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Effective shielding to measure beam current from an ion source[a)]

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To avoid saturation, beam current transformers must be shielded from solenoid, quad, and RFQ high stray fields. Good understanding of field distribution, shielding materials, and techniques is required. Space availability imposes compact shields along the beam pipe. This paper describes compact effective concatenated magnetic shields for IFMIF-EVEDA LIPAc LEBT and MEBT and for FAIR Proton Linac injector. They protect the ACCT Current Transformers beyond 37 mT radial external fields. Measurements made at Saclay on the SILHI source are presented. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4829736]

I. REASONS FOR SHIELDING

In a general way, current transformers bandwidth is limited at low frequencies by the magnetic core geometry: section A and circumference l, the winding turns number N, the core material permeability μ_r, and the load resistance R_L,

$$fc_{low} = \frac{R_L}{2\pi\mu_0\mu_r\frac{AN^2}{l}}. \quad (1)$$

Without shielding, a DC transverse magnetic field causes the partial saturation of the transformer core, which can be viewed as a decrease of its magnetic section. The direct effect of this partial saturation is a lower winding inductance and thus a higher low cutoff frequency. The field density at which the core saturates depends mainly on the nature of its material and is defined by its saturation flux density Bs.

In the particular case of ACCT where the active electronics compensates the transformer droop to achieve low frequency measurements,[1] the effect of a DC transverse magnetic field is slightly different: as long as the electronics gain can compensate the loss of inductance, the field effect is compensated. When the electronics cannot compensate anymore the saturating field effect – basically when the core is almost saturated – the low cutoff frequency increases drastically (Fig. 1).

Core saturation is the consequence of its magnetic domains alignment when submitted to a magnetic field. Field density is induced in the core by the field, a function of the core material permeability, and the field line path length through the material in respect to the total magnetic path length. As a result, the induced field density varies depending on the core orientation in respect to the magnetic field vector.

Three configurations are of special interest: the field vector is axial to the core, radial to the core, or transverse to the core (Fig. 2). For a typical transformer core (axial length < diameter/20), induced field density is more than 10 times higher for a transverse field than for either axial or radial field. Therefore, simulations and measurements focus on transverse fields to qualify the shield effectiveness and radial fields, which is the solenoid stray field configuration seen by the transformer.

In LEBT and MEBT where available space is restricted, diagnostics can be located close to solenoids and magnets where strong stray magnetic fields are present. It is then essential to adopt a compact well-designed magnetic shield.

In the LIPAc LEBT, an ACCT is installed next to a solenoid where up to 8-mT surrounding field is present. On the MEBT, another ACCT combined with a FCT is also to be located next to a quadrupole where a transverse field of about 25 mT is expected.[2,3]

For the FAIR injector, an ACCT is to be placed near a solenoid where a 15-mT radial field is expected.

Another reason to shield sensitive diagnostics from stray magnetic field could be the presence in their vicinity of 50 Hz fields from devices such as vacuum pumps. Contrary to DC fields that show an effect on the ACCT response only when the core is saturated, AC fields caught by the transformer are directly visible in the electronics output since their spectrum is present in the instrument's output bandwidth. Fig. 3 shows the influence of an AC field on the ACCT output.

Without shielding, ACCT is sensitive to AC fields as low as a few mGauss. With no field, ACCT output is about 1 mVrms: the electronics offset. An appropriated shield reduces the AC field sensitivity by a few orders. Cable loops are also susceptible to pick up AC fields.

Since their effect on ACCT is directly detectable, AC external fields, e.g., 50 Hz, can also be used to measure the shield effectiveness. To control the field intensity and make accurate measurements on shields, devices such as Helmholtz coils whose field maps are well known can be used as illustrated in Fig. 4.

II. SHIELDING TECHNIQUES

In general, the total loss through a shield is the sum of losses by absorption and losses by reflection.[5] At DC and low frequency, the shielding effectiveness of magnetic shields is

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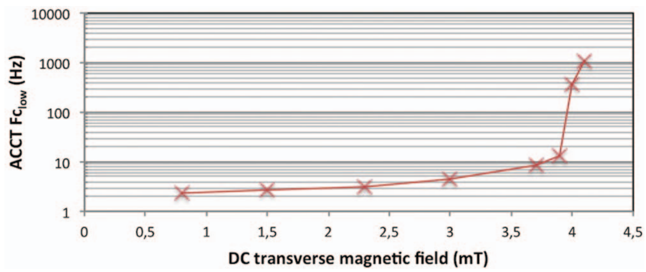

FIG. 1. Influence of DC transverse H field on unshielded ACCT.

FIG. 2. Magnetic field configurations.

