Large Hadron Collider Project

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Review on Boundary-Induced Coupling Currents

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Abstract

Boundary-Induced Coupling Currents (BICCs) are generated in multistrand superconducting cables during a field sweep if a) the field sweep and/or b) the electrical contacts between the strands of the cable vary along the cable. Typical parts in a coil which cause large BICCs are the connections between two cables in or outside a coil and the coil ends of racetrack magnets.

In the first part of the paper several approaches for describing and calculating BICCs are reviewed. Attention is paid on the steady-state as well as the time dependent solutions.

In the second part of the paper the consequences of BICCs on the behaviour of magnets are discussed. These are additional field variations along the magnet length, additional coupling losses and a non-uniform distribution of coupling losses and current among the strands, resulting in a reduced stability. Several effects are illustrated by means of measurements on model dipole magnets. It is shown how the additive effect of all the BICCs in a coil is rather unpredictable so that similar coils can have rather different BICC related behaviour.

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1. INTRODUCTION

It is well known that Interstrand Coupling Currents (ISCCs) are generated in superconducting multistrand cables subject to a field variation dB/dt . These ISCCs are usually calculated assuming that dB/dt and the contact resistances R_a (between adjacent strands) and R_c (between crossing strands) are uniform along the length of the cable. However, in all practical coils spatial variations of R_a , R_c and dB/dt are present along the length of the cable. Typical variations, present in almost all coils are summarized in Table 1.

The effect of spatial variations on the coupling currents can be easily illustrated by means of a cable having two twisted superconducting strands, connected through contact resistances and subject to a field variation dB/dt for $z>0$ as illustrated in Fig. 1. In each circuit for $z>0$ an ISCC will be generated equal to i (in steady-state). However, the current in circuit 5 generates a voltage iR_c in circuit 4 which has to be compensated for since

Table 1. Survey of various types of non-uniformities or boundaries in R_a , R_c and dB/dt which are present in a coil and cause BICCs.

Non-uniformities in the contact resistances	
Soldered connections	large effect
Strong variations of the transverse pressure in the coil ends	mediate effect
Weak variations of the transverse pressure over the entire cable	small effect
Manufacturing tolerances (including local 'shorts')	small effect
Non-uniformities in the field sweep rate	
Strong variations in the coil ends and the terminals	large effect
Weak variations over the entire cable	small effect

$dB/dt=0$ in circuit 4. This is achieved by an additional current $i/2$ with alternating direction being generated in all contacts. This results finally in a large current loop where one strand carries positive current and the other negative current. The increase/decrease of the strand current along the cable corresponds to the currents that enter/leave the strand through the contact resistances. The strand currents are maximum at $z=0$ and decay to zero towards the ends of the cable.

Figure 1. Illustration of the generation of BICCs due to a step increase in dB/dt . The arrows denote the direction of the currents through the contact resistances.

The additional large current loops caused by these spatial variations are referred to as “Supercurrents”, “Super Coupling Currents” or ‘*Boundary-Induced Coupling Currents* (BICCs)’. The name BICCs will be used throughout the paper since the term ‘boundary’ indicates the origin of BICCs, i.e. geometrical boundaries, boundaries in dB/dt and internal boundaries such as changes in R_a and R_c . It is important to make a clear distinction between BICCs and a non-uniform distribution of the transport current. Both current patterns have usually large time constants and cause similar effects in magnets. BICCs are however generated if a cable is subject to a field sweep dB/dt , they increase with increasing dB/dt and decay to zero once the field sweep has become zero. A non-uniform distribution of the transport current is usually due to a variation in the connection (or joint) resistances among the strands. The variation of the transport current among the strands increases with increasing current excitation, and does not decay to zero at constant current level (except at 0 A).

The main methods of calculating BICCs and general results are given in section 2. Their effect on magnet performance is dealt with in section 3. Experimental evidence of BICCs is given in section 4.

2. CALCULATING BICCs

First calculations of the coupling losses in cables subject to spatially changing ac fields show that the coupling current in a strand satisfies a diffusion equation^{1,2,3}. The calculations were intended to study the change in the coupling losses of LCT conductors for the cases where a) only part of the cable is subject to a field change, or b) a finite length of cable is entirely subject to a field change. It was shown that the whole system of N strands, leading to N coupled differential equations, can be decoupled by introducing an effective inductance, and hence an effective diffusion constant, depending on the dimensions of the strand and the cable and on the spatial distribution of the strands in the cable.

