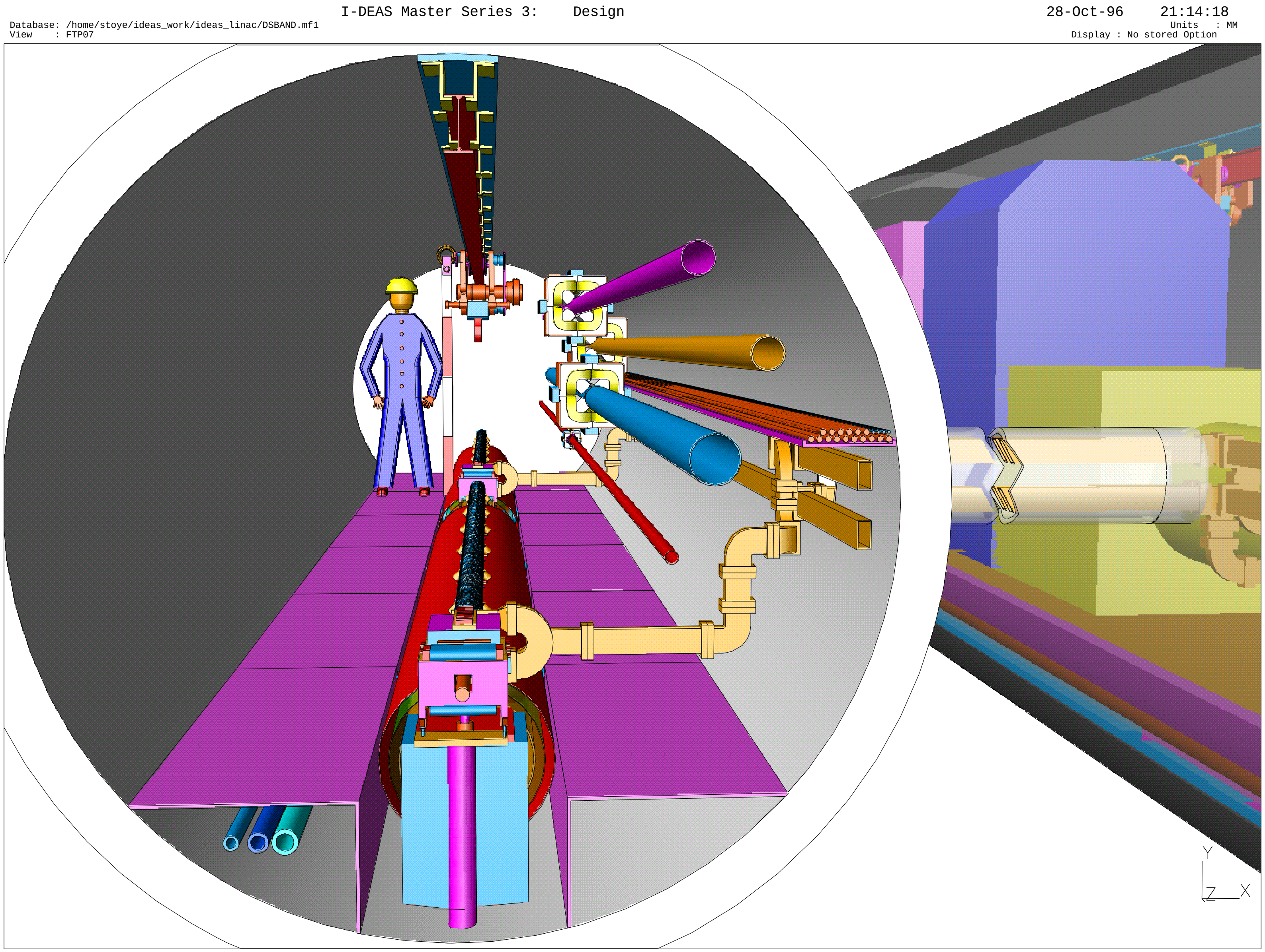
Chapter 4

S-Band Linear Collider

SBLC Collaboration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Contents

4.1 Overview

4.1.1 S–Band Concept

The two most important aspects of very high energy linear colliders are their luminosity requirements and their costs. To do meaningful physics in the energy range of 500 GeV cms luminosities above 10^{33} per cm^2 and per sec are necessary, one to two orders of magnitude larger than in existing colliders. On the other hand unit costs of accelerators (costs per GeV) must be considerably smaller than those of existing machines to make these new installations economically feasible.

