1 nA BEAM POSITION MONITORING SYSTEM

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Abstract

A system has been developed at Jefferson Lab for measuring transverse position of very low current beams delivered to the Experimental Hall B of the Continuous Electron Beam Accelerator Facility (CEBAF). At the heart of the system is a position sensitive cavity operating at 1497 MHz. The cavity utilizes a unique design which achieves a high sensitivity to beam position at a relatively low cavity Q. The cavity output RF signal is processed using a down-converter and a commercial lock-in amplifier operating at 100 kHz. The system interfaces with a VME based EPICS control system using the IEEE 488 bus. The main features of the system are simple and robust design, and wide dynamic range capable of handling beam currents from 1 nA to 1000 nA with an expected resolution better than 100 µm. This paper outlines the design of the system.

1 INTRODUCTION

The Thomas Jefferson National Accelerator Facility, or Jefferson Lab, is a basic research laboratory built to probe the nucleus of the atom to learn more about the quark structure of matter. The underground recirculating accelerator uses superconducting radio-frequency technology to drive electrons to energies between 800 MeV and 4 GeV. The electron beam can be split for use by three simultaneous experiments in the end stations.

The middle one of the three experimental stations, hall B, requires beam currents in the range from 1 nA to 1000 nA. A new BPM system was needed to accommodate beam position measurements at such low currents. We selected a system using position sensitive resonant cavities as pickups and phase-sensitive synchronous demodulators. The project started in January 1996.

2 SYSTEM OVERVIEW

Number of BPMs	3
Beam Energy	800 MeV - 4 GeV
Operating Range	1 nA - 1000 nA
Parameters to be Measured	x and y positions, current
Nominal Measuring Rate out of control system	1 orbit/s
Position Measuring Range	$\|x\|, \|y\| \leq 5$ mm
Absolute Accuracy	≤ 1 mm
Resolution	≤ 100 µm @ 1 nA CW
Linearity Within	$\partial x/x \leq 10$ %
Measuring Range	$\partial y/y \leq 10$ %
Current Dependence	≤ 50 µm peak-peak @ required current ±50 %
Stability, Drift	≤ 25 µm rms in 8 hours

Table 1: System specifications.

Concept selection was the most difficult part of this project. We searched at Jefferson Lab as well as at other laboratories and industry for alternative concepts that would give us a good starting point.

At the time the project started, CEBAF was equipped with a Switched Electrode Electronics BPM system (SEE) covering dynamic range from 1 µA to 1000 µA [1]. We initially hoped to increase the sensitivity of the beam-pickups and the electronics each by factor of thirty to make a BPM system that works down to 1 nA. However, we soon realized that we could increase the SEE electronics sensitivity by no more than factor of five. The key limitation of the system was a quasi-synchronous demodulator around which the electronics was built. The problem does not lie in the particular circuit that we use, but in the quasi-synchronous demodulation concept, where signal to be demodulated is also used to generate a demodulation carrier. A phase-sensitive demodulation scheme appeared to be the only feasible solution for electronics. A similar system that uses phase-sensitive synchronous demodulation is operational at Mainz Microtron in Germany [2]

A position sensitive resonant cavity came at the top of our list among alternatives for beam pick-ups. It was the only type of pick-up that promised an increase in position sensitivity by factor of approximately 30 with respect to the wireline BPMs used at CEBAF accelerator [3]. We evaluated different resonant cavity configurations: circular, rectangular, off-centered TM010. We selected a design that is conceptually similar to the RF separator cavity design used at CEBAF to split electron beam to three experimental halls [4]. This position sensitive cavity, explained in detail below, gives approximately 10 dB greater position sensitivity than a circular TM110 cavity.

Figure 1 shows a system block diagram. A position measurement is done by taking the signal from a position sensitive cavity (x or y) and normalize it with the one from a current cavity. To get x, y positions and beam current we need three dedicated electronic channels.

