

NAL PROPOSAL No. 19

Correspondent: Donald R. Tompkins  
Physics Department  
University of Georgia  
Athens, Georgia 30601

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A Cerenkov Counter Search For Monopole Production By 200 BeV Protons

A Cerenkov Counter Search For Monopole Production By 100 BeV Muons

D. R. Tompkins, R. E. Williams  
University of Georgia

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## I Two Experiments Proposed for the Enrico Fermi Accelerator

### Abstracts

#### 1. A Cerenkov counter search for monopole production by 200 BeV protons

By comparing pulse amplitudes from equal thickness ( $\text{g/cm}^2$ ) Lucite and gas Cerenkov counters it is possible to recognize monopole production inside the counters (the pulse amplitudes then differ by the square of the refractive index ratio). It is proposed to place one thick and one thin Lucite counter in the proton beam to see if any large amplitude signals (characteristic of monopole production) occur. If none appear then either a negative result has been obtained or the relativistic range of the monopoles is too limited by bremsstrahlung. If large signals appear a gas counter will be placed in the beam for comparison. This experiment seeks to identify relativistic monopoles. With four weeks of parasite beam time monopole production can be recognized at a production cross-section of  $10^{-39}$  ( $10^{-38}$ )  $\text{cm}^2$  for the thick (thin) counter.

#### 2. A Cerenkov counter search for monopole production by 100 BeV muons

This experiment is similar to the above experiment except that the beam intensity is reduced by a factor of  $10^3$  and the Lucite counter target thicknesses are increased by a factor of  $10^3$  (hence the cross-section limits obtained are the same). This target thickness is very unusual and a significant advantage. In this experiment a Fluorichemical rather than gas counter may be used for comparison.

Experimenters.....Donald R. Tompkins and Robert E. Williams

Date.....June 1970

Correspondent.....Donald R. Tompkins  
Physics Dept., Univ. of Ga.  
Athens, Georgia 30601

## II. Physics Justification

Schwinger's construction in 1966 of a consistent quantum electrodynamics which included magnetic charge<sup>1</sup> ended all attempts to prove the nonexistence of monopoles. In spite of the negative results of all experiments seeking monopoles the fact that monopoles might explain CP noninvariance has made resolution of the monopole problem a fully serious business. Thus with the availability of increased accelerator energies it is worthwhile to bring forward another effort to find the elusive monopole and that is what both proposed experiments are about.

For the mass range under  $3 \text{ BeV}/c^2$  monopoles have been sought in several accelerator experiments.<sup>2</sup> The methods used have been classified according to physical implication. The strongest type of experiment was considered to be one which sought to identify relativistic monopoles because then assumptions on low energy properties of monopoles were avoided. We will only seek to identify relativistic monopoles here.

The fact that the Cerenkov emission from a relativistic monopole depends on the refractive index in a manner different from that for a relativistic electric charge can be used to distinguish electric and magnetic charges in a fundamental way which does not depend on the value of magnetic charge or mass.<sup>3</sup> There are two ways the dual Cerenkov counter method can be used. One is to allow a monopole to pass through a pair of counters and then compare the pulse amplitude ratio obtained with

that from electric charges (the ratios should differ by the square of the ratio of the refractive indices). Another is to use two relatively thick Cerenkov counters all of whose properties are very similar (especially the radiation length) except the refractive indices, and expose the counters to an accelerator beam independently. The counters are then sufficiently thick so that the relativistic range of most monopoles produced inside these counters is contained entirely inside the counters. This has been called the Cerenkov counter target method.<sup>4</sup>

The relativistic range of monopoles is determined by bremsstrahlung and ionization loss. It has been suggested that at large values of  $\gamma$  the bremsstrahlung loss be described by the radiation length

$$X_{\sigma} = \frac{1}{2} (e/\sigma)^4 (M/m)^2 X_e \quad (1)$$

where  $M$  and  $\sigma$  ( $m$  and  $e$ ) are the monopole (electron) mass and charge.<sup>2</sup> The fact that bremsstrahlung is a quantum mechanical effect and that the magnetic charge strength invalidates perturbation theory means that Eq. (1) could seriously underestimate the bremsstrahlung contribution. However the value of  $\gamma$  for massive monopoles produced by a 200 BeV accelerator is so low that the bremsstrahlung loss could be negligible. The ionization loss of relativistic monopoles in a polarizable medium has been calculated to be  $(\sigma/e)^2$  times that of a relativistic unit charge.<sup>3</sup> This is more of a semi-classical effect and so is relatively immune to the lack of perturbation calculations.

Schwinger insists that the allowed values of magnetic charge are<sup>1</sup>

$$|\sigma| = n |371e| \quad (2)$$

$$n = 2, 4, \dots$$

although there is some discussion<sup>5</sup> of the possibility  $n=1, 2, 3 \dots$ .

Table I gives some relativistic parameters for monopoles. For monopoles in the experiment we are discussing, the relativistic range could be set by the ionization loss alone, but a significant bremsstrahlung contribution is a possibility. Such a bremsstrahlung loss is excluded by the perturbation type of calculations on which Eq. (1) is based and so would probably not be described by Eq. (1). However Eq. (1) is the only guide available on what the bremsstrahlung loss might be.

The reason we are so concerned about the possibility of bremsstrahlung loss is because both the Cerenkov emission and ionization loss increase as  $\sigma^2$  while according to Eq. (1) the bremsstrahlung increases as roughly  $\sigma^4$ . If the ionization loss dominates the relativistic range then as  $\mathcal{N}$  increases the rate the Cerenkov emission increases compensates for the decreased range so that the total Cerenkov emission stays constant. However if bremsstrahlung loss is dominant then the relativistic range drops as roughly  $1/n^4$  so the total Cerenkov radiation drops as roughly  $1/n^2$ . If this happens we could still identify monopoles but the Cerenkov counters would need to be thinner in order to lower the beam background.

In the mass range of  $3-10 \text{ BeV}/e^2$  the present limits set by cosmic ray work are  $10^{-43}$  to  $10^{-41} \text{ cm}^2$  ( $10^{-43}$  for  $3 \text{ BeV}/e^2$ ).<sup>6</sup> These limits are all based on monopole trapping experiments and include all monopole production by cosmic rays. For monopole production by muons the cross-sections limits are roughly one order of magnitude less because the very high energy muon flux at

sea level is roughly 4 orders of magnitude less than the primary cosmic ray flux and for muons these ocean bottom experiments had 3 orders of magnitude more effective target thickness than is available to the very high energy portion of most cosmic rays.

