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NON INTERCEPTING HIGH RESOLUTION BEAM MONITORS

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Toroid Current Monitor

Introduction

In literature we find many articles about beam current transformers for accelerators, designed for their special use. The beam current-monitor developed at IKO distincts itself from the others by a break-through in the convential design. The main difference in the design of this toroid current monitor is the idea to split up the frequency spectrum of the beam-pulse signal in two discrete parts.
Each frequency region has its own toroid transformer. This possibility leads to an optimum design of the transformer in combination with the cabling and electronics for the special limited frequency region. At last the outputs of both optimized electronic circuits are added together to deliver the ultimate output response that gives an exact representation of the whole frequency spectrum produced by the primary beam-pulse. Monitor specifications are:
Dynamic current range of 10µA to 50mA, rise time 100 nsec, droop 1% at 50 µsec and accuracy of 1%.

System design

A schematic diagram of the toroid monitor including the cabling and electronics is shown in fig. 1. The two toroids are placed outside the beam pipe to reduce the vacuum outgassing problems. The beam pipe is interrupted by a ceramic isolator. This vacuum joint is made by alumina helicoflex rings.

Two types of toroid monitors are now in use. One with an inside beam-hole diameter of 5 cm and the other with an inside diameter of 10 cm.

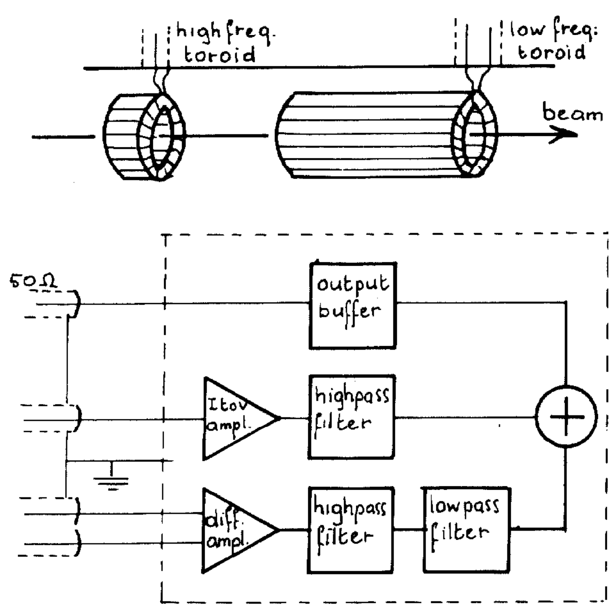

Fig. 1. Toroid current monitor system design

The 10 cm toroid really exists of:

- A low frequency toroid made of two supermumetal band-wound cores and one 3Hz ferroxcube core, stacked together with a 40 turn 0,5 mm Cu/Em wire winding.
- A high frequency toroid made of one 3Hz ferroxcube core with 25 turns of 0,5 mm Cu/Em wire.

The 5 cm toroid exists of:

- A low frequency toroid made of four stacked ferrite cores with a 100 turn 0,5 mm Cu/Em wire winding.
- A high frequency toroid made of one ferrite core (the same material as used for the low frequency toroid) with 25 turns of 0,5 mm Cu/Em wire.

The toroids are connected by a triaxial and differential cable of about 25 meters to the electronics in the modulator hall. Care must be taken for shielding and earth problems.

Electronic design

The electronic circuit of the current to voltage amplifiers, filters and adding network is given in fig. 2. Some details of the design vary, depending on the type of toroid used and the number of turns on them. The output of the low frequency toroid is fed by a differential cable, to reduce the 50Hz hum, to the differential amplifier. The main features of this amplifier are:
- High open loop gain
- Low noise
- High common mode rejection
- High slew rate.

To reduce the low frequency noise, generated by this amplifier, it is followed by a high pass second order active filter with 160Hz corner frequency. A second passive filter limits the frequency band to about 160 KHz. The high frequency toroid signal is send through a triaxial cable to the preamplifier and is responsible for the frequency band above 160 KHz.
So the high frequency amplifier is followed by a high pass active filter with corner frequency of 160 KHz.

