WP 4.3 - Insulation materials for HFM magnet coils and conductors

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Strategy for HFM electrical insulation systems

- The objective is to propose a novel electrical insulation system to enhance HFM **performance** and **reliability**
- Currently the activities are mainly addressed to requirements and specifications of Nb3Sn magnets type cosΘ (i.e. 12T VE magnet) and block (i.e. 14T magnet).

R&D

Definition of requirements and specifications

MATERIALS

- Impregnation systems (e.g. epoxy)
- Fibers (e.g. glass, ceramic)
- Binder

PROCESSES

- Optimization of impregnation process parameters
- Fiber sizing and de-sizing

FUNDAMENTALS

- Impact of radiation sources and radiation environmental conditions
- Adhesion epoxy vs. coil parts

Implementation

Mock-ups and manufacturing studies

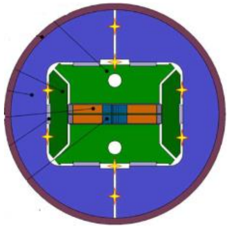
INSULATION SYSTEMS

- Cable insulation
- Interlayer
- Quench heaters

Validation

SHORT MODEL COILS

-> SMC (see 14T+)
-> 12T mirror (see TDP)



R&D

Definition of requirements and specifications

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Processes
- Optimization of **impregnation process** parameters
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Validation

Validation in short model coils
-> SMC
-> 12T
-> 14T

R&D Impregnation systems: **Epoxies**

Some criteria to screen an **epoxy system** for HFM magnets:

Fracture toughness (K_{1c} > 2 MPa*m1/2 at 77K)
Processability (< 400 cp for 8 hours)
Radiation resistance (stable up to 30 MGy - tbd)

Several epoxies have been characterized in collaboration with ETHZ.
The main ones:

- CTD101K
- MY740 (MSUT)
- MY750
- Mix61 (NHMFL)

Epoxies in the **SMC resin program**

1) Compare **impregnation systems**

2) **Adhesion** conditions (e.g. pole)

(see J.C. Perez -14T + presentation)

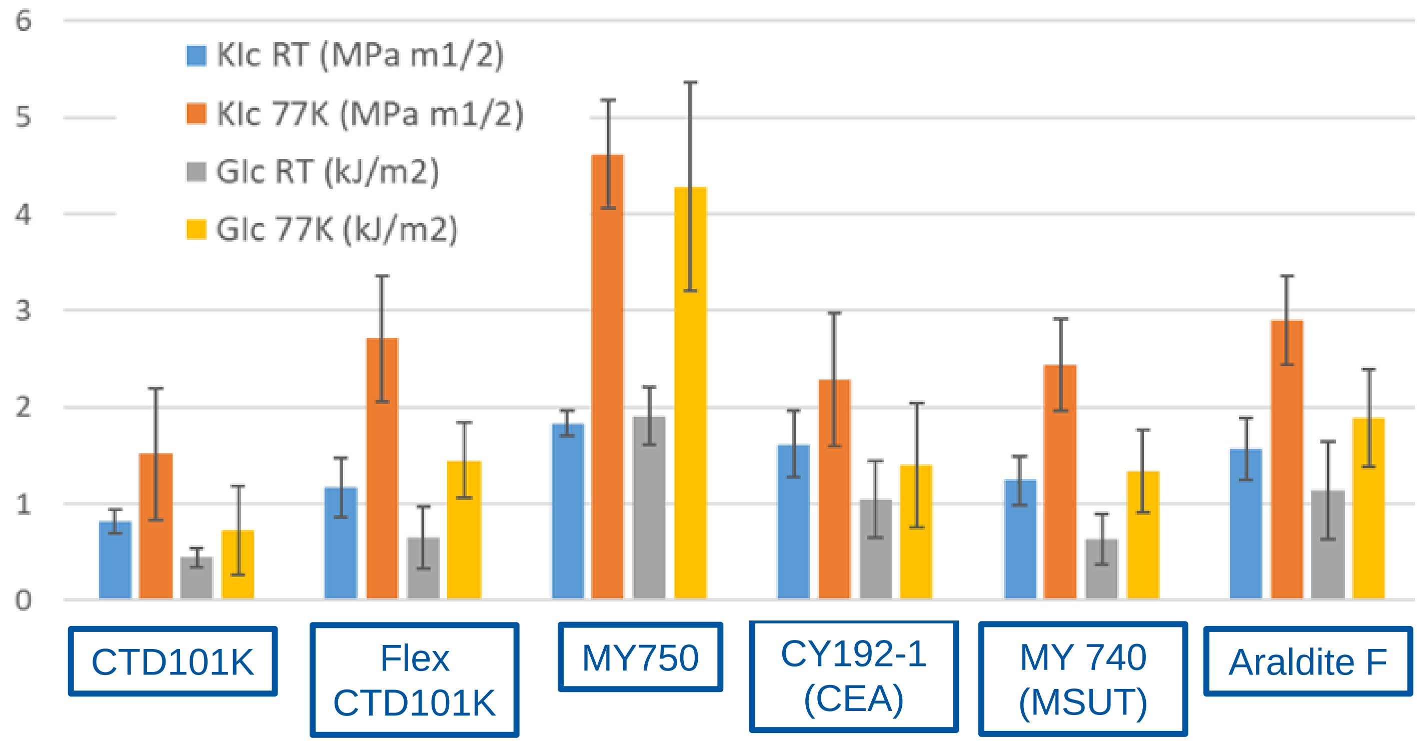
Other epoxies system:

