X-RADIATION FROM VAN DE GRAAFF ACCELERATOR ION SOURCES*

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The intensity of x-radiation was measured as a function of position along the ion source axis of the model JN and model CN positive ion Van de Graaff accelerators of the University of Virginia. The measurements were made with two x-ray spectrometers built to accommodate the different physical arrangements of the JN and CN accelerators. Back streaming electron beam profiles are deduced from the intensity distributions. Suggestions for reducing the x-radiation emanating from the accelerators are given.

Introduction

Although Van de Graaff accelerators have been used as research tools for over fifteen years, no work has been published on the location and intensity of radiation emanating from the accelerator during its operation. From the point of view of radiological health, a knowledge of the source and intensity of x-radiation could lead to effective use of shielding as well as modifications of design resulting in the reduction of radiation hazards for personnel.

The University of Virginia model JN and model CN Van de Graaff accelerators, designed and manufactured by High Voltage Engineering Corporation, are capable of accelerating singly charged positive ions up to 1 MeV and 5.5 MeV, respectively. During the process of being accelerated, the positive ions may collide with residual gas or electrodes in the accelerator tube, or both, thus liberating electrons which are accelerated toward the ion source. These electrons upon striking the aluminum electrodes of the accelerator tube and components of the ion source produce bremsstrahlung.[1] Small orifices in the path of the back streaming electrons may become point sources of radiation which can be easily detected by an x-ray spectrometer with appropriate spatial resolution.

Two spectrometers with spatial resolution defined by lead collimators were built to accommodate the different physical arrangements of the model JN and model CN accelerators. The spatial resolution was measured by displacing a Co^{60} source perpendicular to the axis of the spectrometer, the Co^{60} source being at the same distance from the spectrometer detector as from the vertical axis of the accelerator tube during the course of the experiment. The spectrometers were then used to measure the location, intensity, and energy of the x-radiation external to the insulating tanks of the accelerators while viewing along the axis of the accelerator tube, the ion source and source gas bottles.

Experimental Method

Description of the Apparatus.

The arrangement of the apparatus used with the JN accelerator is shown schematically in Figure 1. The x-ray spectrometer-detector was pointed toward the axis of the accelerator tube. The collimator in front of the detector was made of two Pb bricks separated by a distance of 38 cm. Both blocks were 10.2 cm wide, 13.3 cm high, 7 cm thick and had a 1.3 cm diameter hole through their centers. The rear lead brick was placed directly in front of a 23 cm long cylindrical Pb shell which served as a shield for the detector from the scattered radiation. The wall thickness of the Pb shell was 2.5 cm. The detector included a 5.1 cm diameter by 5.1 cm long NaI(Tℓ) scintillator coupled to an RCA 6342A photomultiplier tube enclosed by a Mu metal shield. The lead collimator and the cylindrical lead shell enclosing the detector rested on a mobile cart whose height was such that the detector axis was at the same height as the accelerator tube axis. The detector could then be moved along the external side of the accelerator tank and parallel to the accelerator tube and ion source axes. The forward edge of the detector collimator was 91.4 cm from the accelerator tube axis. The spectrometer spatial resolution was 4.3 cm at this distance.

A similar spectrometer was used for the measurements on the CN accelerator as shown in Figure 2. In this arrangement, consideration was given in designing the spectrometer shield and collimator to the high level of background radiation in the vicinity of the accelerator under normal operating conditions. The resulting spectrometer shielding and collimator contained more lead than that used with the JN accelerator.