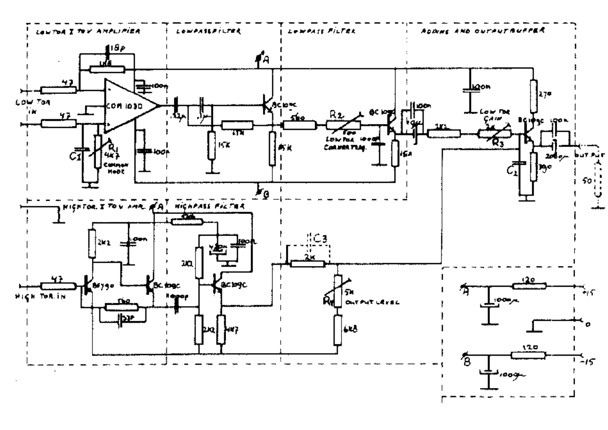

Fig. 2. Electronic circuit Toroid monitor

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A balanced adding of both outputs delivers the actual output signal over the whole frequency spectrum. After buffering, this signal is fed to a 50Ω high video data highway for monitoring in the central control room.

Calibration procedure

First R_1 is set for maximum common mode rejection. Calibration is achieved by setting the resistors R_2 to R_4 and C_1, C_2 according to the next procedure. We feed a current pulse through the calibration winding and monitor this pulse on an oscilloscope. The output signal of the toroid current transformer electronics is shown on the same scope. Now R_3 is set for the right balancing between the high-and low frequency amplifier outputs. R_2 is set for the final high cutoff frequency of the low frequency toroid signal. R_4 is set for the desired output level. The sensitivity of the monitor must correspond to 10 mV/mA. This resistor at the same time effects both low- and high frequency output signals. C_2 and C_3 are set for the final rise time. Because of some spreading in the total combination of the toroids, cables and electronic circuits, it is important to do the calibration procedure in the final confuguration.

Results

The final toroid transformer design is shown in fig. 3. There are about 10 toroid monitors installed at the accelerator, beam-switch yard and experimental rooms. They are installed on strategic points. Just behind the injector and at the end of the accelerator, in front of all bending magnets and experimental targets. These monitors are an indispensable measuring device in determine the exact peak beam current at all these points. Because of the accuracy of this monitors it is possible to detect current loss through the beam transport system within a few percent. For higher current loss another device will interrupt the electron gun for safety.

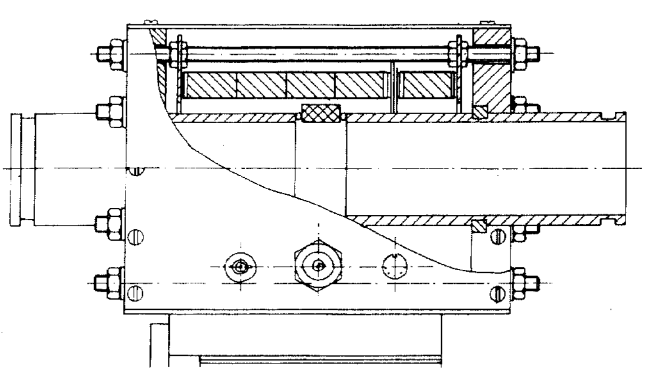

Fig. 3. Final Toroid transformer design

Travelling wave position monitor

Introduction

The X-Y-Ø SLAC-type cavity position monitor is a very expensive monitor to manufactor. For the lower peak currents of 1 μA to 10 mA used at IKO this monitor needs a R.F. signal processing system to upgrade the monitor sensitivity. Other experiments at SLAC with a phase sensing position monitor of higher sensitivity seemed to be a better solution to IKO's demands. This position monitor transducer is easier to manufactor and finally demonstrates extreme sensitivity and high position resolution in combination with the electronics. Exact center and beam displacement is defined by calibration. Calibration is possible at every moment.