A similar approach, based on the solution of the diffusion equation, was applied to a two-wire configuration coupled through a transverse conductance^{4,5,6}, in order to explain the periodic field variations and ramp-rate limitations in accelerator magnets wound from Rutherford-type cable. The coupling currents were treated as a superposition of ISCCs, with a relatively small time constant, and BICCs, exhibiting very long characteristic times. The BICCs were expressed by a Fourier expansion, where each component has its own time constant. A typical solution of the diffusion equation is shown in Fig. 2, in the case of a 20 m long cable subject to a dB/dt at the centre of the cable ($z=0$) over a length of $L_p/2$ and for a time of 1000 s. During the first 1000 s the BICC diffuses into the cable, and decays after 1000 s. Note that after 1000 s the BICCs can locally still increase although the average decreases. This approach is not well suited to obtain quantitative results since the extrapolation from 2 to N strands is difficult due to the inductive coupling. The time and space dependence of the BICCs is however expected to be qualitatively similar.

Diffusion equations are as well used to describe the current loop decay⁷ and the distribution of the transport current⁸ in Rutherford-type cables at low and high excitation.

Calculations performed on one twisted pair of monofilament superconducting wire, in the frame of the ITER project, also showed the possibility of enhanced losses due to the terminal effect and longitudinal non-uniformity of dB/dt ⁹. Depending on the exact geometry the effect could sometimes be imperceptible or even absent.

Figure 2. Time-dependent behaviour of a BICC caused by a local dB/dt at the centre of a cable ($z=0$) over a length $L_p/2$ and during a 1000 s.

The coupling currents in finite and infinite Rutherford-type cables subject to a uniform dB/dt was also investigated by modelling the cable as a network of rhomboidal cells^{10,11}, similar to the method originally used to calculate the ISCCs for uniform dB/dt and contact resistance¹². It was shown that the periodicity of the cross-over currents provide the minimum of total losses whereas the energy dissipation is locally much larger than if the coupling currents were constant. Only if the cable is infinitely long, there is one degenerated solution for which the crossover currents are not periodic but uniform along the cable. The same method was also used to calculate the coupling currents in finite and infinite Rutherford-type cables subject to, especially, sinusoidally varying magnetic fields along the cable axis^{13,14}. Only the steady-state current pattern could be modelled.

A complete description of the coupling currents in Rutherford-type cables is based on a further extension of the network model in which the entire cable is modelled by a 3D network of nodes interconnected by strands and contact resistances^{15,16,17,18}. Self and mutual inductances are implemented in this model, as well as the superconducting to normal transition and the contact resistances between both crossing and adjacent strands. With this model it is possible to obtain *quantitative* results of the steady-state and time dependent BICCs due to any kind of longitudinal variation in R_a , R_c , and dB/dt . Another important advantage of the network model is that the entire current distribution in the cable is calculated, taking into account the interaction between the BICCs, ISCCs and transport current. It is as well possible to model the BICCs if some strands (or regions of some strands) enter the resistive transition.

In the 3D network approach the possibility of an effective longitudinal resistivity that the BICCs ‘see’ is incorporated. This resistivity ρ_{bi} could be related to the diffusivity of the BICCs from the contacts into the filaments, and can be different from the strand resistivity related to the resistive transition of the superconductor. The result of ρ_{bi} is that the BICCs decrease quasi-exponentially along the cable (with the maximum at the non-uniformity) and do not tend to flow through the entire cable. The results of the network model agree qualitatively to the 2-strand diffusion approach as described above. Only for relatively large ρ_{bi} the solutions deviate after a certain time: where the BICCs are limited in magnitude in the network model they can become orders of magnitude larger if $\rho_{bi}=0$.

Typical curves of the steady-state current in a strand and the steady state coupling power along the length of a cable (subject to $dB/dt > 0$ for $z > 0$) are shown in Figs. 3 and 4 for small and large ρ_{BI} . The strand current can be regarded as a superposition of three components:

1. The transport current (in this case constant and equal to 20 A all along the strand).
2. The oscillating term (see also Fig. 1) with a period equal to the cable pitch L_p and an average equal to 0, related to the ISCCs which are mainly present for $z \geq 0$.
3. The BICC which is maximum close to the dB/dt -step and decays along the cable length.

Figure 3. The steady-state current in one of the strands of a Rutherford-type cable subject to $dB/dt=0$ for $z < 0$ and $dB/dt=0.01$ T/s for $z > 0$ for zero and finite ρ_{BI} .

Figure 4. The average steady-state coupling loss over the cross-section of a Rutherford-type cable subject to $dB/dt=0$ for $z < 0$ and $dB/dt=0.01$ T/s for $z > 0$ for zero and finite ρ_{BI} .

A periodic pattern in the loss is present (with a period equal to the cable pitch) where parts having large and small local power alternate, whereas the BICCs cause as well an increase in the average loss everywhere in the cable. Half of the strands, which carry large BICCs, are more heated than the average, and ‘hot spots’ are present at those places where strands with large positive and negative BICCs cross. So the BICCs cause both an increase in the average loss and local hot spots over lengths of about $L_p/2$. The local power depends on the local contact resistance.