The detector, detector shield, and collimator rested on a platform suspended along the outside of the CN Van de Graaff insulating tank by means of a service crane. Steel rollers on the accelerator end of the spectrometer platform constrained the spectrometer to move along two tracks fastened to the insulating tank. The distance from the collimator forward edge to the axis of the accelerator ion source was 119 cm. The end apertures of the 40 cm long collimator were .5 cm, resulting in a spatial resolution of 1.5 cm at the ion source axis. A 7 cm thick lead brick was used as a shutter for background measurements during the runs. Vertical positioning of the spectrometer and activation of the shutter was done remotely from the Van de Graaff control room. The horizontal positioning was done by dropping plumb lines fore and aft of the spectrometer onto a line perpendicular to and intersecting the accelerator tube axis. A vertical position indicator whose output was read in the accelerator control room was attached to the spectrometer platform. The vertical position of the spectrometer along the insulating tank was reproducible to within 2 mm. Marks on the external side of the insulating tank corresponded to the height of various parts of the ion source

measured from the top of the accelerator base plate. The intensity of x-radiation versus position along the ion source was measured with a model CN R.F. ion source with and without modification for nanosecond pulsing.

The operating conditions of the accelerator were selected in such a way as to duplicate operating conditions existing for a large number of d.c. beam experiments being conducted with the CN Van de Graaff accelerator of the University of Virginia. These conditions are: (1) 200 psi of insulating gas; (2) adjusting the ion source parameters until a d.c. beam of 4 microamperes of protons is extracted from the accelerator; and (3) varying the terminal potential from 3 to 5 million volts in steps of 1 million volts. No measurements were taken with the modified ion source operating in its pulsing mode.

Spatial resolution and energy calibration measurements

Before x-radiation intensity measurements were undertaken, the spatial resolution of the spectrometer was determined. The criterion for selecting the spatial resolution was motivated by the speculation that a narrow pencil of back streaming electrons could enter the exit canal of the ion source glass bottle and strike the glass baffle, thus creating a source of bremsstrahlung in a plane above the top of the accelerating region. Preliminary measurements on the JN accelerator spectrometer indicated that about 4 cm spatial resolution at the ion source axis would be sufficient to detect any such effect. Preliminary measurements with the CN spectrometer, however, indicated structure in the radiation yield curve originating from components other than the glass baffle and which could be resolved with 1.5 cm spatial resolution. The spatial resolution of the spectrometers could be varied by altering the size of the collimator apertures.

The method used to measure the spatial resolution of the CN spectrometer is shown in Figure 3 together with the resolution function. The same method was employed with the JN spectrometer. A Co^{60} γ-ray source was positioned in the line of sight of the spectrometer at a distance from the front face of the spectrometer collimator equal to that of the accelerating tube axis in the course of making the actual measurement. In the case of the CN spectrometer, this distance was 119 cm; for the JN spectrometer it was 91 cm. The vertical height of the source was read from a cm scale. The signals from the NaI(Tl) scintillator-detector were fed to a fast scaler after being properly shaped and amplified. The full-width-at-half maximum of the locus resulting from measuring relative yield per unit time versus γ-ray source position was defined as the spatial resolution. This was 1.5 cm for the CN spectrometer and 4.3 cm for the JN spectrometer.

A Na^{22} γ-ray source was used for the energy calibration of each spectrometer with the electronic configuration shown in Fig. 3. In the case of the JN spectrometer, pulse height discrimination was made on pulses from the detector corresponding to a bias equivalent to a pulse height from .93 MeV γ-rays. Linearity of output versus photon energy extended to 0.9 MeV. In the case of the CN spectrometer, the pulse height discriminator level setting was fixed by trial and error while observing x-radiation from the CN accelerator. The high counting rate measured in this configuration resulted in appreciable blocking time of the multichannel analyzer and scaler when no pulse height discrimination was used. At 5 million volts on the accelerator terminal, the discriminator level, adjusted to make blocking time negligible, corresponded to 280 keV x-rays. This was done after the amplifier dynamical range was adjusted such that 3 MeV of x-radiation could be detected.