Theory

The transducer part of this monitor is a simple length of S-band wave-guide with the beam apertures centrally placed in the broad walls. Each end of the wave-guide is terminated by a well matched wave-guide to coax transition, so there are no standing waves in the guide. Fig. 4 shows one arm of this position monitor principle.

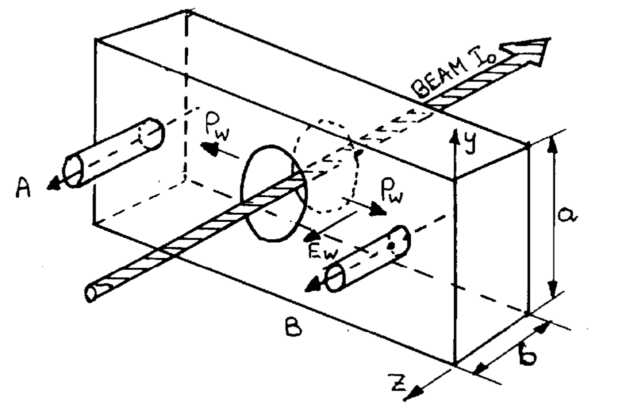

Fig. 4. Travelling wave position monitor principle

A current I_o passing through the aperture parallel to the axis, induces a power P_W flowing in the TE_{10} mode towards the transitions where:

$$P_W = M^2 \frac{b}{a} \eta \frac{\lambda_g}{\lambda_c} I_o^2$$

(η = free space impedance, λg = guide wave-length, λ_o = free space wave-length, M = gap transit factor). For S-band wave guide at 2856 MHz $\frac{P_W}{I_o^2}$ = 180 μW/(mA)^2).

Measured at IKO about 100 μW/(mA)^2 with a beam hole diameter of 4 cm. With the beam centered in a symmetrical structure the signals at A and B are in phase. When the beam moves a distance towards B the phase of the signal at B leads A by Ø, where

$$\emptyset = 4 \frac{\pi x}{\lambda g} \quad \text{radians.}$$

at 2856 MHz in S-band wave guide $\frac{d\emptyset}{dx}$ = 4,8 degrees/mm. For both horizontal and vertical position monitoring, two orthogonal wave-guides connected by a tube of a certain diameter completes the whole monitor transducer. Beam displacement in the y-direction does not alter the phase relation in the x-guide.

System design

The R.F. signals from the monitor are mixed with a local transistor oscillator signal to produce an intermediate frequency of 10 MHz. A trimmer phase-shifter is used in each channel for phase balancing and beam deflection calibration. System setup is shown by fig. 5. The 10 MHz signals are amplified in limiter-amplifiers, where the amplitude information disappear.
The phase information is detected by a phase detector and gives the desired beam position information.

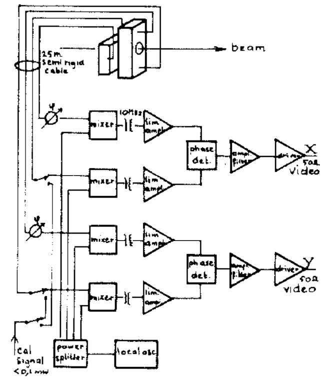

Fig. 5. Travelling wave monitor system design

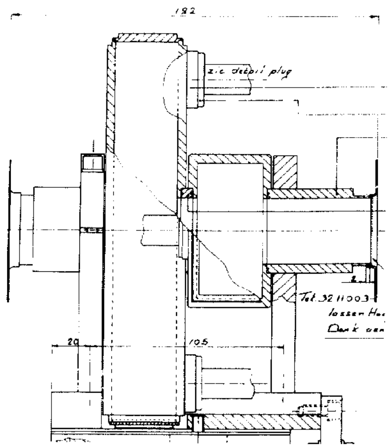

Fig. 6. Final monitor transducer design

Beam center calibration is possible by feeding a 2856 MHz test or reference signal into one arm. This signal couples through the beam hole and simulates the beam induced signal in the other guide. With a well made symmetrical structure this position corresponds with the exact center of the beam hole. By trimming the phase-shifter in one output it is possible to tune to the correct point of the phase detector response. The same is possible for the other arm. Beam deflection calibration is possible if a calibrated phase shifter is used.

