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APPLICATION OF MICROWAVE ENERGY COMPRESSION TO PARTICLE ACCELERATORS*

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High-gradient-copper linac accelerator structures capable of surface field gradients in excess of 100 MV/m exist, but present klystrons can not provide sufficient peak power to obtain these field gradients. In earlier work, it has been suggested that the microwave energy-compression technique could be applied to this problem. In addition, it offers an approach for trading duty cycle for beam energy at a fixed total input energy. Here we discuss further some aspects of this technique as it applies to the accelerator problem.

I. INTRODUCTION

We have been studying a microwave energy-compression method for producing high-power microwave pulses that involves the accumulation of microwave energy in a resonant structure and the subsequent release of this energy using an interference switch.[1–5] Here we discuss the possible application of this technique to increasing the energy of particle accelerators.

Figure 1 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. 1(a), 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, due to losses in the walls of the T, a perfect null is not achieved, 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. 1(b), 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 obtained[4] gains of 50 and switched power levels of order hundreds of megawatts.

As discussed below, only modest power gains of order 10 are sought for the present application; therefore, a room-temperature system is feasible. There are, however, questions associated with mode mixing in the high-Q, overmoded storage resonators that must be strongly coupled to the switch port to achieve the dump times desired. In addition, because power levels 10 times those we have previously switched will be needed, 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 ports[4] and

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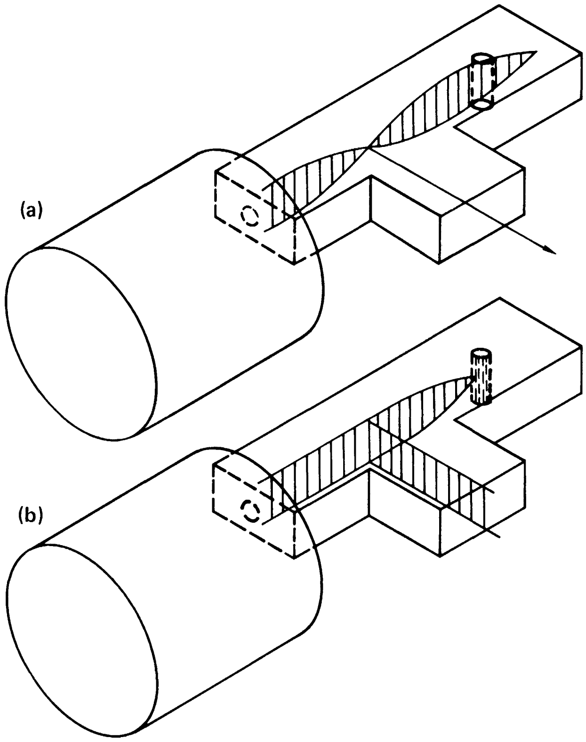

FIGURE 1 Schematic of microwave cavity and H-plane T showing the electric field envelope in (a) the storage state, and (b) the dump state.

on work using split spherical cavities.[6] We then outline some ideas for developing a low-pressure, high-power plasma switch.

II. 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 and into 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-μsec pulse one would want a ringing time τ_s in the storage state of order 4 μsec. One would, in fact, want to 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

$$\tau_D \approx \frac{2V}{v_g A}\left|\frac{\frac{4}{\pi}B_\omega}{B_0}\right|^2, \qquad (1)$$

where B_ω/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 μsec in length and take $\tau_D = 0.4$ μsec.* Combining this with a $\tau_s = 4$ μsec 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, which is 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 filling factor, which is large. 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 μsec 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., $\tau_s \approx 4$ μsec), 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. (1) is of order several tenths of a microsecond; a $\tau_D \approx 0.4$ μsec should therefore be obtainable.

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* Note that if the optimum pulse length for the accelerator were less than this, say 0.1 μsec, 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.

To achieve this rapid dump, the ports between the reasonator 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 waveguide.[4] 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*-band 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. In Sec. III we discuss our current ideas for a high-power switch.

III. 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. This insertion loss *I* of the switch is strongly dependent on the electron charge density of the electrons. The results of the calculations of I versus charge density for plasmas with different diameters are shown in Fig. 2.

