversion into the 3rd harmonics. These nonlinearities lead to modifications of the pulse waveform during the transition through the optical path of the laser system. Unfavorable influences of these nonlinearities on the pulse shape can probably be avoided, if the pulse shaper is positioned at the exit of the laser system.

7.5. Summary on the photocathode lasers

The requirements for the photocathode laser define the upper limits for laser parameters attainable with the currently available technology. Reaching these parameters requires a novel design concept in comparison to the TTF photocathode laser. The MBI proposes such an advanced design concept, which is based on a combination of the following laser technologies:

- Generation of short laser pulses ($\tau << 1$ ps) with a TiSa oscillator;
- Amplification of the laser pulses with large bandwidth in an optical-parametric amplifier (OPA);
- Efficient pumping of the OPA by a frequency-doubled Nd:YLF laser with extremely high power of the picosecond pulse trains;
- Correction of the wave front deformations caused by thermal lensing in the final booster amplifier of the pump laser by means of computer-controlled optics.

Furthermore, the concept allows the laser to be extended to generate pulses with a tunable wavelength between 750 and 850 nm. This means that an appropriately modified laser system could serve as a photocathode driver for the generation of polarized electrons with GaAs cathodes.

The MBI has a great interest in the application and further development of the above-mentioned technologies since they are particularly important for the creation of femtosecond lasers of high average power.

8. Contribution of DESY: The Test Stand for RF Electron Sources

The planned test stand for rf electron sources is supposed to fulfill the following tasks:

- test of simulation calculations and theoretical predictions.
- conditioning and test of optimized cavity resonators for subsequent operation at the TTF linac or the VUV FEL.
- test of newly developed components for the laser and new cathodes under realistic conditions independent of the operation of the free electron laser.
- test and further development of diagnostic components.
- integrated optimization of all components necessary for a rf electron source.
- test of new concepts for the design of rf electron sources e.g. for the production of flat beams.
- on a longer term basis possibly investigations for the design of polarized sources for linear colliders.

The test stand which now exists at DESY will be described in the following. This test stand was designed for the commissioning of the first electron source built at DESY and was set up inside the TTF shielding. This offers the advantage of direct access to many operation components as e.g. klystron, laser, water, power supplies and the TTF control system. However, since the commissioning of an rf electron source at the linac many of these components are in use and no longer available for further tests.

An additional disadvantage of the current location is that the test stand cannot be operated during construction work at the linac and that access to the test stand is limited during linac operation.

The test stand consists of three sections that follow each other: the cathode system, the rf electron source and the diagnostic section (Fig. 8).

The Cesium Telluride cathodes have a limited lifetime of only a few month and are very sensitive to contamination by gases. Therefore, they must always be kept under ultra high vacuum conditions. In the cathode system are up to six active cathodes, which can be inserted into the rf electron source without breaking the vacuum by means of vacuum manipulators.

The rf electron source consists of a cavity and a coupler for the radio frequency. Due to the large induced rf power a very good cooling of the resonator is necessary. Two solenoid magnets for beam focusing surround the resonator. The magnets are mounted on motors for exact positioning. Along beam direction behind the rf coupler the port for the laser beam is located. The laser beam is directed onto the cathode by means of an adjustable mirror in the vacuum system.

As the solenoids produce a strong stray field, the girder for the central section is fabricated out of stainless steel.

The diagnostic section consists of a pepper pot for transverse emittance measurements which is located in the straight direction and a dispersive arm for the measurement of the beam energy and energy width. At the end of both arms the charge can be determined by means of Faraday Cups. Beam screens, a beam position monitor as well as a quadrupole triplet complement the diagnostics possibilities.

