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A LOOK AT ENERGY COMPRESSION AS AN ASSIST
FOR HIGH POWER RF PRODUCTION

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A LOOK AT ENERGY COMPRESSION AS AN ASSIST
FOR HIGH POWER RF PRODUCTION*

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ABSTRACT

The desire to construct electron linacs of higher and higher energies, coupled with the realities of available funding and real estate, has forced machine designers to reassess the limitations in both accelerator gradient (MeV/m) and energy.

The gradients achieved in current radio-frequency (RF) linacs are sometimes set by electrical breakdown in the accelerating structure, but are in most cases determined by the RF power level available to drive the linac.

In this paper we will not discuss RF power sources in general, but rather take a brief look at several energy compression schemes which might be of service in helping to make better use of the sources we employ. We will, however, diverge for a bit and discuss what the RF power requirements are.

INTRODUCTION

Energy compression is applicable whenever the duty factor required is less than unity. The concept is pictorially illustrated in Fig. 1a. It simply involves the storage of energy supplied by a lower power source for some length of time and then delivering this energy at a high power level and for a shorter time to a load. While this technique of power multiplication can be applied to energy in various forms, it is the compression of microwave energy, as illustrated in Fig. 1b, with which we will primarily concern ourselves here.

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EDB

Figure 1a. Basic concept of energy compression.

Figure 1b. Basic concept of microwave energy compression.

It is worthwhile to take a moment to review the power requirements for high energy electron linacs. The RF power requirement, P_0 , for a structure of length L , with average accelerating gradient E_a , and unloaded energy gain V_0 can be written in the form

$$P_{RF} = \frac{V_0}{\bar{r} f(\tau)} = \frac{\bar{E}_a L}{\bar{r} f(\tau)} \quad (1)$$

Here $\bar{r}$ is the average shunt impedance per unit length determined as

$$\bar{r} \equiv \frac{\bar{E}_a^2 Q}{2\pi\nu \bar{\epsilon}} \quad (2)$$

with Q being the structure Q , ν the drive frequency, and $\bar{\epsilon}$ the average stored energy per unit length. For constant impedance (CZ) and constant gradient (CG) structures, $f(\tau)$ is given by

$$CZ : f(\tau) = \left(\frac{2}{\tau}\right) (1-e^{-\tau})^2 \quad (3a)$$

$$CG : f(\tau) = (1-e^{-2\tau}) \quad (3b)$$

where τ , the attenuation parameter, is given by

$$\tau = \frac{2\pi\nu L}{2VgQ} = \frac{2\pi\nu}{Q} T_F \quad (4)$$

with Vg being the structure group velocity, and T_F the structure filling time.

It is useful at this point to define the loss parameter K as

$$K \equiv \frac{\bar{E}_a^2}{4 \bar{\epsilon}} = \frac{2\pi\nu}{4} \left(\frac{\bar{r}}{Q}\right) \sim (2\pi\nu)^2 \quad (5)$$

$$= \frac{\bar{E}_a^2 L}{4 P_{RF} \cdot T_F \eta_s} \quad ,$$

where η_s is the structure efficiency given by

$$CZ : \eta_s = (1-e^{-\tau})^2 / 2 \quad (6)$$

$$CG : \eta_s = (1-e^{-2\tau}) / 2 \quad .$$

We can now write the power requirements as

$$P_{RF} = \frac{V_0 \bar{E}_a}{2K \eta_s} \sim \frac{V_0 \bar{E}_a}{2(2\pi\nu)^2 \eta_s} \quad (7)$$

For a given energy, it is clear that a low gradient and a high value for the structure parameter K are desirable. Since $K \sim (2\pi v)^2$, this implies that a high operating frequency is also desirable. However, a low gradient uses up real estate and the frequency will usually be limited by the beam diameter. There must also be sufficient energy stored per unit energy gain to handle the energy reduction to do beam loading placing an additional limitation on K and, therefore, v .

The maximum gradient will also be limited by breakdown initiated by electric fields at the surface of the structure. This breakdown field may be a function of frequency, pulse length, and vacuum conditions. It may also depend on the detailed physical and chemical properties of the metal surface. If $\bar{E}_s$ is the peak electric field anywhere on the surface of a structure and $\bar{E}_a$ is the average gradient in the structure, the ratio $\bar{E}_s/\bar{E}_a$ will be important in determining the maximum achievable gradient. For the SLAC disk-loaded structure, $\bar{E}_s/\bar{E}_a = 2.1$. The SLAC structure has been tested in a traveling-wave resonant ring to $\bar{E}_a = 40$ MV/m without breakdown. The maximum surface field was therefore about 85 MV/m at an effective pulse length on the order of $1 \mu s$ at 2856 MHz. The value of $\bar{E}_s/\bar{E}_a$ can be lowered to about 1.6 in a disk-loaded structure by proper disk shaping, and even lower values of this ratio have been reported. It is also generally expected that breakdown fields should increase with increasing frequency and decreasing pulse length. A gradient of 100 MV/m, therefore, does not seem unreasonable for very short pulse lengths and at frequencies somewhat higher than 3000 MHz, assuming also that careful attention is paid to the details of structure geometry and surface conditions.

