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CONSTANT AMPLITUDE RF TO PERIODIC PULSES CONVERTER*

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Introduction

This note describes a system CARTOP that converts with nearly 100% efficiency a constant amplitude (CW) RF power to periodically pulsed RF power whose amplitude is 4 times the CW power amplitude.

Some of the applications are: coding CW Radar, improved communications, and increasing the peak energy of particle accelerators, especially those with high beam current.

The CARTOP system is shown in Fig. 1. The CW RF

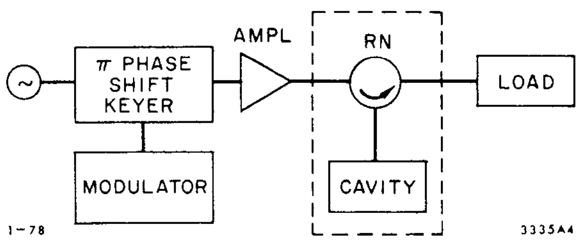

Fig. 1. CARTOP System

is applied to a phase shift keyer (PSK) which is controlled by a waveform from the modulator so that it shifts the phase of the RF π radians during the pulse. This phase coded RF is then applied, generally through an amplifier, to a resonator network, RN, which converts it into periodic pulses. The RN network consists of an energy storing device and a means to separate the fields flowing toward and away from the device, such as a circulator and a cavity as shown, a 3 dB hybrid and two cavities[1], a ring resonator, etc.

CARTOP is a form of pulse compression. It uses 180° biphase modulation, and energy storage in a cavity instead of linear frequency modulation and a dispersive structure.

Theory

The RN output RF amplitude E_r is related to its input RF amplitude E_i by[2]

$$E_r = E_e - E_i \ , \tag{1}$$

where E_e is related to E_i by the differential equation

$$T_c \, dE_e/dt + E_e = \alpha E_i \ . \tag{2}$$

E_e is the field emitted from the cavity. E_i^2 is the power flowing toward and E_r^2 is the power flowing away from the cavity and into the load. α is the steady state emitted field, and T_c is the cavity time constant. In terms of cavity internal (unloaded) and external quality factors, Q_o and Q_e respectively, α and T_c are given by:

$$\alpha = 2/(1+Q_e/Q_o) = 2\beta/(1+\beta) \tag{3}$$

$$T_c = Q_e/\pi f(1+Q_e/Q_o). \tag{4}$$

$Q_o/Q_e = \beta$, the cavity coupling coefficient.

If E_i is a piecewise function of time and is constant during each time interval, then the solution to Eq. (2) during each time interval is:

$$E_e = \alpha E_i + (E_{ei} - \alpha E_i)e^{-t/T_c} \tag{5}$$

where E_{ei} is the value of E_e at t = 0. t is reset to zero at the beginning of each time interval. Substitute t_n for t and $E_{e(n-1)}$ for E_{ei} to obtain E_{en}, the emitted field at the end of the nth time in interval. Thus,

$$E_{en} = \alpha E_{in} + (E_{e(n-1)} - \alpha E_{in})e^{-t_n/T_c} \tag{6}$$

$$E_{rn} = E_{en} - E_{in} \ . \tag{7}$$

If we know E_i at all time intervals and E_e at the beginning of the first time interval, then we can find E_e and E_r for all time intervals.

For CARTOP, the magnitude of E_i is constant. However, the PSK causes the sign of E_i to be plus during the first part of the period, interval A, and minus during the pulse, which is the second part of the period, interval B.

If the period and pulse width are properly chosen, the resonator maintains an emitted field E_e nearly equal to E_i. The incident field E_i subtracts from E_e in between pulses, interval A, and adds to it during the pulse, interval B. Thus, $E_r = 0$ during the time between pulses and $E_r = 2E_i$ during the pulse.

Quantitative Description – Refer to Figs. 2 and 4.

Let:

t_2 = period;
t_b = duration of interval B, pulse width;
t_1 = duration of interval A, time between pulses;
$\tau_2 = t_2/T_c$; $\tau_b = t_b/T_c$; $\tau_1 = t_1/T_c$; $\tau = t/T_c$;
$|E_i| = 1$; $E_i = 1$ during interval A; $E_i = -1$ during interval B;
E_{e1} = E_e at the beginning of interval B (end of interval A);
E_{e2} = E_e at the end of interval B (beginning of interval A);
E'_{ra} = E_r at the beginning of interval A;
E''_{ra} = E_r at the end of interval A;
E'_{rb} = E_r at the beginning of interval B;
E''_{rb} = E_r at the end of interval B.

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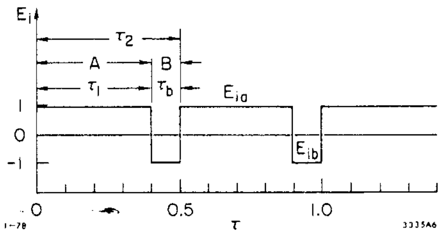

Fig. 2. RF Amplitude applied to RN

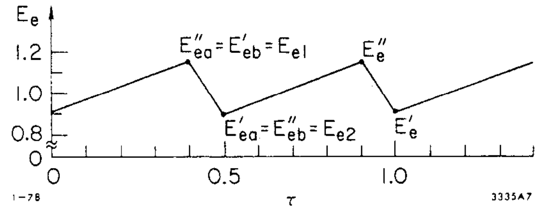

Fig 3. Emitted field amplitude.

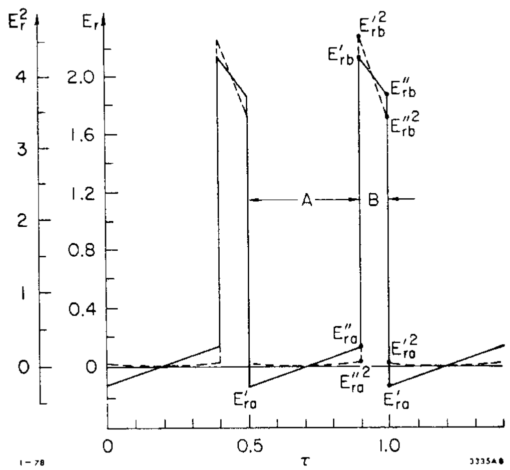

Fig. 4. RN output waveforms: E_e, E_r, and E_r^2.

Substituting for E_i in Eq. (6) and using the value of E_e at the end of one interval as the initial value of E_e for the next interval, we obtain

$$E_{e1} = \alpha + (E_{e2} - \alpha)e^{-\tau_1} \qquad (8)$$

$$E_{e2} = -\alpha + (E_{e1} + \alpha)e^{-\tau_b}. \qquad (9)$$

Solving the above two simultaneous equations we obtain:

$$E_{e1} = \alpha(e^{-\tau_2} - 2e^{-\tau_1} + 1)/(1 - e^{-\tau_2}) \qquad (10)$$

$$E_{e2} = \alpha(e^{-\tau_2} - 2e^{-\tau_b} + 1)/(1 - e^{-\tau_2}) \quad . \qquad (11)$$

Using Eq. (1) we obtain:

$$E'_{ra} = E_{e2} - 1 \qquad (12)$$

$$E''_{ra} = E_{e1} - 1 \qquad (13)$$

$$E'_{rb} = E_{e1} + 1 \qquad (14)$$

$$E''_{rb} = E_{e2} + 1 \quad . \qquad (15)$$

Equating E''_{ra} to $|-E'_{ra}|$ we obtain the relationship between τ_b and τ_2 that must hold for maximum conversion efficiency of CW to periodic pulses, namely:

$$\tau_2 = \ln\{(\alpha e^{\tau_b} - 1)/(\alpha e^{-\tau_b} + 1)\} \qquad (16a)$$

$$\tau_b = \ln\{\{(ke^{\tau_2}/2)^2 + e^{\tau_2}\}^{1/2} - ke^{\tau_2}/2\}, \qquad (16b)$$

where $k = (1 - e^{\tau_2})/\alpha$. The values of E_{e1} and E_{e2} are obtained by substituting the values of τ_1, τ_b and τ_2 related by the above equation into Equations (10) and (11). Then, using Equations (12)-(15), the values of E_r at the beginning and at the end of intervals A and B are obtained. Plots of E_i, E_e, E_r (and E_r^2) all versus τ, for $\alpha = 1.67$ ($\beta = 5$), $\tau_2 = .5$ are shown in Figs. (2), (3) and (4) respectively. An oscillogram of an experimentally obtained CARTOP output waveform with $t_b = .1\mu s$, $t_2 = .6\mu s$ and $\tau_2 = .313$ is shown in Fig. 5.

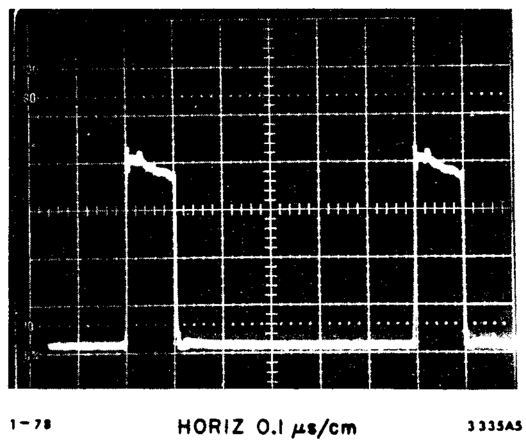

Fig. 5. Experimentally obtained CARTOP waveform. $t_b = .1\mu s$, $t_2 = .6\mu s$ $Q_o = 10^5$, $Q_e = 20{,}000$.

CARTOP compresses the energy contained in a time interval P, equal to the modulation period t_2, into a time interval equal to a pulse width t_b. Define the compression factor $C_f = P/t_b = \tau_2/\tau_b$. We choose C_f such that E_e settles in the neighborhood of one. It is constrained to stay within equal excursion above and below unity.

