Submitted to Physical Review Letters

UCRL-20811
Preprint

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June 1971

AEC Contract No. W-7405-eng-48

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A LIQUID-FILLED PROPORTIONAL COUNTER*

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We report properties of single-wire proportional chambers and multiple-wire ionization chambers filled with liquid xenon. Proportional multiplication is seen for anode fields $>10^6$ volts/cm (anode-cathode voltage > 1 kV for a 3.5-μ-diam anode wire). The efficiency for detecting ionizing radiation is ≈ 100%. The time resolution of the chambers is $\pm 10^{-7}$ sec. We attained a spatial resolution of ± 15 μ with a multiwire ionization chamber, considerably better than that of any other real-time particle detector.

Conventional spark chambers and multiwire proportional counters are unable to achieve a spatial resolution much better than ± 200 μ. This limit appears to be caused by a combination of electron diffusion (≈ 500 μ for a typical chamber), the small number of ion pairs produced in a 1-cm gap (typically about 100, which limits the ability to find the center of the diffusing electrons), the production of long-range δ rays (which can deposit considerable energy up to 5 mm from the original track), and the fact that a particle traversing a thick chamber at an angle necessarily deposits its ionization over a large transverse dimension. Alvarez suggested[1] that these funda-

mental difficulties could be overcome if one decreased the thickness of the chamber and increased the density of the detecting medium by replacing the gas in the chamber with a liquefied noble gas. The advantage of narrow gaps and high densities has been demonstrated by recent work with high pressure spark chambers.[2,3] Several attempts to build liquid-filled spark chambers[4-6] have been unsuccessful. Proportional chambers using liquid argon have been reported,[7-11] but they have either been extremely inefficient (detecting fewer than 20% of the charged particles passing through them) or required the heating of a thick (100-μ-diam) anode wire. (A thick wire is unsuitable for high spatial resolution.) Our immediate aim has been to achieve high spatial resolution with a multi-line proportional chamber. Liquid-filled chambers could be made thin (200–500 μ, <0.02 radiation length) for the accurate localization of minimum-ionizing particles, or thicker (sacrificing spatial resolution) for efficient γ-ray conversion.

We report here the successful operation of a single-wire proportional counter using liquid xenon. The maximum gain that we observe for proportional amplification (≈ 100) is sufficient that a like gain in a multianode chamber, 500 μ thick, would yield 15-mV signals (on 10 pF) for minimum-ionizing particles. We also report a measurement of the spatial resolution attainable with a multiwire liquid xenon chamber.

A diagram of the single-wire chamber is shown in Fig. 1. The geometry is similar to that of a standard gas-filled proportional counter, except that the anode wire is extremely fine (as small as 3.5 μ in diameter). A very fine anode wire seems to be necessary in order to have high gain without spurious electrical discharges. The chamber is made of glass, Kovar, and stainless steel. The high voltage cathode is a conductive SnO coating on the inner surface of the glass. A radioactive source, consisting of a small piece of

aluminum impregnated with ^{241}Am, is attached to the cathode inside the chamber. The chamber is washed with alcohol, and baked in a vacuum of less than 10^{-6} torr at 100° C for several hours before filling. Xenon gas is purified by circulation for several hours over a hot (200° C) copper-catalyst preparation, and a cold (-78°C) Linde molecular sieve 4A. Details of the purification system are published elsewhere.[8, 12] The presence of only a few parts per million of electronegative impurities can seriously impair the performance of the chambers. Our early inability to remove the impurities in xenon delayed progress in this work, but we now have this problem under control. Xenon supplied by the purifier is condensed by submerging the chamber in a cold Freon-11 bath.[13]

We have studied the proportionality, efficiency, and gain of our chambers, with their outputs attached to a charge-sensitive amplifier. For anode fields less than 3×10^6 V/cm, our chambers behave much like gas-filled proportional counters. A typical low voltage pulse-height spectrum for the internal ^{241}Am source is shown in Fig. 2. The two prominent peaks are those due to the 5.5-MeV α particles (reduced in pulse height by a factor of ≈ 15 due to columnar recombination) and the 60-keV γ rays. Most of the width of the alpha spectrum is due to variations in recombination for α particles emitted at different angles with respect to the electric field.