Results and Discussion

The results of the measurement on the JN accelerator are presented in Fig. 4. The yield of x-radiation is plotted as a function of position along the ion source. The smooth curve was drawn to connect the points. The centroid of the most intense peak falls between the second and third electrodes of the accelerator tube. The second peak of much less intensity seems to be correlated in position with the ion source gas reservoir which consists of a gas bottle of hydrogen and one of deuterium. This intensity distribution was measured for a *deuteron beam current of 10 microamperes with a* hydrogen gas pressure of 10^{-6} cm of Hg in the accelerator tube. The terminal voltage was .75 million volts. It was found that the presence of a positive ion beam (deuterons) was necessary for the production of any significant radiation. This agrees well with the view that the ion beam ionizes the residual gas in the accelerator tube and the liberated electrons strike the aluminum electrodes of the accelerator tube and components of the ion source resulting in the emission of bremsstrahlung. A likely explanation for the existence of the second peak is that it is due to x-rays produced in the low energy end of the accelerator tube and scattered at 90° by the gas *reservoir by Compton scattering* processes. The shoulder on the right hand side of the main peak could be attributed to x-rays produced by electrons striking the baffle of the glass bottle of the source. An estimate of the electron beam profile which can be made from the intensity distribution and the dimensions of the orifices of the ion source[2] is that about 15 percent of the electron beam is contained within a diameter of 3.5 cm.

The measurement made on the d.c. beam R.F. ion source of the CN Van de Graaff is shown in Fig. 5(a). This intensity distribution was measured while accelerating a beam of 4 microamperes of protons with a hydrogen gas pressure of 4×10^{-6} cm of Hg in the accelerator tube. The accelerator terminal voltage was 4 million volts. The intensity of x-radiation was

measured at every 1.5 cm position increment along the upper part of the accelerator tube and the ion source. The centroid of the most intense peak falls at a position corresponding to the base of the ion source bottle. A second peak is measured at the upper shoulder of the focus electrode nozzle. Appreciable radiation is emanating from a point just above the base of the focus nozzle. There is also an indication of radiation coming from the first electrode of the accelerator tube. There was an appreciable amount of radiation from the upper accelerator tube and ion source region when the beam was turned off. In fact, with 4 million volts on the terminal and no beam, the intensity distribution measured closely duplicated that with a beam, the only difference being that the magnitude of the intensity was decreased by a factor of 2 with no beam. This implies that a large fraction of the electrons striking material inside the upper end of the accelerator tube and the ion source are set free by the potential difference between the accelerator tube electrodes. Similar intensity distributions were observed with 3 and 5 million volts on the terminal. The peak heights at 3 million volts were a factor of 12 lower than those at 4 million volts; those at 5 million volts were 1.5 times higher. No significant radiation was observed from the glass bottle. It is estimated from the intensity distribution measured with the d.c. beam ion source that 66 percent of the electron beam has a diameter of 3 cm.

Fig. 5(b) shows the x-radiation intensity distribution measured with the model CN ion source modified for nanosecond pulsing. The intensity was measured at each 1.5 cm increment of spectrometer position along the upper accelerator tube and ion source. This distribution was measured with 4 million volts on the terminal, 4 microamperes of proton beam and 4×10^{-6} cm of Hg of hydrogen pressure in the accelerator tube. The centroid of the most intense radiation falls on the upper shoulder of the focus electrode nozzle and the nozzle aperture. The intensity distribution measured with this ion source exhibits more structure than that measured with the d.c. beam R.F. ion source. This is consistent with the fact that components are incorporated into this ion source which are absent in the CN source described above. It is interesting to note that an appreciable amount of electrons strike the extraction electrode and glass baffle of the source bottle as evidenced by the sizable bremsstrahlung peaks observed in the distribution.

Summary

The presence of a positive ion beam of the JN accelerator was necessary for the production of any significant radiation. Most of the bremsstrahlung produced is a result of electrons striking the focus electrode and the third electrode of the accelerator tube. For the operating conditions discussed above, this source of radiation was about five times as intense as a 1 millicurie Co^{60} source placed at an equivalent distance from the JN spectrometer. A second source of radiation of less intensity was found to originate in the vicinity of the gas reservoir above the ion source. This could be due to bremsstrahlung being scattered at 90° by the reservoir bottles. From these results, it is recommended that the region around the focus electrode of the accelerator tube be shielded more effectively or that the material of the electrode be changed to a smaller Z material (e.g. beryllium) to reduce radiative loss of the electrons.