The proton beam experiment:

In this experiment we propose to operate two Lucite Cerenkov counters simultaneously. One would be 2.54 cm thick and one would be .254 cm thick. The thicker of these counters would be replaced by a 7 cm thick counter if the data indicated the possibility of monopole production with range effects present ( $n=1$  case). These counters are thin enough so that any relativistic monopoles without dominant bremsstrahlung loss would be easily recognized. For a 1 second burst of  $10^{10}$  protons every 4 seconds for 4 weeks these counters could detect monopole production at a cross-section of  $10^{-39}$  and  $10^{-38}$   $\text{cm}^2$ . These counters can be run behind another experiment so all we need is parasite time. This experiment offers at least a chance of detecting monopoles with  $n$  all the way from  $\frac{1}{2}$  to 100.

Two other monopole experiments have been proposed for the proton beam. One is by the Alvarez group and we assume it will use the same method that group used in their experiment with moon samples.<sup>6</sup> This method depends on magnetic trapping but not on magnetic field extraction of monopoles. This experiment can probably be run on parasite time. The other experiment is by Nezeric and Carrigan of N.A.L. This experiment is similar to the

type III experiment done by Amaldi et al.<sup>7</sup> This experiment seeks to identify relativistic monopoles by extracting them (as they are produced) from some sort of target with a magnetic field and passing them through a detector. If the detector used is a nuclear emulsion as was the case in the experiment of Ref. 7 then it may not be possible to run this experiment on parasite time as scattering from the forward experiment may fog the emulsions.

#### Muon beam experiment:

Here the beam intensity is only  $10^7$  muons per burst so we can use much thicker counters without having trouble from beam background. We also need not be concerned about a background contribution from excessive cascade showers within the counter. Here we propose to use ten Lucite Cerenkov counters which are 2.5 meters long each. By adding the pulses from these counters and also analyzing one separately we can set the same cross-section limits as in the above proton beam experiment. These counters can be run behind another experiment so again all we need is parasite time. As far as we know no other monopole experiments are planned for this beam.

Here the Cerenkov target method is truly unique in allowing such a large target thickness. The muon beam energy is only 100 BeV so we can only go up to a monopole rest mass of roughly  $7 \text{ BeV}/c^2$ .

### III. Experimental Arrangement

#### Proton beam experiment:

The Lucite counters we will use are shown in Figure 1. The counters acceptance region is much larger than the accelerator beam diameter. This permits us to use a divergent beam and also reduces the possibility of disturbing the counter calibration by misaligning our counters with the accelerator beam. Our counters will be calibrated with cosmic rays. Each of these counters is connected to a separate scalar and pulse analyzer.

Our photomultiplier tube time constants are 100 nsec. When the counters are placed in the beam a certain background level appears. This level is determined by the number of beam particles within 100 nsec so we expect the beam background to be  $10^3$  times the single particle calibration levels. We can measure this level with an oscilloscope. The scalars are then set so that the lowest channel lies above the beam background. Hence the beam is not scaled. For the production of a monopole pair whose relativistic range is dominated by ionization loss the Cerenkov emission level should be approximately 1,500(150) times the beam background level in the .25 (2.5) cm thick counter. When the Cerenkov pulse exceeds a certain scalar amplitude it is read out onto digital tape. The reader threshold is determined by the deadtime resulting from the reader. Here we may use the fact that a beam pulse is available only every 4 seconds. Thus we want our reader threshold set so that we do not have more than one or two reader level pulses per second of live beam time. The distribution of pulses



from monopole production would have the appearance shown in Fig. 2. The lower amplitude contributions result from the range effects noted previously.

If the monopoles relativistic range is significantly affected by bremsstrahlung loss then the Cerenkov counter pulse amplitude is reduced. The reason we are selecting counters which are so thin is so that we can observe monopole production even if bremsstrahlung is present.

If we find Cerenkov pulses significantly above the beam level, and if they form a peak in the distribution then we will proceed on to the gas counter runs. The gas counter design is shown in Fig. 3. If we find Cerenkov pulses significantly above the beam level but they are dispersed and do not seem to form a peak then we will try using a thicker counter to reduce range effects. The shift in the Cerenkov counter pulse distribution from any monopole production is so drastic in the Lucite-gas counter combination that we would not need a very well formed peak to recognize monopole production.

#### Muon beam experiment:

The beam intensity here is  $10^3$  times less than in the proton beam and our counters are  $10^3$  times thicker. Thus the Lucite counter discussion above also applies here. The Lucite counters here are shown in Fig. 4. These counters have a smaller diameter than do the proton beam counters so they will need to be aligned carefully. The counters we made in sections (signals added) so

they can be calibrated with cosmic rays and transported.

If we found what appeared to be monopole production in the 25 m Lucite counter from four weeks of accelerator time then we could check it by constructing a gas counter like that shown in Fig. 3 but with  $25 \text{ g/cm}^2$  of effective target thickness. This counter could then need to be run for 400 weeks to check the Lucite counter data. This would be quite an effort but would seem worthwhile if a peak which could be interpreted as monopole production were obtained from the Lucite counter. If the peak found in the Lucite counter was sufficiently narrow then we could instead check for monopole production by using a Fluorichemical counter as shown whose design is similar to the gas counter shown in Fig. 3. Here the amplitude, if due to monopole production, would shift by only

$$(N_{\text{Lucite}}/N_{\text{Fluorichemical}})^2 = 1.37 .$$

Our counters will be portable and can be easily rolled into place. We expect to be able to set all scalar and reader levels within one day of beam time.

