RF PULSE COMPRESSION FOR LINEAR COLLIDERS

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Abstract

In the high gradient electron linacs at X or S band, a conventional klystropn driver cannnot supply short pulses that a linear collider operation requires. Therefore, some RF pulse compression system that can compress the RF pulse length and at the same time heighten the peak RF power become necessary. Such an RF pulse compression system has been already utelized successfully in the S-band electron linacs of several laboratories. In the studies of the X-band linear accelerators, such RF pulse compression systems, SLED (SLAC Linac Energy Doubler) [1] or its direct successors SLED2 [2] and VPM (VLEPP Pulse Multiplier) [3][4] were studied and developed as the RF pulse compression system for the future machines. These system are all based on the same principle that the RF pulse energy is once stored in some storage circuit (a resonance cavity or a delay line) and thereafter emitted within short time to create the shorter RF pulse. Instead of these schemes, BPC (Binary Pulse Conpression) [5] and DLDS (Delay Line Distribution System) [6] use the delay lines as the tool to make the RF pulse shorter (BPC), or to adapt the longer RF pulse into the shorter linac driving pulse (in case of DLDS). A DLDS was recently introduced as an RF pulse compression equivalent system based on the different operation principle from an ordinary pulse compression system. DLDS is expected as the RF pulse compression equivalent system for the future RF system of X-band linear colliders.

1 INTRODUCTION

As the typical example of the modern X-band linear collider, general parameters of JLC (Japan Linear Collider) are summarized in the Table 1 [7].

To achieve an accelerating gradient of ~70MeV/m or greater in an accelerating strcture with shunt impedencec of ~80Mohm/m, the RF power fed per unit length of the linear collider should be around 100MW/m or higher. Duration of the RF pulse should be 250nsec, which is the sum of the filling time of and to time length of the multi-bunch train that consist of 90 bunches each separated by 1.4 nsec.

In the JLC design, to provide a peak power up to 130MW/mto the accelerating structure, klystrons are distributed every 4-5m to feed 3-accelerating units with the RF power totaling 390MW. Clearly, such a high peak power is out of reach for a single klystron, even with the most advanced modern klystrion technologies. In addition, the required RF pulse duration of 250ns is too short to drive klystrons efficiently. Present high voltage modulators with a step-up pulse transformer can never drive a klystron with the rise time much shorter than 100ns.[7][8] Thus the klystron modulator systems will suffer from poor efficiency if it were to drive klystrons with output pulses of 250ns.

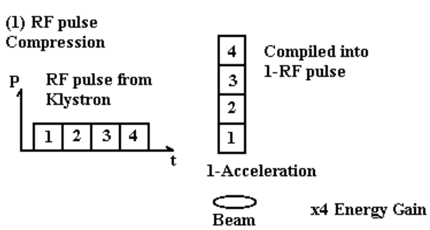
Table 1. General parameters for the next generation linear colliders

RF frequency(GHz)	11.4
Accelerating gradient(MeV/m)	
Unloaded/Loaded	76/57
Active linac length(km)	9.2
Total linac length(km)	10
Peak power /meter(MW/m)	100
Structures/power unit	6
Structure length per power unit(m)	7.8
Total number of power unit	1180
Total number of klystrons	4720
Total number of modulators	2360
Repetition rate(pps)	150
RF pulse length at str.(nsec)	250
Peak beam current(mA)	0.79
Total average RF power at Str.(MW)	34.5

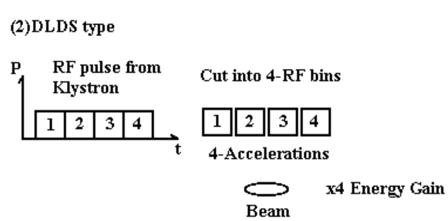
Consequently, the RF power system of the X-band linear collider must supply the RF power that is shorter in pulse length and at the same time higher in peak power, than the present technology could achieve. This requirement imposes a notable change in the RF power system of the X-band linear colliders. As shown above, the energy consumption of the future collider is considered to reach to several hundred megawatts, it is quite important to supply these RF power with high conversion efficiency. Thus the major change was introduced to the X-band RF power system. It is, the introduction of the RF pulse compression stage to compress the klystron RF output pulse shorter about factor 4. This difference are due to the fact that the X-band RF power system has to deliver about factor 4 shorter RF pulse than S-band system. The most important difference between the S and X-band Rf power echnogy is that an RF pulse which dirves an X-band linac is about 4-times shorter than that of S-band case. Therefore, 4-times longer RF pulse that is created by the present klystron modulator technology limit must somehow adapted to this 4-times shorter linac driving pulse length. On this point, there is the absolute necessity of the RF pulse compression measure.[7][8]

