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ATLAS PARAMETER STUDY

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PREPARED BY NORTH STAR RESEARCH CORP.

FOR

LOS ALAMOS NATIONAL LABORATORIES

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1.0 Introduction

The purpose of this study is to make an independent assessment on the parameters chosen for the ATLAS capacitor bank at LANL. The specific tasks from the contractual Statement Of Work are shown below.

Statement of Work

The contractor will perform a study of the basic pulsed power parameters of the ATLAS device with baseline functional parameters of >25 MA implosion current and <2.5 microsecond current risetime. Nominal circuit parameters held fixed will be the 14 nH from the vacuum interface to the load, and the nominal load impedances of 1 milliohm for slow loads and 10 milliohms for fast loads. "Single Ended" designs, as opposed to bipolar designs, will be studied in detail. Specific items studied will be:

The optimum voltage of the device for circuits which are undamped, and damped to varying degrees.

The optimum amount of damping for the device including the trade-off between low and high reversal capacitors.

The best type of circuit for use in the device, including alternate types of Marx Generators.

The optimum charge voltage of the device.

In order to perform the tasks above, the first action item was to go to LANL and get some consensus on the load which would be of greatest interest. This task was facilitated by Mark Parsons who arranged for a number of meetings with program members.

There are 3 basic classes of loads:

1) X-ray production loads without opening switches (30 - 60 mg with 30 mg. typical)

2) X-ray production loads with opening switches (10 mg typical)

3) Heavy liners (.1 - 30 grams with a typical mass of 1 gram)

Loads 1 and 2 have a different goal from load 3. In the case of 1 and 2, the highest velocity is the best velocity. In the case of load 3, the load velocity should only exceed .5 - 1 cm/usec if special means (such as the plasma armature suggested by Reinofsky) are initiated to avoid melting of the liner. In the table below, we outline a number of parameters associated with each load based on the discussions at LANL.

Parameter	X-ray	X-ray/sw.	Liner
Typical Mass (mg)	30	10	1000
Max. Mass (mg)	60	20	30,000
Min. Mass (mg)	20	5	100
Implosion Ratio	10 - 20	10 - 20	2 - 5
Length (cm.)	2	2	3 -5
Velocity (cm/us)	>30	>50	<2
Power Flow Inductance (nh)	14	14	14

The optimization parameter for the X-ray shots is implosion velocity, while the optimization parameter for the heavy liner shots has tentatively been chosen to be the energy transferred to the liner.

2.0 Approach

Based on the simplicity of the parameters of interest for this study, and the difficulty of implementing an imploding load in SPICE, a simple circuit/implosion code has been written in order to provide velocity and voltage reversal information. This code is called ATLAS3, and where specific predictions are made in this work, they are is primarily based on that code.

In performing an analysis constrained by energy, Gribble used the parameter α = bank voltage/600 kV. This parameter is convenient since it makes it easy to parametrize the parameters as a function of fixed energy. In general L_b (bank inductance) varies as α^2, C_b varies as1/ α^2, and L_t (transmission line inductance) varies as α. The energy chosen in the pre-CDR studies is much higher than the energy imparted to any of the loads. There is no reason to

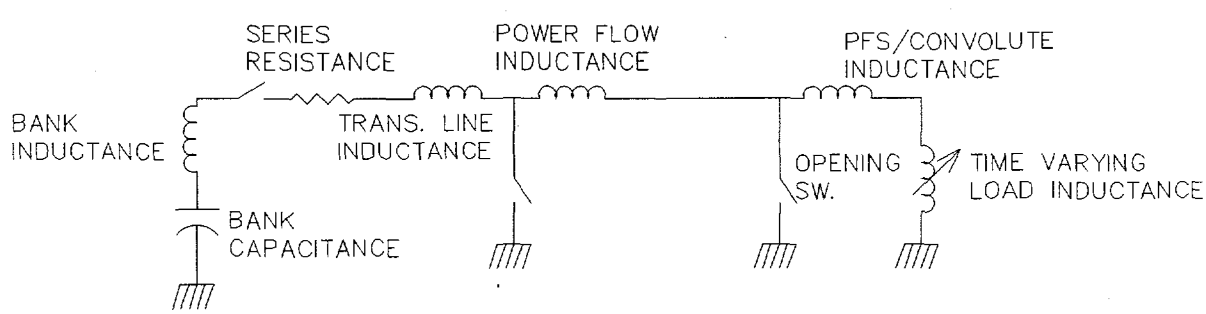

Figure 1 The circuit simulated is shown above. The Atlas3 code simulates the circuit without the opening switch, and Atlas4 simulates the opening switch.

increase the energy above the CDR level unless there is evidence that it leads to increased energy transfer. We will discuss the potential for reducing stored energy without compromising performance elsewhere in this document. The circuit is shown in Figure 1. The interface is assumed to "crowbar" when the voltage reaches a given preset value (where not explicitly stated, that value was set to 400 kV or 400α kV).

