HFM
High Field Magnets

Nb_3Sn Conductors for HFM

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Introduction

- One of the two main objectives for the HFM programme, as identified by the update of the European Strategy for Particle Physics, is to demonstrate Nb_3Sn magnet technology for large-scale use.
- In terms of conductor development, this includes:

  1. Overcoming the current limitations linked to stress/strain sensitivity and resulting performance degradation,
  2. Pushing the Nb_3Sn performance to its ultimate limits, towards the 16 T/4.2 K target required for the FCC-hh dipoles (i.e. 1500 A/mm^2) and
  3. Driving the industrialization of improved superconductors.

- Due to challenging needs in both conductor and coil performance, requiring serious technological breakthrough, the HFM programme is divided into two sub-programmes:
  - the 12 T value-engineered (VE) dipole and
  - the 14+T dipole.

Nb_3Sn Conductor: approach for 12 T dipole

- For the conductor of 12 T VE dipole sub-programme, the approach is:

  1. Continue partnership with **Bruker OST** for **R&D** and in synergy with HL-LHC;
  2. **Procure** and **characterize strands** for HFM needs of both CERN and collaborators;
  3. **Manufacture** and **characterize cables** for HFM needs of both CERN and collaborators;
  4. To pursue efforts to qualify **additional suppliers** on top of Bruker OST for the production at **industrial** scale of wires starting with **MQXF**-type **requirements** (i.e. non-Cu $J_c \geq$ **1000 A/mm²**, 16 T and 4.2 K, technical requirements to be potentially reviewed in due time). This is of crucial importance in order to **mitigate risk** and high **cost** of **sole supplier**.

Nb_3Sn Conductor: approach for 14+T dipole

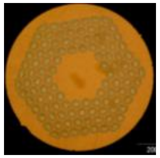
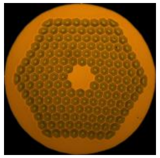
- The non-Cu J_c target for 14+ T is at least **1500 A/mm²** at 16 T/4.2 K: a **salient breakthrough** vs ~ 1100 A/mm² for current wire designs, e.g. 108/127 (MQXF).
- This target will **not** be **achievable** within **2-3 years**, therefore there is a need to select conductor based on **known designs**.
- For the **short term**, **existing** wire/cable **designs** to be used for collaborators to develop 14+ T technology (*e.g.* ***CEA to use RRP 162/169 for R2D2 HF)***.
- The idea is to **review different** strand/cable **designs** and see if one could be more promising as **14+T wire** for **medium term**. Designs RRP 162/169, 132/169, 150/169, 120/127 and 108/127 to be considered and tested for:
  - ➢ V-I stability measurements made on strands extracted from existing cables,
  - ➢ Virgin strands measured under compressive stress at UNIGE,
  - ➢ Heat treated/impregnated cable samples submitted to various levels of transverse stress and cable cross-sections examined for defects/broken sub-elements.
  - ➢ Combined study to allow selecting adequate strand/cable design.
- In parallel, continue ongoing **heat treatment optimization** of BOST wires (e.g. to optimize balance of stability, J_c and RRR) and ongoing R&D efforts to achieve **1500 A/mm²** at 16 T/4.2 K, e.g. by the **Internal Oxidation** process.

Progress update: needs of Nb_3Sn wire for HFM (1)

- Cabling machine of B103 to manufacture Rutherford cables for both CERN and collaborating institutes (CEA, CIEMAT, INFN, PSI) in coming months/years (more details on cables to be produced later on).
- Coil designs may evolve (e.g. CIEMAT) thus wire quantities as well. For 12 T, **original estimates** (based on MQXF cable for 12 T) were of ~15 km of cable needed, corresponding to about 600 km of wire. On this basis, on top of ~360 km of RRP 108/127 wire at longer term (2028), it was needed to order ASAP from BOST:
    1. 33 km of RRP 162/169, 1.1 mm,
    2. 41 km of RRP 60/91, 0.7 mm,
    3. 80 km of MQXF wire, RRP 108/127, 0.85 mm.
- However, intention of HFM Programme to **align 12 T VE dipole with FalconD**
- It is worthwhile to compare the wire/cable types used in each case (next slides):
    - RRP 162/169 at **1.0 mm** (FalconD)
    - RRP 108/127 at **0.85 mm** (MQXF)

Progress update: needs of Nb_3Sn wire for HFM (2)

- The ERMC-1 wire has a J_c higher than that of MQXF by **up to 9 %,** but poorer stability
  - J_c difference of ~2 % if heat treatment adjusted for improved stability
- In addition, it has a low Cu/non-Cu ratio of ~0.9 as compared to ~1.2
- Altogether, higher J_e by **up to ~27%**
- In terms of production maturity:
  - ➢ 21 tons of MQXF wire produced versus 2 tons for 162/169 wire
  - ➢ Production yield higher for MQXF wire
  - ➢ Recent production at BOST has shown degraded yield, I_c and RRR for 162/169, hence **40% higher cost** (by weight!)

