BEAM MONITORS FOR THE
S-BAND TEST FACILITY

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Abstract

The design of electromagnetic monitors for observation of beam charge and position of single bunches in long bunch trains is presented. With a repetition rate of 50Hz, each of the 125 bunches in the linac's macropulse has to be observed simultaneously. Resistive wall current and button pick-up stations will monitor the beam along the injector. Betweeen the S-band acceleration structures precision stripline pick-ups will be used. Here a one micron position resolution within 16ns bunch-to-bunch spacing may be obtained in combination with well matched broadband rf-electronics.

For future linear colliders these bunch by bunch measurements are required to fulfill the constraints given by advanced beam-based alignment techniques.

I. INTRODUCTION

At `Desy`'s S-Band Test Facility major components for a future Linear Collider layout are studied [1]. These are four 6m long travelling wave accelerating structures (3GHz, 17MV/m) with quadrupole triplets in between, two klystrons (150MW for 3μs), two modulators and a position feedback on the accelerating structures.

For comissioning and measurement of essential parameters like *beam current* and *beam orbit*. the Test Facility has to be equipped with *beam monitors*. To study the *bunch trains* behaviour in detail, monitors with enhanced performance are required. Therefore *position*- and *intensity*-monitors should have a single-bunch/single-pass measurement capability. For the investigation of transverse beam motions due to higher order modes (HOM) along the accelerating structures beam position monitors (BPM) with 1μm resolution are required. To analyse the HOM-effects, all the bunches in the *same* bunch train (!) have to be measured by the BPM's.

The electrons for the testlinac are served with 50Hz repetition rate by an injector [2]. In the standard operation mode a train of 125 bunches with 16 ns spacing is provided. To reproduce a single bunch in this train by the monitor its system *bandwidth*[1] has to be at least

$$B_{\mathrm{3dB}} \;=\; f_{h,\mathrm{3dB}} - f_{l,\mathrm{3dB}} \;\approx\; 80\ldots 100\mathrm{MHz}.$$

Other operation modes with 8 (or 24ns) bunch spacing will be studied further and require more (or less) bandwidth. To reach an average current of 300mA, each bunch has to be charged with 4.8nC ($3{\cdot}10^{10}\,\mathrm{e}^-$). Out of the thermionic gun the full-width half-maximum (FWHM) *bunch length* is expected to be 2.5ns. Assuming Gaussian particle distributions we get the corresponding 3dB *cutoff frequency* by the relationship $t_{\mathrm{FWHM}}\, f_{\mathrm{3dB}} = 0.43$, for 2.5ns: $f_{\mathrm{3dB}} \approx 172$MHz. Passing the injector, the bunches will be compressed down to 50ps ($\equiv\ 50^0$ @ 3GHz). Through the linac the bunch length remains constant with less than 10ps ($\equiv\ 10^0$ @ 3GHz). The corresponding cutoff frequencies are in the order of several 10GHz and the beam excites TM waveguide-modes in the circular vacuum chamber. With its diameter of 32, sometimes 34mm the TM_{01} cutoff frequency is 7GHz. Above this frequency the beam-to-pick-up signal transfer is "disturbed". As a consequence bunch length measurements with electromagnetic beam monitors are *not* possible everywere, but only in the injector before the 3 GHz travelling wave buncher cavity (TWB).

In this paper we present the designs for electromagnetic monitors to measure beam position and intensity – and related parameters – along injector and linac.

For the S-band Test Facility two monitor units are developed:

- At the injector a compact *monitor module* was constructed, holding a *resistive wall monitor*, a *inductive monitor* and a *button-BPM*.
- The monitoring in the linac will be done with *"stripline"-BPM*'s, and resistive wall monitors as an option.

II. INJECTOR MONITOR MODULE

Four locations along the injector are foreseen for monitor instrumentation, one between the gun and the 125MHz subharmonic buncher cavity (SHB), two between the 125Mhz and the 500MHz SHB and a fourth one behind the 3GHz TWB. Three monitors are arranged into a 125mm long piece of vacuum chamber with 34mm diameter:
An electrostatic "button" pick-up, mainly used as a beam position monitor (BPM), a resistive wall monitor and an inductive current transformer. The last two are forseen for beam current monitoring (CM), but – with little modifications – may be used also as BPM's. As the three monitors have different characteristics (sensitivity, bandwidth, etc.) we have the flexibility to experiment with their signals.

