20 T Hybrid Nb3Sn-HTS Block-coil Accelerator Dipole with Stress-Management

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20 T Hybrid Nb_3Sn-HTS Block-coil Accelerator Dipole with Stress-Management

E. Rochepault, P. Ferracin, G. Vallone

Abstract— **In the framework of studies for high energy particle colliders, design concepts for high field dipoles are being explored. In particular, relatively compact 20 T magnets can be achieved in a hybrid configuration, combining a High Temperature Superconductor (HTS) and a Low Temperature Superconductor (LTS). Preliminary concepts have been previously proposed using Bi2212 for the HTS and Nb_3Sn for the LTS. One of the main difficulties of 20 T magnets is the management of the very high stresses developing during operation. The design concepts rely on a rectangular block-coil layout, which offers the advantage of aligning the conductors with the main magnetic field, therefore submitting the conductors to a perpendicular electromagnetic force for a better control of the stresses. In addition, the layout allows a specific stress management, with adequate horizontal and vertical plates to intercept the stresses. The paper presents the improvements provided to the initial concept. In terms of magnetic design, the field quality has been improved, and a preliminary quench protection study has been included. In terms of mechanical design, the stress management has been optimized to provide a compact coil with a reduced peak stress on the HTS. Concepts for flared-end coils with joints in the coil-ends are finally presented.**

Index Terms—**High Field Magnet, Hybrid Magnet, HTS, Nb_3Sn, Magnetic Design.**

I. Introduction

HYBRID Nb_3Sn-HTS 20T magnet concepts are under study in order to provide inputs for the feasibility of high energy particle colliders, beyond the reach of full-Nb_3Sn magnets. This work requires conceptual studies to probe the viability of hybrid Nb_3Sn-HTS design concepts, considering many constraints: minimal use of the conductors, operational margins, stresses on the conductors, field quality, or quench protection. A dedicated working group is working on this topic, within the US-MDP program. A first set of preliminary designs such as the Cos-theta (CT), the Canted Cos-theta (CCT), the Stress Management Cos-theta (SMCT), the Block-type (BL) and the Common-Coil (CC) has been compared [Ferracin 22]. The next step is to push the concepts further and try to meet the main criteria required for an accelerator magnet. The work presented in this paper is focused on the Block-type (BL) design. A CT version [Marinozzi 23] and a CC version [Gupta 23] have also been proposed, and together with this BL version (see Fig. 1), are compared [Ferracin 23]. The previous design [Rochepault 22] will be reminded and the starting assumptions listed. Then the resulting updated magnetic design will be presented. The corresponding mechanical design will be described, followed by concepts for coil-ends and joints between coils.

II. Starting point of the design

A. Original Design

The design presented in [Rochepault 22] was made of Bi2212 (HTS) and Nb_3Sn (LTS) Rutherford cables, wound in double pancake coils. It generated a field of 20 T with 16 % margin on the load-line. The layout included vertical ribs between the HTS and the LTS within the coils to decouple the horizontal S_x stress, as well as a horizontal plate between the top and bottom coils, to decouple the horizontal S_y stress. The stress in the LTS was acceptable (160 MPa), but the stress in the HTS with higher than the target (139 MPa). The original design assumed two double-pancakes per pole to minimize the number of coils. The field, stress, and overall magnet parameters are detailed in [Rochepault 22].

B. Impact of iron

It has been shown, and this is verified for each design version, that the iron is not impacting much the parameters of an optimum design. For a set bore field of 20 T, the difference in

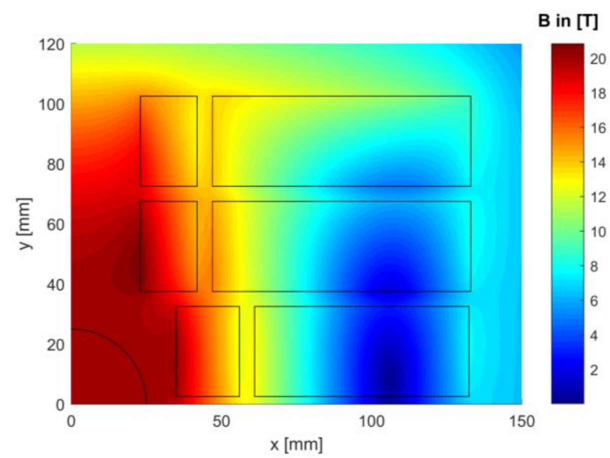

Fig. 1. Field map for the updated design, generating 20 T in the bore. Each block represents a double-layer pancake.

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peak fields with and without iron is within 0.2-0.3 T. The current to reach the same field is about 10 % lower, which corresponds to an additional margin of about 1%. The current being lower for the same field produced, the peak stress is slightly lower with iron. These observations are the same at short sample, the achieved bore field being almost the same with or without iron.

