EU RD&D program for quench protection: phase 1 sample

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WPMAG final meeting

16/01/2026

SWISS PLASMA CENTER

Content

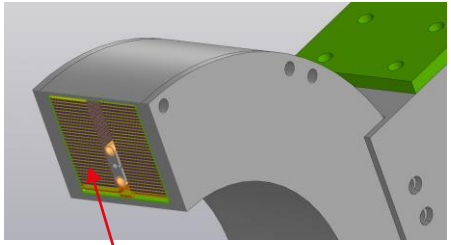
(1) Double pancake Design (MAG-T.04.02-T002-D001)

(2) Double pancake Procurement and Fabrication (MAG-T.04.02-T002-D002)

(3) Double pancake Quench Testing (MAG-T.04.02-T002-D003)

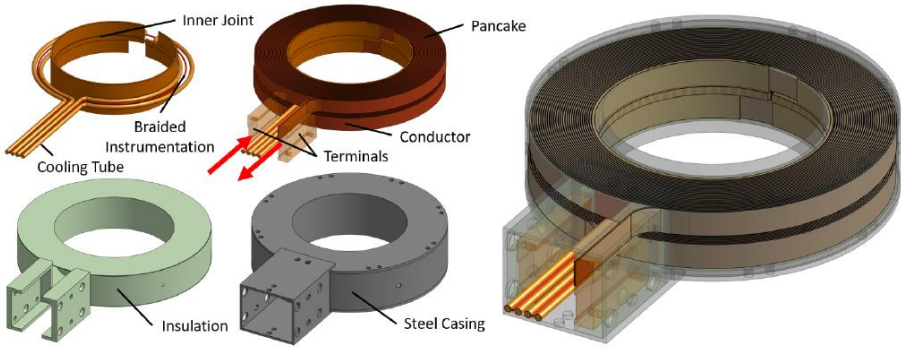
HTS model coil program – Phase 1 sample

Step	Stored Energy	Operating current	HTS tape length (4 mm wide)	Objective	Planning
Double pancake	0.1 MJ (0.4 MJ at Ic)	> 10 kA (Ic~20 kA)	1.2 km	Proof of principle for quench detection method(s)	Made and tested at EPFL-SPC
Small Coil	~10 MJ	10 kA (~Ic)	23 km	Quench detection and protection in a sub-scale integrated coil	Made by industry Tested at EPFL-SPC
Model Coil	~300 MJ	50 kA (~Ic)	TBD	Quench detection and protection in a full-scale VNS-representative coil	Made by industry Tested at TBD



Double pancake HTS insulated coil made by:

- 15-tape LASSO conductor of ~50 m total length split in 3 sections
- Bore 200 mm, 29 turns per pancake, ~1 mH
- Temperature-based quench detection by a co-wound strip containing **SQD wires, thermocouple chains and optical fibers**
- Inter-pancake and intra-pancake joints, cooling pipe placed between the pancakes



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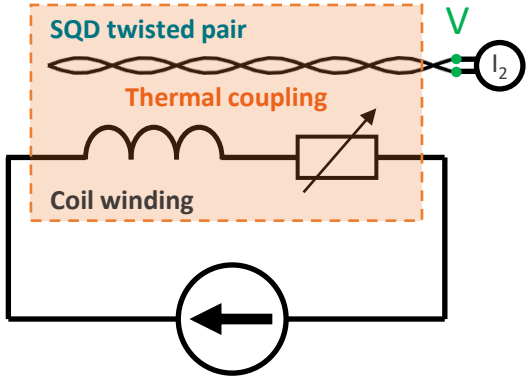
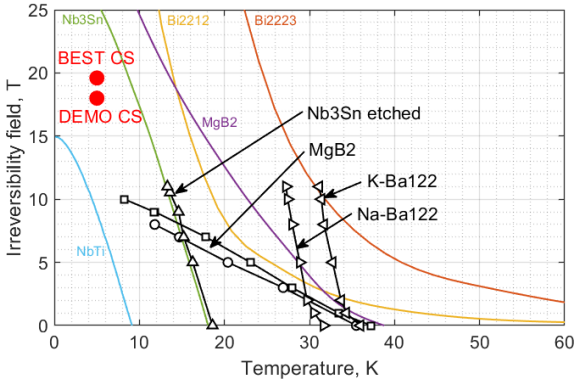
SQD





→ measuring resistance of insulated thermally-coupled SC wire:

- Distributed spatial sensing
- Sensitivity controlled by I_2 and wire off-state resistance
- Twisted-pair SQD allows eliminating inductive noise and necessity of electrical contact with the main winding (no HV penetration!).
- SQD practically immune to mechanical strain
- $T_c(B_{max})$ of SQD wire > conductor Tq
  Tq of LTS conductors ~ Tc (i.e. ~10 K)
  Tq of HTS conductors? It depends… (10 to 40 K)

→ **We will use Nb_3Sn bronze-route 0.2 mm wire**

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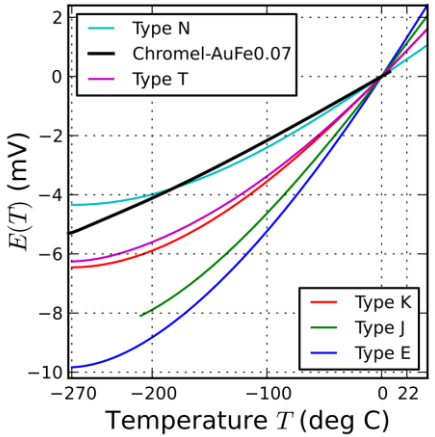
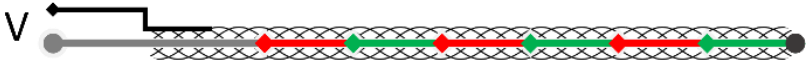
Thermocouple chain

Conventional thermocouple:
response on ΔT **only at the ends**

$$V = \int_{T_{\text{ref}}}^{T_{\text{sense}}} \left(S_+(T) - S_-(T)\right)\, dT = E(T_{\text{sense}}) - E(T_{\text{ref}})$$



Array of thermocouple wires connected in series:
response on ΔT **along the length**

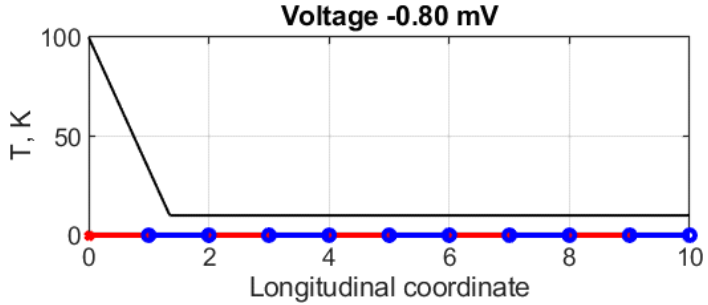


→ measuring voltage over series connected thermocouple wires:

Continuous response on T gradient among joints

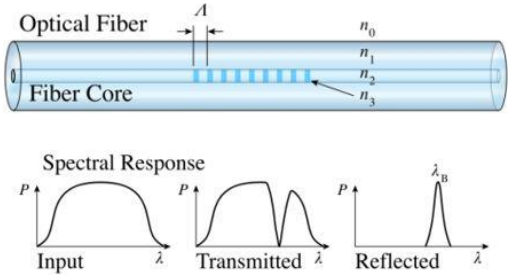
Immune to EM noise by using shielding sleeve

Varying sensitivity due to discrete sensing



Optical fibers

FBG studied by Hugo Bajas at SPC till mid-2024



→ measuring spectral shift of light reflected by each FBG:

Continuous temperature monitoring at each FBG location

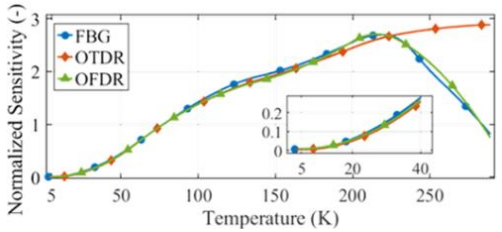
Decoupled mechanically by Teflon tubing

Brittle; high spatial resolution over long length is cumbersome

SPC samples in 2025 will include bare fibers for Distributed Fiber Optic Sensing (DFOS) using:

1. **Rayleigh OFDR by ENEA:**

   Spatial resolution ~5 mm, Rate ~100 Hz, Range ~0.1 km

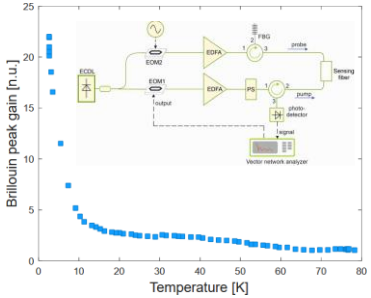


Sensitivity decreasing at low temperature

https://doi.org/10.1109/TASC.2025.3532931

2. **Brillouin OFDA by University of Campania:**

   Spatial resolution ~10 mm, Rate ~10 Hz, Range ~0.3 km



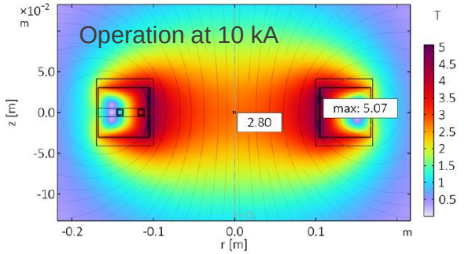
Closed-loop sensing

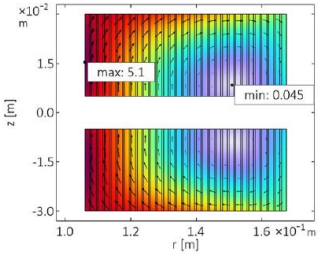
Sensitivity increasing at low temperature (!)

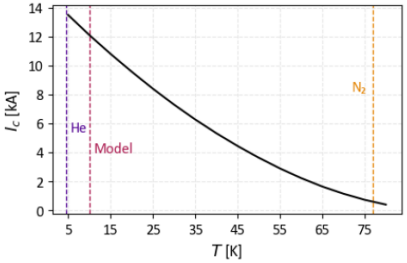
https://doi.org/10.1109/SAS60918.2024.10636574

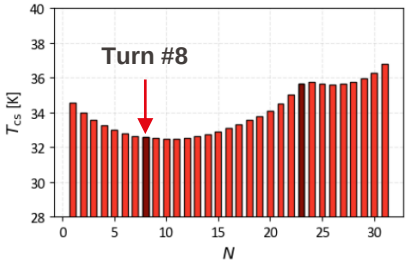
Modelling of the Phase 1 sample

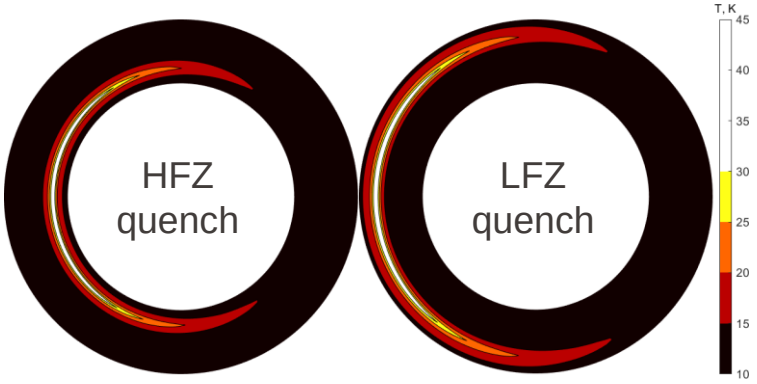
3-D COMSOL model developed by Noël Strasser (Master thesis)

