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Summary

The development of wire chambers for positron emission tomography continues at CERN. In its present form, the basic detector is called a High Density Avalanche Chamber (HIDAC). Owing to the Penning effect, electron avalanche multiplication is obtained in the gamma-ray converter: coincidence time resolution is reduced to 20 ns and stable chamber operation is achieved with a safe, non-polymerizing gas mixture. Spatial resolution remains at 2-3 mm FWHM. A rotating camera consisting of two 20 x 20 cm chambers has now been under evaluation at Geneva Hospital for one year. Multilayer printed-circuit techniques are now used to construct chambers with multiple converters, thus raising detection efficiency from 7.5 to 20%. Read-out electronics and back-projecting memory are being developed to handle the high data rate from these chambers. A four-chamber positron camera designed to achieve 100,000 coincidences s^{-1} is nearing completion.

1. Introduction

The current generation of positron emission tomographs¹ consists essentially of one or more rings of bismuth-germanate crystals with each crystal individually coupled to a photomultiplier tube. Spatial resolution is limited to ~ 10 mm and the volume-imaging capabilities are severely limited. Such cameras are also very expensive.

Eight years ago, a new type of two-dimensional gamma-ray detector, based on the multiwire proportional chamber, was demonstrated² at CERN. Its basic properties were those of the wire chamber:

- i) High spatial resolution (1 mm)
- ii) Fast resolving time (20 ns)
- iii) High rate capability ($\sim 10^6 s^{-1} cm^{-2}$)
- iv) Large area for low cost.

In its present form, this detector is called a High Density Avalanche Chamber (HIDAC). A pair of such chambers has been in use for some years for the measurement of the angular correlation of positron annihilation radiation for solid-state physics research^{3,4}. A similar system is now being constructed elsewhere⁵. A chamber is being built for imaging gamma-rays from fusion reactions⁶. The principle is being applied to calorimetry in high-energy physics research⁷. At CERN and the Geneva Hospital we are using these chambers for positron emission tomography for medical purposes, as is now beginning elsewhere^{8,9}. Our goal is fully three-dimensional imaging at high spatial resolution (2-3 mm) for a reduced cost. In this paper, the basic operation and properties of the HIDAC are reviewed, the performance of the present camera is presented in conjunction with a second paper¹⁰, and the construction of the next camera, due to be in operation in 1983, is outlined.

2. Properties and Operation of the HIDAC

2.1 The HIDAC Principle

In making a wire chamber sensitive to gamma-rays, the difficulty is to retain the wire properties whilst efficiently converting the photons into an ionizing form suitable for detection by the wire chamber. At CERN this problem has been solved by the addition of a high-

Fig. 1 The principle of the high-density avalanche chamber. Photons are stopped by the lead and produce fast electrons that can escape to an adjacent hole. The electric field multiplies and extracts the resulting ionization. Note that ionization can be produced ahead of the point of impact of the photon: this shortens the time resolution.

density converter, the principle of which is shown in Fig. 1. The converter consists of a sandwich of lead and fibre-glass sheets glued together, in which a large number of holes are drilled close together. Photons interact in the lead bars, and produce fast electrons which can escape to an adjacent hole. The free electrons, resulting from gas ionization in a hole, may be multiplied and extracted by a strong electric field and detected by a standard wire chamber. The top of the converter is covered with a lead sheet, to close the converter electrically and to prevent electrons from drifting backwards to the chamber window which is at earth potential. Early work examined the possibility of using lead-glass tubes² and channel-plate technology¹¹ for the converter. This approach has now been developed by another group¹².

Until 1979 the choice of gas in the chamber followed standard practice: argon-hydrocarbon mixtures. Then neon-hydrocarbon¹³ and later neon-carbon dioxide¹⁴ mixtures were introduced. Several important advantages are obtained:

- i) A fourfold improvement in time resolution owing to the higher electron drift velocity in neon.
- ii) Electron avalanche multiplication during the drift through the holes in the converter implying:
 - a) an improved wire chamber stability owing to operation at lower gain,
 - b) a higher over-all gain so that electronic noise is less important,
 - c) a minimization of electron losses in the converter as they are multiplied as soon as they are created.
- iii) A non-flammable, non-toxic gas mixture for safety in a hospital environment.
- iv) A non-polymerizing gas mixture for a long chamber life.