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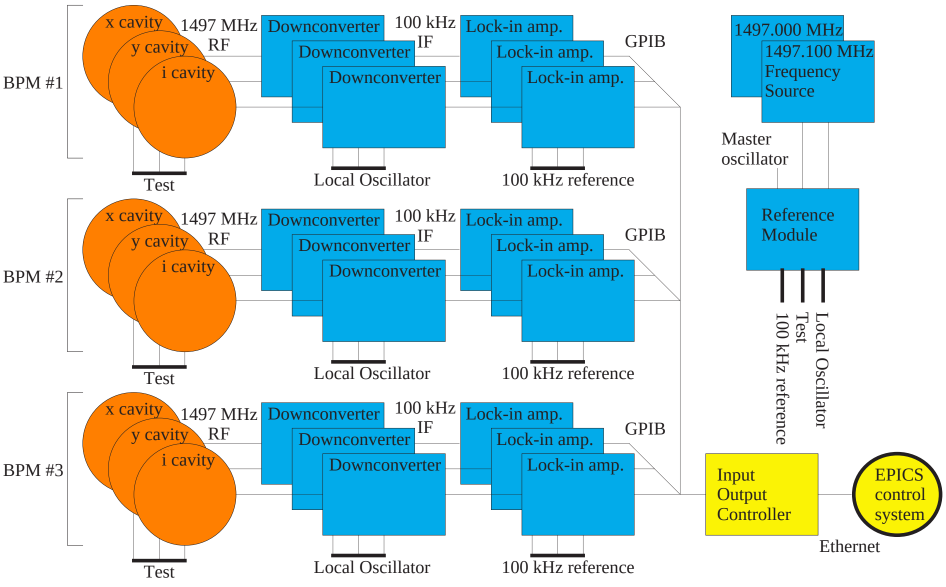

Figure 1: 1 nA BPM system block diagram.

3 POSITION CAVITY

Information about the beam is provided to the electronics by three room temperature RF cavities operating at the third harmonic of the 499 MHz bunch frequency. Two of the cavities are position monitors with one producing an X position x current signal and the other a Y position x current signal. The third cavity is a CEBAF Beam Current Monitor [5] that provides beam current and phase information necessary for position signal amplitude scaling and sign correction.

Bunching Frequency	499 MHz
Beam Line Aperture Restriction	3.0 cm diameter minimum
BPM Resolution	70 pV/µm (-150 dBm @ 100 µm)@1nA
Longitudinal Beam Line Space	90 cm maximum
Position measuring range	|x|, |y| ≤ 5 mm
Resonant Frequency	1497 MHz
Loaded Q	3500
Diameter	19.0 cm
Depth	9.5 cm
Rod Gap	3.0 cm
Material	Copper Plated Stainless Steel

Table 2. Position cavity specifications.

The position cavity is a new design that offers excellent stability and transverse sensitivity and mode isolation. The cavity is a pillbox with field perturbing rods operating in a dipole type mode (see figure 2). Resolution is defined here as the ratio of the change in the cavity output signal voltage divided by the change in the beam position for a given current. The longitudinal electric field of the mode goes through a null point (and sign reversal) in the center of the cavity resulting in a shunt impedance of zero and no output signal for a centered beam. The position cavity is designed to measure accurately beams that travel through a one centimeter square window centered on the cavity axis. Inside this window the electric field amplitude changes linearly with position and the resolution is at its highest value.

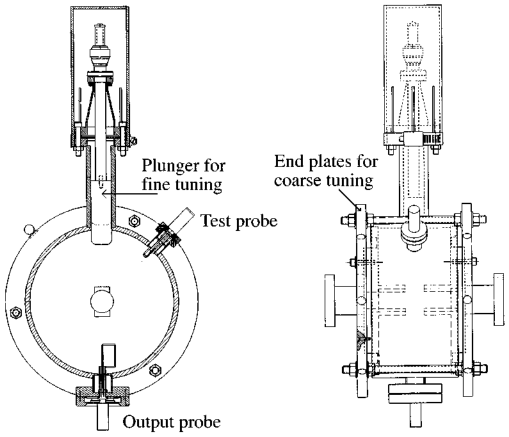

Figure 2. Position cavity front and side view.