Presuming that a gradient of 100 MV/m is feasible, Eq. (7) can now be applied using the structure parameters given in Table I to compute the average RF power requirement of a 300×300 GeV collider with a length of 3×3 km and a repetition rate of 210 Hz. The result is given in Table II. Also listed is the peak power $\hat{P}_0$ and the energy per pulse, $W_0 = w_0 T_f$, required from each RF source, assuming there are 1000 sources spaced 6 m apart. The expressions listed above are used to compute n_s , w_0 , and $\hat{P}_0$ from the structure parameters, and the pulse length T_p is taken to be equal to the filling time, T_f .

For reference, some other important parameters of these structures are given in Table I, while sketches of the accelerating structures are provided in Fig. 2a and 2b.

ENERGY COMPRESSION

The use of energy compression as a means of power multiplication is not a new idea. Energy compression has been employed either directly for multiplication of the RF output power from a source or for DC pulse compression in the modulators driving these sources. Here we will primarily address the former, but a brief description of the latter will be included.

TABLE I. Comparison of accelerating structures.

	r (M Ω /m)	k_1 (V/pC/m)	Q	V_g/c	L (m)	T_f (μ S)	τ
2856 MHz							
Disk-loaded ($a = 1.6$ cm)	56	19	13,300	0.012	3	0.83	0.57
Disk-loaded ($a = 1.50$ cm)	46	16	13,000	0.035	6	0.57	0.40
Disk and washer ($a = 1.16$ cm)	85	10	40,000				
Jungle gym ($\pi/2$) (1/2 diag. = 0.84 cm)	51	25	9,000	0.22	6	0.09	0.09
Jungle gym ($\pi/3$) (1/2 diag. = 0.90 cm)	60	30	9,000	0.10	6	0.20	0.20
4040 MHz							
Jungle gym ($\pi/2$)	61	50	7,500	0.22	6	0.09	0.15
Jungle gym ($\pi/3$)	71	60	7,500	0.10	6	0.20	0.35
5712 MHz							
Jungle gym ($\pi/2$)	72	100	6,500	0.22	6	0.09	0.26
Jungle gym ($\pi/3$)	85	120	6,500	0.10	6	0.20	0.57

TABLE II. RF Power requirements for a 3 x 3 km collider
with $E_a = 1000$ MV/m.

	T_p (μ S)	W_o (J)	η_s	P_o (MW)	$\bar{P}_{rf}$ (MW)
2856 MHz					
Disk-loaded ($a = 1.16$ cm)	0.83	1320	0.58	1600	275
Disk loaded ($a = 1.50$ cm)	0.57	1340	0.68	2350	280
Jungle gym ($\pi/2$)	0.09	650	0.92	7000	135
Jungle gym ($\pi/3$)	0.20	620	0.82	3100	130
4040 MHz					
Jungle gym ($\pi/2$)	0.09	350	0.86	3600	75
Jungle gym ($\pi/3$)	0.20	350	0.71	1750	75
5712 MHz					
Jungle gym ($\pi/2$)	0.09	190	0.78	2000	40
Jungle gym ($\pi/3$)	0.20	210	0.58	1050	45

Fig. 2a. The jungle gym bar-loaded accelerating structure.

Fig. 2b. Diagram showing the important features of a five-cell π -mode structure with magnetic field coupling.

There exist three known forms of RF energy compression. We will designate them by the titles SLED (SLAC Energy Development), SES (Switched Energy Storage), and PS (Pulse Slicing).

SLED

The best description of the technique which has been employed at SLAC is provided by the following excerpt from the paper¹ written by the inventors:

"Since the accelerator energy is determined by the peak RF input power, and since many experiments are not now limited by average beam power, it was felt that some method for enhancing peak RF power at the expense of RF pulse width might be the answer for increasing SLAC's energy without at the same time increasing the average input power consumption. Standard pulse compression schemes were considered and rejected. One approach that seemed to hold promise, however, came as a result of our experience at SLAC with superconducting cavities. In the course of making measurements on superconducting cavities, it is a common observation that the power radiated from a cavity that is heavily overcoupled approaches four times the incident generator power immediately after the generator has been

switched off. Normally this radiated power travels as a reverse wave back toward the generator. There are, however, several microwave networks which can direct this radiated power into an external load; for instance, two identical cavities attached to a 3-db coupler, as shown in Fig. 3. Using overcoupled cavities, we have in principle a power multiplier which can enhance peak power by up to a factor of four. This is accomplished, of course, at the expense of pulse width, since the radiated power decays away with a time constant given by the cavity filling time. A further development which enhances the viability of the SLED concept is the observation that if the RF source is reversed in phase rather than simply being switched off, the peak power can be increased by up to a factor of nine. How this comes about is described qualitatively in the following section.