It has been proposed¹⁵ that photoionization in these gas mixtures provides the electron multiplication, but it is now clear that the reason is the Penning effect¹⁶. In this effect, electron collisions excite gas atoms to metastable states which cannot decay by photon emission; instead, the excited atoms ionize the secondary gas by collision, provided that the metastable-state energy exceeds the ionization potential of the secondary gas. Heylen has systematically studied argon mixed with one of the following: ethane¹⁷; methane, propane¹⁸; pentane, ethylene, acetylene¹⁹; n-octane, cis-butene-2, benzene²⁰; and krypton mixed with ethylene, propylene²¹. He shows that at reduced electric field values $\sim 10 \text{ V cm}^{-1} \text{ Torr}^{-1}$, the Penning effect greatly dominates over photo- and direct ionization. The secondary gas reduces the second Townsend coefficient by several orders of magnitude, i.e. quenches photon-induced breakdown in the usual way, and at the same time raises the first Townsend coefficient by as much as an order of magnitude through the Penning effect. High-gain, stable electron avalanching results. Penning gas mixtures are also now used for improving the energy resolution of X-ray proportional counters^{22,23}.

2.2 Chamber Read-Out

Many methods exist for reading out a wire chamber. We use the amplifier-per-wire technique on the orthogonal cathode planes²⁴, which gives the advantages of sensitivity and linearity owing to the direct coupling of the wires to the amplifiers. Cost is significantly reduced by using the coded centre-of-cluster principle¹³ (Fig. 2). Cathode wires are taken in pairs to give two outputs. One output is a group output and connects with adjacent wires. The other output is a channel position within the group and connects with corresponding channel wires in other groups. The number of amplifiers required may be reduced by a maximum factor of $\sqrt{N/2}$, where N is the number of wires coded. The intrinsic resolution remains the wire pitch. The reduction in the number of read-out lines simplifies the subsequent decoding. The lines may be strobed into a read-only memory (ROM), precoded with the coordinated values for all valid group and channel patterns. All invalid patterns resulting from spurious signals (e.g. noise, cross-talk, too-wide distributions, double events in the chamber) are set to return a veto condition. Thus, in one memory access, the signals are decoded, checked for validity, and the coordinate is returned. When a large number of wires are coded, ROM sizes may be reduced by using a two-level decoding scheme.

Fig. 2 The principle of coded centre-of-cluster readout. Thirty-two wires are encoded into four groups of four channels. Resulting signal patterns are decoded into a coordinate in one memory access.

2.3 Chamber Construction

Wire-chamber construction follows standard practice, the important parameters currently being: anode wire diameter 20 μm and pitch 2.0 mm, cathode wire diameter 70 μm and pitch 1.0 mm, anode-cathode spacing 3.0 mm.

A chamber is equipped with two 6 mm thick converters, each of which consists of sixteen 0.2 mm thick sheets of antimonial lead (96% Pb/4% Sb) and sixteen 0.1 mm thick sheets of fibre-glass reinforced epoxy-resin. A converter is made in the same way as a multi-layer printed circuit. The sheets are first bonded together in a heated press and then drilled out by a numerically controlled drilling machine. Using a four-head machine, four $30 \times 30 \times 0.6 \text{ cm}^3$ converters, each with 83,000 holes are drilled in eight hours. A chemical treatment after drilling removes lead burrs and dust. Persistent short circuits can usually be removed by discharging a large capacitor (e.g. 20,000 μF at 6 V) through the affected layers of lead.

2.4 Detection Efficiency

The detection efficiency of a chamber depends not only on the converter design, but also on the chamber operation. There are several factors governing the probability of detecting a gamma-ray:

- i) photon interaction in the converter,
- ii) electron escape into a hole,
- iii) ionization of the gas in the hole,
- iv) loss of ionization during extraction,
- v) total amount of amplification.

The last two factors have been overcome by the introduction of electron amplification during extraction from the converter. But the use of neon implies less ionization in a hole than with argon. Pressurizing the chamber would help. This is under consideration but practical problems of safety in a hospital might forbid it. The second factor is improved by making the bars between the holes as thin as practicable. Some calculations have been made¹¹. The present converter geometry is 1.00 mm diameter holes on a hexagonal pitch of 1.155 mm ($2/\sqrt{3}$) which is the minimum distance compatible with drilling quality. The first factor is obviously dependent on the amount of lead, i.e. the overall thickness of the converter. A chamber with two 6.0 mm thick converters, one on each side of the wire chamber, achieves a detection efficiency of 7.5% for 0.5 MeV photons. This is lower than the previous chambers¹³ (8.5%) for two reasons: a) the lower specific ionization of neon, and b) no contribution from gamma-rays converting directly in the wire chamber since such events receive only wire-chamber amplification. The chamber design, described in Section 4, improves the detection efficiency by nearly three times, i.e. to 20%, by the use of multiple converters.