Define U_p as the pulse energy

$$U_p = \int_0^{\tau_b} E_{rb}^2 \, dt, \qquad (17)$$

P_{ap} as the pulse average power

$$P_{ap} = U_p/\tau_b \, , \tag{18}$$

P_{pp} as the pulse peak power

$$P_{pp} = E'^2_{rb} \, , \tag{19}$$

E_f as the efficiency, the ratio of energy contained in the pulse to the energy contained in a period.

$$E_f = U_p/\tau_2 \, , \tag{20}$$

P_c as the fraction of power (or fraction of energy per period) dissipated in the cavity,

$$P_c = (1/\tau_2)\left(\int_0^{\tau_1} E_{ea}^2 \, d\tau + \int_0^{\tau_b} E_{eb}^2 \, d\tau\right)/\beta \, , \tag{21}$$

V_{g2} as the average field during t_b

$$V_{g2} = (1/\tau_b) \int_0^{\tau_b} E_{rb} \, d\tau \tag{22}$$

P_a as the fraction of energy dissipated in the load during interval A

$$P_a = (1/\tau_2) \int_0^{\tau_1} E_{ra}^2 \, d\tau \tag{23}$$

In evaluating the above integrals, use was made of the fact that the integrals from zero to τ of the function E and of the square of E where $E = E_f + (E_i - E_f)e^{-\tau}$, E_i is the value of E at $\tau = 0$ and E_f is the value of E at $\tau = \infty$, are:

$$\int_0^t E d\tau = E_f \tau + (E_i - E_f)(1 - e^{-\tau} \tag{24}$$

$$\int_0^\tau E^2 d\tau = E_f^2 \tau + 2E_f(E_i - E_f)(1 - e^{-\tau})$$

$$+ .5(E_i - E_f)^2(1 - e^{-2\tau}) \tag{25}$$

If $\tau_2 \to 0$ and $\alpha \to 2$ then $E_e \to 1$, $E_{ra} \to 0$, $E_{rb} \to 2$, $C_f \to 4$, $E_f \to 1$, $P_c \to 0$, and $V_{g2} \to 2$.

The two factors that prevent the attainment of 100% efficiency are: losses in the cavity ($\alpha \neq 2$) and power transmitted to the load during the interpulse period A, P_a ($\tau_2 = P/T_c \neq 0$). The former can approach zero if we make Q_o very large and the latter if we make Q_e (and Q_o) and hence T_c very large or P very small.

The average value of the field during the pulse and hence the pulse power remains essentially constant as α decreases or τ_2 increases. The decrease in efficiency shows up as an increase in C_f narrowing of the pulse if the period is fixed. The efficiency is nearly $4/C_f$, and approaches 1 as C_f approaches 4.

CARTOP is most useful where, due to other constraints, we have a CW source and we need closely spaced pulses of width t_b. If the period has to be greater than $4t_b$ then with CARTOP a pulse power equal to 4 times the input power can be achieved.

CARTOP Design

The cavity parameters Q_o, Q_e, Q_L and bandwidth B as a function of α and T_c are:

$$Q_L = \pi f T_c; \; B = 1/\pi T_c; \; Q_e = Q_L/(\alpha/2);$$

$$Q_o = \beta Q_e = Q_L/(1 - \alpha/2).$$

Using $T_c = P/\tau_2 = t_b/\tau_b$ we obtain

$$Q_L = \pi f P/\tau_2 = \pi f t_b/\tau_b; \; B = \tau_2/\pi P = \tau_b/\pi t_b \, .$$

Define $Q_{Lnp} = Q_L/fP = \pi/\tau_2$; $Q_{Lnb} = Q_L/ft_b = \pi/\tau_b$; $B_{np} = BP = \tau_2/\pi$; $B_{nb} = Bt_b = \tau_b/\pi$. Thus $Q = Q_{np} fP = Q_{nb} ft_b$; $B = B_{np}/P = B_{nb}/t_b$.

The values of τ_1 (TAU 1), τ_b (TAU B), C_f (CF), E_{e1} (E1), E_{e2} (E2), B_{np} (BWNP), Q_{onp} (QONP), P_{pp} (PPP), P_{ap} (PAP), P_a (PDLA), P_c (PDC), E_f (EF), V_{g2} (VG2), UC, US, UDCA vs. τ_2 (TAU 2) for fixed values of α (A) or β (BETA) are listed in Table 1, where

UC = power going into cavity during t_1,

US = power going into cavity during t_1 to be stored, and

UDCA = power going into cavity during t_1 to be dissipated.

Several requirements that simplify the design will be considered: (1) P is fixed, (2) t_b is fixed, (3) C_f is fixed. A possible further constraint is that Q_o is fixed. The following design examples are both illustrative and practical.

a. Fixed Period

Typical applications are a circulating charge with a given voltage gain as it traverses a cavity located at a fixed position in the path of the circulating charge.

Given: $E_f = .87$, P = 1 μs, f = 2856 MHz. We look in Table 1, at $E_f = .87$, for an α,τ_2 combination for which Q_{onp} is a minimum. This occurs at $\alpha = 1.818$, $\tau_2 = 1$. Using the values at that point given in Table 1 and the above expressions we obtain $T_c = P/\tau_2 = 1\,\mu s$ $t_b = \tau_b T_c = .217\ \mu s$, $C_f = 4.1$, B = .32/P = 320 kHz, $Q_L = \pi f T_c = 8972$, $Q_o = 35Pf = 10^5$, $Q_e = Q_o/\beta = 10^4$, $V_{g2} = 1.989$. If we require a longer period and we are

TABLE 1. CONSTANT AMPLITUDE RF TO PULSE TRAIN CONVERTER PARAMETERS, MAXIMUM EFFICIENCY.

TAU2	TAU1	TAUB	CF	E1	E2	BWNP	QONP	PPP	PAP	PDLA	PDC	EF	VG2	UC	US	UDCA
BETA= 5.0	RB=0.200	A=1.667														
0.1	0.080	0.020	5.00	1.03	0.97	0.03	188.50	4.108	4.000	0.000	0.200	0.800	2.000	0.800	0.640	0.160
0.2	0.160	0.040	5.01	1.05	0.95	0.06	94.25	4.216	4.000	0.001	0.201	0.799	2.000	0.800	0.639	0.161
0.4	0.321	0.079	5.03	1.11	0.89	0.13	47.12	4.435	3.998	0.003	0.202	0.795	1.999	0.798	0.636	0.163
0.6	0.482	0.118	5.07	1.16	0.84	0.19	31.42	4.655	3.996	0.007	0.205	0.788	1.997	0.796	0.630	0.166
0.8	0.644	0.156	5.13	1.21	0.79	0.25	23.56	4.873	3.993	0.012	0.210	0.778	1.995	0.793	0.623	0.171
1.0	0.808	0.192	5.20	1.26	0.74	0.32	18.85	5.087	3.989	0.018	0.215	0.767	1.992	0.789	0.613	0.176
1.2	0.973	0.227	5.29	1.30	0.70	0.38	15.71	5.295	3.985	0.026	0.221	0.753	1.989	0.785	0.602	0.183
1.4	1.141	0.259	5.40	1.34	0.66	0.45	13.46	5.493	3.980	0.035	0.228	0.737	1.985	0.780	0.589	0.191
1.6	1.310	0.290	5.53	1.38	0.62	0.51	11.78	5.681	3.975	0.044	0.236	0.720	1.982	0.775	0.575	0.199
1.8	1.482	0.318	5.67	1.42	0.58	0.57	10.47	5.856	3.970	0.055	0.245	0.701	1.978	0.769	0.560	0.209
2.0	1.657	0.343	5.83	1.45	0.55	0.64	9.42	6.018	3.966	0.066	0.253	0.680	1.974	0.762	0.544	0.219
2.2	1.834	0.366	6.01	1.48	0.52	0.70	8.57	6.165	3.961	0.078	0.263	0.659	1.971	0.756	0.527	0.229
2.4	2.013	0.387	6.20	1.51	0.49	0.76	7.85	6.298	3.956	0.090	0.272	0.638	1.967	0.749	0.510	0.240
5.0	4.501	0.499	10.02	1.65	0.35	1.59	3.77	7.033	3.928	0.226	0.382	0.392	1.946	0.674	0.313	0.361
10.0	9.491	0.509	19.64	1.67	0.34	3.18	1.88	7.111	3.931	0.333	0.467	0.200	1.945	0.616	0.160	0.456
BETA= 10.0	RB=0.100	A=1.818														
0.1	0.078	0.022	4.45	1.03	0.97	0.03	345.57	4.128	4.000	0.000	0.100	0.900	2.000	0.775	0.697	0.078
0.2	0.155	0.045	4.45	1.06	0.94	0.06	172.79	4.257	4.000	0.001	0.100	0.899	2.000	0.774	0.696	0.078
0.4	0.311	0.089	4.47	1.13	0.87	0.13	86.39	4.520	3.998	0.004	0.101	0.894	1.998	0.772	0.693	0.079
0.6	0.467	0.133	4.50	1.19	0.81	0.19	57.60	4.785	3.995	0.009	0.103	0.887	1.996	0.769	0.688	0.081
0.8	0.624	0.176	4.55	1.25	0.75	0.25	43.20	5.050	3.991	0.016	0.106	0.878	1.993	0.764	0.680	0.084
1.0	0.783	0.217	4.60	1.30	0.70	0.32	34.56	5.312	3.987	0.025	0.109	0.866	1.989	0.758	0.671	0.087
1.2	0.943	0.257	4.68	1.36	0.64	0.38	28.80	5.568	3.982	0.036	0.113	0.852	1.985	0.750	0.659	0.091
1.4	1.106	0.294	4.76	1.41	0.59	0.45	24.68	5.815	3.976	0.048	0.117	0.835	1.980	0.742	0.646	0.096
1.6	1.271	0.329	4.86	1.46	0.54	0.51	21.60	6.050	3.970	0.062	0.122	0.817	1.975	0.733	0.632	0.101
1.8	1.438	0.362	4.98	1.50	0.50	0.57	19.20	6.271	3.964	0.076	0.127	0.797	1.970	0.723	0.616	0.106
2.0	1.608	0.392	5.10	1.55	0.45	0.64	17.28	6.478	3.958	0.092	0.132	0.775	1.964	0.712	0.600	0.112
2.2	1.781	0.419	5.25	1.58	0.42	0.70	15.71	6.668	3.952	0.109	0.138	0.753	1.959	0.701	0.582	0.118
2.4	1.956	0.444	5.41	1.62	0.38	0.76	14.40	6.841	3.946	0.126	0.144	0.730	1.955	0.689	0.564	0.125
5.0	4.417	0.583	8.58	1.80	0.20	1.59	6.91	7.833	3.909	0.330	0.214	0.456	1.923	0.553	0.351	0.202
10.0	9.403	0.597	16.75	1.82	0.18	3.18	3.46	7.941	3.908	0.496	0.271	0.233	1.920	0.445	0.180	0.265
BETA= 20.0	RB=0.050	A=1.905														
0.1	0.076	0.024	4.21	1.03	0.97	0.03	659.73	4.139	4.000	0.000	0.050	0.950	2.000	0.762	0.724	0.038
0.2	0.153	0.047	4.22	1.07	0.93	0.06	329.87	4.280	4.000	0.001	0.050	0.949	1.999	0.762	0.723	0.038
0.4	0.306	0.094	4.23	1.14	0.86	0.13	164.93	4.567	3.998	0.005	0.051	0.944	1.998	0.759	0.720	0.039
0.6	0.459	0.141	4.26	1.20	0.80	0.19	109.96	4.858	3.995	0.011	0.052	0.937	1.995	0.755	0.715	0.040
0.8	0.614	0.186	4.30	1.27	0.73	0.25	82.47	5.150	3.991	0.019	0.053	0.928	1.992	0.748	0.707	0.041
1.0	0.770	0.230	4.35	1.33	0.67	0.32	65.97	5.439	3.986	0.029	0.055	0.916	1.987	0.741	0.698	0.043
1.2	0.928	0.272	4.42	1.39	0.61	0.38	54.98	5.723	3.981	0.042	0.057	0.901	1.982	0.732	0.686	0.045
1.4	1.088	0.312	4.49	1.45	0.55	0.45	47.12	5.997	3.975	0.056	0.059	0.885	1.977	0.721	0.673	0.048
1.6	1.251	0.349	4.58	1.50	0.50	0.51	41.23	6.260	3.968	0.072	0.062	0.866	1.971	0.710	0.659	0.051
1.8	1.416	0.384	4.68	1.55	0.45	0.57	36.65	6.509	3.961	0.090	0.065	0.846	1.965	0.697	0.643	0.054
2.0	1.583	0.417	4.80	1.60	0.40	0.64	32.99	6.742	3.955	0.108	0.068	0.824	1.959	0.683	0.626	0.057
2.2	1.754	0.446	4.93	1.64	0.36	0.70	29.99	6.957	3.948	0.128	0.071	0.801	1.953	0.669	0.609	0.060
2.4	1.927	0.473	5.07	1.67	0.33	0.76	27.49	7.154	3.942	0.148	0.074	0.777	1.947	0.654	0.590	0.064
5.0	4.373	0.627	7.97	1.88	0.12	1.59	13.19	8.307	3.900	0.397	0.114	0.489	1.908	0.478	0.371	0.107
10.0	9.357	0.643	15.55	1.90	0.10	3.18	6.60	8.437	3.899	0.602	0.147	0.251	1.905	0.333	0.190	0.143

