AN IMPACTOMETER FOR THE ISR

W. J. Willis

Yale University and Brookhaven National Laboratory

I. Introduction

The importance of a total solid angle array of total absorption spectrometers (calorimeters) for very high energy physics has been emphasized.[1] By an impactometer, we mean such a device which is designed so that fast analogue computations of interesting physics quantities may be made on each event: quantities such as total transverse momentum within an azimuthal sector, total energy, longitudinal and transverse momentum unbalance, multiplicity, etc. Thereby, very rare categories of events may be selected efficiently without hard-to-evaluate biases. Obvious examples are "central collisions" producing transverse jets of hadrons or large multiplicity.

This device detects and measures the energy of all hadrons, including neutral particles. Muons and electrons are identified, though only the latter have their energy measured accurately. The presence of a neutrino may be inferred under certain conditions. Thus, given the large solid angle and the possibility of examining all the hadrons associated with produced leptons or photons, this is an almost ideal device for searching for the electromagnetic and weak reactions which we expect to detect at high energies.

To accomplish these goals, the device should be capable of handling the largest rates the ISR can provide. Clearly, it must provide adequate energy and angular resolution. The difficulty of meeting these requirements with a device of reasonable size and cost has been an obstacle up till now. We propose to build a facility based on the use of segmented ion chambers, with finely-divided plates and liquid argon as the working medium. This allows a high effective density, and thus, a relatively small device which provides good angular resolution, while maintaining good energy resolution.

As the characteristics of the impactometer are described, it will become clear how a very wide variety of further experiments can be done. For example, it may even prove advantageous for the study of large angle elastic scattering. In this connection, it is worth noting that most of the physics program can be done simultaneously, adding different triggers, since there are rather fewer auxiliary devices than with other large electronic facilities. This means that the integrated running time will be larger than that usually considered. This effective boost in the luminosity, coupled with the total solid angle coverage, allows very small cross section limits to be reached.

II. The Ion Chambers

We propose a device in which the calorimeters are ion chambers, detecting the electrons collected on metal plates immersed in liquid argon.[2] Since this is a novel detector, we present a discussion of its properties in this section before going on to a description of the construction of the impactometer.

An important advantage which is gained by the use of this technique is high density. The overall mass in a 4π detector of fixed surface density is inversely proportional to the density squared. On the other hand, if the ionization is sampled between plates of dense material, the plates must be rather thin to avoid degradation of the energy resolution. These requirements are met by a structure which will consist, typically, of 1½ mm steel plates separated by a 2 mm gap filled with liquid argon (LA) with a density of 1.4 gm/cm^3. A somewhat denser structure is used closer to the interaction region, leading to an average density of about 4.3 gm/cm^3, an interaction length of about 23 cm, and a radiation length of about 3½ cm.

The liquid argon is used as the working medium, instead of a gas, in order to get a sufficient quantity of charge so that amplifier noise is not a problem. Many questions can be asked about the performance of such a novel device. We believe we have performed tests which answer the important ones, as in the following.

<u>What is the response time?</u> The unclipped rise time of the integrated charge measured in the apparatus shown in Fig. 1 is about 250 ns, as shown in Fig. 2. We would use a bipolar shaping network with a rise time of about 200 ns in the production circuit, with gaps which are 20% narrower. We believe that the inductance in full scale modules will not affect this performance. (Such a module is now under construction.) The timing signal derived from zero crossing is expected to have a <u>time resolution</u> of about 10-20 ns. We will enforce a system <u>dead-time</u> of about 1 μs, to cover the pulse shaping, and to allow neutrons from a previous event to die away.

<u>Is high purity argon essential for electron collection?</u> No, in the sense that we obtain similar results from welding grade argon, and from Linde "Gold Label" high purity argon. The welding grade, in fact, contains very little oxygen. We get very nearly the charge expected theoretically, as shown in Fig. 3. It might be wise, in a large system, to have a modest purification capability.

<u>What fields are needed?</u> We have used fields between 4 and 40 kV/cm. The electron mobility is nearly constant over this range of field. We have not observed breakdown up to fields of 40 kV/cm.

<u>Is amplifier noise a problem?</u> It is possible to design the system so noise is never a serious limitation.[3] This is best illustrated in the test measurement pictured in Fig. 4. The capacitance of 0.1 μF is comparable with

that of the largest module contemplated in the proposed detector. The observed noise was < 10^5 electrons, but we will take a more generous allowance of 2 × 10^5 electrons as our performance specification. In our detector, we see about 18,000 electrons per MeV of energy loss in LA. This noise is equivalent to about 10 MeV, or about ± 50 MeV of total energy loss, counting the plates. The noise we expect in a single module then is probably determined by energy from stray neutrons associated with the event which triggers the system, rather than by electronic noise.

Is stray noise a problem? With reasonably careful shielding only very intense interference, such as that from nearby spark chambers, is found to enter the test ion chamber system. The final system would probably have symmetrical inputs to a balanced amplifier to further reduce pickup. Of course, if it is necessary to have spark chambers nearby, the noise due to them can be gated out.

How well can it be calibrated? Each module has a small capacitor through which a test pulse can deliver an accurately known charge to the ion chamber. Thus the charge sensitivity can be accurately checked at any time. Feedback keeps the system gain constant to better than 1% in any case. Further, we have found that the ionization is reproducible and, in fact, closely equal to that expected. Therefore, the total ionization in the LA will be measured with good accuracy and continuously checked.

