A Low Loss Drive Line Concept for Linear Colliders

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Abstract

In a linear collider, the drive line is the power feed line which is used to excite the high power klystrons, along the linac tunnel. The drive line typically has to fulfill a number of requirements, e.g. phase stability, amplitude and phase control as well as power distribution. A concept, especially fitting the needs of a linear collider, is presented.

Introduction

Following the multibunch energy compensation concept presented in another paper [1], amplitude and phase control are required at every klystron along the linac. In the proposed 500 GeV center of mass S-Band linear collider [2] for example, 2500 klystrons will require approximately 400 W drive power each. These klystrons are distributed along the 30 km long accelerator. Therefore approximately every 12 m the drive line has to deliver this amount of power with the appropriate phase and amplitude control within one pulse and with the required pulse to pulse stability. So far different ideas have been discussed to solve this problem. For example, a low power glass fiber could be used to drive a solid state preamplifer in front of every klystron, or a special drive klystron could power groups of klystrons. While the first version turns out to be a rather cost intensive one, it has certainly the greatest flexibility, because the low power rf can be manipulated in front of every klystron. The second version is certainly cheaper but also requires a widely distributed rf control network. Both systems involve a dedicated distribution system for the low power rf and consist of a large number of components which tend to fail or have to be replaced according to their lifetime. In this paper a technical solution will be discussed which is based on the idea of using a single high power drive line for many klystrons. This drive line would be powered by the same type of klystron used to feed the accelerating structures (150 MW peak power) and is a passive system which should not require any maintenance. Such a drive line system has a number of implications but also many advantages.

General Description

The main problem of a very long drive line is dispersion and energy propagation velocity. The rf pulse which fills the accelerating structure and accelerates the beam is only $2.8\,\mu$s (≈ 900 m) long. To excite every klystron in time, the drive pulse has to travel with the speed of the beam pulse, here the velocity of light, along the linac. At the same time the pulse shape (amplitude and phase) is not allowed to change (mainly due to dispersion and mode conversion), especially if phase or amplitude modulation is used within each single rf pulse.

There are basically two concepts for realizing such a drive line. Either a transmission line which supports a TEM mode or a shielded waveguide without inner conductor may be used. Both approaches will be discussed.

Transmission line

The main advantage of a coaxial transmission line compared with any other waveguide is that it supports an almost dispersion-free TEM mode. The remaining dispersion is due to the finite conductivity which increases the series inductance of the line. Nevertheless, the increase in the inductance due to wall losses does not lead to a significant dispersion for practical lines.

Therefore the maximum length of such a drive line is limited by damping. Fig. 1 shows the attenuation constant α of a coaxial transmission line for various geometries. Let us assume a radius of the outer conductor of 10 cm and a ratio $a/b = 0.3$. With these parameters a damping of only $6 \cdot 10^{-3}$ dB/m is achievable if the drive line is made of

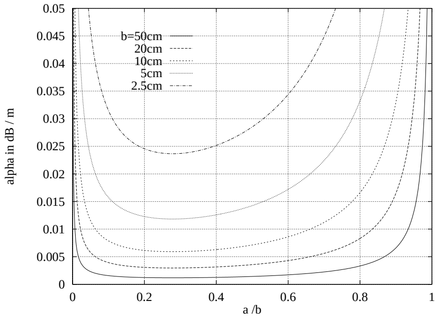

Figure 1: Attenuation constant corresponding to the fundamental mode of a coaxial waveguide versus the ratio of the radii of the inner and outer conductor a and b, respectively. The radius of the shielding serves as parameter.

copper with a conductivity of $5.8 \cdot 10^7\,\mathrm{S/m}$. If we assume 150 MW rf power the maximum electric field strength is about 3 MV/m which is sufficiently small to avoid breakdown.

Up to this point of the discussion we have considered the drive line as a pure transmission line. Nevertheless a coaxial line is also a waveguide which supports TE and TM modes. Assuming a geometry as given above and a frequency of 2.998 GHz, ten propagating higher order modes exist. Some of the power of the fundamental TEM mode is converted into higher order modes at the output couplers and at the struts, see Fig. 2, which are necessary to support the inner conductor. Two serious effects arise from this mode conversion. Obviously some of the power in the fundamental mode is lost if it is converted into other modes with higher damping. The second more serious effect gives rise to signal distortion if the fundamental mode is converted into higher order modes and some of the power of these modes is converted back into the fundamental mode at a position further along the waveguide. In order to avoid signal distortion by conversion and reconversion the undesired modes have to be suppressed (attenuated) to avoid reconversion. Due to the large variety of traveling higher order modes it seems to be impossible to construct mode filters in order to suppress all of these modes. Therefore the cross sectional dimensions of the coaxial line have to be reduced down to the single mode operation regime in order to obtain mode stability. This requirement limits the radii of the inner and the outer conductor to 0.75 cm and 2 cm, respectively. On the other hand, the damping of such a drive line amounts to $24 \cdot 10^{-3}\,\mathrm{dB/m}$ which is not acceptable because less than 2 km could be fed only.