A. Button BPM

The button monitor is an electrostatic device with four round plates, the "buttons", of 19mm diameter. These are fixed on the inner pin of coaxial feedthroughs in symmetric positions around the vacuum chambers cross-section. Denote them *north* (N), *south* (S), *west* (W) and *east* (E). To avoid an aperture reduction at these points the vacuum chamber is made out of a massive block with indentions for the buttons, which have radial shaped inner surfaces on top. The button BPM is very compact and quite simple to manufacture.

The electrical equivalent circuit for a single button is just a capacitive voltage divider loaded with 50Ω.[2] The button-to-wall

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[1] gaussian-like transfer functions assumed

[2] for bunches longer than the buttons diameter

capacitance stays constant, while the beam-to-button capacitance varies with the beam-to-button distance (beam position). This causes a highpass-like transfer characteristic, so the output at the feedthrough delivers a totally differentiated impulse when a bunch passes. Wire measurements show a rather "hilly" magnitude response with a lower cutoff frequency of $f_{l,3\mathrm{dB}} \approx 100\mathrm{MHz}$ [3]. Beam position measurements can be done simply by comparing the peak amplitudes of two opposite buttons, i.e. W- and E-button for the vertical, N- and S-button for the horizontal axis.

B. Resistive Wall Monitor

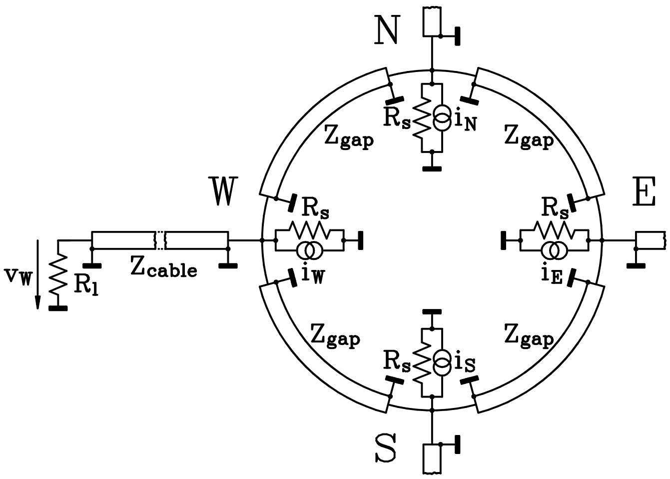

Figure. 1. Equivalent circuit of the resistive wall monitors "4-resistor" operation (only one output shown)

The monitor module has a 5mm wide ceramic (Al_2O_3 aluminia, $\epsilon_r = 9.7$) gap for the resistive wall monitor. In the "4-resistor operation" we bridge the gap only at the N-, S-, W-, and E-positions with high quality rf-chip resistors. Together with the 50Ω "read-out" cables at the same points they form the equivalent circuit shown in Fig. 1. The beam induced *wall currents* concentrate in the four current sources $i_\mathrm{N} + i_\mathrm{S} + i_\mathrm{W} + i_\mathrm{E} = i_\mathrm{beam}$. For CM operation the output signals v_N, v_S, v_W and v_E are summed in a broadband power combiner. To analyze the circuit we measured the gaps *azimuthal* transmission-line parameters by impulse-reflectometry: $Z_\mathrm{gap,az} \approx 56\Omega$, $\epsilon_\mathrm{eff} \approx 3\ldots4$. Now the monitors upper frequency limit can be estimated from the total gap capacitance[3] $C'_\mathrm{gap} = \sqrt{\mu_0\epsilon_0\epsilon_\mathrm{eff}}/Z_\mathrm{gap,az}$ and the total load resistance. We choose $R_l = Z_\mathrm{cable} = R_s = 50\Omega$ which results in 6.25Ω. Together with $C_\mathrm{gap} \approx 13.5\mathrm{pF}$ we find $f_{h,3\mathrm{dB}} \approx 1.9\mathrm{GHz}$. The monitors lower frequency limit depends on the impedance (inductance) characteristics of the "DC-bypass". Without a metal-housing this DC-path is often rather long; via cables, shieldings, racks, etc. so that $f_{l,3\mathrm{dB}}$ might be quite low, but in someway "undefined". A metal-housing shields the monitor and delivers a well defined DC-path, but it raises $f_{l,3\mathrm{dB}}$. This effect can be reduced with *ferrite toroids* inside the housing to increase the DC-path's inductance. In general it is difficult to estimate the lower cutoff frequency, we measure mostly some 100kHz.
At $R_l = Z_\mathrm{cable} = R_s = Z_\mathrm{gap}$ the gaps azimuthal transmission-lines are terminated in their characteristic impedance. In this case no beam position dependence is observeable. Analysing the "4-resistor" schematics by varying R_s in a range of typical values we found a beam position depedence of the output signals at frequencies above some 10MHz.