Placing rods within the cavity draws the electric field maxima locations of the mode closer to the cavity axis. This field redistribution increases the resolution by a factor of 2.5 compared to a cavity with no rods (see figure 2). The rods also have a polarizing effect in the cavity, locking the orientation of the fields and eliminating the transverse mode. This improves the x-y isolation and permits greater overall system accuracy. The rods also introduce loss and the Q of the mode is reduced by half. The resulting broader resonance is then beneficial in reducing drifts for improved long term measurement stability.

4 ELECTRONICS

A separate electronics package processes the 1497 MHz radio frequency (RF) signal coming from each cavity. Nine equivalent electronic channels use phase-sensitive demodulators to digitize and extract amplitude and phase of the signals.

Operating Frequency	1497 MHz
Dynamic Range	-156 dBm to - 40 dBm
Demodulation scheme	IF sampling, digital I-Q
Dynamic reserve	100 dB
Stability, Drift	≤ 0.5 % rms in 8 hours
Channel-channel isolation	55 dB
Baseband time constant	10 µs - 10 s
Testing capabilities	Frequency sweep ± 1 MHz

Table 3: Electronics specifications.

The 1497 MHz signal from each cavity is first amplified in a low noise amplifier, mixed with a 1497.1 MHz local oscillator (LO) signal in a dual-balanced mixer and then low pass filtered. This yields an IF frequency signal of 100 kHz that can be processed by a lock-in amplifier; the latter sets the limit on to how high the IF frequency can be. The lock-in amplifier is a commercial off-the-shelf model 7200 available form AG&G. This DSP based instrument samples 100 kHz signal and demodulates it in a numerical (DSP) I-Q demodulator using an externally supplied 100 kHz reference. Use of the digital demodulator significantly improves the accuracy, stability and flexibility of the system.

The 100 kHz reference, LO and 1497 MHz test signals are generated by a reference frequency module. Figure 3 shows a simplified block diagram of the module. The 100 kHz reference is generated by mixing 1497.1 MHz signal form the LO frequency source with a 1497 MHz RF signal received from the CEBAF machine master oscillator. It was a design challenge to generate a 1497.1 MHz LO signal with minimum content of 1497 MHz RF signal. It turns out that 1497 MHz signal in the LO channel limits system performance at the lower signal levels; a weak 1497 MHz signal in the LO path enters the mixer in a downconverter module, where it couples to the RF port of the mixer and gets reflected back to the RF port. This process generates an unwanted 100 kHz signal. This phenomenon can be easily observed by terminating the downconverter input to 50 Ω and taking a reading from the lock-in amplifier. This explains use of isolators in LO and RF signal paths.

The connection to the CEBAF EPICS [6] control system is a dedicated input output controller (IOC). Each lock-in amplifier communicates with and is controlled by that IOC via a GPIB bus. Our estimate is that bandwidth of the GPIB bus will permit obtaining 10 readings of all lock-in amplifiers per second which is 10 times faster than is required.

The system is to be installed in the transport line tunnel close to the cavities to minimize signal loss due to cable attenuation. A modular design was chosen to facilitate maintenance and minimize time to repair in case of a failure. The modules conform to 3U, 220 mm Eurocard standard and use DIN type M connectors with RF inserts.

5 SUMMARY

The system is to be installed in September 1997. Cavities are under construction. We have tested electronics in our laboratory. The measured sensitivity of the system is -156 dBm and the worst case channel to channel isolation greater than 55 dB. We now plan to install the system in the tunnel and repeat the measurements to check performance in situ since a system with such a high sensitivity is more susceptible to any externally generated interference.

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