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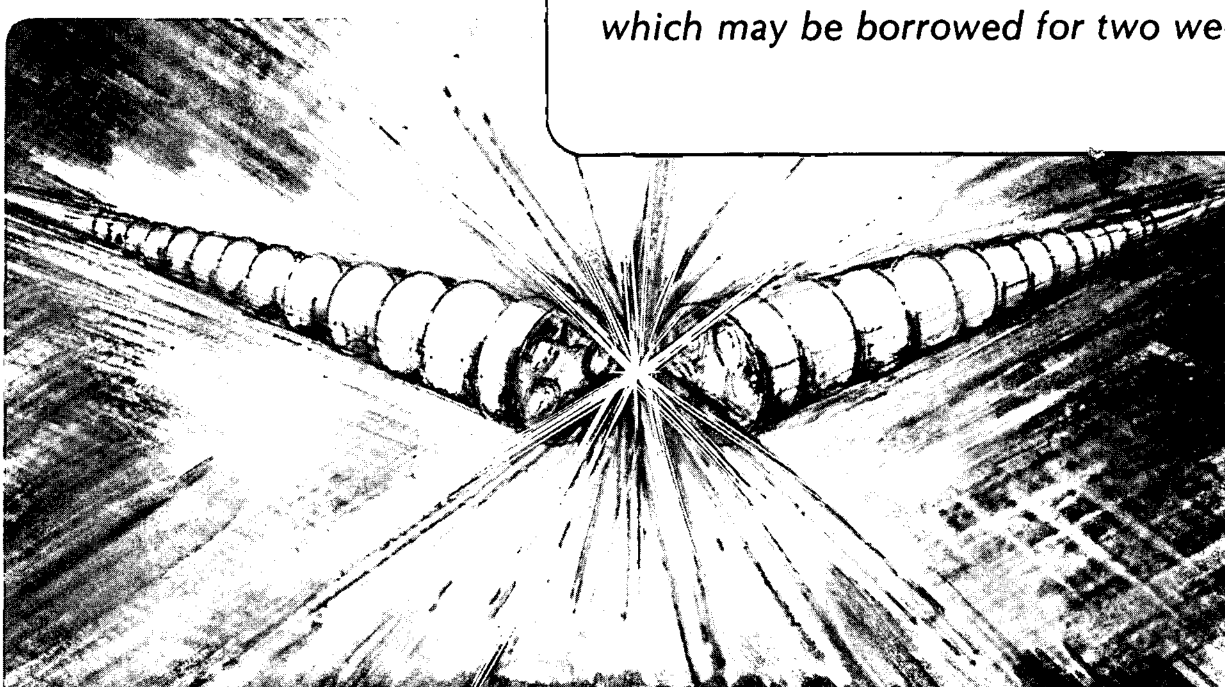

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LSAP Note 40

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BEAM IMPEDANCE OF FERRITE KICKER MAGNETS*

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Abstract

We have measured the longitudinal beam impedance of a typical pulsed magnet that will be used in the Advanced Light Source. The magnets are of a ferrite window-frame design with a single plate conductor on each side. Two separate power supplies are used to drive current in opposite directions in the two conductors. The continuity of the ferrite yoke is interrupted by two copper plates 1 mm thick in the center of the top and bottom of the window frame. This increases the reluctance of the magnetic path, and thus decreases the flux which couples the beam.

The measurements were made by exciting a 1/8" rod along the beam path through the magnet. This makes a 185 ohm transmission line, and it was terminated in a resistive divider at the exit end. A 3 GHz network analyzer was used to measure S_{21} through the magnet, and longitudinal beam impedance was calculated from this data. The impedance is dominated by two low frequency resonances in the magnet winding and drive circuit.

Introduction

We want to determine the beam impedance of various devices that will be in the ALS beam line. Some of these introduce substantial discontinuities in the wall of the beam pipe, and may contribute large beam impedances. Examples are the kicker magnets and the accelerating cavities. We utilize some simple models that predict beam impedance qualitatively for some of these devices, and we want to confirm their correctness as well as determine actual values of magnitude and frequency.