The fundamental bank architecture described by LANL at it's design reviews was assumed during this analysis. That consists of two 60 kV, 17 µF capacitors in series connected by a low inductance railgap switch. This architecture leads to low inductance systems, and there is a data available on all components. A bank using those components and that architecture is likely to be reliable, and to have controllable costs and schedule. The nominal parameters for α = 1 are a bank inductance of 9 nh., a transmission line inductance of 5 nh, and a power flow channel inductance of 14 nh.

2.1 Series Resistance

The first study undertaken was a study of the effect of series resistance on the X-ray loads. The purpose of the study was to verify that the series resistance could be added without compromising the load parameters. The result of this study is shown in figure 2. We discuss the effect of series resistance on the heavy liner case in the heavy liner section. The conclusion on series resistance is that the use of series damping resistance is very effective for X-ray loads primarily because the X-ray load currents are determined by inductive rather than resistive effects. In the X-ray parameter regime the series resistance eliminates serious reversal without significantly reducing the current at early times.

2.2 Shunt Resistance

Shunt resistance has not been explicitly studied since it is affected, to a very great degree by factors outside of the scope of this study such as charging mode.

3.0 Scaling for Heavy Liners

The heavy liners are an important class of load, and they differ from the other two types of load in their natural time scale. For a 5 cm. radius liner imploding to 1 cm/us, the typical run-in time is 2 X 5 cm/(1 cm/us) = 10 us. A 10 cm. load has a time scale which is about a factor of 2 longer. This is in contrast to the X-ray loads which must reach velocities a factor of 10 - 40 higher and which therefore have natural run-in times in the range of 0.3 - 3 us. We show data for 3, 10, and 30 gram liners starting from a 10 cm. radius in Figure 3 in order to show the general scaling. Note that the runs assume a small irreducible inductance, but that the main inductance in the problem is the nominal 12 nanohenry inductance change in the load. The optimum liner velocity occurs at 530 kV, 280 kV, and 180 kV for 3, 10, and 30 grams respectively. The 530 kV, 3 gram data is somewhat irrelevant since for all bank voltages, the velocity is far above the present practical limit of 1 cm/usec. The force applied to the liner varies as the square of the current, and unlike the X-ray case, the series resistance has a significant effect on the peak current and hence on the final velocity. For example with a 30 gram load, the final velocity at a 240 kV input is .69 cm/us for 10 % reversal, .94 cm/us for a 20 % reversal, and 2 cm/us for an undamped bank (60 % reversal). Note that the required series resistance is different than in the X-ray load case because the interface flashes in the X-ray implosion case, and it doesn't in the

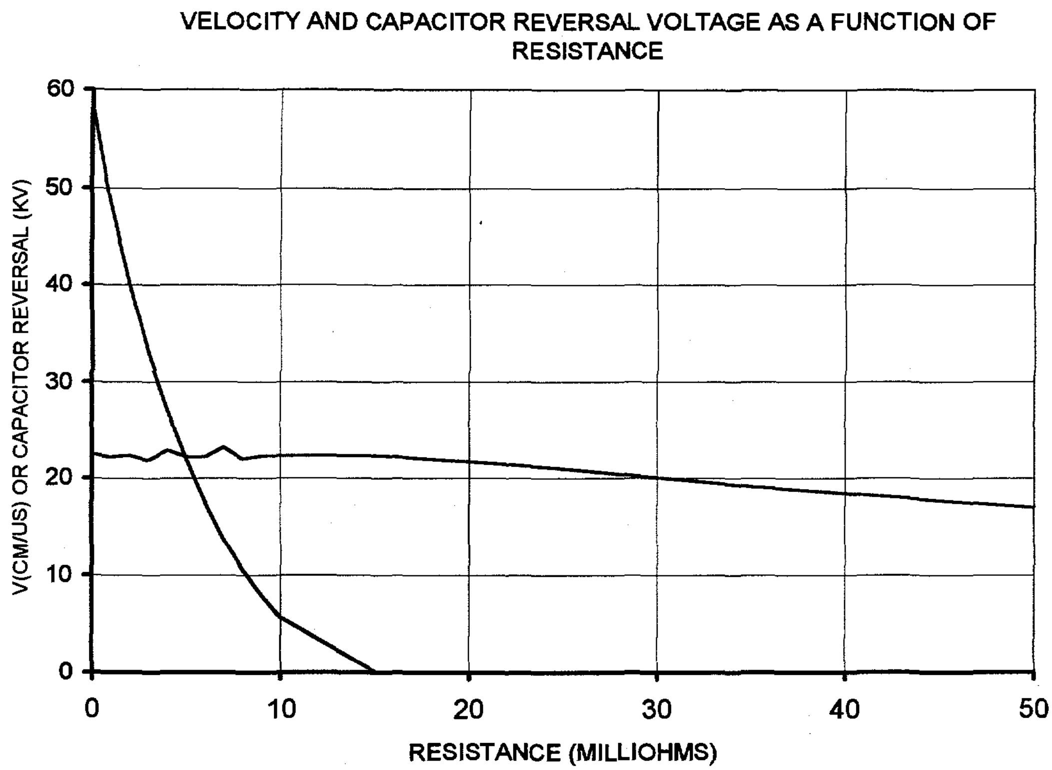

Figure 2 Implosion velocity as a function of series resistance for the baseline case of 36 mg and 600 kV.

heavy liner case.

