Analysis of Nb$_3$Sn Rutherford cable production and strand deformations

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A Luca e alla mia famiglia.
Nothing great was ever achieved without enthusiasm.

R.W. Emerson
Abstract

The development of cutting-edge 11-12 T superconducting magnets made from Nb$_3$Sn technology is one of the major milestones for the upgrade of the Large Hadron Collider at CERN. The upgrade, called High Luminosity LHC Project, was planned in order to reach higher luminosity and discover new particles. Replacing the NbTi superconductor with the Nb$_3$Sn makes it possible to reach a practical operating magnetic field limit of up to 16 T. The superconducting coils are formed by Nb$_3$Sn Rutherford cables with a trapezoidal cross section and composed of 40 strands. Since the superconducting phase of Nb$_3$Sn is very brittle and it is reached after a thermal cycle, the Nb$_3$Sn Rutherford cable needs to be wound in a coil before the thermal treatment. The cabling process is a delicate step in the production of high performing cables that need different systems to control their quality.

This work aims to provide practical tools to analyze the Nb$_3$Sn Rutherford cable production and the strands deformations due to the high aspect ratio of the Rutherford cable. Thanks to these tools it was possible to monitor the fluctuations of the mechanical tensions of the strands during cabling, localize the manufacturing defects and find the critical mechanical distortions inside the strands which cause degradation in the electrical performances. The results of the fluctuations in mechanical tensions are compared to the size variation of the lateral facets of the cable and the data related to the number of critical deformations are compared to the degradation of the electrical performances; the comparisons were performed in order to investigate a possible specific correlation. However, further measurements are foreseen to confirm the results.
Sommario

La seguente tesi è composta da 5 capitoli:

1 - L’attuale speranza dei fisici è di superare il modello standard e scoprire nuove particelle in grado di spiegare i misteri dell’universo. Sorge dunque la necessità di costruire e adoperare acceleratori sempre più avanzati e potenti in modo da ottenere un numero maggiore di collisioni alle energie più elevate. Il più grande acceleratore di particelle mai costruito è il Large Hadron Collider (LHC), installato al CERN. L’LHC è un sincrotrone, ossia un acceleratore circolare con fasci di particelle controrotanti, che dispone di quattro punti di collisione dove i prodotti risultanti dalle interazioni tra le particelle vengono analizzati da specifici rilevatori. In un sincrotrone le particelle cariche vengono accelerate mediante campi elettrici (cavità e quadrupoli a radiofrequenza) e vengono manipolati tramite l’induzione magnetica (elettromagneti). In condizioni relativistiche, l’energia delle particelle $E_{beam}(\text{TeV})$ è proporzionale al prodotto dell’induzione magnetica dei dipoli $B(\text{T})$ e del raggio di curvatura del fascio (in km):

$$E_{beam} \simeq 0.3BR.$$  \hspace{1cm} (1)

L’energia massima delle particelle in un acceleratore circolare di dimensioni definite è pertanto limitata dall’induzione dei dipoli. Nell’ LHC, che impiega 1232 NbTi dipoli superconduttori generando un’induzione massima di 8,3 T, le particelle si muovono su una traiettoria circolare di 4,3 km raggio e quindi hanno un’energia di collisione pari a 14 TeV al centro di massa dello scontro. Il funzionamento del LHC dal 2009 ha permesso al CERN di annunciare nel 2012
la scoperta del bosone di Higgs, la particella che dà una massa alle particelle elementari. La comunità scientifica si interroga sulla possibilità di indurre collisioni tra particelle a energie superiori rispetto a quelle prodotte da LHC. Proprio con questo intento il CERN ha pianificato l’upgrade di LHC, chiamato HL-LHC, ovvero High-Luminosity LHC. L’obiettivo è di incrementare la luminosità di LHC, grandezza riferita al numero di particelle per superficie di impatto per unità di tempo, da 10^{33} \text{cm}^{-2}\text{s}^{-1} a 10^{34} \text{cm}^{-2}\text{s}^{-1}. È quindi necessario sviluppare magneti superconduttori all’avanguardia in grado di raggiungere campi magnetici di 11-12 T in modo da sostituirli ad alcuni degli odierni magneti. La tecnologia scelta è basata sul Nb_3Sn, lega superconduttiva che permette di raggiungere campi magnetici fino a 14 T.

La corrente che circola nelle bobine supercondutrici dei magneti è molto elevata e in caso di quench, fenomeno per il quale il materiale superconduttivo perde le sue proprietà superconduttive diventando altamente resistivo, la corrente deve essere rapidamente ridotta per evitare surriscaldamenti localizzati e quindi danni al materiale. Per questo motivo il materiale superconduttivo è unito ad un materiale metallico a bassa resistività come il rame, in grado di condurre la corrente proveniente dal materiale superconduttivo e limitare il calore Joule prodotto. Il Nb_3Sn è un composto intermetallico fragile con una struttura cristallina di tipo A15, corrispondente alla formula chimica A_3B, dove A rappresenta il metallo di transizione e B un qualsiasi altro elemento. Due sono i processi attualmente utilizzati per ottenere un filo a base di Nb_3Sn: Rod Restacked Process (RRP) e il metodo Powder-In-Tube (PIT). Il primo si basa su filamenti di stagno posti al centro di una matrice di rame con inserite barrette di niobio o di lega di niobio; a sua volta la struttura viene posta in una billetta di rame ad alta purezza ottenendo un filo di diametro dell’ordine del millimetro. È possibile raggiungere una corrente critica pari a 3000 A/mm^2 a 4.2 K e 12 T, dove per corrente critica s’intende la corrente massima raggiungibile da un materiale superconduttore prima che diventi resistivo. Il secondo metodo invece consiste nell’inserire
un filamento composto da una polvere di NbSn\(_2\) in una barra di niobio, il tutto posto in una matrice di rame. La corrente critica raggiunta in questo caso è di 2300 A/mm\(^2\) a 4.2 K e 12 T. Il Nb\(_3\)Sn necessita di un ciclo termico a 650\(^\circ\) per alcuni giorni, dopo il quale risulta estremamente fragile. I fili devono quindi essere piegati per ottenere prima il cavo, che a sua volta deve essere avvolto per formare una bobina prima del trattamento termico. La necessità di utilizzare cavi con una struttura a multi-filo è dovuta, oltre a ridurre le dimensioni del superconduttore, a ragioni di protezione in caso di quench. Permette infatti di mantenere il potenziale induttivo entro i limiti del potenziale di isolamento grazie al fatto che l’induttanza nel caso del cavo multi-filo risulta notevolmente ridotta. Inoltre se un filo risultasse danneggiato localmente la corrente può ridistribuirsi negli altri rimanendo quindi operativo.

2 - Il cavo multi-filo al Nb\(_3\)Sn è formato da 40 fili, detti strands, ed è di tipo Rutherford, cioè caratterizzato da una geometria piana, alta compattezza e capacità di trasportare una densità di corrente molto elevata. Ha una sezione trasversale trapezoidale in modo da adattarsi al meglio alla forma ad arco romano dei dipoli e quadrupoli. Il processo di cablaggio è un passaggio delicato nella produzione di cavi ad alte prestazioni e richiede l’installazione di diversi sistemi di controllo qualità: CMM per il controllo delle dimensioni del cavo, CIS per monitorare la forma e la planarità del cavo, CEIS per misurare le dimensioni delle facce laterali del cavo e infine il sistema per monitorare le tensioni meccaniche dei fili. Gli ultimi due sistemi sono stati implementati soltanto nel 2016 e grazie a questo lavoro sono stati sviluppati strumenti pratici per analizzarne i dati raccolti. Innanzitutto è stato possibile osservare mediante una telecamera le fluttuazioni registrate nelle dimensioni delle facce laterali del cavo durante la produzione e definire valori di soglia in modo da salvare le foto solo se superati i suddetti limiti. Inoltre lo studio delle fluttuazioni rispetto alla tensione meccanica nominale dei fili durante il cablaggio ha permesso di capire da un lato, che i picchi negativi tipicamente
corrispondono al punto in cui il filo raggiunge il bordo del rocchetto e subisce un allentamento della tensione e dall’altro, di individuare il rocchetto che presenta il maggior numero di spikes risolvendo direttamente il problema.

3 - Il campo magnetico finale generato da un magnete superconduttore dipende fortemente dalle prestazioni elettriche del superconduttore di cui è costituito. Un modo per garantire l’efficienza del superconduttore è testare la corrente critica di singoli strands e dell’intero cavo e la Residual Resistivity Ratio (RRR), ossia il rapporto tra la resistività del filo a temperatura ambiente e quella ad una temperatura poco sopra la $T_c$, a cui avviene la transizione a stato superconduttivo. La corrente critica ($I_c$), ossia uno dei principali parametri di un superconduttore, riflette la capacità di trasporto di corrente macroscopica di un superconduttore. Essa viene determinata ad una specifica temperatura e campo magnetico sia nel caso di singolo strand sia in un cavo. La corrente critica si trova dalla curva di tensione-corrente individuando la proiezione sull’asse delle ascisse del punto d’intersezione tra la tale curva e il criterio di campo elettrico pari a $0.1 \mu V/cm$, valore valido per tutti i materiali superconduttori a bassa temperatura critica. Per ottenere la degradazione in corrente critica si misura la corrente critica in uno strand puro e in uno estratto da un cavo e si calcola la riduzione. Per quanto riguarda la misura di RRR di un filo si determina la resistenza a temperatura ambiente e a $20\,K$ misurando la caduta di tensione in seguito ad un incremento di corrente. Sono state effettuate misure di degradazione di corrente critica e di RRR di fili di cavi per dipoli e quadrupoli e di un filo estratto da un cavo con lo strand crossover. La degradazione in corrente critica di fili di diversi tipi di cavi verrà confrontata con la percentuale di deformazioni critiche all’interno di uno strand.

4 - Un elevato rapporto d’aspetto nel cavo Rutherford al $\text{Nb}_3\text{Sn}$ è uno dei requisiti più importanti nella progettazione di magneti superconduttivi.
per acceleratori ed implica una grande deformazione plastica soprattutto ai bordi del cavo. Quest’ultima può causare distorsioni meccaniche nei sottoelementi all’interno dei fili al Nb₃Sn. I danni alle barriere dei filamenti di uno strand e la relativa fuoriuscita di stagno nella matrice di rame durante il trattamento termico può risultare in una degradazione in $I_c$ e in $\text{RRR}$. È stato definito uno spessore minimo che deve avere l’area multifilamentare (per i fili RRP) e il tubo di niobio (per i fili PIT) di ogni singolo sottoelemento per evitare la fuoriuscita dello stagno, se non rispettato si considera difettoso ossia caratterizzato da una deformazione critica. La geometria del cavo Rutherford deve assicurare un limitato degrado delle prestazioni elettriche dei fili al Nb₃Sn reagiti, ma anche una relativa stabilità meccanica per l’avvolgimento della bobina. La stabilità meccanica del cavo, tra gli altri parametri, è direttamente legata alla compattazione dei fili ai bordi del cavo. L’ottimizzazione dei cavi ha come obiettivo quello di garantire la $\text{RRR}$ dei fili estratti maggiore di 100 e la degradazione di $I_c$ al di sotto del 5%. Per studiare le deformazioni meccaniche all’interno dei filamenti RRP o PIT di diversi tipi di cavi e correlarli alla degradazione di $I_c$, è stato sviluppato un codice Matlab che automatizza lo studio manuale e permette di ottenere i grafici del rapporto d’aspetto e della riduzione in spessore di ogni sottoelemento di uno strand in funzione della posizione angolare e radiale.

5 - I risultati sembrano mostrare che non esista alcuna correlazione specifica tra le fluttuazioni di tensione meccanica dei fili durante il cablaggio e le dimensioni laterali del cavo e né tra il numero di deformazioni critiche e la degradazione in corrente critica di cavi RRP per dipoli e quadrupoli. Tuttavia ulteriori misurazioni anche su cavi PIT sono previste per confermare i risultati attuali. Inoltre il lavoro si può proseguire in futuro migliorando sempre più il controllo della produzione per impedire fenomeni come lo strand crossover in un cavo. Un modo è quello di studiare un design migliore di rocchetto che permetta di diminuire l’allentamento di tensione una volta che il filo giunge
al bordo del cavo. Infine l'intento è di ottimizzare il codice creato affinché sia
in grado di migliorare l'individuazione dei bordi dei filamenti con utilizzo di
tecniche più sofisticate.
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# Contents

List of Figures xix  
List of Tables xxv  

Introduction 1  

1 Background 3  
1.1 CERN 3  
1.2 Superconducting accelerator magnets 5  
1.3 Superconducting materials 7  
1.3.1 Brief history of superconductivity 8  
1.3.2 Superconductors 11  
1.3.3 NbTi Superconductor 14  
1.3.4 Nb$_3$Sn Superconductor 16  
1.3.5 Comparison between NbTi and Nb$_3$Sn 21  
1.3.6 Operating limits of a superconductor magnet 23  
1.3.7 Nb$_3$Sn Cables 24  
1.4 Hi-Lumi project 25  
1.4.1 11 T dipoles 26  
1.4.2 QXF quadrupoles 27  
1.4.3 Development of High Field Magnets 28  

2 Production of Nb$_3$Sn cables 31  
2.1 Geometry of Rutherford cable 31  
2.2 The cabling machine 33  
2.3 Rutherford Nb$_3$Sn cables for HL-LHC and FRESCA2 35  
2.4 Quality control of cable production 38  
2.4.1 Cable Measuring Machine 39  
2.4.2 Cable Inspection System 40  
2.4.3 Cable Edges Inspection System 42  
2.4.4 Strand Tension Monitoring System 49  

3 Electrical performances of Rutherford cable 57  
3.1 $I_c$ and RRR measurements 57  
3.1.1 Strand’s critical current 58  
3.1.2 Strand’s RRR 62
3.1.3 Cable $I_c$ measurement .......................... 66

4 Strand deformations in Rutherford cables 73
   4.1 Metallography ........................................ 74
   4.2 Manual analysis of the filaments deformations ............... 76
   4.3 Automated analysis of the filaments deformations .......... 80
      4.3.1 SEM images of rolled strand ...................... 80
      4.3.2 Optical Microscope Images of cables .............. 85

5 Conclusion and future works ............................ 101

Bibliography .............................................. 103
# List of Figures

1.1 CERN's accelerator Complex ........................................ 4
1.2 Current density distribution for a dipole and quadrupole. The first two produce a perfect dipole field and third one the quadrupole field ........................................ 6
1.3 On the left the sector coil configuration and on right the block coil configuration ........................................ 6
1.4 Half cross section of LHC dipole coil ............................ 7
1.5 LHC dipole magnet cross section. ................................. 7
1.6 Magnetic flux in a superconducting material above and below $T_c$ on the left. Magnetization versus magnetic field for Type-I superconductors (explained in paragraph 1.3.2) on the right. ........................................ 9
1.7 Cooper pairs overlapping in a metal lattice ..................... 11
1.8 Temperature dependence of the electrical resistivity of a normal metal and an high performing superconducting material. ........................................ 12
1.9 Critical surface of a superconductor composed of critical temperature ($T_c$), critical field ($H_c$), critical current density ($J_c$) .............................. 13
1.10 Variation of magnetization with applied magnetic field intensity for type I and type II superconductors .............................. 14
1.11 Distribution of flux lines in the material. $\Phi_0$ indicate the flux lines produced by vortices of current .............................. 15
1.12 NbTi strand used in LHC. ........................................... 16
1.13 On the left The NbTi crystal structure. On the right the $Nb_3Sn$ crystal structure ........................................... 17
1.14 Binary phase diagram of the Nb-Sn system ..................... 18
1.15 3 different processes for the manufacture of $Nb_3Sb$ wires, in order: bronze process, Internal Sn process and PIT process ........................................... 19
1.16 Example of $Nb_3Sn$ strand with a diameter of 1.0mm. On the left the RRP strand and on the right the PIT strand ........................................... 20
1.17 Non-Cu $J_c$ in PIT and RRP conductors versus magnetic field ........................................... 21
1.18 On the left the critical surface of NbTi and $Nb_3Sn$ in 3D-space. On the right the critical current density at 4.2 K of NbTi and Nb$_3$Sn ........................................... 22
1.19 Magnetic field versus the sector width for NbTi and $Nb_3Sn$ magnets at 4.2 K ........................................... 23
1.20 Fabrication process of NbTi and $Nb_3Sn$. ........................................... 23
1.21 Definition of superconducting magnet operating point 24
1.22 Rutherford cable 25
1.23 LHC/ HL-LHC Plan 26
1.24 Present NbTi LHC dipole (top) to be replaced by two Nb$_3$Sn dipoles with collimator unit in the middle 27
1.25 Cross section designs of the 11 T dipole 27
1.26 QXF magnet cross-section 28
1.27 Inner-triplets made by the two kind of quadrupoles at different lengths (Q1, Q2a-Q2b,Q3) before the collision point (CP). Image by E.Todesco. 28
1.28 Geometry of FRESCA2 dipoles and block configuration 29

