A NEW RF PULSE-COMPRESSOR USING MULTI-CELL COUPLED-CAVITY SYSTEM

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Abstract

A new idea to compress the rf-power into a flat pulse is proposed. It uses 3-cell coupled-cavity as an energy storage, which is compact, having a length less than 1 m, and its diameter is 160 mm. To maximize the power gain, the stored energy distribution was optimized by tuning the coupling constants between cells. To obtain a flat pulse, we apply AM-modulation on the input power to the compressor. By combining the output power from two klystrons in a 3-dB hybrid, and rotating the phase into the opposite direction to each other, the phase modulation(PM) is converted to amplitude modulation(AM). A computer simulation predicted that this system can compress the power into a flat pulse with a gain of 3.5 and the nominal efficiency of 70 %.

1. INTRODUCTION

In the future e^+e^- linear collider at 500 GeV to 1 TeV c.m. energy range, in order to achieve high beam energy within a limited site length, the higher peak-power is required to drive the accelerating structures. To obtain the high peak-power while limiting a requirement on the output power to the klystron, we use an rf pulse-compression technique.

For the multi-bunch operation, we need a flat-pulse output from the rf-compressor. For this purpose, the SLED-II was presented by A. Fiebig and C. Schieblich[1] in 1988, then developed at SLAC[2] as the X-band NLC component. The SLED-II stores the energy of input rf into two delay lines, and compress the pulse into a square-pulse by reversing the input rf phase. A unique idea "DLDS" was devised by H. Mizuno[3], in which a delay-time of the rf-power to propagate along a low-loss delay-line is utilized to cancel the traveling time of the electron beams to go down the beam-line. By overlapping two or four traveling-waves in hybrid combiners, we can multiply the rf-power two or four times with sufficient efficiency. This is a candidate to solve the power efficiency problem at the higher frequency bands.

One difficulty to use these schemes at lower frequency bands is the physical length of the delay-line. The required rf-pulse length to fill the disk-loaded accelerating structure becomes longer at lower frequency bands. At the C-band (5.712 GHz) frequency, it becomes 500 nsec including the beam pulse length, which request a delay line of 75 m long. This is too long and it would cost much.

To solve this problem, we propose a new method which uses (1) a coupled-cavity system as an energy storage in the pulse-compressor and (2) apply AM-modulation on the input rf-power to obtain a flat pulse.

2. COUPLED-CAVITY PULSE COMPRESSOR

Here we consider a coupled-cavity system with uniform impedance (each cavity has the same Q-factor, the resonance frequency and the cell-to-cell coupling constant). We consider the $\pi/2$-mode (the phase advance per cell is $\pi/2$). Since $\pi/2$-mode stays in middle of the passband, the rf phase does not deviate from zero during the transient time. To avoid the field cancellation at the 1st cell, we can use only odd number for the total number of the cells, that is, N = 1, 3, 5, 7,..

In case of the uniform coupled-cavity pulse compressor, we can estimate the performance using the SLED II theory. We define a compression ratio,

$$C_r = \frac{\text{Klystron pulse duration}}{\text{Compressed pulse duration}} = \frac{T_{in}}{T_{out}} \qquad (1)$$

The compressed pulse duration is equal to the round-trip propagation time of rf-pulse in the coupled-cavity chain, which is given by

$$T_{out} = \frac{2(2N-1)}{k\omega} \qquad (2)$$

from which we can determine the coupling constant k.

The one-way attenuation constant is given by

$$\tau = N / kQ. \qquad (3)$$

The input voltage-reflection coefficient is

$$s = \frac{k - 2/Q_{L1}}{k + 2/Q_{L1}}. \qquad (4)$$

Where Q_{L1} is the loaded-Q of the 1st cavity. According to the SLED-II theory[4], there is an optimum value of s to maximize the power gain (loss less case),

$$s_{opt} \approx 1/\left[C_r - 1/2\right]^{-1/(C_r - 3/2)} \qquad (5)$$

Using eqs.(4) and (5), we can determine Q_{L1} .

