# NOVEL PICKUP FOR BUNCH ARRIVAL TIME MONITOR

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## *Abstract*

For an optical-modulator-based BAM, a decisive parameter of the pickup output signal is the slope steepness. We suggest a novel pickup with flat thin electrodes in a transverse gap. Increasing the electrode width makes the steepness greater in proportion to the signal increase. For a given width, reducing the electrode thickness allows the ultimate steepness to be reached. Wave processes in the pickup were investigated on a large scale model, using the technique described in [1]. The DESY 40GHz button pickup was used as a reference. It was found that for the same overall dimensions the steepness of the flat electrode pickup can be increased by the factor of two. A way is shown to keep the steepness as high with transition to a more practical bandwidth 20GHz. The investigation results are the basis of a final pickup optimisation using electrodynamic simulation.

## INTRODUCTION

In the electro-optical-modulator-based bunch arrival time monitor (BAM) [2], 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.

This modulator feature makes slope steepness the main parameter that defines modulator sensitivity and resolution.

A suitable for BAMs pickup is a button pickup with its bunch response as a single sine-like wave. Using button pickups, a resolution of 10fs is achieved for the bunch charge 500pC. [3] Demands of new FELs for low bunch charge (down to 20pC) initiated refinements of the button pickup and its signal path to achieve the highest steepness. [3] For a circular cone-shaped button pickup the wave half-period is expected to be about 12ps which corresponds to the bandwidth 40GHz.

In a circular button pickup, both the wave magnitude and its half-period are related to one and the same parameter. Generally, the pickup electrode signal magnitude is proportional to the electrode transverse width, the wave half-period to its longitudinal length. For a button pickup both sizes are equal approximately to the button diameter, and the ratio half-period to magnitude doesn't depend on it. With, for instance, some increase of diameter the signal increases but the spacing of the half-waves also increases which results in the slope steepness staying constant. The consideration above leads to the conclusion that an ultimate steepness limit is present because of the button circular geometry.

Applying the consideration above to the pickup in [3], one can note that some increase of button diameter would allow lower required bandwidth for the same steepness. Generalising, one can say that the steepness does not depend on electrode sizes, if the ratio $d/D$ (a button pickup, the diameters) or $w/g$ (a flat electrode pickup, the electrode width and gap length) is kept constant. This feature has a practical importance. It makes the pickup bandwidth that is of the order of c over $2g$ or over $2D$, a free parameter.

With the tendency to use lower bunch charge (in the CLARA project [4] it is 10pC), we attempted to break the limit above. Here we suggest decoupling the two key parameters, width and length, by using a flat thin electrode. This allows maximisation of the magnitude for a given charge and then independently, setting a half-wave period to obtain the required steepness. Note, moving the steepness up requires widening the signal path bandwidth. Here there is a limit put by the modulator bandwidth.

We investigated both this novel electrode and the cone-shaped button electrode, on a large scale bench. Using a probe, we measured the waves that propagate in the gaps as well as the output signals, excited by a short 'bunch' which was a pulse in a coaxial line. Some general results are presented in [1]. Here we, with reference to [1], present the results, some analysis and conclusions concerning the BAM pickup.

## MEASUREMENT TECHNIQUE

The bunch was modelled as a pulse propagating in a coaxial line. The available generator can deliver a pulse of half-height width 18ps which corresponds to the length 5.4mm. To model the real BAM pickup condition that is the bunch length less than the electrode/gap width/length, we increased scale of the pickup model about five times as regards to the pickup of [3].

We simplified the construction and used not circular but linear arrangement. A model is shown in Fig. 1. The left corner part is turned out clockwise to make visible a coaxial line (the copper strip seen over a white conducting bottom plate), and a transverse electrode (the copper width-tapered blade hanging down from the output N-connector). A bunch pulse propagates along the strip from the right (the input SMA connector is not seen) to the strip's open end on the left.

The top plane has a transverse variable-length gap (from 10mm to 50mm) to which two transverse plates are attached connected at the top. The electrode (length 15cm) is placed between these plates.

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On the top plate, the electrodes are displayed. A cone-shaped button electrode is on the right, together with its enclosure. A set of flat electrodes of various widths and thicknesses is shown on the left.

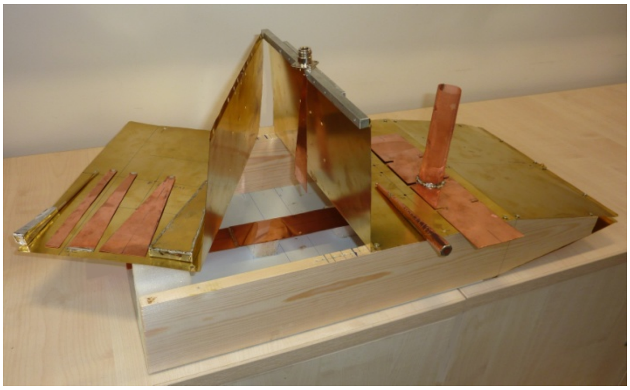

Figure 1: The pickup model.