limited to the Q_o of 10^5 then we must accept a lower efficiency. For example, if $P = 2\mu s$, then $Q_{onp} = Q_o/fP = 17.5$. We now look in Table 1 for a point where E_f is maximum. This occurs when $\alpha = 1.818$, $\tau_2 = 2.0$, and $E_f = .775$. The values of T_c, B, Q_L, Q_e and of course Q_o do not change, but now $t_b = .395$, $C_f = 5.1$, and $V_{g2} = 1.964$. Note that the decrease in V_{g2} is 1.3% even though the decrease in E_f is 11.7%. The decrease in E_f manifests itself essentially not in a decrease of V_{g2}, but in a decrease in duty cycle, which is $5.1/4.6 = 10.9\%$.

For large P, and reasonable efficiencies, the required Q_o becomes too large and we have to resort to superconducting cavities. In that case, the design is as follows. The total unused power is $P_{cs} + P_a$ where $P_{cs} = P_c(1 + R_f)$ and R_f is the refrigeration factor, the ratio of power into the refrigerator to power removed by the refrigerator. Thus, when the cavity is SC, then $E_f = 1 - P_cR_f - P_a$. If we approximate P_c by $1/\beta$ then $\beta = R_f/(1 - E_f - P_c)$. The superconducting Q_o is the improvement factor, I_f times the room temperature Q_o, Q_{or}. Thus, $Q_o = I_fQ_{or} = (1 + \beta)\pi fP/\tau_2 = \beta\pi Pf/\tau_2 = R_f\pi fP/(1 - E_f - P_a)$, and

$$Q_{or}/fP = (R_f/I_f)(\pi/\tau_2)(1 - E_f - P_a) .$$

For niobium[6] at 4.2 ^oK $R_f = 500$, $I_f = 5 \times 10^3$, $Q_{or} = .1\pi fP/\tau_2(1 - E_f - P_a)$. Let the required E_f be .77 and we can choose $\tau_2 = 1 \rightarrow P_a = .033$, $T_c = P$. $Q_{or}/fP = 1.571$, $B = 1/\pi P$. At 2856 MHz, $Q_{or} = 4486P$. If also $P = 20$ μs, then $Q_o = 4.5 \times 10^8$, $Q_{or} = 89{,}000$, $Q_e = 179{,}000$, $B = 16$ kHz, $t_b = 4$ μs.

Thus, the power required for the same beam energy is .8(4) = 3.2 times the power required with CARTOP, a CARTOP power gain G_{cp} of 3.2.

If the structure is SW, and if it's time constant is t_b, the power required is $G_{cp} = (.8)\{(.63)(2)\}^2 = 1.27$; if it is $t_b/2$, then the power required is $G_{cp} = (.8)\{(.86)(2)\}^2 = 2.37$. The reason for the power gain over a CW input power source is that we pay less in dissipated power if we store the field energy, when it is not being used, in a high Q storage cavity, then by leaving it, during the time it is not being used, in the accelerating cavity.

b. <u>Fixed Pulse Width t_b</u>

This condition is applicable to a CW or long pulse accelerator with a fixed filling time. CARTOP converts a CW beam to periodic pulses and a long pulse beam to a burst of pulses. This is especially useful in applications such as stroboscopic radiography[4] where it is desirable to have a succession or a burst of very narrow high current pulses, the accelerator is refilled between two pulses and each pulse can take all the available energy.

These types of machines are described in Ref. 4, from which the following is quoted:

> "For the study of very fast moving parts, inaccessible during experiment, such as detonating explosives, explosive-driven shock waves, extreme states of matter, exolution of jets, interaction of jets with jets, cratering, spalling, some special types of machines have been built, which can deliver a succession of very short pulses, 30 to 100 ns long, with a distance between pulses of a fraction of a microsecond."

V_{g2} is the voltage gain of an electron passing through at an accelerator section whose filling time is t_b, if the voltage gain without CARTOP is one. We will consider the case of vanishingly small beam current pulse width. We fill up the accelerator section with energy and then pass a charge through it that removes most of this energy.

If the current pulse width is not extremely small, then its amplitude must be so chosen that it negates the transient rise in unloaded beam energy.

Illustrative Design: Decide on efficiency E_f and look in Table 1 for an α, C_f combination for which Q_{onp} is a minimum. Then use

$$P = C_f t_b,\ T_c = P/\tau_2,\ Q_o = Q_{onp} Pf,\ Q_e = Q_o/\beta.$$

Suppose we wish to convert to CARTOP the HRC[5] accelerator, $t_b = .194\ \mu s$, $f = 2856$ MHz, with $E_f = .87$. Q_{onp} is a minimum in line $\beta = 10$, $Q_{onp} = 34.56$. Using the parameters in that line we obtain: $P = .892\ \mu s$, $T_c = .892\ \mu s$, $Q_o = 98{,}000$, $Q_e = 9{,}800$, $V_{g2} = 1.989$, $t_t = 1.12\ \mu s$. A finite time t_t has to elapse before E_e reaches the value of E_{e1} and CARTOP is in "steady state." Equating E_{e1} to $\alpha(1 - e^{t_t/T_c})$ we obtain $t_t = T_c \ln\{\alpha'/(\alpha' - 1)\}$, where $\alpha' = \alpha/E_{e1}$. For large β, $\alpha = 2$ and $t_t = .693\ T_c$. The efficiencies given do not take into account the energy lost while reaching periodic steady state. The number of bursts is given by $(P_w - t_t)/P$.

The MIT modulator-klystrons[4], with 15 μs pulse width P_w, 4 MW peak power with the accelerator section described above and CARTOP constitutes a system suitable for stroboscopic radiography with design parameters given in Ref. 4.

c. Arbitrary Compression Factor

Table 2 lists the values of τ_2, τ_1, C_f, E_{e1}, E_{e2}, P_{pp}, P_{ap}, E'_{rb} (ERBP), E''_{rb} (ERBDP), P_a, P_c, E_f, V_{g2}, ΔE (DELE), A_p (AP), ΔE_r (DELER), for fixed τ_b. Let $\Delta E = E_{e1} - E_{e2} = E'_{rb} - E''_{rb}$; $A_p = |E'_{rb}| - |E''_{ra}|$; $\Delta E_r = \Delta E/A_p$. The other lines are obtained by using the same expression as for Table 1, except that τ_b and τ_2 are not coupled by Eqs. (16a) and (16b).

If both t_b and P are fixed then we are not free to choose the optimum C_f. If C_f is increased above optimum then V_{g2} increases, although the efficiency goes down. If C_f decreases from optimum then V_{g2} goes down, but the efficiency increases slightly and then starts to decrease, as seen in Table 2. The next to the last line lists the

TABLE 2. CONSTANT AMPLITUDE RF TO PULSE TRAIN CONVERTER PARAMETERS. ARBITRARY COMPRESSION FACTOR.

