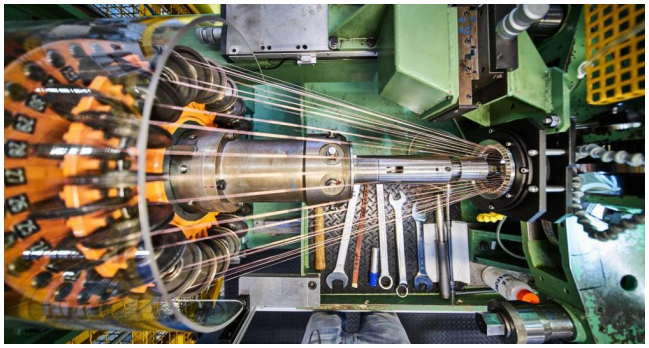
Rutherford cables for HL-LHC magnets

J. Fleiter

Acknowledgements to A. Bonasia, A. Ballarino
and the colleagues in buildings 103-163

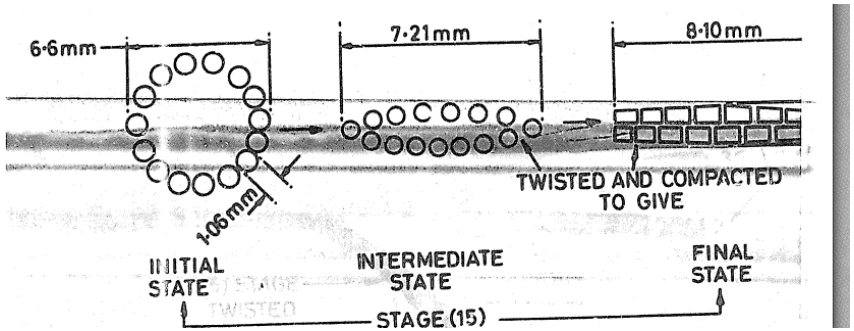


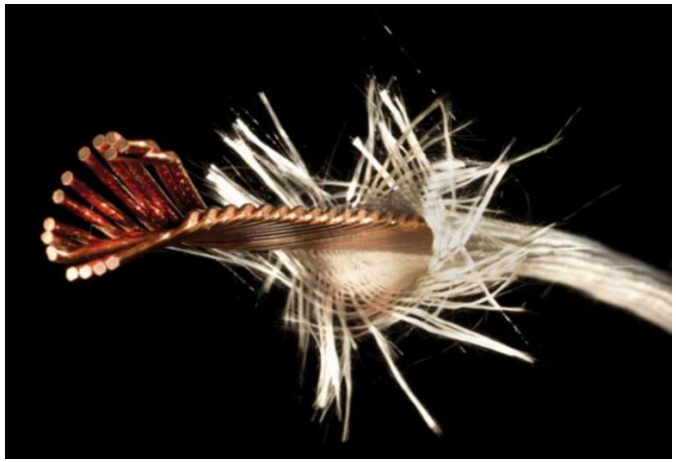
TE/MSC Seminar 23rd of September 2021

Outline

- Genesis and main parameters of Rutherford cables
- HL-LHC Rutherford cables' technical specification
- Production of Rutherford cables at CERN
  - Cabling plan
  - Cabling machine
  - Quality Control tests
- Overview of produced cables
- Conclusions

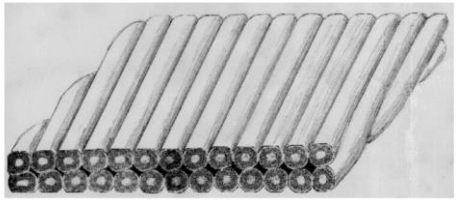
Genesis and main parameters of Rutherford cables



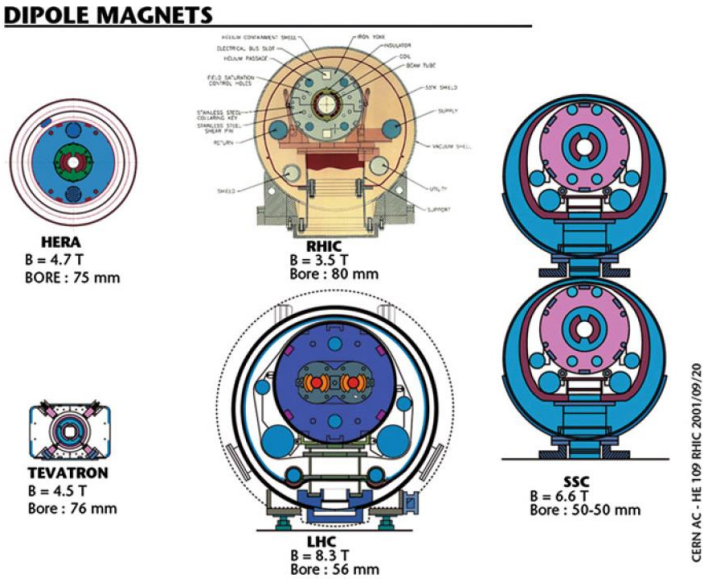


Genesis of Rutherford cables

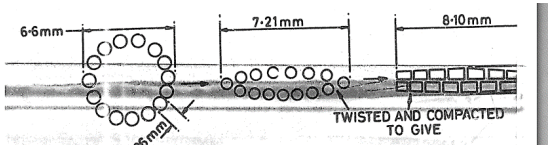
- The **Concept of Rutherford cable** was developed at the **Rutherford High Energy Laboratory** (RHEL, UK) in the **early 1970**'s, and is **attributed to G. Gallagher-Daggit**.

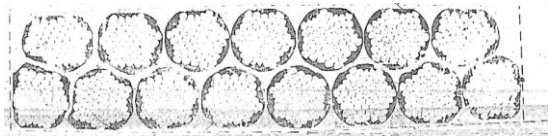


- Accelerator magnets, where the superconducting coils need large current density and controlled geometrical dimensions, rely on Rutherford cables.



- Rutherford cables have been used in all large scale colliders (RHIC, Tevatron, HERA), including the LHC.



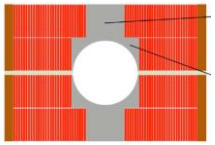


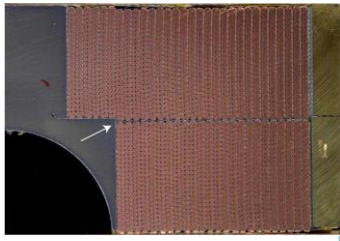
	Tevatron	HERA	RHIC	LHC
Dipole field	4.4 T	5.3 T	3.5 T	8.3 T
Number of strands	23	24	30	28-36
Cable current	4 kA	5.5 kA	5 kA	11.8 kA

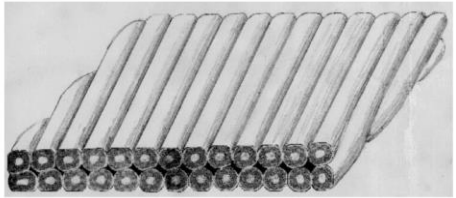
G. Gallagher-Daggit, "Superconductor cables for pulsed dipole magnets", Technical report Rutherford Laboratory Memorandum No. RHEL/M/A25, 1973

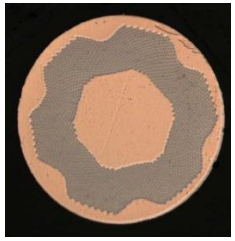
Rutherford cables

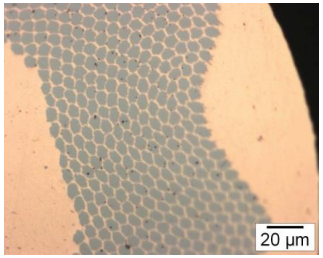
- **The final cross section of a Rutherford cable can be:**
  - **rectangular** for block coils or bus-bar,
  - **trapezoidal** for cos-theta coils or bus-bar
- **Made from ~10-60 round multi-filamentary twisted strands**
- **Strands are arranged in a two-layer structure.**
- **The main parameters are:**
  - Number of wires N_{wire}
  - Strand diameter d_{wire}
  - Cable mid-thickness t_c
  - Cable outer thickness t_o
  - Cable inner thickness t_i
  - Cable width w_c
  - Keystone angle φ
  - Transposition pitch and direction



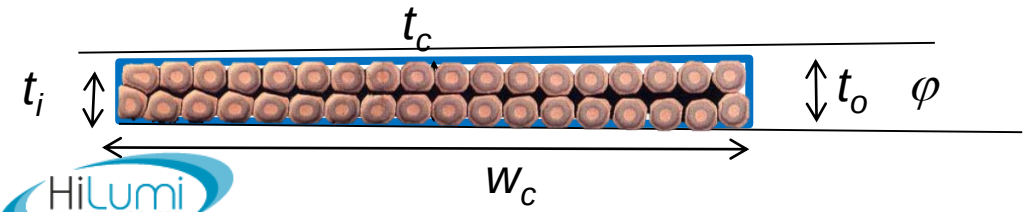


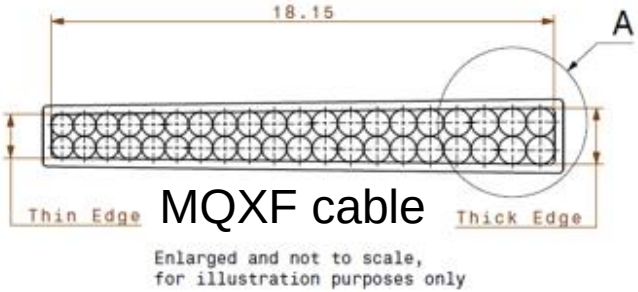






LHC NbTi strand 0.48 mm diam

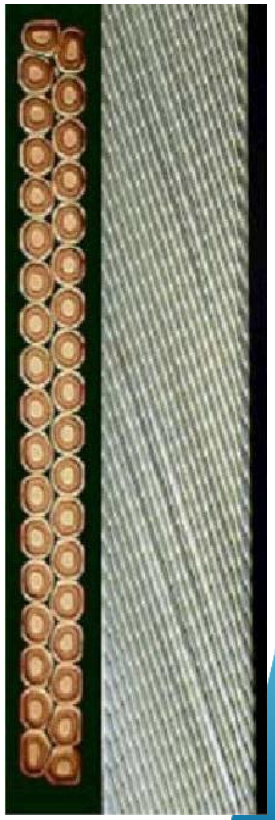




MQXF cable

Rutherford cable topology: pro and cons

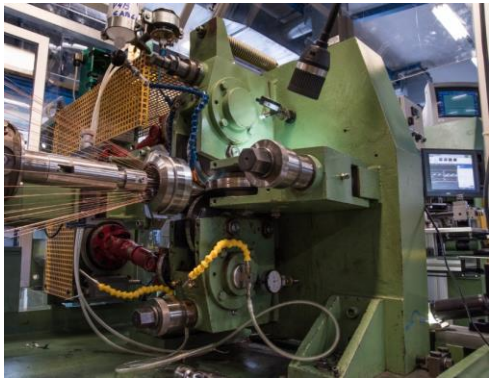
- **With respect to other types of high current cables, the Rutherford-type cable has the advantages of:**
  - Low void fraction and high engineering current density (~500-700 A/mm^2)
  - Improved flexibility for easy bending around the ends of small aperture magnets
  - Easy stacking of cable in the coil straight parts
  - Small thickness that allow fine tuning of field quality
  - Well controlled geometry over long lengths (~km) for precise winding
  - Reduced losses thanks to transposition of the strands
  - Good mechanical stability, coupled with a minimum amount of degradation of the strands following compaction
  - Reproducible low resistance splices promoting good current distribution.



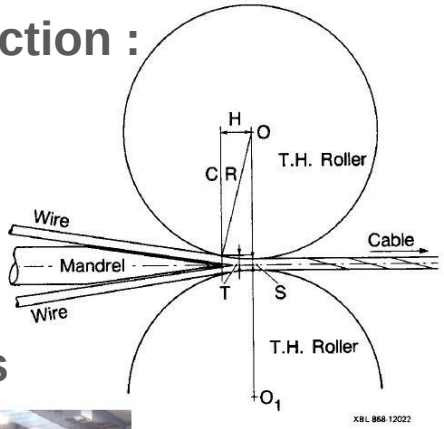
- **The main challenges of Rutherford cable are:**
  - Large transverse Lorentz stress accumulation towards the coils that can become detrimental when dealing with brittle conductors
  - Full impregnation (mechanics, insulation) resulting in modest heat transfer
  - Mechanical stability of the cable in narrow coil heads
  - Stability versus external perturbations (energy releases) inducing training.

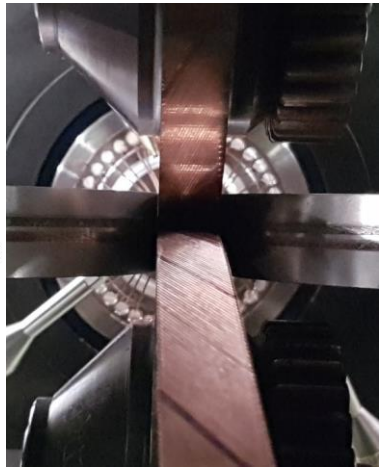
Rutherford cables production

- Rutherford cables are fabricated by a planetary cabling machine (to allow for torsion free cabling)
- Strands are wound on spools mounted on a rotating drum
- Strands are twisted around a mandrel into an assembly of rollers (Turk's head) – the rollers compact the cable and provide the final shape of the cable (window)



- **Typical control parameters during production :**
  - Width
  - Thickness
  - Twist pitch
  - Wire tension





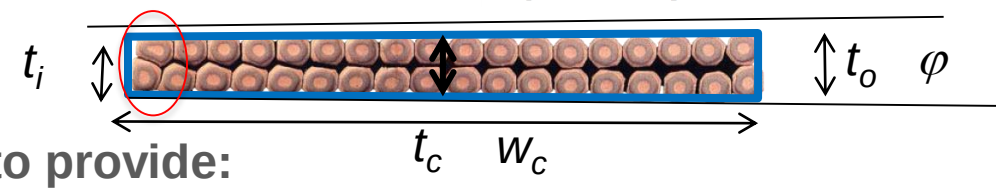
- **More details on production in next slides**

Cabling machine in Building 163

Cable compaction and strand deformation

- **Compaction of a Rutherford cable is a delicate balance between cabling deformation, electrical performance and cable mechanical stability.**
- **Cable compaction quantified via three parameters:**
  - **With compaction (Cw)**
  - **Thickness compaction (Ct)**
  - **Packing factor (PF)**

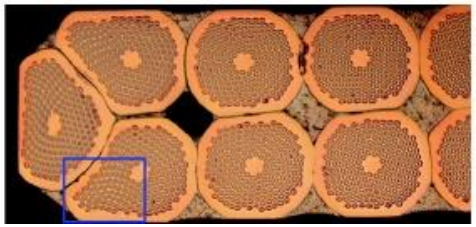
$$c_w = \frac{w}{\left[\frac{N}{2\cos(\theta)} + 0.732\right] d} - 1 \qquad C_t = \frac{t}{2d} - 1$$



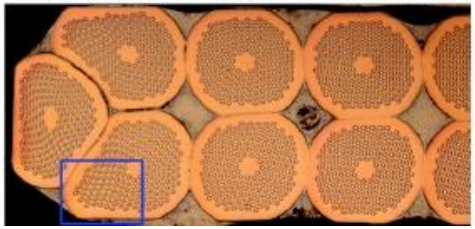
- **The cable compaction is chosen to provide:**
  - **Good mechanical stability (to prevent from popping strands and collapse),**
  - **High current capability, leaving enough space for helium cooling or epoxy impregnation**
  - **Non excessive deformation of the conductor that results in I_c , RRR degradation and strand stability limitations (best results obtained when strands are supported in all directions).**

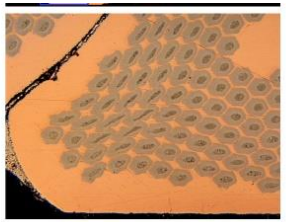
- **For HL-LHC Nb_3Sn cables the maximum tolerable Ic degradation is 5%, with RRR > 100.**
- **Cable design parameters should not exceed the superconducting material limitations.**

