CONCEPTUAL DESIGN OF 20 T DIPOLES FOR HIGHER ENERGY LHC

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Acknowledgements: B. Auchmann, F. Borgnolutti, L. Bottura, A. Milanese

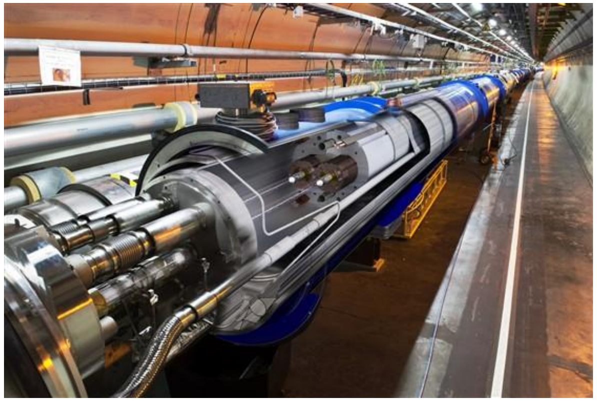
This is an update of the work presented in

R. Assmann, R. Bailey, O. Bruning, O. Dominguez Sanchez, G. De Rijk, M. Jimenez, S. Myers, L. Rossi, L. Tavian, E. Todesco, F. Zimmermann « First thoughts on a Higher Energy LHC » CERN ATS-2010-177

MAIN CONSTRAINTS

- Design is driven by
  - Transverse space in the tunnel → transverse size of the magnet
    - 570 mm diameter for the cold mass in the LHC
    - We assume 800 mm diameter for the HE-LHC
    - Coil must be reasonably compact
  - Cost
    - Magnet has to rely on Nb_3Sn and on HTS
    - Cost of Nb_3Sn: 4 times Nb-Ti
    - Cost of HTS: 4 times Nb_3Sn

      → grading of material is necessary
  - Margin
    - We ask to work at 80% from critical surface, i.e., we have to design a magnet for 25 T



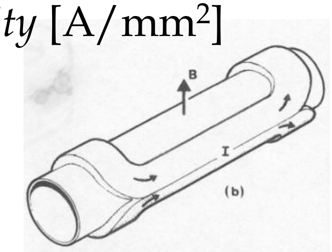
24 T dipole for LHC tripler proposed in [P. McIntyre, A. Sattarov, PAC 2005, 634]

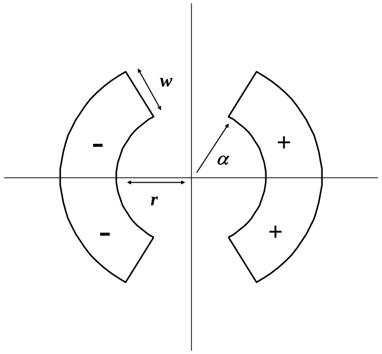
Coil layout – first order

- Field is proportional to current density and coil thickness

B [T] ~ *0.0007* × *coil width* [mm] × *current density* [A/mm^2]

