US HL-LHC Accelerator Upgrade Project

Design Criteria for MQXFA Superconducting Elements

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Revision History

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Contents

1 Scope

This document presents the technical criteria and guidelines for the design and manufacturing of the superconducting components of the MQXFA magnets, to be installed in HL-LHC as the Q1 and Q3 inner triplet optical elements in front of the interaction points 1 (ATLAS) and 5 (CMS). A pair of ~4.5 meter long MQXFA magnets is assembled in a stainless-steel helium vessel, including the end domes, to make the Q1 Cold Mass or the Q3 Cold Mass. The US HL-LHC Accelerator Upgrade Project is responsible for the design, manufacturing and test of the Q1/Q3 Cold-Masses and the complete MQXFA magnets [1]. CERN provides the cryostat components and is responsible for integration and installation in HL-LHC [2].

The design criteria listed in this document result primarily from the R&D carried out by the LHC Accelerator Research Program starting in 2003 [3] and from fundamental R&D on high field conductors and magnets performed by national laboratories, universities and industrial partners under the DOE General Accelerator R&D program during the previous 10-15 years and continuing in parallel with the LARP program [4].

The scope of this document does not include the detailed specification of individual components of the MQXFA magnets. These specifications were developed based on the general findings and criteria described here, and are provided in separate documents.

2 Related US-HiLumi Project Documents

(1) US-HiLumi.Doc.36 MQXFA Functional Requirements Specification
(2) US-HiLumi.Doc.140 Q1/Q3 Cryo-assemblies Conceptual Design Report
(3) US-HiLumi.Doc.40 Specification for Quadrupole Magnet Conductor
(4) US-HiLumi.Doc.74 Specification for Quadrupole Magnet Nb_3Sn Cable
(5) US-HiLumi.Doc.826 MQXFA Electrical Design Criteria

3 Superconducting Strand

High critical current at high field is the main motivation for adopting Nb_3Sn technology in the low beta quadrupoles of the High Luminosity LHC. This leads to improved performance relative to Nb-Ti, in particular by increasing the aperture available to the beam and to the radiation absorbers located in the magnet bore [5]. However, several critical requirements need to be addressed in order to realize the potential of Nb_3Sn in accelerator magnets. A primary concern is avoiding thermo-mechanical instabilities driven by flux-jumps at low field, due to the combination of high J_c and large filament diameter [6]. The heat release associated with flux-jumps can propagate along the conductor causing a quench in the magnet low-field regions well below the design current. In order to control these effects, Nb_3Sn wires are composed of individual superconducting units (sub-elements) embedded in a pure Cu matrix. The critical parameters to achieve sufficient stability are small sub-element size and high thermal conductivity of the matrix, which can be characterized by the ratio the electrical resistivity at 273 K divided by that at 20 K (Residual Resistivity Ratio or RRR) [7-8]. Small sub-element size and twisting of the wires also help control the effect of strand magnetization on field quality.

Finally, a mechanically robust wire design is critical to minimize damage to the sub-elements due to cabling and applied loads.

The Nb_3Sn strand technology adopted by HL-LHC AUP is the Rod-Restack-Process RRP® developed by Oxford Superconducting Technology (Now Bruker-OST since 2017) with support from the DOE OHEP Conductor Development Program [9]. RRP wires are composed by an array of hexagonal sub-elements embedded in a high purity copper matrix. Each sub-element is composed of Cu-clad Nb rods (and a few Nb-Ti rods for doping purposes) assembled around a Sn core and surrounded by a Nb barrier. During the first part of the reaction, below 600°C, the Cu diffuses into the sub-element core and mixes with the Sn. Then, above ~600°C, the Sn diffuses out into the Nb rods and barrier, producing a Nb_3Sn ring with a Cu/void core within each sub-element [10]. The Nb barrier is not fully reacted in order to protect the Cu matrix from Sn contamination. This design can provide high fractions of Nb and Sn with optimal stoichiometry and dopant concentrations, leading to higher current-carrying capacity than has been achieved with other approaches. However, each Nb_3Sn bundle has an effective diameter comparable to the sub-element size (40-80 µm) requiring a careful optimization of the conductor and magnet parameters in order ensure sufficient stability and minimize hysteretic losses.

The RRP® conductor was first validated in short dipole models built by the HEP General Accelerator Development (GARD) program, where it demonstrated the ability to sustain fields above 15 T in accelerator-type dipole coils, operating under mechanical stresses approaching 200 MPa [11]. Subsequently, it was utilized in a large number of model quadrupoles and technology tests by the LHC Accelerator Research Program [2]. These models explored a range of magnet parameters and prompted in-depth studies and further optimization of the wire design and processing, in particular to improve stability and strain tolerance [13-14-15]. The main guidelines from these studies are:

- The residual resistivity ratio (RRR) of the stabilizing copper after heat treatment should be above 150. High RRR (above 100) needs to be preserved throughout the cable and coil fabrication process, magnet assembly, cool-down, and powering.
- Reducing the ratio of tin to niobium provides better control over RRR and flexibility for heat treatment schedule at the expense of a slightly lower J_c.
- Alloying with Ti allows a more robust heat treatment schedule with lower reaction temperatures and provides a higher resilience to applied strain.
- The combined strand diameter and number of sub-elements should be such to maintain the effective filament diameter (roughly corresponding to the sub-element size) below ~55 µm.
- The heat treatment parameters aim at maximizing the critical current density at high field, while preserving high RRR. Experience has shown that $J_c > 2.4$ kA/mm^2 (12 T, 4.2 K) can be reliably achieved while meeting the above constraints on sub-element diameter and RRR.