2 RF PULSE COMPRESSION SYSTEMS

The RF pulse compression system is generally considered as the measure that can make an RF pulse shorter and higher while preserving its total RF pulse energy as much as possible. As an linac RF power sources, this condition is can be re-considered as follows. If an RF pulse that is several times longer than the linac driving pulse can drive a linac utilizing all its RF energy i.e. its longer pulse, this system has the same effct as the ordinary type pulse compression system driving a linac. Thus, the present Rf pulse compression methods can be divided into two categories. Firstly, the conventional RF pulse compression schemes such as SLED, SLED2 and VPM etc. [9] These methods are based on the same operational principle that the RF pulse are once stored in some energy storage system such as a resonnant cavity or cavity equivalent system, and later extracted as the shorter and higher RF pulse. In other words, the RF pulse is re-shaped into the shorter



case-1)



case-2)

Fig. 1. Two types of RF shortening scheme

but higher RF pulse. On the other hand DLDS and its application are based on the fact that the RF pulse are applied on the beam in the different linac position to achieve the multiple acceleration by each RF bis that are cut from the longer original RF pulse. The main important feature of this DLDS like methods are that the RF pulse is divided into several shorter RF pulses (bins) and each pulse accelerates the same beam in the different position of the linac to adjust the time delay. Fig. 1 illustrates these operation principles in case of factor 4 compression ratio for each case. The ordinary RF pulse compression is illustarted in case-1) in this Figure. Longer RF pulse from the klystron is re-shaped into the shorter and higher RF pulse using the energy store system mostly resonnant cavities. On the other hand, as illustrated in case 2), RF pulse is divided into 4 RF bins in time domain and each shorter RF bin accelerates the same beam independently instead being piled up to the higher pulse like SLED type pulse compression system. In this DLDS system the longer RF pulse from the klystron are only divided into shorter pulses and steered into the different parts of the linac to meet the identical beam. These two systems can be considered as essentially the same, because both utilizes the longer Rf pulse to drive the linac that has 4-times shorter driving pulse. And the beam also gain the energy that is 4-times more than expected from the klystron output peakpower. Thus, this second type can be also called as the RF pulse compression system of the factor 4 compression ratio.

3 SLED SLED2 & VPM (SLED-FAMILY)

The operational principle of this SLED group is illustrated in Fig. 1.[1] All of this family has the same operational principle as the original SLED operation. As shown in the figure, RF energy is once stored in the resonnant cavities and later extracted through 3-dB hybrid which steers the RF pulse into the output port direction within short period.

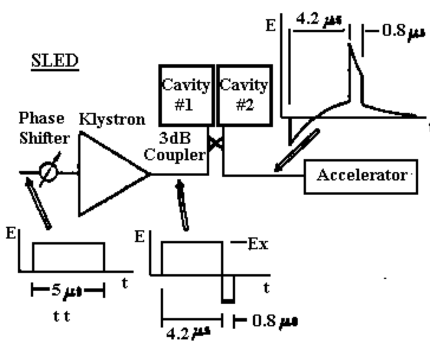


Fig. 2. Principle of operation of SLED

This kind of system necessarily has the two main causes of the energy loss in their operation process, firstly the reflection of the incoming RF pulse while the build up period especially at the early part of this stage and this reflection can never be avoided as long as the RF output pulse from the klystron are flat shape.[9] This device and the necessity of the time to build up RF energy in these storage cavity or cavities, mainly determines it’s energy efficiency. The energy losses in this system are consist of following two categories, (1) The wall loss on the inner surface of the energy storage cavity, (2) the RF reflection while the storage period. and the RF energy left after extraction of the energy from the storage devices. The main part of loss in this stage, is the reflection of the input RF pulse while the build up period of the SLED operation. Thus the energy efficiency of this system is about 80% even neglecting the possible wall loss.