4.1.1.1 The Rationale for using S-Band Technology

To reach luminosities in the $10^{33}...10^{34}/(\mathrm{cm}^2{\cdot}\mathrm{sec})$ range, large bunch charges and unprecedentedly small beam cross sections at the collision point are necessary. Also, the bunch collision frequency must be large. These requirements automatically lead to linear collider designs with large pulse currents, many bunches in each pulse and extremely small beam emittances, combined with very small beta functions (i.e. strong focusing) at the interaction point. Typical cross sections at the collision point must be of the order of one hundredmillionth of a square millimeter, five orders of magnitude smaller than typical collision point cross sections in circular colliders. The main problem of large bunch charges and large pulse currents combined with ultra small beam emittances are bunch instabilities in the linear accelerator structures. Such instabilities have been observed almost in all high current linear accelerators since their invention 50 years ago. They are due to electromagnetic wake-fields of the beam current acting through the accelerating structure back on the particle bunches. Transverse single and multibunch instabilities are due to transverse alignment errors between the beam and the accelerating structure and increase with the third power of the accelerating frequency f_{RF} in otherwise scaled accelerating structures. Longitudinal wakefields can create an untolerably large energy spread within the particle bunches, an effect which scales quadratically with the accelerating frequency.

It is evident, that small accelerating frequencies have great advantage. On the other hand there are economical arguments for not going too low in frequency, mostly having to do with the increasing component costs associated with the large stored power for linac pulses at lower frequency. This is the reason, why linear accelerators with warm (i.e. nonsuperconducting) structures seldom are built for frequencies lower than S-band (3 GHz). But avoidance of beam instabilities, preservation of ultra small beam emittances and more relaxed structure and alignment tolerances are strong arguments for choosing S-band technology over designs at higher frequencies.

In S-band structures accelerating fields in excess of 30 MV/m have been used. Recently it has been shown that even with gradients as large as 80 MV/m dark currents from field emission can be kept small, provided the structures were built in clean rooms and with the proper surface treatment [1]. The most economical gradient in a linear accelerator is given by a compromise between length and RF peak power: The lowest costs are reached if the sum of all costs which are proportional to length (structure costs, tunnel costs, etc.), referred to as linear costs, are about equal to the sum of all costs for creating RF-power (klystrons, modulators, power consumption, etc). For our S-Band design this cost minimum seems to occur at gradients of the order of 20 MV/m. This value is far below the gradient, which in S-band structures can safely be generated. An energy increase at a later stage can therefore be done by simply increasing the peak RF power. Even at twice this gradient safe operation with negligible field emission current and negligible vacuum arcing is possible.

S-Band technology for linear accelerators has been in use for the last 50 years. It is by far the most developed and refined technology and almost the only one in use for linear accelerators. A wealth of experience and knowledge make realistic designs and cost estimates possible. This is another strong reason to favor this technology. Design studies during the last few years have shown that S-band colliders are as efficient as colliders designed for higher frequencies and that luminosities are comparable.

The largest S-band accelerator which has ever been built is the 50 GeV SLAC linac. It has about 20% of the size and energy of each of the two linacs needed in a 500 GeV cms collider. Although built 30 years ago and at that time considerably less sophisticated than the next linear collider will be, it still may be considered to be a prototype of the linear collider to be built, sufficiently close to make unexpected problems much less likely. Colliders to be built with new and different technologies cannot refer to a representative existing prototype. They certainly will have to be built in 2 to 3 stages, each stage having to wait for the previous one to be completed and thoroughly tested. This of course will have a strong effect on costs and time schedules. An important example for this statement is the emittance dilution in this linac, one of the most important aspects in linear colliders: These dilutions have been measured in the SLC and found not to be far off from the tolerable amounts in the SBLC. The final focus test beam FFTB [1] at the SLC produced already vertical beam sizes within a factor of two from the goals of SBLC, considering the larger adiabatic damping to be expected in the SBLC due to the higher energy. These observations represent important confirmation of the technical feasibility of an S-band collider, which so far are lacking for colliders at very different, especially higher, frequencies.

We therefore believe that a linear collider at S-band frequency is a cost efficient and safe choice. Reliable performance predictions and cost estimates can be made.

4.1.1.2 The Basic Collision Cycle

The 2 linear accelerators working at the S-band frequency f (f=3000 MHz, wavelength 10 cm) accelerate trains of electron and positron bunches respectively to energies of 250 GeV (375 GeV in the second stage) and direct them such, that individual elctron bunches will collide with individual positron bunches almost head-on [1]

Before injection and acceleration in the two linacs, the two 600 m long bunch trains, each containing 333 bunches of electrons and positrons respectively, were stored in two damping rings for times of 20 ms, to damp transverse and longitudinal particle oscillations to minimal transverse and longitudinal emittances. Bunch compressors between

[1] A small crossing angle of 6 mrad ensures that particle beams collide only at the interaction point.

the damping rings and the linear accelerators shorten the lengths of the individual bunches to 0.3 mm. At the entrance of the linac, a feedback system will remove jitter and bunch to bunch offsets. The combination of very small transverse emittances and very small beta functions at the interaction point (IP) produce there the extremely small beam dimensions of 335 nm $\times$ 16 nm and lead to average luminosities of $5{\cdot}10^{33}/(\mathrm{cm}^2{\cdot}\mathrm{sec})$. Again a feedback system is installed to stabilise the orbit of the incoming bunch train. These feedback systems, at the entrance of the main linac and at the IP, make more than 80 % of the SBLC bunch train practically immune to mechanical vibrations which otherwise could dilute the emittance or separate the beams in the IP.