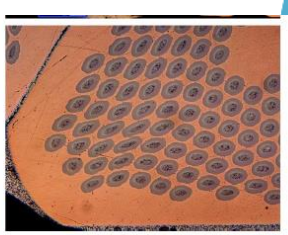
40 strands of 1 mm, 20.4 mm cable width



40 strands of 1 mm, 20.9 mm cable width

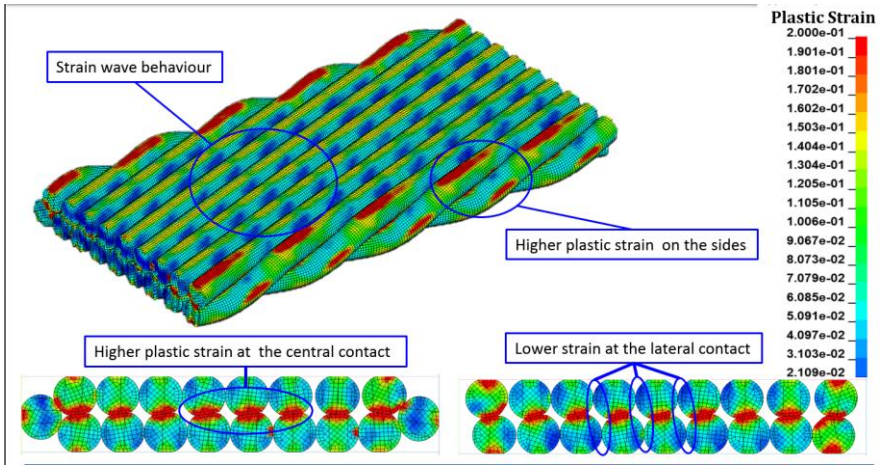




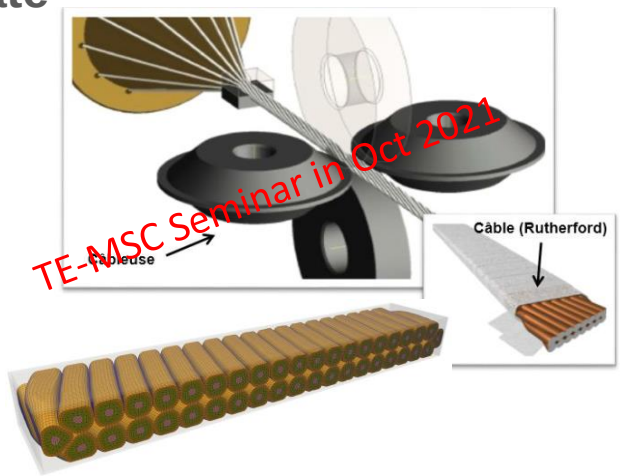


Deformation of strands in a cable

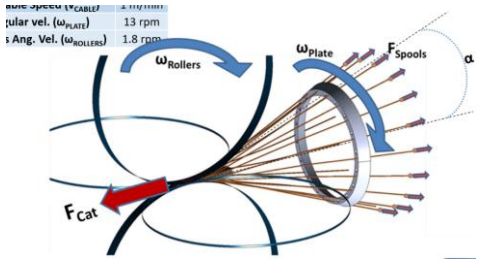
- **Several numerical cabling model developed for studying strand deformation in cable and their strain state**



J. Cabanes and B. Bordini "Simulation of the cabling process for Rutherford cables: An advanced finite element model," Cryogenics, vol. 80, no. 3, pp. 333-345, 2016



Cocascope, CEA Saclay P. Manil, F. Nuno



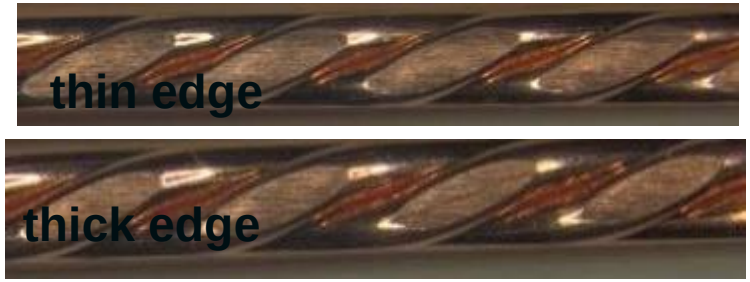
- **Cable design parameters should not exceed the superconducting material limitations =>Conductor limitation shall be known with accuracy**
- **A cable design could suit to one strand layout but not to another one more sensitive to strain/deformation.**

Rutherford cable facets

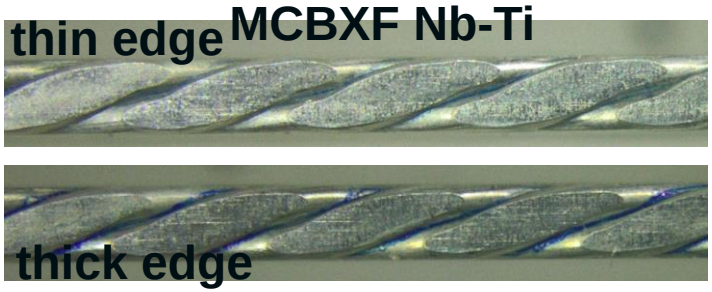
- At cable sides, the strand deformation determines:
  - Reduction of the filament cross-sectional area (Nb-Ti)
  - Distortion of sub elements and breakage of reaction barrier with incomplete tin reaction (Nb_3Sn)
  - Reduction of RRR, instabilities

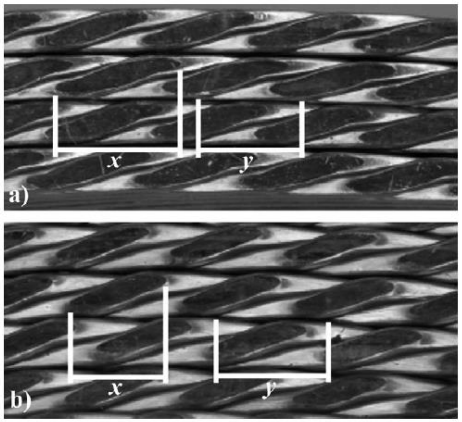
- General rule to minimize deformation and associated electrical degradations in Nb_3Sn cables: **no overlapping of consecutive facets x/y<1**

MQXF RRP

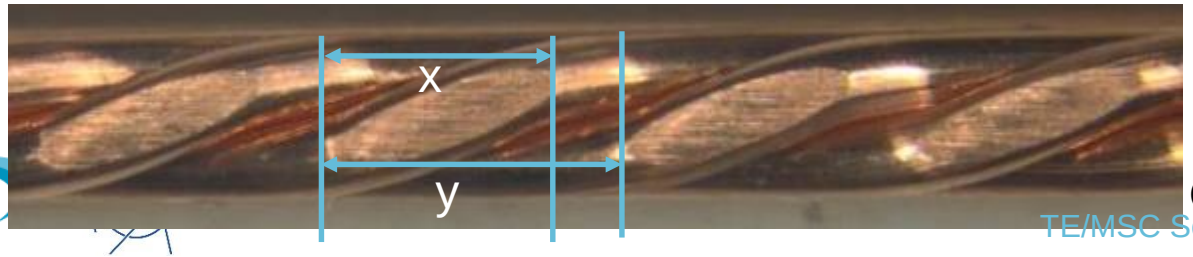


MCBXF Nb-Ti



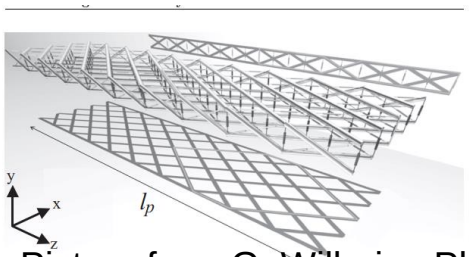


D.R. Dietderich et al., Cryogenics 48 (2008) 331–340

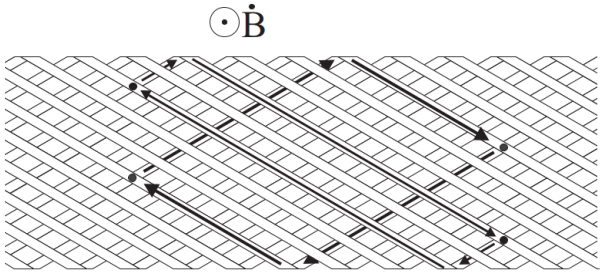


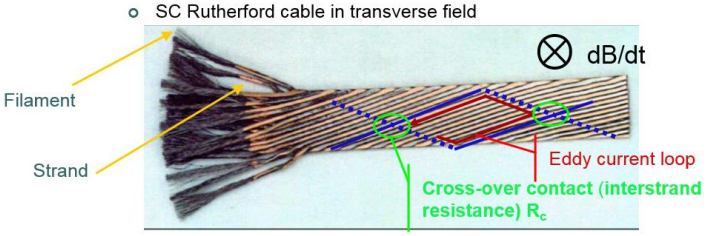
Control of inter-strand resistance

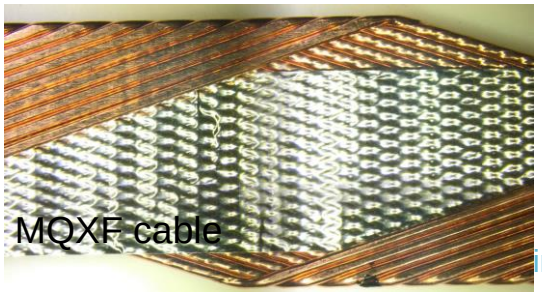
- Control of resistance at cross over (Rc) of strands is mandatory in Rutherford cables:
  - **Excessive** resistance at strand's cross over is limiting cable stability against thermal excitation and current redistribution
  - **Too low** resistance at strand's cross over allow for coupling currents, resulting in field distorsion and energy losses (reducing operating margins).
- Typical Rc resistance of about 20-40 μΩ for NbTi cables is provided by oxidation of the coating of strands.
- In Nb_3Sn cables stainless-steel core inserted between the strands and covering the ~2/3 of the width of the cable is providing Rc of about 0.1-0.5 mΩ



Picture from G. Willering PhD thesis

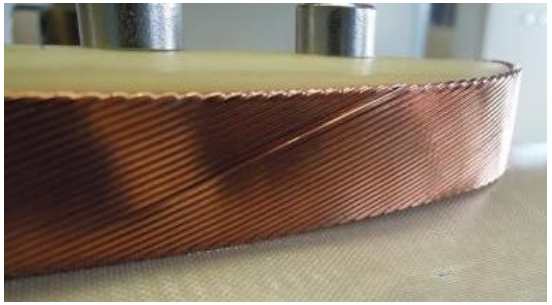


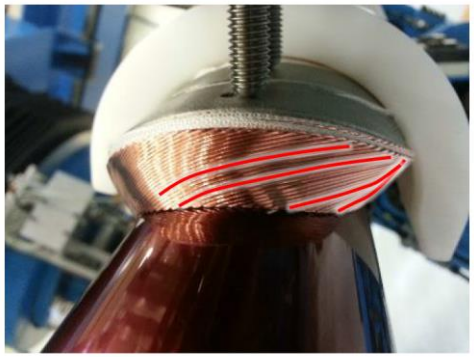


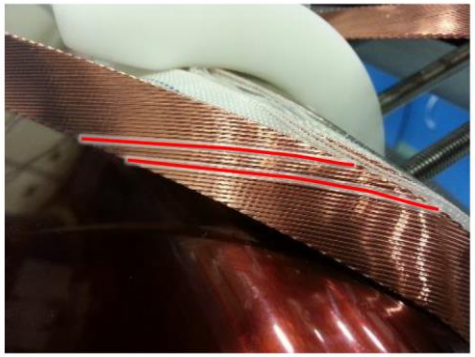


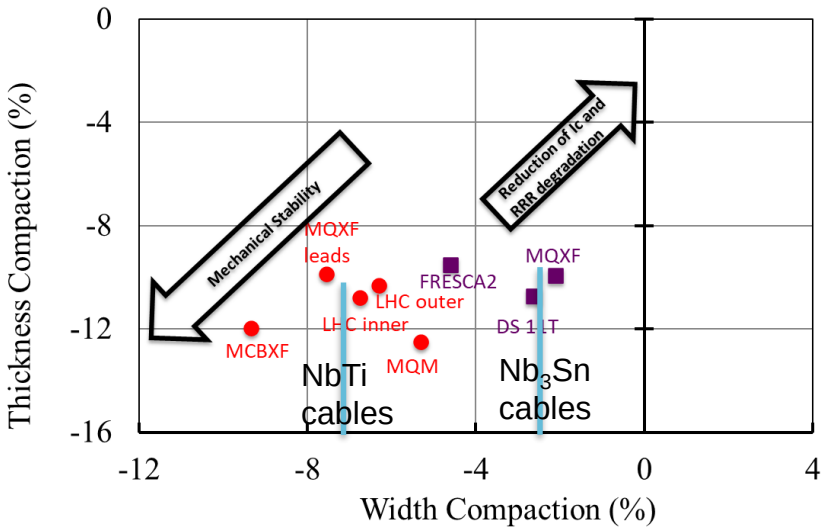
Winding of Rutherford cables

- To minimize degradation of electrical performance, Nb_3Sn cables are less compacted than Nb-Ti and therefore are more prone to popping/roping during winding stage.
- The plastic deformation of the strands provides a locking force
- Diameter of strand plays a major role in locking force
- The mechanical loading of the cable during winding may exceed this locking force
- Popped strands in coils result in magnet performance limitation









Picture from D. Pulikowski, Windability of the Rutherford cable

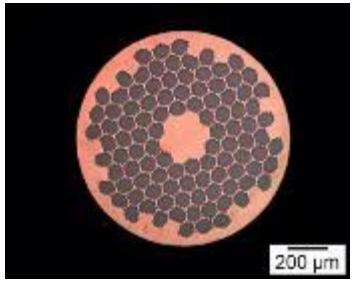
HL LHC Rutherford cables Technical specifications

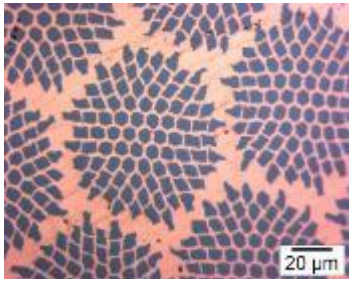
LHC Rutherford cables

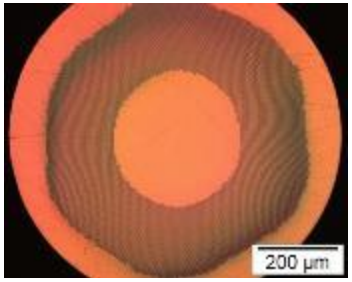
~7500 km of Nb-Ti Rutherford cables in the LHC

Nb-Ti is ductile: strands superconducting when cabled

	Type 01	**Type 02/03**	**Type 04**	**Type 05**	**Type 06**
Number of strands	28	36	36	34	22
Width (mm)	**15.09** +/- 0.01	**15.09** +/- 0.01	**8.80+0/-0.02**	**8.30+0/-0.02**	**8.30+0/-0.02**
Mid Thickness (50MPa)	**1.900** +/-0.006	**1.480** +/-0.006	**0.840+/-0.005**	**0.845+/-0.005**	**1.275+/-0.005**
Keystone Angle (deg)	**1.250** +/- 0.05	0.900 +/- 0.05	0.91+/-0.05	0.90+/-0.05	1.72+/-0.05
Transposition pitch (mm)	115	100	66	66	66
Cable Ic (kA)	**13.8 (1.9K,10T)**	**12.9 (1.9K,9T)**	**6.8 (4.2K,5T)**	**6.4 (4.2K,5T)**	**11.3 (4.2K,5T)**
Cabling degradation (%)	<5	<5	<5	<5	<5
Unit Lenght (m)	460	750	530 / 760	760	660
Produced length (km)	**2370**	**4100**	**246**	**71**	**32**







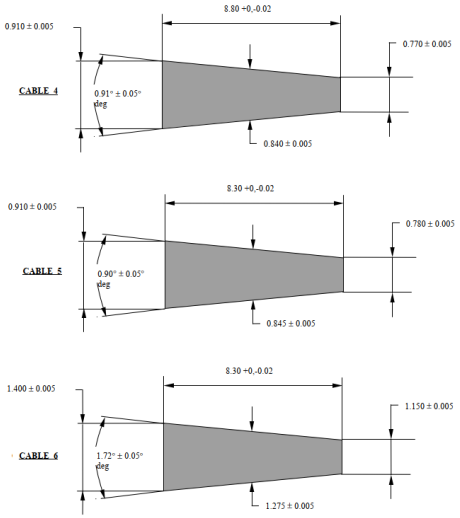


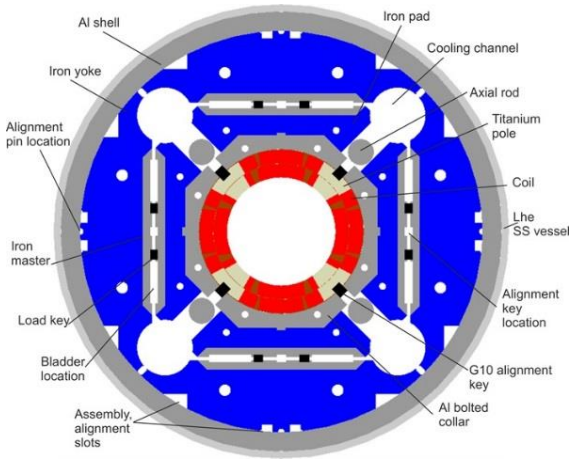
Fig. 1. Cross-sections of Cable 4, 5 and 6. All dimensions are in millimeters. Drawing not to scale.

