Performance limits of accelerator dipole and quadrupole for the Muon Collider

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WP7 – Task 4

Introduction

- A Python code is used to implement the **analytic formulas** for the dipole and quadrupole in cos-theta and sector coil approximation.

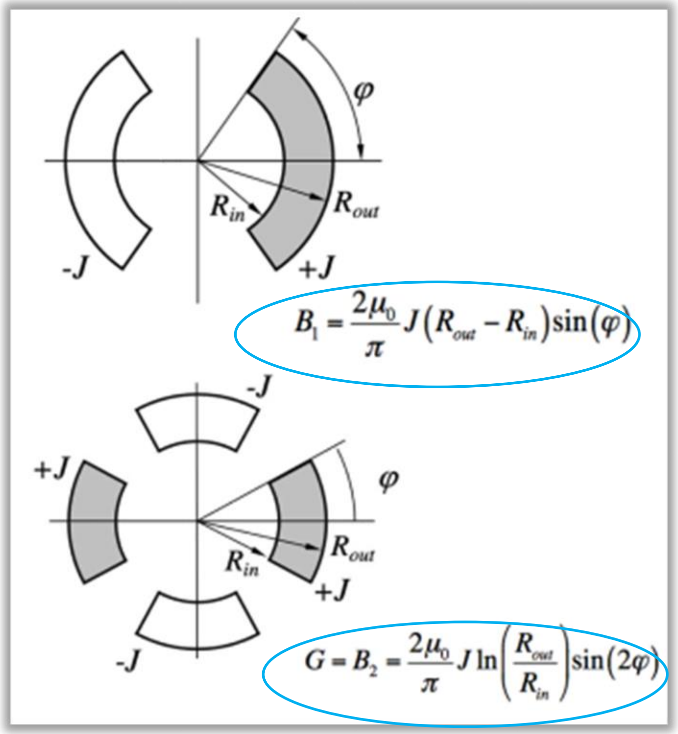
- Starting from the fit of the critical current density, the short sample magnetic field (dipole) and the short sample gradient (quadrupole) are computed, for three different operating temperatures and superconductors. This provides the **limitations due to the nature of the superconductor itself** as a function of temperature, type of material and quantity of material (coil width).

- By adding a **margin** to the short sample values, the graphs become more realistic. This is followed by a discussion of margin in terms of enthalpy and temperature

- A graph of the bore diameter versus magnetic field is useful to show the allowed region taking into account the **mechanical (stress), cost and protection limitations**.

- Some approximations are used to validate the procedure, and then more complicated configurations will be studied (for example sector magnets at a higher order of approximation, with iron yoke and grading on the current density).

General Assumptions



- This work is under the no-iron hypothesis.
- Analytic formulas in cos-theta approximation or, similarly, in sector coil (60° for the dipole and 30° for the quadrupole) at the first order of approximation.

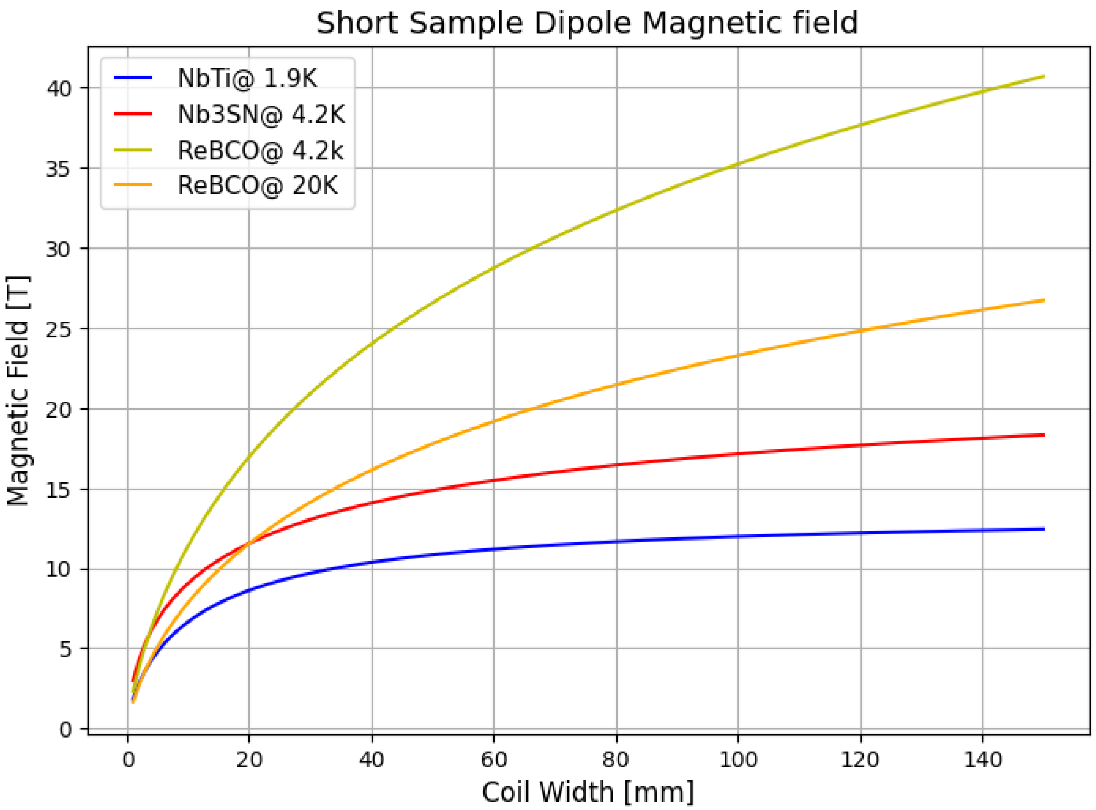
- Temperature of the cold mass, 3 options:
  - 1.9 K → NbTi
  - 4.2 K → Nb_3Sn and ReBCO
  - 20 K → ReBCO

