Structure Design for a 500 GeV S–Band Linear Collider

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Abstract

Constant gradient structures with an accelerating gradient of 20 MeV per meter are commonly used with S–band frequency. The well known features of these travelling wave tubes provide a dedicated design for their use in the next generation linear collider. Some of the required design parameters for this tubes are presented within the whole concept of this collider with an active length of about 30 km. The choice of these parameters is explained and calculations concerning the structure are presented.

Introduction

In order to have a realistic design for a 500 GeV e^+e^--collider for the near future, almost conventional rf–technology has to be used. This leads to an overall list of parameters for this type of collider, which is presented in another paper [1]. Multi-bunch operation with current pulses much longer than one filling time of the accelerating tubes, peak power limitations from the klystrons and *beam breakup* considerations are the strongest restrictions, which have a great influence on the design of these travelling wave tubes (**twt**).

The bunch population is $7 \cdot 10^9$ particles per bunch with approximately 170 bunches per pulse (≈ 100 mA) and a rf–pulse length of $\approx 3\,\mu$sec. With a low repetition rate of 50 Hz a luminosity of $\mathcal{L} = 2.4 \cdot 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$ will be reached. With these values the boundary conditions which come from the general list of parameters [1] are summarized.

General Layout

Several reasons lead to our decision to choose S-band frequency for the Linear Collider design. Wake fields impose strong limitations on the number of particles that can be accelerated. Transverse wake fields are scaling with ω^3 and longitudinal wake forces are proportional to ω^2. This accomplishes the design of a very high frequency accelerating structure, because for every cavity in the tube transverse mode damping is unavoidable [2] due to the scaling laws given above. Preliminary calculations have been done with a geometry identical to the SLAC cell nr. 45. For a $\sigma = 0.1$ mm long bunch the longitudinal wake potential has been computed [3] and is shown in Fig. 1. The maximum wake potential within the bunch is 260.74 V/pC/m leading to a single bunch energy spread of 1.7 % [4], which stays within the acceptance of the final focus. Due to the small bunch- to wavelength ratio, the energy spread can not be reduced by acceleration on the slope of the wave.

Having fixed the operating frequency of ≈ 3 GHz, due to scaling, a set of parameters can be derived within an accuracy of a few percent. For example, the shunt impedance per meter will be $\approx 53\,\mathrm{M}\Omega$/m and the Q-value of the copper cavities is $\approx 13\,000$. The maximum length of one **twt** which can be fed by one klystron is 12 m and given by the peak power limit. This technical limit today seems to be ≈ 130 MW per klystron with a rf-pulse length of $\approx 3\,\mu$sec provided by the modulator and the Pulse Forming Network (PFN).

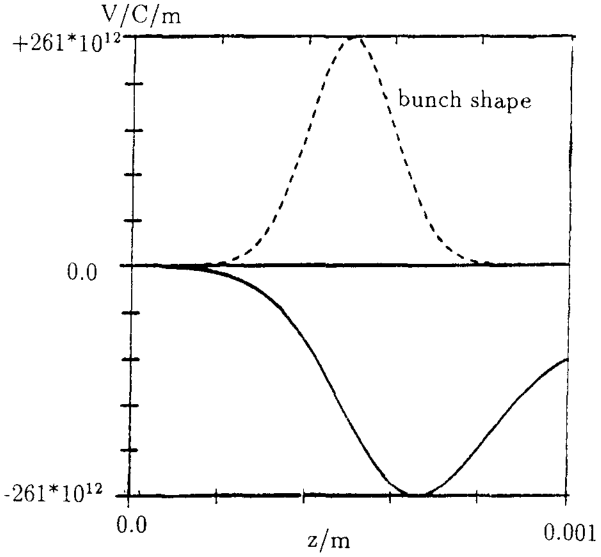

Figure 1: *Wake potential for a* $\sigma = 0.1$ mm *long bunch.*

Actually a structure length of 6 m is chosen to increase the average shunt impedance due to the smaller iris holes and as a consequence, the smaller required group velocity. At least only the attenuation parameter τ, defined in the following way:

$$\frac{P_{\mathrm{out}}}{P_{\mathrm{in}}} = e^{-2\tau} \qquad (1)$$

is variable. τ relates the input peak power for one **twt** to the outgoing power and as well determines most of the properties of the accelerating structure.

Peak Power Requirements

Obviously, for a given gradient in the structure, the required electric energy which has to be provided by the klystrons per pulse should be lowered in order to minimize operational costs.

