Design and development of deflector cavity for the non-interceptive bunch length measurement system

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Abstract. A non-interceptive bunch length detector system for the measurement of bunch width of accelerated beam has been designed and developed. This detector system is based on emitted secondary electrons produced by a primary ion beam hitting a thin tungsten wire placed in the beam path. The measurement of the longitudinal beam shape for wide range of beam energy, intensity as well as ion species is possible with this detector. One of the main components of the detector system is a RF deflector cavity used to deflect electrons in correlation with rf phase of the accelerator. The detailed design, development with measurement results of the deflector cavity resonator have been reported in this paper.

1. Introduction
A Radio Frequency Quadruple (RFQ) Linear accelerator of the upcoming Radio Active Ion Beam facility (RIB) at VECC has been designed and developed [1], [2]. RFQ resonating at 37.8 MHz would be the first post-accelerator which will accelerate RIBs from 1.7 keV/u to 100 keV/u. Further acceleration to 400 keV/u will be carried out in the subsequent Inter-digital-H type Linacs. Efficacy of acceleration in consecutive accelerators critically depends on matching the longitudinal emittance of beam to the longitudinal acceptance of the subsequent accelerator. Thus, measuring the bunch length of ion beam accelerated by RFQ is of paramount importance for accelerating beams to higher energies without particle loss. Different types of measurement techniques have been developed for diagnostic of longitudinal beam bunch length [3]. A non-interceptive bunch length detector system based on secondary electron emission, produced by a primary ion beam hitting on a tungsten wire, is a more attractive and widely used system for achieving better resolution specially when the beam current and energy is low [4], [5]. In this method, the measurement is based on a coherent transformation of the longitudinal shape of the primary beam into a transverse distribution of a secondary electron beam through the phase scanning of rf applied on the deflector electrode. In order to have half wavelength resonator is a limited space many researchers [6], [7] have used the special design of the cavity by replacing the inner conductor of the coaxial resonator by helical coil. This kind of resonators gives quite reasonable Q value and other RF properties. This prompted us to choose the capacitive loaded helical resonator for our deflector system. The detailed design of the helical resonator of deflector cavity together with RF measurements developed for bunch length detector system has been reported in this paper.
2. Description of bunch length detector

The principle of the bunch length detector device is illustrated in figure 1. A negative high voltage DC biased tungsten wire is placed in the beam line. When the primary beam hits the wire, secondary electrons are emitted and they pass through the deflector gap in the rf cavity. Depending upon the rf phase many electrons get deflected and finally non deflected ones are detected by channeltron or MCP placed after a slit. The resonating frequency of the deflector cavity is same as that of the accelerator (RFQ). The deflection depends on the relative phase of the deflecting cavity with respect to RFQ. This would reflect in counts detected by the channeltron or MCP for different relative phases. Thus, this device converts the information in time domain to space domain.

![Figure 1. Schematic of the bunch length detector](image1)

![Figure 2. Deflector cavity](image2)

3. Design of deflector cavity

A DC voltage is required in the deflector cavity for efficient focusing and maximizing the count in the detector when no RF voltage is applied. So we need to develop a resonating structure where an RF signal modulates over and above a DC level. An open ended λ/2 configuration is a promising structure for our requirement. Using code SIMION [8], the geometry of the rf deflector electrode has been optimized to have desired electric field for better resolution in measuring the bunch width. The RF frequency of applied on the electrodes is 37.8 MHz, which is same as the frequency of the RFQ. To obtain the maximum deflector voltage with limited amount of driving power, a high Q resonating structure is required. A capacitive loaded half wave coaxial line resonator is a good choice. The length of an unloaded half wave coaxial resonator at an operating frequency of 37.8 MHz is 7.5 m. The resonator length can be reduced if the inner conductor of half wave coaxial line is replaced by a coil. Therefore, an alternative type of capacitance-loaded helical resonator cavity has been designed and developed. In this way we can get the reasonable Q value of the resonator and hence required deflector voltage with reduced cavity length. The resonator consists of a shielded helical coil connected to a deflector plate in one end and a tuning plate at other end as shown in figure 2. The gap between the deflector plates and the gap between the tuning plates are modeled as capacitors. The rest of the cavity is a coaxial line with helical inner conductor where the magnetic field is high. So, this part of the cavity has been modeled as an inductor. The cavity resonant frequency is given as:

