Electromagnetic Design of the FCC Lattice (MS) and Corrector (MCS) Sextupoles and Lattice Octupoles (MO)

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Context

- Maximum strengths for different technologies (Nb-Ti and Nb_3Sn) have been evaluated based on analytical equations including the iron effect
- The sextupoles and octupoles with reasonable technological risk have been selected
- Based on these results Roxie 2D electromagnetic models are presented for the sextupoles and octupoles
- Quench protection for powering the magnets in series has been considered

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Assumptions

General assumptions :

- Sector coils
- Iron screen
- Optional iron poles
- Aperture radius r_{a} = 25 mm
- 20% margin on the load line
- J_{Cu} ≤ 1000 A/mm² (rule of thumb to ensure the quench protection of a SC magnet powered in series)

Tools developed :

- Analytical expressions of strength $\boldsymbol{S}$ and magnetic field on conductor $\boldsymbol{B}$ for sector coils with iron screen and poles (considered as saturated) were derived
- Algorithm to numerically solve the (non-linear) equation associated with the margin on the load line and the $\boldsymbol{J}_{\mathbf{sc,c}}$ dependence on $\boldsymbol{B}$ for Nb-Ti and Nb_3Sn was programmed

Scaling law

Analytical expressions for 2N-upole sector coils with N ≥ 3 :

- Strength S in T/m^{N-1} : $S = S_{\mathrm{current}} + S_{\mathrm{sat\ pole}}$ 2N : number of poles (e.g. N=3 → sextupole)

J_0 : current density in coil

w : coil width

$$\begin{cases} S_{\mathrm{current}} = \frac{\mu_0\sqrt{3}}{\pi}\frac{J_0}{(r_a+w)^{N-2}}\left(\frac{1}{N-2}\left[\left(\frac{r_a+w}{r_a}\right)^{N-2}-1\right]+\frac{A_\mu}{N+2}\left[1-\left(\frac{r_a}{r_a+w}\right)^{N+2}\right]\right) \\ S_{\mathrm{sat\ pole}} = \frac{\mu_0 N}{\pi}\frac{M_{\mathrm{sat}}}{(r_a+w)^{N-1}}\left(\frac{1}{N-1}\left[\left(\frac{r_a+w}{r_a}\right)^{N-1}-1\right]+\frac{A_\mu}{N+1}\left[1-\left(\frac{r_a}{r_a+w}\right)^{N+1}\right]\right) \end{cases}$$

Term due to iron screen, $A_\mu \leq 1$ if partly saturated

M_{sat} : saturation magnetization of iron

- Expression of magnetic field on conductor B too heavy to be displayed

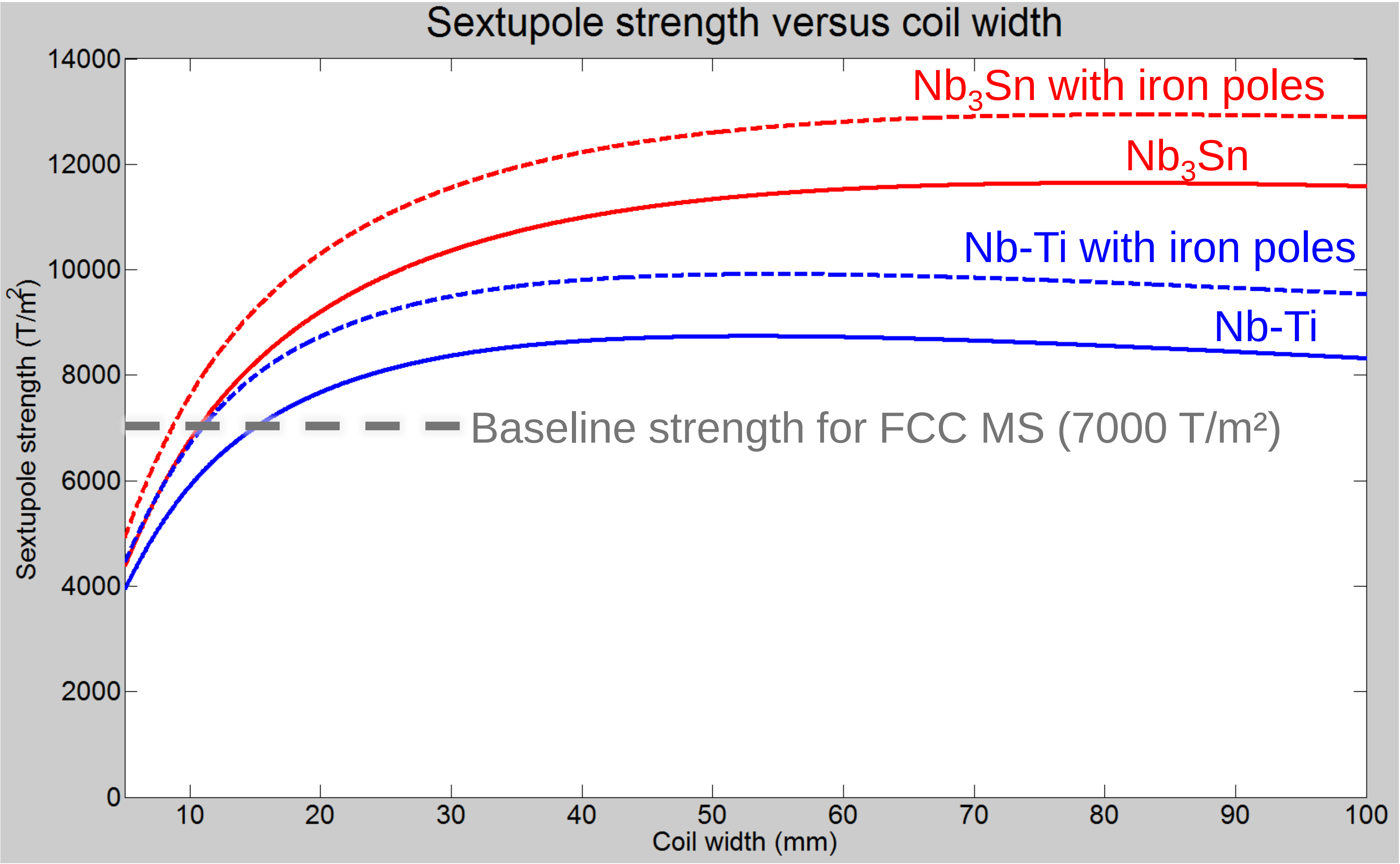
Equations to ensure margin on the load line and quench protection :

$$\begin{cases} J_0 = \frac{f.L_{\mathrm{line}}}{1+CuSc}.J_{sc,c}\left(B_p\left(\frac{J_0}{L_{\mathrm{line}}}\right)\right) \\ J_0 = \frac{f.CuSc}{1+CuSc}.J_{\mathrm{Cu\ max}} \end{cases}$$

→ ensures that percentage along the load line is L_{line}= 80%

→ ensures that copper current density equal to $J_{\mathrm{Cu\ max}}$ = 1000 A/mm²

Results for the Sextupole

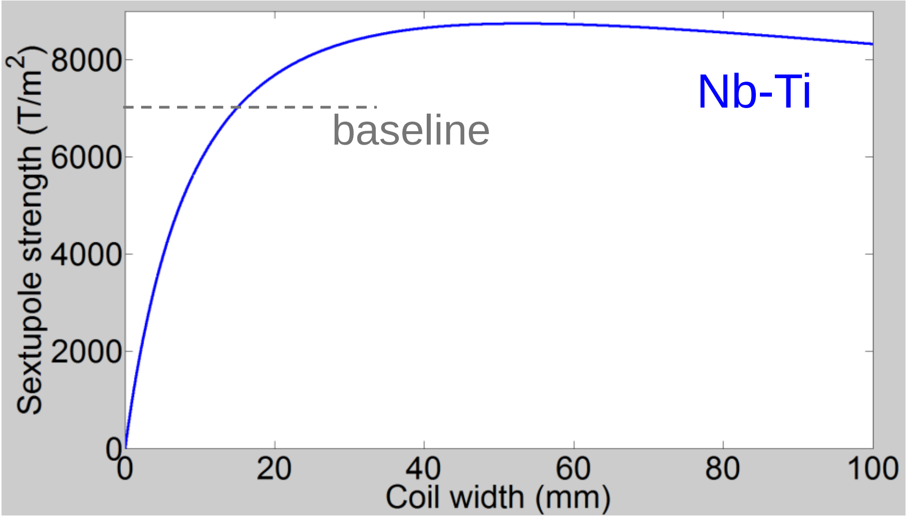


→ Nb_3Sn allows ~15-30% higher strength than Nb-Ti

→ iron poles allow ~10-15% higher strength but yield to poor field quality (b_9~80 units)

→ coil with Nb-Ti conductor and small width seems reasonable with respect to cost and complexity

Selecting the optimal width



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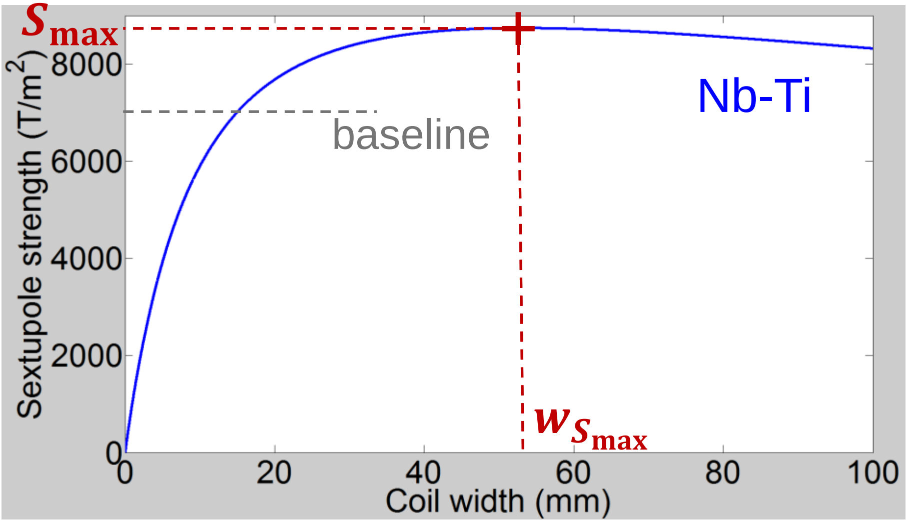

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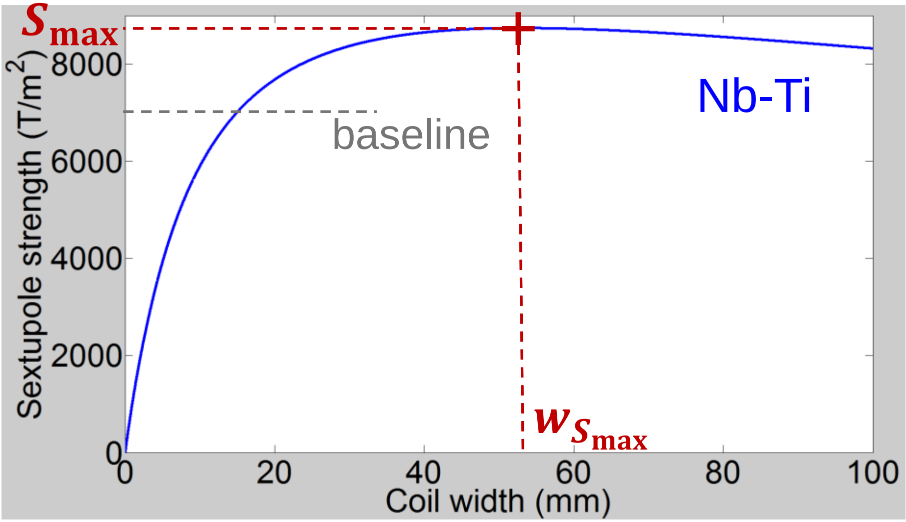

