The Future of HERA and TESLA

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With the advent of HERA a new phase of deep inelastic scattering experiments has begun, the results of which are the main topic of this workshop. In this contribution the status and future perspectives of the scientific program of DESY are presented. They include the luminosity upgrade of HERA and the plans for an electron-positron linear collider, TESLA, with an integrated X-ray free electron laser.

1. INTRODUCTION

This talk was scheduled to be given by Björn H. Wiik, who initiated the HERA electron-proton collider project and was the project leader of the 820 GeV superconducting proton ring. This very high proton energy was essential to reach a centre-of-mass energy where the electromagnetic and weak forces become equal in strength. With HERA in full operation DESY, again inspired by B.H. Wiik, began to plan its long term future. In this paper first the upgrade plans for HERA are discussed, then the TESLA project, on which the long term future of DESY is based, and finally a possible combination of HERA and TESLA as an option for deep inelastic scattering probing nature at even shorter distances than HERA.

2. THE STATUS AND FUTURE OF HERA

HERA has been in operation for experiments since 1992. In Fig. 1 the integrated luminosity as delivered by HERA is shown as function of time, for the years 1992 to 1999. As can be seen from this plot HERA is performing very well this year. The luminosity is a measure of the amount of data collected by the experiments. The luminosity delivered during 1999 was 15 pb^{-1}, averaging to 1 pb^{-1} per week. An extrapolation until December yields 35 pb^{-1} and roughly 50 pb^{-1} until the luminosity upgrade in May 2000. The collaborations will decide soon if they want to switch back to positrons or if they want to stay with electrons for the remaining part of the year.

The electron polarisation, which is presently of central importance only for the HERMES experiment, is stable and reaches on average 55 %. During a long shutdown in 2000 spin rotators will be installed also for H1 and ZEUS. A common taskforce from the three experiments H1, ZEUS and HERMES was formed to improve the measurement of polarisation, aiming at an accuracy of 1-2 %.

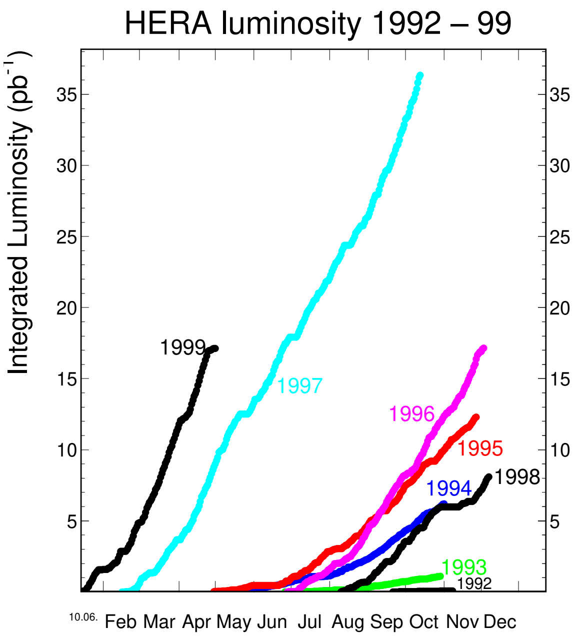

Figure 1. Integrated luminosity as delivered by HERA as function of time, for the years 1992 to 1999.

After a short shutdown in May and June 1999 the data taking will continue, to be interrupted monthly by a three day access period to allow the HERA-B collaboration to complete its detector and to take first data at the beginning of 2000, before a long shutdown will start in May 2000.

During this shutdown HERA will be modified to deliver a higher luminosity for the experiments H1 and ZEUS. This is achieved by substantial modifications of the interaction regions, in order to focus the beams more strongly. Special magnets will be inserted into the collider detectors, combined with major changes of the machine lattice in the vicinity of the experiments. This will result in an increase of the luminosity by roughly a factor four, as compared to the design luminosity. In total, 70 new magnets will be installed. Higher luminosity and beam polarisation will give access to the electroweak physics. In addition to the modifications of the machine also substantial detector upgrades are planned for H1 and ZEUS to better exploit the new data. They include the improvement of the forward trackers, new or upgraded silicon vertex detectors and many other modifications. The shutdown will last eight to nine months, with a restart of the machine foreseen for January 2001. It is foreseen to exploit the high luminosity and spin options of HERA roughly until 2006.

