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Author

Voelker, F

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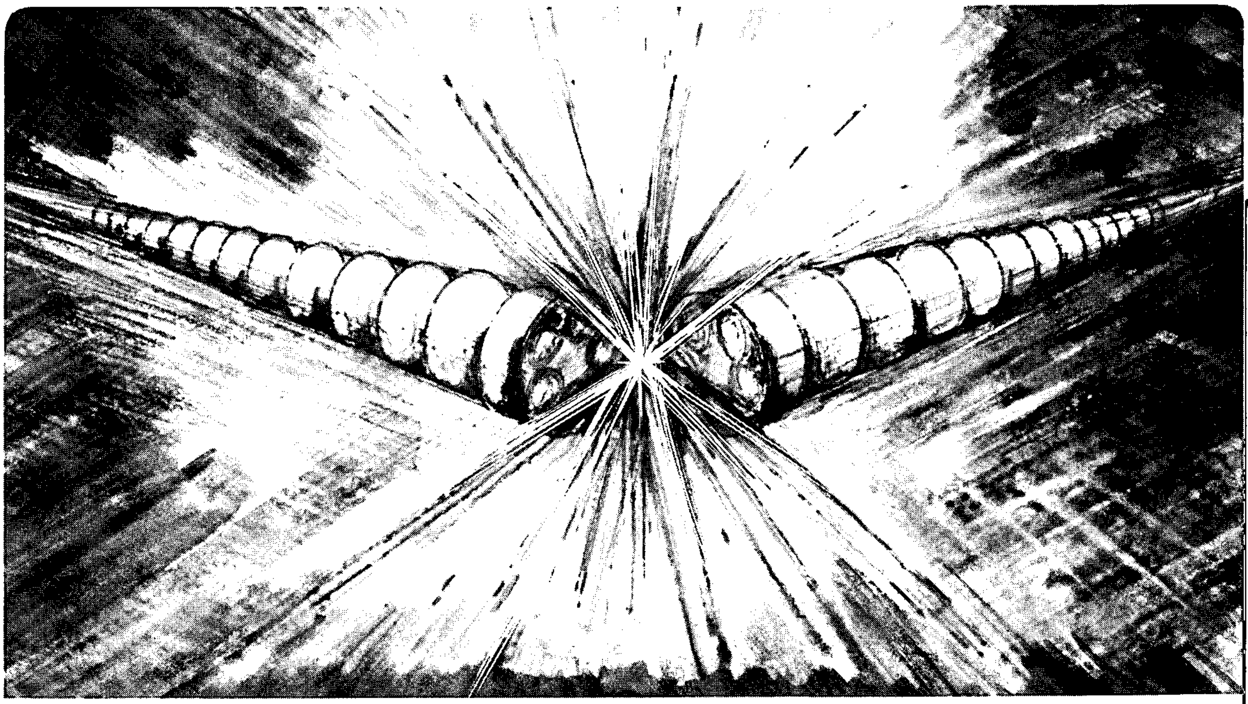
ALS Longitudinal Kickers

F. Voelker

October 1992



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ALS Longitudinal Kickers*

F. Voelker

Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

The 1992 Accelerator Instrumentation Workshop,
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ALS LONGITUDINAL KICKERS

F. Voelker
Lawrence Berkeley Laboratory, Berkeley, CA 94563

ABSTRACT

This paper discusses the coupled-bunch instability and how it applies to the ALS accelerator. The longitudinal ALS kicker is part of the bunch-to-bunch feedback system planned to control coupled-bunch instabilities in the ALS. The mechanical features of the kicker are described, and the analytic tools developed to aid in the design are discussed. A method to predict the performance of the kicker in the accelerator from measurements on a prototype are described.

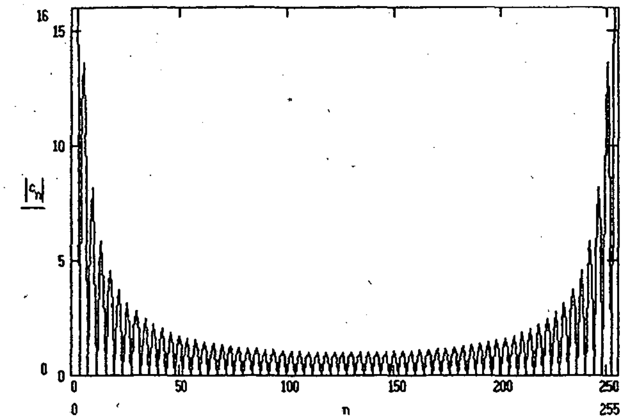
INTRODUCTION

ALS longitudinal kickers are part of the feedback system designed to damp the coupled bunch oscillations. Any given bunch passing through an rf cavity or other resonant structure in the beam path excites electric and magnetic fields that persist long enough to affect the following bunches. This coupling of one bunch to succeeding bunches can result in growing oscillations that destroy the beam. Both longitudinal and transverse resonances can be excited, but in this paper we are concerned with the hardware necessary to control the longitudinal modes.

If all the rf buckets in the ALS were filled there would be 328 beam bunches; in the multibunch mode as many as 250 may be filled. Consequently, there are 250 to 328 possible modes that can be excited. Even a likely fraction of these is a large number to control with individual tuning devices, and a bunch-to-bunch feedback system working in real time will be used to damp these modes. Calculations of the cavity mode impedances and estimates of beam errors at injection indicate that the longitudinal kicker needs a 3 kV kick. A single strip line with an impedance of 50 ohms would require 22.5 kW of wide-band power costing of the order of $150 per watt. It is clearly necessary to use an array of kickers designed to reduce the power. Choice of operating frequency is influenced by space available for the electrodes and the band-width of the array.

COUPLED-BUNCH MODES

If there is a single bunch in the machine, an electrode in the beam pipe sees a current impulse every revolution. The signal induced on the electrode has Fourier components at multiples of the revolution frequency hf_0. Since the bunches are about 30 picoseconds long, the signal has harmonics up to 20 GHz. In the ALS in the multibunch mode, all the rf buckets are filled except for a gap in the beam. This is an amplitude modulation of the current and modulates the intensity of the lines at hf_0 in a characteristic way that repeats at each multiple of Mf_0, where h is the harmonic number and M is the number of bunches if the machine is completely filled. An example of amplitude modulation of the spectrum for a beam with 25 % of the rf buckets empty is shown below. A Fast Fourier Transform (which requires 2^m points) was used for the calculation, so this example has M = 256 rf buckets.



Amplitude Modulation of Spectrum by 25 % Gap

Figure 1

The amplitude modulation of the beam should not be confused with the phase modulation caused by bunches oscillating around the synchronous phase angle at the synchrotron frequency f_s. Amplitude modulation is not related to coupled-bunch motion, but it does cause line spectra that the feedback components must be able to live with. It is a sort of noise that the feedback system must work with. Phase modulation appears as a variation of the arrival time of the bunch on each revolution. Coupled-bunch motion is related to this phase modulation. The time modulation results in a splitting of the spectral lines into upper and lower side bands. Since the modulation is small, we will be concerned only with the strongest side bands represented by lines at $hf_0 \pm fs$.