Using an oscilloscope, we measured time-domain envelopes of electromagnetic waves that propagate in the model. The oscilloscope (mainframe HP86100C-M1 and sampling module AT86112A from Agilent Technologies) had the rise time about 17ps (bandwidth 20GHz).

The electrode output signal was measured directly through a 50Ohm cable. To pick up the electric field in various model cross-sections, a capacitive probe (the 1:1 probe P6150 from Tektronix, Fig. 2 left) was used connected to this cable and inserted through hole in the wall.

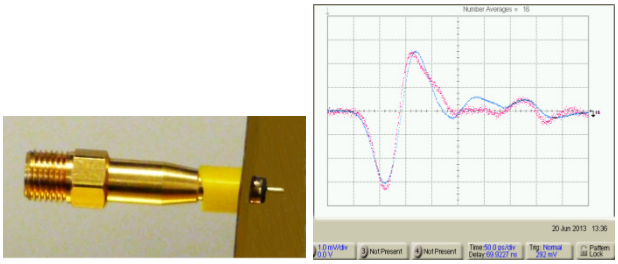

Figure 2: Left: The probe inserted in the wall. Right: Probe signal (red) in comparison with direct signal (blue), 50ps/div and 1mV/div.

A characteristic feature of the capacitive probe loaded on 50Ohm is that its output signal is proportional to the derivative of the electric field envelope. To restore envelope, integration should be done. Instead of integrating output signal, we integrated beam. Measuring with probe, we used a step (directly from generator, fall time 12ps). Measuring the electrode output signal, we used a derivative of this step, obtained with a differentiator. The derivative half-height width was 18ps (generator 4015D-RPH and Impulse Forming Network 5208 as differentiator, both are from Picosecond Pulse Labs). One can compare the results. In Fig. 2, two signals are shown measured at the same point at the N-connector, directly and with probe (the probe was inserted in a transverse hole in N-SMA adaptor's body). The voltage electrode signal from 'bunch' is blue, and the electric field probe signal from 'beam' as a step is red (scaled in magnitude to match the blue one). One can see that the method works satisfactorily.

More model details can be found in [1].

## ONE-GAP ELECTRODE

First, we investigated an elementary electrode structure. It is a one-gap transverse flat thin electrode. Its edge looks at beam and has a circular profile same as the adjacent vacuum pipe edges. The electrode has gaps on each side but one only gap interrupts the wall current induced by beam. In a linear model, all the edges are linear, and a long strip was used to short-circuit the passive gap.

The opposite electrode end is connected to a feed-through coaxial connector pin. In our model, this end was also made short and open to identify the waves.

A BAM pickup is the superposition of two one-gap structures and has each gap open. A button pickup has gaps not linear but semi-circular. Such gaps can be represented by linear gaps, and a circular electrode by a square electrode of the size that is the effective distance between the gaps.

Waves excited in a single-gap electrode structure were measured at either gap at four points: at 1cm, 5.5cm, 10cm, and 14.5cm distance from the electrode edge. It was observed that the waves propagate as TE-like compact packets guided by the electrode. The packet length was about gap length over c and for a bunch length shorter than this didn't depend on bunch length. This observation leads to a conclusion that the pickup electrode has a principal time-domain limit that is gap length over c.

At the point where the electrode is connected to the coaxial connector, four lines are interconnected: a gap excited by beam, a passive gap, with its own impedance, an output 50Ohm coaxial line, and one more, internal coaxial line with the electrode as a central wire. The voltage and current at this point, generated by the incident packet, excite reflected and passed packets in the gaps, and a TEM-wave packet in each coaxial line. One of them is the output signal.

In this four-line structure, the gap excited by beam principally can't be matched. We didn't try to find an optimal trade-off of the impedances to get the output maximised. This can be better done using simulation package.

Multiple reflections that take place in this structure produce at the output packets spaced by double electrode length over c.

## BAM PICKUP

A two-gap electrode of BAM pickup has each gap open. The rear gap is excited by beam later than the front gap. For a thin electrode, the delay is minimal and is of the order of gap length over c. Packet propagation and reflection occur analogously to one-gap electrode, with that difference that one of the gaps and the internal coaxial line are now not short but open. The electrode

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output is superposition of two opposite polarity pulses spaced by gap length over c. The output (divided by 2) is shown in Fig. 3 left as green, the packets in the front/rear gap (measured at the third point) are in blue/red. The electrode width was 30mm that tapered down to 10mm at the connection point. The each gap had the length 15mm that tapered down to 5mm at the end.