After collision, following the interaction point, the electron beam goes through an undulator (see section 4.4.2) in which it produces an intense 30 MeV photon beam. This in turn is directed on a thin target to produce positrons, whith a small transverse emittance. These positrons are then accelerated to an energy of 3 GeV and injected into the positron damping ring. Both high energy beams, after collision and after the electron beam has produced the positrons for the next cycle, are dumped in special beam dumps. The electron bunch train for the next collision cycle is formed by a grid controlled electron gun. Electron bunches are also accelerated to energies of 3 GeV befor they are injected into the electron damping ring. To reach the design luminosity of $5{\cdot}10^{33}/(\mathrm{cm}^2\mathrm{sec})$ the cycle just described is repeated at the rate of 50 Hz.

4.1.1.3 The General Layout

The collider to be built, because of its length ($\approx$33 km), cannot be accomodated on the existing DESY site. But it still will be of great advantage to have one end of its long tunnel at DESY to use existing infrastructure more efficiently. Like most of the HERA-tunnel the SBLC-tunnel will have to be under existing housing, roads and industries. Access from the surface will be limited to the ends of the collider tunnel and near the interaction area, located halfway down the machine. The interaction region with its large experimental hall and additional services buildings will require a larger piece of land, on which also the circular tunnel for the two damping rings, the beam dumps and the 3 GeV preaccelerators for electrons and positrons are located. The far end of the collider tunnel must also be located on an available piece of land to locate the necessary service buildings and the 180°-loop for the injection of the low emittance beam coming down from the central damping rings through the collider tunnel. Except for these 3 points, i.e. the two ends of the linac and the central region, no further accesses are planned. All services like electric power, air, cooling water and all control cabling will enter and leave only at those 3 points. Figures 4.1.2, 4.1.1 and 4.1.3 show schematically the end of the SBLC machine as it is located on the DESY-site, the central region, about 16.5 km away from the DESY-site and the far end of the SBLC- machine, about 33 km away from the DESY-laboratory. The tunnel is kept straight even in the beam delivery section, so it can later be used to install linac structures to allow for an extension to 1.5 or 2 TeV. In Fig. 4.1.1 is schematically shown the:

1 the central experimental hall with one IP installed and the possibility to arrange a beam line for the second IP

2 the 600 m long electron and positron damping rings, arranged on top of each other

3 the injection of 3 GeV electron and positron beams into the damping rings

4 the two beam transfer lines guiding the low emittance beams of electrons and positrons from the damping rings back into the electron and positron accelerator tunnels, were they are taken back to the injection ends of the two accelerators

5 the two 3 GeV preaccelerators

6 the undulator and target for positron production

7 the two high energy beam dumps

8 Also shown are a 200 MeV positron preaccelerator which accelerates the positrons coming from the target

9 a 180 ° achromatic isochronous bend to inject the 200 MeV positrons into the 3 GeV accelerator and, on the other side,

10 the electron gun

There are plans to use the first section of the main electron accelerator also to produce low emittance beams with energies up to 50 GeV suitable for driving free electron lasers (see chapter 5). These lasers will produce coherent photon beams with energies up in the x-ray (Å) range and with unprecedented brilliance. The laboratories, in which these x-ray beams are used for research in a wide range of different disciplines, will also be part of the central region complex.

