POSITRON PRODUCTION WITH THE USNRL LINAC

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Summary

Positrons produced by electrons peaked at energies of 9.6, 10.8, 11.7, 13.5, 15.0 and 16.6 MeV incident on a 0.8 radiation length gold target, were accelerated to 35 MeV. Their spectra were measured by means of a defining slit system, set for 2 percent energy transmission, located at the focal point of a 90° achromatic deflection system. Experimental values of conversion efficiency were fitted by the expression $\epsilon = 3.3 \times 10^{-7}(E-4.7)$, where E is the energy of the incident electrons. The expected positron current for the highest repetition rate (720 pulses per second) is approximately 4×10^{-10} amperes over electron energies from 10 to 14 MeV.

Introduction

Recently built electron linear accelerators have sufficient electron currents to produce beams of monoenergetic positrons. When these positrons undergo in-flight annihilation the photons in the forward direction are also monoenergetic and can be continuously varied in energy by the selection of the energy of the positrons. The laboratory at Saclay[1] produces positrons at the end of the accelerator and monoenergetic positrons are selected by a set of "orange-section" magnets. The group at Livermore at first used the magnetic selection of positrons to study the production process and the photon spectrum resulting from the positron bombardment of a beryllium target.[2] This group then produced positrons at the end of the first section of their linac and accelerated them in the second section for their study of the positron-annihilation photons[3] and the use of the monoenergetic photons for photoneutron cross-section measurements.[4] The process of positron production and acceleration has been calculated as a design study for the Saskatchewan Linac[5] based on the theoretical studies of Katz and Lokan.[6] At General Atomic measurements and calculations have been made of positron yields from a 45-MeV L-band electron linac.[7]

Linac Design

The USNRL Linac is a three-section S-band (2856 Mc/sec) electron accelerator with pulses variable in length from 0.02 to 0.6 µsec and variable in repetition rate from a single pulse to 720 pulses per second. The electron energy is variable up to 60 MeV and the electron beam current at 40 MeV can be as much as 400 ma peak. The gold positron-converter target, located between the first and second sections, can be raised for electron acceleration. At the end of the first section a pre-stripper limits the diameter of the beam of electrons falling on the converter to 0.4 inches. A second collimator at the end of the linac has an exit diameter of 5/16 in. The small diameter beam of electrons or positrons is bent through 90° and energy analyzed by the achromatic magnet and slit system discussed in papers DD-13 and 14 of these Proceedings.[8] Focusing solenoid coils surround the accelerating waveguides, on which are placed longitudinal wires for beam steering, that is, for cancelling the effect of the earth's magnetic field. A thin magnetic lens is located between the positron converter target and the second section. Pulse beam current transformers calibrated to ± 0.5% are located at the end of the linac and at the exit of the 90° magnet system.

Procedure

To obtain values for the efficiency of positron production which could be compared with those found by the General Atomic group,[7] measurements similar to theirs were made. The first section of the linac was adjusted to accelerate electrons to the desired energy with a reasonably sharp spectrum. The electron current was measured by current transformers before and after deflection with the slits set for 9% energy transmission. In addition, a graph of the 2% electron spectrum was obtained by means of an x-y recorder with a calibrated lead brick acting as a Faraday cup.

The 0.10-inch thick gold target was then lowered and the second and third sections were tuned to accelerate positrons for maximum energy. With the slits set for 2% energy transmission the positron spectrum was recorded with an ion chamber as the detector to obtain a good signal-to-noise ratio. As positron currents are too small to give an indication on a pulse current transformer, the ion chamber was calibrated by comparison with the lead brick and found to have a gain of 90 ± 20. The incident electron current on the insulated converter target was measured directly. After each positron spectrum was recorded, the gold target was raised in order to verify the electron current and spectrum. All measurements were made with the linac operating at 60 pps but were extrapolated to 720 pps.

The positron spectrum obtained when 13.5 MeV electrons were incident on the converter is shown in Figure 1 with the electron spectrum shown as the insert. The electron and positron spectra for other energy incident electrons, at 9.6, 10.8, 11.7, 15.0, and 16.6 MeV were similar in shape. In each case the positron spectrum peaked near 35 MeV.