QUALITATIVE DESCRIPTION OF SLED

In the case of the present SLAC accelerator, klystrons provide a $2.5 \mu\text{s}$ RF output pulse which travels through a waveguide directly into the accelerating sections as indicated schematically at the top of Fig. 4. In the case of SLED, the high-power waveguide system is broken near the klystron and the power divider/dual-cavity assembly shown schematically in Fig. 3 is inserted. The cavities are assumed to be identical and tuned to resonance. After the RF pulse is turned on, the fields in the cavities build up and a wave of increasing amplitude is radiated from the coupling apertures of each cavity. The two emitted waves combine so as to add at the accelerator port of the 3-db coupler, while they cancel at the klystron port. In addition to the wave emitted from the cavities, a wave travels directly from the klystron to the accelerator. This direct wave, which is just the wave that would appear at the accelerator if both cavities were detuned, is opposite in phase to the combined emitted waves. If the cavities are overcoupled, the emitted wave grows in time to an amplitude which is larger than the direct wave. The net field at the input to the accelerator, which is the sum of the direct and emitted waves, then goes through a phase reversal as shown at the right-center of Fig. 4. One accelerator filling time ($0.8 \mu\text{s}$) before the end of the RF pulse, the π phase shifter reverses the phase of the output wave from the klystron as shown by the waveform at the bottom of Fig. 4. Immediately after this phase reversal, the emitted and directed waves add in phase at the accelerator, since the emitted wave (which is proportional to the stored fields in the cavities) cannot change instantaneously. Therefore, when the klystron phase is reversed, the field at the input to the accelerator increases by two units (assigning one unit to the direct wave, E_k), since at any instant the load wave is the sum of the direct and emitted waves. Following the phase reversal, the fields in the

cavities (and hence the emitted wave also) decrease rapidly as the cavities try to charge up to a new field level of opposite phase. The resultant wave at the accelerator decreases also, as is shown qualitatively in Fig. 4. At the end of the RF pulse, the direct wave goes to zero and the emitted wave only is present at the accelerator. It then decays to zero with a time constant given by the cavity filling time."

Fig. 3. Schematic of the SLED microwave network.

Fig. 4. A comparison of the present SLAC and SLED RF systems.

The energy compression supplied by the existing installation at SLAC is accomplished with an efficiency of 65 percent.

The reader is referred to Ref. 1 for a detailed description of the SLED concept, and for a derivation of the energy gain enhancement ratio R in the case of a constant gradient structure. The enhancement ratio is defined as the energy gain with SLED divided by the energy gain that would be obtained with the klystron power flowing directly into the accelerating structure.

To illustrate the enhancement ratios that can be achieved with SLED, we give without detailed derivation the expression for R for the case of a constant impedance structure:

$$R(\text{SLED}) = \frac{1 - \beta}{1 + \beta} + \frac{2\beta}{1 + \beta} (2 - e^{-\mu'}) \frac{e^{-\nu'} - e^{-\tau}}{\tau - \nu'} \frac{\tau}{1 - e^{-\tau}}$$

$$\mu' \equiv \frac{T_p - T_s}{T_0} (1 + \beta) \quad (8)$$

$$\nu' \equiv \frac{T_s}{T_0} (1 + \beta)$$

Here τ is the attenuation parameter for the accelerating structure, β is the coupling coefficient for the storage cavities, $T_0 = 2Q_0/\omega$ is the unloaded filling time for the cavities, T_p is the total klystron pulse length and T_s is the filling time of the structure. If τ is not too large, Eq. (8) will also be a good approximation for a constant gradient structure. We see that the maximum enhancement ratio that can be attained with SLED is $R = 3$ for $T_0 \gg \beta T_s$, $T_p \gg T_0$, and $\beta \gg 1$. The efficiency of the compression is given by

$$\eta = \frac{R^2 T_s}{T_p} = R^2 \frac{\nu'}{\mu' + \nu'} \quad (9a)$$

ENERGY STORAGE CAVITIES WITH SWITCHING

Another form of pulse compression with the potential capability of yielding very high peak pulsed RF power is energy storage with active switching. As in SLED, energy from a klystron pulse is stored over a relatively long time in a high- Q resonator, and then switched out rapidly in about a filling time of the structure. In the case of SLED, this switching is accomplished passively by making a 180° phase reversal in the input drive to the klystron. In the case of switched energy storage (SES), the switching is accomplished by making a large change in the coupling coefficient of the output port of the storage cavity by means of an active

switching element. One possible form for an SES device is shown in Fig. 5. The length of the waveguide stub on the left is chosen to be about $\lambda_g/2$ so that before the switch is fired there is a voltage null at the side branch leading to the accelerator. Thus, in this state there is very little coupling between the cavity and the accelerator. When the switch is fired, the shorting plane at the end of the stub is effectively moved by $\lambda_g/4$, which now produces a heavy coupling between the cavity and the accelerating structure.

Fig. 5. RF pulse compressing using an energy storage cavity with switching.

Figure 6 shows a schematic illustration of the basic idea. A storage cavity operating in a TE mode is coupled to an H-plane T that acts as the interference switch. In the storage state, shown in Fig. 6a, a standing wave is produced by reflections off a short in one arm of the T. Ideally, a null appears at the output port and no power is fed to the load. In practice, a perfect null is not achieved due to losses in the walls of the T, but sufficient isolation can be achieved so that the storage time τ_s is determined by the cavity Q. In this storage state, the cavity is filled with energy from a microwave source.

In the dump state, illustrated in Fig. 6b, a plasma is created approximately $\lambda_g/4$ from the shorted end of the T. This couples the microwaves directly to the output load. Note that the output pulse is phase-locked to the drive. Various types of plasma discharge mechanisms have been studied: the spontaneous microwave breakdown of a gas, a high-voltage plasma discharge, a vacuum arc discharge, and an electron beam. When a well-developed plasma is formed, the intrinsic switch losses are negligible. If τ_D is the decay time of the energy stored in the cavity in this dump state, the power gain $G = \tau_s/\tau_D$. With a superconducting system, a gain of 3×10^4 has been observed and 10^5 should be obtainable. In a superconducting system, we have switched modest power levels of order tens of kilowatts. At room temperature, we have obtained⁵ gains of 50 and switched power levels of order hundreds of megawatts.

