PICKUP ELECTRODE ELECTRODYNAMICS INVESTIGATION

A. Kalinin*, ASTeC, STFC Daresbury Laboratory, Warrington, UK

Abstract

We conducted 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 to model a bunch. We developed a capacitive-probe-based technique for wave electric field measurements. The probe signals were measured by a 20GHz oscilloscope. We introduced an elementary electrode structure as a one-gap transverse flat thin electrode. It was found that in the gap between the electrode and wall, a shorter-than-gap bunch excites a TE-like packet which length is of the order of gap length over c. The packet propagates forward along the electrode to a coaxial connector. At this low impedance common point the packet partially reflects back and partially passes into the opposite gap. The voltage appearing at the impedance excites two TEM-wave packets: one propagates backwards, another one propagates forward through connector. The three packets propagating backwards reflect at the electrode end and come back to the summing point and generate output in a similar way. The same processes occur in a two-gap electrode. This phenomenological picture can be used as a guide in pickup design and simulation.

INTRODUCTION

For a charged particle beam non-intercepting monitoring three basic structures can be differentiated. Those are electrode, cavity, and loaded gap. Being inserted in the vacuum pipe, the structure delivers a signal induced by the beam, that bears information on its parameters.

For single short ultra-relativistic bunch the cavity has a multi-band response. The loaded gap and electrode have broadband responses. The band of the latter usually has a low frequency cut-off. In high frequency range, the electrode's frequency envelope may have some multi-band structure.

In routine electrode-based monitoring systems, some filters are usually used. First of all, the cable transmitting the electrode signal is a kind of low-pass filter. In addition, band-pass filters are widely used to simplify the following amplification and detection. For a short bunch the response grows with shifting the band-pass to higher frequency. In electron machines, the frequency is chosen usually not higher than 1GHz due to engineering trade-offs.

Introducing the equivalent wavelength $\lambda \geq 30$cm, one can see that for the case above the condition $\lambda \gg b$ is valid where b is a characteristic size of the electrode. This condition allows use of quasi-static electrode models in which the wave processes with characteristic times of the order of b/c and shorter are considered being averaged.

Some remarkable quasi-static models can be found in [1] (telegrapher's equation solution for strip line pickup, see an exposition of this paper (and other models as well) in [4]), [2] (loaded gap), and [3] (button pickup).

Advance of novel accelerators to shorter bunches and development of new specific diagnostic instruments as an optical-modulator-based beam arrival time monitor, call for development of electrode models that would cover a time domain extended up to and over b/c.

As for our knowledge, in the present no mature analytical electrodynamic models are there for this time domain, that models that would provide with solutions for fields and signals and could be used as a guide in development of real devices. When the whole conception of the device is laid then the available simulation packages become useful to verify it and to refine and optimise the design.

As an initial step to get some qualitative understanding of the wave processes in the system electrode – vacuum pipe, we constructed a model and using a probe, measured time-domain envelopes of the propagating waves as well as the output signal, excited by a short 'bunch' which was a pulse in a coaxial line. The bunch half-height length was about 5mm, the electrode characteristic sizes were in range 10mm to 50mm, and the gap lengths in range 5mm to 25mm. We used transverse electrodes of two kinds: a novel one, a width-tapered flat thin electrode, and a conventional cone-shaped button. Here we present the results, and some analysis and conclusions.

PICKUP LARGE SCALE MODEL

The bunch was modelled as a pulse propagating in a coaxial line. The available generator can deliver a pulse of half-height width 18ps (measured in a regular part of the line, see below) which corresponds to the length 5.4mm. This length that ideally is to be significantly less that the electrode/gap size, lays down a model scale as regards to a typical pickup. We put the scale as approximately 5:1 and the sizes as shown above.

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. This line is arranged as a thin 4.5cm-width strip between two 30cm-width plates distanced by 10cm. The transition from the SMA

*alexander.kalinin@stfc.ac.uk

ISBN 978-3-95450-127-4

connector to the line regular part is made tapered and has length 20cm.

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.

