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High Gradient Linac Prototype: A Modest Proposal*

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1. Introduction

This note proposes an experimental test of a single accelerating gap of a pulsed linac. This accelerating gap consists of two parallel coaxial disks; an electromagnetic wave injected uniformly at the outer periphery of the disks (initial amplitude V_0) grows while traveling towards the center to GV_0, G being the transformer rates, or voltage gain, of the structure.

An analytical study of the radial line transformer concept has given a simple expression for the 'gain' of a set of parallel disks. The expression[1] is:

$$G = 2\sqrt{\frac{2R}{\tau_R c + g}} \tag{1}$$

where R is the radius of the disks, g the gap between them, τ_R is the risetime of the pulse applied at the outer periphery of the disks, c the velocity of light. Expression 1 shows that gains of the order of 10 (or more) can be achieved for reasonable values of the radius and gap, *provided* the product $\tau_R c$ is of the same order of g. Therefore the main problem (at least at this stage) is how to generate and inject a fast risetime wave into the radial line. Weiland[2] is developing an accelerator based on the injection of a wave by means of an annular relativistic electron bunch traveling near the periphery of a set of disks. J. Stumer[3] has performed an extensive computer simulation of a photocathode switch, following a proposal of Willis;[4] Our proposal suggest the use of a high pressure gas avalanche switch; like the photocathode switch, it will be driven by a fast laser pulse.

2. The Switch

Apart from high speed, the switch must have the following properties:

1) Excellent stability. The EM wave travelling towards the disks center must have an uniform front. Any instability of the wave front will produce transverse fields acting on the beam.
2) High efficiency. The energy needed to trigger the switch plus the energy dissipated by the switch must be small compared to the EM wave energy injected in the radial line.
3) Ease of fabrication. As mentioned before, a substantial amount of simulation has been done for a switch that uses photocathode surfaces generating current under a short pulse of laser light. This switch is a very distinct possibility, but it is not easy to fabricate and to maintain (photocathodes need very clean, high vacuum).
4) High voltage capability. The radial line transformer can amplify the electric field applied to the switch by at least an order of magnitude; but since this increase goes as the square root of the transformer radius, it will be difficult to have much higher gains. In other words, in order to obtain large gradients the switch must be able to hold high fields.

The gas avalanche switch described below should satisfy the requirements set by 2), 3) and 4). The stability requirement however, awaits experimental verification.

The quantitative description of an electron avalanche in gas goes back to Townsend.[5] Starting from N_0 free electrons in a gas, the avalanche growth under an external electric field can be written as:

$$N(x) = N_0 \; e^{\alpha x} \qquad (2)$$

where x is the distance travelled by the avalanche, α the (first) Townsend coefficient. Experimentally the coefficient α is a function of E/p (electric field/pressure) and it can be calculated with good approximation if a detailed knowledge of the cross sections of all electron interactions is available. The usual parametrization of α is:

$$\alpha = A\, p\, e^{-B\frac{p}{E}} \tag{3}$$

A, B are the constants that depend upon the detailed knowledge mentioned before: these constants are measurable (in many ways) and are valid for an extended range of E/p for a given gas.

The avalanche growth between two electrodes produces a current

$$I(t) = Q_0\, \frac{v}{s}\, e^{\alpha v t} \tag{4}$$

having replaced x by $v \cdot t$ (v is the drift velocity of the electrons); s is the spacing between the electrodes, Q_0 is the charge present at $t = 0$ in the gap.

The current grows until the dipole field in the avalanche reaches a value close to the external electric field. At this point, further growth must occur via a different mechanism, *i.e.* by photon ionization: photons escaping from the avalanche ionize a region where the applied field is still high, and start another avalanche. Photoionization is present also at earlier steps of the avalanche and its effect is included in the values of A and B. The photoionization becomes important (dominant) when

$$\alpha v t = \ell n\, \frac{N}{N_0} \simeq 20 \tag{5}$$

i.e. when the "gain" has reached $\sim 5 \times 10^8$. This is called Meek's condition, and it is a good rule of thumb to describe the transition onset. After this transition the "classical" Townsend description of Eqs. (2) and (3) is not correct; but up to a gain of $\sim 10^7$ ($\alpha v t \simeq 16$) we are on "safe" grounds.

These arguments have been applied to the study of avalanche counters,[6] where the ionization left by a charged particle in Argon (high pressure gas) between two parallel plates starts an avalanche that reaches Meek's condition very rapidly ($\sim$ 200 ps). In these conditions the timing of the electrical pulse generated by the avalanche has a small time jitter (measured as $\sim$ 50 ps) with respect to the passage of the particle.

