The New Method of the Transient Beam Loading Compensation for the Next Generation of TeV e+e- Linear Collider.

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Abstract

In this paper, a new method of transient beam loading compensation for the next generation of TeV e+e- linear collider with multibunching is presented. The method is based on applications of the $\pi/2$ - mode standing wave accelerating structure with the reflected wave used for beam loading compensation. Various compensation methods for transient beam loading for the constant gradient traveling wave and $\pi/2$ standing wave structures are compared. It is shown that the proposed method provides an approximately 10 % higher efficiency of the RF source energy utilization than that for the traveling wave accelerating structure.

Introduction

The multibunch regime of the linear collider operation requires close control over the energies of the bunches in the train. For certain reasons, the bunch-to-bunch energy fluctuations need to be less than a few parts per thousand [1], therefore special methods of the transient beam loading (TBL) compensation are required. These methods exploit basically the idea that the RF structure has to be filled with a sufficient extra energy between bunch passages to make up for the decelerating fields deposited by the previous bunches in the train. In this case, during the compensation, the first bunch of the train is accelerated at the moment when the amount of the RF energy stored up in the structure reaches some certain minimum value. The stored energy growing up, the energies of the subsequent bunches are the same and equal to the energy of the bunch accelerated in the steady state regime.

In the majority of the TBL compensation methods under development [1,2,3], it is presupposed that only some certain portion of the RF energy produced by an RF source reaches the traveling wave structure (the simplest example -- the partially filled accelerating structure [2]). This, evidently, reduces the amount of the RF energy extracted by the beam from the RF source. From this standpoint, the application of the $\pi/2$ standing wave (SW) accelerating structure is somewhat advantageous compared to the conventional traveling wave constant gradient (CG) structure. The principal idea here is that in the $\pi/2$ SW structure a partial build-up of the compensating extra energy takes place automatically if the head bunch of the train is injected just after the structure is filled one way. It has also been established that for the $\pi/2$ SW structure the shape of the RF feeding pulse should be close to the exponential decay so that the required bunch-to bunch energy spread compensation level (better than 0.1%) could be provided. This means that the RF source energy is made the best use of when a simplest single cavity RF pulse compressor (like SLED [4], or VPM [5]) is applied in the RF driving system.

1. Parameters of 11.424 GHz π/2 - mode standing wave structure.

A biperiodic (π/2-mode) standing wave (BSW) accelerating structure is a well-developed class of accelerating structures. Here we will not discuss the specific features of such structures, since a detailed BSW theory can be found elsewhere [6]. In our investigations, we did not pursue the aim to design some particular BSW structure. However, to determine the more or less realistic range of the effective shunt impedance and Q-factor, a simple BSW structure with a radial coupling slot was studied (see Fig. 1).

