BEAM POSITION MONITORING BASED ON HIGHER BEAM HARMONICS FOR APPLICATION IN COMPACT MEDICAL AND INDUSTRIAL LINEAR ELECTRON ACCELERATORS*

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Abstract

The usability of conventional BPM topologies in compact linear accelerators used for medical and industrial applications is very limited due to tight space restrictions in such systems. To overcome these limitations, a different approach is introduced which is based on integrating the pickups into low-field regions of the accelerating structure and evaluating higher beam harmonics. Applications based on this approach will require RF frontends in frequency ranges beyond those covered by BPM dedicated hardware which is currently commercially available. Therefore, a demonstrator setup is presented which is capable of investigating suitable RF frontends for the proposed method. The demonstrator uses capacitive pickups of the button type for displacement sensing and allows for control of the beam position with the help of feedback steering coils which are typically used for compact linacs. Representative sensitivity measurement results based on the evaluation of the 2nd S-Band beam harmonic are also presented in this paper.

INTRODUCTION

New cancer treatment facilities based on accelerated protons or heavy ions have emerged in the past. Yet, electron linac based radiotherapy systems are still widely applied due to their relatively low operational costs, high efficiency and compact size [1]. In such systems, photon radiation is used for most of the treatments: Accelerated electrons in the 6-20 MeV range strike a high-Z photon conversion target. The gamma radiation is then transmitted through different collimator and cone filters to tailor its profile to the shape of the tumor. High precision of the beam position on target is required, as deviations from the intended position even in the sub-mm-range deteriorate the shape of the dose profile. Beam-on-target position control would thus further enhance the performance of radiotherapy linacs.

However, the application of conventional BPM technology is limited due to the compact size of most modern medical or industrial linacs. Neither in radiotherapy linacs nor in industrial systems for imaging purposes there is much space available for additional BPM sections between the accelerator and the target. Therefore, a different approach is needed which overcomes this restriction. In this paper, a possible solution is presented. Furthermore, the setup and preliminary results of a demonstrator are presented which is capable of investigating the performance of new RF frontend architectures which are required by the presented approach.

DISPLACEMENT SENSING IN COMPACT LINAC SYSTEMS

The tight space limitations given in compact linear accelerators could be overcome by the direct integration of suitable pickup probes into the accelerating region. High effort would then have to be made to prevent the beam induced signal from being superimposed by acceleration fields. In the cavities, the latter is higher by orders of magnitude compared to the further. However, within the small irises between adjacent cavities in standing wave (SW) linacs the accelerating field is theoretically zero in space and time during the bunch passage. Integration of pickups into these irises is a promising approach to drastically reduce the amount of parasitically coupled field-induced waves into the probes. Furthermore, the beam-induced signal amplitude is larger compared to conventional pickup configurations due to the small distance between the probes and the beam (Fig. 1).

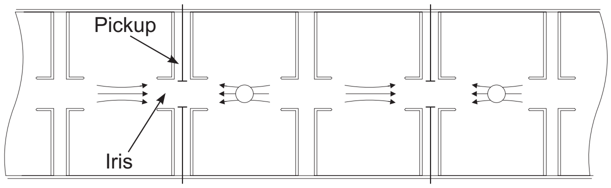

Figure 1: Integration of button pickups into low-field regions of the accelerating structure to account for limited space available in compact SW-accelerators.

The possibility to derive beam position information from each harmonic in the beam spectrum can be used to further reduce the amount of parasitic RF coupling. Due to waveguide dispersion, the accelerator's higher eigenresonance frequencies do not coincide with higher beam harmonics. Thus, by selecting a beam harmonic at a frequency with considerable spectral distance to an eigenresonance of the accelerator, the beam induced, beam position dependent signal can be separated from RF signals which may be par-

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asitically generated by the accelerating field, beam loading within the cavities or saturation and nonlinearity effects in the RF generator.

Most modern radiotherapy or industrial linacs employ S-Band or X-Band acceleration. By choosing higher beam harmonics as described above, the RF signals to be processed settle at multiples of the accelerating frequency. As to the best knowledge of the authors, BPM dedicated hardware is not yet commercially available above 3 GHz, the presented approach described in this paper also requires RF architectures covering higher frequency ranges than conventional ones applying high freqency logarithmic amplifiers, diode amplitude detection or even heterodyning of the selected beam harmonic.