3.1 Optimization of the wire design for high field accelerator magnets

First generation RRP wires for accelerator applications used the 54/61 layout, an arrangement of 61 hexagonal elements in which the innermost 2 layers (7 elements) are made of pure copper, and the subsequent 3 layers (54 elements) are made of Nb_3Sn. This design achieves J_c>3 kA/mm^2 (12 T, 4.2 K) with RRR > 250 and multi-km piece length. However, the effective filament size is about 80 µm in a 0.8 mm wire. The main focus of the wire development performed in conjunction with the LARP magnet R&D program was to reduce the effective filament diameter while preserving high J_c and RRR. In particular, a new RRP design with using 127 sub-elements (108 superconducting and 19 pure copper) was fully validated in LARP models and adopted as the new baseline in 2012. The reduction in effective filament size is about 30 µm in a 0.8 mm wire. However, the new design required a careful optimization in order to achieve high critical current and RRR, as well as long piece length.

The first modification is decreasing the amount of Sn within the sub-element. The optimal Nb:Sn atomic ratio was found to be 3.6:1, compared with 3.4:1 used in the 54/61 design. This corresponds to a reduction of the Sn content by about 5%. With the lower Sn fraction, RRR values increase from 50-100 to 150-250 with minimal impact (a few %) on J_c [16].

The second modification is an increase of the Nb fraction allocated to the barrier relative to that allocated to the rods surrounding the Sn core. A 30% increase of the barrier thickness was shown to roughly double the RRR for filament size in the range of 40-50 µm. Similar to the reduction in Sn content, this change causes some loss of J_c since the layer J_c in the barrier region tends to be lower than that of the filament region.

The third modification is the addition of Ti rods in the sub-element pack. The addition of either tantalum or titanium as dopants has long been known to increase the upper critical field in Nb_3Sn wires, and in turn the critical current density at high field [17]. Optimum compositions are reached at about 1.5 at.% Ti or 4 at.% Ta. While Ta-alloyed Nb rods were used in first-generation RRP wires, subsequent studies demonstrated that Ti-doping brings significant advantages in terms of strain tolerance and heat treatment parameters, as detailed in the following sections. In addition, the use of Ti was shown to provide better uniformity of composition and properties [18]. Following these studies, Ti-doped wires were introduced in HQ/LHQ model coils and were eventually adopted as part of the LARP wire specification.

Improvements in the processing steps were also critical in developing wires with a larger number of sub-elements. Examples include better rod cleaning and modifications of the drawing schedule. These refinements account for approximately 10% of the achieved J_c [14].

3.2 Dependence of Nb_3Sn superconducting properties on axial strain

Nb_3Sn properties are strongly dependent on applied strain. These variations are reversible within a limited range, beyond which the conductor will not recover its original properties when returned to the original state. In the reversible regime, the strain state affects the transport current capability through changes in the upper critical field, critical temperature, and maximum bulk pinning force [19]. At larger strain, cracks develop in the brittle A15 material causing irreversible damage and performance degradation.

The fundamental factors which determine the dependence of the superconducting properties on axial strain are well understood [20]. Results from computational models based on microscopic theory are consistent with experimental measurements performed in highly homogeneous laboratory samples. However, wires are more complex due to compositional inhomogeneity and thermal contraction differentials between matrix materials and Nb_3Sn [21]. As a consequence, the zero applied axial strain condition during sample preparation at room temperature for the wire corresponds to a non-zero 3D strain (negative axial strain) at the filament level at cryogenic temperature, causing a shift in the strain dependence of the critical properties. In order to describe these effects, scaling relationships were developed by combining microscopic theory and fitting parameters derived from experimental data [22].

Building on this framework, specific studies of strain dependence and limits in LARP wires were performed with the following results [15]:

- The $I_c(\varepsilon)$ curve peaks at a tensile strain ε_{max} —corresponding to a minimum 3D strain experienced by the Nb_3Sn filaments after cool-down from the heat treatment temperature to 4 K. Taking ε_{max} as reference, the irreversible tensile strain limit (ε_{irr}) is ~0.25% in Ti-alloyed wires, while a much lower limit of ~0.04% is found in Ta-alloyed wires for heat treatments at 640 °C for 48 hours, aiming at optimizing critical current density and RRR.
- The reversible reduction of the critical current density at $\varepsilon_{max}+\varepsilon_{irr}$ is of the order of 15%, and a similar reduction is found at $\varepsilon_{max}-\varepsilon_{irr}$
- The initial comparison between Ti and Ta doping performed on RRP wires with 0.7 mm diameter and 54/61 architecture (sub-element size ~65 μm) is also representative of RRP wires with higher sub-element count and smaller sub-element size.

A detailed study of the effects of heat-treatment temperature revealed a precipitous change of the irreversible strain limit as a function of this parameter, over a very narrow temperature range of 25°C or less. This behavior was named the Strain Irreversibility Cliff (SIC), and occurs in RRP wires doped with either Ti or Ta [23]. SIC is shifted to lower temperatures by about 10 to 12°C for the Ti-doped wires. The remarkable abruptness of SIC adds to the complexity of selecting heat-treatment conditions that optimize the wire's critical-current density, RRR, and ε_{irr} all at once. Such optimization was found to be met only over an extremely narrow temperature range of ±3°C or less in RRP wires having a standard Sn content. Fortunately, wires with reduced-Sn content exhibit a much wider range of ±60°C [24].

3.3 Dependence of Nb_3Sn superconducting properties on transverse compressive stress

Studies of tensile stress and strain are useful to investigate the fundamental properties of Nb_3Sn and to characterize and compare different wire designs. However, conductor degradation due to transverse compressive stress from pre-load and Lorentz forces is the main concern in accelerator magnets. Critical current measurements performed in wires show much higher sensitivity to transverse loads, with comparable degradation occurring at about one order of magnitude lower stress than with axial loads [25]. However, it is difficult to design a wire experiment which reproduces the conditions experienced after cabling, coil fabrication, magnet assembly and powering. For this reason, experiments performed on cables and magnets under transverse loads are the primary basis for defining the design criteria in this area, as described in section 5.2.

3.4 Dependence of Nb_3Sn superconducting properties on the heat treatment

The heat treatment schedule needs to be developed in conjunction with the wire design in order to achieve optimal properties. In general, higher temperature and duration of the reaction stage result in higher critical current at the expense of lower RRR, with a potential negative impact on magnet stability and protection.