Therefore, the parametric analyses and the optimizations are done analytically [Rochepault 20], without iron, which allows very fast and accurate computations. At the final step of the optimization, the results are verified with iron, using a Finite Element Model (FEM).

C. *Updated assumptions*

This original design has been re-optimized taking into account the following assumptions [Ferracin 23]:

- No iron
- 20 T in the bore
- 15% margin in both HTS and LTS (on the load-line)
- Sx and Sy <120 MPa in HTS
- Sx and Sy <180 MPa in LTS
- 10 mm bore thickness
- 5 mm ribs between the HTS and LTS blocks
- 5 mm horizontal plate between top and bottom blocks
- Double layer pancakes
- Blocks aligned outside

These assumptions are considered realistic regarding past experience on fabrication and test of Nb_3Sn block-coil magnets [Ferracin 10, Marchevsky 14, Rochepault 19].

III. 2D Magnetic Design

A. *Parametric Analysis*

In order to explore a large parameter space, matrices are first automatically generated using 3 nested loops:

1. Grading factor (= J_{LTS} / J_{HTS}) ranging from 0.7 to 1.2.
2. Total area of conductor in one quadrant ranging from 7000 to 11000 mm^2.
3. Ratio A_{LTS}/A_{HTS} (boundary between HTS and LTS).

For each case, the current is varied to give exactly 20 T in the bore. The cases satisfying the criteria are then selected and compared.

An overall parametric analysis is then carried out, generating a 3-D matrix for each set of parameters. The following parameters are explored:

1. Block height from 30 to 60 mm.
2. Minimum radius x_{min} from 15 to 30 mm.
3. Mid-shim thickness from 0.25 to 2.5 mm.

Varying the block height allows finding more efficient designs (same target field with a lower amount of conductor), while overall decreasing the peak stresses (the blocks are narrower, therefore the stress accumulated in the x horizontal direction is lower). Varying the grading factor allows adapting the load-lines and equilibrating the margins for a higher efficiency. Table I illustrates a selection of cases for several block heights, with a resulting grading between 0.8 and 1.1, quadrant areas around 8000-9000 mm^2, peak stresses between 110 and 121 MPa in the HTS, and between 124 and 176 MPa in the LTS.

TABLE I
SELECTION OF CASES WITHOUT THE FIELD QUALITY CONSTRAINT, WHEN VARYING THE BLOCK HEIGHT.

Block height	Grad.	Area	Margin HTS	Margin LTS	Sx peak HTS	Sx peak LTS
[mm]		[mm^2]	[%]	[%]	[MPa]	[MPa]
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Assuming x_{min} = 23 mm and mid-shim = 0.25 mm.

B. *Optimization of the Field Quality*

To be representative of accelerator dipoles, the harmonics must be within +/- 3 units [Ferracin 23]. Varying the block height to tune the field quality is not sufficient. The cases listed above produce a b_3 harmonic between 30 and 80 units. A further