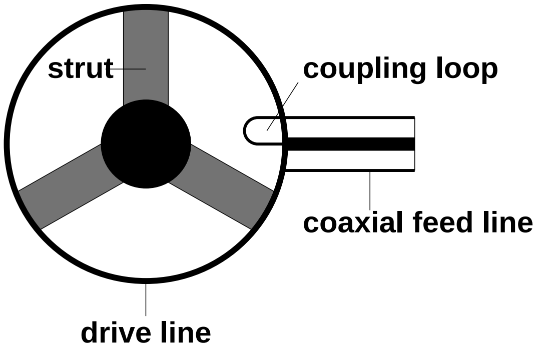

Figure 2: Cross section of a coaxial drive line with struts for the inner conductor and a loop coupler.

From the above discussion it can be concluded that a coaxial waveguide is not suitable for a long drive line because a low loss coaxial line with a large cross section tends to mode instability while a structure with reduced cross section has too excessive losses.

Waveguides

In a waveguide which does not support a TEM mode, signal distortion occurs due to the non-linear frequency dependence of the propagation constant β. Different parts of the signal travel with different velocities leading to a dispersed output signal, because no unique signal velocity exists. Nevertheless, for narrow band signals the transmitted signal is identical to the input signal, apart from the amplitude and a time delay. Let us assume an operating frequency of 3 GHz, a bandwidth of 1 MHz and a group velocity of $98\% \cdot c_0$. In order to achieve such a high group velocity the corresponding mode has to be far above cutoff. With these parameters and $L = 2\,\mathrm{km}$, one obtains $\Delta v_{gr}/v_{gr} = 1.4 \cdot 10^{-5}$ corresponding to a transmission time error of $\Delta T = 90\,\mathrm{ps}$ which is small compared to the rf pulse length.

Nevertheless one has to keep in mind that delay lines with well-defined length have to be inserted between the drive line and each individual klystron feed, if the group velocity is smaller than the velocity of light, in order to keep the drive pulse synchronous with the particles (see Fig. 3). The length of the first delay line is chosen to be 40 m according to $(1 - v_{gr}/c_0)\,L\,\mathrm{m}$ whereas the last accelerator feed is directly connected to the drive line. In between, the length of the delay lines has to be linearly decreased. For practical reasons one would realize the delay lines as coaxial cables which unfortunately suffer from a high damping, typically 0.4 dB/m. Hence the first delay line leads to an additional damping of 16 dB which is not serious because the full klystron power of 150 MW is available at the beginning of the drive line. However no significantly smaller group velocity is allowable due to the high damping of the delay lines.

Circular waveguide

If we consider the use of a circular waveguide as a drive line, it would be desirable to use a TE_{0m} mode due to

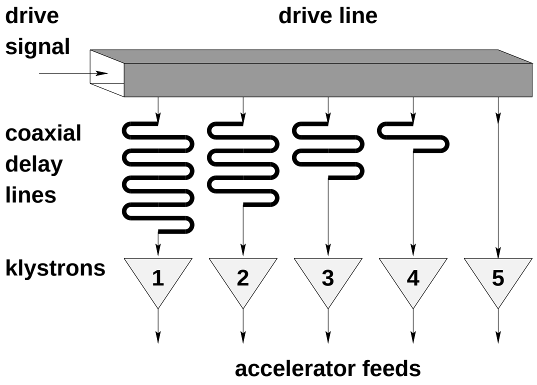

Figure 3: Schematic drawing of a drive line system with five feeds in which the group velocity of the drive line is less than the velocity of light.

the unique damping property of these modes, namely, the attenuation decreases as $f^{-\frac{3}{2}}$ for high frequencies. This feature of the TE_{0m} modes makes it possible to construct a very low-loss drive line in the case of $f \gg f_{c,0m}$. On the other hand, the circular waveguide must have a radius of more than 30 cm in order to achieve a group velocity of $98\% \cdot c_0$. This however seems not practicable. Besides the fact that such an overmoded waveguide in general generate mode instabilities, mode conversion turns out to be especially crucial using TE_{0m} modes because of the degeneracy of the TE_{0m} and the TM_{1m} modes. In order to avoid this problem a mode filter which suppresses modes with current flow directed along the waveguide axis (TM_{1m} modes) is necessary. Nevertheless such a filter leads to a rather complicated structure of the drive line.