In addition to improved strain tolerance over a wider range of reaction temperature, Ti doping was found to provide faster development of the Nb_3Sn layer and lower the optimal reaction temperature for maximum J_c and B_{c2} by about 30°C (from ~695°C in Ta-doped wires to ~665°C) [13]. This has significant advantages since at higher reaction temperatures it is difficult to control the reaction time to achieve high J_c while preventing over-reaction of the barrier resulting in Sn contamination of the matrix. With the adjustments in barrier thickness and Sn content described in section 3.1 it is possible to approach the 665°C reaction temperature while maintaining high RRR, provided that the duration of the high temperature stage is limited to ~50 h. The 665°C temperature also provides good margin with respect to the 640°C limit below which a significant drop of ε_{irr} was observed in recent studies [23-24].

3.5 Critical current parametrization and short sample limit calculation

The main factors which determine the critical current density of Nb_3Sn at high field are the maximum pinning force density and the upper critical field. These parameters depend on the microscopic characteristics of the conductor and their optimization requires identifying how composition, grain size and strain state influence the superconducting properties. A comprehensive review of studies performed in homogeneous samples is provided in [19]. This fundamental knowledge provides a basis for developing parametrizations of wire critical current as function of field, temperature and strain [22-26]. Systematic measurement and characterization of strands used in LARP model magnets led to the adoption of standard methods for computing the conductor-limited short-sample performance, including the J_c scaling, as well as self-field and strain parameters. Critical current measurements of extracted strands at 4.2 K are used to calculate the fitting parameters which in turn allow calculating the conductor and magnet performance at 1.9 K. A detailed description of the critical current parametrization, wire characterization and magnet short sample calculation methods developed by LARP and adopted for MQXFA is found in [27].

3.6 Stability current

Transport current measurements of wire and cables can be used to characterize the stability thresholds and their dependence on conductor parameters. Standard critical current measurements are performed by increasing the current at constant field until the onset of a resistive voltage. If the conductor is unstable, quenches will occur at currents significantly lower than the critical current. These instability quenches are typically observed at lower applied field while the resistive transition can be reached at higher field. While these experiments can give an indication of the stability margins, performing field sweeps at constant current (following the approach in [28]) was found to be a more effective approach to studying instabilities in high performance Nb_3Sn wires and cables [7]. With this approach, a stability current I_s can be defined as the highest current for which a full field sweep can be performed without quench. These measurements are affected by the heat transfer within the conductor and with the coolant bath, as well as the disturbance spectrum which are quite different in wire, cable or magnet experiments. Nevertheless, they provide useful information in assessing the stability margin for a specific conductor and magnet application. For LARP models, a factor of two margin between the stability current and the operating current was used as a practical reference to avoid performance limitations due to instabilities, provided that no significant conductor damage and I_s degradation occurs during cabling, coil fabrication, magnet assembly and test.

3.7 Radiation effects

The radiation load in HL-LHC IR quadrupoles is dominated by secondary particles from proton-proton collisions emitted at small angles with respect to the beam direction. While less than 10% of the secondary particles escape the detector and absorbers protecting the IR magnets, they carry a large fraction of the total energy, corresponding to 3.8 kW of power on each side of the interaction points at the nominal HL-LHC luminosity of 5×10^{34} $cm^{-2}s^{-1}$.

The radiation effects on Nb_3Sn superconductor and copper stabilizer are generally characterized as a function of integrated neutron fluence and DPA (displacements per atom) over the magnet lifetime [29]. Since impurities and dislocations can act as pinning centers, the critical current density can initially increase with dose, until more extensive damage occurs and J_c starts to degrade. The initial increase is less pronounced in materials which are already fully optimized for flux pinning, such as ternary Nb_3Sn. In [30], the threshold for degradation was found to be around 1 10^{19} cm^{-2} for binary material but only 0.5-1 10^{18} cm^{-2} for ternary. However, recent studies performed on the Ti-doped RRP wires selected for MQXF [31] showed that J_c is still improving at 1-2 10^{18} cm^{-2}. Therefore, a 3 10^{18} cm^{-2} threshold seems more representative of these wires, consistent with earlier studies [32]. Detailed energy deposition studies for the inner triplet found that the peak fluence is ~2 × 10^{17} cm^{-2} for integrated luminosity of 3000 fb^{-1}, which is safely below these limits even taking into account the recent increase to a 4000 fb^{-1} target for HL-LHC [33]. In general, the radiation effect on the superconductor can be considered less critical relative to other magnet components such as the epoxy resin for coil impregnation [34].

3.8 Summary of strand design criteria

Parameter	Symbol	Unit	Value
Effective filament diameter	D_{eff}	µm	<55
Residual Resistivity Ratio (strand)	RRR		>150
Residual Resistivity Ratio (magnet)	RRR		>100
Superconductor composition			Ti-alloyed Nb_3Sn
Nb:Sn atomic ratio			3.6:1
Irreversibility strain	ε_{irr}		>0.25%
Reaction temperature		˚C	665
Reaction time		h	<50
Stability current margin	I_s/I_{op}		>2
Maximum neutron fluence between anneals		cm^{-2}	3 10^{18}
Maximum displacements per atom between anneals	DPA		2×10^{-4}

4 Superconducting Cable

4.1 Cable geometry

The Nb_3Sn Rutherford cable design process follows guidelines initially established based on experience from the General Accelerator R&D programs, and later adopted and further refined by LARP [35]. A careful optimization and balance among competing objectives is required. In particular, high compaction provides mechanical integrity during coil winding, but results in plastic deformation potentially leading to wire damage and degradation of the critical current and RRR. Shearing of the sub-elements is of particular concern, as it can damage the diffusion barrier and cause Sn to leak into the Cu stabilizer, increasing its electrical resistance. Deformation and potential merging of the sub-elements also result in increased effective filament diameter [36]. These effects cause a reduction of the current carrying capability of the wire, and may strongly affect its stability threshold. Based on these considerations, Nb_3Sn cables are limited to lower compaction than for Nb-Ti. In fact, it was found that the overall compaction factor does not provide an accurate characterization as is the case for Nb-Ti, and the Nb_3Sn cable parameters need to be independently optimized.