#### IV. Apparatus

The construction of a four channel scalar has just been completed. These are 7-stage binary ripple counters with additional 1-stage scalars. Here gated scalars with crystal controlled oscillators digitize the time internal output of an analog pulse height-to-time conversion of the photomultiplier tube signals. All pulses at or above the first channel threshold are scaled but the scalars can be reset without printing their output onto digital tape. The scaling time interval is

$t = (n \pm 1) \tau_c$  where  $\tau_c = 1/f = \text{oscillator period}$  and  $n$  is the number of oscillator pulses counted. The pulse amplitude  $A$  is thus

$$A = A_0 e^{(n \pm 1) \tau_c / \tau}$$

where  $A_0$  is the pulse height to time converter level (zero channel of scalar) and  $\tau$  is the photomultiplier tube decay constant. The error is the constant amount  $\pm \tau_c / \tau$ . If a tape print out is initiated then the scalars (of a given ripple counter) are inhibited to protect the information stored from noise signals. After readout the scalars are automatically reset.

We will use this pulse analyzer to calibrate the Cerenkov counters. One counter is now completed (the 2.54 cm counter). We have a digital tape recorder. We have yet to construct the rest of the Cerenkov counters or to calibrate any of the counters but we do have the coincidence counters and circuitry for such calibration.

We can have the proton beam experiment ready by January and the muon beam experiment ready by next summer.

We can furnish our own manpower to run the experiments. We would like to have a computer available to print out the digital tapes. This would not need to be on-line.

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Table I Ionization and bremsstrahlung parameters for relativistic monopoles with low  $\gamma$  values.

Magnetic charge ( $\mathcal{N}$ )	Monopole mass (BeV/c <sup>2</sup> )	Relativistic ionization range (g/cm <sup>2</sup> )	$X_{\sigma}$ (g/cm <sup>2</sup> )
1	3	1.2	1.6
	10	4	16
2	3	.3	.1
	10	1	1
4	3	.07	.02
	10	.25	.06

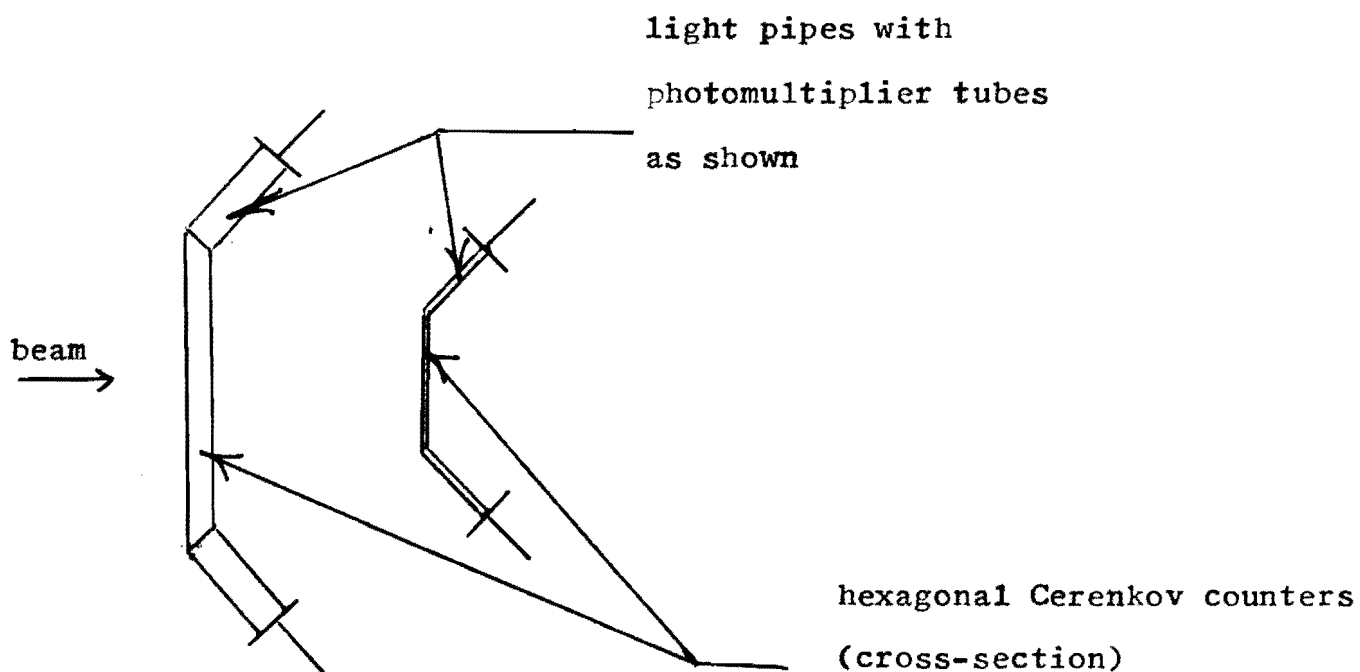


Fig. 1 Lucite Cerenkov counters for proton beam experiment.

Counters are hexagonal with six light pipes attached as shown.

