Preload, training and pole movements in HL-LHC Nb$_3$Sn magnets

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Based on published data of MQXFA, MQXFB, 11T
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CONTENTS

- The issue and some historical remarks
- Training versus preload
- Field quality
A paradigm in magnet design is that the coil pole should always be in contact with the winding pole (nose) during energization.
The 80’s: 4 T, Tevatron epoque in US

“The field is enormously sensitive to these [pole] angles – they must be maintained to an accuracy of 0.025 mrad for adequate field quality. The force are so large that, with the elastic modulus available in the insulated coil packages the compression of the coil would exceed far this limit. As a result, when the coil is constructed, it is preloaded in the azimuthal direction to the extent that the elastic forces are greater than the magnet force”


Interesting to note that the main reason for Palmer and Tollestrup to have preload was field quality and not quench performance or fast training

With an incredibly small tolerance on the pole angle (misprint?)
The 90’s: 6 T, SSC prototypes in US

Principle: full preloading:
“To compensate the effects of the azimuthal component (of electromagnetic forces), the coils are pre-compressed azimuthally at room temperature”

Observation of higher loss of prestress from RT to 1.9 K:
“Originally, this (coil) unloading was not intended”

Indications that there is pole unloading:
“The fact that at high currents the pressure does not change while the Lorentz force is still increasing indicates that the collar pole unloads and that the average pressure exerted by the coil against the pole face becomes zero.”

Conclusions: no major treat to magnet operation:
“This shows that although unloading cannot be ruled out as a cause of some of the training quenches, it is not a major threat to the magnet operation”

The 90’s: 8 T, LHC models and prototypes

- The short model program (D. Tommasini et al.) confirm that full preload is not a hard requirement

“Although in some models the inner layer reaches zero clamping pressure at fields as low as 7 T (unloading field), these models had good training behaviour at much higher fields.”

Preloading

- The 00’s: 8 T, LHC production
- Prestress target at room temperature:
  - $70 \pm 15$ MPa inner layer
  - $75 \pm 15$ MPa outer layer
  - Due to large prestress loss during cool down, LHC dipoles have $\sim 30$ MPa at 1.9 K, i.e. only a partial preload

Prestress loss from room temperature to 1.9 K measured on short models
The 00’s: 12 T, LARP quadrupoles

“The specs for the magnet stress at 4.5 K were set to prevent any possible coil-island separation in the straight section and in the ends”

[S. Caspi, “Fabrication and test of TQS01”, IEEE TAS 17 (2007) 1122]
PRELOADING

- The 10’s: 12 T, HL-LHC production
- This is the topic of the seminar …
The 20’s: 16 T, FCC models
   - The design criteria aims at having full preload at 16 T

“We set a baseline design such that the coil is loaded until the nominal magnetic field in the aperture of 16T”

but soon after this sentence D. Schoerling at el. write

“This will leave the opportunity, in a model magnet, to explore different configurations of pre-stress, including the ones unloading the coil at a lower field than the nominal one (for example setting an unloading target at 15T).”

D. Schoerling, «16 T dipole design options: input parameters and evaluation criteria» Eurocircol-P1-WP5

B. Caiffi et al. write about the cos-theta design:

“At this stage of exploring, the coil must not detach from the pole tip (13). This is also a conservative constrain, aimed to avoid unwanted movements and consequent quenches in the magnet.”

In general, there is gap between requirements at the levels of design and during construction

- Everybody asks for full preload, but nobody is really convinced that this is needed
- Moreover in general the prestress loss in SS collared structures is much larger than modelled

This requirement can be extremely difficult to reach in the design phase for the FCC magnets, aiming at 16 T

- Is this really needed? Can we get rid of the full preload paradigm?
- What is the experience of HL-LHC Nb$_3$Sn magnets?
CONTENTS

- The issue
- Training versus preload
- Field quality
MQXF and 11 T

- We consider the MQXF and the 11 T programs, showing performance vs strain measurements of coil unloading
  - Note that we rely on measurements, not on models


