Test Results on the model
\( \text{Nb}_3\text{Sn} \) dipole TAMU2

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TAMU2 is a second model of our Nb$_3$Sn block-coil technology

The ultimate goal: 16 T
- Stress management of conductor
- Flux plate suppression of multipoles
- Bladder preload

TAMU2: a 6 T learning model
1 single-pancake winding, no aperture mirror geometry, ITER superconductor
Built to give first validation of the Nb$_3$Sn coil technology, stress management
Stress management
Coil winding

Etching Cr from ITER cables for splices

Coil in coffin ready for reaction bake
Reaction bake

Coffin supported on end, furnace segments lowered onto it.

- 210C for 100 hours
- 340C for 48 hours
- 650C for 180 hours

Heat treat furnace in operation
Nb$_3$Sn/NbTi Splices

Preparing the cable ends

One joint assembled with heater module

Cross-section of practice splices
Vacuum Impregnation

Coil in coffin, fitted for epoxy supply/purge, being inserted into retort

Impregnated coil with leads and test connections
Assembly in flux return, pressurization of preload bladders

Preload of coil in flux return, flux return in Al stress shell, both provided by pressurized bladders:

- Heat assembly to 80 C
- Evacuate bladders, fill with molten Wood’s metal, pressurize to 2000 psi
- Cool to freeze Wood’s metal while holding pressure
Short sample data
ITER strand and cable

Strand data measured at U. Twente
Cable data measured by Dietderich at NHMFL
TAMU2 Load Lines

Current (A) vs. Field Strength (T) for different conditions:
- Inner
- Outer
- Cable Short Sample
- Max Field
- TAMU2 Calculated
- TAMU2 Measured

Graph showing the relationship between current and field strength for various conditions.
Testing of TAMU2 at LBNL

- First quench at 8920 A
  - 93%-98% of edge-on short sample

![Graph showing quench number vs. current (Iq) with annotations for current data and bolt arc on current bus.]
Power supply was unable to ramp faster than ~1 kA/s because of small load inductance (single-layer coil).
Every quench originated at the same location

Innermost turn at return post
Stress measurements

We expect that stress management should *decouple* Lorentz stress on inner winding so that only the Lorentz stress on outer winding loads the transducer.

But the observed stress equals the sum of both stresses!

Conclude that laminar spring must have collapsed or filled with epoxy

Awaits postmortem analysis

Calculated stress @ 9 kA:  
- Inner winding: 30 MPa
- Outer winding: 20 MPa

Measured stress on transducer:  
- 52 MPa (left)
- 54 MPa (right)
Block-coil geometry *intrinsically* suppresses AC losses

AC losses arise from currents induced to flow between filaments within strand and between strands in the cable.

Block-coil dipole: cables are oriented edge-on

\[ \vec{B} \parallel \hat{n} \]

Result: minimum induced current loop, minimum AC losses

\[ \cos \theta \text{ dipole: cables oriented face-on} \]

\[ \vec{B} \perp \hat{n} \]

Result: maximum induced current loop, maximum AC losses
Block-coil geometry suppresses snap-back

Snap-back is caused by the re-distribution of magnetization current loops:

• Ramp field $h_i \rightarrow h_o$, induce magnetization current loops in subelements
• Cycle dipole at injection to reduce magnetization, set on charging side of hysteresis
• Dwell at fixed field for injection – magnetization loops migrate under gradient force
• Begin ramp – sudden return to charging curve – snap-back

\[ \vec{F} = (\vec{\mu} \cdot \vec{\nabla}) \vec{B} \]

Suppression of BICs is evident in short-sample measurements of cable:

$I_q$ is \(~10\%\) higher edge-on than face-on.
This suggests an interesting possibility for rapid-cycling dipoles (superPS, superSPS, GSI)

• Block-coil dipole using fine-filament bronze-process Nb$_3$Sn
  – Readily available, least expensive Nb$_3$Sn strand
  – <1 μm filament size suppresses intrinsic AC losses
• Edge-on cable orientation suppresses extrinsic AC losses, snap-back.
• Flux plate suppresses multipoles at injection.
Our TAMU model dipole geometry could provide an excellent test bed to evaluate rapid-cycling optimization.
Conclusions

• TAMU2 went to >90% short sample on first and every quench
• Ramp rate studies indicate very robust rapid-cycling performance
• Evaluation of stress distribution indicates need for post-mortem study of laminar spring
• The intrinsic suppression of AC losses, snap-back make Nb₃Sn block-coil dipoles an interesting candidate for applications requiring rapid-cycling