Questions of the calorimeter energy resolution will be answered after the Impactometer construction is described.

III. The Impactometer

The Impactometer consists of three units: a sphere covering the large angles, most of 4π; and two conical sectors of about 0.2 sr which measure forward particles with greater angular resolution. We will first describe the spherical unit, shown in Fig. 5.

This is a sphere of outer radius 2.25 m. There is an inner sphere of 0.5 m radius which surrounds the interaction point, and which contains multiwire proportional counters, whose configuration may vary with the experiment. The ion chambers fill the intervening space in the form of truncated hexagonal pyramids, whose diameter has been chosen to be one interaction length in diameter in the middle. The diameter at the base is then 0.45 m, and about 400 such units are needed to fill the sphere. Each of these is divided radially into three distinct chambers. The innermost, with a diameter of 10 cm at the inner radius, contains fifty plates of high-Z material, making up five radiation lengths. This portion is used in identifying electrons and photons by their large energy release here, compared to the following sections. (One might consider as an option, perhaps in a later phase, subdivision of these modules into smaller ones, with the aim of resolving the two photons in pi-zero decay up to higher energies, thus distinguishing them from single photons.)

The next module extends 0.80 m radially, tapering from 0.13 to 0.29 m diameter. It would contain 230 steel plates, 1½ mm thick. This plate array has a special structure to allow the nuclear effects to be evaluated, which will be described below.

The outermost module is also 0.8 m long, tapering from 0.29 m to 0.45 m diameter, containing 230 steel plates, 1½ mm thick.

Each of the modules is read out separately by a charge sensitive amplifier. The total surface density in the three modules making up one unit is about 730 gm/cm^2, about 22% of this in the LA. These plate structures weigh about 160 T, with about 35 T of LA.

Figure 6 shows a view from the center of the sphere, along directions near one of the outgoing beams. It will be seen that seven hexagonal units are omitted from the sphere in the forward direction, being replaced by one of the forward detectors, with finer subdivision. This also permits the entry of the other, incoming, beam pipe. The sphere is split to allow assembly of the plate structure, whose main weight is carried by the outer sphere, and access to the inner detector.

The forward angle detectors are similar in construction, except that the radial extension is about 2.2 m, to give a surface density of about 1000 gm/cm^2. It would be divided into 24 units. These parameters make it suited to the high energy particles expected in the forward direction.

The plate arrays are constructed by stacking the steel plates, separated by ceramic washers, on three tie rods. We have not observed any problems with edge breakdown, etc., on the small modules we have built.

The LA at about 85° K is refrigerated by a liquid nitrogen cooling loop, as in our small devices. It may be sufficient to cool only at the top, and rely on convection to maintain temperature uniformity. We have found that no particular care is necessary to avoid freezing the LA.

IV. Resolution and Particle Identification

The particles of interest at the ISR range from 0.2 GeV to 30 GeV. The most critical region for large transverse momentum studies is 1 - 5 GeV. For particles of these energies, it is necessary to pay careful attention to nuclear effects if it is hoped to understand the important aspects of the nuclear cascade. This is a formidable task since hundreds of nuclear collisions may be involved. Fortunately, the group of R.G. Alsmiller, et al., at Oak Ridge National Laboratory have developed a set of rather refined intranuclear and internuclear cascade calculations. Their in this energy region validity has been checked by many tests,for example, by measuring the radioactive nucleides produced at different depths in an absorber,[4] or by comparison with the measurements in a tin phantom by E.B. Hughes and R. Hofstadter.[5] Once this validity is established, it is possible to use these routines to reach an understanding of the physical processes which is very difficult to attain from experimental results alone.

Without expanding at length on the subject, it may be said that the energy resolution in the device proposed here is not likely to be limited by the leakage of energy (about 98% of the energy is contained), or by sampling fluctuations (because of the very thin plates), but by the fluctuations in unobserved forms of energy. The most important of these is nuclear binding energy. This is found to average about 20% (13% in CH_2, 21% in Fe), but it undergoes large fluctuations. This energy lost in disrupting nuclei does not show up in ionization in any form, but there are other forms of energy which may be unobserved in practice; such as very slow protons or heavier nuclei outside the range of linear response of the detector, or slow neutrons which are still bouncing around when the signal is gated.

Calculations show that the fluctuations due to these sources give width of about ± 15%, at 2 GeV. The device may still be very useful with this performance, but we have been exploring a way to improve the resolution.

This method is based on the close correlation which must exist between the different forms of unobserved energy. (The precise extent of this correlation is now being extracted from the programs.) Then, for example, if we measure what proportion of the energy is in the form of densely ionizing particles, we can correct, event by event, for all the forms of unobserved energy. This should improve the energy resolution and get rid of the annoying bias of hadrons toward lower energy, with respect to photons and electrons.

The properties of the ion chamber allow a convenient method for making this measurement. Consider two interleaved ion chambers operating with different electrical fields and [illegible]gnals I_1 and I_2. This may be realized in the ways, as shown in Fig. 7.

