Report of the LARP/HL-LHC International Review of the Superconducting Cables for the HL-LHC Inner Triplet Quadrupoles (MQXF)

International Review Committee:

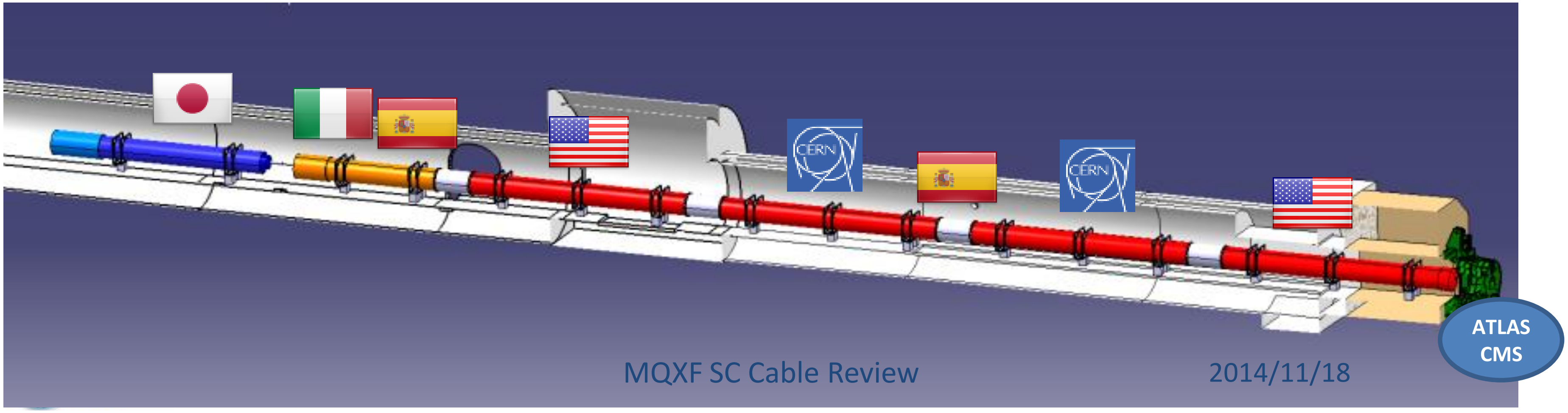
Arnaud Devred (Chair: ITER-IO), Herman ten Kat (CERN)
David Larbalestier (NHMFL), Bruce Strauss (DOE)
Akira Yamamoto (KEK)

held at CERN, 5 – 6 November, 2014

Courtesy: G. Ambrosio

MQXF Main Parameters

- 140 T/m in 150 mm coil aperture
- Q1/Q3 length: 8 m
- Q2 length: 6.8 m
- Max outer diameter: 630 mm
- 1.9 K operating temperature
- Radiation strength: > 33 MGy
- Field quality: see WP3 page at *https://espace.cern.ch/HiLumi/WP3/SitePages/Home.aspx*