As illustrated above, this original SLED can only re-shape the RF pulse into the exponentially decaying pulse waveform. However, several methods that can shape the RF pulse into a flat pulse are proposed. One is SLED2 that uses a pair of delay lines instead of the resonant cavities. Others uses the chain of the RF cavities for energy strage. One more possibility is to control the phase, amplitude or both to make a flat pulse. Detail of these sre omitted but the essential character of the system remains almost the same.[3][4]

4 BINARY PULSE COMPRESSION (BPC)

One more RF pulse compression system based on the different operational principle from these energy storage type pulse compression of the SLED family is the BPC (Binary Pulse Compression). This pulse compression system was proposed by D.Farkas and the first high power test was successfully achieved in SLAC.[10]

The operational principle of this BPC system is graphically illustrated in Fig. 3 in case of the compression factor of 4. This system is driven by two independently phased klystrons and their output pulses are divided into 4-short pulses respectively. The phase of each part of the RF pulse are coded as shown in Fig. 3. Through the 3-dB hybrid and delay lines, RF pulse trains from each klystron are combined and at the same time sterred to the two output port of the hybrid.

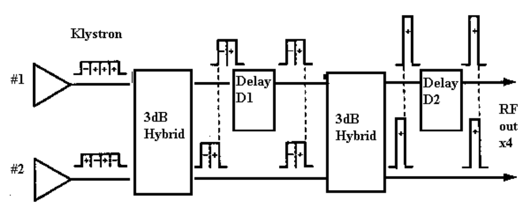


Fig. 3. Principle of ooperation of BPC

One port of the hybrid is connected to the delay lines which gives the necessary delay time to the first half of the RF pulse to meet with the following half of the RF pulse just in time at the input of the next 3dB hybrid. Through next hybrid, first and the second part of RF pulse are combined to give the twice peak power with one half of the original pulse duration. And as illustrated in the figure, this RF pulse again guided to the next stage as the figure illustrates. Repeating this process as shown in Fig. 3, 2^n pulse compression could be achieved. If the wall loss of the delay lines are neglected, it is quite easy to find that an n-stage of the BPC system can give the factor 2^n times higher pulse with 2n-th of a original pulse duration. It is also easy to recognize that in this BPC system the intrinsic energy efficiency could reach to 100% in case of the loss-less delay lines.

Due to this rather cumbersome configuration of the system, this BPC has been considered as of secondary importance even it can achieve better energy efficiency of close to or more than 90% in case of compression factor 4.[5]

5 DELAY LINE DISTRIBUTION SYSTEM (DLDS): A NEW RF POWER DISTRIBUTION METHOD EQUIVALENT TO A PULSE COMPRESSION SYSTEMS

Recently, the new RF power distribution system named DLDS(Delay Line Distribution System) which works as the replacement of an ordinary RF pulse compression system and has the better energy efficiency was proposed by the authors [6][7]. This system is based on the new operational principle different from the existing any other RF pulse compression systems. Like BPC, in this new DLDS, the short pulse trains that are divided into from the long klystron output pulse are led to the different parts of the linac respectively. The most specific point of this new system is that the divided RF pulses are never compiled again like SLED family or BPC. In this new system, the flight pass of the beam itself works as the delay line in the BPC, thus the half of the delay time necessary for the divided short RF pulse trains is given by the beam flight itself. In this new system, the length of the delay lines and consequently their losses can be decreased by about factor 2 compared to that of BPC. The operation principle of this new system DLDS is described in some detail below.