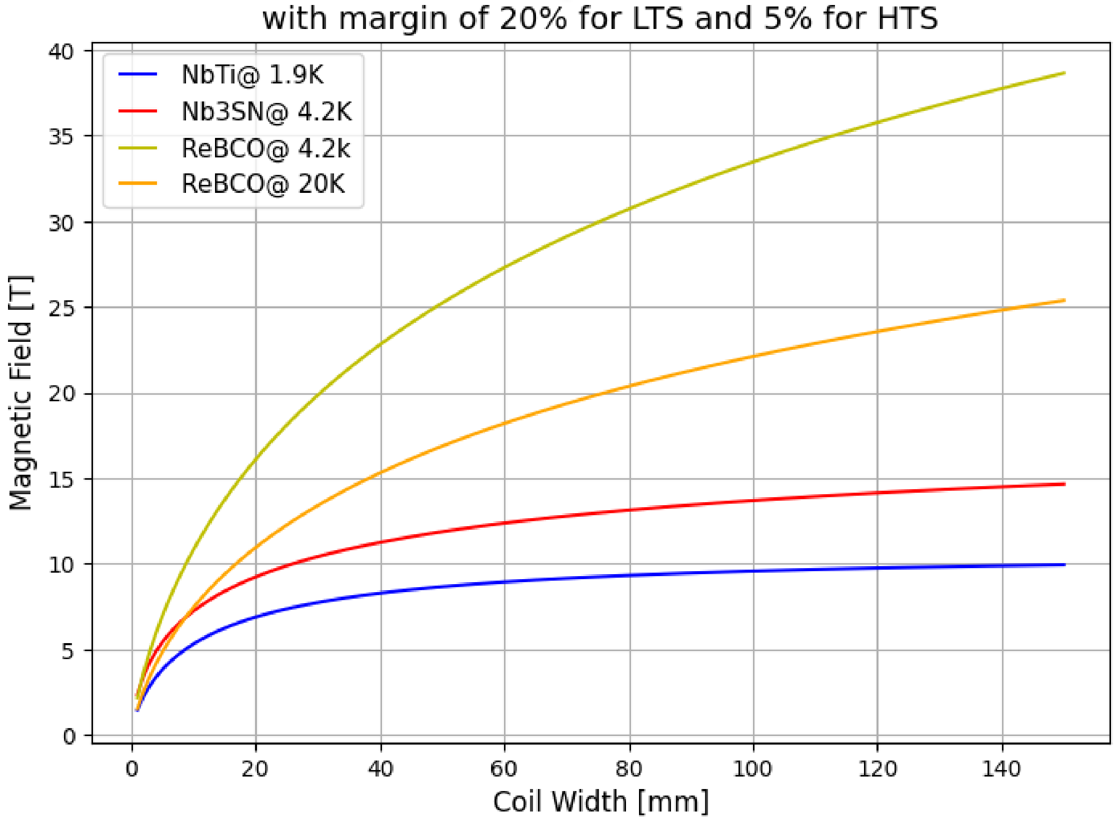
- Superconducting materials:
  - NbTi → the *LHC cable* as a reference → Filling factor of pure superconductor = *0.27*
  - Nb_3Sn → the *FCC target performance* as a reference → Filling factor of pure superconductor = *0.3*
  - ReBCO → the *Fujikura FESC AP tape* as a reference → Filling factor of pure superconductor = *0.02*

Dipole Magnetic Field

- The coil width will be strongly limited by the cost.
- The magnetic field will be strongly limited by the stress.

These margins are indicative;
they are used to observe behaviour.