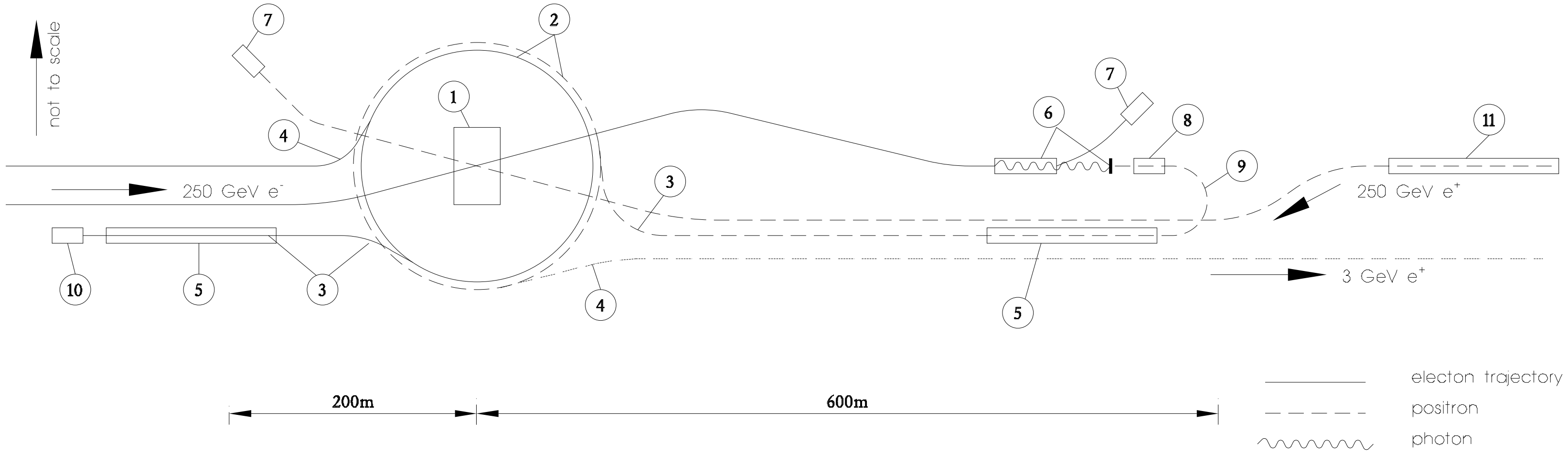

Figure 4.1.1: *Sketch of the SBLC central region. (1): experimental hall, (2): damping rings, (3,4): injection/extraction lines, (5) 3 GeV preaccelerator, (6): positron source, (7): beam dump, (8) 200 MeV positron injector, (9): achromatic isochronous bend, (10): electron gun, (11): main linac.*

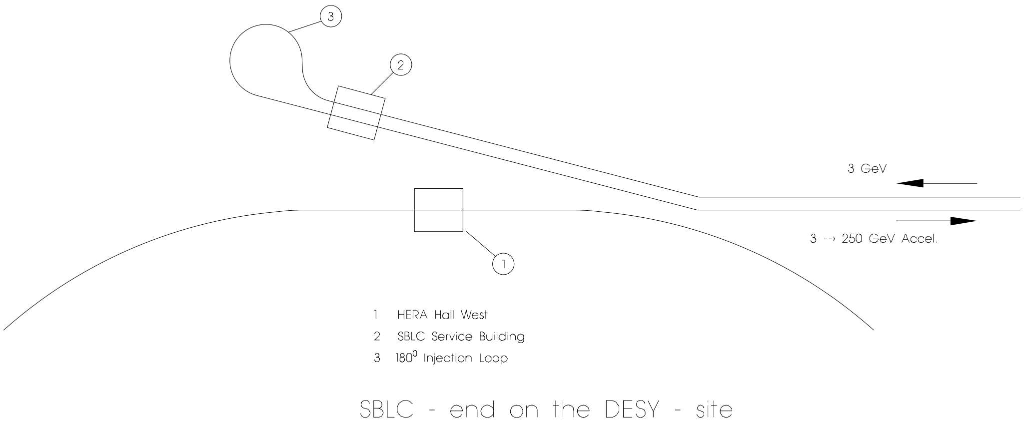

Figure 4.1.2: *The electron linac end at the DESY site.*

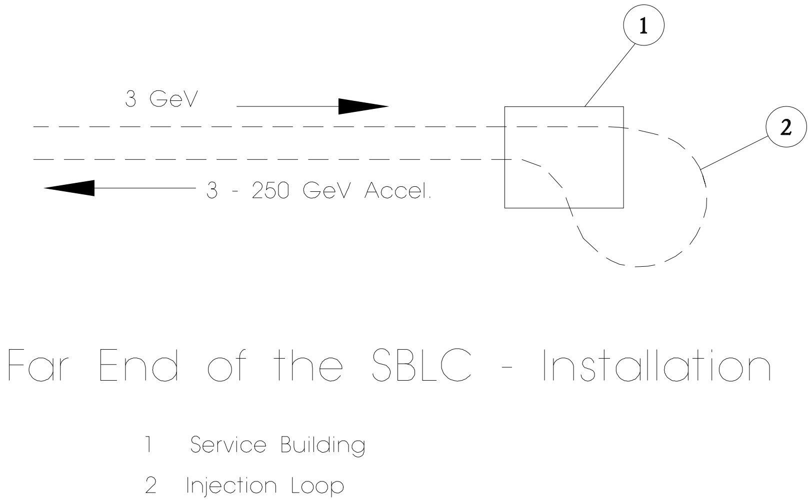

Figure 4.1.3: *The far end of the positron linac.*

Fig. 4.1.2 shows schematically the one end of the SBLC- installation on the DESY site. The tunnel is arranged tangentially to the HERA tunnel. It would be possible to use part of the SBLC as an injector for high energy electrons, up to 25 GeV, in HERA. These electrons can then be stored in HERA and ejected at a slow, continuous rate for Nuclear Physics experiments (see appendix B). Additional linac pulses will be used for the Nuclear Physics and the free elctron laser facilities. Also shown in

Fig. 4.1.2 is the beam loop (3) which turns the low emittance 3 GeV electron beam coming from the central electron damping ring 180° around for injection into the main electron accelerator. This loop contains the feedback system to stabilize the bunch train in front of the linac.