Nb-Ti Rutherford cable, a mature technology mastered also by industry

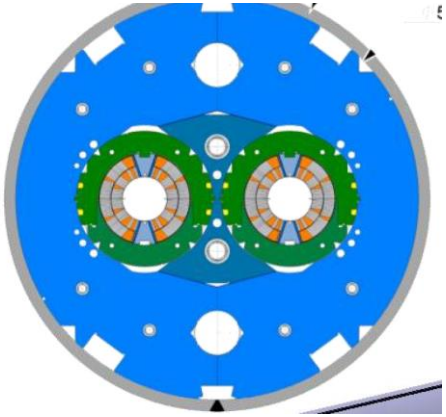
HL-LHC Magnets

- **Rutherford cables "inside"**

Rutherford cable Inside



MQXF



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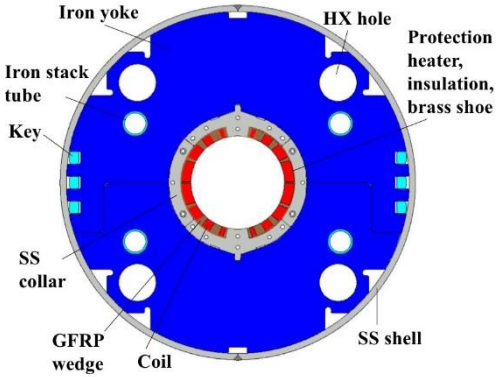
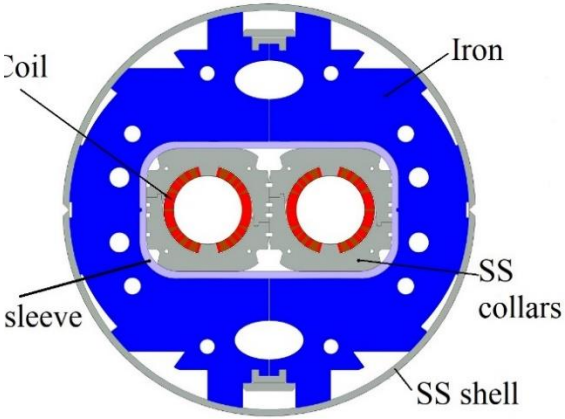


D1



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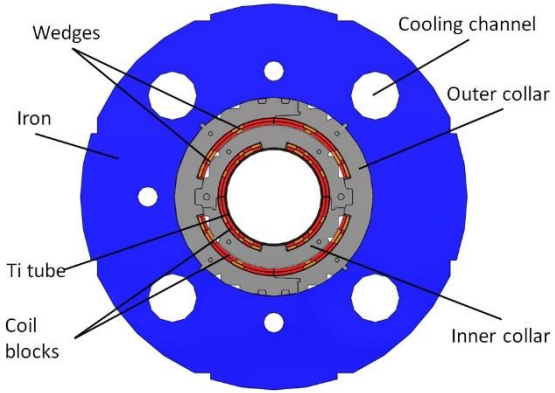


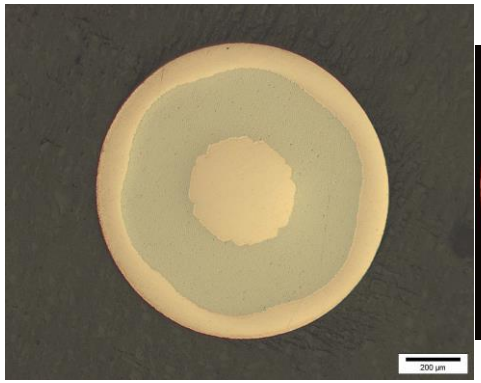
HL-LHC Rutherford cables

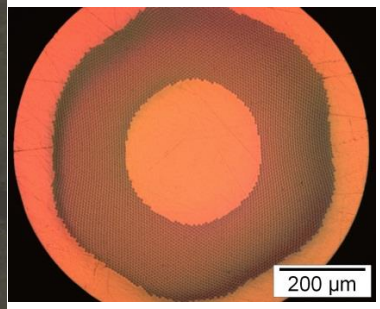
- **Nb-Ti cables**:
  - **D1 and D2,** Type 02 LHC (outer layer of MB)
  - **MCBXFA(B), new cable** 18 strands, Ø= 0.48 mm,
  - **MQXF bus bar, new cable** 34 strands, Ø= 1.07 mm
- **Nb_3Sn cables**:
  - **11 T,** 40 strands Ø=0.7 mm
  - **MQXF,** 40 strands Ø= 0.85 mm

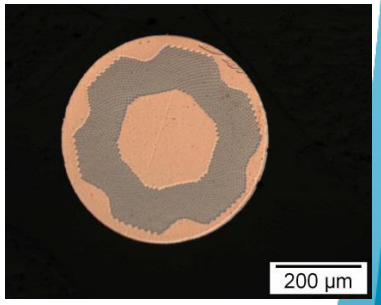
	Nb-Ti HL LHC cables		
	LHC type 02	MCBXF	MQXF leads
Number of strands (-)	36	18	34
Diameter of strands (mm)	0.825	0.48	1.065
Mid thickness (mm)	1.48	0.845	1.92
width (mm)	15.1	4.37	18.15
Keystone angle (deg)	0.9	0.67	0
Transposition pitch	100	33	125

HL-LHC Nb-Ti strands' specifications

	MQXF LEADS	D1 &D2	MCBXFA/B
Strand ID	**Type 01 LHC**	**Type 02 LHC**	**NEW Type 05 LHC**
Technical specification	**IT-2472 (1997)**	**IT-2471 (1997)**	**IT-4153 (2017)**
Quantity of strand required (km)	**~100**	**~1500**	**~1500**
Wire diameter after coating	**1.065 ± 0.0025 mm**	**0.825 ± 0.0025 mm**	**0.4800 ± 0.0025 mm**
Filament diameter	7.0±0.1 µm	6.0±0.1 µm	6.3 ± 0.1 µm
Cu to Sc volume ratio	1.65 ±0.05	1.95 ±0.05	1.75 ±0.05
Twist pitch after annealing	18.0 ± 1.5 mm	15.0 ± 1.5 mm	15.0 ± 2 mm
Twist direction	Right handed screw		
Minimum Ic at 4.2 K	532 A at 7 T	387 A at 6 T	194 A at 5 T
Minimum Ic 1.9 K	**515 A at 10 T**	**390 A at 9 T**	**189 A at 8 T**







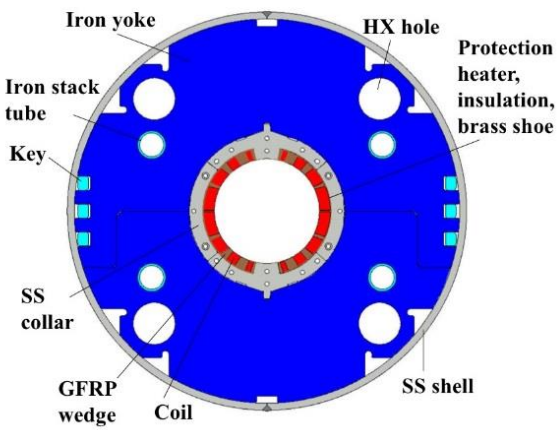
Type 05 Nb-Ti conductor procured in 2017, being electroplated (control of inter-strand resistance), EDMS 2393180

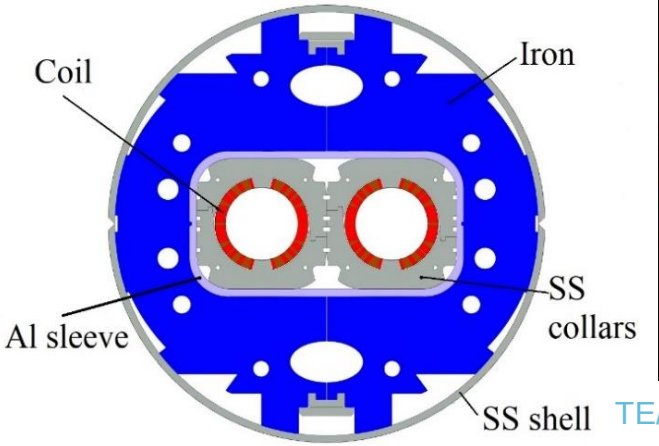
HL-LHC D1 and D2 Rutherford cable

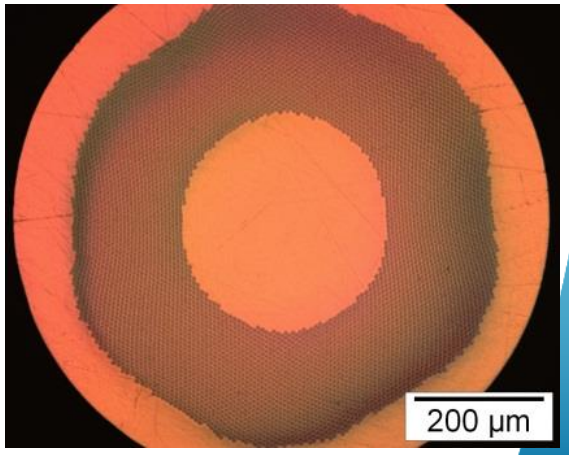
- Type 02 LHC cable (outer layer MB)
  - 36 strands, 0.825 mm diameter
  - 15.1 mm x 1.48 mm
- Quantity of cables for HL-LHC magnets
  - D1: **35 UL** of 600 m
  - D2: **22 UL** of 740 m
- **Bare cables delivered in 2019** from LHC stock

D1 and D2 Cable Parameters (LHC MB outer layer)	
No. of strands	36
Strand diameter (mm)	0.825 +/-0.0025
Cable mid-thickness (mm)	1.48 +/-0.006
Cable width (mm)	15.10 +0/-0.02
Key-stone angle (°)	0.9 +/-0.05
Pitch (mm)	100 +/-5

Technical Specification of the dipole outer layer and quadrupole superconducting cable for the LHC", IT-2471/LHC/LHC, CERN, July 1997



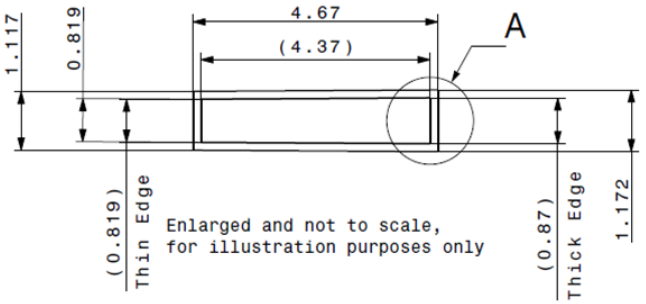


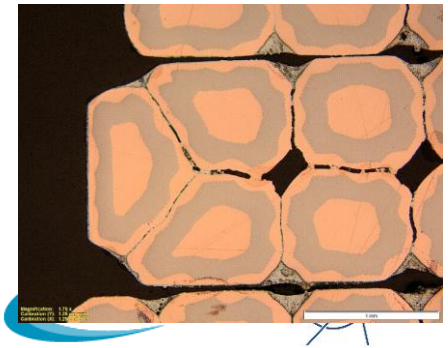


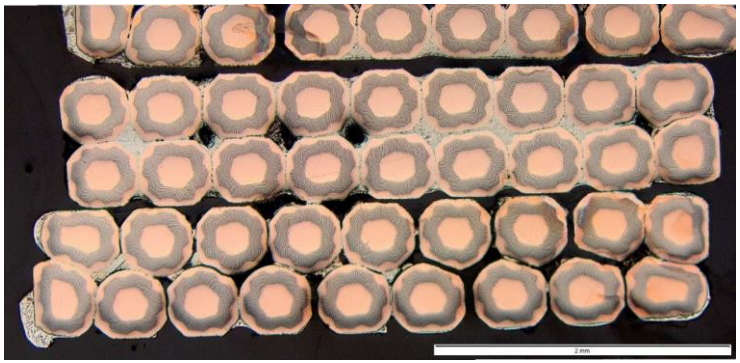
HL-LHC MCBXF Rutherford cable

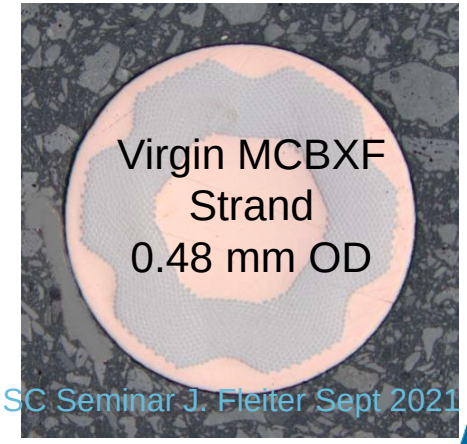
- **New cable** based on Type 05 LHC strands
- Conductor procured in 2017, being electroplated
- 18 strands, 0.48 mm diameter
- Quantity of cables for series
  - MCBXFB:
    - Inner coils: 30 UL of 390 m
    - Outer coils: 30 UL of 510 m
  - MCBXFA:
    - Inner coils: 18 UL of 670 m
    - Outer coils: 18 UL of 910 m

MCBXF Cable Parameters	
No. of strands	18
Strand diameter (mm)	0.48 +/-0.0025
Cable thickness (mm)	0.845 +/-0.01
Cable width (mm)	4.37 +/-0.05
Key-stone angle (°)	0.67 +/-0.15
Pitch (mm)	33 +/-3



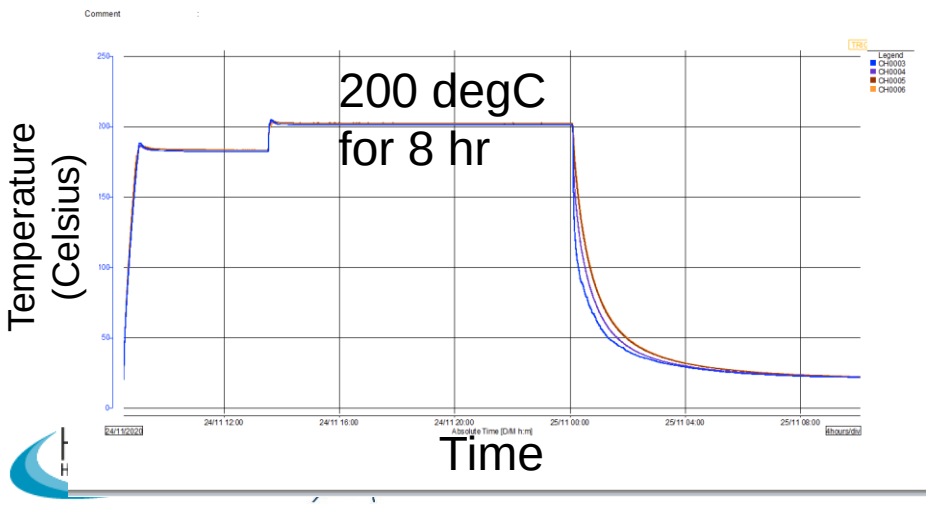


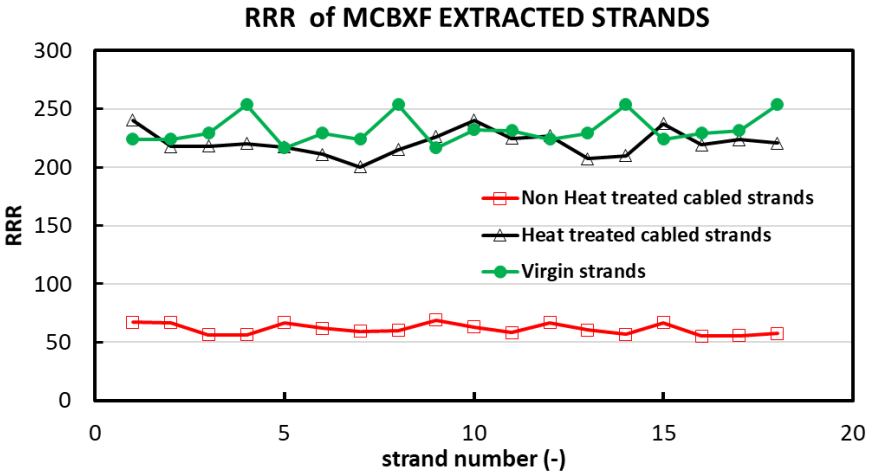




Nb-Ti Cable heat treatment

- All HL-LHC Nb-Ti cables (except MQXF bus bar) are **heat treated in air @200 ºC** for 8 hrs **after production**:
  - Releasing residual strain on the conductor
  - Increasing RRR of the strands (>150) that was reduced to ~80 during cabling (Cu plastic strain)
  - Forming the oxide layer at surface of strand that is governing the inter-strand resistance