There are, however, questions associated with mode mixing in the high-Q, overmoded storage resonators which must be strongly coupled to the switch port in order to achieve the desired dump times. In addition, because needed power levels are 10 times higher than presently achieved, special requirements are placed on the switch plasma. In this paper, we propose a solution to the overmoded resonator problem based on our past experience with fully opened output ports⁵ and with split spherical cavities.⁷

Fig. 6. Schematic of microwave cavity and H-Plane T showing the electric field envelope in (a) the storage state, and (b) the dump state.

REQUIREMENTS

In practice, the storage time τ_s and the dump time τ_d are set by matching them so as to achieve optimum energy transfer from the microwave source to the accelerator. For our present estimates, we simply take τ_s equal to the pulse length T of the microwave source. Thus, for a $4\text{-}\mu\text{s}$ pulse one would want a ringing time τ_s in the storage state of order $4\text{ }\mu\text{s}$. One would achieve this by overcoupling a cavity having a higher internal Q so as to optimize the energy transfer.

The dump time τ_d depends on the volume V of the cavity, the total area A of the output ports, and the output-guide group velocity v_g . It also depends upon the geometry of the cavity mode and the positions of the port. An estimate of τ_d is

$$\tau_d \approx \frac{2V}{v_g A} \left| \frac{\frac{4}{\pi} \frac{B_w}{B_0}}{\frac{B_w}{B_0}} \right|^2, \quad (9b)$$

where B_w/B_0 is the ratio of the B field at the port to the maximum B field in the cavity. Here the factor 2 enters because of the standing-wave nature of the field. For example, a spherical cavity of radius 20 cm with 4 output ports each of area 15 cm^2 gives τ_d of order several tenths of a microsecond. For our

estimates, we assume that the accelerator section requires a pulse $0.4 \mu\text{s}$ in length and take $\tau_D \approx 0.4 \mu\text{s}$.^{*} Combining this with a $\tau_S = 4 \mu\text{s}$ would give a power gain of 10.

If the klystron supplies a 30-MW pulse, the resonator must store of order 100 J. Based on our x-band experiments with spherical cavities, we propose that a spherical resonator 20 cm in radius operating in the TE_{202} mode at about 3 GHz be used to store the energy. The stored energy density near the cavity wall would be of order 10^3 J/m^3 , similar to stored energy densities obtained previously in our x-band experiments. The major advantage of a spherical resonator, besides its mechanical properties, is its large filling factor. In addition, by splitting the cavity along its equator, the TM modes can be separated from the desired TE mode.

The calculated Q for the TE_{202} mode of a spherical copper resonator 20 cm in radius and operating near 3 GHz is such that storage times τ_S of order $10 \mu\text{s}$ should be obtainable. As previously discussed, the resonator will be overcoupled** to the klystron so that the loaded Q will correspond to a value of τ_S that matches the pulse length of the klystron (e.g., $\tau_S \approx 4 \mu\text{s}$), driving the cavity in such a way that maximum energy is ultimately transferred to the linac when the cavity is dumped. For this structure, the minimum τ_D from Eq. (9b) is of order several tenths of a microsecond; a $\tau_D \approx 0.4 \mu\text{s}$ should therefore be obtainable.

To achieve this rapid dump, the ports between the resonator and the switch must be strongly coupled. This raises the question of possible mode mixing produced by the perturbation of the port on the closely spaced modes of the cavity resonator. In x-band experiments on cylindrical cavities, we investigated the effect of increasing the cavity-switch coupling by using larger coupling holes. A natural limiting case was obtained by having the port open to the full dimensions of the wavelength.⁵ In practice, we found this worked extremely well; mode-mixing problems were minimal. Physically, this can be understood by realizing that, in the absence of a plasma, the short on the end of the switch section maps over the port opening. The port then appears closed from the point of view of the cavity modes.

We have successfully switched x-bands overmoded spherical cavities at low powers. However, at the proposed energy density of 10^3 J/m^3 , the electric fields are of order 10^7 V/m . Such high fields impose stringent requirements on the plasma switch. In our opinion, this remains the dominant technical problem.

* Note that if the optimum pulse length for the accelerator were less than this, say $0.1 \mu\text{s}$, one would have to consider using either a smaller cavity, a larger port area, or multiple ports.

** For a loss-less cavity, the optimum $\tau_S \approx 0.8T$, where T is the pulse length of the klystron and where approximately 80% of the energy is transferred.

A LOW-PRESSURE-DISCHARGE MICROWAVE SWITCH

We are investigating a switching mechanism based on a low-pressure discharge with the mean free paths of the electrons comparable with the dimensions of the switch. Here, unlike the vacuum arc, the switching mechanism depends strongly on the space-charge neutralization produced in the rarefied gas enclosed in the waveguide. This neutralization allows the discharge to pinch tightly, forming a dense plasma filament with a very small RF penetration depth. The insertion loss I of the switch is strongly dependent on the electron charge density of the electrons.

