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PULSE POWER FOR 0.3 - 0.5 μ s DURATIONS

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MASTER

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PULSE POWER FOR 0.3 - 0.5 μ s DURATIONS

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PULSE POWER FOR 0.3 - 0.5 μ S DURATIONS

1. Introduction

Conceptual design studies indicate that the KrF lasers which would drive inertial confinement fusion reactors will obtain their energy from multi-megajoule electron beams with pulse durations of perhaps three to five tenths of a microsecond. There have been few applications for large beam systems in this pulse range. Designers of small systems have found it convenient to use "run-down" circuits in which a simple capacitor, in the form of a Marx, discharges by about 10 - 20% from its initial voltage, then is crowbarred; this leaves 60 - 80% of the Marx energy unused, which is unacceptable in large systems and reactors. Thus an optimum pulse power has not been developed for these pulse durations. Well established cost-data are not available for extrapolation to future systems, which adds to the uncertainty of reactor costs; these costs are uncertain anyway because of the need to develop repetitive, reliable systems, but if single-shot costs were available, a comparison could at least be made on that basis with other drivers with pulse durations in the ranges less than 0.1 μ s (protons, electrons) and greater than 1 μ s (CO_2 lasers), for which development of large systems has already taken place. Further, it is desirable to know the dependence of costs on pulse duration, since the choice of drive pulse duration for KrF lasers in the first place must be a compromise between the higher cost of pulse power at short durations and the increased cost associated with compression or stacking to obtain the 10 ns light pulse when a long drive pulse duration is used in a laser medium that does not store energy.

The purposes of this paper are to list the techniques that seem to be candidates for making 0.3 - 0.5 μ s pulses cheaply and efficiently, and to document initial thoughts about how best to use them and about their advantages and limits. Each technique is given a separate section, in which existing technology is applied to the design problem and a little consideration is given to how the design might be adapted for a reliable reactor.

The general requirements are taken to be a current density of about 30A/cm^2 at a voltage of 1 to 2 MV. The power density is approximately 0.5 TW/m^2 . This is associated with a desire to use laser modules with apertures as large as possible, of the order of one meter in diameter. Smaller apertures do not need such high power densities in the driving circuit, and this could ease the pulse power design at the expense of needing more laser modules.

It is anticipated that the power for each laser module will come from a number of pulser modules operating in parallel. It would be convenient if each driver module matched the size and shape of a diode or a vacuum interface of a laser module. If the size of a diode module is set by beam pinching (as when no external magnetic field is used) it must be no more than about 40 cm in diameter. A simple, flat vacuum interface would have to be larger than this, perhaps 1 - 2 m in diameter for reliable long-pulse hold-off. Thus already possible conflicts can be foreseen. However, there are ways to overcome these, such as magnetically-isolated diodes, thermionically limited cathodes, stacked insulators (which can easily be resistively graded at this pulse duration), and converging vacuum lines that make vacuum insulator size

independent of cathode size. Therefore little or no attention will be paid to the interface between the pulser module and the laser module, and it is assumed that the pulser module current, size and shape can be chosen optimally for each approach.

Similarly no attention is paid here to cathode design. Cold cathode technology is reasonably understood in this duration regime, though improvements will doubtless be made. Hot cathodes are now emerging for this current density range. Gridded guns may prove feasible too, but if these are used as switches the vacuum region including the interface must stand a higher voltage, for a longer time; this seems undesirable, and consequently designs using this approach are not considered.

The pulse power needs for KrF lasers have much in common with those for linear induction accelerators of ≥ 1 GV heavy ions for inertial confinement fusion. In present ion accelerator designs pulse durations of a few hundred nanoseconds are called for at the high energy end of the accelerator where the pulse duration is least, the beam current greatest, and consequently the pulse power demands are greatest. Both the voltage and current of a pulser module can be chosen with considerable freedom, since the accelerating voltage per stage is quite arbitrary and one pulser module may power a number of stages in parallel.

Designers of heavy ion accelerators have suggested using enough pulsers to reduce the switch current to less than 10 kA in order to facilitate repetitive operation. This option is also open for the KrF laser designer. It is likely to carry a cost penalty because of the increased number of pulsers needed in parallel and because of the fact that where pulse-lines are used the small

current requires the use of oil dielectric rather than water, and hence about ten times the volume. However, in view of the uncertainties associated with obtaining reliable repetitive operation this approach of division into low energy units should not be ignored.

2. Pulse Forming Lines

The most straight forward adaptation of existing technology is to use water dielectric pulse lines. For pulse durations of 0.3 - 0.5 μ s these become 16 - 28 feet long. Because of the long pulse, they must be charged fairly slowly, perhaps in 1.5 - 2 μ s. Present practice for large single-shot systems charged in this time is to use charging fields of about 100 kV/cm on the positive electrode. Some unknown de-rating will be required in a reactor.

