EXPERIMENTAL VERIFICATION OF PARTICLE-IN-CELL SIMULATION RESULTS CONCERNING CAPACITIVE PICKUP DEVICES*

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Abstract

For beam position monitoring purposes, three different approaches have been applied to investigate and compare pickup button and electron beam spectrum characteristics. Results on this simulative approach are presented. Induced pickup currents have been calculated both with an analytical and a numerical method. An experimental validation of these simulation results has been conducted with the 6-MeV electron beam from a linear accelerator for medical purposes. The measurements were conducted under non-vacuum conditions. Good agreement between particle-in-cell simulation and experimental data was achieved concerning pickup power spectral distribution and dependence from beam current and beam displacements although non-negligible electron spread during air passage of the electron beam cannot be avoided.

INTRODUCTION

Multi-energy particle accelerators are widely used in cancer treatment facilities [1]. High efforts are being made to ensure precise generation of the beam as well as high precision irradiation and thus to minimize the risk of harming the patient. However, in a clinical environment, unavoidable effects can influence beam position. For multiple-angle treatment, medical accelerators usually comprise rotatable gantries, where the effects of mass and earth's magnetic field can cause beam displacements. Moreover the vicinity of magnetic resonance systems, even if positioned in a different treatment room, was found to be responsible for minor misalignments to the intended beam path. Besides other measures to monitor and stabilize the beam profile, position measurement and correction of the beam is advantegeous for radiation stability.

In this paper, investigations on capacitive pickup devices are presented. A comparison between analytically calculated pickup characteristics and simulation results obtained with the software package CST PARTICLE STUDIO (CST PS) is given. Moreover, particle-in-cell (PIC) simulation results are compared to measurements conducted with test probes and the 6-MeV electron beam from a Siemens medical linear accelerator. In contrast to usual beam position monitoring, these measurements have been conducted under non-vacuum conditions, as in therapy applications particles propagate through a certain distance in air before reaching the patiet.

SIMULATIVE APPROACHES

To calculate the induced current on pickup probes and their spectral distribution, two alternative approaches based on different calculation methods have been applied:

Analytic Calculation in Matlab

An analytic approach for calculating the beam induced currents on capacitive pickups has been implemented in *Matlab* software. The developed tool is based on a numerical analysis given in [2]. The induced current on a pickup probe is calculated from the displacement current across the area of the pickup device. The influence of different bunch shapes is accounted for by the useage of weighted point charges. Therefore, the point charge is spread over a normalized distribution describing the bunch shape. The induced current on the button is then obtained by integration of the individual weighted point charge contributions at every sample of a given time interval. The total current can be calculated by considering the total number of particles and thus, the total charge in the bunch.

For spectral analysis of the pickup signals, the developed tool applies a Fast-Fourier-Transformation (FFT) to the signal in time domain which comprises the currents induced from a selectable number of bunches in a bunch train. The power levels contained in the beam spectrum fundamental and a number of bunch harmonics are then derived.

Particle-in-Cell Analysis in CST PS

To introduce pickup geometry parameters not covered by the Matlab analytic approach, like metal thickness and RF feed, PIC simulations [3] have been conducted in the full 3D electromagnetic solver software package *CST PARTICLE STUDIO*. Open boundaries have been chosen to avoid reflections of beam generated fields in the simulation volume. The induced currents are observed by mode selective time domain monitors in the vicinity of the waveguide ports. Further data processing is done in CST's postprocessing toolbox.

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Comparison of Calculation Methods

To validate the later experiment, Matlab analysis and PIC simulations were applied to a setup also used in the conducted measurements. The test setup consists of disk-shaped pickup plates connected to a 50 Ω semi-rigid coaxial line (see below). Plate geometry as well as beam characteristics were chosen as the input parameters of the Matlab tool. The complete test pickup geometry was fully modeled in CST PS as indicated in Fig. 1.

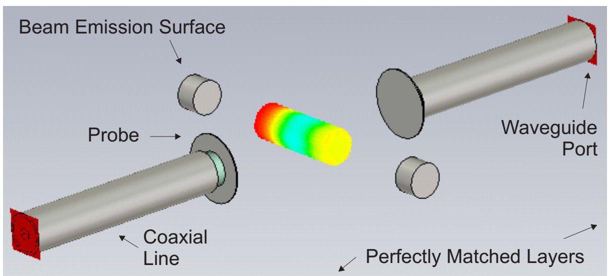

Figure 1: 3D model of CST PS simulation setup showing two opposite circular pickups as well as emission surfaces for the beam.

