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**Pulsed Power for Particle Beam Accelerators
in Military Applications**

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**Pulsed Power for Particle Beam
Accelerators in Military Applications***

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Abstract

Techniques useful for generating and conditioning power for high energy pulsed accelerators with potential weapon applications are described. Pulsed electron accelerators are exemplified by ETA and ATA at Lawrence Livermore Laboratories and RADLAC at Sandia Laboratories Albuquerque. Pulse-power techniques used in other applications are briefly mentioned, including some that may be useful for collective ion accelerators. The limitations of pulse-power and the general directions of desirable development are illustrated. The main needs are to increase repetition rate and to decrease size.

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Introduction

This is a written version of a talk given at the AFOSR/ARO Particle Beam Workshop held at the USAF Academy in Colorado Springs on 9-10 January 1980. The talk was one of the series that introduced the workshop, in which speakers dealt with kill mechanisms, beam propagation, accelerators, beam sources and power and conditioning. These talks were all unclassified.

The talk on power and conditioning was intended by the author to illustrate the technology used to date in the types of accelerator of possible interest as weapons; to point to the present limitations of this technology; to indicate the general range of improvements that may be desirable; and to suggest what avenues seem profitable for development work. The reader should recognize two reservations about indications and suggestions for the future. First, the actual power requirements are still uncertain and will be determined largely by the other subjects dealt with in the other talks already mentioned, when the outcomes in these areas eventually become clear. Secondly, the views given here are those of only one person.

The accelerator types of interest here are Electron Accelerators and Collective Ion Accelerators. In each case both power conditioning and prime power must be considered. Both accelerator types employ pulsed acceleration. The Collective Accelerator has poorly defined power requirements because a number of different Collective Acceleration mechanisms are possible and because the scaling of all of them is less than certain. The situation in Electron Accelerators is much clearer, and therefore these will receive more attention.

The first section proper of this paper describes the power technology used in two existing developmental electron accelerators, the Engineering Test Accelerator (ETA) at Lawrence Livermore Labs and the Radia. (Radial Line Accelerator) at Sandia Labs, Albuquerque. For the sake of completeness, the

differences in acceleration technique between the two are discussed along with the power considerations. Some other pulsed-power techniques are mentioned, including some more suitable for Collective Acceleration.

The following two sections deal with technology improvements needed in the areas of high repetition rate and achieving smaller size, weight and cost. The development of new components and system approaches is clearly of interest. Potentially fruitful technology areas are suggested.

Neutral Beam accelerators are not discussed here. They have quite different power requirements, principally for continuous RF power. In contrast with pulsed power, it appears that a fairly conventional approach (turbo alternators and klystrons) is appropriate, with component optimization the main need.

1. Existing Pulsed Accelerator Technology

We begin by illustrating the technology used in two existing experimental accelerators, ETA and Radlac. Both of these accelerate electron beams through a series of identical pulsed modules.

ETA

The Engineering Test Accelerator (ETA) at LLL, Fig. 1, is a Ferrite-core Linear Induction Accelerator (LIA) that accelerates a 10 kA 10-20 nS electron beam through a series of accelerating gaps each of which adds about 0.25 MeV to the electron energy. The beam is injected at 2.5 MV and accelerated to 5 MV through ten such gaps. The final energy could be indefinitely increased by the use of more stages of accelerating gaps. The acceleration principle that allows this is that the metal tube through which the beam passes returns to ground on both sides of the accelerating gap, passing through a Ferrite core, Fig. 2; the inductance associated with the Ferrite is sufficient that

the conducting path to ground shunting the accelerating gap does not load down the circuit that provides the accelerating voltage.

The device that generates the 0.25 MV pulse for each acceleration gap is also shown in Fig. 2. It is a coaxial, water-dielectric Blumlein; it comprises three concentric stainless steel cylinders, the intermediate of which is charged to 250 kV to store the energy for the pulse. A triggered high pressure gas spark gap switches this charged cylinder to the outer ground, producing a rectangular 250 kV pulse that propagates into the coaxial transmission line formed by the inner and outer conductors. This transmission line eventually delivers the pulse to the accelerating gap.

