# EVALUATION OF PULSED POWER ARCHITECTURES FOR ACTIVE DETECTION*


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*Abstract:*

Intense pulsed active detection (IPAD, [1]; also see presentations at this conference by B.V. Weber, et al., D.P Murphy et al., S.B. Swanekamp et al. and J.C. Zier, et al.) has been proposed as a means of detecting contraband fissile material from a distance. In this approach, an intense bremsstrahlung pulse is used to induce photo fission, the products of which are detected. In this work, we report on an initial effort to evaluate the applicability of various pulsed-power architectures to this approach. The electron energy is 12 MeV with an effective electron charge at 12 MeV of 3 mC to 5 mC delivered in ≤ 100 ms, in either a single pulse or a burst. The eventual goals for the accelerator are compactness, especially short length; relatively light weight; transportability; and ease of setup and operation in the field.

We first consider designs that could be constructed in a few years with minimum development. We compare induction voltage adders (IVA), ferrite-core linear induction accelerators (LIA), and linear transformer drivers (LTD). Conceptual point-designs are developed for each approach using essentially demonstrated technology, though the LTD assumes scaling and repackaging. The IVA design was considered for further design development [2].

We then sought approaches that are not demonstrated technology but have promise for achieving substantially less weight and volume. We considered recirculating LIAs, auto-accelerators, air-core LIAs, dielectric wall accelerators, and vacuum inductive stores with plasma opening switches. A partial pre-conceptual design of a 100 kA, single-pulse air-core LIA suggested that this might be a promising advanced candidate, and it is described here. An evaluation of the other advanced concepts will be published elsewhere [3].


## INTRODUCTION

This work compares a number of approaches to accelerators that can provide bremsstrahlung pulses thought to be suitable for detecting fissile material from a distance. The use of a pulsed source gives access to the strongest responses of the fissile material, prompt and delayed neutrons and delayed gammas. Based on a notional detection scenario, the specifications for the accelerator architectures to be compared were determined.

Induced fissions from the irradiated fissile material vary as a high power (9-12) [1] of bremsstrahlung endpoint up to 14 MeV, and 12 MeV was chosen as a compromise between increasing the induced fissions and limiting accelerator size and collateral photoneutron activation. The large exponent also gives an incentive to make the energy or voltage pulse square; the pulse shape was accounted for in each possible design by calculating the relative fission yield for each element of accelerated charge from the voltage at which it was delivered and determining a total equivalent charge at 12 MeV. The goal for this equivalent charge was 3 mC in the case of a paraxial electron beam. Pulse durations of up to 500 ns were acceptable for this application, but the accelerators described here have durations in the tens of ns range because they are desired to be compact, especially in length, and lightweight; longer pulse durations increase the dimensions and weights needed to insulate or inductively-isolate them. For approaches that cannot deliver the required charge in a single pulse, multiple pulses with lower charge per pulse were allowed in up to 100 ms.

The first assessment was of accelerators that might be constructed in a few years, with little development: the Induction Voltage Adder (IVA), the Linear Induction Accelerator (LIA), and the Linear Transformer Driver (LTD). Point designs for each were evaluated and are described here. Then an initial exploration was made of more developmental designs to identify ones that could greatly reduce size and weight, and estimate how much; one promising concept is reported here, and exploration of the others can be found in [3].

## NEAR-TERM DESIGNS

*Induction Voltage Adder (IVA)*. An IVA is a series of induction cells threaded by a stalk that delivers the added cell voltages to an electron diode [4]. The stalk is magnetically-insulated and therefore carries a large current, making it suitable to deliver the IPAD charge in a single pulse.