- Araldite F (CERN)
- CY192-1 (CEA)

SMC in building 927 (CERN)

R&D Impregnation systems: **fracture toughness**

- MY750 has the highest fracture toughness
- CTD 101K has the lowest fracture toughness
- **CTD 101K + DY040** displays an increase K_{1c} 77% at 77K -> flexibilized CTD

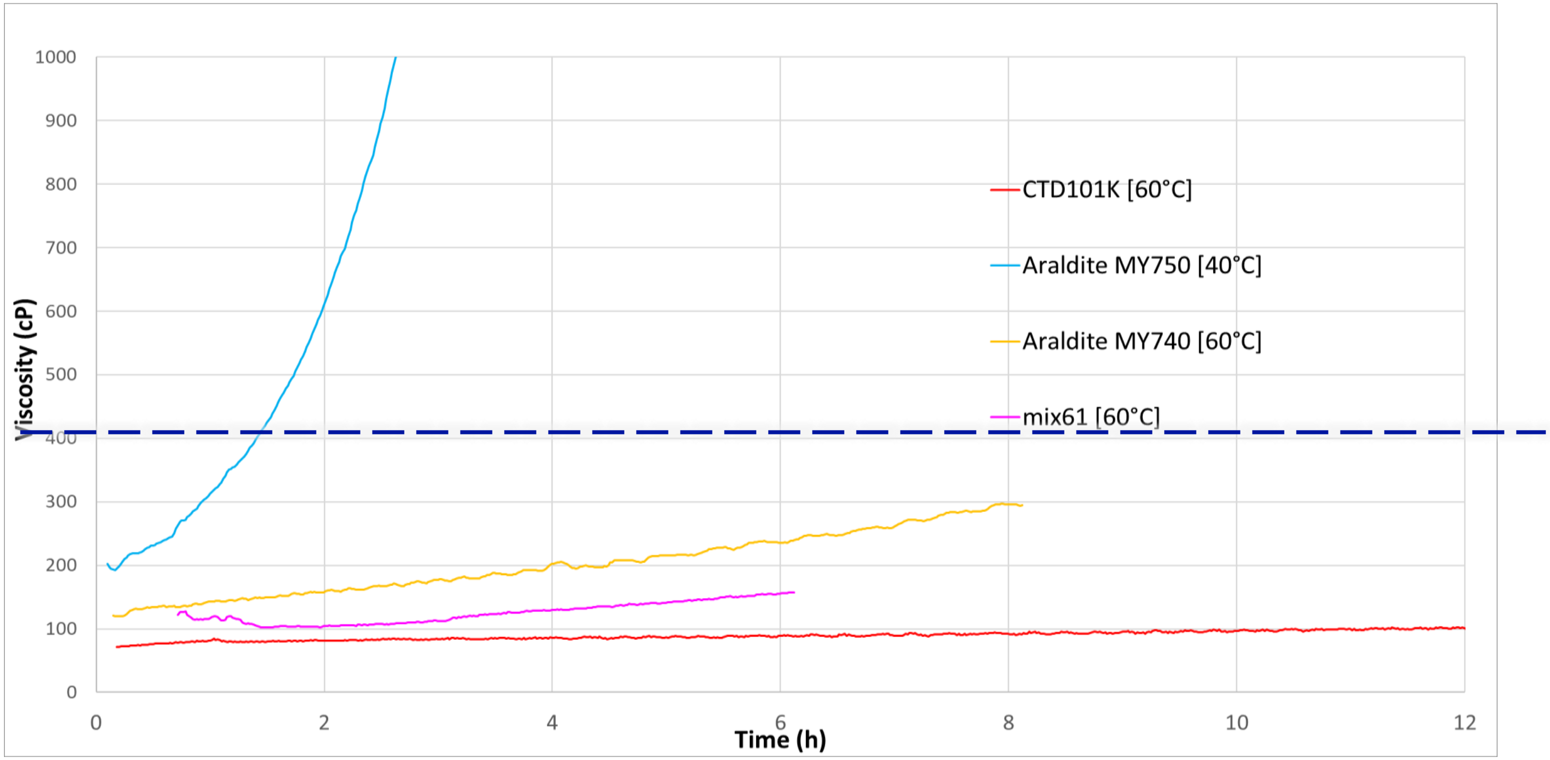


A. Gaarud, D. Mate Parragh, S. Clement, C. Scheuerlein, R. Piccin, R. Lach, "Improved fracture toughness at cryogenic temperature of irradiation hard epoxy system for superconducting coil impregnation", http://ssrn.com/abstract=4478135

R&D Impregnation system: **processability**

- Impregnation of an accelerator-size magnet requires an impregnation system with low viscosity (< 400 cP) for at least 6 – 8 hours.

