Fast capacitive probe for short and high intensity electromagnetic pulses diagnostic

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Abstract

Fast and high intensity electromagnetic pulses are constantly request especially for FEL of new generation and other scientific and industrial machines. Nowadays fast current or voltage pulses of sub ten picoseconds can be recorded in real time by fast digitizing oscilloscopes. To get good results it is necessary realize fast probes. Fast capacitive probes are conceived like a transmission line and it is indispensable to construct it with electrodes of suitable dimensions and form. The instrument we realized has got the central electrode folded in order to present a skin dimension close to external electrode sides and a particular configuration for containing the integrating resistor to avoid electromagnetic interferences. It is suitable for measuring fast voltage and current pulses propagating in coaxial structures of known characteristic impedance. Analysing the behaviour of the probe for pulses propagating in a 50 Ω coaxial structure the voltage amplification resulted of $(3.6 \pm 0{,}1)\text{x}10^{-4}$ and as a consequence the current attenuation factor of 56±1 A/V. The rise time response was very interesting. It was less than 350 ps, value limited by oscilloscope bandwave.

INTRODUCTION

Fast probes are devices routinely used to detect particularly current and voltage pulses especially present in particle accelerators. Their use is not very easy when incognito signals of short time duration must be detected. Nowadays the construction of new pulsed electron beams requires pulses of more and more sub nanosecond. For this reason the design parameters of probes must be adjustable to the characteristic of the accelerators in order to record pulses in real time. One of the last researches, e.g. free electron lasers (FEL), utilise electron bunches of the order of ten picosecond[1]. In them, due to the absence of fast probe development for monitoring current or voltage in real time, the diagnostic is only performed on pulse integration. In this way no exact information on the time evolution of the signals can be obtained and the exact time duration remains incognito. To capture such signals, very fast recording devices are necessary. Modern fast digitizing oscilloscopes have got sampling rate of more than 40 GS/s and bandwave up to 13 GHz which enhances the possibility to record fast waveform pulses.

Therefore, nowadays fast current or voltage pulses of sub hundred picoseconds could be recorded in real time by fast digitizing oscilloscopes, but for getting good results it should be necessary to realize fast probes suitable to the experimental set up.

The more common devices utilised for diagnosing fast current pulses are resistive shunts and auto-integrating current coils. The firsts can be invasive if utilised by Faraday cups and the input current is determined by the voltage signal on the shunt resistors[2]; the seconds are inductive and the input current is given by the attenuation factor of the instruments called auto-integrating loops[3] or Rogowski coils[4, 5]. The response of an inductive divisor closed on a load of resistance R_L and excited by a Heaviside function $I=I_0u(t)$ is given by the following expression:

$$I_{out} = I_0 \frac{k\sqrt{L_1 L_2}}{L_2} e^{-t/\tau} \qquad (1)$$

where L_1 and L_2 are the primary and secondary inductance, respectively, k is the coupling coefficient and τ is the relaxing time given by L_2/R_L. For pulse duration τ_p less than τ the signal is auto-integrated being ($R_L << L_2/\tau_p$) and the Eq. 1 can reproduce the input signal. Fig. 1 shows a sketch of the inductive divisor.

The more common devices utilised for voltage pulse diagnostic are resistive divisors of high input impedance and capacitive ones. Both instrumentations are not invasive due to their high impedance values. The firsts often use resistors of

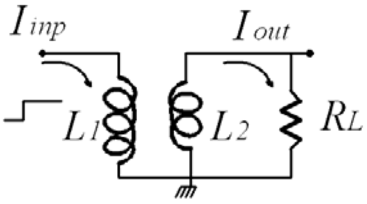

Fig. 1. Schematic diagram of an inductive current divisor: L_1 is primary inductance, L_2 is the secondary inductance.

high voltage, while the seconds ones use high voltage capacitors with high output resistive load that makes them auto-integrating capacitor devices.
Generally, the response of a capacitive divisor closed on a load resistance R_L and excited by a Heaviside function like $V=V_0u(t)$ is given by the following expression:

$$V_{out} = V_0 \frac{C_1}{C_1 + C_2} e^{-t/\tau} \qquad (2)$$

where C_1 is the capacitance of the input capacitor (between the inner conductor and the divisor electrode of radius R_C), C_2 is the one of the output capacitor (between the divisor electrode and the ground), and τ is the relaxing time given by $R_L (C_1+C_2)$. Fig. 2 shows a sketch of the device. Even in this case, for pulse duration τ_p less than τ the signal is auto-integrated being $R_L>>\tau_p/(C_1+C_2)$ and the Eq. 1 can reproduce very well the input signal.

