

# DESIGN AND SIMULATION STUDIES OF THE NOVEL BEAM ARRIVAL MONITOR PICKUP AT DARESBUARY LABORATORY

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## Abstract

We present the novel beam arrival monitor pickup design currently under construction at Daresbury Laboratory, Warrington, UK. The pickup consists of four flat electrodes in a transverse gap. CST Particle Studio simulations have been undertaken for the new pickup design as well as a pickup design from DESY, which is used as a reference for comparison. Simulation results have highlighted two advantages of the new pickup design over the DESY design; the signal bandwidth is 25 GHz, which is half that of the DESY design and the response slope is a factor of 1.6 greater. We discuss optimisation studies of the design parameters in order to maximise the response slope for bandwidths up to 50 GHz and present the final design of the pickup.

## INTRODUCTION

In an electro-optical-modulator-based bunch arrival time monitor (BAM) [1], the electromagnetic wave produced by the bunch at the pickup output is sampled by a reference ultra-short laser pulse in the modulator. Bunch arrival time variation causes modulation of the laser pulse output intensity which is detected. The wave is sampled at the slope to distinguish whether the bunch passes earlier or later than the reference pulse, with the zero point at the moment where the slope passes over zero.

In most cases a coaxial button is utilised as the pick-up such that the beam first induces a positive signal in the first longitudinal gap then a negative signal in the second longitudinal gap with the zero crossing occurring when the beam is at the centre of the button. The sensitivity of this device is therefore proportional to the slope  $dV/dt$  on the zero crossing. The slope is a function of both the pick-up geometry and of the beam profile itself. Using button pickups, a resolution of 10fs is achieved for the bunch charge 500pC, however for future FELs low bunch charges may require greater steepness to obtain the same resolution. A project was launched at Daresbury laboratory to design a pick-up with the maximum possible slope for a given charge with a very short bunch, at the VELA and CLARA accelerators.

The slope of the BAM pick-up depends on the maximum voltage induced in the gap and the distance between the two peaks, hence there must be a compromise between the area of the pick-up, the impedance of the pick-up and the distance between the gaps. Previous studies have focussed on circular pick-up cross sections [2], in this paper we will show that better performance can be obtained for short bunches by utilising thin rectangular pick-up cross sections.

## THEORY

A model of the behaviour of the BAM pickup can be developed by considering mode matching between the beams field and the TEM mode in the pick-up [3]. Here we will focus on the magnetic field only for simplicity, and assume the beams field is azimuthally constant over the pickup and only varies in the longitudinal direction. The power induced in the pick-up is roughly

$$P \propto \frac{H_{\text{beam}} \cdot H_{\text{pickup}} dA}{Z}$$

Where A is the area where the beams field overlaps the gap and Z is the TEM mode impedance. For short bunches the beam doesn't cover the whole gap hence we can approximate the area as the pick-up width integrated over the bunch length

$$P \propto \frac{awQ}{Z\sigma_z} \int \exp\left(-\frac{z^2}{2\sigma_z^2}\right) H_{\phi,\text{pickup}}(z) dz$$

Where the width of the strip is w, a is the beampipe radius, Q is the bunch charge, and  $\sigma_z$  is the bunch length.

The power produced is reduced as the beam traverses the pickup as the overlap between the beams azimuthal field, and the azimuthal field in the pickup is reduced. The azimuthal (x) magnetic field component in the pickup cross-section is shown in Figure 1. As can be seen the field increases as we approach the strip then goes to zero in the centre of the strip before flipping sign. It can be seen that the fields rotate around the strip and the azimuthal field doesn't go to zero instantly as soon as it reaches the strip. For bunches which are shorter than the strip the change in the amplitude with time,  $dV/dt$ , is caused by the change in the azimuthal field across the strip. For longer bunches the time variation is caused by the bunch covering both sides of the strip hence inducing opposite polarities which destructively interfere in this case the thickness of the strip is less important.

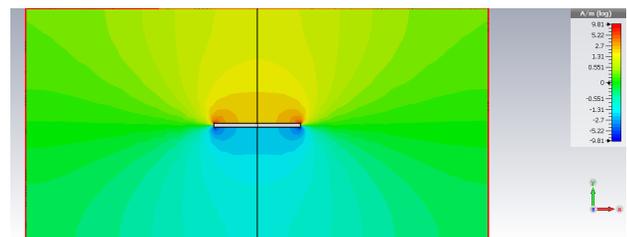


Figure 1: Azimuthal magnetic field component around the strip.

If we assume a short rectangular bunch as a simple approximation, and that the magnetic field varies linearly

with longitudinal position,  $z$ , across the pick-up then the power induced can be approximated as

$$P \propto \frac{awQ}{\sigma_z} z$$

If we assume that the pick-up tapers to a 50 Ohm line then the voltage in the coaxial line is proportional to the square of the power. If we assume a linear variation in the integrated magnetic field across the strip then the slope  $dV/dt$  can be approximated as being proportional to

$$\frac{dV}{dt} \propto \frac{1}{t} \sqrt{\frac{awQ}{\sigma_z}}$$

Hence the ideal BAM for a short bunch is wide and thin.

