LINEAR COLLIDER STRUCTURES

Toshiyasu Higo
KEK, National Laboratory for High Energy Physics
1-1 Oho, Tsukuba-shi, Ibaraki-ken 305, Japan

Abstract

In the present paper are described the present status on the design, the fabrication, and the high field studies on the structures for the linear colliders by showing various structure studies in such projects[1] as VLEPP, CLIC NLC, JLC and DLC.

The structure design for a single bunch machine is almost finished. Even the cost estimation of the CLIC structure cell for the case of mass production was already obtained to be 17SF/cup. On the contrary, those of the structures for the multi-bunch operation are still under design stage. Many calculation methods of the long-range wake field in the detuned structures are proposed trying to make the estimation realistic and precise. On the other hand, the measurement of the long-range wake field in a detuned structure was successfully performed and the measurement method proved to be a nice tool for the evaluation of design and fabrication of the structure.

An heavily damped structure, called choke-mode structure, which assures the damping of the higher order modes without tedious calculation as above, was designed and fabricated at S-band. It was conditioned without any problem and proved to be operated stably at 33MV/m with 4.5μsec width.

Stable operation of the disk-loaded X-band structure at 50MV/m level was easily obtained in various disk-loaded structures. This level is understood to be feasible in high field point of view.

Many fabrication studies are proceeded in addition to the high field tests in all projects focusing on various issues such as a good alignment, cheapness, less dark current, etc., depending on the project.

Introduction

Accelerating structures for linear collider main linac are designed at as a high frequency as possible from the structure efficiency point of view. However, higher frequency structures cause larger wake fields which increase the emittance both in single-bunch and multi-bunch sense. Though there are various beam-based correction schemes proposed to suppress these effects, the structure should also be designed to suppress the wake field itself.

The design of the structure for a single-bunch operation is rather straight forward and fairly fixed. The fabrication of the prototype structures were already finished and the issues such as the mass production are studied[2].

The design of the structure for a multi-bunch operation should have a significant consideration on the higher order modes in the structure. Various structures to suppress the long-range wake field within a train of bunches were proposed but two types of them remain to be the actual candidates. One of them is a heavily damped structure called "choke-mode structure"[3] and the other the "detuned structure"[4]. An S-band choke-mode structure was fabricated and already tested in high field recently which is described briefly in the present paper. The idea of the detuned structure and various methods to analyze the wake field in the structure are also described.

Prototype structures and some realistic ones have been fabricated in all the laboratories following their own thoughts and available methods. The status is also surveyed as much as possible.

On the other hand, the feasibility study of the stable operation of the structure at fairly high accelerating field is also being performed. Some experimental studies on the behavior of the structure at high field are described.

Requirements

In order to preserve the single bunch emittance, the alignment of the beam hole aperture is essential. Such a tolerance as 5μm cavity misalignment was presented in a single bunch machine, CLIC, for the case of one-to-few correction scheme where the bunch intensity is $6X10^9$/bunch and the structure frequency is 30GHz[5]. The tolerances for the fabrication and alignment of the accelerating structure should be better than this value. Another single bunch machine VLEPP designs the 14GHz structure with tolerable bend along 1m structure to be 10μm(rms)[6].

On the other hand, the tolerances against the single-bunch emittance growth in such multi-bunch cases as NLC, JLC and DLC become loose due to adopting low frequency structures without increasing the number of electrons per bunch too much. However, all these machines will be operated in a multi-bunch operation to obtain a high luminosity under relatively low repetition rates. In this case, not only the alignment itself but also the characteristics of the long-range wake field is needed to make sure that the multi-bunch emittance growth is small. A rule of thumb for this multi-bunch emittance preservation in the case of X-band structures is to damp the excited wake field by a factor of 100 at the next bunch. The necessary damping factor in the case of utilizing the cancellation of the wake field within a structure is also in the same order of magnitude. A criterion of the alignment for this type of structure, a detuned structure for NLC, was presented to be about several μm level for keeping the emittance increase $\delta\varepsilon$ less than 25%[7], resulting in the required tolerance of a few μm level for $\delta\varepsilon$ <5%.