Fig. 4.1.3 shows schematically the far end of the SBLC installation with the loop and the feedback system for the positron injection into the main positron linac. Also shown are service buildings housing tunnel ventilation systems, power supplies, electrical facilities etc. as they also exist in the central service buildings and on the DESY-site.

In order to reach efficiently large integrated luminosities, a machine of such complexity and size will need continuous servicing and maintenance. It is imperative to minimize those parts of the machine, which during normal operation are inaccessible for reasons of radiation safety. But klystrons, their power supplies and all auxilliary equipment, and most of all electronics and controls should be accessible at all times to be serviced and maintained by a relatively small service group. Fig. 4.1.4 shows in cross section two parallel tunnels.

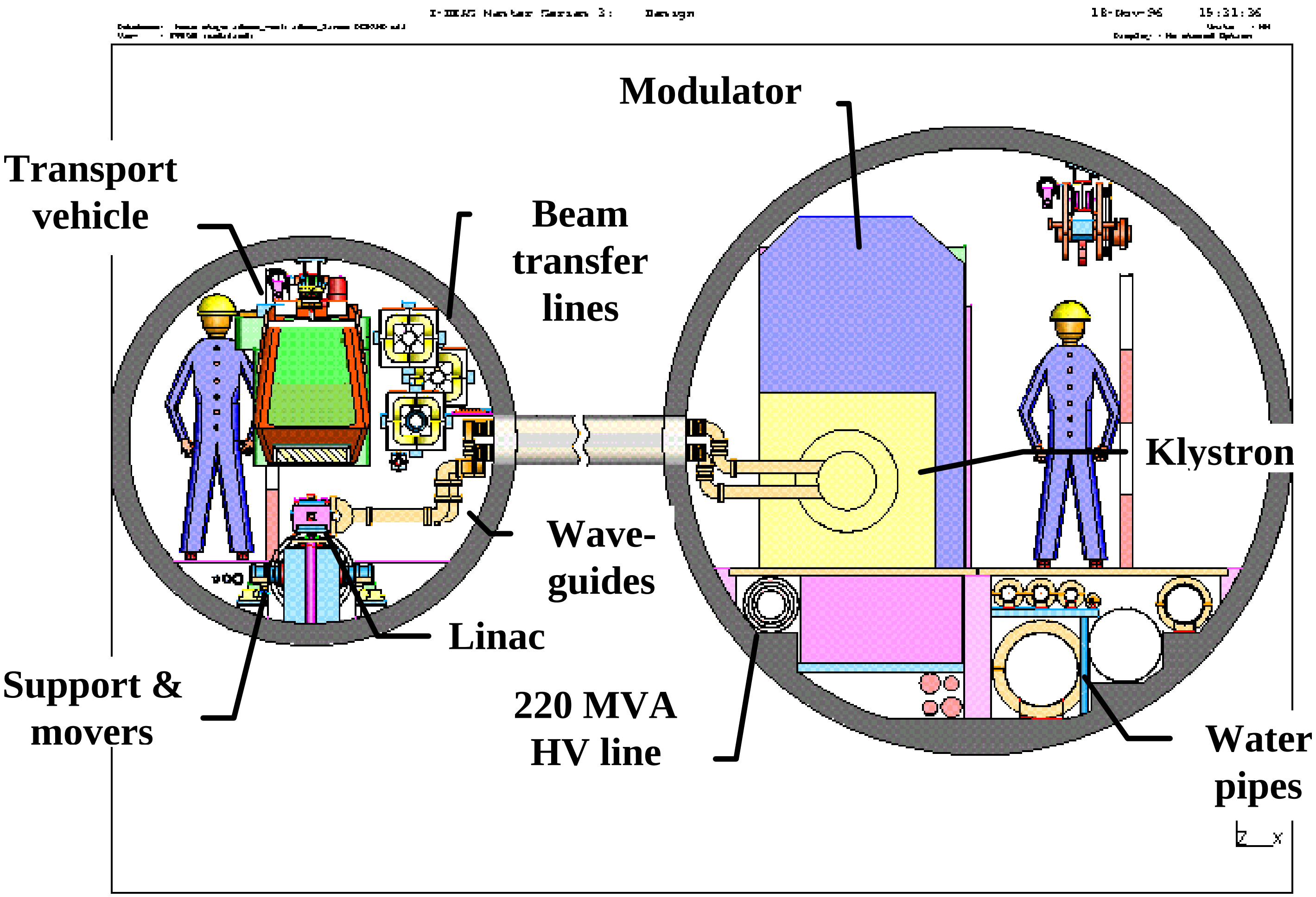

Figure 4.1.4: *Cross section of the SBLC tunnels in the periodic part of the linac. The smaller tunnel, housing the linac, has a diameter of 2.5 m. The larger tunnel, housing the RF-sources, has a diameter of 4 m. The tunnels are separated by 5 m.*