Superposition of reflected and passed packets is seen in Fig. 3 left on the right from the grid central line. The two packets in a pair are spaced by gap length over c. In the front gap (blue) the first packet is a packet that reflected from the connection point. The second packet is a packet that has passed from the rear gap over the connection point. In the rear gap (red) the first packet is that passed from the front gap, the second one is the reflected packet (here passed packets are about three times reflected ones).

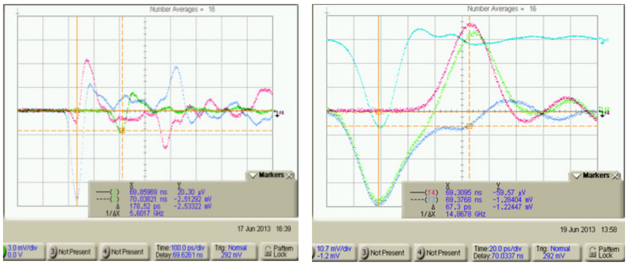

Figure 3: Left: Two-gap electrode, packets in gaps and the output (divided by 2), 100ps/div and 3mV/div. Right: Output signal of two-gap pickup, 20ps/div.

Figure 3 left shows one more effect. The incident packet in the front/rear gap is followed/preceded by a small packet of opposite polarity. These packets are due to spreading of the incident packet around the electrode into the opposite gap. Spreading is roughly proportional to distance from the electrode edge. For a flat electrode, the spreading is noticeable as in Fig. 3 left when the incident packet has passed about 2/3 of the electrode length.

Superposition that produces the output signal of a two-gap pickup is shown in Fig. 3 right for the incident packets measured at entries of the front (blue) and rear (red) gaps. The sum of them as an output signal is shown in green. The bunch pulse is shown at top-right. Taking into account the oscilloscope rise time, the bunch half-height length was 18ps, the packet half-height lengths were 32ps, and the packet spacing was 67ps. One can calculate an effective gap length as 10mm which is 2/3 of the gap length (15mm). The effective distance between the gaps is 20mm which is 4/3 of the gap length. These values specify the estimation above for both the packet length and the packet spacing as 'of the order of gap length over c'.

The half-waves of the output signal in Fig. 3 right are not symmetric due to some tail/ringing of the front gap packet which reduces the second half-wave. Here it is most probably due to some imperfectness in the model. But asymmetry of this kind is also distinctly seen in Fig. 3 left that was measured close to the output connector. We explain this feature as occurring due to spreading the front gap packet around the electrode which was mentioned above. The resulting packet in the opposite rear gap is first, delayed as regards to the front gap packet and second, has the polarity opposite to that of the rear gap incident packet. The superposition of this packet and the rear gap incident packet that is also delayed results in a half-wave of lower magnitude and different shape.

A cone-shaped button electrode that was investigated had a cone of diameter 14mm that tapered to 5mm at the end. The coaxial enclosure had diameter about 28mm. It was made from copper mesh and squeezed between the gap walls, so its cross-section which was circular at the gap entry was getting a racetrack shape that was widening with the distance.

Propagation, reflection, superposition occurred in the cone-shaped button pickup in ways similar to those in the flat electrode pickup. The difference was in the spreading of the incident packets around the electrode which occurred significantly earlier. This can be explained to be due to first, the smaller size (half-circumference 21mm against width 30mm) and second, due to the cross-section shape (smooth circular against sharp-edged).

For this kind of electrode the spreading establishes a 'virtual' point where four lines are interconnected and where the TE-like packets convert to TEM-packets. It is actually not a point but some length. As it is not far from the electrode edge (at the length of the order of electrode diameter), the reflected packets are adjacent to the incident packets. The superposition of them makes the output half-waves asymmetrical in magnitude/shape which is seen in the simulation plots in [3].

## SLOPE STEEPNESS

We compared slope steepness of the flat electrode to that of the cone-shaped button electrode. The flat electrode had the gaps 15mm to match the wave half-period to that of the button electrode. Both the electrodes had the TEM impedance close to 50Ohm.

As a measure of steepness, the angle was used between the plot horizontal axis and a straight line that was tangent to the slope at the zero point. The plot is given in Fig. 4 left. The left wave is the button electrode signal, 20ps/div and 4mV/div. The next wave is the flat electrode signal, 20ps/div and 8mV/div. The wave half-periods are 56ps. The slopes in the vicinity of zero point are shown zoomed to 5ps/div and 4mV/div. For the flat electrode the steepness is 1.35, for button electrode 0.71, their ratio is 1.9.