The time needed to reach Meek's limit is also (approximately) the risetime of the electrical pulse induced by the avalanche and it can be calculated as follows. The electric of drift velocity v depends on E/p as (μ is the mobility)

$$v = \mu \, \frac{E}{p} \tag{6}$$

Using Eqs. (3), (5) and (6) we obtain for t:

$$t = \frac{e^{-B\frac{p}{E}} \ell n \frac{N}{N_0}}{pA\mu\frac{E}{p}} \tag{7}$$

This expression shows that for E/p fixed, the time decreases linearly with p. One of the avalanche counters was run in the following conditions:

$\text{gap} = 185$ microns
$V = 5.8$ kV
$t = 200$ ps
$p = 4530$ Torr (6.2 Atm)
$E/p = 70$ V cm^{-1} Torr^{-1}

The gas was Argon with about 16% of organic quenchers adder to prevent avalanche spread; the time to reach 5×10^8 gain was 200 ps; or 160 ps to reach a gain of 10^7. By increasing the pressure and the voltage by a factor of 40 the time will be reduced to 4 ps. The parameters in our case will be

$$\begin{aligned} \text{gap} &= 185 \text{ microns} \\ V &= 232 \text{ kV} \\ t &= 4 \text{ ps} \\ p &= 1.8 \times 10^4 \text{ Torr} \quad (250 \text{ Atm}) \\ E/p &= 70 \text{ V cm}^{-1} \text{ Torr}^{-1} \end{aligned}$$

It is important to notice that the avalanche counter held the electric field on the 185 micron gap continously (D.C.). In general well treated, smooth electrode surfaces show correct scaling for voltage breakdown, *i.e.* the breakdown depends only on E/p; a deviation from scaling manifests itself as a lower breakdown field then expected from the increase in pressure. We assume (and hope) that if there is a deviation from scaling in our case, it will be compensated by the fact that the high voltage will be applied for a very short (1-2 ns) time, rather than attempting to hold the voltage D.C.

The ionization left by the charged particle crossing the avalanche counter was very small: less than 4 electrons in the example given above. We will trigger the avalanche with the electrons released by an ultraviolet laser pulse from the anode of the switch. Although the quantum efficiency of bare metals is low ($\sim 10^{-3}$), the laser energy required will be small (order of nanojoules). In fact, let us assume that the current needed is 100 kA. Equation (4) gives

$$Q_0 = 5.8 \times 10^7 \ , \quad \text{electrons} = 9.25 \times 10^{-12} \text{ Coulombs}$$

for the following values of

$$\begin{aligned} \text{drift velocity} &= 2 \times 10^7 \text{ cm/sec} \\ s &= 185 \text{ microns} \\ e^{\alpha v t} &= 10^7 \end{aligned}$$

with a quantum efficiency of 10^{-3}, the energy needed by a UV (5 eV/photon) laser is 46 nJ. The laser pulse duration must be shorter (or ~ equal) to 4 ps.

3. The Radial Line Transformer (RLT)

There are two possible configurations for the single stage phototype RLT (see Figs. 1 and 2). The first can be thought of as a line injecting a current through the switch S into the RLT. If the impedance of this structure is equal to the input of the RLT, there will be a loss of 50% of the voltage applied. The second can be thought of as a Blumlein structure injecting a current into the RLT by closing the switch S to ground. In this case the voltage injected will be the full V_0 applied, while the current through the switch must be twice as large as the current injected into the RLT. While the second structure can be used for a repetitive, many gaps accelerator, the first is easier to build, and has somewhat lower electric stresses on the insulator that forms the high pressure vessel (see the details on Figs. 1 and 2).

In either case one of the two disks have a hole in the center, so that an electron bunch can be extracted by a fraction of the light from the same laser that drives the switch, appropriately timed. This is the only practical way to measure the electric field in the accelerating gap.

The expected energy gained by electrons is of the order of a few MeV, easily measurable with a single permanent magnet analyzer. By varying the relative delay between the trigger and the extraction pulses one can map the accelerating field as a function of time. Some (tentative) values of the RLT dimensions are (refer to Figs. 1 and 2)

disk spacing	$g = .15$ cm
disk radius	$R = 3.5$ cm
pulse risetime · c	$\tau_R c = 1.5$ mm
gain (Eq. (1))	$G \cong 9.7$
charging voltage	$V = 230$ kV
Voltage at center of RLT	$V_f = 2.25$ MV
switch gap (Eq. (4))	$s = .180$ mm
gradient	1.5×10^9 V/m
injected current	89.4 kA
laser energy required to trigger	41 nJ

4. The High Voltage Modulator

The RLT high voltage electrode will be pulsed for 1.5 ns by a 75 Ω Blumlein pulse forming line. The main Blumlein switch (a spark gap) will be triggered by the same ultraviolet laser, in order to guarantee synchronous timing between the RLT switch and the high voltage applied to it. The Blumlein will be pulse charged by a small Marx generator. The combination of Marx plus Blumlein is an old workhorse for high voltage pulse generation, and it does not pose any particular difficulty. The following list contains some of the parameters relating to the Marx generator and Blumlein line.