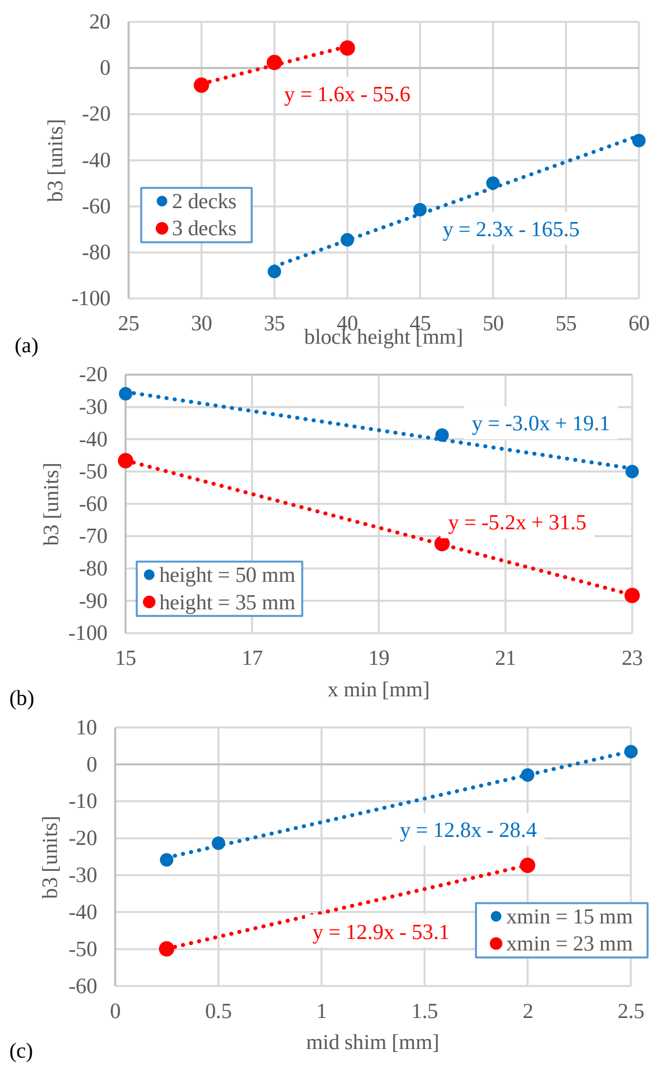

Fig. 2. Parametric analysis to explore the field quality, illustration with b_3. (a) Variation of the block height for different number of coil decks, with x_{min} = 23 mm and mid-shim = 0.25 mm. (b) Variation of x_{min} for different block heights, with mid-shim = 0.25 mm. (c) Variation of the mid-shim for different x_{min}, with block height = 50 mm.

optimization is then required, changing the minimum radius x_{min} and the mid-shim thickness. These parameters allow tuning the b_3, as shown in Fig. 2. However, $b_3 = 0$ can only be achieved with 3 decks (see Fig. 1) instead of 2. By selecting with the above mentioned criteria among all the generated solutions, a satisfying solution is found. The field computed analytically without iron gives 14.5 % margin on the load-line at 20 T, the stress is 122 MPa in the LTS and 145 MPa in the HTS.

C. *Verification with a FEM*

The solution found analytically is then implemented in the FEM to confirm the validity of the results. Iron pads and an iron yoke are placed around the coils, as shown in Fig. 3. The stress with iron is first obtained using the FEM and considering rigid boundaries (0 displacement) around the coil. Table III compares the different harmonics computed. The results are very similar between the analytic model and the FEM: the difference may be attributed to the numerical errors of the FEM. In addition, there is an impact of the presence of iron on the b_3 of +5 units to be taken into account. If necessary, the field quality can be further improved easily by tuning the mid-plane shim thickness or the inner position of the blocks (x_{min}), as suggested by Fig. 2. In addition, we verify that the stress computed with the FEM is very close to the stress computed analytically. The corresponding conductors are described in Table III. The parameters and load-lines are shown in Table IV and Fig. 4.

TABLE II
COMPARISON OF HARMONICS OBTAINED AT NOMINAL CURRENT IN DIFFERENT CONDITIONS.

		Matlab Analytical Without iron	Ansys FEM Without iron	Ansys FEM With iron
Bore field	T	18.64	18.62	20.01
b3	unit	2.31	2.28	7.43
b5	unit	-0.546	-0.549	-0.605
b7	unit	0.373	0.395	0.382
b9	unit	0.168	0.150	0.132

TABLE III
CONDUCTOR PARAMETERS.

Parameter	Unit	HTS	Nb_3Sn
Number of strands		28	24
Cu:Sc		1.2	1.15
Thickness compaction		0.9	0.9
Width compaction		1.05	1.08
Insulated Thickness	mm	2.10	2.33
Insulated Width	mm	15.00	15.00
insulation	mm	0.15	0.15
J_0/J_{SC}		0.317	0.320
J_0/J_E		0.698	0.688

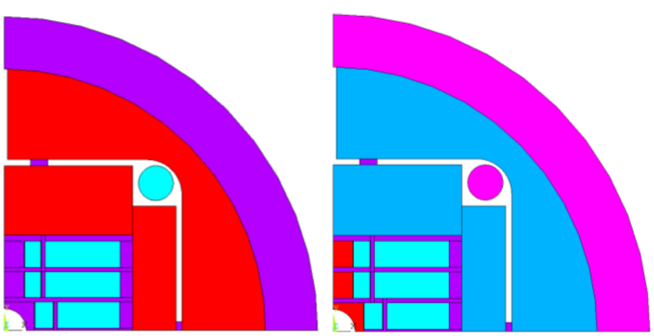

Fig. 3. 2D magnetic (left) and mechanical (right) FEM.

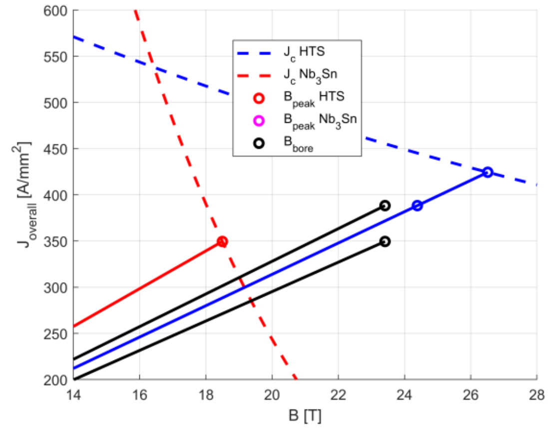

Fig. 4. Load-lines for the design optimized for field quality.