The electric field is chosen so that for I_1, it is just above the value (3 ~ 4 kV/cm) which eliminates columnar recombination for minimum ionizing particles, while in the gaps of I_2, it is about four times higher. Then the signal per unit length from a densely ionizing particle is twice as great in I_2 as in I_1, relative to a particle of minimum ionization. We then define

$$IS = I_1 + I_2$$
$$ID = fI_2 - I_1$$

and adjust the gain, f, so that ID is zero for muons (or electrons or photons). Calculations then lead us to expect ID/IS to average 0.15 for hadrons. The energy is then given by

$$E = C(IS + kID)$$

where C is known a priori, and k is a correlation to be established by calibration.

It will not have escaped the reader's notice that if this technique works, it is a powerful additional means of particle identification. Electrons and photons are distinguished from hadrons also by their fractional energy deposit in the small high-Z chambers, and by the absence of energy in the third module. The ID signal in the second module would be an additional element in the identification. Thus, the overall separation factor should be very good.

(The tentative plan would be to provide the interleaved ion chambers only in the central module, where 80% of the hadron energy is deposited.)

The identification of the muons is also twofold: they give a Landau distribution of energy in each of the three modules, and they give the characteristic signal ID $\simeq$ 0, with fluctuations yet to be determined.

It seems probable that for both electrons and muons the background is given by the fundamental limits of internal conversion of photons, and pi-mu decay.

In seeking neutrinos, the technique is to observe a missing momentum which passes through the apparatus without interaction. In this case, neutrons are rejected by a factor of $\sim 10^3$. If this is combined with an observed lepton of large transverse momentum in the event, it will be possible to see a very small cross section.

Angular resolution is set both by the angular size of the units, and by the finite spread of the cascade. The number of units is sufficiently large so that events with 50 or so particles, which can be expected to be seen according to recent models, will still not have serious overlap problems. Also, the error on transverse momentum will not be dominated by the angular resolution.

Although the modules have been described as if they were mounted in line radially, they would probably be staggered, to gain some additional angular resolution. This would be easy to do because it is envisioned that the outer layer of modules would be assembled first, with the adjacent modules fastened together with clips to form a rigid structure. They then can support the next layer, which is much less massive.

V. Signal Processing

There are two important aspects to signal processing in the Impactometer. First there is the analogue manipulation of the signals to produce a wide variety of well-defined and selective trigger conditions. Then, once a trigger configuration has been satisfied, the signal levels must be strobed, stored, digitized and read out.

The signals from the ion chambers are amplified to levels of millivolts or greater by the preamplifier nearby, and then transmitted on balanced lines the required distance to the main electronics racks. There they undergo further amplification and shaping of a bipolar form. These signals are available for analogue manipulation. Certain functions which it would definitely be desirable to implement are:[1]

i) total energy,

ii) total energy in each hemisphere,

iii) total transverse "momentum" in each of about 12 azimuthal lunes,

iv) sum of iii),

v) unbalance in opposing lunes in iii),

vi) number of units with energy exceeding a given threshold,

vii) a muon signature; i.e. signals in the acceptable interval in the first two modules of a unit, and ID consistent with zero.

Thresholds or logical requirements may then be placed on these functions to define trigger conditions. When one of these is satisfied, a strobe signal is generated to store the signal level in each module on a capacitor. This occurs at the time of the second peak in the bipolar waveform, which follows the first by ~ 400 ns. Thus, that amount of time is available for analogue signal processing and trigger generation, though we will attempt to do this in 200 ns for reasons given below.

There might be more restrictive requirements which are applied through computation with the on-line computer at this stage. If these are satisfied, the digitization and readout of the stored signals begins. This is not done if the stored charge does not exceed a certain amount appropriate for each type of module. This means that only a (usually small) fraction of the ~ 1800 modules has to be digitized. It may take a few milliseconds to read out all the information and restore the system to a live state.

The method so far described does not take advantage of the timing accuracy inherent in the detectors. To do this, we would utilize the zero-crossing information in the shaping circuit. We think this has a dispersion of 10 - 20 ns. The average of these signals would be used to define the timing of the signal storage strobe. We would like also to be able to eliminate accidentals as well as possible. The best way to do this would be to digitize the time of each zero-crossing to an accuracy of a few bits with a least count of a few ns. Particular modules with accidentally coincident signals may then be eliminated if they are outside the acceptable range. This may be too elaborate, at least for the first phase. A simpler alternative which may be suggested is to add the signals derived from discriminated zero crossing signals, and sample and digitize the resulting time distribution every few ns over the interacting region. A single event will show a Gaussian distribution with a half-width of 10 - 20 ns. However, the number of entries in this distribution is of the order of 50 to 200, so the width is determined for a given event to 1 to 3 ns. If there are really two nearly coincident events present, this should be revealed if they are separated by 5 - 10 ns. With rates of $\leqslant$ 100 kHz, this means that accidental subtraction should not be too serious, even without help from the auxiliary detectors in the inner volume. With their aid, it will be possible to recognize tracks originating at different points in the interaction volume, if two events are involved. If the reconstruction is fairly accurate, so that the origins are defined within a volume of a few mm^3, the accidentals will be highly suppressed.

This more refined geometrical analysis, and the physics analysis, must be performed off-line, on a larger computer.

VI. Cost

The metal plate array for the whole system weighs 210 T. The cost for fabricating this system may be approached by comparing with the experience for pulsed magnets, which are made with similar punched sheets. The material quality and the tolerances have much tighter requirements for the magnets, but the problem of maintaining insulated gaps is not present. Our estimate is 2000 SF/T, or 420 KSF.

