DESY LABORATORY REPORT

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Abstract

The performance of the accelerators at DESY which serve a large scientific community, the e-p collider HERA and the synchrotron radiation source DORIS, will be presented as well as the planning for the future of these machines. The latest results from the R&D work for the international TESLA project, a superconducting linear collider with an integrated X-ray FEL laboratory, will be given. The status of the TTF (Tesla Test Facility) at DESY and the plans to use the facility for an FEL laboratory will be described. Finally an outlook on the planning of the TESLA project will be given.

1 INTRODUCTION

The purpose of DESY is to support basic research in natural science by the construction and operation of particle accelerators, especially for research in elementary particle physics and for the scientific use of synchrotron radiation. The laboratory in Hamburg has a staff of about 1100 people with an annual funding of about 250 MDM supplied by the German Federal Government (90 %) and by the city of Hamburg (10 %). In 1992 the former institute for High Energy Physics in Zeuthen near Berlin with a staff of 130 people became part of DESY on the recommendation of the Science Council of the German government.

Research in elementary particle physics is being pursued at the Electron Proton Storage Ring Facility HERA. Two experiments, H1 and ZEUS, are investigating the reactions of collisions between 920 GeV protons and 27.5 GeV electrons or positrons. The two other experiments make use of the individual beams via internal targets, HERMES is studying the spin structure of the nucleon by measuring the reactions of the circulating polarised electron or positron beams with polarised gas targets, and HERA-B will determine details of CP-violation looking for B and $\overline{B}$ mesons produced in wire targets exposed to the halo of the proton beam.

The general interest in the physics potential of the HERA facility caused a substantial outside contribution (22 % from 11 countries) to the construction cost of the facility. At present about 420 scientists from 20 German universities 800 scientists from foreign universities and institutions are working at HERA.

The storage ring DORIS supplies synchrotron radiation to researchers from many scientific areas: solid state and surface physics, geology, chemistry, material science, molecular biology and medicine. At present the facility is being used by 1600 scientists from 150 German institutions and 450 scientists from 32 foreign countries.

The user community of both facilities increased from about 500 in 1980 to about 3300 at present, the strongest increase being due to users of synchrotron radiation for molecular biology.

The laboratory site in Hamburg is located in a built-up area and while the storage ring PETRA stays mostly within the boundaries of the laboratory, the storage ring HERA is located mainly outside the DESY site and runs in part underneath residential areas. The accelerators which have been built in the past are still in operation [1,2,3,4,5] and are used in the pre-accelerator chains for DORIS and HERA.

2 THE SYNCHROTRON RADIATION SOURCE DORIS

The storage ring DORIS, which originally was built as an e^+e^- collider up to 5 GeV, has been used as a dedicated synchrotron radiation source since 1993. The machine is being operated at 4.5 GeV, mainly with a current of 150 mA e^+ in 5 bunches [6]. There are 10 beamlines for radiation from special wiggler magnets and 30 beamlines using synchrotron light from the bending magnets (Fig. 1). The machine is typically operated for about 5000 hrs/year with running periods of 5 weeks followed by a week for maintenance and machine development. A very respectable operating efficiency of 90.7 % has been achieved.