During the next month two workshops will look at additional options for HERA. A workshop on polarized protons is to continue the exploration of the physics potential of experiments using polarized protons and electrons. The main emphasis will be on machine issues, on how to produce high intensity polarized proton sources, on the spin dynamics during acceleration and storage. In addition the question how to measure the proton spin will be addressed. The second workshop will look at HERA as collider for electrons and nuclei. The topics of this workshop are QCD nonlinear dynamics, diffraction and nuclear scattering, parton propagation through nuclear media as well as machine and detector aspects.

Concluding on HERA, the electron-proton running will continue roughly until 2006 with four times the present luminosity and polarized electrons and positrons. The scientific potential and technical aspects of two other options, the storage of nuclei and polarized protons, are under study. The realization of either of these options will directly be linked to the realization of the TESLA project. A preliminary decision on TESLA is expected in 2002 or 2003. At that time DESY will also have to take the decision whether to pursue the polarized electron-proton and electron-nuclei options, with three to four years lead time to realize the modifications necessary to do these experiments.

3. THE TESLA PROJECT

The long term future of DESY is based on a 500 GeV e^+e^- collider with integrated X-ray laser facility, which has been outlined in a Conceptual Design Report published in 1997 [1]. As shown in this report such a machine would offer outstanding and unique scientific possibilities, not only for particle physics, but also for many other fields of science, including solid state physics, chemistry, geology, biology etc.

3.1. Overview

High energy e^+e^- collider have in the past been essential tools in the search for the fundamental constituents of matter and their interactions and have thus made important contributions to the validation of the Standard Model. Due to the rapid increase with energy of the synchrotron radiation power emitted by the electrons in circular machines, colliders aiming at energies above LEP energies (200 GeV) have to be built as linear colliders. The main design criteria for an e^+e^- collider are a center-of mass energy of 500 GeV and a high luminosity (several 10^{34} cm^{-2}s^{-1}) due to the small cross sections at these energies. At a later time the energy should be upgradable to roughly 1 TeV. One inherent advantage of a linear collider is that it can provide beam polarisation for electrons (80 %) and also for positrons (60 %). The option to collide electrons with electrons, electrons with photons and also photons with photons are also available, but have so far not been studied to the same depth as electron-positron collisions.

Technically the best solution for the realisation of such a collider is based on superconducting cavities. This has a number of reasons: Superconductivity leads to a high power conversion efficiency, the ratio of beam power to mains power. This efficiency is around 20 % for a superconducting machine. As superconductivity suppresses power losses in the cavity walls one can store long (ms) RF pulses in the cavities. As a consequence, many bunches of particles, 300 ns apart, can be accelerated during one RF pulse. They can therefore be brought to collide head-on and can be corrected in their position by an active bunch-to-bunch feedback system, thus optimising the luminosity.

Superconducting cavities operate most efficiently around 1 GHz. This in turn is an ideal frequency to maintain low emittance beams during acceleration. The emittance dilution, i.e. the widening of the beam during acceleration, is in transverse direction proportional to the third power of the frequency. As a consequence, accelerators operating at much higher frequencies will have much larger problems with wakefields than TESLA. A low emittance beam is at the same time of key importance for driving a Free Electron Laser.

When limiting the power consumption to 100 MW, assuming a vertical beam height of $\sigma_y^* = 5$ nm, and an efficiency $\eta = 17$ %, the TESLA luminosity is calculated to be $3 \cdot 10^{34}$ cm^{-2}s^{-1}. One can directly compare the TESLA performance with that of other linear collider designs, such as the X-band technology, operating at 11.4 GHz, by assuming the same beam power and vertical beam size at the interaction point for both machines. Under these assumptions TESLA provides four times the luminosity, mainly due to the larger number of bunches per pulse train which is possible due to the use of the superconducting technology. In addition, the large bunch distance makes it possible to use an active feedback, providing a continuous optimisation of the luminosity, while the low frequency leads to less problems with wakefields and the preservation of the emittance during the acceleration.