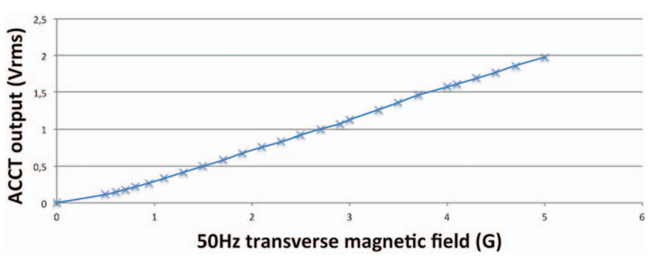

FIG. 3. Influence of AC transverse H field on unshielded ACCT.

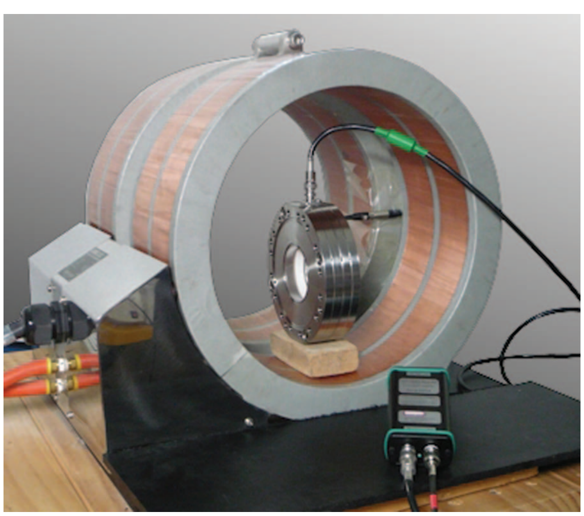

FIG. 4. Shield effectiveness measurement using Helmholtz coils[4] in transverse field configuration.

TABLE I. Magnetic material specifications.

	Bs	μ_r
Vitrovac 6025[7]	0, 58 T	70 000–100 000
Mumetal	0, 76 T	350 000–500 000
Supra 36[6]	1, 3 T	30 000
Low-carbon steel	2, 15 T	1500

very low. Thus, rather than attenuating the field, at low frequency, the magnetic shield aims to deviate the field lines off their original path. The optimum shielding efficiency is obtained by multiple layers made of a combination of adequate materials. The assembly order of these materials is of primary importance and depends on their saturation flux density. Stray magnetic field has to be diverted step by step without saturating any of the shielding layers. Indeed, at field density above saturation, the permeability falls off rapidly and the shield looses its efficiency. To avoid layer saturation, materials showing a high permeability at low fields – typically low-Bs materials – must be used as inner shielding layers. High-Bs materials are devoted to external layers. As it happens, high-Bs materials also have a higher permeability at high fields. Typically, low-carbon steel is used for outer shielding to deviate high fields; several layers might be used to reduce sufficiently the stray field magnitude. Layers of Supra[6] – NiFe 64/36 – and Mumetal – NiFe 80/20 –, exhibiting a lower Bs than low-carbon steel, allow achieving a finer shielding. To deviate the weakest field lines, layers of low-Bs material such as Vitrovac – amorphous cobalt alloy – or Ultraperm[7] can be used. Nanocrystalline alloys are typically too fragile to be used as shielding foils.

The maximum permeability of magnetic materials occurs at field strength mid-level. At both higher and lower field strengths the permeability, and hence their shielding efficiency, is lower.[5] High-Bs materials are therefore less efficient for low stray fields. The best shielding efficiency is obtained by a combination of materials (see Table I).

The shield geometry is an important factor to take into account. Best shields are made of continuous, smooth, and closed geometry. Any edge in the shield surface causes breaks in the field lines propagation resulting in a loss of shielding efficiency. To shield the ACCT, a concatenation of several cylindrical boxes is used as shown in Fig. 5. Two boxes of Supra 36 material are used on the outer side of the shield, two Mumetal

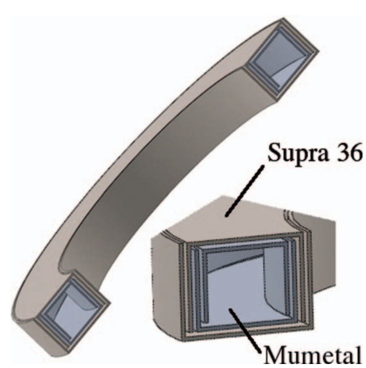

FIG. 5. ACCT concatenated shield.

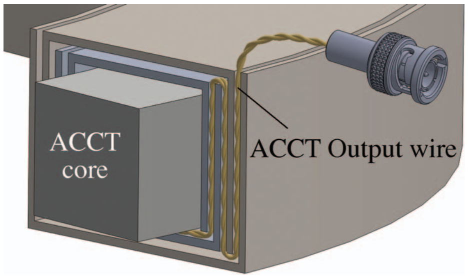

FIG. 6. ACCT Output wire through shield layers.

boxes on the inner side. Vitrovac tape was rolled around the transformer core as ultimate inner shield layer.