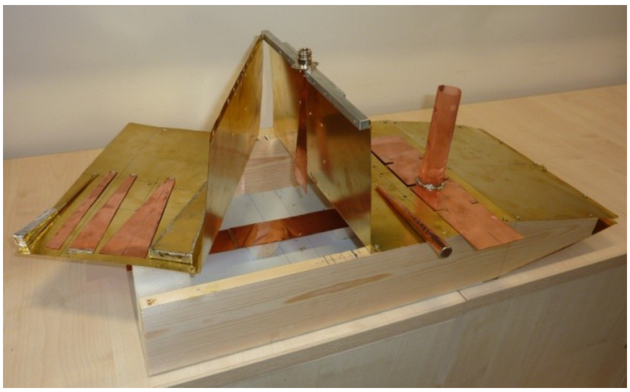

Figure 1: The pickup model.

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.

MEASUREMENT TECHNIQUE

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 was used connected to this cable and inserted through hole in the wall.

The 1:1 probe (P6150 from Tektronix) is shown in Fig. 2 left as inserted in the wall near its edge. The hole diameter is 3.5mm. The probe body protrudes from wall by about 1mm, the tip length is 2mm.

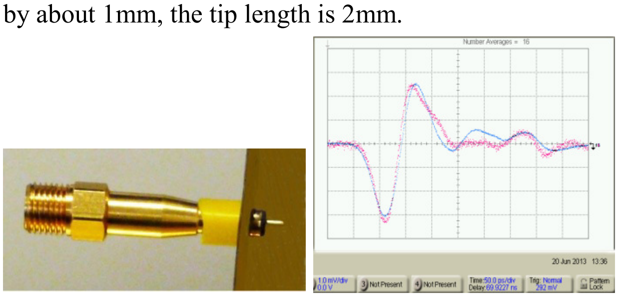

Figure 2: Left: The probe inserted in the wall. Right: Probe signal (red) in comparison with direct signal (blue), 50ps/div and 1mV/div.

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 right, 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.

We tried also an inductive probe to measure the magnetic field. An attractive feature of the inductive probe is that it produces the envelope but not its derivative (with the loop of about 6mm^2 and load 50Ohm). From other side, it has parasitic coupling to the electric field which considerably contaminates the output with derivative. Effective electric shielding of the loop was found difficult to achieve.

Signals from an unshielded inductive probe (same P6150 probe with a rectangle loop connected to the pin and body) taken in regular part of the beam line before the gap, are shown in Fig. 3. For a short pulse, the green and

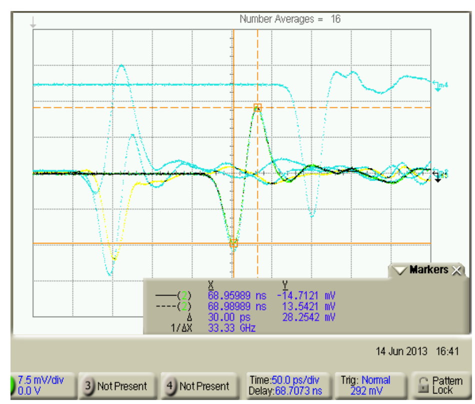

Figure 3: Signals of inductive probe, 50ps/div.

blue derivatives in the middle (they merge) are two signals induced at the inductive probe by the electric field when the probe is turned so that its loop is parallel or anti-parallel to the magnetic field. On the left, two blue signals are shown taken when the loop is perpendicular and anti-perpendicular to the field. The difference of them which is a pure magnetic signal is shown in yellow. Compare it to a capacitive probe signal from a beam as a step (top right, blue).

BEAM CHARACTERISATION

Propagation of the wave along the beam line (of 20mm width) was measured at four points over the line axis: at 10cm and 1cm before the gap front edge, at 1cm and 10cm after the gap rear edge. Gap length was 20mm. The signals are shown in Fig. 4, left. A magnitude difference

ISBN 978-3-95450-127-4

~10% of the pulses 1 and 2 characterises loss in the line on the length 10cm. Pulse 3 is significantly less than pulse 2 but pulse 4 is again big (differs by same 10% from pulse 2). We interpret this as following. See Fig. 4 right. The first cursor marks pulse 1, the second cursor is placed at the moment when a pulse reflected from the gap is expected to come. No short-pulse reflection occurs! Some low-magnitude slow wave seen at the marker is probably a back response of a gap which length is significantly bigger than the pulse width. Most probably, pulse 3 is a superposition of an incident wave electric field and a quasi-static electric field of opposite polarity left in the gap. Use of simulation computer package would clarify this interpretation.