TABLE IV
MAGNET PARAMETERS COMPUTED USING THE FEM WITH IRON AND RIGID BOUNDARIES

	Hybrid		HTS only	LTS only
	20T	SS	SS	SS
Area [A/mm^2]	9100	9100	1760	7340
B0 total HTS+LTS [T]	20.0 5.7+14.3	23.4 9.1+14.3	10.8	17.2
Bp HTS [T]	20.8	24.4	12.55	-
Bp LTS [T]	15.9	18.5	-	18.63
J HTS [A/mm^2]	328.1	388.3	616.6	0
J LTS [A/mm^2]	295.3	349.5	0	340.0
Current [A]	10336	12232	19425	11899
Margin HTS [%]	24.7	10.8	0.0	-
Margin LTS [%]	15.5	0.0	-	0.0
Sx HTS [MPa]	115.3	159.3		
Sx LTS [MPa]	146.6	203.0		
Sy [MPa]	69.8	96.5		

IV. 2D MECHANICAL DESIGN

A. *Layout*

In order to explore further the concept of stress management, all the components in contact with the coil are freed (deformation taking into account real material properties), and the external structural components are kept rigid (fixed nodes). The layout is shown on Fig. 5. The main goal of this layout is to

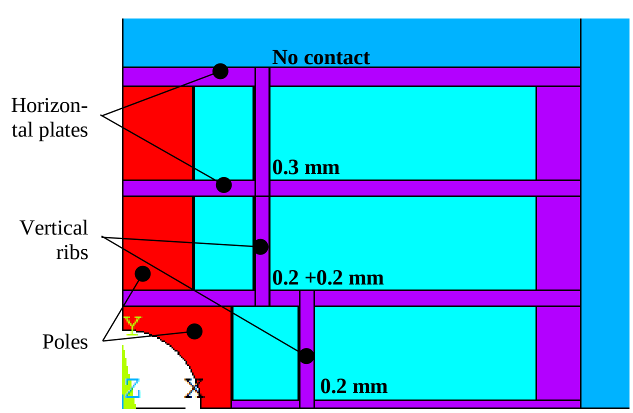

Fig. 5. View of the coil and inner components. The various clearances between the ribs and the horizontal plates are indicated locally.

decouple the horizontal stress S_x between the HTS block and the LTS blocks, by transferring as much force as possible from the HTS block to the inner structure. This stress management relies on the following inner components:

- Ti poles: The HTS coil blocks can slide with friction and are free to separate with respect to the poles.
- Stainless steel vertical ribs: coil blocks can slide with friction and are free to separate on both sides. The ribs are leaning against the horizontal plates, so the Lorentz forces are transmitted from the HTS blocks to these plates. The ribs can slide with friction and are free to separate on both sides.
- Stainless steel horizontal plates: the Lorentz forces are transmitted to the external structure via these plates. They can slide with friction and are free to separate on top and bottom.

The friction coefficient is 0.2, and all other contacts between components are sliding with friction and separation allowed.

B. *Exploration of different scenarios*

Several layout and contacts scenarios have been compared, with the objective to maintain the stress levels in the coils below the allowed limits. First, the coil blocks have been positioned vertically to place 5 mm-thick horizontal plates between all the coils (see Fig. 5). This allows decreasing significantly the bending of the ribs, therefore decreasing the peak stresses in the corner of the coil blocks from about 700 MPa to about 400 MPa. In addition, the contacts between the components, initially bonded (with standard contacts between the coils and the components), were set to standard, which also help decreasing the peak stress from about 400 MPa to 300 MPa. Finally, in order to further reduce the bending of the ribs, some clearances are introduced between the ribs and the horizontal plates (see values in Fig. 5), so the plates will firstly push slightly on the LTS coil blocks before bending, and secondly enter in contact with the horizontal plates to transmit a large part of the Lorentz forces. The resulting stresses are shown in Fig. 6. The horizontal stress S_x is below 120 MPa everywhere in the HTS, except for a very localized peak at 140 MPa in a corner, and below 180 MPa everywhere in the LTS. The vertical stress S_y is below 90 MPa, with a localized peak at 100 MPa. These stresses are overall close to the estimates considering rigid boundaries (see Table III). Regading the LTS blocks, since part of the Lorentz forces are first transmitted by the ribs, the stress on the inner turms is around 100 MPa, and increase to 180 MPa, instead of being around 150 MPa in a totally decoupled situation.

