The Design of Argon Filled Coaxial Beam Loss Ion Chambers at CEBAF

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1. Introduction

"Heliax"type air cored coaxial cables have been used in the past on many accelerators as beam loss monitors (Balsamo 1977, Clarke-Gayther 1988, Nakagawa 1980, Witkover 1979). It is proposed to adopt a design similar to these for use on CEBAF. It must be emphasised that such devices are not intended for making accurate measurements of radiation fields but to respond quickly to excessive beam loss conditions and if appropriate terminate the beam to permit corrective action. The use of long ion chambers has particular usefulness at accelerators because the ion chamber can be used to monitor beam losses along the length of the vacuum chamber through which the beam is steered.

To estimate likely performance from such devices we used the expressions applicable to chambers filled with gases (in this case argon) which only produce positive ions and consequently removes ion recombination effects (Hine and Brownell 1956, Lapsley 1953).

Under conditions of high space charge such as can be produced by a large pulse of radiation from an accelerator, the liberated electrons can be trapped by the space charge and hence reduce the chamber response.

The purpose of this experiment was to determine approximately the limiting voltage at which this screening occurs and compare the result with theory.

2. Radiation From Stopped Electron Beams

The radiation field close to a target in a high energy electron beam is dominated by the bremsstrahlung yield. A number of expressions have been published for calculating approximate dose rates close to stopped electron beams; the parameterizations of Sullivan (1992) and also the expression given by Jenkins (Swanson 1990) are considered here.

Sullivan's expression gives dose rates for angles greater than 20 degrees and a beam of 1 kW stopped in copper or iron. Jenkins' expression is based on a $17X_0$ iron target and gives results for angles greater than 10 degrees.

The local dose rate is seen to be a function of emission angle and it also varies as target thickness and also the presence of local thin shielding which rapidly attenuates the soft component of the radiation field. The soft component is more evident at the higher electron energies. In any exposure conditions around an electron target the influence of rather thin layers of absorber can be extremely marked (Dinter 1971).

From figure 1., we note that the dose rates at 1 m lateral to a beam loss of 1 kW fall in the range 1 krad/hr to 10 krad/hour (10 Gy/h - 100 Gy/h) but the actual values will depend upon target geometry and to some extent, electron beam energy.

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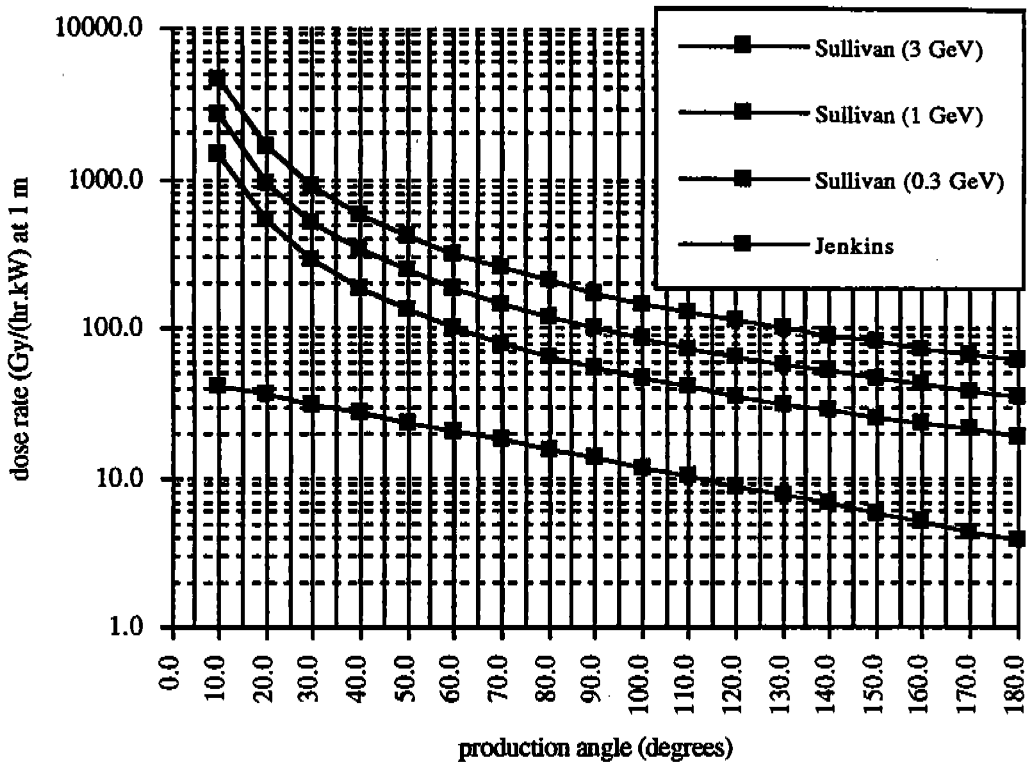
Figure 1. Dose Rate from Targetted Electron Beams