Damped structure design

Radial slotted

A damped structure with radial slots in the disk was first proposed by R. Palmer[8] and gave the impact on "damped structure" for linear collider. However, this type has only been studied on the damping behavior of TM110-like mode which prove to be as small as 8[4] but has little estimate on the accelerating mode characteristics. In the case on changing the slot while keeping the bridge to make the beam hole circular and mechanically strong, no slot mode appears below accelerating mode but the accelerating mode deteriorates about 30% and the damping behavior becomes very sensitive to the beam hole aperture, preventing it from using as a linear collider structure[9]. Gradually the study faded out.

Circumferential slotted

On the other hand, the damping mechanism of the higher order modes in the structure with circumferential slots in the outer wall of each cell is much clear to understand and stable against dimensional change. The characteristics of this kind of structure was seriously analyzed[10] using MAFIA[11]. The Q values of higher order modes can be damped well, though the impedance of the accelerating mode is degraded by 25% if the Q value of the TM110-like mode is less than 15. However, the same kind of structure can be used for medium damping mechanism for the detuned structure described in the next section without sacrificing the characteristics of the accelerating mode.

Choke mode

An extreme of the above circumferential slot, i.e. opening the slot over 2π while trapping the accelerating mode inside the cell by choke, was proposed by T. Shintake[3]. The idea is very clear and shown in Fig. 1. This choke-mode structure damps beautifully almost all the relevant modes in the cell with sacrificing the shunt impedance of the accelerating mode by 25%.

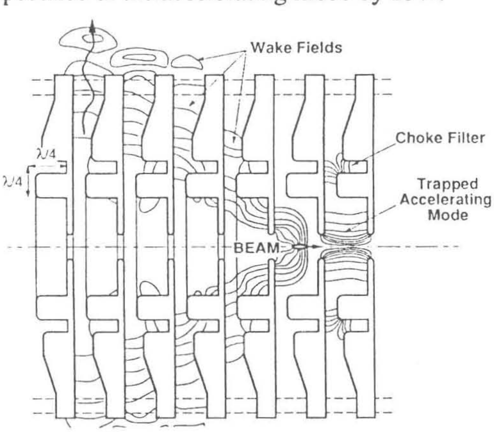

Fig. 1. Idea of choke mode structure.

An S-band choke-mode structure with 12 choke-mode cells and two coupler cells was fabricated for a proof of the high power operation[12] and tested in high power[3]. The structure was conditioned first up to 33MV/m with 4.5μsec pulse width in a flat pulse mode and then up to the input peak power of 120MW in SLED mode without any problem. Such characteristics as the wave form of RF pulse, the group velocity and the impedance of the accelerating mode, etc. were just as estimated. This experiment proved the feasibility of this type of structure in actually a high power use.

Detuned structure design

Gaussian detuning

If the losses in the accelerating mode in the heavily damped structures should be reduced, it seems that the cancellation of the wake field is inevitable method instead of damping. Such mechanisms as making the kick field zero crossing at the following bunches[13] or beating two frequency wake field and making the following bunches in the waist using two type of structures[14] was proposed but these ideas work usually only for one mode, i.e., the mode of largest wake field.

Meanwhile, a gaussian-type distribution of the relevant dipole mode in the cells was proposed, which makes the wake field damping also as gaussian, resulting in no early recoherence[15]. The structure with this type of cancellation is one of the structures called "detuned structure". The wake field calculated for a detuned structure using an equivalent circuit model[16] is shown in Fig. 3(b), showing good cancellation through the entire beam pulse.

Since fairly precise estimation is needed for actual use of this type of structure, various approaches are being tried by various authors and some of these are described below.

Equivalent circuit model

The above equivalent circuit model[16] estimated the wake field of the lowest mode(TM110) in the presence of the second mode(TE111). K. Bane showed the importance of the effect from the higher passbands, especially the 6th one, and treated them as independent coupled chain of single passbands[17]. In the result, he proposed to vary the thickness of the disk to distribute the frequency of the 6th mode effectively.

