Summary of WG1 discussions at the LARP-CM18

WG1 - Conductor development, testing standards, qualification plans

Arno Godeke, Daniel Dietderich, LBNL; Arup Ghosh, BNL

# Wire testing

## Is a standard holder required?

A number of iterations within the ITER worldwide benchmarks for strand testing during the 1990’s have resulted in a standard Ti-6Al-4V holder with machined copper end rings. This worked well for ‘medium’ current Nb3Sn wires, but many labs experienced stability issues, related to the current entrance region of the barrels, when testing modern 3000 A/mm2 wires. Most labs have therefore modified their holders to accommodate reliable measurements on high current wires, mainly through increasing the copper cross-section and length at the ends of the Ti-alloy barrels. Even though the measurement holders differ between the two labs that are presently involved in LARP (BNL and LBNL), very good consistency is achieved between the data from both labs. For now, there does not seem to be a reason to switch to a standard holder.

## Is a standard criterion required?

So far, BNL has been using a resistive criterion of 10‑14 Ohm-m, whereas LBNL has been using an electric field criterion of 10‑5 V/m. In calculating the resistivity, a cross-section for the wire has to be used. This initiates an uncertainty in what cross-section should be used (before or after reaction) as well as the exact value of the cross-section, which might vary slightly along the length of the wires. It was therefore agreed that an electric field criterion is less ambiguous, since it only involves the measured voltage and length along which the voltage is measured, and future critical current values will be reported using an electric field criterion of 10‑5 V/m.

## How to straighten XS and mount wires on barrels?

There is no consistent way to straighten XS for mounting on barrels, but wires are straightened manually. Mounting tension of the wires is 10 N for most labs. LBNL and BNL both do not glue the wires to the barrels.However, LBNL uses solder flux to retain the wires, which seems to work as well as mounting with Stycast and is far easier. Even though XS are straightened manually, there is, for now, no clear indication that this causes ambiguous results.

## Database

BNL uses a Microsoft Access database for their results, whereas LBNL uses an online spreadsheet system. So far, these seem sufficient, but if it comes to production, LARP would like to benefit from the database system that CERN has setup for the LHC production.

## Wire layout

OST 54/61 and 60/61 are both reliably manufactured and reach a non-self-field corrected >3000 A/mm2 non-Cu Jc at 12 T . 60/61 has reached a record of 3500 A/mm2 at 12 T, 4.2 K in one round wire sample. Both have RRR values that are far above 100 (mostly >200).

OST 108/127 is consistently manufactured, but unit length, Jc, and RRR are not optimal. For the 169 stack less statistics is available, but FNAL mentions good Jc and RRR. For the 217 stack, a redesigned sub-element is being pursued through the CDP program, to mitigate the reduced RRR. It is suggested that this stack will need a lower requirement for Jc (>2400) to become acceptable for LARP. CERN was absent from the WG1 discussion, but PIT seems to converge to a comparable filament size at 0.8 mm (40-50 micrometer) while carrying around 2500 A/mm2. CERN retains its push for filaments <30 micrometer, but that is likely at the expense of lower Jc and RRR, and will take time to mature into a production wire. It is suggested to develop 108/127 as a baseline conductor and pursue the 217 stack for finer filament size. A finer filament size is more relevant for arc dipoles than it is for IR-quadrupoles, since the latter only comprise a small fraction of the machine.

# Insulation and Epoxies

## Cable Insulation

So far LARP coils have been fabricated using S-2 glass woven into a sleeve that is put around the cable like a sock. However, this method is very labor intensive and not suitable for long unit lengths of cable.

For the past year, other options have been investigated, primarily directly braiding insulation on the cable as well as conventional wrapping of tape.

Braiding options:

* S-2 glass fiber (work done at New England Wire Co.)
* 3Al2O3-2SiO2 (Mullite) fiber without sizing - development at a Japanese vendor

Initial braiding trials at NEWC used 2-ply 150/1 S-2 glass with 636 binder which is typically also used for producing the sleeve. However, after reaction at 640C/48h, the binder leaves behind a lot of carbon residue. Note: LBNL removes the 636 binder by treating the sleeve at 400C and then coating with palmitic acid. Recent trials used S-2 glass with Silane binder 933.

* Product literature indicates that 933 sizing is stable at processing of temperature of 670°F and above. It is also compatible with epoxy and cyanate esters.
* Trials at LBNL show that 2% by weight is lost by heat treating at 665C, mostly volatiles.
* CERN is also experimenting with braiding similar yarn. Tests at CERN to 550C show no decomposition of the binder. Tests will be extended to higher temperatures.
* Recently, single ply S-2 glass 75 1/0 with 933 silane binder was successfully braided onto a 15 mm wide HQ cable producing insulation at the nominal thickness of 100 m with good coverage. Subsequently, 100 m long HQ cable was insulated and has been wound into a coil (HQ-C17). CERN too has been developing S-2 fiber braiding at CDP (?). Another possibility is the use of ECR glass fiber which does not contain boron which is present in E-glass.

Tape wrapping option:

* E-glass (75 m thick), S2-glass (150 m thick), 3Al2O3-2SiO2 (90 m thick), pure SiO2 (75 m thick)
* Tape insulation typically will produce insulation thickness in the range of 125-150 mm, half over-lap or double butt-wrap.
* For the 11 T model magnet FNAL is using E-glass tape wrap for cable insulation. Prior use in a TQ coil was quite successful.

## Radiation-hard Epoxy

Some options:

* Cyanate Ester (CTD-403)
* Cyanate Ester / Epoxy Blend (CTD-425)
* Matrimid 5292

It is agreed that to qualify these epoxies, we need to be consistent in sample preparation and testing in order to make accurate comparisons. Suggestion made to use same tooling or replicate for use at another lab. Some issues for the various choices are listed below:

* Matrimid has issue with temperature/viscosity
	+ High working temperature – 125 C and short pot life ~ 60 min
	+ High cure temperature – 200 - 250 C
	+ Lines need to be actively heated to prevent solidification / blocked lines.
* CTD-425 – Epoxy/Cyanate Ester Blend (60 / 40).
	+ Mixing / Processing Temperature 45-60 C
	+ Cure: Slow ramps, 22 hours at 100 C, 24 hours at 170 C.
* Cyanate Ester/Blends have safety issues with possible exothermic reaction.
	+ Will require precise control of epoxy temperature from mixing through impregnation.
		- Additional TC’s on impregnation fixture, some deep close to the coil not just on surface as is the present practice with CTD-101K epoxy.
		- Need to establish control system for epoxy pot during mixing, de-gassing and impregnation.
	+ May require ability to cool epoxy pot and may need ability to cool impregnation fixture in case there is a thermal runaway.

Use of Matrimid has been investigated at FNAL. Steve Krave made a presentation of the work being done there.

* Building on previous experience, he has developed tooling to impregnate 36” coil stacks and has successful impregnated 36” cable stacks. Next step is to follow-up with impregnating a TQ Coil
* He is using 10-stack for material characterizations at room temp and 77K (or 4.2K) and plans to do them for the following samples
	+ 10-mm wide TQ cable with Cynate Ester, Matrimid and CTD
	+ 15-mm wide HQ cable, and
	+ 11 T cable
* Two TQ 10- stacks have been completed and are awaiting testing:
	+ TQ-Matrimid and TQ-CTD101K

Some open questions that remain to be answered are the effects from radiation in the accelerator environment and also the thermal properties. Are there fillers that are compatible with these epoxies that can improve thermal conductivity of they composite.