THE S-BAND LINEAR COLLIDER TEST FACILITY

N. Holtkamp for the SBLC study group,
Deutsches Elektronen-Synchrotron DESY,
Notkestr. 85, 22603 Hamburg, Germany.

ABSTRACT

Since 1991 a study group investigates the feasibility of a large scale Linear Collider operating with an rf - frequency of 3 GHz. Based on the widely spread technology in this frequency range, in 1992 an R & D program started at DESY to push the development of all the necessary technical components. The development program concentrated especially on those components that are inevitable to ensure the beam stability of the low emittance bunch train used in the Linear Collider and on the cost driving items of such a facility. The S-Band Test Accelerator, which is the main facility under construction right now, as well as the other facilities being in use will be presented in the paper.

1. INTRODUCTION

The S-Band Linear Collider Test Facilities under construction at DESY serve as a test beds for the necessary technical developments of a large scale 2×250 GeV e^+e^- Linear Collider. The different sub-components which are investigated, using a number of different test stands, will finally be installed and tested in the S-Band Test Accelerator. The linac consists of two modular units, similar to those to be installed in a Linear Collider tunnel (see also [1]). The module itself basically consists of a klystron with a peak rf power of 150 MW, connected to 350 MW peak power modulator. Each klystron drives two accelerating structures with a length of six meter each. In addition each rf module requires beam diagnostics and focusing.

The R & D program started in 1992 and concentrates on those aspects that are indispensable for the S-Band Linear Collider design:

- To increase the available rf peak power per station to what seems achievable within the time scale of the R & D program, based on the existing technology. This requires the development of new klystrons and modulators as well as the construction and test of the essential high power components.
- To develop a reliable HOM control concept taking into account the rapidly increasing knowledge of the behaviour of higher order modes (HOM's) in travelling wave accelerating structures with many (>100) coupled cavities.
- To investigate and test components which passively or actively control single- and multibunch emittance dilution.
- to construct and operate an injector which is suitable to produce a bunch train as being required for Linear Collider operation

2. THE S-BAND TEST FACILITIES

S-Band linear accelerator technology is well accepted and used around the laboratories and in industry. This fact is considered to be the basis of the necessary developments for the main components of the collider while many standard items are avialable already. The demands for an S-Band Linear Collider on the other hand are not a simple extrapolation from the only existing large scale linear accelerator, the **SLC** [2] at SLAC. According to the items listed above the construction of a number of specialized facilities began in 1993.

2.1 *The Resonant Ring*

The resonant ring is a travelling wave cavity, which is used to produce high rf peak power with comparatively small stored energy. The cavity is assembled using a closed rectangular waveguide coupled to the rf source via a 10 dB coupler, which matches the incoming rf power to the attenuation of the circulating power in the ring cavity. The ring is tuned to an integral number of wavelength via a phase shifter and matched to the travelling wave by a tuner, which cancels any VSWR for the propagating rf. The whole set-up is shown in figure 2.The advantage of a resonant ring is the ratio of the energy lost per turn compared to the stored energy which is equivalent to a high quality factor (≈7000). This allows for a low power rf source, 20 MW in this case, but still achieve high circulating power to test high power rf components, with a smaller risk of damage. The parameters of the ring are given in Table 1.

Parameter	Unit	
circumference	m	4.5
number of wavelength		35
input coupler	dB	10
source power	MW	22
maximum power	MW	220

Table 1: Parameters of the travelling wave resonator for high power tests.

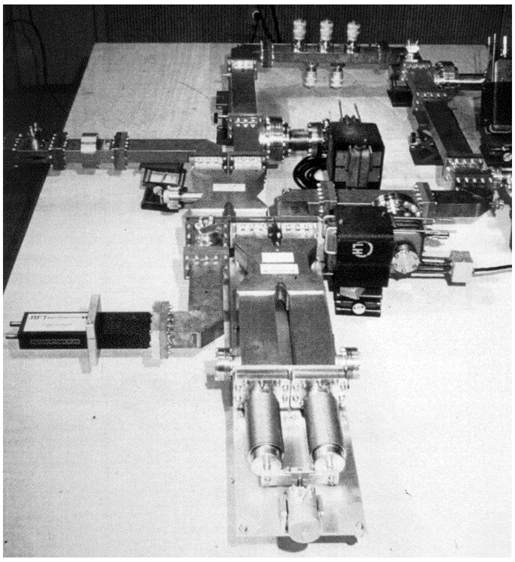

Figure 1: The travelling wave resonator, assembled from a closed waveguide, and coupled to a power source via a 10 dB coupler.