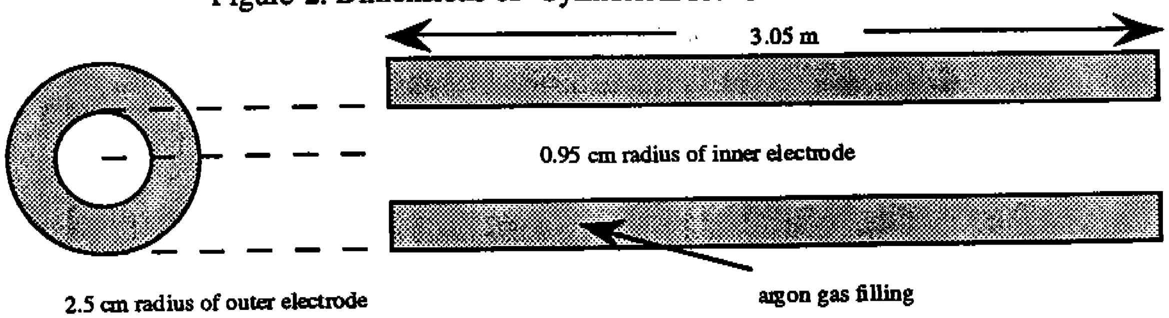
2. <u>Long Ion Chamber Design</u>

We were concerned with specifying a cost-effective solution to providing a comprehensive and rugged beam shut-off ion-chamber system for use in the CEBAF accelerator tunnel.

We used standard copper tubing of two diameters, the smaller mounted concentrically inside the larger with insulating spacers and argon as filling gas. Each ion chamber was pressurised to two atmospheres (1 atmos gauge) to enable leaks to be checked and to reduce the risk of contamination from air. The pressure being retained by a simple schrader valve. This technique proved to be reliable and effective in maintaining pressure and permitting the chamber to be topped up when necessary.

The design was intended to be rugged and able to withstand radiation damage effects to some degree. The electrometer was designed to cover the wide range of dose rates required from 0.1 rad/h to 10000 rad/h (0.001 Gy/h - 100 Gy/h) and higher.