For the rest of this discussion, to avoid confusion with the amplitude modulation, we will consider what happens with no gap and all buckets filled. Let M be the number of bunches if the machine is completely filled. (M = 328 for the ALS.) The modes can be characterized by the phase shift between adjacent bunches. For the nth mode, the phase shift between adjacent bunches is $2 n \pi / M$, for $0 > n > M-1$. Any phase pattern of the bunches in the machine is made up of a combination of these modes, and this pattern repeats at multiples of Mf_0. Shown below is a mode spectrum without amplitude modulation; the modes are numbered

0 to M - 1; notice that each mode appears at two frequencies within each frequency interval mMf_o to $(m+1)Mf_o$.

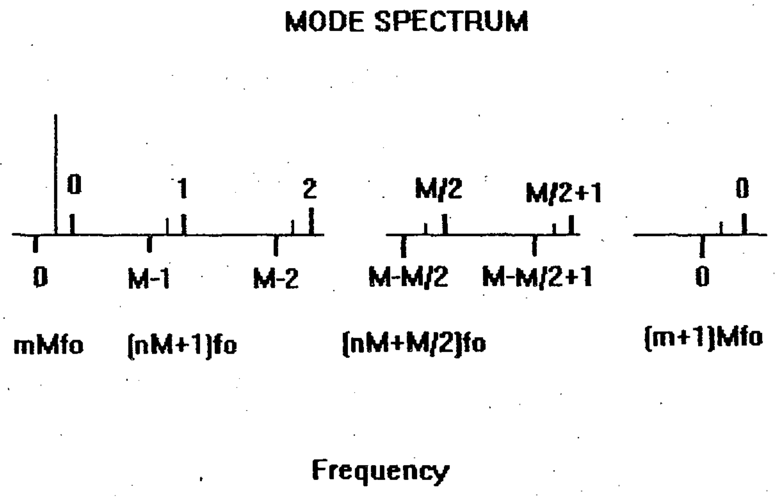


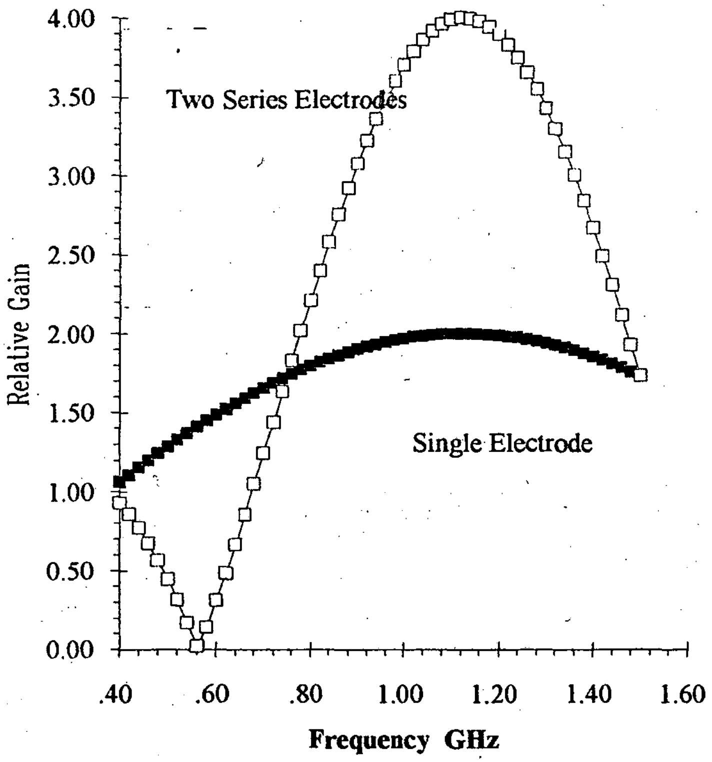
Figure 2

The discontinuities in the beam pipe such as cavities, bellows, etc. have resonances that present impedances to the circulating beam, and these are distributed over the whole spectrum. A typical resonance in the beam pipe devices extends over many spectral lines, and there are a large number of resonances with a variety of Q's. Remember that the spectral lines generated by the circulating beam bunches represent current at discreet frequencies. The product of current and the real part of the beam impedance results in electromagnetic field being developed in the particular device that produces the beam impedance. The fields in a resonator persist long enough to affect the following bunches. The $hf_o + f_s$ lines represent bunch motion that grows in reaction to the induced fields, and the $hf_o - f_s$ lines represent motions that damp. The total driving force for the nth coupled-bunch mode is determined by adding up the sum of the real part of the beam impedance at the frequencies $mMf_o + nf_o + f_s$, and the sum of the real part of the beam impedance at $mMf_o + (M-n)f_o - f_s$. The difference in these sums is the driving force that excites or damps the nth mode.

The mode pattern repeats at each multiple m of $M f_o$. Notice that all M spectral lines are included once in the frequency range from 0 to $M/2\ f_o$. This is a sufficient band width for a real time kicker to control all the coupled-bunch modes. Since in the ALS $f_o = 1.523$ MHz and $M/2\ f_o = 249.8$ MHz, a kicker with a band width of 250 MHz is sufficient, if it is centered to cover a multiple of 0 to $M/2\ f_o$. A center frequency of 1.125 GHz was chosen for the ALS kicker.

DESIGN CONSIDERATIONS

Figure 3 shows a schematic of two electrode kicker of the kind we discuss next. Building a sophisticated (and expensive) kicker array that requires less power, can reduce the total cost of the feedback system because wide-band power is so costly. Since it is the voltage on the gaps that we want in the kicker, the power for a given kick can be reduced by using a number of identical kickers. Unfortunately not enough space is available in the ALS to carry this far enough. Another way to reduce the required power is to use series electrodes in a kicker. Doing this increases the gain of the kicker at the expense of band width. Using two series electrodes at a center frequency of 1125 MHz, we can still get the required 250 MHz band width. The figure below shows relative kick versus frequency for a single electrode and for a two-electrode ideal kicker.