Electronic design

It can be shown that the phase difference between the I.F. outputs of the two mixers is the same as the phase difference between the beam induced microwave inputs. This is true for square law and linear mixing. The I.F. signals are passing through two CA 3076 limiter amplifiers with a lower limiting threshold of 50 μ Volt. These I.C.'s perform the function of current normalization, since their clipped output wave forms carry the phase (position) information independent of input amplitude (current). With an amplifier input impedance of 200Ω the minimum I.F. power required to drive the 3076's to the lower limiting threshold is 12,5 p Watt. Using the measured obtained R.F. power induction rate of 100 $\mu W/(mA)^2$ and assuming 9 dB mixer loss and 3 dB semi-rigid cable loss, the minimum beam current pulse which will give a usable position signal will be 2 μA. The 3076 amplifier will accept I.F. signals up to 5 Volt. This indicates an upper beam current of over 50 mA. The 3076 amplifiers are followed by an MC 1596 balanced phase detector and low frequency amplifier-filter. A 50Ω driver delivers the position video signal to the video data highway. This highway transports the video signal to the control room. Sensitivity of this signal is 30 m Volt/degree or 140 m Volt/mm beam displacement.

Transducer design

The wave-guide length of both arms X and Y is chosen in a way that all possible resonances are far enough away from the accelerator frequency. It works out to a length of 20 cm of S-band wave-guide. The wave guide coax transitions are tuned according to a special procedure. The R.F. coupling between the guides by the beam-pipe hole is the sum of the R.F. coupling between the two guides for zero wall thickness, and the R.F. attenuation in the beam-pipe hole. The attenuation in the beam-pipe hole for the responsible R.F. mode is below the cutoff frequency of the used hole diameters. The numbers for several hole diameters are:

Hole diam. in mm.	Hole coupling in dB	Beam-pipe hole att. in dB/mm
20	- 31.96	2.02
30	- 21.39	1.29
40	- 13.90	0.92
50	- 8.09	0.65

The choice of the beam-pipe length is determined by:
- the desired isolation between the two guides
- the used beam-pipe diameter

Chosen is for an isolation of about 25 dB between the two guides based on:
- the influence of the X-channel to the Y-channel must be low enough
- the calibration signal coupled through the beam-pipe hole must be high enough, starting with a moderate reference signal in the modulator hall.

Results

The monitor transducer is a totally brazed unit. Materials used are stainless steel and OFHC copper. The coax feedthroughs are from alumina oxide. A drawing of the final monitor is given in fig. 6. The endplates of the guides are tig welded in place after the tuning procedure. Between the transducer in the beam center line and the electronics in the modulator hall there are four ½" prodlines from spiroline about 20 meters long. These semi-rigid cables are bounded together to minimize phase differences caused by temperature variations. Because of the massive outer conductors it is impossible to radiate microwave power into these cables from neighbouring R.F. cables. Care must be taken to prevent every possibility of radiating R.F. power into this measuring system because of its extreme sensitivity. There is no need to thermostrate the wave-guide transducer part, because it is not a high Q resonating system. Special care must be taken into account of the limiting amplifiers of the channels with respect to equalness and noise performance. About 25 position monitors are built of this type now. They are installed at the accelerator, beam switch yard and experimental rooms, and have demonstrated their extreme sensitivity and position resolution. This position monitor is demonstrated at M.I.T. Bates Accelerator during 1980 because of their interest in a very sensitive position monitor with high position resolution. M.I.T. Bates has decided to build the same monitor for their beam recirculator, based on specifications and costs.

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