Quantitative optimization of the two chief free parameters of a 12 MV IVA delivering a fixed total charge – current (or pulse duration) and cell voltage--was addressed in a later effort [2]. Here, a current of 150 kA was chosen, for which a relatively fast risetime could be generated by a single pulse forming line (pfl) and for which the diode impedance (80 ohms) was in a familiar


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range in which the angle of electrons with the axis could be estimated from existing designs. Though this angle was quite small, about ±5 deg, the bremsstrahlung polar diagram reduces x-ray intensity in the forward direction so that 5 mC equivalent at 12 MeV is needed to induce the same number of fissions as a paraxial 3 mC beam. The pulse must therefore have an effective flat-top duration at 12 MV of 5 mC/150 kA ≈ 33 ns.

It was also decided to use a cell voltage of 600 kV. This is lower than the 1-2 MV range of previous IVAs, but would have the benefits of reduced Marx insulation distance and reduced vacuum insulator inductance. It also took advantage of allowing scaling from a design being developed by L-3 for another application.

The IVA conceptual design is shown in Fig. 1. The twenty 0.6 MV Metglas-core cells needed for 12 MV total are each driven by a single water pfl. These are charged to 1.3 MV in about 1 μs, in pairs, by ten Marx generators. This allows small Marxes to be distributed along the length of the IVA; it also speeds the pfl charge because of the reduced capacitance of each circuit, and so reduces pfl and switch dimensions and risetime. The Marxes are insulated by 15 psig $SF_6$ rather than oil, to reduce weight.

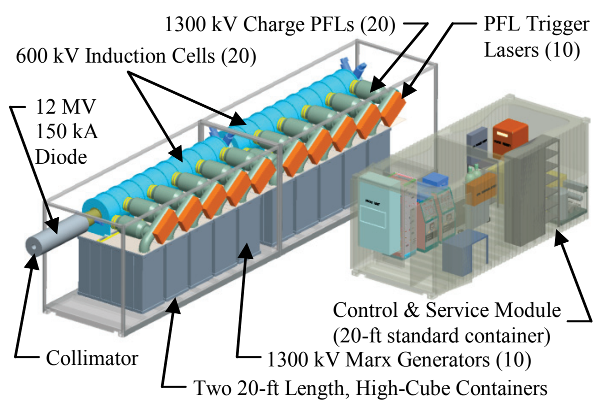


**Figure 1. Induction Voltage Adder (IVA).**

The impedance profile along the pfl length was iterated to give the flat-top pulse shown in Fig. 2; the fwhm of the power is about 45 ns, 12 ns longer than the 33 ns effective flat-top. The pfl output switches are laser-triggered $SF_6$ spark gaps.

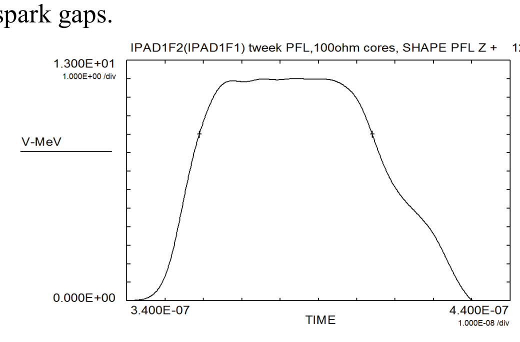


**Figure 2. IVA cell voltage waveform.**

The IVA is about 34-ft. long, and can be parted into two lengths for transport in two 20-ft. long high-cube iso-containers. An ancillary 20-ft-long container of standard cross-section (Fig. 1) houses controls and service modules (power supplies, Marx triggers, and water, air, and $SF_6$ systems). Use of aluminum in the Marx tanks and cells results in a total IVA weight of about 80 klb; the ancillary container is 14 klb and the total about 94 klb. A breakdown of these weights is shown in Table 1.

At one pulse per ~100s, the IVA design is conservative and low risk. Issues for this application involve the front end. The electron beam direction may need to be aimed at an object, independent of the IVA axis; this may be possible using an applied magnetic field, but this has not been demonstrated with a high current diode fed by a magnetically-insulated coax. The electron beam area must be of order 100 in.$^2$ to ensure single-shot anode survival, and for this large an x-ray source there may be challenges in the design of the collimator, which must also be aimed.