The larger one accomodates the 2500 klystrons with their modulators, power supplies and controls, water supply lines, controls and mixing valves for local supplies, electrical power distribution, transformers and circuit breakers and accelerator control and electronics. The second smaller tunnel houses the accelerator: Accelerating wave guides, focusing quadrupoles, vacuum pumps and beam lines for the 3-GeV low emittance beams, the low emittance beams for the FEL laboratory and possibly beams for the Nuclear Physics installation. At intervalls of 25 meters connecting pipes between the tunnels allow the transfer of RF power lines, water pipes and control circuitry. Connecting tunnels with larger cross section at 1.5 km spacing allow personell access to the accelerator tunnel, when the linacs are not running. This two tunnel arrangement provides for convenient emergency exit routes and simple ventilation systems. It also seems possible to arrange all the components mentioned above in a single tunnel with a somewhat larger cross section. This was the set-up under study in the passed years. It was assumed, that the two tunnel version with its many obvious advanteges would be considerably more expensive and would be technically more difficult. Recent advances in the technology of tunnel construction seem to have resolved many of the earlier difficulties such that the 2- tunnel arrangement now seems to be preferable.

4.1.2 Parameters at 500 GeV

The second key parameter for a linear collider, besides the center-of-mass energy of the colliding beams, is the luminosity L. It is given by

$$L = \frac{n_b N_e^2 f_{rep}}{4\pi\sigma_x^*\sigma_y^*} \times H_D \tag{4.1.1}$$

n_b	number of bunches per pulse
N_e	number of electrons (positrons) per bunch
f_{rep}	pulse repetition frequency
$\sigma_{x,y}^*$	horizontal (vertical) beam size at interaction point
H_D	disruption enhancement factor (typically $H_D \approx 1.5$)

Introducing the average beam power $P_b = E_{cm} n_b N_e f_{rep}$, the luminosity can be written as

$$L = \frac{P_b}{E_{cm}} \times \frac{N_e}{4\pi\sigma_x^*\sigma_y^*} \times H_D \tag{4.1.2}$$

An important constraint on the choice of interaction parameters is due to the effect of beamstrahlung: the particles emit hard synchrotron radiation in the strong space-charge field of the opposing bunch. The average fractional beam energy loss from beamstrahlung is approximately given by [3]:

$$\delta_E \approx 0.86 \frac{r_e^3 N_e^2 \gamma}{\sigma_z(\sigma_x^* + \sigma_y^*)^2} \tag{4.1.3}$$

r_e	classical electron radius
γ	relativistic factor E_{beam}/m_0c^2

Beamstrahlung causes a reduction and a spread of the collision energy and can lead to undesirable experimental background. The energy loss δ_E therefore has to be limited to typically a few percent. By choosing a large aspect ratio $R = \sigma_x^*/\sigma_y^* >> 1$, δ_E becomes independent of the vertical beam size and the luminosity can be increased by making σ_y^* as small as possible. Since $\sigma_y^* = (\epsilon_{y,N}\beta_y^*/\gamma)^{1/2}$, this is achieved by both a small vertical beta function at the IP and a small normalized vertical emittance. The lower limit on β_y^* is given by the bunch length ("hourglass effect"). Setting $\beta_y^* = \sigma_z$, the luminosity can be expressed as:

$$L \approx 5.74/rmm^{-3/2} \cdot 10^{20} \times \frac{P_b}{E_{cm}} \times \left(\frac{\delta_E}{\epsilon_{y,N}}\right)^{1/2} \times H_D \tag{4.1.4}$$

The choice of a low drive frequency for the linacs results in relatively small transverse