TAUB=0.20 BWNB=0.06

TAU2	TAU1	CF	E1	E2	PPP	PAP	ERBP	ERBDP	PDLA	PDC	EF	VG2	DELE	AP	DELER
BETA= 5.00 RB=0.200 A=1.667 QONB= 94.25															
0.40	0.20	2.00	0.17	-0.17	1.36	1.00	1.17	0.83	0.50	0.002	0.499	0.994	0.332	0.332	1.000
0.44	0.24	2.20	0.33	-0.03	1.77	1.32	1.33	0.97	0.39	0.007	0.600	1.144	0.362	0.663	0.546
0.48	0.28	2.40	0.47	0.08	2.16	1.62	1.47	1.08	0.31	0.018	0.676	1.269	0.387	0.937	0.413
0.52	0.32	2.60	0.58	0.18	2.51	1.90	1.58	1.18	0.24	0.032	0.731	1.374	0.408	1.169	0.349
0.56	0.36	2.80	0.68	0.26	2.83	2.16	1.68	1.26	0.18	0.048	0.770	1.463	0.426	1.367	0.312
0.60	0.40	3.00	0.77	0.33	3.13	2.39	1.77	1.33	0.14	0.065	0.797	1.541	0.442	1.538	0.287
0.64	0.44	3.20	0.84	0.39	3.40	2.60	1.84	1.39	0.10	0.082	0.814	1.608	0.455	1.687	0.270
0.68	0.48	3.40	0.91	0.44	3.64	2.80	1.91	1.44	0.08	0.098	0.823	1.668	0.467	1.818	0.257
0.72	0.52	3.60	0.97	0.49	3.67	2.96	1.97	1.49	0.06	0.114	0.827	1.720	0.477	1.934	0.247
0.76	0.56	3.80	1.02	0.53	4.07	3.14	2.02	1.53	0.04	0.129	0.827	1.767	0.487	2.000	0.243
0.80	0.60	4.00	1.06	0.57	4.26	3.29	2.06	1.57	0.03	0.143	0.823	1.809	0.495	2.000	0.248
1.00	0.80	5.00	1.24	0.71	5.00	3.89	2.24	1.71	0.02	0.205	0.777	1.965	0.526	2.000	0.263
2.00	1.80	10.00	1.55	0.97	6.51	5.09	2.55	1.97	0.13	0.361	0.509	2.250	0.583	2.000	0.292
1.04	0.84	5.22	1.27	0.73	5.13	3.99	2.27	1.73	0.02	0.216	0.764	1.991	0.532	2.000	0.266
3.20	3.00	16.00	1.64	1.04	6.54	5.44	2.64	2.04	0.23	0.431	0.340	2.326	0.599	2.000	0.299
BETA= 10.00 RB=0.100 A=1.818 QONB= 172.79															
0.40	0.20	2.00	0.18	-0.19	1.40	1.00	1.19	0.82	0.50	0.001	0.499	0.994	0.362	0.362	1.000
0.44	0.24	2.20	0.36	-0.03	1.85	1.35	1.36	0.97	0.38	0.004	0.615	1.157	0.395	0.723	0.546
0.48	0.28	2.40	0.51	0.09	2.28	1.69	1.51	1.09	0.29	0.011	0.703	1.293	0.422	1.023	0.413
0.52	0.32	2.60	0.64	0.19	2.66	2.00	1.64	1.19	0.21	0.019	0.769	1.408	0.445	1.275	0.349
0.56	0.36	2.80	0.75	0.28	3.05	2.28	1.75	1.28	0.16	0.029	0.816	1.506	0.465	1.491	0.312
0.60	0.40	3.00	0.84	0.36	3.38	2.55	1.84	1.36	0.11	0.039	0.849	1.590	0.482	1.678	0.287
0.64	0.44	3.20	0.92	0.42	3.69	2.79	1.92	1.42	0.08	0.049	0.871	1.664	0.496	1.840	0.270
0.68	0.48	3.40	0.99	0.48	3.97	3.01	1.99	1.48	0.06	0.058	0.885	1.728	0.509	1.983	0.257
0.72	0.52	3.60	1.05	0.53	4.22	3.21	2.05	1.53	0.04	0.068	0.892	1.786	0.521	2.000	0.260
0.76	0.56	3.80	1.11	0.58	4.46	3.40	2.11	1.58	0.03	0.077	0.894	1.837	0.531	2.000	0.265
0.80	0.60	4.00	1.16	0.62	4.67	3.57	2.16	1.62	0.02	0.085	0.892	1.882	0.540	2.000	0.270
1.00	0.80	5.00	1.35	0.78	5.52	4.24	2.35	1.78	0.03	0.122	0.848	2.053	0.574	2.000	0.287
2.00	1.80	10.00	1.69	1.06	7.25	5.62	2.50	2.06	0.22	0.215	0.562	2.363	0.636	2.000	0.318
0.92	0.72	4.58	1.28	0.72	5.20	3.99	2.28	1.72	0.02	0.107	0.871	1.991	0.562	2.000	0.281
3.20	3.00	16.00	1.78	1.13	7.75	6.02	2.78	2.13	0.37	0.256	0.376	2.447	0.653	2.000	0.326
BETA= 20.00 RB=0.050 A=1.905 QONB= 329.87															
0.40	0.20	2.00	0.19	-0.19	1.42	1.00	1.19	0.81	0.50	0.001	0.500	0.994	0.380	0.380	1.000
0.44	0.24	2.20	0.38	-0.04	1.90	1.37	1.33	0.96	0.37	0.002	0.623	1.165	0.414	0.757	0.546
0.48	0.28	2.40	0.54	0.09	2.36	1.72	1.54	1.09	0.28	0.006	0.719	1.307	0.442	1.071	0.413
0.52	0.32	2.60	0.67	0.20	2.78	2.05	1.67	1.20	0.20	0.011	0.790	1.427	0.466	1.336	0.349
0.56	0.36	2.80	0.78	0.29	3.17	2.36	1.78	1.29	0.14	0.016	0.843	1.530	0.487	1.562	0.312
0.60	0.40	3.00	0.88	0.37	3.53	2.64	1.88	1.37	0.10	0.021	0.880	1.618	0.505	1.758	0.287
0.64	0.44	3.20	0.96	0.44	3.86	2.90	1.95	1.44	0.07	0.027	0.905	1.695	0.520	1.928	0.270
0.68	0.48	3.40	1.04	0.51	4.16	3.13	2.04	1.51	0.05	0.032	0.921	1.763	0.534	2.000	0.267
0.72	0.52	3.60	1.10	0.56	4.43	3.35	2.10	1.56	0.03	0.037	0.930	1.823	0.546	2.000	0.273
0.76	0.56	3.80	1.16	0.61	4.68	3.55	2.16	1.61	0.02	0.042	0.933	1.876	0.556	2.000	0.276
0.80	0.60	4.00	1.22	0.65	4.91	3.73	2.22	1.65	0.02	0.047	0.932	1.924	0.566	2.000	0.283
1.00	0.80	5.00	1.41	0.81	5.63	4.45	2.41	1.81	0.04	0.067	0.891	2.103	0.602	2.000	0.301
2.00	1.80	10.00	1.77	1.11	7.69	5.93	2.77	2.11	0.29	0.118	0.593	2.428	0.667	2.000	0.333
0.86	0.66	4.32	1.29	0.71	5.24	3.99	2.29	1.71	0.02	0.054	0.924	1.990	0.579	2.000	0.290
3.20	3.00	16.00	1.87	1.18	8.23	6.37	2.87	2.18	0.46	0.141	0.398	2.516	0.684	2.000	0.342

parameters for optimum C_f; and the last line for nearly maximum V_{g2}.

Mode 2. Residual Emitted Field is α.

There are applications where we wish to obtain a train of pulses from an amplifier without being concerned with efficiency. Nevertheless, the RF input cannot be on-off modulated because the amplifiers are saturated and become unstable if the input RF is turned off. Also, they cannot take the additional heat dissipation, due to power not being converted to RF. Modulating the D.C. supply is slow and impractical. In this case CARTOP is much more versatile if it is used in a mode where that cavity field is nearly always in a steady state, i.e., E_e nearly always equals α. This is achieved when $\tau_1 > 3$. Then $E_{e1} = \alpha$, $E_{e2} = \alpha(2e^{-\tau_b} - 1)$. The expression for E_r during the pulse is $E_{rb} = -(\alpha - 1) + 2\alpha e^{-\tau}$. If we increase τ_1 past 3, the peak pulse amplitude will not change as τ_1 is further increased. $E''_{ra} = (\alpha - 1)$, $E'_{rb} = (\alpha + 1)$. The last line in Table 2 lists the values for $\tau_1 = 3$.

Mode 3. Residual Emitted Field is Zero.

There is another mode where varying the period above a certain minimum value will not affect the pulse shape. In this case $E_{e2} = 0$, $E_{e1} = \alpha(1 - e^{-\tau_1})$, $\tau_b = \ln(2 - e^{-\tau_1}) = \ln(2/(e^{-\tau_2} + 1))$, $\tau_1 = \ln(1/(2 - e^{-\tau_b}))$. Increasing the period above $\tau_2 T_c$, when τ_1 and τ_b are related as indicated above, does not change the pulse shape. Note that the relationship between τ_b and τ_1 is independent of α. Table 3 lists the values of the same parameters as Table 1 except that τ_b and τ_2 are related by the zero residual emitted field condition instead of the maximum efficiency condition.

Illustrative Design: Given: P = 2.6 μs, t_b = .8 μs, $C_f = P/t_b = 3.25$, f = 2856 MHz. From Table 3 we obtain:

Q_{onp}	Q_o	V_{g2}
5.24	40,000	1.435
10.47	80,000	1.543
19.20	140,000	1.593

A waveform is shown in Fig. 6.

Mode 4.