The following conclusions about BICCs can be drawn from the computational models described above:

- In any coil the coupling loss varies periodically along the cable length with a period equal to the cable pitch. The loss can be much larger than expected if only a small part of the cable is subject to a varying field. This would for example make loss measurements on long cables, partially in a pulsed magnetic field, very problematic.
- A regular pattern exists in the magnitudes of the BICCs. In each cross section of the cable opposite strands carry BICCs with the same magnitude but with opposite sign. Adjacent strands have only slightly different BICCs.
- In general, longitudinal non-uniformities cause large BICCs if the variation is large over a distance comparable to the cable pitch. Hence, BICCs in racetrack magnets (e.g. accelerator dipole and quadrupole magnets), with their non-uniform coil ends, will usually be much larger than in solenoid magnets (assuming both types of magnet are made from the same cable).
- Especially those sections in a coil having small contact resistance could enhance the magnitude of the BICCs, even if these sections are located in a low-field (and low dB/dt) region of a coil.
- A variation in the contact resistances over the cable width (e.g. due to variations in the transverse pressure on the cable, the keystone of the cable and manufacturing tolerances) or a variation of dB/dt over the cable width changes the distribution of the ISCCs but does not cause BICCs.
- The BICCs are qualitatively similar for variations in R_a , R_c or dB/dt . Quantitative calculations for dB/dt and R_c variations show that BICCs increase with increasing cable size and decreasing contact resistances. An increase in R_c suppresses the BICCs partially but still rather large BICCs can be generated through the contact resistances R_a between adjacent strands.
- Typical characteristic times of BICCs are of the order of 10^2 - 10^5 s. The magnitude of BICCs per strand at field sweep rates of about 0.1 T/s can be easily of the order of 10 - 10^3 A.
- BICCs will as well be present in the filaments of multifilamentary wires, and not only in the strands of multistrand cables.
- Whereas the interfilament and interstrand coupling loss depend linearly on the time constant of the interfilament and interstrand coupling currents, such a direct relation between the loss generated by the BICCs and the average time constant (or characteristic time) of the BICCs is not present.
- Small random spatial variations in the contact resistances do usually not create large BICCs since most of the BICCs cancel.

3. EXPERIMENTAL EVIDENCE OF BICCs

The most convincing evidence of BICCs is the experiment where a 1.3 m long Rutherford-type cable is locally exposed to a dB/dt (at $z=0$) over a length of about $L_p/2$ ¹⁹. The sinusoidal field caused by the BICCs is measured all along the cable and decays from the maximum at $z=0$ to 0 at the cable ends (see Fig. 5).

Figure 5. Typical sinusoidal field pattern measured along a 1.3 m long cable locally subjected to a field change.

A similar experiment was performed by subjecting only a part of a coil (without transport current) to an external varying field²⁰. A field modulation appeared over the whole length of the coil. Locally the BICCs could be removed by a heater. Once the heater was again switched off, the BICCs would reappear in this region. This was explained by the diffusion from the adjacent unheated parts in which the BICCs persisted to flow also during the time that the small region was heated.

The decay on large current loops in superconducting cables has been measured on several samples of different length and with different contact resistance²¹. Currents were found to diffuse through the cable with time constant of the order of 10^2 - 10^3 s which increased with the square of the cable length.

4. INFLUENCE OF BICCs ON THE BEHAVIOUR OF MAGNETS

In each coil a number of spatial variations are present, each causing BICCs with their own magnitude and characteristic time. Even for a coil with completely transposed strands and uniform contact resistance BICCs will be generated during ramping due to space variation of dB/dt , inherent to the design of the magnet. The superposition of all these BICCs will affect the behaviour of a coil with respect to field distortions, additional losses (i.e. heat load) and reduced stability. Important is that this superposition can lead to an increase as well as a decrease of BICCs. Especially the effect of BICCs on the stability, which is a very local effect, can be very different for a series of identically built magnets and wound from the same conductor. Field distortions and additional losses, both effects which have a more global character, are believed to vary less for similar magnets. In the following subsections these three effects will be illustrated by means of measurements on accelerator magnets.

4A. Field errors

The BICCs, flowing through the strands over long lengths, create a sinusoidal field (present for all harmonic multipoles), with a period equal to the cable pitch^{17,22}. The regular pattern of BICCs, where adjacent strands in the cable have only slightly different current, is likely to cause more pronounced field errors in magnets than a random distribution of the transport current among the strands, due to e.g. different joint resistances.

Sinusoidal variations in the axial direction of the magnet have been observed for the first time in HERA magnets²³. Since the amplitude and the phase depend strongly on the actual and preceding excitation cycles but not on dB/dt and its direction, induction is not responsible for the field oscillation. The effect is therefore very likely to be related to a non-uniform distribution of the transport current among the strands and *not* to BICCs.