Table 1. IVA Weight Breakdown.

| Description | Quantity | Wt. (lbs) |
|---|---|---|
| **Accelerator Unit** | | |
| Marx, aluminum tank SF6 insulation | 10 | 18,130 |
| Transmission lines, aluminum | 10 | 1,060 |
| PFLs | 20 | 12,280 |
| Accelerator cells | 20 | 20,000 |
| Containers | 2 | 14,120 |
| **Accelerator Subtotal** | | **80,470** |
| | | |
| **Ancillary Unit** | | |
| DI water, oil, SF6 systems | Lot | 2,635 |
| Power, controls, core reset | Lot | 4,100 |
| Container | 1 | 7,350 |
| **Ancillary Subtotal** | | **14,085** |
| | | |
| **IVA System Total** | | **94,555** |

*Linear Induction Accelerator (LIA).* In an LIA an electron beam is transported through the induction cells instead of threading them with a stalk. Beam transport tends to limit the current, and for the conceptual design here a current of 5 kA was used. This is lower than the 10 kA accelerated to somewhat higher energies in the repetitive 50 MeV ATA [5] at LLNL. The conceptual LIA design was based on theATA, and it is shown in Fig. 3.

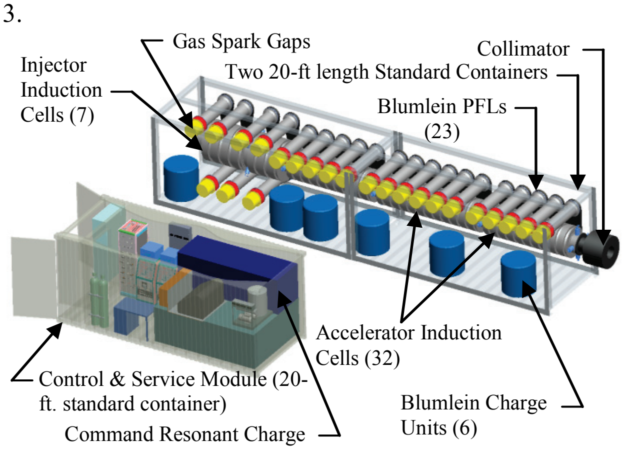


**Figure 3. Linear Induction Accelerator (LIA).**

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The induction cells use ferrite isolation cores, because the lower flux swing of ferrite compared to Metglas results in smaller and more constant magnetizing currents through the cores in parallel with the beam; time-variations of these currents tend to reduce the flatness of the voltage pulse, which is needed for good beam transport, as well as for efficiency in the IPAD application, as noted earlier. Thirty-two 33-in. diameter induction cells each provide 320 kV of acceleration to the 5 kA beam from a 2 MV injector. The accelerator cells are similar to those of ATA, with the bore reduced about 40% to 3.125-in. as allowed by the smaller beam current and total acceleration or number of cells. The injector has larger, 48 in diameter cells, to allow the vacuum bore to be 18-in. It is configured as a voltage adder, though not magnetically-insulated – the electric fields on the smooth stainless steel negative surfaces are below electron emission threshold. Seven 320 kV cells provide 2 MV in the injector.

Analysis of a recent ATA Blumlein waveform obtained in the NDCX II program at LBNL (Fig. 4) indicated that the effective flat-top voltage duration can be 50 ns assuming that a rather shorter beam current pulse is used in order to hold-up the leading and trailing edges slightly and so extend the flat-top. The effective charge per pulse is therefore 0.25 mC. Thus twelve pulses are needed to supply the 3 mC that is assumed to be adequate because the LIA beam can be essentially paraxial. In the 100 ms allowed for the burst, the pulse separation is 9 ms corresponding to 110 Hz.