Given the significant effect of the series resistance on final heavy liner velocity, the consequences of running with a smaller bank and allowing voltage reversal was checked (based on 10 kJ/can instead of 30 kJ/can). The two banks came out about the same in terms of final energy. Any bank which uses series resistance will have two advantages: better overall reliability, and the fact that the designer isn't dependent on a manufacturers usually fraudulent claims about series resistance.

The optimization data of Figure 3 is important if 30 gram liners are to be considered, or if practical methods are found in the future to exceed the 1 cm/usec limit. For example Reinofsky has suggested a plasma armature type of approach which could overcome this limitation.

The significance of the 30 gram data at 5 and 10 cm. shows how changing the radius amounts to changing the time constant. Much better energy transfer is achieved at high voltage when the 5 cm. radius liner is used. Perhaps most important is the observation that lower voltages (200 - 300 kV) are optimum for larger (10 cm. radius) liners.

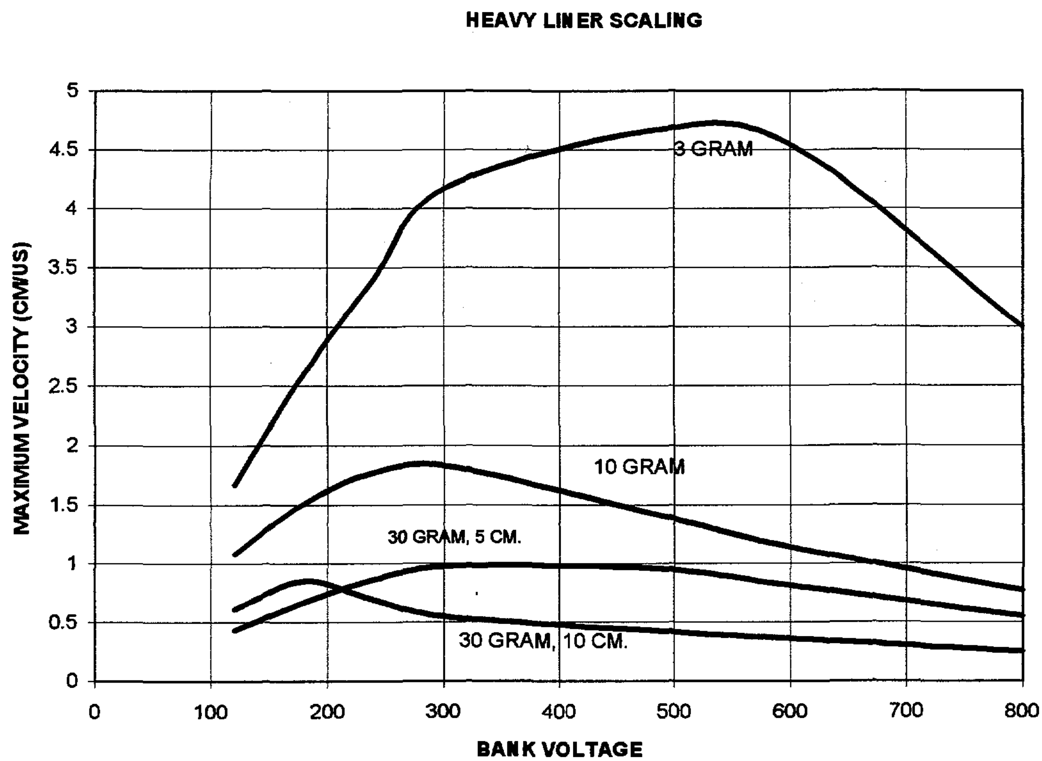

Figure 3 Heavy liner velocities for 3, 10 and 30 grams with 5 and 10 cm. radii studied for the 30 gram case.