Marx generator:	34 stages, 17 gaps, 1400 pF/stage, oil insulated
Output capacity:	41 pF
Maximum charging voltage:	± 40 kV
Nominal output voltage (max.):	1.36 MV
Energy stored @ 250 kV output:	1.3 Joules
Blumlein, oil insulated:	
Output, impedance:	75 Ω
Pulse length:	1.5 ns
Equivalent capacity:	40 pF

5. The Laser

The laser requirements are rather modest. The energy needed to trigger the Blumlein should be of the order of .5 μJ. For the electron beam extraction from the anode of the RLT (see Fig. 6) we need about 8 nJ for 10^7 electrons. Including the inevitable losses in the optics needed to generate the different light beams, it appears that 1 μJ laser energy could suffice. Such a laser exists at the Los Alamos National Laboratory, and it is currently generating the 1 μJ in 4 ps at 234 nm wavelength,[7] at a repetition rate of a few hertz.

6. The Experimental Set Up

The components described above will be assembled on the optical bench that supports the laser, to guarantee alignment and stability (Fig. 3). The light pulse will be split in three parts, to trigger the Blumlein switch, the RLT and to extract the test electron bunch. The wave going to the RLT requires some optics (to be designed) to form the light annulus needed for uniform triggering. The Marx generator and laser are triggered by a common electrical pulse, and we expect some difficulties in synchronizing these two parts. The variable delays needed have a range of a few nanoseconds, with a step size of the order of a few picoseconds: they are made of a corner cube reflector mounted on micrometric stages that change the light path length.

The light going to the RLT anode will be focussed on a small spot ($\sim$ 20 microns); the electrons extracted will be accelerated, and deflected by a permanent magnet (500 gauss, 5 cm length); the angular deviation will be about 18 degrees, for a 2.5 MeV beam energy.

7. What Do We Hope To Learn

The main purpose of these tests is to determine whether the gas avalanche switch satisfies the high speed required by the RLT. One could think that a measurement of the switch risetime could be made using a simpler arrangement. Unfortunately there is no diagnostic system capable of measuring risetimes of a few picoseconds: sampling scopes have response time an order of magnitude slower than needed, and require high repetition rate, not available from the laser. More exotic electro-optic techniques (in conjunction with streak cameras) cannot be used easily because electro-optic materials do not work at ultraviolet wavelengths, and have not been used at the high values of electric field we hope to achieve near the center of the RLT. Therefore we propose to measure the energy of the electrons accelerated by the RLT as the only practical way to determine the switch risetime. Furthermore a few very small holes off center at different radii of the RLT can be used to study the electric field behaviour as a function of R (and time). If the switch works as expected, we could establish the maximum gradient possible with a switched power structure.

8. Conclusions

The gas avalanche switch triggered by an ultraviolet laser may be sufficiently fast for use in the RLT structure. The experimental apparatus described requires a modest investment, and it could lead to a switching technique useful in other applications.

