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$_3$Sn) 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.
Assumptions

General assumptions:

- Sector coils
- Iron screen
- Optional iron poles
- Aperture radius $r_a = 25$ mm
- 20% margin on the load line
- $J_{Cu} \leq 1000$ A/mm$^2$ (rule of thumb to ensure the quench protection of a SC magnet powered in series)

Tools developed:

- Analytical expressions of strength $S$ and magnetic field on conductor $B$ 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 $J_{sc,c}$ dependence on $B$ for Nb-Ti and Nb$_3$Sn was programmed
Scaling law

Analytical expressions for 2N-upole sector coils with $N \geq 3$:

- Strength $S$ in T/m$^{N-1}$: $S = S_{\text{current}} + S_{\text{sat pole}}$

$S_{\text{current}} = \frac{\mu_0 \sqrt{3}}{\pi} \frac{J_0}{(r_a + w)^{N-2}} \left( \frac{1}{N-2} \left( \frac{r_a + w}{r_a} \right)^{N-2} - 1 \right) + \frac{A_\mu}{N+2} \left[ 1 - \left( \frac{r_a}{r_a + w} \right)^{N+2} \right]$  

$S_{\text{sat pole}} = \frac{\mu_0 N}{\pi} \frac{M_{\text{sat}}}{(r_a + w)^{N-1}} \left( \frac{1}{N-1} \left( \frac{r_a + w}{r_a} \right)^{N-1} - 1 \right) + \frac{A_\mu}{N+1} \left[ 1 - \left( \frac{r_a}{r_a + w} \right)^{N+1} \right]$  

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

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

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

1. $J_0 = \frac{f \cdot L_{\text{line}}}{1 + CuSc} \cdot J_{\text{sc,c}} \left( B_p \left( \frac{J_0}{L_{\text{line}}} \right) \right)$ → ensures that percentage along the load line is $L_{\text{line}} = 80%$

2. $J_0 = \frac{f \cdot CuSc}{1 + CuSc} \cdot J_{\text{Cu max}}$ → ensures that copper current density equal to $J_{\text{Cu max}} = 1000$ A/mm$^2$
Results for the Sextupole

$\rightarrow$ $\text{Nb}_3\text{Sn}$ allows $\sim$15-30% higher strength than $\text{Nb}$-Ti

$\rightarrow$ iron poles allow $\sim$10-15% higher strength but yield to poor field quality ($b_9 \sim 80$ units)

$\rightarrow$ coil with $\text{Nb}$-Ti conductor and small width seems reasonable with respect to cost and complexity
Selecting the optimal width

![Graph showing the relationship between coil width (mm) and sextupole strength (T/m²) with a baseline and Nb-Ti marks.]
Selecting the optimal width
Selecting the optimal width

Normalized strength $S/S_{\text{max}}$

Normalized Sc area $A/A_{S_{\text{max}}}$

Sextupole strength (T/m²)

Coil width (mm)
Selecting the optimal width

\( S_{\text{max}} \)

Normalized strength \( S / S_{\text{max}} \)

Normalized Sc area \( A / A_{\text{Smax}} \)

Normalized length \( l / l_{S_{\text{max}}} \)

Normalized Sc volume

\( V / V_{S_{\text{max}}} \)
Selecting the optimal width

Small increase in $l$…

($l \propto 1/S$)

Normalized strength $S/S_{\text{max}}$

Normalized Sc area $A/A_{S_{\text{max}}}$
Selecting the optimal width

Small increase in $l$…

$(l \propto 1/S)$

… results in substantial $V$ saving
Selecting the optimal width

Small increase in \( l \)…
\( (l \propto 1/S) \)
… results in substantial \( V \) saving

Stop when increase in length is more than decrease in volume

Slope = -1
Selecting the optimal width

- Here, increasing the minimum required length by ~13% divides the required Sc volume by ~5
- \( w_{\text{op}} = 20 \text{ mm}, \ S_{\text{op}} = 7700 \text{ T/m}^2 \)
FCC lattice sextupole (MS) design

