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Anderson

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[45] Sept. 24, 1974

[54] BEAM CURRENT REGULATOR FOR ELECTRON BEAM MACHINES

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[73] Assignee: **United Aircraft Corporation,** East Hartford, Conn.

[22] Filed: **May 21, 1973**

[21] Appl. No.: **362,152**

[52] **U.S. Cl.**..... **315/291,** 219/121 EB, 250/492, 315/311

[51] **Int. Cl.**..... **G05f 1/00,** H05b 37/02

[58] **Field of Search**..... 219/121 EM, 121 EB; 250/409, 492 A; 315/291, 293, 307, 311

[56] **References Cited**

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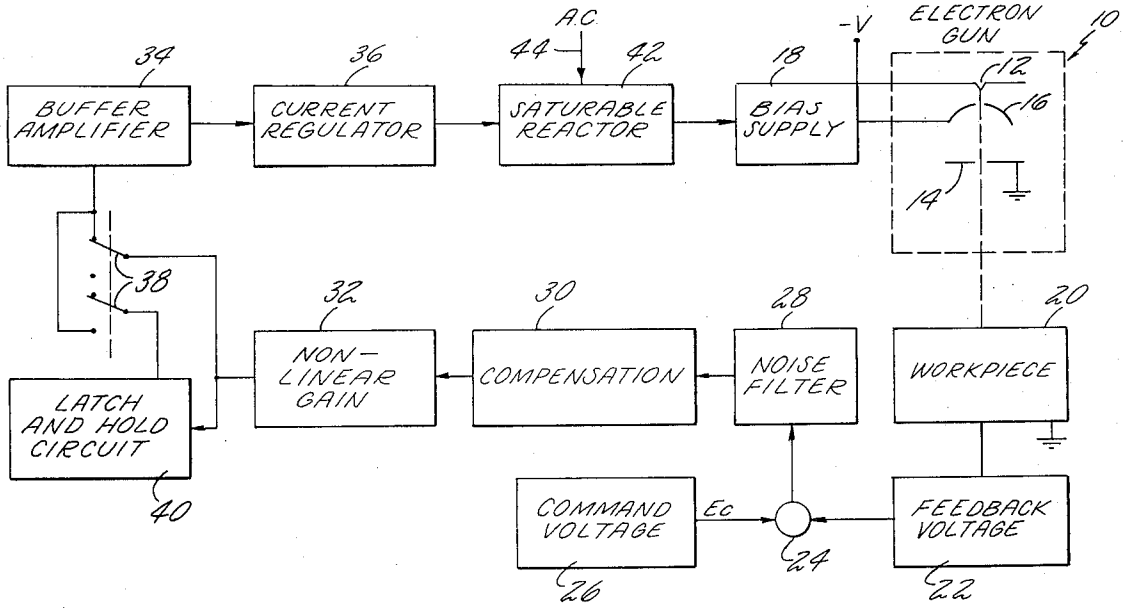
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Primary Examiner—Harold A. Dixon
Attorney, Agent, or Firm—Donald F. Bradley

[57] **ABSTRACT**

In an electron beam machine for welding or cuting a workpiece, the current produced by the electron gun is regulated by a beam regulating system to maintain a programmed value. A feedback voltage proportional to beam current is compared with a commanded voltage proportional to desired beam current, any difference therebetween in the form of an error voltage being used to vary the bias voltage of the electron gun and modify the beam current. A novel saturable reactor circuit permits the bias voltage which is at a high potential to be varied by a DC current which varies about ground level. A novel latch and hold circuit permits the beam current regulator to be bypassed when the electron gun filament is "peaked". A novel current adder circuit permits the automatic programming of multi-level beam currents.