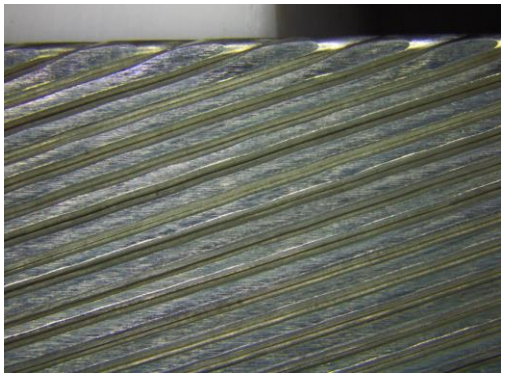


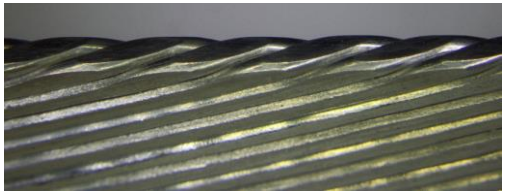


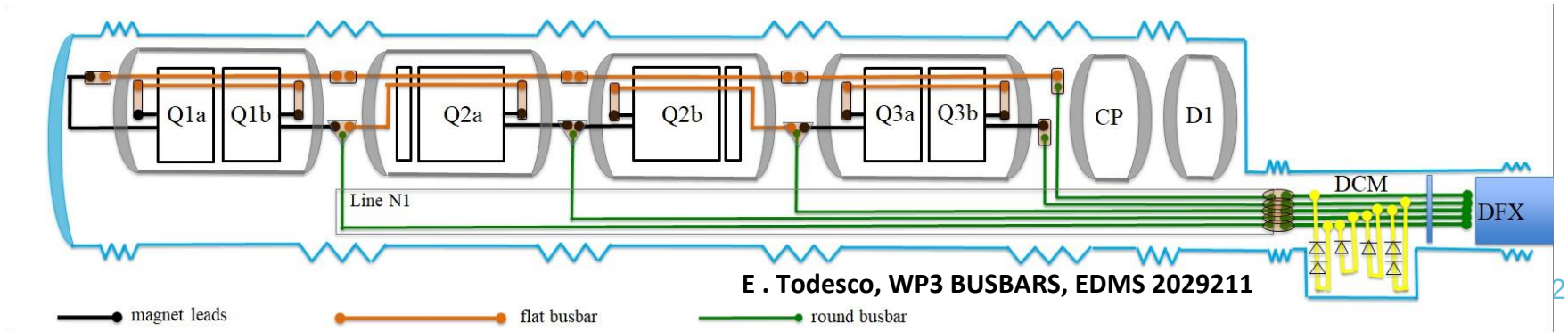
HL-LHC MQXF bus bar Rutherford cable

- **New cable** based on Type 01 LHC strands, 34 strands, OD of 1.065 mm
- Cable with same width as MQXF Nb_3Sn cable
- Use for “magnet leads” and bus-bars.
- ~5 km required for HL-LHC
  - 0.5 km produced in 2017
  - 1.8 km produced in 2019
  - 2.4 km produced in Jan 2021
- Cable is not heat treated after cabling

MQXF Leads Cable Parameters	
No. of strands	34
Strand diameter (mm)	1.065 +/-0.0025
Cable mid-thickness (mm)	1.92 +/-0.01
Cable width (mm)	18.15 +/-0.05
Key-stone angle (°)	0.0 +/-0.1
Pitch (mm)	125 +/-3







21

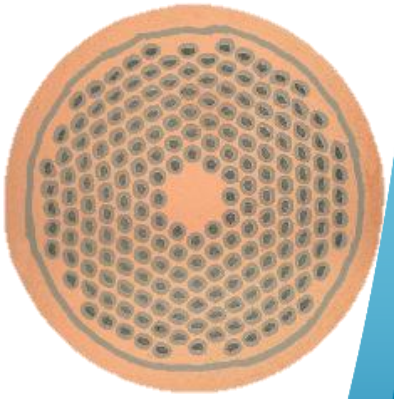
HL-LHC Nb_3Sn strands' specification

	11 T dipole RRP	MQXF Quad. RRP	MQXF Quad. PIT
Wire diameter Φ	0.700 ± 0.003 mm	0.850 ± 0.003 mm	0.850 ± 0.005 mm
Nominal sub-element diameter	< 50 µm	< 55 µm	< 55 µm
Copper to non-copper ratio	1.15 ± 0.1	1.2 ± 0.1	1.2 ± 0.1
Wire twist pitch	14 ± 2 mm	19 ± 3 mm	19 ± 3 mm
Wire twist direction	Right-handed screw	Right-handed screw	Right-handed screw
Minimum Ic @ 4.22K, 12T	438 A	632 A	590 A
Minimum Ic @ 4.22K, 15T	-	331 A	331 A
RRR (after full heat treatment)	> 150	> 150	> 150
n-value @ 4.22K, 12T	> 30	> 30	> 30
J_c(4.22 K, **12** T)	**2450 A/mm^2**	**2450 A/mm^2**	**2290 A/mm^2**
J_c(4.22 K, **15** T)		**1280 A/mm^2**	**1280 A/mm^2**

- Procured **PIT conductor** will **not** be **use** for the **series**
- **Series conductor RRP 108/127**
- **11 T** RRP 108/127 ~1000 km
- **MQXF** RRP 108/127 ~1500 km

Technical specification EDMS No.: 1419926, 1419924

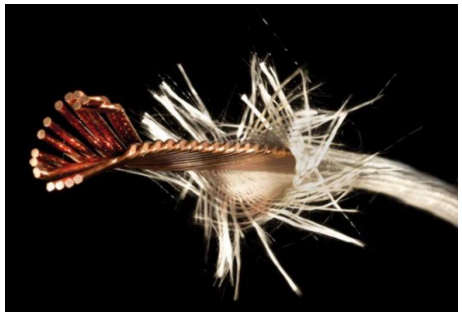
RRP 108/127



PIT 192 Bundle Barrier

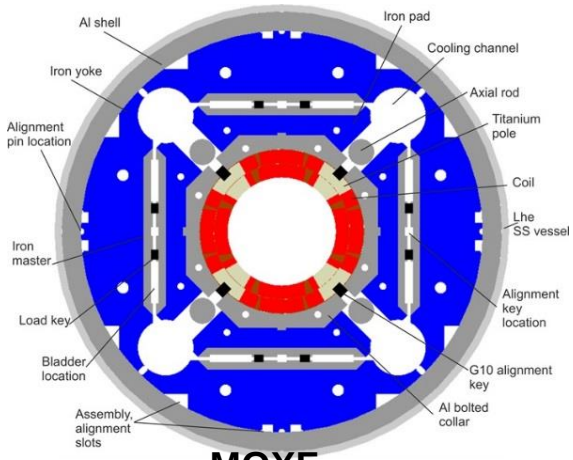
HL-LHC Nb_3Sn cables' specification

- MQXF Q2 and 11 T cables produced at CERN
- MQXF Q1 and Q3 cables produced in US
- Series conductor: RRP 108/127

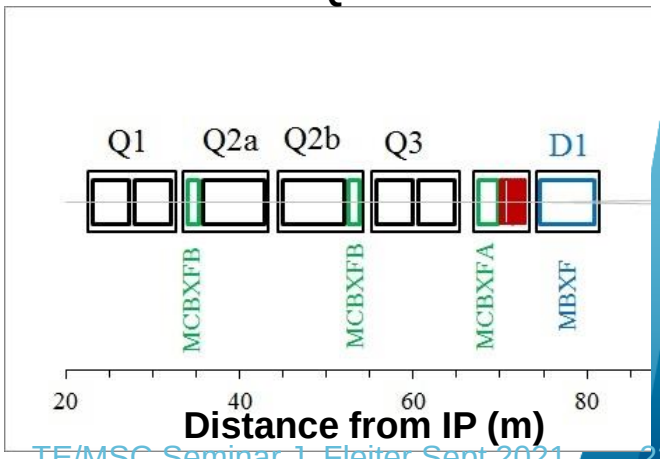


Cable Type	11 T	MQXF
Number of strands	40	40
Pitch direction	Left	Left
Cable mid thickness (mm)	1.25 ±0.01	1.525±0.01
Cable width (mm)	14.70 ±0.05	18.15±0.05
Cable Keystone (deg)	0.79 ±0.1	0.40±0.1
Continuous Cable length without cross over or inclusions (m)	>655	>760
Pitch (mm)	100 ±3	109±3
Core Material	EN 1.4404	EN 1.4404
Core width (mm)	12 ±0.1	12±0.1
Core thickness (µm)	25 ±1.5	25±1.5
Facets length at thin edge(mm)	2.4±0.5	2.4±0.5
Facets length thick edge (mm)	1.9 ±0.5	2.1±0.5
Sharpness at thin edges (mm)	>0.1	>0.1 mm
Cabling I_c degradation (measured on strands @4.3 K and 12 T)	<5%	<5%
RRR extracted strands	>100	>100

MQXF

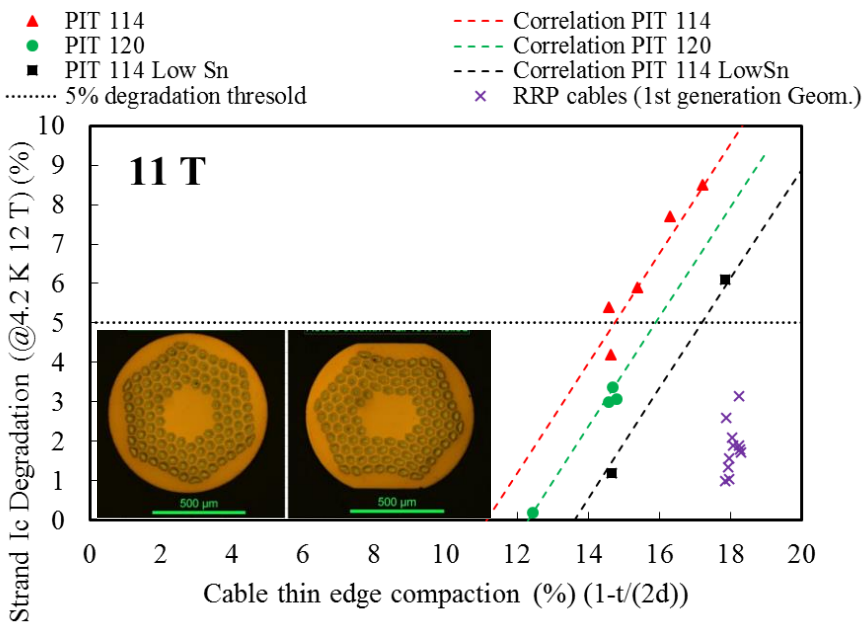


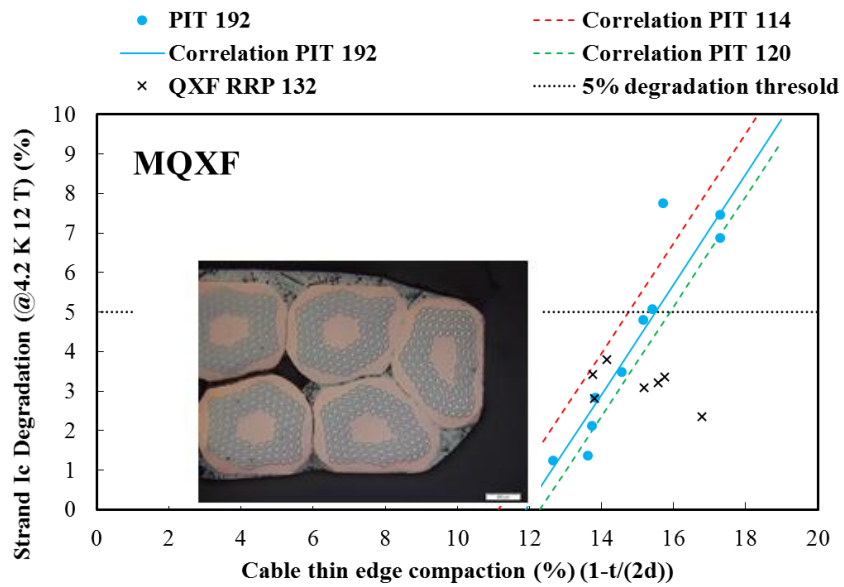
MQXF



HL-LHC Nb_3Sn cables strand I_c degradation vs. cable compaction

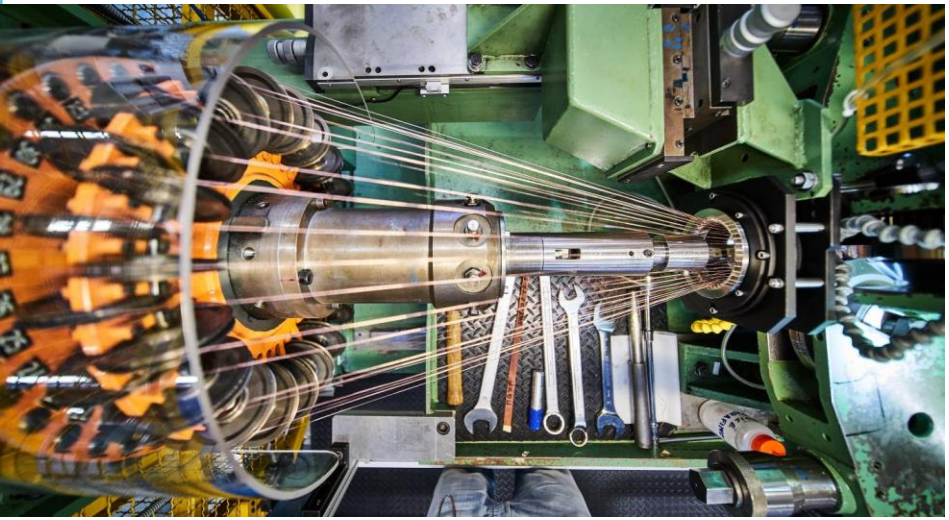
- **I_c degradation vs cable compaction investigated at the beginning of theproject**
  - **PIT** Cable I_c degradation less than 5%, if thin edge compaction less than **16%**
  - **RRP** cables are **not sensitive** to thin edge **compaction** (in the range 14-18%)
- **Reduction** of **thin edge compaction** is **beneficial** to the **RRR** of **RRP** and **PIT** cables
- **Cable I_c degradation** also depends on **width compaction** and **pitch angle** (shear stress)
- **Cable MQXF geometry was modified 2016** (reduction of keystone angle) in order to reduce compaction at thin edge (cable specs. in next slides)





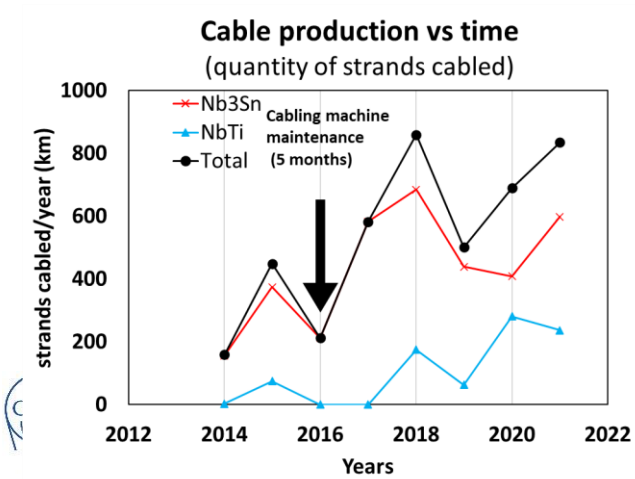
Fabrication of HL-LHC cables

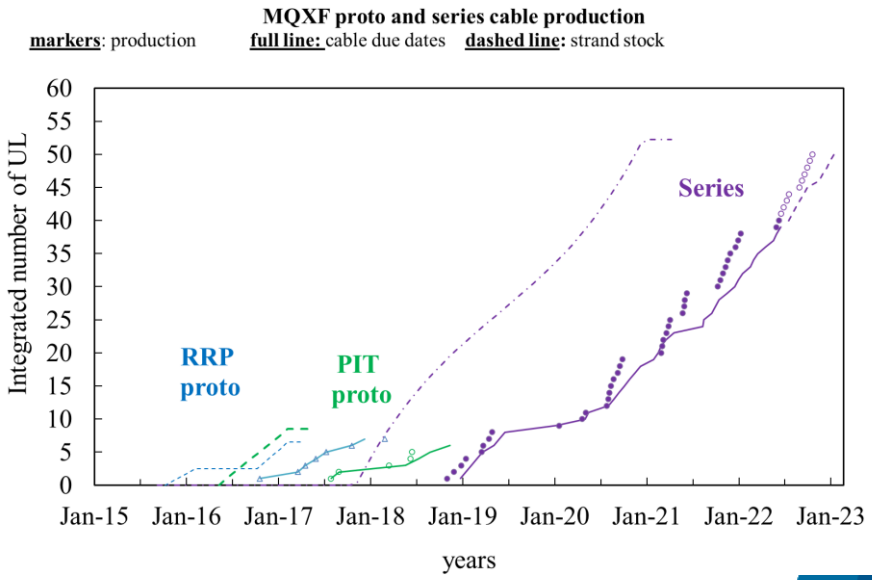
- Cable production plan
- CERN Rutherford cabling machine
- Cable production QC