The CN accelerator ion sources exhibit more structure in the intensity distribution measurements. This structure persists at 3, 4, and 5 million volts on the terminal, although the intensity of the x-radiation observed increases rapidly with terminal voltage. The most intense radiation observed with the d.c. beam R.F. ion source came from the base of the ion source glass bottle. Intense bremsstrahlung was also observed as originating at the upper focus electrode nozzle shoulder and at the base of the nozzle. Fabrication of these components with low Z material would significantly reduce the intensity of the radiation observed. The bremsstrahlung intensity distribution measured with the model CN nanosecond pulsing kit exhibited appreciably more structure than that measured with the d.c. beam ion source. The most intense radiation was found to originate at the upper focus electrode nozzle shoulder and aperture, which warrants appropriate measures for shielding or altering fabrication of these components to reduce such intensities. Significant radiation appears to originate at the baffle of the glass bottle.

A study of the electron beam profile shows that the beam of back streaming electrons in the CN accelerator appears to be smaller in cross section than that in the JN accelerator. No estimate is made of the electron current striking the ion source components because of the complexity of the scattering which bremsstrahlung undergoes before reaching the spectrometer.

Acknowledgement

The authors wish to acknowledge the advice given by Dr. Lawrence Cranberg and Mr. Denis Hills during the course of this experiment. Part of this work was subject for M.A. theses of two of the authors (N.V.L. and J. L.R.) under the direction of Dr. Lawrence Cranberg.

References

1. R. D. Evans, The Atomic Nucleus (McGraw-Hill Book Co., Inc., 1955) p. 600.
2. The dimensions were obtained from drawings of the 1 MeV Van de Graaff accelerator furnished by High Voltage Engineering Corp., Burlington, Mass.

Footnotes

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Footnotes

Continued:

+ Present address, Saigon, South Viet Nam.

++ Present address, U. S. Army Combat Developments Command, Air Defense Agency, Fort Bliss, Texas.

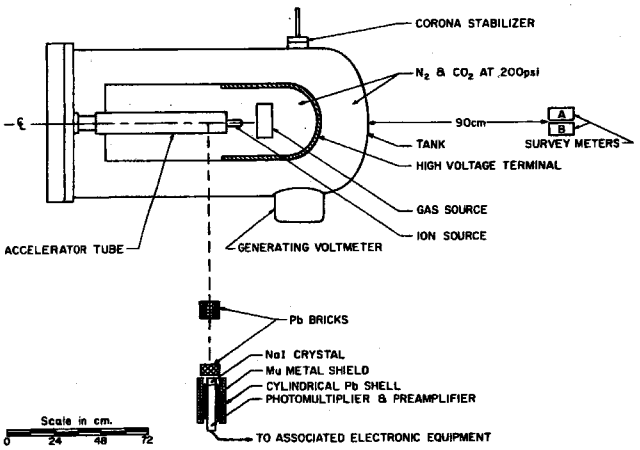

Fig. 1. A schematic diagram of the x-ray spectrometer used in measuring the x-radiation intensity distribution of the model JN Van de Graaff positive ion accelerator.

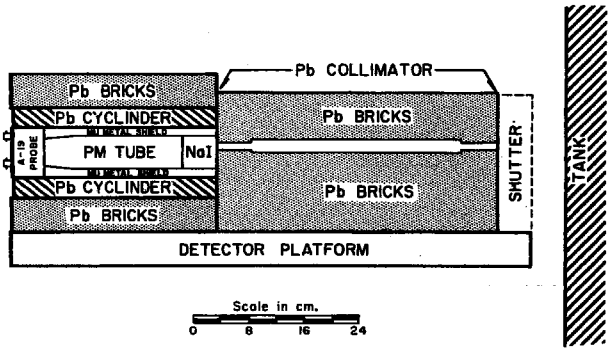

Fig. 2. A schematic diagram of the x-ray spectrometer used in measuring the x-radiation intensity distribution of the model CN Van de Graaff positive ion accelerator.