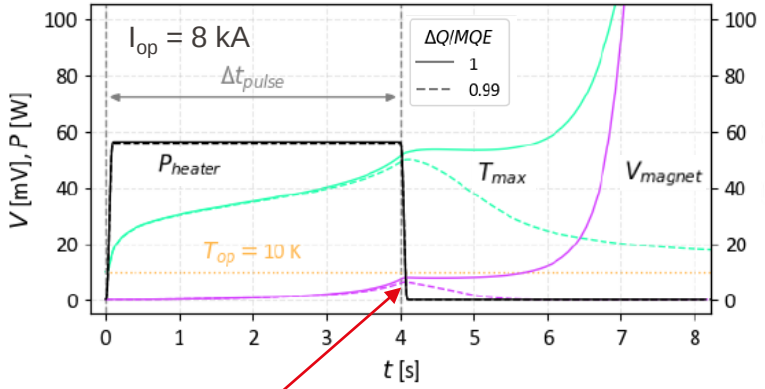


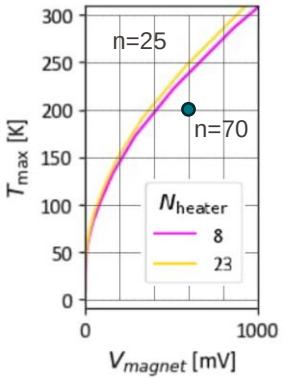






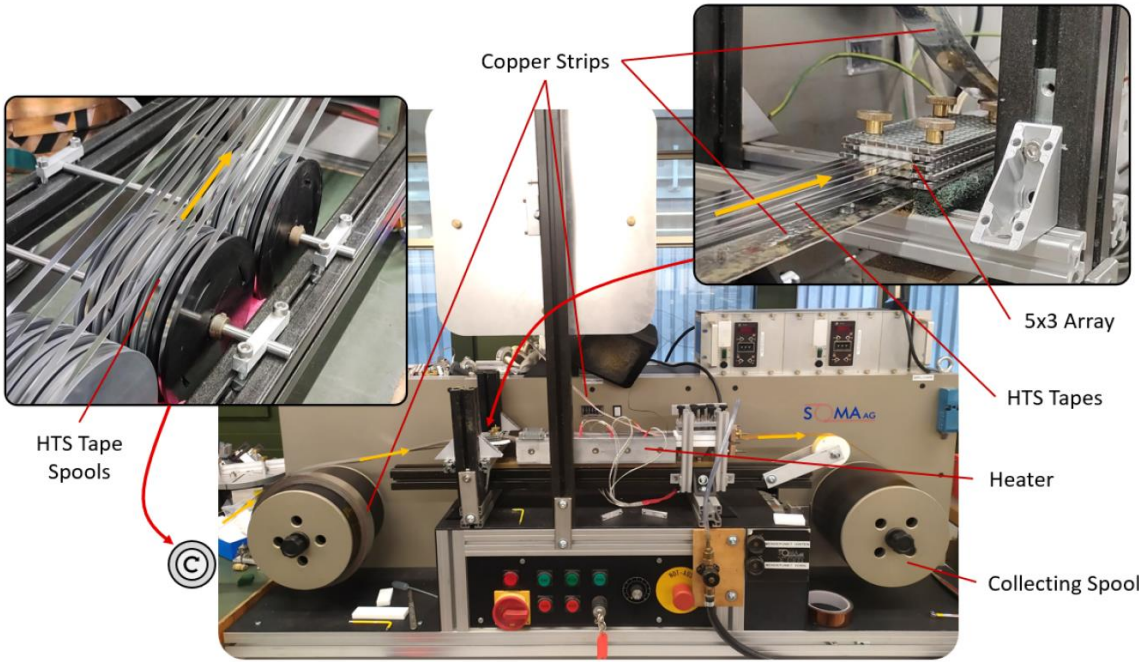




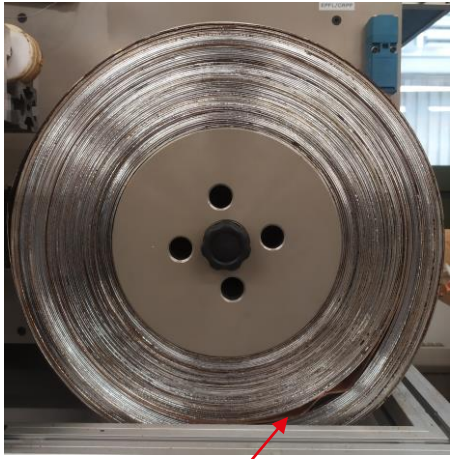


Thermal runaway once magnet voltage exceeds **~8 mV** (nearly independent of studied cases)

Construction: LASSO cable



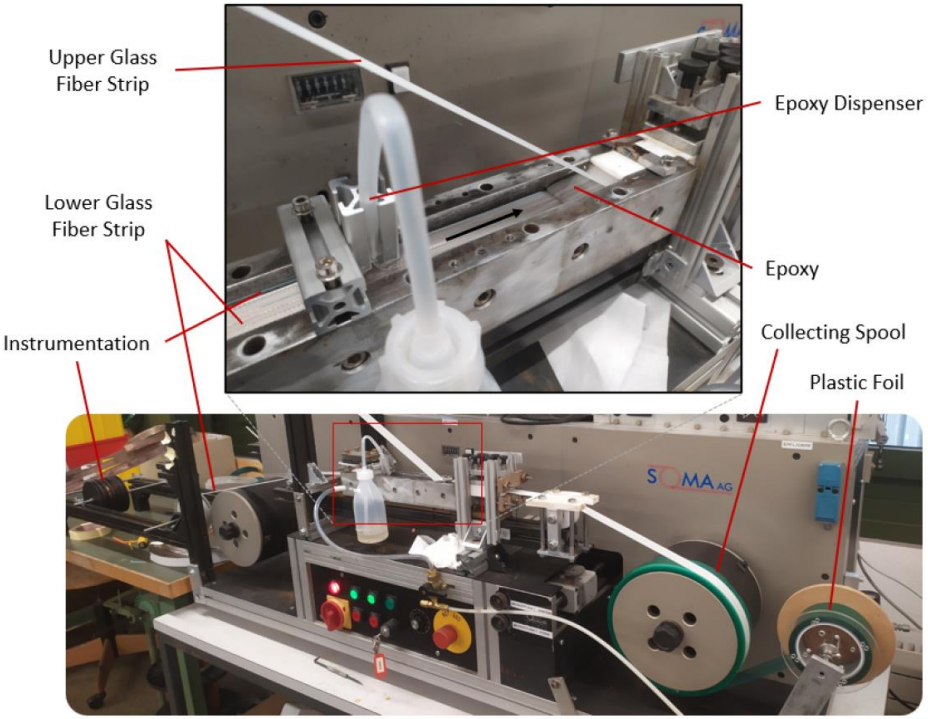
~50 m long LASSO cable



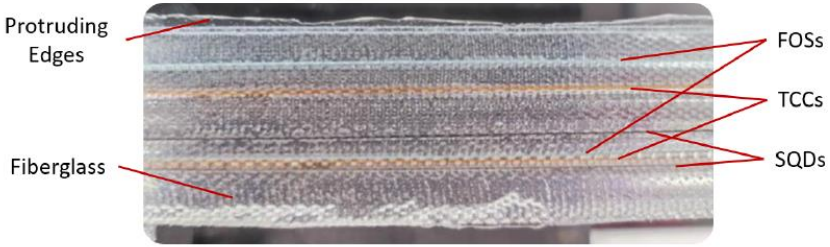
‘Buckled’ region caused by winding non-soldered section

Construction: QD strip

'If all you have is a hammer, everything looks like a nail…'

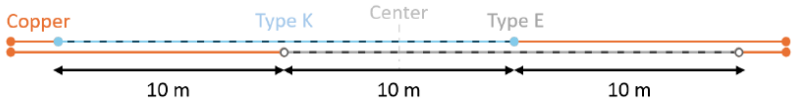


~60 m long strip
(ends suitable for fiber splicing)