The low emittance beam can at the same time be used as a drive beam for an X-ray free electron laser. Such a laser is schematically illustrated in Fig. 2. The basic principle [2] makes use of the fact that an electron beam of sufficient quality, passing a long undulator magnet, exponentially amplifies an existing radiation field, if the photon wave length λ_{ph} matches a resonance condition determined by the undulator parameters and the beam energy. Coherent stimulated emission is achieved because a bunch density modulation of the electron beam builds up during the passage of the bunch through the undulator. At very short wave length the spontaneous undulator radiation in the first part of the undulator provides the necessary radiation field. This is called the SASE (self amplified stimulated emission) principle [3]. As no optical elements are needed in this device, a SASE FEL can deliver light with wavelengths in the Angstrom range. In the upper part of Fig. 2 the principle lay out is shown, while in the lower part the increase in radiation power as function of the bunch distance from the entrance into the undulator is shown.

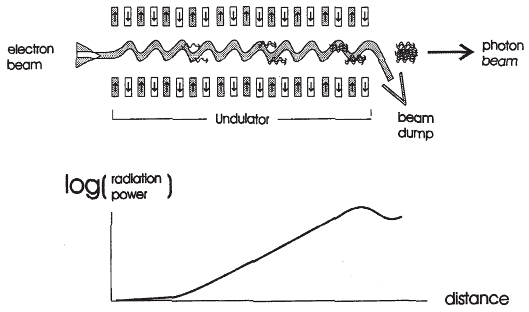

Figure 2. Schematic diagram of a single–pass Free Electron Laser (FEL) operating in the Self Amplified Spontaneous Emission (SASE) mode, [1].

The TESLA facility as a whole in shown in Fig. 3: It includes a source, a damping ring, a linear accelerator with a beam delivery system for both electrons and positrons, an interaction region for particle physics, and a beam outlet for the X-ray FEL. The positrons are generated by photons from an undulator through which the electron beam passes. The length of the whole structure is roughly 30 km.

3.2. The Scientific Potential for Particle Physics

The scientific potential of a e^+e^- collider at around 500 GeV energy has been discussed extensively [4], also in comparison with the potential of the Tevatron and the LHC. In e^+e^- collisions the initial state is well defined, as are the final states, with well defined quantum numbers. The physics can be extracted with a minimum of assumptions. LEP has illustrated the potential of an e^+e^- collider as a machine for precision measurements. A comparison with the Tevatron illustrates the complementarity between an e^+e^- collider and a hadron machine.

The potential of a linear collider can be exemplified using the Higgs mechanism. It is one of the three building blocks of the Standard Model as the fundamental particles acquire mass through the interaction with a scalar field with non-zero strength in the ground state. The only unknown parameter in the Higgs sector is the mass of the Higgs particle. From the measurements at LEP and Tevatron one can derive limits, through electroweak radiative corrections, for the region where to expect the Higgs particle. Fig. 4 shows the χ^2 of the global electroweak fit in terms of the Higgs mass m_H. Therefore the present limits constrain the Higgs mass to lie between 90 and 260 GeV with 95 % confidence level. This region has been roughly stable for the last four years. This low Higgs mass points to the fact that the Standard Model may be valid up to very high energies like 10^{16} to 10^{18} GeV.

The observation of the Higgs particle is only the first step in testing the Higgs mechanism. In addition one has to measure all possible branching ratios of the Higgs, for which the standard model makes precise predictions, with the highest accuracy possible. Detailed studies have shown that these branching ratios can be measured at a linear collider with an accuracy of less than 10 % [6].

Within the Standard Model, the Yukawa couplings of the leptons and quarks with the Higgs particle are uniquely determined by the particle