2.5 Spatial Resolution

The physical limit on spatial resolution for positron emission tomography is determined by the departure from collinearity of the two gamma-rays and the distance travelled by the positron before annihilation. Both of these factors may be less than 1 mm^{25,26}. The camera limitations are the chamber wire pitch, read-out precision, converter hole geometry and converter parallax error. The first three considerations are $\sim 1 \text{ mm}$ by construction. The parallax error may also be kept to 1 mm. See Fig. 3. Consider a gamma-ray pair striking opposed converters at an angle θ . The photon-interaction probability may be assumed to be constant with depth in the converter and the error in the position detected by the chamber will be the projection of the square response on the front face of the detector,

solid line is the measured response. Considering the behaviour below 0.5 MeV it may be seen that the equivalent energy resolution at 0.5 MeV is 43% HWHM. For a camera with more converters the result will be better, as the detection efficiency for higher energy photons improves due to greater absorption, but at low energies there is little change as full absorption already occurs. For 8 converters the effective resolution is 25% HWHM. Finally, it is theoretically interesting to extrapolate to 100% absorption at all energies. A 12% HWHM results. These results are applicable for the particular converter geometry in use. Clearly, the HIDAC possesses a very useful degree of energy discrimination. In making comparisons with BGO and NaI systems it should be borne in mind that their electronic energy resolution is usually not used, owing to the loss of detection efficiency incurred since many events do not interact photo-electrically.

3. The Present Camera

A brief summary of the characteristics of the camera currently in operation is now given. Much more detail, particularly concerning the mathematical reconstruction, can be found in the second paper¹⁰. Medical imaging results can be found elsewhere^{13,14}.

The camera currently installed in the Department of Nuclear Medicine at Geneva Hospital consists of two $20 \times 20 \text{ cm}^2$ HIDACs, mounted 34 cm apart on a rotating gantry. See Fig. 7. Rotation is now employed to overcome the distortions of limited-angle tomography. Transverse or longitudinal tomography is possible with a matrix of $128 \times 128 \times 16$ voxels. Data are accepted up to $\pm 15^\circ$ from the camera axis from six detector positions and back-projected into this matrix. Reconstruction is performed by:

- i) a three-dimensional Fourier transform of the back-projected matrix,
- ii) multiplication of each frequency amplitude in the transformed matrix by the corresponding filter value,
- iii) an inverse Fourier transform of the filtered matrix back into real space.

Fig. 7 A general view of the positron camera

The hardware that performs these tasks is shown schematically in Fig. 8. Chamber read-out and back-projection is performed by MICE, a fast micro-coded PDP11 emulator and the mathematical operations are performed by a PDP11/44. Subsequent display of the images is on an interactive colour image processor (NUMELEC PERICOLOR).

Fig. 8 The layout of the present positron camera

A typical picture is taken at a camera rate of 3,000 coincidences s^{-1} . About 40% of this rate is accepted after the angular cut of $\pm 15^\circ$ and 160,000 events are recorded in 2.2 min in each of six views, to give a total imaging time of 13 min for 1,000,000 events. Of these, typically 200,000 will be random coincidences within the 20 ns time window. But they are uniformly distributed over the entire imaging volume and so the accidental contribution per $2 \times 2 \times 4 \text{ mm}^3$ voxel will be $\sim 1\%$. Thus imaging may be performed at apparently high (20%) random coincidence rates.

A cylinder 6 cm in diameter and 1 cm deep containing 500 μCi of ^{22}Na was imaged in three dimensions, as described above. Figure 9 shows a cross-section through one 4 mm thick slice, before and after reconstruction. The recovery of information after reconstruction is clearly illustrated. The broad scatter and random coincidence contributions are seen. The dip at the top is due to the lack of an attenuation correction.

Fig. 9 Cross-sections through a 6 cm diameter cylinder of uniform activity (a) after back projection and (b) after reconstruction. The dip in the top of (b) is due to photon attenuation. The broad background of random coincidences and scattered radiation is also seen.

Fig. 3 Positional error due to parallax in the converters. All events at an angle θ are contained within the tube shown by dashed lines of full width $t \tan \theta$ and triangular response.

Fig. 4 The spatial resolution of the camera for different line sources

i.e. a square response of width $t \tan \theta$. The response for the pair of detectors is the convolution of two such square functions, i.e. a triangular function. As the coordinate on a plane between the detectors is the mean of the two measurements, the full width of the triangular function is $(t \tan \theta + t \tan \theta)/2$, i.e. $t \tan \theta$, and the FWHM is $(t \tan \theta)/2$. Thus for $t = 6.0 \text{ mm}$ the FWHM is $< 1.0 \text{ mm}$ provided $-18.5^\circ < \theta < +18.5^\circ$ and this is greater than the limit of $\pm 15^\circ$ imposed on θ by the data-acquisition software to ensure a stationary point response function¹⁰.