2.1 Geometry of a Rutherford cable 32
2.2 Interstrand coupling currents in the cable. 32
2.3 Rutherford cabling machine located in the laboratory. 33
2.4 On the left planetary cabling: All the spools rotate in the same direction, opposite in comparison to the disk rotation. On the right, lateral 2D view of turkshead. 35
2.5 Cross section of RRP strand of 11 T dipole cable with a 0.7 diameter and 108/127 layout. 36
2.6 MQXF cable strands: On the left the RRP strand 108/127 geometry, on the right the PIT strand 192 subelements. Both have a 0.85 mm of diameter. 36
2.7 On the left the RRP strand 132/169 geometry of FRESCA2, on the right the PIT strand with 192 subelements. 38
2.8 Cross section of samples of the three different Nb$_3$Sn cables produced at CERN. 38
2.9 Cable Measuring Machine (CMM): lateral view on the top and frontal view on the bottom. 40
2.10 Angle, width and thickness of RUN172 QXF cable versus length(m) 41
2.11 View of the Cable Inspection System (CIS) 42
2.12 On top: the 1st level of analysis of the CIS. On bottom: the second level of analysis of the CIS. 42
2.13 Cable thin edge: Feret diameter x and y. 43
2.14 Facets of cable being recognized by the CEIS. 43
2.15 Cable Edges Inspection System (CEIS) installed on Rutherford production line. 43
2.16 Plots for thin edge of 11 T RUN174A versus time of production: feret diameter x on top left, feret diameter y on top right, perimeter on bottom left, area on bottom right. 45
2.17 Feret diameter x of thin edge of RUN174A versus time: zoom on a range of time of the order of seconds. 45
2.18 Plots for thick edge of RUN174A versus time of production:
   feret diameter x on top left, feret diameter y on top right,
   perimeter on bottom left, area on bottom right. . . . . . . . . . 46
2.19 Artefact due to brightness difference in the facet. . . . . . . . 47
2.20 Feret x at thin and thick edge in function of the number of
cables produced for 11 T dipoles cables and QXF cables . . . . . 48
2.21 Sketch of the strands arrangement in the cabling machine. . . 50
2.22 Mechanical tension versus time for the strand 1 during produc-
tion of cable 174A. . . . . . . . . . . . . . . . . . . . . . . . . . 51
2.23 Zoom of the oscillation in mechanical tension versus time for
the strand 1 of cable 174A. . . . . . . . . . . . . . . . . . . . . . . 51
2.24 Number of valleys less than 40 N for each strand for RUN174A . 52
2.25 Angle reached from the strand at the border of the spool. \( \alpha \) is
the angle and D is the distance from the center of the spool to
the disk in front. . . . . . . . . . . . . . . . . . . . . . . . . . . 52
2.26 RUN174A: Number of fluctuations versus mechanical tension’s
thresholds. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 53
2.27 RUN174: Comparison between data recorded in the first day
and second day of production. The number of fluctuations are
divided for the length of the cable. . . . . . . . . . . . . . . . . 54
2.28 Comparison between feret diameter x versus time and mechan-
ical tension of strand 1 versus time. . . . . . . . . . . . . . . . . 55
2.29 Strand crossover: on the left, the view from the top; on the
right, the view from the lateral side. . . . . . . . . . . . . . . . . 55
2.30 Top: cross section of the cable with the strand crossover circled
in red at two different point of the cable. Bottom: zoom of the
crossover of the strands. . . . . . . . . . . . . . . . . . . . . . . 56

3.1 Sketch of a CERN strand critical current test station . . . . . 59
3.2 Electric-field criterion for determining the critical current from
a set of V-I curves obtained at different magnetic fields. . . . . . 60
3.3 Critical current versus magnetic field for virgin and extracted
PIT QXF strand at 1.9 K and 4.2 K. . . . . . . . . . . . . . . . . 61
3.4 Critical current measurements on extracted strand of 11 T
dipoles and MQXF cables at 4.3 K and 12 T. . . . . . . . . . . 62
3.5 Resistivity of copper versus temperature for different values of
RRR. RRR of copper is determined by \( \rho(273 K)/\rho(4K) \). . . . . 63
3.6 RRR sample holders . . . . . . . . . . . . . . . . . . . . . . . 64
3.7 A sketch of RRR station. . . . . . . . . . . . . . . . . . . . . . 64
3.8 RRR measurements for virgin and extracted strands from 11 T
dipoles RUN173A cable. . . . . . . . . . . . . . . . . . . . . . 66
3.9 Layout sketch of the sample. On the right the bottom joint, in
the center the Nb\(_3\)Sn cable and on the left the NbTi cable. . . 67

3.11 Sketch of FRESCA test station. The number 1 indicates the first cryostat, the number 2 shows the second cryostat.

3.12 Critical current versus magnetic field at 4.3 K

4.1 Specimen preparation system used at CERN in the laboratory

4.2 Sample preparation steps: on the top left is shown the sample after the grinding with P1200 paper, on top right the sample after the polishing with 9 μm size particles, on bottom left after polishing with 3 μm size particles and at the end on bottom right after polishing with 0.05 μm size particles. The sample is a PIT wire with a diameter of 0.7 mm characterized by niobium bundle barrier. This PIT wire with a bundle barrier is an object of study because it can reach an high value of RRR and only the 19% of the filaments remain unreacted (23% for non-bundle PIT).

4.3 Rutherford cable with RRP strands with 0.7 mm of diameter.

4.4 11 T PIT cable: strand at thin edge with defects emphasised in red.

4.5 Analysis of the cable RUN174A: 5 samples are studied.

4.6 The SEM image of a PIT strand rolled down to 20% with 120 filaments showed in 3 configurations, from the left: image adapted for the recognition of the external and internal surface of the Nb tube of each filament and the last one is for the margin of the strand. The original image was edited by Marina Garcia Gonzalez.

4.7 Binary version of the images in Fig. 4.6.

4.8 Picture of the PIT strand with the identification of the external and internal surface of the Nb tube of each filament in red and the external surface of the strand in blue.

4.9 Coloured filaments according to different levels of deformations: minimum thickness less than 5.2007 μm in red, less than 6 μm in pink, less than 7.5 μm in green and less than 9 μm in blue.

4.10 Sketch of the rings of the strand.


4.12 RUN174, RRP strands-Left: Surface good to study. Right: Surface with scratches and not good focus.

4.13 On the left filament of RRP strand and on the right filament of PIT strand.
4.14 The Graphical User Interface developed for the analysis of optical microscope images. 88
4.15 Deformations of the three strands at the thin edge of the cable PIT QXF RUN155A. In the legend the thresholds of minimum thickness are expressed in micrometer. 89
4.16 Histogram of the deformations at the thin edge of cable RUN155A 90
4.17 Comparison of the deformations of the strand at thin edge of three RRP cables for 11T dipoles. 92
4.18 Comparison of the deformations of the strand at thin edge of three RRP cables for QXF magnets. 92
4.19 Cross section of the strand at the thin border after the analysis of the code of RUN173A which is a 11T cable. 93
4.20 Cross section of the strand at the thin border after the analysis of the code of RUN178A which is a QXF cable. 93
4.21 QXF PIT RUN155A: a- Thickness reduction versus angular position. b- Thickness reduction versus radial position. c-Aspect ratio versus angular position of external border. d-Aspect ratio versus radial position of external border. e-Aspect ratio versus angular position of external border. f-Aspect ratio versus radial position of external border. 95
4.23 RRP QXF RUN178A: a- Thickness reduction versus angular position. b- Thickness reduction versus radial position. c-Aspect ratio versus angular position of external border. d-Aspect ratio versus radial position of external border. e-Aspect ratio versus angular position of external border. f-Aspect ratio versus radial position of external border. 97
4.24 Critical current degradation versus critical deformations for RRP QXF and 11T cables. 98
List of Tables

1.1 Dipole parameters .............................................. 8
1.2 Parameters of main superconductors. .......................... 15
1.3 Characteristic parameters of Nb$_3$Sn ............................. 17
1.4 NbTi vs Nb$_3$Sn .................................................. 22

2.1 Specification of the 11 T and QXF Nb$_3$Sn wires .................. 37
2.2 Specification of the 11 T and QXF Nb$_3$Sn cables ............... 37
2.3 Parameters of the FRESCA2 cable ................................. 37
2.4 Results obtained for 11 T RUN174A ............................... 44
2.5 Results obtained for 11 T RUN174B ............................... 46
2.6 Comparison between the dimensions of the thick and the thin edges detected by the microscope and by the Keyence system for 11 T dipoles cables. .................................................. 48
2.7 Comparison between the dimensions of the thick and the thin edges detected by the microscope and by the Keyence system for QXF cables. .................................................. 49

3.1 Critical current measurements, Degradation in critical current and n value of extracted strands of 11 T dipoles and QXF cables. 62
3.2 RRR measurements of extracted and virgin strands of 11 T dipoles and MQXF cables. ................................................. 65

4.1 All the defects of the samples studied with manual method are reported in the table. ................................................. 78
4.2 Table of the deformations at the thin border for the RUN155A. 89
4.3 Quantitative analysis of the deformations of the extreme strand A in case of samples of 11 T cables and QXF cables. ................ 91
Introduction

The following dissertation, carried out at CERN, the European Organization for Nuclear Research, deals with the Nb$_3$Sn Rutherford cables that will be implemented in the superconducting accelerators magnets for the upgrade of LHC, which is called High-Luminosity LHC. In particular the aim of the thesis is to analyse the production of Nb$_3$Sn Rutherford cable production and to quantify the strand deformations in order to obtain high performing cables.

The first part of this work is about the theory behind the project and it has the main aim of understanding the reason why the superconducting material of Nb$_3$Sn is chosen for reaching higher magnetic field. After an introduction of CERN and accelerators magnets, a description of superconducting materials and its properties is provided. Then, the comparison between the NbTi, the superconducting material used in LHC, and Nb$_3$Sn, the one used for Hi-Lumi upgrade, is reported. All the types of strand based on Nb$_3$Sn, the importance of Rutherford cable in the fabrication of the superconducting accelerators magnets and Hi-Lumi Project magnets are presented.

The second section of this thesis focuses on the production of the Nb$_3$Sn Rutherford cables. The cabling machine and different kinds of cables are described and the different systems to control the quality of the cable are illustrated. The results obtained from the tools developed for the analysis of the mechanical tensions of each strand and the dimensions of lateral facets of the cable are explained and then compared to understand if a possible
correlation between both exists.

The chapter three deals with the discussion of how the tests of the electrical performances of Nb$_3$Sn Rutherford cables are performed. Critical current ($I_c$) and RRR measurements of virgin and extracted strands were done and also test of the $I_c$ of the cable was carried out. The results need to be compared to the ones from the analysis of the high plastic deformations.

The development of the automatized method able to study the strand deformations at the edges of the Nb$_3$Sn Rutherford cables is explained in chapter four. The description of the manual method is also provided. Finally, it is showed the comparison between the degradation in critical current and the critical deformations of the filaments inside the strands.

In chapter five all the obtained results are summarized and the possible future works are related to further measurements and improvements of the developed tools.
Chapter 1

Background

1.1 CERN

The actual hope of physicists is going beyond the Standard Model and finding new particles in order to understand dark matter and dark energy. The place where their dreams can come true is CERN, the European Organization for Nuclear Research, founded in 1954 and located on the Franco-Swiss border, near Geneva. It is the world’s most important research center with the aim of studying the basic constituents of matter, well-known for the Higgs boson discovery (2012), the birth of the World Wide Web and antimatter experiments. The accelerator complex at CERN, show in Fig. 1.1, is a succession of machines that accelerates the beam of particles (protons or heavy ions) to increasingly higher energies. Each machine boosts the energy of a beam of particles, before injecting the beam into the next machine in a sequence and at the end the particles collide. The properties of subatomic particles generated by the collision of the proton or heavy ions is measured in the main four experiments: ATLAS, CMS, ALICE and LHCb.

The LHC hadron source particles is a bottle of hydrogen gas where an electric field strips hydrogen nuclei of their electrons and then the protons start to be accelerated from the complex of accelerators composed of: Linac 2, linear accelerator where particles reaches the energy of 50 MeV and gained 5%
in mass; **Proton Synchrotron Booster (PSB)**, where bunches achieve the energy of 1.4 GeV in synchrotron rings; **Proton Synchrotron (PS)**, where the acceleration of the protons brings them to the energy of 25 GeV; **Super Proton Synchrotron (SPS)**, with 7 km of circumference it is the second largest machine at CERN where the energy of particles reached is 450 GeV; the last accelerator is the biggest one and is called **Large Hadron Collider (LHC)**, it is a ring of 27 km where the beams travel at close to the speed of light; at the moment is able to achieve the energy of 6.5 TeV per beam, designed to be 7 TeV per beam.

Protons are not the only particles accelerated in the LHC. Lead ions for the LHC start from a source of vaporized lead and enter Linac 3 before being collected and accelerated in the **Low Energy Ion Ring (LEIR)**. They then follow the same route to maximum energy as the protons.

Along the LHC accelerator complex, the charged particles are accelerated by electrical field. Radio-frequency cavities are an example of accelerating systems, they are spaced at intervals along the accelerator and they are shaped to resonate at specific frequencies (400 MHz in the LHC), pulling charged particles along the machine in closely spaced bunches. To keep the charged
particles on the circular orbit of the collider, normal and superconducting
electromagnets are used. They generate a dipolar magnetic field perpendicular
to the orbit. Thanks to dipole normal conducting magnets, one can generate
an ultimate field of about 2 T whereas with superconducting dipoles a field of
8.3 T is generated in LHC [2].

1.2 Superconducting accelerator magnets

Superconducting magnets is the core technology of LHC. The main type of
magnets are the dipoles and the quadrupoles, the first ones bend the particle
beam and keep it in its orbit and the second ones are used to focus the beam;
there are also higher-order magnets (sectupole, octupole..) which correct the
chromaticity and field distortions. In a circular collider the bending magnetic
field determines the final energy of the beam and thanks to a very simple
relation it is possible to know the energy of the beam ($E_{\text{beam}}(\text{TeV})$), given the
dipole field ($B(\text{T})$) and the radius of the beam orbit ($R(\text{km})$):

$$E_{\text{beam}} \simeq 0.3BR$$

(1.1)

If normal conducting dipole magnets were used for LHC, the accelerator would
have been 120 kilometers long in order to reach 7 TeV per beam.

Accelerator magnets require a high level of field quality in order to pro-
vide beam stability. In superconducting accelerator magnets the field quality
is mainly determined by the position of the conductor around the beam apen-
ture. In the case of dipoles, a perfect dipolar flux density is reached by two
simple coils geometries: overlapping of two uniform current density flowing in
cylinders with opposite directions or the intersection of two ellipses carrying
equal current density in opposite directions. A perfect quadrupole field is however obtained overlaying two crossed ellipses carrying equal current density in opposite direction as showed in Fig. 1.2.

In a perfect dipole, the $J = J_0 \cos \theta$ dependence of the current density
Background

Figure 1.2: Current distribution for a dipole and quadrupole. The first two produce a perfect dipole field and third one the quadrupole field[3].

Figure 1.3: On the left the sector coil configuration and on right the block coil configuration[4].

can be approximated by shells or blocks of constant current density \((J_w)\) as can be seen in Fig. 1.3. In the first configuration, called sector coil layout, the current is distributed in sector shells of constant current density. The cables are, therefore, situated around the circular aperture to create a roman arch and the cable cross sections present a non-zero keystone angle to facilitate the formation of the roman arch. In the second configuration, called block coil layout, the \(\cos \theta\) current density is approximated by rectangular blocks of constant current density [4]. The transverse cross-section of LHC main dipole coil (Fig. 1.4) is formed by two superposed layers, each layer being made of few sectors.

The coil assembly is surrounded by an iron yoke for improving the magnetic field in the center of the bore. In turn it is covered by a liquid helium cryostat for its cooling down to temperature of 1.9 K. The LHC dipole cross section is reported in Fig. 1.5 as an example [3]. In the table 1.1 the LHC
1.3 Superconducting materials

Superconducting accelerator magnets are built using superconducting materials that will be deepened in this section. More precisely, in the first paragraph 1.3.1 the superconducting properties and theoretical models are briefly introduced and the paragraph 1.3.2 moves on the main parameters of superconduc-
Table 1.1: LHC Dipole Parameters [7].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operational field</td>
<td>8.4 T</td>
</tr>
<tr>
<td>Coil aperture</td>
<td>56 mm</td>
</tr>
<tr>
<td>Magnetic length</td>
<td>14.2 m</td>
</tr>
<tr>
<td>Operating current</td>
<td>11'500 A</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>1.9 K</td>
</tr>
<tr>
<td>Coil turns per aperture inner shell</td>
<td>30</td>
</tr>
<tr>
<td>Coil turns per aperture outer shell</td>
<td>52</td>
</tr>
<tr>
<td>Distance between aperture axes</td>
<td>180 mm</td>
</tr>
<tr>
<td>Outer diameter of cold mass</td>
<td>580 mm</td>
</tr>
<tr>
<td>Overall length of cold mass</td>
<td>~15 m</td>
</tr>
<tr>
<td>Overall mass of cryomagnet</td>
<td>31 t</td>
</tr>
<tr>
<td>Stored energy for both channels</td>
<td>7.4 MJ</td>
</tr>
<tr>
<td>Self-inductance for both channels</td>
<td>119 mH</td>
</tr>
<tr>
<td>Resultant of e-magnetic forces in the first coil quadrant $\Sigma F_x$ (1.70 MN/m)</td>
<td>24.0 MN</td>
</tr>
<tr>
<td>Inner layer $\Sigma F_y$ (- 0.14 MN/m)</td>
<td>- 2.0 MN</td>
</tr>
<tr>
<td>Outer layer $\Sigma F_y$ (- 0.60 MN/m)</td>
<td>- 8.5 MN</td>
</tr>
<tr>
<td>Axial e-magnetic force on magnet ends</td>
<td>0.52 MN</td>
</tr>
</tbody>
</table>

tors and their classification. The term ”superconductor” refers to an electrical conductor that exhibits superconducting properties, in order to technically exploit the superconducting material, it is assembled with a low resistive metal, as copper. In 1.3.3 and 1.3.4 a description of the NbTi and $Nb_3Sn$ superconductors is given. Finally, in 1.3.6 the working margins of a superconducting magnet are furnished and an introduction of $Nb_3Sn$ cables is presented in 1.3.7.

