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HIGH SPEED ELECTROSTATIC PHOTOMULTIPLIER TUBE FOR THE 1.06 MICROMETER WAVELENGTH

"CUP AND SLAT" DYNODE CHAIN COMBINED WITH FLAT CATHODE AND COAX OUTPUT PRODUCES 0.25 nsec RISE TIME

(NASA-CR-152494) HIGH SPEED ELECTROSTATIC PHOTOMULTIPLIER TUBE FOR THE 1.06 MICROMETER WAVELENGTH. CUP AND SLAT DYNODE CHAIN COMBINED WITH FLAT CATHODE AND COAX OUTPUT PRODUCES 0.25 nsec RISE TIME Final (Varian G3/33

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16. Abstract
The Varian "cup and slat" dynode chain was modified to have a flat cathode. These modifications were incorporated in an all-electrostatic photomultiplier tube having a rise time of 0.25 n sec. The tube delivered under the contract had a flat S-20 opaque cathode with a useful diameter of 5 mm. The design of the tube is such that a III-V cathode support can be mounted in place of the existing cathode substrate. This cathode support would be designed to accept a transferred III-V cathode and maintain the cathode surface in the same position as the S-20 photocathode of the tube described in this report. The tube with an S-20 cathode is designated VPM-152D. With an InGaAsP photocathode, the tube is designated VPM-152A.

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Preface

Objective

The objective of this program is construction of a high speed all electrostatic photomultiplier capable of meeting the specifications of the NASA Statement of Work. These specifications include a rise time of 250 picoseconds with a multiplier gain of 10^3 to 10^4 in an envelope of 1.5" diameter and 3" length. In addition, the photocathode of the device must be flat and so disposed in the structure that it may be replaced at some future date by a III-V cathode.

Scope of Work

The work on this contract may be conveniently divided into three parts. First, the existing Varian "cup and slat" high speed dynode chain was modified to accept a flat cathode having a minimum useful diameter of 2 mm. Second, the results of the many electron optical studies were incorporated into a rugged metal-ceramic construction consistant with the rigid dimensional requirements indicated by the computer simulations. Third, the completed photomultiplier tube was tested using the beat frequency of a dual mode gas laser and a sampling oscilloscope.

Conclusions

A rise time of 250 picoseconds (10% to 90%) was achieved with a gain of more than 10^3. The pulse width (FWTM) was determined to be approx. 0.5 n sec. Useful cathode diameter was measured to be more than 5 mm. In general the performance of the device was as specified in the original design goal of the "cup and slat" dynode chain. We conclude that small, lightweight high-speed laser detectors with high gain are here demonstrated to be practical.

Recommendations

Further work on the "cup and slat" dynode chain is definitely warranted by the success achieved to date. Other work at Varian, outside the scope of this contract, indicates that this type of structure provides a stable environment for III-V cathodes. Therefore, incorporation of a III-V cathode such as InAsP is expected to result in a very satisfactory communication detector for the 1.06 micrometer wavelength.

LIST OF FIGURES

Requirements for Communication Detectors for 1.06 μ

The development of the family of III-V photocathodes in the past few years has made possible the use of modulated near infrared laser beams as high data rate communication links in applications where detector gain is important. In particular, the transmission characteristics of 1.06 μ radiation, which is produced by the ND:YAG laser combined with available modulators, make it well suited for communications links through the atmosphere. Laser data links capable of gigabit response are now available.

A detector for the 1.06 μ wavelength must have sufficient sensitivity at 1.06 μ combined with low dark current and enough gain to give a reasonable signal-to-noise ratio at the output for distant signals. As in all communication systems, the useful signal at the output of the primary detector will determine the limiting distance and power requirements of the transmitter.

Varian "Cup and Slat" Dynode Chain

Subsequent to the development of the III-V photocathodes and coincident with their continuing development Varian LSE began a series of computer studies, using the Varian E-GUN program, to advance the state-of-the-art in all electrostatic high speed dynode structures. We were looking for a configuration that could give high speed response on the order of 0.25 nanosecond for a five stage system and at the same time reduce the degradation in response in previous schemes due to stray electrons. The general approach was to devise a means whereby stray electrons would be so grossly "out-of-focus" as to be inconsequential to the system as a whole. The result was the "cup-and-slat" system described later. The main feature of the system is an accelerating electrode so disposed that "out-of-focus" or unwanted secondaries remain out of the signal pulse for all practical purposes. See Figure 1, 2, and 3; "Electron trajectories."

Design Features of the "Cup-and-Slat" Dynode Chain

The following described design features are responsible for the superior performance of this device and Varian applied for patent protection in January of 1972.

1) Placement of an accelerating electrode, whose potential is higher than that of the next dynode, between each pair of dynodes.

2) Electrically isolating the accelerating electrodes from any of the dynodes so that the potential of the accelerating string can be adjusted independent of the dynode chain.

3) High speed coaxial output connector integral with the output of the dynode structure.