Gain for a One-Electrode and a Two-Electrode Kickers

Figure 3

In an ideal two-electrode kicker, the electrodes are a quarter wave-length long, and are coupled in series by a half wave-length delay-line. The delay line reverses the phase of the voltage on the second electrode and so doubles the voltage across the center gap. The rf voltage V at the drive end of the kicker is

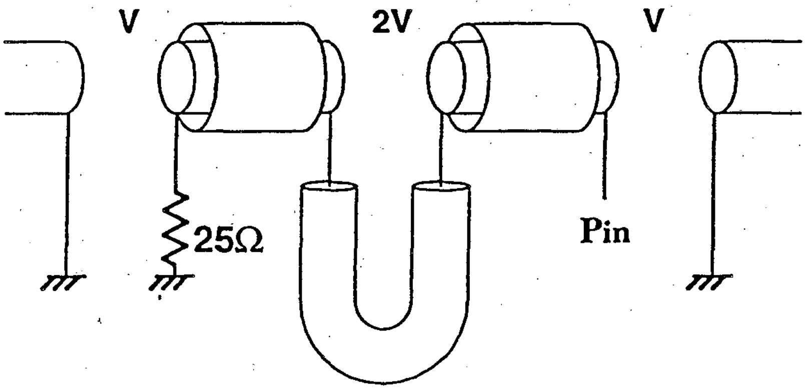


Figure 4: Schematic of Two-Electrode Kicker.

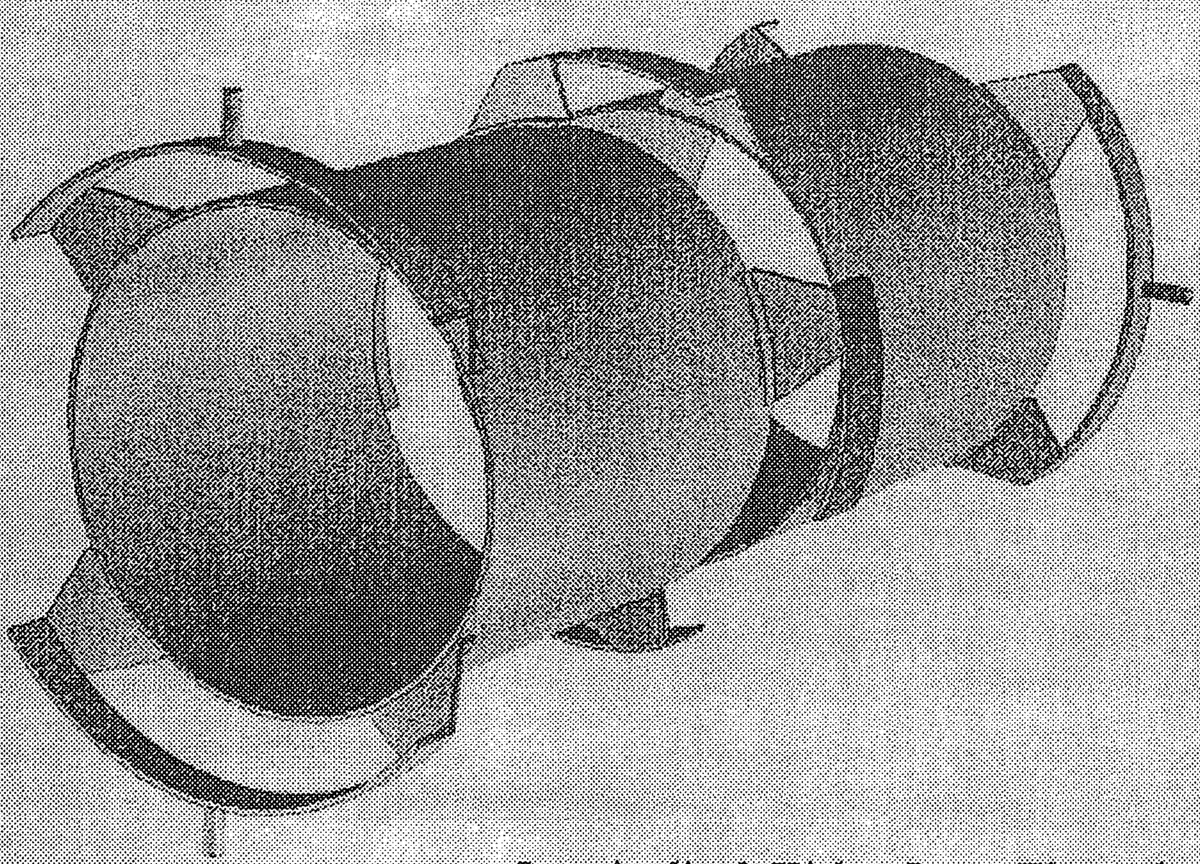
phased so that a beam bunch entering at the load end of the kicker gets a kick of V volts at the load gap. The bunch travels against the voltage wave on the electrodes, and the timing is such that the bunch receives an additional kick V at each end of the center gap, and at the drive gap. At mid-band all the kicks are in phase giving a total kick of 4V. Since a single quarter-wave electrode gives a kick of only 2V volts, a two electrode kicker needs only one fourth as much power as a one-electrode kicker. Further reduction in driving power is obtained by distributing amplifier power to an array of four two-electrode kickers, but requires four times more length in the accelerator. With this array of kickers the required power is 10 to 16 times less than using one single-electrode kicker.

There are many complications in a real kicker. The inner electrode is shown in figure 5 and the open end view of the prototype kicker is shown in figure 6. Capacitances across the center gap and at the electrode ends, complicate the behavior of the kicker response. Transverse strip lines connect the electrode ends, and these must be spaced away from the electrodes ends to avoid distributed coupling along their length. Longitudinal conductors (that act as inductors) connect the strip lines to the electrodes. These lumped capacitances and inductances affect the impedance match at each end of the electrodes, and cause multiple reflections which reduce the efficiency of the kicker.

PROTOTYPE KICKER

The shape of the electrodes is too complicated for the MAFIA program that we have available for electromagnetic cavities. The first step in the our kicker development was to develop a prototype and the measurement technique to allow us to evaluate our design. See figures 5 and 6. In the initial design, we treated the center region and the ends separately. In the center region we foreshortened the delay-lines, and reduced the value of Zo to compensate for the capacitance and series inductance. The strip lines were fastened with screws to let us easily change the length or width of the strip-line components. In the ALS kicker the center electrode has the same inside diameter (7.5 cm) as the beam pipe. The outer diameter of the outer cylinder was chosen to give the kicker a Zo = 25 ohms.