**SIMULATIONS**

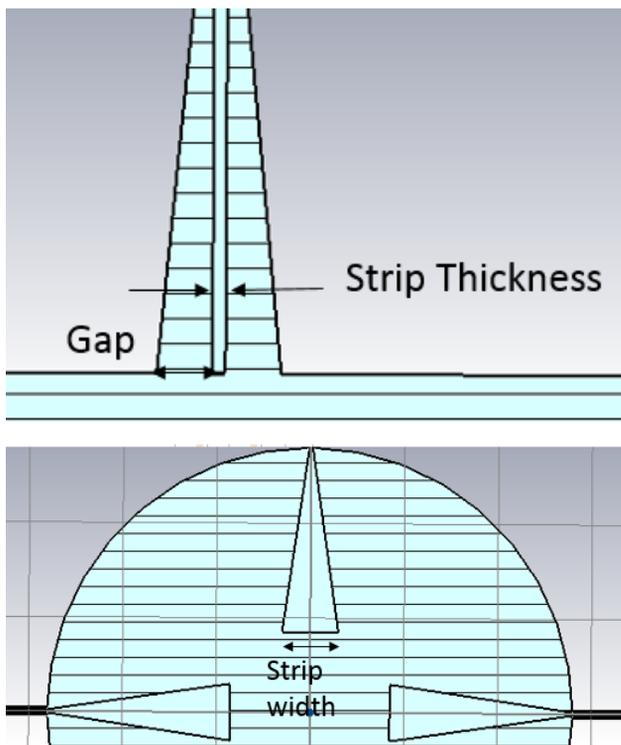


Figure 2: BAM pick-up geometry.

A model of a pick-up was created in CST Particle studio [4] in order to assess the validity of the theory developed above. The geometry is shown in Fig. 2. The pickup tapers down to a 50 Ohm coaxial line. The strip thickness was taken as the same width as the inner conductor on the coaxial line, 0.7 mm.

First we studied the effect of the width of the strip. Initially the voltage induced is proportional to width however at a certain point it starts to decrease with width, as can be seen in Fig 3. This is due to two reasons, firstly the beam doesn't have equal fields along the width of the strip for large widths. This is likely due to the greater distance from the beam position to the edge of the strip along the edge, hence the voltage is maximised at around 10-15 mm, shown in Fig 4. Additionally the beam excites

two modes on the stripline, the TEM mode and the TE11 mode. The TEM mode is transferred to the coaxial line at the top of the strip, while the TE11 mode is reflected. As the strip gets wider additional higher order modes are excited as well which are also reflected, leading to a drop in the TEM mode amplitude.

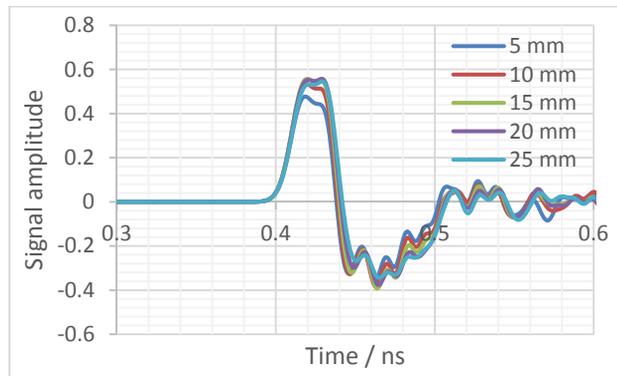


Figure 3: The signal induced by the beam in the pick-up's coaxial line as a function of strip width.

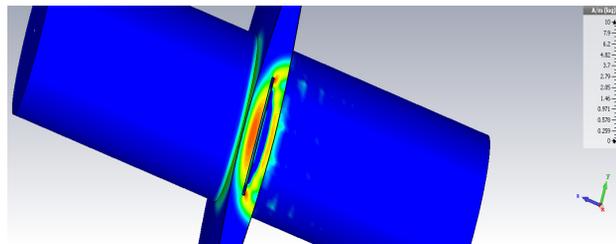


Figure 4: The magnetic field amplitude induced by the beam around the strip.

It can be seen that the magnitude of  $dV/dt$  also varies with the gap between the strip and the wall, as shown in Fig 5 and Fig 6. The signal shown in the figures is the square of the power, hence the voltage can be obtained by multiplying by the square of twice the impedance, ie 10. It appears that for large gaps the field in the two gaps are not symmetric and there is an oscillation after the bunch has passed. This suggests that there is a resonance in the pickup. An eigenmode simulation of the pick-up was performed and it was found there is a trapped mode at 5.1-5.3 GHz with a Q factor of around 800-1200. As the gap decreases the impedance mismatch between the top and bottom of the strip decreases and so does the Q of this mode, in addition the impedance of the mode also reduces as the gap gets shorter. At around a gap of 5 mm this mode seems to disappear and no oscillation is seen after the bunch has passed the pickup.