Field matching techniques

In the above equivalent circuit model, it is difficult to incorporate the effects from the higher modes over than the second. On the other hand, we have analyzed for many years the periodic structures with irises taking as any number of modes as needed into account using field matching technique[18]. The technique was extended to deal with the non-periodic, detuned structures[19,20]. This method assumes the beam hole to be right edged.

Open mode expansion technique

In order to incorporate the higher order mode up to any desired mode and also to make it possible to take the accurate structure shape into account, Yamamoto[21] developed extensively a model called "open mode expansion", which is originally described by Bevensee[22]. Each cell boundary is defined as the volume between the centers of two disks facing to the cell. All the modes in each cell are described as a sum of "open modes", which is magnetically shorted at both sides of a cell. The coupling between modes are calculated following Maxwell's equation directly.

Periodic structures with beam holes of right-angle edge were calculated and obtained an excellent agreement throughout the passband in frequencies and kick factors up to the highest passband but one. A detuned structure with varying both beam hole aperture and disk thickness was analyzed using this method. The obtained kick factors of modes up to 8th passband as a function of frequency is shown in Fig. 2(a). The gaussian-like distribution of the first passband and the fairly large contribution from the 6th passband can be seen in the figure. The distribution of the strength of the open mode up to 8th in some of the modes are shown in Fig. 2(b). The large mixing of the higher modes into the lower modes is clearly seen. In Fig. 2(c) is shown the envelope of the wake field of the above detuned structures with four interleaved frequencies.

Further studies on detuned structure

Manifold damping

The frequency tolerance of the X-band detuned structure has known to be loosened by adding a external medium damping of the order of 2000, though no good method was proposed till recently[23]. N. Kroll analyzed a "manifold damping" method which utilize the manifolds running along the accelerating cells to transport the higher-mode energy into two terminals without perturbing accelerating mode due to the difference of the phase velocities. This method will make the detuned structure practical.

Damping cells

The S-band structure for DLC is basically the constant gradient (CG) one. In addition to the detuning effect arising from CG, some kind of damping mechanism is necessary to make the required Q value of the order of 2000. To suffice this damping, the analysis based on such an model as the mode matching[19], three damping cells are designed at three positions along the structure. The damping mechanism is studied and found that the group velocity of the relevant mode should be increased to make the heavily damped cells work effectively[24].

Measurement of long-range wake field

The measurement of the wake field is essential to judge the structures for multi-bunch operation, because all the theoretical estimates of the long-range wake field described above have various assumptions and suffer from the unknown precision. The long-range wake field can be analyzed by measuring all the modes in the structure but the estimate by this measurement is also very difficult due to the difficulty especially in measuring the field of all the modes. On the other hand, the facility called "ASSET" at SLAC can serve an ideal tool for measuring the wake field[25].