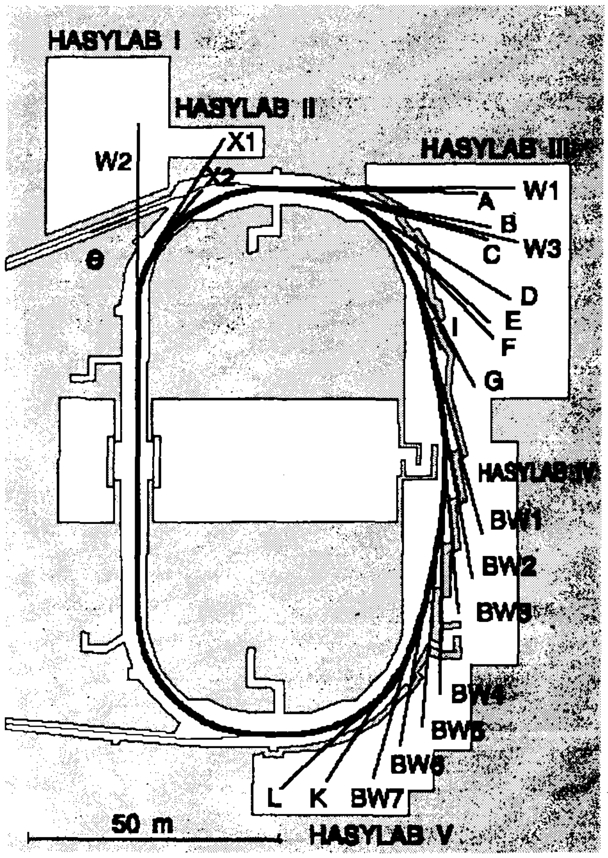

Figure 1: Layout of DORIS Beam Lines.

A very promising medical application of synchrotron radiation, which is being pursued at DORIS, is coronary angiography [7]. Two gamma rays of different wave length are focussed on the heart of a patient and detected in separate, space resolving detectors about 2 m behind the patient. By moving the patient upwards sufficiently fast, a scan of the heart and the surrounding blood vessels can be made within a small fraction of a heart beat. An image of the heart and the blood vessels is obtained by enriching the blood with iodine, selecting the frequencies of the gamma rays slightly above and below the K-shell of iodine, and subtracting the detector signals for the two gamma rays. The image clearly shows cross sections of the narrowed blood vessels and allows malfunctions of the vessel system to be detected.

In contrast to conventional coronary angiography the iodine is injected into the arm, instead of directly into the heart by a cannula, thus reducing the risk of fatal complications for the patient. The method is being evaluated by independent referees at present. If the evaluation yields a positive result, DESY will consider proposing the construction of a dedicated angiography synchrotron radiation source at a hospital in Hamburg. The design of such a machine is underway at DESY in collaboration with IHEP Protvino.

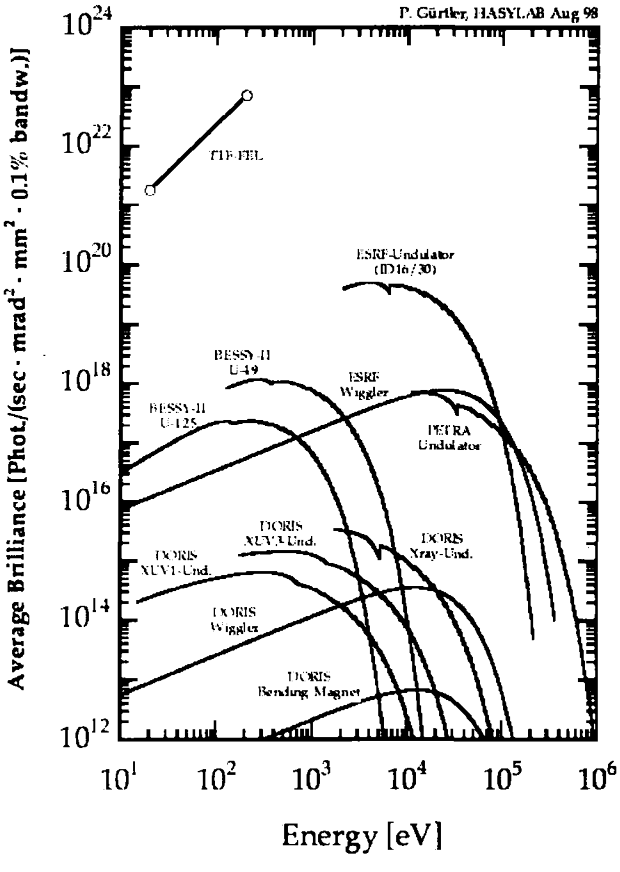

Figure 2: Brilliance of the PETRA Undulator

3 PETRA

Besides serving as an injector for electrons or positrons at 12 GeV and protons at 40 GeV for HERA, PETRA is being used as a source of hard X-ray radiation during the time available between HERA injections. For this purpose the machine is operated with positrons at 12 GeV with a special low emittance optics. The X-ray radiation is generated in a 4 m long permanent magnet undulator with a period length of 33 mm and a variable undulator gap down to 14 mm at a magnetic field of 0.6 Tesla [5].