In order to study a pulse response of the coupled-cavity system, a computer simulation code has been made, which solves an equivalent circuit model in time-domain[5]. Figure 1 shows a simulation result on a pulse-compressor using 3-cell coupled-cavity, where the input rf-phase was flipped as the same manner in SLED-II. The 1st cavity voltage shows a step-by-step build-up pattern. Each step corresponds to the round-trip rf propagation along the coupled-cavity chain. When the rf-phase flips, the compressor emits a sharp spike at the beginning followed by a swing. The average power gain is close to 3.5, which is the expected value by the SLED II theory.

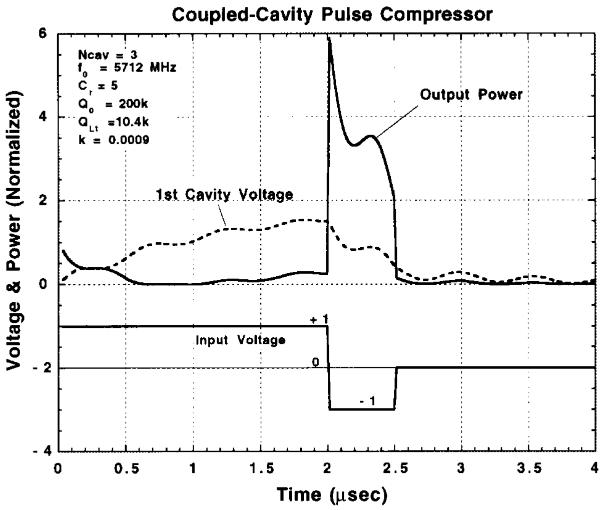

Fig. 1. Three-cell coupled-cavity compressor with a simple phase-flip.

3. FLAT PULSE GENERATION BY PM-AM MODULATION

Figure 2 shows the pulse compression system for a C-band linear collider[6]. To make a flat pulse, we apply AM modulation on the input rf power of the pulse compressor. However, it is not a good idea to directly modulate the amplitude of the input rf power to the klystron, because the klystron has a non-linear input-output characteristic, and the power gain is quite sensitive to any change in the beam parameter. To stably operate a klystron, we usually use a saturation mode. In our system, we keep the input rf power at a constant level, but control the rf-phase and combine the rf-power from two klystrons by a 3-dB hybrid combiner. By rotating the phase into the opposite direction to each other, the phase modulation (PM) is converted to the amplitude modulation (AM). The vector sum goes to the pulse compressor, and the vector difference (quadrature component) goes to a dummy load attached to the hybrid.

Figure 3 shows the simulated output waveform. The power gain of 3.5 and the nominal efficiency of 70 % are achieved. To obtain the high Q-factor of 200,000 at C-band, we use a low loss mode TE0,1,15 in a pillbox cavity having a diameter of 157 mm, a length of 400 mm. We use three pillbox cavities in a series. Since the middle cavity stores less energy, we can reduce the length of the middle cavity. The total length of the cavity is about 1 m. The detail of the cavity is under design.

In the multi-bunch beam operation, the accelerating gradient inside the structure decays exponentially due to the beam loading effect. To compensate this, we slowly increase the power during filling-time. When the wave front reaches to the end of the structure, we start the beam pulse and keep the input power at the maximum level. In Fig. 3, the input rf-power was controlled to follow a programmed waveform, which starts from 0.3 normalized power, and linearly goes up to the maximum power of 3.5 during the filling time of 280 nsec, then stays constant at the maximum.