In conclusion it has to be stated that a circular waveguide exhibits excellent damping properties. Nevertheless this design is not suitable for a drive line because a small signal delay due to the frequency dependence of the propagation constant requires a large cross sectional dimension of the waveguide which directly implies mode instabilities.

Ridge waveguide

In order to keep the group velocity close to the velocity of light it cannot be avoided to use a highly overmoded waveguide. Such a waveguide may be used if one can control the higher order modes.

In a ridge waveguide, see Fig. 4, the electromagnetic field is concentrated in the vicinity of the ridges whereas higher order modes extend throughout the cross section of the waveguide. These modes can be suppressed by suitable absorbers located at the side walls. Furthermore the fundamental mode of the ridge waveguide has a relatively low cutoff frequency due to the high capacitive loading associated with the ridges. This leads to a high group velocity compared with conventional waveguides.

A ridge waveguide with outside dimensions of $(a = 200\,\mathrm{mm}) \times (b = 100\,\mathrm{mm})$ and a ridge radius of $r = 33\,\mathrm{mm}$ is assumed. Due to the high field strength in a drive line it is not recommended to use rectangular ridges which may lead to discharge close to the edges. Instead, circular ridges seem to be more suitable. Fig. 5 shows the transverse electric field of the fundamental mode ($v_{gr} = 98.4\% \cdot c_0$). Again, for a 2 km long drive line a coaxial delay line of 32 m has to be used at the first klystron feed (see Fig. 3).

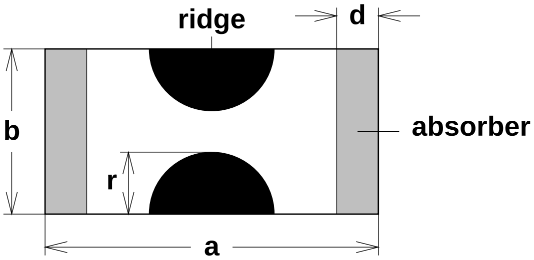

Figure 4: Cross section of a ridge waveguide with circular ridges and absorbers at the side walls.

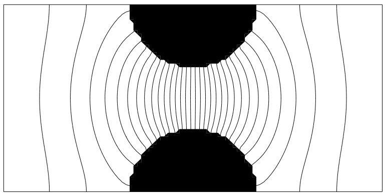

Figure 5: Fundamental mode. $\beta = 61.83\,\mathrm{m}^{-1}$.

The attenuation of the dominant mode (7.11 dB/km) is comparable to the above discussed coaxial drive line. Since the field distributions of all higher order modes are spread throughout the cross section of the waveguide these modes are strongly attenuated by losses at the side walls, whereas the damping of the fundamental mode is not significantly increased. If we insert two absorbers of 4 mm thickness and a loss tangent of 0.2 at the side walls of the waveguide the attenuation of the fundamental mode is increased by only 3.29 dB/km whereas the increase in damping for the higher order modes is much higher. The absorbers give rise to an attenuation of at least 35.1 dB/km for the third higher order mode which seems to be strong enough in order to guarantee mode stability.

Conclusions

A drive line concept for a linear accelerator has been presented which allows the simultaneous and synchronous excitation of a large number of high power klystrons. Various types of waveguides, namely, coaxial transmission lines, circular waveguides and ridge waveguides have been investigated. From the different types proposed here only the ridge waveguide fulfills all the necessary requirements which are low losses, low signal distortion due to dispersion and good suppression of higher order modes. From the calculation provided in this paper, it seems feasible to supply a 2–3 km long subsection of the linear collider with a single drive line if one of the 150 MW high power klystrons is used to generate the drive signal.

References

[1] N. Holtkamp and A. Jöstingmeier, *Transient beam loading compensation in traveling wave linear accelerators,* Deutsches Elektronen-Synchrotron DESY, DESY-96-043, March 1996.

[2] K. Balewski et al, *Status Report of a 500 GeV S-Band Linear Collider Study,* Deutsches Elektronen-Synchrotron DESY, DESY-91-153, December 1991.