Up to date 220 MW of circulating power have been achieved. The standard components required in a waveguide network of a linear accelerator (couplers, flanges, pumping ports etc.) have been tested and peak powers of more than 150 MW are typically achieved. Klystron windows, which are one of the most important components because their performance often limits the achievable peak power, contribute to klystron failure and therefore directly influence the operation. Investigation of reliable high power klystron windows together with industry has been started for this reason and a test window has been operated up to 80 MW. Finally this specific window failed due to a crack in the ceramics, most probably caused by a local hot spot, and heated due to field emission, which is a typical reason for window failure. Further tests are necessary and planned.

2.2 The RF- Power Source Developments

In order to achieve a gradient of 20 MV/m in the accelerating structure, the total rf peak power amounts to almost 400 GW for a 500 GeV center of mass Linear Collider. Because the klystron and the modulator are the most expensive single item, the development of a more powerful RF source to reduce the total number of sources, has been one of the main items of the program. A dedicated R & D program together with SLAC, the technical University of Darmstadt, PHILIPS (Hamburg) and DESY started in 1993. Following an earlier development at SLAC, being done in 1985, when a 150 MW, 1 µsec-klystron with an efficiency of more than 50 % was build [3], the goal now was, to construct and operate a 150 MW klystron with a pulse length of 3 µsec and a repetition rate of 50 Hz. In 1994, only $1^1/_2$ years later, the klystron has been tested meeting the specifications. A second klystron with a slightly modified output circuit geometry and improved HOM damping in the drift tube has been tested during summer 1995 and proved very stable operation as well as slightly larger efficiency. The operating parameters achieved with the two different klystrons being constructed so far are listed in the next table. Both klystron are at DESY already. As a part of the development both klystrons have been simulated with 2 D and 3 D codes extensively to optimise the overall layout[4].

	5045	Nr 1	Nr 2	
Beam Voltage	350	527	508	kV
µ-Perveance	2.0	1.78	1.8	$A/V^{1.5}$
Output Power	67	153	150	MW
pulse length	3.5	> 3.0	>3.0	µsec
Electronic eff.	46	42.7	45	%
Drive Power	350	380	300	W
Solenoid Field	0.12	0.18	0.18	T

Table 2: Parameters of the 150 MW klystron being tested in 1994 at SLAC and the SLC standard klystron, the 5045.

The modulator considered to drive the 150 MW klystron is a PFN type modulator with pulse forming network connected to a pulse transformer. Four lines in parallel charged by a 50 kV supply 18 kA of current via two thyratrons to the primary winding of the 1:23 pulse transformer. A similar modulator has been constructed already at SLAC to test the klystron at full power and at a maximum repetition rate of 60 Hz [5]. Two modulators are build at DESY for the test accelerator. The modulators are designed for a maximum voltage and current of 550 kV and 700 A. For the test facility, the first klystron is installed already and operating while the second socket is under construction right now. Additional tests will be done with modular 50 kV high voltage solid state power supplies which directly charge the PFN. A significant size reduction and efficiency increase is expected as compared to the standard set-up using a power supply and a charging choke.

2.3 Production of the Section

The section is a standard 2 π/3 mode constant gradient type section which is designed to have a continuous group velocity taper from the beginning to the end. Up to date four 5.2 meter long structures have been assembled, tuned and high power tested. Three of those are already installed at their final position of the LINAC II, the e^+e^- injector linac at DESY, and operate continuously. The first two 6 meter long structures for the test facility are under production. The parameters of both types of sections are given in Table 3. The resonators and the couplers as well as all the sub-components are produced in industry. The assembly and the brazing is done at DESY. Sub-assemblies are high temperature brazed in a vacuum oven and finally at full length horizontally under a hydrogen atmosphere.