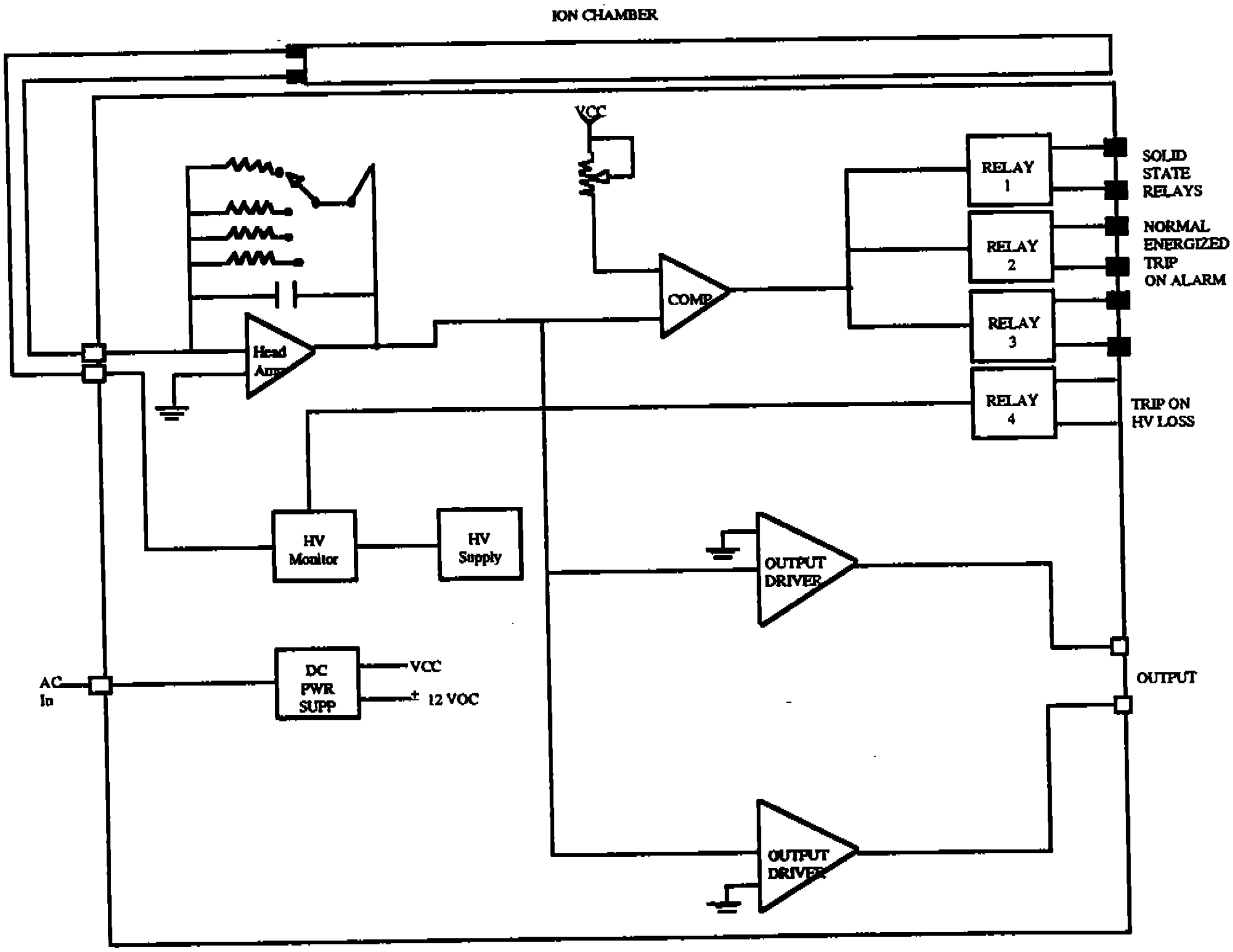
Figure 2. Dimensions of Cylindrical Ion Chamber



3. Electronics

The ion chamber shown in figure 2., presents the radial dimensions; the lengths of the test chambers was 30 cm, although the final design planned would be 3.05 m in length. Calculation indicated that the ionization current would be approximately 6 pA /cm length for a dose rate of 1 rad/h (0.01 Gy/h). For the determination of ionisation currents of this magnitude, relatively simple electrometers are sufficient.

The schematic for the circuit used is shown in figure 3:-



4. Results of Measurements

Two sets of measurements were performed, one set using a standard calibrated radioactive isotope irradiator and the other using a medical accelerator .

Standard Radiation Source Tests

The ionization current can be expressed approximately:

$$I = \frac{\delta U 100 \dot{D}_c}{3600 W} 10^{-7}$$

where	I	ionization current (A)
	$\dot{D}_c$	dose rate (rad h^{-1}) (1 rad = 0.01 Gy = 0.01 J kg^{-1})
	U	chamber volume (cm^3) {note: actually cross sectional area per unit length}
	δ	density of gas in the chamber (g cm^{-3})
	W	energy in eV to liberate one ion pair from the chamber gas

Substituting values for δ and W

δ	0.0033 g cm^{-3}
W	26 eV
U	16.8 cm^3 from the chamber dimensions given in figure 2:

$$I = 5.93 \times 10^{-12} \dot{D}_c$$

Note that the units for I is amps per cm length of chamber exposed to radiation.

