ELECTROSTATIC PICK-UPS FOR DEBUNCHED BEAMS AT INR LINAC

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Abstract

Pick-ups are one of the most widespread non-destructive diagnostics at charged particle accelerators. These detectors, also known as beam position monitors, are generally used for the center-of-mass position measurements of bunched beams. The paper describes the research results for infrequent case of debunched beams operation. Measurement peculiarities and distinctive features of electronics are presented. The results of test bench-based measurements and 3D finite element simulations are discussed.

INTRODUCTION

The main idea of pick-ups is to measure the charges induced by the electric field of the beam charged particles on an insulated conductive plates [1]. For a bunched beam the measurement is performed using radio frequency methods [2]. However in case of a debunched beam it is transformed into measurement of quasi-steady-state charge during a macropulse. The name "electrostatic pick-up" is better suited for this application, which became urgent recently at multipurpose research center (MRC) based on the linear accelerator of INR RAS. For some time passed the beam is accelerated up to 209 MeV of 600 MeV and is transported near $L_{Drift} \approx 400$ m to the research facilities without acceleration. Due to the momentum spread ($\Delta p/p \approx \pm 3.5 \cdot 10^{-3}$ at the base) the beam bunch structure ($T_{Bunch} \approx 200$ ps, $f_{RF} = 198.2$ MHz) is lost and the measurements are done for the debunched coasting beam [3].

THEORY FORMALISM

INR electrostatic pick-ups consist of two pairs of cylindrical signal split-electrodes with so-called "linear-cut" (Figure 1). Projection of the cut between adjacent electrodes on the vertical and horizontal planes is a diagonal line. Three guard rings at ground potential minimize asymmetric fringe field effect and reduce cross-talk between pairs.

It is known, that in linear-cut pick-ups induced charges are proportional to the actual plate length at the beam center-of-mass position [1].

In ideal 2D electrostatic approximation for cylindrical split-electrodes with inner radius R beam positions are determined by Difference of the charges over their Sum (DoS) [4]. In practice, because of the capacitive coupling between the adjacent electrodes and asymmetry of the electric field at their edges, positions are:

$$X = K_X \frac{\Delta Q_{Horizontal}}{\sum Q_{Horizontal}} + \delta_X, Y = K_Y \frac{\Delta Q_{Vertical}}{\sum Q_{Vertical}} + \delta_Y,$$

where K_X, K_Y – "pick-up constants" (the smaller the K, the larger the DoS for the same beam position), and δ_X, δ_Y – so-called "pick-up offsets" of the geometrical center with respect to the electrical center, defined by $\Delta Q = 0$.

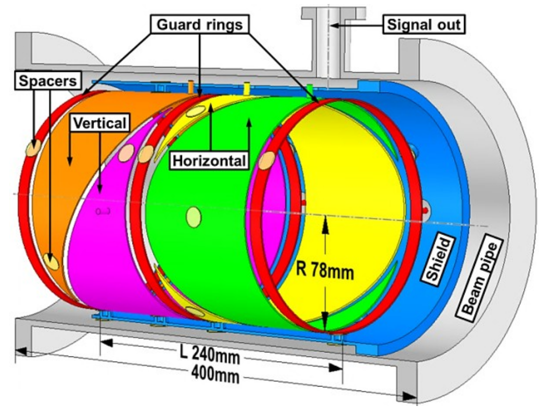

Figure 1: 3D-design of INR electrostatic pick-up.

BENCH-BASED CALIBRATION

Prior to the beam operation it is necessary to map the relationship between the beam position and the DoS, which is actually measured. A simple test bench was assembled for this purpose. The test bench consists of a copper pipe (10 mm diameter) placed between two grid dielectric plates at either sides of the pick-up. The copper pipe rests in two corresponding holes in the front and back grid plates and can be manually positioned accurate within ±0.5 mm. A signal generator produces a voltage pulse (500 mV, 100 μs, 50 Hz) at the pipe, imitating the debunched proton beam.

Electronics

Pick-up-based measurements require a conversion of beam-induced charge on detector plates to voltage. Generally, plate charge Q_p is integrated on the total pick-up capacitance C_p, producing voltage $V_p = Q_p/C_p$. Then voltage amplifier (Figure 2a) is used to provide gain. C_p is composed of a pick-up plate-to-ground capacitance (~110 pF for INR pick-ups) plus the capacitance of the interconnecting cable.

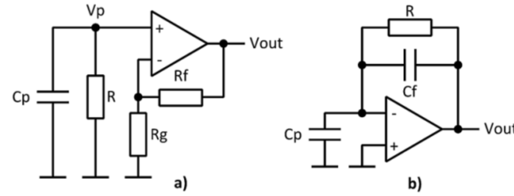

Figure 2: Pick-up electronics operation modes: (a) voltage amplifier, (b) charge amplifier.

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Alternatively it is possible to perform conversion and amplification in one step by means of charge amplifier (Figure 2b). Unlike floating potentials of the electrodes in case of voltage amplifier, charge amplifier actively keeps the electrodes at zero potential. Its output voltage is always $V_{out} = -Q_p/C_f$ and depends on feedback capacitance C_f only, so pick-up calibration can be done with an arbitrary cable length.