Strain measurements in MQXF

- Strain gauges available for all models, clear evidence of unloading
  - The different level of loading for the different models was set to explore the parameter space
MQXFS1: conservative loading for the first magnet, unloading at 65% of short sample
MQXFS3a: larger loading for the first magnet, unloading at 75% of short sample
MQXFS5: upper limit loading for the third magnet, unloading at 85% of short sample (close to the theoretical condition)

Training and unloading in MQXFS5
PRELOAD VS PERFORMANCE

- MQXFS4: back to levels of MQXFS3 levels, that shall be used for prototypes

![Graph showing MQXFS4 performance](image)

**ITEQ**: MQXFS3 levels

Test at CERN

Unloading

Ultimate current

MQXFS4

Training and unloading in MQXFS5
CONCLUSIONS FOR MQXF

- MQXF preloaded at 65%-85% of short sample current
  - No visible impact of unloading on performance or training speed
Strain gauges available for four cases (2 single and 1 double aperture) clear evidence of unloading

- Much lower preload due to collar structure
**PRELOAD VS PERFORMANCE**

- **MBHDP102**: assembled with two single apertures already tested, low level of prestress
  - Note: lack of training due to previous powering

![Graph showing training and unloading in MBHDP102 (non virgin coils)]
PRELOAD VS PERFORMANCE

- MBHPP106: low level of prestress

Unloading

Ultimate current

MBHSP106
- MBHPP107: very low level of prestress
  - The best performance of 11 T short models
CONCLUSIONS FOR 11 T

- 11 T is using a very low level of preload (30%-60% of short sample)
  - No visible impact of unloading on performance or training speed

![Graphs showing quench numbers and ultimate currents for MBHDP102, MBHSP106, and MBHSP107.](image-url)
CONTENTS

 The issue

 Training versus preload

 Field quality
Field quality is a powerful tool to see coil pole movements

- Impact of partial loading on pole position, in case of no friction (FEM model)
- Preload at \((I/I_{\text{ult}})^2=0.50\), \((I/I_{\text{ult}})=0.70\), \(I/I_{\text{ss}} = 0.60\) at ultimate we have 0.25 mm pole displacement
- 0.1 mm gives 2.3 units of \(b_6\), so if we load at 60% of short sample \(b_6\) at ultimate should change of 5.7 units

![Pole unloading in MQXF](image)

E. Todesco
Field quality measurement: straight part

- We have to include in simulations the 3D effect (short magnet)
- We have to include in the simulation the magnetic shimming
- What is shown is the measurements minus the model
  - No movement, flat curve
  - Pole movement linear curve in $I^2$

$b_6$: Difference between measurements and model in the straight part of the MQXF short models
EVIDENCE OF POLE DISPLACEMENT: MQXF

- We see no evidence of unloading within 0.05 units, corresponding to 0.005 mm (5 micron) of pole displacement
  - If the pole were totally detached and free to move it would move of 0.1 to 0.2 mm according to different preloads

\[ b_6 : \text{Difference between measurements and model in the straight part of the MQXF short models} \]
EVIDENCE OF POLE DISPLACEMENT: 11 T

- We see evidence of unloading with 1 unit of $b_3$, corresponding to 0.04 mm of pole displacement
  - The displacement is larger for the less preloaded magnet (SP107)
  - If the pole were totally detached and free to move it would move of 0.2 mm according to different preload

![Graph showing $b_3$ vs $(V/V_{ult})^2$]

$b_3$: Difference between measurements and model in the straight part of the 11 T short models
CONCLUSIONS

- In the past, full preload at maximum current is always required in the design phase but it is rarely achieved in manufactured magnets.

- For HL LHC Nb$_3$Sn magnets:
  - MQXF was preloaded for 65-85% of short sample, and aims at operating at 85% (ultimate).
  - 11 T was preloaded for 30-60% of short sample, and aims at operating at 85% (ultimate).
  - Wide range of prestress can give performance – no evident correlation of performance with preloading.

- Magnetic measurements postprocessing provide the following relevant information:
  - MQXF does not show any sign of pole detachment within 5 micron (less than 0.05 units of $b_6$).
  - 11 T clearly shows pole detachment of up to 0.04 mm (1 unit of $b_3$) – this is 5 times smaller what expected from frictionless model.