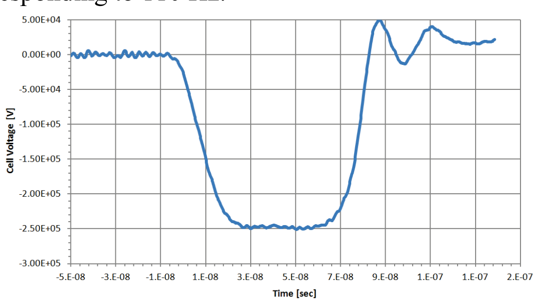


**Figure 4. ATA Blumlein waveform.**

One water Blumlein drives each of the seven injector cells and two each accelerator cells, so that 23 Blumleins are needed in all. The Blumleins are charged to 300 kV in a unipolar 10 µs pulse rather than the 20 µs bipolar pulse of ATA, and this allows a diameter of 12-in. to be consistent with conservative water stress, compared with 18-in. in ATA. The number of Blumleins and the repetition rate are both about an order of magnitude less than in ATA, and this also helps allow a higher water stress. The Blumleins are charged by six Blumlein-charging units (BCU); a BCU comprises 30 kV capacitors, a thyratron switch and a 10:1 iron-core pulse transformer, and is insulated by 30 psig $SF_6$. Each is capable of charging four Blumleins, through cables. The BCUs are housed alongside the Blumleins (Fig. 3). An ancillary unit houses three 20 kV command resonant charge units, which are air-insulated; as well as fluid supplies, triggers, and controls. The Blumleins are switched by coaxial V/2 field-enhanced spark gaps like those in ATA. ATA demonstrated 1 kHz with high speed gas flow, and 110 Hz 12-shot bursts will require much less flow.

For the injector cathode, a thermionic design is the only one with demonstrated 110 Hz capability. However, it is likely that a cold emission cathode would be adequate. In a private communication Caporaso at LLNL reported that Birx found that velvet cathodes operated continuously at up to 60 Hz, above which they had a life of only seconds. A 12-pulse burst at 110 Hz might therefore be possible with velvet; glass fiber or carbon filament cathodes may be superior.

Calculations for an assumed anode design of 1 mil of Ti, 16 mils of Ta and 0.9-in. of Al, showed that a beam diameter as small as 2 in. will avoid target melt or damage in the 12-pulse burst. This small beam size will make it relatively easy to collimate the x-rays. Another inherent advantage of the LIA is that it is easy to aim the electrons and x-rays rapidly using applied magnetic fields to deflect the drifting electron beam.

Like the IVA, the 40-ft.-long LIA fits in two 20-ft-long iso-containers, of standard cross section in this case, that are separated for transport and have a total weight of about 134 klb. A 35-ft.-long standard-width ancillary container weighs about 20 klb. The total LIA system weighs about 114 klb. A breakdown of these weights is shown in Table 2. The LIA is heavier than the IVA, primarily because of the induction cells. These contain similar volt-seconds to the IVA, but ferrite with its much lower flux density swing has a larger weight and volume for the same volt-second requirement; and the number of cell structures also adds to the weight. The repetitive pulse charging contributes to a still greater weight when ancillary containers are included.

Table 2. LIA Weight Breakdown.

| Description | Qty | Wt. (lbs) |
|---|---|---|
| **Accelerator Unit** | | |
| Injector cells, support stds & vacuum | 7 | 14,866 |
| Anode and cathode structures | 1 | 2,117 |
| Accelerator cells | 32 | 37,276 |
| BCU | 6 | 13,224 |
| Blumleins and cell connections | 16 | 21,728 |
| Output hardware | 1 | 2,100 |
| Accelerator containers | 2 | 13,700 |
| **Accelerator Subtotal** | | **113,775** |
| | | |
| **Ancillary Unit** | | |
| BCU Drivers | 3 | 8,769 |
| DI water system | 1 | 1,000 |
| Oil System | 1 | 1,500 |
| Controls and diagnostics | Lot | 1,000 |
| Ancillary container | 1 | 7,350 |
| **Ancillary Subtotal** | | **19,619** |
| | | |
| **IVA System Total** | | **133,394** |