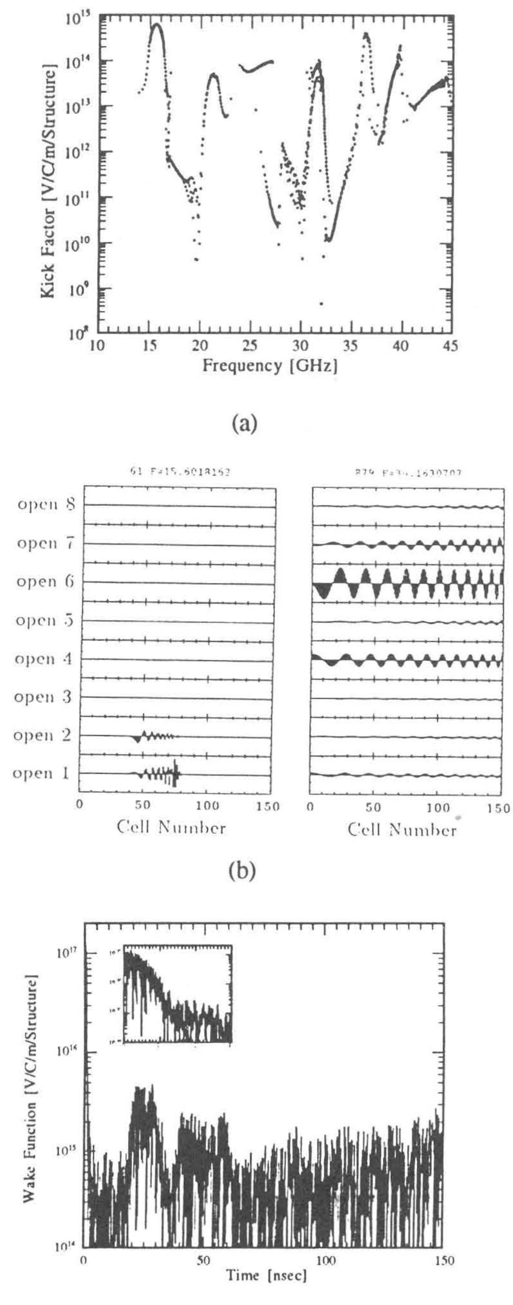

Fig. 2. Results of the analysis by the open mode expansion on a detuned structure. (a): kick factors vs. mode frequency, (b): the field strengths decomposed into 8 open modes for the two example modes in the first and the 6th passband and (c): the envelope of the wake field with four type of detuned structure with interleaved frequencies.

A single positron bunch passes through the structure with offset with respect to the structure axis and drives the wake field. The electron bunch passes the same structure with a time delay controlled precisely by the phase difference between the two damping rings. The kick obtained by the electron bunch was measured in a downstream linac BPM's.

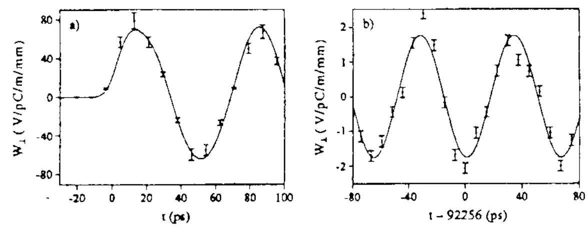

Fig. 3(a) Measured wake field as a function of time separation between drive and witness bunch.

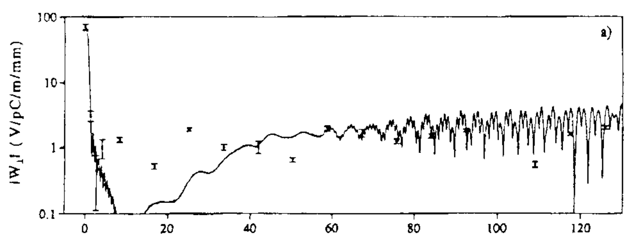

Fig. 3(b) Envelope of the measured wake field as a function of time separation between drive and witness bunch. The solid line is the estimation calculated by equivalent circuit model[16].

In Fig. 3(a) is shown a typical measurement of transverse kick as a function of time delay. It clearly shows the zero wake field before t=0 and also show the contribution of a remaining dominant mode at later times. The dependence of the kick on the offset of the drive bunch was observed sitting at the time of the maximum wake field and the slope was analyzed to obtain the amplitude of the wake field. The result is shown in Fig. 3(b). This procedure proved the sensitivity of 0.1V/pC/mm/m which is roughly 1/1000 of initial wake field. Since the rule of thumb of the required damping for X-band structure is 1/100, this sensitivity is large enough. It makes the serious comparison to the theoretical estimations possible.

High field characteristics

A 7-GHz standing-wave structure was high power tested up to 90MV/m for VLEPP in 1978.

After that, the breakdown limits were elaborately studied for standing wave structures in late 1980's at SLAC/Varian[26]. They showed the surface field limit higher than Kilpatric criterion by a factor of 8 with frequency dependence of $\sqrt{\omega}$. This gives us nearly 300MV/m for traveling wave structure where $E_p/E_{acc}\sim2$ at X-band, which is well above the design field of all projects.