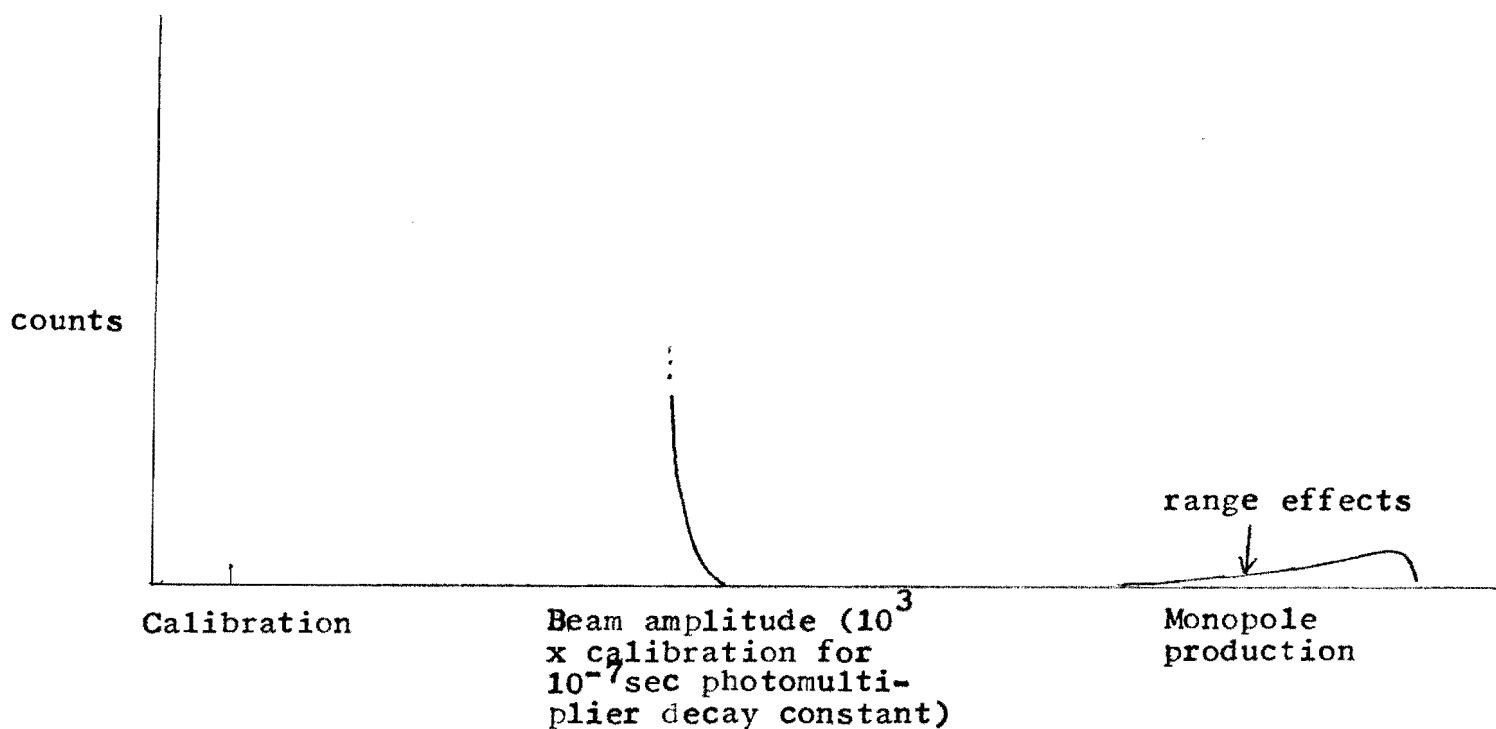


Fig. 2 Schematic of pulse distribution with monopole production present (not to scale).