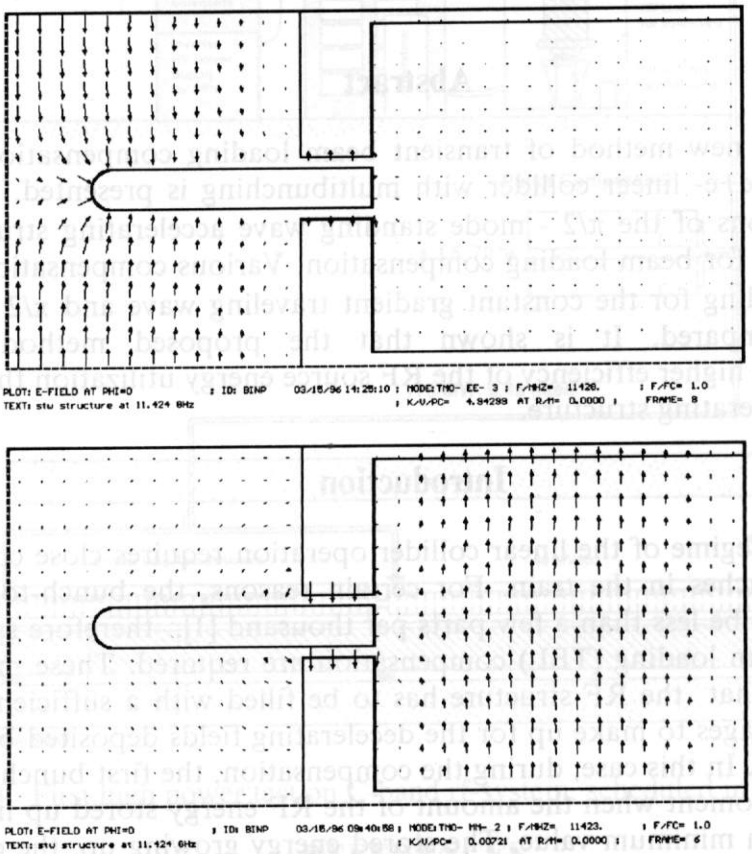

Figure 1. Geometry of the 11.424 GHz BSW structure and electric fields distributions for the even mode (upper) and odd mode (lower) by URMEL-T.

The geometry of the given structure was optimized with the URMEL-T code. In Fig. 2, the calculated parameters of the BSW structure for different widths of the coupling slot, t, are shown. The beam aperture was chosen to be 2a=6mm.

For the most part of the coupling slot width range, the Q-factor of the BSW structure period approaches 7.3x10^3. Now, if we compare the obtained results with the parameters of the 11.424 GHz NLC- type, 1.8 m long CG structure (β_{gr} = 6%) [8], we can see that R_{sh} of the BSW structure is about twice as low as that for the CG structure, while the Q-factor is slightly higher. This comes clear from the fact that while a traveling wave propagates in the BSW structure, some portion of the RF energy (about one-half) does not participate in the acceleration but is stored in the coupling cells. In the steady state regime of operation, this effect is compensated for by that an accelerating field in the BSW structure is the sum of the forward and backward waves.

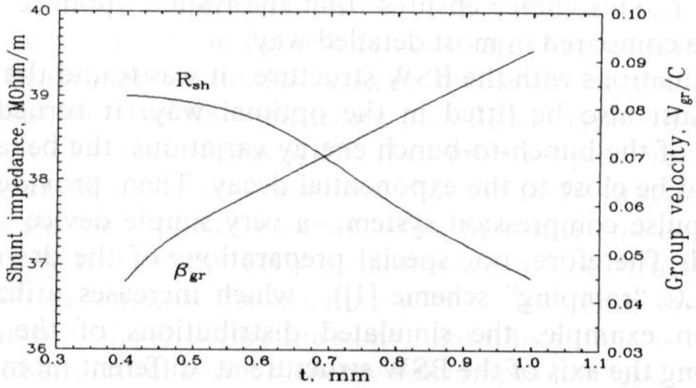

Figure 2. Traveling wave shunt impedance (R_{sh}) and group velocity (β_{gr}) vs. width of the radial coupling slot (t).

2. Simulation of the transient processes in the accelerating structure.

To provide a realistic simulation of the transient processes in the accelerating structures, the computer model of the structures has been developed. As we were mostly concentrated on the interbunch energy spread, we started from the following assumptions that simplify the model of the structure, i.e. make it easily computable, but do not destroy the picture of the processes. The assumptions we used are: (1) each bunch is considered to be a macroparticle and rides on crest of the accelerating wave, (2) the long-range field of the accelerating mode is taken into account while the higher order modes are neglected, (3) the pulse shape is effected by the rise time and an intentionally applied modulation and (4) the timing of the input RF pulse with respect to the beam injection time is considered. Under these assumptions, an N-cell accelerating structure was modeled as a series of waveguides from #1 to #N separated by diaphragms with a given reflection coefficient. A detailed description of the model is given in [7]. The parameters of the waveguides and diaphragms in the model were calculated with a special respect to the given parameters of the structure (length and filing time) and of a single accelerating cell (phase advance, shunt impedance and Q-factor). To take into account the beam-induced wake field of the accelerating mode, we used the discrete excitation of the accelerating cells. In the case of BSW structure, this excitation was applied only to even cells that represented accelerating cells of the BSW structure. This simulation method for the transient processes in the accelerating structure does not require the direct computation of the electromagnetic fields. Therefore, the method is quite suitable for checking fast the beam loading and the externally fed RF properties in an arbitrary accelerating structure that can basically be expressed as described in [7].