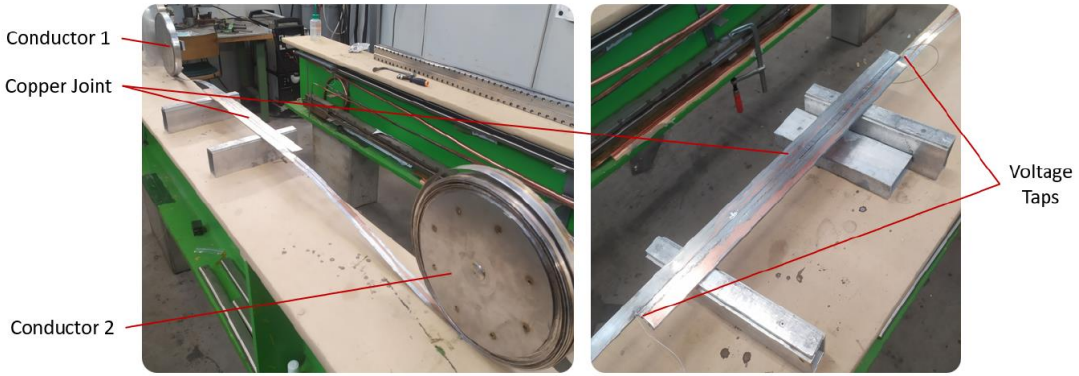


- **FOS**: bare optical fibers, 0.13 mm OD
- **SQD**: Nb_3Sn reacted wires, 0.20 mm OD
- **TCC**: type K and E wires, 0.13 mm OD

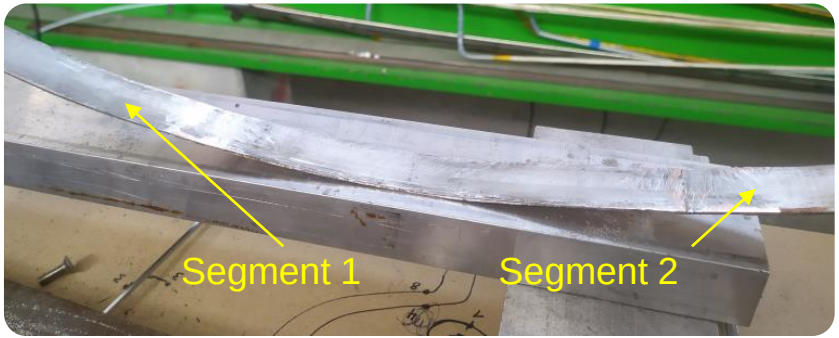
  Two sections of ~20 m length (154 x 13 cm) overlap over ~10 m and can only sense ~30 m central section:



Construction: inter- and intra-pancake joints

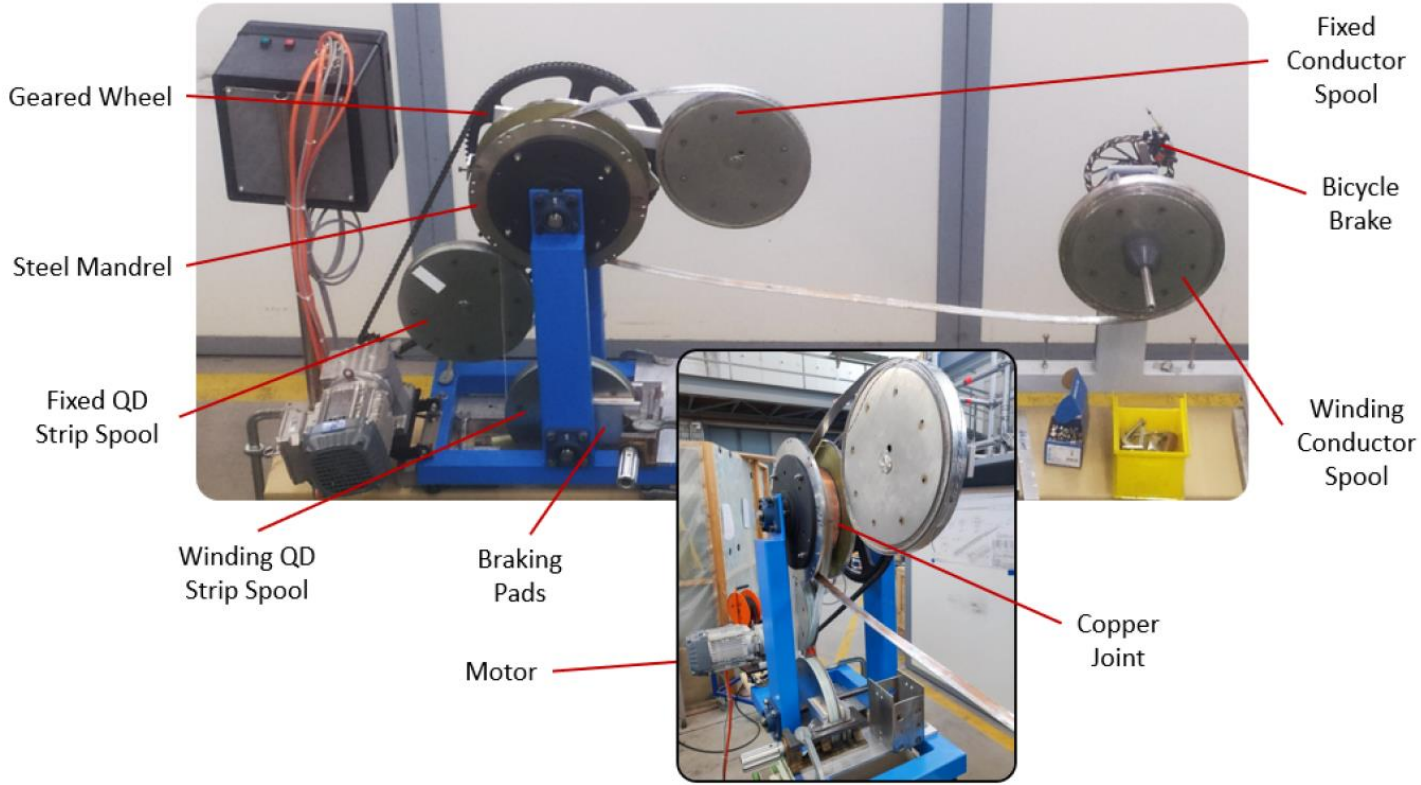


Inter-pancake (copper) joint placed at the innermost turn allows to avoid conductor hard bending