### 1.3.1 Brief history of superconductivity

Three years after the achievement of the liquefaction of helium in 1908, Kamerlingh-Onnes, director of the Low-Temperature Laboratory at the University of Leiden, discovered the phenomenon of superconductivity in mercury at very low temperature (4 K). One of the main feature of superconductivity is the perfect electrical conductivity, demonstrated by the fact that he didn’t notice any reduction in the current flowing in a superconducting ring for years.

The next milestone of superconductivity occurred in 1933, when Meissner and Ochsenfeld found the perfect diamagnetism. They observed that an external magnetic field is excluded from the interior of a material when it becomes
1.3 Superconducting materials

superconducting, below the transition temperature ($T_c$), and also it is expelled if it is originally present. This phenomenon, called Meissner effect, implies the generation of a magnetization in the material able to cancel out the effect of the external field. One immediate consequence of this well-known effect is that superconductivity is a thermodynamical phase, in fact the final state of magnetization does not depend upon the way of cooling below the transition temperature. At this condition the superconductor is a perfect conductor and a perfect diamagnet with magnetic susceptibility of -1 \cite{8}\cite{9}. In the supercon-

Figure 1.6: Magnetic flux in a superconducting material above and below $T_c$ on the left. Magnetization versus magnetic field for Type-I superconductors (explained in paragraph 1.3.2) on the right.

In 1935 the Meissner effect and the zero electrical resistivity were explained thanks to the London equations which come from London brothers. The theory provides a classical model of superconductivity based on a two fluid model and normal conducting electrons \cite{9}. The following equation regards the zero electrical resistivity:

$$J_s = \left[ \frac{n_s e^2}{m} \right] A$$  \hspace{1cm} (1.2)
The equation comes from the Drude model of metals, without the frictional term, to take infinite conductivity into account. The quantity $n_s$ is the density of the super-carriers, $J_s$ is the related current density, $m$ is the electron mass, $e$ is the charge of an electron and $A$ is the vector potential. The other most known equation is:

$$\lambda^2 = \frac{1}{\mu_0} \left[ \frac{m}{n_s e^2} \right]$$ (1.3)

The London penetration depth ($\lambda$) represents the characteristic distance of shielding of the magnetic field, due to the screening currents flowing along the external surface of the superconducting materials. The equation 1.3 shows that $\lambda$ is inversely proportional to the square root of $n_s$, which is the superelectron density. Below $T_c$, $n_s$ increases and the flux penetration decreases as the temperature decreases [9].

The magnetic field dependency on the distance ($x$) inside an infinite slab of superconducting material is given by:

$$B(x) = B_0 \exp\left(\frac{x}{\lambda}\right)$$ (1.4)

The Ginzburg-Landau (GL) theory of 1950 generalizes the London theory and it is valid close to the transition temperature. The theory develops the free energy of a superconductor through the expansion of a macroscopic quantum wave function $\Psi(r)$ and the superconducting electrons local density is given by $|\Psi|^2$. The GL theory is a limiting case of the microscopic theory introduced in 1957 by Bardeen, Cooper and Schrieffer.

Cooper showed that superconductivity is a cooperative phenomenon in which two electrons can overcome the Coulomb repulsion and develop an attractive force through the crystal lattice interaction. The size of the Cooper pair is given by:

$$r = \left[ \frac{\hbar \nu_F}{E_B} \right]$$ (1.5)

where $E_B$ is the binding energy and $\nu_F$ is the Fermi velocity. Since the size of
1.3 Superconducting materials

the Cooper pair is larger than the distance between two electrons there will be an overlapping of the Cooper pairs, see in Fig 1.7. The energy of the system is zero when all the pairs have the same momentum and a phase coherence [9].

Cooper pairs are quasi-particles which follow Bose-Einstein statistics, so they can collectively condense into a lower energy state described by a single complex wave function. The energy gap in the energy spectrum corresponds to the energy necessary to break the pair [9][10]. The BCS theory describes well the thermodynamical properties of the superconductors, the superconducting parameters and also the Meissner effect.

The BCS theory has even been successful in explaining the superconductivity in materials with critical temperature below the 30-40 K, called Low Temperature Superconductors (LTS), but not the High Temperature Superconductors (HTS), discovered as from 1986.

1.3.2 Superconductors

In accelerator magnet a large magnetic energy is stored in the coils, at operating current. If the superconducting material loose its superconducting state, it become resistive and the current needs to be ramped down in few seconds in order to avoid large overheating and possible irreversible damage. The brutal transition from superconducting state to normal one is called a quench, which can occur because the field inside the magnet is too high and/or the
rate of change of field is too large. In case of quench it is important to use a superconductor which is a superconducting material combined with a low resistive metal, in order to limit the overheating of the conductor. Copper is an appropriate metal because it serves as mechanical support and has a key role in protecting the entire magnet. With the purpose of designing the protection system of the superconducting magnet during a quench, the copper-to non-copper ratio (Cu/NonCu) and the critical current density are important parameters to estimate the maximum hot spot temperatures in magnets. Copper has high electrical and thermal conductivity at cryogenic temperatures, even higher than superconducting material in normal state, so, in case of a quench, the electric current tends to flow in it and the Joule heating of the cable is reduced. The temperature dependence of the electrical resistivity of a normal metal and an high performing superconducting material is shown in Fig. 1.8. It is clear that the resistivity of an high performing superconducting material in normal state, at temperature greater than $T_c$, is higher than the one of a metal.

![Temperature dependence of the electrical resistivity of a normal metal and an high performing superconducting material][11]

Figure 1.8: Temperature dependence of the electrical resistivity of a normal metal and an high performing superconducting material[11].

The superconducting state of a superconductor could be described in terms of critical surface, which is defined in a 3D space by three critical parameters: applied magnetic field ($H_{app}$), applied transport density current ($J_{tr}$) and temperature (T). The surface is bounded by: the $J_c$ versus $H_c$ line.
1.3 Superconducting materials

at $T=0\,\text{K}$, the $J_c$ versus $T$ line at $H_{app}=0\,\text{T}$ and by the $H_c$ versus $T$ line at $J_{tr}=0\,\text{A/mm}^2$, see Fig.1.9. The superconducting state can only be achieved below the critical surface.

Figure 1.9: Critical surface of a superconductor composed of critical temperature ($T_c$), critical field ($H_c$), critical current density ($J_c$)[12].

Superconductors can be classified by their magnetic properties into type I and type II.

**Type I**

In type I superconductors the magnetic flux is perfectly shielded from the interior of the superconductor by shielding currents that flows along its surface for magnetic field below the critical one ($H_c$) [10]. The transition from the normal state to the superconducting state occurs instantly below the critical field $H_c$, see Fig. 1.10. They exhibit a perfect diamagnetism below $H_c$. The type I superconductors are pure metals such as aluminum, lead, gallium, tin (see table 1.2) and the typical London penetration depth is of about 50-500 nm. The type I superconductors do not have any practical applications in superconducting magnets because they have an extremely low critical magnetic field ($<0.5\,\text{T}$), as reported in the table 1.2, whereas the type II superconductors can achieve values of tens of tesla.

**Type II**

Type II superconductors are characterized by two critical fields ($H_{c1}$ and $H_{c2}$), below $H_{c1}$, called lower critical field, they behave as Type I superconductors so they are considered as perfect diamagnets. Between the lower critical
Background

Field and upper critical field, $H_{c2}$, they remain superconducting but the magnetic field can partially penetrate in a form of quantized flux vortices, called Abrikosov vortices (Fig. 1.11): superconductors are in the mixed state. The core of the vortex is in normal state whereas the rest of the sample is still superconducting. These flux lines form a lattice with a diameter of 2 times the coherence length $\xi$. The quantum mechanics imposes that each vortex carries a quantum of magnetic flux, called fluxon; their density increases with the field and the normal state transition occurs beyond $H_{c2}$. For practical application in accelerator magnets the flux line needs to be anchored to the inclusions, defects or grain boundaries of the material [10].

![Graph showing variation of magnetization with applied magnetic field intensity for type I and type II superconductors](image)

Figure 1.10: Variation of magnetization with applied magnetic field intensity for type I and type II superconductors [13].

An example of type II superconductors are niobium, vanadium and all intermetallic and ceramic compound listed in table 1.2. There are a lot of type II superconducting materials but only few of them can be manufactured as superconductors for large scale application that requires long single piece length ($\sim$ km) with homogeneous electrical properties. Two valid candidates for accelerator magnets are NbTi and Nb$_3$Sn.

### 1.3.3 NbTi Superconductor

Niobium-Titanium, more precisely Nb-47%Ti, is the dominating material in accelerator industry thanks to its mechanical properties, which make it easy and cheap to manufacture. All the superconducting magnets of the LHC

---

1The coherence length is the minimum length over which a given change in the superconducting electron density can be made, otherwise it destroy the superconducting state.
1.3 Superconducting materials

Figure 1.11: Distribution of flux lines in the material. $\Phi_0$ indicate the flux lines produced by vortices of current [9].

<table>
<thead>
<tr>
<th>Material</th>
<th>$T_c$(K)</th>
<th>$B_{c1}$(T)</th>
<th>$B_{c2}$(T)</th>
<th>$B_{c2}$(T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>1.2</td>
<td>0.010</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>In</td>
<td>3.4</td>
<td>0.028</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Sn</td>
<td>3.7</td>
<td>0.0305</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Pb</td>
<td>7.2</td>
<td>0.0803</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Nb</td>
<td>9.2</td>
<td>-</td>
<td>0.18</td>
<td>2</td>
</tr>
<tr>
<td>NbTi</td>
<td>9.2</td>
<td>-</td>
<td>-</td>
<td>14.5</td>
</tr>
<tr>
<td>$V_3$Ga</td>
<td>14.8</td>
<td>-</td>
<td>-</td>
<td>2.1</td>
</tr>
<tr>
<td>NbN</td>
<td>15.7</td>
<td>-</td>
<td>0.0093</td>
<td>1.5</td>
</tr>
<tr>
<td>$V_3$Si intermetallic</td>
<td>16.9</td>
<td>-</td>
<td>0.055</td>
<td>23</td>
</tr>
<tr>
<td>Nb$_3$Sn compounds</td>
<td>18</td>
<td>-</td>
<td>0.035</td>
<td>23</td>
</tr>
<tr>
<td>Nb$_2$Al</td>
<td>18.7</td>
<td>-</td>
<td>-</td>
<td>32.4</td>
</tr>
<tr>
<td>Nb$_3$(AlGe)</td>
<td>20.7</td>
<td>-</td>
<td>-</td>
<td>44</td>
</tr>
<tr>
<td>Nb$_3$Ge</td>
<td>23.2</td>
<td>-</td>
<td>-</td>
<td>37</td>
</tr>
<tr>
<td>YBa$_2$Cu$_3$O$_7$</td>
<td>93</td>
<td>-</td>
<td>-</td>
<td>$&gt;$100</td>
</tr>
<tr>
<td>Y(123)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bi$_2$Sr$_2$CaCu$_2$O$_8$</td>
<td>92</td>
<td>-</td>
<td>-</td>
<td>$&gt;$100</td>
</tr>
<tr>
<td>Bi(2212)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bi$_2$Sr$_2$Ca$_2$Cu$<em>3$O$</em>{10}$</td>
<td>Cuprates</td>
<td>110</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Bi(2223)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TlBa$_2$Ca$_2$Cu$<em>3$O$</em>{10}$</td>
<td>HTS</td>
<td>122</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Tl(1223)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HgBa$_2$Ca$_2$Cu$<em>3$O$</em>{10}$</td>
<td></td>
<td>133</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Hg(1223)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1.2: Parameters of main superconductors [14][15].

machines and previous high energy collider machines (RHIC, HERA, TEVA-TRON) are made from NbTi. Niobium and titanium have very similar atomic sizes and at high temperatures, they form a body-centered cubic phase, referred to as $\beta$-phase[16]; its crystal structure is shown in Fig.1.13 on the left. Nb-47%Ti has a critical temperature of 9.2 K and a critical field of 14.5 T. At
Background

4.2 K and 5 T the non-Cu critical current density $J_c$ is 3000 A/mm$^2$, whereas at 7.5 T and 4.2 K $J_c$ decrease to 1500 A/mm$^2$. The critical temperature, $T_c$, and the upper critical magnetic flux density, $B_{c2}$, of NbTi are mainly determined by the alloy composition whereas the critical current density, $J_c$, is mainly determined by the alloy microstructure. NbTi is available in long lengths (km scale) in the form of multifilamentary wires where the superconductor is dispersed in a high purity copper matrix. The 1.065 mm diameter NbTi strand of the inner layer of the LHC dipole (see Fig 1.12), consists of 9000 filaments of 7 $\mu$m diameter embedded in a matrix of copper. Filaments with a size of a few $\mu$m are stable against flux jumps$^3$, which make the behavior reproducible and easier to control.

![Figure 1.12: NbTi strand used in LHC.](image)

Due to the extrinsic properties of the NbTi, a maximum field of about 9 T could be produced for an accelerator dipole. For the upgrade of LHC (see section 1.4) higher field is required. Nb$_3$Sn is a good candidate because it has higher critical field, as shown in the Fig 1.19 in the paragraph 1.3.5.

### 1.3.4 Nb$_3$Sn Superconductor

Intermetallic Niobium-Tin is another appropriate superconducting compound for large scale production and for combination with copper. It has a well defined stoichiometry with compositions ranging from about 18 to 25 at. %

---

$^2$Non-Cu critical current density is obtained by dividing $I_c$ by conductor area, excluding the Cu stabilizer area.

$^3$Flux jump is a phenomenon related to the discontinuously change of the magnetization in a superconductor during the sweeping of the magnetic field.
1.3 Superconducting materials

Figure 1.13: On the left The NbTi crystal structure. On the right the Nb$_3$Sn crystal structure [17][18].

Sn. The crystal structure is a cubic A15 lattice, shown in Fig 1.13, but it changes in a tetragonal martensitic phase transformation at $T_m \cong 43$ K. The A15 phases are series of intermetallic compounds with the chemical formula $\text{A}_3\text{B}$: the B atoms, which could be any element, are located at the cube center and in extremities positions and A atoms, which represent a transition metal, are on each face of the cubes. In the binary phase diagram (Fig. 1.14), the region energetically more favourable is within the $\text{Nb}_{1-\beta}\text{Sn}_\beta$ and is indicated by the dashed line.

The atomic Sn content and the absence of the tetragonal distortion influence the main important parameters for wire performance ($H_{c2}$, $T_c$, $\lambda_{ep}$). In the table 1.3 the main parameters of Nb$_3$Sn are presented.

<table>
<thead>
<tr>
<th>Characteristic Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superconducting transition temperature</td>
<td>18 [K]</td>
</tr>
<tr>
<td>Lattice parameter at room temperature</td>
<td>0.5293 [nm]</td>
</tr>
<tr>
<td>Upper critical field</td>
<td>25 [T]</td>
</tr>
<tr>
<td>Lower critical field</td>
<td>0.038 [T]</td>
</tr>
<tr>
<td>Ginzburg-Landau coherence length</td>
<td>3.6 [nm]</td>
</tr>
<tr>
<td>Superconducting energy gap</td>
<td>3.4 [meV]</td>
</tr>
</tbody>
</table>

The critical current density depends on fluxoid pinning sites on the grain boundaries. In order to achieve high $J_c$, Nb$_3$Sn must be processed in a way that a fine and homogeneous structure, with grain diameters between 30 and 300 nm, is obtained [16]. Since Nb$_3$Sn is brittle it must be formed in situ and at its final shape (after coil winding) because it can’t withstand more than 0.3% of mechanical strain without losing superconducting properties. All
actual manufacturing methods starts from large billets of precursor elements Nb, Sn and Cu (necessary for electrical and thermal stability) and then they are extruded. The Nb$_3$Sn is formed by a solid state diffusion treatment at high temperature (around 700°C) and this operation must to be done after the winding of the coil [19][10]. Nb$_3$Sn is currently used to manufacture the inner coils of Nuclear Magnetic Resonance (NMR) magnets. For accelerator magnet applications the Nb$_3$Sn could be produced in these following processes, presented in Fig. 1.15.

**Bronze process**

The bronze process is based on the insertion of Nb rods in a high Sn bronze matrix, divided from surrounding Cu stabilizer with a diffusion barrier (mostly Ta) which avoid the diffusion of Sn to Cu. At quite high temperature $\sim 700^\circ$C, Sn spreads in the bronze matrix and reacts with Nb filaments to form the

Figure 1.14: Binary phase diagram of the Nb-Sn system [10].
1.3 Superconducting materials

Figure 1.15: 3 different processes for the manufacture of Nb$_3$Sb wires, in order: bronze process, Internal Sn process and PIT process [10].