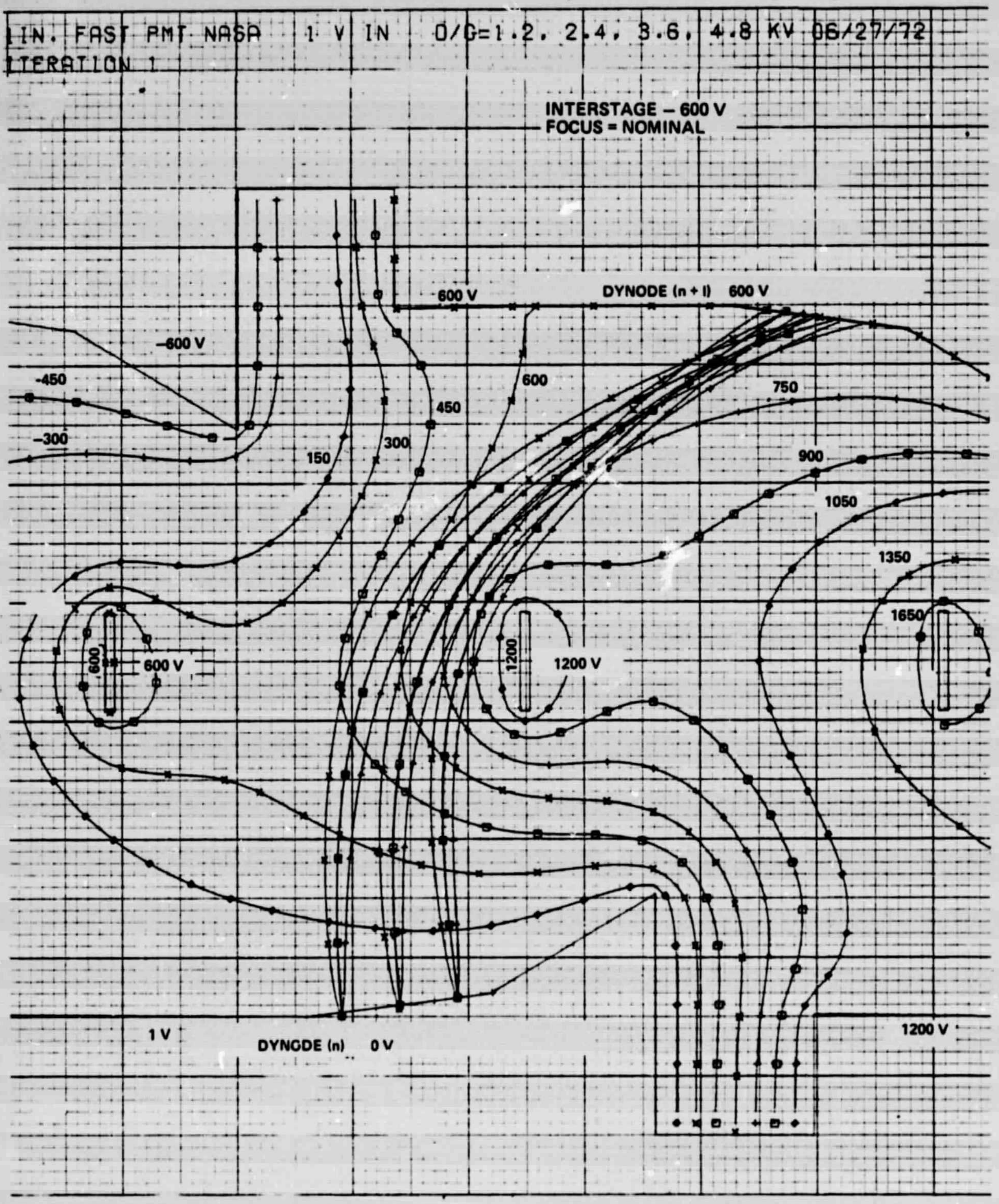


Figure 1. Typical Dynode Stage
Design Center Voltages

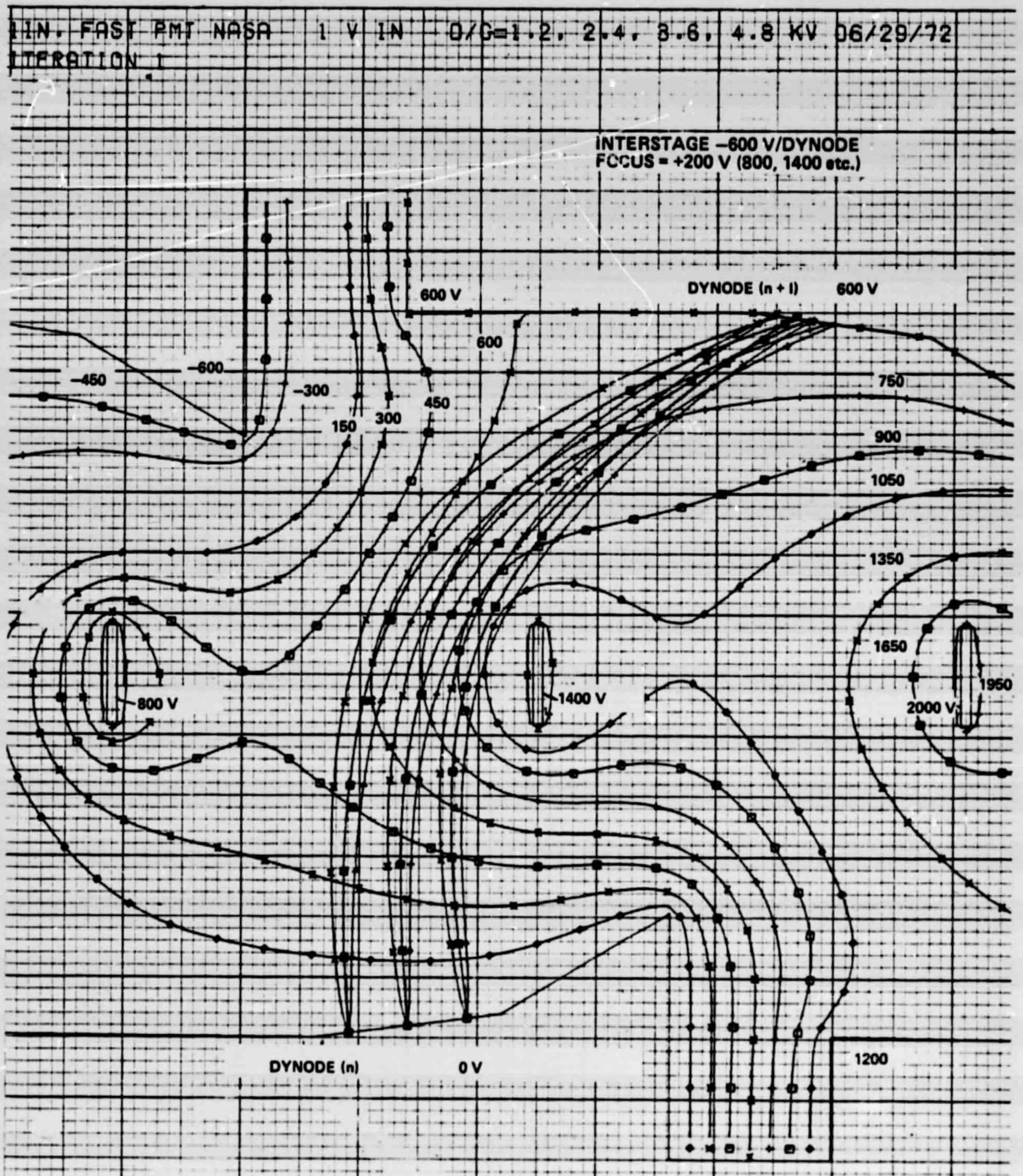


Figure 2. Typical Dynode Stage
Slats 200 V above design center

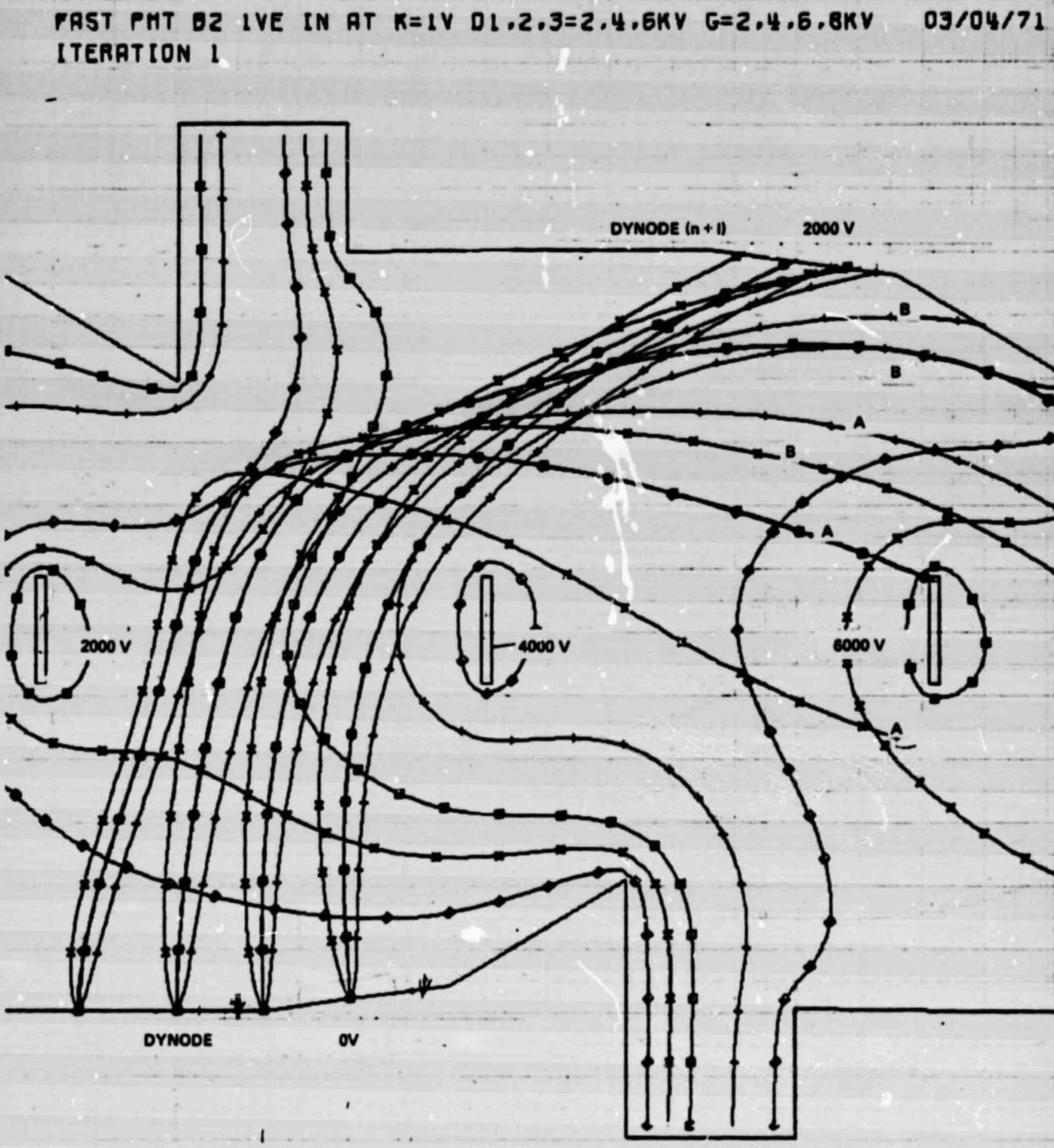


Figure 3. Dynode Stage (Early design phase)
Rejections of unwanted secondaries

4) Modular, ruggedized, metal flange-ceramic disc construction with dynodes welded directly to the metal flanges. This provides capacitance as close as possible to the point of current drain.

5) The metal-ceramic disc construction also provides an optically dense structure which minimizes optical feedback to the photocathode.

Design of the Input

Computer studies were begun in May 1972, to provide an input end geometry incorporating an opaque, flat cathode. These studies, which in general always show "worst case" results, indicated that a cathode diameter greater than 2.5 mm was inconsistant with the primary goals of high speed and low noise. This result was reviewed with the technical officer and it was agreed to proceed with the smaller size. As will be shown in the test results, the useful cathode diameter turned out to be 5 mm. Figure 4 shows a plot of the computer generated electron trajectories from the flat cathode. Note the position of the accelerating electrode and its affect in creating a large electric field at the cathode surface. This causes rapid acceleration at the beginning of the electron trajectories. During the last segment of their path, the electrons experience a deceleration in order to reduce the energy at impact on the dynode to 600 eV. This is done in order to achieve optimum secondary emission gain. The time of deceleration is only a small fraction of the total time of flight. The technique of accelerating and then decelerating results in approximately a fourfold decrease in total time of flight from a continuously accelerating trajectory to an energy of 600 eV over the same distance. See Figure 5, "Table of Electron Time of Flight."