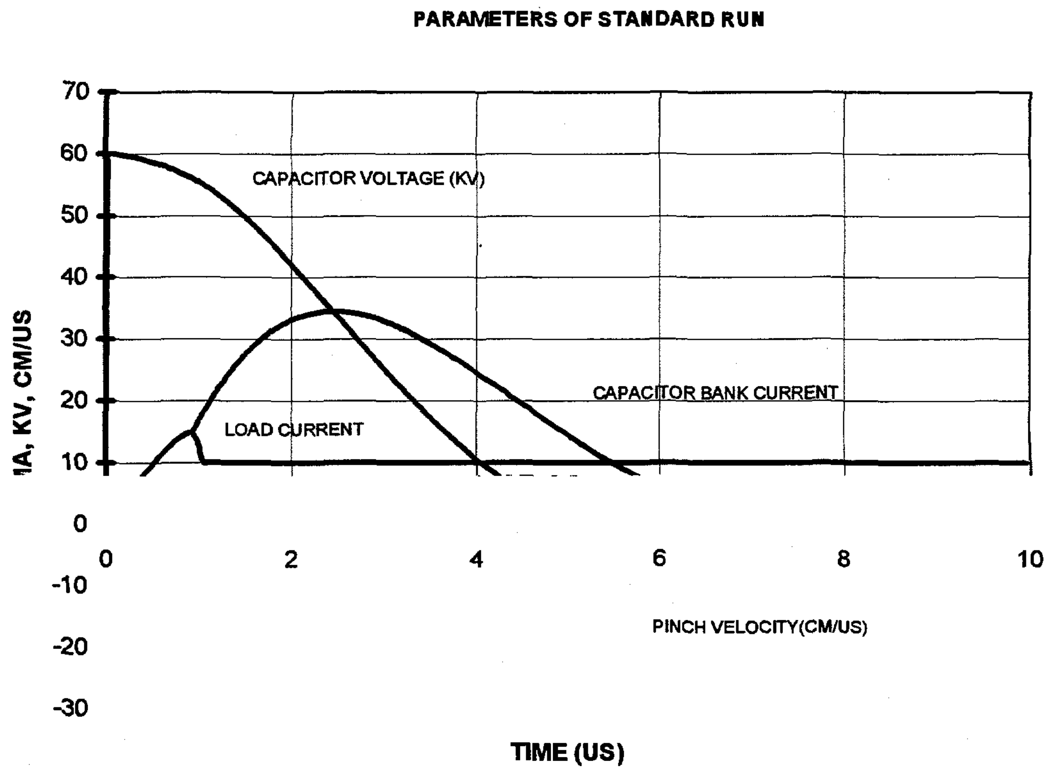

Figure 4 Typical output traces for 36 mg load, 600 kV charge, and 200 uf bank capacitance.

4.0 Scaling of Direct Drive X-ray Loads

In general, the direct drive X-ray loads have parameters similar to those shown in figure 3. The implosion is dominated by the inductance of the feed and the inductance of the bank. The short (about 1 microsecond) implosion time leads to a situation in which most of the bank energy hasn't been extracted when the interface crowbars. In the typical case shown, the bank voltage is at about 80 % of it's starting value when the interface crowbars, and the bank becomes disconnected from the implosion. Note that the high voltage at the end of the implosion has a modest effect on the final velocity. Increasing the crowbar voltage from 350 to 800 kV increases the velocity from 22.3 to 25.0 cm/us. Reducing the total bank energy from 36 MJ to 18 MJ at 600 kV is found to have virtually no effect on the velocity if the inductances are unchanged. If the feed inductance is fixed, the reversal voltage is constrained to be less than 10%, and the transmission line inductance is fixed, but the bank inductance increases as it should (from 9 to 18 nh) the final predicted velocity is 20 cm/us (as opposed to 23 cm/us for the baseline case). The factor of 2 larger bank buys an additional 15 % in velocity and 30 % in energy. Clearly, the physics of implosion limits the velocity that can be achieved for a given voltage and inductance. A more detailed scaling study is shown in Figure 6 where it is clear that bank voltages between about 480 kV and 800 kV give virtually the same direct drive output velocity.

The major method of gaining velocity is to reduce the mass as shown in Figure 4. The only disadvantage of this method of velocity increase is that the smaller masses are impractical, and so must use wire arrays which are inherently less stable than cylinders.

