MODE SELECTIVE WAVEGUIDE BPM

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Abstract

I propose a mode-selective waveguide Beam Position Monitor (BPM). It uses waveguide couplers arranged at the beampipe to create boundary conditions similar to those in slot-coupled cavity BPMs. This structure allows to couple to the differential beampipe mode co-propagating with the beam, and reject the usually much stronger monopole component of the field. As the full dynamic range of the processing electronics can be used for position measurements, and a waveguide is a native high-pass filter, such a BPM is expected to outperform stripline and button BPMs in terms of both spacial and time resolution. In this paper I give some details on the basic principle and the first simulation results and discuss possible ways of signal processing.

INTRODUCTION

A high bandwidth, high resolution BPM could be a useful tool in situations where a cavity BPM is too slow, or can not be used due to its high impedance, and button or stripline BPMs do not provide a high enough resolution. One obvious application would be a high-speed intra-train feedback, although it could be a replacement for the electrostatic pick-ups if the resolution is complemented by an easy manufacturing. Currently this niche is occupied by inductive pick-ups [1], which are very interesting, but complicated devices. In the following sections waveguide BPMs are discussed as a possible alternative.

WAVEGUIDE BPM

Waveguides as BPMs have previously been explored, and several devices were installed and tested in the FLASH (former TTF) accelerator and free electron laser facility at DESY in Hamburg [2]. These devices were made to fit into a very narrow gap within the undulator, and an impressive design using ridged waveguides was produced. Despite the novelty of the position detection principle, the processing required a subtraction of the signals in the opposite arms of the BPM to reject the strong common mode. This was a consequence of tight spacial limitations: the waveguides could not be aligned to the orthogonal axes. The subtraction suffers from tiny differences in the two arms of the BPM, and allows some fraction of the common mode through, leading to a degradation of the dynamic range and systematic effects. A resolution of around 25 μm was measured.

Dropping the spacial limitations, one can imagine using standard waveguides placed orthogonally to the beampipe with their longer side in the direction of the beampipe and coupling to the field of the beam through slots in the beampipe walls, as shown in Figure 1. When the beam is centred in the beampipe, there is no field gradient over the gap of the slot, meaning that the field is not coupled to the TE mode of the waveguide (Figure 2). A beam offset from the centre will create a differential field in the beampipe. Clearly, a gradient is created over the slot's window and this field is coupled strongly.

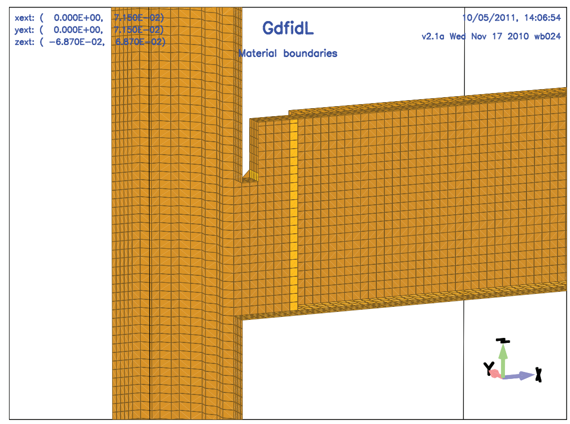

Figure 1: A rectangular waveguide coupling to the beampipe through a rectangular slot.

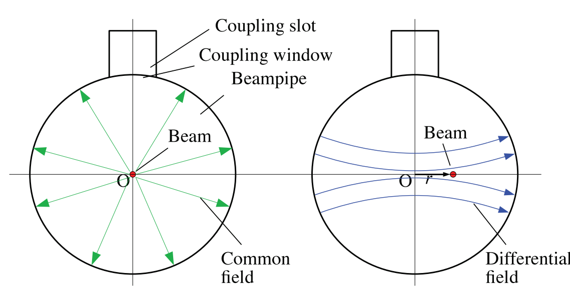

Figure 2: A rectangular waveguide coupling to the beampipe through a rectangular slot.

A beam current $I_b(t)$ in a circular beampipe produces wall currents whose density can be described as [3]:

$$i_w(b, \phi_w, t) = -\frac{I_b(t)}{2\pi b}\left[\frac{b^2 - r^2}{b^2 + r^2 - 2br\cos(\phi_w - \theta)}\right], \quad (1)$$

where b is the radius of the beampipe, (r, θ) the position of the beam, and ϕ_w the angular coordinate of the current element. Rotating the coordinate system to align with the beam position ($\theta = 0$), one gets for small offsets:

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$$i_w(b, \phi_w, t) = -\frac{I_b(t)}{2\pi b}\left[1 + 2\frac{r}{b}\cos\phi_w\right]. \qquad (2)$$

The first component in eq. 2 is the common field, the position independent TEM wave traveling with the bunch, and the second one is the differential field, the TE wave, whose wall currents, and hence the amplitude linearly depend on the position.