This result illustrates the advantage of the flat electrode. Occupying approximately same space as the button electrode (width 30mm against diameter 28mm and total gap length 30mm against diameter 28mm), it has twice higher steepness simply because it has twice broader width (30mm against diameter 14mm).

Output waves of the flat electrode are shown in Fig. 4 right, for four values of the gap length and constant electrode width 30mm. Parameter values obtained from the plot are given in Table 1. The half-period increases with gap length increase but about two times slower. The

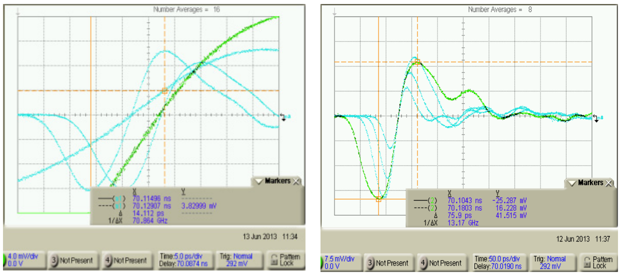

Figure 4: Left: Slope steepness. Cone-shaped button electrode and flat electrode, 20ps/div, 4mV/div and 8mV/div respectively. Zoom 5ps/div and 4mV/div. Right: Flat electrode output waves for various gap lengths, 50ps/div and 7.5mV/div.

magnitude that expected to be constant does increase, in such extent that it keeps the steepness practically constant, instead of the expected decrease. The magnitude increase can be explained to be due to increase of an electrode effective width that increases with gap length increase. Note this effect is generally positive. Note also Fig. 4 right illustrates how the steepness might stay constant in spite of signal bandwidth decrease.

Table 1: Parameters of the Signals in Fig. 4 Right

| gap length, mm | 5 | 8.5 | 15 | 25 |
|---|---|---|---|---|
| half-period, ps | 33 | 44 | 60 | 76 |
| magnitude, mV | 18 | 32 | 42 | 41 |
| steepness, a.u. | 0.99 | 1.33 | 1.37 | 1.20 |

In Table 2, the parameters are combined (taken from three plots like one shown in Fig. 5 right) that are for three electrode widths 17mm, 30mm, 51mm and constant gap length 15mm.

Table 2: Signal Parameters for Various Electrode Widths

| electrode width, mm | 17 | 30 | 51 |
|---|---|---|---|
| half-period, ps | 62 | 60 | 59 |
| magnitude, mV | 36 | 42 | 49 |
| steepness, a.u. | 1.18 | 1.37 | 1.56 |

The half-period stays constant, both the magnitude and steepness increase how it should be but again about two times slower than the electrode width increase. Here for interpretation two effects are necessary. First, for the lowest width 17mm the magnitude got some increase due to bigger effective width (see above). Second, for the biggest width 51mm the magnitude/steepness got some decrease/increase due to effective bunch magnitude/length decrease/increase which is characteristic for the beam TEM-line. The latter effects are described in [1].

All these effects can be verified and specified by use of simulation packages.

Steepness values for the case ratio width/gap length is constant ($w/g = 2$) are combined in Table 3. Note that both the half-period and the steepness value in the first column got some increase due to finite rise time of the oscilloscope. The steepness value in the last column was affected by the beam TEM-line effects mentioned above.

Even for raw data in Table 3, for the half-period deviation from the average (61ps) by $+25\%/-21\%$ the steepness values deviate from their average (1.23 a.u.) by as low as $+11\%/-10\%$ which supports the thesis that the BAM pickup bandwidth is a free parameter.

Table 3: Steepness Values for the Case $w/g = 2$

| electrode width, mm | 17 | 30 | 51 |
|---|---|---|---|
| gap length, mm | 8.5 | 15 | 25 |
| half-period, ps | 47 | 60 | 76 |
| steepness, a.u. | 1.11 | 1.37 | 1.20 |

## SUMMARY

We attempted a model-based investigation of wave excitation and propagation in pickup electrode structures up to the times of the order of gap length over c. A short pulse in a TEM line was used as a beam. We developed a capacitive-probe-based technique for wave electric field measurements.

We investigated an elementary electrode structure that is a one-gap transverse flat thin electrode, a two-gap electrode as a BAM pickup, and a cone-shaped button pickup of [3]. It was found that a flat electrode pickup has the slope steepness twice that of the button pickup. We investigated some effects in these two BAM pickups and tried to interpret them.

The obtained results are the basis for a final pickup optimisation. They can be used as a guide for electrodynamic simulation. From other side, the simulation would provide with verification/specification that some results need.

## REFERENCES

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