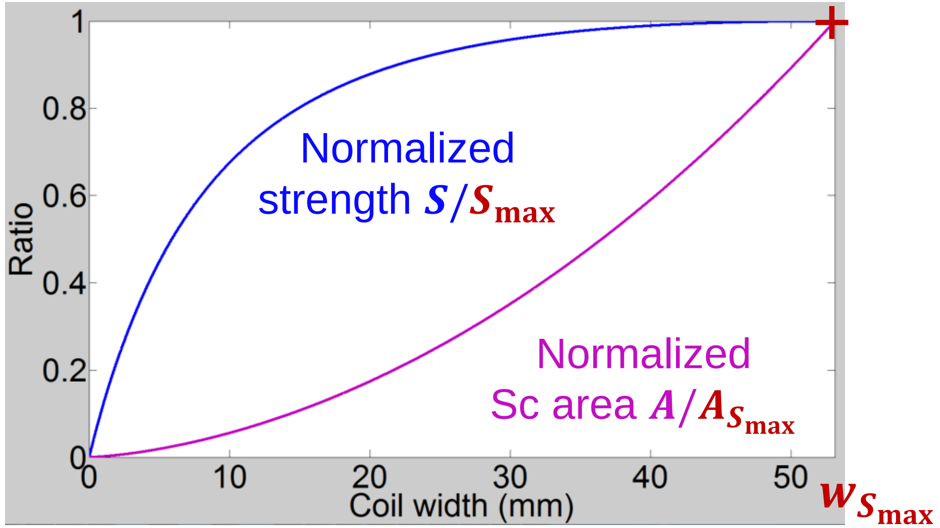

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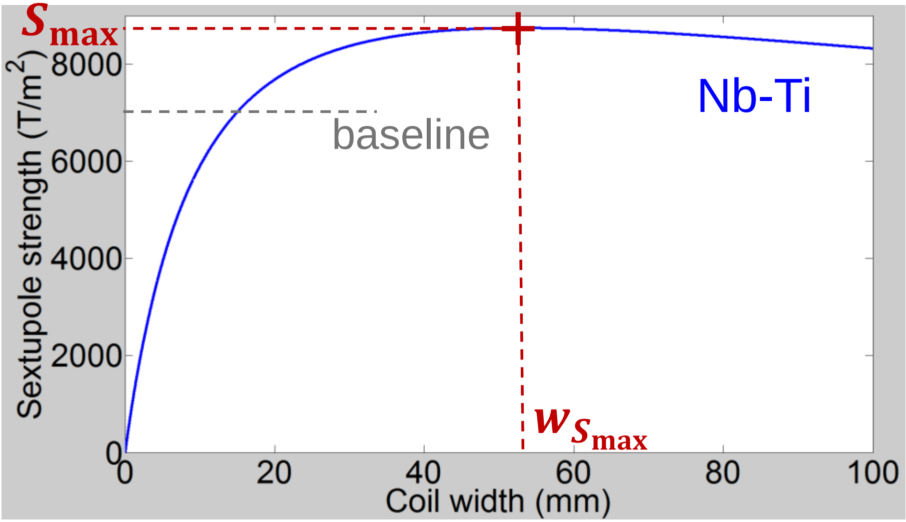

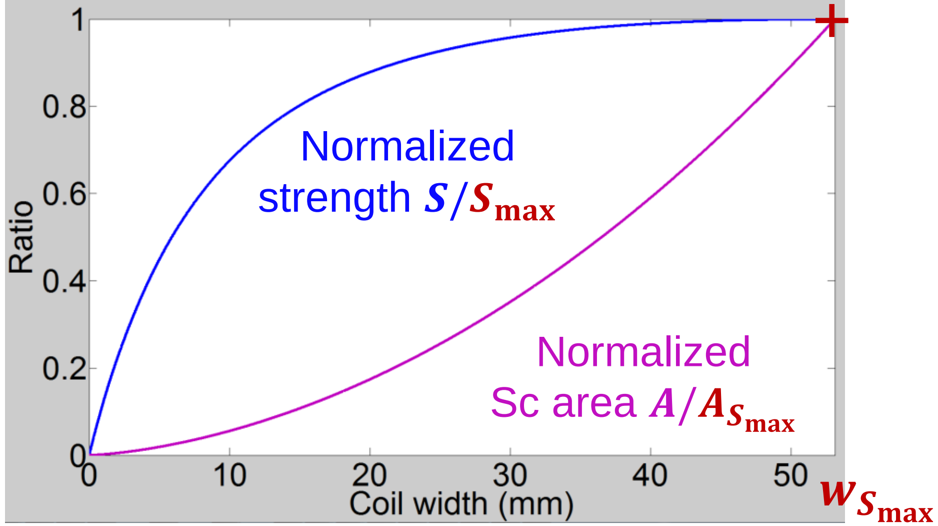

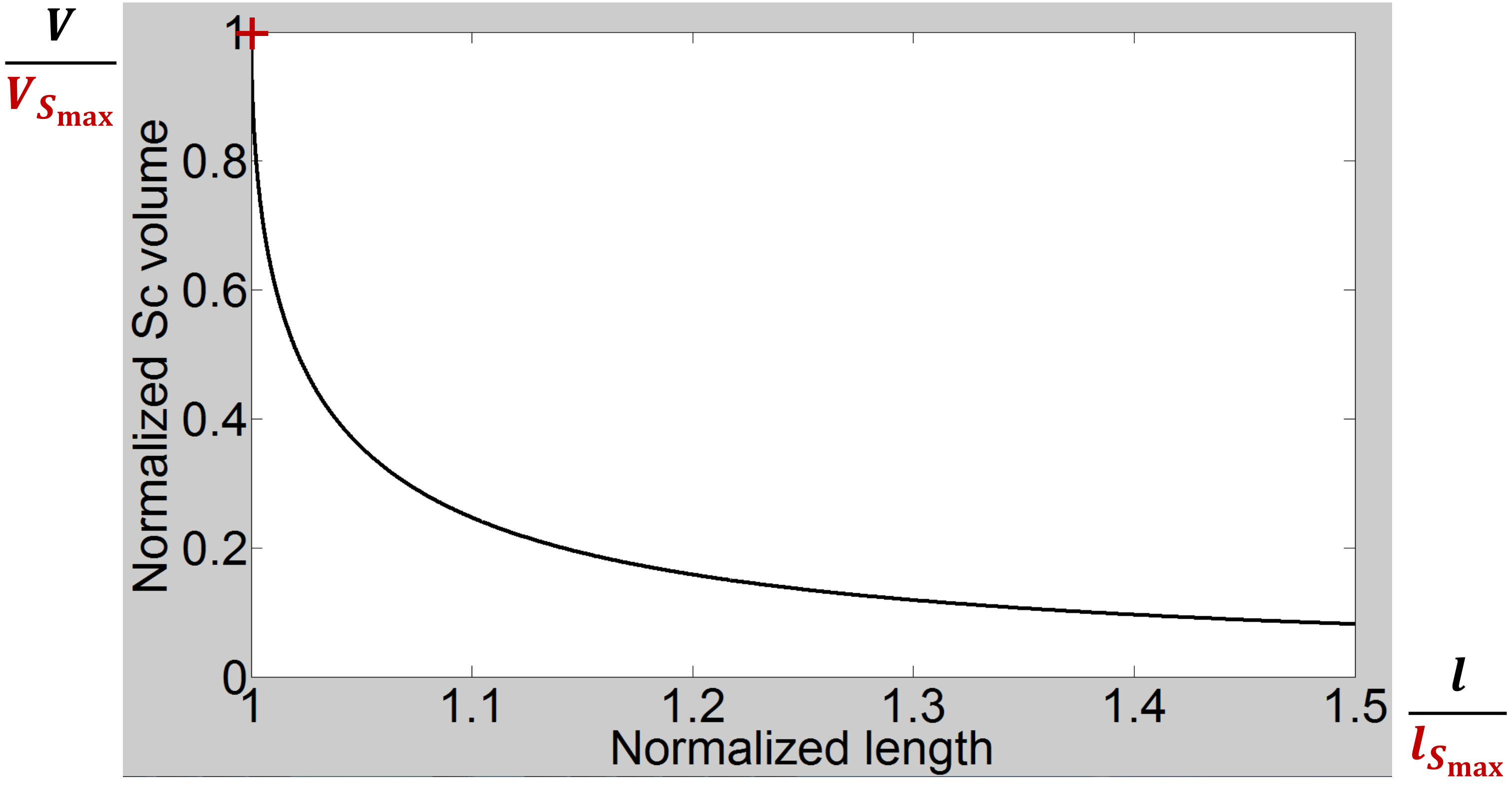

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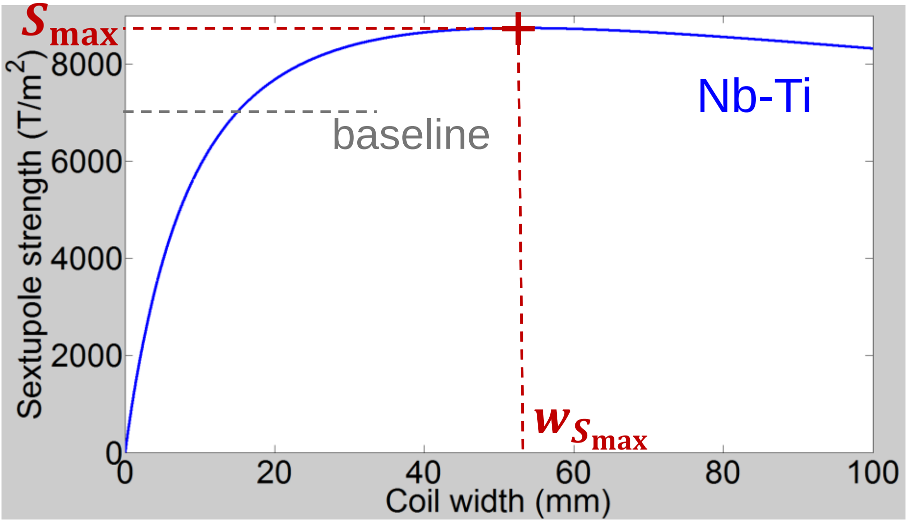