	Linac II	LC	
attenuation	0.5-0.6	0.55	neper
length of the section	5.2	6	m
group velocity	3.3-1.2	4.1-1.3	% c
filling time	750	790	nsec
iris size	1.4-1.25	1.6-1.3	a/λ
aver. power dissip.	700	1400	W/m
alignment toleran.	≅0.50	<0.05	mm
straightness (rms)	0.05	<0.03	mm

Table 3 Parameters of the accelerating sections build (LINAC II) and proposed (LC).

The final required straightness of the section is determined by the tolerable HOM excitation.. While the straightness tolerance is easily met after the vertical braze of typically 1 m long pieces, which have a measured rms deviation of typically 20 µm, the horizontal braze of the complete 5.2 m section has shown deviations of up to 1 mm. They will be removed down to 30 µm rms by a recently developed straightening procedure, which easily achieves 100 µm and will achieve the target value after commissioning of a straightening device constructed for this reason.

In order to tune the structure a semi-automatic tuning machine has been constructed and used for the tuning of the four structures mentioned before. The tuning is performed by slightly indenting the cavity walls. After the tuning the phase error is reduced to about 0.5 ° rms over the full structure length, which guarantees a negligible energy loss. The time required per structure is typically around eight hours with the present set-up.

2.4 The High Power Test Stand

In order to process the structures under high power conditions, a bunker was set-up to operate the section with an easily available 25 MW klystron which can be connected to a SLED cavity to produce a maximum peak power of 110 MW. The typical processing and the integral pressure drop as a function of time can bee seen in Figure 2.

The high power test ended successfully after approximately 50 hours of rf processing over a period of 30 days with a maximum gradient of 25 MV/m within the structure. The vacuum pressure achieved after processing was of the order of 10^{-8} Torr at full power.

Other major technical developments being made so far are a very compact symmetric high power input coupler [6] and the collinear load. The collinear load absorbs the remaining rf-power over the last eight cells of the section while still accelerating the beam. Such a load avoids a second high power coupler (costs), is perfectly symmetric (no transverse kicks due to field asymmetries) and absorbs any higher order mode touching the end of the section.

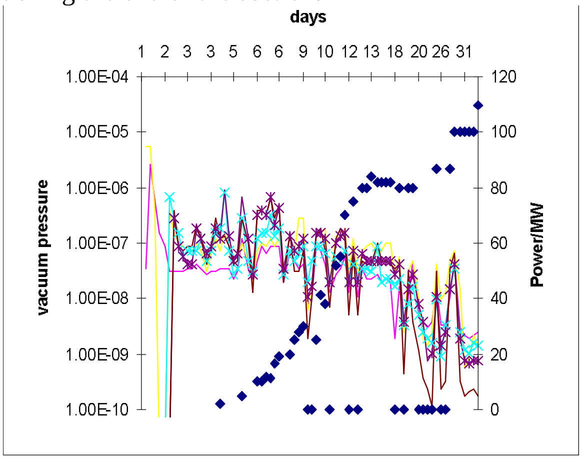

Figure 2: Peak Power Processing of a 5.2 meter section as a function of time. The pressure inside the section and the peak power are given in the same plot.

2.5 Higher Order Mode Damping

Because the accelerating section is the main driving force for multi- and single bunch instabilities which deteriorate the beam emittance, ideas to reduce costs always have to account for the required HOM damping and final straightness as well. Assuming an average Q value of the HOM's of 4000 (natural Q≈13.000) and a bunch population of $3{\cdot}10^{10}$, the tolerance calculated is approximately 30 µm rms (design: $1.1{\cdot}10^{10}$ -> ~ 50 µm rms).

To control the HOM excitation and consequently the beam break-up in a Linear Collider, each section will be equipped with HOM damping. Sputtering a thin (≈20 µm) low conductivity material layer onto the top of the iris strongly damps trapped higher order modes but almost not affects the fundamental mode. First measurements indicate a Q-reduction of the HOM mode by a factor of 5 while the fundamental Q only changes by 5 %. The principle is shown in figure Figure **3**.

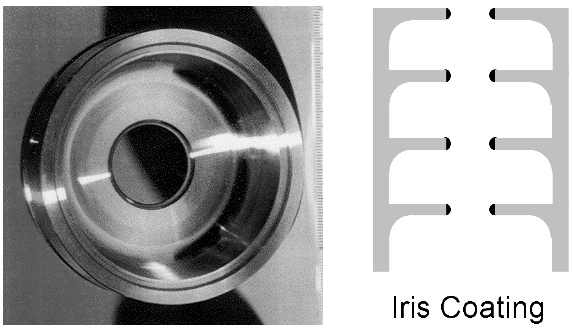

Figure 3: Picture of the iris coating to introduce losses for the HEM_{11} mode with only little effect on the accelerating field.