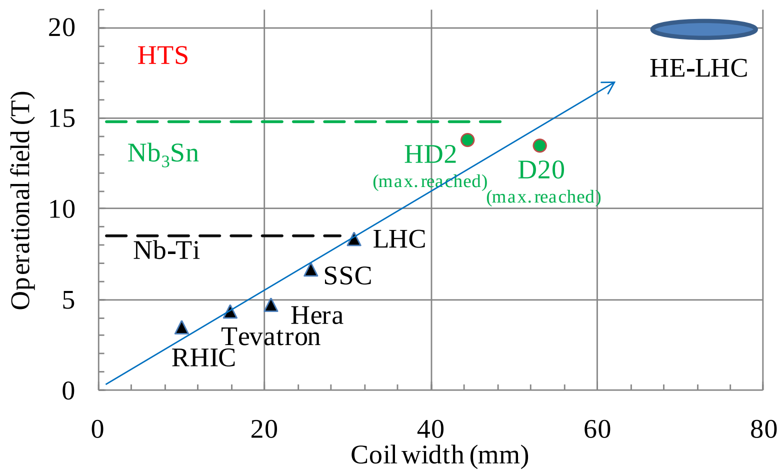
LHC: 8 [T]~ 0.0007 × 30 × 380





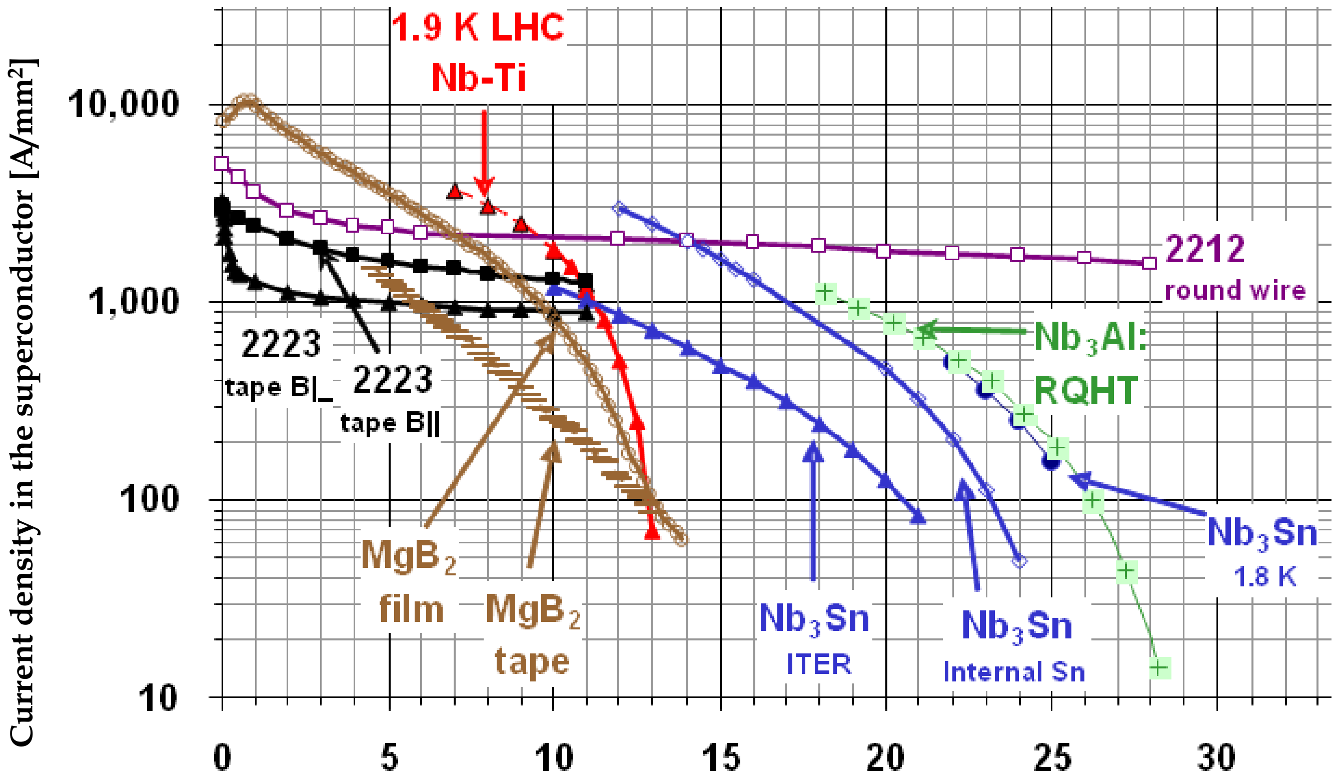
- Accelerators used current density of the order of 350–400 A/mm^2
  - This provides ~2.5 T for 10 mm thickness
  - 80 mm needed for reaching 20 T

- Grading the material:
  - 30 mm of Nb-Ti to get 7.5 T
  - 30 mm of Nb_3Sn to get another 7.5 T
  - 20 mm of HTS to get the last 5 T