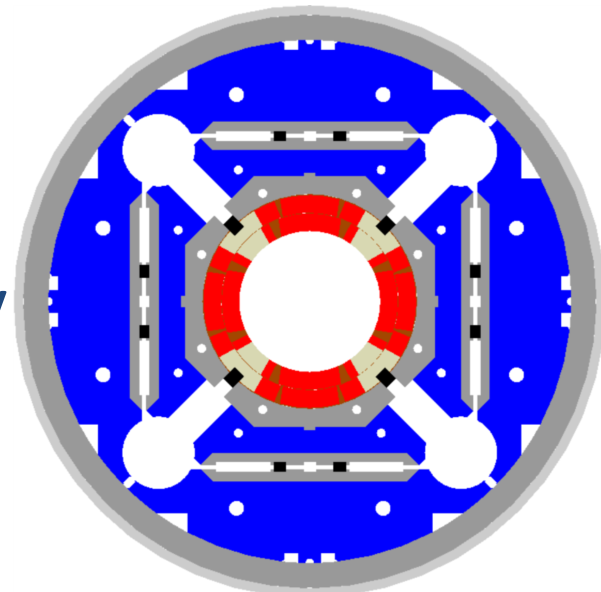


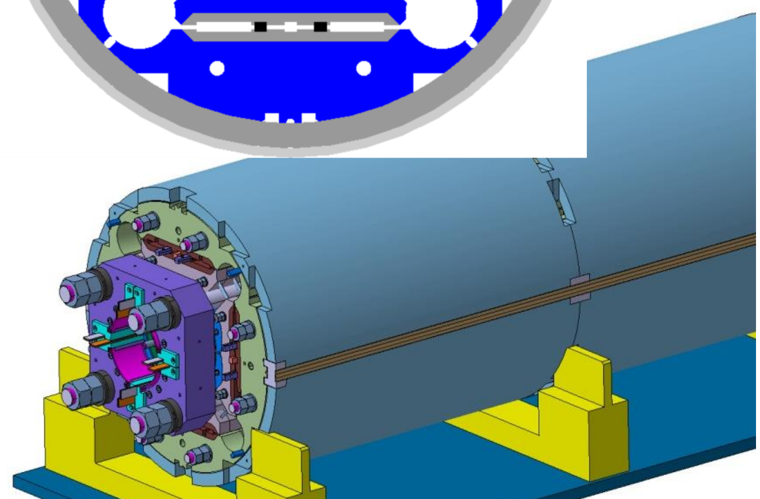
Courtesy: G. Ambrosio

MQXF Main Design Features

Same design for Q1/Q3 and Q2s:

- Two-layer coils
  - Without internal splice
  - With one wedge per layer
- Al shell structure preloaded by bladders and keys
  - Segmented Al shell
- Axial preload by tie-rods
- Quench protection by active heaters
  – and possibly CLIQ





P. Ferracin, *et al.*, “Magnet design of the 150 mm aperture low-β quadrupoles for the high luminosity LHC,” *IEEE Trans. Appl. Supercond.*, vol. 24, no. 3, p. 4002306, Jun. 2014

Courtesy: G. Ambrosio

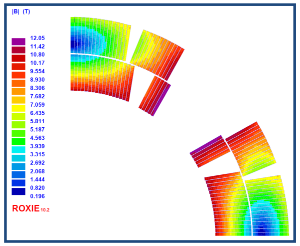
Baseline Conductor

STRAND

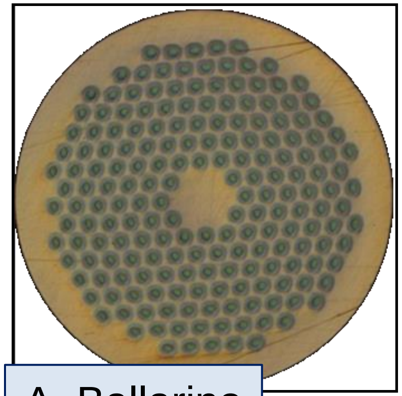
- **0.85 mm** strand
- Filament size **<50 µm**
- Cu/Sc: **1.2 ± 0.1** → 55% Cu
- Critical current at 4.2 K and 15 T
  - **361 A** at 15 T (632 A at 12 T)

CABLE

- **40**-strand cable
- Mid thickness: **1.525 mm**
- Width: **18.150 mm**
- Keystone angle: **0.55 deg.**
- SS core **12 mm** wide and **25 µm** thick