3. Transient beam loading compensation.

In our proposal, we suggest that a time-dependent build-up of the accelerating field in the BSW structure for the multibunch TBL compensation be used: if injection of the first bunch of the train occurs just after one way filling of the BSW structure, then the backward wave can deliver that extra RF energy that is required for the transient beam loading compensation. This method should be adapted to the bunch train whose length is equal to the one way filling time of the structure. In our simulations, the BSW structure length, beam and RF source parameters were chosen to be the same as in the NLC design [8], see Table 1. This choice ensures that the results obtained for the CG and BSW structures can be compared in most detailed way.

After a series of calculations with the BSW structure, it was found that the shape of the feeding RF pulse must also be fitted in the optimal way. It turned out that, for a sufficient suppression of the bunch-to-bunch energy variations the behavior of the input RF pulse shape should be close to the exponential decay. Then, provided the RF driving system contains RF pulse compression system, a very simple device like SLED [4] or VPM [5] can be used. Therefore, no special preparations of the driving RF pulse are required (cf. the NLC "ramping" scheme [1]), which increases utilization of the RF source energy. As an example, the simulated distributions of the accelerating and decelerating fields along the axis of the BSW structure at different moments are shown in Fig.3.

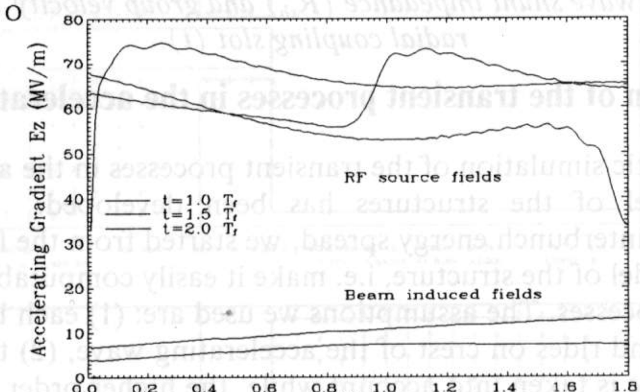

Figure 3. Accelerating/decelerating electric fields $E_z(z)$ along the axis of the BSW structure for different moments of bunch train passes.

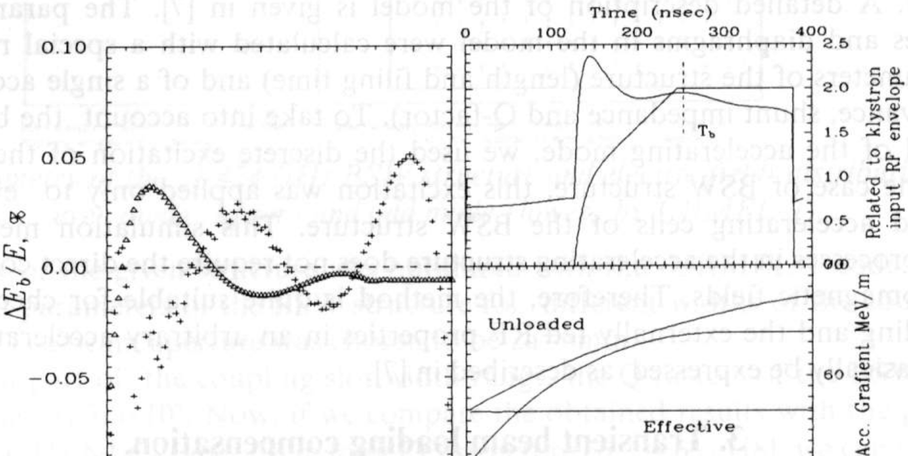

Figure 4. Optimized bunch- to- bunch energy spreads for the CG structure (trian.) and BSW structure (crosses) - left; Envelopes of the input RF pulses - upper right; Unloaded and Loaded (Compensated) acceleration gradients vs. bunch number - lower right.

Similar calculations were made for the NLC-type CG structure, where, in accordance with NLCTA design, the ramping scheme was applied as a method for the transient beam loading compensation [9]. The graphic results of the simulations for both structures are shown in Fig.4. The results of simulations demonstrate that, with the same parameters of the accelerating beam and equal RF energy delivered by the klystron, the loaded accelerating gradient for the BSW structure plus SLED type compressor is about 10% higher than for the CG structure plus SLED II compressor plus "ramping" scheme.