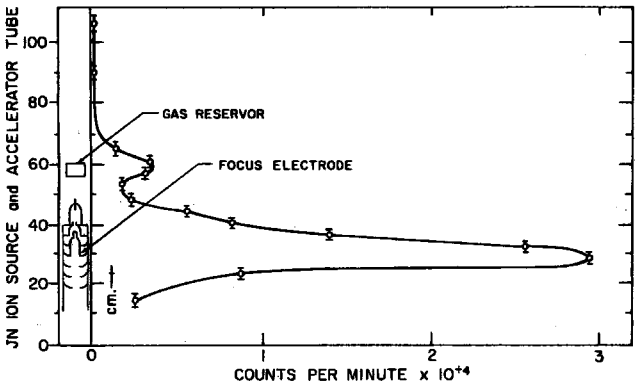

Fig. 3. The graph represents the spatial resolution function of the CN spectrometer. Below is a diagram of the arrangement of the γ-ray source and spectrometer used for measuring the spatial resolution. This arrangement is similar to that used with the JN spectrometer.

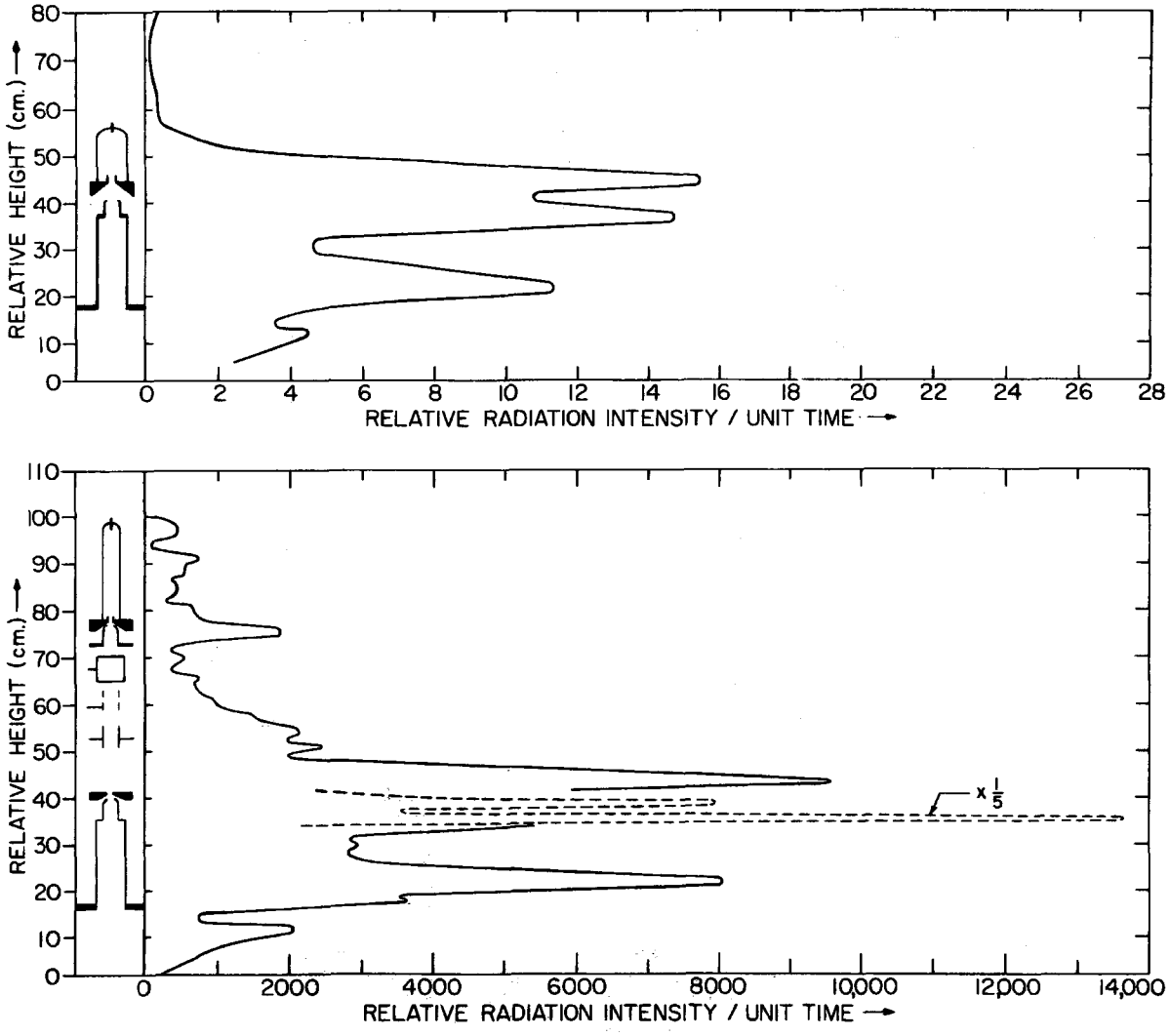

Fig. 4. This graph shows the intensity of x-radiation measured as a function of relative position along the JN ion source. The error bars represent the