SIMULATIONS AND PICK-UP MODIFICATION

Simulations were done using GdfidL [4]. A bunch carrying 1 nC of charge with a transverse offset of 1 mm was simulated, and the signals created in the output couplers were analysed. The beam pipe diameter was set to 23 mm, and standard WR-90 X-band waveguide dimensions were used.

The first result, Figure 3 is the signal produced by the structure shown in Figure 1. There is clearly a short pulse similar to the signal produced by electrostatic pick-ups, created when the bunch enters and leaves the gap of the coupling window. It is clear though, that the signal is small, around 1 mV, in the waveguide, which means a roughly 2 times lower voltage, or 500 μV, in a 50 Ω cable due to the difference of impedances.

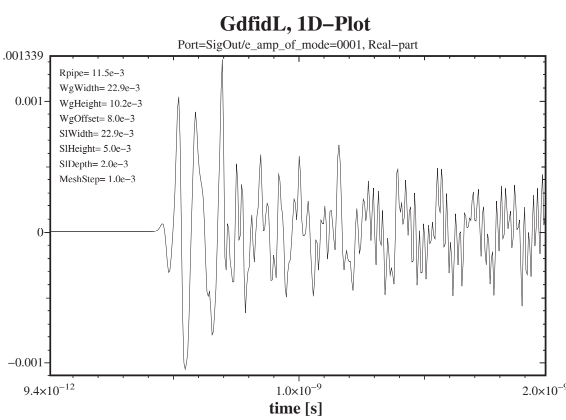

Figure 3: Signal coupled into a waveguide through a rectangular window in the beampipe.

Analysing the frequency spectrum (Figure 4) of the signal, one can see that it is composed of several peaks, each taking a share of the power coupled out. Assuming we want to use a 6 GHz bandwidth ($\pm$3 GHz from 10 GHz), and all the power of the signal is in this frequency range, one gets an optimistic resolution estimate of only about 70 μm (35 μV noise voltage), which is not very encouraging.

In an attempt of improving the beam coupling I decided to sink the coupling slots into the beampipe, creating a structure, which looks like a cavity BPM turned inside out, Figure 5. In this configuration the slot continues into the beampipe by a couple of mm (exactly 2 mm in this example) in the part where it is not opened by the coupling window.

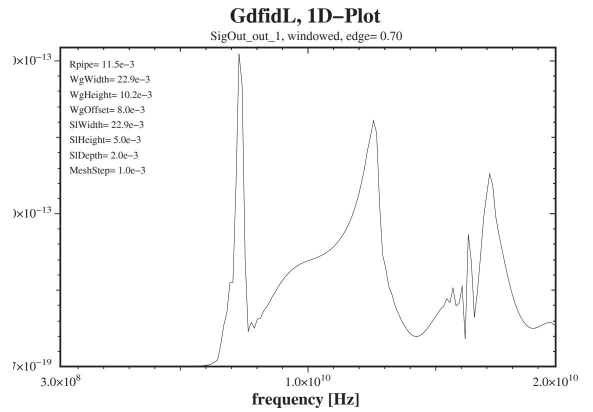

Figure 4: Spectrum of the window-coupled signal.

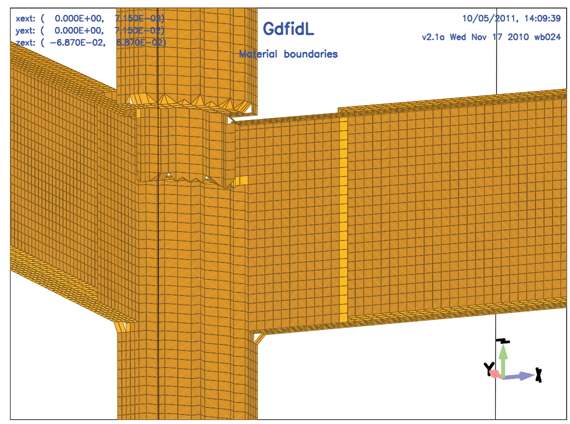

Figure 5: A modified geometry with the coupling slot sunk into the beampipe for increased coupling.

This seemingly small change alters the boundary conditions at the coupling window, virtually moving it inside the coupling slot and thus improving the coupling. The simulated signal for this case is shown in Figure 6. At a 50 Ω load it would peak to almost 1 V, which is comparable with the sensitivity of cavity BPMs. Importantly, the spectrum of the signal has a peak, in this example around 10 GHz (Figure 7), and is well contained within a wide (again, around 6 GHz), but limited bandwidth. The theoretical resolution limit in this case is about 35 nm.

Due to wide bandwidth, the signal is, however, very short even compared to signals produced by low-Q cavity BPMs. The decay time of the simulated is shorter than 0.5 ns. This means that the amount of energy coupled out is very small and most of it is contained in the first few oscillations of the signal. These are produced when the bunch enters and exits the gap of the coupling window, similarly to stripline BPMs. The tail following the initial burst indicates that some energy is stored within the device, most probably in the slots.