The first critical parameter is the cable width. A theoretical width W_{th} can be defined based on the number of strands in the cable (N), the strand diameter (d), and the cable pitch angle (PA) as [35]:

$$W_{th} = d\ (N/2)/\cos\ (PA)$$

In turn, the Width Parameter, WP, measures the relative difference between the theoretical width and the actual width (w): $WP = (w - W_{th})/W_{th}$

A significant increase of the cable width compared with Nb-Ti is essential to prevent damage to the sub-elements at the cable edges. In fact, due to friction effects as the cable is being rolled, any compaction is primarily applied to the region closer to the edge. It was found that the ideal width for Nb_3Sn cables is a few percent larger than the theoretical width, compared to about a few percent smaller in the case of Nb-Ti. In order to partially compensate for the larger width and achieve sufficient mechanical stability, it is preferable to reduce the cable thickness without compromising on the width. However, this strategy limits the keystone angle, since both the edges are constrained to a narrow range of thickness in order to achieve sufficient mechanical stability without exceeding the deformation limit (about 85-90% of the original strand diameter).

Additional strategies used by LARP to mitigate the impact of cabling damage and cope with lower mechanical stability included:

(a) optimization of the coil geometry to minimize strain resulting from winding the cable around the ends [37];

(b) reduction of the cable tension during coil winding, and development of special tools and procedures to better support the cable as it is wound around the ends [38-39];

(c) reducing the reaction temperature and/or time, to prevent Sn diffusion to the matrix, at the expense of a reduction in the cable critical current. Higher reaction temperature could be recovered at later stages of the program, following improvements in the wire design and processing (section 3.1 and 3.4)

4.2 Cable optimization and characterization

The cable design parameters listed in the previous section are used as a starting point for an optimization process consisting of fabrication of cable samples, evaluation of their electrical and mechanical properties, winding tests with the target coil geometry and parts, and iteration of the cable and magnet design parameters until a satisfactory solution was achieved.

In the cable optimization phase, sub-element deformation and damage is assessed through metallographic analysis of cable cross-sections. Internal deformations were found to be closely correlated with the size and shape of the facets imprinted by the rolls on the strands at the edge of the cable. The facet analysis can therefore be used both as a first feedback during preparation of the samples, and for monitoring during cable production.

Critical current degradation due to cabling is assessed by comparing measurements of virgin and extracted strands. Inter-lab comparisons were carried out by LARP to qualify the methods for measurement of high current wires and ensure consistent results. Critical current degradation in optimized cables is typically below 3% [27]. This provides a safe margin with respect to a 5% cabling degradation allowable which may be considered as a reference for accelerator magnets.

Preserving high RRR (>100) in the copper stabilizer requires avoiding tin leakage through the barrier. This can be achieved with a combination of wire design (*e.g.* barrier thickness), cable design (*e.g.* avoiding shearing and barrier rupture), and heat treatment parameters.

Quality control during cable production is directed at ensuring uniformity of cable properties and performance. They include dimensional measurements of cable width, mid-thickness and keystone angle; examination of transverse cross-sections to check for sub-element shearing; checking the cable surface for out of plane or crossover strands, sharp edges or burrs that could damage insulation material; measurements of critical current and RRR of extracted strands.

As a result of the above iterative processes, the program has consistently achieved acceptable mechanical stability for winding, critical current degradation within a few percent, and high RRR with no significant impact on stability thresholds [27].

Cold welds and cross-overs have not been qualified for use in Nb_3Sn accelerator magnets. Therefore, they shall not be accepted in MQXFA cables.

4.3 Cored cables

Large dynamic effects were observed in early LARP models due to cable eddy currents. Starting from the HQ02 model, a stainless steel foil with 25 μm thickness was introduced between the two layers of strands in the cable to reduce losses due to inter-strand eddy current loops during the ramp to high field [38].

The cored cable required significant modification of the cabling process. The cable fabricated for earlier LARP models used a 2-pass process, where the cable is initially made with slightly larger dimension, then annealed at 205°C for 4 h, and re-rolled to its final dimension. These steps were found to be incompatible with the presence of a core, and were replaced by a 1-pass process where the cable is made directly to its final dimensions. The 1-pass process was implemented successfully but cables were found to be less mechanically stable, requiring further improvements in the coil design and winding process [40]. In addition, the 1-pass cable is subject to larger contraction during heat treatment, requiring an increase of the pole gaps in order to accommodate the reduction in coil length. The 1-pass cabling process initially used pre-annealed wires (185°C for 4 h, or 165°C for 20 h for improved temperature uniformity) in order to reduce the cable contraction during heat treatment. More recent analysis showed that the annealing step can be eliminated without a significant impact on the cable properties, although 1-pass cables without pre-cabling annealing may have a higher residual twist than 2-pass cables with intermediate annealing or 1-pass cables with pre-cabling annealing..

The width of the stainless steel core versus the required reduction of the eddy current effects while preserving sufficient current sharing between strands for stability against disturbances was studied [41]. Using a core width of approximately 80% of the available space was found by modeling to provide one order of magnitude improvement in field quality without any noticeable effect on stability. In practice, with epoxy infiltration, a core width at 60% width coverage is sufficient. The core position is biased toward the major edge in the cable where transverse compaction is lower, helping to avoid over-compaction at the narrow edge. Detailed studies of the core configuration and impact on the magnet ramp rate dependence and field quality performed during the HQ program are reported in [42].