The single-wire proportional chamber is approximately 100% efficient in detecting the α particles from the internal ^{241}Am source. We calibrate the source strength by operating the chamber as a gas-filled proportional counter. The ratio of α-particle count rates for the same chamber operated in the liquid-filled and gas-filled modes is 1.04 ± 0.03. (The gaseous xenon was cooled to -100° C to increase its stopping power and to maximize its detection efficiency. The range of the alphas in liquid xenon is $\approx 50\ \mu$.) The error

of 0.03 arises from the overlap of the α and γ peaks in Fig. 2. Due to heavy columnar recombination, the net ionization of the alphas is similar to that of a minimum-ionizing particle passing through 0.7 mm of liquid xenon.

Pulse height as a function of voltage is shown in Fig. 3 for a variety of anode diameters. The low voltage behavior of the chambers can be understood in terms of electron avalanche (the first Townsend process) with a first Townsend coefficient (the number of secondary electrons per cm per primary electron) between 10^4 and 4×10^4 cm^{-1} in an electric field of 2×10^6 V/cm. The first Townsend coefficient depends critically on both electric field and impurity content of the liquid; we tentatively attribute differences in the slopes of the pulse-height–vs–voltage curves for different runs to slight variations in impurity content.

At higher voltages the pulse height no longer increases with voltage, but saturates at a gain of ≈ 100. In addition, we observe pulses of a second class which become more numerous as the voltage is increased, and have a pulse height of 1-4 pC, independent of initial ionization. Finally, at higher voltages ($\gtrsim 5$ kV), sparking occurs. We have operated a chamber as a d.c. spark counter at these voltages, but with a very low efficiency. For the larger-diameter anode wires sparking occurs at lower anode fields, and we do not observe either the saturation of the proportional pulses, or the appearance of the picocoulomb (pC) pulses (see Fig. 3).

Whereas the proportional pulses rise in about 150 nsec, consistent with a positive xenon ion mobility[14] of 3×10^{-4} $cm^2/Vsec$, the pC pulses rise in less than 30 nsec. Their fast rise time could be due to an anomolous increase in the positive ion mobility in extremely high electric fields (and a corresponding reduction in the space-charge limit to pulse height), or to the increased importance of ultraviolet radiation at high voltages (the second Townsend

process). In the latter case, the fast rise time would be due to the motion of the electrons towards the anode at a saturated drift velocity[15] of 3×10^5 cm/sec.

For some runs we observe spurious pulses at the higher voltages. We have not yet been able to determine if these pulses are due to a process in the liquid. They, the sparking, and the picocoulomb pulses may be due to the second Townsend process. We are attempting to control these phenomena by introducing quenching agents. We may be able to inhibit sparking by using a resistive cathode. We have developed such a cathode, consisting of germanium deposited on glass with a resistivity of $\approx 10^8$ ohms/square.

We measured the time resolution of our chamber by using the two collinear annihilation γ rays from ^{22}Na, detecting one with our liquid xenon chamber, and the other with a plastic scintillator. Our technique is described in more detail in Ref. 8. For this test we used the larger 3-pC fast-rise-time pulses. The xenon avalanche pulse occurred on the average 100 nsec after the scintillation, with a jitter of $\pm$ 100 nsec. The jitter was probably due to variations in electron transit time to the anode. For this test the effective diameter of the chamber was somewhat smaller than 8 mm due to the presence of electron-attaching impurities. For a thin ($<200\ \mu$) chamber the electron transit time would be less than 60 nsec.

