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A TARGET BEAM MONITOR USING SECONDARY ELECTRON EMISSION*

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ABSTRACT

The secondary electron emission from a thick target is used as a monitor of 18 GeV electrons striking the target. Experimental production coefficients are reported for seven different targets of various materials and geometries. For some targets, the coefficient exceeds unity. Production mechanisms are discussed and roughly calculated. For targets 0.3 radiation length thick, the predominant production mechanisms are knockon electrons and Compton electrons. The usefulness of such a monitor is discussed in terms of its simplicity, its sensitivity, its fast time response, its nonsaturating characteristic, and the fact that it monitors only beam which has actually struck the target.

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INTRODUCTION

Workers here and at CERN[1] have observed that when beams of extremely relativistic charged particles strike a thick target, large yields of secondary electrons are produced. For a favorable geometry, the secondary electron current can be larger than the beam which produces it.

The effect was seen here on the two-mile linear accelerator when it was decided to monitor the beam in a particle physics experiment by means of a secondary emission monitor[2] in which the experimental target was used also as the emitting electrode. Such a monitor, the subject of this paper, we will call a target secondary emission monitor, or TSEM. We define the "production coefficient" of such a device as the number of secondary electrons leaving the target, per primary particle traversing the target.

In the experiment for which the TSEM was built, the need was for a simple monitor which would register only beam particles which actually struck the target. By combining the target and the monitor, this objective was automatically achieved. In addition, the large production coefficients reported here make this type of monitor a rather sensitive device.

MEASUREMENT METHOD

All of the results reported are from targets traversed by primary beams of electrons, of energy ranging from 14 to 18 GeV. The accelerator produced beam pulses of 1.5 microseconds duration, with currents of 1 to 3 milliamperes during the pulse. The repetition rate varied from 10 to 360 pulses per second. In addition, the beam has 2856 megacycle microwave bunching into tight bunches less than 10° wide.

Target currents were measured (see Fig. 1) primarily by means of an oscilloscope, which displays the 1.5-microsecond pulses, but which ignores the microwave structure. In addition, the pulses were integrated over the duration of particle physics runs, to provide a measure of the total charge incident on the target during a run. The production coefficient for a given target was measured by comparing this oscilloscope pulse with a pulse of similar shape obtained from a beam induction transformer, when it could be determined that substantially the entire beam was striking the target.

Table I is a list of the targets used, along with their dimensions and the measured production coefficients. Most of the targets were supported by steel wires, from a light frame which intercepted only 10% of the solid angle about the target. This target assembly is suspended inside an evacuated cylindrical steel target chamber 14 inches in diameter. The pressure is maintained at 10^{-4} torr or less.

ANALYSIS OF TARGET No. 1 - BERYLLIUM

The largest amount of data was taken with target No. 1, so its properties are known best. It is a square prism of beryllium, 0.6×0.6 cm, 10 cm long in the beam direction (0.3 radiation length). The measured production coefficient for emission from this target is 1.25, indicating that the monitor current is somewhat greater than the beam current itself.

In attempting to account for this quantity of emission, we have found several mechanisms of charge production which can be expected to make significant contributions. It is interesting that all of them result in emission of negative charge from the target.

"Knockon" Electrons

The "knockon" process is illustrated in Fig. 2a, for target No. 1. This process is the result of the Coulomb interaction between electrons in the target atoms and the beam electrons, and is synonymous with the well-known delta ray production process. The number of knockons in the energy range E_1 to E_2 per gram per square centimeter of material is given approximately by[3]

$$n = 0.30\ ZA^{-1}\beta^{-2}\left(mc^2/E_1 - mc^2/E_2\right) \qquad E_1,\ E_2 \ll E_0\ , \tag{1}$$

where Z and A are the atomic number and mass number of the target atoms. β is the relative velocity of the primary electron, whose energy is E_0. For our case, E_1 and E_2 lie in the range of 0.1 MeV to 100 MeV.

For very relativistic primary electrons, the emission angle ϕ is given to good approximation by

$$\mathrm{Cos}\ \phi = E_1\left(E_1^2 + 2E_1 mc^2\right)^{-1/2} \qquad E_1 \ll E_0\ . \tag{2}$$

From range-energy curves for electrons in beryllium, it is determined that for a primary electron traversing the central axis of the target, all knockon electrons having energy greater than 2 MeV will leave at an angle such that they can escape. Using Eq. (1), each primary electron will produce, in the 10-cm target length, 0.67 knockon electron of energy sufficient to escape through the sides of the target.