5.1 Basic factor 2 DLDS

In this new scheme, as shown in Fig. 4, the RF power from two klystrons that are independently phase controlled are combined together through the 3-dB coupler. One output port of the 3dB hybrid is connected to the upstream of the linac about one half of the linac operating time apart from the klystron location through the low-loss waveguide, and another port is connected to the structure located close to the klystron position. The first half of the RF pulse which is equal to the sum of the filling time and the bunch train is sent to the upstream of the linac through the delay line shown in the figure. The second part of the RF pulse is fed to the structure close to the klystron without delay. Delay line gives the delay time of Tdelay=L/Vg and the beam flight time between two structures is Tbeam=L/c. If these time delay satisfies next relation neglecting the delay time in the other RF transport system such as 3dB hybrid etc.,

$$T_{delay} + T_{beam} = L/V_g + L/c = t_a$$

where t_a is the pulse length of the linac operation, just the sum of the structure filling time and the duration of the bunch train. It is easily recognized that the timing of the bunch train and the RF pulse is adjusted to accelerate the beam and the beam is accelerated just as the ordinary linac pulses. Thus, The factor 2 DLDS (Delay Line Distribution System) which works equivalently as the factor 2 RF compression system can be constructed. The timing relation of this delay line scheme is illustrated in the “train diagram” shown in Fig. 5 in case of the RF pulse from the klystrons are divide into two consecutive RF bins.

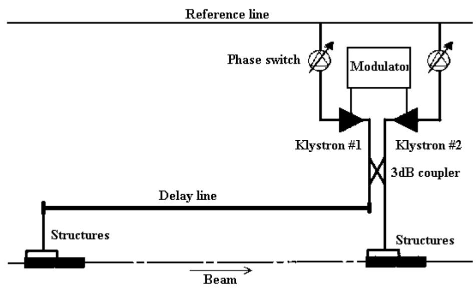


Fig. 4. A schematic diagram of the simplest factor-2 delay line distribution system

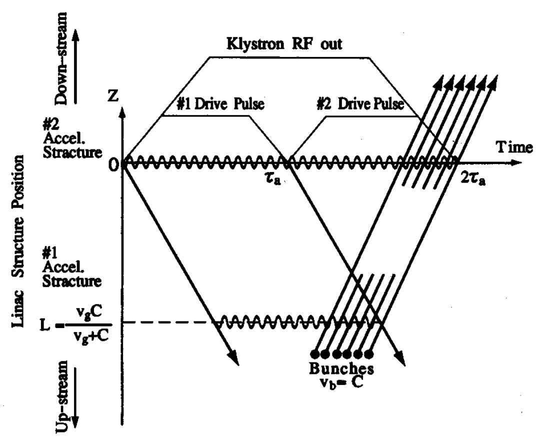


Fig. 5. A train diagram of factor 2 DLDS

In general , this scheme can be extended to the factor 2^n combined pulse height as follows. Each of the 2-klystrons in the factor-2 scheme mentioned in the previous section, can be replaced by the pair of 2-klystrons combined through a 3-dB hybrid coupler, thus this new system also works as factor-2 system, and remaining 2-output ports of the 2-hybrid couplers can be connected to the one more 3-dB hybrid coupler which serves as the additional factor 2 DLDS same as Fig. 4.

This process can lead to the construction of the factor-2^2 DLDS system. It may be easy to understand this procedure illustrated in the Fig. 6. Apparently, the train diagram of this factor factor-2^2 DLDS is easily understood as the extension from the factor 2DLDS case.

It should be noted that in this scheme the time domain compression equivalent factor i.e. klystron pulse length can be chosen from 1 to 2^n times longer than the linac operational RF pulse length. This system is generally noted as factor 2^n/m Delay Line Distribution System(2^n/m DLDS), 2^n represents the number of independent RF sources, and m represents the time domain compression equivalent factor. In this case, the (2^n - m) ports left unconnected to any structure.

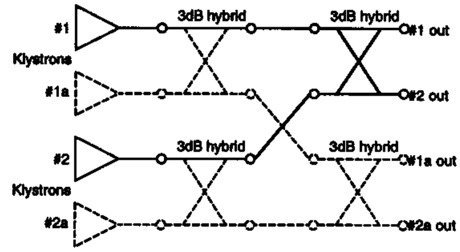


Fig. 6. A factor-4 DLDS built from factor-2 DLDS blocks.