spatial resolution of 4.3 cm of the spectrometer. A profile of the ion source is illustrated.

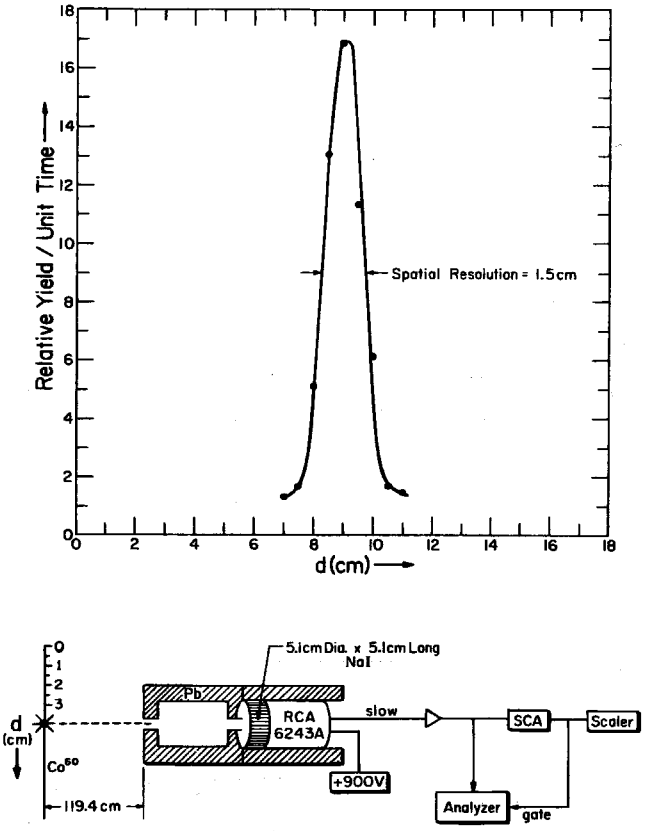

Fig. 5. The intensity of x-radiation measured as a function of relative position along the CN ion source (a) without and (b) with modification for nano-second pulsing. The spatial resolution in each case was 1.5 cm. A profile of the unmodified and modified ion source is illustrated. The maximum count rate in (a) is 17.4 x 10^4 counts/min, in (b), 6.8 x 10^4 counts/min.