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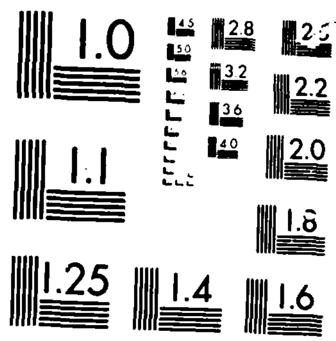

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER ARO 17852.1-PH-H	2. GOVT ACCESSION NO. N/A	3. RECIPIENT'S CATALOG NUMBER N/A
4. TITLE (and Subtitle) Feasibility of Investigating Smith-Purcell Free-Electron Laser Configurations by Electron Energy Loss Studies		5. TYPE OF REPORT & PERIOD COVERED Final. September 1980 through December 1985
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Leslie C. Speller, Ph.D. (UDC) Prof. of Physics Arthur N. Thorpe, Ph.D. (HU) Prof. of Physics		8. CONTRACT OR GRANT NUMBER(s) DAAG29-80-G-0013
9. PERFORMING ORGANIZATION NAME AND ADDRESS University of the District of Columbia Howard University Washington, D.C.		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS U. S. Army Research Office Post Office Box 12211 Research Triangle Park, NC 27709		12. REPORT DATE June 9, 1986
		13. NUMBER OF PAGES Nine (9)
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

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18. SUPPLEMENTARY NOTES

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Smith-Purcell; Electron Energy Loss; Free-Electron Laser

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An electron beam of enegies 20 - 25 KeV were passed over an optical metallic grating (600 lines/mm) and the energy loss spectrum was obtained. The loss peak values, determined to be between ~(1.8 - 1.9eV), were in fair agreement with the predicted values. However, these results could not be reproduced.

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FEASIBILITY OF INVESTIGATION SMITH-PURCELL FREE-ELECTRON LASER CONFIGURATIONS BY ELECTRON ENERGY LOSS STUDIES

FINAL REPORT

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June 9, 1986

U. S. ARMY RESEARCH OFFICE

DAAG29-80-G-0013

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INTRODUCTION

Smith and Purcell[1] have demonstrated that an electron beam traveling close to a metallic grating, parallel to the surface of the grating, and perpendicular to its rulings will emit electromagnetic radiation. They obtained for the fundamental wavelength of the radiation

$$\lambda = d(\frac{c}{v} - \cos\theta) \qquad (1)$$

where d is the grating spacing, v is the speed of the electron, c is the speed of light, and θ is the angle between the direction of motion of the electron and the emitted ray.

Recently, the Smith-Purcell effect has generated a large interest to many workers[2-5] because it has shown much promise in the tunable laser technology. Sources of tunable coherent electromagnetic radiation are highly desirable in application of many areas in applied physics, e.g., radio-isotope separation, plasma physics, and Intelligence Surveillance and Target Acquisition (ISTA).

The Free-Electron laser, based on the Smith-Purcell effect, shows promise of a truly tunable laser because, in principle, any wavelength can be obtained by merely changing the velocity of the incident electron, however, the proper choice of grating spacing must be taken into account.

The purpose of the research was to investigate the feasibility of a Smith-Purcell type Free-Electron laser by using electron energy loss techniques. A non-relativistic electron beam was passed over and close to the surface of a metallic grating, parallel to the surface of the grating, and perpendicular to its rulings. Measurements of the energy loss of the electron beam, after traversing the grating, were measured and compared with *the predicted energy loss due to radiation. The electron energy loss measurement should give a direct measure of the radiative efficiency of this type of device.*

THEORETICAL BACKGROUND

The energy loss of an electron beam that traverses a metallic grating, parallel to its surface and perpendicular to its ruling was studied as a function of the energy of the incident electron beam and as a function of the geometrical configuration of the grooves of the grating. The parameters and information from this study are very important in the design of a Smith-Purcell Free-Electron laser.

An estimate of the time average of the total rate at which the energy of a moving charged particle is converted into radiation as it moves across the grating is given by the expression[6]

$$\left(\frac{dW}{d\tau}\right) = \frac{\pi^4 e^2 c}{75\ d^2} \quad \frac{\qquad}{(1 - \beta^2)^2} \quad \frac{\text{ers}}{\text{sec}} \qquad (2)$$

where e is the electronic charge and $\beta = \frac{v}{c}$.