The energy per pulse can be devided into the energy which has to be delivered during the filling time (T_f) and the energy required during the current pulse of length T_I. The first part is wasted in the sense that it can not be used for acceleration of particles. Therefore a low repetition rate and long current pulses are preferred. In terms of the attenuation parameter τ this is shown for a constant gradient structure in equation (2).

$$W_\Sigma = W_f + W_I \tag{2}$$

with :

$$\begin{array}{lcl} W_f & = & P_0 \cdot T_f = P_0 \cdot \frac{2Q}{\omega} \cdot \tau \\ W_I & = & P_0 \cdot T_I \end{array}$$

The meaning of other symbols is:

$$\begin{array}{lcllcl} P_0 & = & \text{klystron peak power} & = & \alpha \cdot (1 - e^{-2\tau})^{-1} \\ & & & & \alpha = G^2\, L/R'_s \\ G & = & \text{unloaded gradient} & \approx & 18.5\ \text{MeV/m} \\ L & = & \text{structure length} & = & 6\ \text{m} \\ R'_s & = & \text{shunt impedance} & = & 53\ \text{M}\Omega/\text{m} \\ T_I & = & \text{current pulse length} & = & 2\mu\text{sec} \end{array}$$

Calculation of the minimum leads to an implicit equation:

$$\tau = \frac{1}{2} \cdot \ln\left(1 + 2 \cdot \tau + \frac{\omega}{Q} \cdot T_I\right) \tag{3}$$

The minimum is found to be $\tau = 0.855$ and, as can be seen from equation (3), in this approximation is independent of α.

Due to transient beam loading ($\approx$ 7–10 % in our case), which depends on τ itself, the required peak power per meter, to reach a fixed loaded gradient of 17 MeV/m, is increased and therefore τ will be lowered. In Fig. 2 the required energy per pulse and per meter is shown as a function of τ (beam loading included). From this picture the minimum energy per pulse for the loaded structure is given with $\tau = 0.7$. Because of the flat minimum of the curve, the required energy is not very sensitive to modifications of values between 0.5–0.8 .

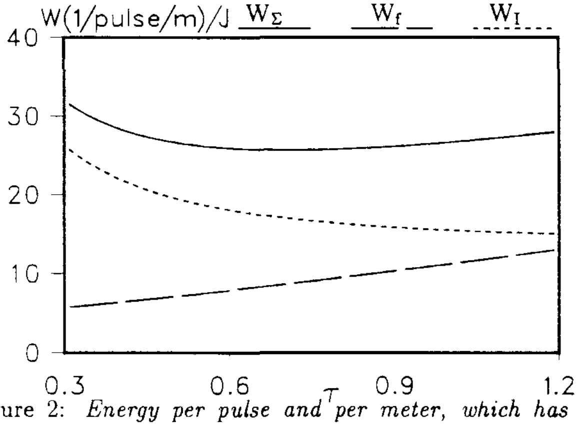

Figure 2: *Energy per pulse and per meter, which has to be provided by the klystron as a function of the attenuation parameter* τ *for a S-band structure with a loaded gradient of* 17 MeV/m.

For other proposed schemes (e.g.: **JLC, NLC, VLEPP** etc.) the current pulses are much shorter than one filling time which is one reason for the smaller envisaged attenuation parameters of $\tau \leq 0.5$. Short accelerating structures and high peak power levels for the klystrons are some of the consequences. For a loaded gradient of 100 MeV/m, typical current pulse length's of 10 nsec, a pulse current of $\approx$ 1.3 A and a 0.7 m long structure with a frequency of 11.424 GHz the same calculation is shown in Fig. 3 (current injection before the structure is completely filled to reduce the bunch to bunch energy spread, is taken into account).

The minimum is obtained for $\tau \approx 0.25$, which would require a peak power of $\approx$ 270 MW/m for this type of structure. In contrast to the S-band linac with long current pulses during operation, most of the energy is dissipated while the structure is filled (see W_f in the figures) and only the minor part is used to accelerate the beam.