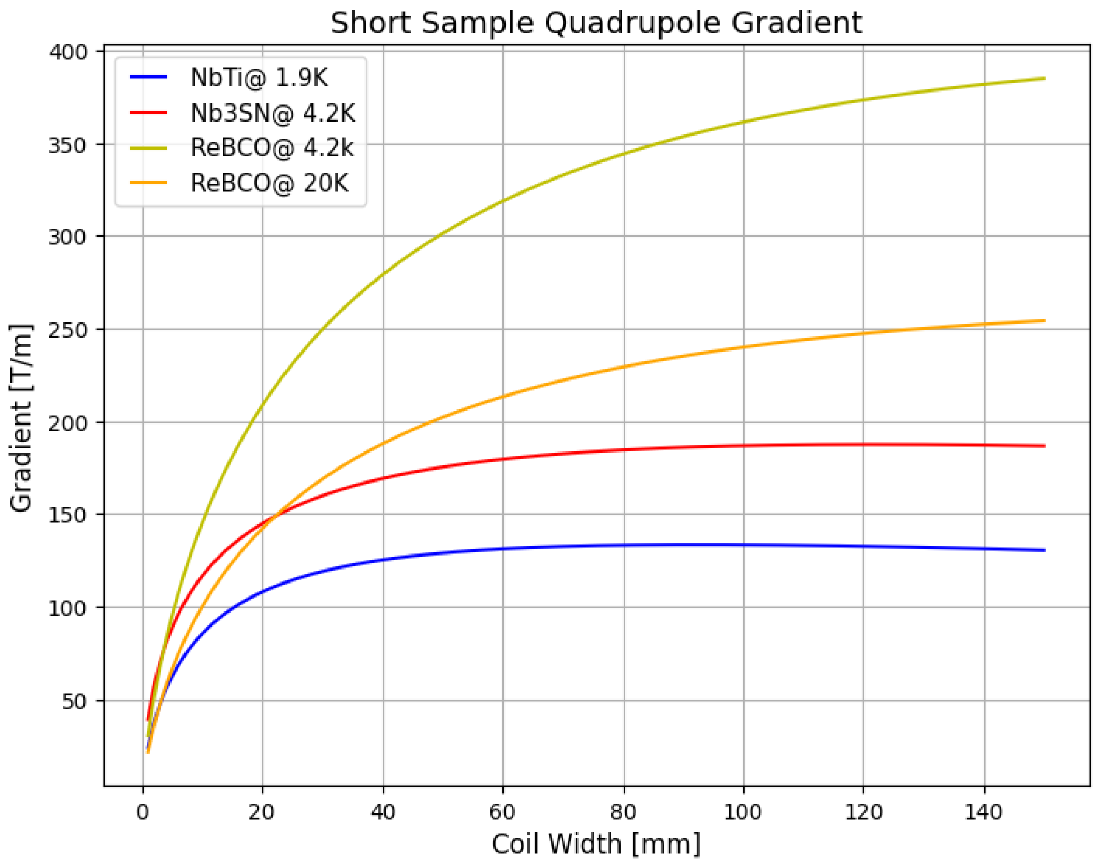


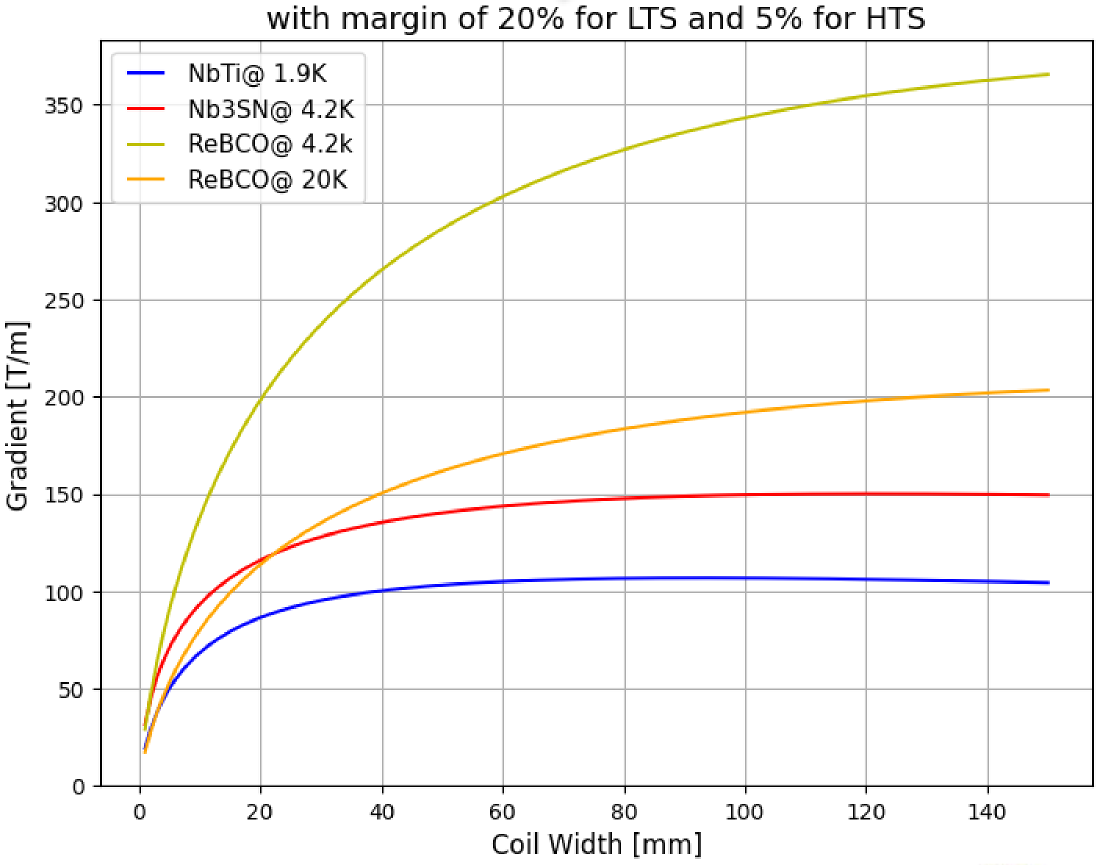


Quadrupole Gradient

- The coil width will be strongly limited by the cost.
- The gradient will be strongly limited by the stress.

These margins are indicative;
they are used to observe behaviour.

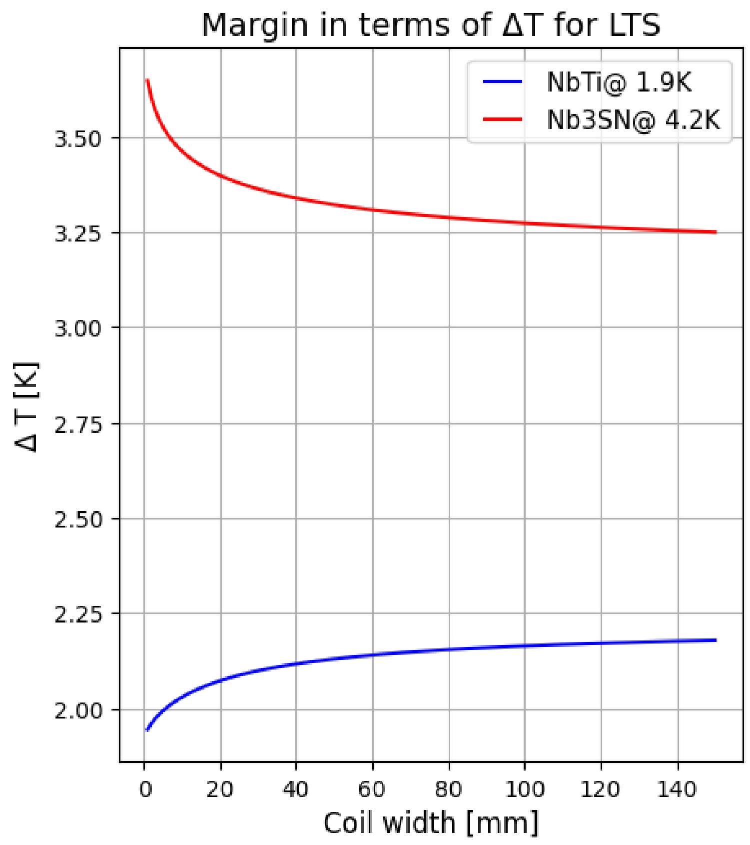




Discussion on the Margins

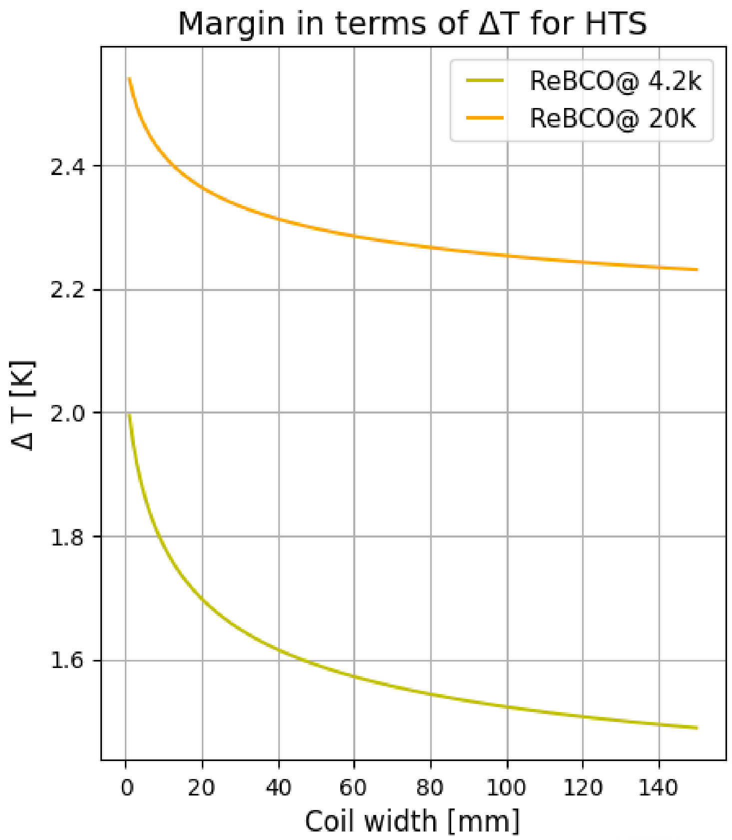
- The margin on the load line can be expressed in terms of margin in temperature.

We have chosen two indicative and reasonable values for margins on the load line for LTS and HTS, which are: 20% for the LTS (graph on the left) and 5% for the HTS (graph on the right).



- We can reduce (below 20%) the margin on the load line for the Nb_3Sn.

- We can reduce (below 5%) the margin on the load line for the ReBCO at high temperatures.



Discussion on the Margins

- It's more physical talking about the enthalpy margin,
which is linked to the temperature margin through the thermal capacity of the materials and the compositions of the strands.