For the same V_{out} voltage amplifier has lower noise than charge amplifier but this difference diminishes for large gains. Charge amplifier using operational amplifier with JFET inputs and $C_p = 110$ pF, $C_f = 10$ pF, $R = 100$ MΩ was built for the test bench. With second stage gain of 10 and input referred noise of $16\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$, the output noise is 15 mV peak-to-peak.

High value resistor R defines DC gain and provides a path for the bias current to flow. In parallel with C_p or C_f it forms a high pass filter that causes pulse droop. Small droop can be assumed as linear for compensation by simple baseline restoration algorithm after digitization.

Pulse droop is about 10% for 100 µs beam pulse and component values mentioned above. Besides plate-to-ground capacitances C_p there is a capacitance, which consists of plate-to-plate capacitance of the detector (a few pF for INR pickup) and mutual capacitance between the signal wires.

The RF component of the signal due to the residual modulation of the beam is outside the amplifier bandwidth. Therefore, in a first approximation, the output signal of the amplifier corresponds to a steady component of the beam electric field, which is determined by the average pulse current of the beam. The convenient feature of DoS-measurement is that common mode hum is subtracted from the weaker signal corresponding to beam position and does not spoil it.

Test Results

Results of bench-based measurements for horizontal plane (Figure 3a) show expected DoS linearity across the whole aperture of the pick-up, though the sum and the difference are nonlinear per se. Deviations from the linear fit are smaller than ±0.5%. Constant $K_X = 75.3$ mm is 3.5% better than 2D-ideal approximation and is primarily caused by variation of beam pipe shape and size near the electrodes in spite of guard rings presence [4]. The offset $\delta_X = 2.7$ mm is observed. For vertical plane $K_Y = K_X$, but the offset $\delta_Y = 4.1$ mm.

As expected, the obtained results are independent of the total pick-up capacitance. The pick-up operation as a current monitor is complicated because of considerable nonlinearity of the sum signal.

Taking into account electronics noise ±7.5 mV of the sum and the difference signals, one can estimate the pick-up resolution (precision) ΔX specifying the ability to measure small beam position displacements $X_{real} = X_{measured} \pm \Delta X$ (Figure 3b). It is about ±0.5 mm around the work region for the electrodes signals induced by 0.5 V voltage at the test pipe.

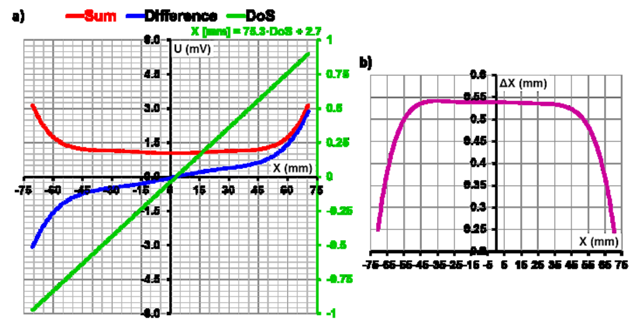

Figure 3: (a) Bench-based calibration results for horizontal plane. (b) Position resolution.

The pick-up accuracy specifies the beam position offset relative to the known fixed origin, for instance the symmetry axis of a quadrupole doublet, and is mainly determined by the pick-up offsets (δ_X, δ_Y) as well as mounting tolerances.

SIMULATION-BASED CALIBRATION

Conductive wires or pipes are usually used as beam imitators for test bench-based measurements. However it is obvious, that conductive object with uniform surface distribution of a fixed voltage cannot be an equivalent of a beam charged particles distribution. Therefore we need a complementary method for pre-tests based on 3D finite element simulations, for example, using ANSYS code.

Firstly, electrostatic equivalence between the model and a real pick-up must be established. For this purpose the bench-based measurements with copper pipe are reproduced in simulations. The results are in good mutual agreement: linear dependences $X[mm] = 75.3 \cdot DoS + 0.5$ for horizontal plane and $Y[mm] = 75.3 \cdot DoS - 0.8$ for vertical plane. Offsets δ in the simulation results indicate slight asymmetry of the electric field caused by asymmetric positions of the electrodes with respect to the shield edges. The greater quantities of experimental offsets are determined by manufacturing mechanical tolerances. Also results independence of the total pick-up capacitance is confirmed.

Beam Position Measurements

A debunched beam is simulated as five nested coaxial vacuum-material "pipes" with the outer radius $5/4/3/2/1 \cdot \sigma_{beam} = 2$ mm and the central cylinder with radius $0.5 \cdot \sigma_{beam}$. To decrease the edge effects the simulation region of the beam and beam pipe are extended up to 690.5 mm. The total charge corresponds to 10 mA pulse proton current (typical beam current).

The 2D Gaussian distribution of charged particles in cross section of the real beam is approximated by percentage discretization of the total charge into the σ-charges with following uniform distribution of these σ-charges inside volumes of congruent components of the beam model. Simulations show that a beam "surface" voltage distribution (Figure 4) differs considerably from the uniform surface voltage distribution of a conductive pipe, and this difference increases with a beam offset.