This expression was obtained from a harmonic analysis of a zig-zag path similar to the contour of a typical optical grating which yields d/20 as the amplitude of the fundamental oscillation, and from the classical formula for the time average of the total rate of radiation from an accelerated charge instantaneously at rest.

Choosing $\theta = 90^{\circ}$ in Equation (1), and making the assumption that the total rate of radiation should be about four times the rate of radiation in the first harmonic[6], the combination of Equations (1) and (2) gives the expression for the conversion of electron energy into electromagnetic radiation per unit electron path as

$$\left(\frac{\overline{dW}}{dx}\right) = \frac{4\pi^4 e^2}{75\lambda^2} \frac{\beta}{(1 - \beta^2)^2} \frac{\text{erg}}{\text{cm}} \quad (3)$$

As can be seen from Equation (3), the efficiency of the conversion of electron energy into radiation increases with increasing β and decreasing λ, and decreases with decreasing β and increasing λ.

Consider a typical optical grating (600 lines/mm) which gives a grating spacing of approximately 1.7×10^{-4}cm. If the kinetic energy of an electron is 25 KeV, the corresponding wavelength ($\lambda = d\beta^{-1}$) would be $\sim 5.48 \times 10^{-4}$cm (infrared). The corresponding electron energy loss estimated from Equation (3) would be ~0.94eV/cm which would not be difficult to observe.

For a frequency 230Ghz (λ = 1.3mm), the energy loss for a 25 KeV electron (β = 0.31) and a grating spacing of 0.4mm would be approximately 1.7×10^{-7}eV/cm. This loss value would be much too small for us to observe. Even if a 1 MeV electron (β = 0.89) and a grating spacing of 1.16mm were considered, the energy loss would only be roughly 10^{-4}eV/cm.

However, the electron energy losses based on beam and grating parameters obtained in the infrared wavelength range can be extrapolated to the near-millimeter-wavelength region, and would be useful in obtaining optimum conditions for the operation of a Free-Electron laser (Orotron) as the one developed by Leavitt et. al.[5] at Harry Diamond Laboratory.

EXPERIMENTAL SET-UP

The electron scattering apparatus that was used to measure the electron energy loss of the beam due to radiation has been described previously by Marton and Simpson[7] and Mendlowitz[8]. The data-recording system has been described previously by Speller[9]. The electron scattering apparatus has five basic components: (1) tele-focus electron gun; (2) specimen chamber; (3) decelerator; (4) magnetic velocity analyzer; and (5) accelerator. The data-recording system is a photomultiplier detector coupled with a multichannel analyzer and a micro-computer.

RESULTS AND DISCUSSION

The electron beam was passed over an optical metallic grating (600 - lines/mm) and the loss spectrum obtained is shown in Figures (1) and (2). The loss peak values were determined to be between ~(1.8 - 1.9 ev) for kinetic energies of the incident electrons at 20 KeV - 25 KeV, respectively.

From Equation (3), in the previous section, we see that if the kinetic energy of an electron traversing this particular grating is 25 KeV, the estimated electron energy loss should be ~0.94 eV/cm. The width of the grating used was 2.6cm, thus giving a loss estimate of ~2.4 eV.

Because of the fact that our measured loss values are in fair agreement with the predicted values, and because they completely disappear when the grating is moved away from the beam, we strongly feel that the loss peaks observed are due to the grating. However, more data and other related energy loss experiments are necessary for confirmation and for a full understanding of the loss mechanism of this type.

We checked to determine if there was a surface plasmon loss for gold in the energy region ~2.0 eV. From previous electron energy loss measurements of gold made by Speller, no loss was observed in this energy region.

Numerous attempts were made to reproduce these results, however, we failed to see the "loss effect" again. Different metallic gratings, as well as the original grating, were used, yet the electron energy loss spectrum still could not be reproduced. We must note that the passage of the electron bean parallel to the surface of the grating and at the proper distance above the grating (glazing) are critical factors in observing the "loss effect." Many adjustments were made before the electron energy loss spectrum was measured the first time.

We have not yet given up on this experiment because we believe that energy loss spectrum obtained is real. With an improved method of adjusting the beam relative to the surface of the grating, and modifications in the detection and data acquisition systems, hopefully, the reproducibility of the energy loss spectrum can be obtained. We feel this type of information is very important and could have significant impact on the Strategic Defense Initiative (SDI) program.