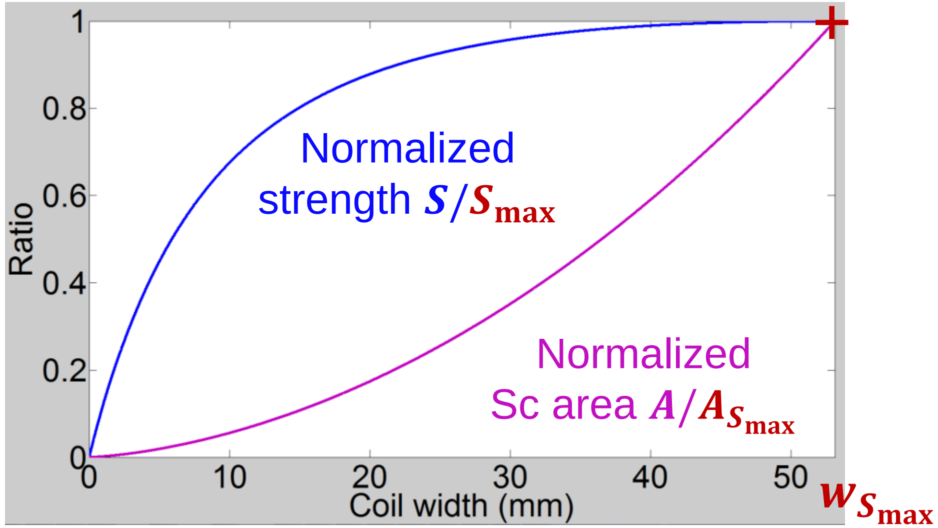

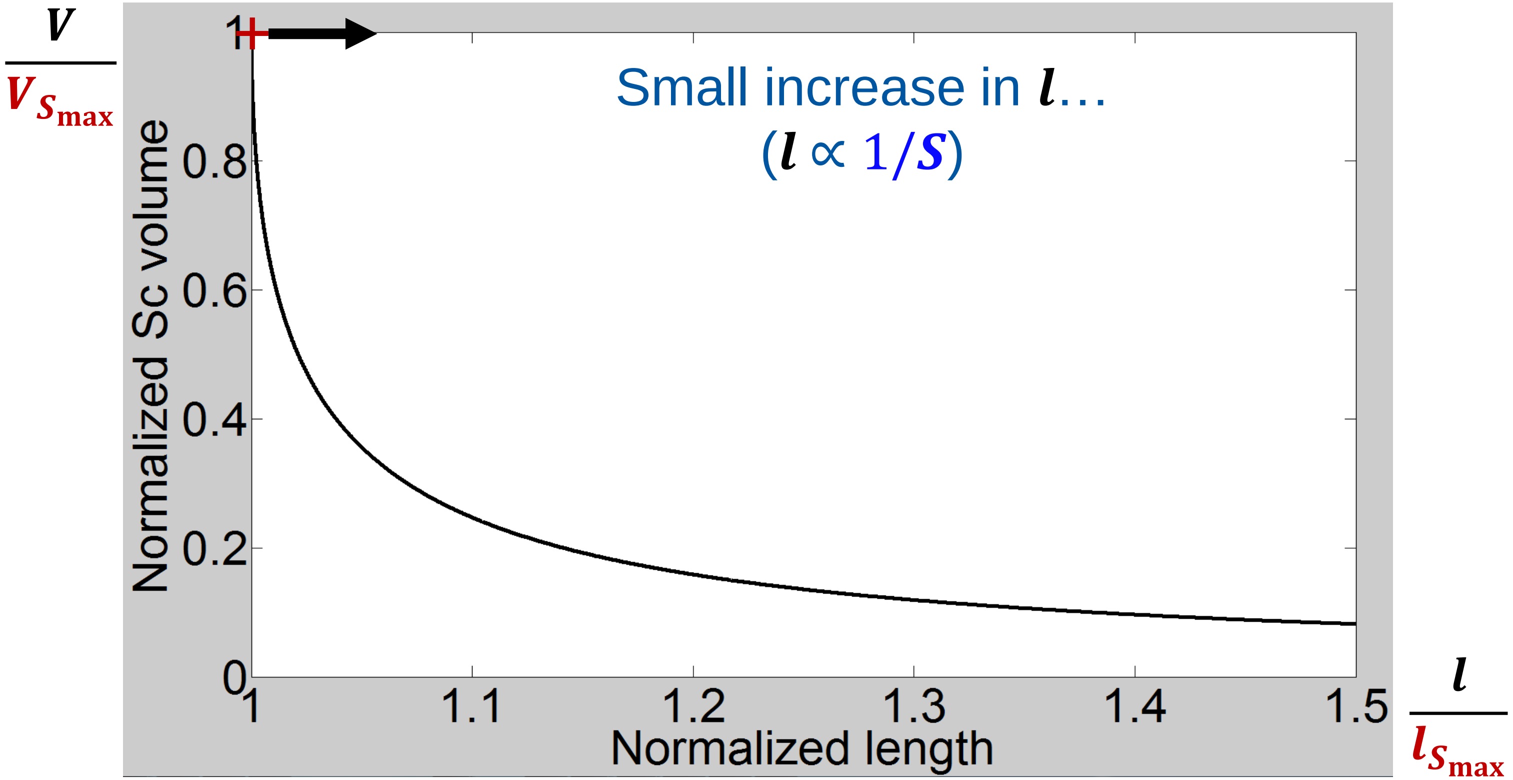

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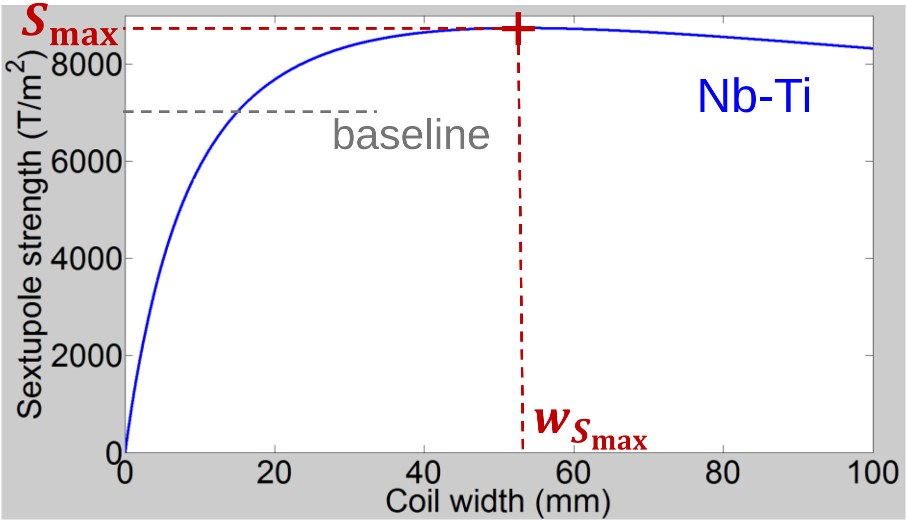

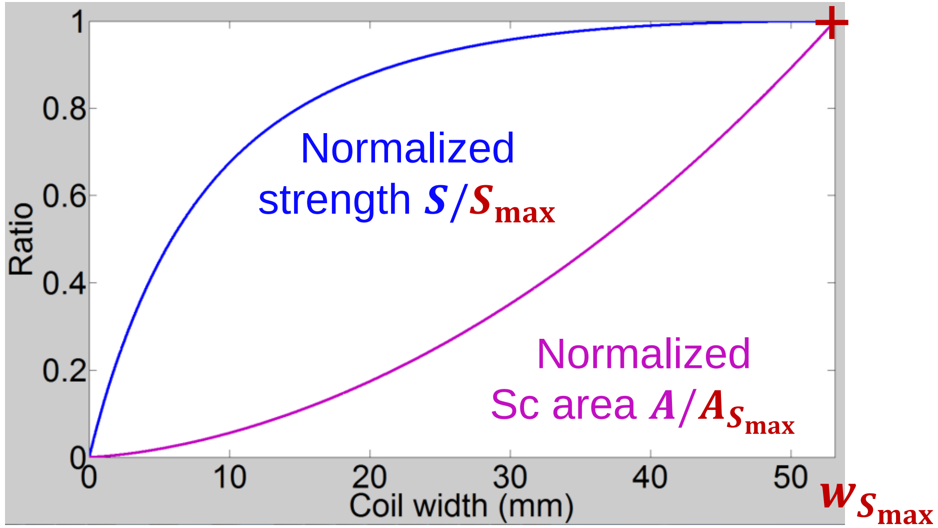

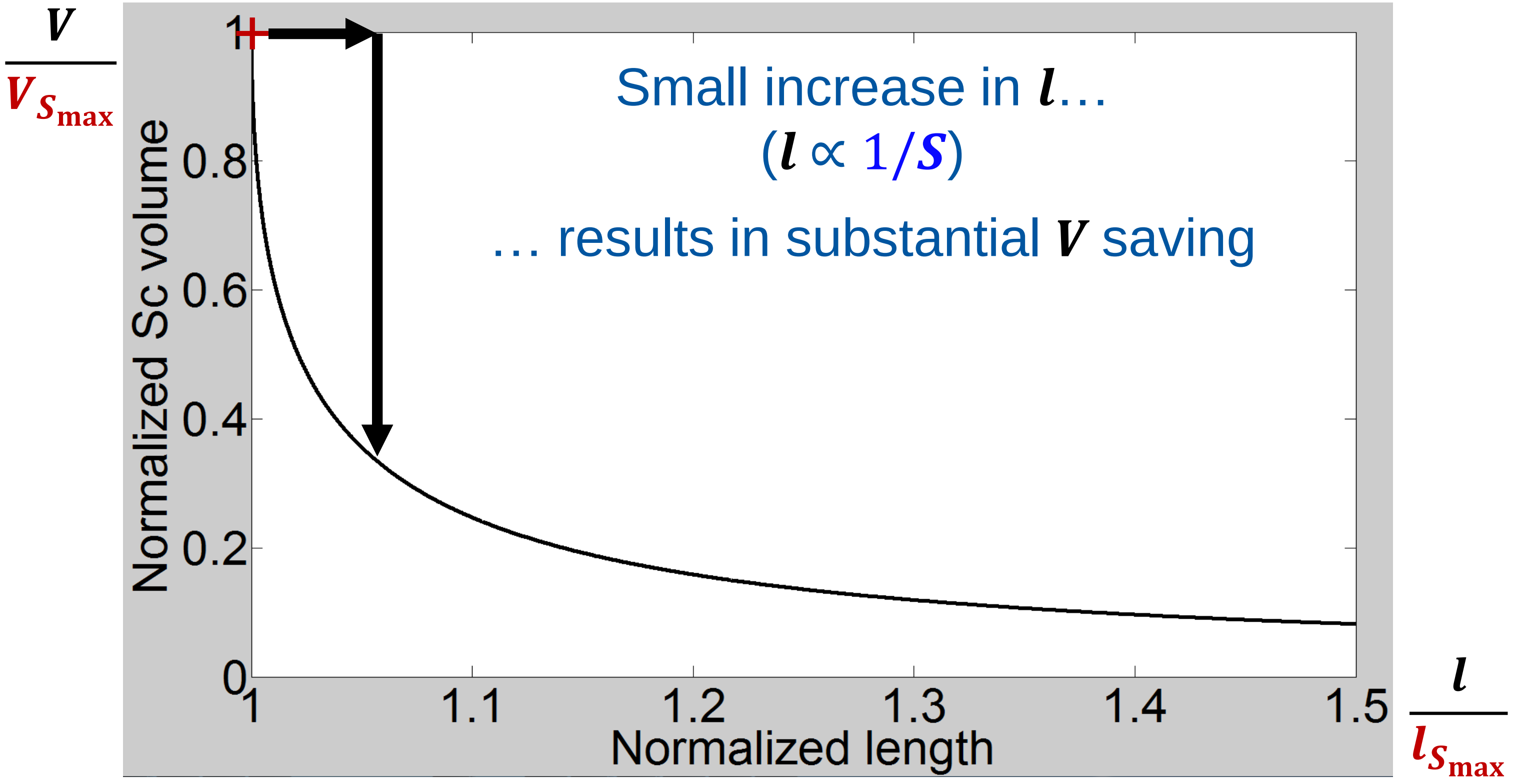

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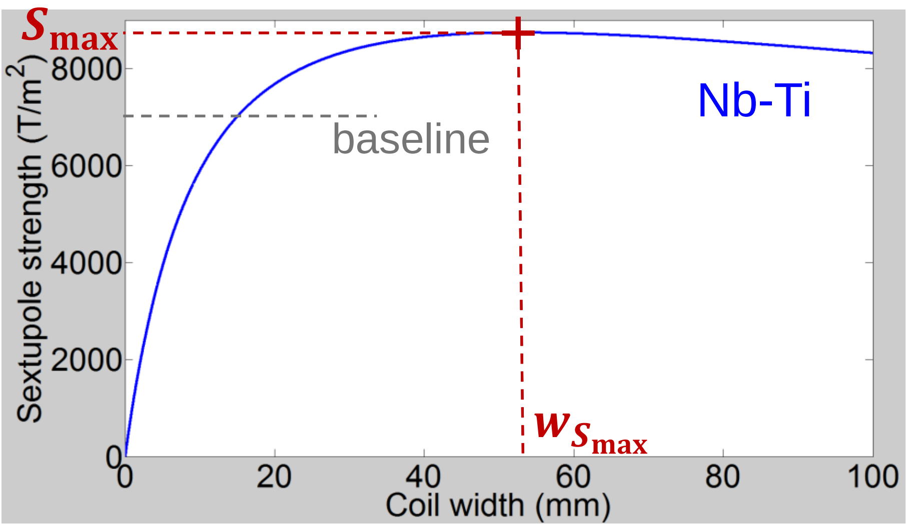