\[ f_o = \frac{1}{2\pi \sqrt{L_{eq} \times C_{eq}}} \]  (1)
where, \( C_{eq} \) is the total capacitance consisting of the deflector capacitance, tuning capacitance and self capacitance of helix of resonator. The inductance \( L_{eq} \) consists of inductance due to the optimized length of the helical line and that of the normal coaxial line which is in between helical resonator and deflector plate. The self capacitance and inductance of the helical resonator can be theoretically estimated for a given length of the helical line. The characteristic impedance of coaxial line with helical inner conductor is:

\[
Z_{0ff}(\Omega) = 183n_d \left(1 - \left(\frac{d}{D}\right)^2\log\left(\frac{d}{D}\right)\right)^{1/2}. \tag{2}
\]

Here \( D \) is the inner diameter of outer conductor (shield), \( d \) is the mean diameter of conductor in inch and \( n \) is the number of turns per inch. The use of a helical coil allows for an inductor to be made with a low self-capacitance and resistance for maximizing the \( Q \) factor. The field is more concentrated near deflector plates and the resonant frequency depends strongly on this. The fringing field effects are important input considerations during theoretical analysis and modeling of this resonator cavity. In [9], an expression for calculation of fringing field capacitance has been proposed. Using this, the capacitance of deflector plates and tuning plates have been calculated. The length of the helical resonator whose diameter of outer shield is \( D \) and mean diameter is \( d \) can be approximated for the design frequency using Eq. (2). The optimized helical length for 37.8 MHz is 330 mm with \( d/D \) ratio 0.67 and number of helical turns 17.

The required deflector voltage for desired resolution as predicted by SIMION is around 1.5 kV, which is 1.12 times of the Kilpatrick limit. The tuner plate disk diameter is 80 mm with 2mm thickness and there is a gap of about 15 mm between the plates and the cavity top ceiling. The top of cavity ceiling can be moved in or out for frequency tuning. Cavity fields and \( Q \)-value have been optimized using eigenmode simulations in CST Microwave studio [10]. The simulated resonant frequency, \( Q \)-value and shunt impedance are 37.83 MHz, 2000, and 10 k\( \Omega \) respectively.

4. RF Measurements
We have performed the RF measurements using VNA. The measured resonance frequency is 37.801 MHz. The measured \( Q \)-value (Unloaded) using two pick-up loops under more than 98% reflection of power (-56 dB) is about 1200. The capacitive tuner can be moved over a range of 20 mm. The positions corresponding to the frequencies 37.3 MHz and 38.9 MHz are 8mm and 28mm respectively from the drift tube assembly. The measured tuning range with the gap variation of the tuning plate is shown in figure 3. The tuning range obtaining from the variation of gap from 13mm to 33mm is around 1 MHz without any appreciable change in the \( Q \) value.

The electric field pattern on the axis of buncher has been measured at low power levels using bead perturbation technique [11]. The total \( E_z \) field as a function of position along a path parallel to the \( z \)-axis has been obtained by pulling a Teflon bead of 1mm diameter through the resonator with a nylon thread. The measured \( E_z \) field for two different positions of the deflector plates is shown in figure 4. The shunt impedance measurement is necessary to determine the power requirement of cavity. The estimation of shunt impedance \( R_p \) is generally done by the capacitance variation method [12]. In this method the inter electrode capacitance of deflector is perturbed by putting a known small dielectric sheet between the plates of the deflector. \( R/Q \) is then determined as follows:

\[
\frac{R}{Q} = -\frac{\Delta \omega}{\Delta C} \cdot \frac{1}{\omega_0^2} \tag{3}
\]

where \( \Delta C \) is the perturbing capacitance and \( \Delta \omega \) is the drift of resonant frequency due to perturbation. The estimated \( R_p \) value from the measured data is ~5.4 k\( \Omega \). Thus the maximum RF power needed for required voltage of 1.5 kV is 220 W. It is to be noted that the measured \( Q \) and \( R_p \) values are around 70% of the estimated values which are quite reasonable.
5. Conclusion
A capacitive loaded helical resonator cavity for a non-interceptive bunch measurement device has been designed and fabricated. The measured RF characteristics of the resonator, such as frequency, $Q$ value and shunt impedance have been found to be close to the analytical estimation and simulation results. In future, power coupler for RF matching and pick-up loop for feedback control will also be incorporated in the cavity. It is also planned to include a low level control mechanism in the RF system to keep the deflector voltage stable during operation.

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7. References
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