A pulse repetition rate of about 1 kHz is achieved, limited by the spark gap, which is shown in Fig. 3. Gas (a mixture of SF_6 and N_2) is flowed through this at about 5×10^3 cm/s in order to remove hot gas between pulses. A five-pulse train or burst is possible for ETA, and a ten pulse burst is planned for the Advanced Test Accelerator (ATA) now being developed.

The Blumlein is recharged between pulses from a pulse transformer, Fig. 4. Charge time is 10-20 μs . A series of five separate energy storage capacitors (ten in ATA), all pre-charged to up to 35 kV, is switched in turn into the transformer primary, Fig. 5. The switches used here are thyratrons; they must recover voltage hold-off in the ~ 1 ms between pulses, but each actually switches only once per burst, by contrast with the 0.25 MV gas spark gap in the Blumlein, which operates on every pulse. The capacitive stores are re-charged after each burst by an accurately regulated power supply, and it is possible to operate continuously at one burst every few seconds.

Radlac

Radlac is an air-core Linear Induction Accelerator that is designed to accelerate a 100 kA 10-20 nS electron beam through a series of ~ 2 MV

accelerating gaps, to 10 MeV -- again an indefinite number of additional stages of further acceleration could be added. As in ETA, in each stage the accelerating gap is inductively grounded. A smaller inductance can be used, avoiding the need for Ferrite, primarily because (1) the beam current is much higher so that more current can be "wasted" in the ground inductance; (2) the driving circuit is designed to produce a bipolar voltage at the accelerating gap, with small $\int V dt$ so that the current induced in the inductance at the end of the acceleration cycle is small. Air-core accelerators of this type can efficiently achieve gradients (in MV/m) of up to about I/t , where I is the beam current in kA and t the pulse duration in nS. If I/t is such that an acceptable gradient is not possible, then it is necessary to use ferromagnetic cores.

In this design the grounded cavities that contain the accelerating gaps also contain the pulse forming circuits, Fig. 6. Each cavity has two radial (or biconic) transmission lines formed by a annular central conductor, which is charged to 3 MV, and the grounded wall. The dielectric is oil. After charging, the central conductor is switched to ground at its inner circumference, starting the voltage waveform at the accelerating gap.

The switching in each stage consists of multiple spark closures in the oil itself. These take place at a number of specially field-enhanced points around the accelerating gap. To make the closures occur simultaneously in parallel, with very low jitter, the high voltage must be applied rapidly, in about 0.1 μ S.

The charging circuit is shown in Fig. 7. A number of low inductance capacitors are charged to 3 MV and then a 3 MV gas sparkgap is triggered so that energy flows rapidly from the capacitors to the radial lines. The low inductance capacitors were previously charged by a 3 MV Marx generator in a time of about 1 μ S, determined by the inductance of the Marx. The Marx has

200 kV dc capacitor stages, switched by pressurized SF_6 sparkgaps.

Radlac is used in single-shot mode. Its repetition rate is limited by the oil switches, which need to be cleared of oil spark products and which do not have long lifetime. Consistent with this operation, the Marx is charged in about one minute.

Fig. 8 shows Radlac with one accelerator stage assembled to the injector. The Marx (at left) and intermediate energy store are visible.

General Comments

ETA and Radlac between them illustrate most of the technologies now used to generate short (10-100 nS) high power pulses. The use of liquid dielectrics is convenient because they are self-healing after breakdown and are easily formed into large specially shaped volumes. Water is preferred where possible, since its high permittivity (80) gives high energy density and helps make a compact design. Sometimes the impedance needed can only be achieved using oil (permittivity 2.3).