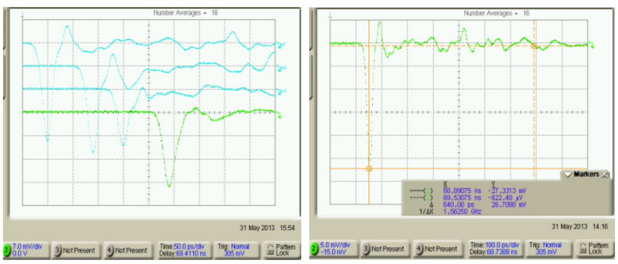

Figure 4: Left: Propagation of a short pulse along the ‘beam’ line, 50ps/div and 7.5mV/div. Right: Back response of a long gap, 100ps/div and 5mV/div.

A wave of a strip placed between two conductive planes decays with distance from the strip. Fig. 5 illustrates this for the case of strip width 45mm. It shows the electric field (at the gap front edge) at the central point (the green pulse), and then at four points along the edge distanced by intervals 20mm. One can see that pulse magnitude decreases with distance. This plane geometry effect causes the electrode signal be non-proportional to the electrode width.

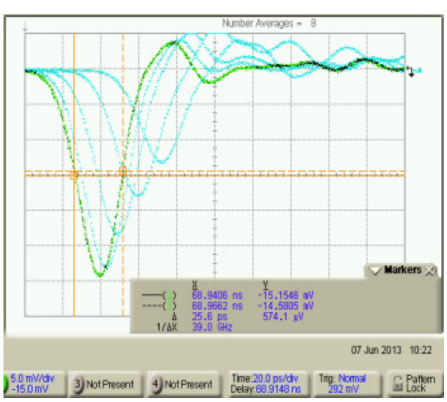

Figure 5: Magnitude and arrival time of the bunch electric field measured at the gap front edge, 20ps/div and 5mV/div.

At the transition from the SMA connector (coaxial circular) to the strip (coaxial flat), the pure TEM wave transforms to a pseudo-TEM wave with non-zero longitudinal components. The latter wave has a constant phase surface not as a plane but as a convex centred at the transition. Fig. 5 illustrates this for the case of strip width 45mm. It shows that the pulse arrival time increases with distance from strip. One can interpret this as effective bunch lengthening with increase of electrode width.

ONE-GAP ELECTRODE

Define 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. Name it the active gap (it can be front or rear gap, no difference). Another gap (passive) is short-circuited by a circular ring which connects the electrode edge to one of the vacuum pipe edges. In a linear model, all the edges are linear, and instead of ring a long strip was used to short-circuit the passive gap.

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

An example of such structure is a one-end-short-circuited strip line pickup where the second gap is screened by the strip itself. A button pickup is the superposition of two one-gap structures. Real structures may have gap(s) not linear but semi-circular, like a button pickup has. Such gaps can be modelled by linear gaps, and a circular electrode by a square electrode of the size that is the effective distance between the gaps.

The 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. First

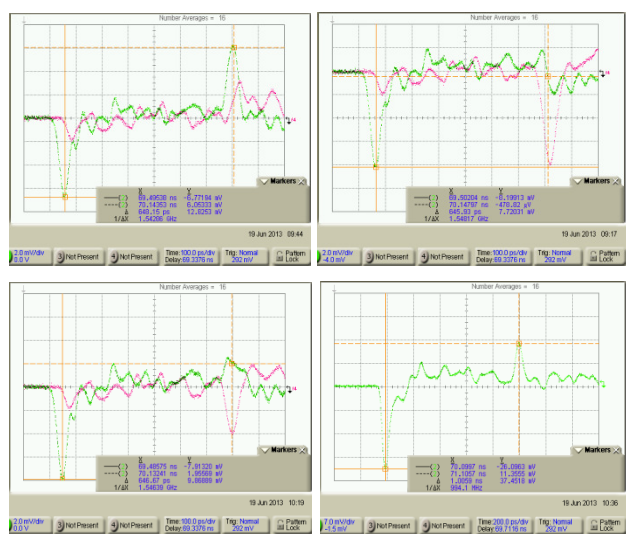

Figure 6: Top left/right: One-gap electrode end is short/open. Bottom left: The end is connected to pin. For these three plots 100ps/div and 2mV/div. Bottom right: Electrode output signal, 200ps/div and 7mV/div.

of all, 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

ISBN 978-3-95450-127-4

electrode has a principal time-domain limit of the order of gap length over c.

For the second point of each gap three plots are shown in Fig. 6. They are (from left to right) for the end short, open, and connected to pin. The electrode width was 30mm that tapered down to 10mm at the connection point. Each gap had length 15mm that tapered down to 5mm at the end. The passive gap was rear. The plots for the active/passive gap are in green/red.