The results of a separate set of measurements in which the linac was tuned for optimum positron production, without regard for the incident energy distribution, are shown in Figure 2. The highest yield resulted when magnetic fields from the thin lens and the solenoids were used and is shown by the spectrum labelled "lens on and solenoids on." The effect of the 1000 gauss field of the converter lens in aiding the capture of the positrons by the accelerating field is shown by the difference between this spectrum and the one for "lens off and solenoids on." Comparison of the latter spectrum with that for "lens off and solenoids off" shows the importance of the 400 gauss field of the solenoids in retaining positrons in the accelerating waveguide and focusing them through the exit collimator. The improvement in yield at the peak of the spectra from the condition with lens off and solenoids off to the yield with them on is 10.8 for the one percent spectrum of 38.7 MeV positrons. For comparison with the General Atomic[7] result (gain of 6.2 at 2.5% width) our gain value is 10.

Calculations

The total number of positrons produced for each of the electron bombarding energies and accelerated in the second and third sections of the linac was obtained by integrating the spectrum and correcting for ion-chamber gain. The values of electron current obtained from the current pulse measurements at the end of the linac, I_{main}, were always less than those from the converter, I_{conv}, primarily due to the presence of the 5/16 inch-diameter collimator at the end of the linac. Also the deflected beam current through 9% slits was considerably less than I_{main}. To obtain the electron current effective in producing positrons, I_{eff}, the current through the 9% slits was first corrected to include energies as low as 25% below the peak energy. This quantity, I_{peak}, was then corrected for the loss in current between the converter and the linac exit by multiplying by the ratio I_{conv}/I_{main}, giving

$$I_{eff} = I_{peak} I_{conv}/I_{main} \quad .$$

The I_{eff} calculated from this formula is I_{conv} less its low energy component if I_{main} has the same spectral distribution as I_{conv}. The correction, considered as a percentage of I_{conv}, ranges from 18% at 16.6 MeV to 49% at 9.6 MeV; hence, for the low energy points the uncertainty in I_{eff} is large.

Results

The efficiency of positron production, ϵ, is the ratio of the total positron current to I_{eff}. The six values of ϵ with the estimated uncertainties are plotted in Figure 3 versus their corresponding electron energies. Due to the uncertainties involved in determining I_{eff}, and therefore the efficiency values, only a straight-line fit to the data is justified. The expression, $\epsilon = 3.3 \times 10^{-7}(E-4.7)$, where E is the electron energy in MeV, is shown as the solid line on the graph. The dotted and dashed lines indicate the estimated band of uncertainty. For comparison, the General Atomic measurements gave efficiencies which were fitted by the expression $\epsilon = 3.8 \times 10^{-6}(E-6.6)$. The optimized positron yield measurement gave an efficiency value of 3.05×10^{-6} and is shown on the graph as the circled x placed arbitrarily on the central line as the incident electron energy spectrum for this measurement was not recorded. Consistency designates an effective electron energy of 13.9 MeV. This energy together with the measured electron current gave a point on the average electron current versus energy load line, shown in Figure 4, which is consistent with the design load line of the linac.

The magnitude of average positron current expected at the maximum repetition rate of 720 pps is also shown in Figure 4 as a function of electron energy. These curves, calculated as the product of average electron current at a given electron energy (obtained from the load line) and the corresponding positron production efficiencies (from Fig. 3), show the region of optimum electron energy and the expected positron yield. This yield is approximately an order of magnitude less than that reported by the General Atomic group.[7] A factor of four may be due to the difference in beam sizes as they report theirs to be 1.6 cm in diameter and ours is limited by the 0.80 cm collimator. However, we desire a parallel beam of small diameter in order to obtain good collimation of the annihilation-in-flight photons.

An improvement in yield is expected to result from increased capture of positrons by the accelerating field due to the replacement of the wire-wound thin lens by two aluminum-tape-wound water-cooled solenoids. In addition more solenoid focussing is planned for the accelerating waveguides in order to enhance the magnetic confinement. The question of whether the peripherally-cooled gold target will survive long bombardments at 720 pps remains to be answered. The obtaining and measuring of narrow positron spectra variable in energy remains to be accomplished before using them to produce in-flight-annihilation photons.