In this mode the RF is turned off after t_2, and the residual emitted field E_{e2} is allowed to decay to zero. The period P can have any value as long as P/T_c is greater than $\tau_2 + 3$. In effect, a single uncompressed pulse of

TABLE 3. CONSTANT AMPLITUDE RF TO PULSE TRAIN CONVERTER PARAMETERS, RESIDUAL EMITTED FIELD IS ZERO.

TAU2	TAU1	TAUB	CF	E1	E2	BWNP	QONP	PPP	PAP	PDLA	PDC	EF	VG2	UC	US	UDCA
	BETA= 5.0		RB=0.200		A=1.667											
0.1	0.051	0.049	2.05	0.08	-0.00	0.03	188.50	1.173	1.085	0.471	0.000	0.529	1.041	0.042	0.042	0.000
0.2	0.105	0.095	2.11	0.17	-0.00	0.06	94.25	1.360	1.172	0.441	0.002	0.557	1.082	0.084	0.083	0.001
0.4	0.220	0.180	2.22	0.33	-0.00	0.13	47.12	1.766	1.354	0.383	0.007	0.610	1.160	0.167	0.162	0.004
0.6	0.344	0.256	2.35	0.49	-0.00	0.19	31.42	2.207	1.539	0.328	0.016	0.656	1.232	0.246	0.236	0.010
0.8	0.478	0.322	2.48	0.63	-0.00	0.25	23.56	2.668	1.722	0.279	0.028	0.693	1.300	0.319	0.301	0.018
1.0	0.620	0.380	2.63	0.77	-0.00	0.32	18.85	3.134	1.901	0.236	0.042	0.722	1.361	0.384	0.356	0.028
1.2	0.770	0.430	2.79	0.90	-0.00	0.38	15.71	3.591	2.070	0.200	0.058	0.742	1.416	0.442	0.401	0.041
1.4	0.927	0.473	2.96	1.01	-0.00	0.45	13.46	4.029	2.228	0.172	0.076	0.752	1.464	0.490	0.435	0.056
1.6	1.091	0.509	3.14	1.11	-0.00	0.51	11.78	4.438	2.371	0.151	0.094	0.755	1.507	0.531	0.459	0.072
1.8	1.260	0.540	3.33	1.19	-0.00	0.57	10.47	4.813	2.500	0.136	0.113	0.750	1.543	0.564	0.475	0.089
2.0	1.434	0.566	3.53	1.27	-0.00	0.64	9.42	5.150	2.614	0.127	0.132	0.740	1.575	0.590	0.483	0.106
2.2	1.612	0.588	3.74	1.33	-0.00	0.70	8.57	5.448	2.714	0.123	0.151	0.725	1.602	0.609	0.485	0.124
2.4	1.794	0.606	3.96	1.39	-0.00	0.76	7.85	5.709	2.800	0.123	0.170	0.707	1.625	0.624	0.483	0.142
5.0	4.314	0.686	7.28	1.64	-0.00	1.59	3.77	6.993	3.212	0.223	0.336	0.441	1.729	0.640	0.324	0.316
10.0	9.307	0.693	14.43	1.67	-0.00	3.18	1.88	7.110	3.249	0.330	0.444	0.225	1.738	0.600	0.167	0.434
	BETA= 10.0		RB=0.100		A=1.818											
0.1	0.051	0.049	2.05	0.09	-0.00	0.03	345.57	1.190	1.093	0.467	0.000	0.533	1.045	0.046	0.045	0.000
0.2	0.105	0.095	2.11	0.18	-0.00	0.06	172.79	1.395	1.189	0.434	0.001	0.565	1.089	0.091	0.090	0.001
0.4	0.220	0.180	2.22	0.36	-0.00	0.13	86.39	1.847	1.389	0.370	0.004	0.626	1.174	0.180	0.177	0.002
0.6	0.344	0.256	2.35	0.53	-0.00	0.19	57.60	2.340	1.595	0.311	0.010	0.680	1.254	0.263	0.257	0.006
0.8	0.478	0.322	2.48	0.69	-0.00	0.25	43.20	2.859	1.800	0.259	0.017	0.725	1.327	0.339	0.328	0.011
1.0	0.620	0.380	2.63	0.84	-0.00	0.32	34.56	3.386	2.001	0.215	0.025	0.760	1.394	0.405	0.388	0.017
1.2	0.770	0.430	2.79	0.98	-0.00	0.38	28.80	3.906	2.191	0.180	0.035	0.785	1.453	0.461	0.437	0.024
1.4	0.927	0.473	2.96	1.10	-0.00	0.45	24.68	4.405	2.369	0.155	0.045	0.800	1.506	0.507	0.474	0.033
1.6	1.091	0.509	3.14	1.21	-0.00	0.51	21.60	4.872	2.532	0.138	0.056	0.806	1.553	0.544	0.501	0.043
1.8	1.260	0.540	3.33	1.30	-0.00	0.57	19.20	5.301	2.678	0.129	0.067	0.804	1.593	0.571	0.518	0.053
2.0	1.434	0.566	3.53	1.38	-0.00	0.64	17.28	5.687	2.807	0.126	0.079	0.795	1.627	0.590	0.527	0.063
2.2	1.612	0.588	3.74	1.46	-0.00	0.70	15.71	6.029	2.921	0.129	0.090	0.781	1.657	0.603	0.530	0.074
2.4	1.794	0.606	3.96	1.52	-0.00	0.76	14.40	6.329	3.019	0.136	0.101	0.763	1.682	0.611	0.527	0.084
5.0	4.314	0.686	7.28	1.79	-0.00	1.59	6.91	7.806	3.488	0.321	0.200	0.479	1.795	0.542	0.354	0.188
10.0	9.307	0.693	14.43	1.82	-0.00	3.18	3.46	7.941	3.531	0.491	0.264	0.245	1.805	0.440	0.182	0.258
	BETA= 20.0		RB=0.050		A=1.905											
0.1	0.051	0.049	2.05	0.10	-0.00	0.03	659.73	1.199	1.097	0.465	0.000	0.535	1.047	0.048	0.048	0.000
0.2	0.105	0.095	2.11	0.19	-0.00	0.06	329.87	1.416	1.199	0.430	0.001	0.569	1.093	0.095	0.095	0.000
0.4	0.220	0.180	2.22	0.38	-0.00	0.13	164.93	1.893	1.410	0.363	0.002	0.635	1.182	0.187	0.186	0.001
0.6	0.344	0.256	2.35	0.55	-0.00	0.19	109.96	2.418	1.627	0.301	0.005	0.693	1.266	0.273	0.269	0.003
0.8	0.478	0.322	2.48	0.72	-0.00	0.25	82.47	2.971	1.846	0.248	0.009	0.743	1.342	0.350	0.344	0.006
1.0	0.620	0.380	2.63	0.88	-0.00	0.32	65.97	3.535	2.059	0.204	0.014	0.782	1.412	0.416	0.407	0.009
1.2	0.770	0.430	2.79	1.02	-0.00	0.38	54.98	4.092	2.262	0.171	0.019	0.810	1.475	0.471	0.458	0.013
1.4	0.927	0.473	2.96	1.15	-0.00	0.45	47.12	4.628	2.452	0.147	0.025	0.828	1.530	0.515	0.497	0.018
1.6	1.091	0.509	3.14	1.26	-0.00	0.51	41.23	5.129	2.626	0.133	0.031	0.836	1.579	0.548	0.525	0.023
1.8	1.260	0.540	3.33	1.36	-0.00	0.57	36.65	5.590	2.782	0.128	0.037	0.835	1.621	0.572	0.543	0.029
2.0	1.434	0.566	3.53	1.45	-0.00	0.64	32.99	6.006	2.921	0.130	0.043	0.827	1.657	0.587	0.552	0.035
2.2	1.612	0.588	3.74	1.52	-0.00	0.70	29.99	6.374	3.042	0.137	0.049	0.813	1.688	0.595	0.555	0.040
2.4	1.794	0.606	3.96	1.59	-0.00	0.76	27.49	6.697	3.147	0.149	0.055	0.795	1.714	0.598	0.552	0.046
5.0	4.314	0.686	7.28	1.88	-0.00	1.59	13.19	8.290	3.652	0.389	0.110	0.501	1.833	0.474	0.371	0.103
10.0	9.307	0.693	14.43	1.90	-0.00	3.18	6.60	8.437	3.697	0.599	0.145	0.256	1.843	0.332	0.190	0.142

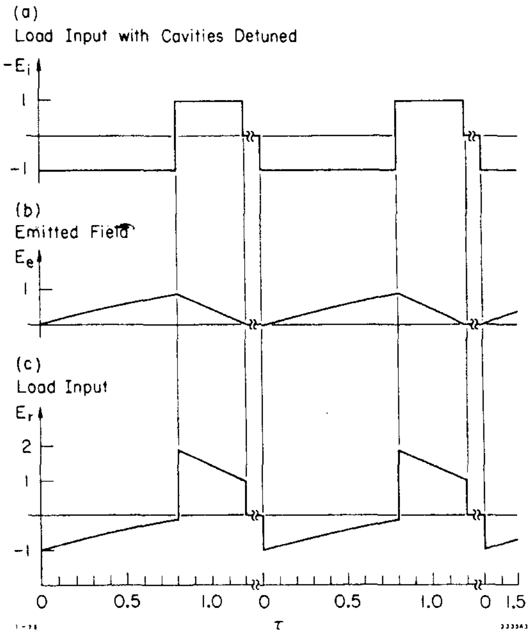

Fig. 6. Field amplitudes CARTOP 3

width t_2 is compressed into a pulse of width t_b. During τ_1 most of the incident power flows into the cavity and the rest unavoidably flows into the load. During τ_b both cavity and incident power flow into the load. See Fig. 7. For a given C_f, if τ_2 is much less than

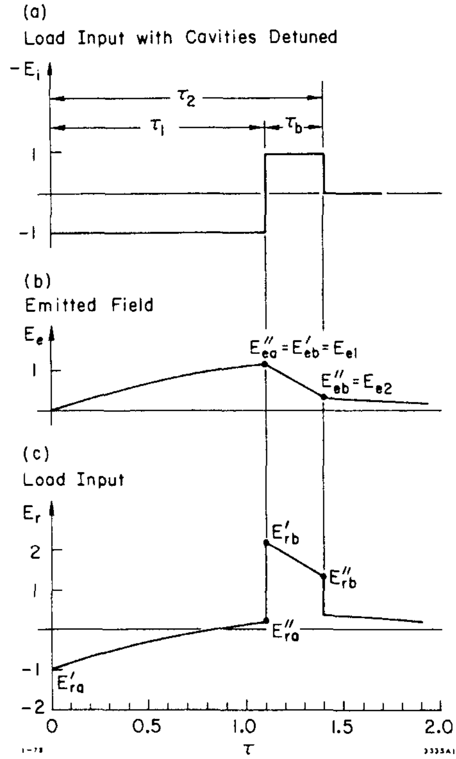

Fig. 7. Field amplitudes CARTOP 4
$Q_o/fP = 13.5$ $\alpha = 1.667$

TABLE 4. CONSTANT AMPLITUDE RF TO PULSE TRAIN CONVERTER PARAMETERS, SINGLE PULSE.