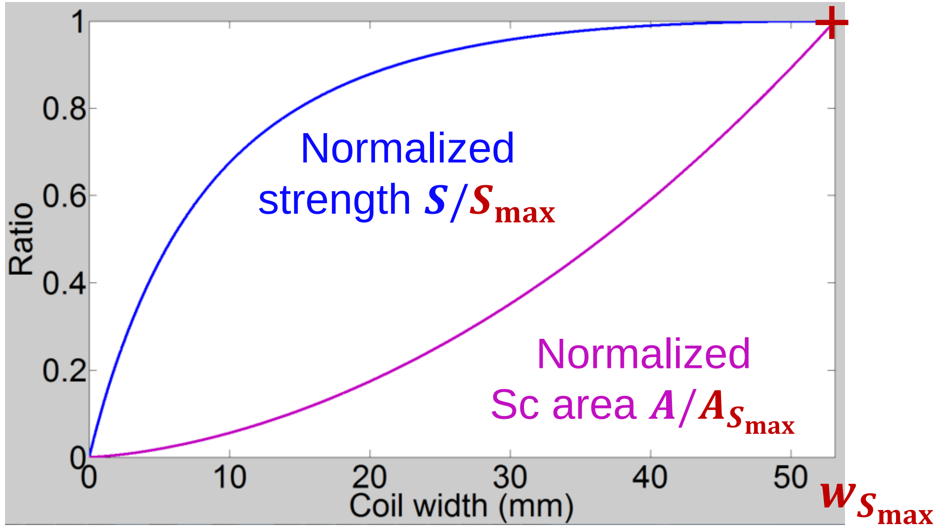

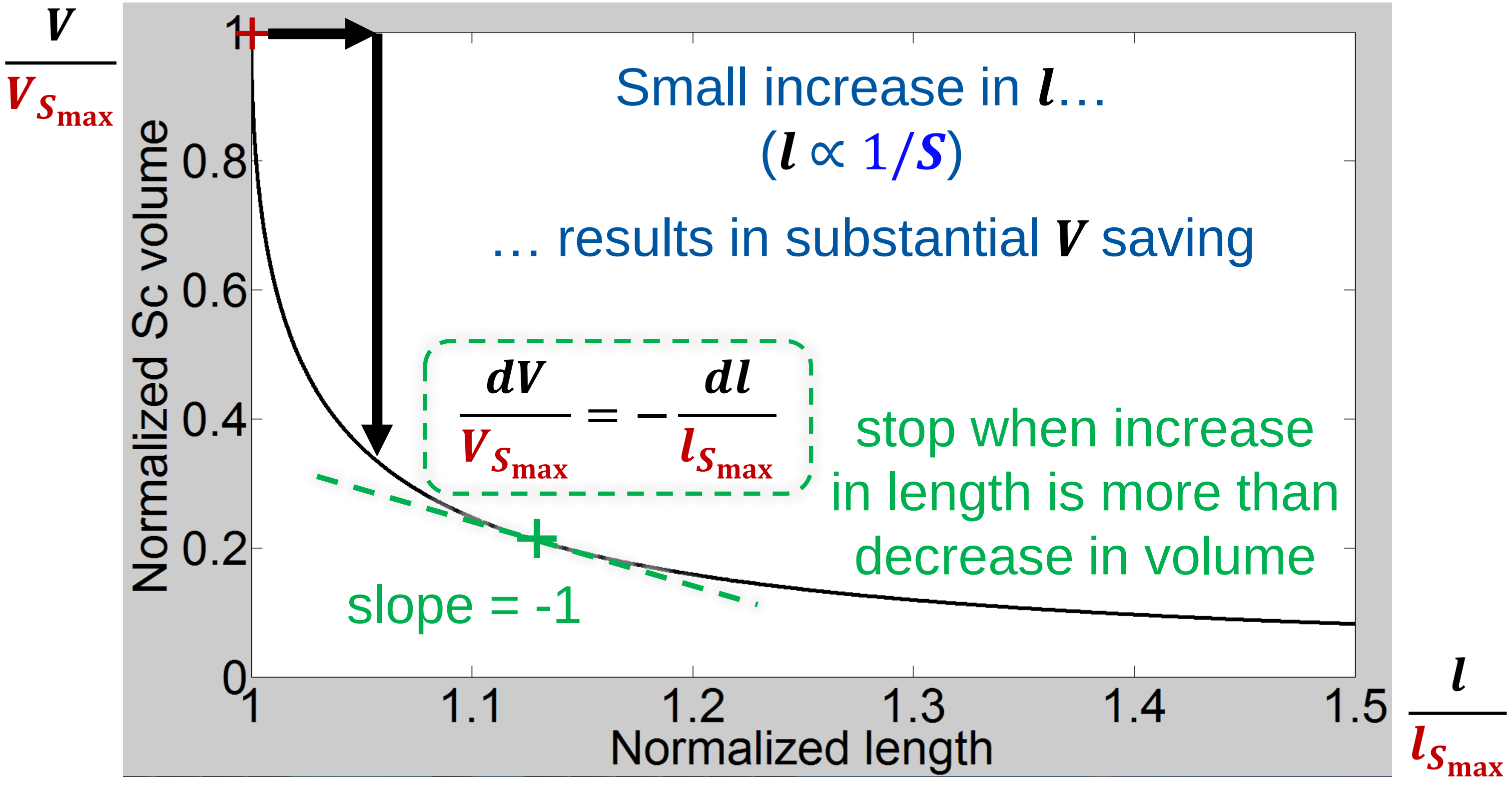

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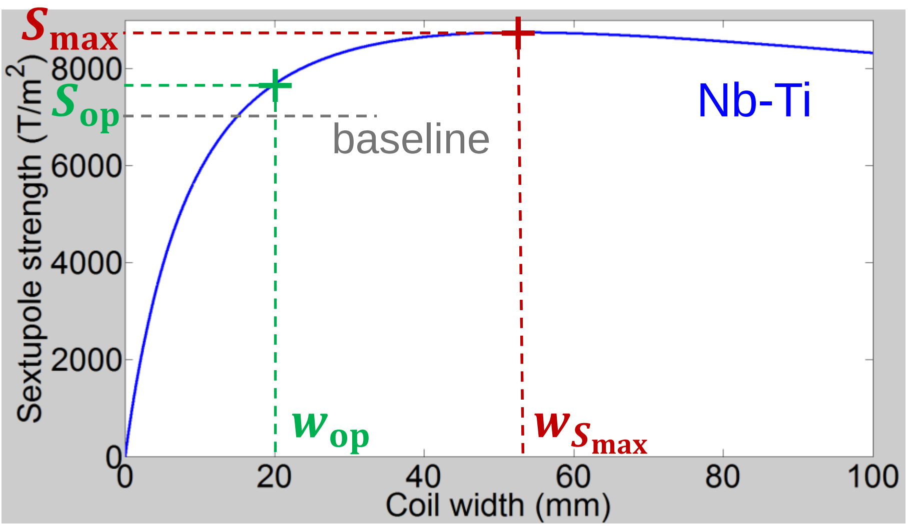
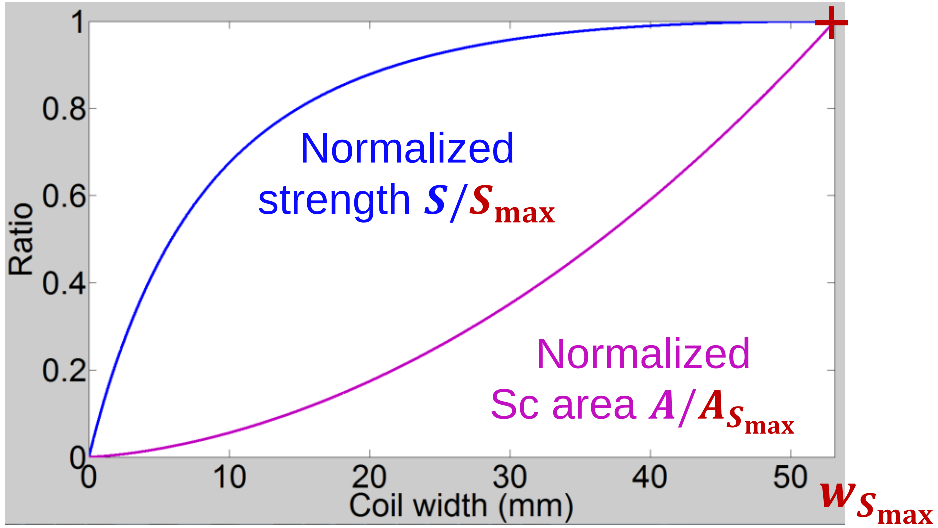
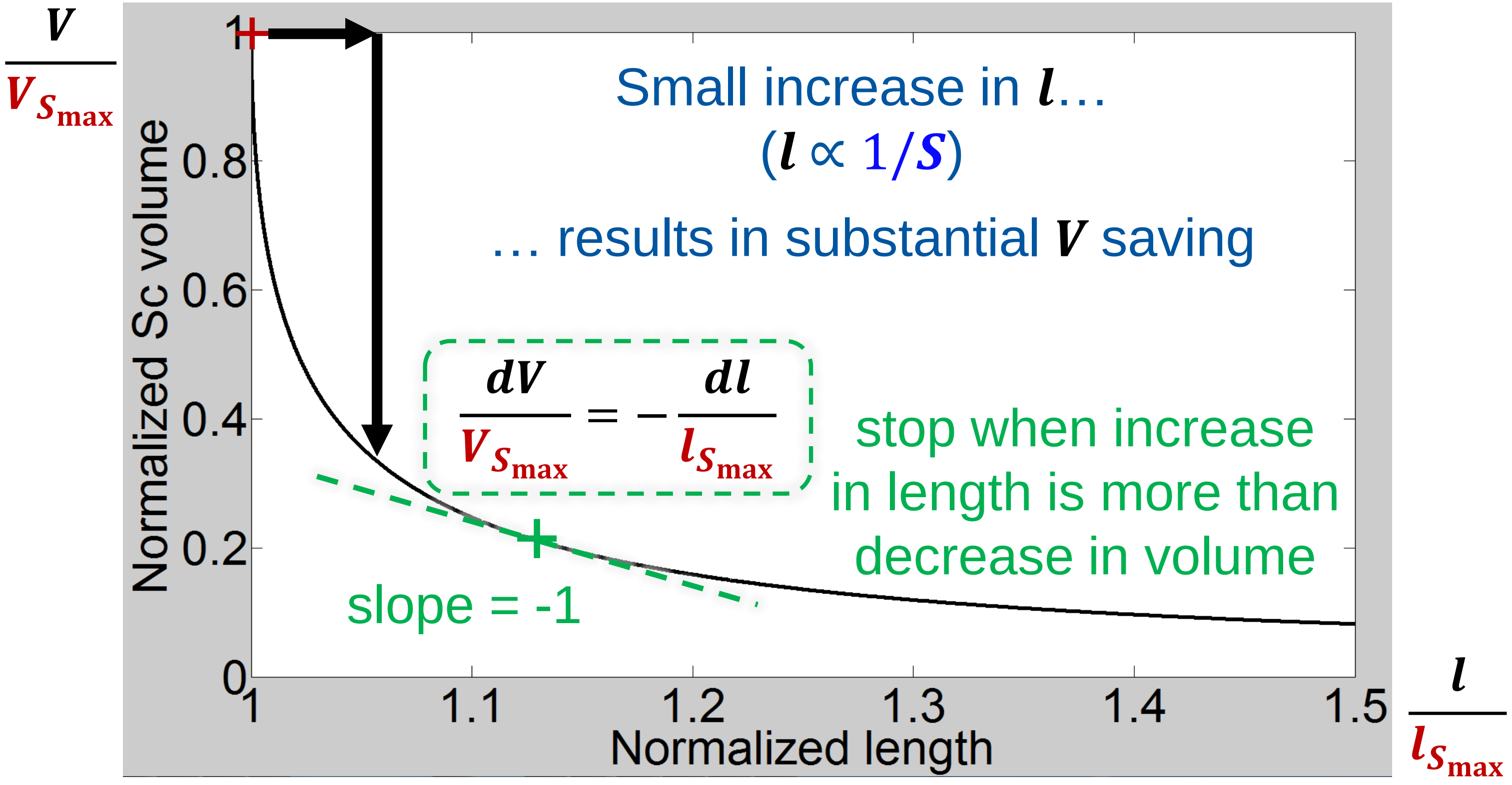






→ Here, increasing the minimum required length by ~13% divides the required Sc volume by ~5