For the 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.[5] There, a low pressure of about 100 mm of Hg was continually present in the cavity switch.

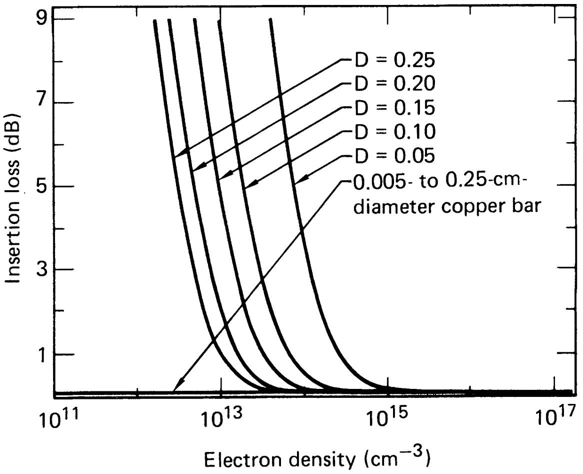

FIGURE 2 Insertion loss $I = 10 \log_{10}(1 - |\Gamma|^2)$, where $|\Gamma|$ is the reflection coefficient, versus electron density for plasmas of different diameters *D* (cm).

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, but since the accelerator vacuum should be 10^{-7} to 10^{-8} mm of Hg, an

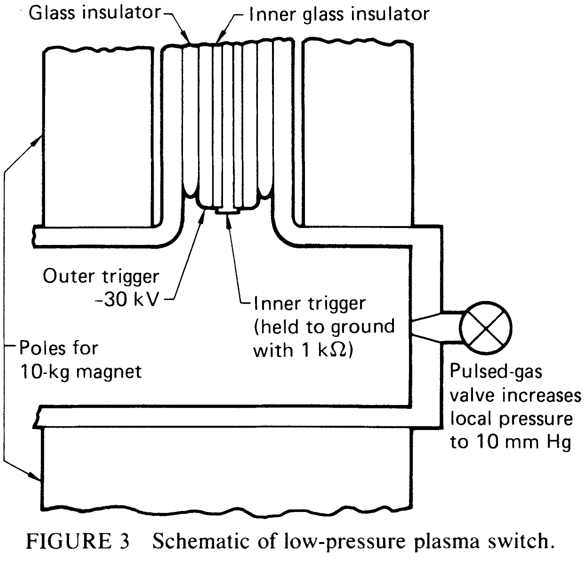

FIGURE 3 Schematic of low-pressure plasma switch.