We have scanned the length of the chamber with a collimated 60-keV gamma source (beam width $\approx$ 1 mm) to see if the entire length of the wire would avalanche. The avalanche was found to occur all along the length of the wire, although the gain dropped off near the ends of the chamber, where the electric field was reduced due to edge effects. In addition we found several "hot spots," which average about one per cm, where the gain corresponded to that of a field perhaps 30% greater. The enhanced gain at these hot spots was

probably due to irregularities on the anode surface, and the resulting locally higher electric fields.

We made a preliminary measurement of the spatial resolution attainable in liquid xenon by constructing a multiwire ionization chamber using 12-μ-diam wires. (These thick wires were used to simplify chamber construction, although they prohibited us from observing proportional amplification in the same chamber.) The wires were spaced by 50 μ. The opposing cathode had a small wire coated with ^{241}Am inserted into a groove cut into its surface.[16] The cathode (and hence the source) could be moved with respect to the anode wires by means of a micrometer screw. The anode-cathode spacing was 0.7 mm. All the anode wires were grounded except one, which was connected to a charge-sensitive amplifier. The counting rate on this wire as a function of the micrometer setting is shown in Fig. 4. A source profile is seen, with a full width at half maximum of 40 μ, and a root-mean-square deviation from the average, $\sigma_{rms} = 15\ \mu$. We have not attempted to unfold the finite width of the source; the error introduced by the chamber may be less than σ_{rms}. This resolution is considerably better than that of any other real-time particle detector. It can probably be improved further by decreasing the wire spacing.

Although a multiwire chamber is adequate to determine the intrinsic spatial resolution of liquid xenon counters, development of a practical high-resolution chamber of large size requires replacement of the stretched fine wires by conductive strips laid down on an insulating substrate. In a preliminary investigation, we were able to observe electron multiplication on such strips. We have also been considering the readout problem for large chambers, and are investigating several simple schemes that do not require

connections to individual conductive strips.

We are indebted to Joe Savignano, Tony Vuletich, and Buck Buckingham for their skill and patience in building and maintaining our equipment. We are grateful to A. J. Schwemin for his numerous contributions to this work. We thank Carl Pennypacker for his assistance, and Dane Anderberg for his excellent glass work.

FOOTNOTES AND REFERENCES

*Work supported in part by the Atomic Energy Commission and in part by the National Aeronautics and Space Administration.

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FIGURE CAPTIONS

Fig. 1. A typical single-wire chamber. The anode wire is soft-soldered at both ends.

Fig. 2. A pulse-height spectrum from the internal ^{241}Am source at 2300 V (liquid-gain $\approx$ 20). The two prominent peaks are those due to the 60-keV γ rays and the 5.5-MeV α particles. Recombination has reduced the initial α ionization by a factor of about 15, and broadened the peak.

Fig. 3. Pulse height vs voltage for single-wire chambers having different anode diameters. For α particles the unrecombined ionization varies slowly with cathode field, averaging about 2 to 4×10^{-15} C between 1 and 5 kV chamber voltage. Data for the 3.5-μ tungsten and 9-μ Chromel wires could not be taken above 4.5 to 5 kV because of sparking. With the 25-μ nickel wire, sparking did not occur until 9 kV. The curves are to guide the eye.

Fig. 4. Image of an alpha source as detected by a 0.7-mm-thick liquid xenon ionization chamber. The counts on one wire were recorded while the source was moved by means of a micrometer. The zero of the source position was defined as the center of the distribution.