4 Claims, 6 Drawing Figures



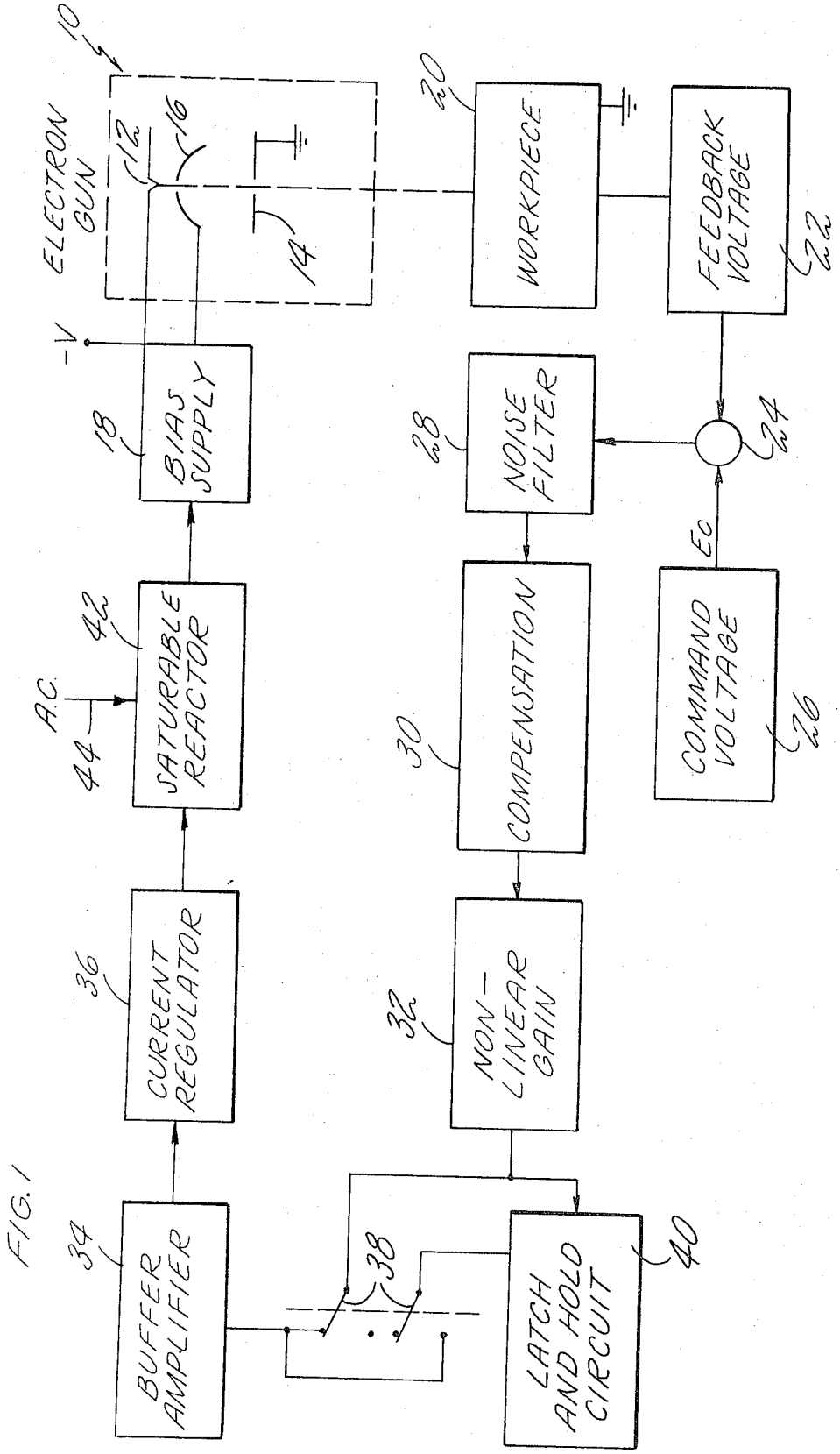

10
ELECTRON GUN
12
16
14
20
WORKPIECE
FEEDBACK VOLTAGE
22
-V
18
BIAS SUPPLY
28
NOISE FILTER
24
Eo
COMMAND VOLTAGE
26
A.C.
44
42
SATURABLE REACTOR
30
COMPENSATION
36
CURRENT REGULATOR
32
NON-LINEAR GAIN
34
BUFFER AMPLIFIER
38
LATCH AND HOLD CIRCUIT
40

