Switching Notes
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Results from Two Pressurised Edge Plane Gaps

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EXPERIMENTAL SET UP

This note summarises a short set of experiments with 2 pressurised edge plane gaps which were built for use in a pulse charged line of low impedance. Gap A was at one end of the line and was the start gap. The impedance of the line was changed during the course of the experiments but was of the order of 0.6 ohms for most of them. The effective impedance (with multichannel operation) was of the order of 1 ohm, when the inductance of the gap is included. Physically the gap was within a 1 1/2 inch OD perspex tube and consisted of a 1/2 inch OD brass rod as the plane electrode and a 1/2" wide brass edge of 32 thou thickness. The gap was 0.70 cm and was uniform to about .005 cm. The width of the gap (excluding the tapered ends) was about 20 cm. The edge was not very well made and may well have affected the results at low pressures. It was tapered on about a 20° angle and finally had a radius of about 0.01 cm, but this was far from uniform. Initially this edge was fairly rough, but it may well have become smoothly eroded as the experiments went on. Unfortunately the gap was built into the line and it was a major job to take the edge out and sharpen it, so it was not possible in the time available to prove that the edge was sharp enough not to have affected the results in the low pressure range.

Gap B was a sharpening gap located 2-1/2 metres down the line, just ahead of the load region. This gap was in a 1" OD perspex tube and consisted of a 1/4" OD brass rod and an 0.7 cm edge, again made out of 32 thou brass. The edge plane gap in this case was 0.61 cm at minimum and was significantly less uniform, the gap increasing by up to 0.02 cm along significant lengths of the edge. The length of this edge plane gap was 55 cm and it was fed from a total impedance (including gap inductance) of about 1 ohm, when operating in the multichannel mode (which it did with delightful regularity), as did the start gap. The edge of this gap had an angle of about 15° and a radius of about 0.005 cm. Because of the long length of this gap, its strong operation in the multichannel mode, and the fact that the residual charging bank current did not flow through it to a great extent after Gap A closure, any erosion smoothing in Gap B would be expected to be much less than that taking place in Gap A.

DEFINITION OF T_{eff}

Originally, when point plane breakdown experiments were studied at AWRE, the "usual" definition of t_{eff} was employed, i.e., full width at 63 per cent of peak. This work showed that over a rather limited range of parameters the answers could be crudely fitted to a relationship of the form $F(t_{eff}\ d)1/6 = kp^n$ where k was in general polarity-dependent and n was a rough fit over a very limited pressure range of data. Later, the original rather sparse data was extended (for air at least) and other published data included, and the "correct" definition of t_{eff} used, i.e. that which would correspond to the full time width of the pulse at 88 per cent of the peak, if the relationship were exact. For air at atmospheric pressure, the range of parameters was: d, a few cm to several metres; t, 50 ns out to tens of microseconds; and the fit was again to 20 per cent or so.

Subsequent work at Physics International showed that for pressurised SF_6 the index of the pressure was not a constant, and also that the time dependency for this case was somewhat variable from about 1/3 power to nearly independent. However, as a crude relationship, the original form gave answers in the right ball park up to pressures of a few atmospheres and has been retained for use in the analysis of these experiments. Thus the definition of t_{eff} used here is the prepulse width at 88 per cent of peak volts. Because the power of t_{eff} is low, the effect of changing the definition of the effective time is small and appears as a shift in the value of the constant. It must however be stressed that very little physical significance can be attached to the relationship; it is just a convenient fudge to package up a lot of data, in order to help gap designers, mainly. In the experiments described in these notes, the d dependency was not investigated, of course. In the original data the value for both polarities of edge in air was 22 (units KV/cm, cm, microseconds) and gaps as small as 0.7 cm were not then investigated. The original pressure dependency found for negative edge was $p^{2/3}$. The new data obtained gives the constant as 23 and the negative edge pressure dependency as $p^{2/3}$ again. As the new values obtained are for a much smaller gap and a shorter time, this means that the parameter range of the ad hoc relationship has been extended significantly.