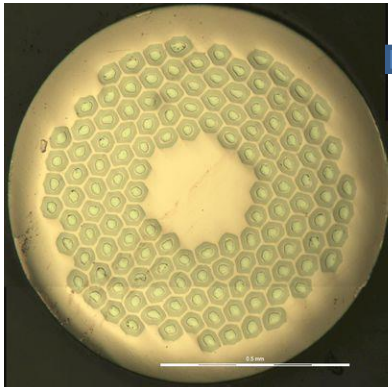


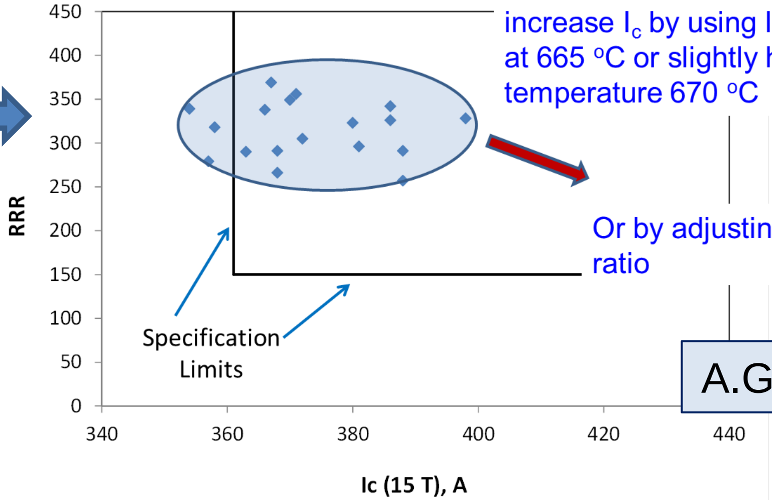
Bruker PIT strand, 192



A. Ballarino

OST RRP strand, 132/169

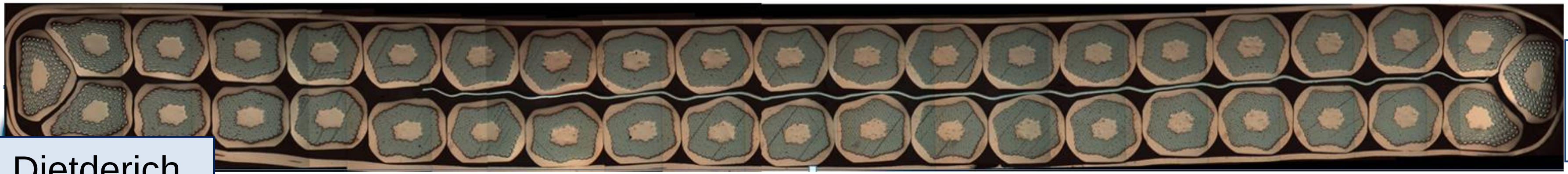




There is headroom in RRR to increase I_c by using longer times at 665 °C or slightly higher temperature 670 °C

Or by adjusting the Nb/Sn ratio

A.Ghosh



RRP cable

D. Dietderich

Courtesy: G. Ambrosio

Recent & Upcoming Reviews

- HL-LHC-LARP International Review of MQXF Cable:

(CERN November 5-6, 2014)

- I_c target not completely reached, try increasing margin (longer magnets)
- Relate conductor requirements to magnet performance
- Reduce keystone angle of PIT cable, consider it for RRP cable
- Keep two/multiple vendors and increase support if one is late

- HL-LHC-LARP International Review of the Inner Triplets Quadrupole (MQXF) Magnet Design

(CERN, December 10-12, 2014)

We plan to discuss recommendation about margin at this review, and then address the comments and recommendations of both reviews

International Review of the Superconducting Cables for the HL-LHC Inner Triplet Quadrupoles (MQXF)

Objectives:

- The replacement of the present inner triplet (IT) quadrupole magnets by new quadrupoles (MQXF),
  - featuring much larger aperture and higher peak field, is the cornerstone of the upgrade plan.
- The SC cable is the most critical component with the longest design, validation and procurement time for SC magnets.
  - This characteristic is even more accentuated with a complex conductor such as Nb_3Sn used in the MQXFs.
- This Review will assess the project preparedness on the front of the SC cable.

Reports given (5 Nov.)

Welcome	L. Rossi
MQXF goals and plan	G. Ambrosio
MQXF design and conductor requirements	P. Ferracin
Mechanical stability and QXF coil winding	P. Feraracin et al.
Conductor technical specification	A. Ballarino et al.
MQXF RRP-strand for Q1/Q3	A. Ghosh
MQXF RRP-strand for Q2	B. Bordini
MQXF cable for Q1/Q3	D. Dietderich
MQXF cable for Q2	Luc Oberli
Lesson learnt from LARP experience	A. Ghosh et al.
US-HiLumi conductor procurement	A. Ghosh
Hilumi conductor procurement	A. Ballrino

Reports given (6 Nov.)