Due to the high beam energy of 12 GeV the spectrum radiated from the undulator extends to very hard photons of several hundred KeV (Fig. 2) at a somewhat higher intensity than can be obtained at other synchrotron radiation sources. However, as PETRA is being operated in this mode only parasitically for about 25 % of the total operating time, considerable flexibility of the users is required.

4 HERA

The first operation of HERA, colliding 820 GeV protons and 27.5 GeV electrons, started in 1993 enabling the collider experiments H1 and ZEUS to take their first data. Since then the performance of the collider facility has been continously improved and the luminosity delivered to the experiments increased. In 1997 the integrated luminosity finally exceeded the design value of 35 pb^{-1} [8,11] (Fig. 3). Longitudinal polarisation of the positron beam, between 50-60 %, could be established routinely for the HERMES experiment. The increase in luminosity was achieved by a steady increase of the stored currents. In 1997 proton currents of 100 mA could be stored routinely, which amount to 2/3 of the design current of 150 mA, and about 40 mA of positrons amounting to 80 % of the design. By stronger focussing of the beam at the IP compared to the design, a peak luminosity of $1.4 \cdot 10^{31}$ $cm^{-2}sec^{-1}$ could be reached, only slightly short of the design value of $1.5 \cdot 10^{31}$ $cm^{-2}sec^{-1}$. The operating efficiency could be increased only moderately, to 42 % in 1997, compared to a maximum value of 75 % for luminosity operation, which is due to the unavoidable time lost during the filling procedure of HERA.

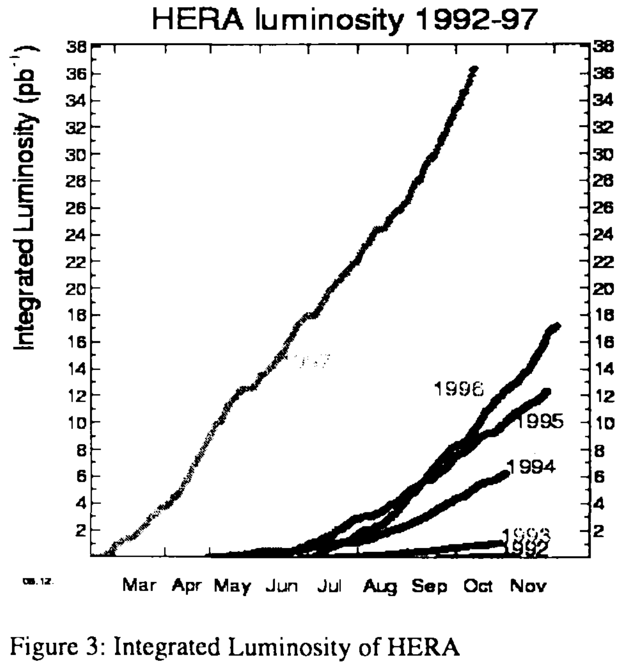

Figure 3: Integrated Luminosity of HERA

Several modifications have therefore been made to the machine systems during the shutdown in 97/98 to increase the reliability of the components and the operating performance. An additional RF-system for the electron ring has been installed in the straight section at HERA hall West, to enable the RF power sources to operate at a lower power level and thus more reliably.

A bias voltage has been applied to the input couplers of the superconducting RF cavities to prevent trips from multipactoring. A new power supply has been taken into operation for the main superconducting magnet circuit. New controls have been implemented, among others for the magnet power supplies of both machines, to gain in operational efficiency.

After extensive tests at energies higher than 820 GeV at the end of the running period '97, it was decided to opererate the p-machine at 920 GeV in '98 [9]. To maintain a similar margin between the operating current and the critical current as at 820 GeV the temperature at the s.c. coils was lowered from 4.5 to 4 K by operating the Helium 2 phase cooling circuit at reduced pressure.