Cable production plan

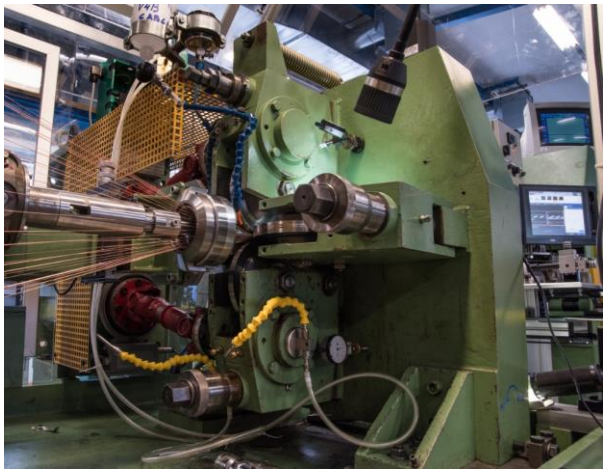
- **Cable production plan** established in accordance with strand delivery and requirements for coils winding EDMS 2002194.
- **Cabling of multiple unit lengths** during the same cabling run :
  - Long piece lengths of conductors (e.g. 2 UL for 11 T up to 10 for Nb-Ti)
  - Cold welds (Nb-Ti) or mechanical junction (Nb_3Sn) removed after cabling
- **First cable series production performed at CERN, completed in 2022**
- **Status of series production:**
  - **11T completed in July 2020 (35 UL)**
  - **MQXF bus bars, D1 and D2 all cables delivered**
  - **MQXF 29 UL over 50 produced**
  - **MCBXF 37 UL over 96 produced**

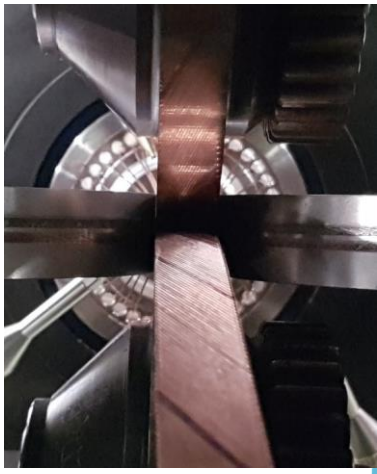




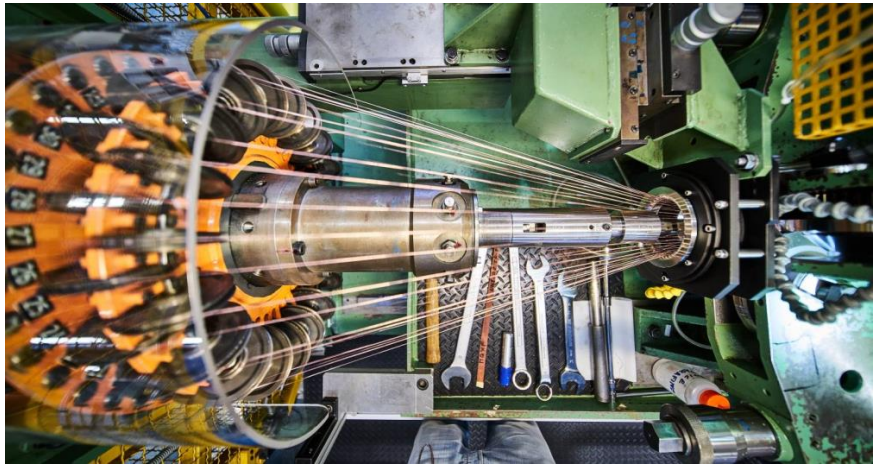
CERN Rutherford cabling machine

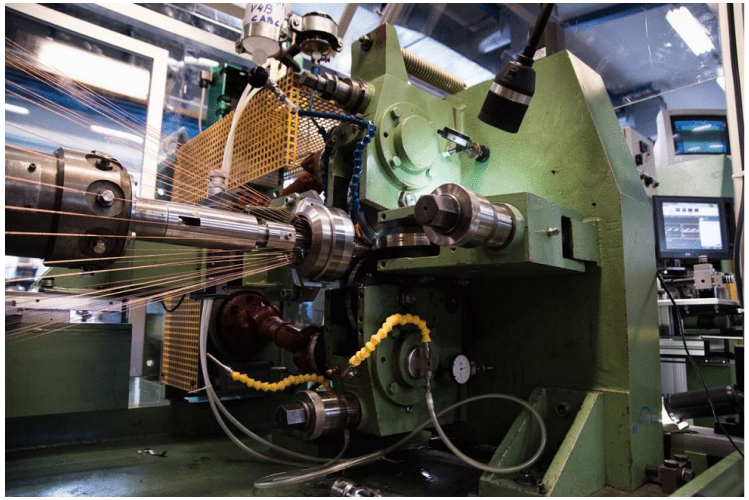
- **Machine installed since 2006 at CERN**
- **Used previously in industry for LHC cabling**
- **All the CERN HL-LHC production performed at CERN**
- **40 spools planetary cabling machine:**
  - Active regulation of strand mechanical tension (~20-70 N)
  - Used for HL-LHC production but also for R&D and other projects.
- **Throughput in operation ~1.5 m/min (Nb_3Sn), and up to 5 m/min for LHC cables**
- **Final shape given at the Turkshead with appropriate rollers and mandrel**





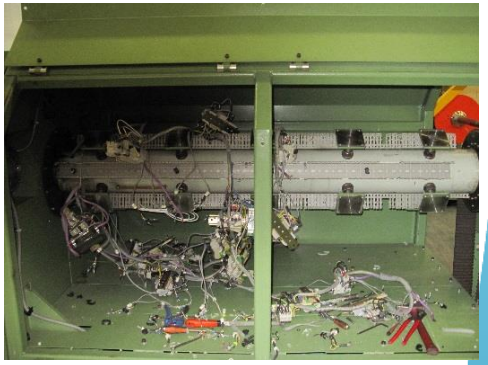
CERN Rutherford cabling machine





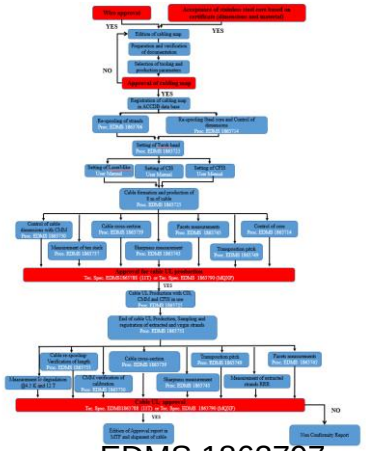
Upgrade of the cabling machine in 2016

- Before start of HL-LHC production, major upgrade of the machine in building 103 was performed
- Replacement of all spool motors and their drivers (controllers)
- New machine supervision
- Machine reliability and regulation of strand tension were improved
- New features implemented for detail monitoring and recording of cabling parameters

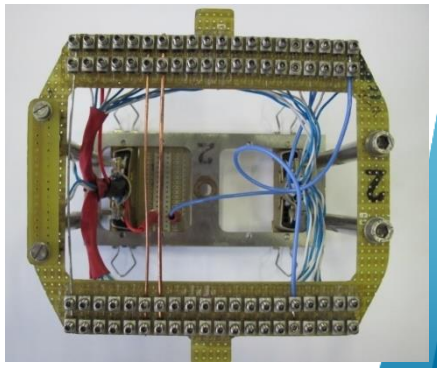


Rutherford cable production :QC tests

- **All QC tests listed in production flowchart EDMS 1863797**
- **Cable Geometry**
  - **Dimensions**:
    - **Ten-stack (point of UL, thickness)**
    - **CMM all along production: thickness, keystone angle and width**
    - **Length**
  - **Cross section** (point and tail of UL)
  - **Sharpness of edges** (point and tail of UL)
  - **Cross over** (detection system run during production)
  - **Facets** (1 pitch long samples: point and tail of UL) and on-line with production
  - **Integrity and shape of SS core** (point and tail of UL) – visual inspection
  - **Scratch on strands** facing the core (point and tail of UL) – visual inspection
  - **Pitch measurements** (point of UL)
- **Strand I_c measurements (@ 4.3 K and 12 T)**
  - Extracted strand
  - Virgin strands adjacent to extracted
  - ➢ **1 pair per billet in the cable** (4 to 5 per UL)
- **RRR measurements**
  - ➢ **1 pair per billet in the cable** (4 to 5 per UL)



EDMS 1863797



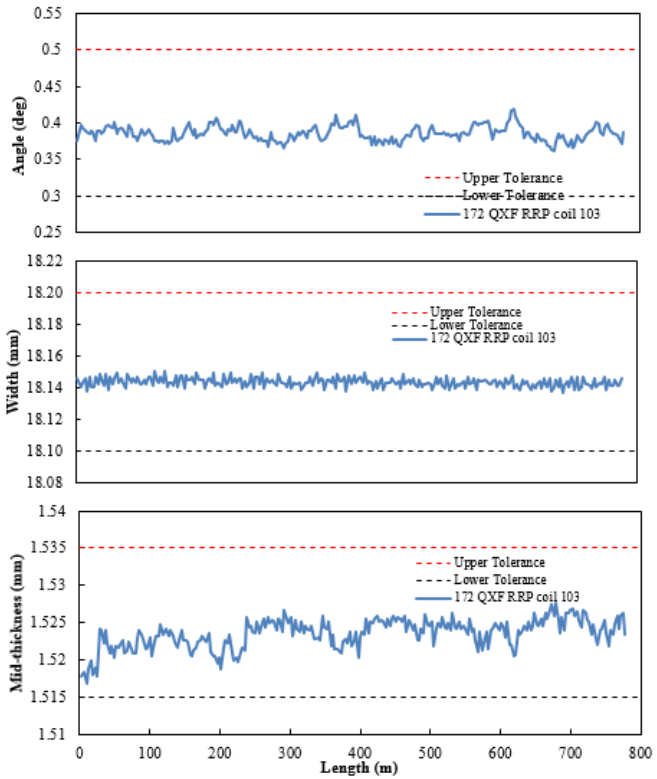
Geometrical homogeneity

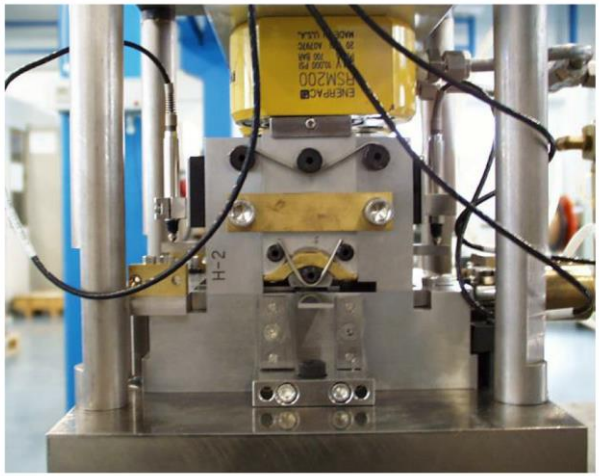
Control of cable geometry along a unit length is crucial. Cable dimensions are monitored on line during production:

- **Cable dimensions**: thickness, width and Keystone measured and monitored online with the Cable Measuring Machine (CMM) **(see next slides)**
- **Strand Tension Monitoring System:** monitoring and recording of mechanical tension applied on each individual strand. **New system as from 2016 (see next slides)**
- **Cable Facets Inspection System (CFIS)**: detect crossovers, abnormal flattening of wires or deviation from its nominal shape and inclusions. **Same system as for LHC**
- **Cable Edges Inspection System (CEIS):** measure facets dimension, **New system**, implemented on production line in 2016. **(see next slides)**

Measurement of cable's dimensions

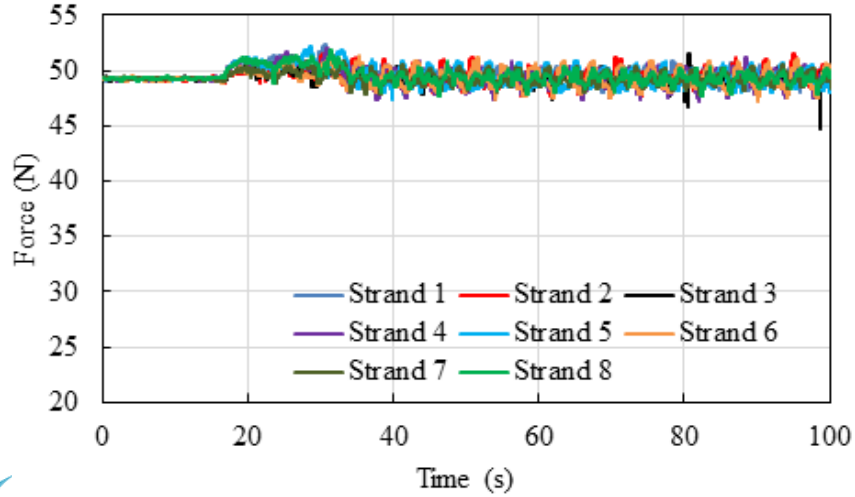
- Cable thickness, width and keystone angle measured online with the CMM: stringent control on cable dimensions
- Same system used as for LHC
- A 10 stack measurement is performed at the beginning of each cabling run, to determinate the absolute value of the cable mid-thickness

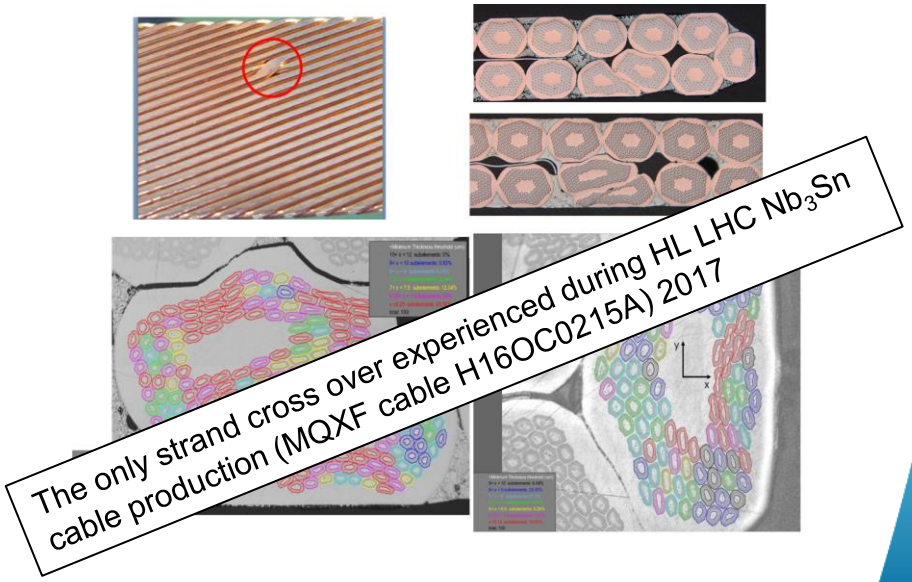




Mechanical tension on single strands

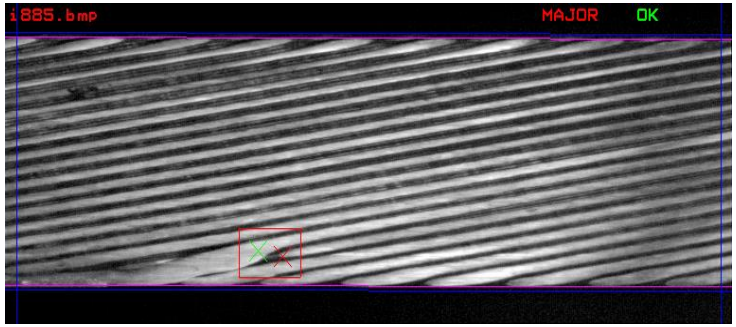
- Good strand regulation is crucial to produce good quality cables
- Loose or tight strand for less than a second may induce strands crossover, resulting in major non conformity, cable could not be use in coil.
- A new system recording at 50 Hz the mechanical tension applied on each single strands in operation since 2016
- Used for the commissioning of the machine and for cable production (log of production)

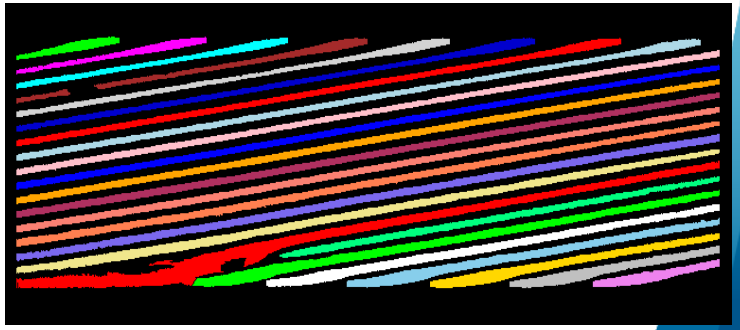




Inspection system of cable's facets

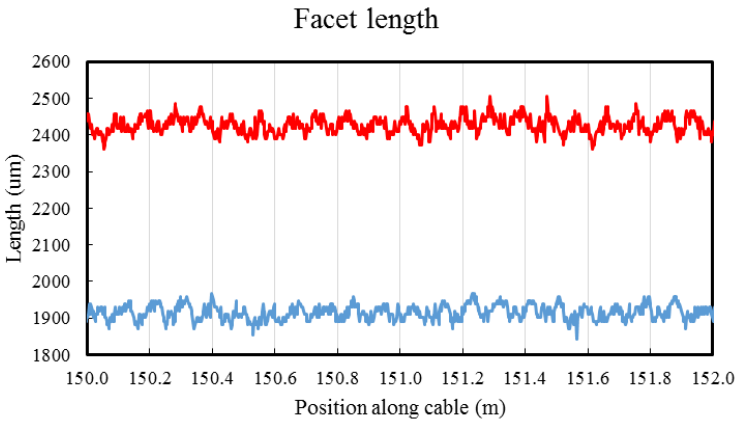
- Inspect in real time the cable on its wide faces
- Detect cable defects and recognise the gravity of the defect (minor or major defect)
- Warn the operator when anomalies occur, and display the defects
- Record all incidents
- Edit a status report at the end of inspection