In our previous reasoning, it was assumed that the BSW structure is connected to the feeding waveguide through one of its ends, while the other end is perfectly shorted. But there is another way to feed the BSW structure when the structure is coupled to the waveguide through its center of the structure with both its ends shorted (BSW/c). In this case, with the length of the structure the same, the filling time is twice as short as that for the side-coupled structure, and RF energy consumption is less. Now, if the first bunch is injected after the two-way filling of each of the substructures of the BSW/c, then the same TBL compensation methods as for the traveling wave structures can again be applied. This modification of the BSW structure was examined with the same configuration of the RF driving system that was previously used for the NLC type CG structure. The results are shown in Fig.5.

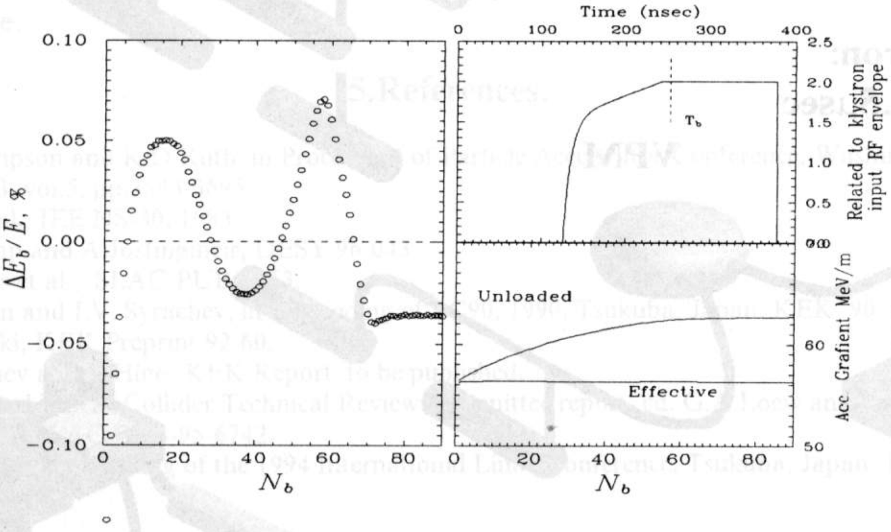

Figure 5. Optimized bunch- to- bunch energy spread for the BSW structure coupled through the center - left; Envelope of the input RF pulse - upper right; Unloaded and Loaded (Compensated) acceleration gradients vs. bunch number - lower right.

Comparing Figs. 4 and 5, we can see that the loaded accelerating gradient for the BSW/c structure is also about 10% higher than for the CG structure.

Finally, for a more complete comparison, various configurations for the linear accelerator single unit, as well as different schemes of TBL compensation, have also been calculated:

- Delay Line Distribution System (DLDS)+ CG structure + ramping scheme
- DLDS + BSW/c structure + ramping scheme
- DLDS+ CG structure × 10 + "staggered timing" method.

Here DLDS is one of the methods to increase pulsed RF power with shortening of the entire RF pulses of the pair of the neighbour klystrons feeding two distant accelerating structures [10]. And "staggered timing" is a method when a series of accelerating structures, each with its individual injection timing, contribute to cancel the individual energy spread after the train passes through the whole series [2,8].