Operational field versus coil width in accelerator magnets

PROPERTIES OF SUPERCONDUCTORS



<8 T: Nb-Ti

<15 T: Nb_3Sn

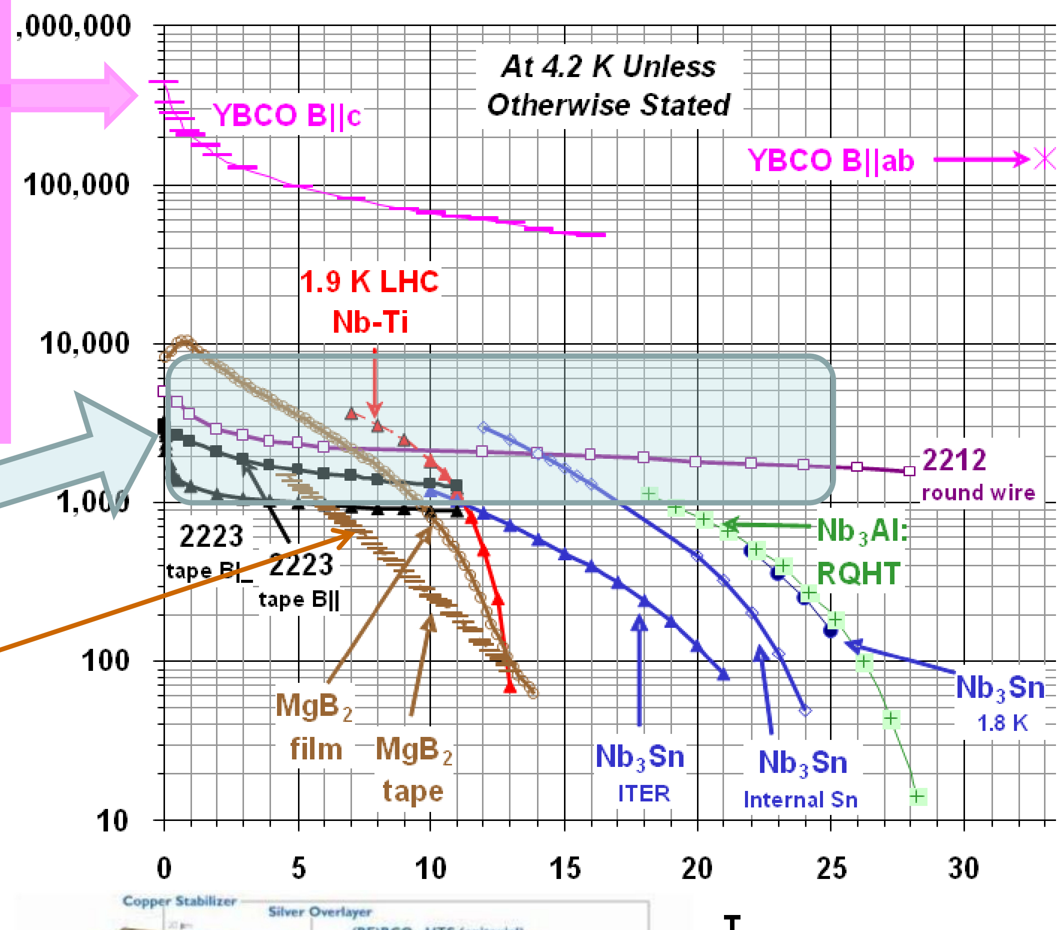
>15 T: HTS

Critical current in practical superconductors [courtesy of P. Lee]

Delimiting the hunting territory above 15 T

YBCO: it is the big hope, much potential but:
stellar price,
filling factor still far from satisfactory,
no round wire, only tape, no big cable

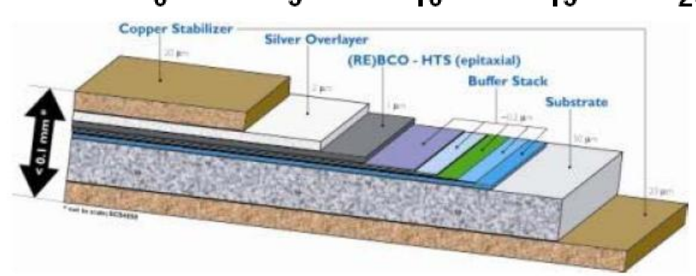
make this material not suitable for our magnets (for the moment…).