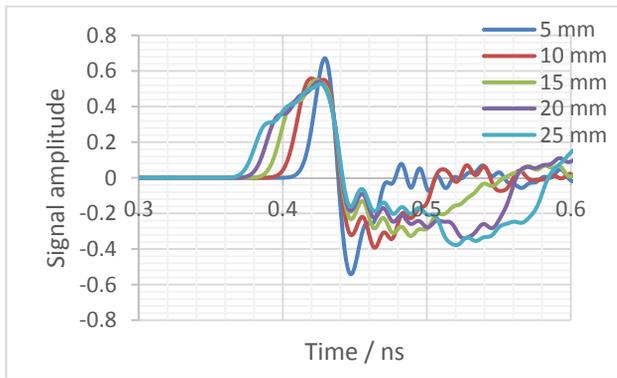


Figure 5: The signal induced by the beam in the pick-up's coaxial line as a function of gap between the strip and the wall.

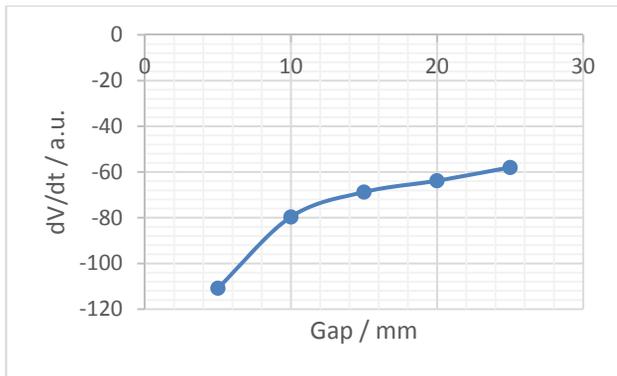


Figure 6: The slope of the signal ( $dV/dt$ ) induced by the beam in the pick-up's coaxial line as a function of gap between the strip and the wall.

Figure 7 shows the spectrum of the signal with a 0.5 mm bunch, for a 5 mm and 10 mm gap. Most of the signal is below the cut-off of the TE<sub>11</sub> in the coaxial line, 50 GHz.

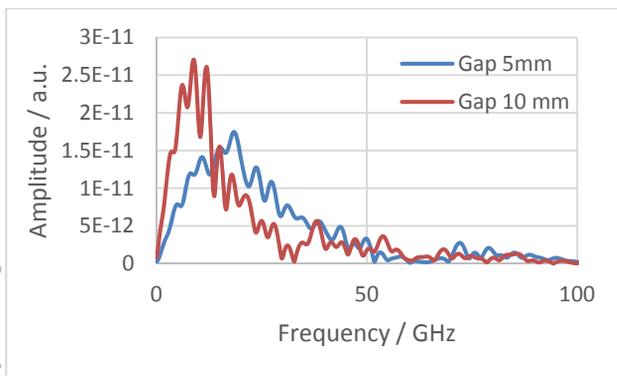


Figure 7: Spectrum of the induced signal in the pick-up as a function of gap between the strip and the wall.

It is not possible to simulate ultra-short bunches due to the mesh requirements for short bunches, hence the dependence of the slope on thickness cannot be properly studied. In order to investigate we simulate a very wide pick-up such that it is wider than the bunch. It was found that the slope is initially steep due to the variation of the charge density over the bunch. However after the whole

bunch is under the pick-up the slope decreases to a constant gradient due to the variation in the azimuthal component of the magnetic field decreasing as the magnetic field rotates around the pick-up.

## MANUFACTURE

The final BAM design was chosen to have a 10 mm gap and a 15 mm strip thickness for the first iteration due to its lower bandwidth, future iterations will likely have a 5 mm gap. This gives a slope of 800 V/ns for a 0.5 mm, 20 pC bunch. The strip will be manufactured using laser cutting, due to its small thickness and large width. The mechanical design of the pick-up is shown in Fig. 8. The pick-up is currently being manufactured and will be tested on the VELA accelerator in 2016.

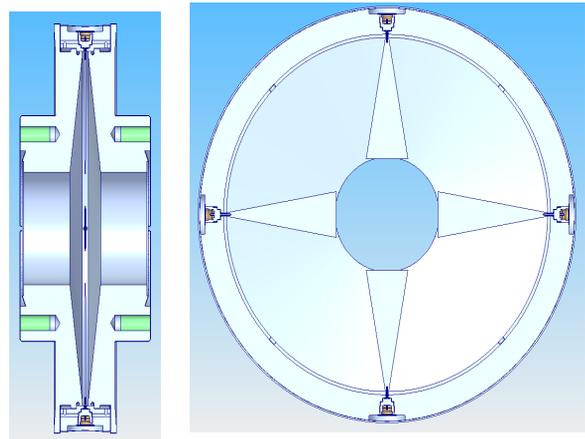


Figure 8: Mechanical model of the BAM pick-up.

## CONCLUSION

A novel beam arrival monitor pick-up has been presented that is optimised for short bunches with low bunch charge. The aim has been to maximise the slope,  $dV/dt$  rather than the signal amplitude. A theoretical understanding of the pick-up, supplemented with CST particle studio simulations has been used to design the BAM pick-up. It is found that a very thin pick-up with a 15 mm width and a 5 mm gap to the wall on either side of the strip is optimal. A prototype is currently under manufacture.

## ACKNOWLEDGEMENT

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