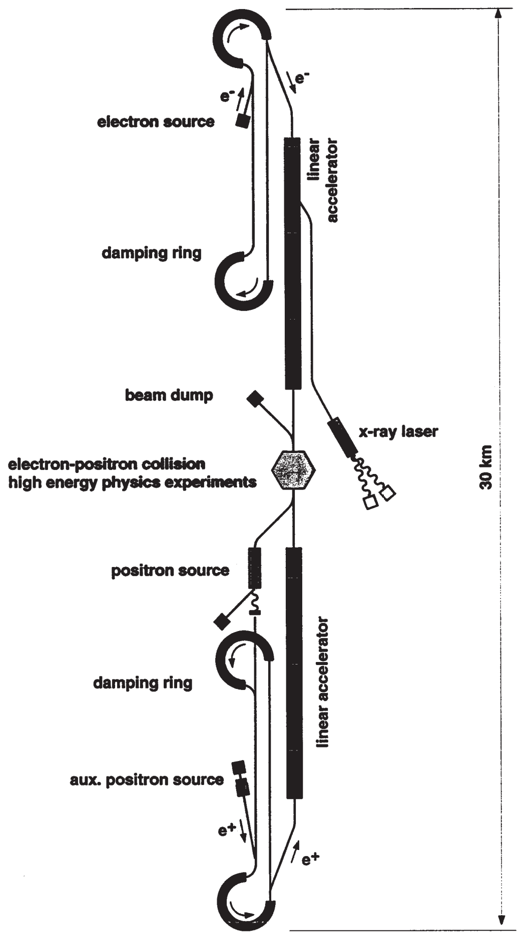

Figure 3. Schematic view of TESLA, [1].

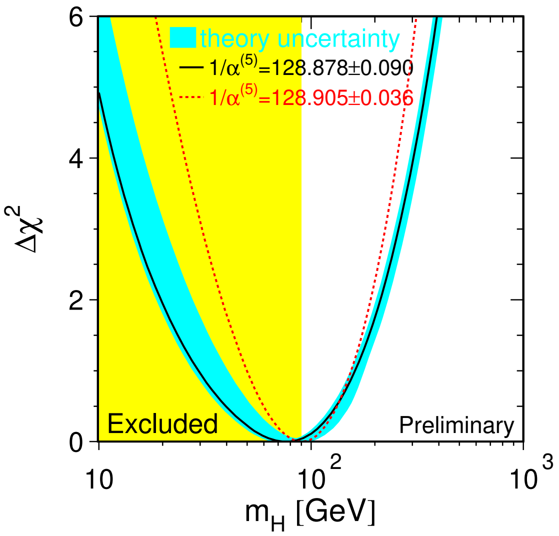

Figure 4. χ^2–constraints on the Higgs boson mass of the Standard Model from electroweak precision data, [5].

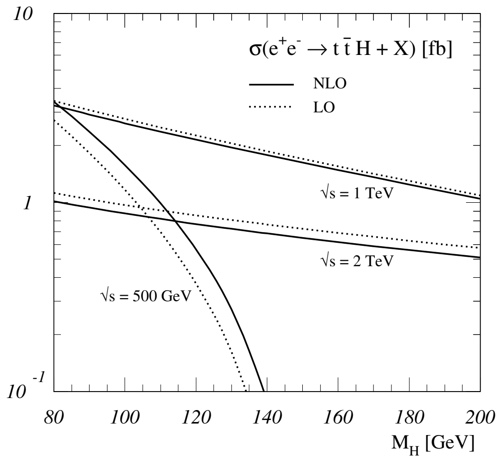

Figure 5. The cross section $\sigma(e^+e^- \to t\bar{t}H + X)$ as a function of the Higgs boson mass for different cms energies, [7].

masses: $g_{ffH} = m_f/v$, where $v = (\sqrt{2}G_F)^{-1/2} \approx$ 246 GeV. The measurement of these couplings provides a fundamental experimental test of the Higgs mechanism. The top-Higgs coupling can be measured directly in the process $e^+e^- \to t\bar{t}H$. In Fig. 5 the total cross section for this process, including QCD radiative corrections is shown for three collider energies as function of the Higgs mass [7]. The plot illustrates the need for high luminosities to measure this important parameter. Assuming for TESLA an integrated luminosity of 300 fb^{-1} per year, a Higgs mass of 120 GeV and a center of mass energy of 500 GeV, one expects a few hundred of these events, required to measure the coupling with sufficient accuracy.

3.3. The Scientific Potential of an X-ray FEL

The scientific potential of the X-ray FEL has been reviewed in detail in [1]. The laser provides first of all a very brilliant photon beam. Fig. 6 shows the average and peak photon flux for three different undulators. One clearly distinguishes between the coherent and incoherent parts of the spectrum. A normal undulator yields typically 10^7 photons/ps in a pulse which is 100 ps wide. In contrast, the FEL delivers a 100 fs pulse with 10^{14} photons/ps. In addition the radiation is coherent. In Fig. 7 the peak brilliance of the TESLA FEL is compared, as function of energy, to several other state-of-the-art synchrotron light sources, such as BESSY II and the ESRF. One notices that the TESLA Free Electron Laser peak brilliance exceeds that of existing machines by many orders of magnitude, in addition to the other features such as time structure, tunability, coherence etc.