TAU2	TAU1	TAU3	E1	E2	BWMP	QOMP	PPP	PAP	PDLA	PDC	EF	VG2	UC	US	UDCA	UCA
	BETA= 5.0		RB=0.200		A=1.667	CP= 3.25										
0.1	0.069	0.031	0.11	0.06	0.03	188.50	1.235	1.176	0.547	0.002	0.362	1.084	0.146	0.144	0.002	0.211
0.2	0.138	0.062	0.22	0.10	0.06	94.25	1.477	1.344	0.438	0.008	0.413	1.159	0.254	0.248	0.006	0.367
0.4	0.277	0.123	0.40	0.16	0.13	47.12	1.969	1.645	0.297	0.024	0.506	1.281	0.395	0.377	0.019	0.571
0.6	0.415	0.185	0.57	0.19	0.19	31.42	2.454	1.896	0.218	0.041	0.583	1.373	0.475	0.443	0.032	0.686
0.8	0.554	0.246	0.71	0.19	0.25	23.56	2.920	2.093	0.173	0.057	0.644	1.439	0.519	0.475	0.044	0.749
1.0	0.692	0.308	0.83	0.17	0.32	18.85	3.359	2.241	0.150	0.071	0.689	1.485	0.542	0.488	0.054	0.783
1.2	0.831	0.369	0.94	0.14	0.38	15.71	3.765	2.344	0.139	0.082	0.721	1.513	0.553	0.490	0.063	0.799
1.4	0.969	0.431	1.03	0.09	0.45	13.46	4.139	2.409	0.136	0.092	0.741	1.528	0.556	0.486	0.071	0.803
1.6	1.108	0.492	1.12	0.03	0.51	11.78	4.478	2.441	0.139	0.101	0.751	1.531	0.554	0.476	0.077	0.800
1.8	1.246	0.554	1.19	-0.03	0.57	10.47	4.784	2.447	0.145	0.108	0.753	1.525	0.548	0.464	0.084	0.791
2.0	1.385	0.615	1.25	-0.09	0.64	9.42	5.059	2.432	0.153	0.115	0.748	1.511	0.539	0.449	0.090	0.779
2.2	1.523	0.677	1.30	-0.16	0.70	8.57	5.305	2.400	0.163	0.122	0.738	1.491	0.529	0.432	0.096	0.764
2.4	1.662	0.738	1.35	-0.23	0.76	7.85	5.524	2.356	0.175	0.129	0.725	1.467	0.517	0.415	0.103	0.747
5.0	3.462	1.538	1.61	-0.96	1.59	3.77	6.835	1.549	0.319	0.216	0.477	1.008	0.373	0.190	0.183	0.539
10.0	6.923	3.077	1.67	-1.51	3.18	1.88	7.102	0.867	0.390	0.344	0.267	0.366	0.303	0.029	0.274	0.437
	BETA= 10.0		RB=0.100		A=1.818	CP= 3.25										
0.1	0.069	0.031	0.12	0.06	0.03	345.57	1.258	1.193	0.534	0.001	0.367	1.092	0.158	0.157	0.001	0.228
0.2	0.138	0.062	0.24	0.11	0.06	172.79	1.525	1.378	0.418	0.005	0.424	1.173	0.274	0.270	0.004	0.396
0.4	0.277	0.123	0.44	0.18	0.13	86.39	2.073	1.712	0.270	0.014	0.527	1.306	0.422	0.411	0.011	0.610
0.6	0.415	0.185	0.62	0.21	0.19	57.60	2.618	1.992	0.190	0.025	0.613	1.406	0.502	0.483	0.019	0.725
0.8	0.554	0.246	0.77	0.21	0.25	43.20	3.144	2.214	0.148	0.034	0.681	1.479	0.544	0.518	0.026	0.786
1.0	0.692	0.308	0.91	0.19	0.32	34.56	3.642	2.381	0.128	0.042	0.732	1.529	0.565	0.533	0.032	0.816
1.2	0.831	0.369	1.03	0.15	0.38	28.80	4.105	2.498	0.120	0.049	0.768	1.560	0.572	0.535	0.037	0.827
1.4	0.969	0.431	1.13	0.10	0.45	24.68	4.530	2.572	0.121	0.055	0.791	1.576	0.572	0.530	0.042	0.826
1.6	1.108	0.492	1.22	0.04	0.51	21.60	4.918	2.610	0.127	0.060	0.803	1.579	0.566	0.520	0.046	0.817
1.8	1.246	0.554	1.30	-0.03	0.57	19.20	5.268	2.618	0.136	0.065	0.806	1.572	0.556	0.506	0.050	0.803
2.0	1.385	0.615	1.36	-0.10	0.64	17.28	5.583	2.603	0.149	0.069	0.801	1.557	0.543	0.490	0.054	0.785
2.2	1.523	0.677	1.42	-0.17	0.70	15.71	5.865	2.569	0.163	0.073	0.790	1.536	0.529	0.472	0.057	0.764
2.4	1.662	0.738	1.47	-0.25	0.76	14.40	6.116	2.521	0.179	0.077	0.776	1.509	0.514	0.452	0.061	0.742
5.0	3.462	1.538	1.76	-1.05	1.59	6.91	7.624	1.652	0.376	0.129	0.508	1.009	0.316	0.207	0.109	0.457
10.0	6.923	3.077	1.82	-1.65	3.18	3.46	7.932	0.968	0.498	0.205	0.298	0.309	0.194	0.031	0.163	0.281
	BETA= 20.0		RB=0.050		A=1.905	CP= 3.25										
0.1	0.069	0.031	0.13	0.07	0.03	659.73	1.271	1.203	0.527	0.001	0.370	1.096	0.165	0.164	0.001	0.238
0.2	0.138	0.062	0.25	0.12	0.06	329.87	1.553	1.397	0.407	0.003	0.430	1.181	0.285	0.283	0.002	0.412
0.4	0.277	0.123	0.46	0.19	0.13	164.93	2.134	1.751	0.256	0.008	0.539	1.321	0.437	0.430	0.006	0.631
0.6	0.415	0.185	0.65	0.22	0.19	109.96	2.714	2.048	0.176	0.013	0.630	1.426	0.516	0.506	0.010	0.746
0.8	0.554	0.246	0.81	0.22	0.25	82.47	3.276	2.284	0.135	0.019	0.703	1.502	0.557	0.543	0.014	0.805
1.0	0.692	0.308	0.95	0.20	0.32	65.97	3.809	2.462	0.117	0.023	0.758	1.554	0.576	0.558	0.018	0.831
1.2	0.831	0.369	1.07	0.15	0.38	54.98	4.305	2.588	0.111	0.027	0.796	1.587	0.581	0.560	0.021	0.839
1.4	0.969	0.431	1.18	0.10	0.45	47.12	4.762	2.667	0.114	0.030	0.821	1.603	0.578	0.555	0.023	0.835
1.6	1.108	0.492	1.28	0.04	0.51	41.23	5.178	2.709	0.123	0.033	0.833	1.607	0.570	0.544	0.025	0.823
1.8	1.246	0.554	1.36	-0.03	0.57	36.65	5.555	2.719	0.135	0.035	0.836	1.600	0.557	0.530	0.027	0.805
2.0	1.385	0.615	1.43	-0.10	0.64	32.99	5.894	2.703	0.150	0.038	0.832	1.584	0.542	0.513	0.029	0.784
2.2	1.523	0.677	1.49	-0.18	0.70	29.99	6.197	2.668	0.167	0.040	0.821	1.561	0.526	0.494	0.031	0.759
2.4	1.662	0.738	1.54	-0.26	0.76	27.49	6.468	2.618	0.185	0.042	0.806	1.533	0.508	0.474	0.034	0.733
5.0	3.462	1.538	1.84	-1.10	1.59	13.19	8.094	1.714	0.415	0.071	0.527	1.009	0.277	0.217	0.060	0.400
10.0	6.923	3.077	1.90	-1.73	3.18	6.60	8.427	1.034	0.570	0.112	0.318	0.276	0.122	0.033	0.089	0.177

TABLE 4. CONSTANT AMPLITUDE RF TO PULSE TRAIN CONVERTER PARAMETERS, SINGLE PULSE.