FIG. 1

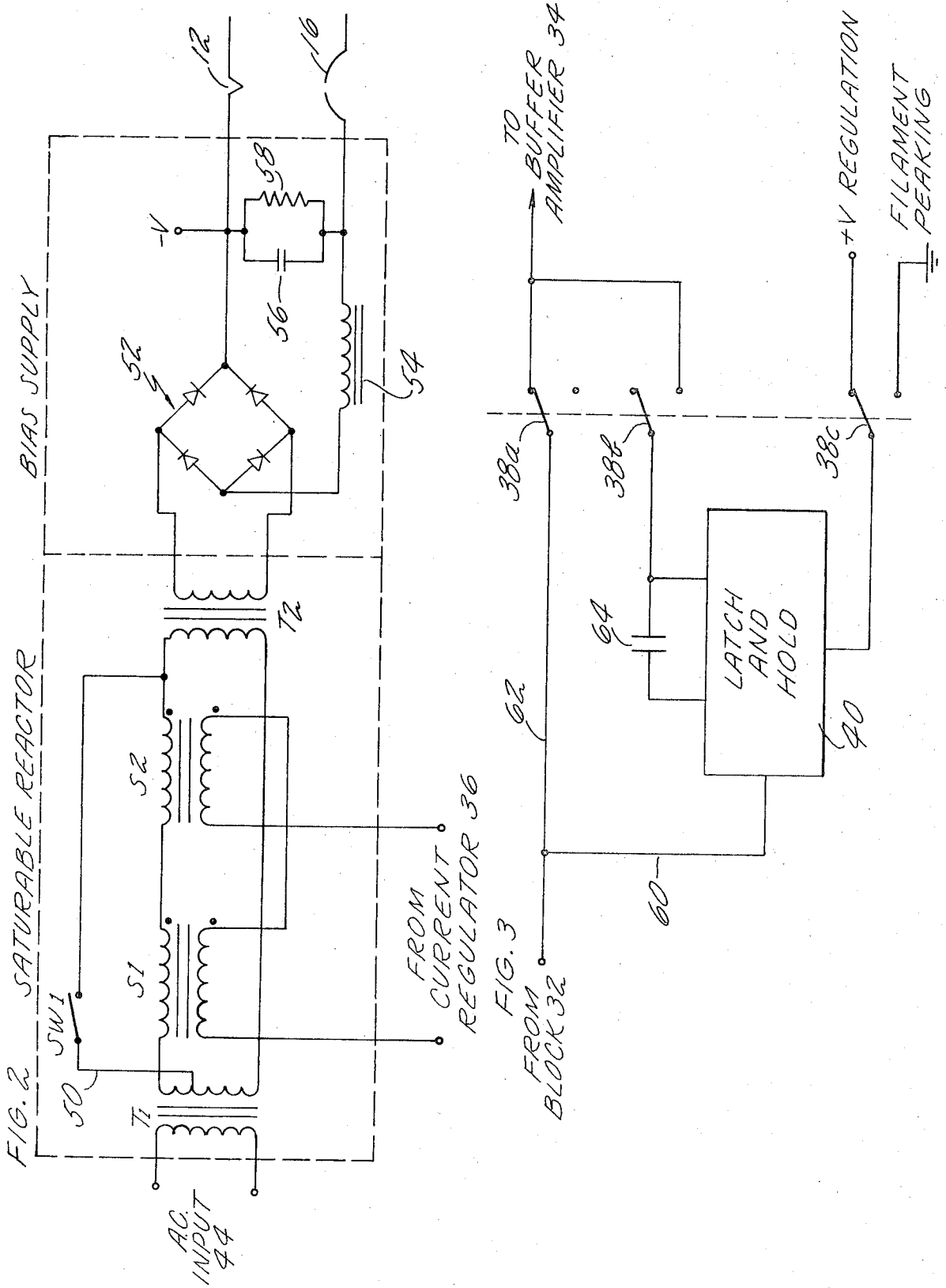

SATURABLE REACTOR
BIAS SUPPLY
SW1
50
T1
S1
S2
T2
52
54
56
58
-V
12
16
AC. INPUT 44
FROM CURRENT REGULATOR 36
FIG. 2
TO BUFFER AMPLIFIER 34
38a
38b
38c
62
64
LATCH AND HOLD
40
60
+V REGULATION
FILAMENT PEAKING
FROM BLOCK 32
FIG. 3