Superconducting phase Nb$_3$Sn. A positive feature of the method is to get very fine filaments ($\leq 5 \mu$m) and to have a large area available for A15 development. One of the problems related to this technique is the limit of the Sn solubility in bronze to about 9.1 at% Sn which causes an upper limit to the non-Cu critical current density to about $J_c=1000$ A/mm$^2$. This method is not exploited anymore for accelerator magnets where critical current density of about 2000 A/mm$^2$ at 4 K and 12 T are required [10][19].

**Internal tin process**

The internal tin process was introduced in 1974 to overcome the limit of the bronze process. One of the most successful high-$J_c$ internal tin processes is called Rod Restacked Process (RRP) and consists of a Sn core, surrounded by Cu matrix with Nb or Nb-alloy rods inserted. This assembly is surrounded by a diffusion barrier that prevents diffusion of Sn in Cu. In turn, the structures are arranged in a high-purity copper billet. The restacking of these assemblies allows a higher reduction of the final subelement size. It reaches high non-Cu critical currents (non-Cu $J_c$) of the order of 3000 A/mm$^2$ at 4.2 K and 12 T if the quantity and quality of the Nb and Sn are optimized. The optimization
Background

of the method is achieved maximizing the amount of superconductor that is formed in the non-Cu fraction and the improvement of the grain dimension, Sn content and the ternary element addition. IT process have excellent productivity and low production cost because the drawing process does not require intermediate annealing. By contrary, the formation of interconnection of the filaments during A15 growth which causes the increase of the filament size is the main disadvantage of the technique. RRP wires are produced by Bruker Energy and Supercon Technologies Inc. (BEST) [10][19].

Powder-in-Tube process

The powder-in-tube process was developed in the mid-1970s in Netherlands. In this method the filament is composed by a core of powder, mostly based on NbSn\(_2\), embedded in Nb rods that are inserted in a Cu matrix. The stacked assembly is drawn or extruded to the final wire size. This method allows to reach an optimal threshold between the dimension of the filament, less than 50 µm, and high J\(_c\), comparable with the previous approach. In fact the maximum non-Cu J\(_c\) is of the order of 2300 A/mm\(^2\) at 4.2 K and 12 T. The difficulty in wire drawing because of the brittleness of the core and the loss of core region for A15 formation are the principal drawbacks of the method. PIT wires are produced by Bruker European Advanced Superconductors (Bruker EAS) [10][19].

Figure 1.16: Example of Nb\(_3\)Sn strand with a diameter of 1.0 mm. On the left the RRP strand and on the right the PIT strand [20].
1.3 Superconducting materials

The RRP and PIT methods are the only two technologies that reach a sufficiently high $J_c$ for High Energy Physics (HEP) applications. In Fig. 1.17 the $J_c$ at 4.2 K of PIT and RRP conductors is reported as a function of the applied field. At 12 T the PIT conductors are less performing of about 17% than RRP strands, but thanks to a higher critical field the $J_c$ dependence of the PIT conductors is less pronounced. At 20 T the $J_c$ of the two conductors are identical.

1.3.5 Comparison between NbTi and Nb$_3$Sn

The performance of a superconducting magnets are determined by the critical surface of the superconducting material and the shape of the coil. Fig. 1.18 shows the critical surface in 3D space and in 2D space of NbTi and Nb$_3$Sn whereas Fig. 1.19 depicts the magnetic field of the two superconductors in the center of the dipole versus the sector width ($B_{ss}$). For both superconductors, $B_{ss}$ saturates to about 9 T and 16 T for respectively NbTi and Nb$_3$Sn when the sector thickness of the coil is increased beyond 60 mm (Fig.1.19). In the superconducting accelerator coils the typical engineering current density is about 600 A/mm$^2$, so considering the critical surface of NbTi at 4.2 K (Fig. 1.18 on the right), the ultimate field that will generate a NbTi dipole is about 9 T. Doing the same for Nb$_3$Sn, the result will be about 16 T. The following table 1.4
Background

confirms the better magnetic field performances of Nb$_3$Sn compared to NbTi, both in terms of material and superconductor. It is also possible to see the higher cost of Nb$_3$Sn material.

Figure 1.18: On the left the critical surface of NbTi and Nb$_3$Sn in 3D-space. On the right the critical current density at 4.2 K of NbTi and Nb$_3$Sn [21].

<table>
<thead>
<tr>
<th>Material</th>
<th>NbTi</th>
<th>Nb$_3$Sn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical Temperature at 0T and 0 strain</td>
<td>9.2 K</td>
<td>18 K</td>
</tr>
<tr>
<td>Critical Magnetic field at 0K and 0 strain</td>
<td>14.5 T</td>
<td>28 T</td>
</tr>
<tr>
<td>Cost per kg of wire</td>
<td>100-150 US$</td>
<td>700-1500 US$</td>
</tr>
</tbody>
</table>

Typical operation conditions in a 0.85 mm diameter strand

| Current                        | 300-400 A | 300-400 A |
| Engineering Current density in the Coil | 600-700 A/mm$^2$ | 600-700 A/mm$^2$ |
| Magnetic field                 | 8-9 T     | 10-16 T   |

Nb$_3$Sn needs a thermal cycle at 650°C during few days. Since it is very brittle after the treatment, the coil has to be wound before that. The thermal and the impregnation cycles require specific tooling for Nb$_3$Sn fabrication so we can observe that the production of NbTi is simpler than Nb$_3$Sn, the comparison is represented in Fig.1.20 [22].

In conclusion, despite Nb$_3$Sn has higher raw material cost and more complicated fabrication process to handle, due to its brittleness after reaction, it is chosen over NbTi for its better magnetic performances.
1.3 Superconducting materials

Figure 1.19: Magnetic field versus the sector width for NbTi and $Nb_3Sn$ magnets at 4.2 K[23].

![Diagram of NbTi and Nb3Sn coils](image)

Figure 1.20: Fabrication process of NbTi and $Nb_3Sn$ coils [22].

1.3.6 Operating limits of a superconductor magnet

The critical surface of the superconducting material limits the performances of the magnets, so the operating current density of superconducting magnet is chosen in order to ensure stability and safe operation. The superconducting magnet cannot be used at its maximum capacity, so it is necessary to define the operating point. The considered margins are:

- the critical current margin: the operating current needs to be below the critical current of the material, otherwise the wires will leave their superconducting state;

- the margin along the loadline: the load line gives the peak magnetic flux density produced by the magnet at a given current. By increasing the current, the load line will cross the critical surface of the superconductor. It is well represented by the solid black line in Fig. 1.21. Typically accelerator magnets are operated at 20% margin on the load line.
Background

- the temperature margin: in order to operate a superconducting magnet some temperature margin is required, typically around 2-4 K, in order to avoid the abrupt phenomena called quench.

![Figure 1.21: Definition of superconducting magnet operating point](image)

1.3.7 Nb$_3$Sn Cables

Accelerators magnets operates at large stored magnetic energy (MJ) and in case of quench the stored energy is dissipated in the winding of the cables forming the magnet. A wire that is used in a cable is called strand. During a quench the intention is to discharge the current in few hundreds of ms in order to limit the hot spot temperature and the possible damage of the superconductor. In order to keep the inductive voltage below voltage insulation limit at values of the order of kV, the inductance of the coil must be reduced. This is the main reason why the multistrands cables shall be preferred to single wires in the construction of a accelerator superconducting coil. A multistrands cable, additionally, allows to reduce the piece length of the superconductor. Moreover, another interesting advantage is the higher reliability, thus, if one strand of the cable is locally damaged, it still works because its current can redistribute locally in the others. The cable design preferred for accelerator magnets is the
Rutherford-type. $\text{Nb}_3\text{Sn}$ Rutherford cable is a multistrand transposed cable with a trapezoidal cross section which will be deeply described in second chapter. Main advantages of Rutherford cable are: transposition of the strands, high packing factor, good control of dimensions, limited degradation of the electrical performance and a good windability.

Figure 1.22: Rutherford cable[25].

### 1.4 Hi-Lumi project

With the aim of discovering new particles and go further with the research, CERN established the High Luminosity LHC Project (HL-LHC) in autumn 2010. The purpose is to increase the integrated luminosity of the LHC machine from 300 to 3000 fb$^{-1}$ for collecting more data and growing the possibility to observe new phenomena by around 2030 [2]. In the experimental point of LHC the number of collisions per second ($N_{\text{event}}$) is given by:

$$N_{\text{event}} = L \cdot \sigma_{\text{event}}$$  \hspace{1cm} (1.6)

where $\sigma$ is the cross section for the event and $L$ is the machine luminosity, a very important parameter for an accelerator. Luminosity is the ratio between the number of collisions ($dN$), that can be produced in a detector, per time ($dt$) and per interaction area ($d\sigma$) [26]:

$$L = \frac{dN}{dt \, d\sigma}$$  \hspace{1cm} (1.7)
The integral of the delivered luminosity over time is called integrated luminosity and it is important to characterize the performance of an accelerator, it is usually expressed in inverse of cross section (i.e. femtobarn$^{-1}$- fb$^{-1}$). Starting from $L \sim 10^{33}$ cm$^{-2}$ s$^{-1}$ in LHC, the goal is to achieve $L \sim 10^{34}$ cm$^{-2}$ s$^{-1}$ for HL-LHC, which means $10^9$ collisions per s and per cm$^2$ in LHC detectors. The total upgrade of LHC corresponds to build about 1.2 Km of a new accelerator, in different places of the LHC ring; the completion of installations is scheduled between 2024 and 2026 as shown in Fig. 1.23 [2][27].

Cutting-edge 11-12 T superconducting magnets made from Nb$_3$Sn technology are required to reach the new purpose. The HL-LHC will need to replace more than 40 superconducting magnets and about 60 superconducting corrector magnets.

1.4.1 11 T dipoles

For the upgrade of luminosity, dispersion suppressors (DS) need to be installed on the machine during the second long shutdown in 2019-2020 (LS2). In order to allow the installations of the 3 m long DS, two standard dipole (8.3 T, 15 m long each) will be replaced by two shorter dipoles (2x5.5 m each one) generating field of 11 T with a 60 mm aperture. In this way it is possible to have the same beam bending strength, which means $B$ (magnetic field) x $l$ (length) and a 4 m
1.4 Hi-Lumi project

space for allowing the incorporation of the new collimators, see in 1.24 [29]. The 11 T Dipole Full Assembly is called MBHFA and it has the same outside diameter as the LHC main bending dipoles (MBs), see Fig. 1.25. The coil is made from Nb$_3$Sn Rutherford cable, which will be described in next chapter, and it is designed to reach 11 T at LHC nominal operation current of 11.85 kA [30].

![Figure 1.24: Present LHC dipole (top) to be replaced by two Nb$_3$Sn dipoles with collimator unit in the middle][27].

![Figure 1.25: Cross section designs of the 11 T dipole][31].

1.4.2 QXF quadrupoles

The pillars of the HL-LHC upgrade are the 24 new interactions quadrupoles (QXF inner triplets) which will replace the inner-triplet made from Nb-Ti.

They are called low-β quadrupoles and provides the optical manipulation for minimizing the dimension of the beam (σ) at collision points in order to increase the luminosity. There are two different lengths of the magnets: 6.8 m
Background

and 4 m and they will reach an operating gradient of 133 T/m, with an aperture of 150 mm, bigger than the current one of the NbTi quadrupoles [32]. A sketch of triplets quadrupoles (Q1, Q2a-Q2b, Q3) located before a collision point (CP) is showed in the Fig.1.27:

![Figure 1.26: QXF magnet cross-section [33].](image1)

Figure 1.26: QXF magnet cross-section [33].

![Figure 1.27: Inner-triplets made by the two kind of quadrupoles at different lengths (Q1, Q2a-Q2b, Q3) before the collision point (CP). Image by E.Todesco.](image2)

Figure 1.27: Inner-triplets made by the two kind of quadrupoles at different lengths (Q1, Q2a-Q2b, Q3) before the collision point (CP). Image by E.Todesco.

### 1.4.3 Development of High Field Magnets

The FRESCA2 dipoles will be used to upgrade the CERN FRESCA test facility, which is used to characterize the electrical performances of superconducting cables at 4.3 K and 1.9 K. The FRESCA test station, based on a NbTi dipole can generate field up to 9.6 T whereas for Nb₃Sn cables characterizations at field of 13-15 T are required. The FRESCA2 dipole is designed to generate
field of 13 T at current of 10.6 kA [34]. The FRESCA2 dipole is 1.5 m long with a 100 mm bore and consist of 4 double-pancake coils as illustrated in Fig. 1.28.

Figure 1.28: Geometry of FRESCA2 dipoles and block configuration [35].

Conclusion

In this chapter the theory behind the project was presented and the reason why the superconducting material of Nb$_3$Sn is chosen for reaching higher magnetic field was explained. After an introduction of CERN and accelerators magnets, a description of superconducting materials and its properties was provided. Then, the comparison between the NbTi, the superconducting material used in LHC, and Nb$_3$Sn, the one used for Hi-Lumi upgrade, was reported. All the types of strand based on Nb$_3$Sn, the importance of Rutherford cable in the fabrication of the superconducting accelerators magnets and Hi-Lumi Project magnets were presented. All the superconducting magnets for the HL-LHC are made from Nb$_3$Sn Rutherford cables that will be deepened in the next chapter.
Chapter 2

Production of Nb₃Sn cables

The superconducting coils of accelerator magnets are made from Rutherford cables with a trapezoidal cross section. A Rutherford cable is a multi-strand twisted cable in which the strands (wires) are wound around a mandrel and then flattened into a rectangular or trapezoidal cross-section. The large compaction in Rutherford cable not only increases the overall current density but also its mechanical stability. In this chapter, in order to understand how the Rutherford cables production works, the cabling machine and the main types of Rutherford Nb₃Sn cables are introduced. The different systems to control the quality of the cables during production are also presented and the obtained results are discussed.

2.1 Geometry of Rutherford cable

The geometry of the Nb₃Sn Rutherford cable is characterized by a trapezoidal cross section with a keystone angle, as reported in the Fig. 2.1. d illustrates the diameter of the strand, t₁ represents the thin thickness, t₂ is the thick thickness, w indicates the width and ϕ is the cabling pitch angle defined in Eq. 2.1. Typically the keystone angle varies between 0 and 1.5 degrees, the Lₚ, which is the pitch length, is ranging from 35 to 160 mm and the width varies
Production of Nb\textsubscript{3}Sn cables

between 4 and 21 mm [36].

\[ \varphi = \arctan \frac{2w}{L_p}. \]  \hspace{1cm} (2.1)

\[ C_p = \frac{2w(t_1 + t_2)\cos \varphi}{n \pi d^2} \cdot \frac{\pi}{4} \cdot 100\%. \]  \hspace{1cm} (2.2)

The thickness compaction factor is the thickness of the cable at a certain point of the cable divided by two times the strand diameter in virgin state and it increases from the thick edge towards the thin edge, see in Fig. 2.1. The compaction factor of the cable is proportional to the cross sectional area of the cable divided by the cross sectional area of the strands in the virgin state, see Eq. 2.2.

![Figure 2.1: Geometry of a Rutherford cable](image1)

In order to avoid the large eddy currents during ramp that may reduce
the performances of the coil, a stainless-steel core (25 \mu m) is inserted to control the interstrand resistance in Rutherford cable (Fig. 2.2) [32].

2.2 The cabling machine

For the HL-LHC superconducting Nb$_3$Sn magnets about 70 Rutherford cables up to 770 m long will be produced at CERN. At CERN, Rutherford cables are manufactured in the TE/MSC-SCD superconducting laboratory located in building 103 using the planetary machine AC250R shown in Fig. 2.3. This machine, constructed and used for the LHC NbTi Rutherford cable production series, was installed at CERN in 2006. Since that time, it was used to perform Research and Development on the Nb$_3$Sn Rutherford cable and to produce prototype cables. The machine is composed of four main components: The rotating cage, where the spools of strands to be cabled are located, the Turk-shead, where the final shape of the cable is given by four rollers, the caterpillar, and finally the pick-up spool.

![Figure 2.3: Rutherford cabling machine located in the laboratory.](Image)

The CERN Rutherford cabling machine is able to produce cable made from up to 40 strands. The spools of conductors are mounted on the rotating cage on 4 separate disks (10 spools per disks). The rotation of the cage is ensured by a motor controlled by the programmable logic controller (PLC) of the cabling machine.
The AC250R is a planetary cabling machine: this prevents torsional stress in the resultant cable, see Fig. 2.4 on the left. From the spools, the strands are guided by rollers up to the Turkshead, the place where the final shape of the cable is given. Before entering the rollers of the Turkshead, the wires are guided on the mandrel. The mandrel, visible in Fig. 2.4 on the right, is a transition positioning tool between the conical surface of the wire array to the keystoneed cross section of the cable. The two wire layers of the cable are contained externally by the Turkshead aperture and internally by the mandrel. The position accuracy of the mandrel is a very critical parameter in the cabling process; the strands should never have enough freedom to cross over each other. The mathematical definition of the surface containing the strands is an hyperbolic conoid. Consequently, the mandrel should look like a conical blade, the edges of which are converging to the width of the turkshead’s aperture and the faces converging to the center plane of the cable; the tip of the mandrel being the last tangential contact point with the strands. In order to reduce the strand tensions during the cabling it is important to lubricate the tip of the mandrel, polish the mandrel and made it of hard material [37][38]. A mechanical tension should be applied on the strands along the full path in between the spools and the rollers of the Turkhead in order to avoid possible cross over of the strands. On the AC250R machine, the mechanical tension on each single strand is controlled thanks to 40 sets of motors, drivers and tension transducers. The mechanical tension applied on the strands is programmed in the PLC of the machine.