During the operation with electrons in 1993 and 1994 we often experienced a sudden drastic drop in lifetime which was accompanied by a local increase of loss rates. These effects could be explained by dust particles trapped in the electron beam [10], which did not occur with a positron beam, therefore operation was switched to positrons in the middle of 1994. The integrated ion pumps could be clearly identified as the source of the dust. As the collider experiments need data with electrons, during the shutdown period 97/98 the integrated ion pumps in the dipole magnets of the electron ring have been replaced by NEG-pumps. It is too early to say whether we have solved all the problems with the lifetime of the electron beam but a comparison between lifetimes over many runs for various currents in 1994 with data obtained in the first few weeks of operation show clearly that the lifetime has been considerably improved.

For the next longer shutdown period we are preparing a modification of the interaction regions at the collider experiments to increase the obtainable luminosity [11]. This will be done by moving focussing magnets closer to the IP. The reduced spot size at the IP will increase the peak luminosity from $1.5\cdot10^{31}$ cm^{-2} sec^{-1} to $7\cdot10^{31}$ cm^{-2} sec^{-1}.

There are three reasons which require a rather complicated design of the magnets in the neighborhood of the Interaction region. The available space is very tight; the distance between electron and proton beam is small; and synchrotron radiation originating from bending magnets close to the IP must be absorbed far away from the detector to avoid excessive background in the detector components. These magnets are designed and constructed in collaboration with the Efremov Institute in St. Petersburg and the Brookhaven National Laboratory.

For the operation of HERA beyond the present programme two options are being considered. One is to do experiments with polarised protons [12]. Studies together with the international spin collaboration indicate that operation with polarised protons at 820 GeV is feasible. The other option is to operate HERA as an electron ion collider. The physics potential of this option has been discussed at a workshop in 1997 organised by DESY, GSI and NUPECC. A decision on the future utilisation of HERA will not be taken before 2001.

5 PLANS FOR THE FUTURE

Within the International TESLA Collaboration, DESY plans to construct an e^+e^- linear collider based on superconducting cavities with an integrated X-ray FEL facility. The low resistive losses in the walls of superconducting cavities yield a high conversion efficiency from mains to beam power.

The frequency dependence of the shunt impedance per unit length for superconducting cavities favours RF frequencies in the range of 0.5 to 3 GHz. This makes them ideally suited to accelerate low emittance beams, as the emittance dilution by wakefields is small ($W_\perp \sim \omega^3$). In addition tolerances on the fabrication and alignment of cavities are very relaxed.

The luminosity of a linear collider is given by [14,15]

$$L \approx const. \frac{\sqrt{\delta_B}}{E_{CM}} \cdot \frac{\eta}{\sqrt{\varepsilon_{yN}}} \cdot P_{AC} \cdot H_D$$

where δ_B is the relative energy loss caused by beamstrahlung, E_{CM} is the centre of mass energy of the $e^+ e^-$ collision, η is the conversion efficiency from mains power P_{AC} to beam power, ε_{yN} is the normalised vertical emittance at the IP and H_D is the disruption factor. Thus, the figure of merit [16] for the luminosity performance of a linear collider is given by $\eta/\sqrt{\varepsilon_{yN}}$. Therefore the combination of high conversion efficiency and small emittance dilution makes a superconducting linear collider the ideal choice with respect to the achievable luminosity.

The major challenges to be mastered so that a superconducting linear collider becomes feasible are to increase the accelerating gradients from about 5 MV/m to 25 MV/m and to reduce the cost per length from existing systems by about a factor of four to obtain ~ 2000 $/MV. Encouraged by results from R&D work at CEBAF, CERN, Cornell, DESY, KEK, Saclay and Wuppertal [17,18,19], the TESLA Collaboration decided in 1991 to set up the necessary infrastructure at DESY [20] to process and test 40 industrially produced 9 cell 1.3 GHz solid Niobium cavities. The aim was to achieve gradients of 15 MV/m at a Q value of $3\cdot10^9$ in a first step and finally to reach 25 MV/m at a Q value of $5\cdot10^9$ suitable for the linear collider. The infrastructure of the TESLA Test Facility TTF consists of cleanrooms, chemical treatment installations, a 1400° C purification furnace, a high pressure water rinsing system, a cryogenic plant to operate vertical and horizontal cavity test stands at 1.8 K and a 1.3 GHz RF source. For more details see [13].