Four 100 ohm strip lines at each end connect the electrodes, the drive line and the load. See figure 5. The strip lines cover a 45 degree arc, and two adjacent lines join together so that there are two places on opposite sides of the kicker where the lines join and present Zo = 50 ohms.. We used a TDR to judge how to modify the shape and spacing of the conductors at each junction for the best match. Power from the amplifier is split into two parts; each half passes through the vacuum wall and drives one of the 50 ohm junction points. Each port drives two 100 ohms lines in parallel, and in turn the four parallel 100 ohm strip lines drive the 25 ohm electrode. A metal wall perpendicular to the beam direction connects the beam pipe to the outer conductor of the kicker, and acts as the ground plane for the circumferential 100 ohm strip-lines. The load end of the



Longitudinal Kicker Inner Electrode

Figure 5

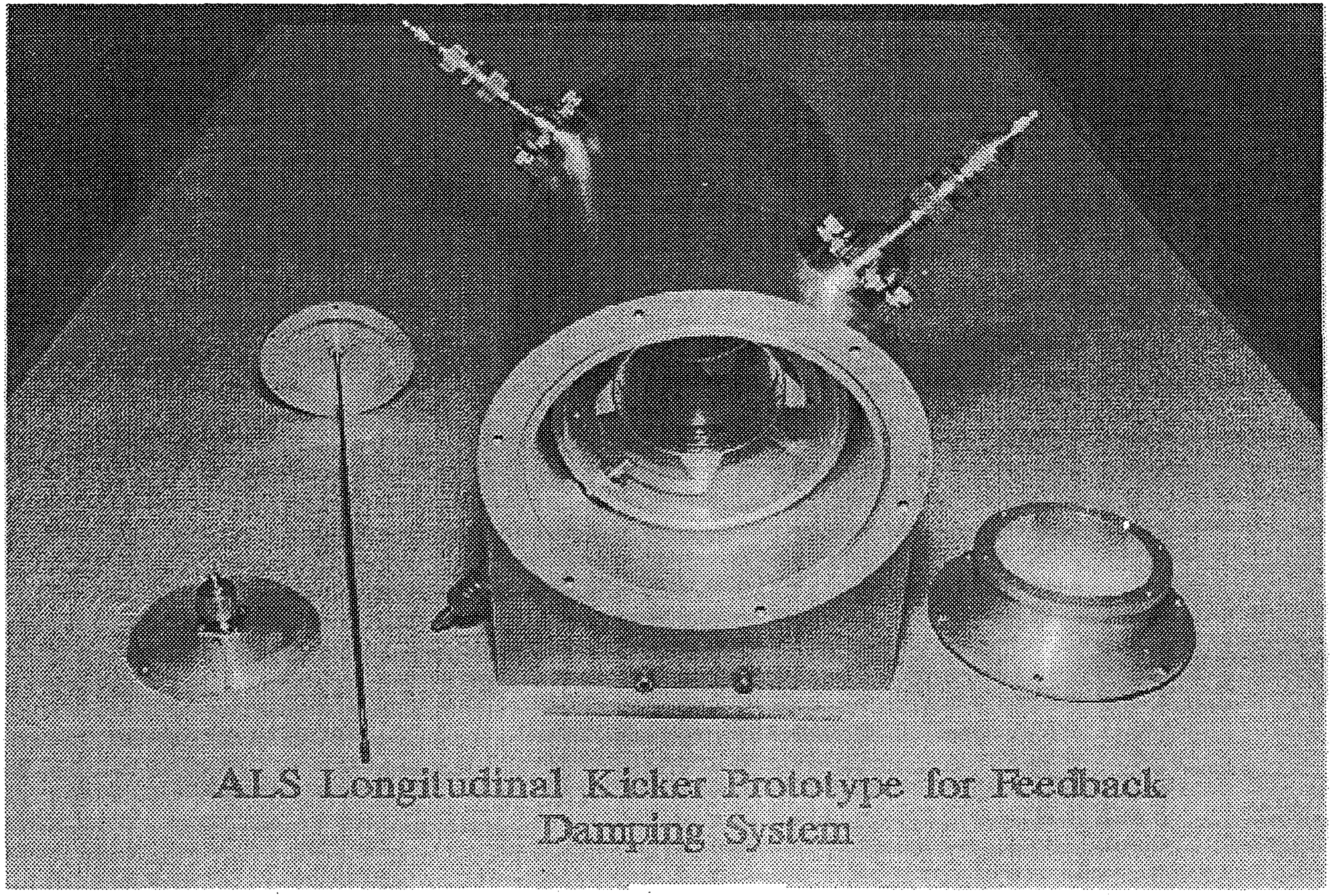

ALS Longitudinal Kicker Prototype for Feedback
Damping System

Figure 6

kicker is a mirror image of the drive end except that the vacuum feed-throughs terminate in 50 ohm loads.

The center region is the more difficult part of the kicker to design. The end of the first electrode and the beginning of the second must be connected together through a delay line. We need a gap large enough to accommodate four circumferential 100 ohm delay lines. This is just as well, because a small gap would have too much capacitance. Early in the design in discussions with the mechanical designers, we agreed to a uniform diameter outer conductor to facilitate assembly of the kicker. This constraint limits the maximum length of the delay line to about 6 cm. The delay lines consisted initially of four circumferential conductors 4.3 cm long and 1.5 cm wide. Together with the outer cylindrical conductor the original conductors were strip lines with Zo = 25 ohms. In a first modification the conductors were lengthened to 6 cm., and in a second modification they were widened to 2.1 cm to lower the Zo to 22.8 ohms.

MEASUREMENTS

The response of the kicker was measured by placing a 1/8 inch wire along the axis to simulate the beam. The beam pipe and the inner electrode together with the wire make a high impedance (195 ohm) coaxial line. The wire was terminated at each end by a series 155 ohm resistor and a 50 ohm SMA connector. The three gaps on the electrode couple to the wire much as the beam does. A network analyzer was used to measure reflection (S_{11}) and transmission (S_{21}) through the electrodes, and from electrode to the wire. Measurements were also made without a wire, allowing us to evaluate how well the various discontinuities in the kicker are matched. The set of electrode-to-wire measurements gives an estimate of the coupling to a beam.

The first prototype was somewhat of a surprise. The prototype was designed for a 250 MHz band width centered at 1125 MHz. Instead the response peaked at about 980 MHz , and the return loss showed a sharp minimum (-30 dB) at 1000 MHz that increased to -9 dB at 1200Mhz. We had expected a more or less flat return loss over the operating band. Also the return loss vs frequency changed substantially when we added the wire, indicating that the process of predicting the beam response from the wire measurements is complicated by the wire loading.

Using a TDR to match the ends of the kicker made only a small change in the return loss behavior with frequency.

EQUIVALENT CIRCUITS

It became clear that we needed more detailed analytic tools to aid us in understanding how the wire modified the kicker response, and how to predict the beam response of the kicker. Two equivalent circuits were developed, one for the wire interaction, and the other for the beam interaction. These are shown in figures 7 and 8. TOUCHSTONE was used to calculate graphs to compare with the network analyzer measurements.

The two electrodes are represented by 25 ohm transmission lines designated as T13 and T14 in the equivalent circuits. The length of these lines is set equal to the physical length of the electrode. The electrodes are coupled together by series inductors (0.6 nH) and a section of delay line. The length of the delay line is set equal to the physical length of the circumferential strips, and the Zo of the delay line was 25 ohms or 23 ohms depending on which width conductor was used. The delay line is designated as T15 in the circuits. Estimated values were put in for capacitance of the center gap (1.5 nH for C12) and for capacitance of the end gaps (2.5 nH for C11 and C13).