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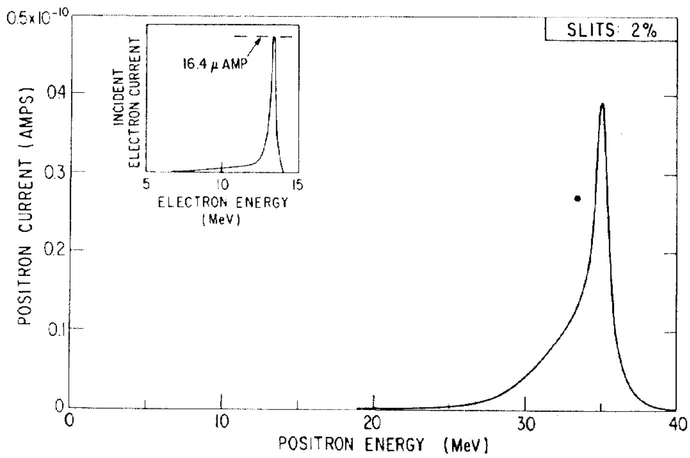

Fig. 1. Positron energy spectrum for 35 MeV peak positrons measured with defining slits set for 2% energy. Insert shows 2% energy spectrum of electrons, peaked at 13.5 MeV, incident upon the 0.10-inch thick gold target.

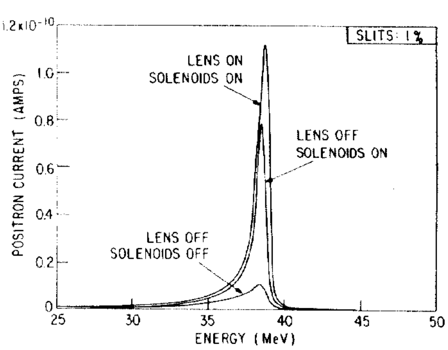

Fig. 2. Optimum yield spectrum for 38.7 MeV positrons shown as maximum curve, labeled "lens on and solenoids on." Spectrum labeled "lens off and solenoids on" shows the decrease in positron yield due to poor capture of the positrons by the waveguide accelerating field. Spectrum labeled "lens off and solenoids off" shows the poor intensity and energy distribution of positrons poorly captured by and confined in the accelerating field.

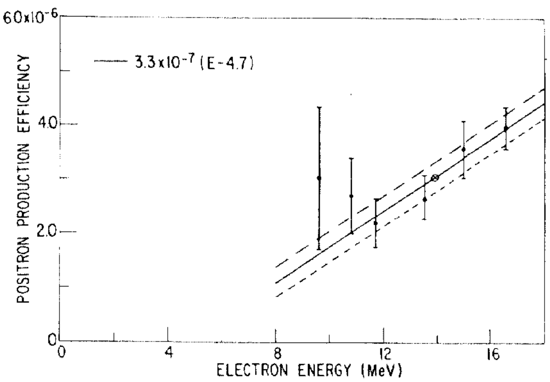

Fig. 3. Positron production efficiency as a function of the energy of the electrons incident on the converter target. Dotted and dashed lines show the estimated uncertainty band.

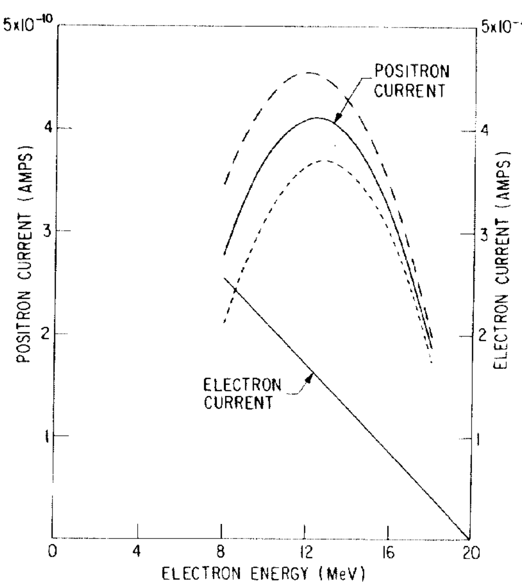

Fig. 4. The straight line shows the average electron current-voltage load line characteristic of the linac's first section. The average positron-current curves show the region of optimum electron energy and the expected positron yield. An additional uncertainty due to the calibration of the ion chamber has not been included.