Knockons which originate near the downstream end of the target such as the particle labeled B, have an especially favorable opportunity to escape through the end of the target. A graphical integration for these shows that an additional .07 knockon is expected through the end, originating up to 0.4 cm upstream from the end.

All of the above calculations neglect multiple scattering of the electrons, which probably does not cause more than a 20% net change in the result. Appreciable contributions come only from knockons of energy greater than roughly 100 keV, for these rational calculations.

Experiments with thin foils[4] and theory[5] indicate that there is a distinct class of very low energy electrons (1 to 100 electron volts) which is generated in an extremely thin layer at the metal surface. In thin-foil secondary emission devices, this is the principal effect, as indicated by the fact that the secondary emission coefficient is substantially independent of foil thickness.[4] We shall call this "surface emission" to distinguish it from the bulk of the knockon electrons, which are of much higher energy.

Referring again to Fig. 2a, surface emission may be expected to occur at the entrance and exit points of the primary electron on the target, and at the exit point for each of the knockon secondaries shown. The efficiency for surface emission on beryllium is about 2% per surface for relativistic particles, so one could expect a 4% contribution from the primary electron, and perhaps another 2% from high energy secondary electrons. There is reason to think that in our measurements, most of these low energy surface secondaries were suppressed by space charge around the target, in view of the bias curve discussed later.

Compton Electrons

Another important process is illustrated in Fig. 2b; the primary electron produces a γ ray by bremsstrahlung, and the γ kicks out a Compton electron. These may be estimated by the following considerations:

a. The bremsstrahlen are directed into a very narrow forward cone. We assume $\theta = 0$ for all of them.

b. The energy spectrum of the bremsstrahlen is to fair approximation a 1/E function.[6]

Since in addition the Compton scattering cross section[7] at high energies is a decreasing function of energy, we need consider only the low energy end of the bremsstrahlung spectrum. There is a low energy cutoff when the Compton electrons do not have sufficient energy to escape through the wall of the target material; hence, for central primaries, the important energy range of bremsstrahlen is only from 2 to 100 MeV.

A rough numerical integration, taken by octaves of energy intervals, indicates a contribution of 0.16 Compton electron per central primary. This is probably correct to within a factor of two.

Pair Production with Positron Annihilation

This process, illustrated in Fig. 2c, would result in emission of a charge of one net electron. For the target in question, however, it is a rare event because it is a third-order process in a target whose thickness is 0.3 of a radiation length. A rough calculation gives .002 such electron per primary for this target; however, its importance would increase rapidly with target thickness.

The total calculated emission from target No. 1 would then be, for a primary traversing the central axis:

Partial Production Coefficients

knockons through target sides	0.67
knockons through target end	0.07
Compton electrons	0.16
surface emission from above	.02
surface emission from primaries	.04
total charge production coefficient	0.96

Comparison with Experiment

The measured value of the production coefficient for this target (No. 1) was 1.25 ± 0.1, with zero bias voltage. This agrees within expected errors with the above estimated theoretical value, but it is measured under conditions which are somewhat different from those the theory assumes. Firstly, the beam was spread out over at least the central 3 millimeters of the target, instead of being concentrated at the center. The effect of this is estimated to be small and hard to estimate.

Secondly, with zero bias on the target, space charge effects are likely to prevent the escape of many of the low energy "surface emission" electrons. A bias curve was obtained for this target operating under otherwise typical conditions (Fig. 3). The substantial increase in current with negative bias on the target may be taken as a direct measure of the low energy electrons normally trapped by space charge. A rough calculation shows that space charge effects should be appreciable under these conditions.

The entire change in current caused by bias may be taken as a measure of the total number of low energy (< 100 eV) electrons emitted from the target surface. This amounts to a 0.55 contribution to the emission coefficient, or almost ten times that estimated above as being attributable to surface emission. This is readily explainable if one assumes that the beam has a weak "halo" around it which extends to the edge of the target. If 10% of the beam is distributed in a uniform square slightly larger than the target, there will be enough primary electrons in the surface layer (assumed 10^{-6} cm thick[8]) to account for the measured low energy emission.