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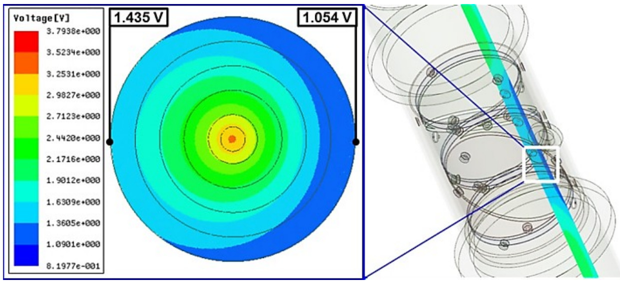

Figure 4: Voltage distribution in the beam with $\sigma_{beam} = 2$ mm and position ($X_C = 60$, $Y_C = 0$).

This effect provides expected qualitative changes of the electrodes responses. The sum and the difference signals dependences lose non-linear tails, so current measurement becomes possible, whereas the DoS dependence is retained perfectly (Figure 5a).

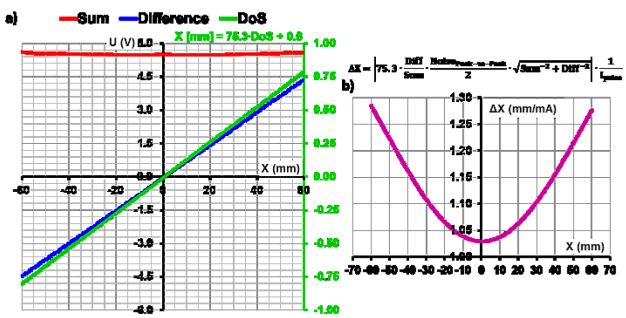

Figure 5: (a) Simulation-based calibration results for horizontal plane. (b) Position resolution.

Besides, the resolution increases together with the beam position offset, but $\Delta X < 130$ µm across the whole aperture for a typical pulse current of 10 mA (Figure 5b). Consequently, bench-based measurements with conducting pipe are suitable for DoS calibration, but can obscure extra pick-up applications.

Extra Measuring Capabilities

Because position, RMS size and pulse current of the beam can be varied during the accelerator operation, it is necessary to compare results for different typical cases.

The comparison of electrodes responses for different position offsets shows that the horizontal-vertical coupling is within the measurement errors (Figure 6).

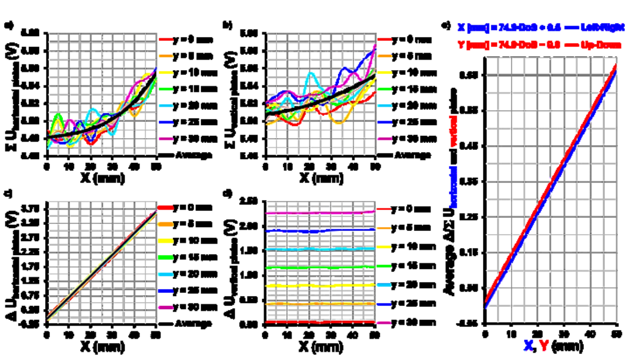

Figure 6: Results for different position offsets.

The comparative simulations for different σ_{beam} with the same total charge show consistency of the results. Besides the electrode responses are directly proportional to the beam pulse current as expected.

As a result, current monitor mode of the pick-up operation is confirmed. The simulated sum signal for 10 mA beam pulse current is about 5.5 V. Consequently, the resolution of current measurements with ±7.5 mV electronics noise is about 30 µA, that enable to cover the entire range of beam pulse current at INR accelerator.

The sum signal deviations because of the beam position and RMS size are less than 0.5%. The relative error of current measurements is less than 3% and is mainly determined by a small nonlinearity of the sum signal dependence. The current measurement capabilities can be used for beam losses monitoring of high-intensity beams at long sections between two electrostatic pick-ups.

CONCLUSIONS

Linear-cut electrostatic pick-ups can serve as multipurpose non-destructive diagnostics for debunched beams. The research for INR RAS linac shows, that for typical beam parameters pick-ups enable to measure beam center-of-mass position with the resolution about 0.2 mm, which corresponds to about 0.1% of the aperture. The initial accuracy can be worse by an order of magnitude and is mainly determined by mechanical tolerances.

Signal-to-noise ratio is limited by total detector capacitance, therefore it is necessary to use a preamplifier, either of voltage or charge type, connected to pick-up with short cable. Charge amplifier is more convenient, because its output signal is independent of total detector capacitance and pick-up calibration can be performed with arbitrary cable length.

Beam current measurements are confirmed and quantified by 3D electrostatic finite element simulations as more beam-similar calibration method, than a test bench with conducting pipe, imitating a beam. The resolution of current measurements is determined by electronics noise of the sum signal and is about 30 µA. The relative error of current measurements is mainly determined by nonlinear variations of the sum signal because of beam position and size and can be decreased down to 0.5% according to simulated dependences.

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