Liquids must be pulse-charged, preferably in a few microseconds or less, to obtain their highest insulating strengths. With pulse-transformers it is hard to achieve the 1 μS range, but transformers are convenient in allowing all primary energy storage and switching to remain near ground. Marxes can deliver their energy in about 1 μS , and with the addition of an intermediate storage capacitor as in Radlac this can be shortened to about 0.1 μS .

The choice of different techniques for ETA (pulse transformer, water dielectric, and gas switches) and Radlac (Marx, oil dielectric, and liquid switches) is not so much the result of their being different accelerator types as of other factors such as repetition rate and stage voltage. To illustrate this, Fig. 9 shows an alternative design for a Radlac-like accelerator (i.e. an air core linear induction accelerator) in which water is used rather than

oil to reduce the size and gas switches are incorporated to allow repetitive operation. The water is used in a coaxial configuration resembling a Blumlein with the addition of a third (uncharged) transmission line to give inductive isolation and allow sequential acceleration. The design shown could be charged directly by Marx generators to 1 - 1.5 MV and would provide 1.5 - 2 MV of acceleration.

Other Power Conditioning Techniques

Rectangular or similarly shaped pulses may be produced from capacitive pulse forming networks (PFNs) as well as from transmission lines. High voltages can be achieved by coupling through a transformer or by "Marxing", Fig. 10. Because of the effect of stray inductance these techniques are usually confined to longer pulses, a few tenths of a microsecond or more, where longer risetimes are acceptable. However, the Soviets have used capacitive PFNs to generate 20 - 50 ns pulses for low-current (2 - 5 kA) Ferrite-core LIAs, improving the rise-time by passing the pulse through Ferrite-loaded transmission lines. The switches used were thyratrons.

One application of long pulse generators based on PFNs would be the charging of the NRL Auto accelerator. In this scheme it might be possible to avoid the need for a very low inductance short pulse output switch, since the final acceleration pulse could be generated by deflection of the electron beam that inductively charges the accelerator. The need for short pulse capacitive energy storage is also eliminated.

Waveforms of complex shape are difficult to produce in the sub-microsecond high power regime. This is essentially because the main pulse-generating element available is the simple closing switch; more complicated devices such as triodes or even diodes have not yet been developed to drive external loads in this power and time regime. However, one interesting example of the

generation of a more complex waveform is shown in Fig. 11, which illustrates a pulse generator built by Physics International Company for Los Alamos Scientific Lab. There separate segments of transmission line are charged to 3 MV by Marx generators and switched independently into a common 20 ohm load, each one through the previous segment. In this way three 1 - 1.5 MV, 100 kA pulses 40 nS in duration are generated with spacing arbitrarily selectable between 0.1 μ S and $\sim$ 1 mS. More pulses could be added, though with each one the rise-time becomes slightly longer.

For moderate total accelerating voltage, about 10 MV or less, direct acceleration may be preferable to staged inductive accelerators. Much of the technology described here was in fact originally developed to build single stage accelerators, often at very high power, 1 - 10 TW. The first and major application for these was the simulation of nuclear weapons effects. It is likely that collective Ion Accelerators will need to be powered by electron beams in this general parameter range, i.e. very roughly 10 MV, 1 MA, 100 nS.

The largest operating example of an accelerator of this type is Aurora at 20 TW, with four 14 MV 120 nS electron beams totalling about 1.5 MA. Aurora (Fig. 12) has four oil - dielectric Blumleins charged to 12 MV by a 5 MJ Marx system and discharged by triggered oil switches.

Aurora is designed for single-pulse operation, and while in principle it could be re-designed for repetitive operation, in practice it might be very difficult with such large energy and voltage present in each individual circuit. This problem would be eased by a staged acceleration scheme, which would also allow the use of water dielectric instead of oil and so greatly reduce the size; thus collective ion accelerators might best be powered by staged accelerators (probably air core linear induction accelerators), provided that the large currents needed can be stably accelerated in stages.