High power tests in a standing wave test resonator have been performed with iris tip fields equivalent to

28 MV/m. This corresponds to a peak power of 260 MW powered into the section. During the tests and finally, after inspection of the iris, no degradation could be identified. In addition an R & D program has been set up with the MPEI in Moscow to develop symmetric high power couplers which couple out the HEM_{11} modes being trapped close to the input end.

In addition to the global damping HOM mode coupler are used, mainly as pick-up stations to measure the beam induced HOM power in the TEM_{11} passband [7].

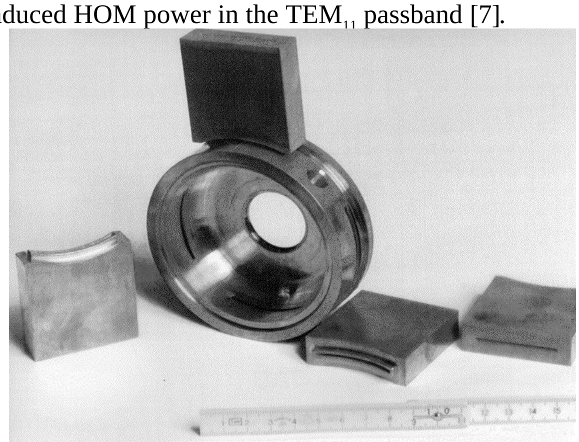

Figure 4: Two higher order moder couplers are integrated in the accelerating structure to coule out and measure the beam induced power in the dipole modes.

One coupler is near the front end and one almost at 2/3 of the section length. Definitely these two couplers are not sufficient for damping all the modes in the HEM_{11} passband because 2/3 of the severe modes in this passband are trapped at different locations of the section. The HOM couplers, in combination with a set of micro movers, will allow to control the beam induced HOM power. The amplitude of the extracted power will be prepared as a control signal for the micro-movers below the section support.

2.6 Micro Mover and Section Support

While the section support has to guarantee the straightness of the section after installation even with thermal transients, the section itself has to be mounted on the girder to within the given tolerance of 30 µm rms before.

With standard alignment techniques the section will be aligned in the tunnel within a few tenth of a millimeter over approximately a betatron wavelength which is ≈ 100 meters. The final alignment to within 30 µm over the same length from girder to girder, which avoids the single bunch emittance growth, is performed with two micro movers, one on each end of the girder. These movers can operate between ± 1.5 mm with a step size of 150 nm. The mover are constructed similar to those in use at the FFTB, a Linear Collider test beamline at the Stanford Linear Collider, to produce a nanometer spot size.

2.7 Ground Motion, Vibration, Feedback

Any kind of quadrupole motion within the frequency range of 2-30 Hz can hardly be damped either in a passive manner or with beam based feedback techniques. Therefore ground motion detectors (geophones and accelerometers) have been tested and further developed [8]. Each quadrupole in the test facility will be equipped with such a detector to feed back on the vertical quadrupole position via piezo movers. Attenuation of amplitudes up to 14 dB within this frequency range has been achieved which corrects the vertical rms quadrupole motion down to the 20 nm range.

In addition a simple and stiff concrete support with mechanical resonances well beyond 100 Hz has been build for the quadrupole to avoid any externally driven excitation. To decouple the vibration introduced by water flow within the coil windings of the quadrupole, the coils are mounted on a separate aluminium support within the quadrupole yoke. This support can be mounted separately to the floor. A picture of the set-up is shown in Figure 5.

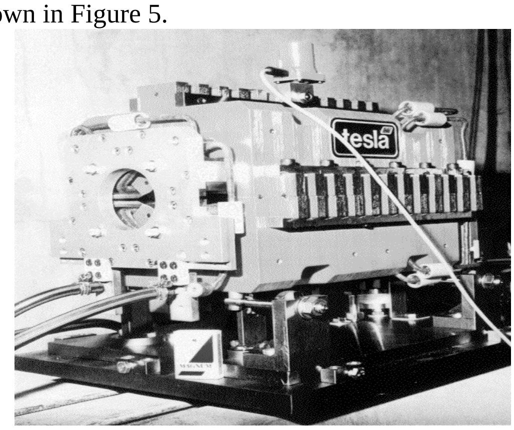

Figure 5: The ground motion detector with the quadrupole, the piezo driven feedback and the concrete support The aluminum support for the coil can be seen in front.