4.4 Summary of cable design criteria

Parameter	Symbol	Unit	Value
Width increase factor(*)			1.02-1.03
Edge compaction		%	85-90
Cabling process			1-pass
Wire annealing temperature, if applied		°C	165 - 185
Wire annealing time, if applied		h	20 - 4
I_c degradation from cabling		%	<5
Core coverage			60-80%
Core bias			Major edge

(*) Target width/Theoretical width

5 Superconducting Coil

5.1 Dimensional changes during heat treatment

During the high temperature heat treatment, changes in the cable length, width, and thickness occur due to stress relaxations, the formation of Cu–Sn intermetallics, differences in the thermal expansion coefficients and mechanical properties of the composites during warm-up and cool down, and the volumetric growth of Nb_3Sn during its formation [21, 43]. Cable processing and the design of the insulating sleeve or braid, and winding tension also have a significant influence on dimensional changes during coil fabrication [38, 44]. In order to prevent excessive strain build-up, the tooling must accommodate these variations while supporting the coil and preserving the design geometry.

Different options were explored during the LARP program. For the TQ/LQ models, a cable transverse expansion of 6% was accomodated by the tooling. Measurements of coil cross-sections after reaction indicated that the cable dimensions grew accordingly. In the initial HQ design, the tooling only allowed for 2% transverse growth. Over-compression and damage to the conductor was observed as a result, and the design had to be modified to provide additional space [45]. In QXF cables, it was found that a direct-braid insulation restricts the cables' transverse expansion more than the loosely fitting sleeve insulation, and consequently direct braiding also limits the cables' shortening during reaction. Following this experience and detailed studies of strand and cable dimensional changes in various conditions, the assumed increase of cable width and mid-thickness is 1.2% and 4.5% respectively [44, 46, 47].

Coil length variations are addressed by segmenting the pole pieces and including appropriate gaps between them, so that no tension is generated in the conductor. In the longitudinal direction, the coil contracts in the range of -0.4% to -0.2% depending on the cable and insulation design. Additional contraction derives by the release of the winding tension as the pole piece is disconnected from the winding mandrel. The optimal size of the pole gaps is difficult to predict, but can be easily adjusted based on data from the first coils of a given design.

5.2 Coil stress during assembly, cool-down and excitation

Superconducting accelerator magnets require special mechanical structures to pre-compress the coil and minimize displacements under Lorentz forces which can lead to premature quenches and negatively affect the field quality. This goal has to be achieved while preventing significant degradation of the conductor performance under the large mechanical loads. In cos(nθ) coils the Lorentz forces are oriented primarily in the direction perpendicular to the cable broad face and accumulate over many turns. Measurements of conductor degradation under transverse compressive loads are therefore most useful in formulating magnet design criteria, provided that the electromagnetic and mechanical conditions are closely reproduced. Keeping in mind the complexities related to cabling, insulation, reaction, epoxy impregnation and loading, studies performed on wires are of very limited applicability. Measurements of cable critical current under transverse pressure also face significant challenges, in particular to provide uniform and accurate loading and field and current conditions over a sufficiently long length to ensure a reliable critical current measurement. There are also very few facilities worldwide for these type of studies, and none of them provides an adequate combination of field strength, uniformity, and bore volume or access for sample loading. For these reasons, the results from cable measurements are limited and often inconsistent [48, 49, 50, 51].

In parallel with these studies, advanced methods have been under development to calculate the three dimensional strain in Nb_3Sn filaments due to macro-scale loading. Of particular interest to the AUP are (a) models of Nb_3Sn strands down to the filament level, using both multiscale and direct FEA techniques, including plasticity and other nonlinear effects, and with a specific focus on the RRP 108/127 design [52, 53]; (b) hierarchical models of Rutherford cables down to the strand and filament level to estimate the three-dimensional strain state and to determine the effective properties from those of individual components [54]. These studies are examples of a large conductor modeling effort in the fusion, NMR and accelerator magnet communities [55, 56, 57, 58, 59] and will be critical for future high field accelerator projects such as the FCC [60]. Nonetheless, at this time these approaches are not yet sufficiently developed to provide reliable strain calculations and performance predictions in the actual experimental conditions. Therefore, LARP has relied on performance demonstrations and studies performed directly on magnets to establish the optimal design criteria and fabrication methods.

When considering the potential effects of stress degradation on magnet performance, the following two mechanisms can be identified:

- Permanent degradation of the conductor properties in the pole region of the coil due to the pre-load. Such permanent degradation of J_c(B) may result in a conductor-limited quench during powering, since this is the highest field location and the first to reach the critical surface. Reversible degradation in this area is acceptable, since the mechanical loads in this area decrease as the magnet is energized, with a corresponding recovery of the conductor properties.
- Permanent or reversible degradation of the conductor properties in the magnetic mid-plane region of the coil due to the combined effect of coil pre-load and Lorentz forces generated during powering. The maximum field at the coil inner radius is only ~10% lower than at the pole. A significant degradation of J_c(B) in this area can therefore lead to a conductor-limited quench before the magnet reaches its operating gradient.

It should be noted that the above mechanisms are solely based on a degradation of the critical current density and do not include any further reduction of the margin to quench due to energy release associated with motion, epoxy cracking etc.

Finite element models are used to perform the mechanical analysis of the magnet at each stage of fabrication, cool-down and operation. While these models can accurately represent the structural components, incorporating the details of the superconducting coil is not feasible due to the range of length scales and the complex material properties and interactions (cable, insulation/epoxy, strand, filaments, and lattice). Therefore, the coil is modeled using elastic material properties averaged among its components, and without plastic deformation. These analyses are compared with strain gauge measurements on the titanium poles with good correlation. This approach has proven effective for designing the mechanical structure and selecting the pre-load targets. Considering that the main compressive loads are in the azimuthal (θ) direction, the limiting condition of the coil composite is assessed based on the azimuthal coil stress from the FEA [61]. Although this analysis cannot provide the actual strain state of the superconductor, the computed stresses can be used as a reference for optimization of the design features and pre-load conditions, and for comparison among different magnets analyzed with consistent methods and assumptions. Of particular relevance are the studies performed in LARP models and comparison with experimental data [62]. These studies resulted in the following design criteria:

- In the transverse plane, azimuthal stress in the coil up to 120 MPa at room temperature and 200 MPa at cold can be tolerated without permanent degradation of the conductor properties. For the mid-plane stress during powering, a 200 MPa level can be tolerated without limiting the magnet performance [63, 64, 65].
- The coil preload is selected to maintaining contact between the coils and poles pieces up to the operating gradient. Localized tension up to 20 MPa at the pole-coil interface is acceptable provided that average compression is maintained across the pole width [66]

- In the longitudinal direction, a coil stain below 0.2% can be considered as a safe boundary based on LARP results [62]. This requires implementing an axial pre-compression corresponding to >50% of the axial Lorentz force generated at full field. Severe performance degradation has been observed for longitudinal strain approaching 0.4-0.5% [67, 68].