Intra-pancake ('hidden') joint allows to repair conductor and to introduce 'grading' (i.e. change ReBCO cross-section)

Construction: double pancake winding



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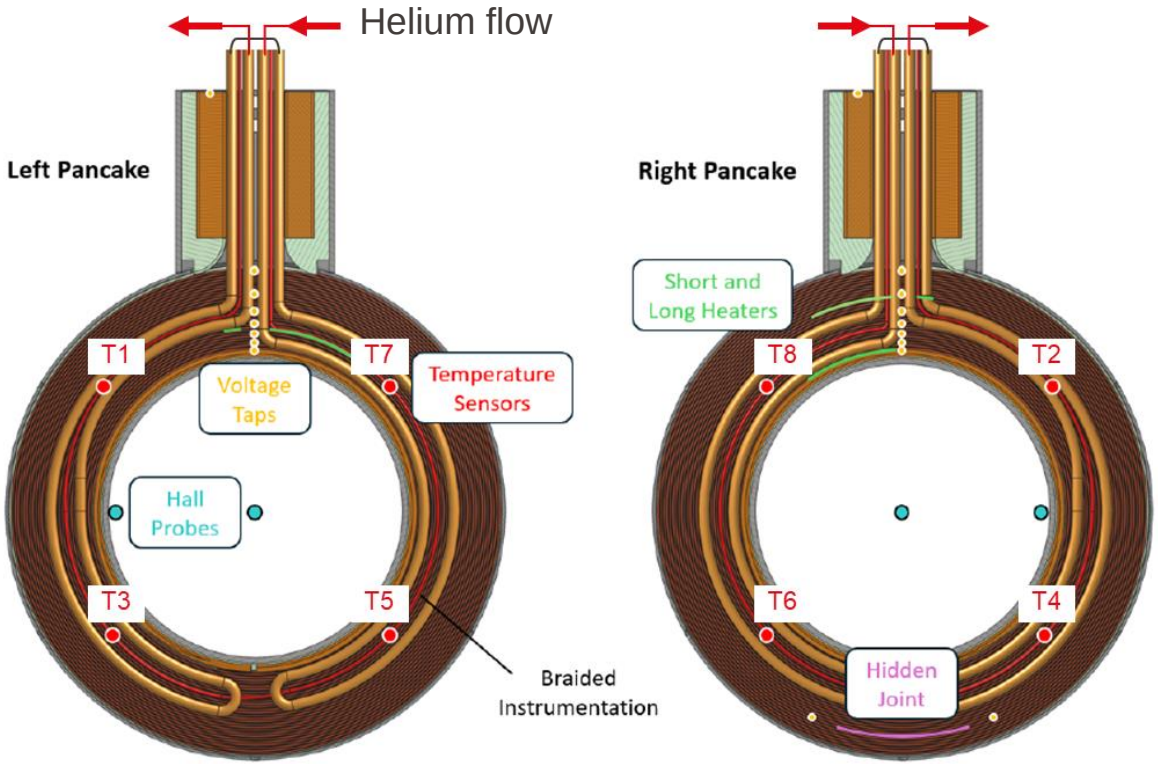
Sample instrumentation



- Voltage taps:

N	$\Delta l_{segment}$ [m]
0-2	1.31
2-5	2.17
5-9	3.06
9-14	4.10
14-21	6.28
21-29	7.93

- CERNOX
- Hall probes
- Foil heaters
- SQD, TCC, FBG

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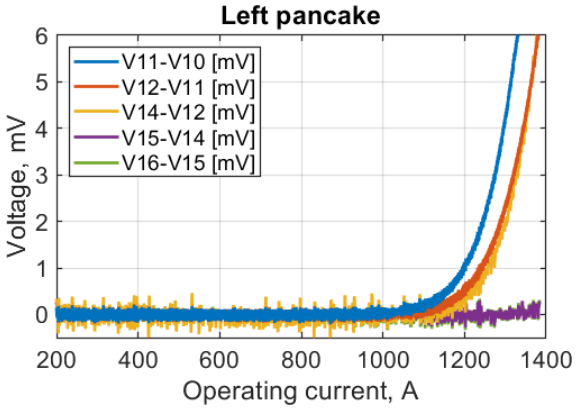
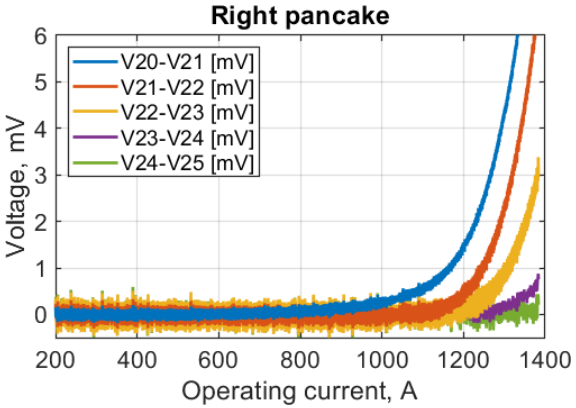
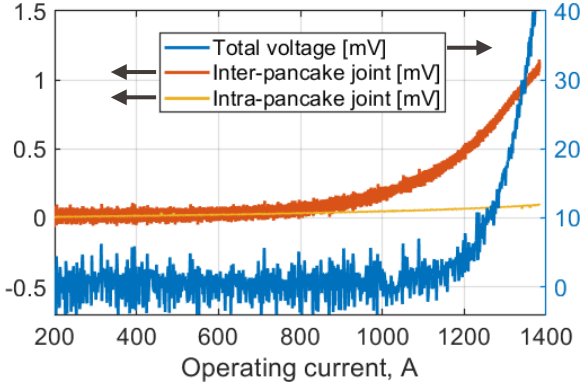
LN2 preliminary check