A word of warning should be given about the range of parameters, in this case gap spacing, time, and pressure for any given gas. At most only two of these are varied in any set of experiments and usually only one: thus the data points tend to cluster along the axes when the field values are plotted on a multi-dimensional graph. It is therefore dangerous to use the expression all over the three-dimensional surface and, say, for air, to use it to deduce the breakdown field for a 5 metre gap at 5 atmospheres for a 10 ns pulse. Indeed, the velocity of light may well have something to say about this case, but in general care should be taken in using it. However, in the absence of any other data, its use may still be better than a blind guess. It should also be added that while the definition of t_{eff} tends to be applicable up to the peak of the pulse, streamer closure can occur, albeit infrequently, beyond the peak below the 88 per cent level, although the rigid application of the definition would say this could not happen.

RESULTS

The major set of results were obtained with gap A and these are shown in Fig. 1.

$\bar{F}$ the mean field, is the breakdown voltage divided by the gap spacing. The effective time that applied to these results varied from some 45 ns to 20 ns and over this range a time power of 1/6th applied. The results given have been reduced to a common time of 30 ns, using this power. One interesting result is that, apart from the noble gases, the slope of all the negative edge data is rather closely the same, and that of the positive edge smaller, but still similar.

A second conclusion is that (noble gases apart, again) the negative edge becomes stronger than the positive one as the pressure (or density) is raised. A third consequence of the data is the attractive nature of pressurised hydrogen as a gap insulant. For this gas the resistive phase is lowest in an edge plane gap. In fact, in general, the pulse rise time provided by the multichannel operation of hydrogen was significantly faster than for any other gas, and it is a very nice gas to use, providing the rather higher pressure its use demands is acceptable.

Some other observations were made during the course of these experiments, the first of which refers to fizzle. This is the passage of current before the real formation of the plasma channel linking the electrodes. In the note on multichannel operation of gaps by one of the authors (JCM), some very ill-judged remarks are made about this being due to a dc/dt term. These remarks are qualified as being speculative and are now known to be totally wrong in the case of gases. (They may very well still be applicable to liquids.) Meryats et al have shown that this phase is body ionisation increasing while the Townsend first coefficient remains above one. However this phase is unstable and after a time, conduction occurs in restricted radius plasma channels which then link across the electrodes. At this stage the physics of the resistive phase of sparks begins to apply. Of course the fizzle phase, which is a nuisance as far as spark gap uses are concerned, is the prime target of laser pumping and for them the onset of the plasma filled spark channels is an event to be delayed as long as possible. However, resolutely donning our spark gap spectacles, fizzle will be regarded as something to be avoided.

The duration of the fizzle phase is crudely defined as the time during which the voltage applied to the gap departs from that which it would have been if no current flowed in the gap up until the main voltage collapse occurs. It is dependent on the length of the edge (getting greater, the longer this length is) and is shorter, the lower the effective impedance driving the gap. The fizzle phase is no real use for switching a gap, since while its onset is quick, the voltage across the gap only falls to a value where the Townsend coefficient is about one, then hangs up there, drifting down slowly until the final collapse occurs as the plasma channels finally form and close. Multichannel operation of an edge plane or triggered gap is difficult during this phase and it is desirable to avoid any prolonged fizzle phase when a gap is required to operate in this mode.

In the experiments the line impedance was about 0.6 ohms and the effective impedance seen by the gap about 1 ohm. The length of the edge in Gap A was 20 cm approximately. Table I gives those gases in which fizzle was seen and the mean field ($t_{eff} \sim$ 30 ns) for which the fizzle was 10 ns, or, in the case of CO_2 negative edge, the fizzle duration at the highest field obtained. Fizzle goes away quickly as the pressure and hence mean field is raised, thus for fields above these values fizzle will be unimportant in general for the conditions Gap A was operating in.