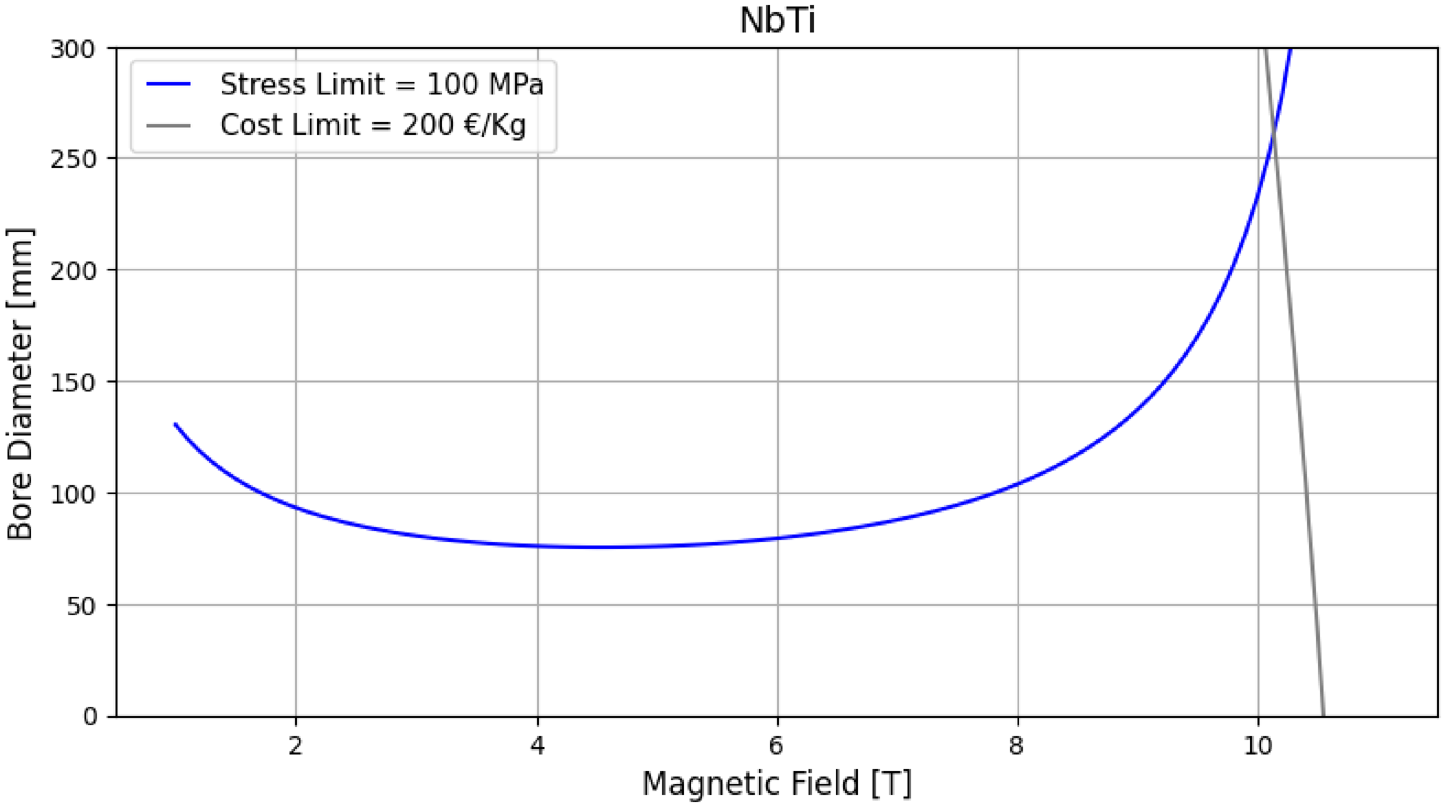
Material	Operating Temp. [K]	Enthalpy Margin [mJ/cm3]	Temperature Margin [K]	Strand fraction	Cost	Stress Limit
NbTi	1.9	5	2	0.75	200 €/kg	100 MPa
Nb_3Sn	4.2	20	4.5	0.70	2000 €/kg	150 MPa
ReBCO	4.2	20	4.8	0.73	8000 €/kg	300 MPa
	20	90	0.35			

- NbTi – LHC standard – Strand Fraction = 0.48 (Cu) + 0.27 (Sc)
- Nb_3Sn – HL-LHC standard – Strand Fraction = 0.40 (Cu) + 0.30 (Sc)
- ReBCO – Enthalpy margin equal to HL-LHC – Strand Fraction = 0.20 (Cu) + 0.02 (Sc) + 0.01 (Ag) + 0.50 (Hastelloy)

- Assume a cost limit of 100 k€ for the bare superconductor (the same limit for each material).

Bore Diameter vs Magnetic Field

Material	Operating Temp. [K]	Enthalpy Margin [mJ/cm3]	Temperature Margin [K]	Strand fraction	Cost	Stress Limit
NbTi	1.9	5	2	0.75	200 €/kg	100 MPa



- Assumption of J0 as Jc for each value of the magnetic field
- For each value of the magnetic field one can compute Jc(B, T)
- Knowing B and J0, the coil width can be computed from the load line formula
- The coil width increase with increasing B and decreasing Jc

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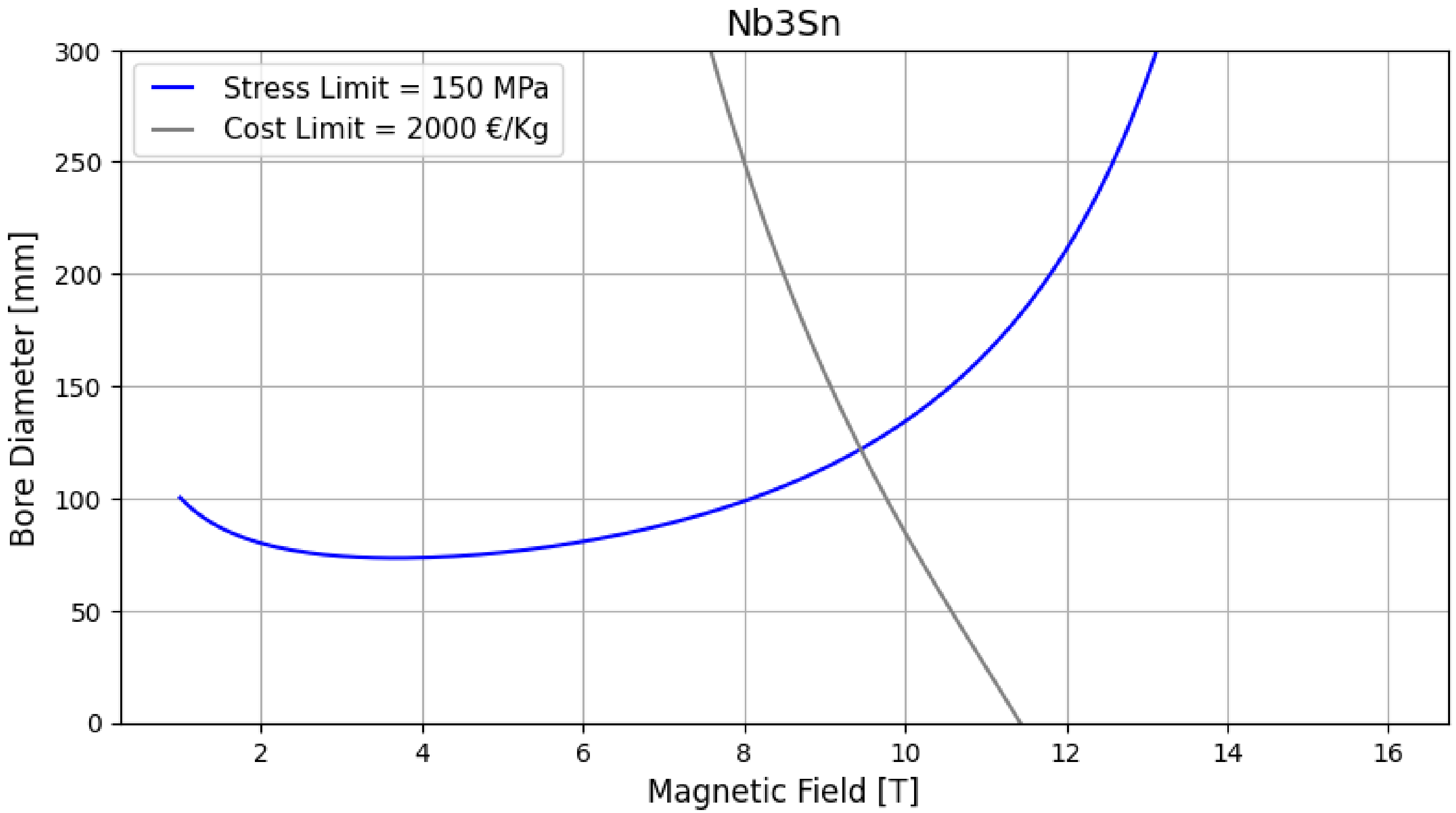