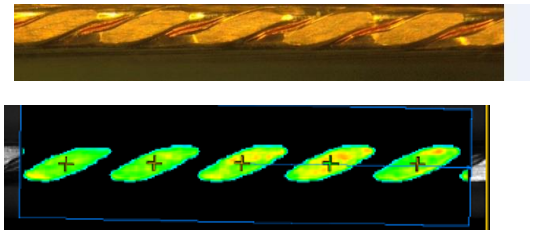


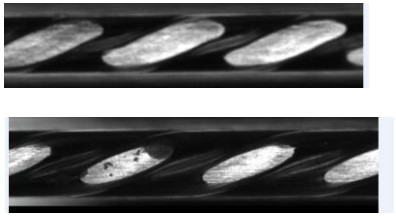


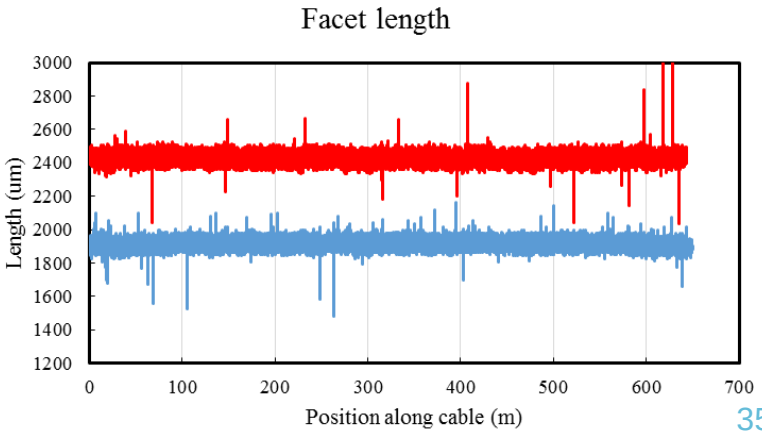
Inspection system of cable's edges

- Dimensions of each facets (at thin and thick edges) over the full cable length are measured since mid 2016
- Measurement performed by Keyence CV-X vision system equipped with cameras
- Threshold of acceptable facet dimensions
- Save photograph of facets with non conformity for off line analysis





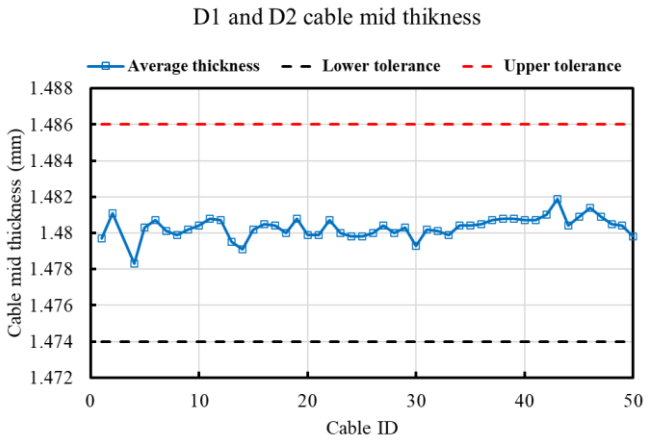




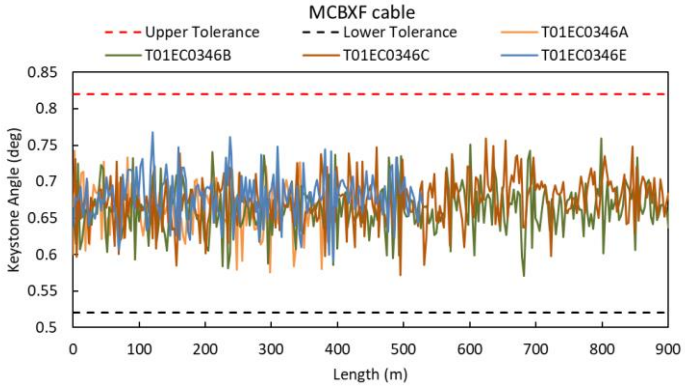
Fabrication of HL-LHC cables
- Overview of produced cables

Nb-Ti cables

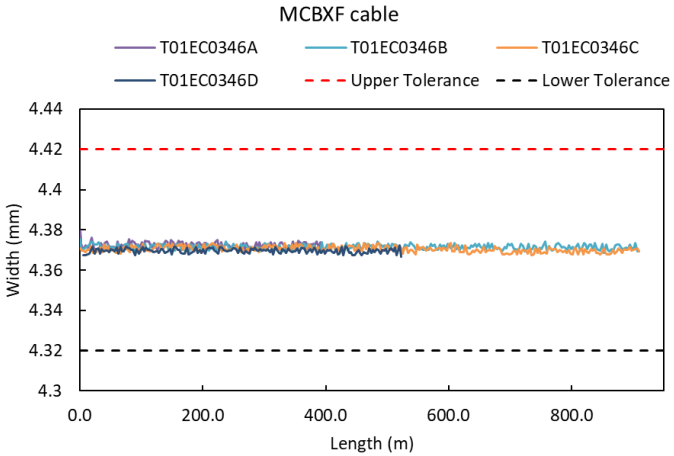
- **All D1 and D2 cables approved** at the time of LHC 2004-2006
  - For all cables, homogeneous width over cable length, no drifting, tiny fluctuations within spec, cable Ic and all other parameters in spec



- **All produced MCBXF cables approved** all parameters within spec
  - homogeneous cable dimensions over cable length with no drifting
  - tiny fluctuations from cable to cable,
  - Extracted strand Ic and RRR OK



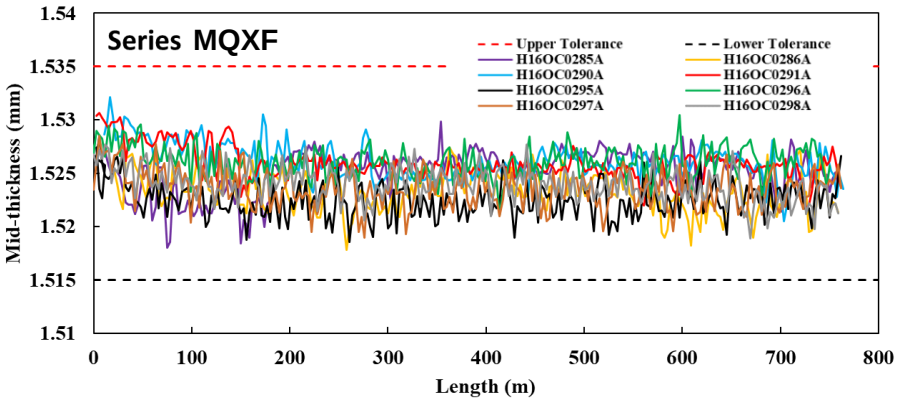
- **All MQXF bus bar cables approved** all parameters within spec

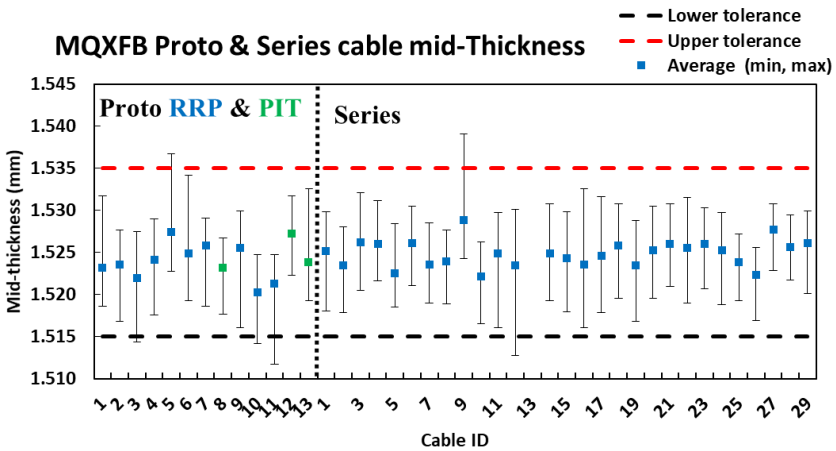


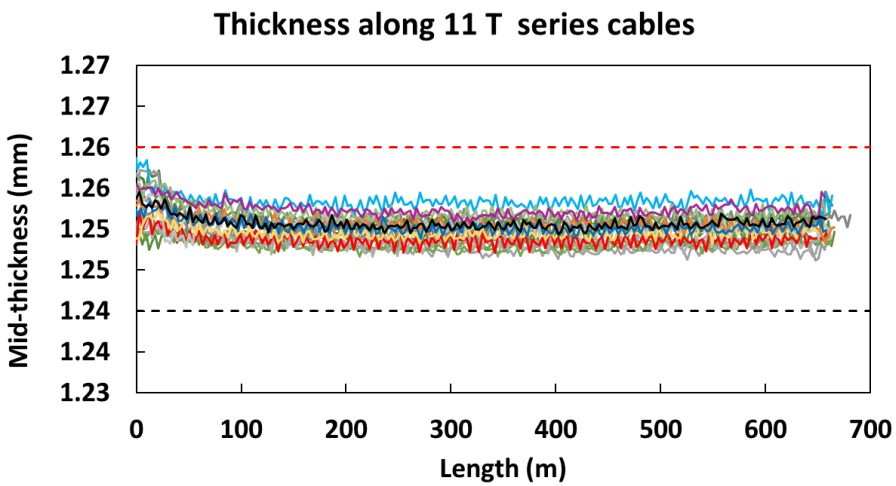
Nb-Ti cable production is under control

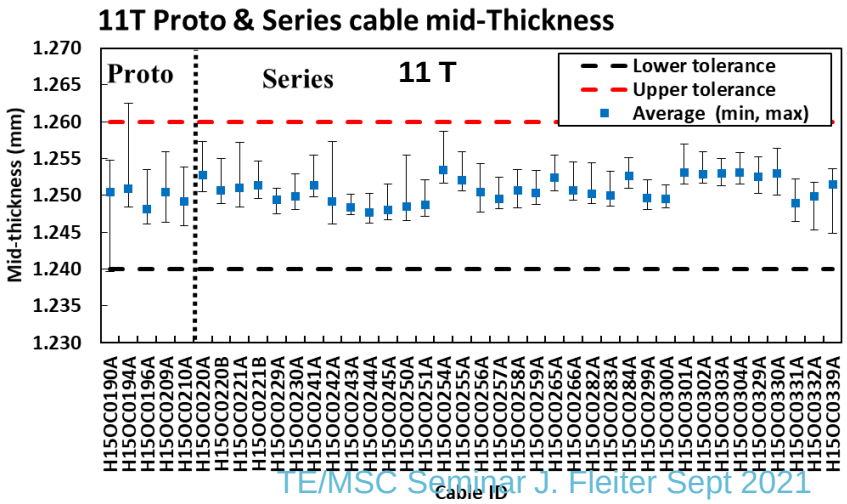
Nb_3Sn cables thickness (@ 50 MPa)

- **All cables to date are in spec,** stable STDEV over production (~2 µm)
- For all cables, small drift (< 1-5 µm) at the beginning of the production
- The **cable thickness** is **under control**



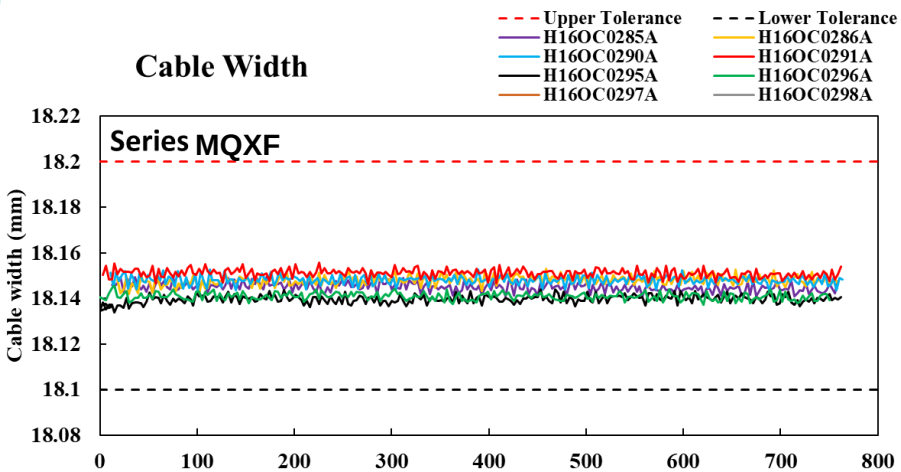


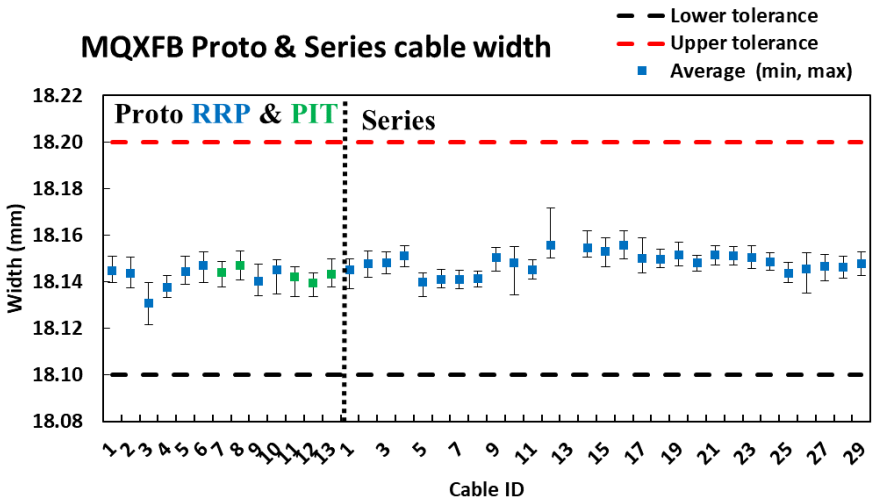


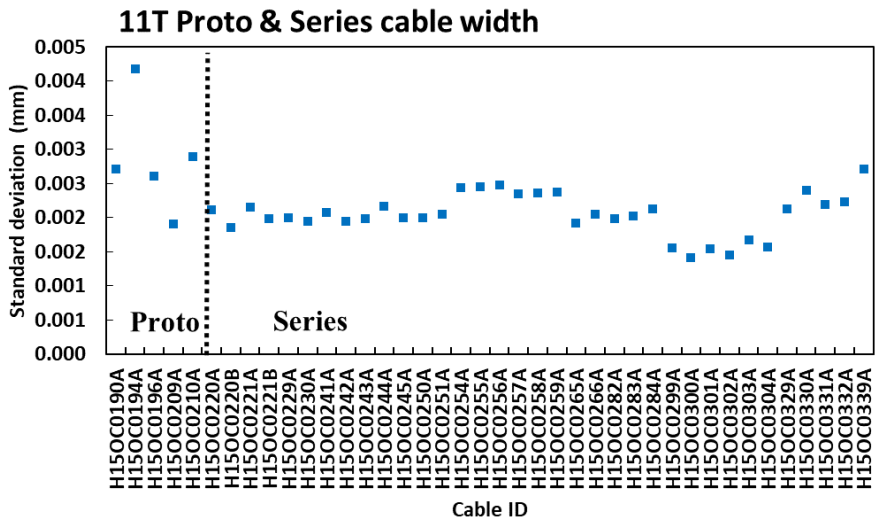


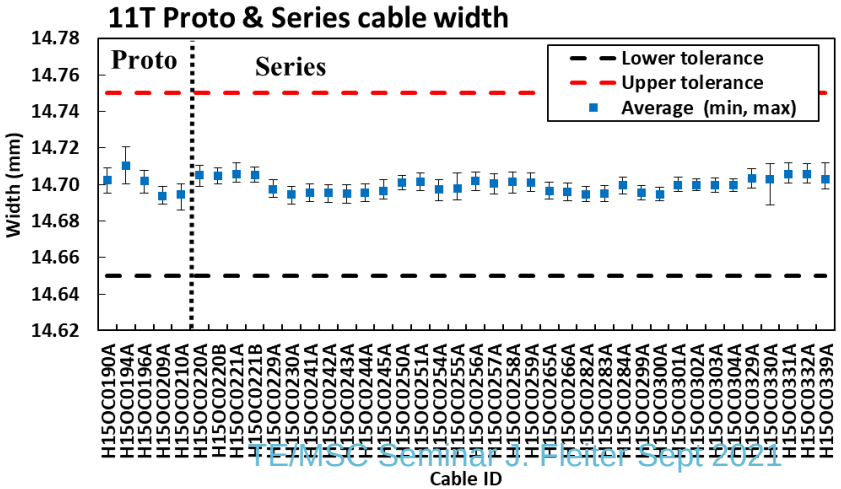
Width of Nb_3Sn cables

- **All cables to date are in spec,** STDEV of 2-3 µm over production
- **For all cables, homogeneous width over cable length, no drifting, tiny fluctuations within spec**
- The cable width is **under control**



