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Fred Coffield
George Caporaso
Jan-Mark Zentler

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THE FAST CORRECTION COIL FEEDBACK CONTROL SYSTEM[*]

Fred Coffield, George Caporaso, and Jan-Mark Zentler
Lawrence Livermore National Laboratory, Livermore, California, USA

A model-based feedback control system has been developed to correct beam displacement errors in the Advanced Test Accelerator (ATA) electron beam accelerator. The feedback control system drives an X/Y dipole steering system that has a 40-MHz bandwidth and can produce ±300-Gauss-cm dipole fields. A simulator was used to develop the control algorithm and to quantify the expected performance in the presence of beam position measurement noise and accelerator timing jitter. The major problem to date has been protecting the amplifiers from the voltage that is inductively coupled to the steering bars by the beam.

1. Introduction

ATA is a linear induction accelerator that is configured to produce a 10-MeV, 8-kA beam. Beam transport is accomplished by solenoidal magnets that provide a magnetic field oriented along the axis of the accelerator. Beam energy variations within a beam pulse and misalignments of the solenoidal magnets combine to produce intrapulse beam displacement errors. These beam displacement errors limit the utility of the electron beam. The Fast Correction Coil (FCC) is an X/Y dipole steering system that is designed to correct beam deflection errors within the 40-ns beam pulse [1]. The feedback control system uses four waveform generators to generate correction waveforms. The correction waveforms are amplified and applied to steering bars to produce time-varying dipole steering fields. This paper covers the design of the feedback control system, initial performance results, and simulation predictions for the FCC system.

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2. System Configuration

A traditional steering coil is too inductive to be driven at high frequency and, because the coils are external to the beamline, the fields could not diffuse through the beam tube rapidly enough. The steering bars are illustrated in Fig. 1. The two pairs of parallel bars provide both X and Y deflection. The diagonally opposite bars are driven by signals that are equal and opposite polarity; this assures midplane symmetry. A splitter/inverter, shown in Fig. 2, takes the unipolar output of the amplifier and produces two outputs of identical shape and opposite polarity. Figure 3 shows how two amplifiers are connected to four steering bars to give X/Y steering.

The splitter/inverter has the additional function of limiting the beam-induced voltage. The steering bars are inductively coupled to the beam. When the beam is centered the beam-induced voltage is identical on two opposite bars. The splitter/inverter subtracts the two voltages, so that the amplifier only sees the difference. As long as the displacement is not too large, the difference in voltage is small enough that the amplifier will not break down.

Bipolar amplifiers with the required performance level are very expensive, so a unipolar amplifier was adapted to this application. An additional dipole steering coil is added around the the FCC to provide a constant steering displacement so that the unipolar amplifier can produce bipolar net steering displacement.

The steering drive signals are applied to the downstream ends of the steering bars. The net beam deflection is the sum of the electrostatic and magnetic deflections. When the steering signal is propagating in the opposite direction to the beam, the electrostatic and magnetic forces are approximately equal and in the same direction. When the steering signal is traveling in the beam direction, the magnetic and electrostatic forces are in opposite directions so that they cancel each other out.

3. Feedback Control Algorithm

The accelerator is designed to operate in burst mode, with one to five pulses per burst and pulse separation of 1.2 ms. Successive pulses in a single burst may vary in shape and relative timing, but corresponding pulses in each burst are fairly repeatable. Therefore, the correction waveforms for successive pulses in a burst must be unique, but they can be calculated from preceding bursts.

The beam deflection, or error signal, is measured by a pair of beam position monitors (beam bugs) separated by a field-free region. Simple geometry is used to calculate the offset and angle of the beam (x, x', y, y'). The matrix equations used to calculate the beam propagation in the forward direction can be inverted to calculate beam propagation in the backward direction by inverting x' and y' and setting B=–B in the solenoids. These equations are used to back-propagate the beam from the beam bug measurement location to the second FCC (see Fig. 4).