5.3 Coil temperature after a quench

The rapid temperature increase following a quench can degrade or permanently damage the superconductor and insulation materials. Additional degradation may result from the increase in mechanical stress due to the thermal expansion of the coil while the surrounding structure is still cold. These issues are of particular concern for Nb_3Sn high field magnets due to high current density, stored energy and inductance, coupled with the superconductor brittleness and strain sensitivity, and the potential for cracking and softening of the epoxy resin potentially degrading its mechanical and insulation properties. A detailed study of the limits on the hot spot temperature deriving from different magnet components and performance requirements was performed during the LARP program and is reported in [69]. This study was guided by the results of experiments aimed at progressively increasing the hot spot temperature and checking for subsequent performance degradation. It was determined that the magnets can tolerate a hot spot temperature up to 350 K without permanent degradation. However, reversible performance degradation can occur at significantly lower temperatures, leading to partial detraining. This depends in part on the magnet mechanical conditions. For these reasons, a maximum hot spot temperature of 250 K can be regarded as a target for quench protection in nominal conditions, while the 300-350 K range is acceptable for failure cases.

5.4 Summary of coil design criteria

Parameter	Symbol	Unit	Value
Coil expansion after reaction (width)		%	1.2
Coil expansion after reaction (thickness)		%	4.5
Coil expansion after reaction (length)		%	-0.4 to -0.2
Maximum acceptable localized tension at the coil-pole interface		MPa	<20
Coil azimuthal stress at assembly	σ_θ	MPa	<120
Coil azimuthal stress at cool-down	σ_θ	MPa	<200
Coil azimuthal stress at powering	σ_θ	MPa	<200
Coil longitudinal strain	ε_z	%	<0.2
Maximum acceptable Hot spot temperature	T_{hs}	K	<350

6 References

1. US HL-LHC Accelerator Upgrade Project, Q1/Q3 Cryo-Assemblies Conceptual Design Report, US-HiLumi-doc-140, July 17, 2017
2. G. Apollinari et al., "High-Luminosity Large Hadron Collider (HL-LHC) Technical Design Report" CERN Yellow Reports: Monographs, Vol. 4/2017, CERN-2017-007-M (CERN, Geneva, 2017) https://doi.org/10.23731/CYRM-2017-004
3. R. Kephart et al., "The US LHC Accelerator Research Program – A proposal", May 2003. http://www.uslarp.org/LARP_Proposal.pdf
4. R. Scanlan et al., "Progress and Plans for the U.S. HEP Conductor Development Program", IEEE Trans. Appl. Supercond., vol. 13, no. 2, pp. 1536–1541, Jun. 2003.
5. G. Ambrosio et al., "Magnets for the Insertions", in High-Luminosity Large Hadron Collider (HL-LHC). Preliminary Design Report, edited by G. Apollinari, I. Béjar Alonso, O. Brüning, M. Lamont, L. Rossi, CERN-2015-005 (CERN, Geneva, 2015), pp. 61-80. DOI: http://dx.doi.org/10.5170/CERN-2015-005.61
6. P. Swartz et al., "A Model for magnetic instabilities in hard superconductors—adiabatic critical state", *J. Appl. Phys.* 39 4991–8 (1968)
7. A. Ghosh et al., "Investigation of instability in high J_c Nb_3Sn strand", IEEE Trans. Appl. Supercond., vol. 15, No. 2, pp. 3360–3363, Jun. 2005.
8. A. K. Ghosh et al., "Dynamic stability threshold in high-performance internal-tin Nb3Sn superconductors for high field magnets", *Supercond. Sci. Technol*. 18 (2005) L5-L8.
9. J. Parrell et al., "High Field Nb_3Sn Conductor Development at Oxford Superconducting Technology", *IEEE Trans. Appl. Supercond.* vol. 13, no. 2, pp. 3470–3473, Jun. 2003.
10. C. Sanabria et al., "Controlling Cu-Sn mixing so as to enable higher critical current densities in RRP® Nb3Sn wires", Accepted for publication in *Supercond. Sci. Technol.* (March 2018). https://doi.org/10.1088/1361-6668/aab8dd
11. A. Lietzke et al., "Test Results of HD1, a 16 T Nb_3Sn dipole magnet," *IEEE Trans. Appl. Supercond.* vol. 14, No. 2, June 2004, p. 345-348.
12. G. Sabbi, "Nb_3Sn IR Quadrupoles for the High Luminosity LHC", IEEE Transactions on Applied Superconductivity, Vol. 23, No. 3 (June 2013) 4000707
13. A. Ghosh et al., "Effects of Reaction Temperature and Alloying on Performance of Restack-Rod-Process Nb_3Sn", *IEEE Trans. Appl. Supercond.* vol. 17, no. 2, pp. 2623–2626, Jun. 2007.
14. J. Parrell et al., Internal Tin Nb3Sn Conductors Engineered for Fusion and Particle Accelerator Applications, *IEEE Trans. Appl. Supercond*., vol. 19, no. 3, pp. 2573–2579, Jun. 2009.
15. N Cheggour et al., "Influence of Ti and Ta doping on the irreversible strain limit of ternary Nb_3Sn superconducting wires made by the restacked-rod process", *Supercond. Sci. Technol.* 23 (2010) 052002.
16. M. Field, et al., "Optimizing conductors for high field applications," IEEE Trans. Appl. Supercond., vol. 24, no. 3, Jun. 2014, Art. no. 6001105.
17. M. Suenaga et al., "Superconducting critical temperatures, critical magnetic fields, lattice parameters, and chemical compositions of bulk pure and alloyed Nb_3Sn produced by the bronze process," *J. Appl. Phys*. 59 840 (1986).
18. C. Tarantini et al., "Significant enhancement of compositional and superconducting homogeneity in Ti rather than Ta-doped Nb_3Sn," *Appl. Phys. Lett*., vol. 108, no. 4, 2016, Art. no. 042603.