The mass of LA required is 50 T, at about 1500 SF/T, or 75 KSF. The vessel cost is rather uncertain, but we estimate 100 KSF.

The cost of electronics is about 80 SF per channel for the preamp and we estimate for the whole system, about 400 SF/channel, for 1800 channels, or 720 KSF. This does not include an on-line computer, which would be necessary. We have not specified the inner detectors yet, but a simple system of PWC might cost 100 KSF.

The LA storage and handling equipment would cost about 200 KSF. The manpower required to assemble the system might be about five to ten man years.

The total of these costs is about 1600 KSF. One of the interesting features of the system which may be relevant is that the most expensive parts, the plate modules and the electronics, are highly modular, and that data taking could begin with a system subtending a large solid angle, but less than 4π. Thus, important results could start to be obtained with about half the final cost, and correspondingly earlier.

In the same spirit, one may imagine further development of the complete system described here. We have mentioned a further subdivision of the high-Z chamber. The fundamental angular resolution would justify a considerable improvement in this regard. One may also consider adding devices to measure the range of energetic muons. It is also noteworthy that LA is an excellent scintillator and that some auxiliary devices can exploit this property.

VII. Summary

We have proposed a device for the ISR which has complete solid angle coverage, and which can detect all types of particles. Its properties may be summarized as follows:

1. Containment of ⩾ 98% of the energy of events.
2. Good energy resolution on all particles except muons of > 1.2 GeV. No tails on the resolution curve!
3. Good angular resolution because of the high density: a few degrees for large angles, better for small angles where the lever arm is about 2½ m.
4. Capable of dealing with particle multiplicities up to ~ 100.
5. Identification of electronic and photon showers.
6. Identification of muons.
7. Enhanced energy resolution and improved hadron identification by means of a measurement of the average ionization density.
8. Good time resolution to reject accidentals.
9. High rate handling capability.
10. Rapid and very accurate calibration procedures.
11. Real time computation of almost any interesting quantity and thus very refined triggering capability.

VIII. Acknowledgment

This work would not have been possible without the support of Brookhaven National Laboratory. I want to thank Drs. R. R. Rau and A. M. Thorndike, and particularly Dr. V. Radeka, who carried out the electronic developments described.

References

1. W.J. Willis, "The Impactometer," BNL Rept. CRISP 72-15, 1972, attached.

2. N. Davidson and A.E. Larsh, Phys. Rev. 77, 706 (1950).

3. V. Radeka, Int. Symposium on Nuclear Electronics, Versailles, France (1968).

4. T.W. Armstrong, J. of Geophys. Res. 74, 1361 (1969).

5. E.B. Hughes, R. Hofstadter, W.L. Lakin, and I. Sick, Nucl. Instr. & Meth. 75, 130 (1969).

6. P. Slattery, Phys. Rev. Letters 29, 1624 (1972); here it is shown that a universal curve fits the high energy charged multiplicity distribution. Appreciable cross sections for multiplicity three to five times the average are predicted by this formula, or 60 - 100 particles at the ISR.

Figure Captions

Fig. 1 Test LA ion chamber.

Fig. 2 Charge pulse due to a 14 GeV pion traversing the ion chamber illustrated in Fig. 1. The horizontal scale is 200 ns/div, the vertical is 50,000 electrons/div.

Fig. 3 The pulse height spectrum of the test ion chamber, (a) gated on 14 GeV/c pions; (b) ungated, in a 1 GeV/c beam of pions and protons. The narrow spikes are calibration signals.

Fig. 4 (a) The test set up to study the amplifier readout properties. (b) The shaped output signal for a charge input of 10 p C, or 6×10^7 electrons, equivalent to about 13 GeV of energy in the proposed modules. (c) The same signal, magnified by a factor of twenty to show the noise and recovery properties. One vertical division is equivalent to about 330 MeV of energy release. The horizontal scale is 500 ns/div.

Fig. 5 The overall view of the Impactometer.

Fig. 6 A view outward from the center of the Impactometer, along one of the outgoing beam pipes.

Fig. 7 Interleaved plate array for measurement of the average density of ionization.

BROOKHAVEN NATIONAL LABORATORY

BY ________	DATE ________	SUBJECT ________	SHEET NO. ____ OF ____
CHKD. BY ________	DATE ________	________	JOB NO. ________
________	________	DEPT. OR PROJECT ________	________

