VARIANTS OF GROUNDING AND SHIELDING IN A BEAM DIAGNOSTICS MEASUREMENT OF LOW SIGNAL CURRENTS

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Abstract

The performance of several variants of grounding and shielding of long measurement cables for small currents against ground potential differences has been estimated analytically.

INTRODUCTION

In the large part, the beam diagnostics at the PSI cyclotrons and beam lines utilize low signal currents of low frequencies generated by the beam. This includes collimators, segmented aperture foils, wire scanners, harps, and ionization chamber based loss, current and profile monitors. The current measurement electronics, in most cases logarithmic amplifiers, are located outside the vault in order to prevent radiation damage and to allow for permanent service access. Hence, signal cables of 30 to 150 m length are needed. In order to preserve the signal quality, the prevention of ground loops is the most important factor. An appropriate grounding scheme, using "floating" amplifiers, has been applied at PSI by L. Rezzonico and U. Frei since 1989 [1]. Nevertheless, in some instances, with the presence of strong noise sources, this comes to its limits. This can be e.g. motors driven by switching power supplies over long cables, having insufficient EMI measures.

There are many possible variants for grounding and connecting the individual cable shields. Figure 1 depicts several variants which have been examined analytically and are discussed in the following. Variant b1) is used at the present diagnostics of the HIPA facility [2], variant c) at the Proscan beam line diagnostics [3]. Variants d1), d2) are under consideration for the diagnostics in the beam lines to the new Gantry 3 at Proscan. Although we restrict ourselves here to a single cable length (50 m) and the parameters of our "LogIV" logarithmic amplifiers [1], quite general conclusions can still be drawn. This is helpful for assessing quantitatively the determining factors and guiding the way to improvements.

MODEL AND DERIVATION

The model for the variants d) and e) (two shields), taking into account or not the "bridge elements" introduced by the DC-DC converters and differential amplifiers isolating a group of four logarithmic amplifiers from "rack ground", is depicted in Fig. 2. For variants b) (only one shield) and a) (only a "shield", which is part of a ground loop) this model is stripped down accordingly.

Based on Maxwell Equations, the definition of conductivity and the utilization of symmetries, the theory of shielded cables was developed in the 1930s. A systematic description is given in the book of Kaden [4], including coaxial cables, skin effect, conductive and magnetic shields and the coupling of a perturbing signal from outside to inside. We adopt this formalism with the additional boundary condition that the shields #1 and #2 are connected galvanically only at one end (and not at both ends or many locations in between as assumed in [4]). Furthermore the capacitive and inductive coupling through the small holes in the braided shield is added in the way given by Vance [5, 6]. Hereby the variants have been described approximatively by analytical equations which have been evaluated numerically [7]. In the following, this procedure can only be adumbrated.

References to equation numbers from [4] are given in curly brackets. We adopt the notation of [4], borrowing in some instances from [6]. Apostrophes are added to indicate the normalization to unit cable length. Tildes are added to indicate time-varying parameters. The subscript notation is adapted to indicate the involved shield numbers according to Fig. 2. The purely ohmic resistance is indicated by the subscript "ohm" (instead of "0" which is used here for the center conductor).