ANALYSIS OF OTHER TARGETS

Target No. 2 - Carbon

An analysis identical to the above produces the following predictions for this target:

Partial Production Coefficients

knockons through target sides	0.586
knockons through target end	0.073
Compton electrons	.081
surface emission from the above	.015
surface emission from primaries	.040
total charge production coefficient	0.785

The measured production is 0.81 ± .08, in good agreement with the above estimate. No bias curves were taken for this, nor for the targets discussed below.

Target No. 3 - Iron

This target has such drastically different geometry from that of targets No. 1 and No. 2 that practically no electrons escape through the sides. The estimates are somewhat simpler, in this case. We estimate the contributions as follows:

Partial Production Coefficients

knockons through target sides	--
knockons through target end	0.125
Compton electrons (through end)	.060
surface emission from above	.001
surface emission from primaries	.040
total charge production coefficient	0.226

This agrees well with the measured emission coefficient of 0.21 ± .02.

Target No. 4 - Iron plus Beryllium

This composite target was arranged so the beam passed first through one cm of iron, then through 10 cm of beryllium. The whole target is about 0.9 radiation length deep, so shower formation is well under way. No estimate has been made of the expected emission of charge, except to note that it should be increased over Target No. 1 by the greater degree of shower development. The measured charge production coefficient is 2.9 ± 0.3 for this target.

Target No. 5 - Thick Beryllium

This target is also complex to analyze, because it is so thick in the beam direction (one radiation length). The width is so great that only a secondary electron of energy greater than 10 MeV can escape the sides. This means that the principal emission is probably from the downstream end of the target.

The measured production coefficient is 2.6 ± 0.3, which is five times as great as we can account for, by the emission processes mentioned for target No. 1.

It was noted for this target that when the beam was swept from the target center outward, the emission increased by about 30%, when the beam was approximately at the edge of the target.

Target No. 6 - Aluminum, 0.3 Radiation Length

The test on this target was made with the target and beam in air instead of in vacuum; this should not cause much error due to ionization, since the target potential was kept at less than one millivolt with respect to its environment during the run. The beam was not well controlled during this measurement, in that its position relative to the target was poorly known. We estimate that as much as 20% of the beam may have been missing the target when the measurement was made. The measured charge production coefficient of 1.35 should have probable errors of +20%, -50% attached.

Target No. 7 - Thick, Narrow Beryllium

This target is expected to have, and has, the largest production coefficient of any of the targets used. This is due to its one radiation length thickness and small width, which allows electrons of low energy to get out the sides. We estimate the following:

Partial Production Coefficients

knockons through sides	2.5
knockons through end	0.1
Compton electrons	1.6
surface emission on above	0.1
surface emission on primaries	.05
positron annihilation	0.1
total coefficient	4.45

The measured production coefficient is 7.0 ± 0.7, in reasonable agreement with the estimate.

PERFORMANCE OF TARGET No. 1 AS A BEAM MONITOR

This target was the principal one used in a particle production survey experiment,[9] and the present beam monitoring method was used. The monitor production coefficient was checked at least every two hours. The "probable fluctuation" of the coefficient was about ± 3%, with extreme variations of ± 10% noted, in twelve 16-hour running periods extending over two calendar months.

We think the fluctuations in coefficient are most probably due to changing beam spot size on the target, which changes the illumination of the edges of the target. The production efficiency for secondary electrons of energy greater than 0.1 MeV by primaries 0.1 millimeter from the target edge is calculated to be about five times the efficiency at the target center. This is qualitatively verified by the beam traverse experiment performed on target No. 5, mentioned above.

The amount of "surface emission" is also critically dependent on the amount of beam at the target edge. However, such surface emission can be eliminated by placing a few hundred volts of positive potential on the target. This was not done in the experiments under discussion.

One of the best ways to stabilize such a monitor against changing beam distribution would be to surround the target with a thin-sheet aluminum absorber which would eliminate the numerous low energy electrons coming from, say, the outermost 0.5-mm layer of the target. The absorber could be wrapped into a cylinder of large diameter (to get it away from the beam) surrounding the target, and electrically connected to the target.

Linearity of Response

One experiment was made to determine the range of linearity of the monitor. It was concluded that for beams of peak current in the range of 0.2 to 1.0 milliampere, the production coefficient has less than a 10% dependence on beam current. According to our understanding of the production mechanisms, the monitor should be strictly proportional to beam current over a very wide range of intensities, if bias is applied to avoid space charge effects from the low energy surface emission electrons.