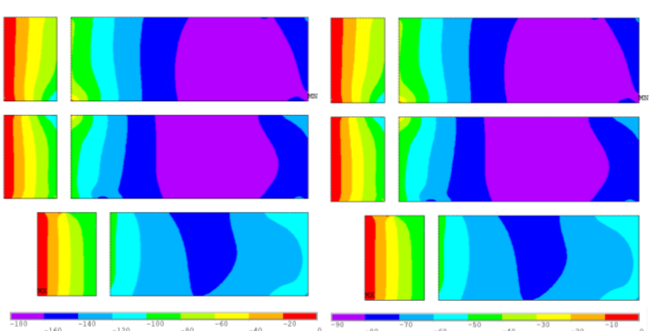

Fig. 6. Horizontal stress S_x (left), and vertical stress S_y (right) in the coils at nominal current (20 T in the bore).

V. 3D Design considerations

A. *Double Pancakes with Layer Jumps*

Following the experience on past coil-block dipoles [Ferracin 10, Marchevsky 14, Rochepault 19], the coils will be made of double-pancakes, with layer jumps on the inner turn. The HTS layer jumps will be in the poles, and the LTS layer jumps in the vertical ribs. The thickness of the pole (10 mm), and the ribs (5 mm), should allow enough space for these jumps. The flared-end areas may be used to reduce the length of the jump, taking advantage of the hard-way bending.

B. *External and Internal Joints Options*

Joints between the HTS and the LTS cables will be necessary. Two options are considered for the joints. The nominal option is to make external joints, as depicted in Fig. 7. The concept relies first on the space between the HTS and the LTS coils, to allow an easy-way bending of the inner exit, and on a hard-way bending to guide the exit below the LTS coil. The exits will then be supported between pancakes by wedges. This should also allow decoupling the HTS and LTS coil components for a separate fabrication. The LTS coils are then assembled on top of the HTS coils, and the joints are made externally. This is the approach developed for the R2D2 [Rochepault 22b] and F2D2 [Rochepault 20] magnets.

An alternative option is to perform the HTS-LTS joints inside the pancakes. This method is in principle more compact, but also more complex because the joint is curved, with a more difficult access, and has to perform at high field.

VI. Conclusion

A hybrid dipole conceptual design has been proposed, producing 20 T in the bore with a block-coil layout and using HTS-Bi2212 and LTS-Nb_3Sn conductors. This design meets realistic criteria such as a margin of at least 15 % on the load-lines, 120 MPa maximum stress in the HTS and 180 MPa in the LTS, and a field quality of the order of a few units. External joints are considered as the nominal option, and the concepts are already being developed for Nb_3Sn.

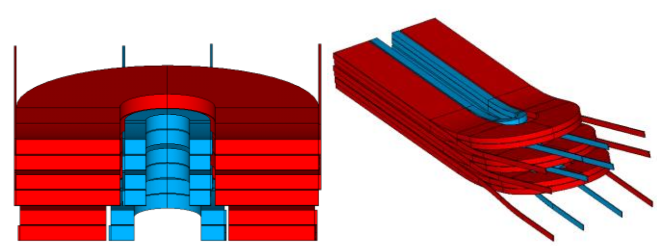

Fig. 7. 3D schematics of the coil-ends layout, showing the paths for the cable exits. The HTS coils are in blue, and the LTS in red.

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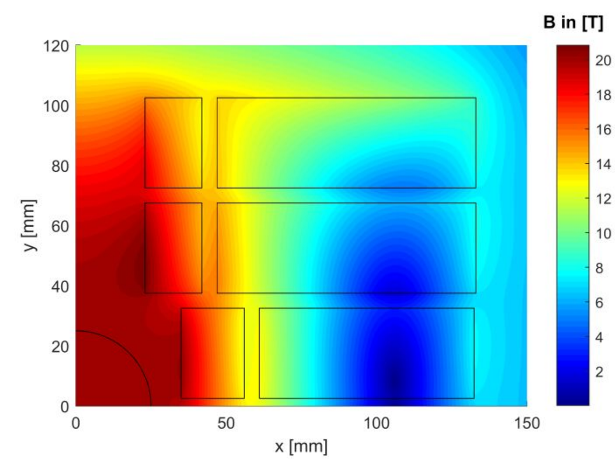

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To be representative of accelerator dipoles, the harmonics must be within +/- 3 units [Ferracin 23]. Varying the block height to tune the field quality is not sufficient. The cases listed above produce a b_3 harmonic between 30 and 80 units. A further