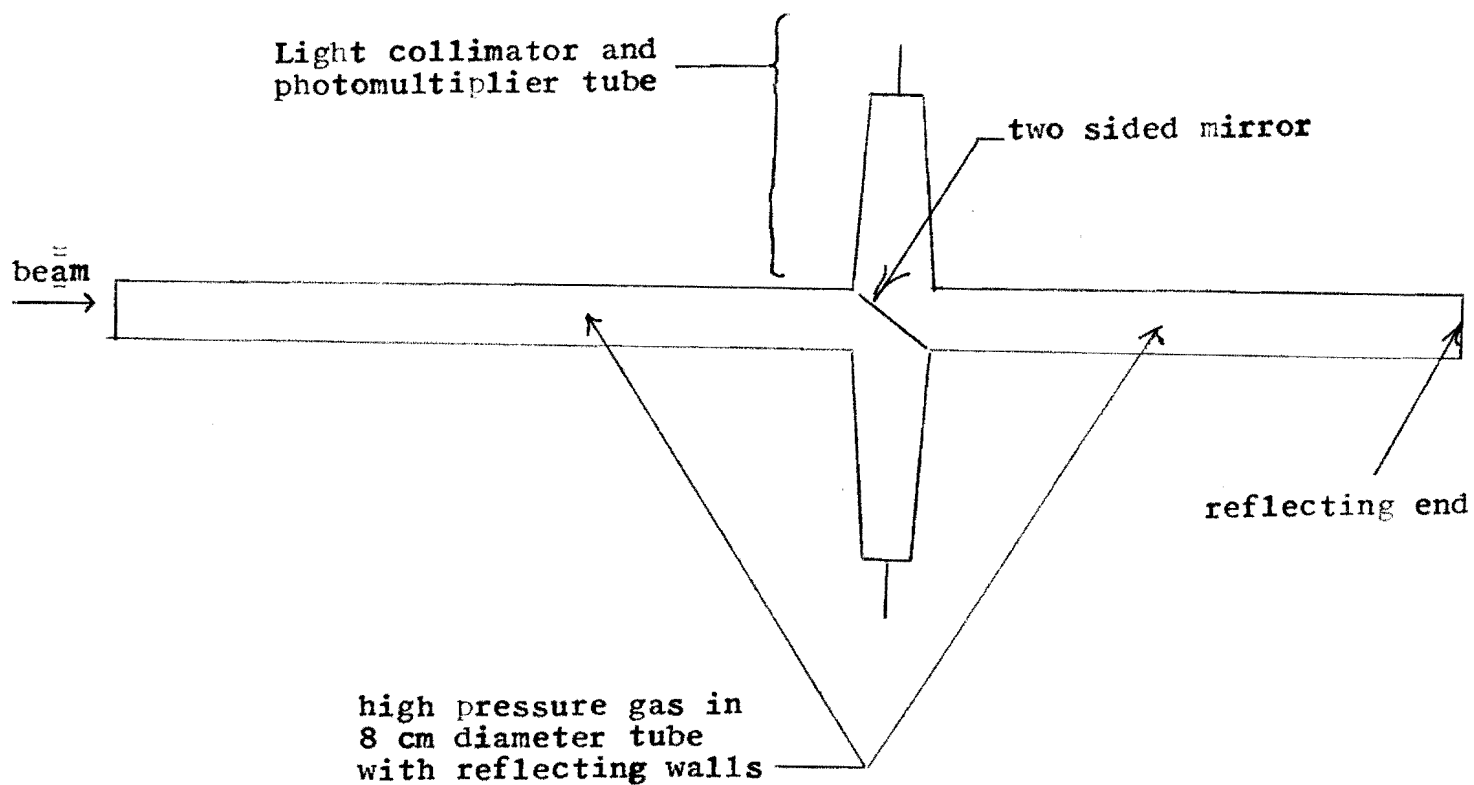


Fig. 3 Gas Cerenkov counter

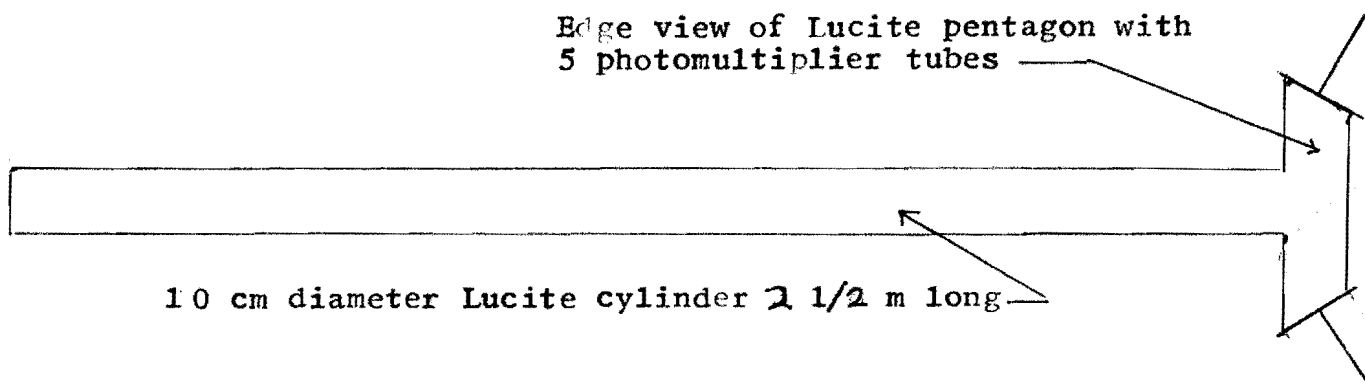


Fig. 4 Lucite Cerenkov counter for muon experiment. A series of 10 such counters will be used for this experiment.



Addendum to Proposal of Donald R. Tompkins  
Two Experiments Proposed for the Enrico Fermi Accelerator

Proton Beam Experiment

The Lucite Cerenkov counters will be replaced by water counters which are 8cm and .8 cm thick. This will do away with the problem of radiation damage to the counters.

The beam level of  $10^3$  protons per 100 nsec (the photomultiplier tube decay time constant) will yield approximately  $3 \times 10^6$  ( $3 \times 10^5$ ) Cerenkov photons per 100 nsec in the 8 cm (.8 cm) thick counters. This would cause the photomultiplier tube photocathodes to fatigue, so we will reduce this level by collecting an unbiased sample of the photons. This can be done by using the approximate cylindrical symmetry which can be obtained if the Cerenkov emission is collected off of a rim at a diameter significantly larger than the beam diameter. In this way the number of photons can be easily reduced by two orders of magnitude or more if necessary. The number of photons can also be reduced by not coupling the counters directly to the photomultiplier tubes but instead having the tubes view a diffuse surface. This has the added advantage that the photons are distributed over the entire photocathode. The counter design shown in Fig. A-1 includes both of these features.

Muon Beam Experiment

Here radiation damage is not a problem and the added refractive index of Lucite over that of water could be a real

advantage if some indication of monopole production is obtained. However in view of past experimental results a negative result should be expected. Long large diameter water counters would probably present a Cerenkov pulse amplitude from any monopole production which was less dependent on where along the counter the monopole production occurred than would be the case for long thin Lucite counters. For this reason we will use water counters in this experiment.

While the beam intensity is reduced from that of the proton beam these counters are much thicker so that the level of Cerenkov light emission from the beam is again a problem. We would use the same methods to attenuate the number of photons as was done for the proton beam counters. The new counter design is shown in Fig. A-2.

One further point on this experiment needs to be clarified. If the possibility of monopole production was found in the water counter results and if the peak found was sufficiently narrow so that it appeared that we could identify monopoles by re-running the experiment with Lucite and Fluorichemical counters then only eight weeks of parasite beam time would be needed to complete the experiment. If the peak found from the water counters was too broad to allow the use of a Lucite counter-Fluorichemical counter comparison then a water counter-gas counter comparison would need to be used and 400 weeks of parasite beam time would be needed to complete the experiment.

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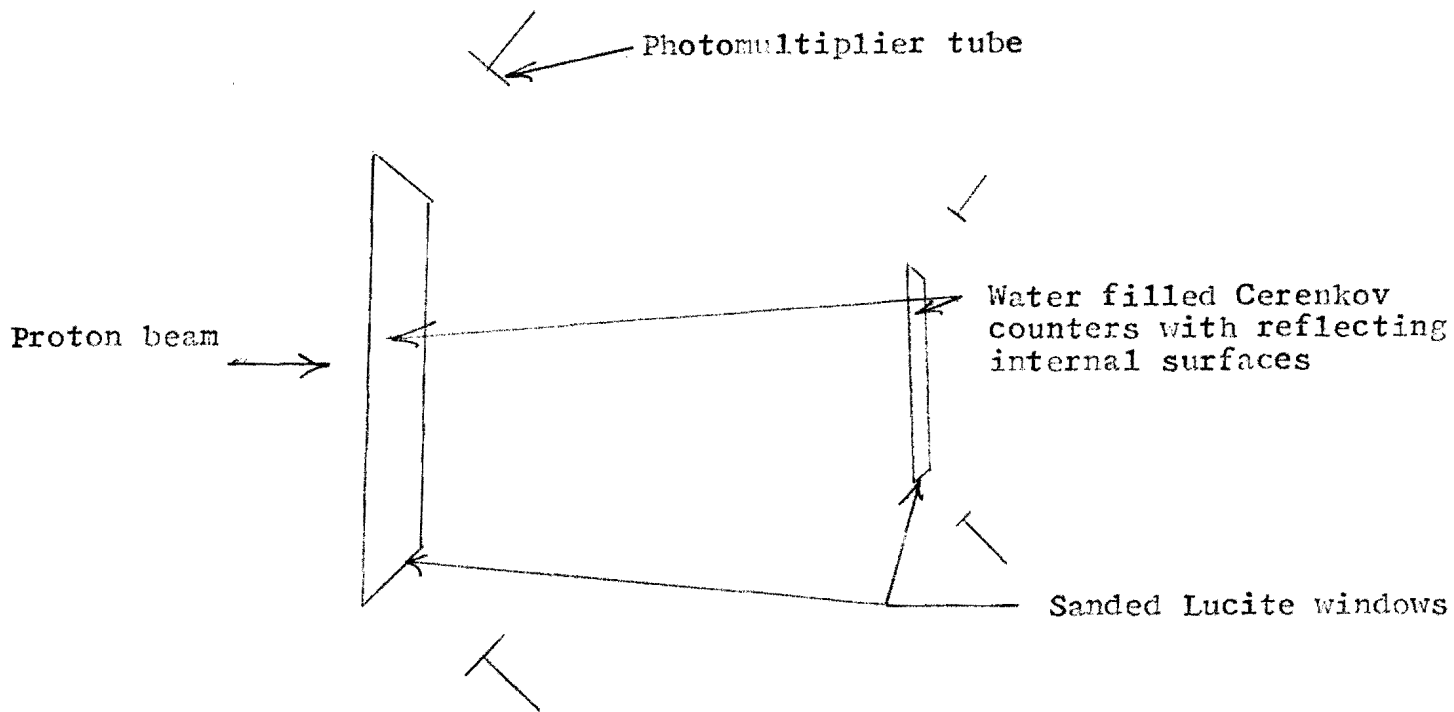