		MQXF	FalconD
Layout		108/127	162/169
Diameter (mm)		0.85	1.0
Cu/non-Cu		1.2	0.9
at 12 T 4.3 K	J_c (A/mm^2)	2890 [a]	3160 [b] / 2950 [c]
	I_c (A)	753 [a]	1323 [b] / 1234 [c]
	J_e	Ref.	+ 27 % [b] / + 18 % [c]
Optical micrograph			

[a] 665 °C 50 h

[b] 650 °C 50 h
[c] 650 °C 30 h

	108/127	162/169
Yield	97 %	90 %
Price per kg	Ref.	+ 40 %
Mean piece length (m)	2907	1386 (1.1 mm) 2243 (1.0 mm)

Progress update: needs of Nb_3Sn wire for HFM (3)

- From **cable** point of view:
  - **>50 km** of **MQXF** cable produced at CERN vs **~0.7 km** for **FalconD**.
  - Mean **I_c degradation** due to cabling **< 3 %** for **MQXF**, cf. **> 5 %** for **FalconD** (but limited statistics).

Layout	*d* (mm)	Cable	I_c degradation (%)
108/127	0.85	MQXF	2.6 ± 1.1
162/169	1.0	FalconD	5.8 ± 0.8
		cf. eRMC	4.3 ± 1.4
	1.1	cf. R2D2 HF	3.3 ± 1.4

- Therefore, **MQXF** wire and cable designs appear to be **more standard** and **reproducible** as compared to **FalconD** wire (still under development, **riskier** choice).
- Intensive discussions held with HFM PL and TE-MSC GL and GL deputy.

Progress update: needs of Nb_3Sn wire for HFM (4)

- It was agreed to **order** from **BOST**:

Description	Quantity [km]	Quantity [kg]
1.1 mm 162/169	74	605
0.7 mm 60/91	110	397
1 mm 150/169	20	136
1.1 mm 108/127	2	17
1.0 mm 108/127	2	14
0.85 mm 180/217 scale-up	non-recurring charges and one restack (up to 60 kg)	

- This provides **strategical reserve** for **60/91** (0.7 mm) and ~2 km margin for 162/169 (1.1 mm).
- **20 km** of **150/169** (1 mm) ordered for cabling trials and **backup option** to 162/169. **162/169** and **150/169** to have an **option** to be drawn down to **1 mm** as well. **108/127** wire (1/1.1 mm) to be ordered for cabling trials as another **backup option**.
- In case both 162/169 and 150/169 options would fail, we have the possibility to use part of **108/127** (BOST amendment #7) for **HFM**.

Progress update: needs of Nb_3Sn wire for HFM (5)

- This **order** provides some **agility** with a few **backup options**.
- **Final offer** expected from BOST **imminently.**
- Last but not least, due to very high tension in Nb market, **lead-time** of **~2 years**, i.e. delivery expected **Q4 2026**.
- Therefore, **important** to give **priorities** between **various** HFM project **needs** (more details to be provided later on).

Progress update: Nb_3Sn cabling for HFM (1)

12 T VE dipole (RRP 108/127, 0.85 mm):

- 9 ULs of 200 m each already manufactured – but is it ***still relevant***?

Delivery dates

	Bare conductor **for insulation**	Actual completion date	Associated development
70 m + 1 unit	Feb 24	Dec-23	winding coil trials
1 unit	Feb 24	Dec-23	Practise coil
2 units	Jun-24	Dec-23, Apr-24	First of series AP
2 units	Jun-24	Apr-24	Mirror AP
2 units	Jan-25	May-24	Single AP Model 1
2 units	Jan-25	1 unit in May 2025	Single AP Model 2
4 units	March 25	June 25	Double AP Model 3

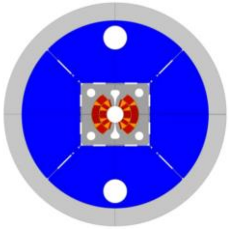
Progress update: Nb_3Sn cabling for HFM (2)

FalconD (RRP 162/169, 1.0 mm):

- Originally, FalconD cables only for **INFN Genoa** but now interest for **CERN** as well (see tables below).
- Wire for the **last two units** (140 m each) available only **end of 2026**.