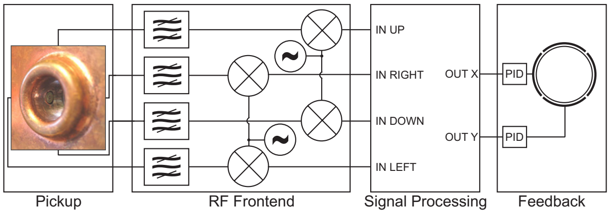

Figure 2: Block diagram of RF frontend and feedback architecture suitable for the described method. Inset: Integration of pickup probes into the iris between two adjacent resonating cells (see text for explanations).

Figure 2 depicts a BPM architecture suitable for processing of the signals generated by the presented method. After the pickup stage a highly frequency-selective RF frontend is applied which downconverts the desired beam harmonic to a frequency range covered by conventional BPM-dedicated hardware [2]. Beam steering is then achieved by PID-controlled feedback coils attached to the linac. In the above example steep filter edges possibly required could be realized by dielectric resonator filters or applying waveguide technology. RF downconverters are commercially available up to well in the GHz range or could be designed from scratch applying microwave engineering procedures.

To investigate the feasibility of the proposed method, a standard S-Band standing-wave accelerator used for radiotherapy treatments was equipped with four capacitive pickup probes as indicated in the inset of Fig. 2. As described, the location of the buttons was chosen within the iris between two cavities which represents a circular waveguide for the accelerating field, operated far below cutoff. The WR-284 RF input waveguide of the accelerator was connected to a vector network analyzer (VNA), and the transmission parameter $|s_{21}|$ from the RF input to the output of one of the probes was measured. As a result, the RF transmission at exactly the second beam harmonic was below the noise floor of the VNA (-110 dB) for this representative accelerator. Moreover, EM simulations do not reveal resonant modes which could be excited by the propagating beam in the direct spectral vicinity of the second beam harmonic, indicating that by applying appropriate RF filtering the described method is feasible.

DEMONSTRATOR SETUP

For preliminary tests of RF equipment suitable for processing signals generated by the presented method, a demonstrator has been built which is depicted in Fig. 3.

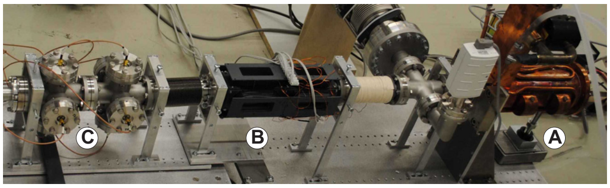

Figure 3: Demonstrator setup with 6 MeV accelerator (A), steering coils (B) and pickup sections (C).

The demonstrator is based on a compact 6 MeV electron accelerator (A). The extracted beam propagates through an evacuated beam pipe equipped with four pairs of Helmholtz steering coils (B). Two pickup sections (C) sense the beam position in the horizontal and vertical plane, respectively. Each section contains four pickups of the button type [3]. Their beam coupling impedance was calculated by EM simulation to roughly 1 Ω. The pickups (Fig. 4) are mounted into 6-way-crosses which allows for integration of a matching network based on a quarterwave coaxial transformer to match the button impedance to the 50 Ω line impedance of the connecting RF cables.

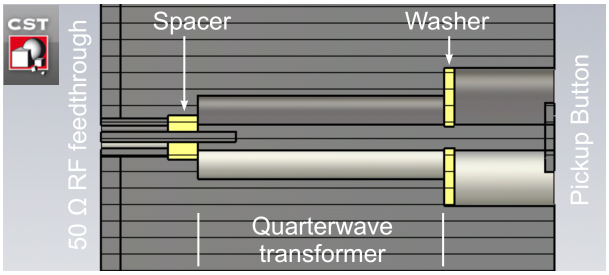

Figure 4: CAD model of pickup button design with quarterwave matching network.