Figure A-1

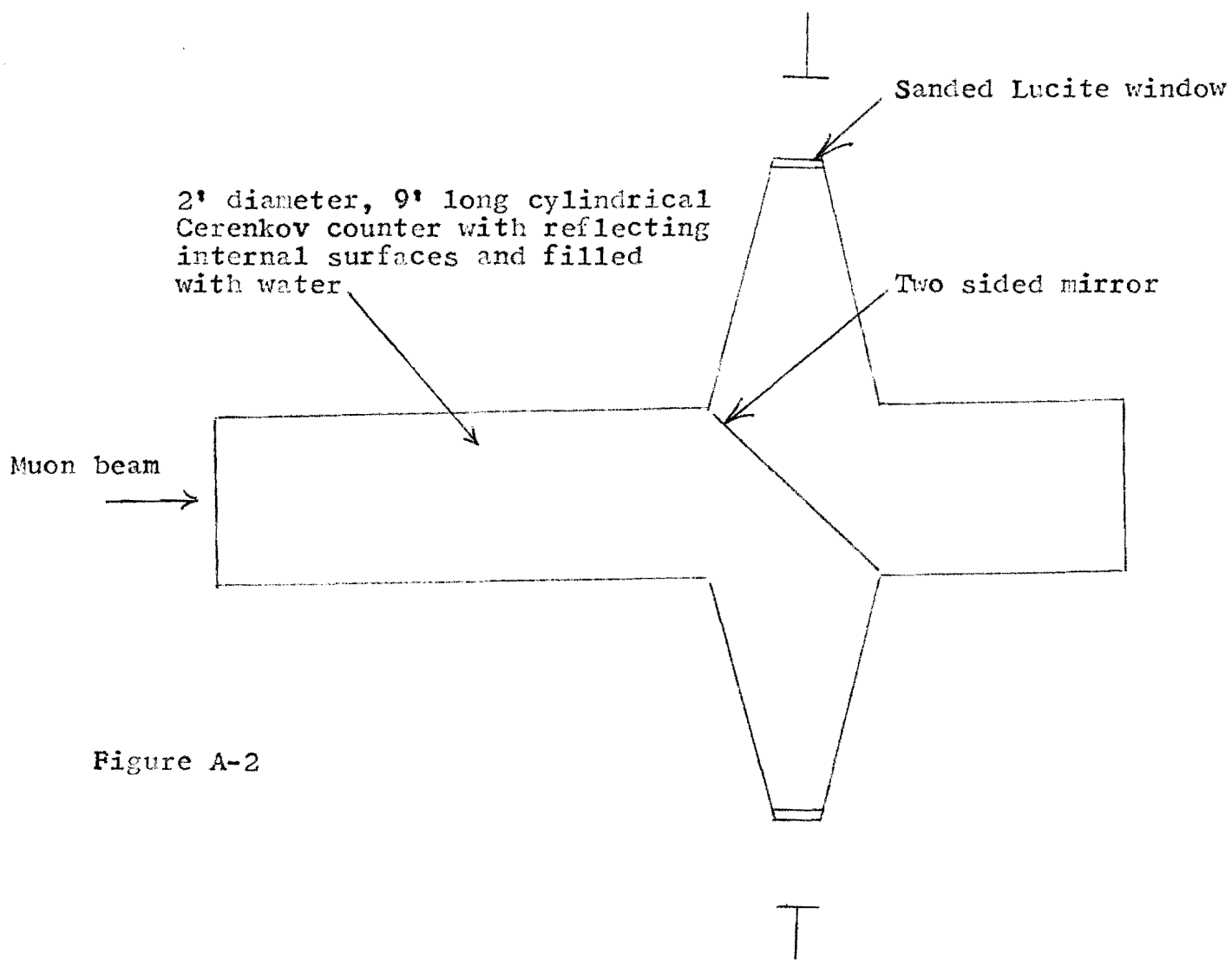


Figure A-2

NAL PROPOSAL No. 19-A

Correspondent: D. R. Tompkins, Jr.  
Department of Physics  
University of Wyoming  
Univ. Station, Box 3905  
Laramie, Wyoming 82070

FTS/Off-net: 307 - 778-2220  
766-1121

A Search for Monopole Production by  
200-500 GeV Protons

D. R. Tompkins, Jr., G. A. Rebka, Jr., A. R. Kunselman  
University of Wyoming

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## II Physics Justification

The present experimental situation on monopoles is that none have been found and cross-section limits as small as  $10^{-48} \text{ cm}^2$  have been set for trapped  $1 \text{ GeV}/c^2$  monopoles. Accelerator experiments have only searched up to  $7 \text{ GeV}/c^2$ . The methods used have been classified according to physical implications<sup>1</sup> with the optimal type of experiment considered to be one which seeks to identify relativistic monopoles. That is the type of experiment we propose to do here.