19. A. Godeke, A. Godeke, "A review of the properties of Nb_3Sn and their variation with A15 composition, morphology and strain state," *Supercond. Sci. Technol.,* vol. 19, no. 8, pp. R68–R80, 2006.
20. M. Mentink, "An experimental and computational study of strain sensitivity in superconducting Nb_3Sn", Enschede, 2014. DOI 10.3990/1.978903653635.
21. [DRD-HT-1998] D. Dietderich et al., "Dimensional changes of Nb_3Sn, Nb_3Al and $Bi_2Sr_2CaCu_2O_8$ conductors during heat treatment and their implication for coil design," *Proc. Adv. Cryogenic Eng*., 1998, vol. 44, pp. 1013–1020.
22. A. Godeke et al., "A general scaling relation for the critical current density in Nb3Sn", *Supercond. Sci. Technol.* 19 (2006) R100-R116. doi:10.1088/0953-2048/19/10/R02
23. N. Cheggour, T. C. Stauffer, W. Starch, P. J. Lee, J. D. Splett, L. F. Goodrich, and A. K. Ghosh, "Precipitous change of the irreversible strain limit with heat-treatment temperature in Nb_3Sn wires made by the restacked-rod process". To be submitted to *Appl. Phys. Lett., 2018*
24. N. Cheggour, T. C. Stauffer, W. Starch, L. F. Goodrich, and J. D. Splett, "Implications of the strain irreversibility cliff on the fabrication of particle-accelerator quadrupole magnets made of restacked-rod-process Nb_3Sn wires", to be submitted in 2018.
25. J. Ekin, "Effect of transverse compressive stress on the critical current and upper critical field of Nb_3Sn", *Journ. Appl. Phys.* 62, 4829 (1987) https://doi.org/10.1063/1.338986
26. D. Arbelaez et al., "An improved model for the strain dependence of the superconducting properties of Nb_3Sn," *Supercond. Sci. Technol.,* vol. 22, no. 2, 2008, Art. no. 025005.
27. A. Godeke, G. Chlachidze, D. Dietderich, A. Ghosh, M. Marchevsky, M. Mentink and G. Sabbi, "A review of conductor performance for the LARP high-gradient quadrupole magnets", *Supercond. Sci. Technol*. 26 (2013) 095015.
28. M. Wilson et al., "Magnetization and stability measurements," *J. Phys. D, Appl. Phys.,* vol. 13, pp. 1547–1561, 1970.
29. Simon, N. J., "Radiation Limits for Nb_3Sn Superconductors for ITER Magnets: A Literature Review", National Institute of Standards and Technology, 1995
30. H. Weber, "Irradiation Damage in Superconductors", Advances in Cryogenic Engineering (Materials), Vol. 32, pp. 853 - 864, 1986
31. R. Flukiger et al., "Variation of (Jc/Jc0) of Binary and Ternary Alloyed RRP and PIT Nb3Sn Wires Exposed to Fast Neutron Irradiation at Ambient Reactor Temperature", *IEEE Trans. Appl. Supercond.* vol. 23, no. 3, Jun. 2013, Art. ID. 8001404.
32. R. Flukiger et al., "Superconductivity for Fusion: the materials development and testing", Nuclear Engineering and Design 73 (1982) 153-169.
33. N. Mokhov et al., "Energy deposition studies for the high-luminosity Large Hadron Collider inner triplet magnets", *PRST-AB* 18, 051001 (2015)
34. J. Polinski et al., Certification of the radiation resistance of coil insulation materials, EuCARD Deliverable Report D7.2.1, July 31, 2013.
35. D. Dietderich et al., Cable R&D for the LHC Accelerator Research Program, *IEEE Trans. Appl. Supercond.* Vol 17, No. 2, pp. 1481-1484, June 2007.
36. E. Barzi, A. V. Zlobin, "Research and Development of Nb3Sn Wires and Cables for High-Field Accelerator Magnets", *IEEE Trans.Nucl.Sci.* 63 (2016) no.2, 783-803
37. J.M. Cook, "Strain energy minimization in SSC magnet winding," *IEEE Trans. Appl. Supercond.* vol. 27, no. 2, pp. 1976–1980, Mar. 1991.
38. F. Borgnolutti et al., "Fabrication of a Second-Generation of Nb_3Sn Coils for the LARP HQ02 Quadrupole Magnet", *IEEE Trans. Appl. Supercond.* vol. 24, no. 3, Jun. 2014, Art. ID. 4003005.