w_{op} = 20 mm, S_{op} = 7700 T/m²

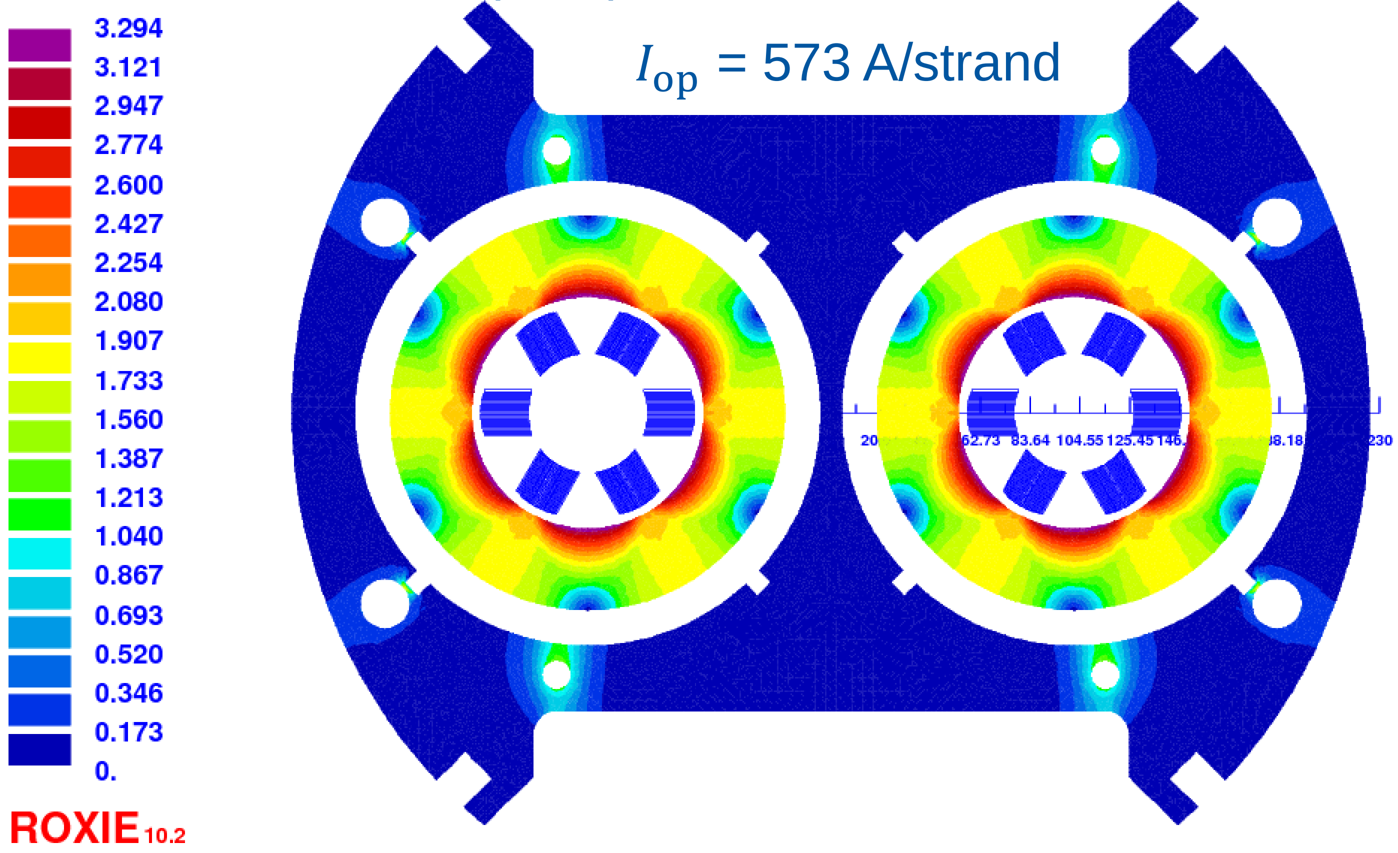
FCC lattice sextupole (MS) design

Conductor

Ribbon cable : (16x1)x26 CuSc = 2.69

Nb-Ti strand (bare) : 0.66x1.18 30 µm insulation

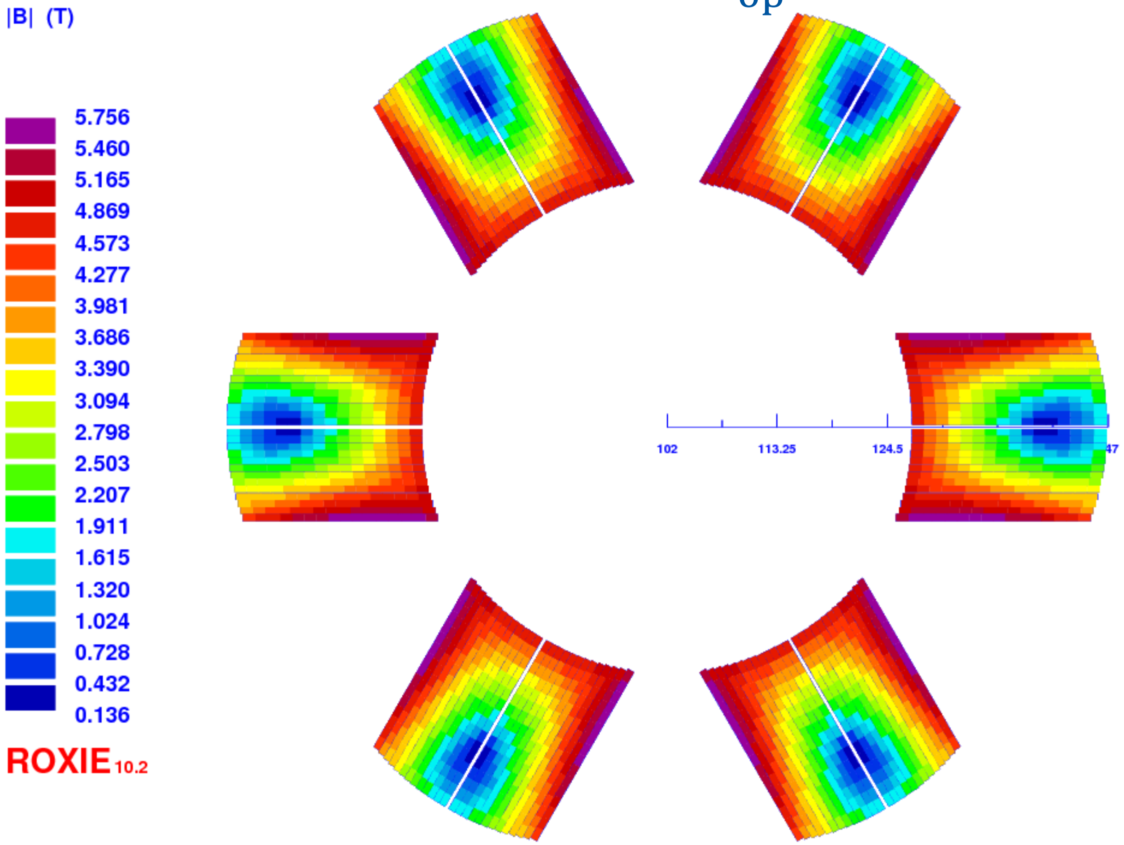
I_{op} = 573 A/strand



In one aperture

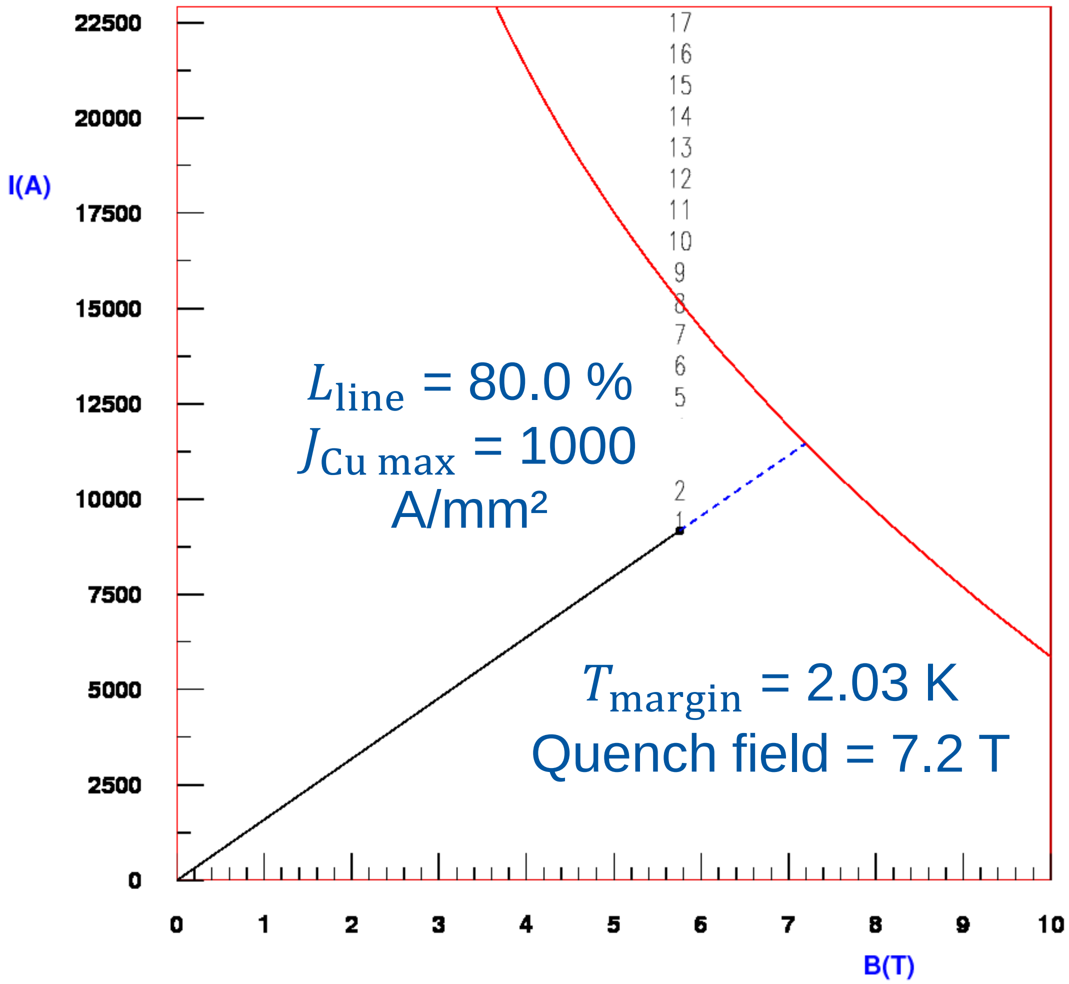
Strength = 7529 T/m² L_{op} = 246 mH/m

Peak field = 5.76 T E_{op} = 38.1 kJ/m

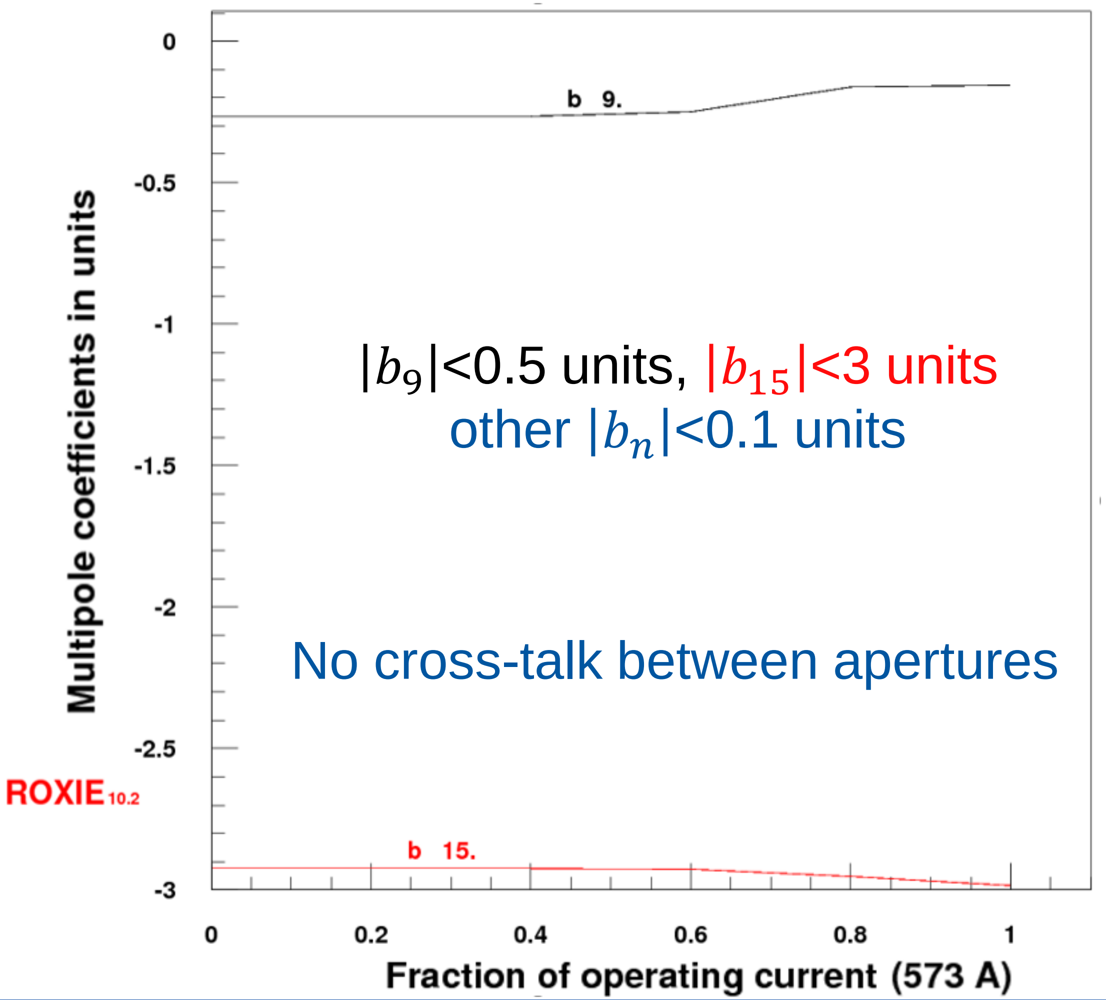


FCC lattice sextupole (MS) design

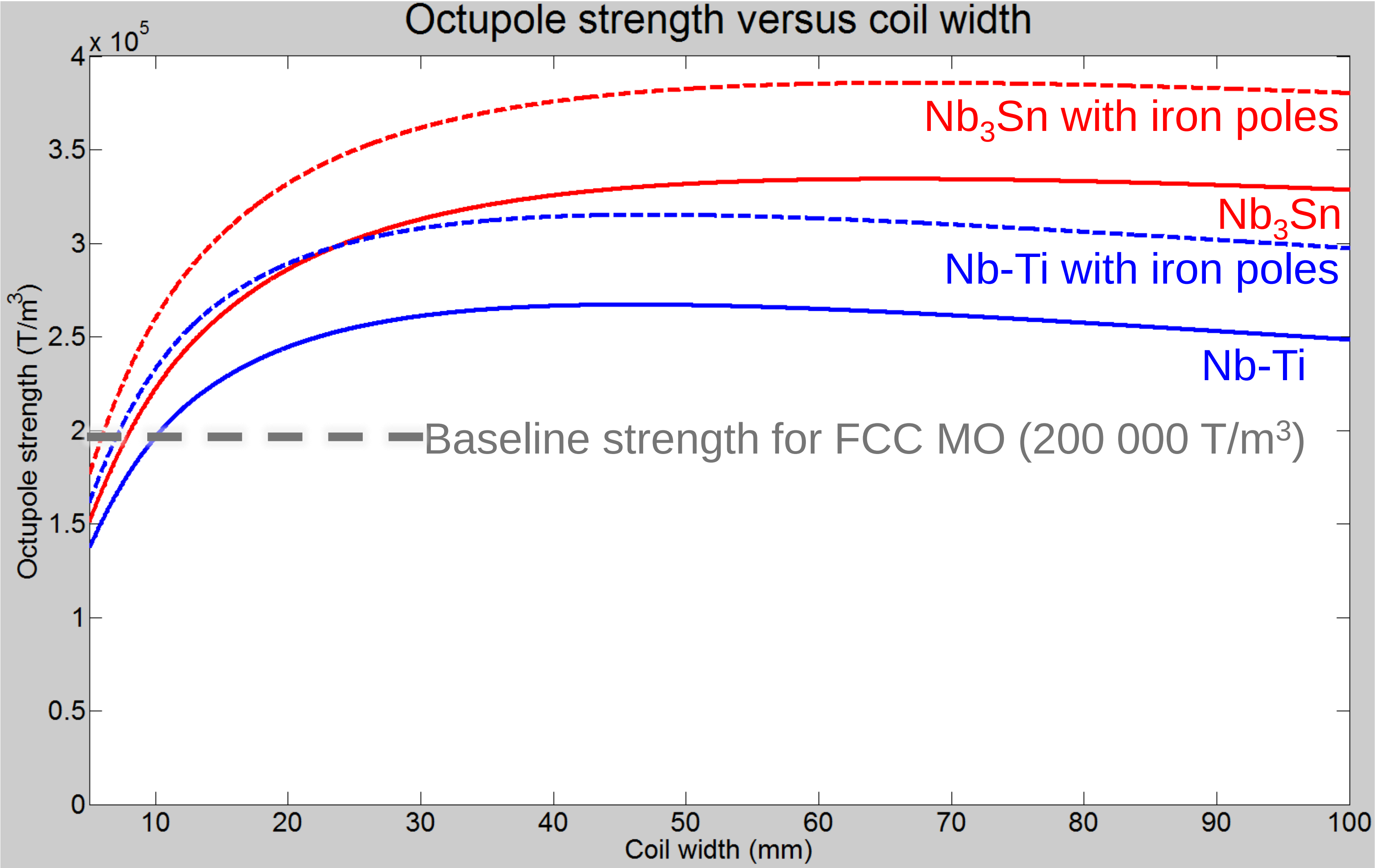
Margin & Protection



Field quality



Results for the Octupole



→ Nb_3Sn allows ~15-25% higher strength than Nb-Ti

→ iron poles allow ~15-20% higher strength but yield to poor field quality (b_{12}~50 units)