For the calibration test we exposed a ^{137}Cs source to a length of detector by making a gap of 8 inches in lead brick shielding. The source strength was 200 rads/h (2 Gy/h) at 1m distance and the detector was placed 2 m away from the source.

The experimental results gave the net ionization current (difference between the current measured with the gap in the lead shield and the current without the gap) 6.6 10^{-9} A., compared with 6 10^{-9} A., for the calculated value. This is quite reasonable for such a simple device.

Response to Pulsed Radiation

For a given polarising voltage the detector should give a linear dose response with increased dose per pulse until the screening limit is reached when the response will cease to be linear. Increasing the polarising voltage should restore linearity until a further screening limit is reached.

To study the response to pulsed radiation we used a Siemens medical accelerator courtesy of Riverside General Hospital, Newport News Virginia.

The basic radiation unit from such a machine is known as a Monitor Unit (MU) and is defined as 1 rad (1 cGy) at a given depth in tissue for a 10 cm x 10 cm field at 1m

distance from the source. The Riverside Hospital medical linac used produces 200 MU/minute at
6 MV with a pulse repetition frequency of 143 Hz (7 ms pulse to pulse) and a pulse width of 3 μs at 71% of peak height. The mechine also operates at 10 MV and 24 MV at 300 MU/minute, however, we confined use to 6 MV.

Thus we had the following 6 MV radiation conditions at 1m:

Average dose rate	≅	$1.2\ 10^4$ rad/hour ($1.2\ 10^2$ Gy/h)
Dose per pulse	≅	23.3 mrad (0.233 mGy)

In order to eliminate the requirement to maintain an exact length of ion chamber irradiated for each measurement and to avoid the lengthy setting up times for each measurement we adopted a proceedure whereby a fixed length of the ion chamber was located at each of five distances from the x-ray source and then polarizing voltage on the ion chamber varied. In effect this produced a plateau at each location where a different dose rate was obtained. The point where the output levels off (plateau) corresponded to the limiting voltage.

The experiments were done on a similar pair of ion chambers having different polarities and the results were plotted as two sets of curves and these are shown in figures 4a and 4b. The greater difficulty of collection when the central electrode is negative is clearly seen and corresponds to Lapsley's observations. Because we wished to study the change in screening voltage against dose/pulse we assumed that the calculated dose rate at each location under the x-ray source was correct and normalized the output at the saturation voltage (or estimated saturation voltage) to correspond to the calculated dose per pulse. The actual responses of the two detectors were slightly different in the same radiation field which could be attributable to the polarity difference or to slight differences in the two chambers or to differences in the experimental set-up. However, these differences are not expected to alter the conclusions with regard to the minimum screening voltages for pulsed radiation. Figure 5 shows the chamber outputs at saturation or estimated saturation against calculated dose/pulse values at the various locations. The straight line is an estimate of the response based on the isotope calibration of a longer ionization chamber of similar construction - multiplying the a corresponding short chamber output by the appropriate conversion coefficient gives the radiation dose rate in rads/hour (remembering from above that 23.3 rad/pulse ≈ $1.2\ 10^4$ rad/hour).