TABLE I
FIZZLE DURATIONS AT SELECTED FIELDS
($\bar{F}$ in kV/cm)

	Positive Edge	Negative Edge
Hydrogen	10 ns at 43	10 ns at 48
Air	10 ns at 43	10 ns at 43
Ammonia	-	10 ns at 44
Methane	-	10 ns at 90
Carbon Dioxide	-	30 ns at 85

For the blanks in the Table, and for the other gases tested but not listed, the fizzle phase was not observed down to the fields corresponding to atmospheric pressure.

A second and alarming observation was that, for a number of gases, operation with either polarity at or near atmospheric pressure gave a large scatter of breakdown voltages compared with that to be expected from the graph given in "Multichannel Gaps." Instead of the fraction of a percent jitter expected, for air towards the end of the series of experiments the standard deviation became as big as 7 per cent at atmospheric pressure. This jitter rapidly diminished as the pressure was raised and became too small to measure. A second, and it is believed related, observation was that as the fairly long series of experiments was continued, the breakdown field at 1 atmosphere for air and other gases rose and the jitter got worse. This effect was very much more noticeable for the edge positive than for it negative. For instance, for air the 1 atmosphere field observed increased by some 30 per cent by the end of the experiments for the positive edge and by some 10 per cent for the negative edge. By this time Gap A had had well over 1000 shots and had been run with a variety of gases, some of which were chemically active after sparking. The same phenomenon was observed in hydrogen, methane and nitrogen, but not tested for the other gases. As the pressure was increased to greater than about 2 atmospheres, the change from initial results to final ones was much less for positive edges and undetectable for negative ones. It seems likely that this was due to erosion of any roughness and rounding of the edge of the "sharp" electrode.

This explanation raises the question as to whether the initial results given in Figure 1 and obtained at 1 atmosphere would have been lowered if a sharper edge had been employed in Gap A, particularly for the positive edge data. This is indeed possible, since presumably the gap was working partly as a sharp edge and partly as a small radius gap which is awaiting the provision of an initiating electron by field emission. However, it is felt that initially the sharp edge was very rough and certainly for the negative 1 atmosphere results, and probably for the positive 1 atmosphere results, the data is not more than 10 per cent too high. As was explained earlier, it was difficult to remove the sharp edge from Gap A and sharpen it considerably, so this could not be proved.

What is alarming about the large jitter observations is that very satisfactory multichannel operation was obtained even at 1 atmosphere. If the theory given in "Multichannel Gaps" is applied, the number of channels obtained would have suggested a standard deviation of gap breakdown of 1/2 per cent instead of the observed shot to shot variation of more like 5 per cent. Thus the gap was working multichannel when apparently it had no business to be. A possible explanation for this potential catastrophe is that the variation shot to shot is just due to the wait for an initiating electron and that sometimes more than 80 per cent of the volts were on the gap before this occurred, thus giving something like a jitter of 10 per cent in final breakdown voltage. However, when the electron was emitted, the avalanche in the high field region close to the sharp edge occurred in about 0.2 ns. Thus a large population of ions and electrons resulted by this time and this provided a burst of UV which moved out, causing the ejection of further electrons from the sharp edge. The rate of expansion of this self-initiated UV excited photo emission could be fairly close to the velocity of light and the whole edge could be nearly simultaneously initiated after the first electron has been provided and the body ionisation phase followed by streamer formation phase could then occur with its jitter not much increased above normal. The above explanation must be considered tentative, of course. However, the way out of the difficulty practically is to use sharper edges, but the experimental observations show that operation with blunt edges may not preclude multichannel operation, even in small spacing gaps. With gaps with large spacings, i.e. higher voltage ones, more field enhancement occurs at the edges or points and the initiating electrons are emitted early enough in the rising pulse. With small gaps and pressurisation, enough volts are applied to the edge to give fields of the order of 100 kV/cm early in the pulse and then these rough surfaces give rise to large numbers of field emitted electrons during the early phase of the rising voltage.