**Conductor**
- Ribbon cable: (16x1)x26
- CuSc = 2.69
- Nb-Ti strand (bare): 0.66x1.18
- 30 µm insulation

\[ I_{op} = 573 \text{ A/strand} \]

**In one aperture**
- Strength: 7529 T/m²
- Peak field: 5.76 T
- \( L_{op} = 246 \text{ mH/m} \)
- \( E_{op} = 38.1 \text{ kJ/m} \)
FCC lattice sextupole (MS) design

**Margin & Protection**

- $L_{\text{line}} = 80.0 \%$
- $I_{\text{Cu max}} = 1000 \text{ A/mm}^2$
- $T_{\text{margin}} = 2.03 \text{ K}$
- Quench field $= 7.2 \text{ T}$

**Field quality**

- $|b_9| < 0.5 \text{ units}$
- $|b_{15}| < 3 \text{ units}$
- Other $|b_n| < 0.1 \text{ units}$

No cross-talk between apertures
Results for the Octupole

- **Nb$_3$Sn** allows ~15-25% higher strength than Nb-Ti

- Iron poles allow ~15-20% higher strength but yield to poor field quality ($b_{12} \sim 50$ units)

- Coil with Nb-Ti conductor and small width seems reasonable with respect to cost and complexity
Results for the Octupole

\[ \begin{align*}
\rightarrow & \quad \text{Nb}_3\text{Sn allows }\sim15\text{-}25\% \text{ higher strength than Nb-Ti} \\
\rightarrow & \quad \text{iron poles allow }\sim15\text{-}20\% \text{ higher strength but yield to poor field quality } (b_{12} \sim50 \text{ units}) \\
\rightarrow & \quad \text{coil with Nb-Ti conductor and small width seems reasonable with respect to cost and complexity}
\end{align*} \]
Results for the Octupole

Nb$_3$Sn allows ~15-25% higher strength than Nb-Ti.

Iron poles allow ~15-20% higher strength but yield to poor field quality ($b_{12} \sim 50$ units).

Coil with Nb-Ti conductor and small width seems reasonable with respect to cost and complexity.

$w_{op} = 17$ mm
$S_{op} = 236\,000$ T/m$^3$
FCC lattice octupole (MO) design

**Conductor**
- Ribbon cable: (14x1)x18, CuSc = 3.48
- Nb-Ti strand (bare): 0.69x1.18, 30 µm insulation

\[ I_{op} = 638 \, \text{A/strand} \]

**In one aperture**
- Strength = 229 062 T/m³
- Peak field = 4.70 T
- \( L_{op} = 108 \, \text{mH/m} \)
- \( E_{op} = 20.6 \, \text{kJ/m} \)
FCC lattice octupole (MO) design

**Margin & Protection**

- $L_{\text{line}} = 80.0\%$
- $J_{\text{Cu max}} = 1000\text{ A/mm}^2$
- $T_{\text{margin}} = 2.00 K$
- Quench field = 5.9 T

**Field quality**

- $|b_{12}| < 0.1 \text{ units}$, $|b_{20}| < 1 \text{ unit}$
- other $|b_{n}| < 0.1 \text{ units}$

No cross-talk between apertures
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

$I_{op} = 420$ A/strand

Baseline strength for FCC MCS = 3000 T/m²

Increased to 28 mm to decrease $b_{15}$
FCC sextupole corrector (MCS) design

Margin & Protection

\[ T_{\text{margin}} = 3.45 \text{ K} \]

\[ J_{\text{Cu max}} = 1000 \text{ A/mm}^2 \]

\[ L_{\text{line}} = 60.2 \% \]

Field quality

\[ |b_9| < 2 \text{ units, } |b_{15}| < 2 \text{ units} \]

other \[ |b_n| < 0.1 \text{ units} \]
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 further 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 azimuthal 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 azimuthal 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 azimuthal 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