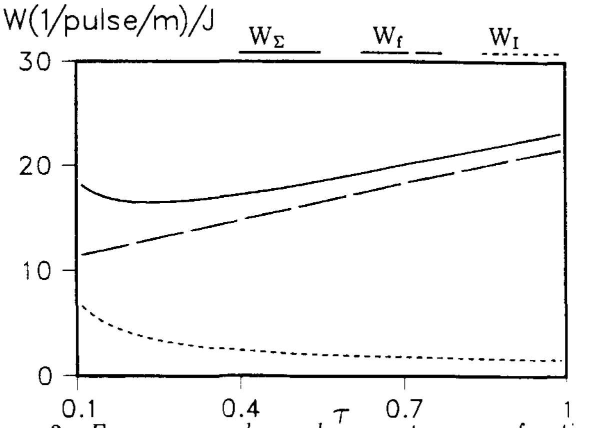

Figure 3: *Energy per pulse and per meter, as a function of the attenuation parameter* τ *for a short high-gradient, high-frequency* X*-band structure with a loaded gradient of* 100 MeV/m.

Structure Layout

Starting with the parameters listed in equation (2) and with an attenuation of 0.7 neper, some more general characteristics for the linac and the structure can be deducted. They are presented in table 1.

One type of structure we used for the calculations is shown in Fig. 4, but first without the banana like coupling holes above the iris. A **twt** with a $2\pi/3$ accelerating mode and a length of 6 m will consist of $\approx$ 180 cells, with a variation in iris diameter of d = 3.07–2.09 cm to provide the required decrease in group velocity along the structure.

Start Parameters		
tot. RF input power/pulse	250500	MW
active length	29411	m
average shunt impedance	53	MΩ/m
average gradient (unloaded)	18.4	MeV/m
average Q	13000	
current	100	mA
average RF power	≈ 38	MW
Structure and Beam Parameters		
0 current energy	543	GeV
loaded energy (100 mA)	500	GeV
trans. beam loading	43	GeV
peak power per **twt**	52	MW
power loss → load	13	MW
rf–pulse length	3.0	μsec
attenuation	0.7	neper
length of one **twt**	6	m
group velocity	3.7–0.9	% of c
filling time	1.0	μsec

Table 1: *List of parameters for the S-band Collider*

In order to save one input coupler per klystron, the possibility of using a combined forward- and backward-wave structure is investigated as well. Filling from both sides through one coupling cell avoids phase- and amplitude asymmetries and can also be done with less couplers in this scheme. The input coupler is placed in the middle of the structure, to provide filling towards both ends of the tube. In the backward wave **twt** the energy flow is up-stream,

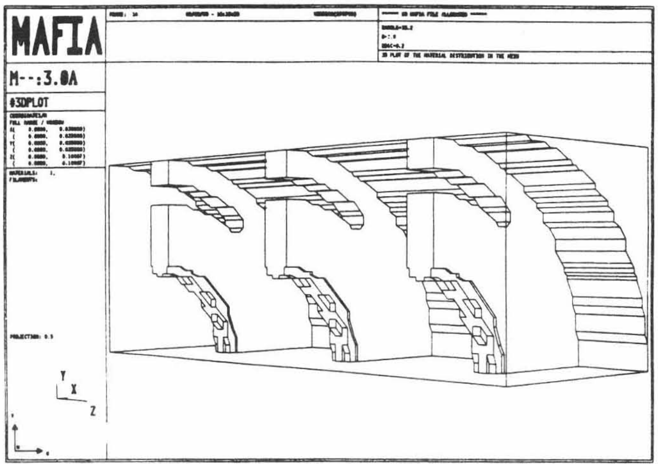

Figure 4: *Backward-wave 3-cell cavity with banana like shaped holes above the iris in order to provide strong magnetic coupling from cell to cell.*

while the phase of the wave is synchronous with the bunch. Therefore a negative group velocity is necessary and e.g. provided by banana like holes above the irises (compare Fig.4). The hole is placed near the maximum of the magnetic field, in order to increase the magnetic coupling from cell to cell which inverts the slope of the dispersion relation in the Brillouin diagram especially for the accelerating mode (compare Fig.5).

Modes which are not azimuthal symmetric split up into two or more curves depending on their symmetry and on the direction of polarization of these modes. For the HEM (or dipole-) modes this can be seen in Fig. 5 as well.