Figure 5 shows the results of a cold back-to-back-measurement, in which two pickups were clamped together and both RF reflection and transmission was measured at the SMA connectors of the vacuum feedthroughs. Low insertion loss and fairly good matching in the frequency range 1-6.5 GHz is the result of the quarterwave impedance transformer. Moreover, good agreement between full 3D EM simulation in CST Microwave Studio and measurement data is achieved. The inset of Fig. 5 shows the input reflection for the case of a radiating probe. There are no resonances in the frequency range of interest indicating that the buttons couple gently to the beam and forward the beam power with low losses and reflections both at the fundamental and the second harmonic of the S-Band bunched electron beam.

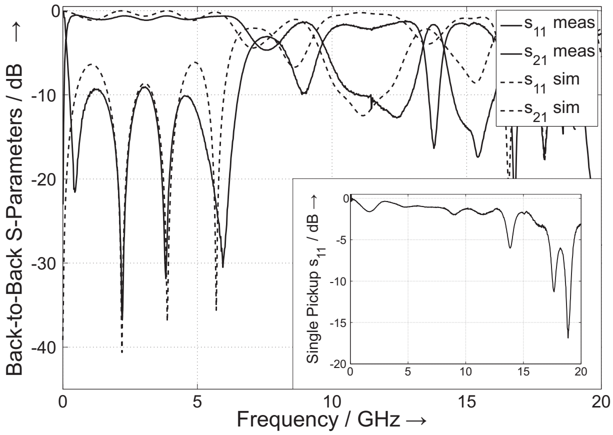

Figure 5: S-Parameter simulation and measurement results of two pickup buttons in back-to-back configuration. Inset: Single button input reflection measurement showing no resonances in the frequency range of interest.

MEASUREMENT RESULTS

To validate the performance of the hardware used for signal processing and feedback, the pickup sections of the demonstrator were mounted on a moveable slab allowing the pickups to be displaced with respect to the beam. As a first representative measurement two opposite probes have been connected to waveguide bandpass filters with a center frequency of 6 GHz to select the 2nd beam harmonic. The filter output was then fed into logarithmic amplifiers in coaxial package (MiniCircuits ZX47-60-S+). The DC representation of the beam displacement (emulated by probe displacement in horizontal direction), measured as the RF frontend response of the logarithmic amplifiers, is shown in Fig. 6.

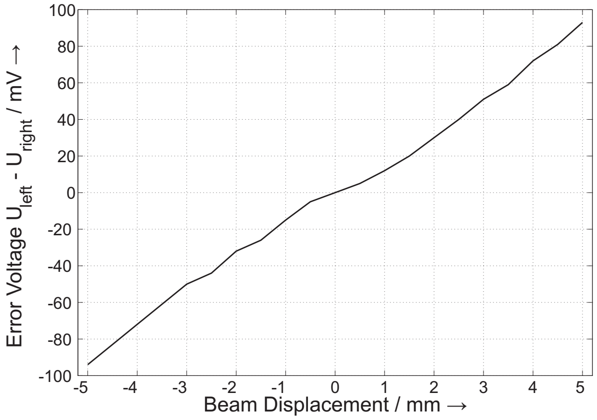

Figure 6: Error Voltage between left and right pickup as a function of beam displacement based on evaluation of the 2nd S-Band beam harmonic.

The results depicted in Fig. 6 prove the concept of evaluating higher beam harmonics for BPM purposes as required by the presented method. As stated in [4], the DC error voltage is nearly linearly dependent of the beam displacement because of the log-ratio processing of the RF signals. The slope of the curve is about 20 mV/mm which already marks a promising result and could be even more improved by the usage of low-drift DC amplifiers. Furthermore, a beam-based calibration technique [5] is needed to exactly determine the center position of the beam. Finally, down-conversion RF frontends will be addressed in the future to account for upcoming radiotherapy linacs based on C- or X-Band acceleration [6].

CONCLUSION

A new topology for a BPM system tailored to requirements given in medical or industrial linacs has been presented. It is based on the approach of integrating the pickups into a low-field region of the accelerating structure and processing a higher beam harmonic to prevent the beam-induced signal from being superimposed by field-induced signals. A demonstrator based on a 6 MeV S-Band electron beam has been built to validate RF frontends and signal processing architectures required by the new method. Preliminary results on the evaluation of the 2nd S-Band beam harmonic have also been presented. A sensitivity in the range of 20 mV/mm has been achieved based on which further optimizations by the useage of low-drift DC amplifiers, beam-based calibration and heterodyning architectures will be addressed in the future.

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