QA/QC plans for Q2 strand	B. Bordini
QA/QC plans for Q2 cable	C. Scheuerlein
QA/QC plans for Q1/Q3 conductor	I. Pong

Charges given to the Committee

1. *Are the Functional or Technical Specification for conductor strand and cable adequate to the scope of the MQXF ? Are they sufficiently developed and reasonably finalized?*

2. *Does the design of strand and cable meet the specifications in terms of minimum Ic, maximum allowed degradation, minimum RRR, maximum* D_{eff}*, stability request, cable size, and unit length ?*

Charges given to the Committee (2)

3. *Assess the likelihood of meeting – with adequate margin – the chosen specifications and requirements based on the decade long experience acquired by LARP in cables and magnet construction and the most recent experience in Europe.*

4. *Is the plan for two types of strand architecture (RRP and PIT) correctly managed inside the program?*

5. *Is the procurement schedule, with associated QA and test plan, credible and adequate for the prototyping phase (where applicable) and for the construction phase?*

Executive Summary (1)

- This is a critical and important project, which provides the unique opportunity to make high-performance, space-effective accelerator magnets using Nb_3Sn conductors and to implement them in a real working accelerator.
  - This significant milestone will open up the route to much higher energy accelerators than the LHC using for the first time superconductors beyond Nb-Ti in its main magnets.
- This project is handled by an enthusiastic transatlantic team bringing a new generation of magnet engineers into the field.
  - There is good communication between the Hi-Lumi and LARP teams, in particular on the magnet side; conductor activities could benefit from strengthened interactions.

Executive Summary (2)

- There has been great progress recently, both on understanding the issues limiting magnet performance and in the industrialization of high-performance Nb_3Sn wire manufacture and cabling.

- The project is confronted with a crucial transition, to become a real and construction project including the professional management needed,
  - after 16 years of R&D effort in the US and 10 years of R&D effort in the EU

Executive Sumarry (3)

- It remains a great challenge, but the committee is confident that, MQXF completion can be achieved.
  - with proper resources, strengthened focus and continuous synergy between the LARP and Hi-Lumi efforts

Status and Scope (1)

- The design goals need to be conservative
  - because Nb_3Sn accelerator magnet technology is still experimental, and impregnated Nb_3Sn coils operated at 1.9 K are prone to self-field instabilities.
- It is noted that, though significant progress has been reported, after more than 20 years of making various model magnets at a few laboratories, still the production technology is not sufficiently mature
  - and a realistic full-size Nb_3Sn based accelerator magnet with a practical bore achieving 11-12 tesla level within 1 to 3 training steps is not yet existing. The team is encouraged to engage in full and push forward the frontier.
- Therefore, the committee unanimously and strongly recommends in this particular case, and in this phase of the project, maximizing the operating margin of the superconductor by all means possible,
  - such as lowering the nominal gradient, increasing the magnet length in an appropriate balance of the magnet reliability with achievable integrated luminosity, revisiting the Cu-to-non-Cu ratio, and so on.

Status and Scope (2)

- Development is necessary of an integrated qualification plan,
  - from virgin and extracted strand tests, to local and full-size cable tests, to magnet model and prototype tests to validate conductor and magnet designs and to assess operating margins; the qualification tests should be the same for both LARP and Hi-Lumi.
- Use of the model and prototype phase for finalizing the wire and cable specifications is essential for project success,
  - including development of clear criteria for acceptance tests on strands and cables.
- It is crucial and today critical, for this project and beyond, to keep at least two strand suppliers.
  - If one supplier shows less maturity in their wire production, more resources shall be allocated to foster its development or industrialization.