In the original work done on edge and point plane jitter, described in "Multichannel Gaps," fairly large voltages were used and such edges as were used were significantly sharper than the one used in Gap A. Points, too, have an additional dimension of convergence, of course, and most of the jitter work was done with these, hence the difficulty found with Gap A would not have applied to the earlier work.

Breakdown data was also obtained with Gap B: however the range of gases used in these experiments was restricted to air, nitrogen and hydrogen. The t_{eff} of the pulses applied to Gap B ranged from about 4 ns to 20 ns and again it was found that applying a 1/6th power of the time dependency gave reasonably unique mean field values for each pressure. Consequently a 1/6th time power was used to reduce the field data to those values applying to a 7 ns value of the effective pulse length. Because of the way the data were displayed oscillographically (the high speed pulse was shown after the charging pulse on an exponential time base), these time values are not very accurate (± 20 per cent). However, because of the lower power law, the resulting error in F is well within the accuracy aimed at.

Table II shows the mean fields obtained for the high speed pulse (7 ns) and those obtained from Figure 1 for the longer pulse (30 ns) and their ratio for nitrogen. The other gases tested (air and hydrogen) gave similar results. The ratio of 30/7 to the 1/6th power is 1.27 and it is seen that this ratio is only approached as the pressure is raised to about 4 atmospheres.

There would appear to be two reasonably plausible explanations for the ratio being too low for pressures below 4 atmospheres. The first is that the F 30 ns values are indeed too high by some 15 per cent at low pressures, as was discussed above, because the edge was not sharp enough. As was mentioned early in this note, the edge of Gap B was considerably sharper than that of Gap A and much longer, so the initial roughness of this edge would have remained during the shorter series of pulses applied to it during the tests. This explanation would suggest that

TABLE II
MEAN FIELD VALUES FOR THE 7 AND 30 ns EFFECTIVE DURATION TESTS FOR NITROGEN
(F in kV/cm)

p/p_o	Positive Edge			Negative Edge		
	F (7 ns)	F (30 ns)	Ratio	F (7 ns)	F (30 ns)	Ratio
2	67	62	1.09	74	70	106
2-1/2	79	71	1.11	93	82	113
3	89	78	1.14	107	92	116
4	102	(91)	1.13	132	(110)	120
5.1	135	(105)	1.28	163	(128)	127
5.7	150	(115)	1.30			

(Figures in brackets extrapolated)