Region of interest is where
$J_c > 1000$ A/mm^2

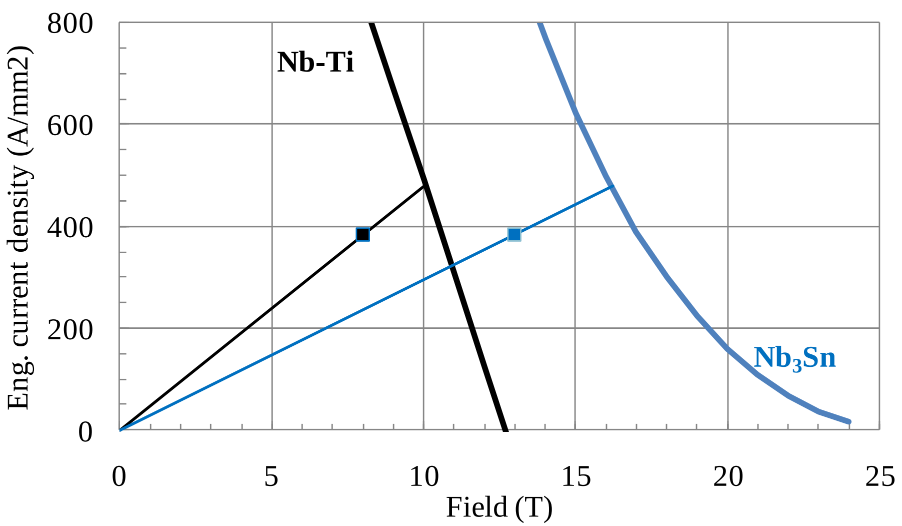
Forget MgB_2 (for 3-5 years)

Best candidate is Bi-2212



Guidelines for the coil

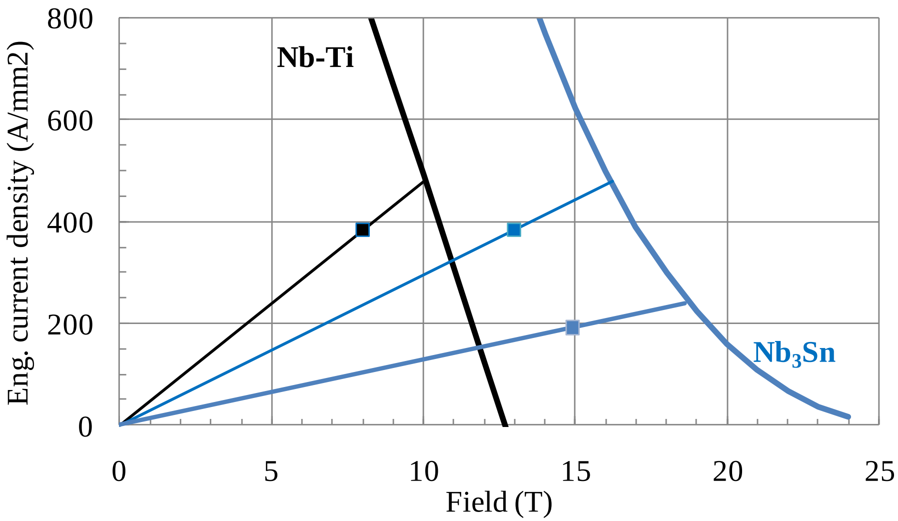
- What material can tolerate 380 A/mm^2 and at what field ?
  - We assume 1/3 of superconductor in the insulated coil
  - For Nb-Ti: LHC performances
  - For Nb_3Sn: 1500 A/mm^2 at 15 T, 4.2 K
- With 20% margin:
  - Nb-Ti up to 8 T, Nb_3Sn up to 13 T (at 1.9 K operational temperature)



Engineering current density versus field for Nb-Ti and Nb_3Sn (lines) and operational current (markers)