Energy Dependence

The primary electron energies employed ranged from 14 to 18 GeV. No correlated change in production coefficient was detected, within the probable limits of ± 5%.

It is a pleasure to thank Roger Coombes for help with making some of these measurements, Finn Halbo for the mechanical design of the target chamber, and the SLAC operating crew for effective running of the accelerator. We are grateful to Professor M. Schwartz et al. for permission to use production data from the target in their experiment, and to E. Seppi for helpful discussions of production mechanisms.

TABLE I

TARGET DATA

Target Number	Material	Length,* cm	Width, cm	Shape**	Measured Charge Production Coefficient
1	Be	10	0.6	square	1.25 ± 0.1
2	C	6.63	0.64	cylinder	0.81 ± .08
3	Fe	0.54	0.74	cylinder	0.22 ± .02
4	Fe plus Be	1.08 10.0	0.60 0.60	square square	2.92 ± 0.3
5	Be	30	3.8	cylinder	2.63 ± 0.3
6	Al	2.5	0.6	cylinder	1.35 ± 0.2, -0.7
7	Be	30	0.6	square	7.0 ± 0.7

*length in the beam direction

**profile presented to the beam

Dimensions of the experimental targets are given, along with the measured values of the secondary electron production coefficient for each.

FIGURE CAPTIONS

1. Equipment layout for measuring electron emission from bombarded target. The current is conducted from the target by means of fine steel support wires.

2a. Production of knockon electrons. High energy knockons are shown at A and B, while surface emission from the primary electron is at C and D. Surface emission may occur also at A and B, where high energy knockons break the surface.

2b. Production of Compton electrons. A γ ray produced by bremsstrahlung at A scatters off an atomic electron at B, which leaves the target at C.

2c. Production of electrons by "pair production plus positron annihilation." The primary electron produces a bremsstrahl at A, which produces an $e^{\pm}$ pair at B in the field of an atomic nucleus. The positron annihilates an atomic electron at C to produce a pair of neutral γ's. This leaves the emission of one net electron, at D.

3. Bias curve for Target No. 1. This is thought to represent a measure of low energy secondary electrons which are strongly influenced by space charge around the target.