Table 1 lists several possible configuration for pulse lines and gives for each the maximum theoretical power densities in terms of the charge field and dielectric constant. The value of this expression is shown for water at 100 kV/cm. Also shown is a power density obtained from some first order designs in which allowance has been made for some practical factors like edge effects and switch sizes. Considering the de-rating needed in the reactor, it seems clear that the water line cross section will be greater than that of the $\sim 1\text{TW}/\text{m}^2$ interface with the laser, and thus some power convergence is needed. This is easily accomplished with passive water lines or vacuum lines.

For the reactor application requiring reliable repetitive operation the developmental items that might entail risk or high costs are the repetitively stressed water dielectric, the high voltage pulse-line switches and the capacitors and the lower voltage switches in the Marx generators that charge

TABLE 1

Power Densities Available from Water Pulse Lines

Configuration	Power Density (TW/m ²)/ $\epsilon^{1/2}E^2$	Theoretical Value for E=80, E=100 kV/cm	"Practical" Value, E=100kV/cm
Flat Blumlein	6.6	0.59	0.25
Coax Blumlein:			
+ charge	4.9	0.44	0.33
- charge	3.7	0.33	0.33
Simple Coax	12 ln G		
	(G = polarity effect)		
	8.3-11	0.75-0.98	0.60

the lines (for the charging times of this application, transformers could be used instead of Marxes; this would not change the requirements on the low voltage switches, but by placing them at ground potential would allow devices such as thyratrons to be used.) The characteristic impedance of water is such that each 1 - 2 MV pulse line switch will carry 150 - 300 kA, 50 - 150 nC per pulse. From the standpoint of inductance, single channel switches are adequate, but to minimize wear multiple channels are most probably desirable. The current per switch and the energy per line element could be reduced by using oil or some other low permittivity dielectric; however, in the case of oil the energy density is less than that of water by a factor of about sixteen at typical single pulse operating fields (about 150 KV/cm), so that a corresponding greatly increased volume of pulse line is required.

For a 1 MJ laser, we may take the stored energy to be 20 MJ and the pulse-line output is about 16 MJ delivered in typically 0.4 μ s, i.e. at 40 TW. If a water line system is employed at a de-rated power density of about 0.15 TW/m², the volume of water line needed approaches 2000 m³. The minimum number of Marxes needed is determined by the time allowed to charge the lines; if this time is 2 μ s and the Marxes are of fairly simple design with $\sim 3 \mu$ H/MV, about 100 Marxes are needed. This assumes that the spark gaps can reliably carry 250 A and 0.4 C.

A desirable development here would be a dielectric with larger energy and power density, that could withstand a significantly longer charge time. This would allow charging from rotating machines such as a fast alternator with a transformer, or a homopolar generator via an inductive store, if a suitable long life opening switch could be developed. Solid dielectrics fit the

description, and these have the advantage of a low permittivity that would reduce current and energy per element if desired.

Plastic at about 1 MV/cm has energy and power densities greater than water at 100 KV/cm². Films such as polypropylene should have reasonable lifetimes at this stress level. If pulse charged, the dielectric edges can be designed for high voltages per section rather than the range of less than 10 V used the d.c. capacitors. The problem in the past has been to obtain high reliability against edge failure, tracking, etc. at high absolute charge voltages, of the order at 1 MV.

Rudakov has expressed an interest in a different dielectric, oil impregnated paper, for similar reasons. He was referring to cables, but if this dielectric is indeed useful it might be more convenient in extruded sheet form. This suggestion could be evaluated by collecting a.c. and d.c. data from cables and performing pulse-life measurements.

3. Pulse Charged PFNs

Assuming that solid dielectrics can be used successfully at high absolute voltages, it would still be difficult to build a pulse line whose physical length is long enough to provide a 0.3-0.5 μ s pulse. It would be more convenient to use discrete elements connected by small lumped inductances, or to construct a Type E PFN. This would probably discharge through a switch in series with the load, since Blumleins using lumped element lines produce poor rise times.

Such a PFN could be formed from lower voltage elements pulse charged in series rather than from high voltage elements. Reliable 100 kV polypropylene sections have been developed for EMP systems. Each element would resemble a low inductance d.c. capacitor.

Generally, the idea expressed here is that pulse charged solid dielectric units, in whatever form -- low voltage or high voltage elements -- may be greatly superior in cost, lifetime and inductance to the d.c. charged capacitors that we use now; and that the pulse charging system might be mainly rotating machinery and add little to the cost of the system while having the property of very long life.