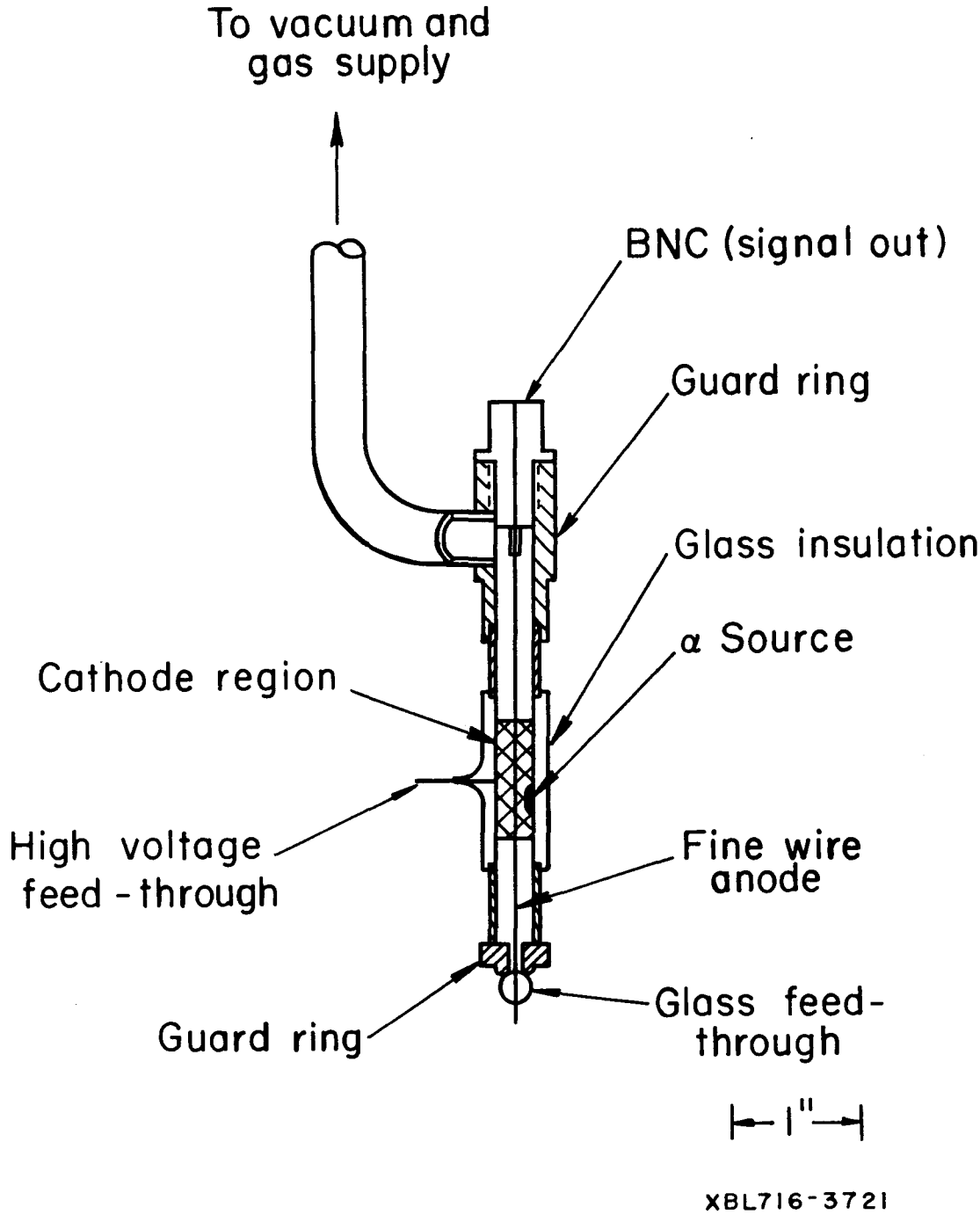
To vacuum and
gas supply
BNC (signal out)
Guard ring
Glass insulation
α Source
Cathode region
High voltage
feed - through
Fine wire
anode
Guard ring
Glass feed-
through
1"
XBL716-3721