The turkshead is composed of 4 rollers that compressed the strands in order to obtain the trapezoidal cross section of the Rutherford cable. The keystone angle of the cable is given by the two vertical roller ground conically to one-half of the keystone angle. The horizontal roller has a cylindrical shape. In order to reduce the tension applied on the cable between the Turkshead and the caterpillar, the two vertical rollers are motorized. The roller rotation is synchronised with the rotation of the cage and the pitch of the cable [37][38].
The caterpillar is the pulling device, perfectly synchronized with the rotating drum of the cabler in order to obtain a constant cable pitch and avoid an accidental overwrap of the mandrel with wires. At the end of the Rutherford cabling machine the pick-up spool which is synchronized with the whole system, is the reel around which the cable is wound.

2.3 Rutherford Nb$_3$Sn cables for HL-LHC and FRESCA2

At present days, the Rutherford Nb$_3$Sn cables are used for the production of three different magnets at CERN: 11 T dipoles, QXF quadrupoles and FRESCA2 dipoles.

11 T dipole’s cables

The 11 T dipole cables are made from 40 RRP strands with 0.7 mm diameter. Each strand is fabricated with 108 subelements and every subelement is in turn formed by 127 filaments; this is called 108/127 layout, see in the zoom of central image of Fig.1.17. One example of RRP strand is represented in Fig. 2.5.
Production of Nb$_3$Sn cables

Figure 2.5: Cross section of RRP strand of 11 T dipole cable with a 0.7 diameter and 108/127 layout.

QXF quadrupole’s cables

Figure 2.6: MQXF cable strands: On the left the RRP strand 108/127 geometry, on the right the PIT strand 192 subelements. Both have a 0.85 mm of diameter.

The MQXF cables are made of two kind of strands with 0.85 mm of diameter: PIT and RRP. The PIT strands are produced by Bruker EAS and they have 192 subelements and the RRP strands have the 108/127 geometry. In Fig. 2.6 it is possible to understand how the strands for the quadrupole looks like. Strands and cables specification parameters are reported in table 2.1 and in table 2.2.
2.3 Rutherford Nb₃Sn cables for HL-LHC and FRESCA2

Table 2.1: Specification of the 11 T and QXF Nb₃Sn wires [39].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>11 T (RRP)</th>
<th>QXF (RRP and PIT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire Diameter</td>
<td>mm</td>
<td>0.7</td>
<td>0.85</td>
</tr>
<tr>
<td>Subelement diameter</td>
<td>µm</td>
<td>&lt;50</td>
<td>&lt;55</td>
</tr>
<tr>
<td>Cu to non-Cu volume ratio</td>
<td>-</td>
<td>1.15</td>
<td>1.2</td>
</tr>
<tr>
<td>Wire twist pitch</td>
<td>mm</td>
<td>14</td>
<td>19</td>
</tr>
<tr>
<td>Minimum Ic 4.22 K (12 T)</td>
<td>A</td>
<td>438</td>
<td>632</td>
</tr>
<tr>
<td>RRR (after reaction)</td>
<td>-</td>
<td>&gt;150</td>
<td>&gt;150</td>
</tr>
</tbody>
</table>

Table 2.2: Specification of the 11 T and QXF Nb₃Sn cables [39].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>11 T RRP</th>
<th>QXF RRP and PIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of strands</td>
<td>-</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Strands diameter</td>
<td>mm</td>
<td>0.7</td>
<td>0.85</td>
</tr>
<tr>
<td>Cable bare width</td>
<td>mm</td>
<td>14.70</td>
<td>18.15</td>
</tr>
<tr>
<td>Cable bare mid-thickness</td>
<td>mm</td>
<td>1.250</td>
<td>1.525</td>
</tr>
<tr>
<td>Keystone angle</td>
<td>deg.</td>
<td>0.79</td>
<td>0.4</td>
</tr>
<tr>
<td>Thin edge compaction</td>
<td>%</td>
<td>17.95</td>
<td>14.02</td>
</tr>
<tr>
<td>Thick edge compaction</td>
<td>%</td>
<td>3.48</td>
<td>6.57</td>
</tr>
<tr>
<td>Transposition pitch</td>
<td>mm</td>
<td>100</td>
<td>109</td>
</tr>
<tr>
<td>SS Core width(thickness)</td>
<td>mm</td>
<td>12 (0.025)</td>
<td></td>
</tr>
</tbody>
</table>

FRESCA2 dipole’s cable

FRESCA dipole is made of Rutherford cables characterized by 20.9 mm width, made up of 40 strands with a diameter of 1.0 mm. The strands are obtained by two different fabrication techniques: RRP and PIT. In the case of RRP the layout is 132/169 whereas for PIT the number of subelements is 192. More details about the parameters of Nb₃Sn are provided in the following table 2.3. The cross section of these cable is reported in Fig. 2.8. see in Fig. 2.8.

Table 2.3: Parameters of the FRESCA2 cable [35].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>FRESCA2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of strands</td>
<td>-</td>
<td>40</td>
</tr>
<tr>
<td>Strands diameter</td>
<td>mm</td>
<td>1.0</td>
</tr>
<tr>
<td>Cable bare width</td>
<td>mm</td>
<td>20.9</td>
</tr>
<tr>
<td>Cable bare mid-thickness</td>
<td>mm</td>
<td>1.82</td>
</tr>
<tr>
<td>Keystone angle</td>
<td>deg.</td>
<td>0.0</td>
</tr>
<tr>
<td>Thin edge compaction</td>
<td>%</td>
<td>9.0</td>
</tr>
<tr>
<td>Thick edge compaction</td>
<td>%</td>
<td>9.0</td>
</tr>
<tr>
<td>Transposition pitch</td>
<td>mm</td>
<td>120</td>
</tr>
<tr>
<td>SS Core width(thickness)</td>
<td>mm</td>
<td>NO</td>
</tr>
</tbody>
</table>
Production of Nb$_3$Sn cables

Figure 2.7: On the left the RRP strand 132/169 geometry of FRESCA2, on the right the PIT strand with 192 subelements.

Figure 2.8: Cross section of samples of the three different Nb$_3$Sn cables produced at CERN.

2.4 Quality control of cable production

The control of the HL-LHC cable geometry is crucial to achieve good performances and this is possible thanks to various monitoring systems [40]: Cable Measuring Machine (CMM), which measure the cable dimensions, Cable Inspection System (CIS) and Cable Edges Inspection System (CEIS), which respectively check the abnormal flattening of the wires and the facets dimensions of the cables and finally the Strand Tension Monitoring System, which monitors and records the mechanical tensions applied on each strand during cable production.
2.4 Quality control of cable production

2.4.1 Cable Measuring Machine

Precise control of cable dimensions is of primary importance in order to meet the high field uniformity required for the dipole and quadrupole accelerator magnets. The control of the dimensions is also of importance in order to control the $I_c$ degradation, especially with the PIT strands [39].

The Cable Measuring Machine system, installed on the cable manufacturing line, measures and records the superconducting cable dimensions. This system was already used for the NbTi Rutheford LHC series production. It provides periodic measurements of the cable mid-thickness, keystone angle and width. The CMM is driven by a mechanical and electrical system. The mechanical function of the CMM is operated by an air actuated hydraulic system. This system controls the pressure applied to the measuring head, see Fig. 2.9. The measuring head clamps the cable in two directions and travels with the cable flow when taking measurements. First, an edge load of 276 kPa centers the cable in the head. Second, a load of 20 MPa compresses the cable thickness. The cable is held at these pressures for a predetermined specified time; typically 4 to 5 seconds allowing the dimensions to stabilize. Three Linear Variable Differential Transformers (LVDTs) are used to measure the position of the measuring head when clamped on the cable. The LVDT output, hydraulic pressure, and cable footage measurements are then sent to the computer for processing. Recorded measurements and calculated dimensions are displayed on the display screen, and saved on disk. A specific procedure of CMM calibration (not reported here) is performed before each production run of Rutherford cable. The measuring head should be cleaned and all the moving parts should be lubricated.

The measured thickness, width and keystone angle during the production of QXF cable RUN172 are reported in Fig. 2.10. Along the full length of the cable (750 m) the cable mid-thickness is within the tight tolerances of the specification $+/-$ 10 $\mu$m. The cable dimensions are very stable along the cable length, which is being produced at a typical throughput of 1.5 m/min.
2.4.2 Cable Inspection System

In order to discard a defective cable from the rest of magnet production, it is important to detect all possible abnormal shape of the Nb$_3$Sn strands. The two wide faces of the produced cable is inspected on production line thanks to a optical imaging system named cable inspection system. The Cable Inspection System (CIS) already in use at the time of LHC Nb-Ti production scans in real time the cable on its two wide faces, detects cable defects and displays them. The study of the cable is performed in two levels of analysis. First, a linear camera detects the facets but, working in the order of milliseconds, it could generate fake alarms. Second, a matrix camera, more sophisticated, is able to analyse the image registered.

During the first level of analysis the periodicity of wires along the cable
and the width of each strand is checked, it should be less than the medium width multiplied by 1.5, if there is no suspicious of defects. The second camera is activated if, for example, the pitch of the wires is more than a defined parameter. In the 2nd level of inspection the system gives an image analysis on 2D picture, see Fig 2.12 on the bottom [41][40].
2.4.3 Cable Edges Inspection System

Defect in cable may also occur on the edges of the cable, a dedicated optical detection system named Cable Edges Inspection System (CEIS) was installed in mid 2016 in order to detect such possible defects. The system is measuring the facets dimensions, the flattened part of the strands at cable edges as reported in Fig. 2.15. The detection system is based on Keyence CV-X vision controller equipped with two macroscopic cameras. The CEIS system is installed on production line in between the Turkshead and the caterpillar. The cable passes between two cameras in order to analyse the thin and thick edge during the whole production line. The system is used in order to detect
abnormal shape of each facet of the cable. The facets are recognized by the controller thanks to the contrast, as depicted in the Fig. 2.14. On each facet, the system is calculating the projected length along cable axis and edge thickness named respectively feret diameter $x$ and feret diameter $y$, as shown in Fig. 2.13. The controller is also measuring perimeter and area of the facets.

Figure 2.13: Cable thin edge: Feret diameter $x$ and $y$.

Figure 2.14: Facets of cable being recognized by the CEIS.

Figure 2.15: Cable Edges Inspection System (CEIS) installed on Rutherford production line.
Results

In this paragraph the facets measurements performed thanks to the CEIS are presented and discussed. Each cabling session is classified with the term "RUN" plus a number and a letter. The number means the cable production order and the presence of the letter indicates that multiple cable unit lengths were produced during the same cable production run.

The Keyence system collects data as a CSV file during the whole time of production, in a form of a table with up 2,000,000 of rows and 18 columns. A matlab code was developed in order to analyse the data. The matlab code is performing statistical analysis and plotting the measurements versus time for each parameter of the facet. In order to observe the evolution of the facets measurements during the whole production, all the values of the quantities analysed for thick and thin edge are expressed in function of the time as reported in Fig. 2.16 and in Fig. 2.18. The data are related to RUN174, which is a 11 T dipole cable. In order to observe the high frequency of the measurements the Fig. 2.17 reports the zoom of the plot of feret diameter x of thin edge of RUN174A where we observe lot of registered values in few seconds. Then, with the purpose of having results easy to compare between different cabling runs, the maximum, minimum, standard deviation and medium values of facets dimensions are computed and reported in tables 2.4 and 2.5.

<table>
<thead>
<tr>
<th>Table 2.4: Results obtained for 11 T RUN174A</th>
</tr>
</thead>
<tbody>
<tr>
<td>RUN174A</td>
</tr>
<tr>
<td>THIN EDGE</td>
</tr>
<tr>
<td>Feret diameter x (µm)</td>
</tr>
<tr>
<td>Feret diameter y (µm)</td>
</tr>
<tr>
<td>Perimeter (µm)</td>
</tr>
<tr>
<td>Area facets (µm²)</td>
</tr>
<tr>
<td>THICK EDGE</td>
</tr>
<tr>
<td>Feret diameter x (µm)</td>
</tr>
<tr>
<td>Feret diameter y (µm)</td>
</tr>
<tr>
<td>Perimeter (µm)</td>
</tr>
<tr>
<td>Area facets (µm²)</td>
</tr>
</tbody>
</table>
2.4 Quality control of cable production

Figure 2.16: Plots for thin edge of 11 T RUN174A versus time of production: feret diameter x on top left, feret diameter y on top right, perimeter on bottom left, area on bottom right.

Figure 2.17: Feret diameter x of thin edge of RUN174A versus time: zoom on a range of time of the order of seconds.
Figure 2.18: Plots for thick edge of RUN174A versus time of production: feret diameter x on top left, feret diameter y on top right, perimeter on bottom left, area on bottom right.

Table 2.5: Results obtained for 11 T RUN174B

<table>
<thead>
<tr>
<th>RUN174B</th>
<th>Max</th>
<th>Min</th>
<th>Stand.Dev</th>
<th>Medium</th>
</tr>
</thead>
<tbody>
<tr>
<td>THIN EDGE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feret diameter x (µm)</td>
<td>2102.4</td>
<td>1382.4</td>
<td>25.6</td>
<td>1941.6</td>
</tr>
<tr>
<td>Feret diameter y (µm)</td>
<td>921.6</td>
<td>720</td>
<td>11.9</td>
<td>825.3</td>
</tr>
<tr>
<td>Perimeter (µm)</td>
<td>8870.4</td>
<td>3744</td>
<td>72.2</td>
<td>4648.0</td>
</tr>
<tr>
<td>Area facets (µm²)</td>
<td>1906225</td>
<td>661466</td>
<td>102689.5</td>
<td>1472921.9</td>
</tr>
<tr>
<td>THICK EDGE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feret diameter x (µm)</td>
<td>4310.4</td>
<td>2208</td>
<td>24.5</td>
<td>2523.0</td>
</tr>
<tr>
<td>Feret diameter y (µm)</td>
<td>1152</td>
<td>768</td>
<td>17.7</td>
<td>938.5</td>
</tr>
<tr>
<td>Perimeter (µm)</td>
<td>15388.8</td>
<td>5596.8</td>
<td>152.7</td>
<td>5966.5</td>
</tr>
<tr>
<td>Area facets (µm²)</td>
<td>2573697</td>
<td>840772</td>
<td>103553.1</td>
<td>2017569.1</td>
</tr>
</tbody>
</table>

From these results all the fluctuations are individuated and it is possible to set maximum and minimum thresholds to the Keyence cameras for saving only the photos at the edges whenever the data recorded are out of the limits.
Almost all of the collected photos are usually related not to real defect but
to artefact of measurements (brightness difference on the facet or on light
reflection as depicted in Fig. 2.19).

![Artefact due to brightness difference in the facet.](image)

**Figure 2.19:** Artefact due to brightness difference in the facet.

**Comparison with the optical microscope measurements**

At the end of each cable production a piece of cable is cut and it is observed
under the microscope: the feret diameter x is measured thanks to the software
associated with the optical microscope. The measurements performed with
the microscope are compared in tables 2.6 and 2.7 and Fig. 2.20 with the
measurements from the CEIS. The parameters found by the Keyence systems
are very similar to the ones measured with the microscope, both for 11 T
dipoles cables and QXF cables. In fact in the following Fig. 2.20 we can observe
that the difference between measurements of feret x by microscope and the
results by Keyence is small. For the RUN 180A in case of feret x there is total
coincidence of the two values but in general the deviation is no more than
50 \( \mu \)m. In the table 2.6 and 2.7 the feret x and feret y are obtained from the
average of the values registered during the whole fabrication process. In the last
two columns the differences between microscope and Keyence measurements
are reported. The dimensions of the facets are homogeneous over the full cable
length.
Production of Nb$_3$Sn cables

Figure 2.20: Feret x at thin and thick edge in function of the number of cables produced for 11 T dipoles cables and QXF cables

Table 2.6: Comparison between the dimensions of the thick and the thin edges detected by the microscope and by the Keyence system for 11 T dipoles cables.

<table>
<thead>
<tr>
<th>11T Cable ID</th>
<th>Thick edge (µm)</th>
<th>Thin edge (µm)</th>
<th>Delta Feret X (µm)</th>
<th>Delta Feret X Thick edge (µm)</th>
<th>Delta Feret X Thin edge (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 173A</td>
<td>1889</td>
<td>838</td>
<td>2463</td>
<td>931</td>
<td>1898</td>
</tr>
<tr>
<td>Run 173B</td>
<td>1914</td>
<td>820</td>
<td>2425</td>
<td>928</td>
<td>1955</td>
</tr>
<tr>
<td>Run 174A</td>
<td>1961</td>
<td>828</td>
<td>2522</td>
<td>937</td>
<td>1955</td>
</tr>
<tr>
<td>Run 174B</td>
<td>1942</td>
<td>825</td>
<td>2523</td>
<td>938</td>
<td>1955</td>
</tr>
<tr>
<td>Run 180A</td>
<td>2032</td>
<td>860</td>
<td>2437</td>
<td>909</td>
<td>2034</td>
</tr>
<tr>
<td>Run 180B</td>
<td>2032</td>
<td>848</td>
<td>2468</td>
<td>913</td>
<td>2034</td>
</tr>
</tbody>
</table>
2.4 Quality control of cable production

Table 2.7: Comparison between the dimensions of the thick and the thin edges detected by the microscope and by the Keyence system for QXF cables.