Status and Plan (3)

- In view of earlier comments and the requirement to deliver within LARP and Hi-Lumi many full-size production magnets within less than 8 years, the schedule is very challenging.
  - To limit schedule risks and to allow corrective actions in an efficient and cost-efficient way, clearly defined decision points between the phases of the R&D model, the first prototype and construction programs shall be developed in the USA and at CERN.
- It is vital to clearly identify risks, such as failure of a wire supplier or cabling machine,
  - so as to enable realistic risk mitigation measures, such as transfer of wire procurement to the other supplier, or arranging a back-up cabling machine.
- Since the project apparently shows a significant risk for serious delay in wire procurement and coil manufacturing because of the volume of wire orders and number of coils to be made; also a plan B covering the case of partial completion has to be addressed
  - in the case goals of magnet production are not met on time for installation in the tunnel.

Technical Specifications

- The specification are not complete at this time:
  - The relationship of superconductor properties to magnet performance has not been clearly defined, making a realistic definition of the margin for the magnet unclear.

  - In particular, magnet design criteria have been extrapolated from those used in the case of Nb–Ti accelerator magnets, where other factors come into play in limiting the performance of Nb_3Sn magnets at 1.9 K. The new constraints of Nb_3Sn in magnets need to be much better understood and a more pragmatic and suitable operating margin defined that would include: cabling degradation, self-field instabilities, stress degradation, and so on.

  - The database of already tested short magnet models and long prototypes can be used as a reference.

Technical Specification (2)

- A requirement on strand cleanliness and surface conditions during transport, cabling and temporary storage, especially for bare OFHC copper strands that are prone to difficult to control oxidation effects, is required. This may have consequences for finding predictable electrical properties between strands and resin wetting and binding quality during impregnation.

- A variety of other issues need addressing:
  - Clarification of the scheme for approval of unit lengths originating from certain billets. Excessive number of breakages during the processing of a billet may be a sign of hidden defects or insufficient homogeneity which cannot be discovered when unit length approval is not referred to billets.
  - The present are the technical specifications of the conductor, all of which are challenging and ones not yet being met in production strands:
    - strand I_c: 361 A at 4.2 K and 15 T;
    - RRR: 150 on virgin strand/100 on extracted strand.
- The allowable values of R_a and R_c in the cables need to be addressed.

RRP Nb3Sn Wires

- It is recommended to go ahead with the 132/169 and lower Sn content layout as proposed by OST.
  - A final decision on strand layout can be made in one year for the series production contract (back up being the 108/127 layout).
- Seriously consider the proposal to reduce cable keystone angle from 0.55° to 0.40° in view of the effort to increase margin and reduce risk, however, the committee does not consider it as a show stopper if for good schedule and procurement reasons the LARP part of the project decides to stay with 0.55°.
- A parallel effort to continue optimization of heat treatment is recommended.

PIT Mb3Sn Wires

- In view of the crucial 2-supplyer policy at CERN that is essential for this project and beyond, the panel highly recommends a substantive support program for the PIT wire to further optimize strand properties and establish performance baseline for series production.
- In the meantime, CERN should go ahead with RRP strands and cabling for its model magnet production and should optimize phasing of strand and cable deliveries between RRP and PIT in order to create maximum flexibility for using the best possible PIT wire and coping with delivery delays.
- In support of the above, define a clear timeline for the decision making process regarding PIT wire development and production.
- Reducing the cable keystone angle in the PIT based cables from 0.55° to 0.40° is a must in order to avoid unnecessary performance risk.

Quality Assurance and Control

- A convincing QA/QC plan and inspections procedures in writing must be finalized during the upcoming model and prototype phase. It shall be reviewed before launching of wire and cables series production contracts.
- ITER experience has shown that the emphasis has to be on benchmarking and cross-checking of the suppliers' acceptance tests, which enable a faster feedback on production. The level of verification measurements at reference laboratories can be phased in time.
- It is recommended to split the series productions in several phases to enable establishment of control limits of statistical process control (SPC).

Quality Assurance and Control (2)

- Promote the development of in-line video quality control of cable, in particular at the thin edge to see out of range local strand damage, as this presently is the only technique that will enable 100% inspection of the cable unit lengths.
- Better identify qualification tests and series production tests.
- Better integrate the QC plan on virgin wires, extracted strands, local measurements and full-size cable tests to ensure consistency and suitable monitoring of wire and cable productions.
- For series productions: all acceptance tests should have clear criteria. The acceptance test requirements and criteria should be identical for both LARP and Hi-Lumi.