FIG. 4

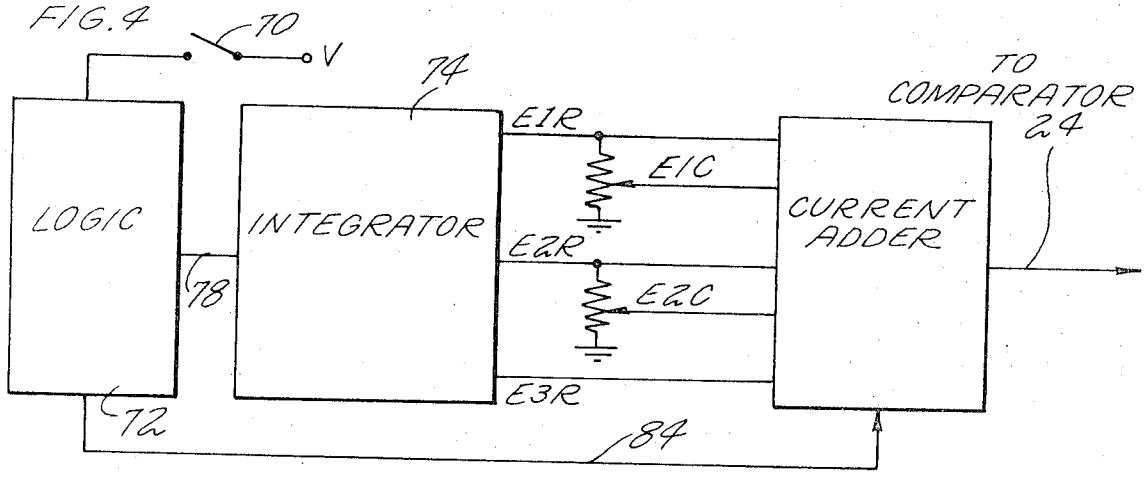


FIG. 5

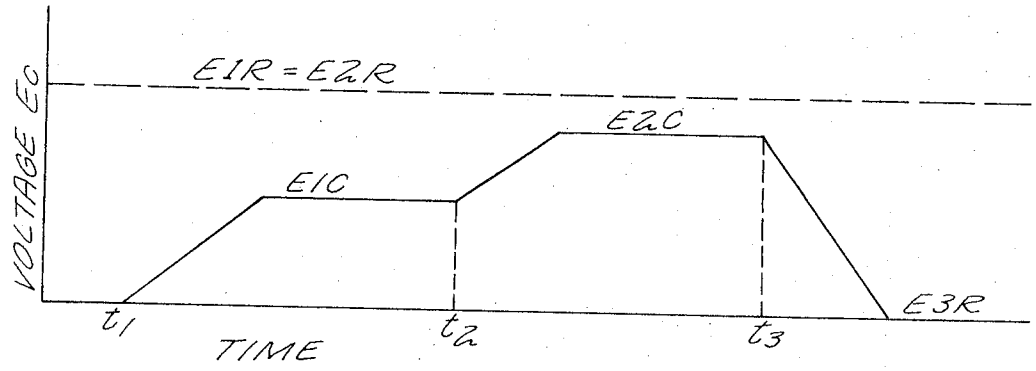
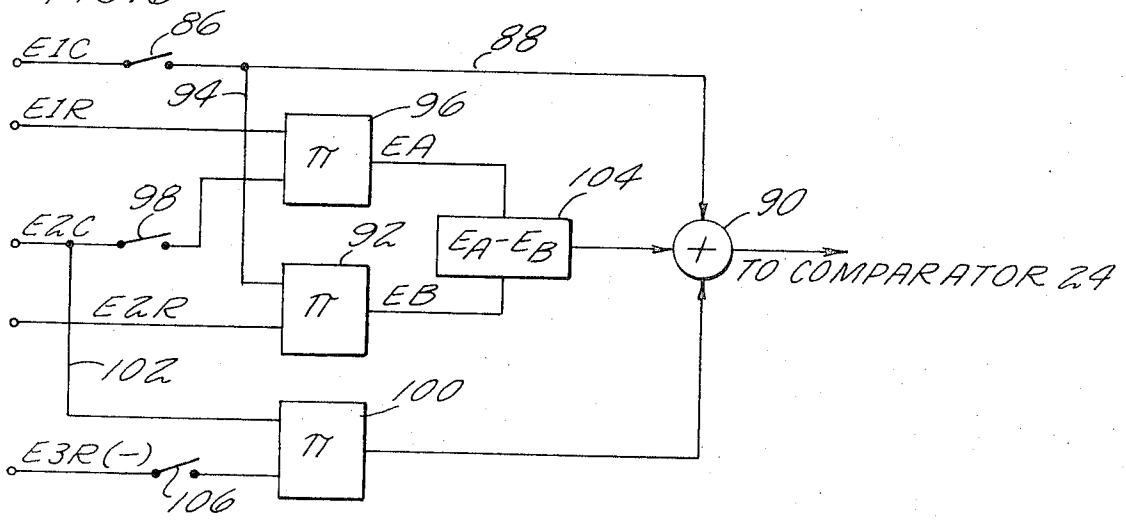


FIG. 6



BEAM CURRENT REGULATOR FOR ELECTRON BEAM MACHINES

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to electron beam machines, and particularly to apparatus for regulating and controlling the beam current. A closed loop feedback control compares actual beam current with a commanded beam current, and any error is used to vary the bias to the electron gun.

2. Description of the Prior Art

Regulation of the high voltage supply in electron guns by means of a feedback system is commonly employed to maintain the voltage at a desired level. When a voltage regulator is employed, changes in the line voltage or load do not appreciably affect the high voltage accelerating potential. However, because the electron gun is commonly situated in an atmosphere of gas and metal vapors created during welding, cutting or other operations, the beam current may vary even though the accelerating potential is maintained constant. Any changes in the perveance of the gun will change the beam current, and as a result the total beam power will change. Variations in beam power will affect the welding or cutting depth or rate and cause undesirable variations in the workpiece.

The present invention provides a beam current regulator which will maintain a commanded beam current regardless of variations in electron gun perveance or other changes in operating characteristics.

In accordance with one aspect of the present invention, there is provided an improved beam current regulator for an electron gun which can be used on existing electron beam machines, is easy to adjust and which performs all logical functions and comparisons at essentially ground potential.

In accordance with another aspect of the present invention, a unique electron gun DC bias control circuit utilizing a saturable reactor is provided for versatile and improved operation of the regulator.

Another feature of the present invention is a novel current adder circuit which enables several sequential levels of beam current to be programmed without returning to the zero current level in between.

A further feature of the present invention is a unique latch and hold circuit which momentarily holds the electron gun bias constant to permit "peaking" of the electron gun filament.