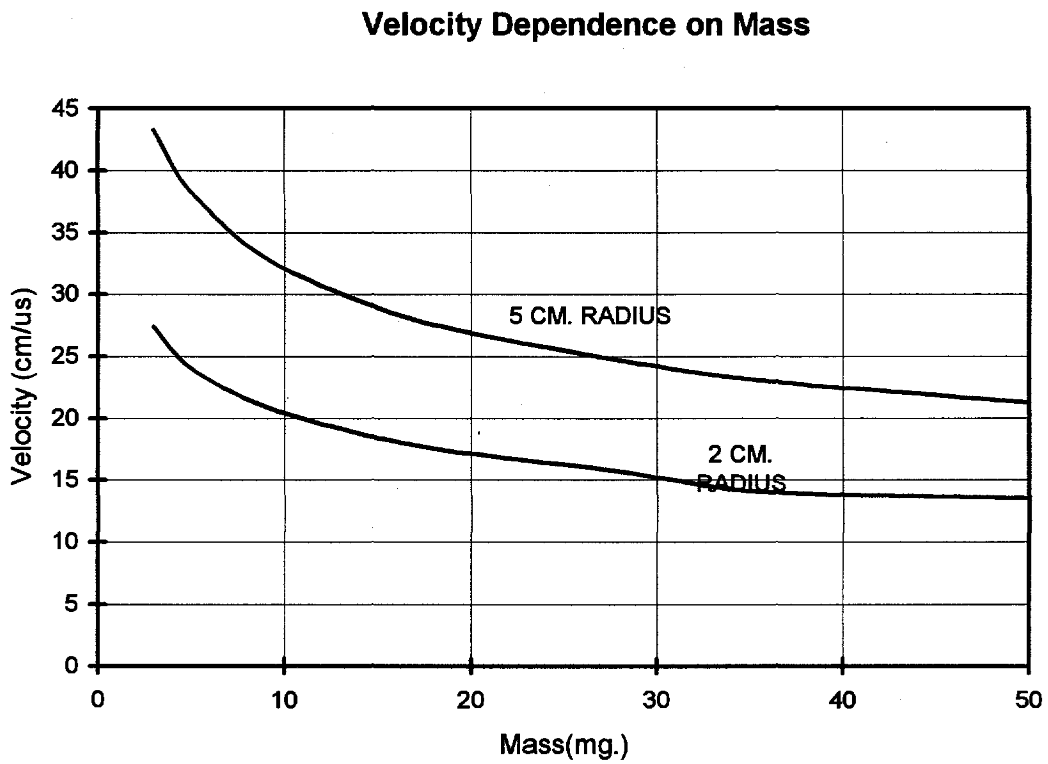

Figure 5 Implosion velocity dependence on mass and radius for direct drive.

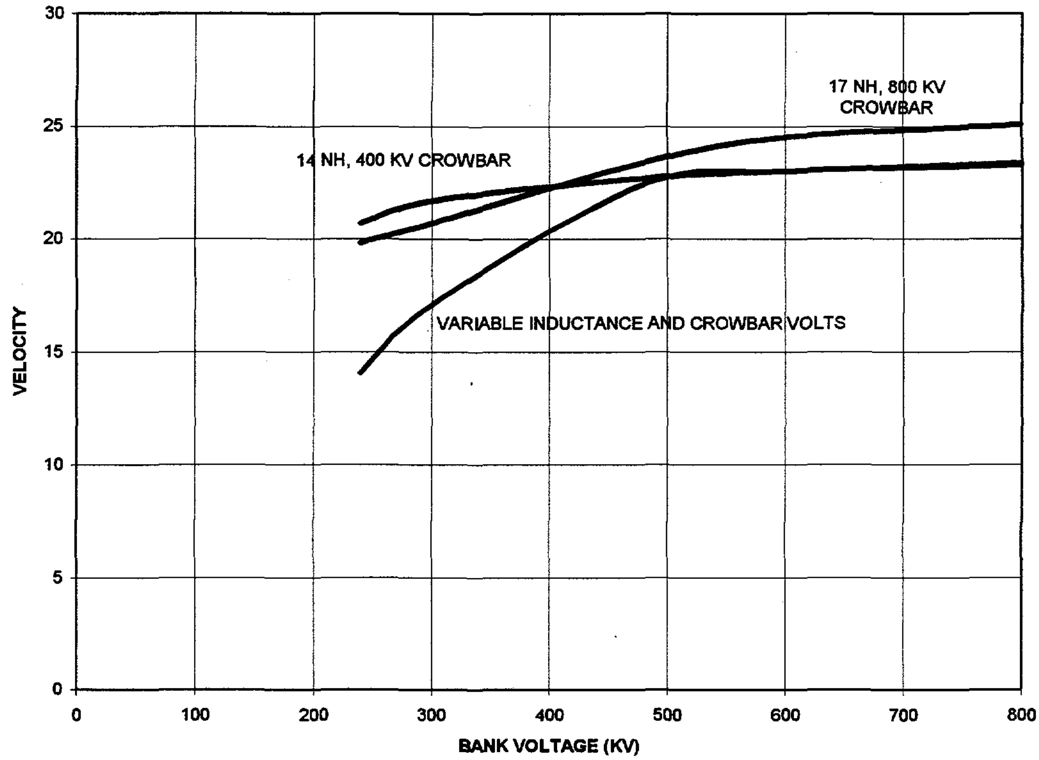

Figure 6 Direct drive implosion scaling with bank voltage. The crowbar voltage and power flow inductance are varied linearly in the variable case.

The velocity is primarily determined by dI/dt, and dI/dt is primarily determined by the ratio V/L where V is the bank voltage and L is the total inductance to the implosion. To the extent that the V/L ratio is constant, the direct drive implosion will be unaffected by the other system parameters. The analysis by Gribble shows that effect quite nicely for a variety of parameters.

The data of figure 6 shows a subtlety in the case where the inductance and insulator flashover voltage ("crowbar voltage" are varied together. When the inductance of the power feed is lower, the crowbar voltage has more effect because in the low inductance case, there is minmal energy for driving the implosion after the interface crowbars.