→ coil with Nb-Ti conductor and small width seems reasonable with respect to cost and complexity

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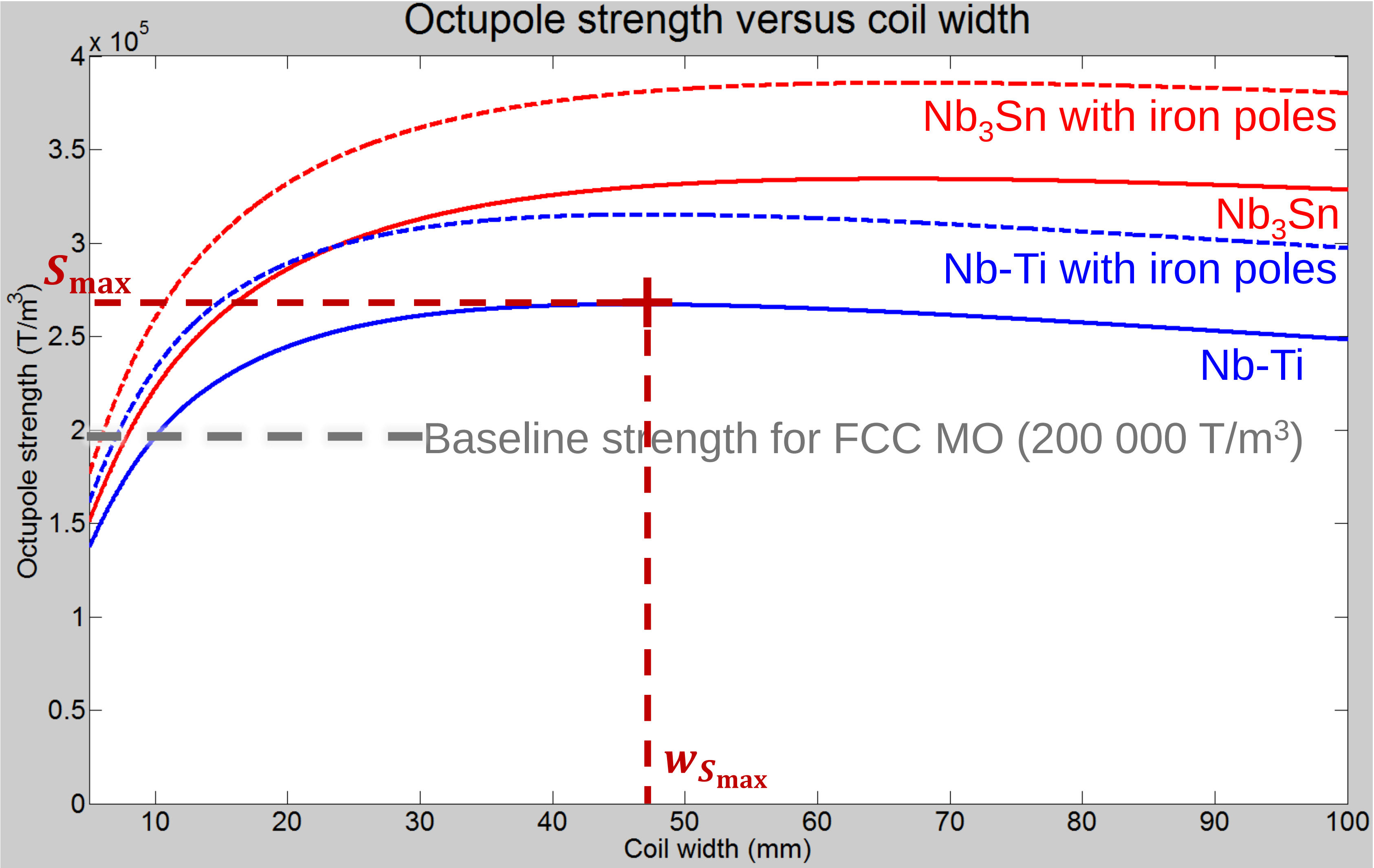

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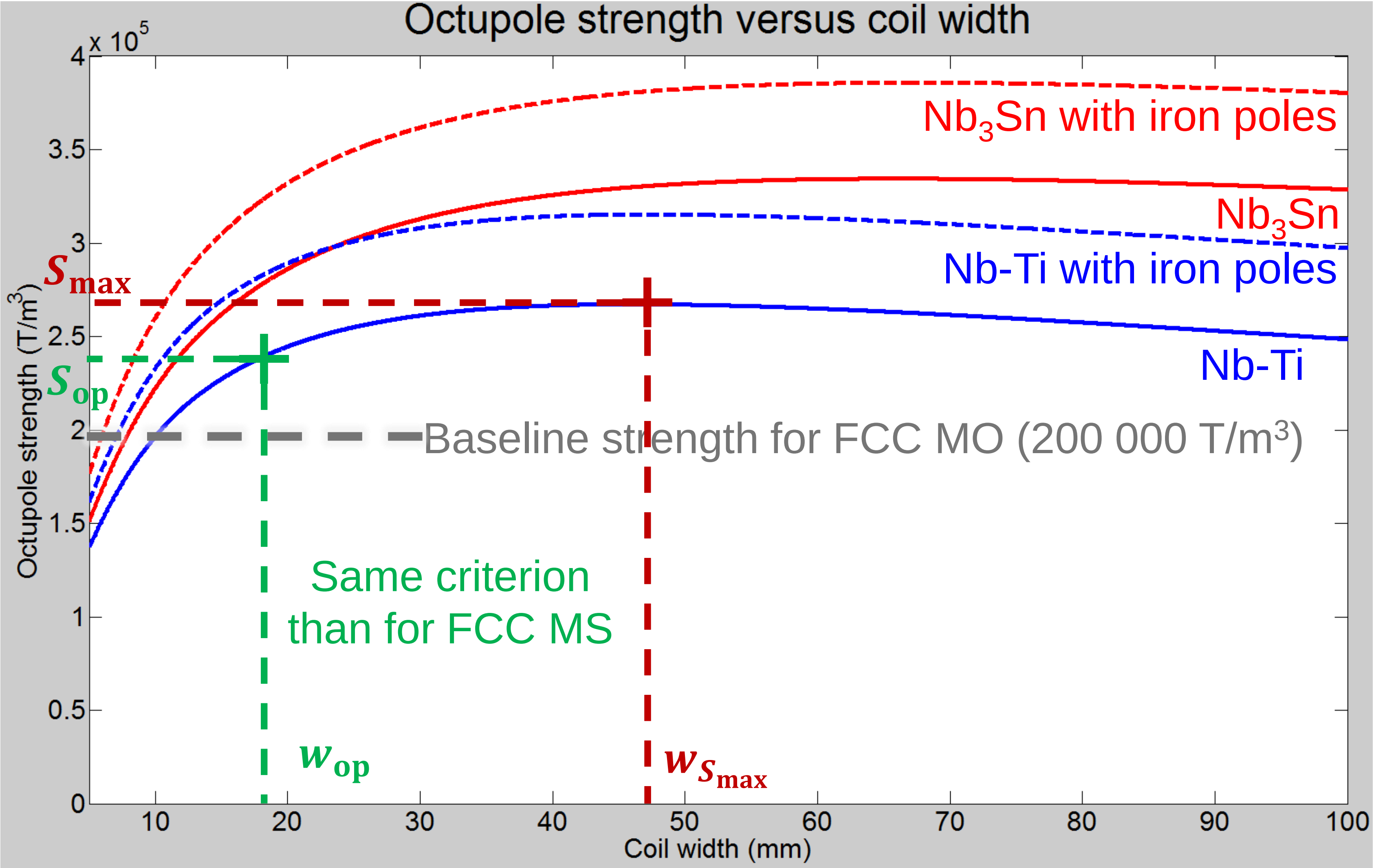

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w_{op} = 17 mm
S_{op} = 236 000 T/m^3