Successful functioning of the present switch depends largely upon the effects of the plasma, incident microwave radiation, and in the present development these effects have been analyzed mathematically, as well as, experimentally. In the mathematical analysis, electron beam is considered equivalent to a rod of dielectric constant given by

$$\epsilon(\omega) = \epsilon_0 \left(1 - \frac{\omega_p^2}{\omega^2} \right) \quad , \quad (9c)$$

with

$$\omega_p^2 = \frac{4\pi N e^2}{m} \quad , \quad (9d)$$

where N is the electron density.

An equivalent circuit for a waveguide containing the centered electron beam extending parallel to the E-plane is provided in Fig. 7. In this equivalent circuit the relationships are as follows:

$$\frac{X_a}{Z_0} - \frac{X_b}{2Z_0} =$$

$$\frac{\alpha}{2\lambda_g} \frac{J_0(\beta)}{J_0(\alpha)} \left[\frac{1}{\beta J_0(\alpha) J_1(\beta) - \alpha J_0(\beta) J_1(\alpha)} - y + \frac{\alpha^2}{4} \right]$$

Fig. 7. Equivalent circuit of a plasma rod in a waveguide.

and

$$\frac{x_b}{z_0} = \frac{\frac{2\alpha}{\lambda_g} \left(\frac{\pi D}{\alpha}\right)^2}{\alpha^2 \frac{J_1(\beta)}{J_1(\alpha)} - \frac{1}{\alpha J_0(\alpha) J_1(\beta) - \beta J_0(\beta) J_1(\alpha)}} - 2 \quad (9e)$$

with

$$\alpha = \frac{\pi D}{\lambda}, \quad \beta = \sqrt{\epsilon} \frac{\pi D}{\lambda},$$

$$y = \ln \left(\frac{4\alpha}{\pi D} \right) - 2 + 2 \sum_{n=3,5}^{\infty} \left(\frac{1}{n^2 - \left(\frac{2\alpha}{\lambda} \right)^2} - \frac{1}{n} \right).$$

In the above, D is the diameter of the electron beam, J_α is the width of the guide, and J_0 and J_1 are Bessel functions of zero and first order respectively.

The calculated insertion loss of an x-band switch as a function of electron beam density, N , and diameter D in cm shown in Fig. 8. An insertion loss of 0.5 dB at x-band and 3 dB at s-band has been experimentally obtained.

These experiments also indicate the power gain achieved by the storing and releasing function of the electron beam switch. Thus, as will be recognized, a microwave resonator driven by a low power source for a period determined by its decay time produces an output pulse upon switch closure at a power level given by:

$$P_{out} = P_{in} \frac{T_{store}}{T_{release}} (1 - \epsilon), \quad (9f)$$

where ϵ = fraction of power absorbed in the plasma and $T_{store} = Q_{cavity}/\omega$.

The results of the calculations of I versus charge density for plasmas with different diameters are shown in Fig. 8.

For intense fields of interest here, the plasma must have positional stability. Inertial stabilization can be provided by the positive ions and, in addition, by a dc magnetic field applied across the gap. A switch of this type without the external magnetic field was used at low power in an x-band experiment on frequency compression.²⁻⁶

Fig. 8. Insertion loss $I = 10 \log_{10} (1 - |I|^2)$, where $|I|$ is the reflection coefficient, vs electron density for plasmas of different diameters D (cm).

There a low pressure of about 100 mm of Hg was continually present in the cavity switch.

To localize the region of the breakdown in the high-field problem, we must reduce the pressure in the cavity well below that in the switch. By pumping on H-plane slots cut in the side of the waveguide, it is possible to maintain a pressure gradient between the switch region and the main cavity and accelerator. However, the accelerator vacuum would be 10^{-7} to 10^{-8} mm of Hg and an excessively large pump would be required to maintain steady state operation.

Related work done by one of our colleagues (E. J. Lauer) suggests a solution to this problem. By using a fast valve, this pressure gradient can be established a fraction of a millisecond before the cavity is charged and dumped, and then discontinued immediately afterward. By attaching a large reservoir to the pump, a very fast impulse pumping speed can be achieved. The volume of the reservoir should be selected so that the gas decay time with the valve closed is approximately equal to the time between pulses (e.g., about 5 μ s at 180 pps). A valve can be constructed by dumping the charge in a low-inductance capacitor into a solenoid in which a low-inertia needle-valve plunger is enclosed. Typical turn-on-off times already obtained are of order 0.1 msec. With gas present in the switch region, a trigger pulse will initiate a space-charge-limited current at the RF voltage across the gap and the neutralization factor will rise, resulting in ever-increasing currents.

In Lauer's experiment (which will soon be outfitted with a 10 kG axial magnetic field, but which at present is functioning with an axial field of only a few hundred gauss) it has been visually noted that the arc pinches down to less than 1 mm in diameter. The current rise was of order 10^{12} A/sec with a 1.5 cm anode cathode spacing and a 150-kV potential. At the peak current of 2×10^4 A, we estimate a plasma density $\rho \approx 5 \times 10^{14}$ electrons/cm³. Recovery times of order 100 μ s were observed. It should be remembered that this behavior was exhibited by a dc arc; extrapolating to an RF discharge introduces some uncertainty.