39. E. Holik, at alt. “Fabrication of First 4-m Coils for the LARP MQXFA Quadrupole and Assembly in Mirror Structure,” *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, Jun. 2017, Art. no. 4003605.
40. G. Ambrosio, “Nb_3Sn High Field Magnets for the High Luminosity LHC Upgrade Project”, *IEEE Trans. Appl. Supercond.* vol. 25, no. 3, Jun. 2015, Art. ID. 4002107.
41. E. Collings et al., “Inter-strand coupling properties of LARP High Gradient Quadrupole cables in response to variations in cable design and heat treatment condition”, *IEEE Trans. Appl. Supercond.* Vol. 27, No. 4, June 2017, Art. No. 0601305.
42. X. Wang et al., “Multipoles Induced by Inter-Strand Coupling Currents in LARP Nb_3Sn Quadrupoles”, *IEEE Trans. Appl. Supercond.* Vol. 24, No. 3, June 2014, Art. No. 4002607.
43. D. Bocian, et al., “Measurements of Nb3Sn conductor dimension changes during heat treatment”, *AIP Conference Proceedings* 1435, 193 (2012).
44. F. Borgnolutti et al., “Fabrication of a Third Generation of Nb_3Sn Coils for the LARP HQ03 Quadrupole Magnet”, *IEEE Trans. Appl. Supercond.* Vol. 25, No. 3 (June 2015) 4002505.
45. H. Felice et al., “Impact of Coil Compaction on Nb_3Sn LARP HQ Magnet”, *IEEE Trans. Appl. Supercond.,* vol. 22, no. 3, Jun. 2012.
46. E. F. Holik et al., “Fabrication and Analysis of 150 mm Aperture Nb3Sn MQXF Coils”, *IEEE Trans. Appl. Supercond.,* vol. 26, no. 3, June 2016.
47. P. Ferracin et al., “Development of MQXF: The Nb3Sn Low-β Quadrupole for the HiLumi LHC”, *IEEE Trans. Appl. Supercond.* Vol. 26, No. 4 (June 2016) 4000207.
48. H. Ten Kate et al., “Critical current degradation in Nb_3Sn cables under transverse pressure,” *IEEE Trans. Appl. Supercond.*, vol. 3, pt. 1, pp. 1334–1337, Mar. 1993.
49. D. Dietderich et al., “Critical current of superconducting Rutherford cable in high magnetic fields with transverse pressure,” *IEEE Trans. Appl. Supercond.* vol. 9, pt. 2, pp. 122–125, Jun. 1999.
50. P. Bauer et al., “Fabrication and Testing of Rutherford-type Cables for React and Wind Accelerator Magnets,” IEEE Trans. Appl. Supercond. vol. 11, no. 1, pp. 2457-2460, March 2001.
51. B. Bordini et al., Critical Current Measurements of High-Jc Nb3Sn Rutherford Cables Under Transverse Compression, *IEEE Trans. Appl. Supercond.* vol. 24, no. 3, Jun. 2014. Art. No. 9501005
52. B. Collins et al., “Introduction of Nonlinear Properties into Hierarchical Models of Nb_3Sn Strands”, *IEEE Trans. Appl. Supercond*. 21, no.3, p. 2320-2323 (2011)
53. B. Collins et al., “Computation of Strain State in a Strand Using Nonlinear Hierarchical Models”, *IEEE Trans. Appl. Supercond.* vol. 22, no. 3, Jun. 2012. Art. No. 4905104
54. D Arbelaez et al., “Cable deformation simulation and a hierarchical framework for Nb_3Sn Rutherford cables”, Journal of Physics: Conference Series 234 (2010) 022002.
55. N. Mitchell, “Finite element simulations of elasto-plastic processes in Nb_3Sn strands,” Cryogenics, vol. 45, no. 7, pp. 501–515, 2005.
56. D. Boso, “A simple and effective approach for thermo-mechanical modelling of composite superconducting wires”, *Supercond. Sci. Technol*. 26 (2013) 045006
57. J. Cabanes et al., “Simulation of the cabling process for Rutherford cables: an advanced finite element model”, Cryogenics 80 (2016) 333–345
58. S. Farinon et al., “Nb3Sn Wire Layout Optimization to Reduce Cabling Degradation”, *IEEE Trans. Appl. Supercond*. 18, no.2, p. 984-988, June 2008

59. E. Barzi et al., "FEM Analysis of Nb-Sn Rutherford-Type Cables", *IEEE Trans. Appl. Supercond.* vol. 22, no. 3, Jun. 2012. Art. No. 4903305
60. D. Tommasini et al., "The 16 T dipole development program for FCC", *IEEE Trans. Appl. Supercond.,* vol. 27, no. 4, Jun. 2017, 4000405.
61. P. Ferracin et al., "Assembly and Loading of LQS01, a Shell-Based 3.7 m Long Nb3Sn Quadrupole Magnet for L:ARP", IEEE Trans. Appl. Supercond., vol. 20, no. 3, June 2010, pp. 279-282.
62. G. Sabbi, "Performance of LARP Quadrupole models under high coil stress", LARP-Doc-1230, April 2018. http://larpdocs.fnal.gov/LARP-public/DocDB/DocumentDatabase
63. H. Felice et al., "Performance of a Nb_3Sn Quadrupole under High Stress", IEEE Trans. Appl. Supercond., vol. 21, no. 3, June 2011, pp. 1849-1853.
64. H. Felice et al., "Design of HQ – a high field, large bore Nb3Sn Quadrupole magnet for LARP", IEEE Trans. Appl. Supercond., vol. 19, no. 3, June 2009, pp. 1235-1239.
65. H. Bajas et al., "Test Results of the LARP HQ02b Magnet at 1.9 K", IEEE Transactions on Applied Supercond. Vol. 25, No. 3, June 2015. Art. No. 4003306.
66. G. Vallone, P. Ferracin, "Modeling Coil-Pole Debonding in Nb3Sn Superconducting Magnets for Particle Accelerators", *IEEE Trans. Appl. Supercond.,* vol. 27, no. 8, Dec. 2017, 4004611.
67. S. Caspi et al., "Fabrication and Test of TQS01 - a 90 mm Nb_3Sn Quadrupole Magnet for LARP", *IEEE Trans. Appl. Supercond.* 17, no.2, p. 1222-1225, June 2007.
68. P. Ferracin et al., "Effect of axial loading on quench performance in Nb3Sn Magnets", *IEEE Trans. Appl. Supercond.* 18, no.2, p. 285-288, June 2008
69. G. Ambrosio, "Maximum allowable temperature during quench in Nb_3Sn accelerator magnets," FERMILAB-CONF-13-593-TD. Presented at, WAMSDO 2013: Workshop on Accelerator Magnet, Superconductor, Design and Optimization: CERN, Geneva, Switzerland, 15-16 Jan 2013, pp. 43–46. http://inspirehep.net/record/1277941/files/fermilab-conf-13-593-td.pdf