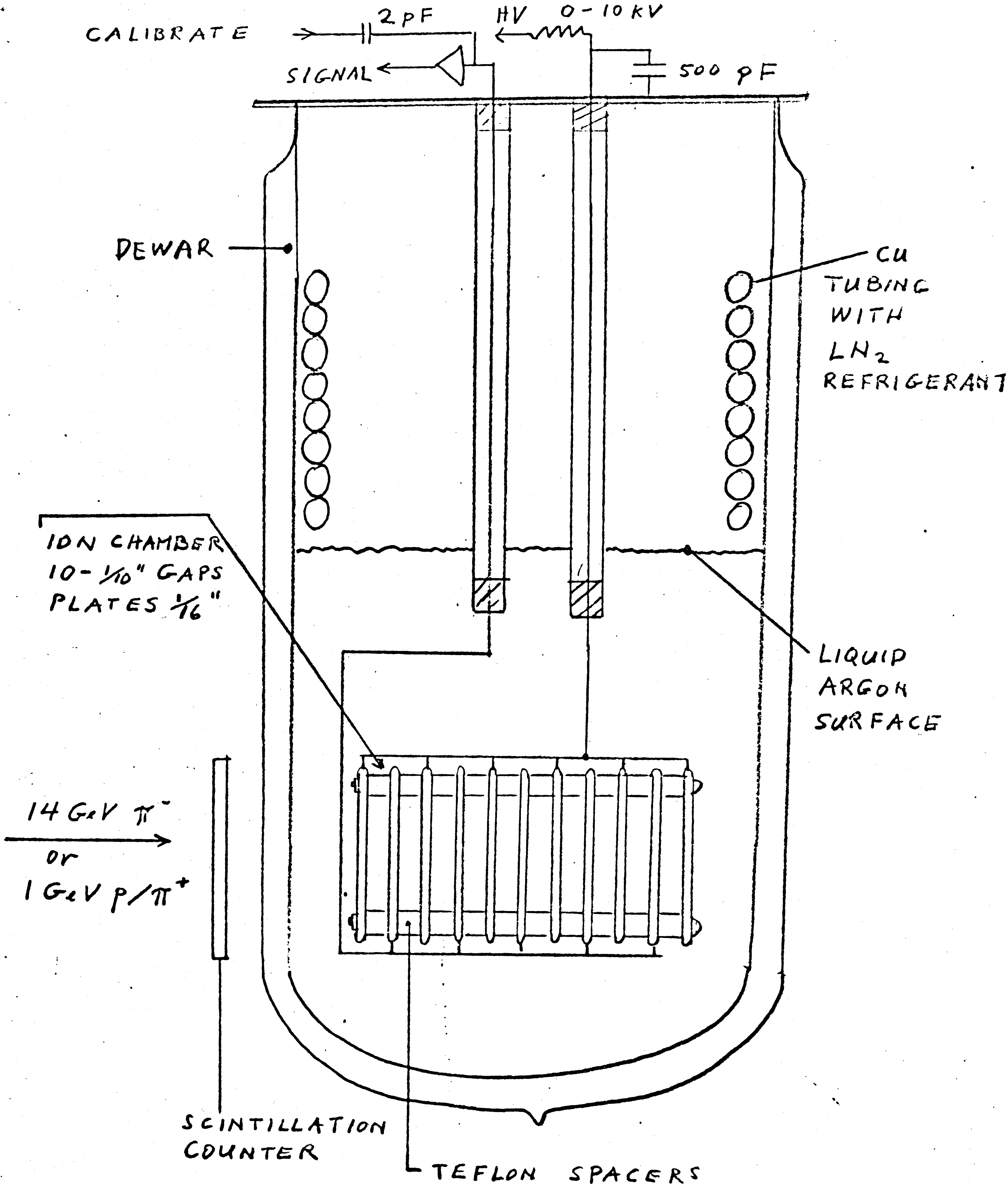
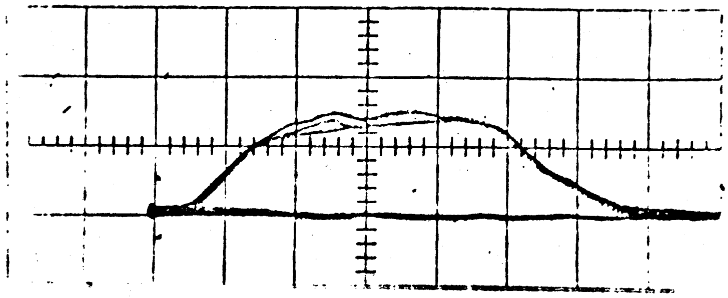


FIGURE 1

SP 11037A

FIGURE 2



(a)

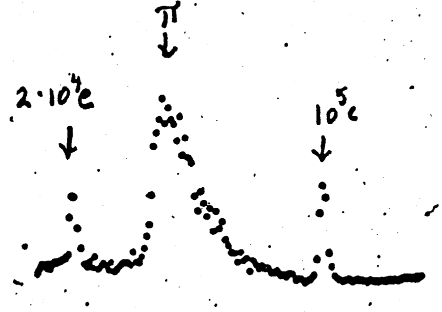
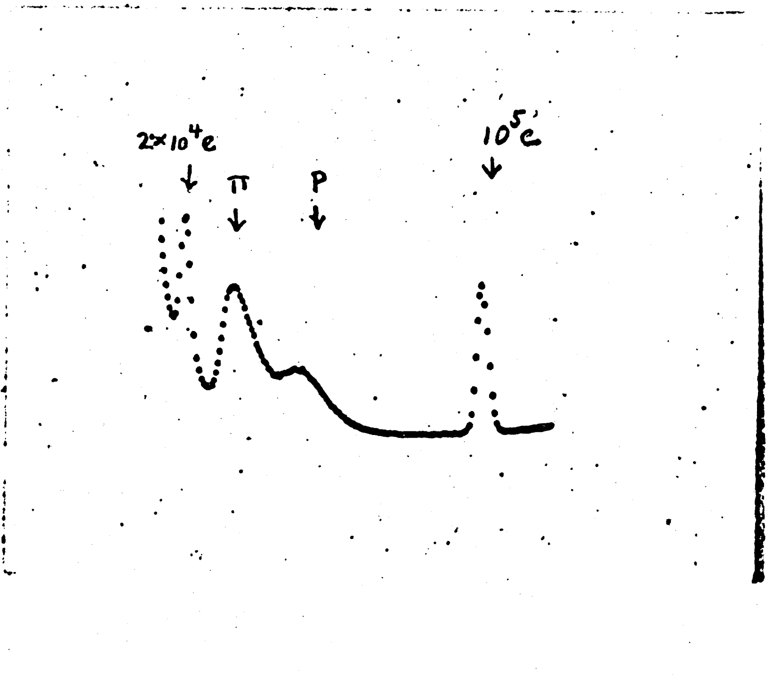