Delivery dates (INFN)

	Bare conductor **for insulation**	Actual completion date
Dummy Cu cable	done acc. to INFN	Sep-22
2 units + 50 m	end April 24	Apr-24
2 units	end April 24	Apr-24
2 units	Oct-24	On time
1 unit	Oct-24	On time



Delivery dates (CERN)

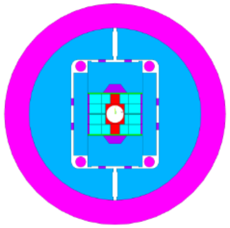
	Bare conductor **for insulation**	Actual completion date
Dummy Cu cable	Mar-25	On time
2 units (practise)	Sep-25	On time
3 units	Jan-26	On time
2 units	Jun-26	Strand available end of 2026

Progress update: Nb_3Sn cabling for HFM (3)

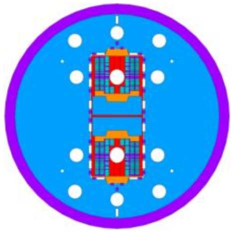
RRP 162/169, 1.1 mm:

Cable of RRP 162/169 1.1 mm wire is needed for:

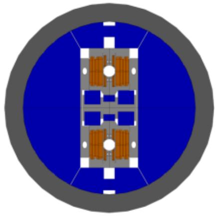
- **CEA** (R2D2, FD, F2D2) – **200 m of R2D2 HF cable** produced
  - No further need before 2nd half of 2026, TBC



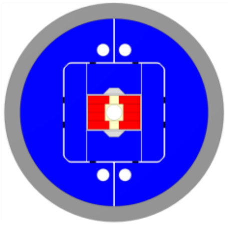
- **PSI** (14 T stress managed) – **170 m of R2D2 HF cable** produced
  - No further need before 2nd half of 2026, TBC



- **CIEMAT** (14 T common coil) – needs not yet finalised, **~15 km of strand** expected around 2nd half of 2026
  - Could wait for new strand delivery Q4 2026, TBC



- **CERN** (14 T block) – planning **8 × 180 m ULs (1440 m)** of **44-strand cable**, to be cabled at LBNL, corresponding to **~70 km of strand**.
  - The idea is to get 4 ULs of 180 m cabled at LBNL in Q1 2025 (~35 km of wire). This is defined as the **highest priority** and it will **deplete** completely the **stock** of RRP **162/169 (1.1 mm)** before the new strand delivery (Q4 2026).



Progress update: Nb_3Sn wire R&D (1)

1. R&D at BOST

- The new strand order from BOST includes an R&D billet with more sub-elements (SEs), RRP 180/217, to be produced in a larger billet (~60 kg versus ~45 kg).
- As well as a step towards up-scaling, increasing billet mass/diameter should facilitate assembly of higher count of SEs into the re-stack billet, for strand with smaller filament diameter.