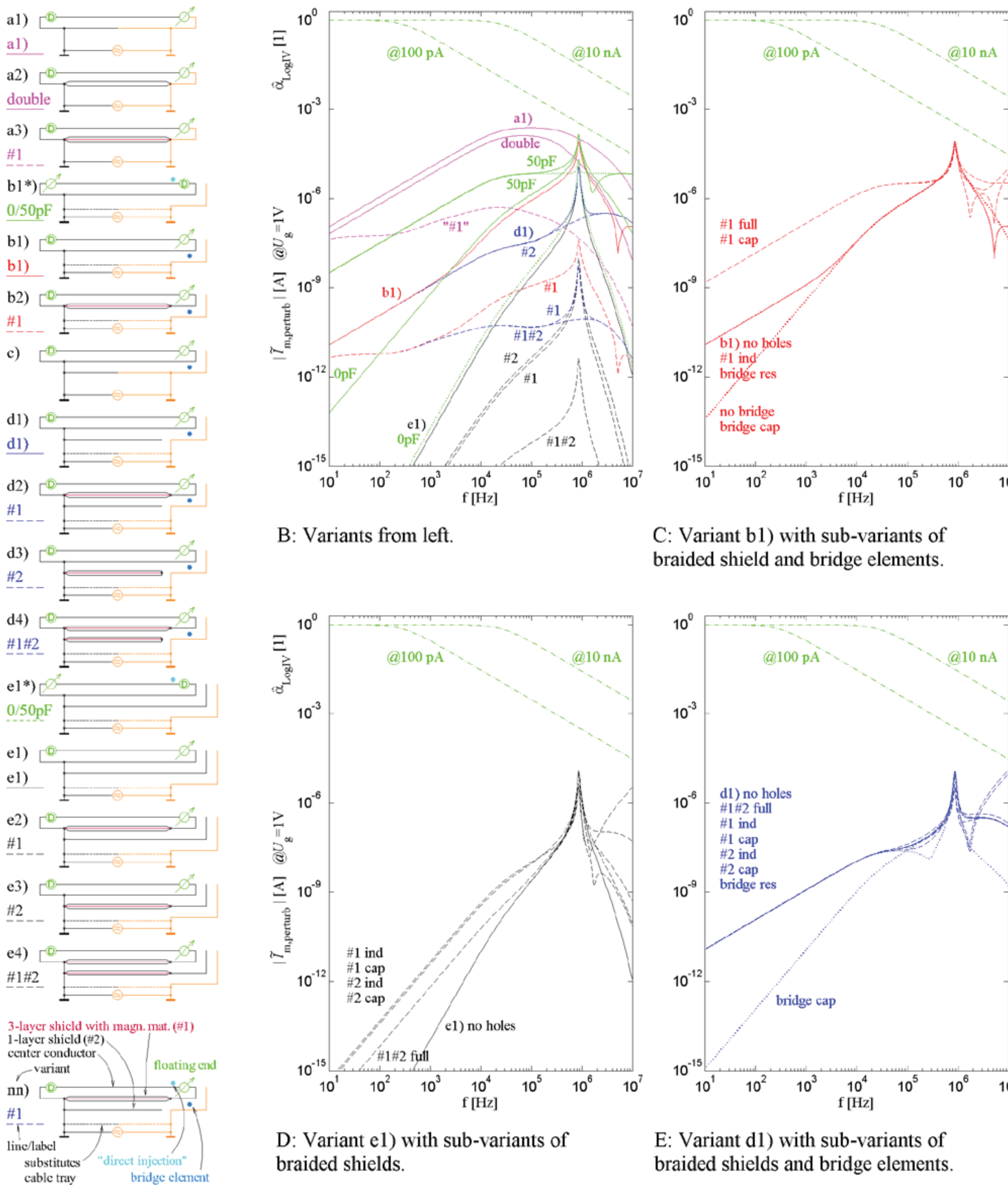
The assumed source of disturbance is the periodic potential difference $\tilde{U}_{\mathrm{g}} = \hat{U}_{\mathrm{g}} \sin \omega t$ between "detector ground" ($\equiv 0\,\mathrm{V}$) and "rack ground" which establishes linearly over the inner surface of "shield" #3 (which substitutes the cable tray). The local current difference $\tilde{I}'_2(s) \approx C'_{23}\, \boldsymbol{\alpha}_{23}\, \dot{\tilde{U}}_{3\mathrm{i}}(s)$ at shield #2 is generated (and mainly determined) by capacitive coupling. (For frequencies below 100 kHz it is $\boldsymbol{\alpha}_{23} \approx 1$.) The integral local current is then $\tilde{I}_2(s) \approx \int_s^{s_{\max}} \tilde{I}'_2(s)\,\mathrm{d}s$, which causes a local voltage drop and hence a potential at the outside of shield #2 of $\tilde{U}_{2\mathrm{e}}(s) = \int_0^s \tilde{U}'_{2\mathrm{e}}(s)\,\mathrm{d}s = \boldsymbol{R}'_2 \int_0^s \tilde{I}_2(s)\,\mathrm{d}s$ with $\boldsymbol{R}'_2 = R'_2 + \mathrm{i}\omega L'_2 = R'_{2\mathrm{ohm}}\, k_{\mathrm{Cu}} d_2^* \coth(k_{\mathrm{Cu}} d_2^*)$ {L23, E23} the inner impedance. The local voltage drop at the inside of shield #2 is then $\tilde{U}'_{2\mathrm{i}}(s) = \boldsymbol{Z}'_2\, \tilde{I}_2(s)$ with the transfer impedance $\boldsymbol{Z}'_2 = \boldsymbol{R}'_{\mathrm{K2diff,1layer}} + \mathrm{i}\omega M'_2$ of shield #2 including the coupling resistance (named also diffusion part) $\boldsymbol{R}'_{\mathrm{K2diff,1layer}} = R'_{2\mathrm{ohm}}\, k_{\mathrm{Cu}} d_2^* / \sinh(k_{\mathrm{Cu}} d_2^*)$ {L25} and already a term for coupling inductively through the braid. If the 1-layer shield is replaced by a compact 3-layer shield with central magnetic layer, the corresponding term is $\boldsymbol{R}'_{\mathrm{K1diff,3layer}} = \frac{\boldsymbol{R}'_{\mathrm{K1Cu}}\, \boldsymbol{R}'_{\mathrm{K1Cu}}}{\boldsymbol{R}'_{1\mathrm{Cu}} + \boldsymbol{R}'_{1\mathrm{Cu}} + \mathrm{i}\omega L'_{1\mathrm{Mu}}}$ with coupling resistance $\boldsymbol{R}'_{\mathrm{K1Cu}}$, inner impedance $\boldsymbol{R}'_{1\mathrm{Cu}}$ {E23} and interspace inductance $L'_{1\mathrm{Mu}}$ {L27}. Integration gives the local potential $\tilde{U}_{2\mathrm{i}}(s) = \int_0^s \tilde{U}'_{2\mathrm{i}}(s)$ along the inside of shield #2.