Calculating the angular deflection required from the first FCC is complicated by the solenoid located between the two FCCs. The solution is to expand the transport equations for x and y at the second FCC, taking into account the drifts between the centers of the FCCs and the solenoid. The FCC deflections can be ignored because the geometric error introduced is negligibly small. An angular term is added to x' and y' at the first FCC to account for the angular kick produced by the FCC. The displacement (x and y) at the second FCC is set equal to zero, and the two simultaneous equations are inverted and solved for the required angular kicks from the first FCC. The new x' and y' at the first FCC are then forward-propagated to the second FCC to calculate the angular kick required to point the beam down the center of the beam pipe. The two FCCs constitute a pointing-and-centering control system.

Both the simulator and the finished control system (Fig. 5) were developed using an application software package called *LabView* that runs on the Macintosh family of computers. This approach was chosen because writing a custom software package with the required performance and flexibility was unreasonable in the time available.

The simulator data is naturally represented by four vectors (Fig. 5). The vectors represent the time history of each parameter. The four vectors are x, x', y, and y' in the transport model. In other parts of the simulator the four vectors represent the four steering fields, four different currents in the FCCs, or four beam-bug waveforms.

4. Purpose of the Simulation

Existing design codes could not be used to simulate the system because they could not easily include the effects of feedback. Applying feedback has many advantages, including the fact that the model does not have to be perfect. The system iterates until it converges to the desired solution. The better the model, the faster the system converges, but it doesn't fail catastrophically if the model is inaccurate. Feedback can also compensate for limitations in the system, such as rise time and nonlinearity. Rise time limitations can be partially compensated for by applying overdrive to the amplifier input. The correction waveforms become distorted after several iterations so that nonlinearity and rise-time-related errors are reduced.

The simulator was developed to test a number of design concepts for the control algorithm, to check the beamline layout, and to verify expected system performance. The simulator is made up of several parts (Fig. 4) that include a simple beam transverse displacement or corkscrew model, the FCC transport model, the feedback control algorithm, the FCC amplifier, and the correction coil model. The corkscrew model takes into account the phase advance of the accelerator, fractional energy variation, flat-top duration, and the initial spatial offset of the beam. The transport model uses first-order beam optics equations to solve for the centroid motion of the beam. It also assumes that the beam is mono-energetic. The feedback control algorithm is a model-based feedback control system where the model accounts for transport through the FCC beamline and also predistorts the correction waveforms to compensate for the impulse response of the FCC amplifier and the FCCs. The FCC amplifier model takes into account the limited bandwidth of the amplifier and its nonlinearity. The FCC model includes the effect of reflections within the structure that are due to impedance mismatches at the feed cable and at the ends of the bars and accounts for the finite transit time of the beam along the length of the bars[2].

The simulator revealed that the major limitations on how well the FCC can correct beam displacement and pointing errors are beam position monitor ("beam bug") measurement noise and timing jitter in the accelerator. The simulator includes timing jitter in the corkscrew model.

and zero-mean Gaussian noise can be added to the simulated beam-bug waveforms before they go to the feedback control algorithm.

5. Simulation Results

The simulator was used to predict the performance of the FCC in the presence of beam-bug measurement noise and accelerator timing jitter. In the absence of these effects, the feedback control system can reduce, in principle, the beam displacement error to zero. In practice, the residual error is sensitive to the level of noise and jitter and can be reduced by lowering the loop gain. Of the two sources of error, jitter was found to be the most critical. The best that can be done is for the correction waveform to time-align to the mean time of the beam and to correct the systematic portion of the beam error. Timing jitter then produces displacement error that is random in amplitude as the accelerator beam pulse aligns with the correction waveform or is mistimed.