Hardware

We have measured a first-generation prototype of a typical kicker magnet. This magnet has a ferrite window-frame design with a 5 mm x 44 mm conductor on each side. The power supply drives current in opposite directions through the conductors. The high permeability of the ferrite, together with the geometry, result in a nearly uniform magnetic field across the magnet aperture. The symmetry of the magnet allows us to insert 1 mm thick copper barriers in the ferrite path at the top and bottom on the centerplane. See Figure 1. These plates have very little effect on the magnetic field when driven from the windings, but increase the reluctance of the magnetic path to flux due to current along the beam path.

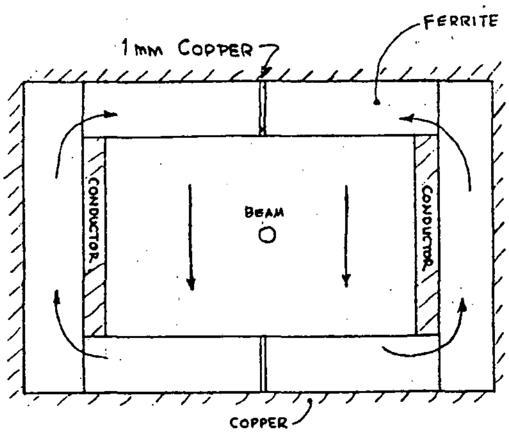

Fig. 1 Cross section kicker magnet

In this version of kicker magnet, each conductor is connected to a separate energy storage device through a thyratron switch. Since the thyratron switches are normally off when current is circulating in the synchrotron, the winding is loaded only by the parallel capacitance of the winding and the thyratron circuit. We have added resistors in parallel to damp the resonances that result. One might expect the windings to act as shorted transmission lines with a series of resonances at multiples of the quarter wavelength, but because the ferrite is increasingly lossy above 4 MHz, the higher frequency resonances are damped.

Measurement Procedure

To simulate the beam we put a 1/8" rod along the beam path, which together with the magnet constitutes a 185 ohm transmission line. The rod is matched by a metal film resistor in series with a 50 ohm SMA connector. This resistor was later measured to be 132.8 ohm. The input end of the rod is also connected to an SMA connector. A 300 kHz to 3 GHz network analyzer was used to measure the value of S_{21} through the magnet.

To convert S_{21} to an equivalent longitudinal beam impedance we use the circuit shown in Figure 2. The beam impedance Z is in series with the terminating resistance of the 185 ohm line. For frequencies below 60 MHz, the magnet is less than 0.1 wavelength long, and we consider it a lumped circuit when calculating the beam impedance. Both S_{21} and Z are complex quantities. From Figure 2, we can write

$$S_{21} = V_2^+/V_1^+ = 2*50/(50+Z+132.8+50), \text{ or}$$

$$Z = 100/S_{21} - 232.8 \text{ ohms.}$$

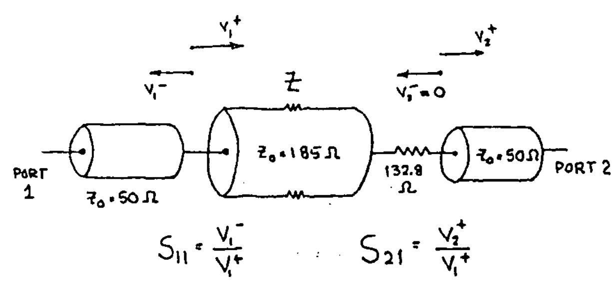

Fig. 2 Circuit for calculating beam impedance

The values of the real and imaginary parts of Z calculated from this equation are shown in Figure 3. The real part has a maximum of 14 ohm at 11.5 MHz and a minimum of 4.5 ohm at 27 MHz. It levels off at about 7 ohm up to about 50 MHz. The imaginary part peaks at 9 ohm at 6 MHz, goes to a minimum at 11 MHz, and then increases with frequency.