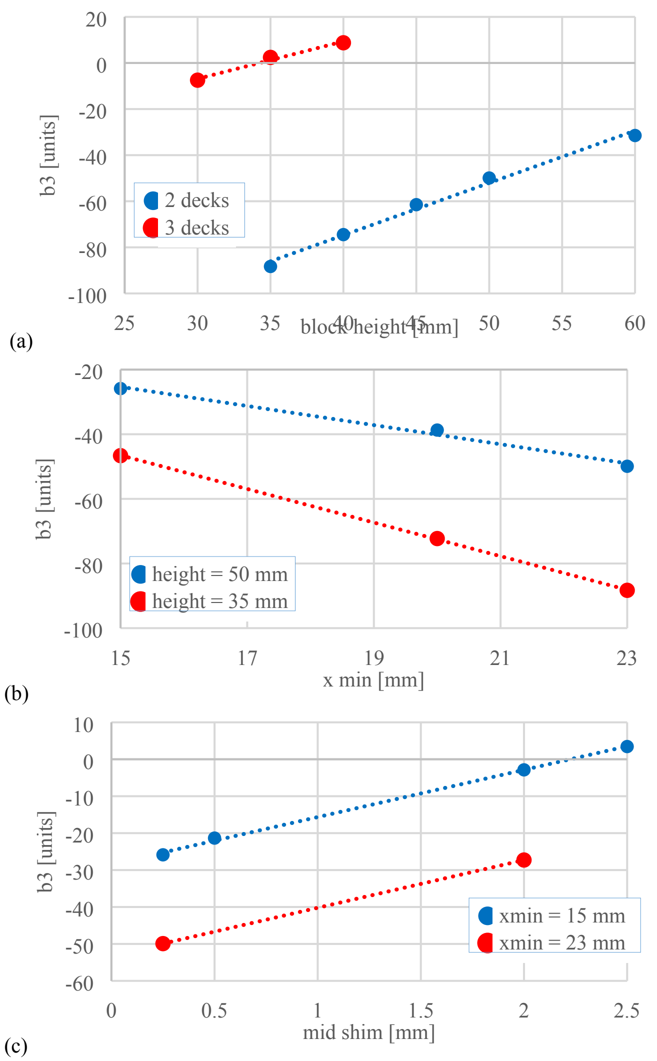

Fig. 2. Parametric analysis to explore the field quality, illustration with b_3. (a) Variation of the block height for different number of coil decks, with x_{min} = 23 mm and mid-shim = 0.25 mm. (b) Variation of x_{min} for different block heights, with mid-shim = 0.25 mm. (c) Variation of the mid-shim for different x_{min}, with block height = 50 mm.

optimization is then required, changing the minimum radius x_{min} and the mid-shim thickness. These parameters allow tuning the b_3, as shown in Fig. 2. However, $b_3 = 0$ can only be achieved with 3 decks (see Fig. 1) instead of 2. By selecting with the above mentioned criteria among all the generated solutions, a satisfying solution is found. The field computed analytically without iron gives 14.5 % margin on the load-line at 20 T, the stress is 122 MPa in the LTS and 145 MPa in the HTS.

C. *Verification with a FEM*

The solution found analytically is then implemented in the FEM to confirm the validity of the results. Iron pads and an iron yoke are placed around the coils, as shown in Fig. 3. The stress with iron is first obtained using the FEM and considering rigid boundaries (0 displacement) around the coil. Table III compares the different harmonics computed. The results are very similar between the analytic model and the FEM: the difference may be attributed to the numerical errors of the FEM. In addition, there is an impact of the presence of iron on the b_3 of +5 units to be taken into account. If necessary, the field quality can be further improved easily by tuning the mid-plane shim thickness or the inner position of the blocks (x_{min}), as suggested by Fig. 2. In addition, we verify that the stress computed with the FEM is very close to the stress computed analytically. The corresponding conductors are described in Table III. The parameters and load-lines are shown in Table IV and Fig. 4.

TABLE II
COMPARISON OF HARMONICS OBTAINED AT NOMINAL CURRENT IN DIFFERENT CONDITIONS.

		Matlab Analytical Without iron	Ansys FEM Without iron	Ansys FEM With iron
Bore field	T	18.64	18.62	20.01
b3	unit	2.31	2.28	7.43
b5	unit	-0.546	-0.549	-0.605
b7	unit	0.373	0.395	0.382
b9	unit	0.168	0.150	0.132

TABLE III
CONDUCTOR PARAMETERS.