In addition the collaboration decided to build a 500 MeV linac as an integrated system test to demonstrate that a linear collider based on s.c. cavities can be constructed and operated with confidence.

Considerable attention has been given to the subject of cost reduction [21,22]. For example:

- The number of cells per accelerating structure was increased to 9 compared to the customary 4-5. This reduces the number of RF input and HOM couplers, tuning systems and cryostat penetrations, it also simplifies the RF distribution system and increases the filling factor.
- Costly cryostat ends and warm to cold transitions were avoided by combining eight 9-cell cavities and optical elements, which were all chosen to be superconducting, into one long, simple cryostat. Also the complete helium distribution system has been incorporated into the cryostat using the cold low pressure gas return tube as a support structure for cavities and optical elements.

From the work started in 1990 [18] a concept for a 500 GeV cm energy superconducting linear collider emerged, operating at 1.3 GHz with a gradient of 25 MV/m at $Q=5\cdot10^9$ and a luminosity of some $5\cdot10^{33}$ $cm^{-2}sec^{-1}$. A conceptual design report (CDR) was published in May 1997 [23] giving a complete description of the machine including all subsystems. The report includes a joint study with ECFA on the particle physics and the detector layout.

Since 1990 interest has grown [24,25] in linac driven X-ray FEL radiation, based on the Self-Amplified Spontaneous Emission (SASE) principle [26,27]. As the requirements on the emittance of the beam for a short wave length FEL are very demanding, again a superconducting low RF frequency linac lends itself as the best choice for such an application. The CDR includes the layout of an X-ray FEL facility integrated into the linear collider as well as various scientific applications of the FEL radiation. Wavelengths in the range of 1 Å are envisaged. This ambitious goal is approached in three steps.

First, a proof of principle experiment for a SASE FEL will be done using the 390 MeV beam of the TTF linac. This test, in which wavelengths down to 420 Å can be obtained, is scheduled for 1999.

Second, the energy of the TTF linac will be upgraded to 1 GeV by installing 5 additional modules. The bunches will be compressed to 50 μm length and an undulator of 27 m length will be installed. The expected wavelength of the FEL radiation is 60 Å . This radiation will be made available to users by about 2003 in a new experimental hall.

Finally, for wavelengths in the range of 1 Å , part of the linear collider will be operated with additional RF-pulses to accelerate low emittance bunch trains to energies between 10 and 50 GeV. The beam will be ejected from the linac into transfer lines to the X-ray FEL facility which is situated at the same site as the experimental hall housing the high energy physics detector. For more details of the FEL facility see [28].

Up to now 25 9-cell Niobium cavities have been tested at the TTF. The majority of the cavities exceeded the initial TTF design goal of 15 MV/m at $Q=3\cdot10^9$. Fig. 4 shows the measurements in the vertical test stand of all cavities excluding only those with a well identified fabrication error. On average a gradient of 22 MV/m at $Q=10^{10}$ is obtained. For more details on the R&D results see [13].

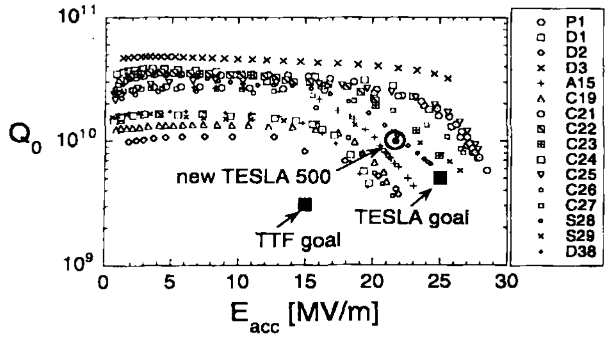

Figure 4: Quality factor Q versus acc. gradient for all 9-cell cavities without fabrication error (vertical test).