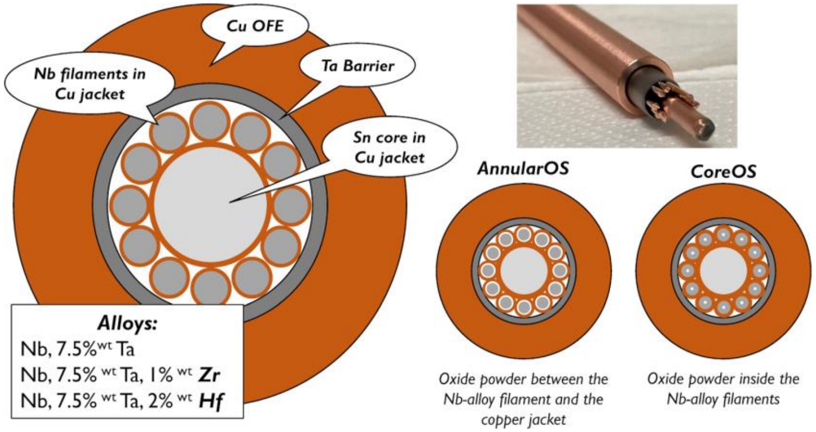
2. KEK/CERN collaboration

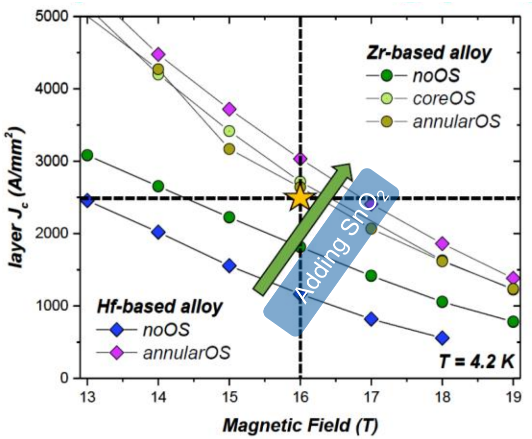
- A new collaboration agreement signed on 19/08/24 with KEK for the development of advanced Nb_3Sn wires for high-field magnets. The KoM will take place on 29-30 October 2024 in Japan.
- The scope is:
  a. To qualify a new wire supplier (JASTEC) for wire performance equivalent to that of MQXF wire (i.e. $J_c \geq 1100$ A/mm^2, 16 T and 4.2 K),
  b. Reinforcement of wire to increase mechanical strength and improve electromechanical characteristics of wire, and
  c. To further enhance J_c performance towards 1500 A/mm^2, 16 T/4.2 K.

Progress update: Nb_3Sn wire R&D (2)

3. R&D at UNIGE (Internal Oxidation)

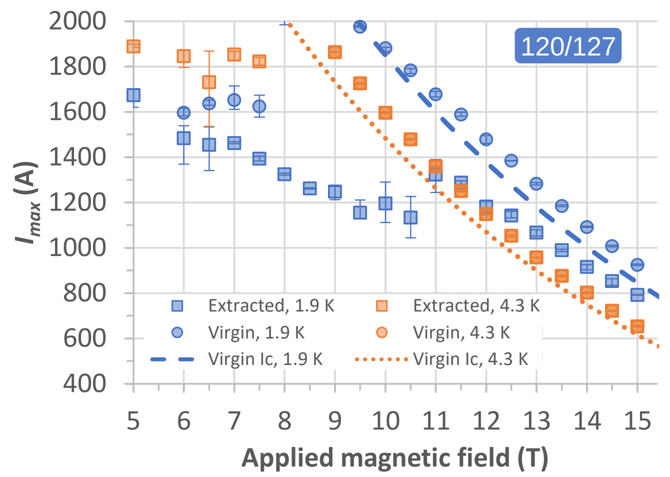
- Studies have:
  - demonstrated J_c enhancement from internal oxidation, with Zr and Hf alloying and alternative SnO_2 oxygen source locations
  - distinguished the pinning contributions of precipitates and grain refinement
- Two billets of sub-elements with alternative oxygen source layouts are currently being processed. Extrusion, drawing and restack attempts are planned to be completed by end of the year.
- Based on results, an oxygen source layout will be selected and the optimized sub-element will be designed and produced in 2025.

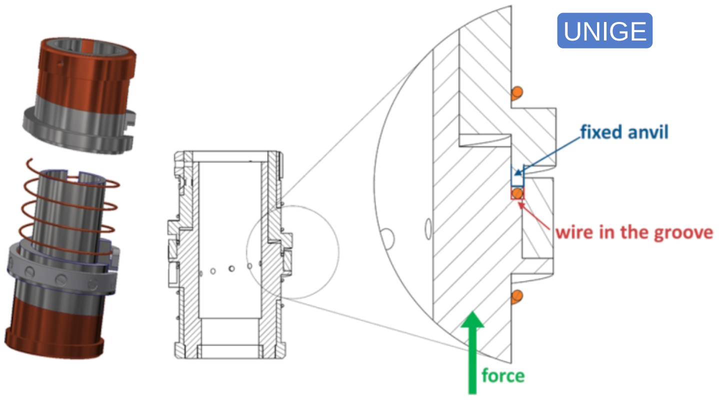




Progress update: 14+ T conductor selection

- **V-I stability measurements** on strands extracted from various strand/cable designs :
  - First measurements (1 heat treatment) completed for each wire layout
  - Second heat treatment cycle early in 2025, with additional tests to follow by end 2025
- **UNIGE** critical current measurements under transverse compressive stress on virgin **strands** on-going and expected to be completed by early 2025.
- **CERN** heat treated and impregnated **cable** samples submitted to transverse stress and cable cross-sections examined for cracks:
  - Tooling in production, due in 2025
  - Preparatory studies starting now:
    - Method development for image analysis
    - Microstructure comparison of reacted wires (without stress) vs. heat treatment
  - Initial results by end 2025.