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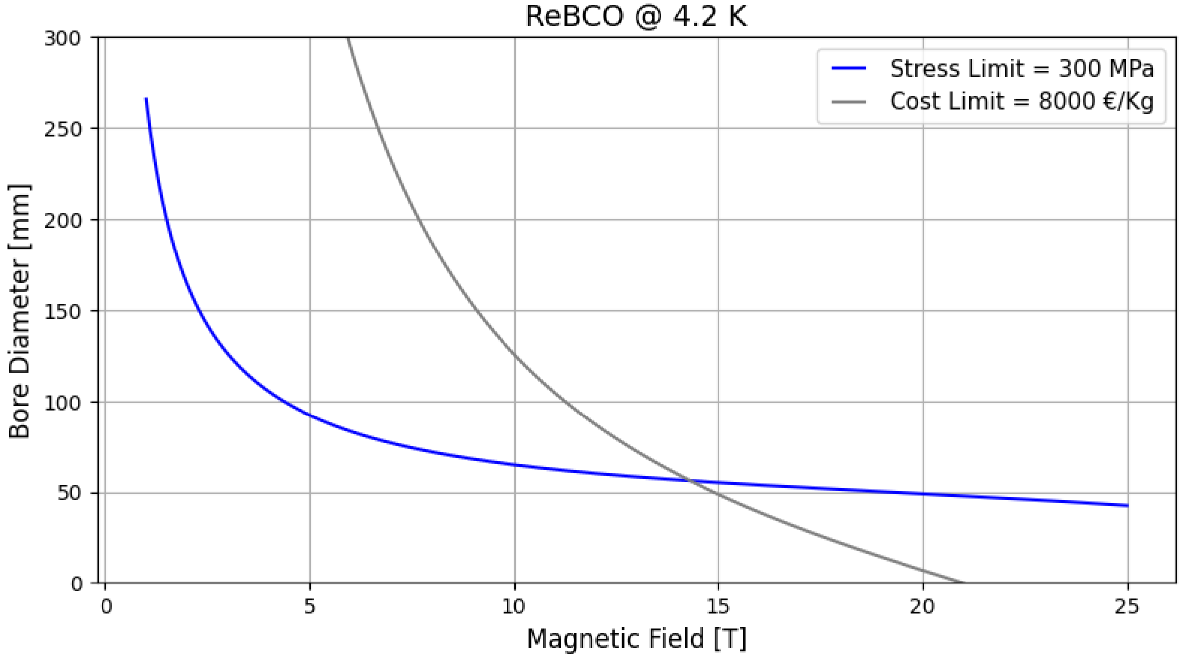