The same procedure is performed for shield #1 including terms for the bridge elements and capacitive coupling through the braid of shield #2.

Coupling to the inner measurement loop is derived using Fig. 2B with the assumption that C_{det}, C_{inj} are relatively small.

The transfer characteristic of the LogIV depends on the DC input current (Fig. 1B-D, upper lines). It is introduced by parametrization of measured [1] cut-off frequencies as

$$\hat{\alpha}_{\mathrm{LogIV}} = \frac{1}{\sqrt{1+\left[f\left(\frac{10^{-12}\mathrm{A}}{I_{\mathrm{m,DC}}}+10^{-5}\right)/3\right]^2}} = \frac{\hat{I}_{\mathrm{LogIVout,perturb}}}{\hat{I}_{\mathrm{m,perturb}}}.$$



B: Variants from left.

C: Variant b1) with sub-variants of braided shield and bridge elements.

D: Variant e1) with sub-variants of braided shields.

E: Variant d1) with sub-variants of braided shields and bridge elements.

Figure 1: A (to the left): Variants of grounding and connecting shields and "shields". B: Performance of these variants. C, D, E: Performance of some variants with added sub-variants. (A label "#2 cap" means that only the capacitive part of shield #2 is assumed to contribute to the coupling through the small holes. "bridge res" indicates that only the resistive part of the bridge is assumed to be present.) Details of the setup are given in Fig. 2. Cable length s_{max}= 50 m.