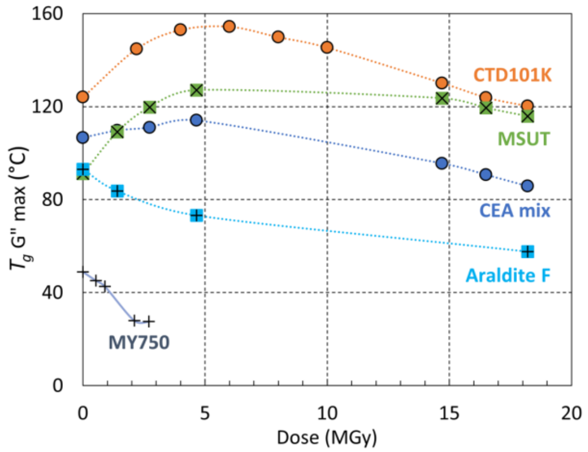
- MY750 has a short pot life. Not suitable for impregnation of long coils if we keep the “standard formulation”

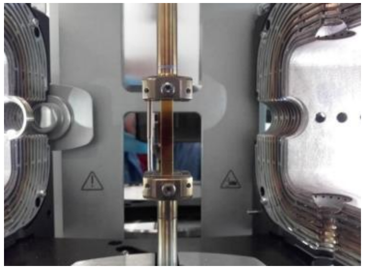


C. Urscheler (MSC-SMT)

R&D Impregnation system: **Radiation hardness**

- Changes of the **glass transition temperature (Tg)** can reveal effects such as irradiation induced crosslinking and chain scission.
- Also, short beam test reveals different radiation response of CTD 101K and MY750. Irradiation of MY740 (MSUT) on going.

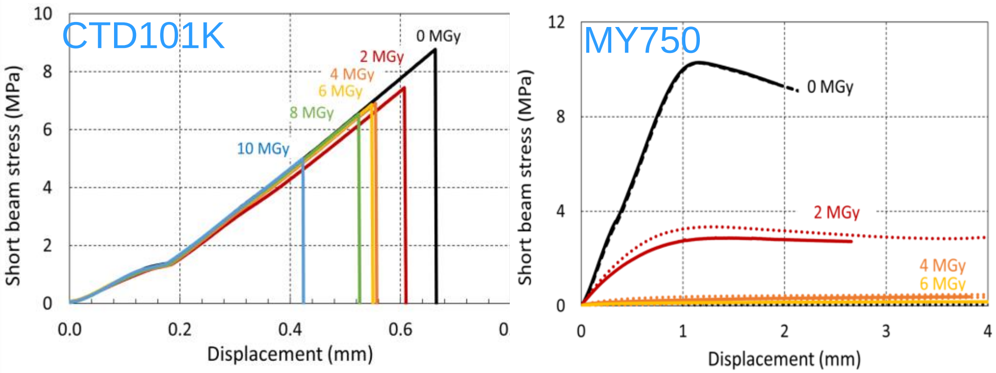




T_g of different epoxy resins as a function of the absorbed dose in ambient air.