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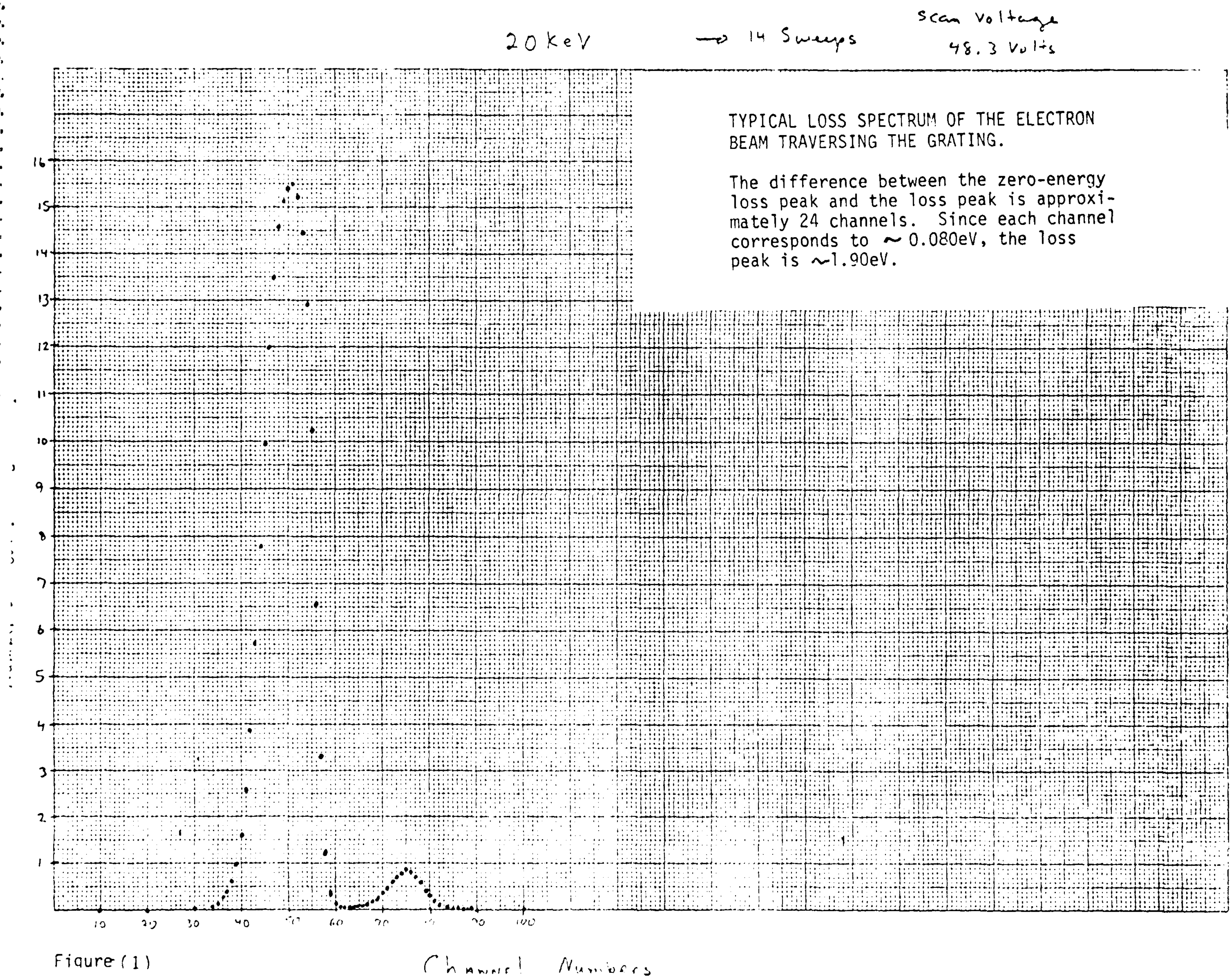

TYPICAL LOSS SPECTRUM OF THE ELECTRON BEAM TRAVERSING THE GRATING.

The difference between the zero-energy loss peak and the loss peak is approximately 24 channels. Since each channel corresponds to ~ 0.080eV, the loss peak is ~1.90eV.