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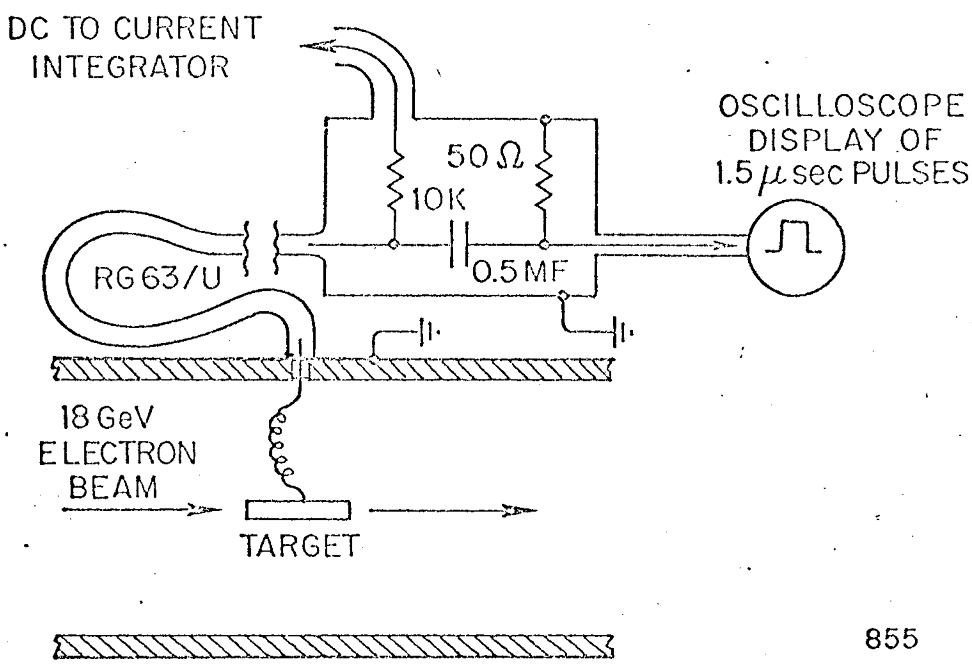
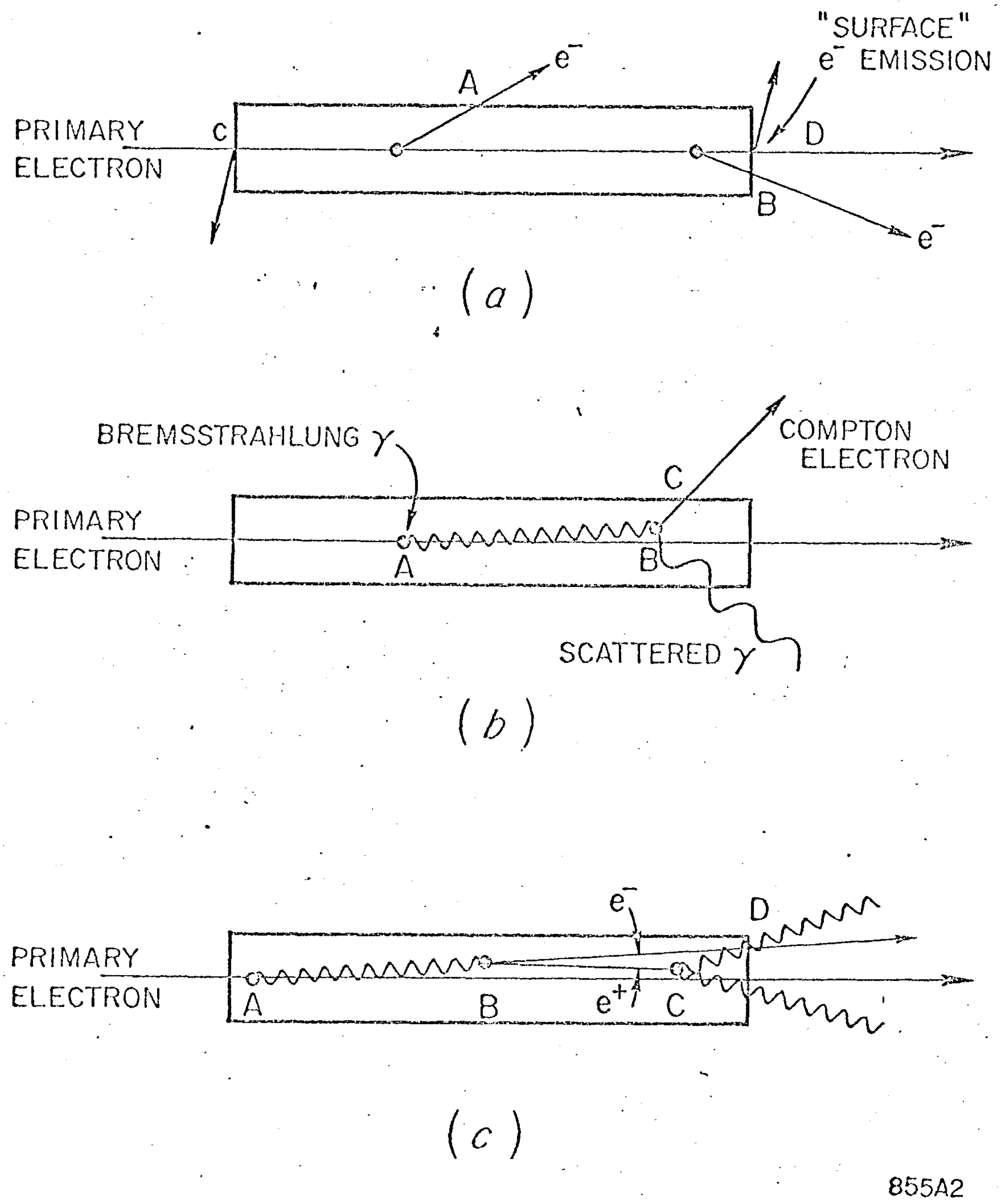

DC TO CURRENT
INTEGRATOR
50 Ω
10K
0.5 MF
RG 63/U
OSCILLOSCOPE
DISPLAY OF
1.5 μ sec PULSES
18 GeV
ELECTRON
BEAM
TARGET

855

FIG. 1



"SURFACE"
e⁻ EMISSION
PRIMARY
ELECTRON
c
A
e⁻
D
B
e⁻
(a)
BREMSSTRAHLUNG γ
COMPTON
ELECTRON
C
PRIMARY
ELECTRON
A
B
SCATTERED γ
(b)
PRIMARY
ELECTRON
e⁻
D
A
B
e⁺
C
(c)
855A2