The axial field variation has been measured using Hall probes on a number of SSC dipole magnets wound from cables with different contact resistance²⁴. Magnets with very small contact resistance exhibited a large axial oscillation depending linearly on the field sweep rate, an effect which can be attributed to BICCs. The amplitude of the oscillation was found to be independent of the ramp rate for magnets having large contact resistance, and is probably related to the non-uniform transport current distribution.

Field measurements along the axis of LHC dipole magnets have as well shown the existence of BICCs. In Fig. 6 an example is given of one field harmonic measured over one twist pitch after the magnet has been ramped to 7.5 T with two different ramp rates¹⁷. The total field oscillation can again be seen as a superposition of two oscillations, one caused by BICCs and one due to a non-uniform distribution of the transport current. The field related to the BICCs depends linearly on the ramp rate and decays with a characteristic time of about 100 s. After a time much larger than 100 s the field pattern related to the BICCs has become almost zero and the remaining pattern, due to a non-uniform transport current, is constant and independent of the field-sweep rate.

Figure 6. Normal quadrupole measured in an LHC model dipole magnet after a ramp to 7.5 T with two different ramp rates.

A clear evidence of BICCs was also found in the axial decay of the amplitude of the oscillation in 10 m long LHC model dipoles²⁵. Large amplitudes were found near the coil ends, a typical place that causes large BICCs (see Table 1), decaying with time constants of about 100-300 s. After a field sweep the amplitude of the oscillation evolves to a baseline value which is approximately constant along the whole magnet length and changes slowly in with a time constant larger than 1000 s.

Sinusoidal field variations are probably not problematic, even for accelerator magnets with their tight field specifications, since the integral of such field over the magnet length is almost zero. However, the field inside the cable changes and can cause a significant variation in the persistent currents (and hence the magnetisation) at constant field, especially if the internal field changes are larger than the penetration field of the conductor. BICCs (and also a redistribution of the transport current) can therefore cause the so-called “snap back effect” observed in accelerator magnets²⁶.

BICCs can also be the cause of the frequently observed increasing field in NMR magnets run in persistent mode. The magnetic flux, related to the BICCs, represents an additional magnetic energy and induces an extra transport current during the decay of the BICCs⁵.

4B. Additional average loss

As already discussed in the previous section, the BICCs generate a coupling power, also in those areas of the conductor where $dB/dt=0$. This additional heat load has to be compensated for by the cryogenic system. Furthermore, important to note is that low-resistance connections in a coil (or between the lead and the cable) reduce the resistive loss, but increase at the same time the BICCs and the associated coupling loss. For coils in which the major part is subject to a field variation, the additional loss associated with BICCs is in general relatively small compared to the loss caused by the ISCCs.

4C. Decrease of magnet stability

The operating margin of a coil is reduced due to the additional BICCs which add to the transport current and due to a possible temperature increase caused by the local losses generated by the BICCs. Especially those parts of the cable having low contact resistance (like connections) should be cooled sufficiently. If the current in one strand of a cable locally exceeds the critical current, it becomes resistive and can either recover or cause the entire cable to quench. Which of the two will occur depends on many parameters, such as the cooling conditions and the speed of current redistribution.

Several convincing examples of a decrease in stability of coils at higher ramp rates exist, which can not only be explained by the loss produced by filament magnetisation, interfilament and interstrand coupling currents. Quench experiments on SSC dipole magnets showed that a number of magnets have a quench current that falls rapidly with increasing field sweep rate but then becomes almost constant (so called “type B” magnets)²⁷. This effect is explained by the existence of large current loops or BICCs with long time constants, due to very low local contact resistances, e.g. caused by cold welds between strands. Various special quench experiments were performed, showing that the quench current depends on the ramp cycle, an effect which could only be explained by the existence of large current loops with a time constant at least 1 or 2 orders of magnitude larger than that of the ISCCs.

Similar results are obtained on several LHC model magnets. One example is given in Fig. 7 where the quench current of two magnets is depicted vs. the ramp rate⁷. For each magnet the quench current is shown for a direct ramp to quench and a ramp which is preceded by a

ramp down at the same ramp rate (quench with precycle). The quench currents of the latter ones are larger because the BICCs generated during the ramp up have opposite sense than the BICCs during the ramp down and are therefore partially cancelled.

Ramp rate limitation phenomena, studied on cable-in-conduit conductors, were also explained by the existence of current loops or BICCs with time constants larger than 100 s passing through the low-resistance joints with the current leads^{28,29}. It is concluded that the surplus current caused by the BICC quenches a strand or subcable leading to a quench of the entire cable if the cooling is not sufficient and the adjacent strands are not able to take the current of the quenching strand.

Figure 7. Scaled quench current as a function of the ramp rate of two LHC dipole model magnets, for direct ramps to quench and ramps with a precycle.

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