Conclusions (1/3)

Response to the Charges/Questions

1. Are the Functional or Technical Specification for conductor strand and cable adequate to the scope of the MQXF ?

- Incomplete; see comments and recommendations here above.

Are they sufficiently developed and reasonably finalized?

- Incomplete; see comments and recommendations given above.

2. Does the design of strand and cable meet the specifications in terms of minimum Ic, maximum allowed degradation, minimum RRR, maximum D_{eff}, stability request, cable size, and unit length ?

- I_C and minimum RRR have to be revisited.
- D_{eff} is not critical around 50 mm.

Conclusions (2/3)

3. *Assess the likelihood of meeting – with adequate margin – the chosen specifications and requirements based on the decade long experience acquired by LARP in cables and magnet construction and the most recent experience in Europe.*
   – Very optimistic, needs more optimization including the balance of long-term magnet reliable operation with integrated luminosity.

Conclusions (3/3)

4. Is the plan for two types of strand architecture (RRP and PIT) correctly managed inside the program?

- PIT needs more support to accelerate since having two suppliers is crucial.

5. Is the procurement schedule, with associated QA and test plan, credible and adequate for the prototyping phase (where applicable) and for the construction phase?

- No yet; need to better articulate the different project phases (construction phase) and the decision points.

Acknowledgments

- We would thank all members those who have been involved to prepare for and to organize the review, and

- Wish the successful the magnet review in December.

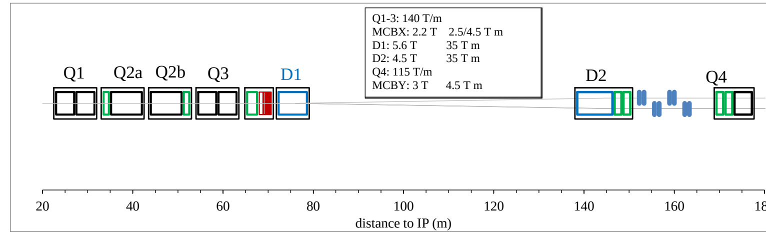
backup

Overview of MQXF design

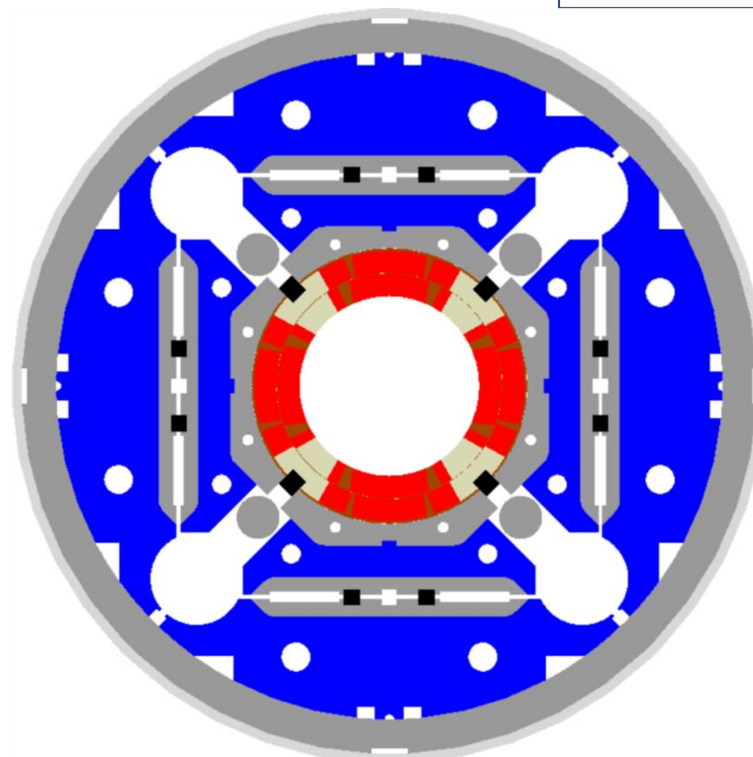
- Target: 140 T/m in 150 mm coil aperture
- To be installed in 2023 (*LS3*)