Figure 2 shows the induced currents on a 3 mm diameter pickup plate calculated both analytically and numerically and the basic agreement between the two. The Matlab generated curve shows the expected derivation of the Gaussian bunch shape, which is not as obvious in the PIC generated plot due to the high β of the beam. The reason for the oscillation following the main peak in the PIC plot can be found by mode separation of the CST signal monitor in time domain: The ringing is due to higher order modes excited in the coaxial line [4].

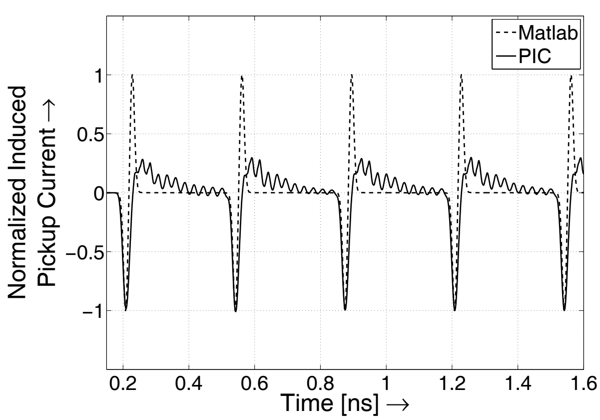

Figure 2: Comparison of pickup current signals in time domain gathered with Matlab analysis (dashed) and PIC code (solid) for a circular pickup with diameter d=3 mm and a 6 MeV electron beam. The curves have been normalized to the maximum induced current obtained by the Matlab calculation.

EXPERIMENTAL VERIFICATION

The application of a charged particle beam to the patient in the case of cancer therapy requires the beam to propagate through a certain distance of air. To validate the calculated pickup behavior, measurements have been conducted with the multi-energy, high-β electron beam generated by a Siemens medical linear accelerator. The measurements have been conducted in an area where in treatment applications the beam already propagates through air towards the patient.

As space is limited in a medical accelerator environment, pickup buttons have been preferred over stripline pickups due to the smaller dimensions of the buttons. The test probes have been manufactured as flat, disk-like extensions of the inner conductor of a 50 Ω semi-rigid coaxial line which was DC-decoupled by means of a Bias-T. The accelerator employs a 3 GHz RF source, thus the pickup current was investigated with a spectrum analyzer covering the frequency range up to 40 GHz.

Spectral Distribution of Pickup Power

In Fig. 3, a comparison between the simulated and measured harmonic content of the pickup signal is given for the first three beam harmonics. For spectral analysis of the simulated time signals, a bunch train of 40 electron bunches has been taken into consideration. The side lobes of the main spectral peaks in Fig. 3 are artefacts of the FFT which was applied to the bunch train in time domain.

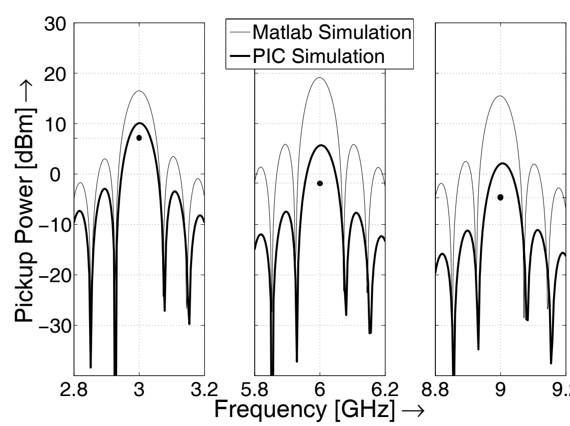

Figure 3: Comparison of spectral power distribution between Matlab simulation (fine), PIC simulation (bold) and measurement (dots). Despite beam spreading, the measured values are in close vicinity to the simulation results.