Only a few examples for the scientific applications of this radiation shall be mentioned here: The high intensity and short pulse length make instantaneous snapshots of physical, chemical and biological processes possible, with atomic resolutions and time scales down to 10^{-13} s. Due to

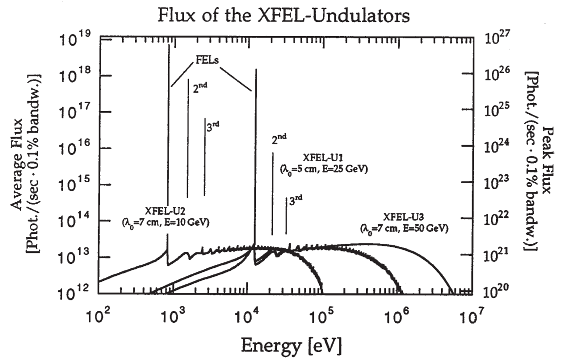

Figure 6. Average and peak flux for undulators 1,2, and 3 at the fundamental, second, and third harmonic, respectively. The average values refer to TESLA parameters, while SBLC numbers are smaller by a factor of two, [1].

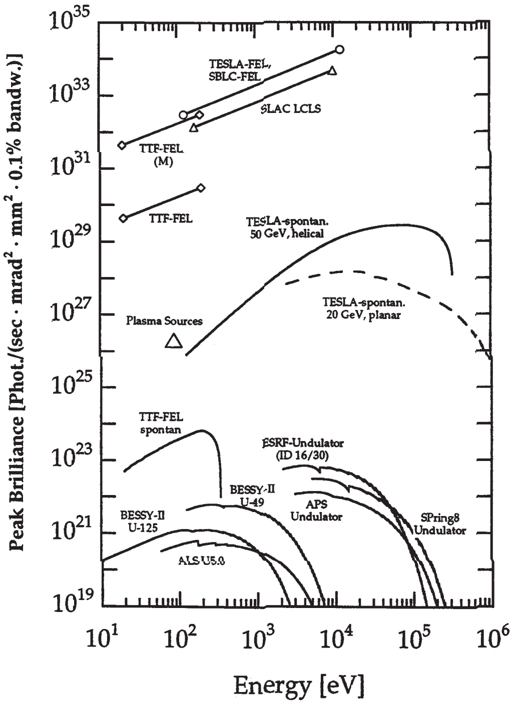

Figure 7. Spectral peak brilliance of XFELs based on SBLC and TESLA linear colliders, together with that of third generation synchrotron radiation sources and the LCLS Free Electron Laser project at SLAC, Stanford, USA. For comparison, also the spontaneous spectra of two XFEL undulators are shown. The peak brilliance of state-of-the-art plasma Lasers is also noted, [1].

the high power density of 10^{16} W/cm^2 one can study non-linear processes. As the wave length of the laser can be tuned by changing the beam energy one can do spectroscopic measurements of unprecedented quality. The temporal and spatial coherence of the radiation opens the possibility to do 3-D holograms of molecules with atomic resolution, e.g. of biological systems. Due to the short pulse structure these measurements can be done with sub-ps time resolution.

3.4. The Status of the TESLA Project

The clear advantages of a super conduction linear accelerator, access to very high luminosities and excellent beam quality, have to be compared to the technological challenges as they were known in 1990 when the work of the TESLA collaboration started. At that time one was able to obtain 5-8 MVM per meter and had to pay 200 $kUS\$/m$. Given these numbers nobody would be able to afford a superconducting 500 GeV collider. In addition the opinion prevailed, that a superconducting machine would be difficult to operate. Today we know from LEP, CEBAF, and HERA that superconducting machines are very stable. An international research and development program was started in the framework of the TESLA collaboration, which includes members from 9 countries. Until today the non-German institutions have invested 20 MDM and 350 man years which has led to the present status of TESLA.