Figure (1)

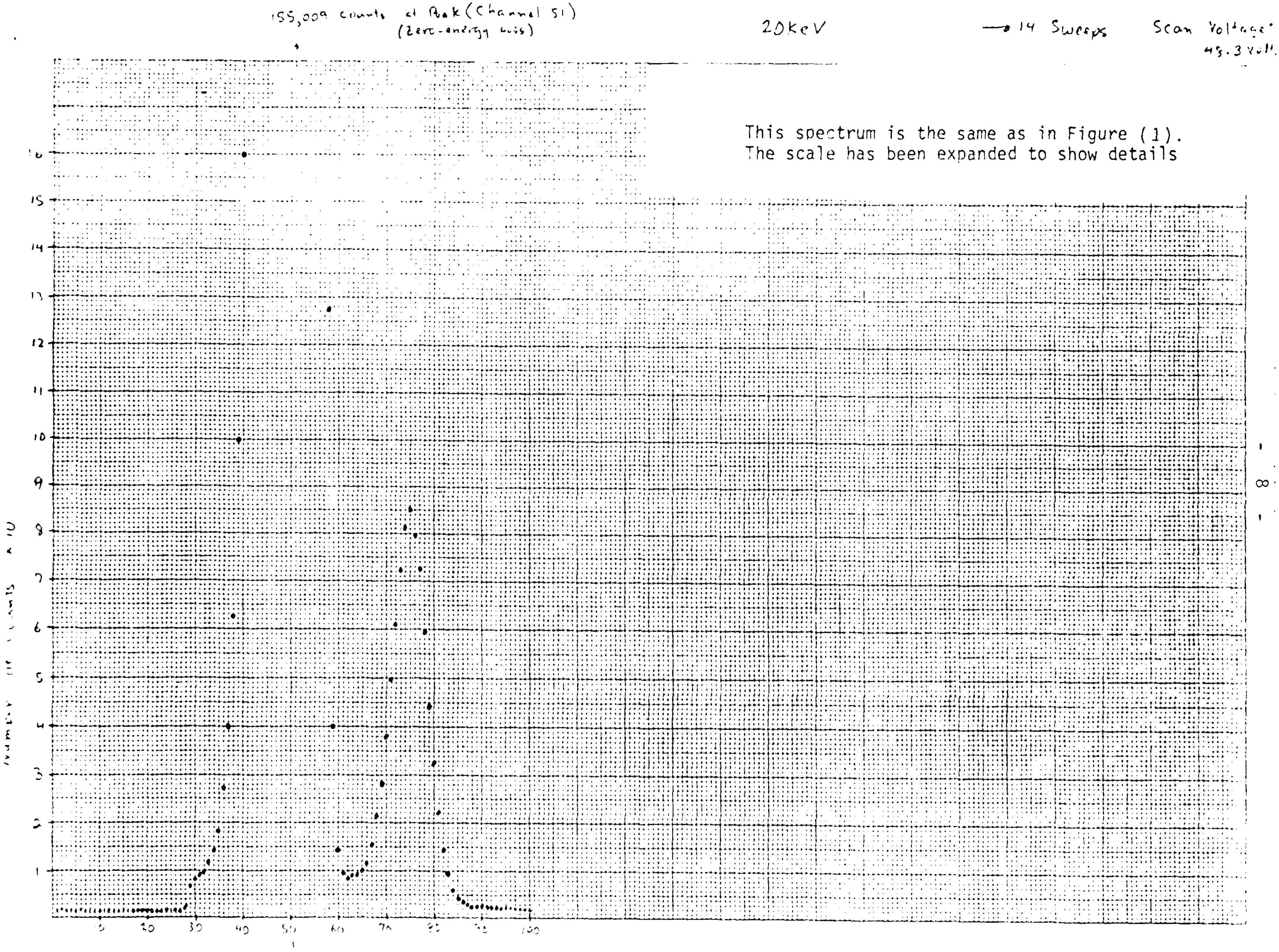
155,009 counts at Peak (Channel 51)
(Zero-energy loss)
20KeV
→ 14 Sweeps
Scan Voltage
43.3 Volt
This spectrum is the same as in Figure (1).
The scale has been expanded to show details
Channel Numbers

Figure (2)

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