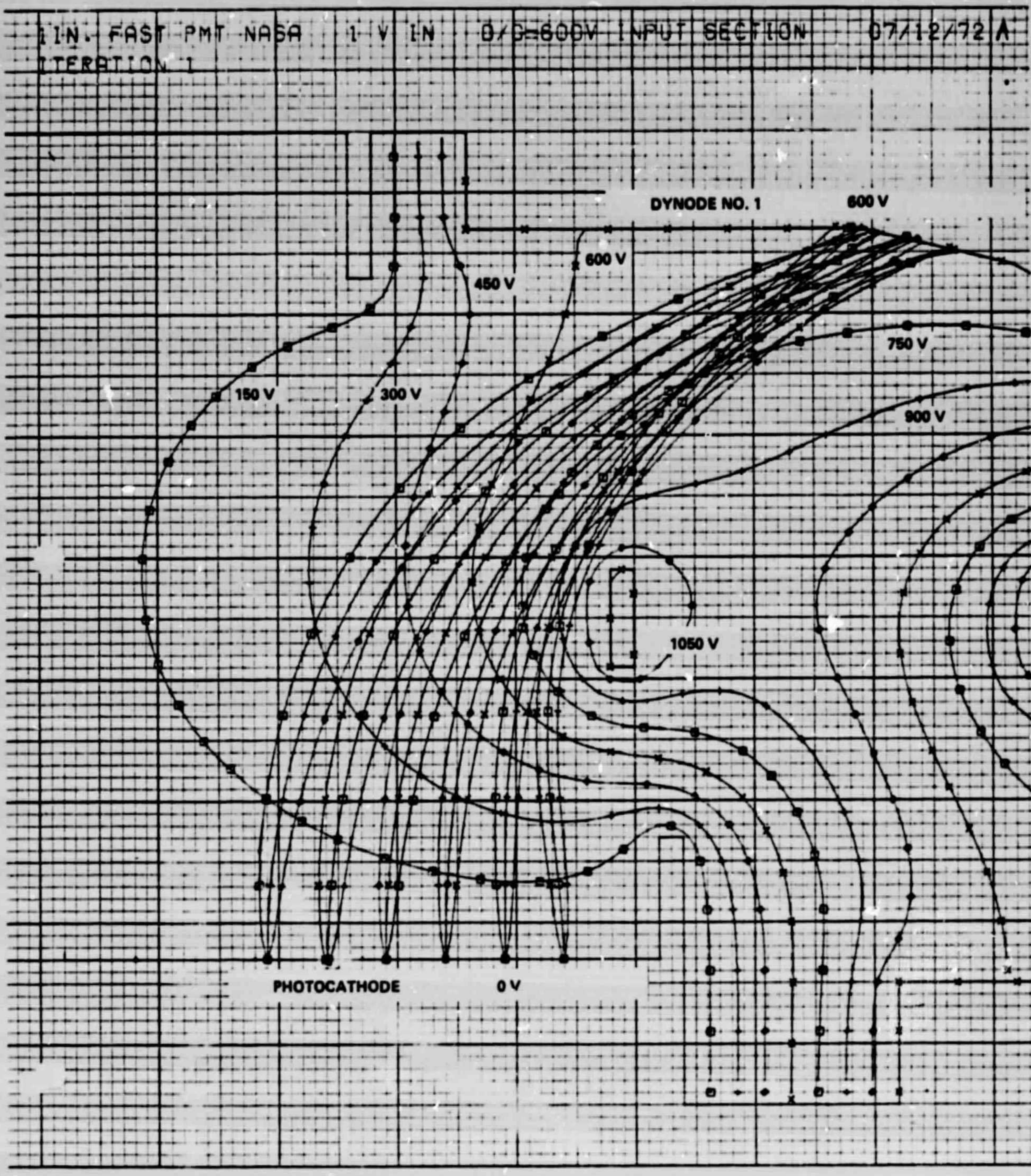


Figure 4. Photocathode
Design Center Voltages

Calculated Electron Time of Flight for a Typical Dynode
at Design Center Voltages

Refer to Figure 1 for position of electrons

Left Hand Group	1.	45° left	9.75×10^{-10} sec
	2.	normal	9.42
	3.	45° right	9.38
	4.	45° into page	9.47
Center Group	5.	45° left	8.45
	6.	normal	8.28
	7.	45° right	8.29
	8.	45° into page	8.35
Right Hand Group	9.	45° left	7.69
	10.	normal	7.50
	11.	45° right	7.53
	12.	45° into page	7.56

Maximum time spread = 2.25×10^{-10} sec.

Time Spread of normals = 1.92×10^{-10} sec.

Figure 5. Table of Electron Time of Flight

The design approach was to incorporate the photocathode directly into the dynode structure in order to achieve the best possible frequency response of the device. With the cathode so disposed, the input signal must arrive at the cathode surface at a large angle relative to the plane of symmetry of the dynode structure. For simplicity, an essentially side window construction was used, although prism and/or mirror systems to provide end-on geometry were considered and ultimately rejected as outside the scope of the project. As shown in Figure 6, "Outline and Internal Structure," the input arrives at an angle of 60° relative to the longitudinal axis of the tube. The input window is an optically polished disc of synthetic sapphire of 0.5" diameter. It is also consistent with the ruggedized construction of the device and the ultra high vacuum technique required for III-V photocathodes.

Design Refinement and Construction

The period of performance under this contract begain with the month of May 1972. The immediate requirement was parts procurement. Accordingly. the design for the dynode chain and the coaxial output were reduced to piece part drawings and sent out for quotes. Simultaneously, the cathode modifications described in the previous section were in progress. Following completion of the cathode-front end design, a final design review of the dynode chain was undertaken. Using the Varian E-gun program, we tested the dynode chain for sensitivity to dimensional variations and to voltage variations. The result of the computer studies was a determination that the original construction method could be significantly improved by holding closer tolerances on the dynodes and focusing electrodes. We elected to follow that approach and redesigned the method of holding the dynodes and focus electrodes in alignment. This caused a one month delay in the schedule but this seemed justified by the improved performance.