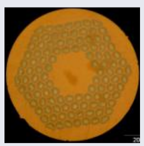
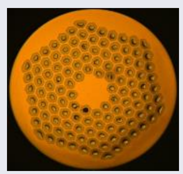
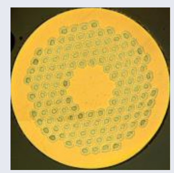
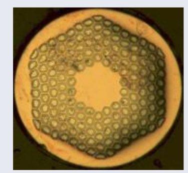
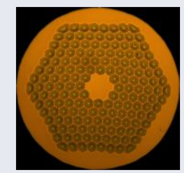
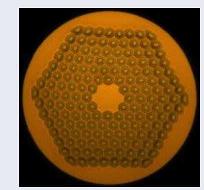
Conclusions

- The main tasks of the WP1.1 are to **procure**, **cable** and **characterize** the Nb_3Sn **strand** for both **CERN** and **Collaborators**, while further **developing** the Nb_3Sn wire towards the challenging performance **targets** of **FCC**.
- There is absolutely no problem with the Rutherford **cabling capacity** of the cabling line of B103.
- The **issue** is about the current stock of HFM strand (in particular RRP 162/169 and 60/91) and the **long lead-time** (~ ***2 years***) for wire procurement due to global **Nb market** under stringent **tension**.
- An HFM strand **order** of **~200 km** of wire will be soon placed to BOST to cope with the needs of HFM. This order will provide some **flexibility** on the **design** of the 1.1 mm strand.
- It is **very important** to communicate ASAP any **change** in the program or any **new need** for cable lengths due to mentioned long lead-time.

Spare Slides

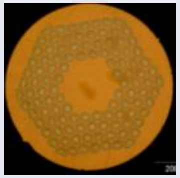
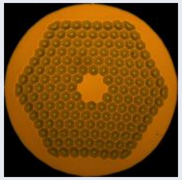
Spare slide: RRP® Strand Characteristics

- BOST (NJ, USA) can produce Nb_3Sn wire by RRP® (Restacked Rod Process) with different designs.
- Various designs of interest are given, showing the various important parameters, in the following table.

	Comparisons				HFM	
	MQXF	ERMC#101	FRESCA 2	ERMC#102	ERMC-1	DEM-1.1
						
***d* (mm)**	**0.85**	**1.0**	**1.0**	**1.0**	**1.0**	**1.1**
Layout	**108/127**	**120/127**	**132/169**	**150/169**	**162/169**	**162/169**
d_s (µm)	54	64	58	57	58	64
Cu/non-Cu	1.2 ± 0.1	1.06 ± 0.1	1.25 ± 0.1	1.08 ± 0.1	0.9 ± 0.2	
Nb:Sn	3.6 (red. Sn)	M-grade	3.4 (std. Sn)	3.6 (red. Sn)	3.4 (std. Sn)	
Ref. HT	665 °C 50 h	665 °C 50 h	650 °C 50 h	665 °C 50 h	650 °C 50 h	665 °C 50 h

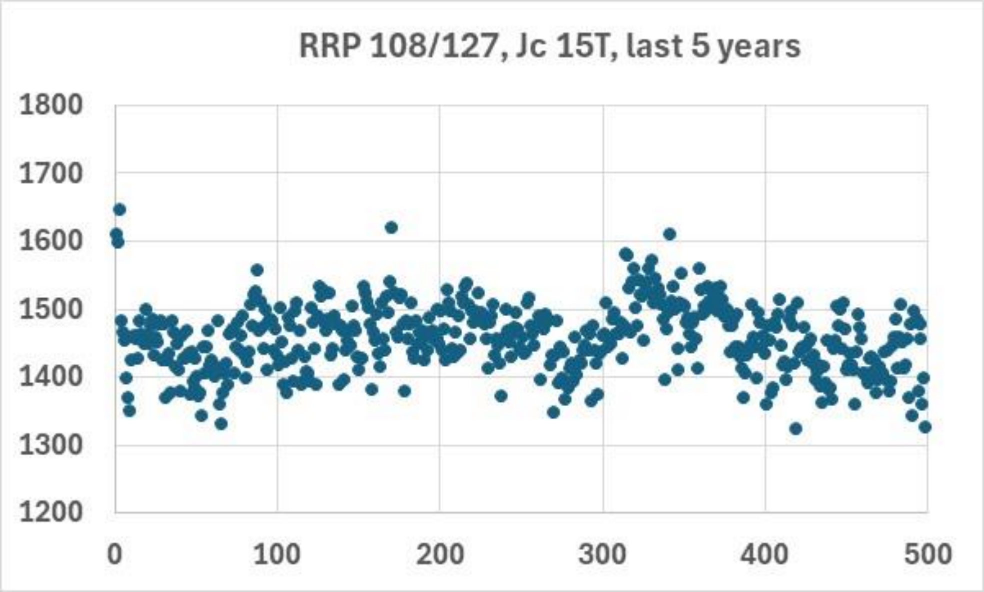
Spare slide: Wire Characteristics and Specification