TAU2	TAU1	TAUB	E1	E2	BWNP	QONP	PPP	PAP	PDLA	PDC	EF	VG2	UC	US	UDCA	UCA
	BETA= 5.0		RB=0.200		A=1.667	CF= 4.84										
0.1	0.079	0.021	0.13	0.09	0.03	188.50	1.271	1.230	0.573	0.004	0.252	1.109	0.222	0.218	0.004	0.280
0.2	0.159	0.041	0.24	0.17	0.06	94.25	1.550	1.456	0.414	0.015	0.299	1.206	0.381	0.368	0.013	0.479
0.4	0.318	0.082	0.45	0.29	0.13	47.12	2.114	1.877	0.220	0.045	0.385	1.369	0.574	0.535	0.039	0.723
0.6	0.477	0.123	0.63	0.37	0.19	31.42	2.664	2.245	0.124	0.077	0.461	1.496	0.671	0.605	0.067	0.845
0.8	0.636	0.164	0.78	0.41	0.25	23.56	3.183	2.551	0.077	0.106	0.523	1.594	0.718	0.626	0.091	0.903
1.0	0.795	0.205	0.91	0.44	0.32	18.85	3.663	2.796	0.056	0.131	0.574	1.666	0.738	0.626	0.112	0.929
1.2	0.954	0.246	1.02	0.44	0.38	15.71	4.099	2.983	0.050	0.151	0.612	1.719	0.745	0.616	0.129	0.937
1.4	1.113	0.287	1.12	0.42	0.45	13.46	4.490	3.119	0.051	0.168	0.640	1.755	0.744	0.602	0.143	0.936
1.6	1.272	0.328	1.20	0.40	0.51	11.78	4.838	3.210	0.056	0.181	0.658	1.777	0.739	0.585	0.154	0.930
1.8	1.431	0.369	1.27	0.36	0.57	10.47	5.144	3.263	0.064	0.191	0.669	1.787	0.731	0.568	0.163	0.920
2.0	1.590	0.410	1.33	0.32	0.64	9.42	5.414	3.284	0.073	0.200	0.674	1.789	0.722	0.551	0.171	0.908
2.2	1.749	0.451	1.38	0.27	0.70	8.57	5.649	3.279	0.084	0.207	0.673	1.783	0.711	0.533	0.178	0.895
2.4	1.908	0.492	1.42	0.22	0.76	7.85	5.853	3.254	0.095	0.214	0.667	1.770	0.700	0.515	0.185	0.880
5.0	3.974	1.026	1.64	-0.48	1.59	3.77	6.945	2.323	0.253	0.274	0.477	1.398	0.542	0.289	0.253	0.682
10.0	7.949	2.051	1.67	-1.24	3.18	1.88	7.108	1.219	0.388	0.362	0.250	0.749	0.407	0.074	0.332	0.512
	BETA= 10.0		RB=0.100		A=1.818	CF= 4.88										
0.1	0.079	0.021	0.14	0.10	0.03	345.57	1.297	1.252	0.554	0.003	0.257	1.119	0.240	0.238	0.002	0.303
0.2	0.159	0.041	0.27	0.18	0.06	172.79	1.606	1.501	0.386	0.009	0.308	1.225	0.409	0.401	0.008	0.515
0.4	0.318	0.082	0.50	0.31	0.13	86.39	2.236	1.971	0.188	0.027	0.404	1.403	0.607	0.584	0.023	0.764
0.6	0.477	0.123	0.69	0.40	0.19	57.60	2.855	2.383	0.096	0.046	0.489	1.541	0.699	0.659	0.040	0.880
0.8	0.636	0.164	0.86	0.45	0.25	43.20	3.443	2.728	0.057	0.063	0.560	1.648	0.738	0.683	0.054	0.928
1.0	0.795	0.205	1.00	0.47	0.32	34.56	3.988	3.005	0.045	0.078	0.616	1.727	0.750	0.683	0.067	0.943
1.2	0.954	0.246	1.12	0.48	0.38	28.80	4.485	3.218	0.046	0.090	0.660	1.784	0.749	0.672	0.077	0.942
1.4	1.113	0.287	1.22	0.46	0.45	24.68	4.931	3.372	0.054	0.100	0.692	1.823	0.741	0.656	0.085	0.932
1.6	1.272	0.328	1.31	0.43	0.51	21.60	5.329	3.476	0.065	0.108	0.713	1.847	0.730	0.638	0.092	0.918
1.8	1.431	0.369	1.38	0.39	0.57	19.20	5.681	3.537	0.078	0.114	0.725	1.859	0.717	0.620	0.097	0.902
2.0	1.590	0.410	1.45	0.35	0.64	17.28	5.989	3.561	0.092	0.119	0.731	1.860	0.702	0.601	0.102	0.884
2.2	1.749	0.451	1.50	0.30	0.70	15.71	6.259	3.557	0.108	0.123	0.730	1.854	0.687	0.581	0.106	0.865
2.4	1.908	0.492	1.55	0.24	0.76	14.40	6.494	3.529	0.123	0.127	0.724	1.840	0.672	0.562	0.110	0.845
5.0	3.974	1.026	1.78	-0.53	1.59	6.91	7.751	2.495	0.329	0.163	0.512	1.435	0.466	0.316	0.150	0.586
10.0	7.949	2.051	1.82	-1.35	3.18	3.46	7.939	1.311	0.516	0.215	0.269	0.726	0.279	0.081	0.198	0.351
	BETA= 20.0		RB=0.050		A=1.905	CF= 4.88										
0.1	0.079	0.021	0.15	0.10	0.03	659.73	1.312	1.265	0.544	0.001	0.259	1.125	0.251	0.250	0.001	0.316
0.2	0.159	0.041	0.28	0.19	0.06	329.87	1.638	1.528	0.370	0.005	0.313	1.236	0.425	0.420	0.004	0.534
0.4	0.318	0.082	0.52	0.33	0.13	164.93	2.307	2.025	0.170	0.015	0.415	1.422	0.625	0.612	0.013	0.786
0.6	0.477	0.123	0.72	0.42	0.19	109.96	2.967	2.464	0.082	0.025	0.505	1.567	0.713	0.691	0.022	0.897
0.8	0.636	0.164	0.90	0.47	0.25	82.47	3.596	2.832	0.049	0.035	0.581	1.679	0.746	0.716	0.030	0.938
1.0	0.795	0.205	1.04	0.50	0.32	65.97	4.180	3.128	0.043	0.043	0.642	1.762	0.752	0.716	0.037	0.947
1.2	0.954	0.246	1.17	0.50	0.38	54.98	4.713	3.356	0.049	0.049	0.688	1.822	0.746	0.704	0.042	0.939
1.4	1.113	0.287	1.28	0.48	0.45	47.12	5.193	3.521	0.061	0.055	0.722	1.862	0.734	0.687	0.047	0.923
1.6	1.272	0.328	1.37	0.45	0.51	41.23	5.621	3.633	0.076	0.059	0.745	1.888	0.719	0.669	0.050	0.905
1.8	1.431	0.369	1.45	0.41	0.57	36.65	5.999	3.698	0.092	0.062	0.759	1.900	0.702	0.649	0.053	0.884
2.0	1.590	0.410	1.52	0.36	0.64	32.99	6.331	3.725	0.110	0.065	0.764	1.901	0.685	0.629	0.056	0.862
2.2	1.749	0.451	1.57	0.31	0.70	29.99	6.622	3.721	0.128	0.068	0.763	1.894	0.667	0.609	0.058	0.839
2.4	1.908	0.492	1.62	0.25	0.76	27.49	6.875	3.692	0.146	0.070	0.757	1.880	0.649	0.589	0.060	0.816
5.0	3.974	1.026	1.87	-0.55	1.59	13.19	8.231	2.598	0.382	0.090	0.533	1.455	0.413	0.331	0.083	0.520
10.0	7.949	2.051	1.90	-1.42	3.18	6.60	8.434	1.368	0.601	0.118	0.281	0.713	0.194	0.085	0.109	0.244

one then the cavities discharge too fast and the P_{ap} approaches zero; if τ_2 is much greater than one then the cavities do not charge and P_{ap} again approaches zero. There is an optimum τ_2 where the pulse average power and average field are a maximum. Table 4 lists the same parameters as Table 1 for C_f = 3.25, 4.88, 6.5. In addition, it lists UCA, the fraction of power going into the cavity during t_1.

Illustrative Design: Given: P = 2.6 μs, t_b = .8 μs, C_f = 3.25, f = 2856 MHz, Q_o = 90,000, Q_{onp} = 12.12. From Table 4 we obtain: $V_{g2(max)}$ = 1.531.

With a single RN, no matter how large C_f is, the maximum peak pulse power gain is 9. It can be increased if several RN's are used in tandem. For n RN's, at least theoretically, the power gain is 9^n. Analysis of more than one RN, applications to coding CW Radar and to digital communication, are the subjects of other notes.

Advantages of CARTOP

Presently the methods of pulse modulating a high power RF amplifier are: hard tube pulser, line type pulser and pulse modulating the RF input. The disadvantages of the first two when compared to CARTOP are:

- Hard tube pulser: it requires a high power grided vacuum "switch" tube, average power (duty ratio) is limited by the amount of average power which the switch tube can dissipate, peak power is limited by high voltage hold off, and peak current capacity of the switch tube.

- line type pulser: interpulse interval must be several times the deionization time of the discharge tube (i.e., >100 μs).

Both of the above require high power active element switches whereas in CARTOP the switching is done at low power. Also, CARTOP pulse has sharper leading and trailing edges.

Pulse modulation of the RF input (4:1) peak power gain, is approximately 4 times less efficient than CARTOP, i.e., requires 4 times as much CW power for the same pulse power; also, the unused power is dissipated in the amplifier itself.

Conclusion

A comparison of CARTOP and other modulation methods is shown in Fig. 8. For each case the unavoidably useless normalized power is noted in a box near the amplifiers, and the efficiency is given. For the same pulse width and pulse repetition frequency CARTOP is 4 times more efficient than OOK. But even when the efficiencies are comparable, CARTOP has the advantage of peak power gain.

CARTOP is useful in applications where high repetition rate, sharp rise time, narrow pulses, and peak power amplification are needed. The last is especially useful in Mode 4, where the output peak power is limited by the peak power capability of the amplifier. The amplifier bandwidth has to be broad enough to transmit the phase modulation, and the RN network, which has only passive components, has to be able to take the amplifier output power. At the Stanford Linear Accelerator Center,

TABLE 4. CONSTANT AMPLITUDE RF TO PULSE TRAIN CONVERTER PARAMETERS, SINGLE PULSE.