5.0 Plasma Flow Switch Drive

A plasma flow switch will be used in radiation production work in order to increase the voltage and dI/dt near the load. That switch must meet a number of criteria. It must conduct for as long as possible (to the peak in the bank current if possible) and then open to very high voltages. We modified the code to cover the plasma flow switch case and assumed that the interface crowbars when the switch opens (this may not be a correct assumption for some of the lower PFS voltages). The parameters assumed in the code were a power flow channel inductance of 14 nh, a bank inductance of 14 nh, and a PFS to implosion inductance of 3.5 nh.

The dominant effect in the PFS study was clearly the PFS voltage. A PFS driven implosion is only advantageous if the voltage from that switch is high enough. For example, taking a 10 milligram implosion at 2.5 microseconds opening to 250 kV in 0.5 microseconds, the velocity is 37 cm/us. The 250 kV voltage isn't high enough to transfer the total current into the load before the implosion is completed. Specifically, the peak implosion current for that case is 14 MA at a time when the total current is 22 MA (down from 27 MA at the time of opening). Since the amount of plasma increases with delay time, and the voltage almost certainly drops as the amount of plasma injected increases, higher currents don't help unless the voltage at the switch increases. For fixed switch voltage profile, the velocity is independent of bank current from 1.5 microsecond switch conduction time to 3.5 microsecond switch conduction time.

6.0 Bank Optimization for PFS and Direct X-ray Drive for Fixed Power Flow Channel Inductance

In both the plasma flow switch and direct drive implosion cases, the critical parameter is the initial dI/dt. Since the PFS conduction time is limited, the current through the switch is approximately τdI/dt where τ is the conduction time (or implosion time for direct drive) and dI/dt will be taken as the initial dI/dt in this analysis. The initial dI/dt is straightforward to calculate since at the start of the pulse the current is zero and resistive loss can be ignored. This admitedly ignores very long conduction times where the total charge in the bank begins to limit the current. The equation is:

$$\frac{dI}{dt} = \frac{\alpha V}{(\alpha^2 L_b + \alpha L_t + L_p)}$$

where we assume that the bank inductance varies as α^2 (based on series parallel operation of equal sections), that the power flow channel inductance will be determined by effects such as the voltage during implosion which are more dependent on current than initial drive voltage and that the same transmission line are will be used for all designs with the thickness varied as required by the voltage.

The analysis of optimization based on dI/dt is summarized in Figure 7 where we show the peak dI/dt as a function of α for various values of L_p. The first obvious conclusion is that the optimum is a weak one. The CDR value of α=1 (600 kV banks) is a good choice for the range of possible inductances. Higher voltage will only be desirable if the inductance must be significantly increased. The basic phenomena embodied in the graph above the limitation of current by V/L_p at low values of α, and the limitation of current by $\alpha V/(\alpha^2 L_b)$ at high values of α.

Based on our study of the problem the fixed L_p case is most relevant. The reason for this conclusion is the observation that the power flow channel must operate properly as the voltage rises during the implosion, and that voltage is typically in the 500 kV (or higher) range for all implosions.