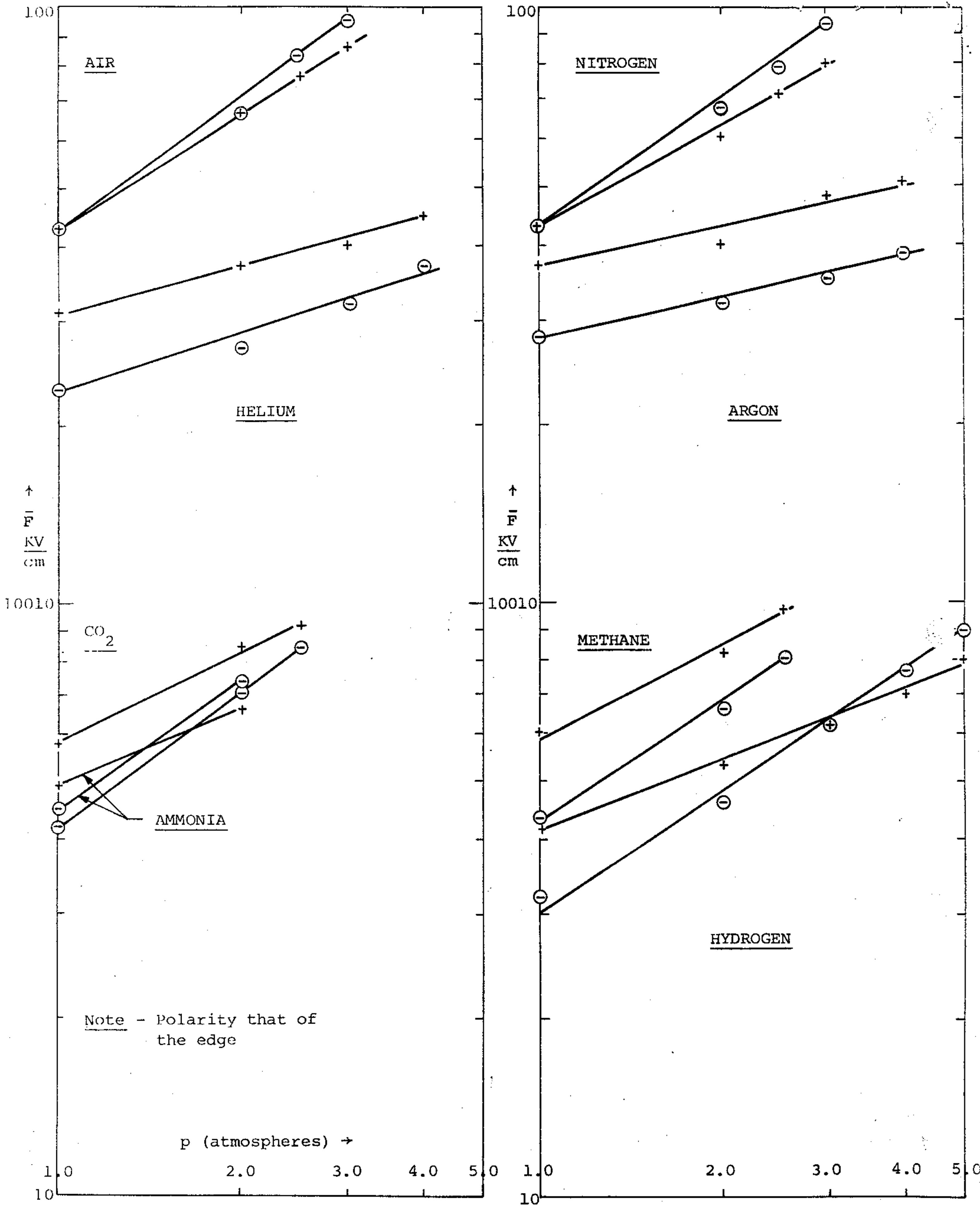
the low pressure points in Figure 1 should be dropped in value by about 15 per cent. However, it is also quite possible that the time dependency at low pressures might only be a 0.1 power law, or lower. As was stressed earlier, the relationship is an overall expression assembling a lot of data to a rather poor accuracy and, as with SF_6, the relationship might be a lot more complex. I personally incline to the belief that both effects are at work, but considerably more effort would have been needed to have sorted this out and time was unfortunately not available for this.

CONCLUSIONS

Data are provided from two edge plane gaps operating in a multichannel mode with regard to the mean breakdown field they could support with different gases in them at different pressures. For air the data is in tolerable agreement with the original approximate relationship proposed, and similar relations can be suggested for other gases (backed by data only over a limited rnage, however). In general, for fast operation pressurised negative edges give higher mean fields and would provide faster rising pulses, providing fizzle does not occur. Pressurised hydrogen is particularly attractive, especially for lower voltage edge plane and most probably for triggered gaps.

Some anomalous behaviour was noted and tentative explanations advanced for this.

It was also shown that edge plane gaps operate satisfactorily in the multichannel mode as pulse-sharpening gaps, down into the few ns range, which was actually the main objective of these experiments. Indeed, a current of about 120 kiloamps was generated with an e-folding rise of 4 ns from a 2 foot wide line, using two gas gaps. With improvements which are reasonably assured, it is considered that a 1 1/2 metre wide line can be made to give 300 kA with an e-folding time of 3 ns, a di/dt of 10^{14} amps per second, which is competitive with solid gaps, with the advantage of a relatively rapid rate of firing.



Note - Polarity that of the edge

FIGURE 1