Caution is required to keep an electrical insulation between each shielding box. If the shield would form a conducting loop around the core section, it would act as a 1-turn winding and short the transformer. This must be avoided. Drilling holes through the shield for passing transformer's readout wires must also be avoided. Any aperture in the shield layers causes drastic loss of its efficiency; wires are thus threaded as illustrated in Fig. 6.

The permeability of magnetic materials is constant at low frequency and starts to decrease above 100 kHz approximately. This leads to the loss of their shielding properties. At high frequency, magnetic fields create eddy currents in conductive materials which strengthen as the material conductivity increases. In summary, magnetic materials are efficient to shield DC and low frequency fields, whereas high conductivity materials such as aluminum or copper must be used to shield higher frequency fields.

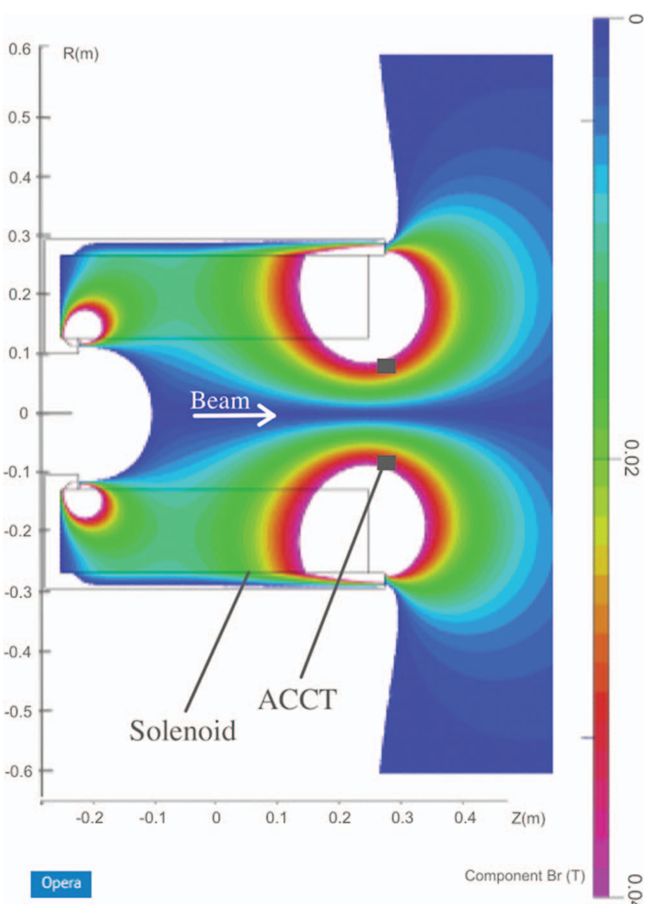

FIG. 7. Br field simulation of unshielded solenoid.

TABLE II. Comparison of measurements with simulation.

Solenoid current (A)	Br simulated at ACCT location (mT)	Br measured at ACCT location (mT)
100	20	21
130	26.5	27
200	41	37

III. MEASUREMENTS ON SILHI SOURCE

To assess the FAIR proton linac LEBT solenoid stray field magnitude at the ACCT location, a simulation showing the radial magnetic field map was made with Opera[9] as shown in Fig. 7.[8]

To test the ACCT with beam and check its shield efficiency against the solenoid stray field, the instrument was installed on the SILHI ion source at CEA/Saclay.[10] To maximize the field effect, it was purposely placed closer to the SILHI solenoid than it will be in the final FAIR injector configuration, and the solenoid shield was removed. The ACCT response to a 100 ms long proton pulse was measured while increasing the current in the solenoid to observe a possible raise in the transformer's droop (see Table II).

The highest Br radial field value achievable with the solenoid at the ACCT location was measured at 37 mT. At this value the ACCT output signal was not affected, guaranteeing the good efficiency of the ACCT shield for this field strength.

IV. CONCLUSION

In low-energy beam lines, space charge effects limit considerably the axial length available to beam diagnostics. This leads to placing field-sensitive instruments close to magnets, RFQs, quadrupoles, and solenoids exhibiting high stray fields. Efficient and compact magnetic shields are required to protect the diagnostics. Such a compact shield was designed for FAIR Proton Linac injector and successfully tested at Saclay on the SILHI proton source where it effectively protected an ACCT from radial fields up to 37 mT. Similar shields have been designed and manufactured for other beam lines, e.g., IFMIF-EVEDA LIPAc LEBT and MEBT.

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