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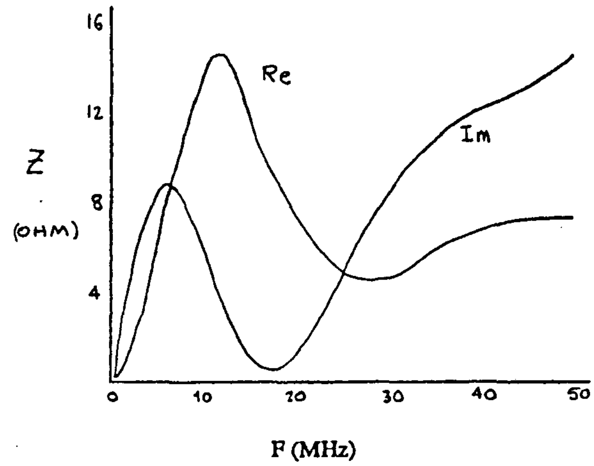

Fig. 3 Beam Impedance

Above 50 Mhz the real part of Z increases with frequency, and is 1370 ohm at 2 GHz. The value Z/n is of more interest to the accelerator physicist, and Figure 4 shows the real and imaginary parts of Z/n as a function of frequency. For the ALS booster n = f/(4 MHz). The region between 300 MHz and 500 MHz has a peculiar behavior that is hard to explain. We think it is caused by the switching and energy storage circuits being coupled through the thyratron cathode to anode capacitance.

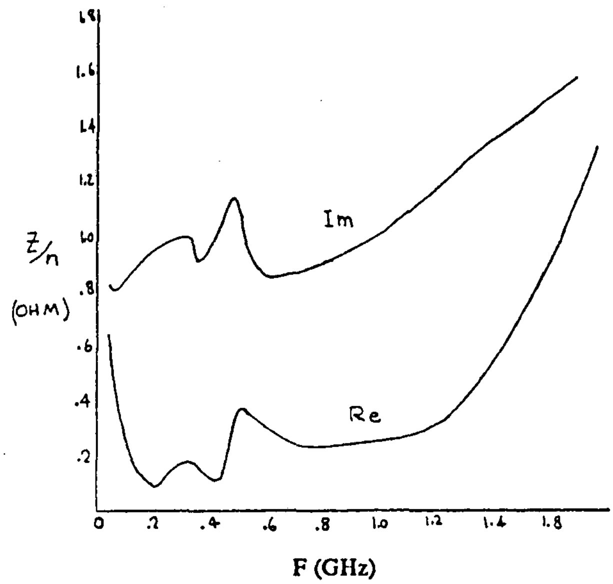

Fig. 4 Beam Impedance/n

Equivalent Circuit

We want to develop an equivalent circuit for the beam impedance to help us understand the frequency response, and to predict what would be the impedance function for similar magnets (such as the bump magnets for the Storage Ring).

An equivalent circuit (Figure 5) for the beam impedance was created by considering the magnet as a transformer. The rod along the beam path is a primary winding, and the conductors are parallel secondary windings. The leakage and mutual inductance of the transformer were calculated using a finite-element program. We assumed current flowing in the same direction in the windings. Part of the flux circulates around the ferrite path passing around the 1 mm copper barriers, and part flows through the air gap. See Figure 6. The first part is coupled to the beam and contributes to the mututal inductance, and the second part is not coupled and contributes to the leakage inductance. The values were 364 nH for the mutual inductance, and 184 nH for leakage inductance.

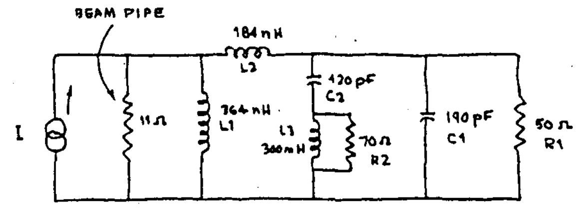

Fig. 5 Spice program equiv. ckt. for beam impedance

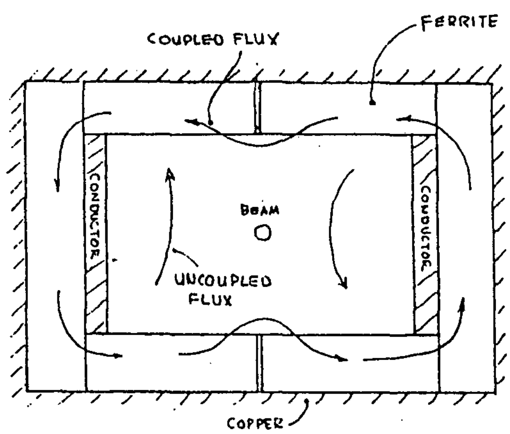

Fig. 6 Cross section kicker magnet

The external circuit components, R1 and C1 are loads on the secondary windings. R1 is the damping resistor, and C1 is the sum of the external capacitance and the equivalent rf capacitance of windings to ground. In this version of the kicker magnet, the conductor is in contact with the ferrite. The capacitance between the conductor and the magnet enclosure is enhanced by the dielectric constant of 13. Our finite element program gives a dc value of 308 pF for this capacitance. Since the magnet is shorted at one end, and because the potential along the conductor is linear, we assume an effective rf capacitance of half the dc value as a first approximation. Our next design will incorporate an air gap to reduce this capacitance.

