DEVELOPMENT OF A BUNCH LENGTH DETECTOR*

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Abstract

A bunch length detector, which can measure current distributions inside a beam bunch, has been designed and is under construction. The device measures secondary electrons that are produced when the beam hits a negatively biased thin wire. Two main components of the device are: 1) an rf deflector to deflect secondary electrons transversely in correlation with the rf phase of the beam bunch and 2) micro-channel plates to measure electron currents. Rf properties of the deflector were first numerically analyzed, and a full-scale cold model was built and examined using a network analyzer. The micro-channel plate detector was tested using a β-emitting isotope source. Electron optics was calculated to design the structure of the bunch length detector, and the actual detector is being constructed and will be tested using a cw proton beam.

INTRODUCTION

Measurement of charge distributions in a beam bunch versus rf time can be used to match the longitudinal beam phase space into the acceptance of an rf accelerator. The bunch shape cannot be precisely predicted by simulations alone due to factors such as nonlinear effects. If the bunch shape in the injection beam line is measured and controlled properly, beam losses could be minimized in the accelerator located downstream.

Different types of diagnostic devices have been developed to measure the longitudinal shape of a beam bunch [1]. We chose to develop a bunch length detector (BLD) that uses a thin wire placed in the beam path to produce secondary electrons [2, 3]. The electrons are then deflected by an rf deflector in correlation with the rf time of the bunch to produce spatial distributions, which are measured by a micro-channel plate (MCP) detector. Optics of the electrons from the source slit to the MCP was simulated using an orbit tracking program.

The fields inside the rf deflector were simulated using 2D and 3D rf electromagnetic analysis programs, and its full scale cold model was built and tested. Its resonance frequencies and quality factors (Q-value) were measured to compare with the calculations. Meanwhile, the MCP was tested using a β-emitting isotope source. Construction of the BLD is under way, and we plan to test it initially using a proton beam in the energy range of 20-50 MeV.

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DESIGN AND TEST OF THE DETECTOR

The principle of the BLD, which adopts the method of measuring secondary electrons, is illustrated in Fig. 1. Electrons produced from the negatively biased wire pass through a slit that defines the emittance of the electron beam. Collimated electrons are then transversely deflected by rf waves synchronized with the rf phase of the beam bunch. As a result, the transverse component of the electron-beam velocity is modulated accordingly. Electrons then drift toward the MCP, where transverse spreads of the electron beam dependent on the rf phase become sufficiently large.

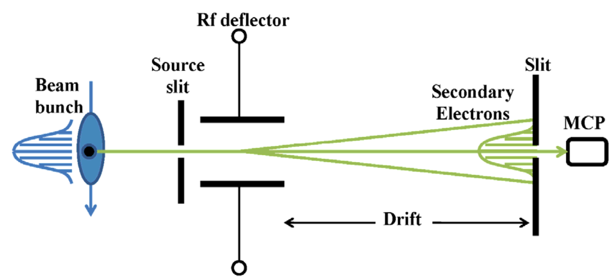

Figure 1: Schematic view of the operation principle of the bunch length detector.

The mechanical design of the BLD has been made based on secondary electron optics, and its two major components, the rf deflector and the MCP, are tested to better understand their characteristics. We expect the detector to have a time resolution below 1 ns and be applicable to a wide range of primary beam energy and currents.

Secondary Electrons Optics

Optics of secondary electrons has been calculated using an orbit tracking program, and electric fields produced in the rf deflector are attained in 2D using SUPERFISH [4]. Transversal distributions of the electrons at the location of the MCP were calculated as shown in Fig. 2 as a function of the relative rf phase between the primary beam and the rf deflector. Rf deflection voltage is 1 kV and the target wire will be applied with a voltage of -10 kV. The rf frequency of the deflector is set to 92.9 MHz, which is the fourth harmonic of the cw beam that is planned to be measured. The primary beam bunch is assumed to have a phase width of 40° and a drift length of 40 cm.

Fig. 2 shows the transverse distribution of the electrons for every 10° of relative rf phase difference. The MCP is fixed at the central location, and a slit opening in front of it determines the measured resolution of the primary beam phase. For current settings, phase dispersion is estimated to be approximately 1.3 cm/40°. A larger dispersion can be obtained with a longer drift and a larger deflection voltage.

In obtaining the results of Fig. 2, the electron beam was assumed to have zero emittance. In reality, the beam needs to be focused at the location of the MCP. Hence, a negative DC voltage is to be applied on the plates. An optics simulation indicates that a voltage of around 500 V can make a point-to-point focus for the current configuration.