GUIDELINES FOR THE COIL

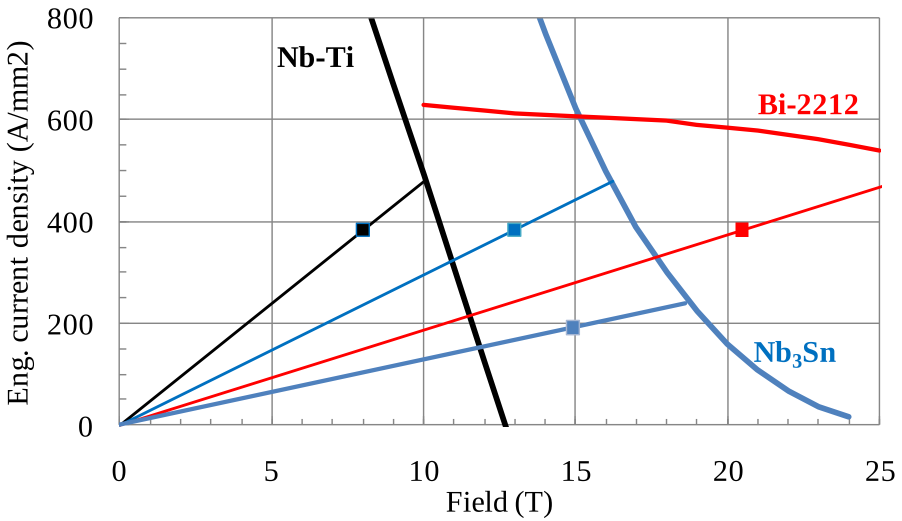
- Ultimate limit of Nb_3Sn
  - To get to ~18.5 T short sample, i.e. 15 T operational we must reduce the current density by 50% → less effective zone (10 mm thickness of coil give 1.2 T instead than 2.5 T) – but we got to 15 T!
  - Further optimization of current density around 20 T ?



Engineering current density versus field for Nb-Ti and Nb_3Sn (lines) and operational current (markers)

Guidelines for the coil

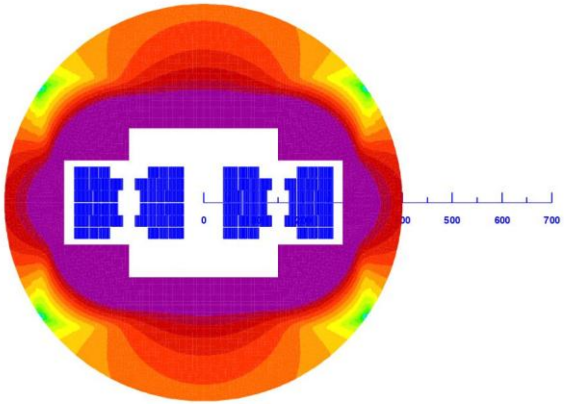
- The last 5 T
  - The last 5 T are given by HTS, whose critical field weakly depends on the current density
  - We ask for having ~400 A/mm^2
    - Today in Bi-2212 we have half, i.e., ~200 A/mm^2



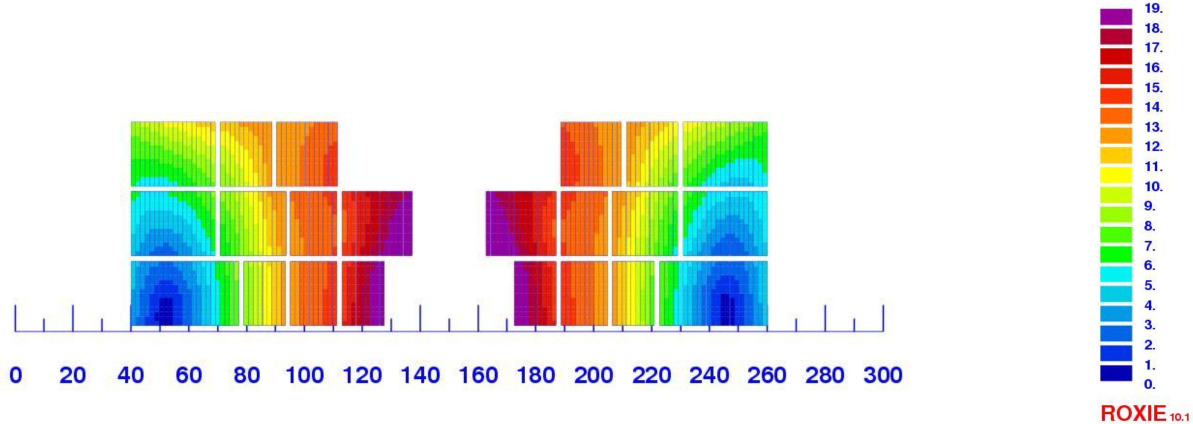
Engineering current density versus field for Nb-Ti and Nb_3Sn and HTS (lines) and operational current (markers)