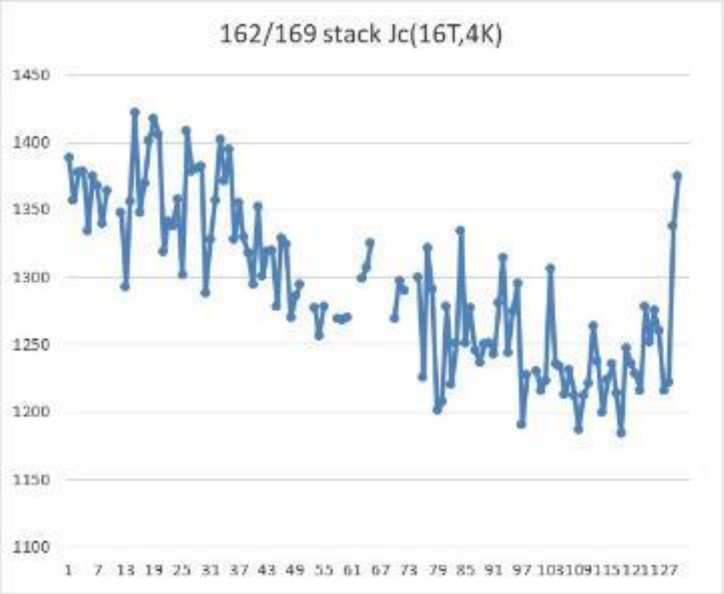
- The wire designs and the technical specification, for both RRP 108/127 (MQXFB) and RRP 162/169 (FalconD), can be found in the tables below.

		MQXF	FalconD
			
d (mm)		0.850 ± 0.003	1.000 ± 0.003
Layout		108/127	162/169
d_s (µm)		< 55	< 60
Cu/non-Cu		1.2 ± 0.1	0.9 ± 0.2
Nb:Sn		3.6 (red. Sn)	3.4 (std. Sn)
Heat treat.		665 °C 50 h	650 °C 50 h
I_c (A)	4.22 K, 12.0 T	> 590	
	4.22 K, 15.0 T	> 331	> 508
	4.22 K, 16.0 T		> 395
n-value		> 30	> 30
RRR	Round	> 150	> 150
	Rolled	> 100	> 100

Spare slide: Wire performance variability

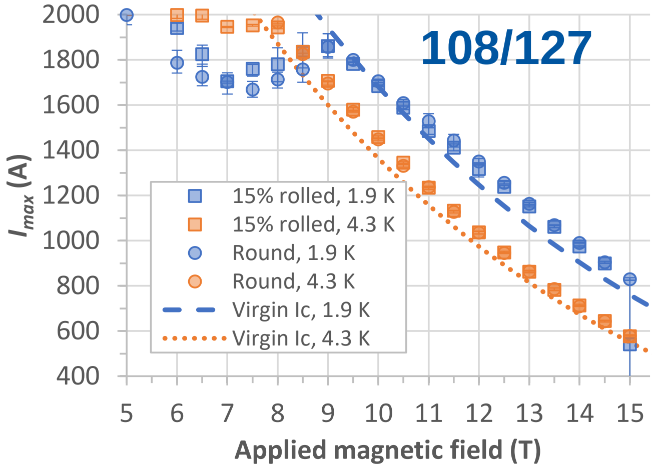
- For RRP **108/127** wire, J_c is stable over production
- For RRP **162/169,** J_c was up to 9% **higher** than 108/127 early in production (CERN procurement), but over time, a **decrease** in J_c of **several %** was observed at BOST (see graph at bottom right):