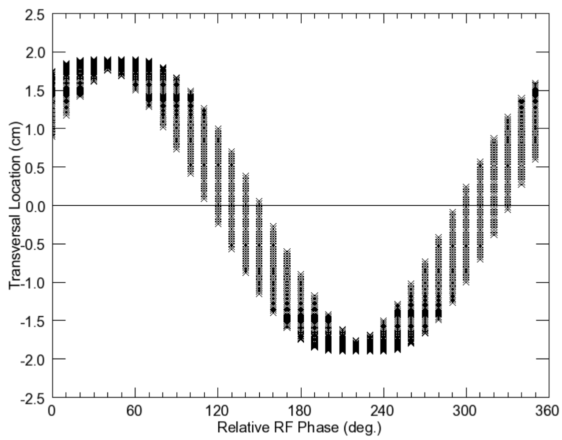

Figure 2: Transversal distributions of secondary electrons versus relative rf phase at the location of the MCP. The frequency is set to 92.9 MHz.

The target wire, where secondary electrons are emitted, is applied with a negatively biased voltage that could be adjusted up to -20 kV. A tungsten wire with a diameter of 1 mm is used for the initial test, and wires made of different materials and with smaller diameters will also be tested.

A rough estimation on secondary electron yields was made for a tungsten wire based on theoretical predictions [5] using the stopping power tables from PSTAR [6]. In the case of using a proton beam of 50 MeV, the number of electrons escaping from the tungsten wire surface and passing through the source slit per incident proton is estimated to be around $10^{-3} \sim 10^{-4}$. The electron current is then expected to be in the range of pA when the primary beam is in the range of nA, if perfect transmission is assumed throughout the detecting system.

Design and a Model Test of the RF Deflector

The rf deflector is a quarter wave resonator (QWR), and the two stems inside the deflector resonate in an out-of-phase mode to produce deflecting rf electric fields. The fourth harmonic rf was chosen to reduce the length of the resonator. The resonant frequency of the rf deflector must be in the range of 90-100 MHz, considering the rf frequency of the cyclotron in which the proton beam to be analyzed originates from.

A full-scale cold model was built with copper tubes, and its S-parameters were measured using the HP 8753C network analyzer as shown in Fig. 3. Measurements for the cold model yielded resonant frequencies of 87.9 MHz and 91.6 MHz for the in-phase and out-of-phase resonances, respectively, while simulation results were 89.7674 MHz and 91.9144 MHz. The slight difference stems from dimensional discrepancies in fabricating the actual model. Unloaded Q-values at the resonant frequencies obtained from simulations and the cold model tests were 1250 and 970, respectively.

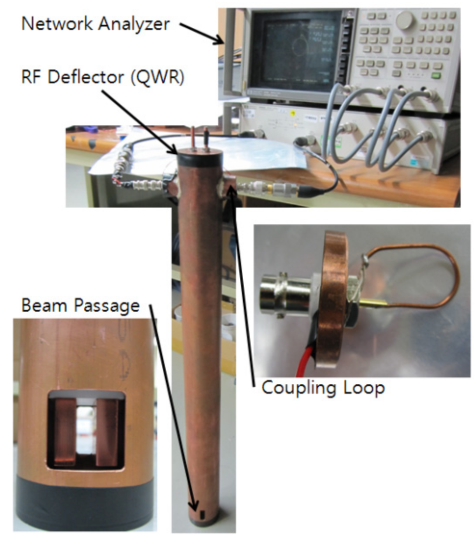

Figure 3: Set-up of the full-scale cold model of the rf deflector, which is shown here connected to a network analyzer.

A simplified connection diagram of the rf driving circuit is given in Fig. 4. A low-level rf control system will be implemented for stabilizing the rf phase, amplitude, and cavity resonance frequency in the circuit. Signals from a directional coupler at the cavity input and from the cavity field probe are used in the low level rf control system which sends control signal to the tuner and the vector modulator that adjusts both amplitude and phase of the RF signal supplied to the amplifier input. The maximum rf voltage needed is around 1 kV, and a 50 W solid-state power amplifier (1~100 MHz, Empower Inc.) is used. A matching circuit has been tested, achieving a return loss of above -20 dB as shown in Fig. 5.