3. THE INJECTOR

The injector under commissioning right now has to produce the full charge bunch train identical to the one planned for the Linear Collider. The small emittance, the single bunch energy spread and bunch length can of course not be achieved in a 3 meter long set-up. The gun part of the injector and the 125 MHz as well as the 500 MHz buncher cavities are commissioned. The current pulses with the design bunch to bunch distances and burst length (3 µsec and 8,16 or 24 nsec distance; compare Table 4) have been produced with a bunch charge of 6.4 nC ($n=4\cdot10^{10}$) per bunch. Behind the 500 MHz cavity a bunch length of 200 psec was expected from PARMELA simulations and 250 psec have been measured yet.

The second 60 cm long travelling wave buncher has been build and tuned already. The second is under construction. The buncher operates in 8π/9 mode with a small group velocity of 0.4 % and large iris diameter which not be possible in a standard 2π/3 mode structures. This increases the attenuation significantly and reduces the required peak power at the operating gradient of 14 MV/m.

4. S-BAND TEST ACCELERATOR

The S-Band test accelerator has two Linear Collider modules, as well as an injector and a beam diagnostics station at the end. The overall parameters of the accelerator are given in Table 4. The operation of the test accelerator will be the most significant part of the whole R & D program at DESY to prove the operability of the concepts which have been proposed and tested separately in the different facilities described before.

Energy at full current	400	MeV
overall length	≅ 40	m
injector energy	≈ 5	MeV
current pulse length	> 2	µsec
modulator & klystrons	2	
number of bunches	1-250	
particles per bunch	$1.5,3,5*10^{10}$	
norm. emittance γε	$\approx 50 \times 10^{-6}$	π mrad
bunch separation	8,16,24	nsec
average beam current	> 300	mA

Table 4: Parameters of the S-Band Test Accelerator

Especially the transient beam loading compensation scheme [XXXX] which is essential for stable operation of a large scale multibunch collider, will have to be investigated. An overview of the layout is presented in Figure 6.

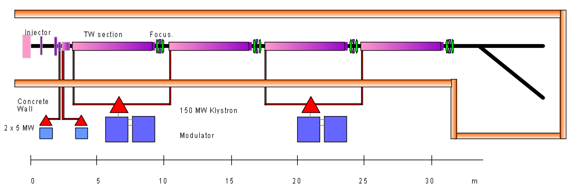

Figure 6: A sketch of the S-Band test facility layout with the injector, two modules similar to those used in a Linear Collider and the beam diagnostic station.

The questions Higher Order Mode excitation, measurement, damping and feedback on the accelerating structure and the quadrupole position are especially important to understand the most crucial aspect of a 15 km linear accelerator namely the beam stability. Especially the concept of measuring the beam induced dipole mode power at the position of the HOM dampers and feedback via the micro-movers on the position of the section is essential. Therefore a transverse mode cavity will be introduced after the first section to modulate the bunch train transversely and excite specific frequencies trapped at different locations in the accelerating structures.

A modular cooling system [ullrich] is another component which has to be studied in detail. The system is designed to handle incident power changes of more than a factor of ten without influence on the energy and the energy spectrum transferred to the beam (less than 0.2 %). Simultaneously every station, belonging to one klystron, can operate at slightly different temperatures, which is one possibility to overcome tuning of the accelerating structures and decouples the circuit from the main water lines. The whole set-up is necessary because in the linear collider the operating temperature is chosen as high as possible for efficient cooling with the smallest possible amount of water circulating.

For beam diagnostics, every bunch in the train must be controlled in terms of transverse and longitudinal emittance as well as in x and y position along the linac. Various types of monitors for position and beam size have been proposed and are under construction right now. They will be installed in the test facility [10].

5. Acknowledgement

I would like to thank all the members of the collaboration from the different institutes and countries for their contributions. The significant progress which has been made during the last 4 years is based on the enthusiasm of the people involved.

6. References

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