We have measured the overall resolution for a 1 mm line source and find, as expected, that the 1 mm limit is approached. See Fig. 4. For ^{22}Na (maximum positron energy 0.5 MeV) in plastic we obtain 2 mm FWHM. For ^{68}Ga (1.9 MeV) the resolution degrades to 3.5 mm . That this degradation is due to positron range is demonstrated by replacing the plastic by tungsten, whereupon the result for ^{22}Na is nearly reproduced.

2.6 Time Resolution

The time resolution of a chamber is dominated by the drift time of the electrons through the converter. Clearly a thinner converter will give a better time resolution, but only at the cost of a reduced detection efficiency. Hence the eventual use of multiple converters. In Fig. 5 are presented measurements of time resolution for different gas mixtures, in a thin converter (4 mm). The overwhelming advantage of neon is evident and the best result is with a relatively high concentration of carbon dioxide. It may be seen that there is an optimum amount (4%) of isobutane that may be mixed with neon because of the slower drift velocity of electrons in isobutane. To improve stability, alcohol may be added, as has been done for many years with

Fig. 5 The coincidence time resolution of a 4 mm thick converter with a fast scintillator. The advantage of Ne/CO_2 is clear.

proportional counters. Up to 2% of isopropyl alcohol may be added to neon-carbon dioxide before the time resolution starts to degrade. The chambers are currently operated with a gas mixture of 82% neon + 16% carbon dioxide + 2% isopropyl alcohol, with a converter electric field of 10.8 kV cm^{-1} .

2.7 Energy Resolution

It is thought that the HIDAC has no energy resolution. This is true in the sense that there is no correspondence between photon energy and chamber pulse height. However, the HIDAC does have an important intrinsic sensitivity to photon energy. As the energy falls, the interaction probability rises owing to the photoelectric effect in the lead converters. This would increase the detection efficiency, but it is more than offset by the fact that the lower energy photoelectron has a lower probability of escaping from the lead bar. This effect has been measured in the existing camera by recording the random coincidence rate for different energy gamma-ray sources. See Fig. 6. The

Fig. 6 The sensitivity of the camera to gamma-ray energy. The curves are normalized to 0.51 MeV .

4. The New Camera

A new camera is now under construction to image larger objects at a much higher counting rate.

The main limitation to the present system is the low detection efficiency of the HIDAC, which limits the maximum counting rate to about 5,000 coincidences s^{-1} . Since a chamber is $\sim 75\%$ transparent to 0.5 MeV photons, this may be considerably improved by increasing the number of converters. A scheme to do this is shown in Fig. 10. Eight anode converters are employed instead of two. Independent anode outputs will be used to record the active converter, whilst cathode planes are bussed together to minimize the quantity of electronics. Photon absorption will be increased by a factor of 2.7 and so detection efficiency will increase from 7.5 to 20%. The chamber size will be increased to 30×30 cm and this will permit an angular acceptance of $\pm 22.5^\circ$ instead of $\pm 15^\circ$. Thus the maximum counting rate will increase to $5,000 \times 2.7^2 \times 1.5$, i.e. 55,000. And by using two pairs of orthogonal chambers, 110,000 coincidences s^{-1} will be achieved.

The new schematic layout is given in Fig. 11. The chamber electronics and decoding read-out modules will have a dead-time of 100 ns to handle chamber signal rates > 1 MHz. Dedicated hardware and a big memory ($128 \times 128 \times 128$) have been designed to back project each event through 128 bins at 100,000 events s^{-1} . By providing a word length of 32 bits in the memory, the back-projected image may be reconstructed at full precision *in situ*. The improvements of the new system are summarized in Table 1. The first chamber is now complete and the full system is due for operation in 1983.

Fig. 10 Stacked converters in the new chamber to improve detection efficiency

Fig. 11 The layout of the new camera. Dedicated hardware is required to achieve an overall coincidence rate of 100,000 s^{-1} .

Table 1

	1982	1983
Status	Installed	Construction
Detectors	2	4
Dimensions	20 x 20 cm	30 x 30 cm
Rotation	180° 6 views	90° 3 views
Acceptance	15°	22.5°
Spatial resolution	2.5 mm	2.0 mm
Time resolution	20 nsec	20 nsec
Max. rate	5000 cps	100000 cps
Accidentals	< 30%	< 30%
Activity	< 0.8 mCi	< 0.8 mCi
Imaging time	~ 20 min	~ 2 min
Image matrix	128 x 128 x 16 64 x 64 x 64	128 x 128 x 128

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