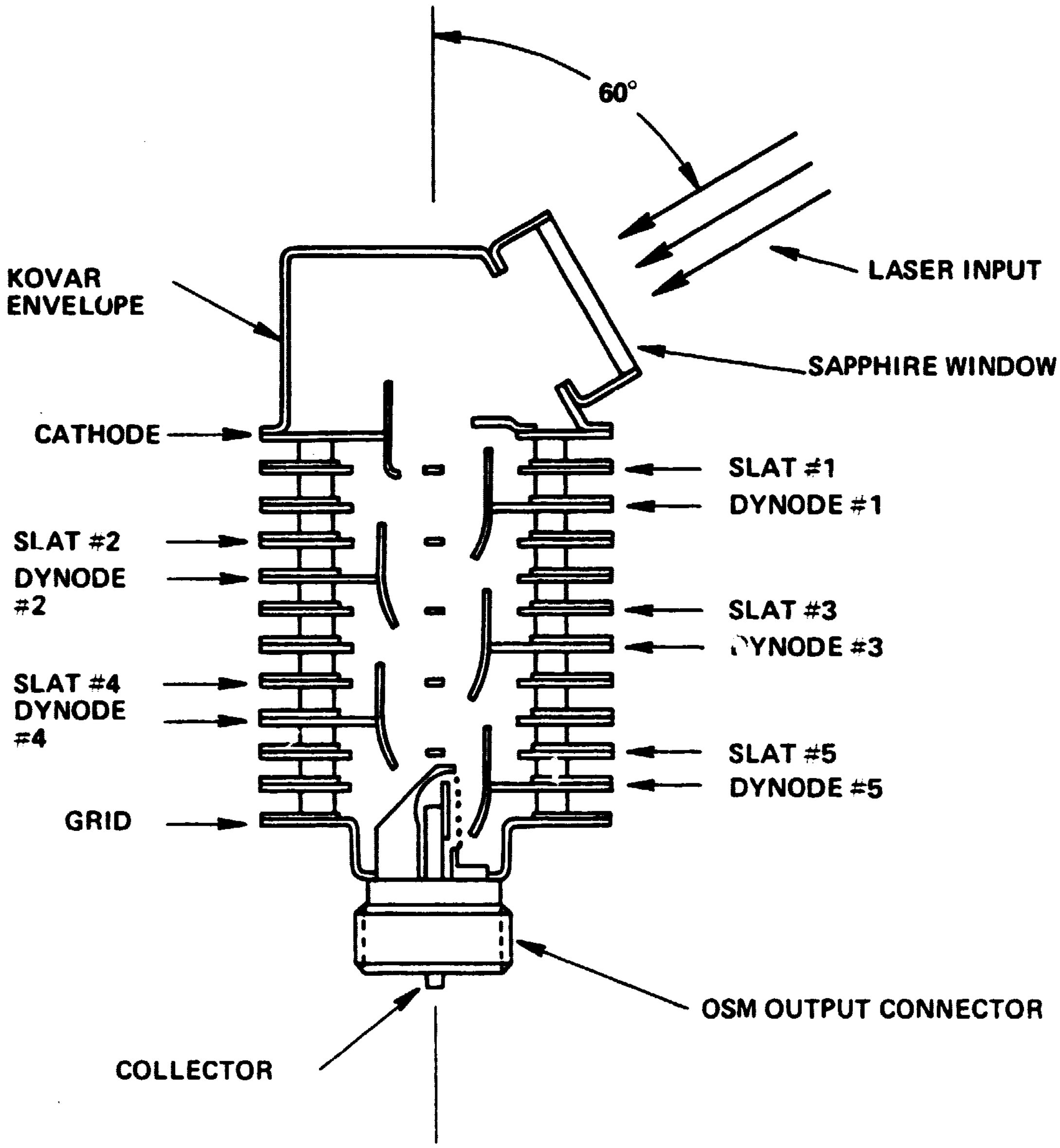


Figure 6. Outline and Internal Structure

At the outset of this program, it was intended to make the cathode and input end components in-house. With the delay introduced by redesign of the dynode chain support system, plus increased loading of in-house machine shop facilities, we finally sent all parts out for bids. This occurred during July, bids were returned and orders were placed in August. During September, most of the tube components were received with the exception of the input end. This part required a difficult forming operation and the order had to be replaced with a second vendor when the first failed to perform.

During August, the required assembly fixturing was drawn and fabricated in-house. By the end of September, all tube components and fixtures were available except the input. This final part was received in November, and the first tube was built and processed with a S-20 photocathode. There were no significant difficulties experienced in assembly of the tube and the first tube built was also the tube shipped. Photocathode processing on this first tube was undertaken with care as the details of the processing schedule are dependent on tube size and geometry. In particular, this tube has its antimony evaporator only 0.150" from the cathode surface during processing. This close spacing requires very careful control of the rate of evaporation.

Observations for Future Tube Construction

It was noted, that an objectionable amount of Sb was evaporated onto the ceramic surfaces behind the cathode substrate. This did not effect overall tube performance but did prevent a full evaluation of the front end characteristics of the tube. Future tubes with antiminide cathodes will incorporate an internal shield to prevent unwanted Sb deposits and their excessive leakage currents.

For better control during photocathode processing, provide more separation between it and the cathode. This will probably aggravate the leakage problem discussed above, but the internal shield will prevent leakage in any case.

Evaluation of Performance

The tube was tested for cathode sensitivity and uniformity, for gain, and for frequency response.

Photocathode Response

The cathode luminous sensitivity was 13 μA/L, due primarily to the difficulty in processing with the Sb evaporator so close to the cathode. Radiant sensitivity is shown in the table below. Note that the quantum efficiency of tube No. 2 is much higher than that of tube No. 2 is much higher than that of tube No. 1. This is due to the increased distance between the antimony evaporator and the cathode plus the processing experience gained in the first tube.

Wavelength (μm)	% Quantum Efficiency Tube No. 1	Tube No. 2
0.400	5.3	22.5
0.530	1.1	8.2
0.600	0.25	4.3
0.700	---	2.2
0.800	---	0.88
Luminous Sensitivity	13.5 μA/L	130 μA/L

Figure 7. Photocathode Sensitivity

The cathode uniformity is shown in the following table. The wide spatial variation in sensitivity is also due to the close Sb spacing. Note anode uniformity for comparison.