2. Technology Improvements for Pulsed Accelerators

Higher Repetition Rate

A flow diagram of a typical pulsed accelerator is given in Table 1. In existing systems the power is drawn from the utility grid, but a self contained weapon system would have its own prime power source with an electrical generator, such as a turbo-alternator or MHD device. The energy for the pulse is delivered by this source to a capacitor bank. A switch then closes to activate a voltage-multiplier circuit (eg. transformer or Marx) that transfers the energy to the fast-pulse generator (eg. Blumlein or radial line). An output switch then closes to energize the accelerator. Typical operation requires a burst of pulses at high pulse repetition rate, with a much lower burst repetition rate.

The principal limitation in existing designs is on the pulse repetition rate, and arises from the output switch. This has more severe requirements in terms of voltage, current, di/dt and jitter than any switches earlier in the power sequence. High pressure gas spark gaps have shown their ability to achieve about 1 kHz while satisfying all of the other requirements listed. The range of 10 kHz and upwards may however be desirable, and it is far from clear that the high pressure spark gap can achieve this range. A list of candidates that might be developed for the role of output switch is given in the upper part of Table 2. It is very difficult to pick leading candidates from the list, since in most cases the desired voltage, current, di/dt and jitter are far from demonstrated even when the repetition rate prospects are good.

In the case of the voltage multiplier switch a solution valid for the desired frequency range does exist, in the form of thyratrons employed as in ETA. However, improvements are highly desirable here too, for several

reasons. The thyratrons limit the charging speed of the fast pulse circuit, they have difficulty with the current reversal that occurs in an optimum transformer circuit, they are fairly expensive, and they require heater power. Moreover, the mode in which each thyatron is only required to actuate once and then recover is undesirable because it multiplies the capacitor bank energy and number of multiplier switches by the number of pulses in each burst; it would be preferable to have only one switch, operating at full repetition rate.

The voltage-multiplier switch has much easier requirements on current, di/dt , jitter and risetime than the output switch, so that additional candidates exist, as suggested in the lower part of Table 2. Perhaps the most reasonable approaches out of the whole list are the triggered vacuum or low pressure spark gaps, since these may yield relatively simple and cheap devices.

Other effects of repetition rate need to be addressed, principally the effect on insulation, especially in liquid dielectrics, in the accelerator vacuum gap, and in the interface between high density and the vacuum. Since it is expected that effects of repetition rate can be overcome by de-rating, these areas appear less important than switching.

Reductions in Size, Weight and Cost

The main identifiable elements of the prime-power and power conditioning systems are the power-source, the energy storage capacitors, and the water-dielectric pulse-lines. In the Ferrite LIA, the Ferrite core of the accelerator is another separable element. The following is a comparison of approximate sizes and weights of all these; auxiliary equipment, mechanical structure and the like are ignored.

The water-lines and energy storage capacitors store almost equal energies for the production of a single pulse. Present capacitors have energy

densities in the range of 10 J/lb. when designed for fairly long life. The ETA Blumleins operate at about 1/2 J/lb. dictated by the repetitive pulses and long charge time. The physical densities of the capacitors and Blumlein are quite similar. Thus in an ETA-like system in which each Blumlein is re-charged for each pulse from a separate capacitive store, the total weights and total volume of Blumleins and of capacitors are roughly equal when there is a total of 20 pulses in the burst. The contribution of the Ferrite is generally similar, though the volume tends to be somewhat less, with a larger density. (The Ferrite volume actually depends on the accelerator gradient, which can be increased at the expense of a larger Ferrite radius and hence volume).

It has been projected that capacitors can be developed with energies in the range of 100 J/lb., which would reduce the size and weight of the capacitive energy storage by as much as a factor of 10. Independent of this, a similar reduction would occur if the capacitors are re-charged between pulses, so that for each Blumlein only one capacitor is needed, storing roughly the same energy. In the case of the accelerator, it should be possible to replace the Ferrite cores with metallic, tape-wound cores having three or four times the magnetic flux-density at saturation; this would reduce the weight and size by factors of perhaps four to six at the same accelerating gradient.