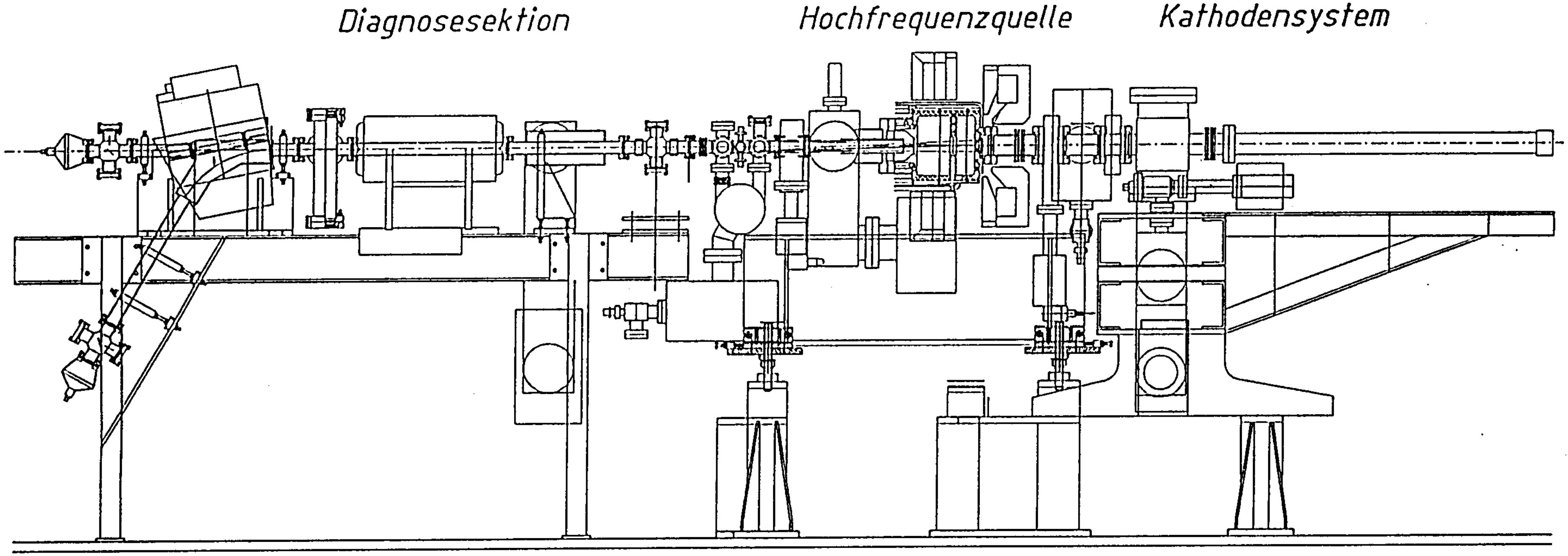

Fig. 8: The test stand for rf electron sources at DESY (length about 5m).

The diagnostic section of the test stand is available for a new test stand at a different location. It can easily be upgraded with an OTR screen for a better diagnostics of the longitudinal phase space. INFN Milan built the cathode system at TTF as a collaboration contribution. A second equivalent system could also be ordered.
The reconstruction of the central section i.e. the stainless steel girder, the solenoid magnets including the magnet motors as well as the small diagnostic cross including the laser port will depend on the construction of the first source. (Improvements will of course be included as experience is gained with the first source.) The inner geometry of the new cavity should be re-optimized. Tests should especially be carried out at higher gradients and with varying laser parameters. Alternatively, the design of a two and a half cell resonator has to be checked.
This simple test stand is especially suitable for the measurement of the transverse emittance. For a complete measurement of the longitudinal phase space the installation of a second resonator (a booster cavity) between the rf electron source and the diagnostic section will be necessary. This will be the second step after the first measurements are completed.
In order to test the production of flat beams a booster cavity will also be necessary. Furthermore, additional solenoid magnets are needed and the diagnostic section will have to be modified.

The infrastructure and operation components necessary for the test stand will be described in the following.

8.1. Resonator and rf coupler development and construction:

The central part of the test stand including solenoids, resonator and rf coupler will be newly constructed. Beforehand the inner geometry of the cavity will again be optimized and the interconnection with the rf coupler will be reworked constructively. Therefore, extensive calculations (beam dynamic simulations and field calculations) have to be done a DESY.

8.2. Site:

It is planned that after the dismantling of the S-band test linac the test stand shall be built in the experimental hall II at DESY. The available shielding also offers sufficient space for the case of a completion of the test stand by a booster cavity (Fig. 9). Parts of the infrastructure built for the S-band linac such as the control room and the personal interlock can be taken over.