THE COIL

- Two in one geometry, with iron
  - Operational current: 13.8 kA
  - Engineering current density: 380 A/mm^2 (190 A/mm^2 in low-j Nb_3Sn)
  - Peak field/central field 1.03
    - Very good ratio, favoured by the large coil
  - Distance between beams: 300 mm
    - Cannot be too short, otherwise cross-talk between aperture and higher peak field



Sketch of the double aperture magnet with the iron yoke – Coils are in blue

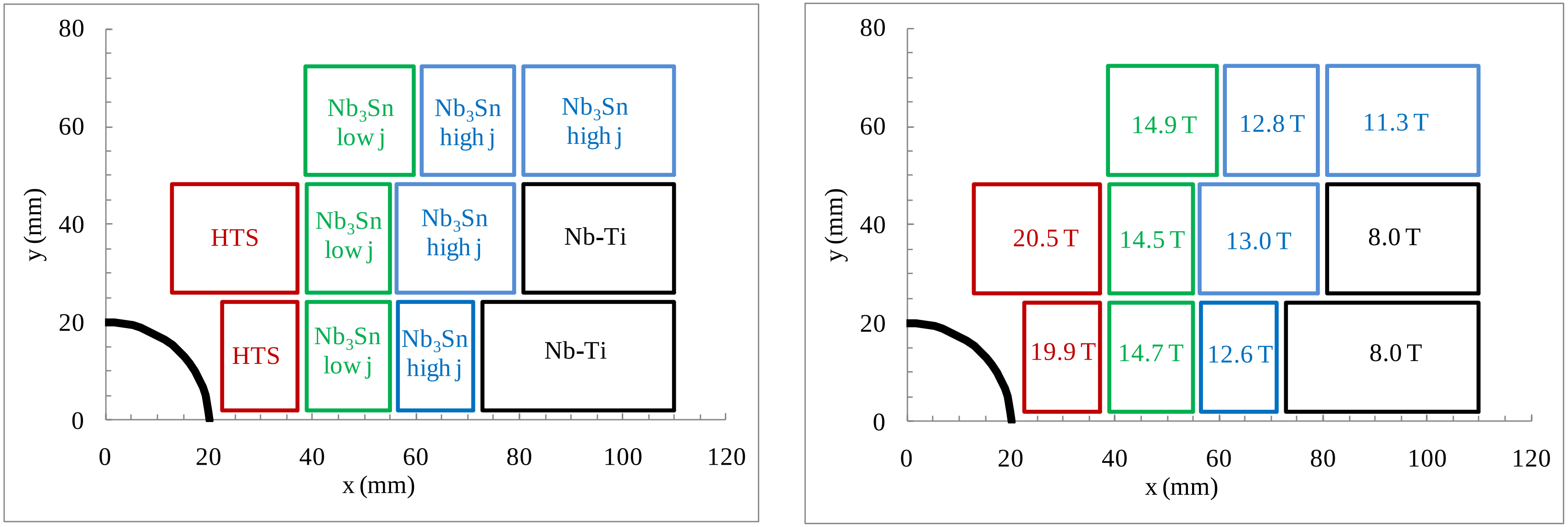


Field in the coil (one pole shown) at 20 T operational field

The coil

- Cable: 22 mm width, 1.62 mm thick, 0.8 mm strand (LBL HD2)
- Three layers are needed for field quality
  - 8 T → Nb-Ti (380 A/mm^2)
  - 13 T → Nb_3Sn (380 A/mm^2)
  - 15 T → Nb_3Sn (190 A/mm^2)
  - 20 T → HTS (380 A/mm^2)