The circuit in figure 7 represents the kicker with a wire. The wire is represented by a two 195 ohm transmission lines (T18 and T19). The length of each line is made equal to the estimated gap-to-gap distance. Matching resistors (R25 and R26) are 155 ohms, which is the nearest standard value to 195 - 50 = 145 ohms..

Ideal 1:1 transformers were used to represent coupling from gap to wire. The primary of each transformer is connected across the appropriate gap, and the secondary is put in series with the transmission lines representing the wire. To convince ourselves that the transformers correctly represented coupling to the wire, we evaluated two circuits representing ideal kickers coupled to a wire. One was for a single quarter-wave electrode, and the other for two series quarter-wave electrodes. Results calculated by analytic methods for an ideal geometry were in very good agreement with the TOUCHSTONE simulation, giving us confidence in the transformers.

The second equivalent circuit, shown in figure 8, uses the same basic circuit to represent the two electrodes. The voltage kick to the beam from each of the three gaps is added. The gap voltages are connected to the input of three voltage-to-current amplifiers. Each amplifier drives a 25 ohm delay line that represents the time for the bunch to travel from the upstream end of the kicker to each gap. The amplifiers have a voltage gain of 10,000 to compensate for a 1 to 10,000 resistive adder that adds the three outputs. The output of the adder accounts for phase of the gap voltage and for the transit time of the bunch, but not for transit time factor of the gap. This transit time factor is nearly one, but the actual values could be included in the amplifier gain.

DETERMINING CIRCUIT PARAMETERS

The first TOUCHSTONE runs showed a large discrepancy from the measured values. This is because many of the initial parameters were estimates.

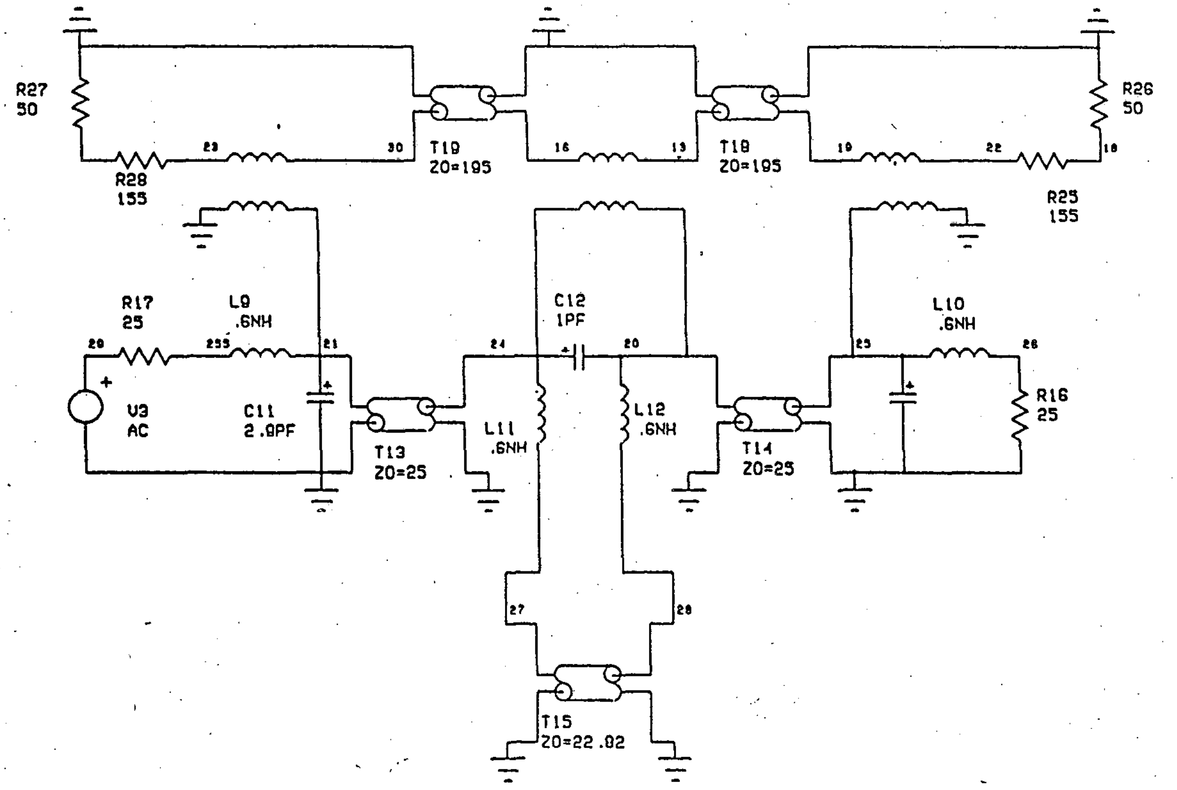


Figure 7: Equivalent Circuit of Kicker with Wire.