Another form of pulse charged PFN is a water line, such as a coax, where the charged conductor is divided into discrete elements with series inductors. This would reduce the length of water line needed for the 0.3-0.5 μ s pulse, and may also help by reducing the current per switch; the power density would be similarly reduced and the cross section area correspondingly increased. This technique might be particularly useful for experimental devices, since the pulse duration could be simply and even remotely changed adjusting the connections at the discrete line-elements.

Series switches triggered with low jitter, probably operating at about twice the load voltage, are needed for pulse charged PFNs. The current per switch can, however, be chosen with greater freedom than in the water line approach.

4. Marx PNY

In order to give a reasonably rectangular pulse, low inductance Marxes must be used, and a considerable number of these are needed in parallel. For example, in a two-section Type A PFN (Fig 1a) with a total rise-time to nominal voltage that is about 20 percent of the power pulse duration T ,

$$T \approx 3(LC)^{\frac{1}{2}}$$

where L and C are the inductance and capacitance of the Marx. Hence

$$C = T^2/9L$$

and the stored energy W_0 is given in terms of the charge voltage V_0 by

$$W_0 = \frac{1}{2}CV_0^2 = T^2V_0/18(L/V_0)$$

In a reactor the PFN can at most be mismatched by a factor of about 2, corresponding to a loss of about 11 percent in energy. The maximum energy can therefore be stored per Marx when the output voltage V is given by $V = 3V_0$, or

$$W_0 = \frac{1}{6} T^2 V \left(\frac{L}{V_0} \right)^{-1}$$

For a moderately low inductance single channel Marx, $\left(\frac{L}{V_0} \right)$ is $\sim 1 \mu\text{H/MV}$, so that if W_0 is in MJ, T in μs and V in Mv

$$W_0 = (1/6) T^2 V \text{ (MJ)}$$

and the output energy W is

(a) Type A PFN

Filter may be distributed within stages of marx. Marx inductance forms a part of ideal circuit.

(b) Type C PFN

Each Marx stage has the circuit shown.

(c) Circuit used for calculations of Type C PFN

Much of the intrinsic Marx inductance appears as L , a stray term.

Fig. 1 PFN Marx Circuits

$$\begin{aligned}
 W &\sim 0.9 W_0 \sim 0.15 T^2 V \\
 &\sim 150 T^2 V \text{ (kilojoules)}
 \end{aligned}$$

For the range 0.3 to 0.5 μ s, at 1 MV, the energy is at least 13-40 kJ.

The energy per Marx might be increased by using a Type C PFN, Figure 1(b), since this uses parallel, rather than series pulse-shaping. However, it is more difficult to characterize this circuit, because when it is used in a Marx generator a large part of the Marx inductance becomes a stray term, in contrast to the Type A PFN where all of the Marx inductance can be regarded as part of the ideal circuit.

Numerical calculations have been made of the waveforms produced by two and three section Type C PFNs with series inductance. The objective is to maximize the permissible ratio of the "stray" inductance L (Figure 1c) to the remaining inductance associated with the main energy storage element, L_1 . The best results were obtained when the PFN parameters were chosen to give a relatively short rise time at the expense of overshoot and ringing for the ideal resistance load. The stray inductance then filters out the ringing. Lowering L_1 and raising C_2 further flattens the voltage waveform generated into a matching resistive load. The third section gives little benefit when the inductance is present, and two sections are adequate.

Figure 2 shows waveforms resulting from this process. These are roughly comparable to the Type A result in general quality, though the mismatched case now gives a slower rise. For the case shown, $L \sim L_1$. Now in a low inductance Marx design with 1μ H/MV the common inductance L includes most of the over-all inductance and the natural contribution to L_1 , which is that of

the capacitor and connections to the spark gaps, is quite a matter. Thus, much of L_1 will have to be added. The current path comprising C_1 , L_1 and L_2 will then have an inductance of perhaps $L_1 + L_2 = 1.5 \mu\text{H}$.

The power pulse in Figure 2 (matched case) has a duration of $C^{1/2} (L + L_1)^{1/2}$. It delivers 84% of the stored energy between the present points (75% in the mismatched case). From this it must be shown that the result for the maximum delivered energy per Marx stage, the same as for the Type A design.

Therefore the Type A and Type C PFNs appear comparable for this application.

Thus it appears that for a 50-100 kJ laser module operating at 1-2 MV with 5% efficiency at least about 25 parallel Marx PFNs might be needed. A megajoule laser would require about 1000 Marxes. This approach is clearly complex, but it may have some positive features. First, it has comparatively low current and charge per spark-gap (30-70 kA, 10-60 nC), which might prove an advantage for reliability; it is consistent with the philosophy advocated for the heavy ion LIA. Second, a few redundant Marxes could be added with little penalty. The wide operating range of a Marx with a good trigger scheme is such that these could remain permanently connected when not in use; the spark gaps could withstand the output voltage of the system without over-pressurization, so that the Marx would be available on a pulse-by-pulse basis as needed. Third, capacitors and low voltage spark gaps are the only critical components needing development for the reactor regime, whereas schemes previously listed require high voltage triggered switches and water lines or other pulse charged high voltage components. The chance of a

Fig. 2 "Optimized" PFN Performance (Type C)

favorable outcome of development is therefore higher. For example, the use of a compensated alternator to pulse charge the Marx (in say 100 μ s) might make great improvements in the life or reliability of both of the critical components, capacitors and switches.