Strong differences in the aging rates of different epoxy resins for coil impregnation:

- CTD101K is known to have a good radiation resistance
- MY740 (MSUT) seems to be radiation "stable"
- MY750 degrades already at 2 MGy (irradiation in air)



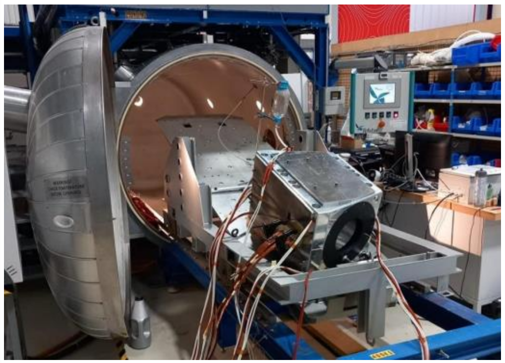
Stress-displacement curves of CTD101K (left) and MY750 (right) after 60Co irradiation in ambient air up to 10 MGy.

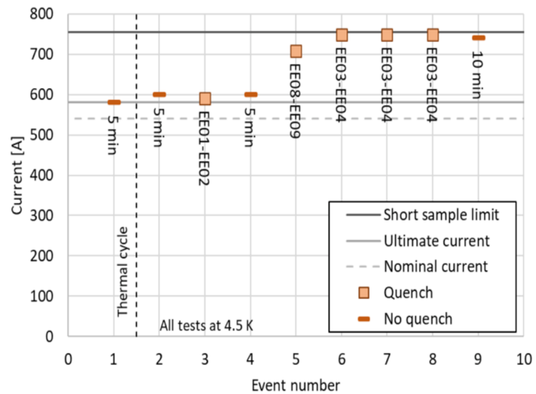
D. Mate Parragh, C. Scheuerlein, R. Piccin, Pezzullo, D. Ternova, M. Taborelli, M. Lehner, M. Eisterer "Irradiation induced aging of epoxy resins for impregnation of superconducting magnet coils". Presented at EUCAS2023

R&D Impregnation system: **CTD101K-FLEX**

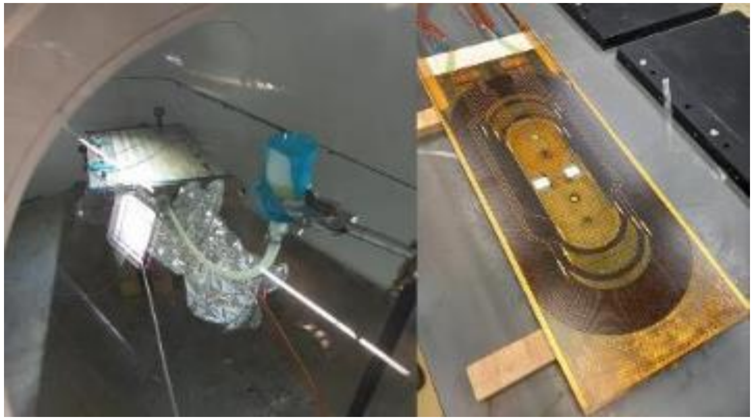
CTD 101K-FLEX has been utilized in two magnets so far:

1. Fusillo subscale #1 (outstanding performance)
2. SMC #107 (to be tested soon)





A. Hazot et al.- Curved-Canted-Cosine-Theta (CCCT) Dipole Prototype Development at CERN – Presented at MT28

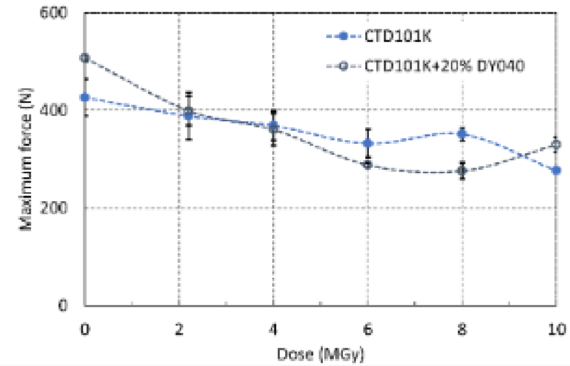


SMC #107 manufactured under CERN-CIEMAT collaboration

- **CTD 101K-FLEX** retains the radiation resistance and the dielectric strength of the original CTD101K, while it displays a **higher fracture toughness**