From Eqs. 1 and 2, in order to have independent responses on time, it is necessary to choose particular values of the circuit parameters on input pulse time duration. Besides all these devices must have suitable structures in order to fit the generat-

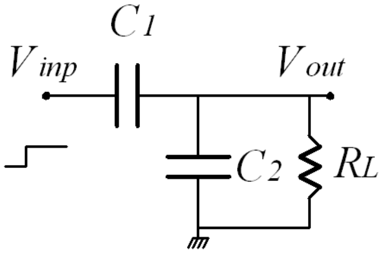

Fig. 2. Schematic diagram of a capacitive voltage divisor: C_1 is the capacitance of divisor electrode and external conductor, C_2 is the capacitance of the internal conductor and the divisor electrode.

ing machine structure and not to modify substantially the propagation of the input pulses. About the load impedance of the divisors it must be chosen taking in account the characteristic impedance of the transmission line cable indispensable to lead the signals to the oscilloscope. Generally the characteristic impedance of the transmission line cable is fixed to 50 Ω and for R_L<<50 Ω or R_L>>50 Ω, a supplementary resistor in parallel or in series will be indispensable, respectively. In any way to record correctly fast signals serious problems have to be resolved.

THEORY and APPARATUS

Generally the presence of current or voltage pulses are due to the propagation of electromagnet signals in guided structures. In this case the waveforms of current and voltage signals are linked and governed by the electromagnetism laws. To be able to perform valid measurements, we must absolutely avoid the instauration of signal reflections which make difficult to write the relationship between current and voltage. When electromagnetic structures are able to match the propagating signals, then the voltage signals can provide the current values and viceversa.

Let us consider a transmission line of characteristic impedance Z_0 having a coaxial structure. The internal conductor radius is r while the external one is R_e. In this case the characteristic impedance of the structure for radial signals is

Fig. 3 shows the schematic diagram of the transmission line containing an inductive auto-integrating divisor and a capacitive auto-integrating divisor. This last is composed by a cylindrical electrode of radius value very near to external conductor one in order to enhance the attenuation factor as can be seen bottom. Let us call R_C the radius of the divisor electrode and consider a short transmission line formed by the divisor electrode long *a-d*, with internal conductor by characteristic impedance Z_1.

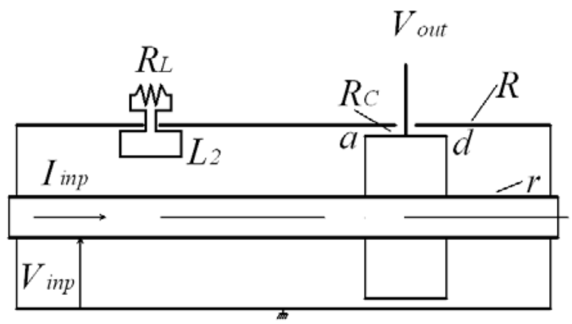

Fig. 3. Sketch of the transmission line, inductor divisor (loop closed on a very little R_L) and capacitive divisor (capacitor closed on very large load) geometry.

In the same way we consider the divisor electrode with the external conductor by characteristic im-

$$Z_0 = \frac{1}{2\pi}\sqrt{\mu\varepsilon}\,\ln\left(\frac{R_e}{r}\right) \qquad (3)$$

pedance Z_2, namely;
Now, applying a voltage function by Heaviside waveform, V_{inp}, on one extremity of the main line a voltage signal propagates as well as a current one of intensity V_{inp}/Z_0. Neglecting the thickness of the divisor electrode the line impedance $Z_0=Z_1 + Z_2$ and the propagating electric field will be divided on

$$Z_1 = \frac{1}{2\pi}\sqrt{\mu\varepsilon}\,\ln\left(\frac{R_C}{r}\right) \tag{4}$$

e

$$Z_2 = \frac{1}{2\pi}\sqrt{\mu\varepsilon}\,\ln\left(\frac{R_e}{R_C}\right) \tag{5}$$

Z_1 and Z_2. In this case closing the divisor electrode on a load resistive of $R\rightarrow\infty$, the potential of the di-

$$V_{div} = \frac{Z_2}{Z_1 + Z_2} V_{inp} \tag{6}$$

visor electrode will be:

$$V_{div} = \frac{\ln(R_e/R_C)}{\ln(R_e/r)} V_{inp} \tag{7}$$

or substituting the Eqs (4) and (5), it become:

This is a theoretical result. Actually the output signal can not be read by a high impedance owing to the low cable and oscilloscope impedance. Besides the divisor electrode can not have got the dimension of the thickness null as previous by the theory. It must have a thickness to allow the electrical connections. In the same time it must be shielded by stray signals and must be very symmetric with respect to the principal axis in order not to induce localized excess of potential that should provoke undesired oscillations.