Thus it will clearly be important in future designs to attempt to develop more compact Blumleins or their equivalent; otherwise the Blumleins are likely to dominate not only the power supply but the accelerator also. Possible routes of interest are the use of higher repetitive stresses in liquid dielectrics and the use of solid dielectrics.

The power supply does not contribute greatly to the size and weight of the system at least if it is only required to re-charge the energy storage

capacitors between bursts, so that a conventional approach like a turbo-alternator can be used. However, if the number of pulses per burst is large or the size or reliability of the capacitors is a concern, it may be desired to re-charge the capacitor between pulses as mentioned above, reducing the capacitive storage needed. Some power supplies that should be considered for this mode of operation are listed in Table 3.

Some of the supplies listed in Table 3 may be able to charge the pulse line directly, eliminating the intermediate capacitor. However, the charge time may be long, and this might increase the size of the pulse-line by an amount greater than that of the eliminated capacitor.

Several of the supplies include an inductive storage stage. For these the development required is in the opening switch. This must operate at the pulse repetition rate, since if it does not the advantage of reducing the capacitive energy storage is lost.

Summary of Development Areas

The most obvious development area is high repetition rate (≥ 10 kHz) closing switches for generating short (≤ 100 ns) fast rise time pulses. Improved switches are also needed for longer pulse (≥ 1 μ s) duty at the same repetition rate in voltage multiplier circuits, especially with a view to speeding the charge of the pulselines. Opening switches at ≥ 10 kHz would be of great interest if feasible.

Magnetic materials may be useful as closing switches and are also of great interest as accelerator materials, as well as for pulse sharpening.

Techniques for circumventing rep-rate requirements, such as multiple pulse circuits and diodes, may also be useful.

In capacitive storage, the need for highly stressed water or other liquid dielectric pulse-lines is of high priority. Tolerance of long (≥ 10 μ s)

charge times would be useful, and the substitution of solid dielectrics for liquids should be pursued.

Conventional capacitors are also an important development item. It may be that one should not separate these from the use of solid dielectrics, for pulse lines referred to in the previous paragraph; both applications may entail capacitor optimization under pulse-charged conditions. In this context cables may be worth examination as energy stores; in any event cables often play a significant role in routing energy and high voltage, and there is a need for better characterization of modern cables in repetitive pulse duty.

Finally, power sources such as MHD and brushless rotary flux compressors are of interest, principally if they can re-charge the first energy storage stage at ≥ 10 kHz.

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TABLE 1

CONVENTIONAL PULSED ACCELERATOR SCHEME

TABLE 2

HIGH REPETITION RATE SWITCH CANDIDATES

1. Output or Voltage Multiplier:

High Pressure Gas Spark Gap

Low Pressure Gas Spark Gap

Thyratron

Vacuum Surface Flashover

Electron Beam Controlled Gas Discharge

Saturable Reactors

Electronic Solid State

2. Voltage Multiplier Only:

Crossed Field Tube

Liquid Metal Plasma Valve

Ignitron

Vacuum Spark Gap

TABLE 3

ALTERNATIVE POWER SOURCES FOR PULSED ELECTRON ACCELERATORS

Compensated Alternator

Brushless Rotary Flux Compressor

Magneto Hydrodynamic Generator (MHD), Continuous or Pulsed

Explosive Magneto Cumulative Generator (MCG)

Inductive Store (Charged by Homopolar Generator, MCG or MHD).

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Existing M-2 pulser which produces three 1.3 MV, 80 kA, 40 ns pulses with pulse separations of 50 ns to 30 μ s. This system can be used with a passive output transformer to produce 5 MV pulses.

Typical M-2 output waveforms with fixed impedance at 50 ns/ division.

Fig. 11

AURORA

Fig. 12