* inductive offset removed

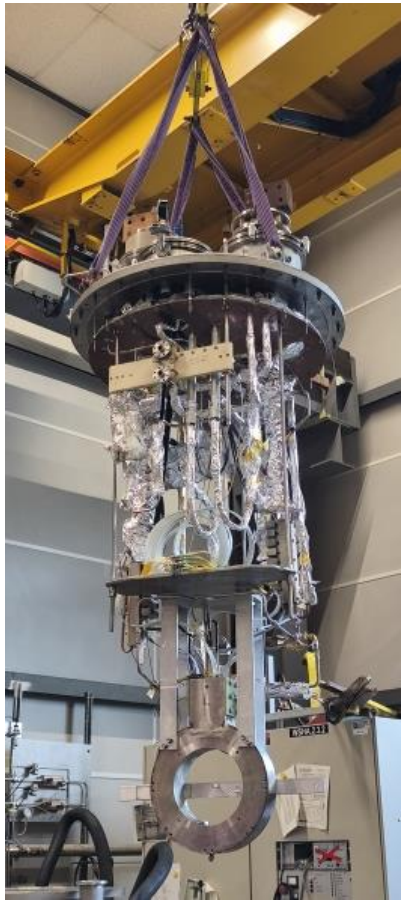


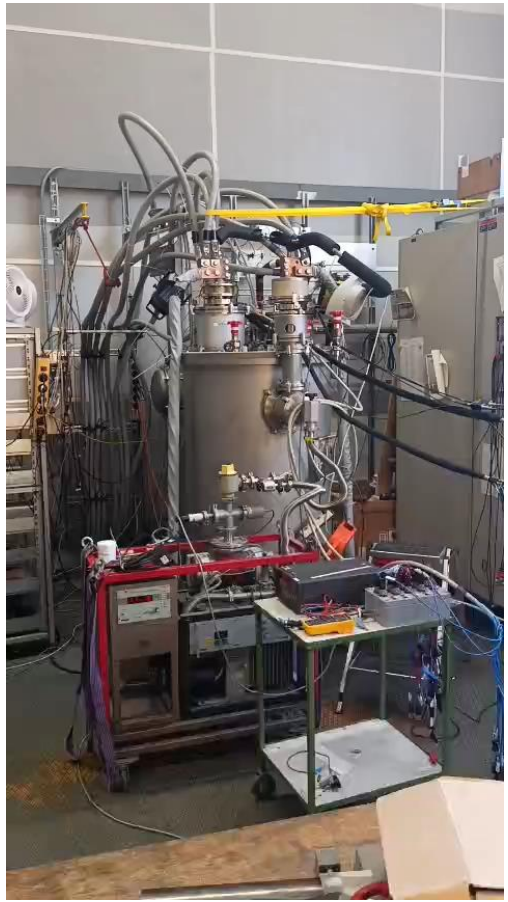


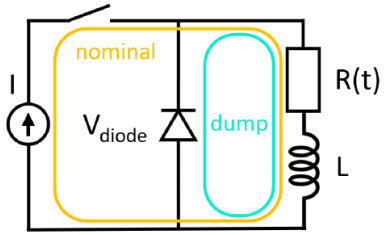


- Coil inductance 1.1 mH
- Copper joint ~30 nΩ (inter-pancake), hidden joint ~40 nΩ (intra-pancake)
- Critical current ~1000 – 1200 A (depending on criterion)