SUMMARY OF THE INVENTION

The present beam current regulator senses the electron beam current produced by the electron gun and converts the current to a DC feedback voltage which is compared with a DC command voltage indicative of desired beam current. Any difference between the feedback and command voltages in the form of a DC error voltage is filtered and compensated, with the appropriate gain being applied thereto, and fed through a differential amplifier into a current regulator where the DC error voltage is converted into a current. The DC current is then supplied to a saturable reactor circuit as a control for the AC current fed to the bias electrode of the electron gun. "Peaking" of the filament may be performed by disconnecting the DC error voltage and applying a constant DC voltage to the current regulator circuit by means of a latch and hold circuit. A novel current adder circuit enables multiple level command voltages to be applied to the electron gun bias sequentially.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** shown in block diagram form the beam current regulating system of the present invention.

FIG. **2** shows in schematic form the saturable reactor and bias supply of FIG. **1.**

FIG. **3** shows schematically the details of the latch and hold circuit of FIG. **1.**

FIG. **4** shows in partial block diagram form a command voltage generator which may be used in conjunction with FIG. **1.**

FIG. **5** is a graph of a representative current waveform produced by the command generator of FIG. **4.**

FIG. **6** shows schematically the details of the current adder of FIG. **4.**

DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring specifically to FIG. **1,** there is shown the beam current regulating system of this invention. A triode electron gun shown generally in schematic form at **10** may be of the type used in any well-known electron beam machine such as a welding machine. In the typical triode electron gun, the filament or cathode **12** is maintained at a high negative potential such as −50 kv or greater relative to an anode **14** which is generally grounded. A bias electrode as shown at **16** is maintained at a potential slightly more negative than the cathode **12,** and variations in the bias potential such as provided by bias supply **18** connected to the bias electrode **16** will control the current produced by the electron gun **10.** Electrons emitted from the filament **12** are accelerated toward the anode **14** and pass through an aperture in its center to impinge on a workpiece shown at **20.** Conventional electron beam machines also contain vacuum chambers, focusing lens, etc. which are not shown in the figure for purposes of clarity.

The beam current which impinges on the workpiece **20** may be sensed by any of several conventional techniques. If the workpiece **20** is grounded, a small resistor (not shown) connected between ground and the high voltage supply will produce a DC voltage drop proportional to beam current as the electrons which comprise the beam current complete the circuit and return to the high voltage supply via the ground connection. The production of the DC feedback voltage proportional to beam current together with any amplifiers required for gain matching are shown in block **22.**

The DC feedback voltage proportional to beam current produced in block **22** is compared in a comparator **24** with a DC command voltage proportional to desired beam current generated in block **26.** In its simplest form the command voltage may be a potentiometer connected to a source of voltage, the operator of the electron beam machine varying the wiper of the potentiometer in accordance with the desired beam current. A more complex command voltage supply in which various beam current programs may be produced will be described in connection with FIGS. **4** and **5.**

If the beam current differs from that set by the machine operator by means of command voltage **26,** a DC error voltage will be generated in comparator **24** which

is proportional to the difference between the desired beam current and the actual beam current. The DC error voltage is fed through a noise filter **28** where the **60** cycle noise inherently present in the feedback signal is removed, and then through a compensation block **30** and a nonlinear gain block **32** where the gains and lags necessary to maintain regulation and stability in the total loop are provided. The nonlinear transconductance of the electron gun and the linear transfer function of the bias supply are combined into a single compensating nonlinear gain in block **32.**

The modified and filtered DC error voltage is then fed into a buffer amplifier **34** where the DC voltage and impedance levels are matched to the input of a current regulator **36.** The current regulator converts the DC voltage from buffer amplifier **34** into a DC current. During "peaking" of the electron gun filament the output from the nonlinear gain block **32** is disconnected from buffer amplifier **34** and the output from a latch and hold circuit **40** is applied to the buffer amplifier **34** through switches **38** as will be described in conjunction with FIG. **3.**

The current regulator or driver stage **36** supplies a DC current proportional to the desireed beam current to a saturable reactor stage **42** to which the high voltage AC is supplied via line **44.** The output from the reactor **42** is an AC voltage having an amplitude proportional to the desired beam current which is then fed to the bias supply **18** which in turn rectifies the AC voltage and provides a DC bias voltage to bias electrode **16.**

The bias supply is a hybrid system which controls bias voltage by direct application of a high potential DC voltage together with an additional bias voltage which is a function of the beam current and which is applied in a negative feedback mode directly to the grid **16.** The additional DC bias voltage is controlled by varying the applied amplitude of the AC voltage supplied via line **44** by controlling the impedance of the saturable reactor **42** in response to a low voltage DC current from the current regulator **36.** Because the bias voltage is at a high potential, it is desirable to regulate it by a low voltage signal and to isolate the high voltage AC from the regulator **36.** FIG. **2** shows in detail the novel saturable reactor circuit which provides the required isolation and enables control of a high voltage system by a low voltage DC current.