Parameter	Unit	HTS	Nb_3Sn
Number of strands		28	24
Cu:Sc		1.2	1.15
Thickness compaction		0.9	0.9
Width compaction		1.05	1.08
Insulated Thickness	mm	2.10	2.33
Insulated Width	mm	15.00	15.00
insulation	mm	0.15	0.15
J_0/J_{SC}		0.317	0.320
J_0/J_E		0.698	0.688

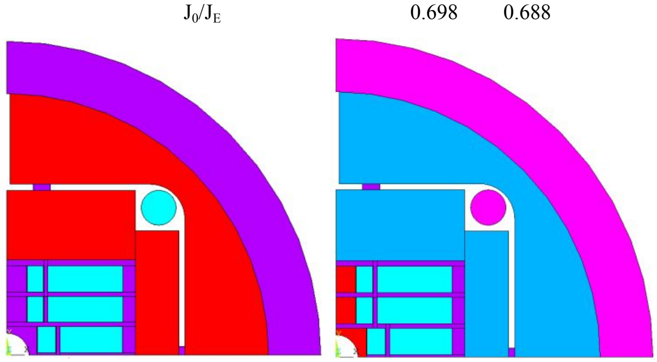

Fig. 3. 2D magnetic (left) and mechanical (right) FEM.

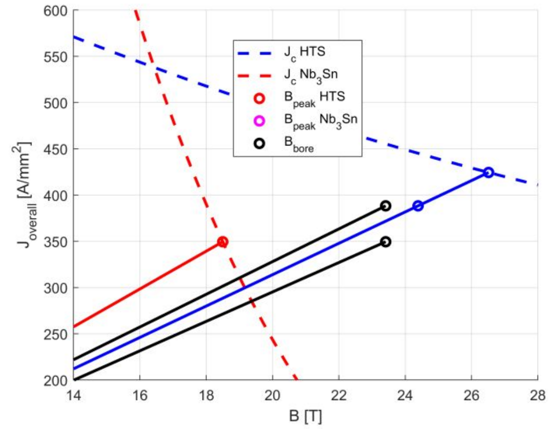

Fig. 4. Load-lines for the design optimized for field quality.

TABLE IV
MAGNET PARAMETERS COMPUTED USING THE FEM WITH IRON AND RIGID BOUNDARIES

	Hybrid		HTS only	LTS only
	20T	SS	SS	SS
Area [A/mm²]	9100	9100	1760	7340
B0 total HTS+LTS [T]	20.0 5.7+14.3	23.4 9.1+14.3	10.8	17.2
Bp HTS [T]	20.8	24.4	12.55	-
Bp LTS [T]	15.9	18.5	-	18.63
J HTS [A/mm²]	328.1	388.3	616.6	0
J LTS [A/mm²]	295.3	349.5	0	340.0
Current [A]	10336	12232	19425	11899
Margin HTS [%]	24.7	10.8	0.0	-
Margin LTS [%]	15.5	0.0	-	0.0
Sx HTS [MPa]	115.3	159.3		
Sx LTS [MPa]	146.6	203.0		
Sy [MPa]	69.8	96.5		

IV. 2D MECHANICAL DESIGN

A. *Layout*

In order to explore further the concept of stress management, all the components in contact with the coil are freed (deformation taking into account real material properties), and the external structural components are kept rigid (fixed nodes). The layout is shown on Fig. 5. The main goal of this layout is

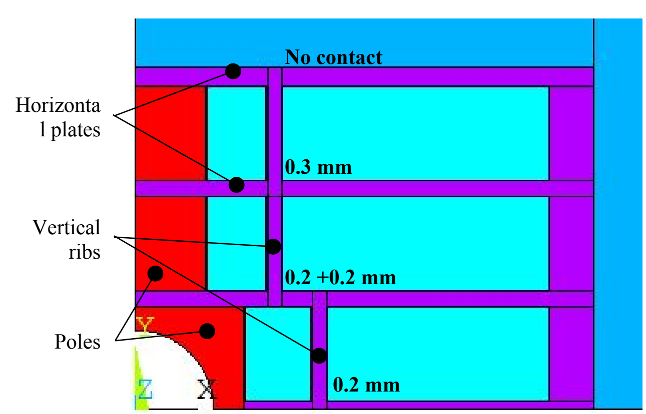

Fig. 5. View of the coil and inner components. The various clearances between the ribs and the horizontal plates are indicated locally.

to decouple the horizontal stress S_x between the HTS block and the LTS blocks, by transferring as much force as possible from the HTS block to the inner structure. This stress management relies on the following inner components:

- Ti poles: The HTS coil blocks can slide with friction and are free to separate with respect to the poles.
- Stainless steel vertical ribs: coil blocks can slide with friction and are free to separate on both sides. The ribs are leaning against the horizontal plates, so the Lorentz forces are transmitted from the HTS blocks to these plates. The ribs can slide with friction and are free to separate on both sides.
- Stainless steel horizontal plates: the Lorentz forces are transmitted to the external structure via these plates. They can slide with friction and are free to separate on top and bottom.

The friction coefficient is 0.2, and all other contacts between components are sliding with friction and separation allowed.