Fig. 1

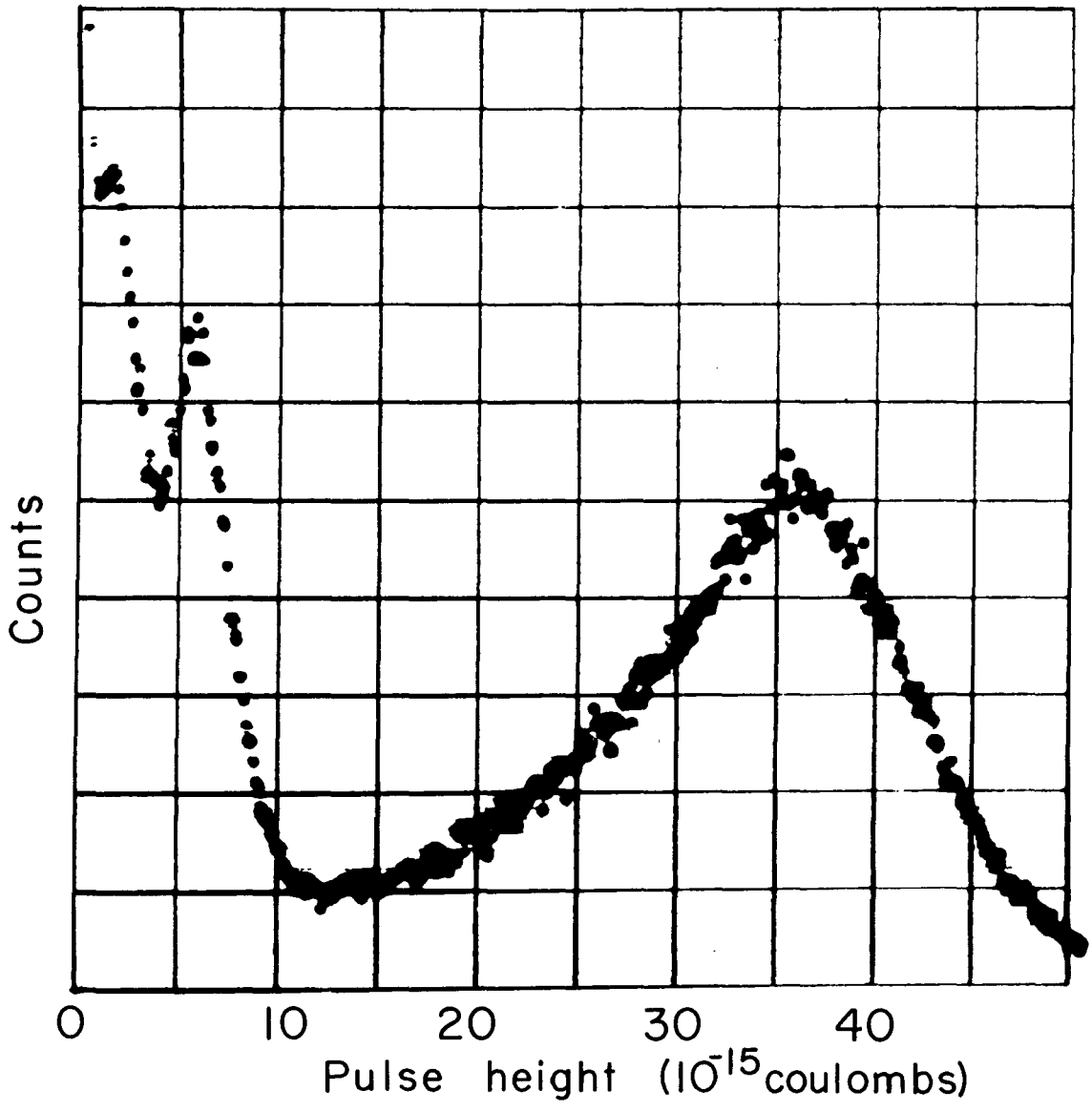

Fig. 2

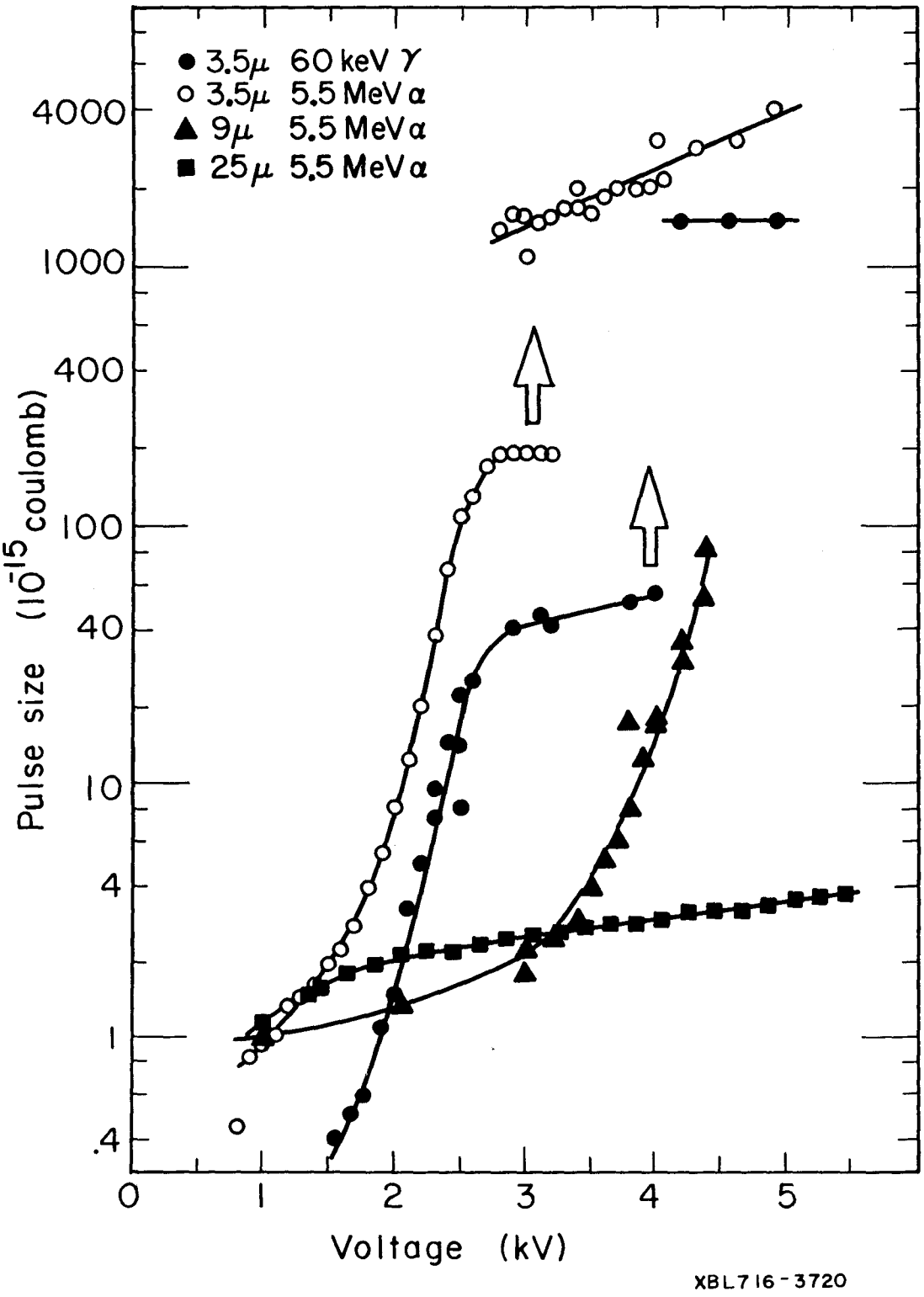
● 3.5μ 60 keV γ
○ 3.5μ 5.5 MeV α
▲ 9μ 5.5 MeV α
■ 25μ 5.5 MeV α
4000
1000
400
100
40
10
4
1
.4
Pulse size (10⁻¹⁵ coulomb)
0
1
2
3
4
5
Voltage (kV)
XBL716-3720