Setting the loop gain to unity means that the control algorithm applies the full amplitude of the predicted correction waveform from the previous pulse to the next pulse. This is a borderline unstable situation because of pulse-to-pulse variation and because the model does not match the accelerator beamline exactly. Reducing the loop gain means that the correction waveform is the weighted sum of the correction waveforms calculated from all previous pulses. The system slowly converges to the desired solution. As the error gets smaller, the correction waveforms are changed very slowly. The only changes are those introduced by noise and jitter and those caused by slow changes in accelerator performance.

Figure 6 shows the predicted performance of the FCC system under realistic conditions. The simulator was run for 1000 iterations to achieve reasonable statistical results. The results show that the experimental requirements can be achieved on a large percentage of pulses.

6. Hardware Implementation

The steering coils are two sets of bars that run parallel to the beam propagation direction. The size and spacing of the bars result in a constant characteristic impedance of 100 ohms. The amplifier driving the steering bars has a bandwidth of 40 MHz and a full-scale output of 120 A. An FCC amplifier utilizes five boards in parallel to achieve a maximum output current of 120 A into 50 ohms (6 kV) [3]. Each of the five boards has two parallel planar triodes that are driven in cascode by a power MosFET. The MosFET is driven by a pair of high-speed operational amplifiers. A simplified schematic is shown in Fig. 7.

The system block diagram is shown in figure 8. The beam bug signals are digitized by a 500-megasample/second transient digitizer with nominal 8-bit vertical resolution. The control software runs on a Macintosh II with an accelerator card that contains a 68030 processor running at 33 MHz. The correction waveforms are downloaded into four waveform generators that operate at 500 megasamples/second. As discussed earlier, timing jitter cannot be tolerated by the control algorithm, so a custom timing chassis was developed. The timing chassis contains a 500-MHz crystal oscillator that provides a clock signal for the digitizer, the delay generator, the accelerator timing system, and gated clocks for the waveform generators.

The waveform generators are driven by gated clocks because unique correction waveforms are required for each of the five pulses in a burst. All five correction waveforms are downloaded as a single waveform, and the clock is gated on and off to output the waveforms at the appropriate times.

7. Initial Results

The FCC is installed in the Advanced Test Accelerator (ATA) beamline. ATA is a linear induction electron accelerator and has been configured to produce 10-MeV beams of up to 8 kA. The FCC has been operated with beams of up to 4 kA. A single amplifier was used to demonstrate beam deflection and time-dependent steering.

The major problem has been protecting the amplifier from the beam-induced voltage pulse generated by the beam's passing through the steering bars. When the beam sweep is large, the beam induced voltage pulses generated on different bars do not cancel. The amplifier is then subjected to these potentially large voltages With the amplifer output tube off, the voltage pulse is doubled because the tube looks like an open circuit. Modifications to the bar structure (changing the shorted end to a 50 Ω termination) are under way, which should reduce these voltages by almost a factor of two.

8. Conclusions

The Fast Correction Coil dipole steering system has been developed to correct beam displacement errors within a 50-ns beam pulse. The 40-MHz bandwidth of the system has been used to demonstrate time-dependent steering. The system is being modified to protect the amplifiers from large beam-induced voltages coupled from the beam.

References

[1] K. Whitham, G. Caporaso, R. Thomas, G. Vogtlin, J. Zentler, and F. Coffield, "Fast Correction Coils for Induction Accelerators," presented at 7th IEEE Pulsed Power Conference, Monterey, CA, June 11-14, 1989.

[2] J-M Zentler, G. E. Vogtlin, and R. A. Thomas, "Modeling of the Proposed ATA Fast Correction Coils," presented at 7th IEEE Pulsed Power Conference, Monterey, CA, June 11-14, 1989.

[3] E. E. Bowles and W. C. Turner, "50 MHz 12 MW Induction Linac Current Modulator," presented at 7th IEEE Pulsed Power Conference, Monterey, CA, June 11-14, 1989.

Figure Captions

Figure 1. FCC steering bars. The graphite shield prevents direct beam strikes on the steering bars.