TAU2	TAU1	TAUB	E1	E2	BWNP	QONP	PPP	PAP	PDLA	PDC	EF	VG2	UC	US	UDCA	UCA
	BETA= 5.0		RB=0.200		A=1.667	CF= 6.50										
0.1	0.085	0.015	0.14	0.11	0.03	188.50	1.289	1.258	0.581	0.006	0.193	1.121	0.265	0.259	0.005	0.313
0.2	0.169	0.031	0.26	0.20	0.06	94.25	1.586	1.514	0.397	0.020	0.233	1.230	0.449	0.432	0.018	0.531
0.4	0.338	0.062	0.48	0.35	0.13	47.12	2.186	2.000	0.181	0.059	0.308	1.414	0.665	0.612	0.053	0.786
0.6	0.508	0.092	0.66	0.46	0.19	31.42	2.767	2.435	0.083	0.100	0.375	1.559	0.763	0.672	0.091	0.902
0.8	0.677	0.123	0.82	0.53	0.25	23.56	3.311	2.805	0.043	0.139	0.432	1.673	0.803	0.679	0.124	0.949
1.0	0.846	0.154	0.95	0.58	0.32	18.85	3.809	3.110	0.031	0.171	0.478	1.760	0.815	0.663	0.152	0.964
1.2	1.015	0.185	1.06	0.60	0.38	15.71	4.256	3.351	0.032	0.197	0.516	1.826	0.814	0.639	0.175	0.962
1.4	1.185	0.215	1.16	0.61	0.45	13.46	4.652	3.535	0.039	0.217	0.544	1.874	0.807	0.614	0.193	0.954
1.6	1.354	0.246	1.24	0.60	0.51	11.78	5.001	3.668	0.049	0.234	0.564	1.907	0.798	0.590	0.207	0.943
1.8	1.523	0.277	1.30	0.58	0.57	10.47	5.305	3.758	0.059	0.246	0.578	1.928	0.787	0.568	0.219	0.930
2.0	1.692	0.308	1.36	0.56	0.64	9.42	5.569	3.811	0.070	0.257	0.586	1.939	0.776	0.548	0.228	0.917
2.2	1.862	0.338	1.41	0.52	0.70	8.57	5.797	3.834	0.081	0.265	0.590	1.941	0.765	0.530	0.236	0.905
2.4	2.031	0.369	1.45	0.49	0.76	7.85	5.992	3.831	0.092	0.272	0.589	1.938	0.755	0.512	0.242	0.892
5.0	4.231	0.769	1.64	-0.13	1.59	3.77	6.982	2.956	0.227	0.319	0.455	1.642	0.619	0.321	0.298	0.732
10.0	8.462	1.538	1.67	-0.95	3.18	1.88	7.109	1.620	0.370	0.381	0.249	1.035	0.476	0.112	0.364	0.563
	BETA= 10.0		RB=0.100		A=1.818	CF= 6.50										
0.1	0.085	0.015	0.15	0.12	0.03	345.57	1.317	1.283	0.560	0.003	0.197	1.132	0.286	0.283	0.003	0.338
0.2	0.169	0.031	0.28	0.22	0.06	172.79	1.646	1.566	0.365	0.012	0.241	1.251	0.481	0.471	0.011	0.569
0.4	0.338	0.062	0.52	0.38	0.13	86.39	2.317	2.108	0.147	0.035	0.324	1.452	0.699	0.667	0.032	0.826
0.6	0.508	0.092	0.72	0.50	0.19	57.60	2.972	2.596	0.059	0.060	0.399	1.610	0.787	0.733	0.054	0.931
0.8	0.677	0.123	0.89	0.58	0.25	43.20	3.588	3.015	0.032	0.082	0.464	1.734	0.815	0.741	0.074	0.963
1.0	0.846	0.154	1.04	0.63	0.32	34.56	4.154	3.360	0.032	0.102	0.517	1.829	0.814	0.723	0.091	0.962
1.2	1.015	0.185	1.16	0.66	0.38	28.80	4.664	3.634	0.045	0.117	0.559	1.901	0.801	0.697	0.104	0.947
1.4	1.185	0.215	1.26	0.67	0.45	24.68	5.117	3.844	0.061	0.129	0.591	1.953	0.785	0.670	0.115	0.928
1.6	1.354	0.246	1.35	0.66	0.51	21.60	5.516	3.996	0.079	0.139	0.615	1.989	0.767	0.644	0.123	0.907
1.8	1.523	0.277	1.42	0.64	0.57	19.20	5.865	4.099	0.096	0.147	0.631	2.012	0.750	0.620	0.130	0.887
2.0	1.692	0.308	1.48	0.61	0.64	17.28	6.168	4.160	0.112	0.153	0.640	2.024	0.734	0.598	0.136	0.867
2.2	1.862	0.338	1.54	0.57	0.70	15.71	6.429	4.186	0.128	0.158	0.644	2.027	0.718	0.578	0.140	0.849
2.4	2.031	0.369	1.58	0.53	0.76	14.40	6.654	4.183	0.143	0.162	0.644	2.023	0.703	0.559	0.144	0.831
5.0	4.231	0.769	1.79	-0.15	1.59	6.91	7.794	3.200	0.319	0.190	0.492	1.700	0.528	0.350	0.178	0.623
10.0	8.462	1.538	1.82	-1.04	3.18	3.46	7.940	1.731	0.507	0.227	0.266	1.038	0.339	0.122	0.217	0.401
	BETA= 20.0		RB=0.050		A=1.905	CF= 6.50										
0.1	0.085	0.015	0.15	0.12	0.03	659.73	1.333	1.297	0.548	0.002	0.200	1.139	0.298	0.297	0.002	0.352
0.2	0.169	0.031	0.30	0.23	0.06	329.87	1.681	1.596	0.347	0.006	0.245	1.263	0.499	0.493	0.006	0.590
0.4	0.338	0.062	0.55	0.40	0.13	164.93	2.393	2.172	0.130	0.019	0.334	1.473	0.716	0.699	0.017	0.847
0.6	0.508	0.092	0.76	0.52	0.19	109.96	3.092	2.691	0.048	0.033	0.414	1.639	0.798	0.768	0.030	0.943
0.8	0.677	0.123	0.94	0.61	0.25	82.47	3.751	3.138	0.030	0.045	0.483	1.769	0.816	0.776	0.041	0.965
1.0	0.846	0.154	1.09	0.66	0.32	65.97	4.358	3.507	0.039	0.056	0.540	1.869	0.807	0.758	0.050	0.954
1.2	1.015	0.185	1.21	0.69	0.38	54.98	4.905	3.801	0.059	0.064	0.585	1.944	0.788	0.730	0.057	0.931
1.4	1.185	0.215	1.32	0.70	0.45	47.12	5.392	4.026	0.081	0.071	0.619	1.998	0.765	0.702	0.063	0.904
1.6	1.354	0.246	1.41	0.69	0.51	41.23	5.822	4.189	0.104	0.076	0.645	2.036	0.742	0.675	0.068	0.877
1.8	1.523	0.277	1.49	0.67	0.57	36.65	6.197	4.300	0.125	0.080	0.662	2.060	0.721	0.650	0.071	0.852
2.0	1.692	0.308	1.55	0.64	0.64	32.99	6.523	4.365	0.145	0.084	0.672	2.073	0.701	0.627	0.074	0.829
2.2	1.862	0.338	1.61	0.60	0.70	29.99	6.805	4.394	0.164	0.087	0.676	2.076	0.682	0.605	0.077	0.806
2.4	2.031	0.369	1.65	0.56	0.76	27.49	7.046	4.392	0.182	0.089	0.676	2.072	0.665	0.585	0.079	0.785
5.0	4.231	0.769	1.88	-0.15	1.59	13.19	8.277	3.345	0.382	0.104	0.515	1.734	0.464	0.367	0.097	0.548
10.0	8.462	1.538	1.90	-1.09	3.18	6.60	8.435	1.798	0.599	0.124	0.277	1.040	0.247	0.128	0.119	0.292

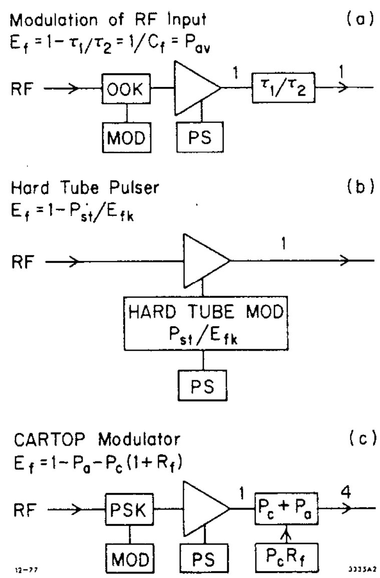

Fig. 8. Comparison of OOK, Hard Tube and CARTOP modulation, highlighting their efficiencies.

as part of the SLAC Energy Development program[2,7], with 40 MW peak 5 μsec pulse into the RN, an output peak power of 240 MW has been achieved.

REFERENCES

1. Z. D. Farkas and P. B. Wilson, "Peak Power Multiplier," US Patent #4009444, February 1977.
2. Z. D. Farkas, et al., "SLED: A Method of Doubling SLAC's Energy," Proc. 9th International Conf. on High Energy Accel., p. 576, May 1976.
3. M. I. Skolnik, "Introduction to Radar Systems," McGraw Hill, 1962, Ch. 3.
4. H. Laboutet in "Linear Accelerators," P. Lapostolle and A. Septier, Eds., North Holland, Amsterdam, Ch. B3.3, Section 4.
5. J. Haimson, et al., "A Wide Dynamic Range 10 MeV High Current Linear Accelerator," IEEE Trans. on Nuc. Sci., Vol. NS-22, No. 3, June 1975.
6. P. B. Wilson, "The Theoretical Surface Resistance for Superconducting Lead and Niobium at High Frequencies," SLAC-TN-70-35, Dec. 1970.
7. Z. D. Farkas, et al., "Recent Progress on SLED, The SLAC Energy Doubler," IEEE Trans. on Nuc. Sci., Vol. NS-22, No. 3, June 1975.