The complexity and hence the cost of Marx PFNs is obviously a strong function of the pulse duration. The PFN becomes cheaper than and preferable to the water line somewhere in the hundreds of nanoseconds pulse durations range. The cross over point is not clear, and in order to find it for this application it will be necessary to develop the PFN to a degree comparable to the present development of water lines, and to understand for each the implications at long life, including the benefits of reduced energy per section and pulse charging. The cross over point will also be affected by the ability to build Marxes with multiple channel switches and lower inductance; again a fast charge of the Marx may be very helpful.

5. Marx Peaking Circuit

This circuit (Figure 3) is in effect a compromise between a Marx-charged pulse forming line and a Marx PFN. The energy that can be delivered per Marx is increased over the PFN case by an active "peaking" circuit comprising a pulse charged capacitor and output switch. This reduces the number of circuits needed. At the same time the pulse charged capacitor is much smaller than the pulse forming line and the output switch is much simpler.

In order to start quantifying the capability of the peaking circuit, a series of calculations was made with the circuit of Figure 3. The peaking capacitance, switch time and load impedance (independent of time) were all varied. The energy delivered to the load was computed in the interval in

In the calculations made here, Z is a linearly decaying resistor, L_p is neglected, and S_2 is closed at a time, t , after the closure of S_1 , given by the phase angle

$$\phi = \left(\frac{C_p + C_0}{L_0 C_0 C_p} \right)^{1/2} \times \frac{180}{\pi} \text{ (degrees)}$$

Fig. 3 Schematic of Peaking Circuit

which the load voltage was between 100% and 75% of the peak. This energy can be maximized by closing the output switch when the current is still rising and using a load resistance somewhat larger than the ratio of instantaneous peaker voltage and circuit current at the time of closure. Under these conditions the load voltage continues to rise gently after switch closure, then begins to fall slowly. This can be compared to the "classical" peaking condition where the current is a maximum at closure and the load resistance equals the instantaneous rates of voltage and current, in which case the load voltage first remains constant then begins to fall. A typical waveform is in Figure 4.

Results are shown in Table 2. For each calculation the relative size of the peaking capacitor, the switch out phase and the normalized load impedance (the input parameters) are shown on the left. The normalized peak output voltage (V_R) is shown. Then the efficiency from stored energy (ϵ) and the normalized duration T_R between 75% points are shown. Values of T_R and n between 90% points are shown on the right.

The normalized energy delivered, W_R , can readily be shown to be

$$W_R = \frac{T^2 V}{(-\frac{L}{V_0})} \left(\frac{n}{2V_R T_R^2} \right)$$

This can be compared with the results for PFNs,

$$W \sim 0.15 T^2 V / (L/V_0)$$

so that the expression $n/2V_R T_R$ gives an indication of how much energy can be stored per peaking circuit as opposed to per PFN. Since the PFNs deliver 70-80% of the stored energy between 75% and 100% of the peak voltage,

$$C_p/C_0 = \frac{1}{3}, \phi = 70 \text{ deg} \quad Z = 1.2 (L_0/C_0)^{1/2}$$

Fig. 4 Typical Peaking Circuit Waveform

TABLE 2
Peaking Circuit Results

C_p/C_o	ϕ (deg)	$Z(\frac{C_o}{L_o})^{1/2}$	$\hat{V}/V_o=V_R$	η	$T/(L_o C)^{1/2}=T_R$	$\eta/2V_R T_R^2=W_R$	W_p/W_{load}	η	T_R
1/3	90	1.5	0.75	.75	1.16	0.37	0.25	0.55	.78
"	"	2.0	0.85	0.79	1.34	0.26	0.30	0.57	0.86
"	"	2.5	0.93	0.71	1.20	0.27	0.41	0.49	0.75
"	80	1.5 *	0.71	0.81	1.38	0.30	0.21	0.64	0.96
"	80	1.7	0.76	0.80	1.36	0.295	0.24	0.60	0.88
"	70	1.2 *	0.62	0.84	1.55	0.28	0.15	0.56	0.93
0.4	80	1.2 *	0.63	0.83	1.41	0.23	0.19	0.67	1.08
"	80	1.4	0.69	0.82	1.40	0.30	0.23	0.68	0.97
"	70	0.9 *	0.52	0.84	1.60	0.315	0.13	0.71	1.29
"	70	1.0	0.56	0.84	1.57	0.305	0.15	0.54	1.00
"	70	1.2	0.63	0.84	1.52	0.29	0.19	0.56	0.92

which is about 1.1 times the nominal, the comparison should be with a coefficient about 0.11 for the PFN rather than 0.15.