B. *Exploration of different scenarios*

Several layout and contacts scenarios have been compared, with the objective to maintain the stress levels in the coils below the allowed limits. First, the coil blocks have been positioned vertically to place 5 mm-thick horizontal plates between all the coils (see Fig. 5). This allows decreasing significantly the bending of the ribs, therefore decreasing the peak stresses in the corner of the coil blocks from about 700 MPa to about 400 MPa. In addition, the contacts between the components, initially bonded (with standard contacts between the coils and the components), were set to standard, which also help decreasing the peak stress from about 400 MPa to 300 MPa. Finally, in order to further reduce the bending of the ribs, some clearances are introduced between the ribs and the horizontal plates (see values in Fig. 5), so the plates will firstly push slightly on the LTS coil blocks before bending, and secondly enter in contact with the horizontal plates to transmit a large part of the Lorentz forces. The resulting stresses are shown in Fig. 6. The horizontal stress S_x is below 120 MPa everywhere in the HTS, except for a very localized peak at 140 MPa in a corner, and below 180 MPa everywhere in the LTS. The vertical stress S_y is below 90 MPa, with a localized peak at 100 MPa. These stresses are overall close to the estimates considering rigid boundaries (see Table III). Regading the LTS blocks, since part of the Lorentz forces are first transmitted by the ribs, the stress on the inner turns is around 100 MPa, and increase to 180 MPa, instead of being around 150 MPa in a totally decoupled situation.

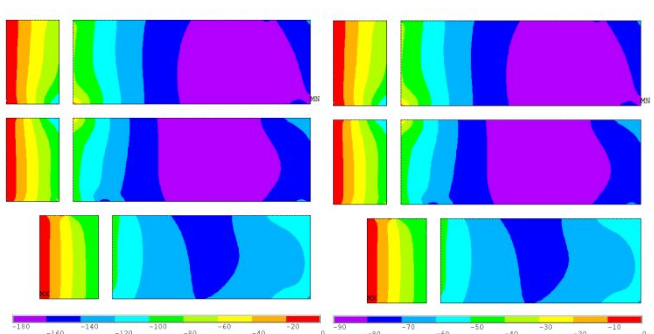

Fig. 6. Horizontal stress S_x (left), and vertical stress S_y (right) in the coils at nominal current (20 T in the bore).

V. 3D Design considerations

A. *Double Pancakes with Layer Jumps*

Following the experience on past coil-block dipoles [Ferracin 10, Marchevsky 14, Rochepault 19], the coils will be made of double-pancakes, with layer jumps on the inner turn. The HTS layer jumps will be in the poles, and the LTS layer jumps in the vertical ribs. The thickness of the pole (10 mm), and the ribs (5 mm), should allow enough space for these jumps. The flared-end areas may be used to reduce the length of the jump, taking advantage of the hard-way bending.

B. *External and Internal Joints Options*

Joints between the HTS and the LTS cables will be necessary. Two options are considered for the joints. The nominal option is to make external joints, as depicted in Fig. 7. The concept relies first on the space between the HTS and the LTS coils, to allow an easy-way bending of the inner exit, and on a hard-way bending to guide the exit below the LTS coil. The exits will then be supported between pancakes by wedges. This should also allow decoupling the HTS and LTS coil components for a separate fabrication. The LTS coils are then assembled on top of the HTS coils, and the joints are made externally. This is the approach developed for the R2D2 [Rochepault 22b] and F2D2 [Rochepault 20] magnets.

An alternative option is to perform the HTS-LTS joints inside the pancakes. This method is in principle more compact, but also more complex because the joint is curved, with a more difficult access, and has to perform at high field.

VI. Conclusion

A hybrid dipole conceptual design has been proposed, producing 20 T in the bore with a block-coil layout and using HTS-Bi2212 and LTS-Nb_3Sn conductors. This design meets realistic criteria such as a margin of at least 15 % on the load-lines, 120 MPa maximum stress in the HTS and 180 MPa in the LTS, and a field quality of the order of a few units. External joints are considered as the nominal option, and the concepts are already being developed for Nb_3Sn.

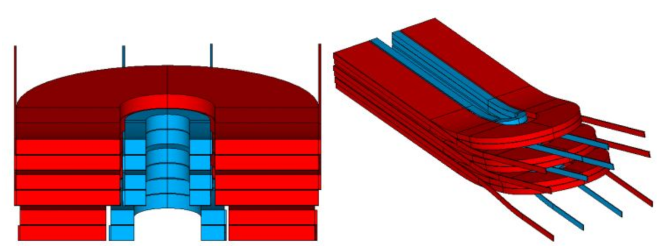

Fig. 7. 3D schematics of the coil-ends layout, showing the paths for the cable exits. The HTS coils are in blue, and the LTS in red.

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