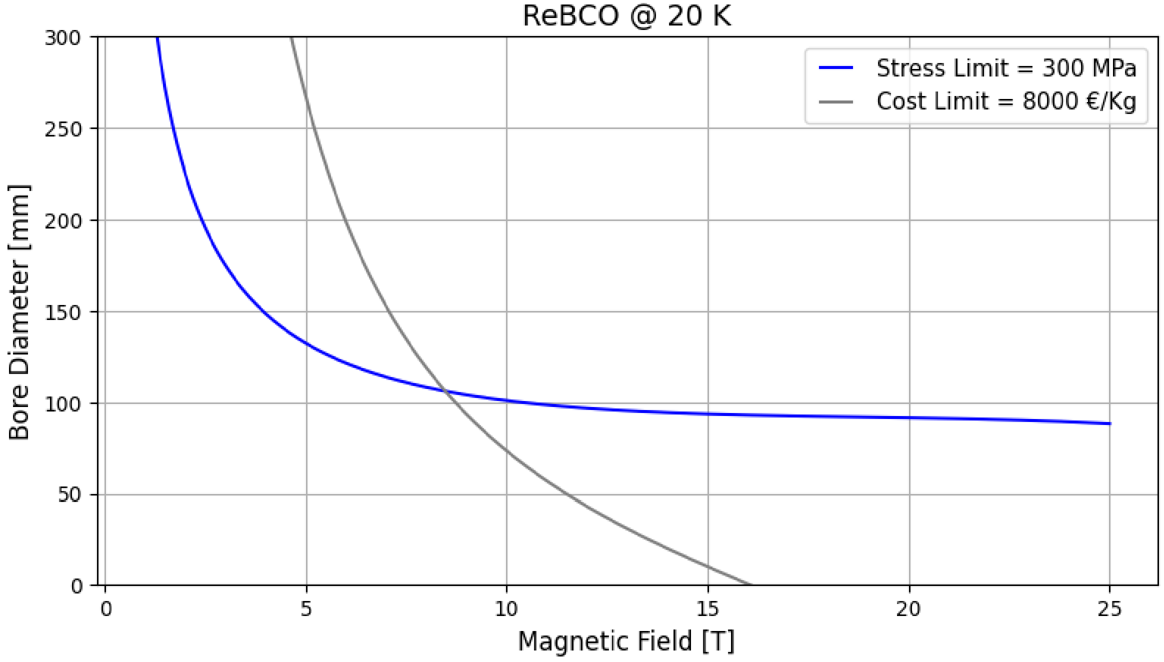

- Assumption of J0 as Jc for each value of the magnetic field
- For each value of the magnetic field one can compute Jc(B, T)
- Knowing B and J0, the coil width can be computed.
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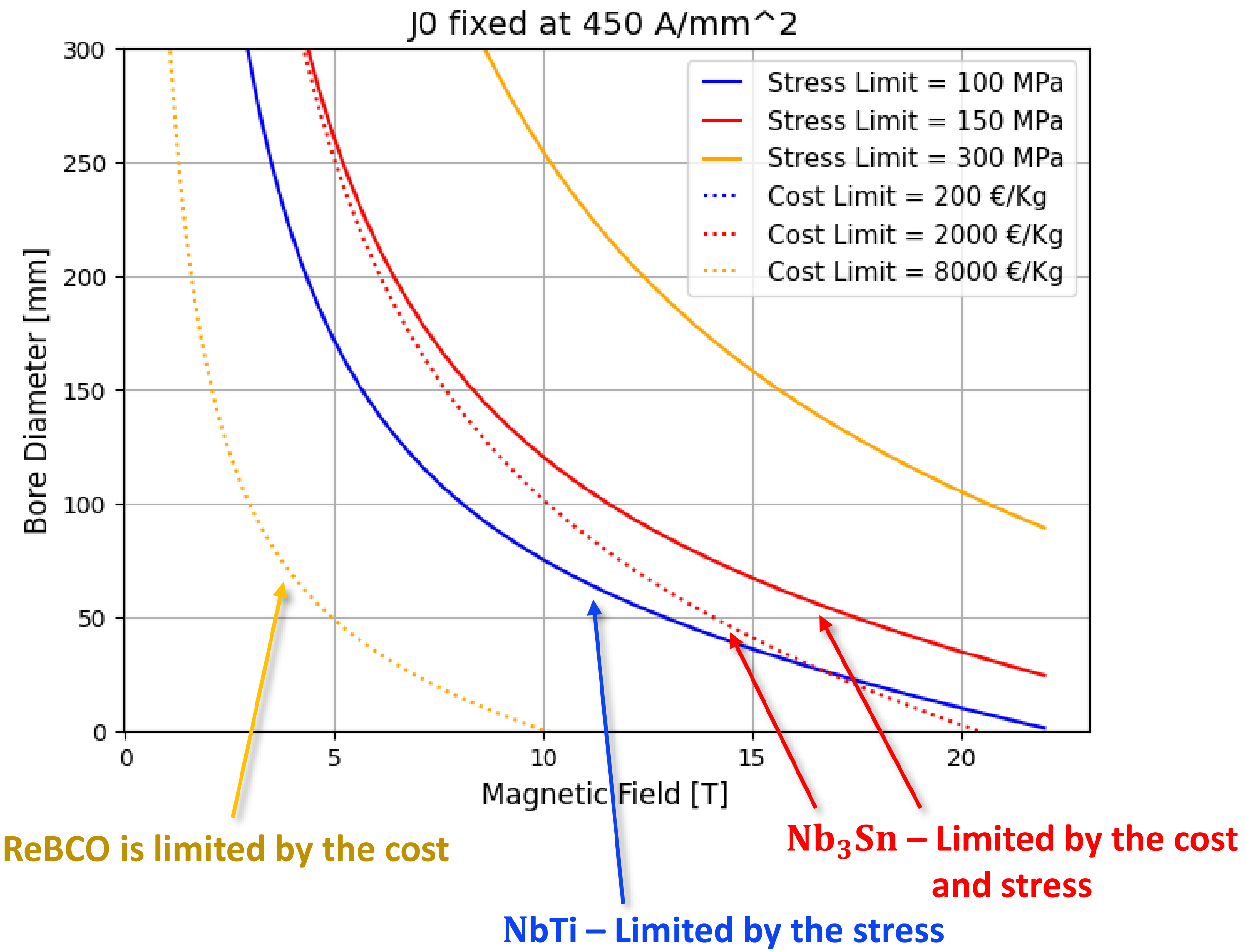
Bore Diameter vs Magnetic Field

- A studied option is to **fix the current density** (450 A/mm2, for example).



This is interesting because using J0 as Jc, in each point of the magnetic field we are using the maximum current density allowed by the properties of the material, but, of course, this is not usually done.

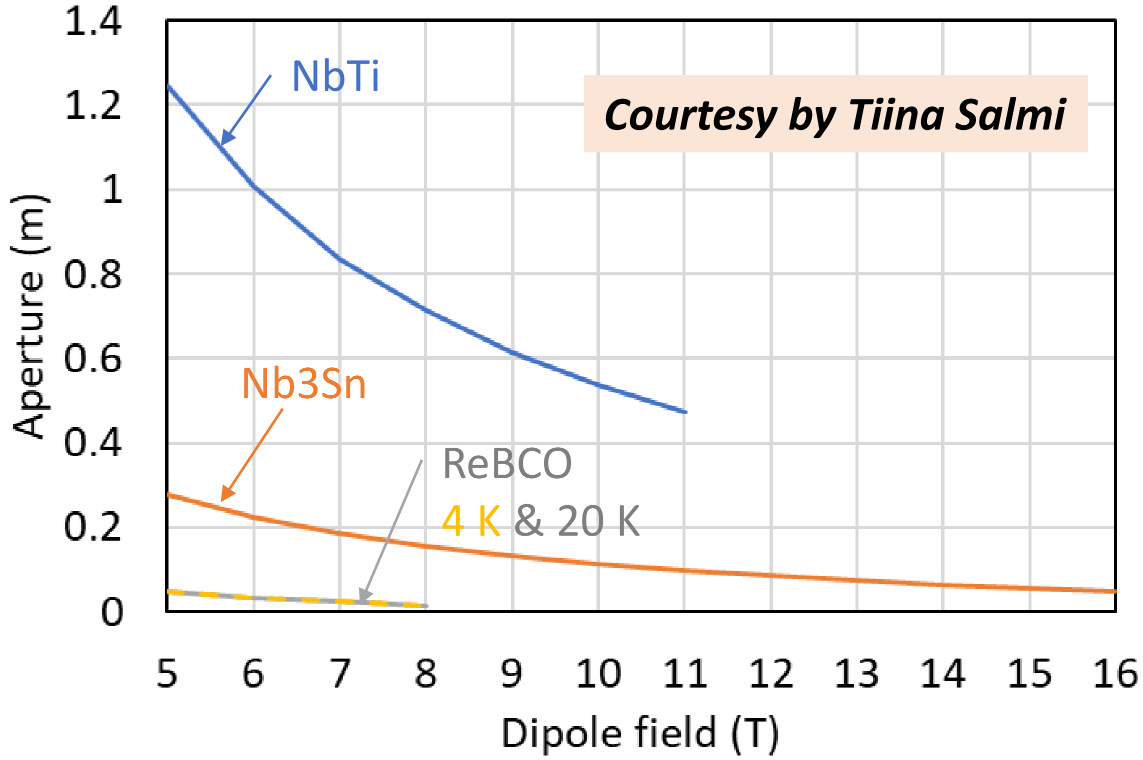
✓ We will **work below the critical current density**, particularly at low fields.

Also, working at the maximum current density can be a problem for the protection of the magnet; it should require huge coil width to dissipate the energy in case of quench.

✓ A solution can be found using a **graded current** density between LF and HF.