The best results obtained are marked in Table 2 with an asterisk. The best values of W_R are typically 0.3 or just over, so that the number of circuits needed is about one third of that when Marx PFNs are employed. The best efficiencies are 80-84%, considering only the energy delivered at more than 75% of peak voltage. This is approximately as good as the PFN case.

The peaking capacitor stores typically 16 percent of the delivered energy. The efficiency can be raised by allowing this storage capability to increase.

In comparing the peaking capacitor with the corresponding pulse forming line it is necessary to take account of the requirements on their wave impedances and of the different stress times. The peaking capacitor must have a wave impedance much less than the load impedance, perhaps by a factor of five to ten, in order to behave like a capacitor. If discharged into a matching load it would generate only half of its peak charging voltage, and would then generate a power $5/2^2$ to $10/2^2$ or 1.25-2.5 times as great. Thus, if limited by the same charging field as the pulse line, the peaking capacitor is capable of only 0.4 to 0.8 times the power density.

Now for the peaking capacitor the effective time at peak electrical stress does not much exceed the output pulse duration, while for the pulse-charged pulse line, it may be several times as long. Therefore the stress in the peaking capacitor can be larger, by a factor that approximately compensates the effect of mismatched wave impedance and make the power densities about equal. The cross sections needed for the peaking capacitor and pulse line are thus roughly equal, and the volume difference is in the length.

It also follows from the above paragraph that the conductor spacing in a peaking capacitor will be less than half that in a pulse forming line, for equal load voltages. Now the volume of the peaker is less by a factor of five to ten, considering the lower energy and higher field; therefore, the electrode area is less only by a factor of two to four, the number of conductors is probably greater, and better tolerances must be maintained. Thus the magnitude of the reduction of the fast capacitor achieved in the peaking circuit is a little misleading if stated in terms of volume alone.

The output switches in the peaking circuit are overvolted quite rapidly. Typically $V/\dot{V}$ at switch closure is one half the pulse duration. Self-closing output switches can probably be used, since an r.m.s. jitter of about 2% in voltage could be obtained, and this translates to 3-5 ns; individual switches can be isolated by transit times longer than this. Self-closing switches are superior to those used in pulse lines since they require neither a trigger system or a sharp-edge electrode that may be subject to wear. The effective stress time is reduced to 0.1 to 0.2 μ s from perhaps as much as 1 μ s. Thus reliability and long life will be easier to achieve.

Thus it appears that the number of peaking circuits required in any specific design is about one third of the number of PFN Marxes, while the volume of water (or other fast dielectric) is one or two tenths of that needed in a pulse-line design. The peaking circuit is intermediate between the pulse-line and the Marx PFN in respect of numbers required and water volume, and also in respect of output switch requirements.

The chief drawback of the peaking circuit as described is the fact that its pulse is not flat-topped. The efficiency actually depends on the pulse flatness required, which may be more stringent than represented by the 75% voltage criterion. Also, if the load impedance falls with time, as when a cold cathode diode is used, the lost energy may be greater than calculated here. For example, if the impedance falls linearly so that it would reach zero in three to four pulse durations, the efficiency for $C_p = 1/3 C_0$, $\phi = 70^\circ$, $\bar{Z}(C_0/L_0)^{1/2} \sim 1.2$ is reduced from 0.84 to 0.77.

A modification of the circuit is therefore desirable to introduce a further degree of pulse shaping, flattening the top of the pulse or at least holding up the start of the fall until more energy has been delivered. No calculations of such circuits have been made here, but it is suggested that those shown in Fig. 5 might be candidates.

6. Other Approaches

Approaches not considered in any detail here but which might be applicable include the "Wave Erection Marx" developed by Maxwell Labs. This might make pulses shorter than 0.3 μ s more economical.

Abramyan has described a modification of a Marx circuit to obtain a flat output pulse, and this circuit is shown in Fig. 6. A few stages of a conventional Marx are placed in series with a single "Ringing Marx" stage, i.e. capacitor charged with reverse voltage. Inversion of this stage boosts the Marx output voltage and compensates the RC voltage decay for some time.

A related scheme considered by the present author is a Marx consisting purely of ringing or LC stages (Fig. 7(a)) triggered at different times and inverted in different half-periods. The idea is that after the closure of the

(a) S_1 and S_2 close at different times

(b)

(c)

Fig. 5 Modified Peaking Circuits

Fig. 6 Circuit Devised by E. Abramyan

C_1, C_2, C_3 represent
different nos. of stages.

$$C_0 \neq C_1 \neq C_2 \neq C_3$$

$$L_1 \neq L_2 \neq L_3$$

S_1, S_2, S_3, S_4 close at
different times.