While the 5 kA beam current of the LIA was chosen as a value that was conservative with respect to that of existing designs of this type, it will be seen below that in considering more developmental accelerators much higher beam currents, up to 100 kA, were assumed. Use of a higher current in the LIA could therefore be considered. It would reduce the number of pulses required. A modest increase, say to >10 kA, < 6 pulses would probably assure that a cold cathode could be used in the injector. But the larger beam current will increase the size of the LIA cells, because a larger bore is needed to transport the higher current beam, and probably because the increased current will increase risetime and hence pulse length. The increased energy stored in the Blumleins will increase their size and weight. Therefore a ~10 kA LIA was not considered promising. However, an increase to ~60 kA would allow a single pulse and greatly reduce the ancillary trailers by simplifying the BCUs and eliminating the CRCs. It might also allow Metglas cores to be used to reduce cell size, because the larger and more time-varying currents through the cores could be tolerated in comparison to the high current beam; this option has not been investigated.

Linear Transformer Driver (LTD). The LTD was also considered a candidate for near-term implementation, although LTD systems have not yet been fielded in operational use and in experimental testing have not exceeded about 2.5 MV. Much less work was done here on the LTD than on the IVA and LIA.

A major challenge for the LTD in the IPAD application is the length. Present LTDs cells or cavities are 8-in.-long and generate roughly 120 kV, depending somewhat on their loading. For 12 MV a length of around 60-ft. would therefore be needed, plus length for pumping. To reduce the length, a scheme was devised where the LTD "bricks" – sets of capacitors – are Marxed to generate twice the voltage per cell. The bricks are still placed side-by-side in a circle and switched at their outer terminals; but adjacent pairs are connected in series by low-inductance transmission lines placed inside the circle, Figure 5.

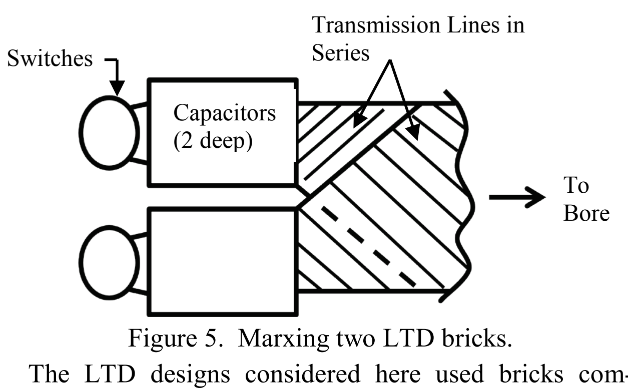


Figure 5. Marxing two LTD bricks.

The LTD designs considered here used bricks comprising two 20 nF, 100 kV GA capacitors in series as in [6], from which the designs also took inductance estimates. Each Marxed brick pair was combined with a similar one formed from pairs of ~2.5 nF, 50 kV ceramic capacitors in series to make a Type C Guilleman network. This was an attempt to improve on the sinusoidal pulse delivered by the high capacitance bricks if used alone, and to obtain the more flat-topped pulse desired in this application.

A first configuration was explored that delivered an effective 10 mC at 12 MV with a peak current of 160 kA. The effective flat-top is therefore 63 ns, and the power fwhm of about 100 ns is substantially greater than the effective flat-top because the pulse is still far from square. This configuration used 20 bricks of each type in an 8-ft. diameter, 10-in.-long, 216 kV oil-filled cavity, of which 56 are required. The vacuum bore was 30-in. diameter, and the stalk tapered to a minimum diameter of 18-in.

Later the IPAD goal of 3-5 mC was adopted, and assuming the LTD was equivalent in electron beam angle to the IVA, a 5 mC variant was very roughly identified. That used 16 bricks of each type in a 7.25 ft. diameter 12 in. long, 290 kV cavity, of which 42 are required. In this case the stalk diameter at the output end is only 2-in., so that the stalk would have to be transiently placed in position on each shot. The small cathode could also make control of electron beam angle difficult, so the 5 mC might be insufficient, and an adequate design might prove intermediate between the two.