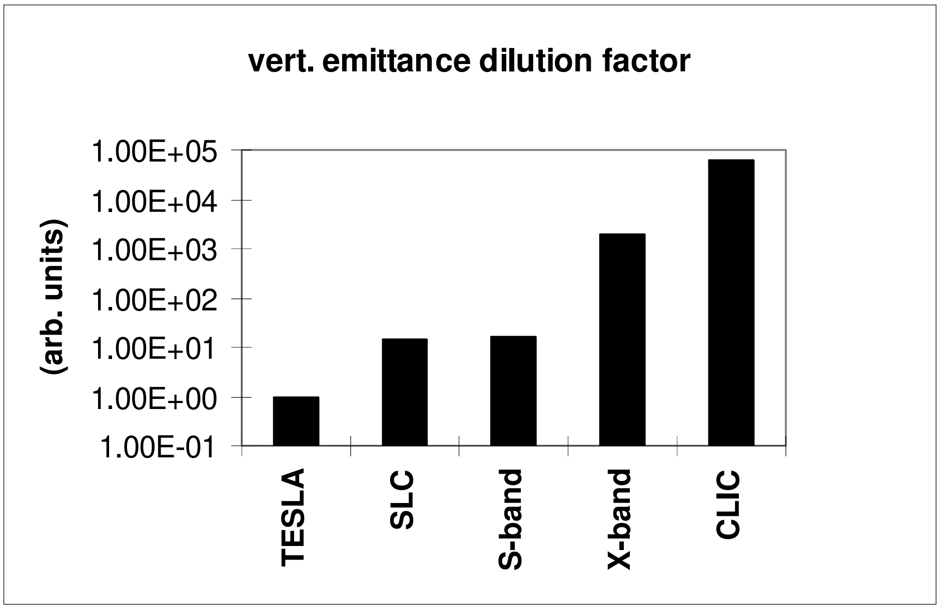

Figure 4.1.5: *Wakefield emittance dilution factor for different 500 GeV linear collider designs. The SLC is included for comparison.*

and longitudinal wakefields in the accelerating structures. Beam dynamics issues are discussed in detail in section 4.3, but it is instructive here to compare the different linear collider design concepts on a basis of simple scaling arguments [4]. One of the most essential contributions to emittance dilution results from short-range transverse wakefields due to random offsets of the accelerating structures w.r.t. the beam orbit. The emittance dilution from this effect can be written as

$$\frac{\Delta\epsilon}{\epsilon} \propto F \cdot \bar{\beta} \cdot \delta y_c^2 \tag{4.1.5}$$

where $\bar{\beta}$ denotes the average β-function in the linac (the stronger the focussing, the smaller $\bar{\beta}$), δy_c the rms-offset of the structures and F the dilution factor which depends on the beam parameters and very strongly on the linac frequency. In particular, F is proportional to the square of the bunch charge. By choosing a small bunch charge ($N_e = 1.1 \cdot 10^{10}$) the dilution factor in SBLC is comparable to the one calculated for typical SLC operation parameters, even though the vertical emittance in our case is more than an order of magnitude below the SLC value. This is illustrated in fig. 4.1.5, where the considerable variation of F for different collider designs is also shown. It becomes clear that SBLC can afford less stringent requirements for the alignment tolerances and for the beam optics compared to other designs at higher frequency (the superconducting TESLA linac operates at 1.3 GHz and has less tight alignment tolerances).

Accelerating gradient g [MV/m]	17
RF-frequency f_{RF} [GHz]	3
Fill factor (act. length / linac length)	0.95
Total site length L_{tot} [km]	33
# of acc. structures	5032
# of klystrons	2516
Klystron peak power [MW]	150
Repetition rate f_{rep} [Hz]	50
Beam pulse length T_P [μs]	2
RF-pulse length T_{RF} [μs]	2.8
# of bunches p. pulse n_b	333
Bunch spacing Δt_b [ns]	6
Charge p. bunch $N_e[10^{10}]$	1.1
Emittance at IP $\gamma\epsilon_{x,y}[10^{-6}$m]	5, 0.25
Beta at IP $\beta^*_{x,y}$ [mm]	11, 0.45
Beam size at IP $\sigma^*_{x,y}$ [nm]	335, 16
Bunch length at IP σ_z [mm]	0.3
Beamstrahlung δ_E [%]	2.8
Luminosity $L[10^{33}\text{cm}^{-2}\text{s}^{-1}]$	5
Beam power P_b [MW]	14.5
AC power P_{AC} [MW]	140

Table 4.1.1: *SBLC parameters for E_{cm}=500 GeV.*

With the bunch charge fixed, the pulse current set to 300 mA (corresponding to 20% beam loading) and the pulse length to 2 μs, the number of bunches per pulse (n_b=333) and the bunch spacing (Δt_b=6 ns) are determined. The other beam parameters are chosen under a number of boundary conditions, such as the damping ring emittance, the single-stage bunch compressor, etc. An overview of the SBLC parameters at E_{cm}=500 GeV is given in table 4.1.1.[2]

4.1.3 Stages of Operation and Energy Upgrade Options

Our detailed study presented in this report focusses on the optimized design for 500 GeV cms energy as described above. In this section, we also take a look at possible stages in which the SBLC can be built and operated and at options which open up an economic way to upgrade the energy beyond E_{cm}=500 GeV.