FIGURE 3

(b)



BY.............. DATE.......... SUBJECT.. SHEET No.......... OF..........
CHKD. BY.......... DATE.......... .... JOB No..........................
.... DEPT. OR PROJECT...................................... ....

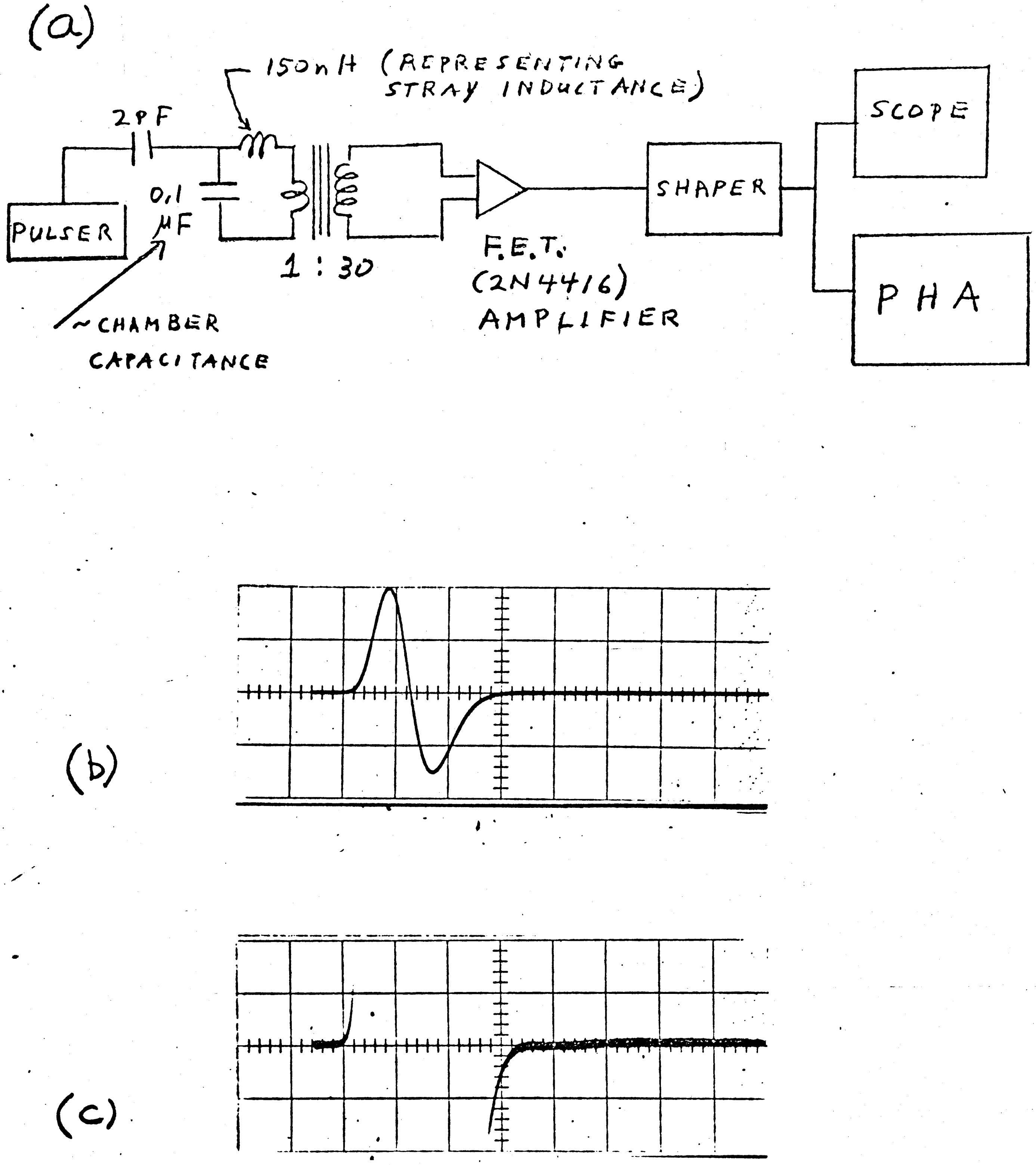


FIGURE 4

BROOKHAVEN NATIONAL LABORATORY

BY________________DATE________ SUBJECT________________________________ SHEET No.________OF________
CHKD. BY________DATE________ ____ JOB No.____________________
________________________________ DEPT. OR PROJECT__________________________ ____________________