Fig. 7(a) Ringing Marx with Controlled
Frequency and Phase of Inversion-
Circuit

Fig. 7(b) Ringing Marx with Controlled Frequency and Phase of Inversion - Waveform

output switch (suitably timed), a square pulse as shown in Fig.7(a) is in effect synthesized under loaded conditions. A more general circuit can obviously be envisioned that combines this with Abramyan's circuit and which comprises straight Marx stages and more than one set of LC stages with different capacitance and inductance per stage and different firing times.

Abramyan states, without giving details, that using the circuit of Fig. 6 he has delivered 50% of the stored energy to an electron beam at $\pm 3\%$ of a nominal voltage --a rather impressive result. By allowing a larger voltage variation and modifying the circuit in the direction of Fig. 8, it would seem likely that efficiencies could be obtained that are comparable to those of PFNs and peaking circuits. It is not obvious what kind of capabilities would result in respect of pulse duration and stored energy per Marx.

7. Conclusions

Extension of Present Technology

The obvious extensions of existing technology are the Marx/water pulse line, the Marx/peaking circuit, and the Marx PFN. The salient features of these are compared in Table 3, which refers to a hypothetical 1MJ laser with about 5% efficiency and 400 nS pump pulse duration. In the order in which the three were mentioned, the number of drivers circuits needed increases, while the volume of water dielectric decreases and the output switch requirements diminish.

Thus the choice appears to be between the complexity of larger numbers and the need for more water dielectric and more difficult output switches. Should it prove desirable to keep the current and energy per switch (either Marx switch or output switch) to a low value in order to increase reliability, this will favour the peaking circuit and PFN approaches.

Fig. 8 General Combination of Marx with
Variable Frequency Ringing Stages

Table 3

Characteristics of "Present Technology" Designs
 Applied to a 1MJ, 5% efficient Laser Pumped at 1MV for 400 nS

<u>Approach</u>	<u>Total number of</u> <u>circuits</u>	<u>Water Volume</u> <u>(m³)</u>	<u>Nature of Output</u> <u>Switch</u>
Marx/Pulse Line (Water Dielectric)	100	2000	1-3 MV, triggered
Marx/Peaking Circuit (Water Dielectric)	300	200	0.75MV self-closing
Marx/PFN	1000	0	None.

It should be borne in mind that if the pulse shape as generated is very far from square it may be necessary to protect the electron beam window by crow barring the pulse generator. It is chiefly a question of how rapidly the pulse voltage returns to zero at the end of the pulse. The peaking circuit, and to a smaller extent the Marx PFN, are much more likely to require a crowbar than the pulse line approach.

Another consideration is that the transition between the relatively low power density Marx and the high power density laser is easier to achieve in the pulse line approach, because it is made at the interface between the Marx and the pulse line where strong inductance is not very harmful. Marxes that drive the laser directly or via relatively small peaking capacitors must be connected with tapering, impedance-matched sections whose design and volume have not been considered here.

8. Long Range Approaches

It appears to the present author that the most promising general approach to improve the economy and reliability of the pulse power system is to replace the dc charging of conventional capacitive energy stores by the fast charging in 100 μ s or less of improved capacitive elements that can be configured to deliver the output pulse directly without the need for a further energy transfer stage.

The compensated alternator is expected to be capable of providing the desired fast charge time, and may be the key element in this approach. The pulse charged capacitive elements most readily identified are, in general, solid dielectric units in which the fast charge allows high dielectric stresses and very high charge voltages compared with the few kilovolts per

element in dc capacitors. For solid dielectrics, the importance of the fast charge is that it may help eliminate corona, perhaps by allowing the use of high dielectric constant, slightly conducting impregnants.

The pulse charged solid dielectrics can be used in several ways, and these conveniently form a progression that starts with designs closely related to existing technology and proceeds to more advanced configurations that may become possible depending on the degree of success achieved in development. The most immediate of these designs is simply a pulse-charged Marx PFN. For this only modest voltage (~ 100 kV) capacitors and switches are needed, and the benefits of pulse charging are (1) smaller, cheaper capacitors, (2) easier and cheaper charging insulation, (3) elimination of dc failure modes in the spark gap switches and (4) possible facilitation of multi-channel spark gap operation. The last two factors will improve the reliability of the switches. All of the factors will tend to reduce the inductance of the Marx, thereby increasing the allowed capacitance and reducing the number of circuits required.