	N. turns	%
Nb-Ti	41	27%
Nb_3Sn	85	57%
HTS	24	16%
Total	150	

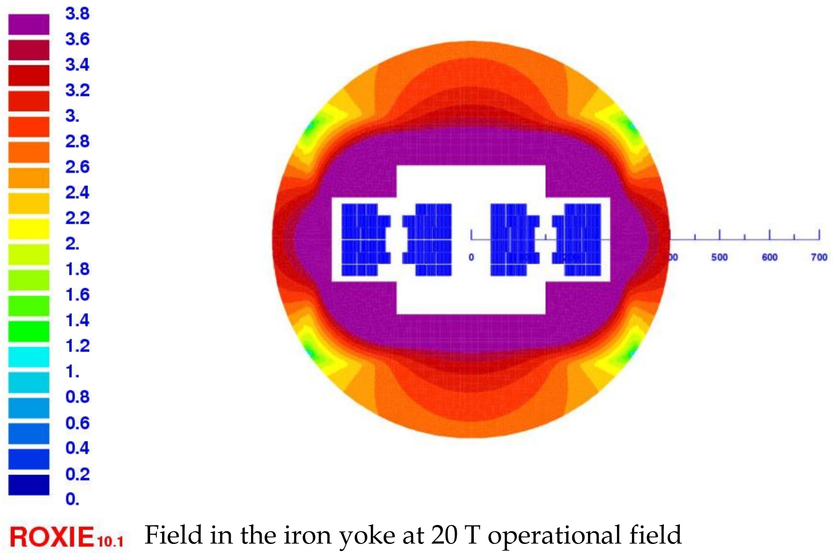


Materials used in the coil (one quarter shown)

Field in the coil at 20 T operational field (one quarter shown)

THE IRON

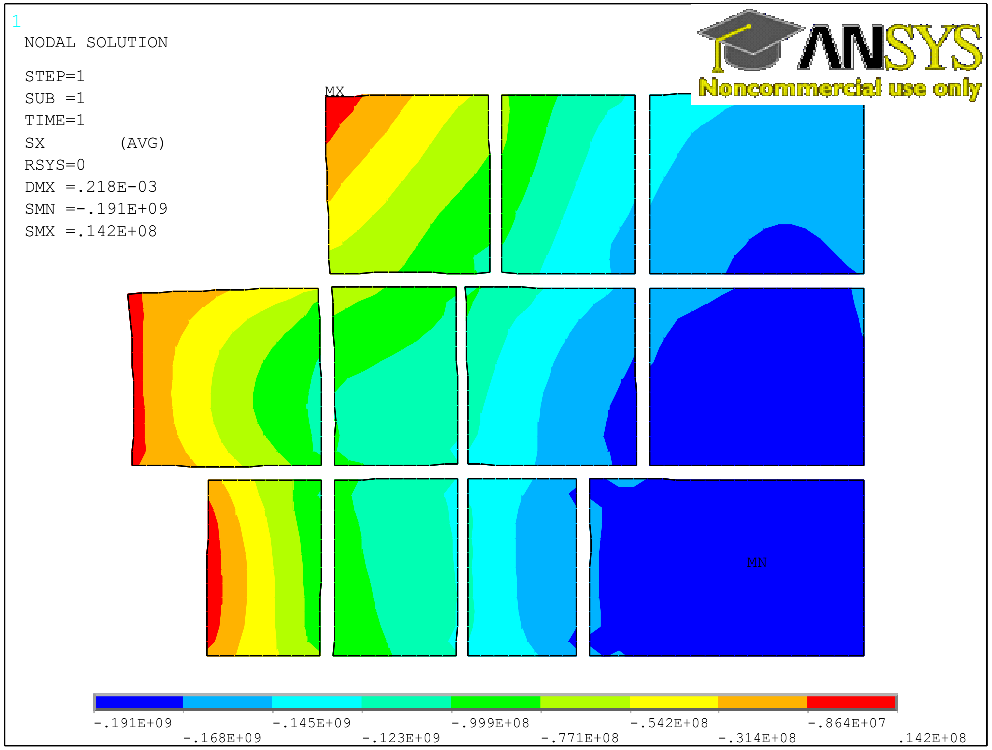
- We assume 800 mm diameter
  - Iron is highly saturated – field at 200 mm from the magnet (i.e. on the cryostat) is 0.05 T
  - Too much? Active shielding?