The mass range to be available for pair production will extend up to  $10 - 15 \text{ GeV}/c^2$ , so we should ask what limits cosmic ray searches have placed on such relativistic monopoles. The only cosmic ray experiment which would have detected relativistic monopoles is the track search done by Fleischer et al,<sup>2</sup> and this experiment only quoted cross-section results for monopole masses above  $10^3 \text{ GeV}/c^2$ . Next we should ask how our cross-section limits compare with theoretical estimates. Such estimates<sup>1</sup> when extrapolated to a rest mass of  $10 \text{ GeV}/c^2$  range from  $10^{-36}$  to  $10^{-40} \text{ cm}^2$ . With 600 hours of beam time at  $10^{10}$  protons/burst (1 burst/15 sec) we can set a cross-section limit of  $3 \times 10^{-38} \text{ cm}^2$  for magnetic charge values of  $n = \frac{1}{2}$  to 4.

The values of magnetic charge which have been theoretically proposed are  $n = \frac{1}{2}$  (Dirac<sup>3</sup>),  $n = 2$  and  $4$  (Schwinger<sup>4</sup>) and  $n = 1$  (others<sup>5</sup>). The value  $n = 1$  corresponds to 137 electron charge equivalents. The beam level prevents us from effectively

searching for magnetic charge significantly smaller than  $n = 1$ . Monopole bremsstrahlung is described by the radiation length

$$X_{\sigma} = \frac{1}{2} (e/\sigma)^4 (M/m)^2 X_e$$

where  $\sigma$  (e) are monopole (electron) charges and  $M$  (m) are monopole (electron) mass and  $X_e$  is the electron radiation length. Monopole bremsstrahlung limits the relativistic monopole range and prevents us from searching significantly above  $n = 4$ . Both the ionization loss and Cerenkov emission increase as  $n^2$  so these effects cancel, but the bremsstrahlung increases as  $n^4$  so it is the effect which limits the total Cerenkov emission and keeps us from going above 4 with the proposed counter design.

Since any monopoles would be produced at different target depths we would observe a distribution of Cerenkov pulse amplitudes from such production. The end point of such a distribution should coincide with  $n = \frac{1}{2}, 1, 2$  or  $4$  if monopoles are being produced according to theoretical expectations.

The only other proposed accelerator experiment we know of which searches for relativistic monopoles from the 200-500 GeV proton beam is that of Fleischer et al.<sup>6</sup> This experiment will search for monopole tracks in thin plastic films where the monopoles are drawn out of the beam by magnetic fields. Our experiment uses Cerenkov counters which have the advantage that even for such large charge strengths as are sought here, the counter performance can be predicted by theory.<sup>7</sup> We should also ask how our experiment is different in terms of monopole properties.

Our experiment could identify the production of monopoles whose free half-lives were as short as  $10^{-11}$  sec which is about two orders of magnitude shorter than the free-half lives required by the experiment of Fleischer et al. Since magnetic charge should be absolutely conserved this shouldn't be an advantage, but one cannot be sure either.

### III Experimental Arrangement

The experimental layout is shown in Fig. 1. The air Cerenkov counter has a threshold at about  $\gamma = 40$ , and so is unlikely to respond to any produced monopoles. Thus the air Cerenkov counter allows us to study the beam microstructure without monopoles. The water Cerenkov counter has a threshold at around  $\gamma = 1.4$  and a response which levels off at around  $\gamma = 6$ . This counter allows us to observe the microstructure of the beam with any produced monopoles.

We expect to gain a 33 nsec resolving time out of our counters, so that the average beam level (based on  $10^{10}$  protons/sec) during a resolving time is  $3 \times 10^2$  protons. Monopoles with  $n = \frac{1}{2}$  to 4 can, if produced in the forward part of the water counter, produce pulse levels approximately  $80 n^2$  times larger than this. This should make it possible for us to accept monopoles and discriminate absolutely against 600 hours of beam.

The electronics block diagram is shown in Fig. 2 and is self explanatory. When pulses significantly above beam level are received from either counter, the amplitudes from both counters

are simultaneously recorded. The discriminator levels are set to gain an acceptable count rate. This should not be difficult since  $n = \frac{1}{2}$  corresponds to a Cerenkov signal about 20 times the beam level.

The water Cerenkov counter is designed to have a high collection efficiency over a large range of monopole production angles. A high energy monopole produced at a wide angle could produce a larger Cerenkov pulse than would forward production but this would again be recognized as monopole production and would only make the identification of  $n$  more difficult.

The photomultiplier tubes are placed behind the targets in order to be away from the elastic recoil protons. These tubes can also be shielded if necessary. If it is necessary to reduce the light levels (from the beam) to these photomultiplier tubes that can be done by filters.

#### IV Apparatus

The Cerenkov counters, complete with photomultiplier tubes and followers will be constructed by us. We would like to obtain the loan of two power supplies (one high voltage), two discriminators and a multichannel analyzer which will analyze two simultaneous pulses. The pulse mixer shown in Figure 2 will be provided by us.