The figure reveals a mismatch between the power spectra obtained with Matlab and PIC code simulation. The deviation between the two curves can be attributed to different time signals. For generation of Fig. 3, the distance of the probe to the beam center has been increased compared to Fig. 2, which results in time domain signal deviations. The measured pickup power values at the fundamental and the

2nd and 3rd harmonic are indicated as bold circles in the figure. The degradation compared to the PIC-generated values is most probably due to beam spreading which occurs when the electron beam propagates through air. However, the measured power levels are still in acceptable vicinity to the simulated values.
It was validated that smaller disk probes lead to a higher sensitivity as stated in [5]. The measured sensitivity of a 3 mm diameter probe was 1.7 dB/mm, whereas the sensitivity of a 12.5 mm probe was measured to be 0.8 dB/mm. As promised by PIC simulations, the beam harmonic with the highest contained power was 6 GHz for the smaller disk and 3 GHz for the larger disk.

Pickup Current vs Beam Current

Figure 4 shows the rising pickup current when the beam current is increased. In the measurement, the beam current was increased by a factor of ten, causing the pickup current to increase by the same amount as expected. The inset of Fig. 4 compares the measurement results to PIC simulations, where the beam current increase was introduced by a rise in total bunch charge. Simulation and measurement are in good agreement. The 6 GHz harmonic of the beam spectrum is the highest component in the pickup spectrum due to button geometry (3 mm diameter in this case).

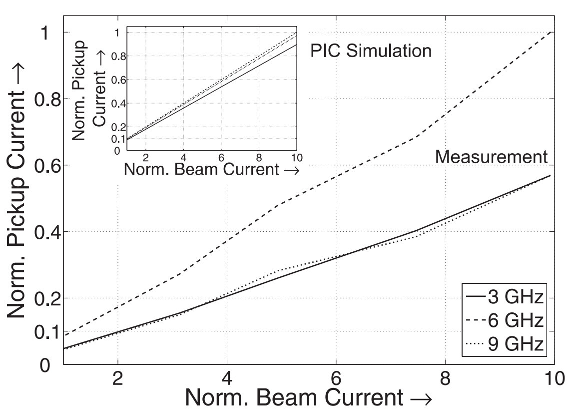

Figure 4: Comparison of PIC simulation and measurement concerning pickup current versus beam current. Both simulation and measurement data are normalized to the maximum ocurring pickup current showing nearly the same linear dependence in the plot.

Pickup Current vs Beam Displacement

Investigations have been conducted concerning the dependence of the pickup current from beam displacements. The distance between the probe and the beam center can easily be varied in simulation. In the test measurements, beam displacement was emulated by displacing the probe instead of displacing the beam.
Figure 5 shows the outcome of both simulations and measurement of the 6 GHz component of the displaced beam. Although non-negligible beam spreading during air passage can be assumed, good agreement between measurement and simulation is achieved.

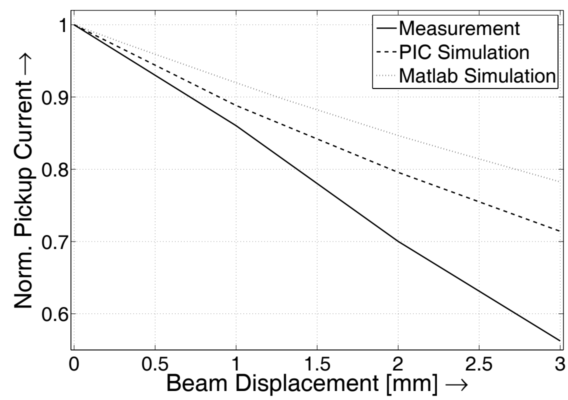

Figure 5: Simulation and measurement results on 6 GHz beam harmonic as a function of beam displacement. "0 mm" refers to the initial distance of the probe to the beam center (15 mm). The plots have been normalized to the respective currents at the initial position.

CONCLUSION

Analytical, numerical and experimental approaches have been applied to investigate the properties of capacitive pickup buttons, to be used for particle beam position monitoring. A Matlab tool has been developed based on the integration of induced currents of weighted point charges. The simulation results have been compared against particle-in-cell simulations conducted in full 3D electromagnetic simulation software. To validate simulation results, measurements with test pickups have been carried out employing the electron beam of a 6- to 25-MeV medical linac. Good agreement was achieved between the two simulation approaches and the measurements, although the beam passed a certain distance in air environment. Consequently, the applied codes represent promising tools for further investigations in this field.

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