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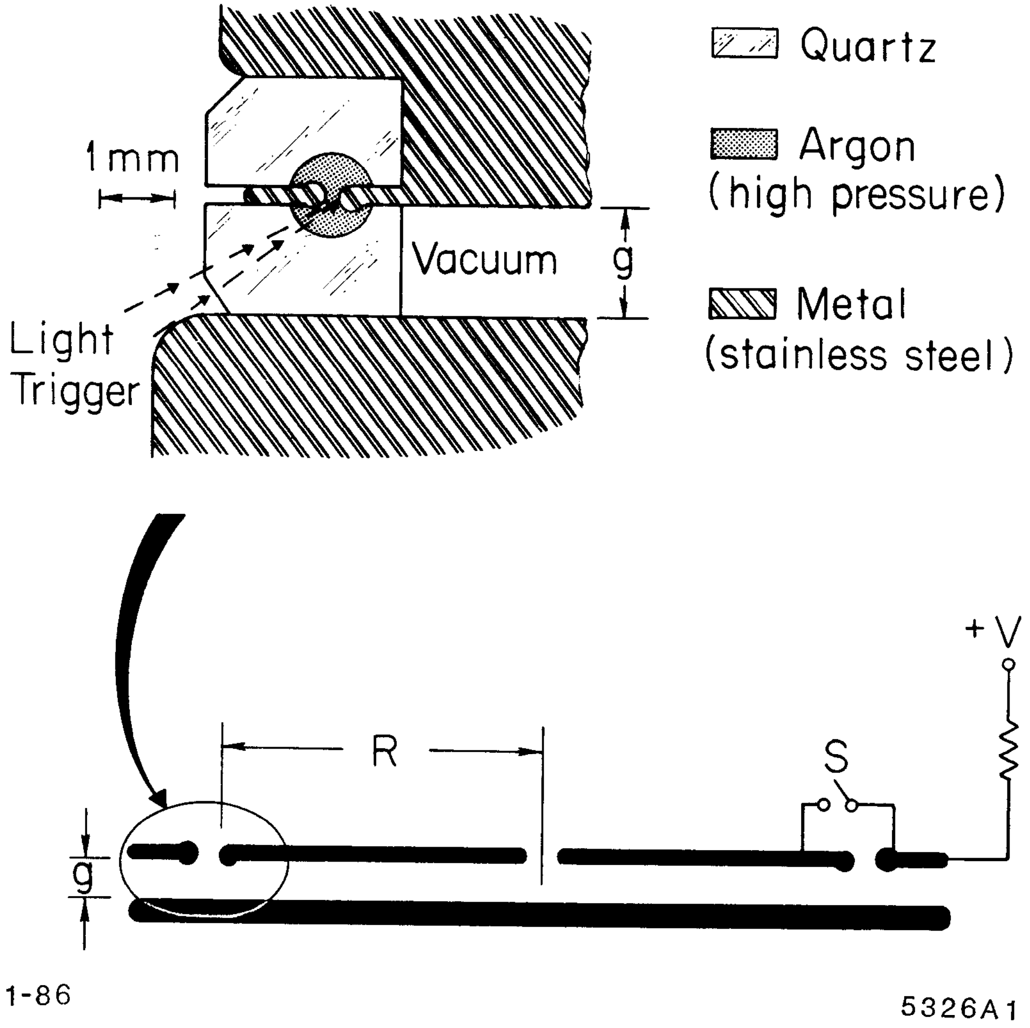
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Argon
(high pressure)
Metal
(stainless steel)
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Vacuum
g
Light
Trigger
+V
R
S
g
1-86
5326A1