At the current state, CTD101K-FLEX and MY740 (i.e. MSUT) are interesting alternatives for HFM magnets (e.g. 12 T VE)

R&D on impregnation systems will continue and shall not be limited to traditional epoxy systems



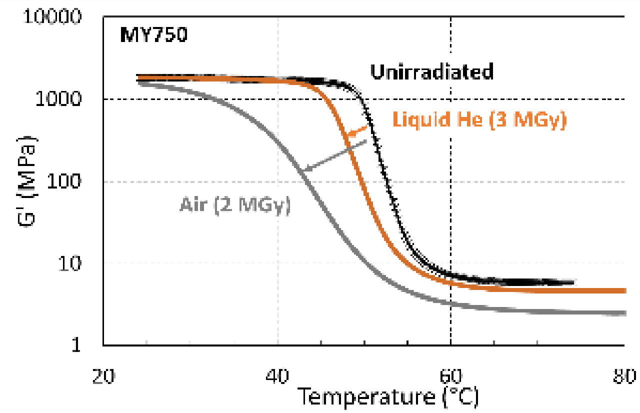
CTD101K and CTD101K+20%DY040 short-beam strength as a function of 60Co gamma irradiation dose.

R&D Fundamentals

Radiation program (C. Scheuerlein)

- The **irradiation environment** can have a strong effect on aging rate of epoxies.
- The same proton dose absorbed in liquid helium has comparatively smaller effect on viscoelastic properties.

Irradiation in liquid He (proton at IRRAD) and with other radiation sources (ISOLDE, n-Tof) shall continue through 2024



D. Parragh, C. Scheuerlein, N. Martin, R. Piccin, F. Ravotti, G. Pezzullo, T. Koettig, and D. Lellinger - "Effect of irradiation environment and temperature on aging of epoxy resins for superconducting magnets" – To be submitted to Polymers (MDPI)

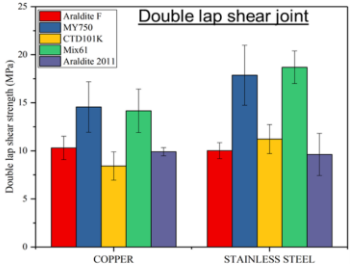
Adhesion analysis (B. Verma)

- Epoxies adhesion to different substrates measured with standards test methods
- Adhesion of epoxies "predicted" by wettability analysis – OWRK model (measurement of surface contact angle + measurement of epoxy surface tension)

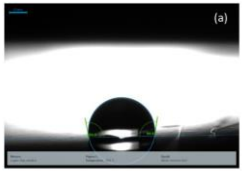
This model widen possibilities of predicting adhesion measuring only two parameters of the adherend surface and the epoxy

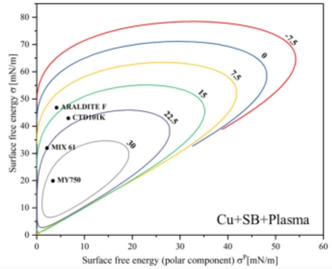
B. Verma, R. Piccin, I.A. Santillana, D. Tommasini - "Adhesion analysis of resin impregnation systems for superconducting magnets" – To be submitted

Destructive adhesion test



Wettability analysis & OWRK model





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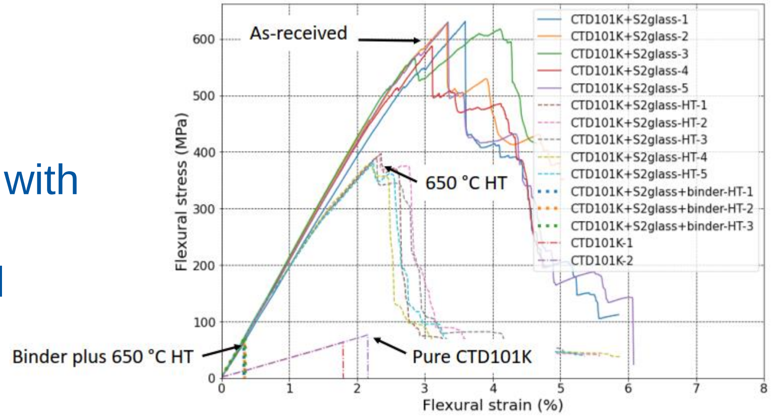
Implementation: Interlayer and cable insulation