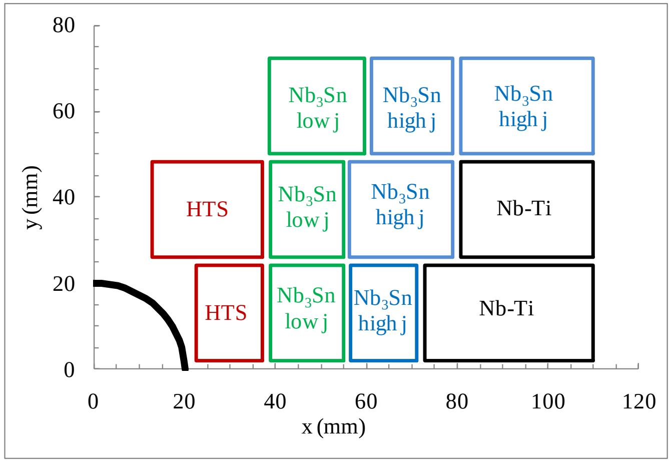


Field in the iron yoke at 20 T operational field

The stress: a good surprise

- Preliminary analysis (no structure, everything is glued)
  - 190 MPa in the Nb-Ti, 120-170 MPa in Nb_3Sn, less in HTS
  - Below the Nb_3Sn limit for degradation (200 MPa) !!
  - Block design allows putting higher stress in lower field region





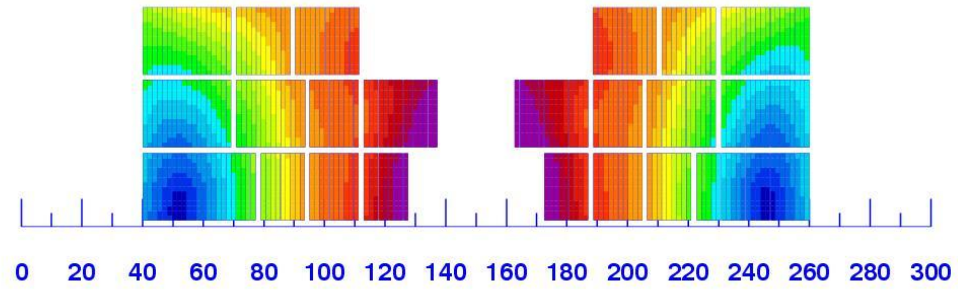
Horizontal stress in the coil at 20 T operational field [from A. Milanese]

FIELD QUALITY

- Field quality is related to ratio coil thickness/aperture
  - Examples

	Coil width (mm)	Aperture radius (mm)	Ratio w/r (adim)
RHIC	10	40	0.25
LHC	31	28	1.11
HE-LHC	82	20	4.08

  - The larger this ratio, the easier the field quality
    - a lot of coil contributing to main field ‘far’ from the aperture → smaller high order multipoles
  - Infact we manage to have all multipoles smaller than 2 units (Rref=13.3 mm) without any wedges!



  - Persistent currents at injection to be checked

COST

- Estimate:
  - Nb_3Sn 4 times more expensive than Nb-Ti
  - HTS 4 times more expensive than Nb_3Sn
- 3.8 M$ of conductor per LHC-like magnet (15 m, 2-in-1)
  - 4.6 M$ including manufacturing (hypothesis: the same as LHC except coil construction increased by 50%)
  - The cost of HE-LHC is dominated by the cost of the superconductor
  - 40% given by the last 5 T
- 1200 dipoles → 5500 M$
  - About five times the LHC for 2.5 times the field

Main open issues

- HTS
  - Critical current: reach 400 A/mm^2 operational current in HTS
    - With 200 A/mm^2 as today, one would reach ~17.5 T
  - Manufacturing of dipoles
    - We start to have experience on solenoids, much less on dipoles
- Building an hybrid coil
  - Different curing for Nb-Ti, Nb_3Sn, HTS
- Stresses
  - At the limit of what tolerable, but do not look so terrible to require stress management

SUMMARY

- We explored the possibility of having 20 T magnets
  - One needs 25 T short sample magnet!
- Constraint: cost – transverse size
  - Grading of the material to save money
  - Operational current of 350-400 A/mm^2 to have "compact" coil
- Coil sketch
  - 8 T with Nb-Ti, up to 15 T with Nb_3Sn, the last 5 T with HTS
  - Stresses are well below 200 MPa in the Nb_3Sn and even lower in HTS
  - Field quality should not be too much critical due to the large ratio coil size/aperture
- Many challenges ...
  - Get to 400 A/mm^2 with HTS, and build dipoles
  - Manage construction hybrid coils