Figure 9 presents a sketch of a proposed microwave switch based on these ideas. The trigger electrodes are recessed into the upper cavity wall in order to minimize RF leakage through the E-field coupling. The outer trigger electrode is driven by a negative 30 kV pulse supplied by a hydrogen thyratron. Until the discharge is fully developed, the pulse should voltage double to 60 kV at the open end. The inner electrode is resistively coupled to ground. The gap between the inner electrode and the outer trigger electrode is adjusted to be about 0.02 cm in the transverse magnetic direction. The trigger plasma acts as a source of electrons which are accelerated through the region free of RF fields by the 60 kV dc potential of the outer trigger electrode.

The electrons accelerated into the waveguide during half the RF cycle will be further accelerated by the RF fields and will undergo multiple ionizing collisions with neutral atoms as they

spiral around the magnetic-field lines and change directions in the alternating RF fields. When the RF fields decay, the plasma will recombine on the walls in approximately 100 μ s and the cavity will once again be configured for charging.

It is useful to consider the efficiency of SES pulse compression in two steps: first, the efficiency η_c for the transfer of energy from the klystron pulse to energy stored in the cavity, and second, the efficiency η_s for the transfer of energy from the cavity to effective energy stored in the accelerating structure.

In terms of the energy stored in the cavity W_c , the energy in the klystron pulse W_k , the effective structure stored energy W_s , the structure parameter k_1 , and the average accelerating gradient $\bar{E}_a$ in an accelerating structure of length L , these efficiencies are:

$$\eta_c = \frac{W_c}{W_k} = \frac{W_c}{T_p P_o} \quad (10a)$$

$$\eta_s = \frac{W_s}{W_c} = \frac{E_a^2 L}{4 k_1 W_c} \quad (10b)$$

The energy gain from an accelerating section is therefore

$$V_a = \bar{E}_a L = (\eta_c \eta_s \cdot 4 k_1 L T_p P_o)^{1/2} \quad (11)$$

In Ref. 12 these efficiencies are calculated to be

$$\eta_c = \frac{2(1 - e^{-\mu})^2}{\mu} \cdot \frac{\beta_1}{1 + \beta_1 + \beta_{20}} \quad (12a)$$

$$\eta_s = \frac{2v(e^{-\tau} - e^{-v})^2}{(v - \tau)^2} \cdot \frac{\beta_2}{1 + \beta_1 + \beta_2} \quad (12b)$$

Fig. 9. Schematic of low-pressure plasma switch.

where

$$\mu = \mu_0(1 + \beta_1 + \beta_{20}) \quad (13a)$$

$$v = v_0(1 + \beta_1 + \beta_2) \quad (13b)$$

$$\mu_0 = T_p/T_0 \quad (13c)$$

$$v_0 = T_s/T_0 \quad (13d)$$

Here β_1 is the input coupling coefficient for the storage cavity, β_{20} is the output coupling coefficient with the switch off, β_2 is the output coupling coefficient when the switch is fired, and as before $T_0 = 2Q_0/\omega$ is the unloaded cavity filling time.

By adjusting β_2 in Eq. (12b), the transfer efficiency η_s can be optimized for fixed values of v_0 and τ . This optimized efficiency is shown in Fig. 10 as a function of v_0 assuming $\beta_2 \gg \beta_1$.

The value of β_2 which maximizes η_s is shown in Fig. 11. The efficiency η_c for the transfer of energy from the klystron pulse to stored energy in the storage cavity can be optimized in a similar fashion by adjusting the input coupling β_1 . Since Eq. (12b) reduces to the same form as Eq. (12a) in the limit $\tau = 0$ (assuming $\beta_{20} \ll 1$ and $\beta_1 \ll \beta_2$), the top curve in Fig. 10 can also be used to find the maximum value of η_c as a function of μ_0 . Likewise, the optimum value of β_1 is given by the curve for $\tau = 0$ in Fig. 11.

The energy gain enhancement ratio for an SES system is also of interest. From the definition $R \equiv V_a/V_0$, where V_a is given by Eq. (11), we obtain

$$R(\text{SES}) = \frac{2(\beta_1\beta_2)^{1/2}}{1 + \beta_1 + \beta_{20}} \cdot (1 - e^{-\mu}) \cdot \left[\frac{e^{-v} - e^{-\tau}}{\tau - v} \cdot \frac{\tau}{1 - e^{-\tau}} \right] \quad (14)$$

This can be compared with $R(\text{SLED})$ given by Eq. (8). While $R(\text{SLED})$ cannot exceed three, $R(\text{SES})$ can, in principle, be made arbitrarily large.

As an example of an SES system, consider an accelerator powered by klystrons with a peak power output of 80 MW and pulse length of 4 μs , operating at 5712 MHz. A copper energy storage cavity with a radius of 30 cm would have an unloaded TE-mode Q of 3.4×10^5 at this frequency (the unloaded Q of a spherical resonator in a TE mode is just the radius divided by the skin depth). Using $T_p = 4 \mu\text{s}$ and $T_0 = 2Q_0/\omega = 19 \mu\text{s}$ in Eq. (13c), $\mu_0 = 0.21$. The top curve in Fig. 10 shows that energy can be transferred to the storage cavity with an efficiency of 67%. Assuming two $\pi/3$ -mode jungle gym structures 3 m in length ($\tau = 0.28$, $T_s = 0.1 \mu\text{s}$, $v_0 = 0.005$), we have from Fig. 10 that $\eta_s = 58\%$. Thus the effective stored energy per unit length is 21J, and using $k_1 = 1.2 \times 10^{14} \text{ V}^2/\text{J-m}$ the unloaded gradient is 100 MV/m. Figure 12 shows the energy that could be obtained from a 3 km accelerator of this design for other pulse lengths. An ideal switch is assumed, and breakdown limitations are ignored.