2. Review of Theory

The expression for the minimum polarizing voltage needed for a given pulse of radiation at the screening limit for a cylindrical chamber is obtained by solution of the Poisson equation in cylindrical symetry and assuming the field to be zero when the radius r = a :

$$V^{+} \geq 2\pi\rho\left(\frac{1}{2}(b^{2}-a^{2})-a^{2}\ln\frac{b}{a}\right)\text{(cgs units)} \qquad (1)$$

where
- V^+ stat volts (1 stat volt = 300 abs volts)
- a,b inner and outer electrode radii (figure 2)
- ρ space charge (esu cm^{-3} - actually esu cm^{-2} and cm length)

$$\rho = 3\times10^{4}\frac{D_{p}\delta}{W} \qquad (2)$$

where
- D_p radiation pulse delivered to the chamber gas (rads)
- δ density of gas in the chamber (g cm^{-3})
- W energy in eV to liberate one ion pair from the chamber gas

substituting equation (2) into equation (1) gives the limiting voltage for screening for a pulse of radiation D_p (rads) absorbed by the chamber gas:

$$V^+ \geq 5.65\times10^7 \frac{D_p\delta}{W}\left(\frac{1}{2}(b^2-a^2)-a^2\ln\frac{b}{a}\right)(\text{volts}) \tag{3}$$

For argon, substituting:

δ 0.0033 g cm^{-3}
W 26 eV

$$V^+ \geq 7.2\times10^3 D_p\left(\frac{1}{2}(b^2-a^2)-a^2\ln\frac{b}{a}\right)(\text{volts}) \tag{4}$$

substituting the values of a and b:

$$V^+ \geq 1.3\times10^4 D_p$$

Equation (4) applies to the chamber when the central electrode is more positive (anodic).

The case when the central electrode is a cathode requires a higher polarising voltage for the screening limit condition.

$$V^- \geq 7.2\times10^3 D_p\left(b^2\ln\frac{b}{a}-\frac{1}{2}(b^2-a^2)\right)(\text{volts}) \tag{5}$$

substituting a and b as before:

$$V^- \geq 2.43\times10^4 D_p$$

Figures 4a and 4b include an approximate representation of the theoretical screening voltages together with experimental values. It is of interest that the theoretical clearing voltages work out to be much lower than the observed plateau voltage, a result which corresponds with the findings of Lapsley. However, a practical fit to the minimum plateau voltage can be obtained by the inclusion of a constant voltage V_0 to both expressions (4) and (5) which we have recast, calling the terms in the brackets F^+ and F^- as appropriate to the voltage on the central electrode. Thus equations (4) and (5) become:

$$V^\pm \geq F^\pm\left(7.2\times10^3 D_p + V_0\right)$$

where V_0 is observed to be approximately 55.6 volts for both polarities.

6. Conclusions

We conclude from these simple measurements that inexpensive ion chambers can be constructed to perform adequately in pulsed and high radiation fields to provide approximate measurements around accelerators and be used as shut-off devices. We have shown that increasing the polarizing voltage used on the ion-chamber, permits increasing doses of pulsed radiation to be measured. Because of power supply limitations this study could not be extended to voltages where gas multiplication occurs.

By modifying the expessions obtained by theoretical analysis we have derived an empirical expression which permits the limiting (screening) voltage to be determined for different doses of pulsed radiation.

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Figure 4b. Ion-Chamber Response for Stated Pulsed Radiation Condition (negative central electrode)