Figure 2. The splitter/inverter is a cable transformer that takes a unipolar amplifier output and produces two outputs of identical shape and opposite polarity.

Figure 3. Two amplifiers provide *X* and *Y* steering. An external steering field is required to enable bipolar steering.

Figure 4. Solenoids 1–3 transport the beam through the FCC beamline. BB1 and 2 are beam bugs used to measure the beam displacement errors that the FCC is designed to correct.

Figure 5. FCC simulator block diagram. The free parameters of the model are indicated as inputs to each block. The variables within brackets indicate the vector quantities that are passed from to block to block.

Figure 6. The histograms show the predicted net performance of the FCC in the presence of typical timing jitter and beam displacement measurement noise.

Figure 7. Simplified schematic of a single amplifier module. Five modules are required for one amplifier.

Figure 8. FCC control system block diagram.

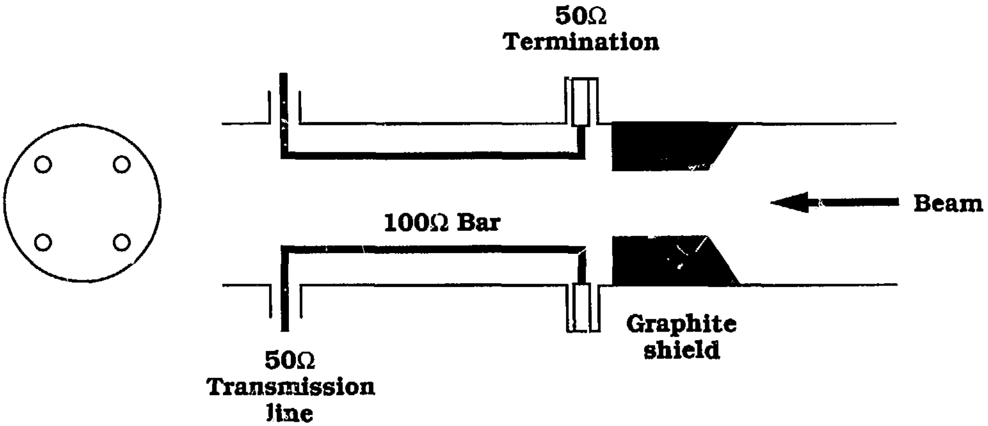

50Ω
Termination
Beam
100Ω Bar
Graphite
shield
50Ω
Transmission
line

Figure 1

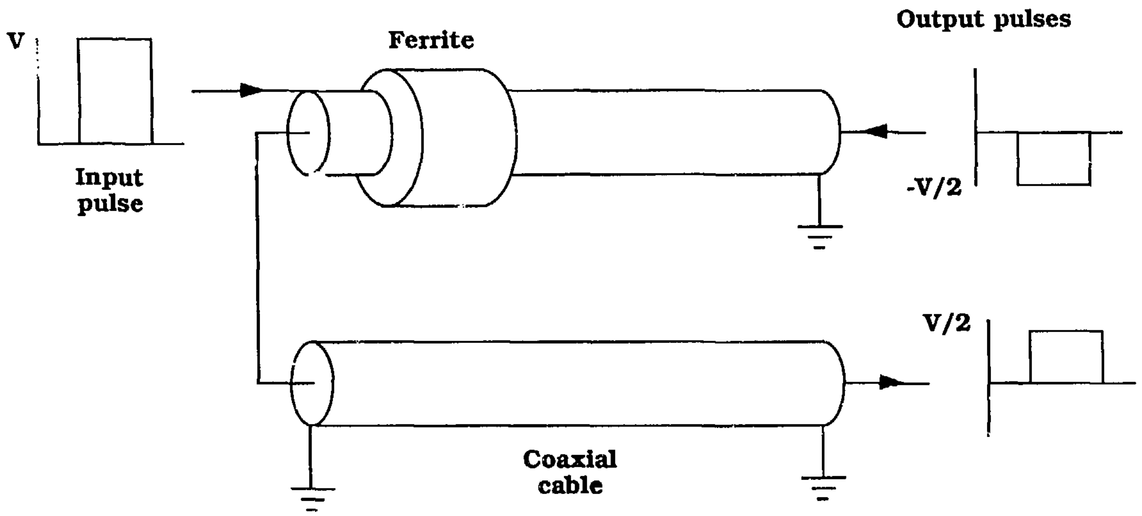


Figure 2

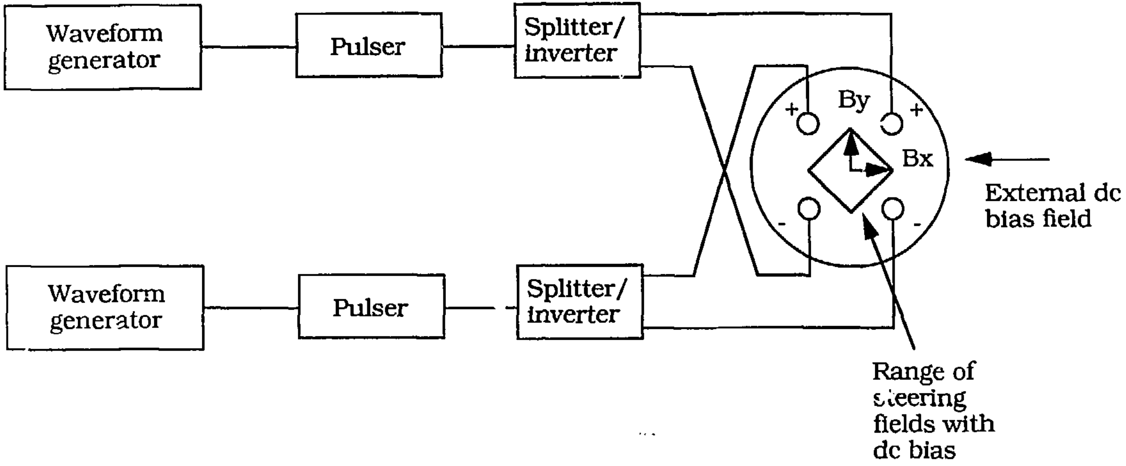

Waveform generator
Pulser
Splitter/ inverter
Waveform generator
Pulser
Splitter/ inverter
+
By
+
Bx
-
-
External dc bias field
Range of steering fields with dc bias