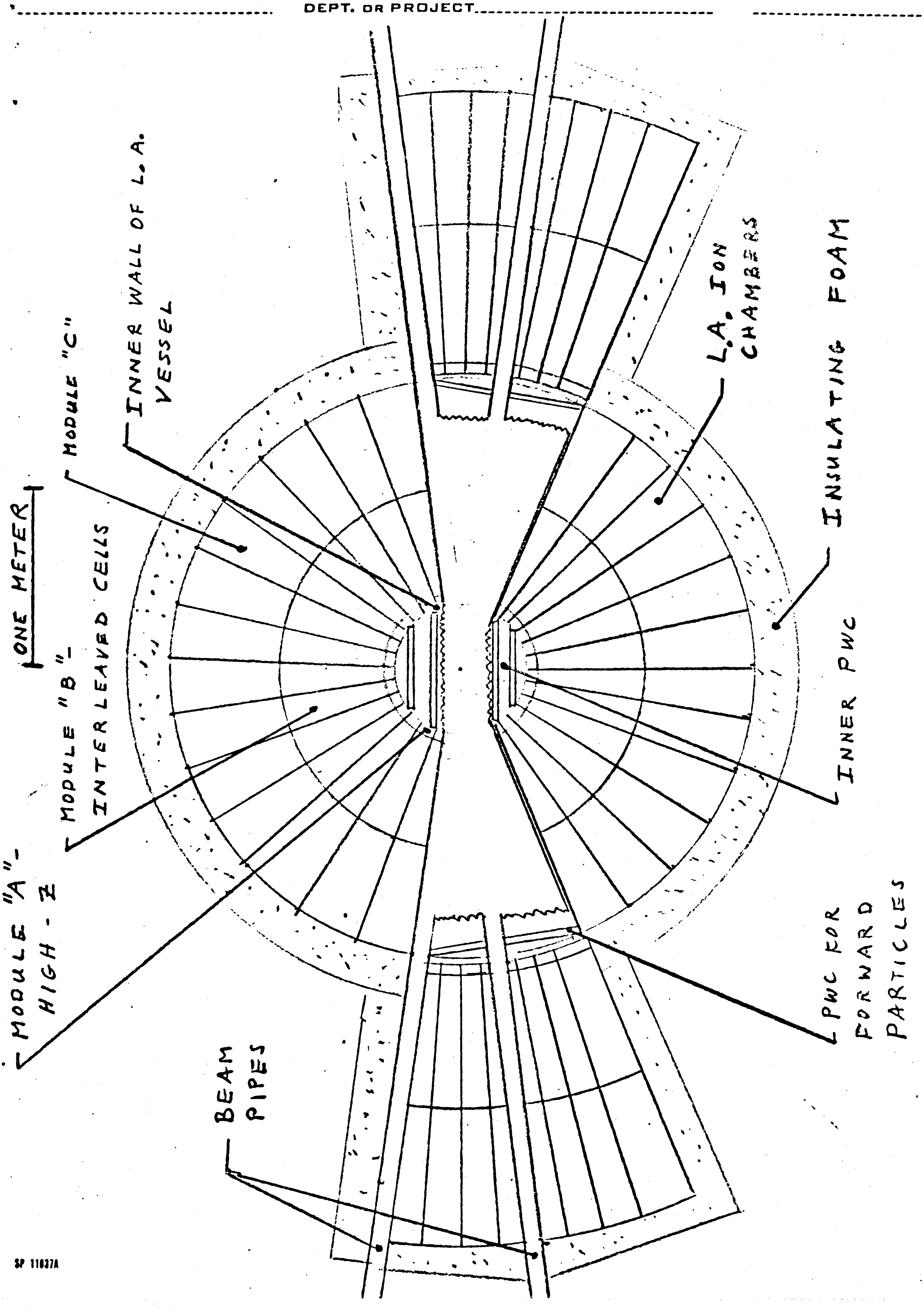


Figure 5

SP 11037A

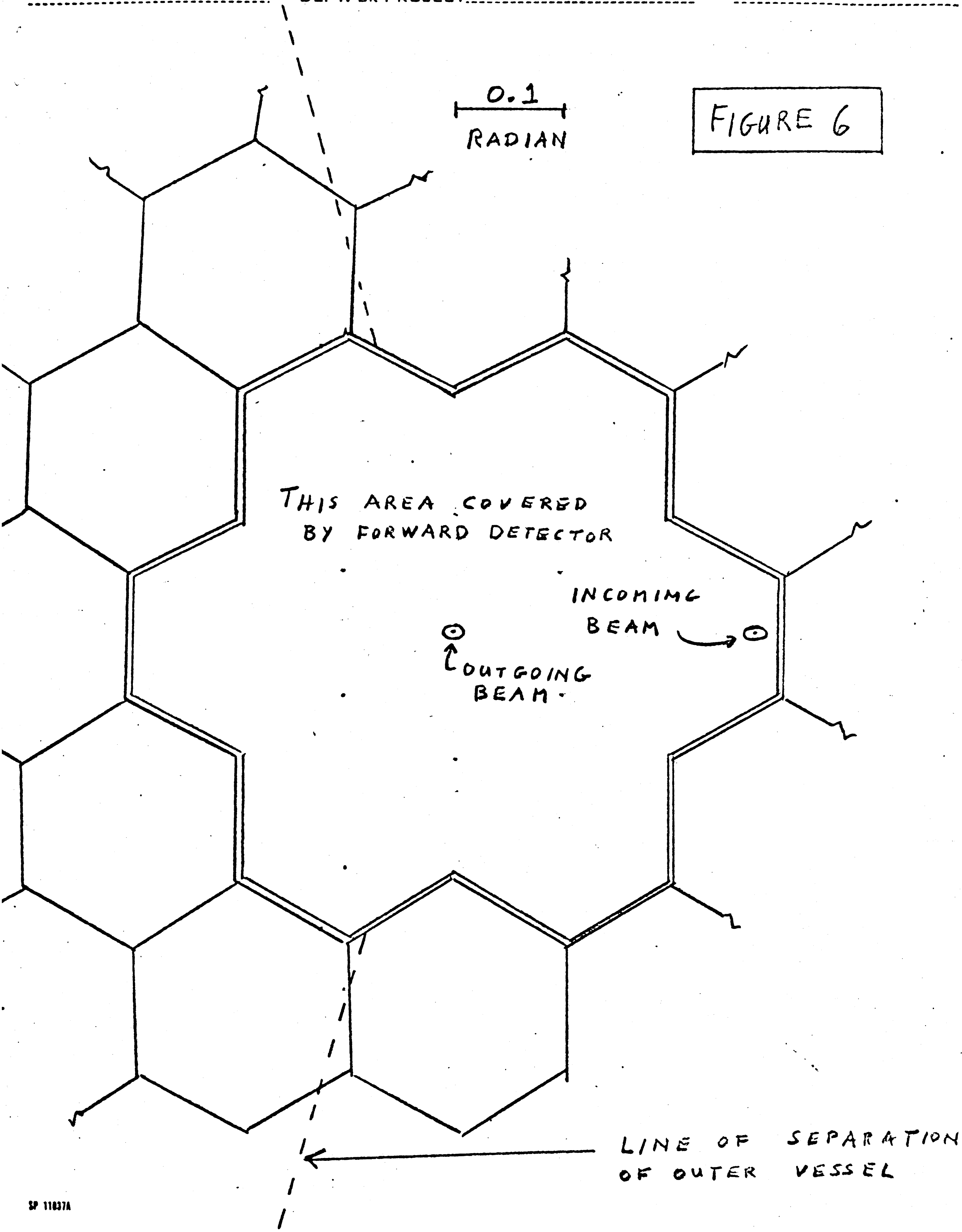
BROOKHAVEN NATIONAL LABORATORY

BY.................. DATE.......... SUBJECT.. SHEET No.......... OF..........

CHKD. BY.......... DATE.......... .... JOB No..........................

.... DEPT. OR PROJECT.................................... ....