The Marx PFN approach makes the least demands for voltage transformation of the compensated alternator output, since the storage voltage could be in the range of tens of kilovolts. However, the Marx will have lower inductance and cost per joule the larger the charge voltage. This will be true even if series capacitor elements are used in each stage, but especially true if the capacitor can be packaged as high voltage units (preferably without even needing series connections internally). Thus there is an incentive to develop a high voltage transformer capability compatible with the pulsed alternator.

If transformer and spark gap technology scale well enough with voltage, this design evolves into a pulse-charged full voltage PFN with a single switch per circuit. Thus might be a Blumlein-like PFN with lumped element lines;

(type E PFN); a cheaper design and a better rise time will be obtained if charge voltages approximately twice the load voltage can be attained, when a Type C PFN with only a few parallel connected elements is feasible.

Full voltage PFNs (either Type C or Type E) could use reduced voltage elements connected in series. However, the best and cheapest designs will result if full voltage capacitors and dielectric layers can be employed. In an ideal design, which is the hardest to achieve of all this sequence, the PFN is packaged as a full voltage single unit. Preferably this would be a Blumlein composed of two ideal transmission lines, as described by Gagnon. This would be about 100 feet long if the dielectric constant is only a few, and folding or the addition of lumped inductance might be needed to make the packing problem tractable.

Within this general approach, other alternatives can be identified. An inductive store is also an acceptable means of fast charging. The opening switch needed is the only serious difficulty, but the absence of such switches has usually been a formidable barrier to the use of inductive store. Work at LASL suggests that for voltages of 100 kV and energy transfer times of 100 μ s a vacuum interrupter will be adequate, so that for the Marx PFN version of this application, at least, the inductive store is a serious candidate. Development of the vacuum switch will need to be towards longer life and higher voltage.

Liquid dielectrics may be an alternative to solids. Since they do not lend themselves so readily to Marx generators, their usefulness here is still more dependent on achieving high charge voltage. They may also be dependent on minimizing charge time, since their breakdown strengths and efficiencies

are better at short pulses. Liquids are perhaps not very promising, but a search for the best liquid energy storage medium for this time regime has not been made and is probably worth carrying out.

A flow chart showing the relation of the advanced designs described above, the alternatives available and the technologies needed to achieve them, is shown as Table 4.

Table 4

PROGRESSIVE DEVELOPMENT OF PULSE CHARGED DRIVERS Requirements:

Compensated Alternator [alternative: Homopolar (or dc), Inductive Store, 100 μ s interrupter (vacuum switch)]

100 kV Transformer $\rightarrow$ Few 100 kV Transformer $\rightarrow$ 1MV Transformer $\rightarrow$ 2MV Transformer $\rightarrow$ (1MV Switch, high current)
Switches Switches Switches

Solid Film Dielectrics [alternatives: oil/paper or liquid dielectric]
High Permittivity or Ionic Impregnant, 100 kV elements
[alternative: conventional capacitors, 10 kV elements]

small 100 kV elements or packages $\rightarrow$ 2MV elements $\rightarrow$ 1MV, large packaged lines

Minimal Risk $\rightarrow$ Increasing Success $\rightarrow$ Ideal Design

APPENDIX

Preliminary Calculations of Abramyan's Circuit

1. Results of Circuit Calculations
2. Practical Circuit Design
3. Estimate of Short Pulse Capability

1. Circuit Calculations

The circuit used is shown in Fig. A1(a). The capacitor C_1 represents an aggregate of normal Marx stages in series, with total dc charge V_1 , switched out by S_1 . The capacitor C_0 represents a different number of stages that are dc charged backwards to $-V_0$, and which at the time when S_1 begins to discharge the circuit are in the process of inverting through the inductor L_0 and the switch S_0 . S_0 is closed some time before S_1 . The load is treated as a resistor--normally of fixed value but sometimes allowed to decay linearly with time.

The parameters that vary include C_1/C_0 and V_1/V_0 , which are independent. This means that not only can the ratio (N_F) of forward to backward charged stages be varied, but also the relative capacitance of the two types of stage. The other variables are the phase (ϕ) of inversion of C_0 at which S_1 closes (given by $\phi = \Delta T / (L_0 C_0)^{1/2}$, where ΔT is the interval between S_0 and S_1 closing) and the normalized load resistance $R' = R(C_0/L_0)^{1/2}$.

A series of more than thirty calculations was made to find the optimum circuit for use with fixed resistor loads. The quantity optimized was the fraction of stored energy delivered to the load at more than 75% of peak voltage.

Fig. A1 Abramyan's Circuit
 (a) As used in the calculations
 (b) With stray inductances added
 (c) With modular construction (showing charge resistors), $N_F = 2$

First the capacitance per stage was kept uniform and the optimum ratio of forward stages to inverted stages was sought. The optimum ratio is expected to be fairly small, since with only a few inverting stages the pulse shaping ability is lost and the circuit tends to a Marx run down.