FIG. 2

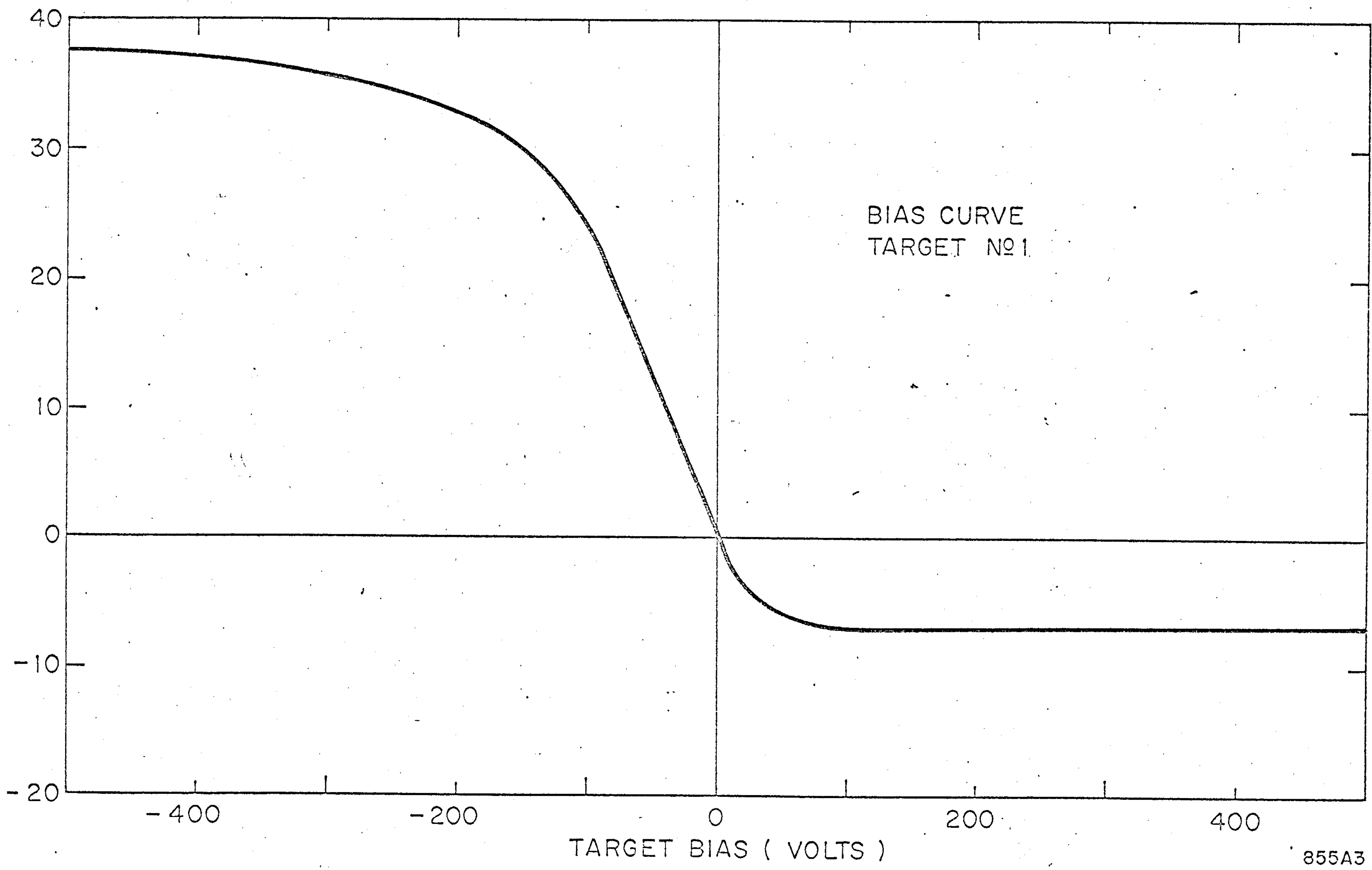

40
30
20
10
0
-10
-20
-400
-200
0
200
400
TARGET BIAS (VOLTS)
BIAS CURVE
TARGET №1
855A3

FIG.3