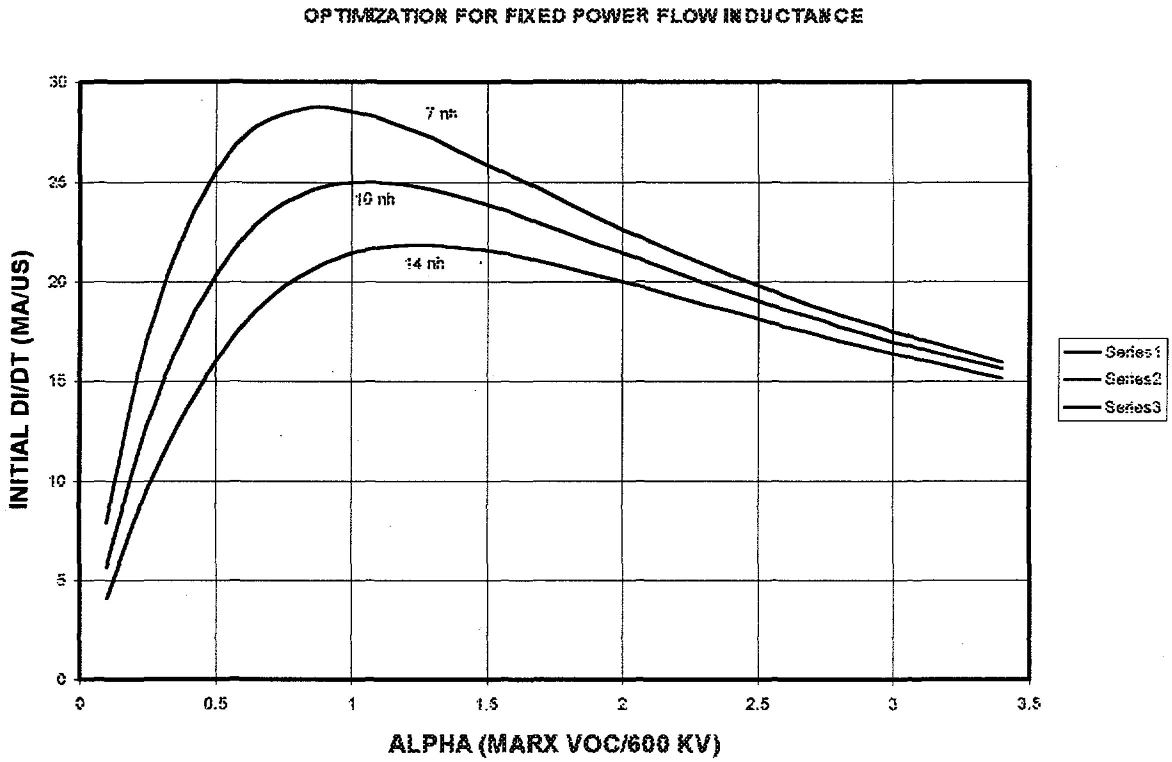

Figure 7 Variation in dI/dt with Bank Voltage.

6.1 Bank Optimization for Variable L_p

The functional dependence of L_p in a case where it varies with α is the critical optimization question. The straightforward case is one where the gap distances are varied with applied voltage. In that case dI/dt is fixed by the constant of proportionality between L_p and V since that constant must always be proportional to dI/dt. For example, at the CDR values of 300 kV and 14 nH, the initial dI/dt= 21 MA/μsec. As stated above, the fixed L_p case is far more relevant.

Other Options - Plasma Opening Switch

There area variety of options for increasing the X-ray yield beyond the direct drive capabilities beyon d the use of a PFS. All of these options must be designed to start the pinch at higher current to avoid the "runaway" effect. The first of these options is the use of a modest plasma opening switch (not a true PFS) to increase the current starting point for implosion. Based on data from ACE-4, it is possible to conduct 7 MA for 1 microsecond and open to a voltage in the range of 400 kV. The Naval Research Lab has demonstrated 2 MV voltages at conduction times of 1 microsecond. If we examine the "baseline" case of Figure 2, it's clear that such results are of interest if they can be scaled to the 1.2 microsecond current of 18 MA. Such a scaling would require a plasma source about twice as dense as the ACE-4 configuration. The velocity of a 10 mg, 1.2 microsecond opening switch driven implosion at 500 kV would be 38 cm/usec. If the plasma opening switch conduction could be pushed out to 1.5 microseconds, the velocity of the 10 mg load rises to 44 cm/us. If we drop the mass to 5 mg, and keep the other parameters the same, the velocity rises to 63 cm/us.

Other Options - Multiple Configuration Capacitor Bank

The area in which the 600 kV bank is not optimum is in driving very heavy, large diameter liners. Large, heavy liners may be the ones which are most desirable as loads for Atlas. A 240 kV bank is a much better match to 30 gram, 10 cm liners than either a 240 kV or 480 kV bank. A conceptually simple solution to the bank optimization problem is to design the bank so that it can be run single sided at 480 kV for X-ray production, and 240 kV double sided for heavy liner loads. Without examining the banks in detail it seems likely that such a change could be made by leaving an extra space half way through the bank, making provision for charging from the top and bottom, and convoluting the current in the vacuum. The polarity of one of the two halves of the bank would also have to be changed.