The first resonance is determined approximately by the product of C1 and the sum of the leakage and mutual inductances. The response shown in Figure 3 can be duplicated by adding a series resonant circuit in parallel with the external load. We don't have a simple way to estimate values for C2, L3 and R2, so they have been determined empirically. Figure 7 shows an approximate fit that is to be compared with Figure 3.

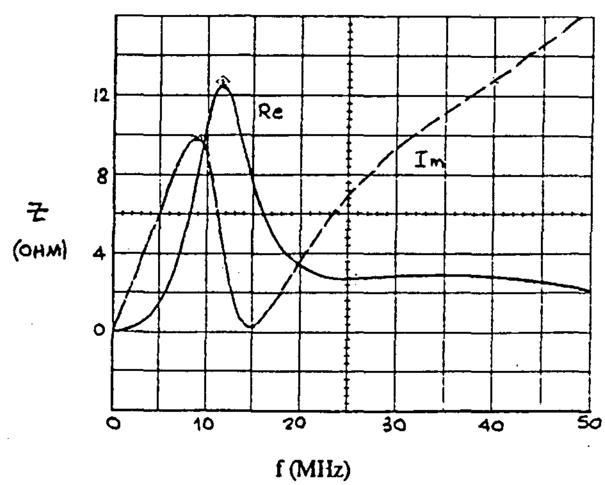

Fig. 7 Spice Analysis

Metallized Beam Tube

The beam pipe through the kicker magnets will be made of ceramic to allow the pulsed magnetic field to penetrate. It will have an evaporated metal coating of between 10 and 16 ohms per square. This is a compromise between letting the high frequency components of the bending field penetrate in, and preventing the high frequency components of the beam excited field from getting outside the beam pipe. With 16 ohms per square, the resistance of the beam pipe will be about 11 ohms. We estimate that the bending field will be suppressed about 1%, with a .2% variation in field inside the pipe. The metal coating acts like a resistance in parallel with the rest of the magnet circuit, and it causes a roll off of beam impedance starting at about 10 MHz.

We estimate the effect of the metallized beam pipe by adding an 11 ohm resistor in parallel to the equivalent circuit as shown in Figure 5. The undesirable impedance of the magnet above 10 MHz is shorted by the parallel resistance of the beam pipe. See Figure 8. We expect a maximum high frequency beam impedance of 11 ohms, and a damping of low frequency resonances.

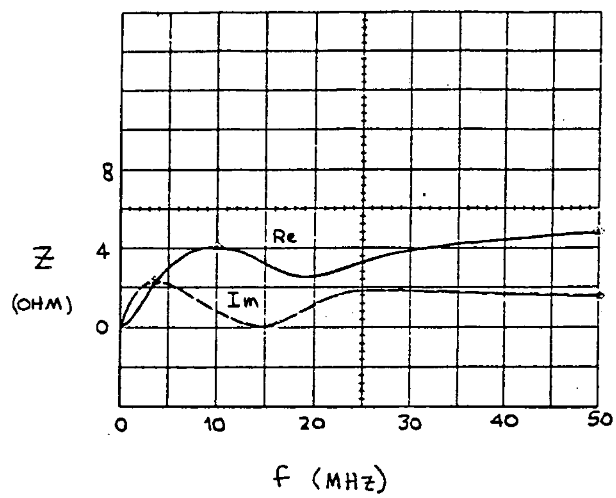

Fig. 8 Spice analysis with beam tube

Another version of the kicker magnet is being constructed in which a transformer drives one conductor positive and the other negative. Measurements of beam impedance will be made on this magnet when it is available. We also expect to measure the magnets with a metallized glass pipe to simulate the actual ceramic pipe.

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