For short-end electrode one can see in the active gap an incident packet and a reflected packet of reverse polarity. In the passive gap, a small packet is seen. Its features as a small magnitude, the same polarity and some delay as regards to the incident packet allow suppose that it is a result of some residue coupling of a shielded gap and beam. For open-end electrode the incident packet passes over the end edge undisturbed into the opposite gap where it is seen as a pulse of the same polarity. For electrode connected to the pin one can see a quite small reverse polarity packet reflected from the connection point, and a quite big same polarity packet in the passive gap. Analysis of the last observation leads to the conclusion that at the connection point the active gap impedance principally can't be matched.

At this point, four lines are interconnected: an active 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 low impedance connection point, generated by the incident packet, excite in the gaps a reflected packed and a passed packet, and a TEM-wave packet in each coaxial line. We didn't measure gap impedance. Analysis and search for optimal trade-off of the impedances can be better done using a simulation package.

The one-gap electrode output is shown in Fig. 6 bottom right. It has some long tail (positive overshot) due to finite pin inductance. The second pulse distanced by about 1ns is superposition of three packets coming back after getting reflected respectively from the active gap open end, from the passive gap short end, and from the internal coaxial line short end.

In quasi-static terms, the one-gap electrode is an inductive pickup, and a two-gap electrode below is an electrostatic pickup.

TWO-GAP ELECTRODE

A two-gap electrode has each gap open and active. The rear gap is excited by beam later than the front gap. For a thin electrode, the delay is minimal and equal to 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 output is superposition of two opposite polarity pulses spaced by gap length over c. The output (divided by 2) is shown in Fig. 7 in green, the packets in the front/rear gap are in blue/red. Superposition of reflected and passed packets is seen on the right from the grid central line. The two packets in a pair are spaced by gap length over c and go in the gaps in reverse orders. Two-gap electrode is considered in detail in [5] where its features as a pickup for bunch arrival time monitor are analysed.

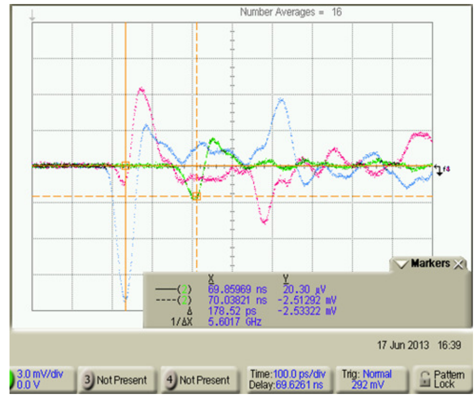

Figure 7: Two-gap electrode, packets in gaps and the output (divided by 2), 100ps/div and 3mV/div.

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 to model a bunch. We developed a capacitive-probe-based technique for wave electric field measurements.

We introduced a one-gap transverse flat thin electrode as an elementary electrode structure. It was observed that in this structure a shorter-than-gap bunch excites TE-like waves that propagate along the electrode as a compact packet of the length of gap length over c. This packet converts to a TEM output signal at the interconnection of the electrode and coaxial connector. We discovered that at this point the packet is principally unmatched which causes multiply reflection.

We investigated also a two-gap structure which represents a button pickup. The output is a superposition of two opposite polarity one-gap electrode signals spaced by an interval which minimal value is gap length over c.

The results can be used as a guide in pickup design and simulation.

REFERENCES

[1] M. M. Karliner, "Coherent Beam Instability in Electron Storage Rings due to Electromagnetic Interaction of Beam and Vacuum Chamber Structures", Vol. 1, Preprint 74-105, Budker Institute for Nuclear Physics, Novosibirsk, 1974. (in Russian)

[2] K. Satoh, "New Wall Current Beam Position Monitor", IEEE Transactions, Vol. NS-26, No 3, 1976.

[3] W. C. Barry, "Broad-Band Characteristics of Circular Button Pickups", Accelerator Instrumentation Workshop, LBL, Berkeley CA, 1992.

[4] V. Smaluk, "Particle Beam Diagnostics for Accelerators. Instruments and Methods", VDM Verlag Dr. Muller Actiengesellschaft & Co. KG, 2009.

[5] A. Kalinin, "Novel Pickup for Bunch Arrival Time Monitor", MOPC42, these proceedings.

ISBN 978-3-95450-127-4