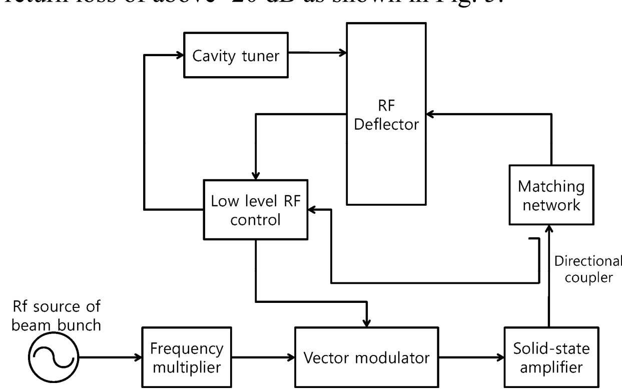

Figure 4: Schematics of the rf driving circuit for the deflector.

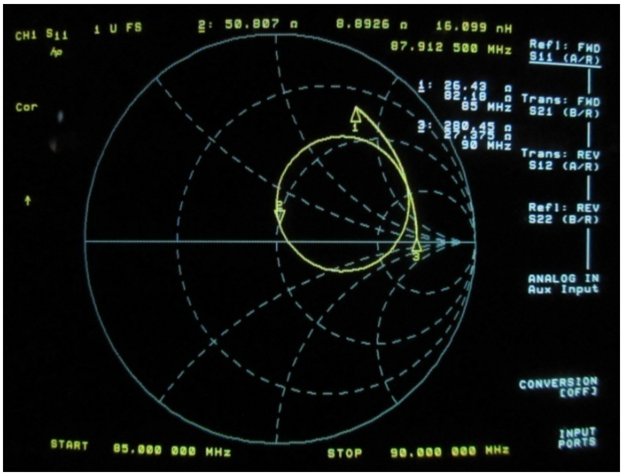

Figure 5: Input impedance (S11) measured by a network analyzer. Impedance is 50.8 + j8.89 Ω at the resonance frequency.

The actual rf deflector, including a vacuum feedthrough located near the deflecting plates and other mechanical details, is analyzed and in preparation. Unloaded Q-values are estimated to be 390 and 490, if the deflector is designed with materials of aluminium and copper, respectively.

Test of Microchannel Plates Detector

MCP is used to obtain a high gain of the electron signal. The MCP (Hamamatsu, F1094-21s) we chose has a two-stage configuration in order to achieve a gain of 10^6. The detection diameter is 20 mm, and the effective detection area is about 60% of the total area. The maximum bias voltage that can be applied is 2 kV. Detection efficiency for electrons is a maximum of 70% for electron energies of 0.5 keV, and it drops below 20% for electrons having energies larger than 10 keV.

Basic characteristics of the MCP, such as dark current and dark count, were checked. Furthermore, to verify the electron detection by the MCP a plastic scintillator was placed between the electron source and the MCP, which are placed inside the vacuum chamber as shown in Fig. 6. A coincidence signal was then measured between the MCP and the PMT, where the PMT was placed just outside the vacuum chamber. The coincidence signal from a β-emitting ^{90}Sr source also confirmed the gain of the MCP to be around 10^6. By using an alpha source, we plan to test secondary electrons produced from the tungsten wire applied with a negatively biased voltage, before the proton beam from the cyclotron is analyzed.

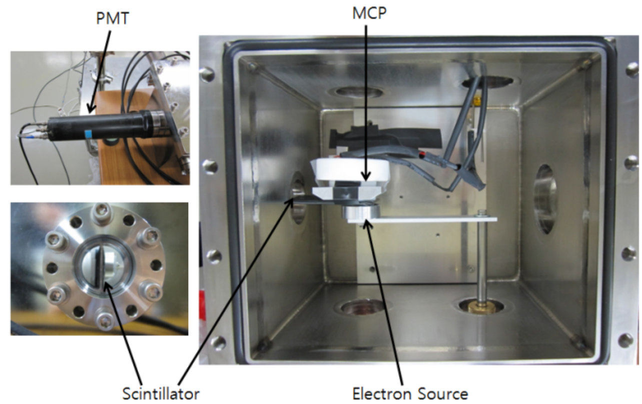

Figure 6: The vacuum chamber where the MCP was tested. A setup employing the coincidence technique to test the electron detection by the MCP is shown.

SUMMARY

The bunch length detector is designed based on beam optics of secondary electrons, which are produced by a primary ion beam hitting a metallic target wire. A cold model of the rf deflector was tested, and its characteristics were found to agree with rf calculations. The MCP detector was tested using an isotope source and is ready to be used. The vacuum chamber to accommodate the detector was built, and the actual rf deflector is soon to be completed. The initial test for the fully assembled detector is planned to be performed using a cyclotron beam.

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