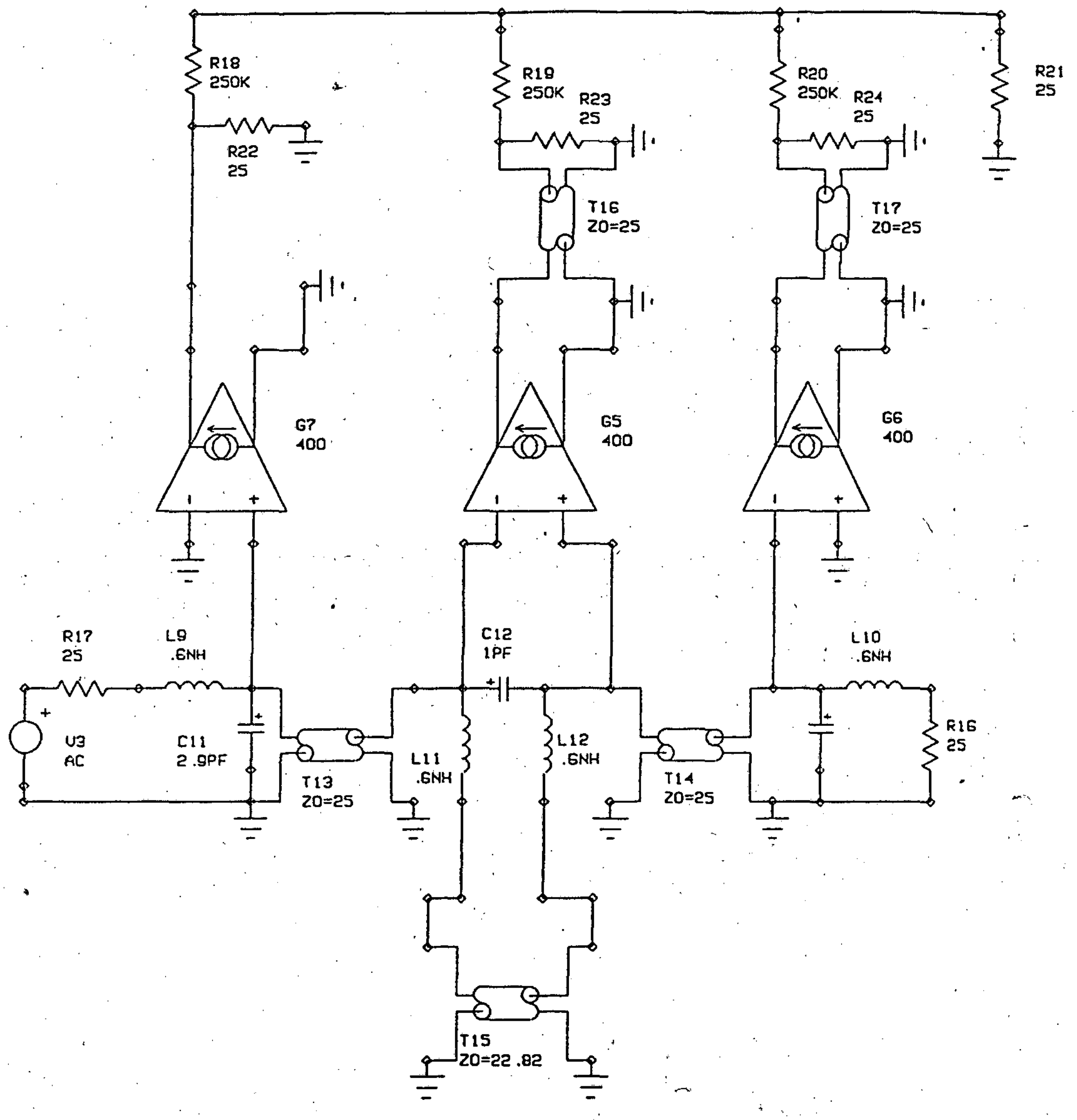
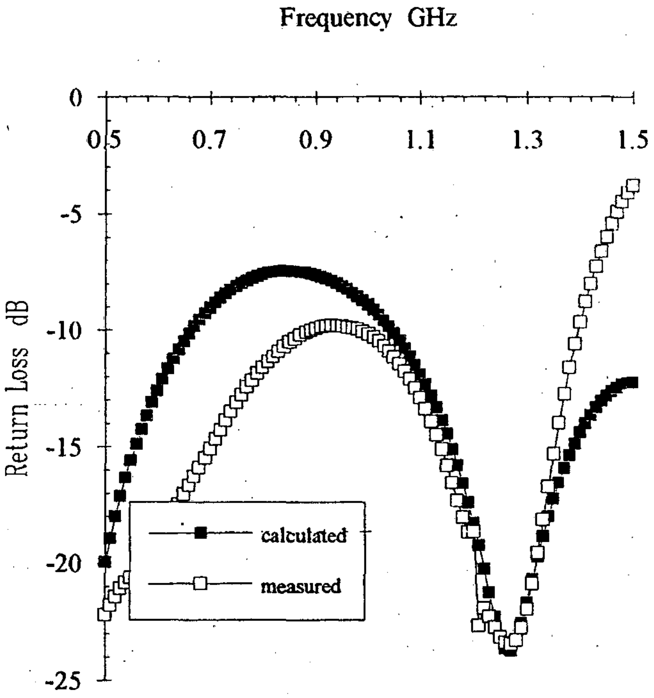


Figure 8: Equivalent Circuit of Kicker with Beam.

There are five parameters to be adjusted. These are C_{gap}, C_{end}, L_{gap}, $Zo_{delay\ line}$, and delays (T16 and T17) representing the distance the beam travels between kicks. The uncertainity of these delays is because the distance between electrical center of the gaps seems to be 0.6 cm longer than the distance from center-to-center of the gaps that we assumed. We adjusted these parameters to make the calculated curves agree with the measured curves over the frequency band from 1000 MHz to 1250 MHz . Three different graphs were compared; these are S11 into the electrode with and without a wire, and S21 from the electrode to the wire.

Adjusting parameters to match these curves is a trial and error process, and because the curves can not be matched exactly, the choice of parameters is somewhat arbitrary. Once the parameters are determined from this procedure, the parameters are used in the second equivalent circuit to predict the performance of the kicker with beam . In an effort to improve the performance of the ALS kicker, the prototype was first modified by shortening the electrode length and increasing the length of the delay-lines to move the center frequency higher. A second modification widened the delay lines to improve the low frequency return loss.

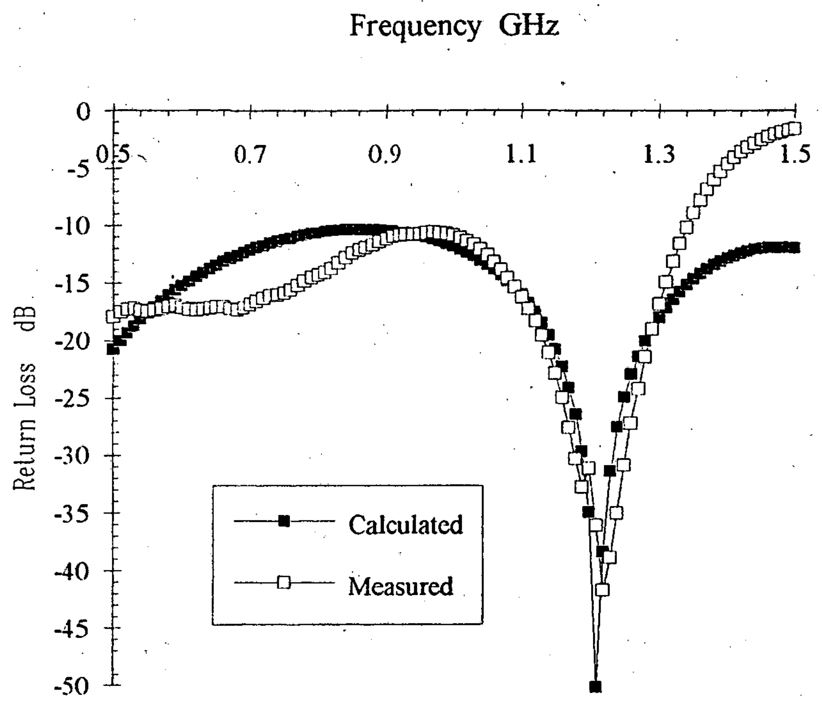
Measurements on the final modified prototype are shown below.



Return Loss with Wire

Figure 9

Figure 9 shows the degree of agreement between the calculated and measured values for the modified prototype. It is somewhat arbitrary whether to adjust the calculated curve down to match the measured data at the low or high frequency end of the operating range. Remember that the operating range of the kicker is from 1 GHz to 1.25 GHz.