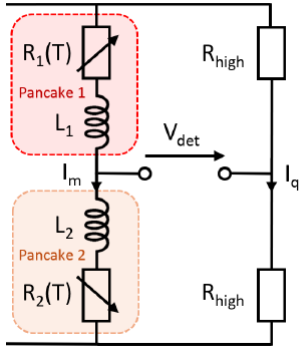
JORDI test – DC performance



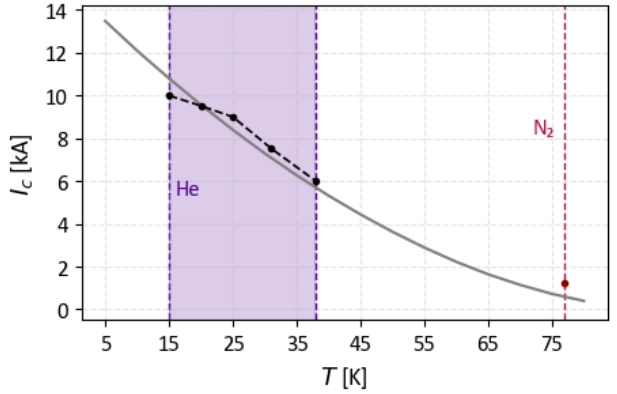




Protection circuit

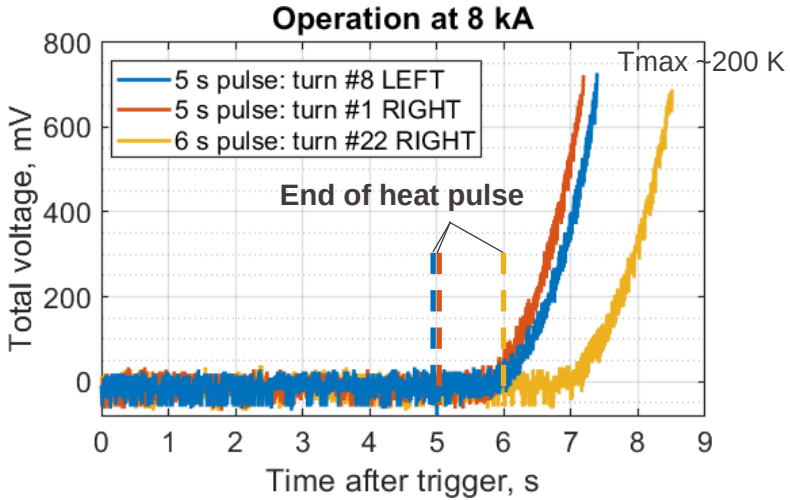


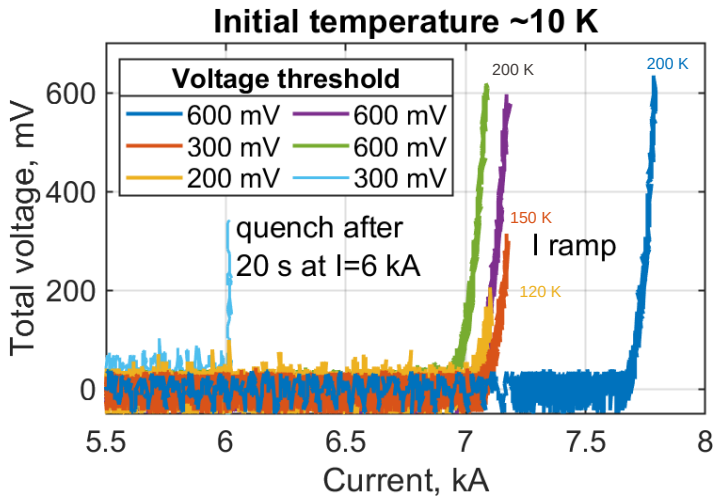
Detection circuit



Copper joint ~6 nΩ, hidden joint ~13 nΩ at 10 K

JORDI test – quench by embedded heaters

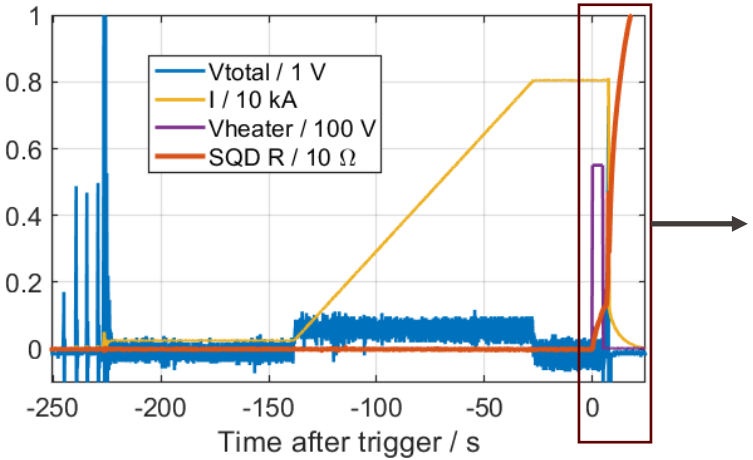


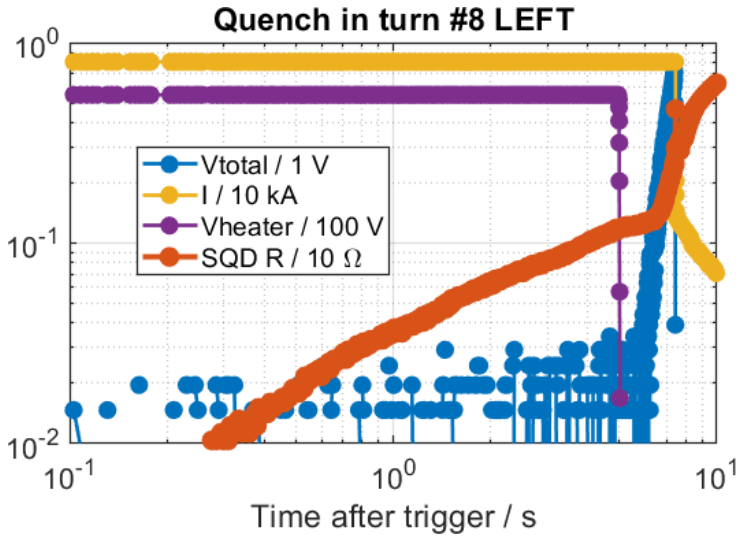


55 W heating applied at 8 kA operation:

- Turn #8 LEFT recovers after **4 s** pulse, but quenches after **5 s** pulse.
  Voltage threshold increased gradually: 135 mV, 400 mV, 600 mV
- Turn #1 RIGHT quenched by **5 s** pulse at 600 mV threshold (reached it from 10 mV in less than 2 s!)
- Turn #22 RIGHT quenched by **6 s** pulse at 600 mV threshold. It resulted in I_c degradation…

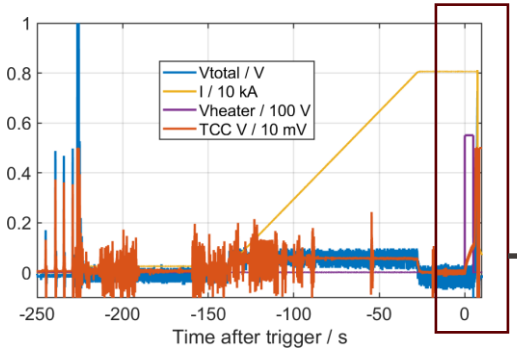
JORDI test – SQD response

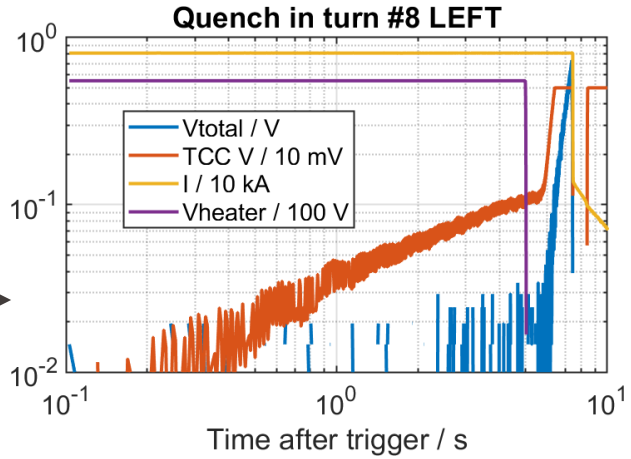


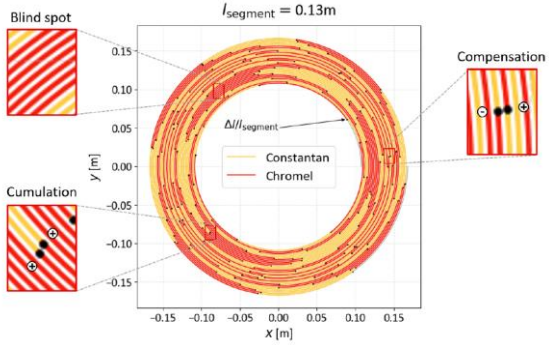


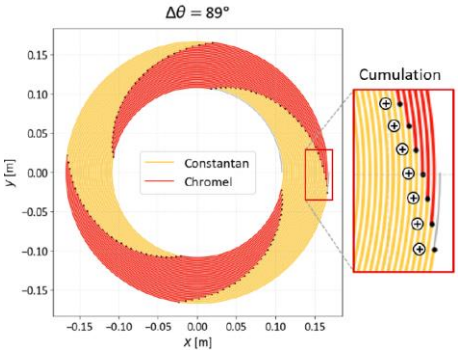
- ✓ Immune to EM noise and mechanical stresses
- ✓ Following temperature evolution → potential to discharge before thermal runaway
- ➢ Limited choice for detection threshold (Nb_3Sn vs MgB_2 vs IBS vs ReBCO)
- ✓ Reliable, i.e. responded on all quenches
- ✓ No issues on longer length, i.e. industrially available and response independent of L
- ➢ Requires calibration (can be obtained during initial 'clean' testing)