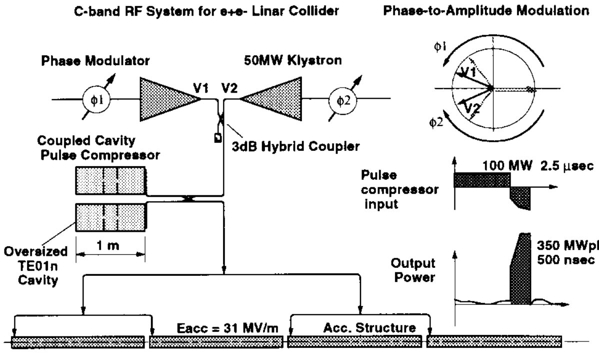

Fig. 2 Application to the C-band rf-system for the e^+e^- linear collider.

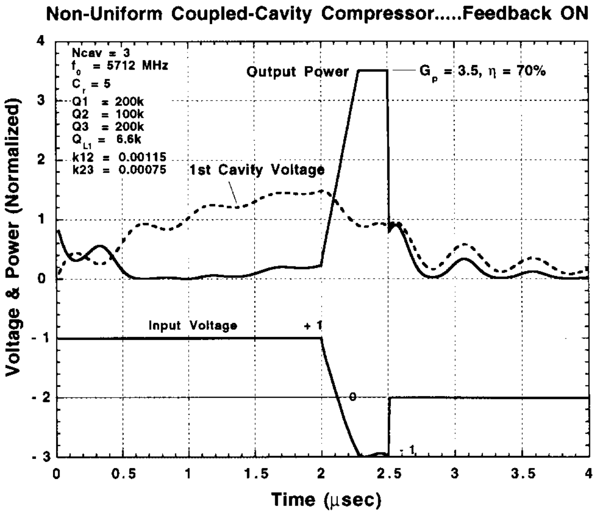

Fig. 3 Non-uniform coupled-cavity compressor with PM-AM-modulation.

Figure 4 shows a variation of the power gain as a function of the total number of the cavity. In case of the uniform coupled-cavity system, the power gain increases as increasing the number of the cavity, and it slowly approaches to a maximum value of 3.5, which is the optimum power gain of an ideal SLED II at τ = 0.02. Therefore, there is no good reason to use large number of the cavities.

The left-most point at the cavity number of 1 corresponds to the conventional SLED system. It is noticeable that by using PM-AM modulation scheme, even a conventional SLED can generate a flat pulse with sufficient power gain as high as 3.1. This feature will be useful to apply the scheme to existing linacs implemented with the SLED system.

The solid circles in the figure represent the non-uniform coupled-cavity case. Since the beam loading compensation needs less power at the beginning of the pulse, it is better to store less energy in the first cell, and larger energy in the 3rd cell. The middle cell acts as like a transformer, which can be used to step-up or down the field intensity in the 1st and 3rd cells. The stored energy ratio is proportional to a square of the coupling constant ratio, in Fig. 3 case it is $U_3 / U_1 = (k_{12} / k_{23})^2 = 2.4$. As seen in Fig. 4, using non-uniform coupled-cavity system, three cell is enough to get a sufficient power gain as high as 3.5.

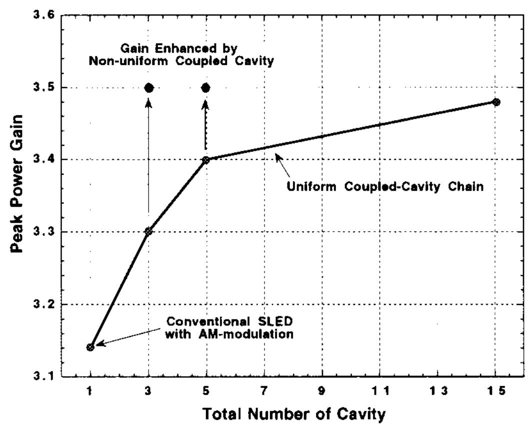

Fig. 4 Gain vs. number of the cavity.