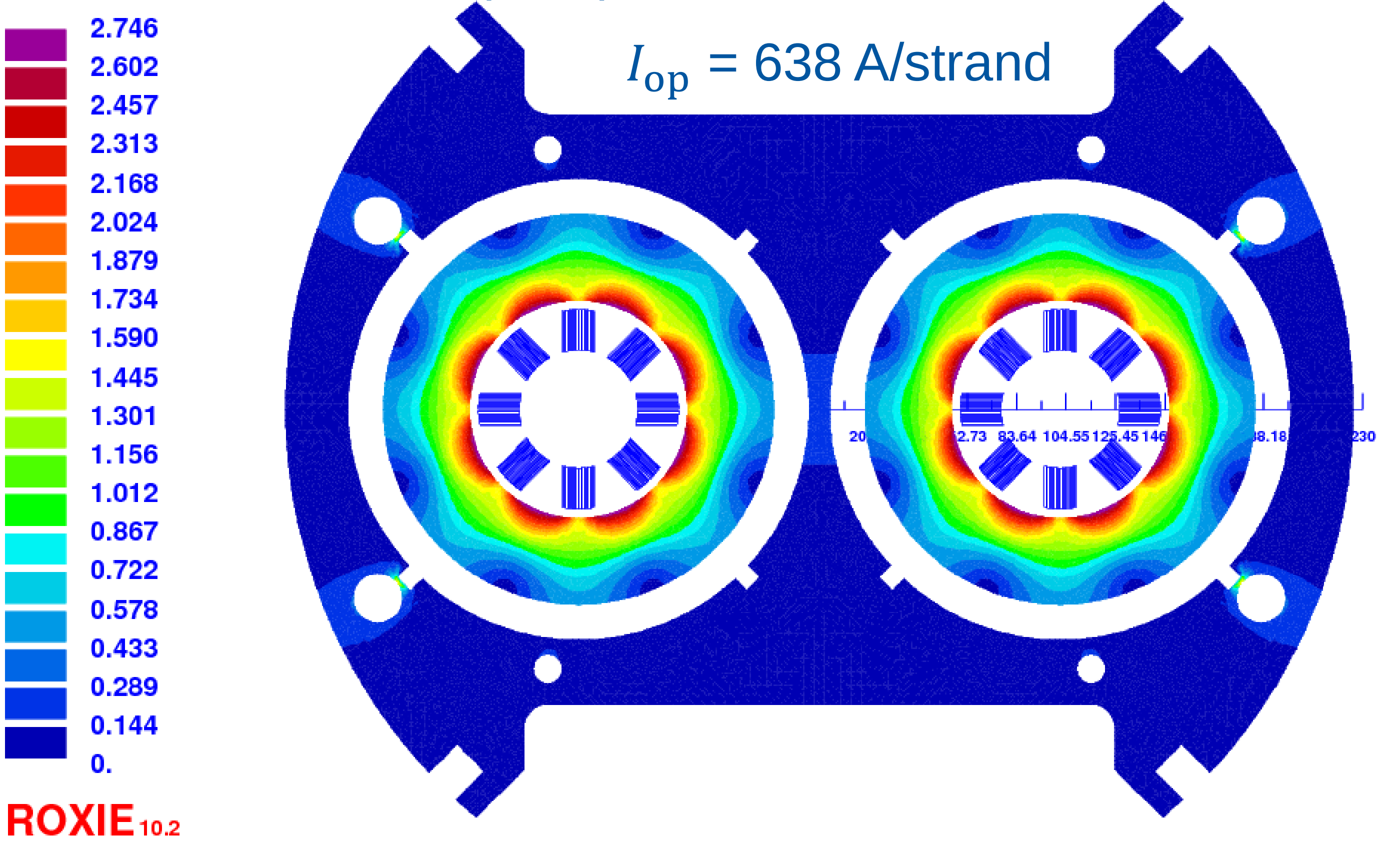
FCC lattice octupole (MO) design

Conductor

Ribbon cable : (14x1)x18
Nb-Ti strand (bare) : 0.69x1.18

CuSc = 3.48
30 µm insulation

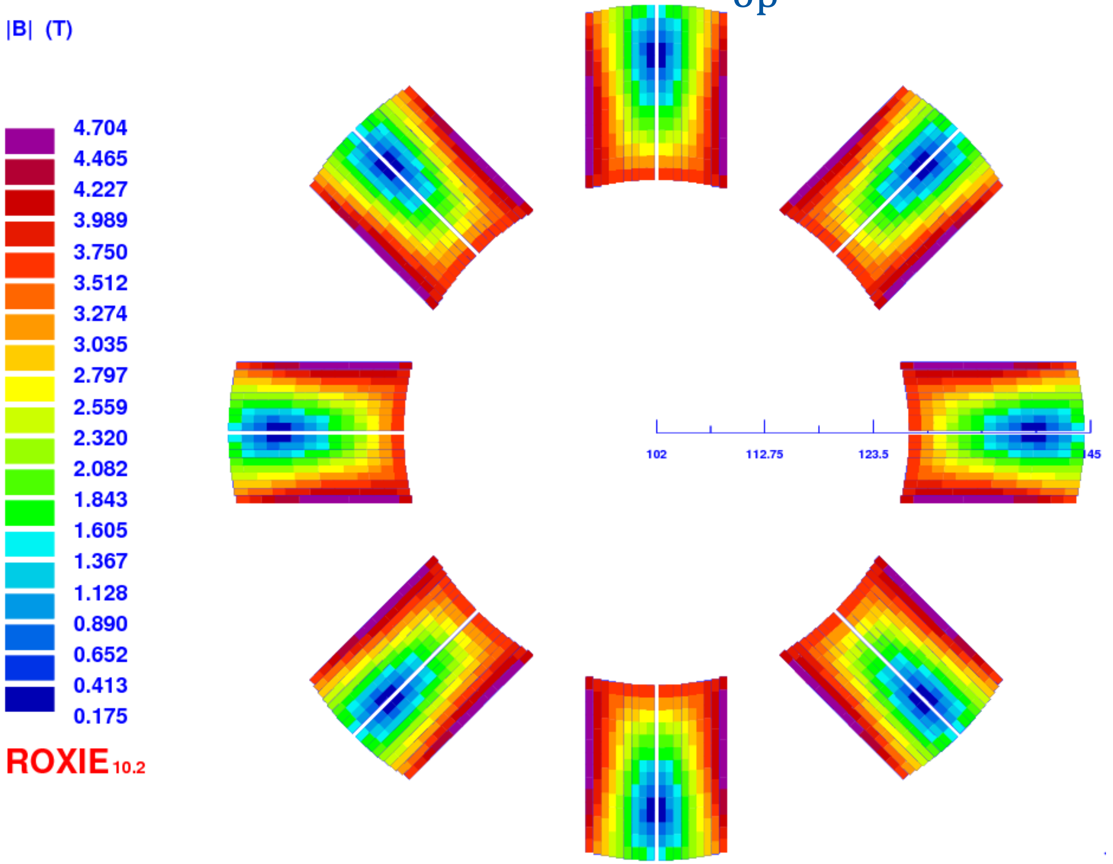
I_{op} = 638 A/strand



In one aperture

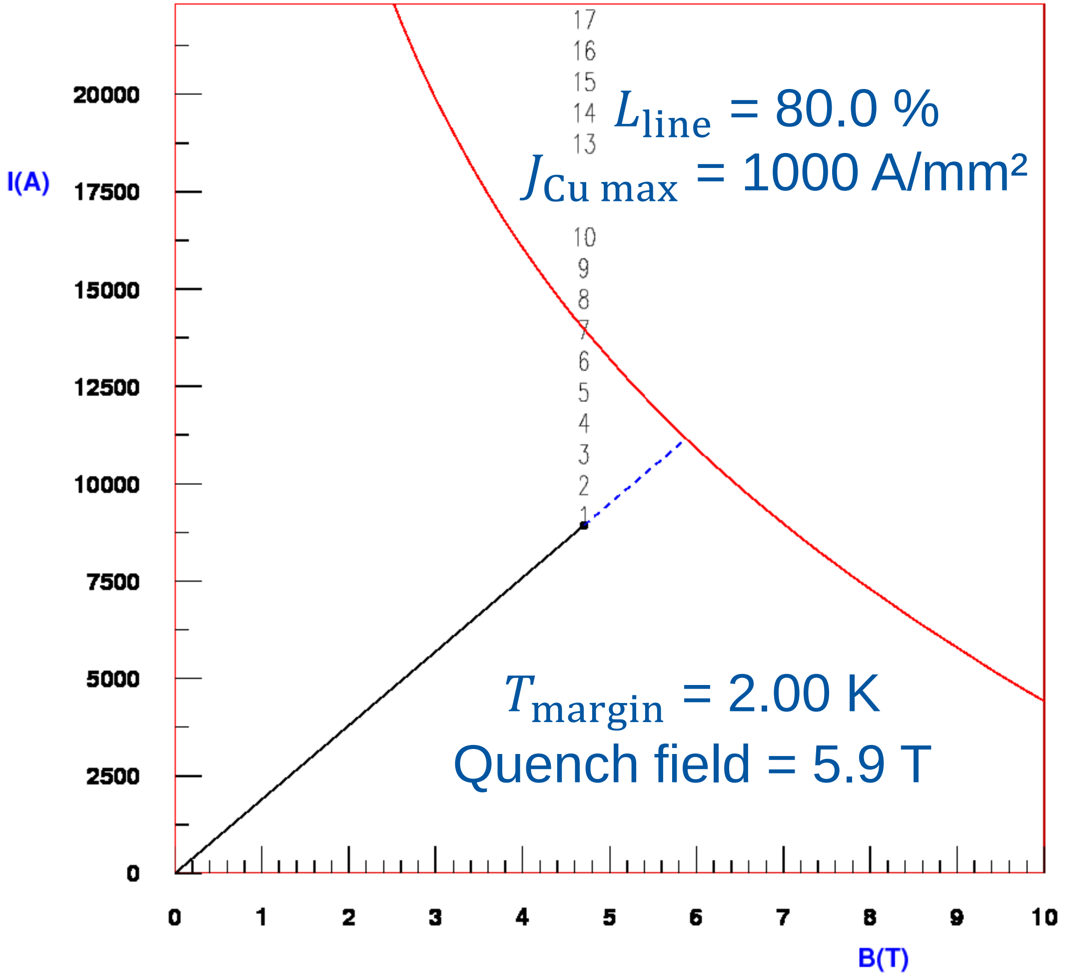
Strength = 229 062 T/m^3
Peak field = 4.70 T