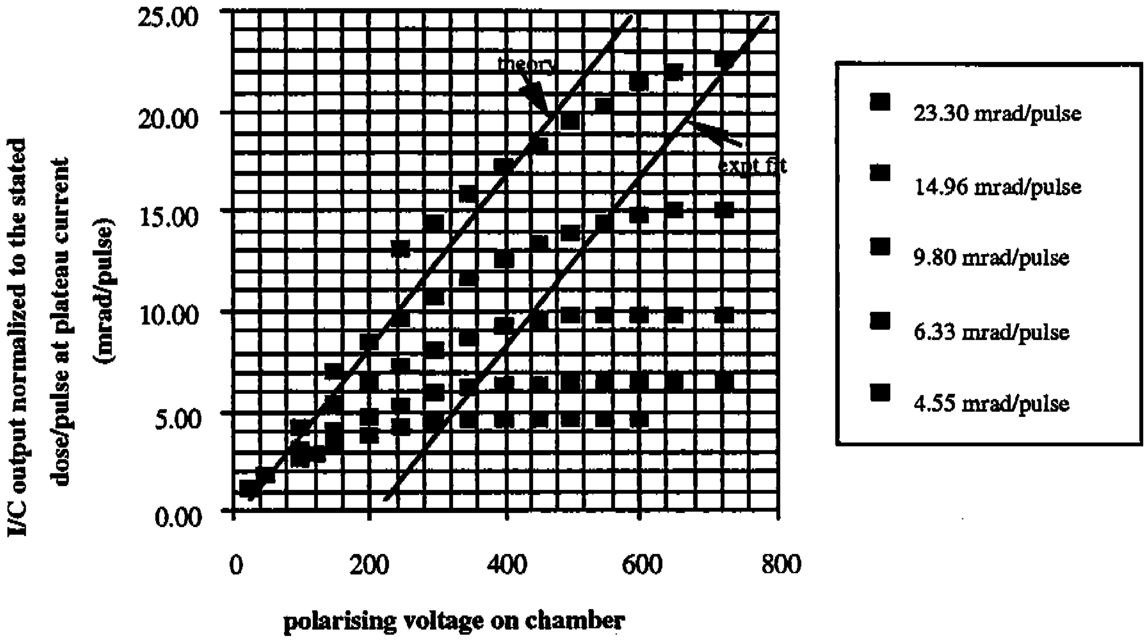

Figure 4a. Ion-Chamber Response for Stated Pulsed Radiation Condition (positive central electrode)

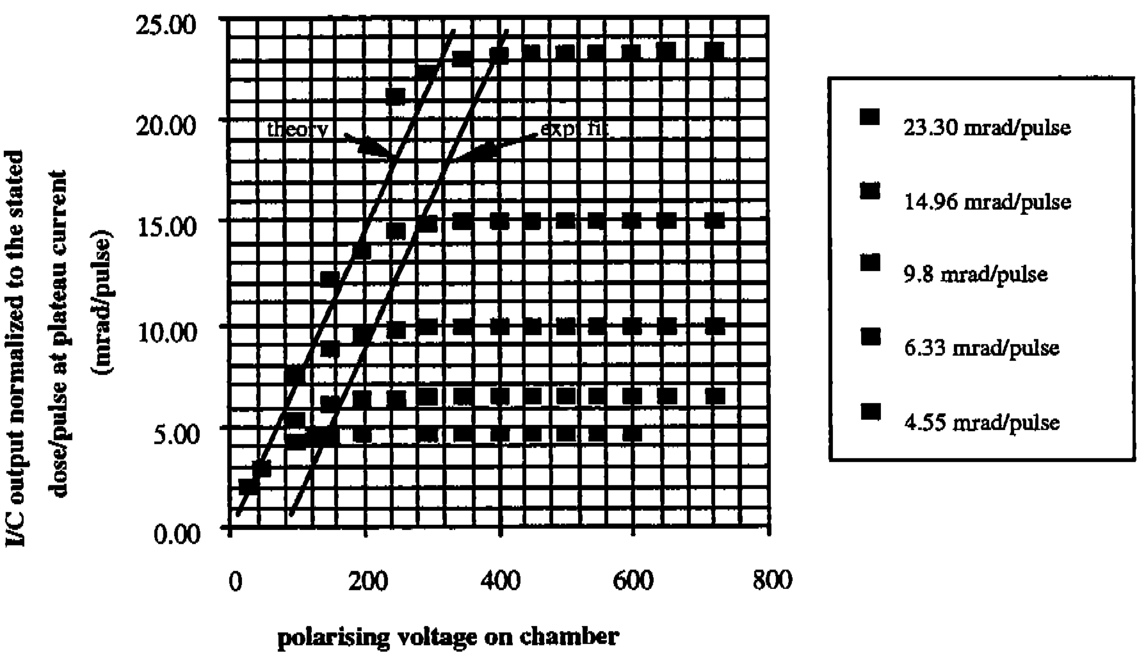

Figure 5 Ion Chamber Responses at Saturation at the Different Dose/Pulse Positions