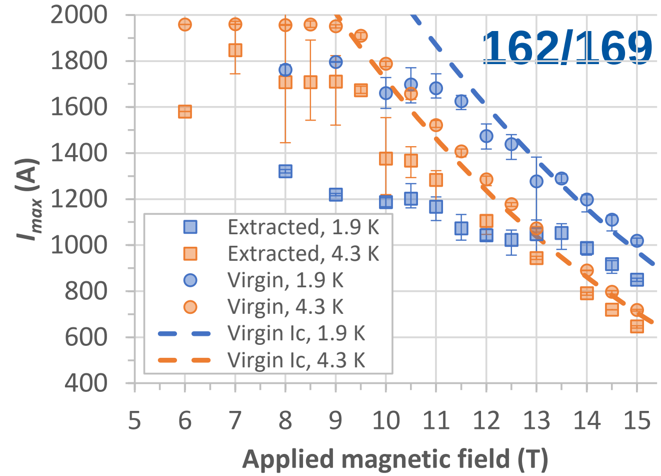




No explanation was found so far

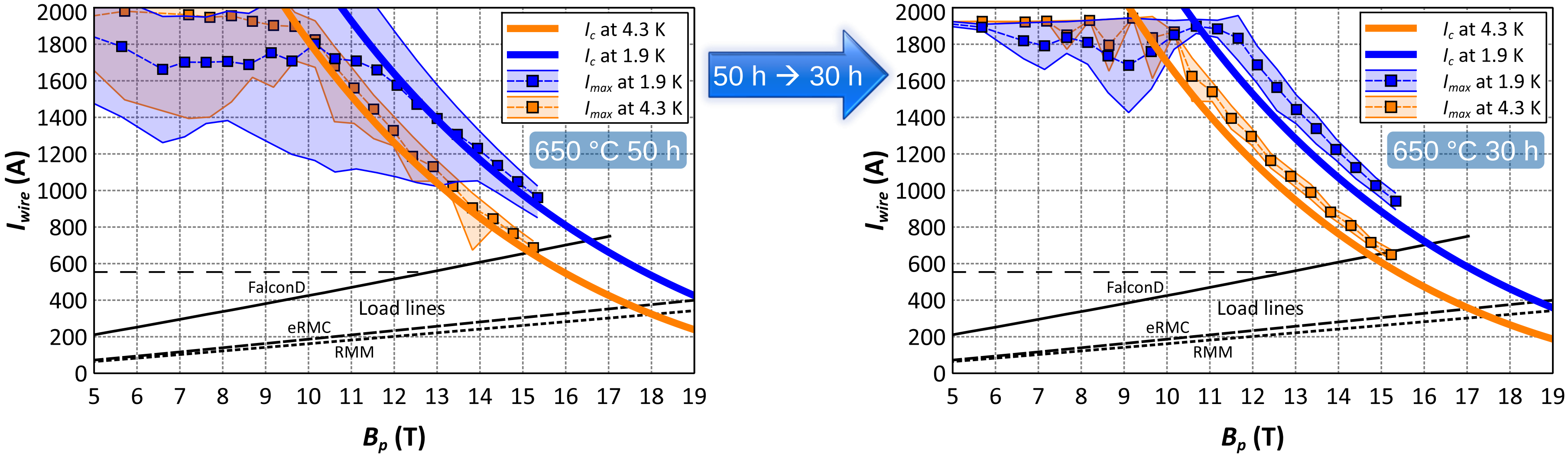
Spare slide: Magneto-thermal stability 108/127 vs. 162/169 at 1 mm





- At 1.0 mm diameter:
  - 108/127 (Cu/non-Cu ~1.2):
    - **no stability limitation** at **4.3 K** (similar to 0.85 mm)
    - at **1.9 K**, limitations at **9 T and below** only, quench current > 1600 A
  - 162/169 (Cu/non-Cu ~0.9):
    - premature quenches significantly below I_c
    - significant variability between samples, see full reports:
      - 1.0 mm FalconD: EDMS 3064867, 1.1 mm R2D2: EDMS 3064865

Spare slide: Magneto-thermal stability 162/169 1.0 mm with heat treatment optimisation



- Significant variability between samples (coloured bands), but…
- Reducing heat treatment duration significantly improves stability at the expensive of ~5 % in I_c

	I_c (B_p=12.5 T, 4.3 K)		RRR	
	I_c (A)	Δ (%)	RRR	Δ (%)
665 °C 50 h	1243	+ 3.5 %	108	- 33.8 %
650 °C 50 h	1189	(ref.)	205	(ref.)
650 °C 30 h	1136	- 5.1 %	324	+ 21.4 %

Spare slide: Cable comparison (1)

- Both **MQXF** and **FalconD** cables are made of **40 strands** (see more details in the table below).
- Between 2019 and 2024, CERN fabricated **53 MQXFB series** ULs for HL-LHC use **(~760 m** each); this represents altogether more than **40 km**.
- This needs to be compared to **FalconD** for which only **7 cable lengths** have been produced for HFM use: three short lengths (10, 30 and 60 m) and 4 lengths of 150 m each), altogether around **700 m** only.