Figure 3

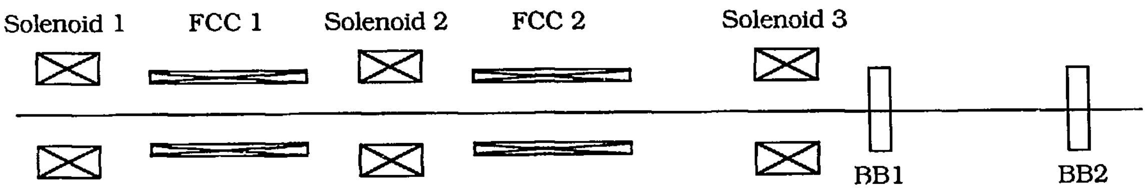


Figure 4

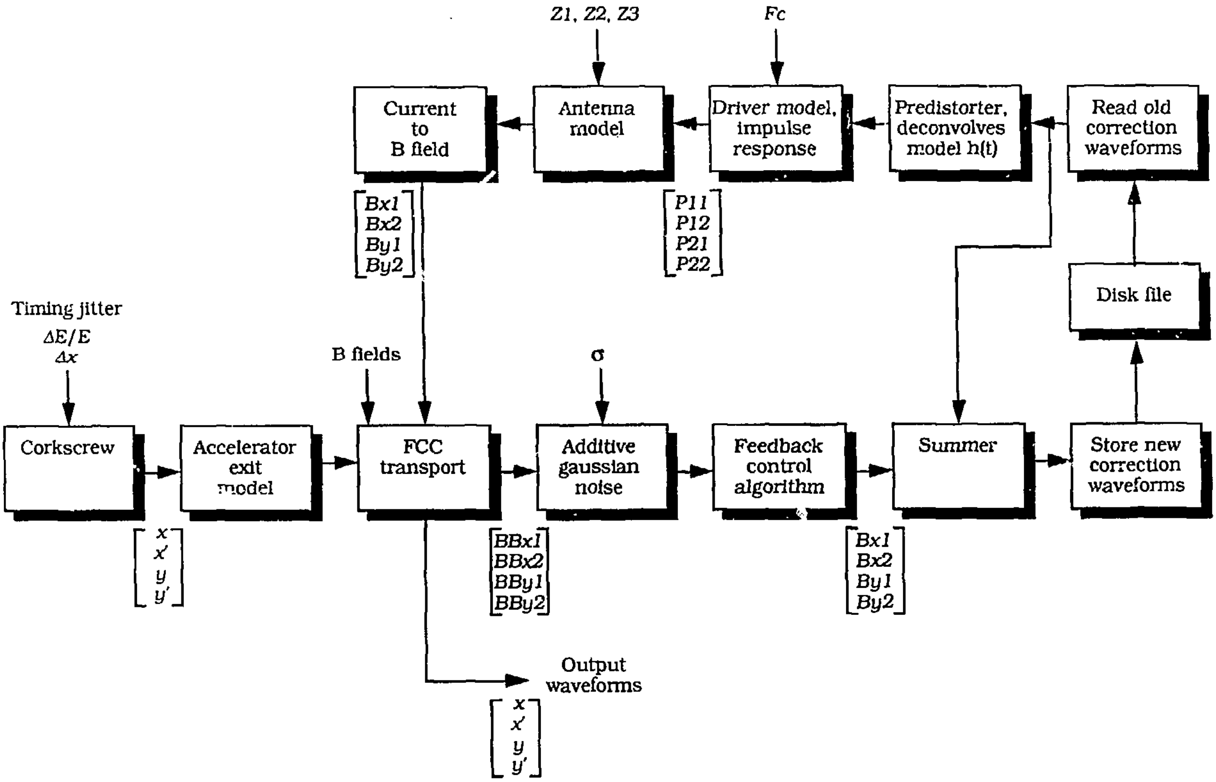
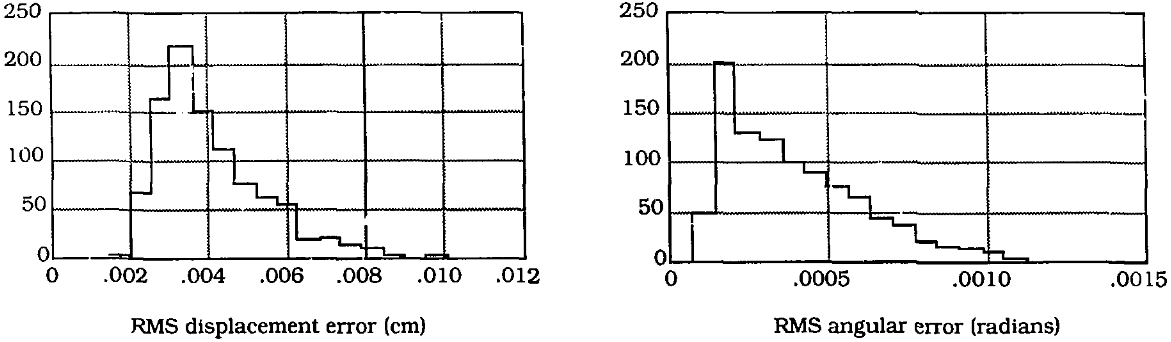