<table>
<thead>
<tr>
<th>MQXF Cable ID</th>
<th>Feret X (µm)</th>
<th>Feret Y (µm)</th>
<th>Feret X (µm)</th>
<th>Feret Y (µm)</th>
<th>Delta Feret X</th>
<th>Delta Feret X</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 165A1</td>
<td>2256</td>
<td>985</td>
<td>2403</td>
<td>988</td>
<td>2101</td>
<td>2346</td>
</tr>
<tr>
<td>Run 165A2</td>
<td>2241</td>
<td>979</td>
<td>2421</td>
<td>982</td>
<td>2100</td>
<td>2344</td>
</tr>
<tr>
<td>Run 168A</td>
<td>2185</td>
<td>958</td>
<td>2464</td>
<td>991</td>
<td>2040</td>
<td>2433</td>
</tr>
<tr>
<td>Run 169A</td>
<td>2081</td>
<td>953</td>
<td>2474</td>
<td>1013</td>
<td>2074</td>
<td>2433</td>
</tr>
<tr>
<td>Run 170</td>
<td>2218</td>
<td>987</td>
<td>2520</td>
<td>1012</td>
<td>2209</td>
<td>2401</td>
</tr>
<tr>
<td>Run 171A</td>
<td>2211</td>
<td>960</td>
<td>2418</td>
<td>988</td>
<td>2057</td>
<td>2365</td>
</tr>
<tr>
<td>Run 172A</td>
<td>2009</td>
<td>978</td>
<td>2344</td>
<td>997</td>
<td>2000</td>
<td>2378</td>
</tr>
<tr>
<td>Run 178A</td>
<td>2015</td>
<td>981</td>
<td>2370</td>
<td>1005</td>
<td>2085</td>
<td>2408</td>
</tr>
<tr>
<td>Run 179A</td>
<td>2044</td>
<td>983</td>
<td>2439</td>
<td>1009</td>
<td>2100</td>
<td>2465</td>
</tr>
<tr>
<td>Run 183A</td>
<td>2010</td>
<td>993</td>
<td>2425</td>
<td>1012</td>
<td>2052</td>
<td>2437</td>
</tr>
<tr>
<td>Run 184A</td>
<td>2094</td>
<td>1014</td>
<td>2384</td>
<td>998</td>
<td>2162</td>
<td>2406</td>
</tr>
</tbody>
</table>

2.4.4 Strand Tension Monitoring System

The Strand Tension Monitoring System records the mechanical tensions applied on each individual strand during cable production. The system implemented in 2016 is recording the tension of each strand at frequency of about 40 Hz, it is displaying the measurements and also saving it on disk. The controller produces 40 matrices in DAT format, each one for a single strand and composed by 2 columns and up to 600,000 rows. The first columns indicates the milliseconds passed from the beginning of the cabling and the second one represents the tensions values. A Matlab tool was developed in order to analyse the registered data. The Matlab code is able to: generate plots of the mechanical tension versus time for each strand, count all the spikes that exceed a fixed threshold for a single or for a group of strands and make the zoom for a specific fluctuation in mechanical tension on a very short range of time, for example of the order of seconds. Each strand is associated to a specific position on the machine. The strands spools are distributed on 4 disk (also named blocks) on the machine as illustrated in Fig. 2.21.
Results

Thanks to the Matlab code it was possible to study the tension applied during production of different cables. As an example the tension applied during RUN174A (for 11 T dipole) is presented and discussed. The plot of the mechanical tension versus time for the strand 1 is showed in the Fig. 2.22: it displays a final spike in correspondence of the stop of the cabling when the tension is set to zero. Moreover, it depicts some fluctuations in mechanical tension compared to its nominal value. The nominal value depends on the kind of cable: 50 N for 11 T cables, 55 N for QXF cable and 60 N for FRESCA2 cable. The zoom of a valley around 10:12 AM for the strand 1 is reported in Fig. 2.23 and thanks to this, we can notice the high frequency of registered values by the Strand Tension Monitoring System.

Using the Matlab code it is also possible to count for each strand the number of spikes in mechanical tension that reaches values below a specific threshold; 40 N is the chosen threshold for generating the Fig 2.24. As we can see the values of spikes for each strand are ranging in between 1 to 20. If the occurrence of valleys is very frequent in one or more spools, we need to check the parameters for strand regulation. During cabling, thanks to the display of the tension applied on each strand it was noticed that the valleys are induced
2.4 Quality control of cable production

Figure 2.22: Mechanical tension versus time for the strand 1 during production of cable 174A.

Figure 2.23: Zoom of the oscillation in mechanical tension versus time for the strand 1 of cable 174A.

by a transient unrolling of the strand near the border of the spool where the transverse force on the strand is the highest one. Fig. 2.25 shows the geometry
Figure 2.24: Number of valleys less than 40 N for each strand for RUN174A of one spool and the forces acting on the strands when located at the border of the spool. On the machine, the wire which is layer wound on the spool, needs to pass by a fixed ring about 50 cm distant ($D$) from the spool before entering the first roller. Knowing the nominal value of tension, such as 50 N, the width of the spool 13 cm and its radius 4.8 cm, it is possible to calculate the angle called $\alpha$, the perpendicular force ($F_\perp$) and the total force acting on the strand at the border respectively equal to: $\sim 14^\circ$, 12.5 N and 51 N.

Figure 2.25: Angle reached from the strand at the border of the spool. $\alpha$ is the angle and $D$ is the distance from the center of the spool to the disk in front.

Since the spools are arranged on 4 disks on the machine, it is interesting to check if a collective effect could be observed for the different disks. The
2.4 Quality control of cable production

Fig. 2.26 displays the number of valleys at different mechanical tension thresholds for each of the 4 disks of the cabling machine. Thresholds are reported in the first column, the sum of spikes of the strands located in the same disk are given starting from the second to the fifth column and the last column represented the sum of the spikes below the threshold for the total 40 strands. Looking at the Fig. 2.26 it is possible to see higher values for the block 4. The reason of this occurrence could be related to the distance \( D \) of the spools of the block 4. In fact for block 4, the distance D in this case is 2 cm less than for the other blocks, so the transverse force on the strands is higher. The graph of the number of fluctuations in function of the mechanical tension threshold reported in Fig. 2.26: the lighter colored line shows the number of spikes of the strands in the fourth disk; fluctuations higher than the nominal value of 50 N were not recorded.

![Graph showing number of fluctuations versus mechanical tension's thresholds](image)

Figure 2.26: RUN174A: Number of fluctuations versus mechanical tension’s thresholds.

There is another interesting issue to be observed: when multiple cable unit length are produced during same cabling run, the software records more fluctuations during the second cable production than during the first one. This phenomenon, visible in Fig. 2.27, depends on the fact that spools are not anymore full, so there is less organization of the wire inside the spool which could cause a greater number of fluctuations in mechanical tension. This time
Figure 2.27: RUN174: Comparison between data recorded in the first day and second day of production. The number of fluctuations are divided for the length of the cable.

the number of spikes is divided by the length of the cable, 670 m, in order to compare properly the results of the two parts of the RUN174.

**Loosening of strands versus defects in the facets**

Furthermore it is important to notice if a loosening of tension involve a defect in the facets. A method for checking this latter point is the comparison between the graph of the mechanical tension and the plot of the facets dimensions versus time in order to find one or more spikes at the same instant. The mechanical tension of strand 1 are taken into account as an example in Fig. 2.28. If we consider one dimension, such as the feret diameter at thin edge, it is possible to see that, fortunately, there is not correspondence to the fluctuations in mechanical tension. We can conclude that these last ones don’t cause real defects in the facets.
2.4 Quality control of cable production

Strand Crossover

Despite all the precautions that were taken to avoid crossover of strands during cabling, it happens once during MQXF cable production: this rare event never happened over more than ten years of production, pointed out the importance of the CIS, CEIS and Strand Tension Monitoring System. As it is clearly shown in Fig. 2.29 and in Fig. 2.30, a strand crossover is a wrong overlapping of the strands which causes the deterioration of their electrical performances.

Figure 2.28: Comparison between feret diameter x versus time and mechanical tension of strand 1 versus time.

Figure 2.29: Strand crossover: on the left, the view from the top; on the right, the view from the lateral side.
Conclusion

The second section of this thesis was focused on the production of the Nb$_3$Sn Rutherford cables. The cabling machine and different kinds of cables were described and the different systems to control the quality of the cable were illustrated. The results obtained from the tools developed for the analysis of the mechanical tensions of each strand and the dimensions of lateral facets of the cable were explained and then, after the comparison, we observed that there is no specific correlation between the two behaviors. In order to characterize the degradation of the electrical performances induced by strand crossover, a test in FRESCA test station of a defective cable is foreseen and the results are reported in the following pages. FRESCA test station and how the electrical performances tests were performed are discussed in the next chapter.
Chapter 3

Electrical performances of Rutherford cable

The ultimate magnetic field generated by a superconducting magnet depends strongly on the electrical performances of the superconductor it is made of. One of the relevant parameters of a superconductor is the critical current ($I_c$). The critical current reflects the macroscopic current transport capability of the superconductor. The critical current of a superconducting wire at a given temperature and field is determined by the voltage–current curve of a wire short sample. In this chapter, the experimental techniques of the superconductor electrical characterization are introduced. The results from the critical current and RRR measurements on virgin extracted strands from Rutherford cables and full-scale Rutherford cables are reported and discussed.

3.1 $I_c$ and RRR measurements

All accelerators which operate as a storage ring\(^1\) at high field (as LHC and in future HL-LHC) need to have magnets behaving equally. One way to guarantee the best performances of the accelerator is the control of the critical current of

---

\(^1\)A storage ring is a type of accelerator where all the energy of two counterrotating particle beams can be used to produce high energy particle interactions.
the single strands and of the cable and the check of the Residual Resistivity Ratio (RRR) of individual wires [42]. The critical current is an extrinsic property that depends on the particular grain-boundary and defects in the structure of a superconductor material and represents the macroscopic current transport capability of the superconductor. The Residual Resistivity Ratio (RRR) is the ratio between the resistivity of the wire at room temperature and that at the temperature just before the transition in superconducting state.

3.1.1 Strand’s critical current

The critical current of a superconductor reflects the maximum transport current that can circulate without losses in a superconductor. Its measurements are conducted both on virgin strands and on the wires extracted from the cable. These measurements allow the quantification of cabling degradation and to compute the coil expected performances.

Experimental setup

The test setup for Nb$_3$Sn strand critical current measurements is composed of a cryostat divided in two baths by a plate made of insulating material called \( \lambda \)-plate. In the lower bath of the cryostat the liquid helium temperature is regulated to 4.2 K or 1.9 K (the operating temperature of Nb$_3$Sn HL-LHC magnets). The sample under investigation is mounted and reacted on an cylindrical grooved titanium barrel (32 mm diameter) named VAMAS. The VAMAS is mounted into a sample holder that will act as current leads. The sample holder is then inserted into the aperture of a superconducting solenoid, located in the lower bath of the cryostat (see Fig. 3.1), generating fields of up to 15 T.

The critical current of the Nb$_3$Sn sample is determined from the V-I curve at given temperature and magnetic field: the current is ramped up from zero with a constant ramp rate of 12 A/s and the voltage between two voltage taps attached to the sample under test (60 cm distant) is recorded thanks to digital multimeter. The direction of the current is such that the Lorentz force press
the strand against the sample holder during the test preventing motion of the sample and premature quench [43]. The recorded voltage along the sample is well fitted by Eq. 3.1, where $E$ is the electric field potential and n-value represents the stiffness of the transition from superconducting state to normal state: the larger is $n$ the stiffer is the transition. The range of $n$ is typically between 20 and 60 for practical superconductors.

$$E = E_c \left( \frac{I}{I_c} \right)^n.$$  \hspace{1cm} (3.1)

Where $E_c$ is the electric field criteria equal to 0.1 $\mu$V/cm for LTS materials. The critical current is the projection point on the abscissa axis of the intersection of the V-I curve with the electric field criteria.

The $J_c$ measurements performed on Nb$_3$Sn samples are limited in number.
Electrical performances of Rutherford cable

Figure 3.2: Electric-field criterion for determining the critical current from a set of V-I curves obtained at different magnetic fields [44].

and do not extend over the various conditions encountered by the conductors in magnet windings. The optimal use of Nb₃Sn conductors requires practical expressions describing their \( J_c \) dependence on magnetic field, temperature and strain. Such expressions allow accurate interpolations, extrapolations and scaling of conductor performance. The \( I_c \) dependence on the magnetic field and temperature is given by the following equation [45]:

\[
J_c(B) = \frac{A}{B} s(\varepsilon)(1 - t^{1.52})(1 - t^2)b^p(1 - b)^q.
\] (3.2)

Where \( b = B/B_{C2}(T) \) is the reduced field and \( A,p, q \) are fitting parameters. The last two values don’t depend on temperature but only on the sample [44][43]. We define the critical field and critical temperature in this way:

\[
B_{C2}^*(B, \varepsilon) = B_{C20\text{max}}^* s(\varepsilon)(1 - t^{1.52}).
\] (3.3)

\[
T_{C2}^*(B, \varepsilon) = T_{C0\text{max}}^*[s(\varepsilon)]^{1/2} \left(1 - \frac{B}{B_{C2}^*(0, \varepsilon)} \right)^{-1/2}.
\] (3.4)

For the analysis performed here, the samples were always investigated at the same level of strain close to 0, so we can assume \( s(\varepsilon)=1 \).
3.1 $I_c$ and RRR measurements

Figure 3.3: Critical current versus magnetic field for virgin and extracted PIT QXF strand at 1.9 K and 4.2 K [39].

The Fig. 3.3 shows the critical current in function of the magnetic field for both virgin and extracted strand at 4.2 K and 1.9 K. The markers stand for the measurements and the continuous and dashed lines are the fit to the Eq. 3.2.

Results

The electrical performances of a Nb$_3$Sn strand extracted from a Rutherford cable is usually lower than that of a virgin wire before cabling. Despite the fragile Nb$_3$Sn phase is formed after cabling, the large plastic deformation during cabling especially at cable edges, may cause severe mechanical distortions of the subelements inside the Nb$_3$Sn strands. The mechanical damages of the diffusion barriers and the associated tin leakage into the copper matrix during reaction result to tin depletion and incomplete filament reaction that leads into severe critical current ($I_c$) and Residual Resistivity Ratio (RRR) degradation.

The measured $I_c$ at 12 T and 4.3 K of strands extracted from the last 11 T and QXF cables produced are reported in Fig. 3.4 and table 3.1. In order to quantify the $I_c$ degradation, a virgin sample of the same spool, extracted directly on the cabling machine, next to the cabled sample is also characterized.
Electrical performances of Rutherford cable

Figure 3.4: Critical current measurements on extracted strand of 11 T dipoles and MQXF cables at 4.3 K and 12 T.

Table 3.1: Critical current measurements, Degradation in critical current and n value of extracted strands of 11 T dipoles and QXF cables.

<table>
<thead>
<tr>
<th></th>
<th>11 T dipole (RRP)</th>
<th>MQXF (RRP)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>run 173A</td>
<td>run 174A</td>
</tr>
<tr>
<td>Ic extracted</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(12 T, 4.3 K)</td>
<td>Average</td>
<td>473.4</td>
</tr>
<tr>
<td></td>
<td>Max</td>
<td>491</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>460.1</td>
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<td>STD</td>
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<td></td>
<td>Max</td>
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<td></td>
<td>Min</td>
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<tr>
<td></td>
<td>STD</td>
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</tbody>
</table>

at 4.2 K and 12 T. The $I_c$ degradation is reported in table 3.1. We can conclude that, since the degradation in critical current is less than 5%, the cables have undergone the critical current acceptance tests.

3.1.2 Strand’s RRR

In case of quench, the full operating current of the superconducting Nb$_3$Sn magnets has to flow into the copper stabilizer for few tens of seconds. Low resistivity copper must be used to first limit the peak temperature on the conductor and to stabilize the conductor from flux jumps in normal operation. The Residual Resistance Ratio (RRR) is an important measure for the quality
of the matrix material within the wire. In a normal conductor the residual resistivity (RR) is due to the scattering of electrons by defects in the crystal lattice: at cryogenic temperatures the interactions of electrons with the lattice vibrations are highly reduced and can be neglected.

The resistivity of the copper, plotted as a function of temperature for different values of RRR, is reported in Fig. 3.5. One can see a constant behavior at low temperatures up to the critical temperature of Nb$_3$Sn.