L_{op} = 108 mH/m
E_{op} = 20.6 kJ/m

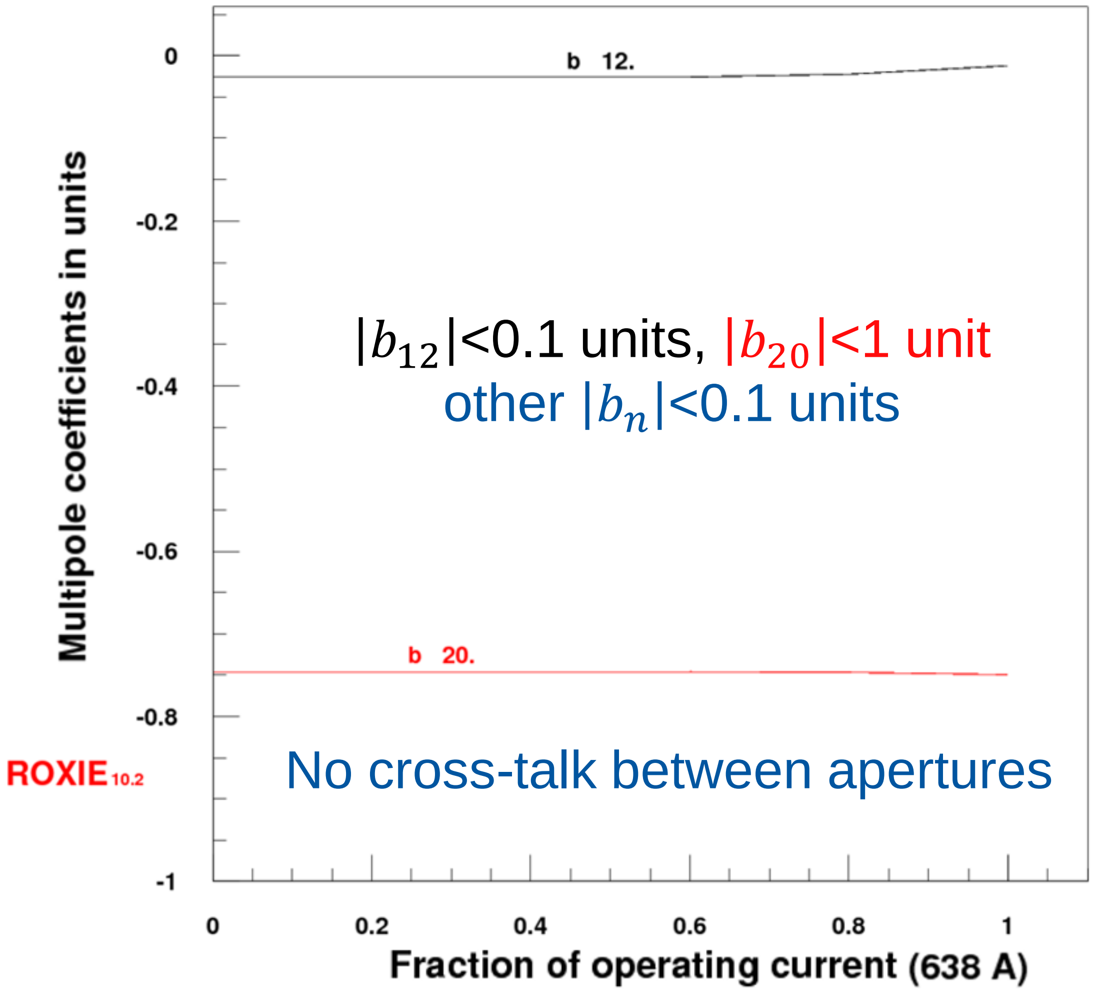


FCC lattice octupole (MO) design

Margin & Protection



Field quality

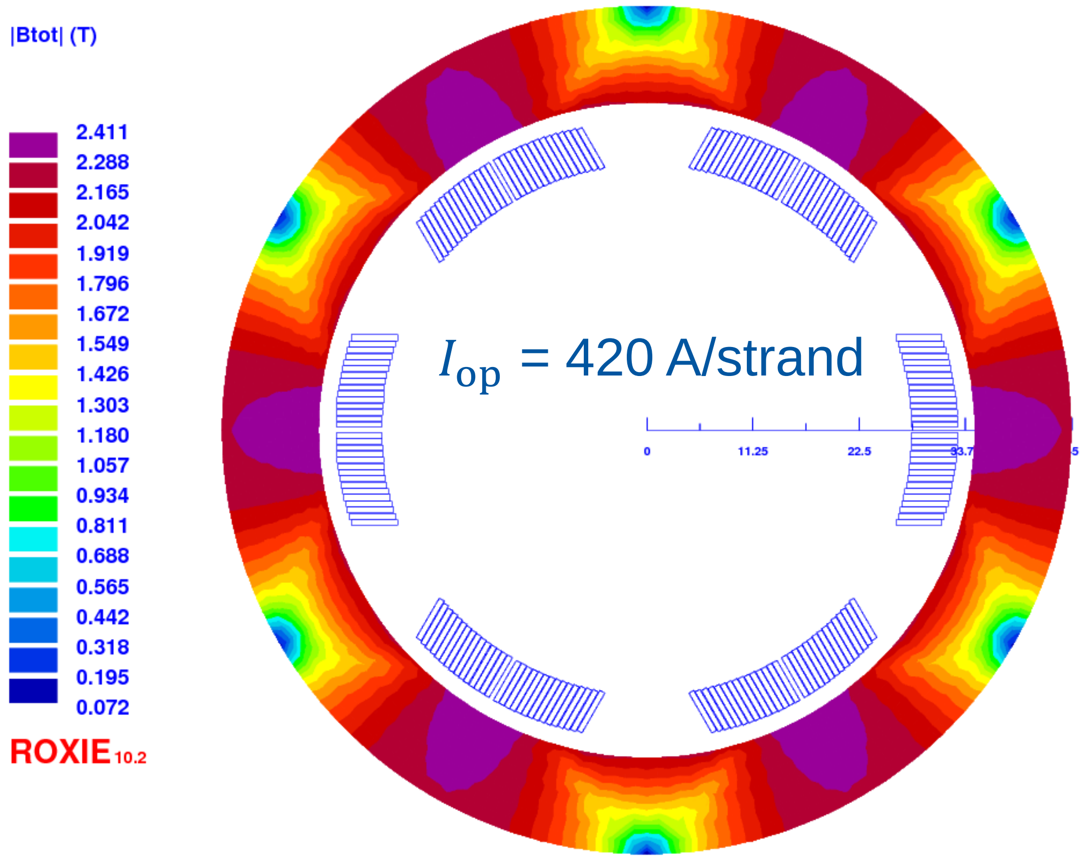


FCC sextupole corrector (MCS) design

Conductor

Ribbon cable : (5x1)x30
Nb-Ti strand (bare) : 0.60x0.93

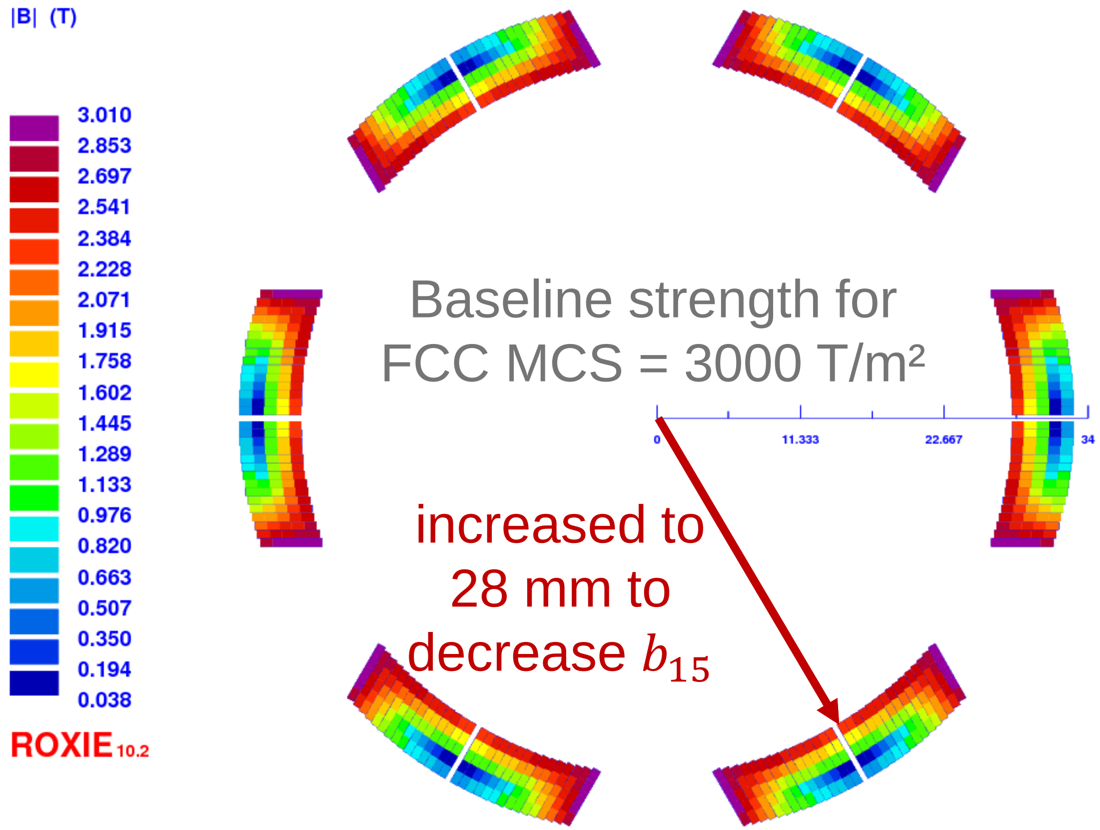
CuSc = 3.10
30 µm insulation



Single aperture

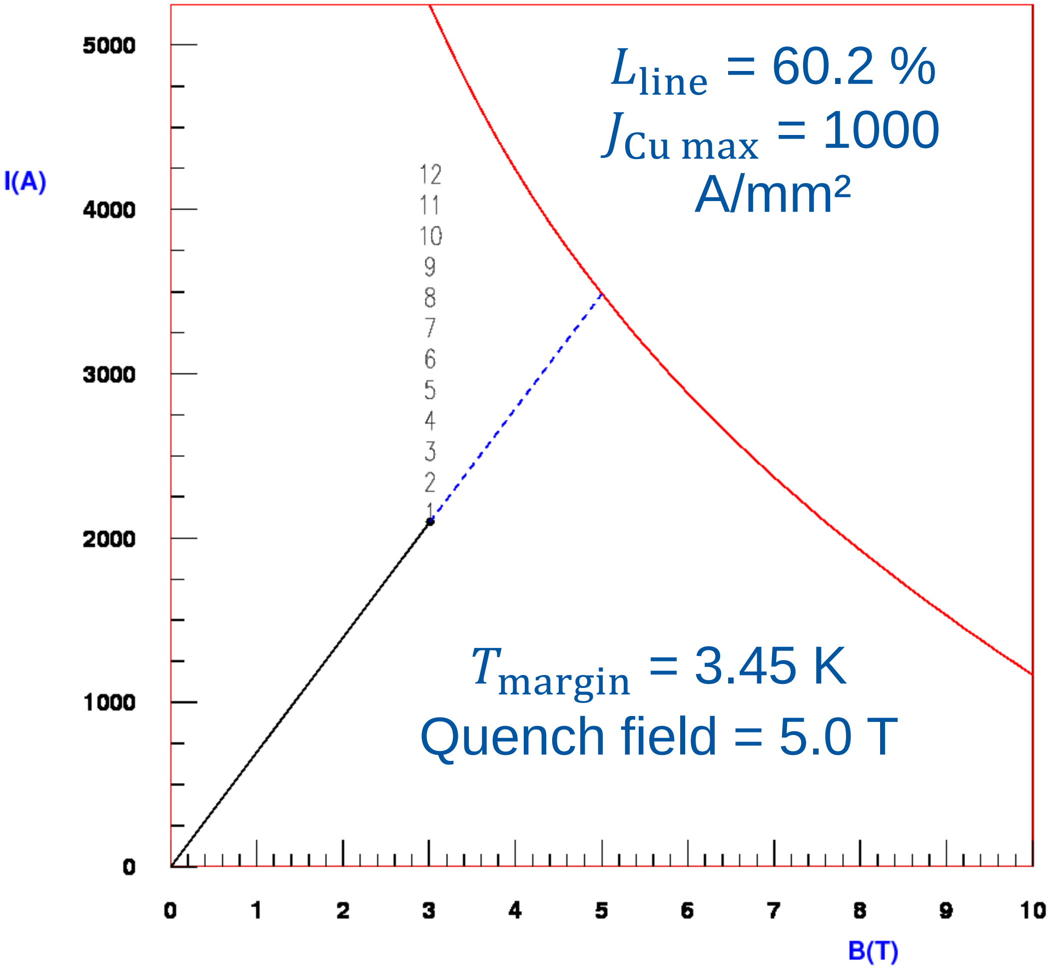
Strength = 3132 T/m²
Peak field = 3.01 T

L_{op} = 49 mH/m
E_{op} = 3.9 kJ/m



FCC sextupole corrector (MCS) design

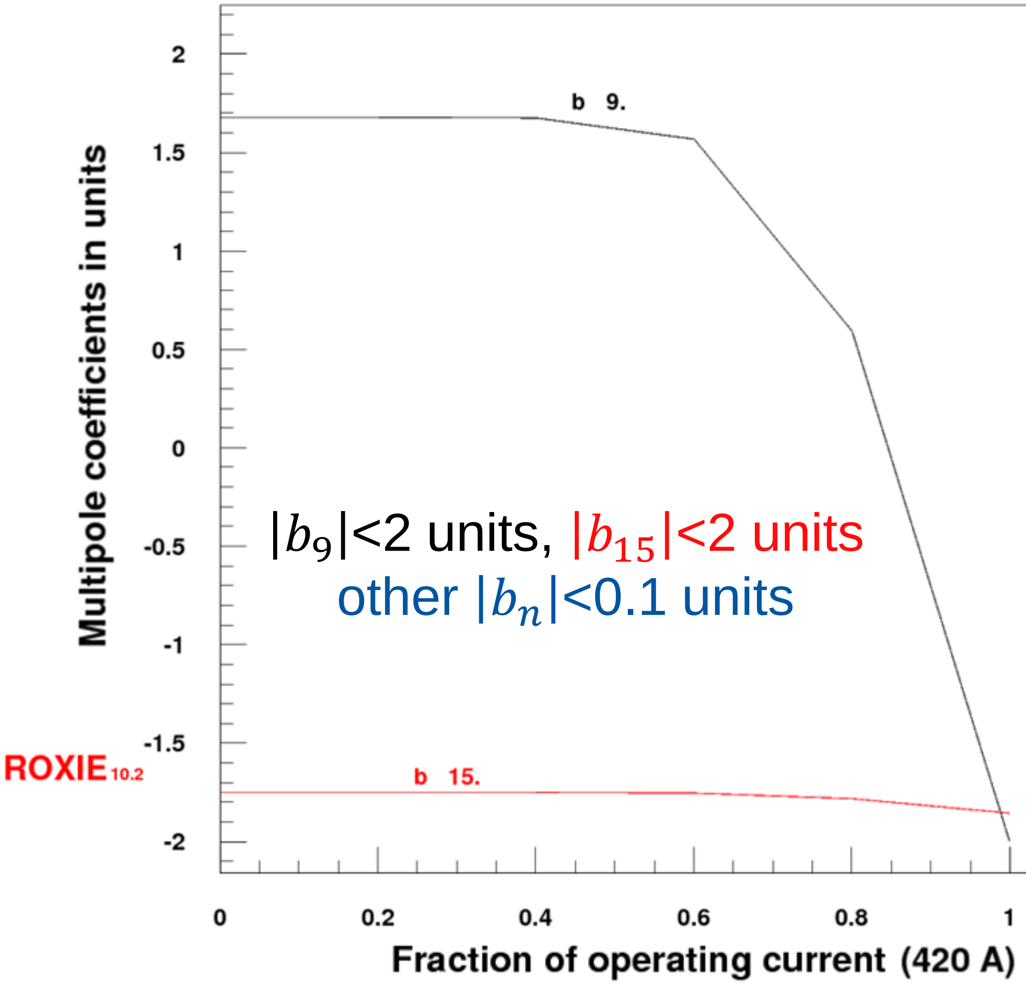
Margin & Protection



L_{line} = 60.2 %
$J_{\mathrm{Cu\ max}}$ = 1000 A/mm²

T_{margin} = 3.45 K
Quench field = 5.0 T

Field quality



$|b_9|$<2 units, $|b_{15}|$<2 units
other $|b_n|$<0.1 units

Conclusion

- Scaling law for *n*-pole magnets derived and used to define initial parameter space
- Electromagnetic design finalized
- Impregnated Nb-Ti conductors operated at 80% along the load line are challenging and may need futher development – an alternative is using non-impregnated Rutherford cables
- Quench protection considered and detailed calculations have been started
- Mechanical models of the proposed designs initiated

LHC Sextupoles and Octupoles (MS,MO,MCS)

Sextupole (MS)

Internal coil radius = 28.2 mm
Ribbon cables : (8x1)x28
NbTi Strand (bare) : 0.61x1.13
CuSc = 1.6
45 µm radial insulation
55 µm azimutal insulation
I_{op} = 550 A/strand
Strength = 4430 T/m²
L_{op}/coil = 97.6 mH/m
E_{op}/coil = 14.6 kJ/m
Peak field = 4.28 T
L_{line} = 60 %
$J_{Cu\,max}$ = 1300 A/mm²

Octupole (MO)

Internal coil radius = 28.2 mm
Ribbon cables : (2x1)x22
NbTi Strand (bare) : 0.61x1.13
CuSc = 1.6
60 µm radial insulation
60 µm azimutal insulation
I_{op} = 550 A/strand
Strength = 63100 T/m³
L_{op}/coil = 5 mH/m
E_{op}/coil = 0.7 kJ/m
Peak field = 1.67 T
L_{line} = 40 %
$J_{Cu\,max}$ = 1300 A/mm²

Sextupole (MCS)

Internal coil radius = 29.2 mm
Ribbon cables : (2x1)x26
NbTi Strand (bare) : 0.61x1.13
CuSc = 1.6
60 µm radial insulation
60 µm azimutal insulation
I_{op} = 550 A/strand
Strength = 1616 T/m²
L_{op}/coil = 7.3 mH/m
E_{op}/coil = 1.1 kJ/m
Peak field = 1.74 T
L_{line} = 40 %
$J_{Cu\,max}$ = 1300 A/mm²