To overcome the above problem we designed a ring electrode sufficiently thick and folded. The thickness ensured the electrical contact while the folding assured an equivalent propagation time of the input electric field for its external path *(a-b-c-d)* and for the internal one (*a-e-f-g-h-i-l-d*) obtaining at the end of the divisor the coincidence of signals. Then the structure of the capacitive divisor assumed the form shown in Fig. 4.

Further, we also operated specific modifications on the ring electrode to diminish eventual localized excess of potential. The localized charge on the divisor electrode can travel along its circumfer-

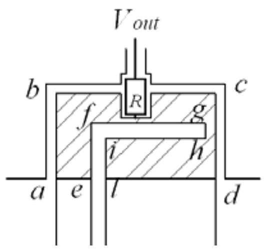

Fig. 4. Cross section of the modified divisor electrode.

ence. The propagation of such signal brings to consider the circumference of the electrode and the ground a transmission line of very low characteristic, about 2 Ω. This low resistance value should induce high currents. If these last cross resistive paths the excess of potential could be damped. To secure all this, the circumference of the divisor electrode was modified by longitudinal cuts in order to introduce periodic impedances. The operated slits were filled by a low conductive material biased on graphite mix.

An other peculiarity of this probe is the position of the integrating resistor R_L very useful to reproduce the shape of the input signal. Its position must be chosen in order to avoid electromagnetic interferences (antenna behaviour). In other hands the resistor must be shielded and placed very close to the divisor electrode.

Fig. 5. Photo of the transmission line containing the capacitor divisor.

EXPERIMENTAL RESULTS

The calibration of the capacitor device was accomplished by a voltage and/or current pulser accomplished by a high voltage power supply connected to a 50 Ω coaxial cable. A fast switch of sub-hundred-picosecond rise time connects the charged coaxial cable to a transmission line containing the capacitor divisor. The transmission line was realized utilising two vacuum tubes of 24 mm in diameter terminated by two NW35CF flanges. To reach the 50 Ω value an internal conductor of 10 mm in diameter, in the transmission line was utilised. The transmission line containing the capacitor was closed at its terminations by two NW35CF flanges equipped with fast BNC connectors. Fig. 5 shows the photo of the apparatus. The signal from the pulser to the divisor was transmitted by a double shielded coaxial cable Suhner 50 Ω and closed on a 50 Ω resistor at second terminator of the transmission line. On this last load a fast resistive probe by 47 attenuation factor was utilized to record the input excitation.

The value of the load resistor was of about 470 Ω in series to the oscilloscope input 50 Ω. The above value was chosen by the following considerations: the value of measured C_2 was about 400 pF, whereas the time duration of our pulses of about 20 ns. The choice resistor brings in a relaxing time of 200 ns, value very higher than 20 ns.

In Fig. 6 we report the waveforms of the input signal (trace C2) and the output signal (trace C3) with the load resistor placed after the divisor electrode. Instead the response of the divisor with the load resistor shielded and placed near the divisor electrode evidences the oscillation absence on the response (trace C3) and an amplification factor of $(3.6 \pm 0,1)x10^{-4}$, Fig. 7. To evaluate the fidelity of our innovator, the response also at short time scale is shown in Fig. 7, namely at 200 ps/div. By these result it is noteworthy observe that the current attenuation factor is 56±1 A/V, while the risetime of input and of the response attains at about 200 ps corresponding at the risetime of the oscilloscope.

