**BEAM POSITION AND TOTAL CURRENT MONITOR
FOR HEAVY ION FUSION BEAMS**

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ABSTRACT

Heavy Ion Fusion requires moderate currents, 1-10A, for a duration of about 1 μ s. For accurate beam transport, the center of charge must be located to within $\pm 100 \mu$ m. Beam position and intensity may be excited at frequencies approaching 10 MHz, and the monitoring system must have adequate bandwidth to respond at these frequencies.

We have modified the Rogowski technique by using distributed reactance multiturn magnetic loops so that it is suitable for measuring current position as well as amplitude. Four identical stripline coils are wound one per quadrant around a non magnetic core. The sensitivity is similar to that of a lumped coil system, with the added advantage of increased bandwidth. The voltages induced on the four separate coils are compared and suitable signal conditioning is performed to recover beam position and intensity information.

INTRODUCTION

The purpose of this paper is to describe the position and total current monitor developed specifically for measuring a one ampere beam of heavy ions with one microsecond duration. The intent of this preliminary development was to determine the feasibility of locating the center of charge of the ion beam to better than $\pm 100 \mu$ m and still maintain a bandwidth of about 10 MHz with a reasonable signal to noise ratio. A variety of methods have been used over the years for non-intercepting beam position monitors (BPM). These position monitors are as varied as the shapes and sizes of beams that they are intended to monitor.¹ A common method of monitoring the position of high current short pulse beams is the wall current monitor.^{2,3} In this method the beam return current produces a voltage proportional to the beam proximity and provides position information simply because this signal level equalizes with a time constant equal to the L/R of the beam pipe; L is the pipe inductance and R is the wall current resistor. This technique is impractical for 1A beams 1 μ s long. Other common methods determine beam position of pulsed beams by coupling to the electromagnetic field of the beam. These methods consist of magnetic loops, stripline detectors and electrostatic pick up. Other more exotic methods use semi-intercepting thin wires, radiation, gas fluorescence, interferometry and beam probing. The best method of beam position monitoring is determined by the type of beam and the specific requirements of the experimental program.

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PHYSICAL LAYOUT AND BEAM PARAMETER CONSIDERATIONS

Heavy Ion Fusion (HIF) requires moderate currents, 1-10A, of short duration, 0.4-1 μ s, and very low duty factor, 10^{-6} . The beam acceleration system consists of induction cells which are added serially to produce an axial electric field of any magnitude. The beam transport system initially uses electrostatic quadrupoles and then uses magnetic quadrupoles at higher beam energy. As in most accelerators, precise beam control requires precise beam position monitors. It is required that the beam center of charge be located to within $\pm 100 \mu$ m. After a brief survey of the most common methods of BPM it was decided that the multiloop electromagnetic approach would be the most suitable. With the beam at the center of the pipe, the voltage induced is $V = NAdB/dt$ and $B = \mu H = \mu I / \pi d$ where N is the number of turns, A is the cross sectional area, d is the mean diameter and I is the beam current. The voltage induced in each coil is $V = (\mu NA / \pi d) dI/dt$. The signal derived is proportional to the rate of rise of the beam current. By integrating the coil signal a voltage proportional to position can be obtained. In order to obtain position information the core must be non-magnetic and non-conducting so that the beam can couple to the individual coils. The beam position information in x and y is derived by subtracting pairs of signals produced by opposite coils. One can see that by increasing the number of turns, N , the signal amplitude or position detector sensitivity can be increased to any desired level. By making N large (L large) the bandwidth of the BPM will, however, be limited by the L/R time constant (Fig. 1a). An obvious way to increase the bandwidth is to increase R . In the case of the ILSE accelerator, however, it will be difficult to locate the amplifier-integrator next to the BPM. The BPM signals must therefore be transported to the nearest signal conditioning chassis by many tens of feet of 50Ω impedance. The desire for 10 MHz bandwidth puts a limit on the number of turns that can be used on the BPM. Putting the amplifier-integrator next to the BPM would allow another degree of flexibility in choosing R and would make it easier to achieve both high sensitivity and wideband. Several attempts at using lumped coils led us to an acceptable beam position sensitivity but with a bandwidth well below 10 MHz. The technique of current monitoring by a continuous loop is often referred to as a Rogowski⁴ coil method. The limitations mentioned above can be avoided if the loop is wound using stripline as the conductor and making the distributed impedance of the line match the cable impedance, 50Ω . This is

Fig. 1 (a) Lumped element equivalent circuit of a multiturn magnetic loop
 (b) Rogowski technique or distributed line equivalent circuit where $\sqrt{L/C} = 50\Omega$