Control of the electron beam gun triode configuration at ground level without the use of mechanical devices was a major problem which has been overcome by the use of a hybrid bias supply. As described above a hybrid bias is one in which the high voltage DC is applied to both the filament and the bias electrode through current limiting resistors with an additional variable DC voltage being superimposed on the high voltage DC. This variable DC is provided from a variable AC voltage through an isolation transformer and rectifier-filter circuit. The amplitude of the variable AC voltage is controlled by a DC current from a current regulator stage.

Referring to FIG. **2,** the AC input from source **44** is applied to the primary winding of transformer T_1. The full secondary voltage from transformer T_1 is fed through two saturable reactor stages S1 and S2 and then across the primary winding of isolation transformer T_2. The AC output from the secondary winding of transformer T_2 is fed to bias supply **18** where it is combined with the high voltage DC, rectified, filtered and fed to the bias electrode **16.** A signal line **50** is connected directly to isolation transformer T_2 through switch SW1. The saturable reactors S1 and S2 are fed by DC current from current regulator **36** to vary the impedance of the reactors and regulate the AC voltage across transformer T_2. Two reactors are used in order to attain a symmetrical AC output and minimize the AC feedback upon the current regulator **36.**

The AC voltage on line **50** with switch SW1 closed is selected to be sufficient to assure cutoff of the electron gun if a malfunction occurs in the regulator system, i.e., switch SW1 is a safety device to turn the beam off when the switch is closed. With the switch SW1 open and maximum current flowing from current regulator **36** through saturable reactors S1 and S2, the impedance of reactors S1 and S2 is at a minimum and the voltage across transformer T_2 is at its maximum value sufficient to supply a bias voltage to bias electrode **16** to turn off the electron gun. With minimum or zero current flowing through reactors S1 and S2 from current regulator **36,** the impedance of S1 and S2 is at its maximum and the voltage across transformer T_2 is at a maximum whereby the bias voltage at bias electrode **16** will produce maximum current in the electron gun.

The reactors S1 and S2 may be operated in their linear region to provide easier stabilization of the beam current control. An increase in DC control current produced by current regulator **36** decreases the impedance of S1 and S2 and decreases the electron beam current, and a decrease in DC control current produced by regulator **36** increases the impedance of S1 and S2 and increases the beam current. The DC windings of reactors S1 and S2 are connected in AC opposition to cancel out any AC feedback, the secondary windings of S1 and S2 appearing as pure DC paths.

Connected to the secondary winding of isolation transformer T_2 is a full wave diode bridge rectifier **52** which converts the AC from saturable reactor stage **42** into DC. A choke **54** and a capacitor **56** connected across the output of bridge rectifier **52** smooth the DC from the rectifier. A parasitic load resistor **58** is connected across the capacitor **56.** The high potential DC voltage for the electron gun shown as −V and which may be −50 kv or more is connected to one terminal of the diode bridge rectifier **52** and to the electron gun filament **12.** The electron gun grid **16** is also connected to the high potential DC voltage −V through load resistor **58.** The rectified DC current from rectifier **52** passes through resistor **58** in a direction to always maintain grid **16** at a negative potential relative to filament **12** by an amount determined by the voltage drop across resistor **58,** normally **100** to 2,000 volts. In other words, the grid **16** is maintained at the high potential DC voltage −V with the additional DC voltage produced by the rectified DC from rectifier **52** superimposed thereon, the additional voltage always maintaining the grid **16** more negative than the filament **12** by an amount determined and controlled by the DC current from current regulator **36.**

Each control stage in the current regulator system except for the bias supply stage **18** is varied about ground potential with only the bias supply **18** being at a high potential.

FIG. **3** shows the details of the latch and hold circuit **40** which is inserted between the nonlinear gain block **32** and the buffer amplifier **34.** When a beam current

regulator system as shown in FIG. **1** is employed to maintain the electron gun current at a programmed value, it is difficult to "peak" the electron gun filament. As the filament heats up, the resulting emission current increases and the beam current likewise increases up to the point of space charge saturation. When a beam current regulating system is used, it is difficult to adjust the filament temperature to its optimum value since any variation in the filament temperature for a fixed bias voltage will cause a variation in beam current, and the regulating system will then adjust the bias voltage to maintain a constant beam current. Thus the attainment of peak operating heat at the filament is masked by the inherent operation of the regulating system and the operator has no assurance that the electron gun is operating in its optimum mode.

This problem is overcome by the latch and hold circuit of FIG. **3.** The beam current error signal produced in comparator **24** of FIG. **1,** which is indicative of the difference between the desired beam current and the actual beam current and which after being filtered, compensated and amplified appears as the output from block **32,** is maintained at a constant value for a sufficient time so that the electron filament temperature may be adjusted to its optimum value without changes occurring in the bias voltage. In other words, the latch and hold circuit effectively disconnects the regulator system from the circuit and in its place maintains the bias voltage at a fixed value while the filament is "peaked".