As a boundary condition the site length is kept fixed and the possibility of extending (or shortening) the machine is not further discussed here. Under this condition, the beam energy is completely determined by the available RF-peak power. Changing the number of pulsed RF-power sources is the most straightforward way to change the peak power. Introducing RF-pulse compression is an alternative to raise the peak power with the advantage of low cost, but at the expense of reduced efficiency. Both possibilities (and possible combinations) are discussed in the following.

Under the assumption that the relative amount of beam loading is kept constant by adjusting the beam pulse current proportional to the accelerating gradient, the latter scales simply as $g \propto \hat{P}_{RF}^{1/2}$ where $\hat{P}_{RF}$ denotes the peak power. If we consider the top quark threshold as a reasonable lower limit for E_{cm} ($\approx$ 350 GeV), the simplest way to begin collider operation with a cost-saving 1st stage is to install only half of the klystrons and modulators. According to the condition of having approximately equal linear cost and RF-cost for the reference design, this 1st stage reduces the investment to about 75 % of the 500 GeV machine. The AC-power is half of that at 500 GeV, as is the luminosity. Applying the same scaling in the opposite direction for an upgrade beyond 500 GeV leads to a 700 GeV machine requiring an additional 50 % of investment (twice the number of klystrons, etc.).

In the context of different operational stages normal conducting linear accelerators allow for an additional degree of freedom. At a given energy beam power can be exchanged against available RF peak power, without increasing the AC power requirement, by using RF pulse compression systems. The pulse compressor scheme intrinsically can not provide as high beam power per pulse due to the limited RF pulse length being available for acceleration (compare section 4.2.8). On the other hand one can later on increase the Luminosity by increasing the repetition rate, which of course would increase the AC power requirement. In that sense, for a given RF peak power installed in the linac, higher energies can be achieved at the expense of less beam power by adding comparatively small investment costs, namely SLED cavities.

By adding the SLED concept to the 500 GeV collider, an upgrade path to 750 GeV cms energy is opened. The machine parameters for this low-cost upgrade are summarised in Table 4.1.2. By the time the accelerator is upgraded, several years of opera-

[2]The site length specified does not yet take into account reserve for energy management and diagnostic and beam extraction sections in the linac. We foresee to increase the accelerating gradient over the first km of both linacs by doubling the RF-power per structure in order to create the required reserve. The beneficial effect on the beam dynamics has not yet been included in the study presented here.

tional experience have passed and ways to further decrease the emittance dilution will have been established. We therefore include here the assumption of a moderately (by a factor of 2.5) reduced vertical emittance for operation at higher energy[3]. The beam delivery system (see section 4.7) is layed out such that this first upgrade step can be accomodated without essential modifications.

In a 2nd step, the SLED concept can be combined with doubling the number of klystrons. This leads to E_{cm}=1 TeV with parameters as shown in Table 4.1.2.

Applying the SLED concept for an economic 1st phase of SBLC leads to the machine parameters shown in the first column of Table 4.1.2. The cms energy (380 GeV) is well above the top quark threshold and still a reasonable luminosity is achieved with a relatively small RF-system (650 klystrons) and low power consumption (35 MW). It is interesting to note that already this version of a next generation e^+e^- collider has twice the cms energy of LEP-II, 10 times the luminosity and roughly half the power consumption.

	SBLC-380	**SBLC-500**	SBLC-750	SBLC-1000
g [MV/m]	13	**17**	26	34
T_P [μs]	0.5	**2**	0.5	0.5
n_b	125	**333**	125	125
Δt_b [ns]	4	**6**	4	4
f_{rep} [Hz]	50	**50**	50	50
N_e/bunch [10^{10}]	1.0	**1.1**	1.2	1.69
$\gamma\epsilon_{x,y}$ [10^{-6}m]	5, 0.25	**5, 0.25**	5, 0.1	5, 0.1
$\beta^*_{x,y}$ [mm]	11, 0.45	**11, 0.45**	13, 0.3	25, 0.3
$\sigma^*_{x,y}$ [nm]	384, 18	**335, 16**	303, 6.4	357, 5.5
δ_E [%]	1.6	**2.8**	4.9	8.3
P_{AC} [MW]	35	**140**	140	240
P_{beam} [MW]	3.8	**14.5**	8.6	17.2
$L[10^{33}\text{cm}^{-2}\text{s}^{-1}]$	1	**5**	5	10

Table 4.1.2: *Parameters for SBLC with SLED pulse compression at different cms energies in comparison with the 500 GeV reference design.*

For energies up to about 1.3 TeV increasing the klystron pulse length together with the pulse compression technique could be an option. However, going to 2 TeV or beyond requires to increase the length of the machine. By this time optimization between linear and RF costs should be reconsidered.

[3]Note that such an emittance reduction is in principle already possible with the methods and tolerances discussed in section 4.3.

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