simply done by choosing the proper width of line, the dielectric and the spacing to the fixture holding the coil. The inductance of the multturn loops is now a distributed inductance and capacitance as shown on Fig. 1b where $\sqrt{L/C} = 50\Omega$. Neglecting fringing fields and leakage flux, the impedance of such a line $Z_0 = 377 d/w \epsilon^{1/2}$ where w is the width of line and d is in the thickness of mylar. The fixture shown on Fig. 2 was constructed to house the BPM inside the beam pipe with the 1/4 inch rod simulating the ion beam. The rod was pulsed with 0.8 A of 0.8 μ s duration. This rod (the beam) forms a single turn primary current that induces a voltage in the x and y multturn coils at 90° from each other. Ideally, such a design offers a bandwidth which is not limited by the L/R of a lumped element coil but only by how well the stripline geometry has been achieved. The BPM shown on Fig. 3 was originally designed for a 1/8 inch stripline filling each quarter circle with 14 turns. The sensitivity of this design was somewhat marginal and it was found that using a 1/16 inch stripline with the same number of turns which occupied only 1/8 circle the sensitivity of the signal doubled with a factor of two decrease in bandwidth. The stripline impedance is now about 100 Ω . Figure 4(a) shows the input current pulse and Fig. 4b shows the x position signals with the rod at $x=0$, $x=\pm 1$ mm and $x=\pm 2$ mm. The waveforms were obtained after amplification and integration of the loop signals as described in the next section. The actual sensitivity corresponds to a signal of 50 mV/mm-A. The one e-fold time constant is 30 ns which corresponds to a bandwidth of 5.3 MHz. As mentioned above, the coil enclosure forms a 100 Ω impedance rather than 50 Ω thus limiting the rise time or frequency response. Using the 1/16 wide stripline we will next rebuild our coil form so that the impedance is correct without sacrificing the sensitivity.

Figure 2. Actual fixture which simulates beam movement in a pipe.

Fig. 3. Cut-away and cross-section of Rogowski beam position monitor.

Fig. 4. Beam position signal for displacements of 0, ± 1 mm and ± 2 mm (a) Input current of 0.2A/div. and (b) x-position at 50 mV/div. ($t = 100$ ns/div).

SIGNAL CONDITIONING

Neglecting the dispersive element of the multiturn loop, the voltage produced by each winding is proportional to $(dI/dt)/r$ where I is the current being measured and r is the distance between the center of charge and the loop. Given that the change in r will be small relative to the average value of r , the relation can be linearized so that the change in output voltage of each coil is approximately proportional to the change in r . As previously mentioned, in order to produce an output signal which is proportional to the deviation of the beam from the center of the pipe, the outputs from two opposite coils must be subtracted, and the difference must be integrated.

The ideal integrator corresponds to a single pole roll-off in the frequency domain which extends indefinitely in either direction. This transfer function is inconvenient to build because it requires an amplifier with infinite bandwidth and infinite DC gain. It is also impractical for use in noisy environments because of the enormous gain at low frequencies. A practical approximation to the integrator is the one shown in Fig. 5. Poles have been added to limit the low frequency gain and to simulate the bandwidth limitations of available parts. The single pole roll-off remains unchanged over a limited frequency range. The placement of the two poles will determine over what frequencies the circuit will behave as an integrator.

The lower pole causes the integrator to misbehave by introducing a phase shift and attenuation to the lower frequency components of the input signal. For our purposes the input signal can be modeled as an impulse function, which is an equal mixture of all frequencies (has a constant value of one in the frequency domain). The ideal integrator has the form $1/s$, which, when multiplied by the impulse function, returns a unit step ($1/s$). The lower pole changes the transfer function of our integrator from $1/s$ to $1/(1+s/\omega)$. The time domain output of this transfer function for an impulse input is $e^{-\omega t}$. This can be thought of as a step function which has a characteristic droop with time constant $\tau = 1/\omega$. For our purposes a droop of 1% over the $1\mu s$ beam pulse is acceptable. This means that the time constant associated with the lower pole needs to be about 100 times $1\mu s$, which corresponds to a pole at 10,000 rad/sec or 1590 Hz. The upper pole is caused by op amp limitations and in our case turns out to be at several MHz. A third pole is added another order of magnitude below the 1590Hz pole to provide DC decoupling between amplifier stages.

Figure 5 shows a simplified block diagram for the actual signal conditioning circuit. Separate amplifier stages are used to perform the required sum/differencing and integration. The first stage has a theoretical common mode gain of zero and a differential gain of 10. Op amp limitations introduce a pole in this stage between 10 and 20 MHz. The integrating stage approximates the model discussed above. The actual circuit is shown on Fig. 6.

As mentioned in the discussion of the modified Rogowski coil technique, the actual stripline impedance is over 100 ohms which will appear inductive when terminated into 50 ohms. The beam position signals of Fig. 3 have a bandwidth of 5.3 MHz. This limited bandwidth is a result of an inductive stripline with some contribution from the bandwidth limits of the first times ten input amplifier.

Fig. 5. Transfer function of the beam position monitoring circuit.

Fig. 6. BPM signal conditioning amplifier-integrator.

CONCLUSION

The preliminary development of a beam position monitor which applies the distributed impedance Rogowski coil techniques has already given a simple piece of hardware which nearly satisfies all the requirements for monitoring the position of a 1A heavy ion beam to less than ± 0.1 mm. The second version of this BPM will have an improved fixture holding the coil and the proper stripline impedance. It is expected that these improvements will result in a greater than 10 MHz bandwidth and the same sensitivity of ± 5 mV/0.1 mm displacement of a 1A beam.

In the real world of noise-rich accelerators more effort will be required to achieve the signal-to-noise ratio obtained on the bench tests of the prototype.

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