Referring to FIG. **3,** the error signal voltage from nonlinear gain block **32** is fed through signal line **60** into latch and hold circuit **40** where the voltage appearing on line **60** is continuously updated and stored when switch **38**c is connected to the positive voltage terminal +V. With switch **38***c* connected to the +V terminal (the "regulate" mode), the error signal voltage from nonlinear gain block **32** also passes through line **62** and through switch **38***a* to the buffer amplifier **34,** to ultimately regulate the electron beam current. At this time switch **38***b* is open.

When switch **38***c* is moved to the "filament peaking" mode which is at ground potential, switch **38***a* is opened thereby disconnecting the error signal voltage on line **62** from the buffer amplifier **34,** and switch **38***b* is closed thereby connecting the stored voltage signal in the latch and hold circuit **40** to the buffer amplifier **34.** The voltage stored in the latch and hold circuit **40** at this time will be the last voltage level which appeared on line **60.** While in the "filament peaking" mode, the output from the latch and hold circuit **40** slowly decays and can be controlled by a capacitor **64** connected across the output from the latch and hold circuit.

Thus, when switch **38**c is in the "regulate" position, normal beam current regulation occurs. With switch **38***c* in the "filament peaking" position, a constant voltage equal to the last occurring error voltage is fed to the regulator allowing the filament to be "peaked" without any changes occurring in the error voltage. After "peaking" has been effected, switch **38***c* is returned to the "regulate" position and normal beam current regulation is resumed. Since the beam current may have been changed as a result of the "peaking" operation, the control loop should be permitted to stabilize before normal operation of the system is resumed.

FIG. **4** shows how the command voltage generator **26** of FIG. **1** may be implemented to permit the electron beam to be operated at several preprogrammed beam current levels in a sequential manner without returning to the zero current level in between. The beam programmer utilizes a logic network to program an integrator and a current adder at the proper times to produce various sequential voltages which cause the electron gun to produce the desired current levels.

Referring to FIG. **4,** when the beam "on" switch **70** is closed, the logic control **72** is activated and transmits activating signals to integrator **74** and current adder **76** in the proper sequence to cause the current adder to produce the desired output or command voltage. Upon actuation of logic block **72,** a signal is sent to integrator **74** via line **78** and the integrator **74** generates three reference voltages, E1R, E2R and E3R, which are proportional respectively to a first maximum current level, a second maximum current level (which may be identical with the first reference current level), and a final current level (which may be zero). The E1R, E2R and E3R voltages are fed to the current adder **76.** Potentiometers **80** and **82** are adjusted by the machine operator or automatically to produce voltage signals respectively proportional to the desired first current level E1C and the desired second current level E2C, and the E1C and E2C signals are also fed to the current adder **76.** Timing signals are fed to current adder **76** from logic network **72** via line **84** to signal the appropriate times for initiating the desired command voltages.

FIG. **5** shows in graph form the generation of a two level ramp command voltage with a return to zero, but it is apparent that other waveforms of beam current are possible, and that step functions may be incorporated in the control. The voltages E1R and E2R are identical and are proportional to maximum beam current. Voltage E1C is proportional to about 50 percent of maximum beam current, while voltage E2C is proportional to about 80 percent of maximum beam current. Voltage E3R is a voltage which subtracts from the programmed beam currents and provides a return to zero beam current.

FIG. **6** shows the implementation of the command voltage programmer in the current adder **76** to produce the command voltage function shown in FIG. **5.** At time t_1 logic network sends a signal via line **84** to the current adder **76,** and in response thereto switch **86** is closed. The voltage E1C (which is shown to be about 50 percent of the voltage E1R) is fed via line **88** to summing junction **90** and voltage E1R is fed to multiplier **96.** At this time all other inputs to summer **90** are zero, and the output Ec from summer **90** is fed to comparator **24** of FIG. **1.** FIG. **5** shows that voltage level E1C is reached by means of a time delay or ramp from the zero voltage level, but the level E1C could be reached by a step function as will be obvious to those skilled in the art. The voltage E1C is also fed to multipler **92** via line **94,** but no output is generated from multiplier **92** and **96** at this time because both E2C and E2R are still zero.

At time t_2 a second signal is fed from logic network **72** to current adder **76** to close switch **98** and apply voltage E2C to multiplier **96.** Voltage E2R is also applied to multiplier **92** at this time, and voltage E2C is fed to multiplier **100** via line **102.** Voltage E2C is shown to be about **80** percent of voltage E2R. The output from multiplier **100** is zero at this time because voltage E3R is zero. As E2R and E2C increase to their

final values, the output from summer **90** increases to a level equal to E2C as explained below.