Taking the 5 mC and 10 mC designs as bracketing the LTD-equivalent of the IVA and LIA described above, the LTD length is in the range 42-56 ft, and estimated weights from 120 klb to 170 klb. No accounting has been made for vacuum pumping, which will increase the lengths somewhat. The total number of bricks is in the range 1344 to 2340. No ancillary or service container has been identified, but this will be smaller than those of the IVA and IPAD because it contains only controls, power supplies, triggers, and oil and spark-gap air supplies – no pulse charge circuits or water or $SF_6$ systems.

The stated weights include the oil. For transport, it would be possible to drain the oil and transport it separately. The estimated hardware weights to be transported then reduce to the range of 50-70 klb. LTD cavities to date have been separate oil volumes, but it would be easy to make the cavity volumes communicate so that they fill and drain together--at the expense of needing to fill and drain the whole LTD when a cavity needs to be replaced.

Relative Assessment. Of the near-term candidates the LTD has a weight advantage when empty of oil, but no size advantage, and has aspects that are developmental, namely the Marxing of bricks, the complexity in terms of the number of active components (which exceeds that of existing LTDs) and the 42-56 cell addition of voltages in vacuum power flow.

The IVA is considerably lighter than the LIA. It is somewhat shorter than the LIA and considerably simpler in construction and operation. The LIA not only has many more components than the IVA, but its setup requires careful alignment and tuning of the electron beam transport system, which must then be maintained. The repetitive operation and possibly a thermionic cathode contribute to a more complex operation. The greater complexity of the design, the hardware, and the operation all lead to a longer fabrication and test period than is needed for the IVA. Therefore the IVA was the approach selected for further design study [2].

## DEVELOPMENTAL DESIGNS

Following the above work on near-term designs, approaches that might result in smaller and lighter systems were briefly investigated. One that appeared promising, the air core linear induction accelerator (ACLIA), is illustrated here. The others are all explored somewhat further in [3]. They are the re-circulating LIA [7], the LLNL dielectric wall accelerator [8] (including a graded solid dielectric based on that described by Chen [9] and on work by Domonkos [10]), the auto-accelerator [11] and a vacuum inductive store with opening switch [12].

The ACLIA is an LIA that has no magnetic material, and instead achieves high efficiency by generating a bipolar pulse that can leave the inductances of the cells empty of magnetic energy after accelerating the beam on the second pulse. The ACLIA might be considered only moderately developmental, since such an accelerator, the Soviet LIA 30 (40 MeV, 100 kA, 25 ns, 1.7 MV/m) operated in the 1990s [13].

LIA 30 (Fig. 6) was based on induction cells having radial versions of a bipolar output transmission line due to Pavlovskii. The design used here, due to Eccleshall and Temperley [14], has advantages including an output voltage 1.5 times the charge voltage and a flatter output pulse. We use it here in a coaxial rather than radial form.

**Figure 6. LIA-30 (courtesy of G. Caporaso, LLNL).**

Figure 7 shows a schematic of the cell; the vacuum interface with the beam is not detailed. The double transit time of each line, 45 ns, is the ideal output pulse duration. The details of the ends of the transmission lines were approximately optimized in a 2-D LSP calculation that also determined that a reasonable switch inductance to give an acceptable pulse shape was 4 nH. The open-circuit pulse from the LSP calculation, with 600 kV charge, is shown in Fig. 8. The beam is injected after voltage reversal, and extracts inductive energy built up in the cell during the first pulse. The beam is one half of the current that would match the 4-ohm output line of the cell, which reduces efficiency from 100% to 75%, The beam current waveform, ~100 kA peak, is assumed to be controlled to load the output line of the cell to maintain a flat 1.25 MV accelerating pulse. If that were done in an ideal way 3.5 mC would be accelerated.