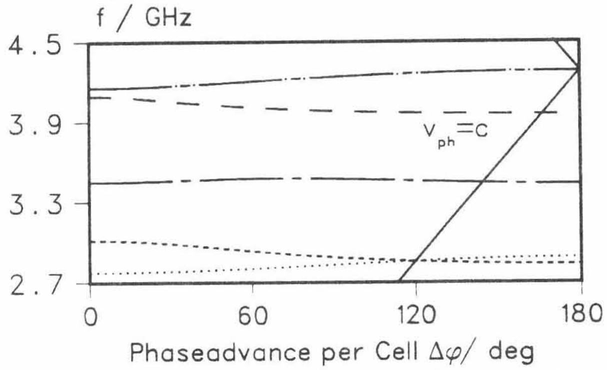

Figure 5: *Brillouin diagram for a forward- and a backward-wave cavity with dispersion relations for the accelerating and the first HEM modes.(acc. forward: ·······, acc. backward: --------, HEM forward: — — —, HEM backward ||: -·· ——·-; HEM backward ⊥: - —— -)*

Beam Breakup Considerations

One obvious method against cumulative *beam breakup* is, to randomly distribute the HEM mode frequencies in different sections of the linac over the entire length. In a backward-wave structure, part of this is done due to the splitting of the curves in the Brillouin diagram. In order to really randomize the HEM frequencies, a simple method for detuning them is required. The disk thickness has been varied in a forward-wave structure by 1 mm, which changes the frequency of the first HEM mode by ≈10 MHz. Because the accelerating mode is shifted as well, the group velocity has to be readjusted in order stay with the constant gradient conditions. The splitting is shown in Fig. 6

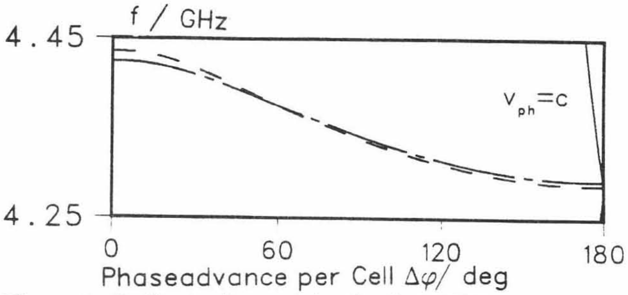

Figure 6: *Brillouin diagram for the first HEM mode. Due to variation of the disk thickness (1 mm) the curves are splitted.*

Preliminary *beam breakup* simulations have been done regarding only one HEM mode frequency driving the transverse amplitude of the bunch train. For the calculation a simple FODO focussing scheme with a phase advance of 90° per FODO–cell has been chosen. One 6 m long structure is thought to be one cavity. The bunches are injected with an energy of 3.1 GeV (the damping ring energy) into a perfectly aligned linac with a transverse injection jitter of 0.1 mm. The dynamic has been simulated over a length of 1 km. With a random distribution of the first HEM mode frequency of ± 5 MHZ, the breakup disappears, as shown in fig. 7.

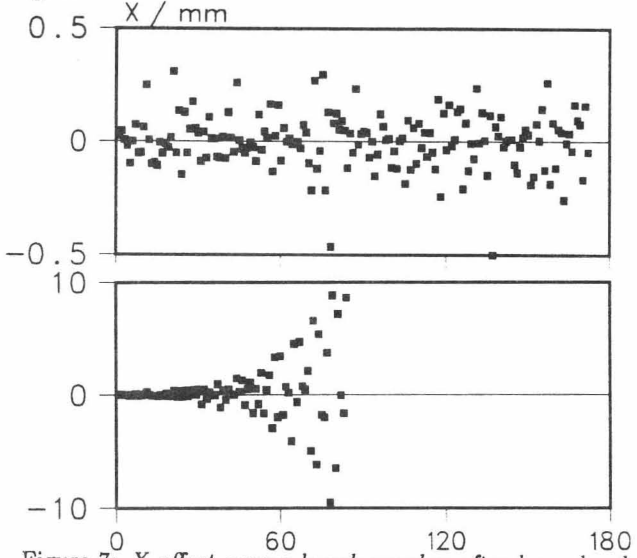

Figure 7: *X-offset versus bunch number after beam breakup simulation over a length of 1 km with (above) and without (below) random distribution of the HEM mode frequencies.*

Summary

Calculations made up to now, have shown, that S-band twt's can be used to build the proposed linear collider. The severest problem, the *beam breakup*, seems to be controllable.

References

[1] *Design Study for a 500 GeV Linear Collider,* T. Weiland, Deutsches Elektronensynchrotron DESY, Hamburg– and Technische Hochschule Darmstadt– Study Group, this conference.

[2] *Damped Acceleration Cavities,* R.B. Palmer, SLAC–PUB–4542, 1988.

[3] T. Weiland, *Transverse beam cavity interaction part 1: short range forces,* NIM 212 (1983),p. 13-21.

[4] R. Klatt, R. Wanzenberg, private communication.