Protection Limit for Constant Cost

Maximum aperture allowed by protection limit, assuming constant coil cross-section (as limitd by conductor cost)



- NbTi, Hotspot temperature limit 350 K : Low conductor cost allows large coil and low current density → protection does not limit design
- Nb_3Sn, hotspot temperature limit 350 K: Higher cost starts to limit the coil size and force higher current density → protection may become a limitation
- ReBCO, hotspot temperature limit 200 K: High cost requires small coil and very high current density → Protection will be a limiting factor
- In all cases we assume 40 ms protection delay between original quench and quench protection system efficiency, see details:

https://indico.cern.ch/event/1240045/

Conclusions

Upcoming developments:

- We are currently working with analytical formulae in cos-theta and **sector coil** approximation.
- We are working to include a linear **iron** yoke (still using an analytical approach).
- We plan to include a **current grading** between LF and HF.
- We are looking for the best way to get the **bore diameter vs magnetic field graph**.

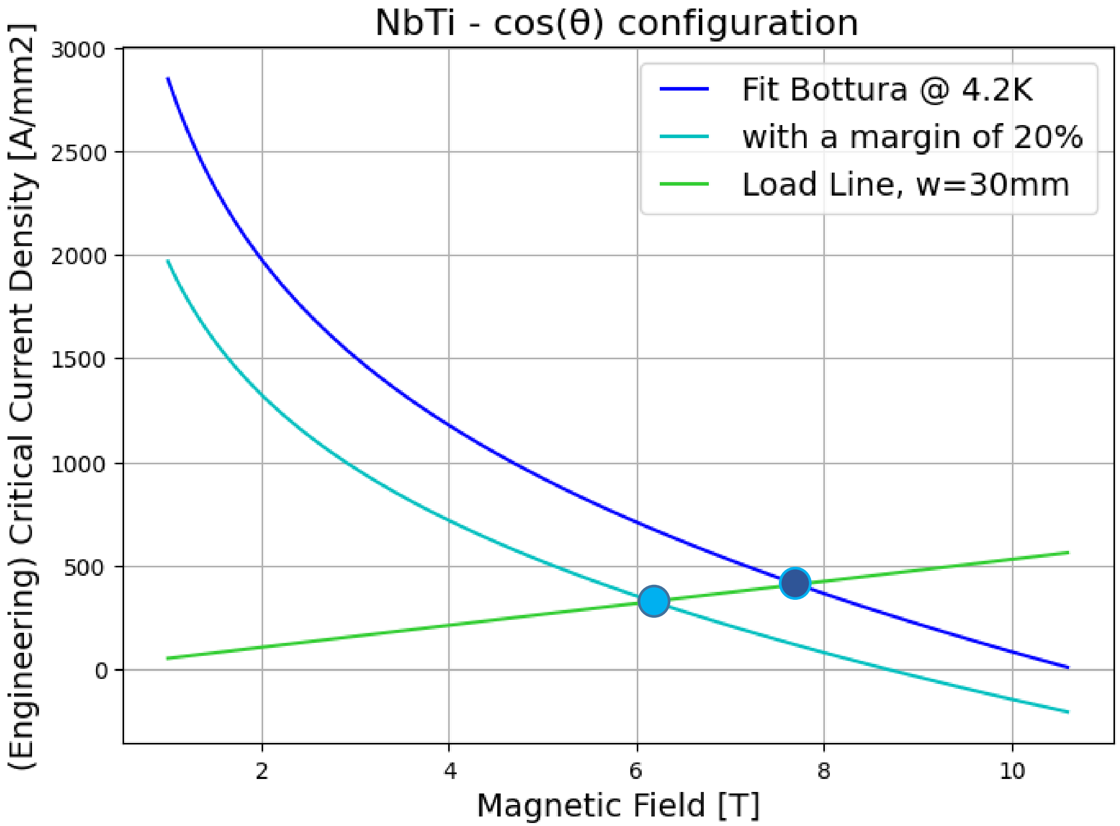
For the future:

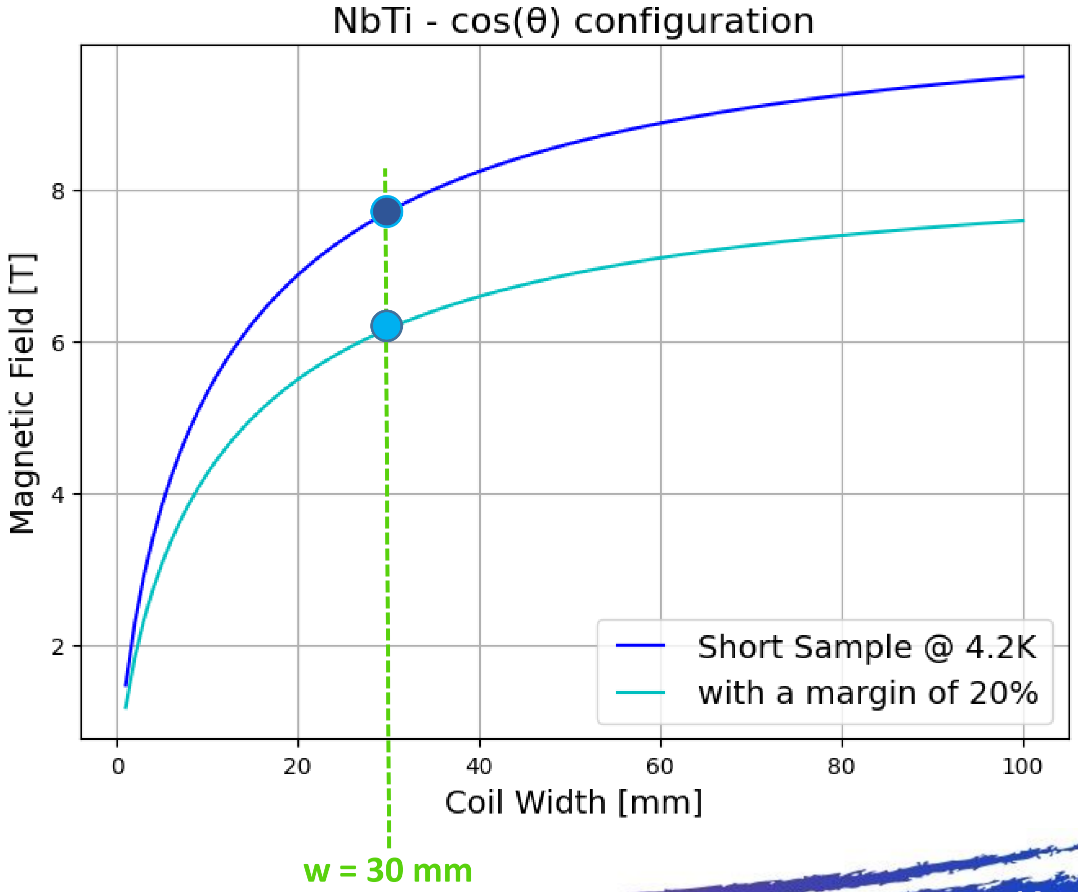
- We would like to implement a **Python** code able to work **with** the **Ansys** software, to solve complex configurations that are not analytically tractable, thus making it possible to study **multipole sectors** and **combined function magnets**.