Other Options - Convolute to Reduce Inductance

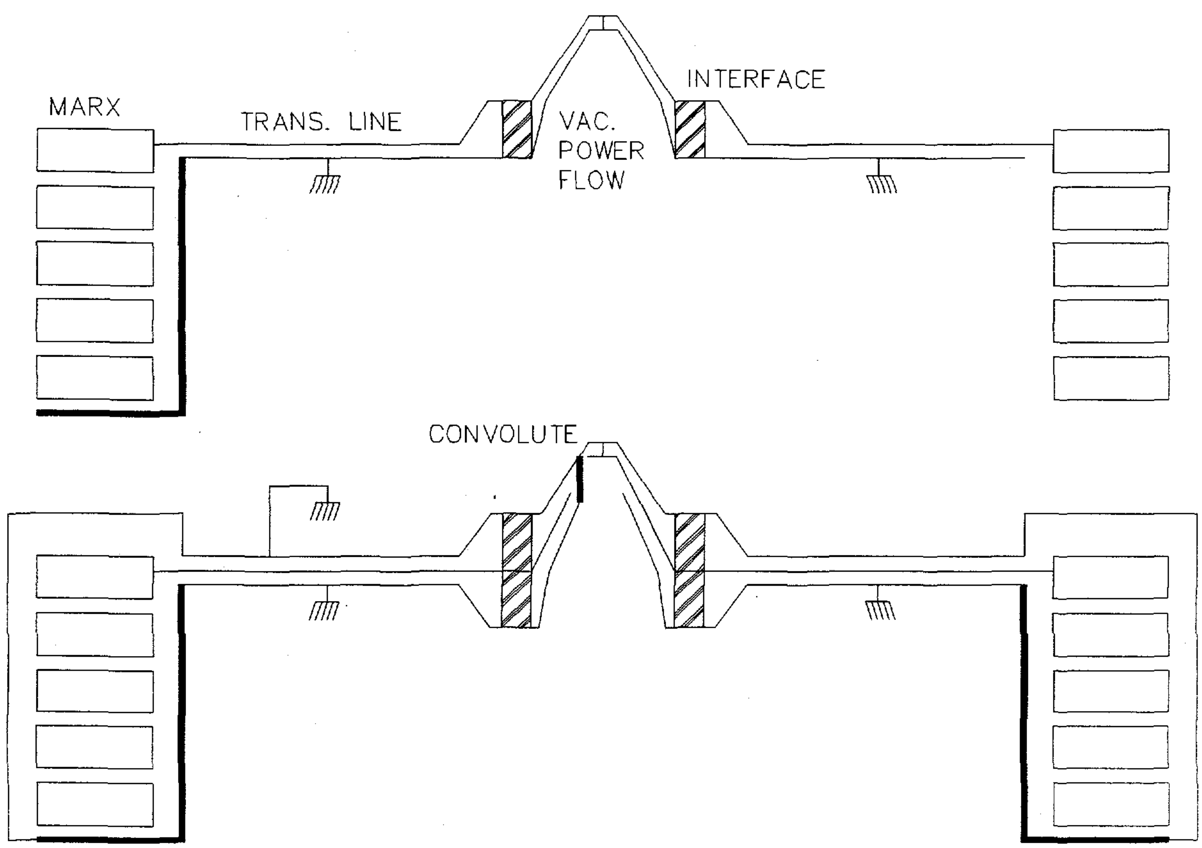

Figure 8 Simplified sketch of the Atlas bank with a convolute supplied to reduce overall inductance.

An interesting option which can increase the energy available to the plasma flow switch, or other opening switch is the use of a second parallel transmission line and convolute. This is depicted in Figure 8. This configuration decreases the inductance by decreasing the Marx inductance (the addition of the second current return estimated to decrease inductance from 9 nh to 8 nh), decreasing the transmission line inductance from 5 nh to 2.5 nh, and decreasing the 14 nh vacuum power flow channel to about 9 nh, for a total inductance of 19.5 nh. In running simulations of this configuration, we found that the reduction in inductance had a limited effect in direct drive mode because of the increase in voltage on the interface. This effect is summarized in the table below.

Mass (mg.)	L Bank (nh.)	L Pwr. Fd (nh.)	V Crow (kV)	Velocity (cm/us)	Comments
5	14	14	400	38.4	Baseline
5	14	28	800	38.0	Double Size Power Feed
5	14	18	800	41.4	Double Size Insulator
5	10.5	14	800	44.8	Double Size Insulator w/Convolute
10	14	14	400	32.0	Baseline
10	14	28	800	31.6	Double Size Power Feed
10	14	18	800	34.4	Double Size Insulator
10	10.5	14	800	37.3	Double Size Insulator w/Convolute

By using a convolute and increasing the size of the insulator to allow higher voltage operation of the system before load flashover, the velocity can be increased by approximately 16 % for very low mass loads.

7.0 Conclusions

The Atlas pulsed power design problem is about inductance. The reason that a 36 MJ bank is required is that such a bank has enough individual capacitors so that the parallel inductance is acceptably low. Since about half the inductance is in the bank, and the inductance and time constant of the submodules is fixed, the variation of output with a given parameter will generally be a weak one. In general, the dI/dt calculation demonstrates that for the real system inductances, 700 kV is the optimum voltage for the bank to drive X-ray loads. The optimum is broad, and there is little reduction in performance at voltages as low as 450 kV. The direct drive velocity analysis also shows that the optimum velocity is between 480 and 800 kV for a variety of assumptions, and that there is less than a 10 % variation in velocity over this range. Voltages in the 120 kV - 600 kV range are desirable for driving heavy liners (in the range of 30 grams). A compromise optimum operating point might well be 480 kV, which is a voltage which will also somewhat simplify operation in air. At 480 kV, all X-ray operation scenarios are within 10 % of their velocity optimum, and heavy liners can be configured to be near optimum if small enough. If liner diameters are increased along with liner masses, the 480 kV operating voltage will be too high, and it will be difficult to get the best performance from the bank.

Based on very preliminary study I believe that the choice of a single operating voltage point (say, 480 kV) is unneccessary, and that a bank engineered for dual operation at 480 and 240 kV will be the best solution to the Atlas problem.

Acknowlegements

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