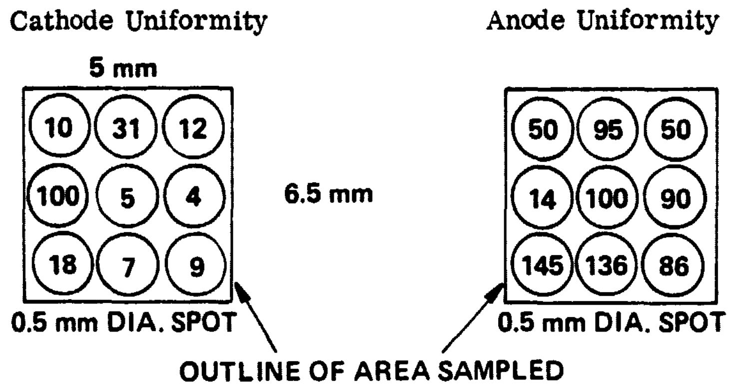


Figure 8. Cathode and Anode Uniformity

Gain

The gain of the tube was measured as a function of overall tube voltage as well as position of signal on the cathode. The latter is characterized by the anode uniformity plot shown above. Gain as a function of voltage was measured using two separately powered bleeder strings. See Figure 9, "Schematic diagram of cup-and-slat photomultiplier and voltage dividers." The tube was initially set up with a 600 V dynode-to-dynode voltage gain with the last dynode 600 V negative relative to the collector. Slat voltages were set at 600 V positive with respect to their succeeding dynodes with the last slat at zero potential. The gain in this configuration was 3×10^3. The slat voltage divider was adjusted with respect to the dynode voltage divider to find best gain. The highest dc gain was found with the last dynode at -400 V (cathode at -3600 V) and the slat chain operating between -2400 V and ground. Gain in this configuration was 6×10^3. It was noted during these measurements that the collector current was only 38% of the last dynode current. A review of the collector design shows that this will be so if there is significant beam spreading. Analysis of the measured electron interception on the slats indicates significant beam spreading. It must be assumed that a similar beam spreading occurs on the region between the last dynode and the output (although there is no slat in this region). Slat

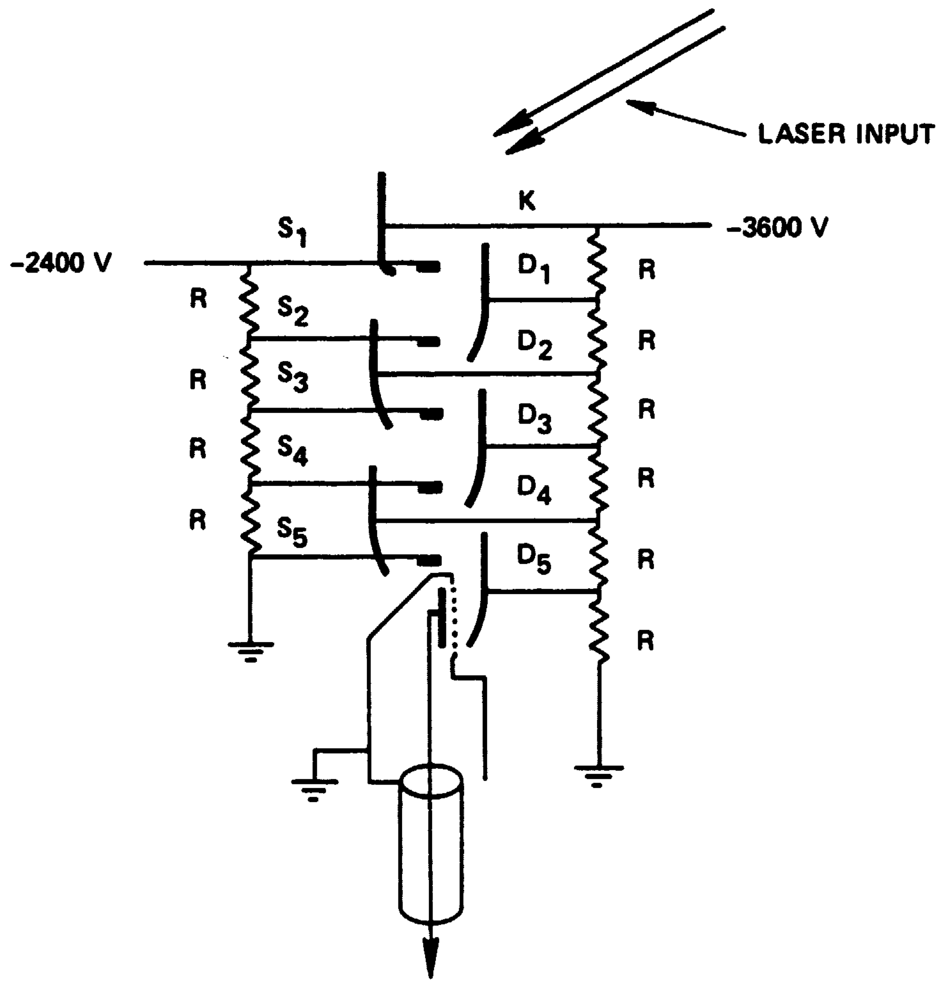


Figure 9. Schematic – PMT and Voltage Dividers

interception averages about 15% of preceeding dynode current on tube No. 1. Tube No. 2 had slat interception of less than 10% and collector efficiency of 75%. Reduction of output signal of tube No. 1 to 38% of last dynode current is surprising and can only be interpreted as an unusual amount of beam spread. Probably the better cathode uniformity of tube No. 2 is a contributing factor in reducing relative slat interception and improving collector efficiency.

Frequency Response

Frequency response was measured at Varian and subsequently at Wright-Patterson AFB by ADP/405B Space Data Relay/Lasar Communication Group. The measurements at Varian were made with a Metrologic Model 410 laser, which conveniently has several modes. Two of the modes have a separation of 400 MHz. There is a third, intermittently excited mode, that produces an 800 MHz heat frequency. The electrostatic PMT was tested for response to these frequencies with the output signal monitored on a Philips Model 3400 sampling scope having 200 psec rise time. Using this method the following observations were made:

1) Response to the 400 MHz input was an approximately sinusoidal wave of 90% modulation.