Finding the best efficiency for a fixed N_F involves varying both ϕ and R' , so finding an exact optimum is tedious. However, it appears to be in the range $3/2 < N_F < 2$. The optimum phase angle for this range is 60 to 70 degree; as N_F increases, the optimum phase angle decreases, which is to be expected from the fact that there is more forward voltage available early in the inversion and a decreasing dynamic voltage range.

Because the case $N_F = 2$ is convenient in practice--it allows a module of just three capacitors and one switch--this was selected and C_1/C_0 varied. It was found that increasing C_1 (i.e. using larger capacitance forward stages) increases the efficiency. Conveniently it also reduced the percentage reversal of the inverted stages, which is good from the standpoint of their lifetime; further reducing the fraction of energy stored in capacitors that reverse is good for a similar reason.

The best efficiency obtained was about 85 per cent. The forward stages in this case have twice the charge of the inverted stages. The latter store initially twenty percent of the energy and reverse about 55-60 percent. The waveshape (Fig. A2) is almost flat at first, then rises about 12% before falling to just below zero. Nominal output voltage is about half the "open circuit" voltage. At zero voltage, ninety five percent of the stored energy has been delivered.

During the course of the calculations Abramyan's claim of fifty percent efficiency within $\pm 3\%$ flatness was verified. In fact, without trying to

Fig. A2 Approximate Optimum for Fixed R Load, $N_F = 2$

optimize for this condition, as much as 67% of the stored energy was delivered within $\pm 3\%$ voltage bounds.

A smaller number of calculations was made with decaying load resistance. This tends to flatten the top of the pulse that was obtained for the optimum efficiency. For that reason, it does not reduce the efficiency very much. Fig. A3 shows the voltage waveform in a case where the impedance decays by about 40% over the useful pulse. The efficiency is still 80%. By the time the voltage returns to zero, 99% of the stored energy has been delivered.

2. Practical Circuit Design

With two forward-charged capacitors for every inverted capacitor, the Marx divides into modules with three capacitors and one series spark gap, all charged to equal voltages, Fig. A1(b). One capacitor has an inversion circuit. The modules are placed in series.

Compared with a normal Marx, two out of every three spark gaps are eliminated from the discharge path. The remaining gap is pulse charged 40-50% above its dc level before triggering. This pulse is so brief it will not add significantly to the hold-off requirements or inductance; in fact, by helping the gap close in multiple channels it should further reduce the inductance. Another benefit compared with PFN Marx is that the open-circuit voltage and gradient never appear, even during erection. Considering all these improvements, it is suggested that the inductance per megavolt should reduce by a factor of two or three compared with a normal Marx.

The inversion gaps may all need to be triggered by an external pulse, in effect, which may limit the number of modules per Marx. A 2MV Marx with 1MV at the load (six or seven 100 kV modules) should be no problem. It should not

Fig. 43 Voltage Waveform on a Decaying Resistive Load

be necessary that all inversion switches close simultaneously as long as the average phase is right. Allowance can be made for late closure of inversion switches farther from ground by reducing their inversion times. The discharge switches are easily triggered, as they can fire each other in normal Marx mode; the only important time is that of the last switch closure. Grading of the inversion voltages among the discharge switches needs to be considered.

3. Estimate of Short Pulse Capability

To find the minimum discharge time it is necessary to consider the effects of the two stray inductances shown in Fig. A5. One is the stray inductance L_m , in the Marx series discharge path. The other is L_i , internal to the inversion capacitor.

The circuit of Fig. A1(c) was not calculated, for lack of time. However, estimates can be made. For the canonical 1MV, 400 ns laser pump case used previously a 2 MV Marx is needed. Suppose this has an inductance of 400 nH/MV i.e. 800 nH, and that a load L/R of 100 nS is needed. The load is 8 ohms and the energy 50 kJ per Marx. The entire laser needs 400 Marxes.

The inversion has to have a frequency of about 1 MHz. It is likely that the capacitor inductance L_c , should be less than the inversion inductance L_0 , by a factor of about ten, to avoid excessive internal voltage drop. This means that the capacitor itself has a ring frequency of about 2 or 3 MHz. This is consistent with standard low inductance design. For a 2MV, 50 kJ Marx made of 100 kV modules, each inversion capacitor is about 0.3 μ F and for a 400 ns pulse the inversion inductance is about 70 H. This is consistent with a 100 kV dc spark gap, though it is possible that two might be needed.

This estimate suggests that the Abramyan circuit is similar to the peaking

circuit in terms of number needed for a given pulse duration, but with no water capacitor or output switch required. The number of circuits is less than that for PFN Marxes, in approximately the ratio of inductances per megavolt. Thus Abramyan's circuit is an interesting approach. As with the peaking circuit and the PFN, the number of circuits decreases with increasing pulse duration, as the inverse square.