Recently, an interesting application of this DLDS operation principle was proposed for a driving beam system for TBA (Two Beam Accelerator)[12]. Each RF bins in DLDS is replaced by the bunched beams that carries the RF power, and these bunch trains are transported to the counter direction to the accelerated beam like the RF bins in DLDS. The ssame operation principle as DLDS can be applied to the driving beam of TWA. Thus, even in TBA, an RF pulse compression equivalent system can be constructed and this scheme can replace the intense drive beam to the less intense but longer drive beam. It is expected that this new configuration could relax the technological problems on the drive beam compared to an ordinary co-direct drive beam cionfiguration.[12]

5.2 Design of a 4/3 DLDS for the JLC X-band main linacs

As an example of DLDS at X-band linear collider, 4/3 DLDS was designed as the RF pulse compression equivalent system for JLC. Fig. 7 schematically illustrates the 4/3 DLDS. Note that the 4-set of the klystrons and 3 groups of accelerating atructures that are seperated to adjust the time delay. The train diagram and the operational principle of this 4/3 DLDS are the essentially the same as factor 2DLDS, therefore further detailed explanation is unnecessary.

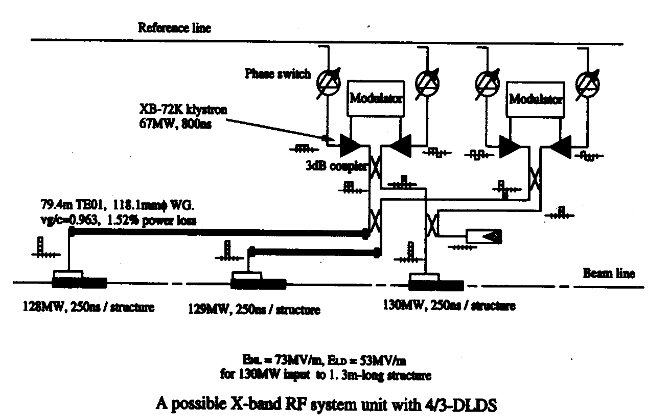


Fig. 7. 4/3 DLDS for JLC

6 MULTI-MODE DLDS

Recently, SLAC group proposed a clever configuration of DLDS which could save the delay line length by the use of multi-mode loading of the lines. This Multi-mode DLDS scheme works as follows. instead of the several delay lines, one delay line is set to have several mode extractor that are inserted on the one delay line to give the delay time as required by the DLDS operation.[11] Each mode extractor is designed as to extract only a specific mode and at the same time to transport the other modes completely. The one end of the delay line where RF sources are located, the mode launcher is attached. Primary RF pulse from the klystron is divided into the short RF bins and each RF bin is converted into the different mode through the mode launcher and lead into the delay line. Thus, each RF bin is extracted, in other words, distributed to the necessary location just as an ordinary DLDS. This new version of DLDS is currently considered as the best candidate for the next linear collider that is under study by joint effort of SLAC/KEK.

This multi-mode DLDS requires several new RF device such as a mode launcher, Intensive R&D plan is now going on at SLAC and KEK aiming the design of 4/4 multi-mode DLDS for their next linear collider.

7 CONCLUSION

The most important advantage of this new DLDS pulse compression equivalent system is firstly the high energy efficiency, as considered in the previous section its intrinsic efficiency could reach 100%. To compare this system efficiency with that of the ordinary SLED2 pulse compression system, , the efficiency of the DLDS is better than that of the SLED2 by about 20%. In comparison between an original DLDS and a muti-mode DLDS, if 4/4 DLDS is intended, a multi-mode DLDS is expected to be less cost due to the saving of delay length by its multi-mode loading of the delay lines. Considering the present status of R&D on the RF pulse compression schemes for an application to X-band linear colliders, following points can be pointed as a brief summary on this subject.

1) At X-band, DLDS especially muti-mode type is considered as the top ranked candidate as an RF pulse compression scheme for linear colliders.
2) DLDS has several advatage to other conventional RF pulse compression systems, howeveer DLDS can be applied only to a long linac such as a linear colilider.
3) traditional RF pulse compression schemes, such as SLED family, will remain as the useful measure for most of electorn linacs especially at S-band.
4) For the realization of the application of DLDS to linear colliders at X-band, technological R&D's such as high power tests, developments of several RF parts and beam operation oriented studies are still needed.
5) The operation principle of DLDS can alsobe applied to TBA drive beam system.

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