Type	Strands × diameter (mm)	Width (mm)	Mid-thickness (mm)	Pitch (mm)	Keystone	Core
MQXF	40 × 0.85	18.15	1.525	109	0.4 °	1.4404 SS, 12×0.025 mm
FRESCA 2	40 × 1.0	20.95	1.82	120	None	None
ERMC	40 × 1.0	20.95	1.82	120	None	1.4404 SS, 14×0.025 mm
FalconD	40 × 1.0	20.95	1.800	110-120	0.5 °	
R2D2 HF	21 × 1.1	12.579	1.969	84	None	None

Spare slide: Cable comparison (2)

- All cable geometrical parameters for the **53 MQXF cable lengths** produced to date were well within specification and under tight control.
- For FalconD, geometrical parameters well within specification but quite low statistics.
- For **MQXFB**, **moderate I_c degradation** at 4.2 K and 12 T due to cabling in **1.3-3.7%** range, well below the 5% specification limit. Wires extracted from MQXFB cables show **very high RRR** values: **291** as averaged over 48 series ULs (minimum value measured: 244).
- For **FalconD**, much **less statistics** (single cable so far tested), typical I_c **degradation of 5-7%**, higher than for MQXFB cable and borderline, and **RRR for extracted** strand around **206** in average (**lower** as well than MQXFB).

Spare slide: HFM cables already produced

Cable type	Description	Cable reference	Cable length [m]	Unit length	Production completed date
R2D2 HF	21x1.1 mm (DEM1.1, RRP 162/169)	C02OC0442A	200	R2D2 coil v1+v2, HF	16/05/2023
R2D2 HF	21x1.1 mm (DEM1.1, RRP 162/169)	C02OC0442B	220	Not known yet	16/05/2023
R2D2 LF	34x0.7 mm (DEM0.7, RRP 60/91)	C03OC0448A	410	R2D2 coil v1+v2, LF	27/06/2023
12 T VE short	MQXF-type cable, 40x0.85 mm	C05OC0459A	200	UL1, Practise coil	18/12/2023
12 T VE short	MQXF-type cable, 40x0.85 mm	C05OC0459A	200	UL2, First of series AP 1/2	18/12/2023
12 T VE short	MQXF-type cable, 40x0.85 mm	C05OC0459A	100	winding coil trials	18/12/2023
12 T VE short	MQXF-type cable, 40x0.85 mm	C05OC0459B	104	winding coil trials	19/12/2023
Falcon D	40x1.0 mm, copper wire	C01UC0424A	155	Dummy copper cable	28/09/2022
Falcon D	40x1.0 mm, copper wire	C01UC0424B	100	Dummy copper cable	28/09/2022
Falcon D	40x1.0 mm (ERMC1.0, RRP 162/169)	C01OC0466E	53	Additional length	15/04/2024
Falcon D	40x1.0 mm (ERMC1.0, RRP 162/169)	C01OC0466A	152	UL1	15/04/2024
Falcon D	40x1.0 mm (ERMC1.0, RRP 162/169)	C01OC0466B	152	UL2	15/04/2024
Falcon D	40x1.0 mm (ERMC1.0, RRP 162/169)	C01OC0466C	152	UL3	15/04/2024
Falcon D	40x1.0 mm (ERMC1.0, RRP 162/169)	C01OC0466D	152	UL4	15/04/2024
12 T VE short	MQXF-type cable, 40x0.85 mm	C05OC0467A	200	UL3, First of series AP 2/2	25/04/2024
12 T VE short	MQXF-type cable, 40x0.85 mm	C05OC0467A	200	UL4, Mirror AP 1/2	25/04/2024
12 T VE short	MQXF-type cable, 40x0.85 mm	C05OC0467A	200	UL5, Mirror AP 2/2	25/04/2024
12 T VE short	MQXF-type cable, 40x0.85 mm	C05OC0468A	200	Single AP Model 1 (1/2)	06/05/2024
12 T VE short	MQXF-type cable, 40x0.85 mm	C05OC0468A	200	Single AP Model 1 (2/2)	06/05/2024
12 T VE short	MQXF-type cable, 40x0.85 mm	C05OC0468A	200	Single AP Model 2 (1/2)	06/05/2024

Spare slide: HFM strand current stock

Strand type	Design	Diameter (mm)	Stock (km)*
ERMC-1	162/169	1.0	60.4
DEM-1.1	162/169	1.1	36.1
DEM-0.7	60/91	0.7	14.5
ERMC-0.7	78/91	0.7	41.0

* on 18/09/2024, in piece lengths exceeding 150 m