Thank you for your attention

Dipole - Performances of NbTi

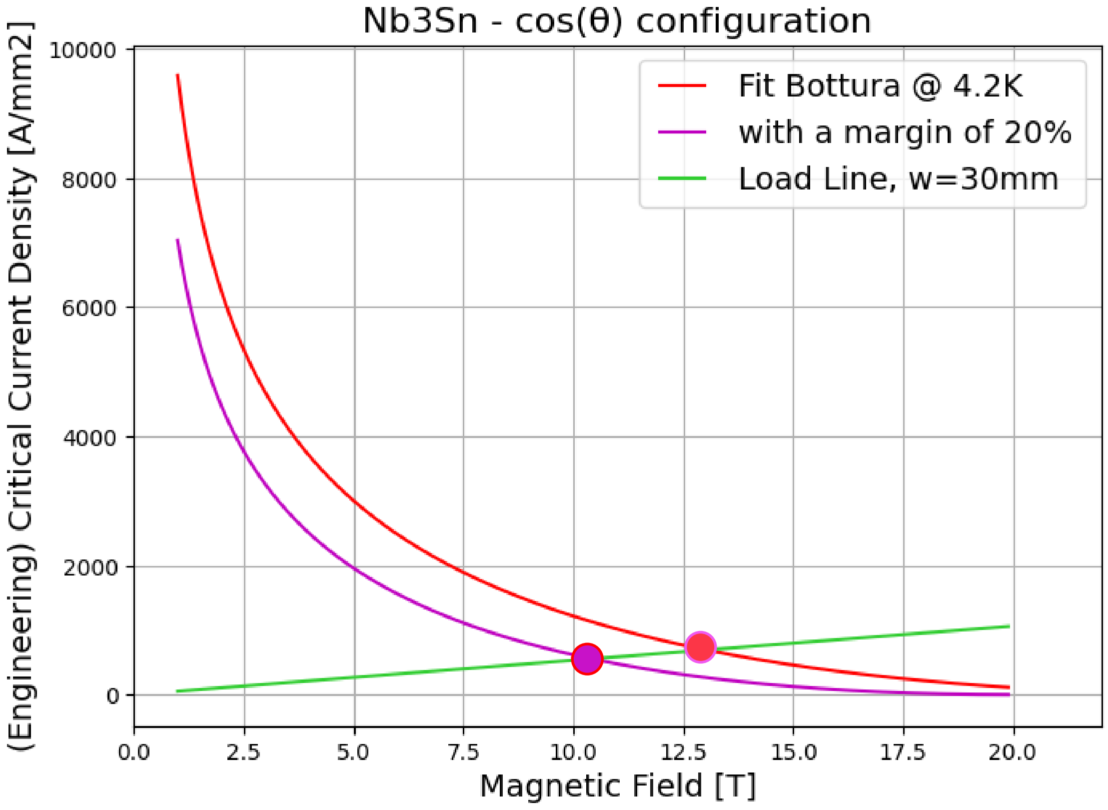
- Fit's data from the LHC cable
- T = 4.2 K
- Fixed aperture = 75 mm
- Filling factor = 0.3
  - Ratio between normal conductor and superconductor.
  - Voids
  - Insulation
- *Cosθ* configuration

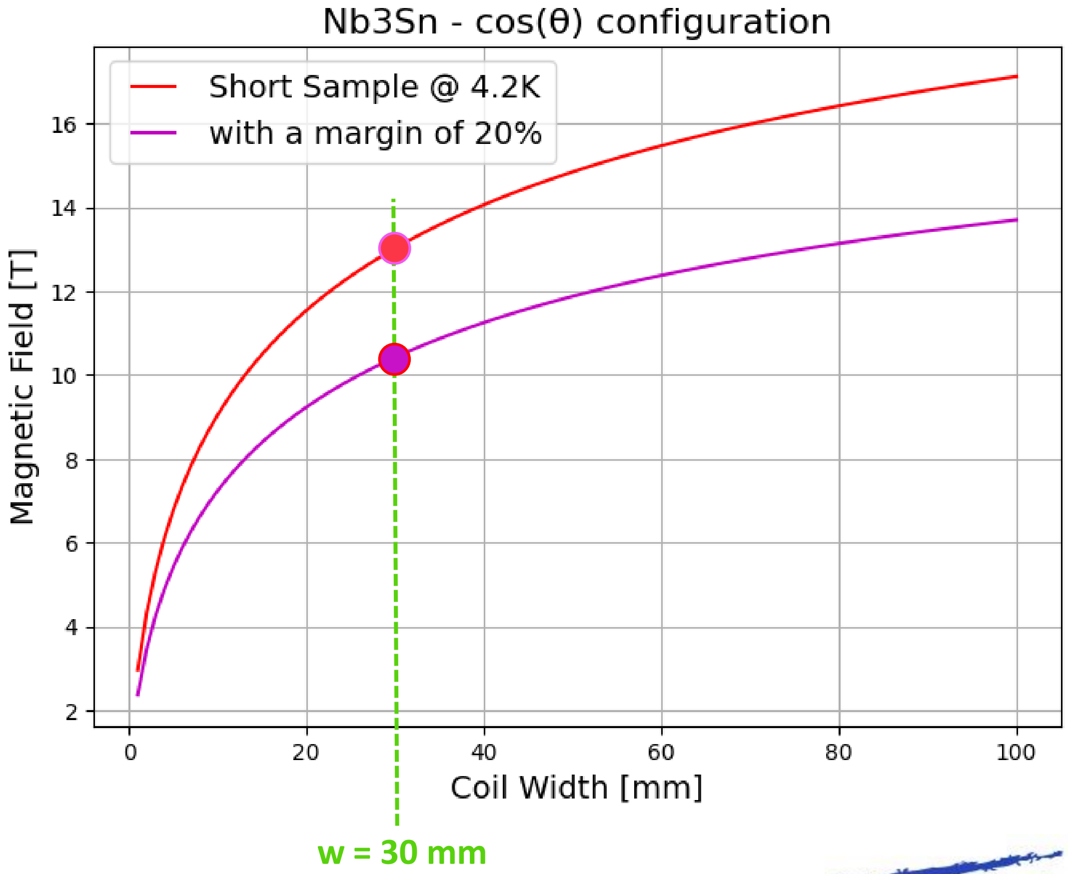




Dipole - Performances of Nb_3Sn

- Fit's data from the FCC target performance
- Fixed aperture = 75 mm
- T = 4.2 K
- Filling factor = 0.3
  - Ratio between normal conductor and superconductor.
  - Voids
  - Insulation
- *Cosθ* configuration





Dipole - Performances of YBCO

- Fit's data from the Fujikura FESC AP tape
- Fixed aperture = 75 mm
- T = 4.2 K
- Filling factor = 0.02 → Ratio between the total area of the cable to the superconductor area.
- *Cosθ* configuration