![Figure 3.5: Resistivity of copper versus temperature for different values of RRR. RRR of copper is determined by $\rho(273 \text{ K})/\rho(4 \text{ K})$.[46].](image)

Nb$_3$Sn is superconducting at temperatures below 18 K, which is well above the temperatures where it is possible to measure the residual resistivity. So, RR of Nb$_3$Sn can be determined at the fixed temperature of 20 K, just above the critical temperature. Measurements of the RRR of superconducting strands is a part of acceptance tests of Nb$_3$Sn strands. It is measured systematically at CERN on 11 T dipole and MQXF virgin and extracted strands. In the virgin state the RRR should be higher than 150 whereas on extracted strands is should stay above 100.

The RRR samples, 110 mm long, are fixed in a window frame fiberglass holder and connected in series up to 20 samples, see Fig. 3.6.
One of the wires is used as a reference wire, the temperature is verified by a carbon-ceramic resistor. In general the electrical resistance is calculated ramping up step by step the current and measuring the voltage drop on each sample, in this way UI-curves are obtained. The non-linearity of UI-curve is used to check, at room temperature, an ohming heating and, at a cold test, the transition from superconductor to normal one. The test at room temperature is performed by arranging the samples on the holder inside a box kept at 20 ± 0.5°C thanks to a thermostat.

The cold environment for measuring the resistivity at cryogenic temper-
3.1 Ic and RRR measurements

Temperatures is reproduced thanks to a liquid helium cryostat. The test station for RRR measurements is illustrated in Fig. 3.7. The heaters need to warm up the samples from 4.2 K of the liquid helium to a temperature slightly higher than the superconductor critical temperature (T*) so the superconductor-to-normal transition takes place. In this case the current used for the measurement is in the range of 1-10 A and the voltages measured are about 0.01-0.02 mV. For both cold and warm test the UI-curve is drawn for all mounted samples. After, the resistances at T_{293 K} and at T* are taken from UI-curve slopes, their ratio gives the RRR with an uncertainty of ± 1% [47].

Results

The measured RRR of extracted and virgin strands from the last 11 T and MQXF cables to be produced are listed in table 3.2. All the RRR measurements for the virgin and extracted strands of the cable RUN173A, a cable for 11 T dipole, is illustrated in Fig. 3.4. We observe that the minimum value of RRR for the extracted strands is 143 and for virgin strands is 236, so both are well above the acceptance values of RRR and these cables have overcome also the RRR acceptance tests.

Table 3.2: RRR measurements of extracted and virgin strands of 11 T dipoles and MQXF cables.

<table>
<thead>
<tr>
<th>11 T dipole (RRP)</th>
<th>MQXF(RRP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>run 173A</td>
<td>run 174A</td>
</tr>
<tr>
<td>RRR</td>
<td>RRR</td>
</tr>
<tr>
<td>ext.</td>
<td>virg.</td>
</tr>
<tr>
<td>Average</td>
<td>157</td>
</tr>
<tr>
<td>Max</td>
<td>204</td>
</tr>
<tr>
<td>Min</td>
<td>119</td>
</tr>
<tr>
<td>STD</td>
<td>35.4</td>
</tr>
</tbody>
</table>
3.1.3 Cable $I_c$ measurement

Cable tests are very significant for magnet performances because it is considered the effect of impregnation and strand-to-strand interactions. The critical current measurements in long samples of full-sized Rutherford cables needs a proper facility in terms of current and magnetic field. In order to apply a uniform magnetic field over the whole length of the sample of about 1-2 m, a specific dipole magnet is necessary. At CERN, the facility used for testing the Rutherford-type cables at a maximum background field of 10 T is called FRESCA. The FRESCA test station was designed in the late 90’s to test the Nb-Ti cables for the LHC and then since 2008 it starts to test Nb$_3$Sn cables [48][49]. The FRESCA2 test station installation foreseen in 2019 will allow to characterize samples up to 13 T.

Sample preparation

The sample preparation of Nb$_3$Sn cables for critical measurements is a very important step for having good results. Two Nb$_3$Sn cables are connected to two NbTi leads because Nb$_3$Sn is not flexible and we need to deform the cable in order to connect it to the current leads; the sketch of the layout of the sample is reported in Fig. 3.9 and Fig. 3.10 on bottom right. The current is injected in one of the two NbTi leads, then it passes inside one cable of
the Nb$_3$Sn arriving at the bottom joint where the current changes the Nb$_3$Sn cable and returns to the other NbTi leads. Some voltage taps are put on the legs for measuring potential differences across the sample. After the heat treatment of Nb$_3$Sn cable the shape of the sample is fixed and it is protect by a glass fiber. Then, the cable is vacuum impregnated with epoxy resin in order to fill the voids in the cable and create the support to sustain the electromechanical forces. The Nb$_3$Sn sample is positioned inside the sample holder, 2 meters long, but the only relevant part is the section corresponding to the Nb$_3$Sn part, which is 1.5 m long. The sample holder is composed of glass fiber reinforced filler pieces, wrapped by a stainless steel plates, called blades, see Fig. 3.10 on bottom left [38].

![Diagram](image)

Figure 3.9: Layout sketch of the sample. On the right the bottom joint, in the center the Nb$_3$Sn cable and on the left the NbTi cable.
Figure 3.10: FRESCA station. On top left: the FRESCA station. On top right: Sample holder attached to the sample insert. On bottom left: the sample holder. On bottom right: the sample.
3.1 $I_c$ and RRR measurements

Experimental setup

![Sketch of FRESCA test station](image)

Figure 3.11: Sketch of FRESCA test station. The number 1 indicates the first cryostat, the number 2 shows the second cryostat [38].

FRESCA test station enables to have the maximum cable test current of 32 kA, a field up to 9.6 T and it is composed of two cryostats [50]. The double cryostats give the possibility to keep the dipole magnet (≈ 5 tons) cold even during the sample change. In fact the outer cryostat shown in Fig. 3.11 with the number 1 houses the magnet which needs long time to cool-down. The magnet is connected through a pair of current leads to a 16 kA external current supply. The inner cryostat, labeled 2, holds the sample and is divided by the lambda plate in an upper and lower half. The lower bath can be kept at 1.9 K by superfluid helium while the upper part is at 4.3 K. The two superconducting cable samples contained in the sample holder, as previously explained, are kept in the lower bath and are connected to the power supply via copper current leads. The current leads are soldered to NbTi busbar cables carrying
the current through the lambda plate. Sample is connected to the busbars by indium clamping joints. Indium is important because it has an acceptably low resistance (2 nΩ vs. 0.5 nΩ in the soldered joint) but it is possible to avoid soldering the currents leads for every sample.

**Measurements**

The maximum current-carrying capacity of cables can be determined from the measurements on short samples as for the wires. The typical voltage-current curves of cable short samples are similar to those of wire short samples and the cable performances can be characterized using the same definitions of critical current and n-value. Critical current measurements performed in FRESCA test station for a RRP QXF cables are reported in Fig. 3.12. The markers are related to the cable measurements and the line is the expected performance of the cable estimated from extracted strands measurements. The $I_c$ measurements of RRP QXF cable without defects is in blue and the RRP QXF cable with the crossover is in red. We can observe that the degradation due to one strand crossover is about 3.3%.

![Figure 3.12: Critical current versus magnetic field at 4.3 K][39](image)
Conclusion

The chapter three explained how the tests of the electrical performances of Nb$_3$Sn Rutherford cables were performed. Critical current ($I_c$) and RRR measurements of virgin and extracted strands were reported and also test of the $I_c$ of the cable was carried out and the results were shown in this chapter. In order to find a possible correlation between the electrical performances and the critical deformations of the strands we need to study the strand deformations that will be presented in the next chapter.
Chapter 4

Strand deformations in Rutherford cables

Reaching an high aspect ratio Nb$_3$Sn Rutherford cable is an important step in the design of superconducting accelerator magnets. The large plastic deformation during cabling, especially at cable edges, may cause severe mechanical distortions of the filaments inside the Nb$_3$Sn strands. The mechanical damages of the diffusion barriers and the related tin leakage into the copper matrix during reaction may result into severe critical current ($I_c$) and Residual Resistivity Ratio (RRR) degradation. There is a minimum thickness for the multifilamentary area in RRP strands and Nb tube for PIT strands that avoids Sn leak, less than this we consider to have a defect, which means a critical deformation in the filament. The Rutherford cable geometry must assure a limited degradation of the electrical performance of the reacted Nb$_3$Sn strands, but also sufficient mechanical stability for coil winding. The cable mechanical stability, among other parameters, is directly related to the strands compaction at the thin and thick edges of the cable. The goal of the cable optimization is to guarantee RRR of extracted strands above 100 and $I_c$ degradation below 5% [39]. In order to study the mechanical deformations inside the RRP or PIT strands and correlate them to the RRR and $I_c$ degradation, metallographies need to be carried out. In this chapter the mechanical deformations in Rutherford
cables will be investigated. First of all the classical method will be presented, then the optimized method will be described. Metallographies of samples with and without defects are shown. The deformations in the filaments will be presented and described in this chapter.

4.1 Metallography

Metallography is the study of the structure of metals and alloys in order to identify defects, voids, impurities and different phases. The most common used approach is microscopy, both optical and Scanning Electron Microscopy (SEM). Samples need to be prepared for the analysis, in case of Nb₃Sn, the specimens are impregnated in epoxy resin and are grinded and polished after 6-8 hours of polymerization under 2 bar of pressure. The machine used for grinding and polishing the samples is the one depicted in Fig. 4.1. The specimens are inserted in one of the specific gaps of the metallic disk mounted on the mechanical arm which is placed above one of the two working wheels. The grinding consists of the use of a series of progressively finer abrasive papers, located on one of the two wheels. The technique helps to flatten the sample, remove the damaged layer introduced by cutting the sample and eliminate the scratches from the previous step. These papers are labeled with the grit size

Figure 4.1: Specimen preparation system similar to the one used at CERN in the laboratory 103 [51].
and it is possible to find the starting point for the grinding knowing the width of the largest scratch existing on the surface of the sample: 16000 divided by the width of the wider scratch in microns. This prevents putting more damage on the specimen. Dividing by two the damage depth we know the abrasive particle size; typically the roughest paper used has a grit size of 180 and the finest one has 1200.

The polishing needs to smooth the surface using discs with soft cloth impregnated with abrasive diamond particles and oily lubricant “MetaDi Fluid”. The steps usually applied are the following discs, in order: 9 microns of particles size for 5 minutes, 3 microns for 6 minutes and 0.05 microns for one minute. Ideally the surface to be examined optically should be flat in order to focus homogeneously the area. This procedure, when applied with care, can produce repeatable polished surfaces that are free from polishing-induced cracks. The whole preparation process requires lot of time and high precision, due to the very fragile nature of Nb₃Sn. Fig 4.2 illustrates the steps necessary to get a clear surface of a single virgin wire.

Once the sample is well prepared, the microstructure of traversal cross section of a single wire and of the whole cable was studied using optical microscope. The microscope Olympus BX51M equipped with different magnifying lenses allows to acquire images at different magnifications. Starting from the middle of the cable it is possible to observe an increasing change in the shape of the single strands towards the edges due to the higher strain. An example of a traversal cross section of two samples cable is given in Fig. 4.3. The specimens are usually composed of more than one pieces of cable (usually five) in order to have more data for statistical analyses and be sure that the analysis is valid for the whole cable. Typically enlarged pictures of the three strands at the thin and thick edges for each piece of cable in the sample are taken.
Strand deformations in Rutherford cables

Figure 4.2: Sample preparation steps: on the top left is shown the sample after the grinding with P1200 paper, on top right the sample after the polishing with 9 μm size particles, on bottom left after polishing with 3 μm size particles and at the end on bottom right after polishing with 0.05 μm size particles. The sample is a PIT wire with a diameter of 0.7 mm characterized by niobium bundle barrier. This PIT wire with a bundle barrier is a Research and Development strand, the presence of the bundle barrier helps to reach high Jc without reducing the RRR of the sample [52].

Figure 4.3: Rutherford cable with RRP strands with 0.7 mm of diameter.

4.2 Manual analysis of the filaments deformations

The first method used to investigate the deformations inside each strand in the Nb₃Sn Rutherford cable is presented in this section. Once the photos are taken by optical microscope it is possible to count defects for each strand by visual inspection at thin and thick edge. Metallographic observations of both edges of the cable show highly deformed strands but with limited distorted filaments in
4.2 Manual analysis of the filaments deformations

the three strands near the edge, labeled with the letters A, B and C. First of all
one need to distinguish between three different edge’s deformations: extreme
(E), medium (M) and weak (F), see Fig. 4.5. We consider a defect when the
multifilamentary area (RRP) or Nb tube (PIT), at least in one point, presents a
reduced thickness, less than the half of medium value of the one not deformed,
see Fig. 4.4. For each strand the defects are counted filling a proper table
shown in the document depicted in Fig. 4.5. One can see the total amount of
defects for every sample thanks to the sum of all imperfections in thick and
thin edge. Finally, the medium value of defects per cable is calculated. Several
samples of FRESCA2, QXF and 11 T cables were examined with this method
as reported in the table 4.1.

Figure 4.4: 11 T PIT cable: strand at thin edge with defects emphasised in
red.

The way to perform the analysis is very simple but very time-consuming
and above all it is not highly accurate. In fact the technique is based on the
identification by eye of the most deformed multifilamentary area or Nb tube
and the measurements of their minimal thickness. The aim is to count the
defects when the thickness in at least one point of the multifilamentary area
Strand deformations in Rutherford cables

<table>
<thead>
<tr>
<th>Table 4.1: All the defects of the samples studied with manual method are reported in the table.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>strand diameter (mm)</strong></td>
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<td>QXF PIT</td>
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<tr>
<td></td>
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<tr>
<td>FRESCA2 PIT</td>
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<tr>
<td></td>
</tr>
<tr>
<td>11 T PIT</td>
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<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>
4.2 Manual analysis of the filaments deformations

Figure 4.5: Analysis of the cable RUN174A: 5 samples are studied.

or Nb tube is less than a half of the medium thickness in undeformed shape.
With this method it is also very easy to make human mistakes so the idea is
to implement a Matlab code able to automatize and optimize the analysis.
4.3 Automatized analysis of the filaments deformations

The analysis of the wires deformations of the cable, in particular at its lateral edges, is very important. In fact, it is demonstrated that damages at the edges of the cables obtained during the cabling cause degradation in critical current and in RRR. Since the cables are continuously produced, a quick feedback of the deformations due to the cabling is required. So, a practical tool able to quantify the deformation in Nb$_3$Sn filaments is developed thanks to Matlab and it is described in the section.

The preliminary study of how the image analysis in Matlab works was needed in order to know which instruments are useful for the purpose. Every picture imported in Matlab is a matrix of pixels where each pixel represents a specific color. For the Matlab analysis the images are turned into gray scale. One purpose of the code is to recognize the external and internal border of each multifilamentary area or Nb tube and the external surface of the strand. The first two are necessary for the investigation of the critical deformations whereas the external surface of the strand is needed for the calculation of the Cu/NonCu ratio. For individuating the three borders we need to prepare three images, starting from the original one and using different filters. Then, the aim is to find the minimum thickness in the multifilamentary area or Nb tube of every filaments and quantify the critical deformations in the strand. In order to develop the Matlab code, SEM image of rolled strands to 20% are first analyzed.

4.3.1 SEM images of rolled strand

The Scanning Electron Microscope (SEM) produces images of very high quality. This is because the signal results by an electron beam which interacts with the atoms of the sample and so the image acquired doesn’t depend on
4.3 Automatized analysis of the filaments deformations

the defects on the surface, for examples on the scratches. With the proposal of finding the three borders in the original SEM image we use the 'Image Viewer' tool of Matlab and we change the contrast and luminosity in three different way. In the following Fig. 4.6 the three images prepared for the analysis of the three borders are showed. After, the images are turned into binary ones

![Figure 4.6: The SEM image of a PIT strand rolled down to 20% with 120 filaments showed in 3 configurations, from the left: image adapted for the recognition of the external and internal surface of the Nb tube of each filament and the last one is for the margin of the strand. The original image was edited by Marina Garcia Gonzalez.](image1)

thanks to “im2bw” function; the binary images are usually marked by “BW”: all pixels assume 1 or 0 values, where 1 means white and 0 means black, so the borders of white objects are what we search. SEM images are showed in the Fig. 4.7. At this point the tool “imfill(BW image, ‘holes’)” is applied to fill holes in the interested objects and “bwmorph(BW image, ‘clean’)” removes isolated pixels. In order to eliminate all the elements with a size less than a specific threshold and to remain with only what we are interested in we use “bwareopen(BW image, threshold)”. The crucial point is now the detection and the counting of the elements present in the image. Scanning all columns

![Figure 4.7: Binary version of the images in Fig. 4.6.](image2)
and rows of the matrix of the picture, one element is counted whenever there are at least 8 white pixels connected using the command “bwconncomp”. Then a matrix with the same size of the original one, labelled with “L”, which contains labels for the all objects with at least 8-connected pixels is obtained with “bwlabel”. The coordinates of the pixel at the border of every filament are thus found thank to “bwboundaries(L,’noholes’)” in order to know the exterior and interior boundaries of the objects. Finally, thanks to these steps we are able to reach the first aim of the automatized method: the identification of all the borders (depicted in the Fig. 4.8).