3.5. The TESLA Cavity Development

The basic elements of TESLA are 9 cell cavity structures made from Niobium, roughly one meter long. The goals of the R+D program within the TESLA collaboration were to improve the gradient, to build cost effective structures, to build a TESLA test facility as a test bed, to prove the SASE laser principle, and to gain operation experience by supplying beams of photons to a VUV-FEL user facility. Fig. 8 shows how well the collaboration has done over the years in raising the gradients of the superconducting cavities.

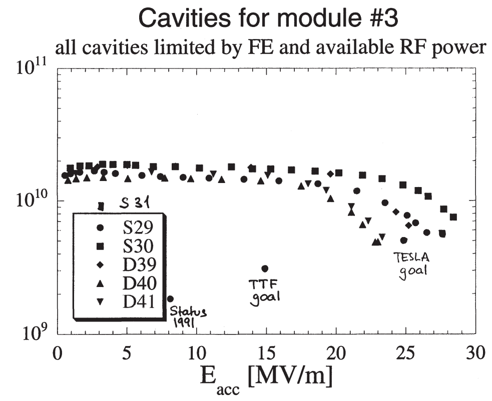

Figure 8. The excitation curves $Q(E_{\rm acc})$ for cavities of module #3.

In 1990, when the program started, the state of the art in superconducting cavities was 8 MVM and a quality factor $Q = 2 \cdot 10^9$. The goal set for the TESLA Test Facility was 15 MVM and $Q = 3 \cdot 10^9$, the TESLA goal was 25 MVM and $Q = 5 \cdot 10^9$. The series of points in Fig. 8 shows the performance of a few of the most recent cavities. It can be seen that their performance already now exceeds the TESLA goal. One can therefore say today that the cavity production is more or less understood.

Nevertheless, attempts are being made to increase the cavity performance even further, e.g by electro-polishing the surface. This work is being done by Saclay together with KEK. In tests with single cell cavities gradients of 37 MVM have been reached.

A potentially weak feature in the cavities are the welds. By making seamless cavities this weakness could be avoided and higher gradients be reached, while allowing at the same time for much easier manufacturing. Several labs within the TESLA collaboration have already produced seamless cavities.

In order to bring the structural costs down, a simplified structure has been developed, combining a string of eight 9 cell cavities into one unit. This has been implemented in the TESLA Test Facility and performed to specifications. In addition, new ideas on how to further reduce the cost per length are being worked on. This includes the reduction of free space between neighbourging cavities, where four cavities are fed through one radio frequency coupler. This decreases the cost and increases the simplicity. It also increases the number of cavities per unit length. In order to build a 500 GeV Linac in the length foreseen would then only require gradients of 22 MVM rather than 25 MVM. These gradients are already reached routinely and from this point of view one would be able to build a 500 GeV superconducting linear collider today.

3.6. Results from the TESLA Test Facility

To gain system and operating experience with a superconducting linear accelerator the TESLA Test Facility (TTF) was built and started in 1997 to deliver first beams. The machine operated very stably and reproducibly. In spring of 1999 a second test phase took place with two modules of eight nine-cell cavities each, the second module reaching on average a gradient of 23.5 MVM. Furthermore, a radio frequency (RF) gun and a second bunch compressor came into operation. The performance of the new components was very satisfactory, the RF gun for example delivered eight times the nominal charge needed for the linear collider, while in a few areas, such as the emittance, the achieved values were still a factor 2 worse than the design goal, but can clearly be improved.

After four months the beam tests were stopped in order to prepare for the proof that the SASE principle for the laser works: Three undulator structures are being installed behind the two accelerator modules, followed by diagnostic tools for both the electron and photon beam. The laser will start to operate this summer and one hopes to see the first laser light in late summer. In parallel an even larger facility is being prepared, by extending the existing test facility by a tunnel of two hundred meters length, to house seven more accelerator modules, one more bunch compressor and a very long undulator. At the end of the beam line an experimental hall will house a user facility for laser light in the far ultra violet, where one will gain experience in doing experiments with the high intensity radiation from the laser. The construction has started in 1997, the tunnel has been finished, the experimental hall has just been started and the commissioning is scheduled for the end of 2001, providing, beside DORIS and PETRA, yet another user facility for synchrotron radiation in Hamburg.