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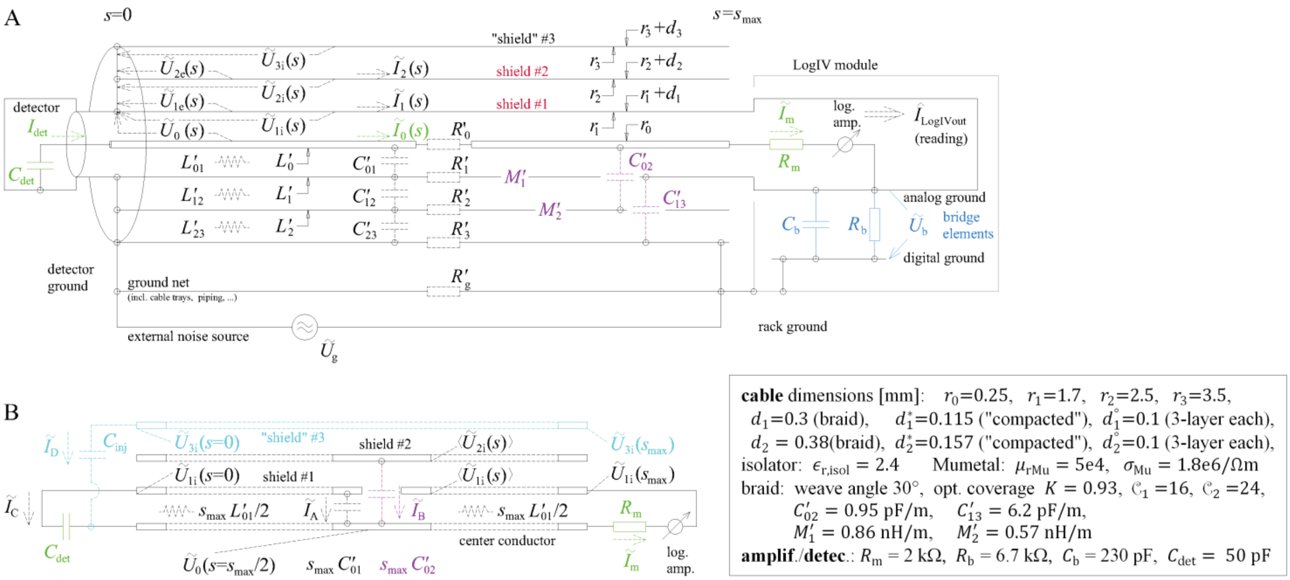

Figure 2: A: Circuit diagram for variants d1)-d4), e1)-e4). B: Simplified circuit for the inner measurement loop.

CONCLUSIONS

From Fig. 1 several conclusions can be drawn for the frequency range of interest below 100 kHz. With a perturbing amplitude $\widehat{U}_g \leq 0.1$ V, which seems "realistic" in our machine environment and a signal current range down to 10 pA, perturbing LogIV amplitudes of 100 pA @$\widehat{U}_g$=1V (including $\hat{\alpha}_{\mathrm{LogIV}}$) are seen as a "reasonable" result.

On this scale a single "shield" a1)-a3), carrying a ground loop, performs inacceptably, even with magnetic material or double layer. The single shield b1)-b2) is below 2 kHz counteracted by the current passing the bridge resistance, but nevertheless performs quite well. A braided shield is unacceptable here (due to the capacitive part) and magnetic material improves a lot. A double shield alone e1)-e4) performs extremely well and even better with magnetic material. Braid is detrimental (because it matters in a near perfect shield). However, with bridge elements d1)-d4), it's advantage compared to the single shield is maintained only above 2 kHz. Braid is tolerable then (because the bridge elements are worse).

In principle, a "floating" detector d1*), e1*) instead of a "floating" amplifier can eliminate the bridge elements needed to isolate the amplifier. However, if the "floating" detector is only a simple electrode (e.g. a collimator) it is directly exposed to the surrounding surfaces grounded at "detector ground". This capacitance of e.g. C_{inj}=50 pF provides "direct injection" of the perturbance into the amplifier input and results in a bad performance. A closed shielding around the detector electrode would avoid this. It is only feasible at low beam currents and seldom used [8], although it would be also beneficial by excluding RF fields and stray particles. If the detector needs a high voltage electrode, as e.g. ionization chambers and in part secondary emission monitors, large capacitances between high voltage electrode and signal cable shield are needed to suppress noise picked up by the high voltage supply cable [9]. This corresponds to a large bridge capacitance.

There are other external changing potentials around, of much higher amplitude than the potential differences at the ground grid. These can e.g. be the conductors of unshielded power cables or an electrostatically charged person walking by (or discharging by touching the grounded cable shield). Although these sources couple capacitively only to a smaller fraction of the full cable surface, their influence can be strong due to the much higher amplitudes. Here a shield or also a multiple grounded "shield" can limit these effects. Separate trays for diagnostics cables are also useful in this sense, but are more important to prevent inductive coupling from AC power cables.

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