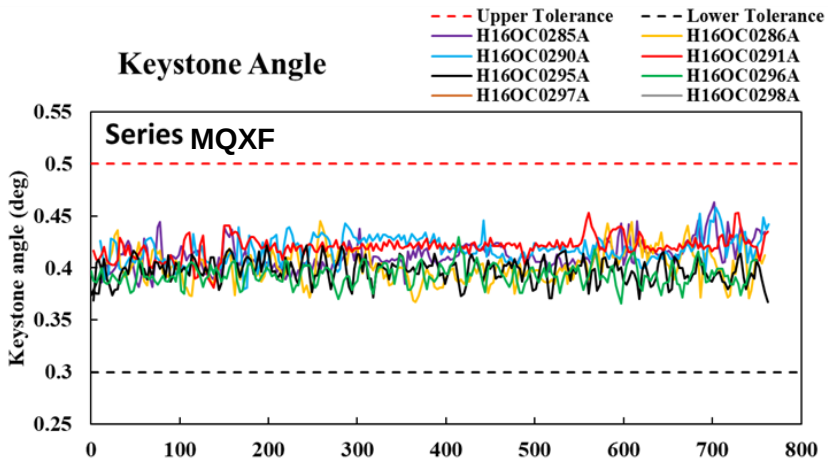


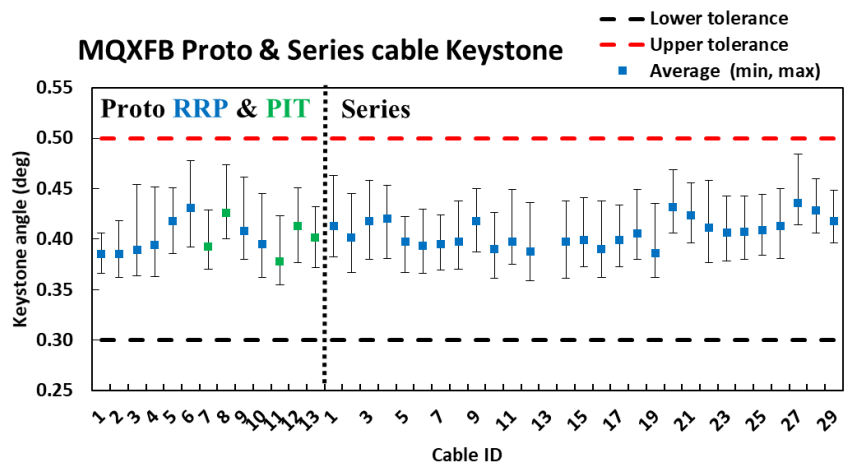


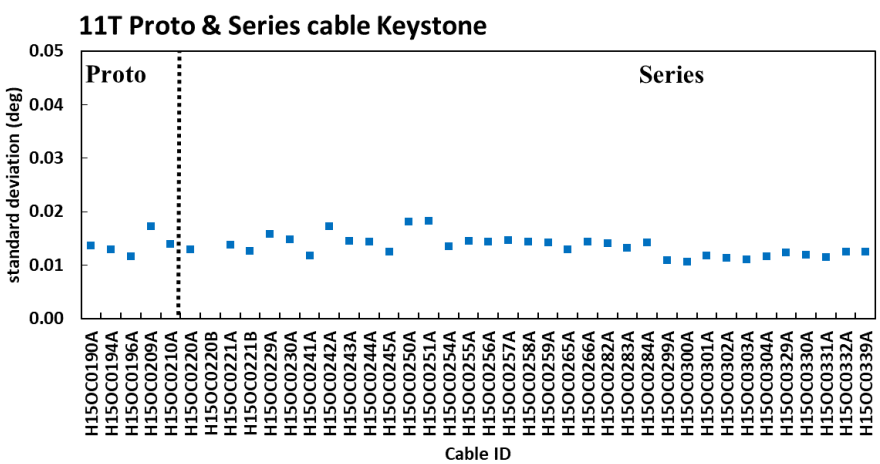


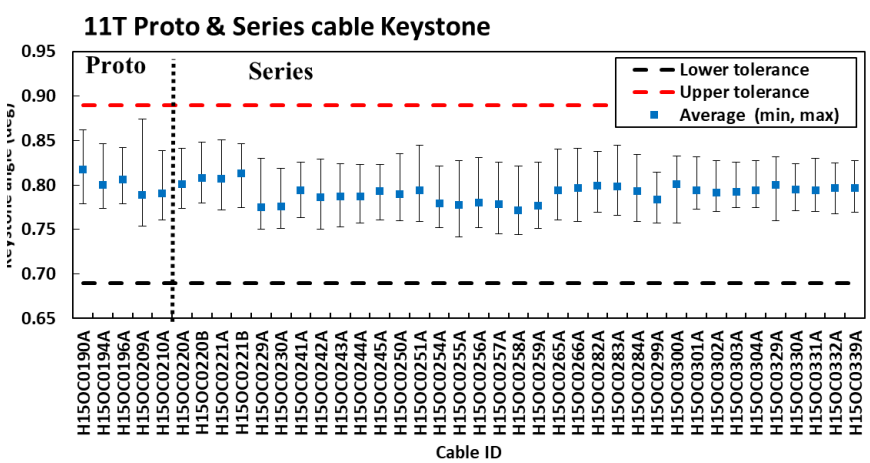
Keystone angle of Nb_3Sn cables

- **All cables to date are in spec,** STDEV of 0.01 deg for full production
- **For all cables, homogeneous keystone angle over cable length, no drifting, tiny fluctuations within spec**
- The cable keystone is **under control**



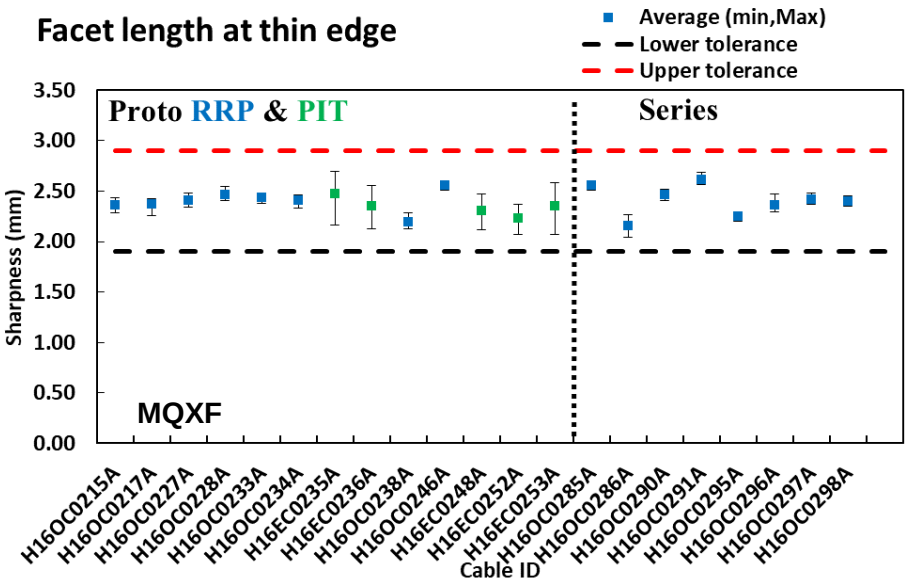


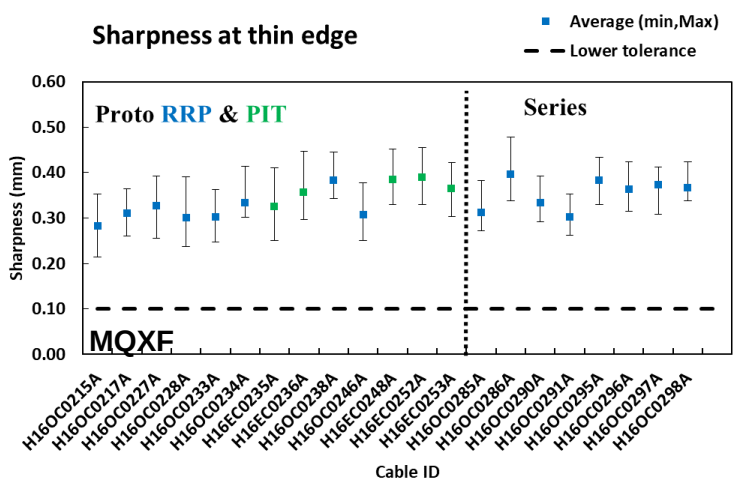


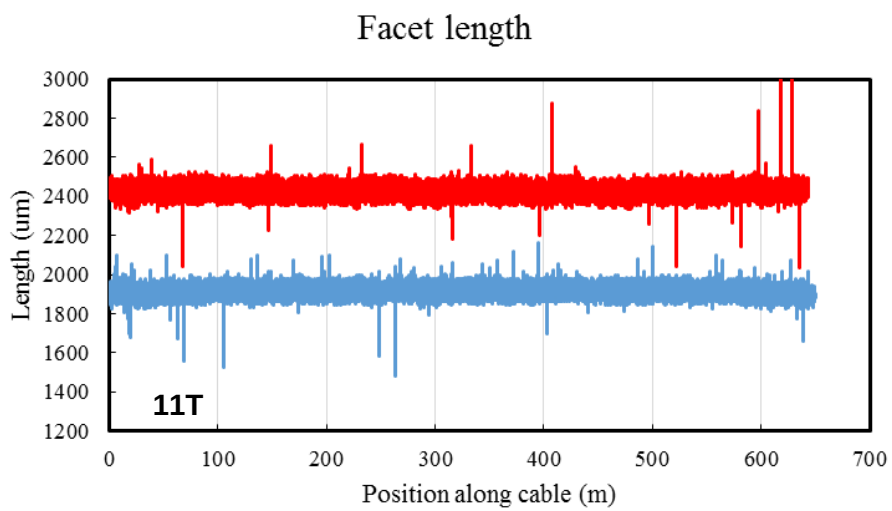


Nb_3Sn cables sharpness of edges and facets

- Facet length @ thin and thick edge:
  - All cables to date are in spec
  - For all cables, homogeneous facet length over production run
  - No drifting of facet length with production
- Cable sharpness:
  - All cables to date are in spec
  - For all cables, homogeneous sharpness between point and tail of UL
  - Both edges behave the same
  - No drifting of sharpness with production
- The cable sharpness and facets are **under control**

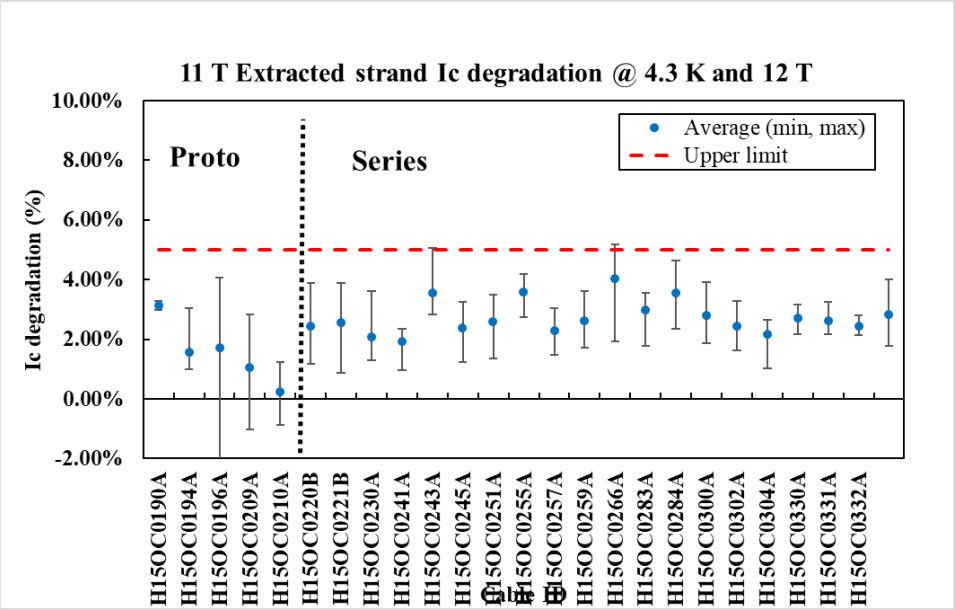


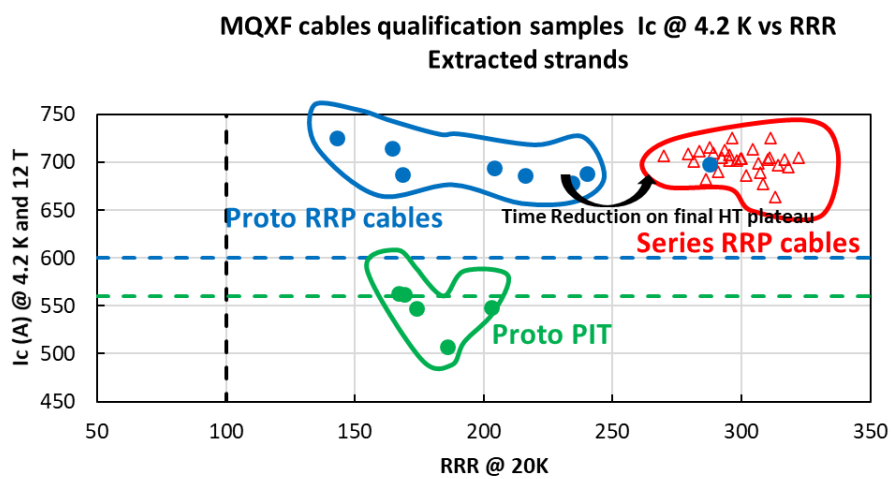


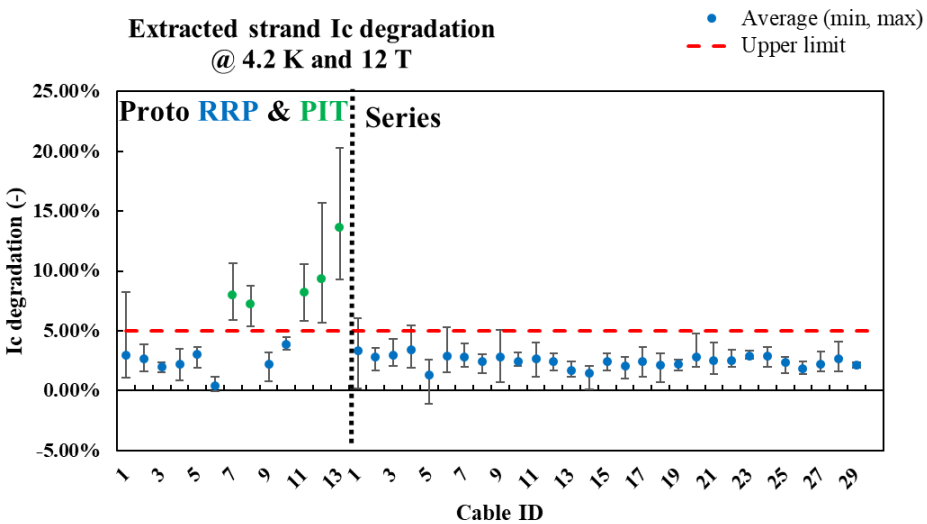


Nb_3Sn cables I_c of extracted strands

- **All RRP cables are in spec**
  - **Average I_c degradation of 2.6% QXF and 2.7% for 11T**
  - **Limited spread: except for few cases**
- The I_c degradation of RRP cables (11 T Dipole and QXF) is **under control**
- All proto QXF PIT cables have average I_c larger than 5% with n- value of about 30-35