FIGURE 6

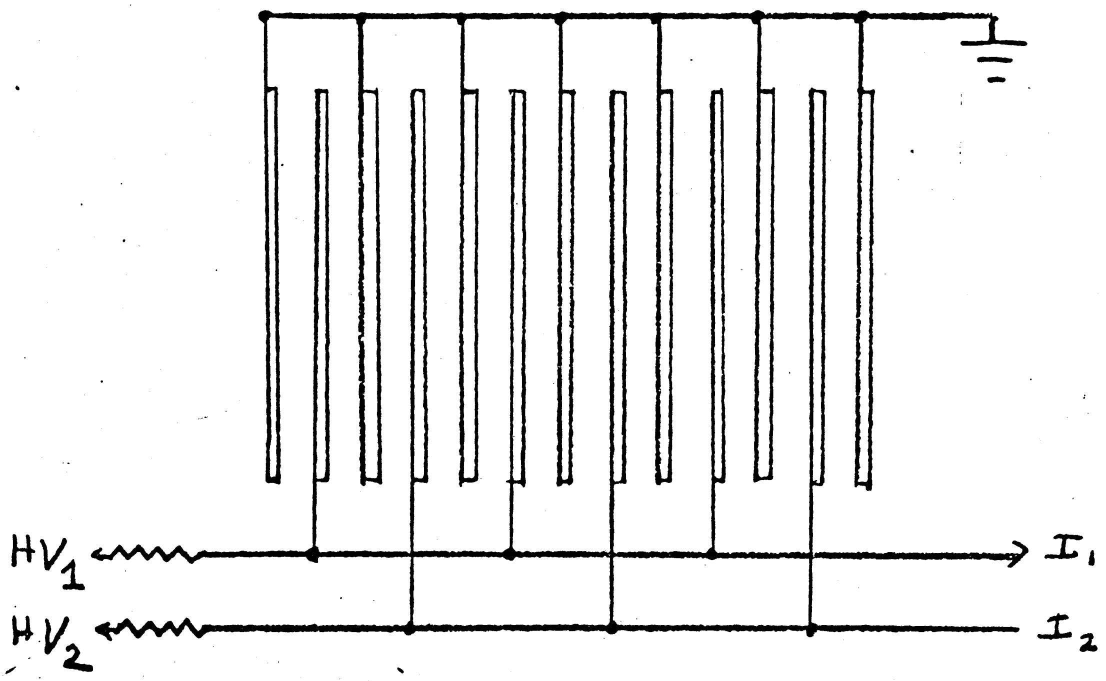


BROOKHAVEN NATIONAL LABORATORY

BY.................. DATE.......... SUBJECT.. SHEET No.......... OF..........

CHKD. BY.......... DATE.......... .... JOB No..................

DEPT. OR PROJECT..............................



$HV_2 \sim 4 HV_1$

Figure 7