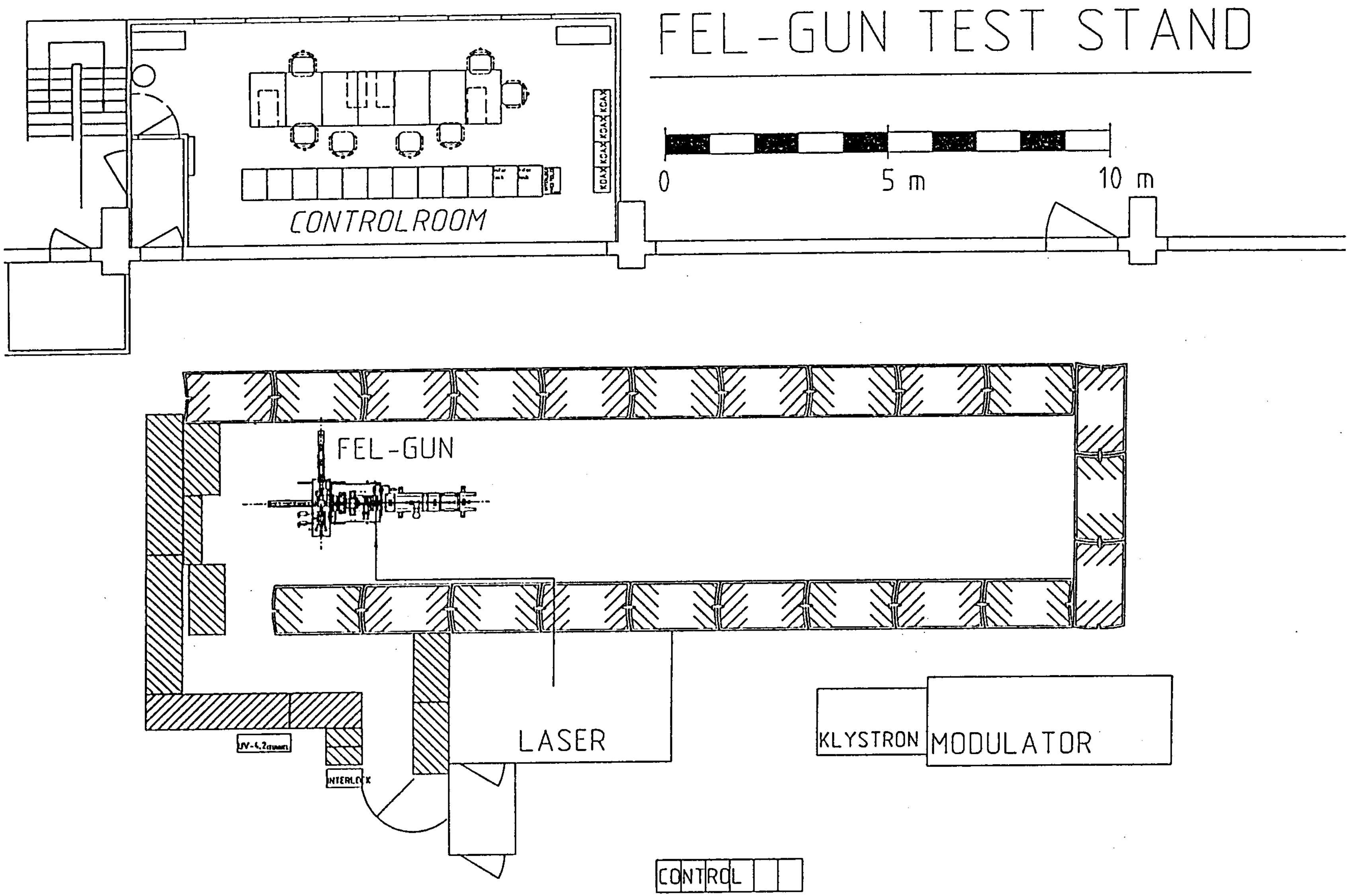

Fig. 9: Planned construction of the test stand in the area of the former S-band test linac.

8.3. Rf supply:

For the separate operation of the test stand a 10 MW klystron including modulator and controls will be necessary. The construction of the wave guide system is not critical but a second high-quality directional coupler (45 dB directivity, Spinner company) and a second rf window are needed. The titanium beta window in operation might be replaced by the cheaper window developed at DESY. However, high power tests are not yet completed.

8.4. Water and power:

Besides the normal cooling water requirements e.g. for the magnet cooling, a separate temperature stabilized cooling circuit is required for the cavity cooling. At the TTF this is realized by an extra pump stand with a temperature control. Two large power supplies (420 A and 320 A) are necessary for the operation of the solenoids besides some smaller power supplies.

9. Contribution of BESSY: Diagnostics and Controls

The situation at the Berliner Elektronenspeicherring Gesellschaft für Synchrotronstrahlung (BESSY) is as follows:

The high brilliance synchrotron radiation source BESSY II successfully started its test operation in spring 1998. Since then all important design parameters have been reached or exceeded so that already in January 1999 the regular user operation could be started. It is generally assumed that the system will allow top-level research for 15-20 years. Further improvements, the extension up to the maximum number of insertion devices and beam tubes as well as optimal user operation have the highest priority at BESSY.

However, the long term future of the institution BESSY in close cooperation with the research programs of the Hahn Meitner Institute will not be storage ring light sources with limited capability for improvement but a new generation of free electron lasers (FELs) on the basis of the SASE principle.

BESSY has begun to move towards FELs both by a participation in the TTF I project and the subsequent further development towards TTF II as well as by its work on the planning for the TESLA project in a cooperation contract with DESY.

Here, BESSY will develop the know-how which is necessary for the construction of an FEL as a future user machine in Berlin Adlershof with a photon spectrum in the range from 10 eV up to a maximum of about 200 eV. This will make radiation of increased brilliance in BESSY's own best spectral range available in about 7 years. Therefore, BESSY will also take part in the immediate future in the development and construction of a rf electron source for electron bunches of extremely short length and small emittance.

The work BESSY takes over focuses on the operation of the beam diagnostics, the computer and timing controls as well as on the data taking (shifts) and data analysis. A new or further development of the master oscillator will the checked.

In the area of the diagnostics the following work is planned:

- characterization of the new Nd:YAG screens.
- work in the area of data taking and analysis (e.g. pepper pot data).
- improvement of the analysis possibilities of the longitudinal phase space by the construction of an OTR station as well as by the use of a streak camera.
- completion of the current measurement by an additional ICT monitor.

Furthermore, the assembly of the laser beam line from the laser hut including beam manipulations by apertures as well as the construction of a virtual cathode for diagnostic purposes will be considered.

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