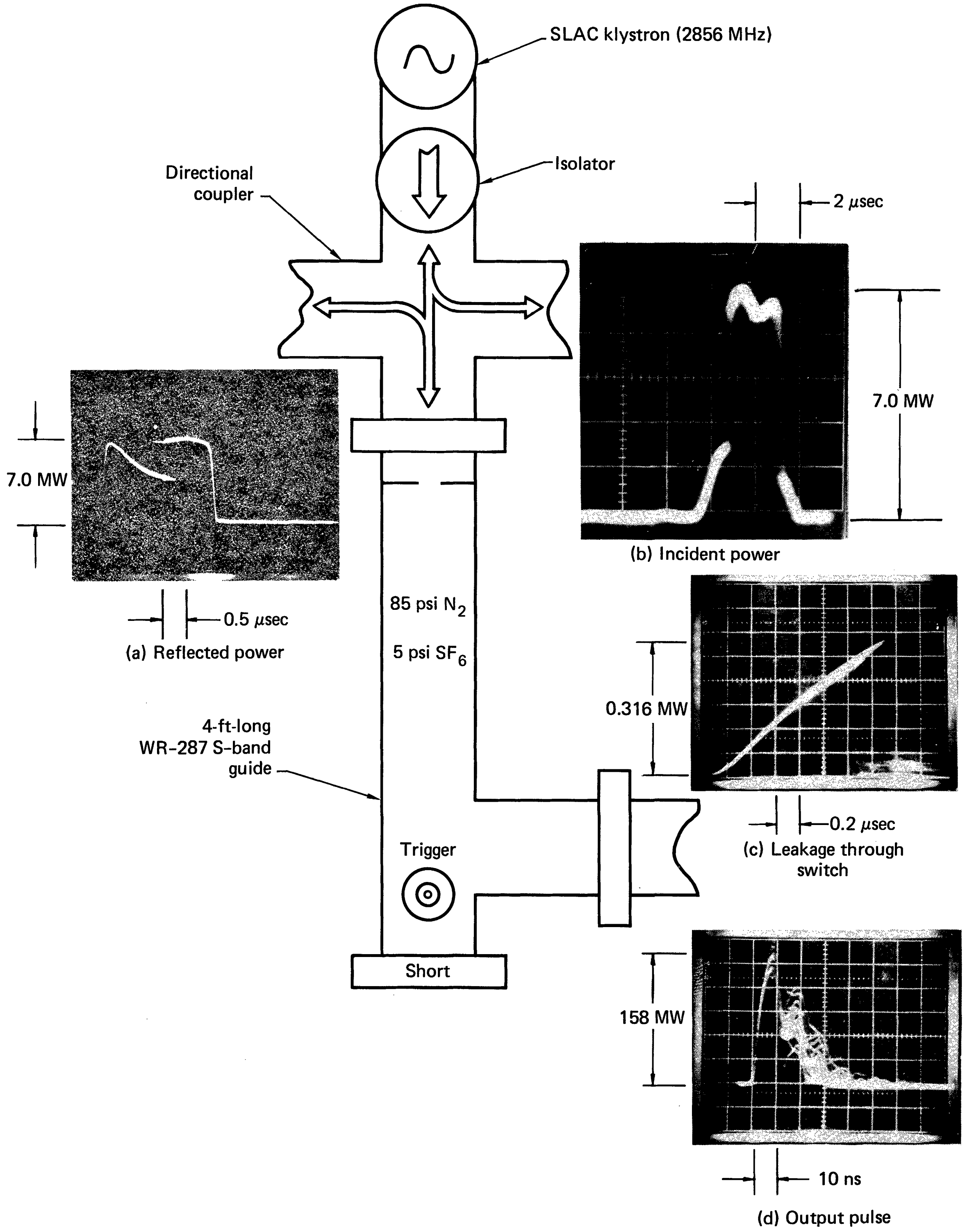

FIGURE 4 A brief schematic description of a recent high-power microwave switch experiment. The Q_L of the storage resonator was 9000; that of the dump Q (Q_0) was 180. The actual gain achieved was 23, which differs from the predicted value of 50 because of the degree of undercoupling.

excessively large pump would be required to maintain this situation in a steady state.

Related work done by one of us (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 msec 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 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/cm^3. Recovery times of order 100 μsec were observed. It should be remembered that this behavior was exhibited by a dc arc; extrapolating to an rf discharge introduces some uncertainty.

Figure 3 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 μsec and the cavity will once again be configured for charging.

IV. CURRENT RESEARCH

A low-pressure switch of the type described above has not yet been constructed, but experiments have been conducted at high power with a high-pressure switch. The results are schematically outlined in Fig. 4.

A 4-ft length of standard OFHC *S*-band waveguide was terminated at one end with an interference switch and coupled to a klystron via an iris in the opposite end. This iris was positioned to give a resonant frequency for this waveguide section of 2856 MHz. In order to avoid breakdowns, the waveguide was pressurized at 85 psi N_2 + 5 psi SF_6.

Approximately 1.6 J was stored in the cavity by the klystron during the 1.5-msec charging pulse. After this time period, the switch was triggered, discharging the stored energy in about 10 nsec. The trigger consisted of a trigatron which initiated a breakdown in the high-pressure gas mix.

Each of the oscilloscope traces shown in Fig. 4 represents an overlay of 10 pulses. Jitter in the trigger system resulted in some pulse-to-pulse variations. The measured gain of 23 rather than the predicted 50 is primarily a result of the undercoupling indicated in Fig. 4(a). The output pulse pictured in Fig. 4(d) indicates a peak output power of about 160 MW.

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* We are also exploring the possibility of surface-flashing a dielectric with an arc.

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