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photomultiplier  
tube

light pipe (air)  
for water counter

light pipe (air)  
for air counter

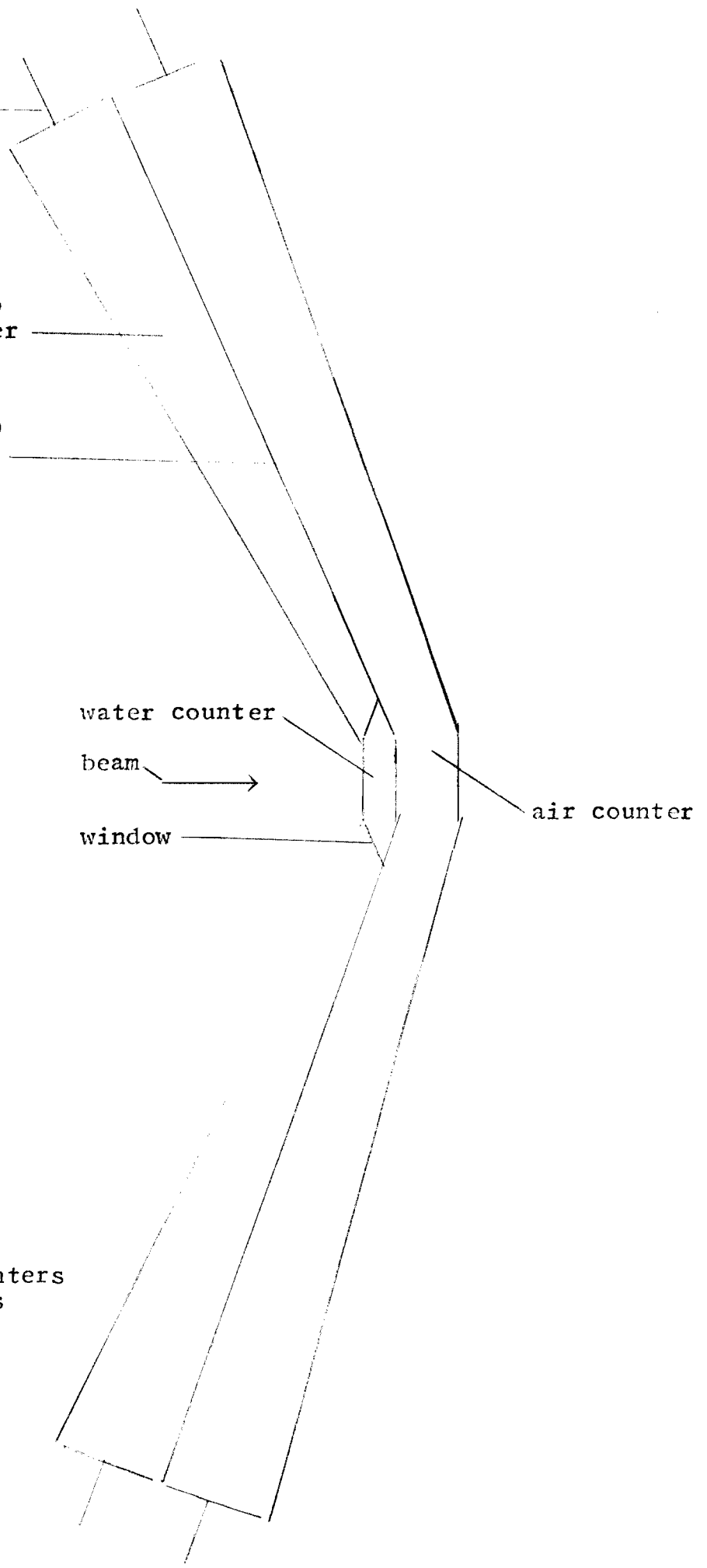
water counter

beam →

window

air counter

Fig. 1 Cerenkov Counters  
All internal surfaces  
(except window) are  
reflecting.



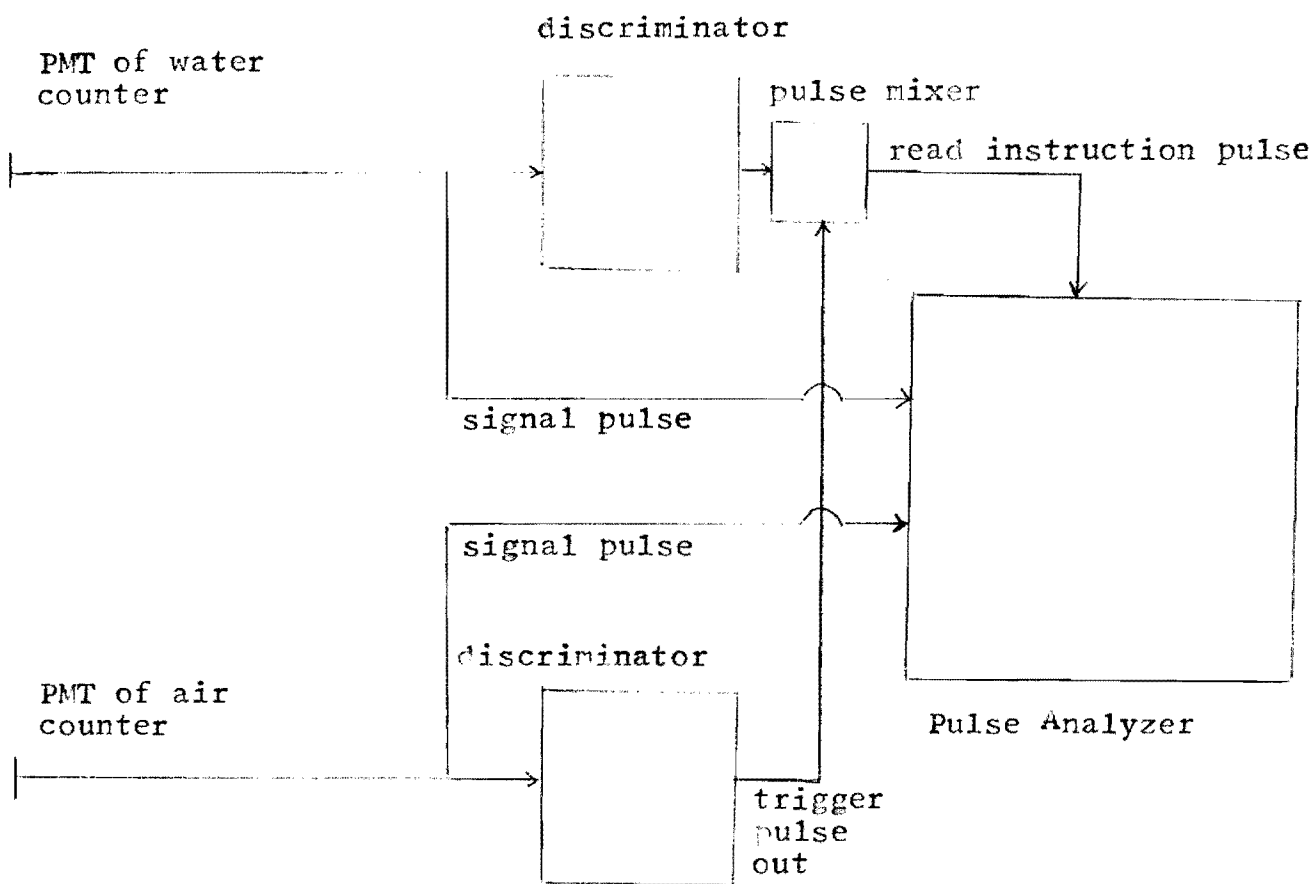


Figure 2  
Electronics Block Diagram