Z1, Z2, Z3
Fc
Current to B field
Antenna model
Driver model, impulse response
Predistorter, deconvolves model h(t)
Read old correction waveforms
Bx1 Bx2 By1 By2
P11 P12 P21 P22
Disk file
Timing jitter
ΔE/E
Δx
B fields
σ
Corkscrew
Accelerator exit model
FCC transport
Additive gaussian noise
Feedback control algorithm
Summer
Store new correction waveforms
x x′ y y′
BBx1 BBx2 BBy1 BBy2
Bx1 Bx2 By1 By2
Output waveforms
x x′ y y′

Figure 5



Initial offset = 0.1 cm

Energy variation = 1.5%

Beam-bug noise (1σ) = 0.025 cm

Beam-bug separation = 50 cm

Timing jitter (1σ) = 1 ns

Loop gain = 0.1

1000 trials

Figure 6

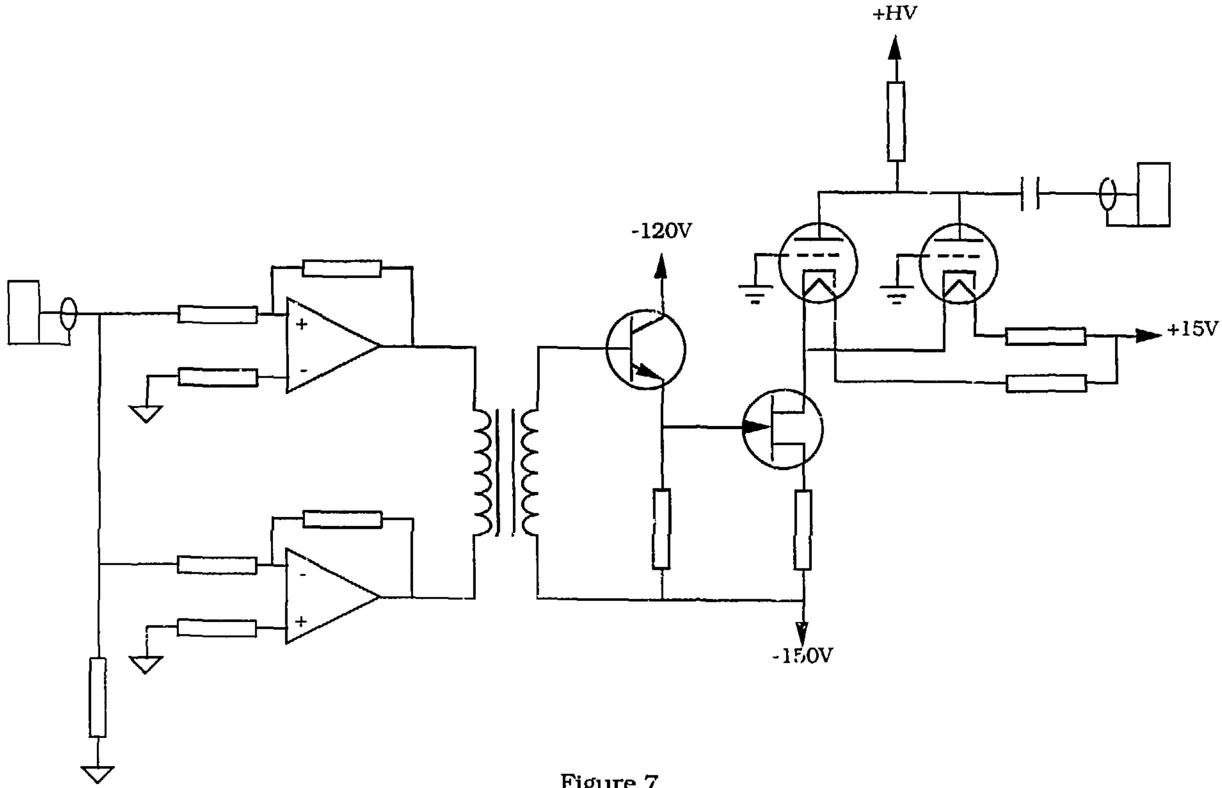


Figure 7

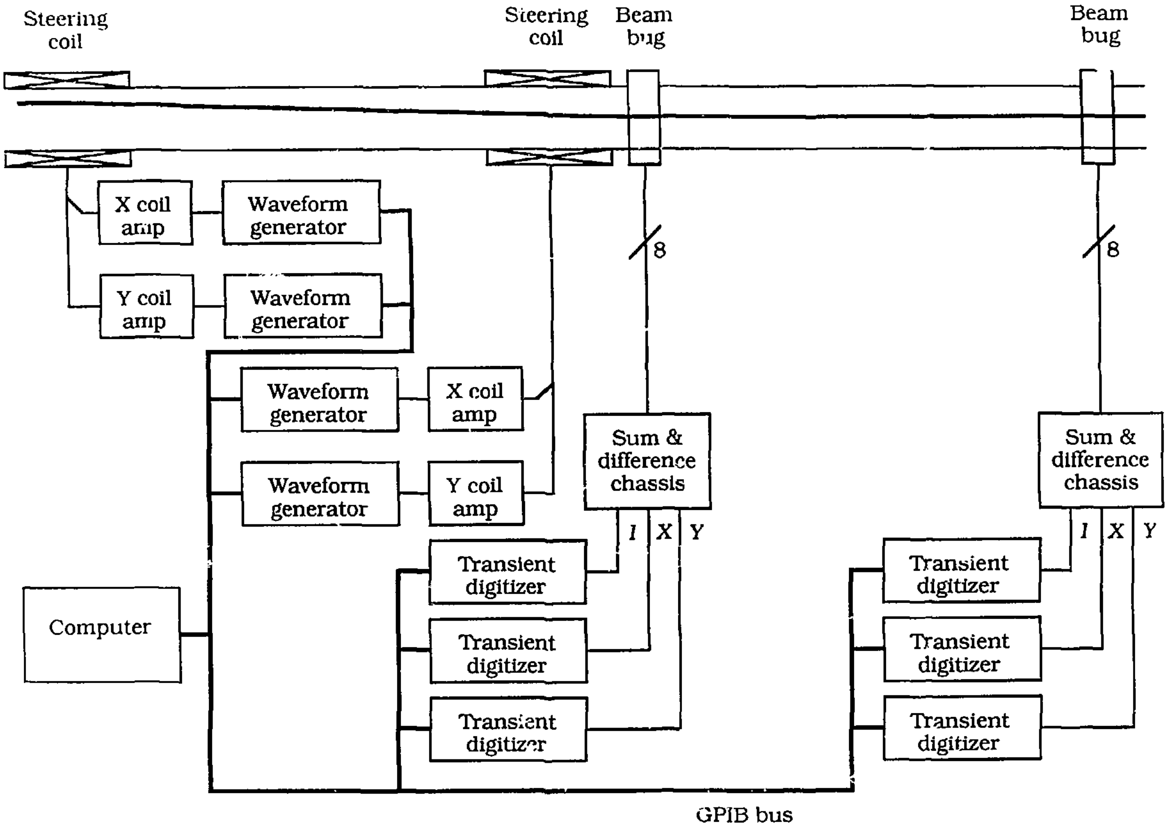

Steering coil
Steering coil
Beam bug
Beam bug
8
8
X coil amp
Waveform generator
Y coil amp
Waveform generator
Waveform generator
X coil amp
Waveform generator
Y coil amp
Sum & difference chassis
Sum & difference chassis
I
X
Y
I
X
Y
Transient digitizer
Transient digitizer
Transient digitizer
Transient digitizer
Transient digitizer
Transient digitizer
Computer
GPIB bus

Figure 8