In preparation for the Technical Design Report TESLA an environmental impact study has been started and industrial evaluations of the subsystems are being performed. DESY has always been very interested in having the TESLA project evaluated by the German Science Council (Wissenschaftsrat), the highest scientific advisory committee to the government, and the Federal Minister for Science, Mrs. E. Bulmahn, has recently informed her colleague in Hamburg that she will initiate such an evaluation.

3.7. Next Steps

In spring 2001 the Technical Design Report will be given to the Science Council for evaluation. In 2002 the result of the evaluation should be known and handed over to the Federal Government and the Länder for a decision in principle. In parallel the international partners in TESLA will be preparing the decisions in their countries. The TESLA project organisation and the legal framework for the TESLA project will have to be finalised. In 2003 the final decision on TESLA could be taken, followed by the start of construction. The construction is estimated to take six to seven years.

Concluding on this part of the DESY future: The TESLA project offers a unique scientific potential in the e^+e^- physics which is complementary to the LHC and opens a huge scientific potential with the X-ray FEL. This simultaneous multidisciplinary use of TESLA is a very attractive feature. The technology for high luminosity and low emittance for linear accelerators with superconducting cavities is very well advanced. Tremendous progress has been made over the last eight years due to the very engaged efforts by a large international collaboration. A lot of work is still to be done to complete the Technical Design Report in early 2001. A start of construction of TESLA in 2003 would match the time scale of completion of the LHC.

4. PHYSICS WITH TESLA AND HERA

TESLA will be housed in a tunnel of 30 km length which will start on the DESY site, in HERA hall West, running tangential to HERA. This direction has been chosen with the clear intention to have the future option to collide electron beams from TESLA with proton beams in HERA. The center-of-mass energy one could reach by colliding 250 GeV electrons with 920 GeV protons is 960 GeV, roughly three times the HERA center-of-mass energy and roughly equivalent to energies one would obtain when colliding beams from LHC and LEP. The physics potential of such a machine has be discussed in a talk by Y. Sirois [8].

The luminosity which can be achieved when colliding beams from HERA and TESLA have been evaluated by R. Brinkmann [9] and is limited by the collision frequency and proton phase space density. The collision frequency in HERA is 10 MHz, that of the linac is 5.6 kHz, limited by the Rf power which can be stored in the beam. Assuming an electron energy of 250 GeV and the HERA proton beam parameters as they are today, one would obtain a luminosity of 1.2 10^{28} $P_e(MW)$. In order to achieve a luminosity of 10^{31}, one would need 1000 MW. One could, however, increase the current by a factor of 2.5 and at the same time improve the proton beam quality by cooling, thus reducing the phase space density which is limited by intrabeam scattering. This is in principle possible, but has so far been demonstrated only at low energies. An advantage of using an electron beam from TESLA would be that the electron polarisation could be higher (80%) than what HERA can deliver at the moment (55%).

Only few studies have been performed so far on the physics potential and the machine aspects of a TESLA-HERA collider [10]. It would be good to include in the Technical Design Report a chapter on the physics potential of electron proton collisions with TESLA on HERA.

One other possibility of a combined use of TESLA and HERA has been described in the Conceptual Design Report, which has been studied by the nuclear physics community, called ELFE at DESY. ELFE was originally planned as a stand-alone facility providing beams of 25 GeV electrons of high current, 30 μA. NuPECC, together with DESY, has studied if one could take a beam out of TESLA at 25 GeV, reinject it into the electron ring of HERA, and use HERA as a storage and stretcher ring to do experiments. The study has shown that this is possible [1].

5. SUMMARY

In this paper the status of HERA and of the future project of DESY, TESLA, was described. HERA with the luminosity upgrade coming up has an exciting scientific future for many years to come. The impressive progress of TESLA is a result of the collaborative work of many people in many countries who have combined their resources and ideas to make this vision become reality. I hope that the project will also in the future be a genuinely international project. DESY, with its experience in accelerator physics, particle physics and also synchrotron radiation, would be an ideal place for such a machine and therefore we will continue to make every effort to get TESLA approved and built. This would be the proper epitaph for Björn H. Wiik, to whom I dedicate this talk in greatest admiration.

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