The 4 nH switch inductance is estimated to be obtainable using ten pressurized $SF_6$ V/N spark gaps distributed around the cell and each triggered by a ~100 kV pulse to obtain ~1 ns jitter; this is not far from US experience, and LIA 30 had a total of 2432 trigatron switches with similar voltage and jitter.

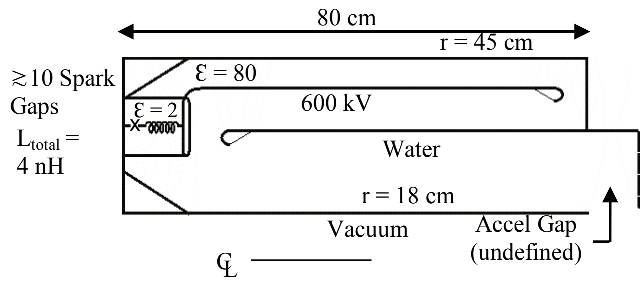


**Figure 7. Coaxial ACLIA cell.**

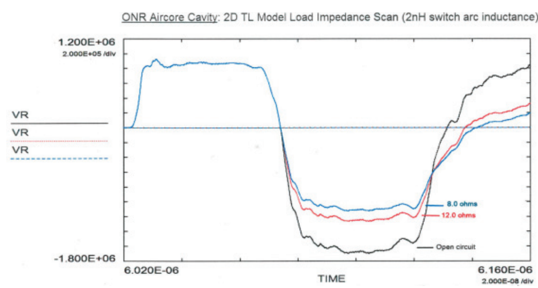


**Figure 8. ACLIA cell output from 2-D TL model.**

A layout for the accelerator is sketched in Fig. 9. Seven cells provide 8.75 MeV of acceleration over about 8m, a gradient of 1.1 MV/m. By comparison, LIA 30 obtained 1.7 MV/m for a somewhat shorter pulse, and sustained this over >20m to reach 40 MeV. The cells are charged in about 500 ns by individual Marxes each having three ±100 kV stages. The Marxes are insulated by 15 psig $SF_6$ in aluminum tanks, and are similar to those in the IVA described earlier but deliver only half the voltage.

The ACLIA has a vacuum bore of 36 cm, roughly the same as the bore of LIA 30 in Ref. 13. Therefore the same 6 kG transport magnetic field should be adequate.

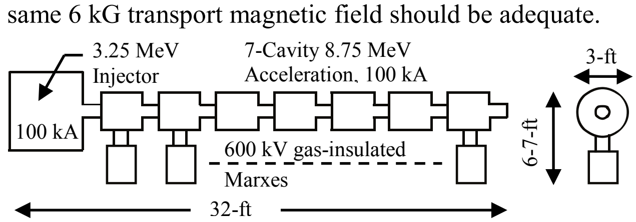


**Figure 9. ACLIA schematic.**

To reach a total energy of 12 MeV, a 3.25 MV injector is needed. In Fig. 9 is sketched an injector with dimensions similar to those of the 4 MeV injector illustrated (only approximately) in Ref. 13. The LIA 30 injector is not understood. It appears to use a magnetically-insulated feed to the cathode; magnetically-insulated power flow to a cathode immersed in a 6 kG magnetic field requires detailed particle-in-cell calculations that are far beyond the scope of this effort. Also, the LIA injector is powered by bipolar transmission line circuits similar to but larger than those of the accelerator. Ideal operation of such circuits requires their loads to be placed immediately at their output terminals, whereas in the LIA injector their outputs are at significant and different distances from the cathode load. However, LIA 30 did in fact operate successfully: and it would be possible if necessary to devise an injector driven by unipolar pulses.

The cells of the 8.75 MeV accelerator, the Marxes and the beam transport capacitor banks are estimated to weigh 20 klb. The 3.25 MV injector will add to this substantially, but the concept may still achieve significantly lower weight than the near-term approaches described earlier, and is considered is the most promising advanced approach for further study or prototyping.

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