Fig. 3

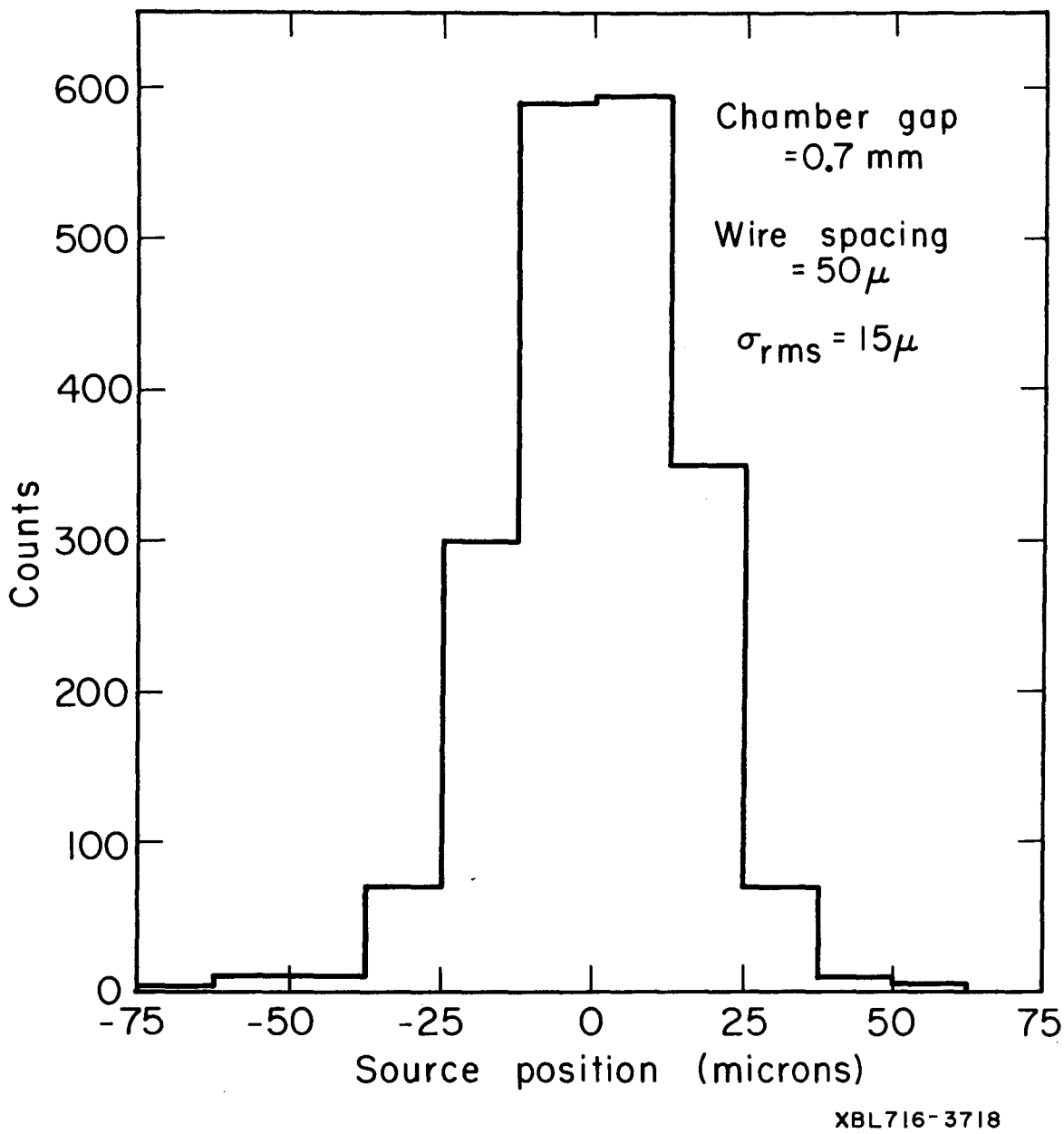
600
500
400
300
200
100
0
Counts
Chamber gap
=0.7 mm
Wire spacing
= 50μ
σrms = 15μ
-75
-50
-25
0
25
50
75
Source position (microns)
XBL716-3718

Fig. 4