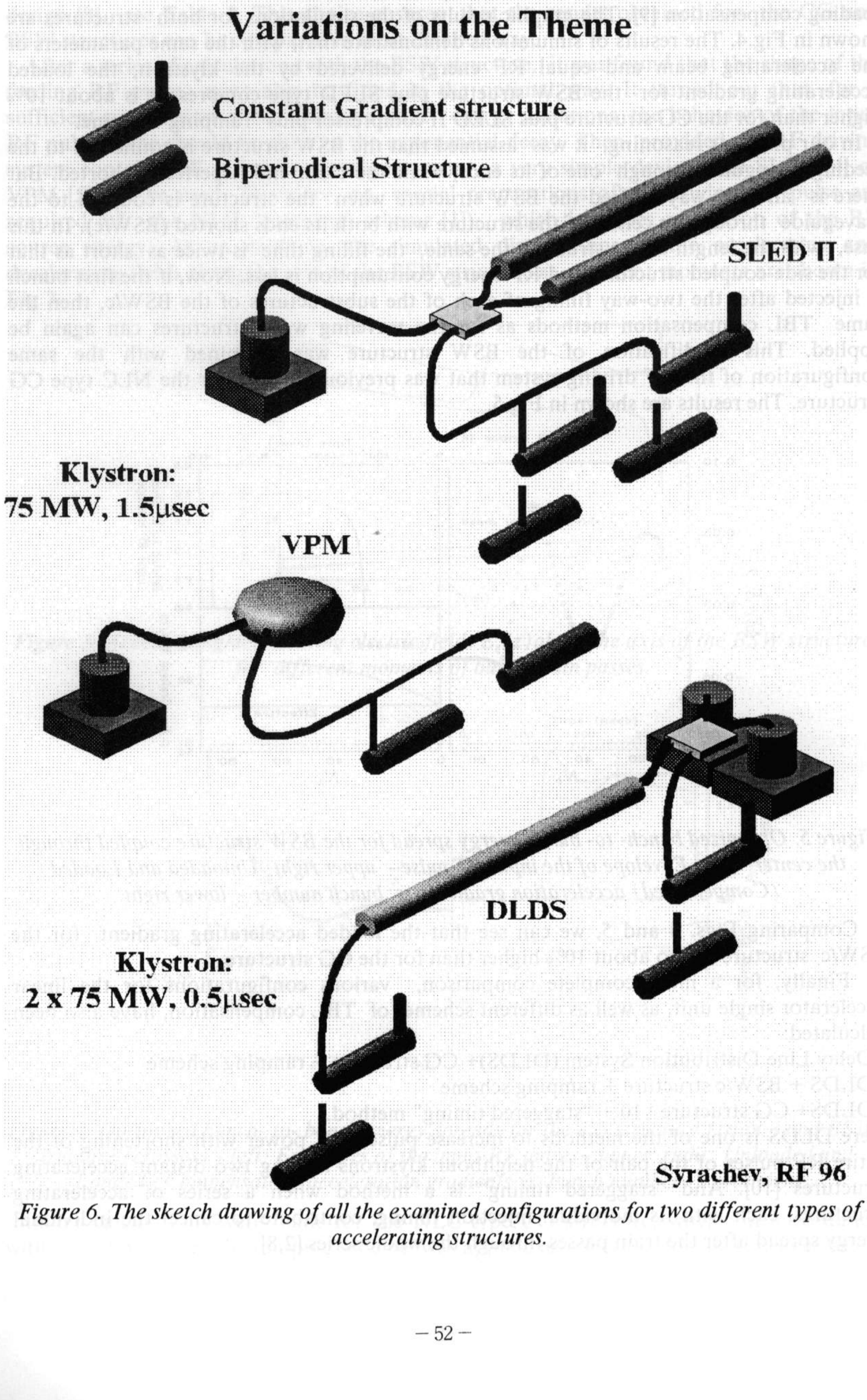

Figure 6. The sketch drawing of all the examined configurations for two different types of accelerating structures.

The sketch drawing of all the examined configurations for two different types of the accelerating structures is shown in Fig.6. The design parameters and general results of the simulations for all the variants are listed in Table 1.

In Table 1, the "total efficiency" as the ratio of the beam-extracted energy to that produced by the RF source is specified.

4. Conclusion.

In this paper, the $\pi/2$ - mode standing wave accelerating structure (BSW) as a part of the regular linear accelerator for the next generation TeV e+e- linear collider with multibunch regime of operation is examined. It is shown that the application of this kind of accelerating structure does not require any special efforts to provide a sufficient suppression of interbunch energy deviations (better than 0.1 %), provided a simple SLED-type RF pulse compression system is applied in the RF feeding circuit. At the same time, the comparison of the results of simulations for BSW and NLC-type Constant Gradient structures obtained for the same design parameters of the beam and RF source revealed that for BSW structure the loaded accelerating gradient is about 10% higher than for the CG structure.

5.References.

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