In a "multi-resistor" operation the gap is completely filled with resistors and forms a low impedance ring. Choosing a value that terminates the gaps *radial* transmission-line impedance results in a very broadband monitor [4]. We compute

$$Z_\mathrm{gap,rad} = \sqrt{\frac{\mu_0}{\epsilon_0}}\,\frac{h}{2\pi r} \approx 5\Omega,$$

where r is the gap cylinders central radius and h its height (equivalent to the "length" in beam direction).
In this operation the lower cutoff frequency of the position dependence is given by [5]

$$f_{l,3\mathrm{dB}} = \frac{.02775}{L'G'r^2} \approx 130\mathrm{MHz},$$

with $L' = \sqrt{\epsilon_\mathrm{eff}\epsilon_0\mu_0}\,Z_\mathrm{gap,az} \approx 350\mathrm{nH/m}$ and $G' \approx 1.6\mathrm{S/m}$.

C. Inductive Monitor

A toroid, made out of a 10×.025mm ferrite[4] bandage, around the ceramic gap couples to the beams magnetic field which produces a proportional flux in it. This is sensed by a single turn of a flat copper wire around the toroid, again four times at the north, south, west and east positions. The delivered broadband signals are impedance matched to 50Ω by rf-transformation, the spectrum ranges from $f_{l,3\mathrm{dB}} \approx 30\mathrm{kHz}$ to $f_{h,3\mathrm{dB}} \approx 250\mathrm{MHz}$ ($\pm 2\mathrm{dB}$). An extra turn is mounted for calibration purpose. This inductive monitor will be basically used as CM. It is also possible to run as BPM, but its position sensitivity is much lower than that of electrostatic monitors (buttons).

As we use the same ceramic gap for this inductive and for the resistive wall monitor, no extra space is required. Now a metal shielding is mandatory, with the ferrite toroid inside its inductance increases and help to lower the $f_{l,3\mathrm{dB}}$ of the resistive wall CM.

D. Signal Processing

For current monitoring the four pick-up signals of each device are summed with commercial power combiners and the resulting signal is transfered via coaxial cables (RG213 quality) into the control room. In case of the BPM's each button signal is delivered seperately there. Later we plan to used delay-lines and broadband combiners to line-up their signals on a single cable. In the control room these signals are switched by a VXI rf-coaxial multiplexer onto a digital oscilloscope for the signal processing. This very simple read-out technique is possible because the number of monitors is small and the required performance is rather moderate (0.5mm position resolution). For the commissioning the instruments are controlled manually, after some experience a computer control (GPIB, HP-VEE or LabView) has to be set up.

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[3] $C'_\mathrm{gap} = C_\mathrm{gap}$ per unit length

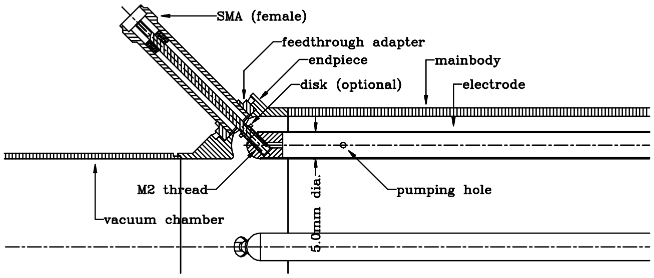

Figure. 2. Stripline BPM for the linac (partial view of the longitudinal cut)