With switch **98** closed, multiplier **96** receives voltages E1R and E2C, and its output EA is E1R·E2C·K (K is a proportionality factor). Multiplier **92** receives voltages E1C and E2R, and its output EB is E1C·E2R·K. The voltage EB is subtracted from voltage EA in differential stage **104,** and the output from the differential stage **104** is fed to summer **90** to be added to the E1C voltage fed to summer **90** via line **88.**

The output from differential stage **104** is E*A*–E*B*.

$$EA = E1R \cdot E2C \cdot K$$

and

$$EB = E1C \cdot E2R \cdot K,$$

therefore

$$EA–EB = E1R \cdot E2C \cdot K - E1C \cdot E2R \cdot K.$$

Since by design $E1R = E2R$,

$$EA–EB = E2R \cdot K\ (E2C–E1C)$$

and if K is set equal to $1/E2R$, then

$$EA–EB = E2C–E1C.$$

The output from summer **90** now is

$$E1C + (E2C–E1C) = E2C.$$

At time t_3, switch **106** is closed by a signal from logic network **72** via line **84,** and voltage E3R (with a polarity opposite that from E1R and E2R) is fed to multiplier **100.** Voltage E2C is fed to multiplier **100** via line **102.** If E3R is made unity, the output from multiplier **100** is – E2C, which is then fed to summer **90** and subtracts from the EC voltage fed to comparator **24.** EC then reduces to zero. E3R can, however, assume other values which would reduce Ec to some voltage other than zero and command a fixed current level.

Upon termination of the command voltage program, logic network **72** instructs current adder **76** to open switches **86, 98** and **106,** and Ec will then become zero.

It is obvious that other combinations of command voltages may be programmed by the novel current adder.

While the present invention has been described with respect to its preferred embodiment, it will be apparent that changes may be made in its construction and operation without departing from the scope of the invention as hereinafter claimed.

I claim:

1. A beam current regulator for an electron gun having a filament and a bias electrode comprising

means for sensing the electron gun beam current and producing a beam current signal indicative thereof,

means for generating a beam command signal indicative of desired electron gun beam current,

a comparator for comparing said beam current signal with said beam command signal to produce a beam current error signal variable as the difference therebetween,

first and second saturable reactors having input and output windings, the output windings of said reactors being connected in series and the input windings thereof being connected in series opposition,

a source of alternating voltage,

means for connecting said alternating voltage source to one end of said series connected saturable reactor output windings,

means for connecting said beam current error signal to the input windings of said saturable reactors to vary the impedance of said saturable reactors inversely with the magnitude of said beam current error signal,

output means connected to the pposite end of said series connected saturable reactor output windings for producing an ac output signal having an amplitude variable with the magnitude of said beam current error signal,

means for rectifying said ac output signal to produce therefrom a dc bias voltage,

and means for connecting said dc bias voltage to said electron gun bias electrode.

2. A beam current regulator as in claim **1** and including

means for producing a high potential negative dc voltage,

means for connecting said high potential negative dc voltage to said electron gun filament,

means for combining said dc bias voltage with said high potential negative dc voltage so that said combined voltage is more negative than said high potential dc voltage by the amount of said dc bias voltage,

and means for connecting said combined voltage to said electron gun bias electrode.

3. A beam current regulator as in claim **1** wherein said means for producing a beam command signal comprises

integrator means producing first and second voltage reference signals of equal magnitude,

means for selectively producing from said first and second voltage reference signals respectively first and second variable command voltage signals, and

current adder means including multiplier means for receiving said first and second voltage reference signals and said first and second command voltage signals, said current adder means producing a beam command signal which will cause said beam current to achieve a first level as a function of said first command voltage signal, and subsequently to achieve a second level as a function of said second command voltage signal.

4. A beam current regulator for an electron gun, said gun having a filament and a bias electrode, comprising

means for sensing the electron gun beam current and producing a beam current singal indicative thereof,

means for producing a beam command signal indicative of desired electron gun beam current,

means comparing said beam current signal with said beam command signal to produce a beam current error signal variable as the difference therebetween,

means responsive to said error signal for generating a dc bias voltage,

means for connecting said dc bias voltage to said bias electrode,

a signal storage circuit,

means connecting said error signal with said storage circuit to store therein the value of said error signal,

and switching means for disconnecting said error signal from said bias voltage generating means and connecting in place thereof the value of the error signal stored in said signal storage circuit.

* * * * *

PO-1050
(5/6?)

UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,838,313 Dated September 24, 1974

Inventor(s) Harry B. Anderson

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Column 2, line 7, "shown" should be --shows--

Column 4, lines 23-24, "maximum" should be --minimum--

Column 7, line 35, both "EC" should be --Ec--

Column 8, claim 1, line 10, "pposite" should be --opposite--

Column 8, claim 4, line 55, "singal" should be --signal--

Signed and sealed this 12th day of November 1974.

(SEAL)
Attest:

McCOY M. GIBSON JR.
Attesting Officer

C. MARSHALL DANN
Commissioner of Patents