![Figure 4.8: Picture of the PIT strand with the identification of the external and internal surface of the Nb tube of each filament in red and the external surface of the strand in blue.](image)

The second purpose of the Matlab code is to quantify the deformations finding the percentage of critical filaments. First, we have to derive the minimum thickness of multifilamentary area or Nb tube of each filament: this is possible calculating the distance between pixels of the internal and the external surface of multifilamentary area or the Nb tube. The deformations in the filaments are subdivided into different levels in Fig. 4.9: the ones that could cause Sn leak in the copper stabilizer are coloured in red. In the case of the Fig 4.9 the minimum thickness is 5.2 µm and less than this value the filament is considered defective. The percentage of defects in the whole strand is 3.33%. As we can observe from the Fig. 4.9, the deformations are stronger.
4.3 Automatized analysis of the filaments deformations

Figure 4.9: Coloured filaments according to different levels of deformations: minimum thickness less than 5.2007 $\mu$m in red, less than 6 $\mu$m in pink, less than 7.5 $\mu$m in green and less than 9 $\mu$m in blue.

Figure 4.10: Sketch of the rings of the strand.

along the main diagonals and in the center, then gradually they are reduced from the center to the external surface of the strand as it will be demonstrated later. In the effort of understanding, improving and controlling the quality of PIT and RRP cables, it has been proposed to study the aspect ratio and thickness reduction of the filaments in function of the radial and angular position in the strand at different rings, see Fig. 4.10. The aspect ratio is considered as the ratio between the maximum dimension of the filament and the minimum one. In Fig. 4.11 the graph of aspect ratio versus radial position clearly shows its decrease from the center to the border and we can see that a
range of values in the radial position corresponds to a specific ring of filaments, marked with crosses with different colors moving from the internal ring to the external one. The filaments are at certain compression state for the flattening in the Turks-head of the cabling machine and the shear stresses are more concentrated. In the plot of aspect ratio in function of angular position we can notice higher values at around 50°-150° and 230°-330° whereas the lower ones are corresponding to 0° and 180°. The highest values of aspect ratio are related to the first two rings as we expected. Regarding the plots of the thickness reduction we can note that: the reduction of the multifilamentary area or Nb tube of the filaments is very high toward the center of the strand and at the angular positions related to the main diagonals and very low at
the border and along x and y axis centered in the middle of the strand.

### 4.3.2 Optical Microscope Images of cables

Optical microscope is easier and faster in taking images than SEM and it is also present in the TE/MSC-SCD superconducting laboratory located in building 103. In order to improve the metallography of the images taken by optical microscope the Matlab code is used. Since these images have lower resolution than SEM images and show defects on the surface of the sample (scratches, dirty particles, oxidation), additional steps preceding the use of Matlab code are necessary. The most important starting point is to take photos at the highest resolution available in the microscope with a proper exposure time and an homogeneous focus. Typically, the sample is not perfectly flat, so a specific tool is used to improve the quality of the focus of the surface. Fig. 4.12 shows a comparison between one picture well prepared and one difficult to analyzed. Then the photos need to be first elaborated with the free software

![Image](image.png)

Figure 4.12: RUN174, RRP strands-Left: Surface good to study. Right: Surface with scratches and not good focus.
Strand deformations in Rutherford cables

called ImageJ. The program is able to split the RGB image, where each pixel is determined by the combination of red, green and blue, to the respective red, green and blue image components in greyscale. The red one emphasises the external surface of the multifilamentary area of each filament whereas the blue images is adapted for the internal surface. The recognition of the external surface of the strand doesn’t depend on the image component chosen. After, the function “threshold” is applied in order to accentuate the elements desired. In case of external borders the images are easier to be prepared for Matlab code than the ones for internal borders because they don’t need more filters. In practice, the difference in color between the core of the subelement and the multifilamentary area or Nb tube is not so well defined and therefore not simple to recognize properly, see Fig. 4.13. The filament of PIT strand is even worse than RRP one in terms of individuation of the internal borders. So, a filter called “Maximum” is able to replace each pixel in the image with the largest pixel value in that pixel’s neighborhood for pointing out the central part of the filament. Furthermore the “Gaussian Blur”\(^1\) function, based on the convolution with a Gaussian function, is good for smoothing. At this point, after the transformation in binary image and the filling of the holes, the

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{fig4.13.png}
\caption{On the left filament of RRP strand and on the right filament of PIT strand.}
\end{figure}

\(^1\)It assumes that out-of-image pixels have a value equal to the nearest edge pixel. This gives higher weight to edge pixels than pixels inside the image, and higher weight to corner pixels than non-corner pixels at the edge. Thus, when smoothing with very large blur radius, the output will be dominated by the edge pixels and especially the corner pixels [53].
images adapted for the internal borders are ready for being elaborate by Matlab code. Then, all the commands previously presented for the SEM images are applied also for optical microscope’s images. The operations ‘erode’, ‘dilate’, ‘thin’ and ‘thicken’ can be used with the command “bwmorph(BW image, ‘function’)” able to remove or add pixels at the border of the objects with the aim of fitting well the borders. A Graphical Users Interface (GUI) based on the Matlab code was developed to have a tool of analysis more user-friendly, see Fig 4.14. Once the original image is chosen, the scale and the number of filaments are inserted by the user. Then, the images for the external and the internal surface of the multilamentary area are studied in order to get the image with all filaments individuated with different colors on the basis of the intensity of the deformation. Thanks to the external surface of the strand the Cu/non-Cu ratio is calculated and reported in the GUI, the coordinates of the mass center of the strand and the medium thickness of the multilamentary area of each filament in a virgin strand are also illustrated in GUI.

In order to show how a cable with PIT strands could be deformed at the thin edge, a piece of the cable RUN155A which is a QXF PIT cable was cut in different points and prepared for metallography analysis. The sample was observed under the microscope and they were studied with ImageJ and Matlab GUI. Looking at the images of the cable at different length we can individuate the one with most deformations. The analysis of the three strands are reported in Fig. 4.15 whereas the table 4.2 is useful for a numerically thin edge quantification of the deformations. Thanks to the histogram shown in Fig. 4.16 it is possible to compare the deformations of the three strands at the border. We observe that for this cable there is no critical deformations since for all the filaments the Nb tube area is always thicker than the the half of the medium thickness in the virgin strand. Furthermore we can also see that the most deformed strand is the one at the edge, labeled A, as expected.

The analysis of the deformations at the thin edge was also performed for many samples with RRP strands, recently the most employed ones, in
Figure 4.14: The Graphical User Interface developed for the analysis of optical microscope images.
4.3 Automatized analysis of the filaments deformations

Figure 4.15: Deformations of the three strands at the thin edge of the cable PIT QXF RUN155A. In the legend the thresholds of minimum thickness are expressed in micrometer.

<table>
<thead>
<tr>
<th>Minimum thickness threshold (µm):</th>
<th>&lt; 5</th>
<th>5 &lt; x &lt; 6</th>
<th>6 &lt; x&lt; 6.5</th>
<th>6.5 &lt; x&lt; 7</th>
<th>7 &lt; x &lt; 7.5</th>
<th>7.5 &lt; x&lt; 8</th>
<th>8 &lt;x&lt; 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>A %</td>
<td>0</td>
<td>0</td>
<td>37.5</td>
<td>41.15</td>
<td>18.75</td>
<td>2.6</td>
<td>0</td>
</tr>
<tr>
<td>C %</td>
<td>0</td>
<td>0</td>
<td>4.69</td>
<td>40.63</td>
<td>54.17</td>
<td>4.69</td>
<td>0</td>
</tr>
<tr>
<td>B %</td>
<td>0</td>
<td>0</td>
<td>3.65</td>
<td>32.81</td>
<td>44.27</td>
<td>18.23</td>
<td>1.04</td>
</tr>
</tbody>
</table>

- Critical filaments: 0%
- Original thickness border: 10 µm

order to find a possible correlation of the strand deformation with the cable critical current presented in the chapter 3. Samples of 11T cables and QXF cables were polished and well prepared for having high quality pictures of the most deformed strand at thin edge which was investigated by the manual
Strand deformations in Rutherford cables

Figure 4.16: Histogram of the deformations at the thin edge of cable RUN155A and automatized method. In the table 4.3 all data of the Matlab analysis are reported. Different thresholds of minimum thickness are chosen according to the type of cable since the measured medium thickness of the multifilamentary area for a filament is different: 10.3 $\mu$m for 11 T dipoles and 12.5 $\mu$m for QXF. This is in line with the strand diameter of 0.7 mm for 11 T cable and of 0.85 mm for QXF cable. The red values are related to the percentage of the critical filaments found at the strand A thanks to the two methods. We observe that the values from the two methods are similar which confirms the accuracy of the automatized method, even if we need to take into account a possible error of 1 $\mu$m due to the individuation of the internal borders. A comparison of the deformations between the cables for the same magnets is reported in the Fig. 4.17 and in the Fig. 4.18. We can notice that the number of deformations for each range of minimum thickness are similar for all the cables analyzed, so we expect to find this distribution also in others cables. Furthermore, in order to illustrate how the critical filaments are distributed in the strand we choose two analysed sample: RUN173A for 11 dipole and RUN178A for MQXF, as reported in Fig. 4.19 and Fig. 4.20, where we can observe lot of defects in the right part following the diagonals of the strand.

The graphs of the analysis of the deformations in the filaments area in the strand A of the thin edge for QXF PIT RUN155, RRP11 T RUN173 and RRP QXF RUN178 cable are respectively reported in Fig. 4.21, 4.22 and 4.23.
Table 4.3: Quantitative analysis of the deformations of the extreme strand A in case of samples of 11T cables and QXF cables.

<table>
<thead>
<tr>
<th></th>
<th>Manual method</th>
<th>Automatized method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Threshold (µm)</td>
<td>&lt;5.15</td>
</tr>
<tr>
<td>Run 173B % of subelements</td>
<td>13.70</td>
<td>14.81</td>
</tr>
<tr>
<td>Run 174B ”</td>
<td>26.67</td>
<td>25</td>
</tr>
<tr>
<td>Run 180B ”</td>
<td>18.52</td>
<td>19.44</td>
</tr>
<tr>
<td>Medium thickness (µm)</td>
<td>10.3</td>
<td></td>
</tr>
<tr>
<td>QXF</td>
<td>Threshold (µm)</td>
<td>&lt;6.25</td>
</tr>
<tr>
<td>Run 172A % of subelements</td>
<td>13.33</td>
<td>13.89</td>
</tr>
<tr>
<td>Run 178A ”</td>
<td>23.15</td>
<td>11.11</td>
</tr>
<tr>
<td>Run 179A ”</td>
<td>17.59</td>
<td>19.44</td>
</tr>
<tr>
<td>Medium thickness (µm)</td>
<td>12.5</td>
<td></td>
</tr>
</tbody>
</table>
Strand deformations in Rutherford cables

Figure 4.17: Comparison of the deformations of the strand at thin edge of three RRP cables for 11 T dipoles.

Figure 4.18: Comparison of the deformations of the strand at thin edge of three RRP cables for QXF magnets.
4.3 Automatized analysis of the filaments deformations

Figure 4.19: Cross section of the strand at the thin border after the analysis of the code of RUN173A which is a 11 T cable.

Figure 4.20: Cross section of the strand at the thin border after the analysis of the code of RUN178A which is a QXF cable.
Strand deformations in Rutherford cables

A light pink line was added manually in each plot to emphasise the behavior of the thickness reduction and the aspect ratio. Moreover, the reference systems considered for calculating the angular and radial position are inserted in Fig. 4.16, 4.19 and 4.20. Starting from Fig. 4.21 we can observe regions colored in pink in the graph a and b where the thickness reduction of the Nb tube area of the filaments is low: from 0° to 50° and in the middle and towards the external surface of the strand. Since the deformations in the QXF RUN155 cable are not so pronounced, the thickness reduction of the the Nb tube area of the filaments is basically independent from the position in the strand, as shown from the great number of points at the same thickness reduction percentage. From the other plots c, d, e and f we can see that the aspect ratio (higher dimension divided by the lower dimension) of both internal and external border of the filaments is very high from 100° to 150° and around 300° and it decreases from the center of the strand to the external surface. All these results confirm that the highest deformations are more localized at the center of the strand and at the range of radial position corresponding to the end of the cable. We can find the same trends of plots c, d, e and f of the Fig. 4.21 also in those of the Fig. 4.22 and 4.23. In particular we see the highest aspect ratio around 30° and 300° and in the center of the strand for both internal and external surface of the multifilamentary area of the filaments. However, we observe more variations of the thickness reduction percentage depending on the position in the strand in a and b plots of the Fig. 4.22 and 4.23, specifically, the reduction is more marked from 0° to 50°, around 120°, around 250° and 350° and in the center of the strand.
4.3 Automatized analysis of the filaments deformations

Figure 4.21: QXF PIT RUN155A: a- Thickness reduction versus angular position.  b- Thickness reduction versus radial position.  c- Aspect ratio versus angular position of external border.  d- Aspect ratio versus radial position of external border.  e- Aspect ratio versus angular position of external border.  f- Aspect ratio versus radial position of external border.
Figure 4.22: RRP 11 T RUN173A: a- Thickness reduction versus angular position. b- Thickness reduction versus radial position. c- Aspect ratio versus angular position of external border. d- Aspect ratio versus radial position of external border. e- Aspect ratio versus angular position of external border. f- Aspect ratio versus radial position of external border.
4.3 Automatized analysis of the filaments deformations

Figure 4.23: RRP QXF RUN178A: a- Thickness reduction versus angular position. b- Thickness reduction versus radial position. c-Aspect ratio versus angular position of external border. d-Aspect ratio versus radial position of external border. e-Aspect ratio versus angular position of external border. f-Aspect ratio versus radial position of external border.
Comparison between critical deformations and $I_c$ degradation

In order to find a possible correlation between the critical deformations and the critical current degradation, the results were compared. After performing all the measurements presented in table 3.1 in chapter 3 and the table 4.3 in chapter 4, they were plotted in Fig. 4.24. Different colors are chosen for the markers for QXF and 11 T cables in order to distinguish the two kinds of cables. We can observe that the $I_c$ degradation in RRP conductors is only marginal reduced with the filament deformations. This result confirms previous observation that the compaction at thin edge has a weak effect on the $I_c$ degradation in RRP cable [39]. The study will be applied on PIT cable in order to investigate possible correlations.

![Figure 4.24: Critical current degradation versus critical deformations for RRP QXF and 11 T cables.](image)

Conclusion

The development of the automatized method able to study the strand deformations at the edges of the Nb$_3$Sn Rutherford cables was explained in this chapter. The description of the manual method was also provided. Finally, it was shown the comparison between the degradation in critical current and the critical deformations of the filaments inside the strands and we observed that
there is no specific correlation between the two results. In the next chapter all the conclusions and future perspectives will be reported.
Chapter 5

Conclusion and future works

This work has investigated the production of Nb$_3$Sn Rutherford cable and the deformations inside the wires in order to obtain high quality cables for high field magnets of HL-LHC.

The first aim of dissertation concerns the two new systems recently implemented in the TE/MSC-SCD superconducting laboratory at CERN in order to control the cable manufacture. During cabling it is now possible to observe the behavior of the mechanical tensions of each strand and take photos of lateral facets of the cable. The elaboration of the data collected from the two systems are carried out thanks to Matlab codes. First, we understand that the highest fluctuations in mechanical tension are due to the unrolling of the strand near the border of the spool. Then, it was possible to set thresholds to cameras for taking photos only when the measured size of the lateral facets is out of the limits and study the behavior of the dimensions of the facets during the cabling process. Finally, it was possible to see that there is no specific correlation between the fluctuations in mechanical tensions and the variations of size of the lateral facets of the cable, so fortunately the peaks and valleys in mechanical tensions don’t cause defects in cables. The rare event of strand crossover, which happened once, pointed out the importance of the monitoring systems. The electrical performances of the cable with strand crossover were tested in order to know if a big defect caused from the cabling process induces
Conclusion and future works

negligible effects in terms of critical current degradation. We find that the
degradation due to one strand cross over is about 3.3%.

The second part deals with the analysis of the deformations inside
the strands at the border of the Nb$_3$Sn Rutherford cable. Large plastic
deformation due to the cabling process could result in mechanical distortions
of the filaments of the strands at cable edges leading to electrical performances
degradations. A Matlab code was able to automatize the analysis finding the
critical deformations and make plots of aspect ratio and thickness reduction
of the multifilamentary area (for RRP strands) and of the Nb tube (for PIT
strands) in function of angular and radial position inside the strand. We
observed that the deformations are more localized at the center and along the
main diagonal of the strand. These analysis were performed for many cables
and for some RRP cables they were compared to the degradation in critical
current. We observed from the results that there is no specific correlation
between the critical deformations and the $I_c$ degradation. So, at the moment
we cannot foresee a precise value of $I_c$ degradation knowing the defective
filaments in the strands.

Concerning the future research, one way to improve the strand tension
regulation during winding would be the design of a new spool for the cabling
machine able to limit the loosening of tensions. Second, it is important to find
methods to avoid light effects on the lateral facets of the cable for reducing
the false defects. Then, more measurements of other RRP cables and also PIT
ones are foreseen in order to see if the absence of a defined correlation between
critical current degradation and critical deformation of filaments is confirmed.
Finally the Matlab code for the analysis of the filaments deformations could
be improved with the application of localized filters in every single filament
or with more sophisticated concepts of computer vision in order to better
recognize the internal surface of the multifilamentary area or Nb tube.
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