2) Response to the 800 MHz input was also an approximately sinusoidal wave of about 50% modulation.

For purposes of approximation we will assume a delta function for the shape of the input pulse (laser pulse) and call the 800 MHz response the high frequency-cut-off or 3 dB point. Using the standard formula for pulse response,

$$t_r = 2.2\ RC = \frac{2.2}{2\pi f_2} = \frac{0.35}{f_2}$$

$$\text{if } F_2 = 0.8 \text{ GHz then } t_r = \frac{0.35}{0.8} \times 10^{-9} = 0.44 \text{ nsec.}$$

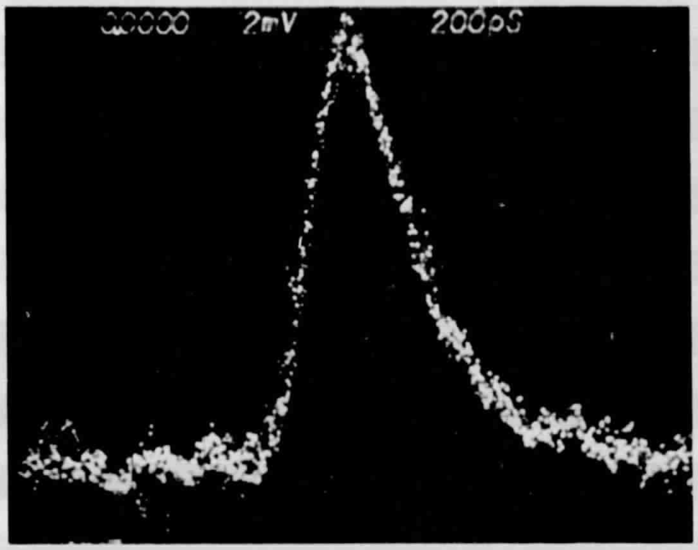
The tube was measured at WPAFB for single pulse response with a Holobeam Nd:YAG mode-locked laser and second harmonic generating crystal. The laser pulse width (FWTM) was measured with a North American Rockwell photodiode and was 110 psec. Under these circumstances, rise time for the system (laser + PMT + scope) could be measured directly. Rise time was found to be strongly influenced by collector effects as should be expected. The best results were obtained with high accelerating voltage to the collector and a small bias between the collector and the last dynode. See Figure 10, "Rise Time and Pulse Width" and Figure 11, "Pulse Response of TI XL55 Avalanche Photodiode and VPM-152 all Electrostatic Photomultiplier Tube."

Device/Configuration	Vacc	Vb	Rise Time t_r (10% to 90%)	Pulse Width FWTM
TI XL 55 Silicon Avalanche Photodiode			150 psec.	650 psec.
VPM-152A S/N 001 Electrostatic Photomultiplier	160 V	0v	500 psec	1600 psec
	620 V	0v	300 psec	1100 psec
	750 V	3v	220 psec	500 psec

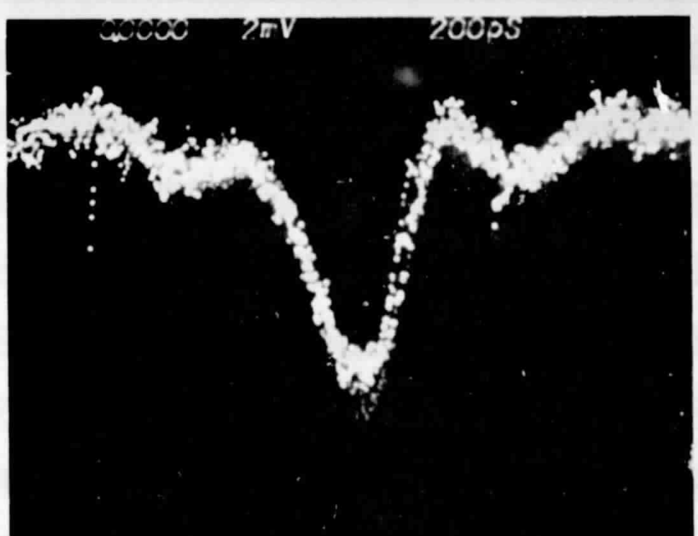
Figure 10. Rise Time and Pulse Width

Using the best value for t_r (220 psec) the bandwidth can be computed from the pulse response formula,

$$f_2 = \frac{0.35}{t_r} = \frac{0.35}{0.22 \times 10^{-9}\ \text{sec}} = 1.4\ \text{GHz}.$$



TIXL55 Silicon Avalanche Photodiode



VPM-152 Varian Electrostatic Photomultiplier

Figure 11 Pulse Response to 110 psec pulse (FWTM) from ND:YAG laser with freq. doubler

It should be noted that gain dropped from about 3000 to 1500 with the rise time at 220 psec. Gain drop can probably be reduced by modifying the design of the collector. This is well within design goals and the pulse width (FWTM) of 500 psec is 20% of the required maximum.

Conclusions

The "cup-and-slat" dynode chain with coaxial output is demonstrated to be a very fast all electrostatic electron multiplier structure. Combined with a 5 mm diameter flat cathode, the resulting photomultiplier has a rise time (10% to 90%) of t_r = 220 psec and a pulse width (FWTM) of 500 psec in response to a laser pulse of 110 psec pulse width (FWTM).