Fig. 1

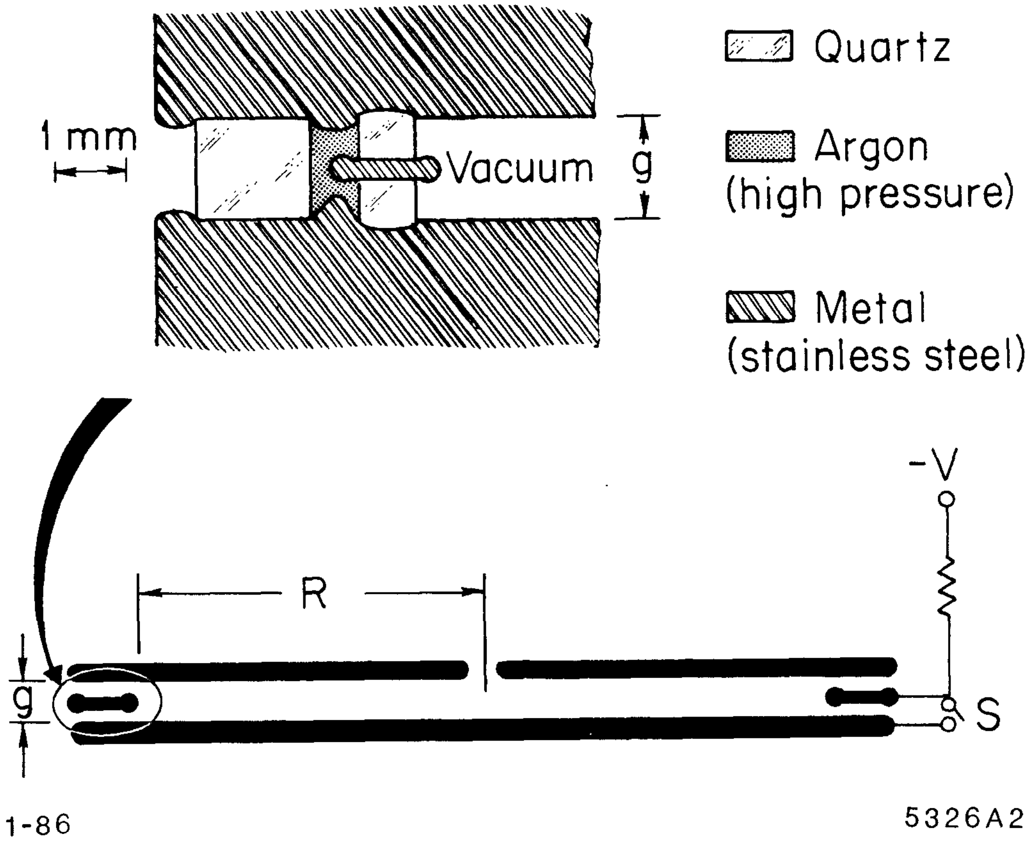
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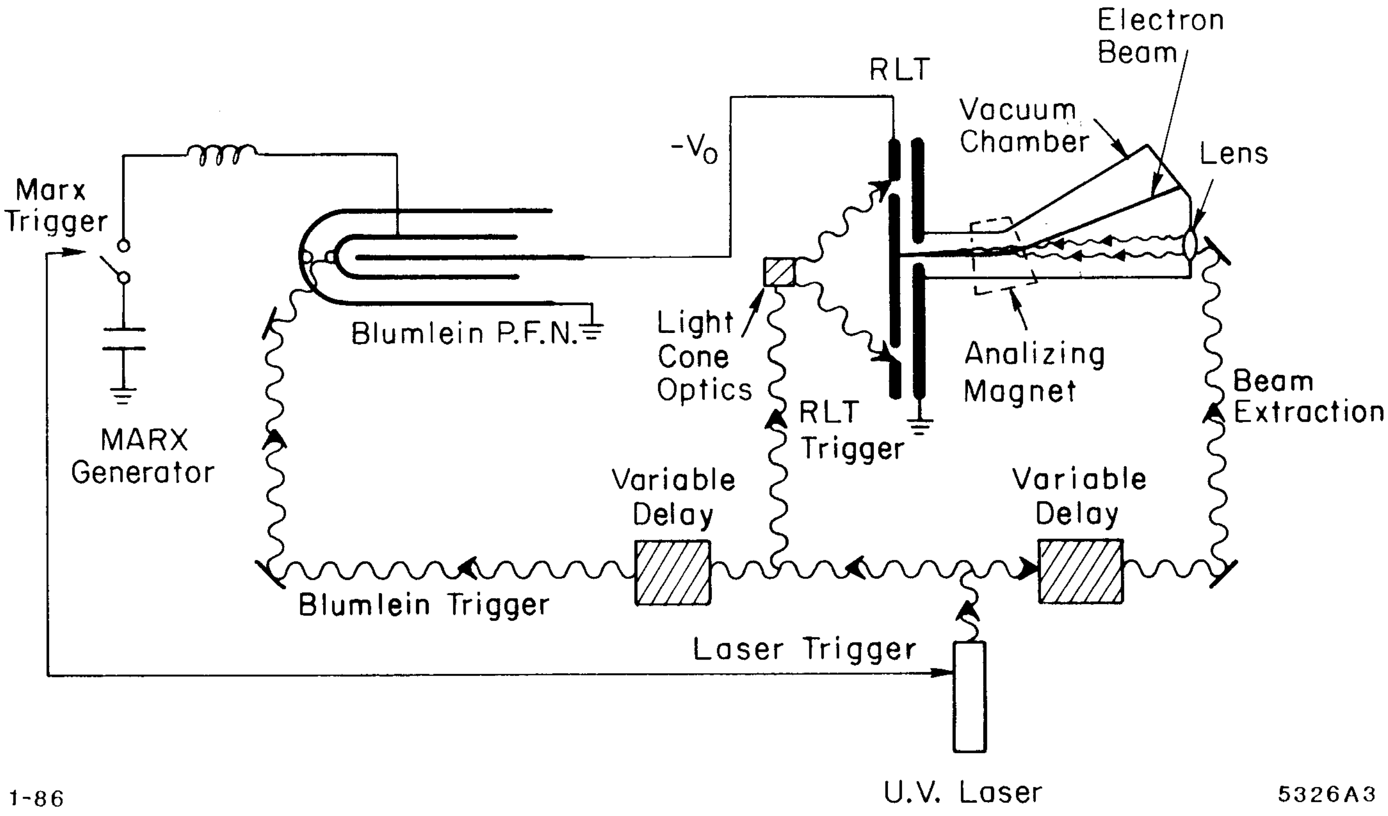
Fig. 2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Analizing Magnet
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RLT Trigger
MARX Generator
Variable Delay
Variable Delay
Blumlein Trigger
Laser Trigger
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Fig. 3