A very important new development was initiated by the proposal of a cavity "superstructure" [29]. In this scheme the spacing between adjacent cavities is reduced from 1.5 to 0.5 RF wavelengths and a group of 4 or more of these closely spaced cavities is supplied with RF power by only one input coupler. In this way the filling factor - the ratio of active to total length - increases from 66 % to 76 % or more, thus reducing the required gradient for 500 GeV cm operation from 25 to 21.7 MV/m for fixed linac length. The cost reductions due to the smaller number of RF input couplers and cryostat penetrations, and the simplification of the RF distribution system are obvious.

In the Conceptual Design Report the machine parameters were chosen such that luminosity and beamstrahlung energy loss were comparable to other linear collider designs [30]. The potential of the superconducting linac to accelerate a very small emittance beam with small emittance dilution was not exploited intentionally, keeping requirements on the alignment and stability of the linac and final focus components quite relaxed. Since the completion of the CDR, however, this strength of the TESLA concept has been investigated to some extent [31] leading to a new parameter set [32] suited for high luminosity operation at 500 GeV cm energy (see Table 1). The benefits of the new "superstructure" concept have been incorporated into the design.

The reduction of the required gradient (25→21.7 MV/m) leads to an increase of the quality factor from $5\cdot10^9$ to 10^{10}. Both effects lower the required power for the cryogenics. This power savings has been invested in the beam power. The resulting lower loaded Q-value corresponds to a shorter filling time of the cavities, which in turn results in an increased conversion efficiency from mains to beam power (17→23 %).

There has been consensus within the collaboration that the linear collider facility must be built at an existing high energy physics laboratory to make use of the existing infrastructure and staff. In the CDR two possible sites have been envisaged, one being DESY, the other Fermilab. Both sites allow for a future option to collide 500 GeV e^-/e^+ with high energy protons circulating in HERA or the Tevatron.

This option fixes the possible direction of the linear collider. At DESY, the tunnel is foreseen with the main linac axis being tangential to the West straight section of HERA, extending about 32 km into the state of Schleswig-Holstein. The countryside is flat at about 10 m above sea level with maximum height variations of some 10 m. The tunnel axis is foreseen at 8 m below sea level, giving more than sufficient soil coverage for radiation protection.

The planned tunnel (diameter 5.2 m) contains the straight sections of the "dogbone" damping ring and several beam lines to the FEL facility. About 625 klystrons and their pulse transformers are installed horizontally below the floor of the tunnel. Each 10 kW klystron feeds 32 9-cell cavities corresponding to a length of about 48 m.

In the present layout the modulators are housed in service halls above ground connected to the pulse transformers in the tunnel by long cables. These service halls will be needed in any case about every 5 km along the collider for the cryogenics supply of the superconducting linac [33]. For more details on the layout see [34].

On the basis of the existing know-how, orders to industry are being issued to evaluate the requirements of large scale industrial cavity production. Together with a detailed layout of all subsystems of the collider the information from the industrial studies will allow for a proposal containing the technical design of the facility, and a reliable schedule and cost evaluation, in about three years from now.

Table 1: Updated parameters at E_{cm}=500GeV in comparison with the original reference parameters.

	TESLA (ref.)	TESLA (new)
site length [km]	32.6	32.6
active length [km]	20	23
acc. Gradient [MV/m]	25	21.7
quality factor Q_0 [10^{10}]	0.5	1
t_{pulse} [μs]	800	950
# bunches n_b/pulse	1130	2820
bunch spacing Δt_b [ns]	708	337
rep. rate f_{rep} [Hz]	5	5
N_e/bunch [10^{10}]	3.6	2
$\varepsilon_x / \varepsilon_y$ (@ IP) [10^{-6}m]	14 / 0.25	10/0.03
beta at IP $\beta_{x/y}^*$ [mm]	25 / 0.7	15 / 0.4
spot size σ_x^*/σ_y^* [nm]	845 / 19	553 / 5
bunch length σ_z [mm]	0.7	0.4
beamstrahlung δ_B [%]	2.5	2.8
Disruption D_y	17	33
P_{AC} (2 linacs) [MW]	95	95
efficiency $\eta_{AC\rightarrow b}$ [%]	17	23
luminosity [10^{34} cm^{-2}s^{-1}]	0.68	3

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