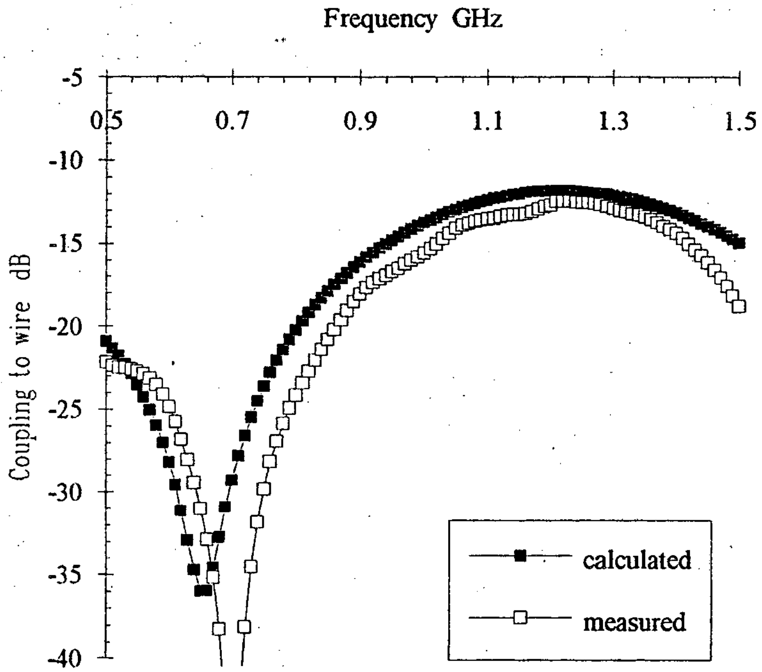


Return Loss without Wire

Figure 10

The figure 10 shows the same information for the kicker without the wire, and represents the actual return loss expected for the kicker in the ALS.

The figure 11 shows calculated and measured coupling from electrode to wire for the modified prototype. The measured coupling at the maximum is 0.8 dB less than calculated. Obviously there are losses in the prototype that are not included in the equivalent circuit. An example of this is the wiggle in the curves at 1.19 GHz. At first we thought this was an artifact of the measuring equipment, but now believe that it is caused by coupling to a resonance in which energy is exchanged back and forth between one side of the kicker and the other.



Coupling to Wire for ALS Prototype

Figure 11

Figure 12 shows the predicted response for the kicker with a beam, and is compared with an ideal kicker covering the same frequency range. The vertical scale is the real part of the beam kick normalized to the rf voltage at the kicker input. The maximum value of 3.3 is lower than we expected but acceptable for use in the ALS.

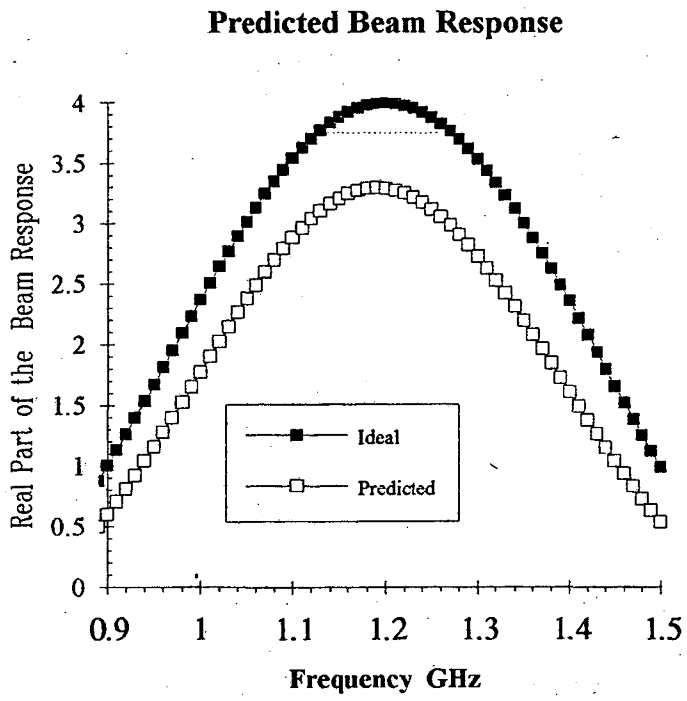


Figure 12

TOUCHSTONE doesn't allow us to conveniently calculate the phase of the voltages in the equivalent circuit, and we used SPICE to investigate the phase of the voltages at the electrode ends and at the kicker load. SPICE calculations showed us that the phase of the voltage across the center gap is 140 degrees instead of 180 degrees at 1.19 GHz, and explains why the maximum kick is less than expected.

A study using the equivalent circuit confirmed that we need longer delay lines. We could do this by increasing the diameter of the outer conductor in the center gap region, allowing us to put delay lines at a larger radius. However, modifying the outer conductor of the kicker is a major design change, and the kicker assembly would be greatly complicated. An alternate way to get enough length , would be to change from four 100 ohm delay lines to three 75 ohm delay lines in the center gap region, allowing 120 degrees for the delay lines instead of the present 90 degrees. It is too late to make this modification now because of time constraints for commissioning the ALS, but it will be investigated as a possible future upgrade.

BEAM IMPEDANCE MEASUREMENTS

Beam impedance measurements have been made on every device put into the ALS. This is to identify and fix devices with excessive beam impedance, and to catalog all the devices so that future problems with the accelerator can be identified with a particular device.

Beam impedance measurements have been made by putting a wire through the various devices and measuring S21 through the wire. The value of S21 can be translated to a series impedance that is related to beam impedance. In the ALS prototype kicker, a strong high Q resonance was observed near 3 GHz, as well as a weak resonance at 1.19 GHz. The wiggles at this frequency in the are related to this resonance. This resonance moved from a higher frequency to 1.19 GHz at the time the delay lines were widened. It seems to be related to energy exchanged from one side of the kicker to the other through the delay lines.

Both the resonances at 1.19 GHz and at 3 GHz are lightly coupled to the kicker electrode, and so are not damped by the 50 ohm termination at the drive and load ends of the kicker. The resonance at 3 GHz is damped using an electric probe through the vacuum wall. The probe is terminated in 50 ohms. We think that beam coupling to the 1.19 GHz resonance is not strong enough to cause a problem.

BEAM LOADING

Initially we questioned whether the beam would load the kicker and reduce its efficiency, particularly in a four-series electrode for the B-Factory. This was studied analytically by Glen Lambertson, and also by simulation on the equivalent circuits. Our conclusions are that the voltage developed in the kicker by the beam and by the amplifiers are completely independent, and can be determined by adding voltages generated by a properly phased current generator at each gap.

Figure 13 shows a modified equivalent circuit with constant current sources driving the gaps to represent the beam. The voltage across the each gap is added and the sum represents the kick given to the beam. The ratio of this voltage kick to the beam current is in effect the beam impedance for the electrode. Figure 14 shows the predicted kick given to the beam for the ALS kicker and for an ideal kicker. The current in these graphs is one ampere, so the curves give the beam impedance in ohms. This circuit also allows us to determine power delivered from the beam to both the load and drive circuit.