Fig. 10. Maximum energy transfer efficiency η_s as a function of ν_0 .

Fig. 11. Cavity coupling coefficient β_2 which maximizes the transfer efficiency η_s .

PULSE SLICING (PS)

The third technique of RF pulse compression has been derated pulse slicing. The basic concept entails slicing the klystrons output pulse into several pieces and transmitting each piece down a delay line of differing length. The lengths are chosen so the pulses arrive simultaneously, and then are superimposed. This procedure would provide a technique of providing power gain while retaining a rectangular pulse shape.

One can envision multiple ways at accomplishing the above described scheme, all of which in practice involve a few more complications than indicated above. We will attempt to describe one possible scheme below.

This scheme hinges on the employment of a hybrid tee. A hybrid tee is a four port microwave device which

Fig. 12. Energy as a function of pulse length for a 3 km accelerator using energy storage and switching.

functions in a manner described as follows. Referring to Fig. 13, if the power supplied to ports I and II is in phase and of equal amplitudes, the output power from port IV will be equal to the sum of the power inputted to port I and II, and the output power from port III will be zero. If the power supplied to ports I and II is equal in amplitude, but 180° out of phase, the output power from port IV will be zero and the output power from port III will be the sum of input power supplied to ports I and II.

A simplified schematic of a power doubling scheme employing these devices is presented in Fig. 14, while the ideal operation is depicted graphically in Fig. 15.

The output power from two klystrons is fed into ports I and II of the first hybrid tee. During the first half of the pulse, the klystrons are driven in phase and the combined output power is delivered through port III into the delay line. The delay line is chosen to have a length approximately one-half the total pulse length.

During the second half of the pulse the phase of the second klystron is rotated 180° so that all the power appears at port IV. The two halves of the pulse are combined simultaneously in the second hybrid tee and the exact length of the delay chosen so that the phase relationship produces pulses of equal amplitude at ports III and IV. The output power level at each port is given by

$$P_{out} = P_{in} (2 - e^{-2\alpha L})$$

where L is the length of the delay line and α is the attenuation constant.

In theory it is possible to continue this process indefinitely. The next level or 4-fold pulse slicing is diagrammed in Fig. 16. In practice this procedure suffers from one serious drawback, at least one-half of the pulse energy must be stored in a delay line for a period of time equal to at least one-half the input pulse length. If we assume the delay line is a room temperature WR 287 copper waveguide, operating at 2856 MHz, the power levels versus pulse length may be predicted as shown in Fig. 17.

MAGNETIC PULSE COMPRESSION

As a final note, we will briefly describe DC pulse compression. This type of compression is being investigated as a technique for achieving the high dc pulse power requirements of some of the new experimental RF power sources.

The basic circuit for magnetic pulse compression is essentially the same as originally conceived in the 1950's. The fundamental principle involved is to use the large changes in permeability exhibited by saturating ferri-(ferro-)magnetic materials in order to produce large changes in impedance. Figure 18a shows the permeability changes in a representative saturable magnetic material, while Fig. 18b illustrates the standard technique⁸⁻¹¹

Fig. 13. Outline of a hybrid tee.

Fig. 14. Simplified schematic of basic power doubler.

Fig. 15. Waveforms supplied by power doubler.

Fig. 16. Simplified schematic of power quadrupler.

Fig. 17. Output power vs input power. For a power doubler (quadrupler) comprised of WR287 cu waveguide operating at room temperature and 2856 MHz.

Fig. 18. Diagrams outlining the operating of magnetic pulse compression. (a) The hysteresis (B-H) loop of a typical saturable magnetic material. (b) Simplified schematic of a magnetic pulse compressor. The elements marked L_1 , L_2 , and L_n are nonlinear inductors. (c) Typical voltage waveforms associated with a magnetic pulse compressor.

for capitalizing on this behavior. First, a repetitive power source (using existing technology) generates the initial pulse. As this pulse propagates through the network, it goes through several states of compression until it achieves the desired output shape.

By using multiple states as shown, it is possible to achieve a much larger effective change in impedance than can be obtained from a single stage. This change is limited only by the physical layout and materials properties. Figure 18c illustrates the results of the compression process.

The operation of this circuit can be described as follows. Capacitor C_1 charges through inductance L_0 until inductance L_1 saturates, becoming much less than L_0 . Once this happens, C_2 will begin to charge from C_1 through L_{sat} , but since L_{1sat} is much less than L_0 , C_2 charges more rapidly than C_1 did. This process continues through the successive stages until C_n discharges into the load through L_{nsat} . To make this process efficient, we design each of these successive stages so that saturation occurs at the peak of the voltage waveform. Segment 1 to 2 in the hysteresis loop of Fig. 18a is the active or high-permeability region during which the inductor impedes current flow; the leveling-off of the curve at point 2, reached at the peak of the voltage waveform, indicates core saturation when the inductor achieves a low impedance. During segment 2 to 4, the core is reset to its original state, ready for the next cycle.