- Q1/Q3 (by US LARP collaboration)
  - 2 magnets with 4.0 m of magnetic length within 1 cold mass
- Q2 (by CERN)
  - 1 magnet of 6.8 m within 1 cold mass, including MCBX (1.2 m)

- Baseline: different lengths, same design
  - Identical short model magnets SQXF



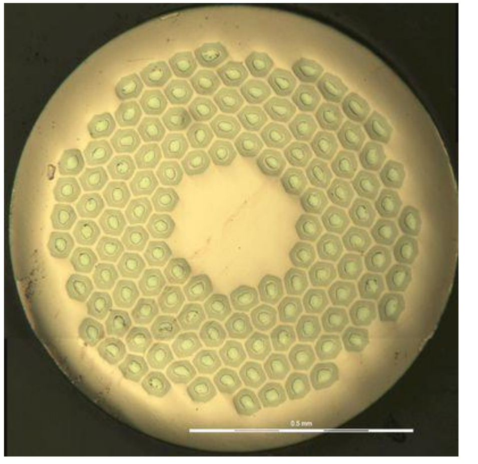
by E. Todesco



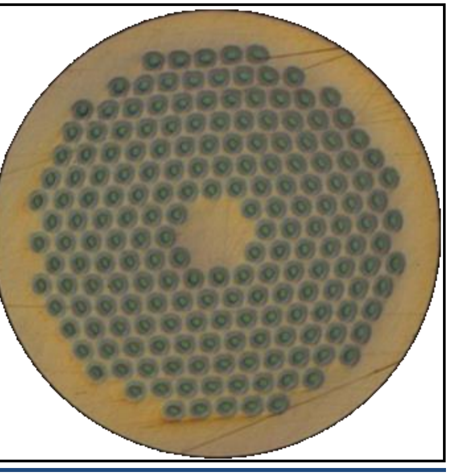
MQXF strand (from CERN technical specification document)

- **0.85 mm** strand
- Filament size **<50 μm**
  - OST 132/169: 48-50 μm
  - Bruker PIT 192: 42 μm
- Cu/Sc: **1.2 ± 0.1** → 55% Cu
- Critical current at 4.2 K and 15 T
  - **361 A** at 15 T