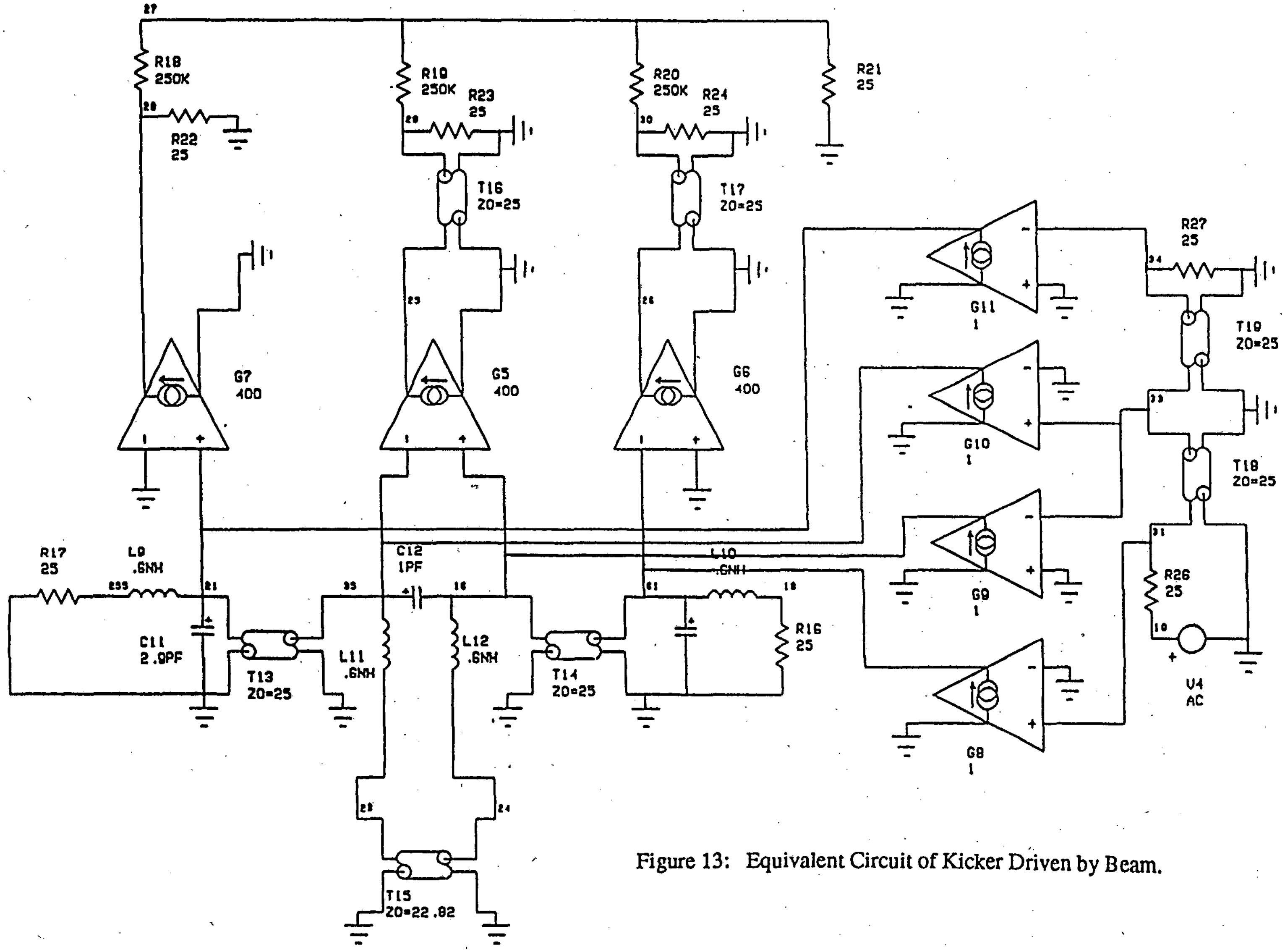


Figure 13: Equivalent Circuit of Kicker Driven by Beam.

Voltage Kick on Kicker Generated by Beam

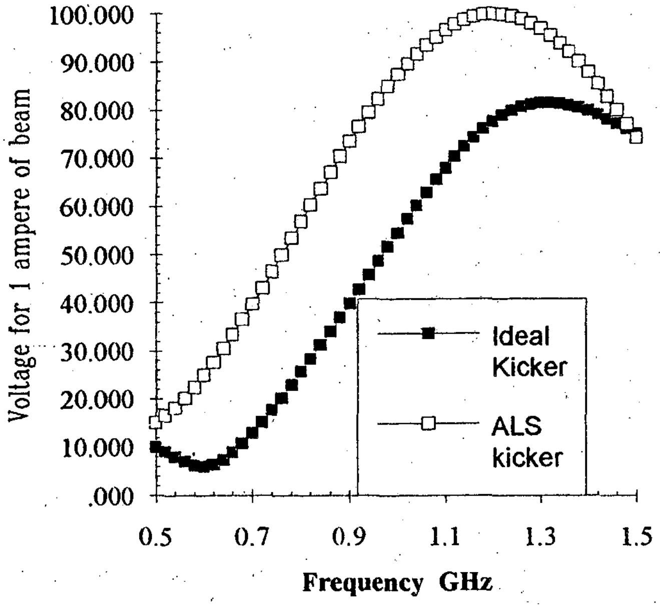


Figure 14

CONCLUSIONS

The present ALS kicker design is adequate to use in commissioning the ALS. We won't know how much kick the longitudinal feedback system actually needs to deliver until the machine is operating. The start up will proceed with one 500 watt amplifier delivering power to all four two-electrode kickers. If coupled bunch instabilities appear as the beam current is increased, the full design complement of one 500 watt amplifier for each kicker will be added. Should even more kick be needed, a combination of upgraded electrodes and additional amplifiers will be considered.

The equivalent circuits are useful tools in the design of this type of kicker. They are quite helpful in determining which parameters do what to the response and in estimating the efficiency and the directivity of a kicker. They also can aid in determining the beam impedance and in estimating beam power delivered to the load and to the input circulator.

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ACKNOWLEDGMENTS

The development of the ALS kickers has been the work of a number of people. Glen Lambertson's insight has contributed a great deal to this work. Jimmy Johnson has contributed in a number of ways. He made most of the network analyzer measurements; he helped set up the TOUCHSTONE calculations; and he acted as the liaison person to the mechanical people who built the prototypes. John Corlett made beam impedance measurements and is working on ways to damp the unwanted modes. We want also to acknowledge the contributions of Bob MacGill, the mechanical designer, and Jeff Leifheit, the technician who assembled the prototypes.

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