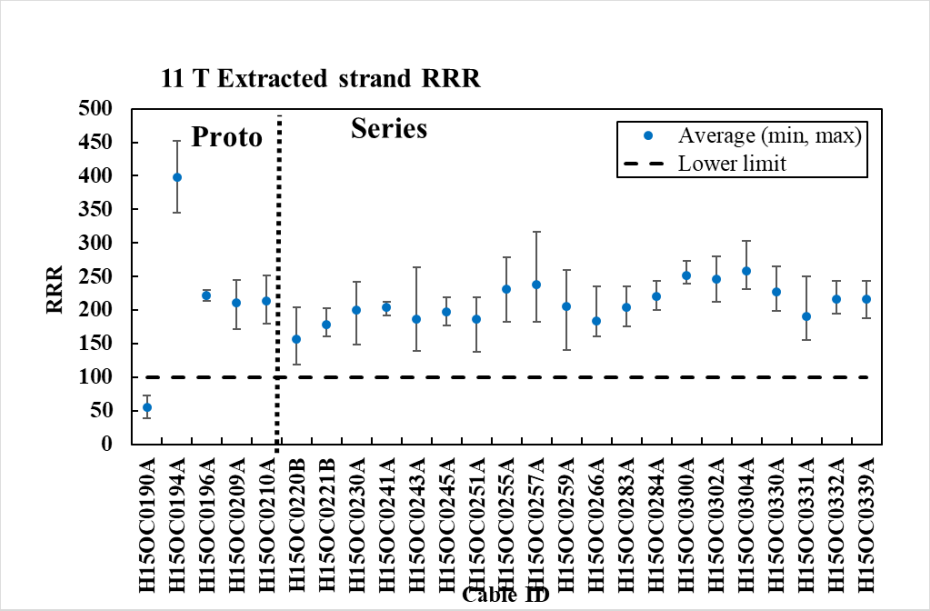


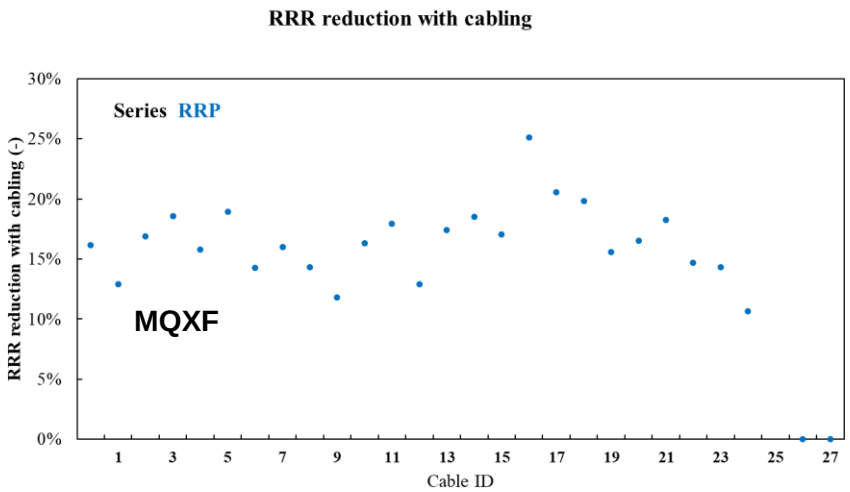


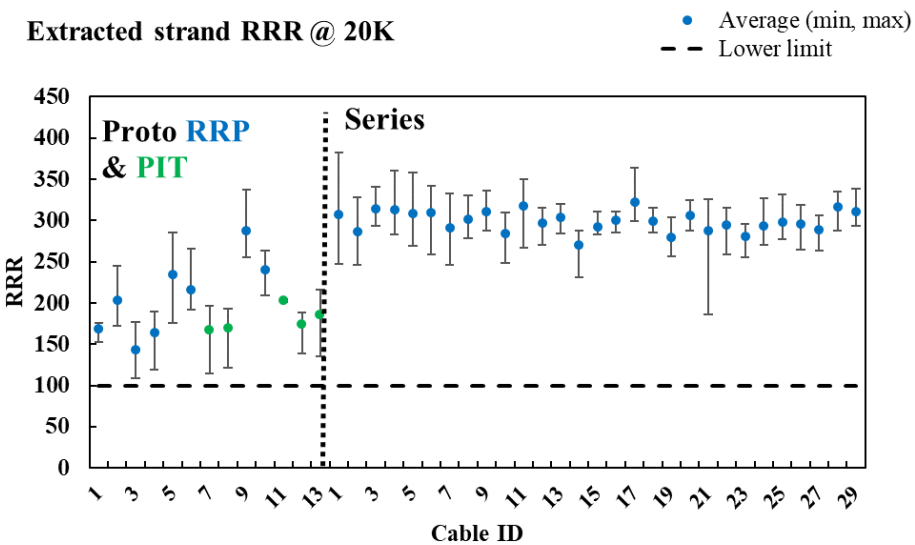


Nb_3Sn cables: RRR of extracted strands

- **Extracted strands' RRR**
  - **All cables to date are in spec**
  - **RRP: typically ~ 24% reduction of integrated RRR with cabling**
  - **PIT: no reduction of integrated RRR with cabling**
  - **Reduction of RRR is stable over production**
- Regarding the extracted strands' RRR, the production **process** is **under control for both PIT and RRP cables**

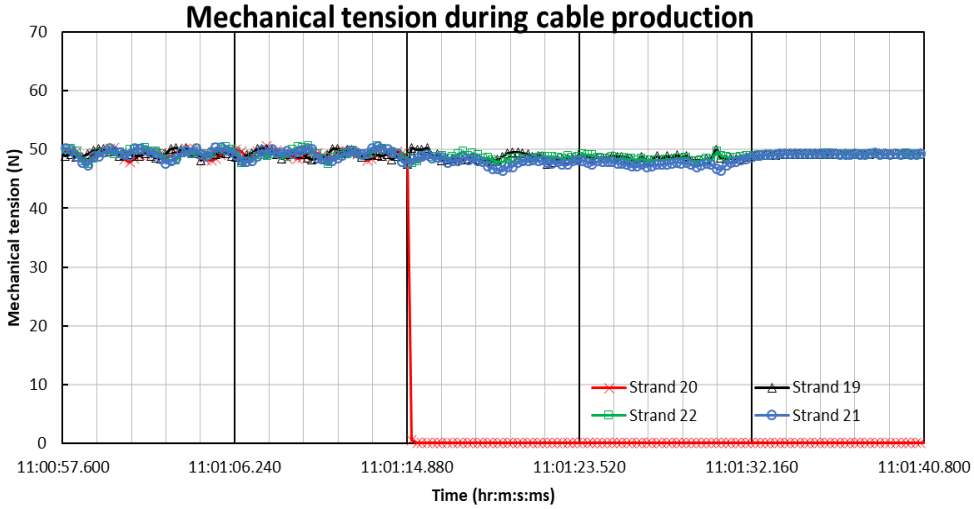






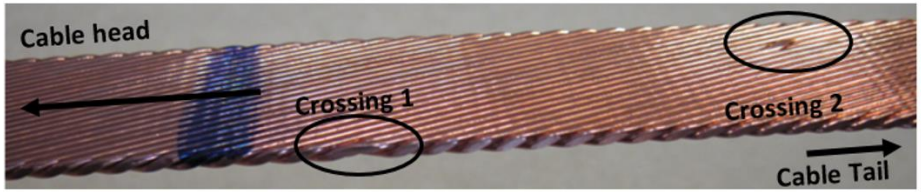
NON CONFORMITIES –11T Cables

- 43 units produced, 42 units fully conform to technical specification
- One non conformity on the last cabling run
- Sudden strand breakage cable H15OC0333A EDMS 2573936
  - At 165 m from start, strand 20 broke suddenly with no precursor
  - Cause was identified to be strand local mechanical weakness

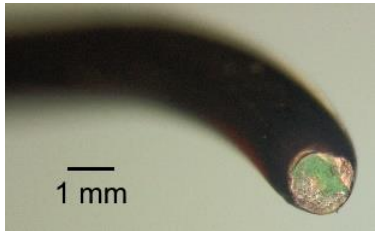


NON CONFORMITIES – MQXF RRP CABLES

- 37 Units produced, two major non-conformities
  - Strand cross over Cable H16OC0215A (expected to be first proto cable)
    - Cable too short for proto coil. It was **regraded** to 4 short models plus archived length (now used for other projects)
    - Preventive action: The procedure of strand spooling before cabling was reviewed (EDMS 1863706 Rev.0.2)



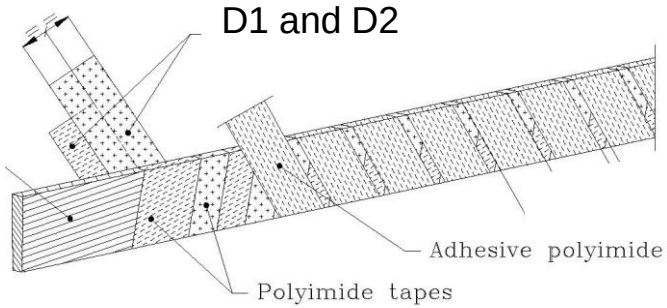
  - Strand breakage Cable H16OC0370A EDMS 2573936
    - At 115 m from start, excessive tension on strands results in breakage
      - **Cable too short** for series coil. Remaining non cabled length of strands were archived
      - 11 preventive actions implemented as reported in NCR EDMS 2573936



Insulation of HL-LHC Rutherford cables

- **The cable insulation must feature:**
  - Good electrical properties to withstand high turn-to-turn voltage during a quench.
  - Good mechanical properties to withstand high pressure conditions
  - Porosity to allow penetration of helium (or epoxy)
  - Radiation hardness
- For D1 and D2 magnets it is a series of overlapped layers of polyimide tapes
- For 11T, MQXF and MCBXF magnets there is a fiber glass braided around the cable (with inclusion of 80-µm-thick C-shaped Mica for 11 T cable). The coil are then impregnated with low viscosity epoxy

D1 and D2



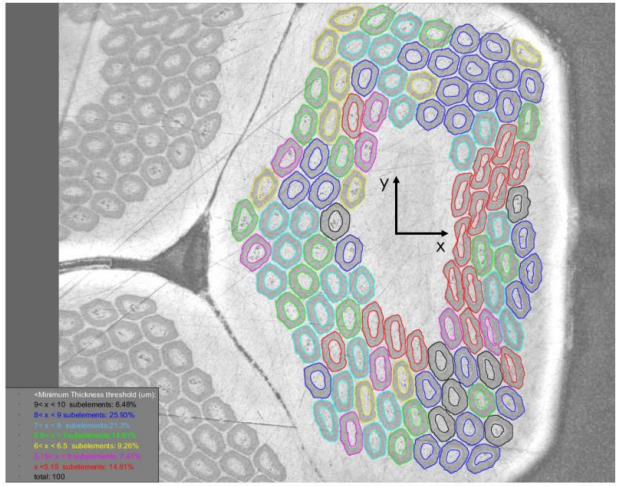
MCBXF, MQXF and 11T

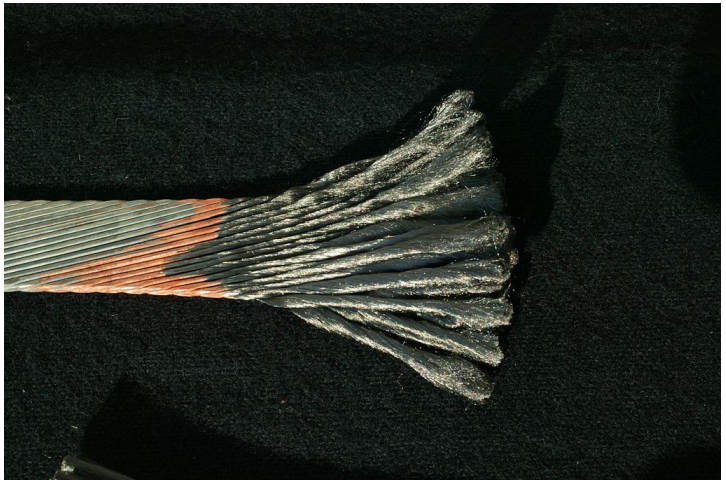
Conclusions

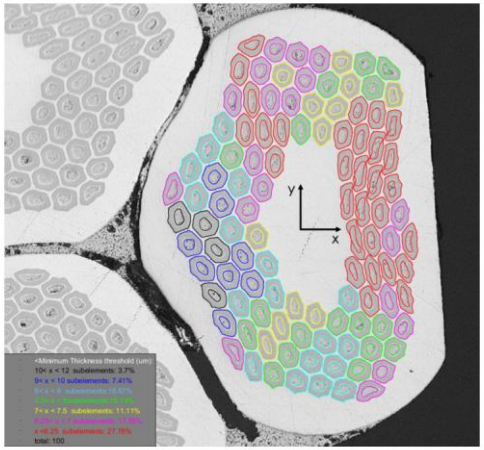
- Rutherford cables have ~50 years history
- Core technology for all high energy superconducting colliders, including LHC
- Five types of cables in HL-LHC magnets:
  - Three Nb-Ti cables (D1 and D2, MCBXF, and MQXF bus bar)
  - Two Nb_3Sn cables (MQXF and 11 T)
- The cables produced are systematically controlled according to QA plan
- All Nb-Ti and Nb_3Sn cables produced (except few cases) are conform to technical specification
- The Nb-Ti and Nb_3Sn Rutherford cable production at CERN is under control
- Production of D1, D2, MQXF bus bar and 11 T completed
- Production of MQXF (58%) and MCBXF (39%) on going planned to be completed by Q4 and Q2 2022
- Not to forget: "A Rutherford cable cannot perform better than the conductor it is made of"

THANKS FOR YOUR ATTENTION

Rutherford cables

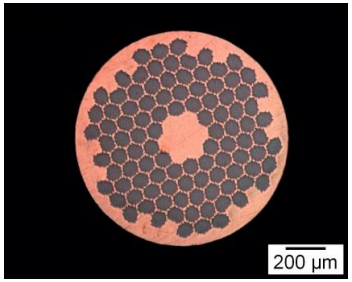


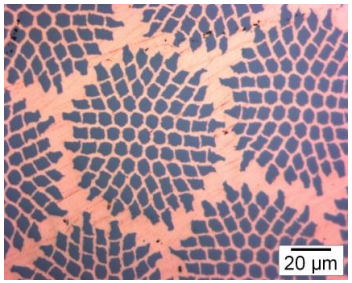


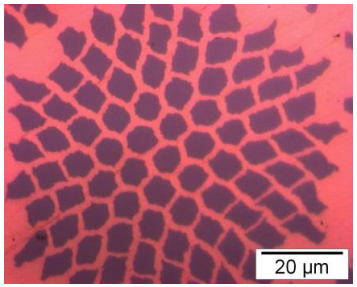


Cross section of LHC strands with NbTi filaments

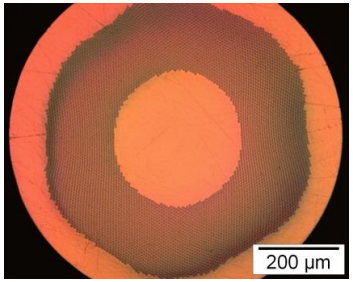
Type 01

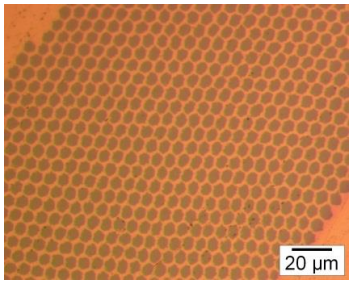


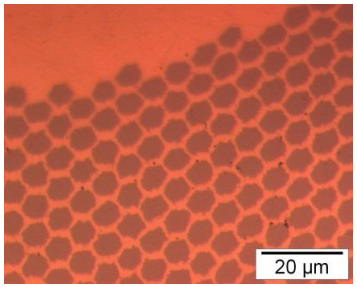




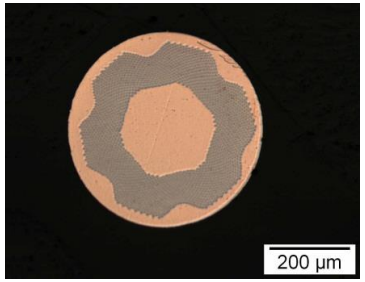
Type 02

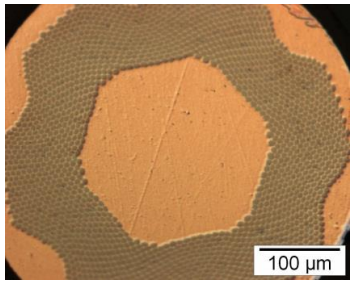


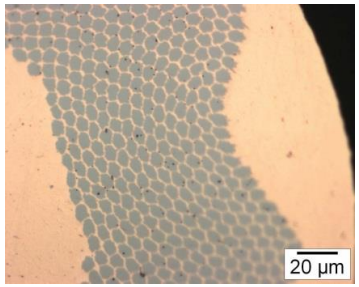




Type 04/05







NON CONFORMITIES MQXF PIT PROTO CABLES

- All PIT proto cables have a NCR related to average Ic degradation > 5%.
  - H16EC0235A: EDMS 1976468, Ic degradation of 8.0%
  - H16EC0236A: EDMS 1976604, Ic degradation of 7.3%
  - H16EC0248A EDMS 2038726, Ic degradation of 8.2%
  - H16EC0252A EDMS 2038737, Ic degradation of 9.3%
  - H16EC0253A EDMS 2068560, Ic degradation of 13.6%
- All above listed cables were accepted by WPE as concession