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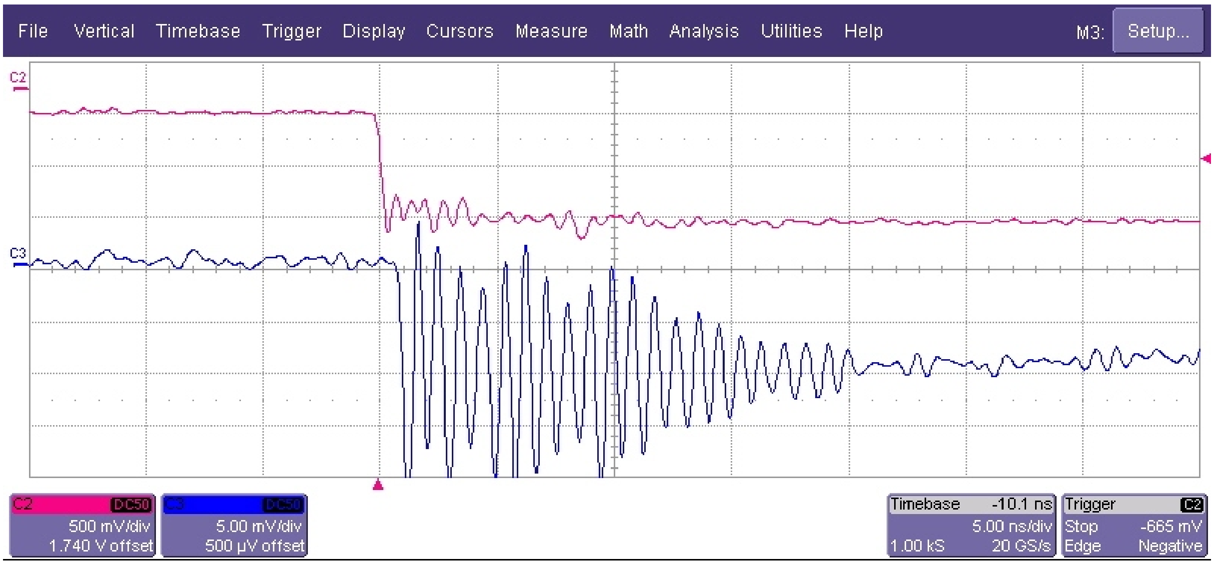

Fig. 6. Waveforms of the input signal (C2) and of the response (C3) at 10 ns time scale with the load after the divisor electrode.

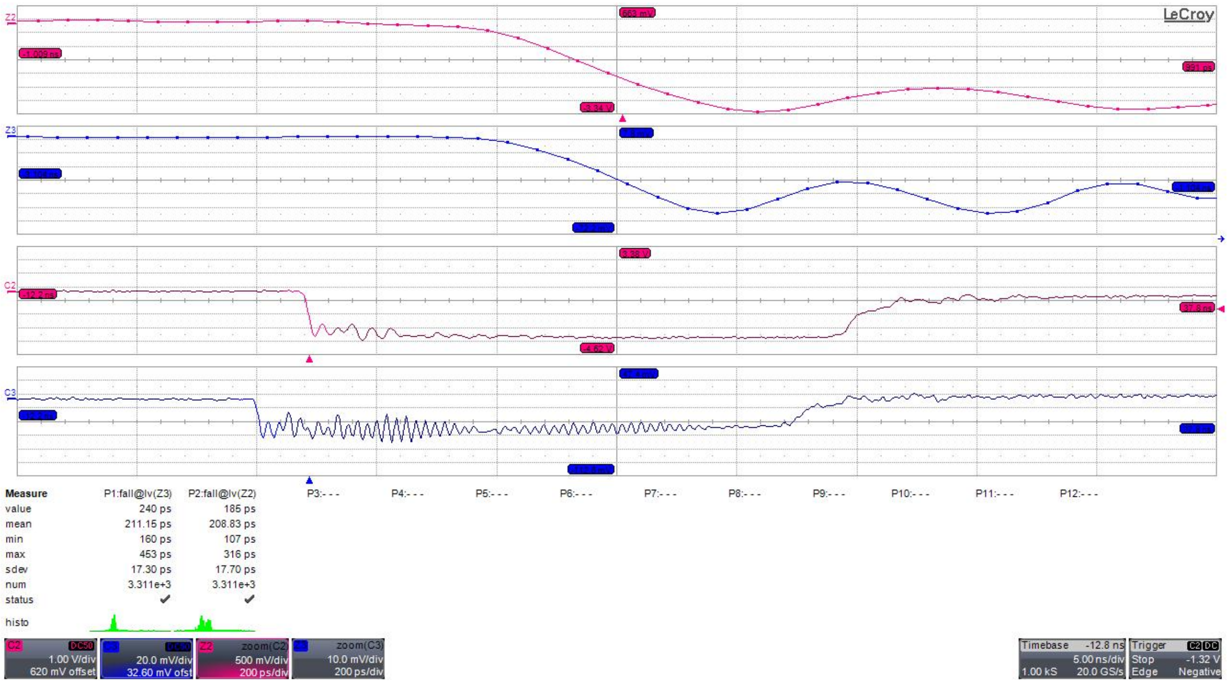

Fig. 7. Waveforms of the input signal (Z2) and of the response (Z3) at 10 ns time scale and at 200ps time scale. In this case the resistor is inserted inside the central electrode.