III. LINAC BPM

A. Stripline Pick-Up

Heart of the linac instrumentation are the BPM's. As pick-up a stripline monitor with four $\ell_{\rm elec} = 20$cm long tubular electrodes (sloted coaxial-lines made with 5mm dia. ×.2mm stainless steel tubes) has been developed. The pick-up body is milled and electro-eroded (EDM)[5] out of three NABE-58 Cu parts which are brazed together. As the monitor fits inside the quadrupole no extra space is required and it is easy to be aligned and calibrated. The pick-up electrodes are fixed at both ends to the center-pin of a 50Ω vacuum feedthrough. A little disk is used to compensate the stray inductance at the pin-end. This minimizes the reflections on the electrode-to-feedthrough transition. Each electrode acts like a directional-coupler to the beam with the transfer function [6]

$$\frac{v_{\rm out}(f)}{i_{\rm beam}(f)} = \frac{k}{c_0\sqrt{C'_{\rm beam}C'_{\rm elec}}}\,\frac{j\sin\Theta}{\sqrt{1-k^2}\cos\Theta + j\sin\Theta}, \tag{1}$$

with $k = C'_{\rm b-e}/\sqrt{C'_{\rm beam}\,C'_{\rm elec}}$ and $\Theta = 2\pi f\,\ell_{\rm elec}/c_0$. With the MAFIA electrostatic solver we found $C'_{\rm elec} = 66.7$pF/m ($\equiv 50\Omega$), $C'_{\rm beam} \approx$15pF/m and the beam-to-electrode capacitance $C'_{\rm b-e} \approx$1pF/m (centered beam), $\Rightarrow k \approx .035$. The time-domain response to the beam follows as

$$v_{\rm out} = \frac{k}{2\,c_0\sqrt{C'_{\rm beam}\,C'_{\rm elec}}}\left[i_{\rm beam}(t) - i_{\rm beam}(t - t_{d,\rm PU})\right] \tag{2}$$

where $t_{d,\rm PU} = 2\,\ell_{\rm elec}/c_0 =$1.33ns. Further analysis of the pick-ups cross-section leads to the *position sensitivity* of two opposite electrodes: $v_{\rm W}/v_{\rm E}$ or $v_{\rm N}/v_{\rm S} \approx$2dB/mm around the center.

B. Signal Processing with Comb-Filters

As usual, the signals of two opposite horizontal and vertical electrodes has to be compared to find the beam position with respect to the vacuum chambers center. The *amplitude ratio-to-phase difference* method is a reasonable way to process the broadband signals from the pick-up electrodes. With an analogue *preprocessing* extension (Σ/Δ-hybrid and rf-amplifier) the sensitivity around the origin can be increased [7]. The processing is based on 90^0, 3dB-hybrids (directional couplers) and require continuous wave (CW) sine-signals. As no "memories" are present, the CW can be replaced by a sinus burst signal

$$\begin{aligned}\tilde{h}(t) &= \sin(2\pi\ f_0\,t)\ \text{ for}: -\frac{n}{f_0} \le t \le \frac{n}{f_0},\ 0 \text{ elsewere}\\ \tilde{H}(f) &= j(-1)^n\,\frac{\sin[2\pi\,n\,(f/f_0)]}{\pi\ f_0[1-(f/f_0)^2]}\end{aligned} \tag{3}$$

of n oscillations, with the frequency matched to the pick-up: $1/f_0 = T_0 = 2\,t_{d,\rm PU}$. For this purpose we designed a sinewave comb-filter, which will be switched between pick-up outputs and signal processing electronics.

The response of this comb-filter to a single bunch signal from the pick-up is a sinewave burst of n = 4 oscillations with $f_0 = 375$MHz. In this way we get a *measurement time* of $4\,T_0 = 4/f_0 = 10.67$ns, which is sufficient to measure the position of every passing bunch within the 16ns bunch-to-bunch spacing. The comb-filter is realized by feeding the pick-ups "quasi"-Dirac[6] doubled outputsignal (2) through a lowpass pulseformer with a "half"-cosine impulse reponse:

$$\begin{aligned}h(t) &= \cos(2\pi\ f_0\,t)\ \text{ for}: -\frac{1}{4\,f_0} \le t \le \frac{1}{4\,f_0},\ 0 \text{ elsewere}\\ H(f) &= \frac{\cos[\pi/2\,(f/f_0)]}{\pi\ f_0[1-(f/f_0)^2]}\end{aligned} \tag{4}$$

Its output delivers a single f_0=375MHz sine oscillation as response of (2). With two commercial broadband 4-way power splitters/combiners and some delay-lines we line-up n=4 oscillations by splitting and delayed recombining of this single period.

References

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[4] VAC Vakuumschmelze type *Permenorm 3601K2*

[5] electrical discharge machining

[6] $t_{\rm bunch,FWHM} \ll t_{d,\rm PU}$ and $f_{h,\rm 3dB,bunch} \gg f_{h,\rm 3dB,LP}$