OST RRP strand, 132/169



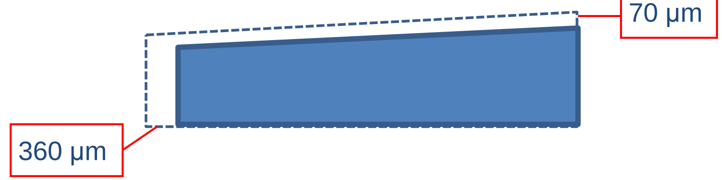
Bruker PIT strand, 192

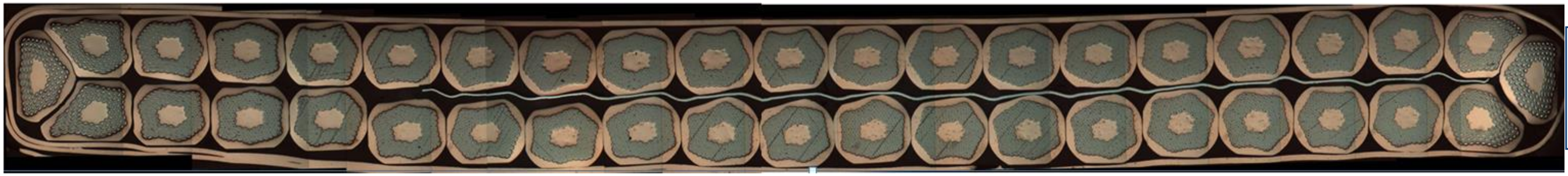


MQXF baseline cable

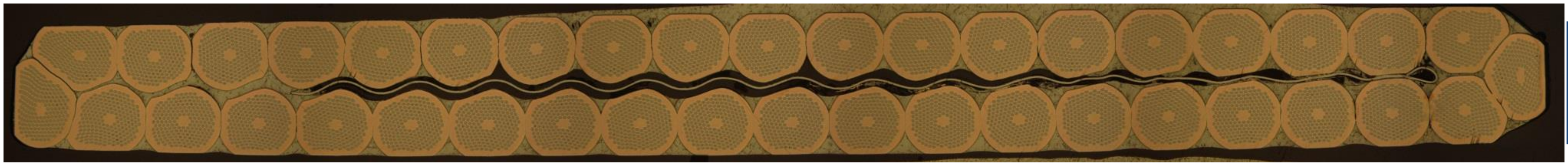
- 40-strand cable
- Mid – thickness after cabling
  - 1.525 +/- 0.010 mm
  - Thin/thick edge: 1.438 /1.612 mm
- Width after cabling
  - 18.150 +/- 0.050 mm
- Keystone angle
  - 0.55 +/- 0.10 deg.
- Pitch length
  - 109 mm
- SS core 12 mm wide and 25 μm thick

- Assumed expansion during reaction
  - 4.5% in thickness: ~70 μm, <u>same keystone angle</u>
  - 2% in width: ~360 μm
- Mid – thickness after reaction
  - 1.594 mm
  - Thin/thick edge: 1.505/1.682 mm
- Width after reaction
  - 18.513 mm





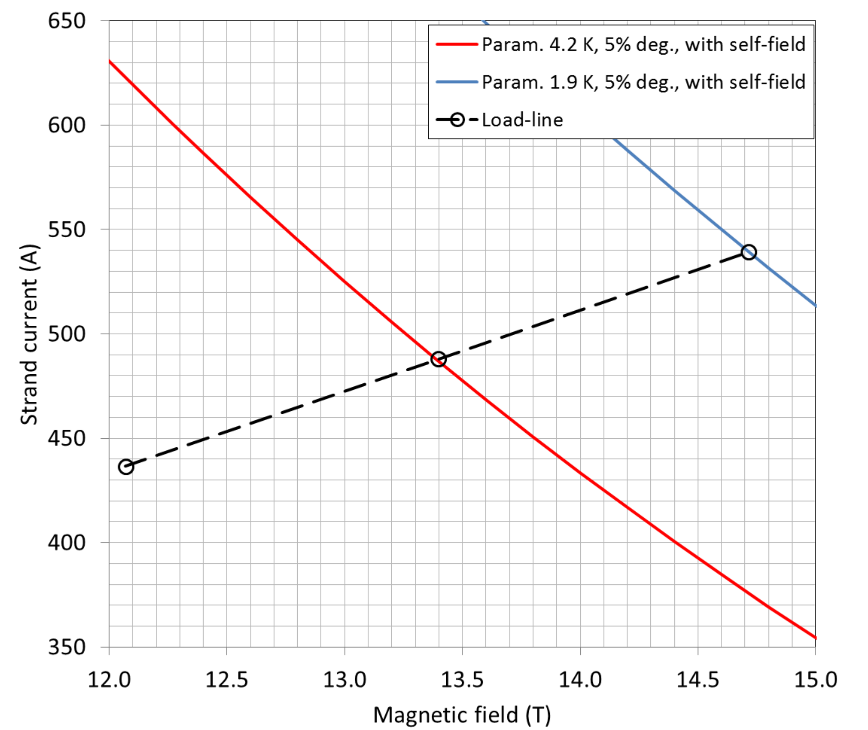
RRP cable



PIT cable

Magnet parameters

- Self field corr. (ITER barrel)
  - 0.429 T/kA
- 5% cabling degradation
- Operational grad.: 140 T/m
  - I_{op}: 17.5 kA
  - B_{peak_op}: 12.1 T
    - 80-81% of I_{ss} at 1.9 K
    - G_{ss}: 171 T/m
    - I_{ss}: 21.6 kA
    - B_{peak_ss}: 14.7 T



- Stored energy: 1.3 MJ/m
- Inductance: 8.2 mH/m

- Impact of higher I_{max} strand
  – +10% increase in critical current → about +3% in I_{ss}

Magnet parameters

- Temperature margin (K)
- Peak field (T)