On the other hand, traveling-wave S-band structures were studied at KEK[27]. They obtained the maximum field of 91MV/m in 0.6m-structure. There is no evidence that this is a breakdown limit, though. What should be noted more is the necessity of the cleanness of the structure for reducing dark current. The "clean structure", which means being fabricated trying not to insert dust inside the structure, gives less dark current by more than a factor of 10. Similar kind of behavior was observed in the 20-cm long X-band structures as shown in Fig. 4[28]. The structure indicated as "CERN" was made by ultra-precision lathe and in a reasonably clean circumference comparing to the other.

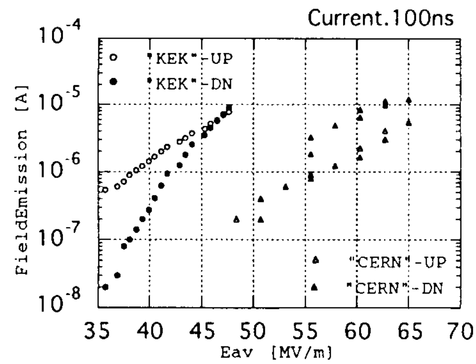

Fig. 4. The comparison of the dark current from two 0.2m structures, CERN made and KEK made.

High field test on traveling wave structures at X-band aiming at the feasibility check for the linear collider use have been performed at SLAC[29] and KEK[28]. The typical parameters are summarized in the Table 1. The obtained field levels are not necessarily limited by the structures themselves. It is fairly easy to reach a stable operation at 50MV/m level without measurable dark current. The accelerating field of even 100MV/m can be reached without severe conditioning but with a dark current of the order of mA. The behavior of this dark current in the realistic structures should be performed from now.

TABLE 1
High-Field Experimental Results

Length(m)	0.2	0.26	0.26	0.75	1.8
Type	CI	CI	CI	CI	Detuned
Maker	CERN	CERN	SLAC	SLAC	SLAC
Input (MW)	39	69	116	130	105
Eav (MV/m)	100	125	101	79	55
Pulse (ns)	100	150	60	75	75
Fill Time (ns)	58	74	27	52	100

An electron counting system can serve as a detector for very low dark current (peak current of 60pA) which cannot be measured directly by Faraday cup[30]. This may contribute the understanding of a relatively low field operation such as the DLC case.

Fabrication

Several sections were already fabricated and waiting for high power test in VLEPP test facility.

Two prototype sections for CLIC were fabricated and being tested in the test facility.

A 1.8m-long detuned structure for NLCTA was fabricated and high power tested as stated above. The wake field in this cavity was also measured and proved the detuning mechanism over than 100nsec. The next structure with the same design but fabricated with ultra-precision lathe to make it more straight and give a better frequency control for higher modes is under way.

In the study for JLC-X band structure fabrication, the diffusion bonding technique has been studied pursuing no tuning process after bonding which makes it certain that the dipole mode frequency distribution is quite precisely determined by machining only. A few 30cm-long structures were fabricated using this technique and waiting for high power test. The cells for this bonding process should be very flat. The present typical flatness over 80mmϕ is 0.3μm. The frequency error of the machined cells is 0.1MHz(rms) for more than 70cells and the errors of their outer diameters ±0.3μm(rms). A test for precise alignment of 1.3m-dummy section through this bonding is under progress.

In the DLC project, a 5.2-m long structures for LINAC II at DESY are being fabricated as a fabrication study. They obtained the straightness of 100~150μm without large care, though the target value for the straightness is 30μm in 6m.

Summary

The structures for single-bunch machine already came to the study for mass production and cost reduction. Variety of codes on the wake field in the detuned structures for multi-bunch case show the incompleteness of the analysis on such structures. The choke-mode structure was found to work well in high power and proved to be a very promising candidate.

High power tests till today show no difficulties to reach a stable high-field operation such as 50MV/m at X-band. More sophisticated performance tests on the more realistic structures are in progress in each laboratories.

Acknowledgment

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