Binder / no Binder

- Binder CTD1202 (ceramic binder) in combination with 650 °C coil reaction heat treatment (HT) leads to **dramatic loss of the S2 glass fibre mechanical strength.** (https://indico.cern.ch/event/1261229/)

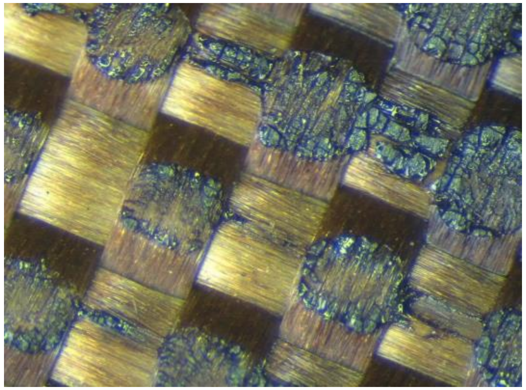


C. Scheuerlein (MSC-SMT)

No binder on OL of "new generation " MQXFB coil.

One of the improvements that allowed MQXFB03 to reach the target performances

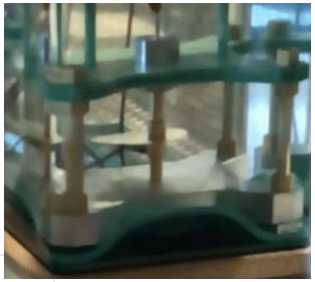
- Research of alternative binders (e.g. PVA) did not lead to satisfactory results: good retention of mechanical integrity of the fibres but electrically conductive.



Priority on design of tooling for coil winding rather than look for alternative binders compatible with heat treatment

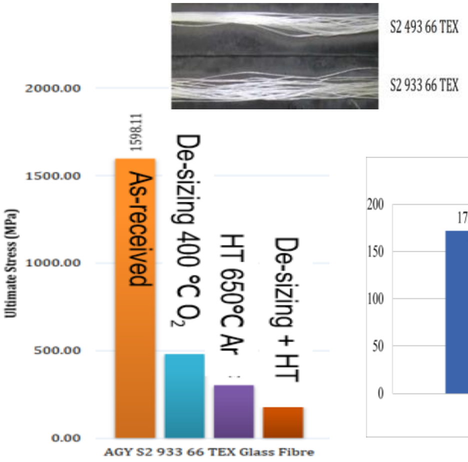
see manufacturing studies for 12T VE

Implementation: Interlayer and cable insulation

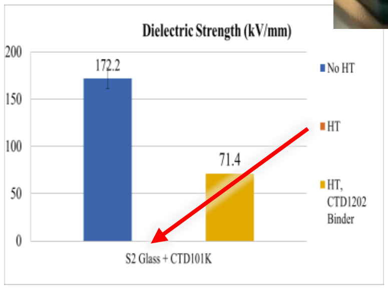


Fibers (basalt, pure SiO2 and S2) and heat treatment

- Reduction of mechanical strength of the resulting composite **after HT** or **thermal de-sizing**
- **Fibers are conductive after HT** (residues of the sizing). This affect the electrical performance of the composite after impregnation.



M. Lopes (MSC-SMT)



J. Osuna & F.O. Pincot (MSC-SMT)

Preliminary contact with ceramic fiber manufacturer for investigating compatible sizing methods

Cable insulation manufacturing

- The current contract is running till Q4 2024
- Call for tender is starting soon for cable insulation manufacturing for HFM magnets

1) Launching the administrative process for the call for tender of the cable insulation contract

2) Manufacturing study on new insulation cable layout: double sleeved

Conclusions

Conclusions

- There are a few promising alternatives to CTD 101K epoxy: CTD101K FLEX and MY740 among them. This does not conclude the research on impregnation systems.
- Continuing the investigation of alternative fibers and sizing compatible with the heat treatment (e.g. sizing easy to remove).
- Studying a robust cable insulation layout to propose for 12T mirror and SMC validation.