Because pulse compressors are passive devices, their operation requires an initial pulse, which we usually obtain by discharging an intermediate storage capacitor through one or more thyatrons. Figure 19 outlines various methods of achieving high repetition rates with this general arrangement. Most of our pulsers operate in the simple command resonant charge mode; the time required to recharge the intermediate storage capacitor combined with thyatron recovery times limits operation to about 15 kHz.

Aside from creating the ability to operate at increased repetition rates, the installation of magnetic pulse compressors appeared warranted on the basis of reliability and low maintenance.

There has been considerable experimental work in this area lately. A unit has been designed and built which compresses a 4.5 μ s thyatron output pulse into an 80 ns pulse with a power gain close to 20. The pulser is relatively inexpensive, and its performance surpasses that of any other system. Table III partially documents the capabilities demonstrated by this prototype. A simplified schematic of this unit is supplied by Fig. 20.

The new unit consists of an input set-up transformer, one stage of compression to charge the transmission line, a second stage of compression, and the output coupling transformer. The output transformer can be housed as part of the magnetic pulse generator or as part of the load for best impedance matching.

Fig. 19. Three kinds of magnetic compressor for use at high repetition rates. (a) The command resonant charge system, used up to 10 kHz. Only one switch before the unit can be pulsed again. (b) The Gatling-gun mode, used up to 30 kHz. Only one switch must recover before the unit is pulsed again, which increases the repetition rate. (c) Branched magnetics for producing a pulse with a high repetition rate (50 MHz). No switch recovery is required before the unit is pulsed again.

TABLE III. Comparison of output pulse parameters of the current spark-gap driver of the Advanced Test Accelerator and the MAG-1 prototype of an upgraded magnetic compression system.

	Spark gap	Magnetic compression
Peak output power, GW	2.5	10
Pulse rise time (10%-90%) per cell, ns	18	15
Pulse length (FWHM), ns	70	80
Pulse energy, J	350	800
Efficiency (including resonant transformer), %	70	80
Voltage (2-cell driver) at 18 kA/cell, kV	100	300
Voltage (1-cell driver) at 25 kA/cell, kV	200	450
Pulse-to-pulse jitter at up to 1 kHz, ns	± 1	± 0.5
Peak burst rate (5 pulses), kHz	1	>10
Peak average repetition rate at 10 duty factor, kHz	0.1	1

Fig. 20. Simplified schematic of the nonlinear magnetic drive.

Adding coupling transformers at both the input and the output of the magnetic pulse compressor improves the system's versatility, by permitting it to achieve the desired output pulse while allowing the compression stages and the input switching device to operate at their most efficient values of voltage and current.

At this point in the evolution of the pulse-shaping hardware, we can design the transformer turns and the interstage capacitors as integral parts of the system. The resulting magnetic compressor is simple and extremely reliable, and it satisfies all the required performance specifications. A sketch showing the cross-section of the above described unit is provided by Fig. 21.

In conclusion, our experience with magnetic compression has shown it to be an invaluable aid in application requiring very high peak powers.

Fig. 21. Cross-sectional sketch of MAG-I, nonlinear compression device.

REFERENCES

1. Z. D. Farkas, H. A. Hogg, G. A. Loew and P. B. Wilson, "SLED: A Method of Doubling SLAC's Energy," Stanford Linear Accelerator Center, Stanford University, Stanford, California.
2. D. L. Birx, G. J. Dick, W. A. Little, J. E. Mercereau, and D. J. Scalapino, Appl. Phys. Lett. **32**, 68 (1978).
3. D. L. Birx, G. J. Dick, W. A. Little, J. E. Mercereau, and D. J. Scalapino, Appl. Phys. Lett. **33**, 466 (1978).
4. D. L. Birx and D. J. Scalapino, IEEE Trans. Magn. **MAG-15**, **33** (1979).
5. D. L. Birx and D. J. Scalapino, J. Appl. Phys., **51**, 3629 (1980).
6. D. L. Birx and D. J. Scalapino, "Adiabatic Compression of a Microwave Field by a Plasma Discharge," J. Appl. Phys. (to be published).
7. R. A. Alvarez et al., "Generation of High Power Microwave Pulses," IEEE Trans. Magn. (to be published).
8. D. L. Birx, E. J. Lauer and L. L. Reginato, "Experiments in Magnetic Switching," Third IEEE International Pulse Power Conference, 1981, p. 267.
9. D. L. Birx, L. L. Reginato and J. A. Schmidt, "An Investigation Into the Repetition Rate Limitations of Magnetic Switches," IEEE Conference Record of 1982 Fifteenth Power Modulator Symposium, June 14-16, 1982, p. 4.
10. D. L. Birx, E. J. Lauer, L. L. Reginato, J. A. Schmidt and M. Smith, "Basic Principles Governing the Design of Magnetic Switches," November 18, 1980.
11. Z. D. Farkas, "Power Multiplier," Technical Note SLAC-TN-73-8, Stanford Linear Accelerator Center, Stanford University, Stanford, California (September 1973), unpublished.
12. P. B. Wilson, "SLED: A Method for Doubling SLAC's Energy," Technical Note SLAC-TN-73-15, Stanford Linear Accelerator Center, Stanford University, Stanford, California (December 1973), unpublished.

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