The waveform in Figure 6 resembles the signals produced by cavity BPMs, therefore a similar type of processing can be applied. As the signal is wideband it can be

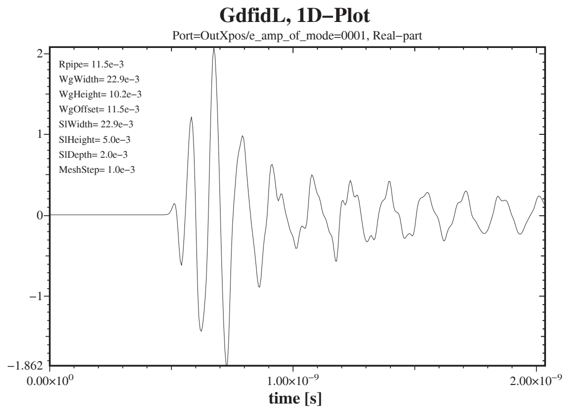

Figure 6: Signal coupled by a sunken slot.

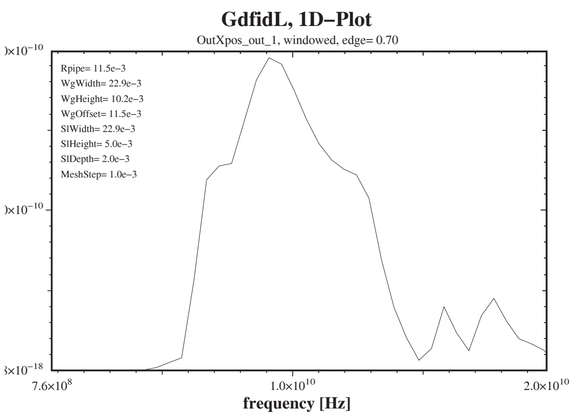

Figure 7: Spectrum of the signal coupled by a sunken slot.

downmixed in one mixer stage and sampled at a point close to the peak for maximum sensitivity.

PROTOTYPE FOR BENCH TESTS

A prototype cavity for "cold" measurements in the laboratory was designed and has recently been manufactured (Figure 8). It uses 4 standard X-band waveguide-to-coax adapters with SMA connectors for coupling, and was machined of a single piece of aluminium using lathe cutting and milling only. A test bench with an antenna moving in transverse direction to simulate the beam is currently being set up for testing.

SUMMARY AND DISCUSSION

This preliminary and somewhat naive study clearly needs to be extended in many directions. However, it seems that waveguide BPMs can become high-resolution, high-bandwidth devices. Below I list (not in any particular order) some features of the design and questions that need to be answered:

- Output is a position-dependant, difference signal, theoretical resolution 100 nm

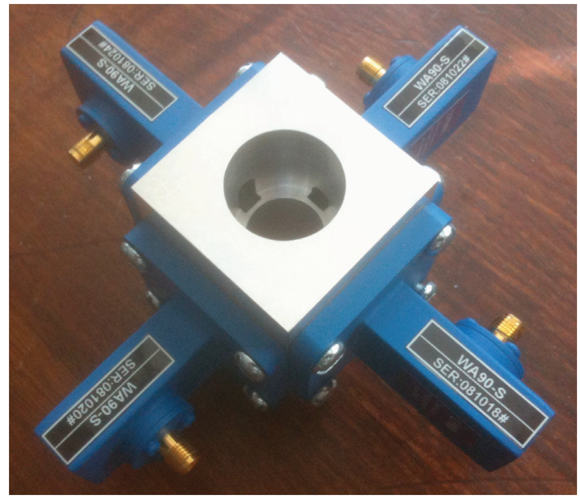

Figure 8: Aluminium prototype for measurements in the laboratory.

- Bandwidth only limited by the passband of the TE_{10} mode of the waveguide
- Simple design and fabrication, can use standard waveguide components
- Requires calibration, charge and phase reference – similarly to cavity BPMs
- Non-linearities and resonances need to be understood
- Wakefields and effects on the optics produced by the reduced aperture need to be investigated
- Self-triggering may be required in the processing electronics to ensure sampling on the peak
- Interference signals traveling in the beampipe may be coupled
- The tail of the signal may affect the signals produced by closely spaced bunches

This is not an extensive list, but it is already clear that some problems have a lot in common with the features of cavity BPMs, therefore some of the technology can be recycled. Measurements with the prototype will give some insight into the working of the device and together with the results shown in this paper may form a basis for a new research project into waveguide BPMs.

REFERENCES

[1] M. Gasior, "An Inductive Pick-Up for Beam Position and Current Measurements", CT1, DIPAC2003, Mainz, Germany.

[2] U. Hahn et al., NIM-A **527**, Issue 3, (2004), doi:10.1016/j/nima/2004.03.178.

[3] R.Shafer, "Beam position monitoring", AIP proceedings, 1989, Upton, NY, USA.

[4] `http://www.gdfidl.de`.