4. FEEDBACK CONTROL FOR BEAM LOADING COMPENSATION

One problem to use the PM-AM modulation scheme in a practical rf-system is how to generate the modulation pattern. We can analytically solve the pulse response of the non-uniform coupled-cavity system for a simple input waveform case[7], which is very useful to optimize the parameters. However, the actual waveform for the energy compensation in the accelerating structure takes complicated form. Additionally, the actual beam current is not a simple and perfect square waveform. As a result, the modulation pattern for the klystron input signal becomes quite complicated form, thus it would be difficult to generate the modulation pattern from the theoretical equations.

To solve this problem, we use a practical method, which use feedback-loops for: (a) a beam-to-rf phase adjustment, (b) an energy gain adjustment, and (c) a water-temperature control. The rf-vector-detector rectifies the rf signal using phase reference from the rf drive line. The detected waveforms are sampled and digitized in the in-phase and quadrature-phase components. They are stored in fast memories in each pulse. The rf waveforms are also monitored at the klystron output and the pulse-compressor output. The microprocessor computes the error in the beam-phase voltage, and corrects the phase-modulation pattern in order to track the target waveform (target energy gain), which is directed from the main control computer. The quadrature-phase voltage gives the phase error, from which the phase-offset in the rf drive line is corrected and the cooling-water temperature is controlled.

Since the energy gain is always monitored and controlled by a microprocessor, a slow variation of the klystron output-power, or a fast but repeatable ripple on the klystron modulator output, will be also compensated. As shown in the schematic, since all feedback loops are closed in one unit of the rf-system, and isolated from the other units, beam operation becomes quite simple and easy. Every unit runs automatically to give a constant energy gain to the beam. In the case of a failure in one unit, the main computer directs other units located in the same sector to increase the energy gain. They follow the new target value within 10 pulses or less, that is, within 0.1 second.

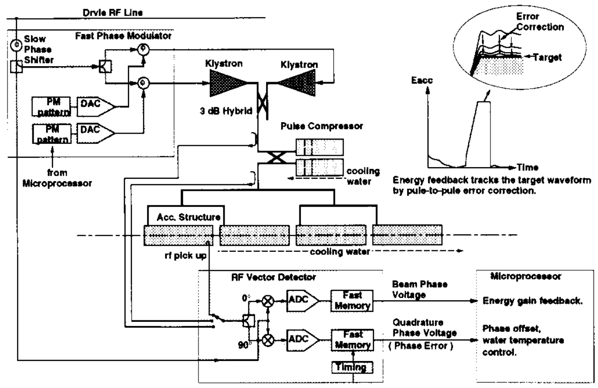

Fig. 5 Feedback System

REFERENCES

[1] A. Fiebig and C. Schlieblich, "A Radiofrequency Pulse Compressor for Square Output Pluses", presented at the European Particle Accelerator Conference, Rome, Italy, June 1988.

[2] P.B.Willson, Z.D.Farkas, and R.D.Ruth, "SLED II: A New Method of RF Pulse Compression", presented at the Linear Accelerator Conference, Albuquerque, New Mexico, September 1990, SLAC-PUB-5330.

[3] H. Mizuno and Y.Otake, "A New RF Power Distribution System for X-band Linac Equivalent to an RF Pulse Compression Scheme of Factor 2^n", Proc. 17th Int. Linac Conference(LINAC94), Tsukuba Japan, August 21-26, 1994, KEK Preprint 94-112.

[4] P.B.Wilson *et al.*, "Progress at SLAC on High-Power RF Pulse Compression", SLAC-PUB-5866.

[5] This is a similar code as that made by C.D.Nantista, "Radio-Frequency Pulse Compression for Linear Accelerators", SLAC-R-95-455.

[6] T. Shintake *et al.*, "C-band RF Main Linac System for e^+e^- Linear Collider at 500 GeV to 1 TeV C.M. Energy", presented at this conference.

[7] K. Akai *et al.*, "Tuning Control and Transient Response of the ARES for KEKB", presented at this conference.