JORDI test – TCC response



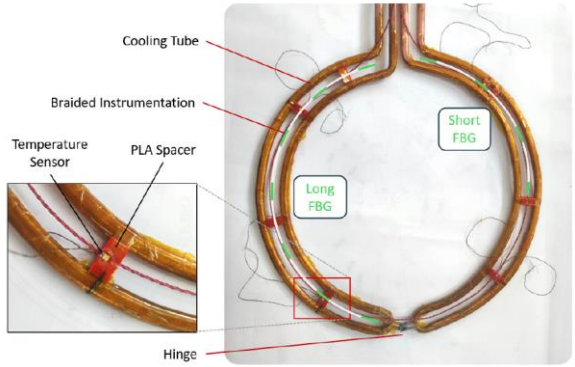


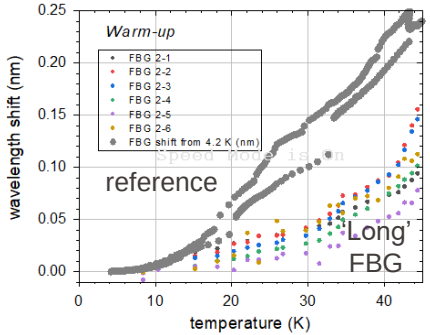


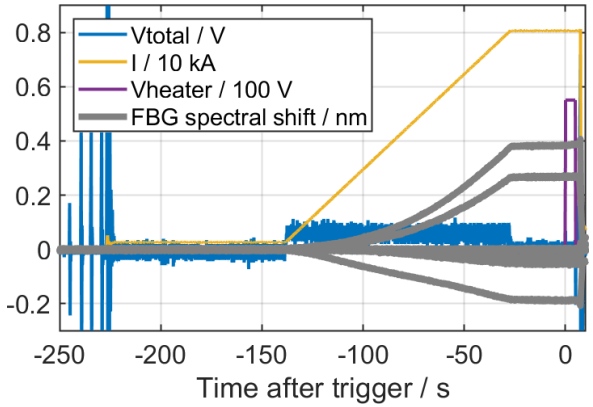


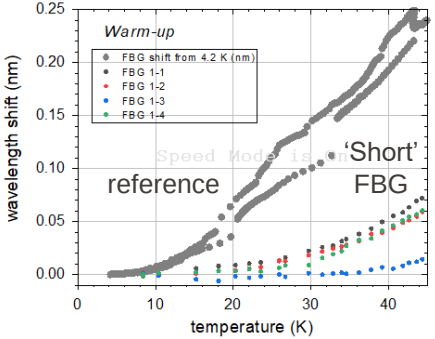
- ➢ Need for improved shielding
- ✓ Following temperature evolution
- ✓ Response on T-gradient at any temperature
- ➢ Requires specific layout to exclude ‘blind’ spots →
- ➢ Requires special tooling to produce in long length
- ➢ Requires calibration (can be obtained during initial ‘clean’ testing)

JORDI test – optical fibers









- Strong attenuation on bare fibers embedded in QD strip → DFOS methods not applicable
- FBGs installed between the two pancakes near the cooling pipe…
- However, weak sensitivity on temperature and strong on mechanical strain

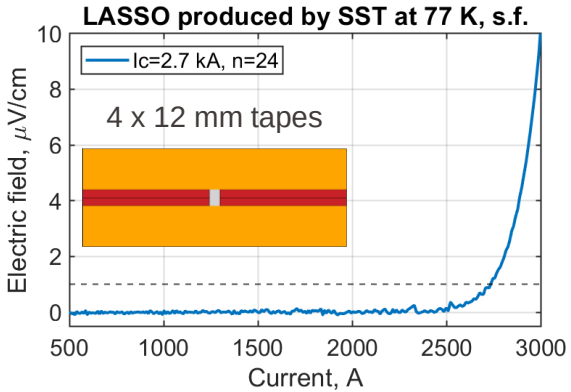
❖ Integration method must be changed

➢ Use on longer length becomes more problematic

➢ Requires calibration

Next steps

Step	Stored Energy	Operating current	HTS tape length (4 mm wide)	Objective	Planning
Double pancake	0.1 MJ (0.4 MJ at Ic)	> 10 kA (Ic~20 kA)	1.2 km	Proof of principle for quench detection method(s)	Made and tested at EPFL-SPC
Small Coil	~10 MJ	10 kA (~Ic)	23 km	Quench detection and protection in a sub-scale integrated coil	Made by industry Tested at EPFL-SPC
Model Coil	~300 MJ	50 kA (~Ic)	TBD	Quench detection and protection in a full-scale VNS-representative coil	Made by industry Tested at TBD



- ✓ Set-up LASSO cable manufacturing by industry
- ➢ Set-up QD strip manufacturing by industry…
- ➢ Set-up coil winding by industry…

SQD: attempting to order long-length iron-based superconductors…

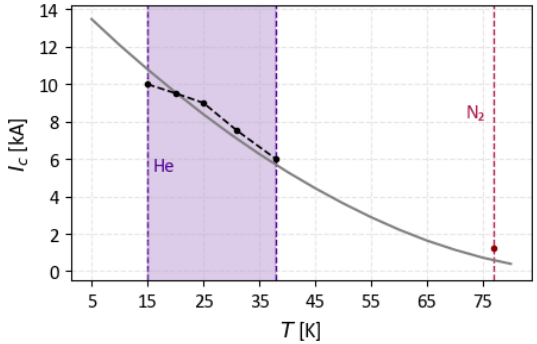
TCC: need for automated manufacturing…

Optical fibers: pending further demonstrations…

- EU RD&D program for quench protection: phase 1 sample

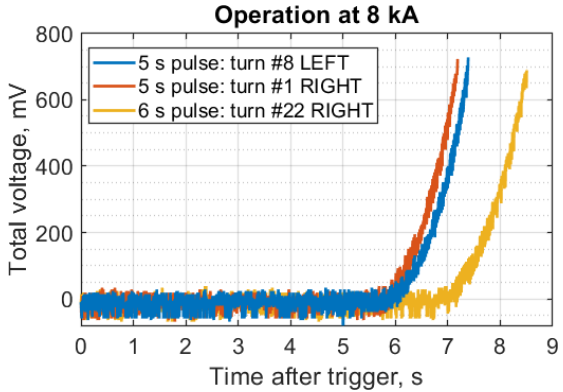
DC Test

File	I Target	dI/dt	T Start	FI1003	V Th (0.5)	V Th tot	t delay	Heater
	kA	A/s	K	mbar	mV	mV	s	label
DC_d190901	6	50	11	22				H2, H1
DC_d190902	10		31					
DC_d190903			25					
DC_d190904			20					H2
DC_d190905			15					
DC_d190906			11	127				
DC_d250901			10	135				
DC_d250902								



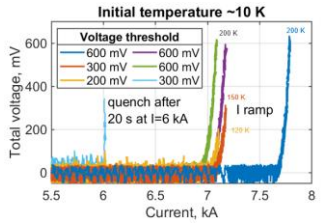
Quench Test

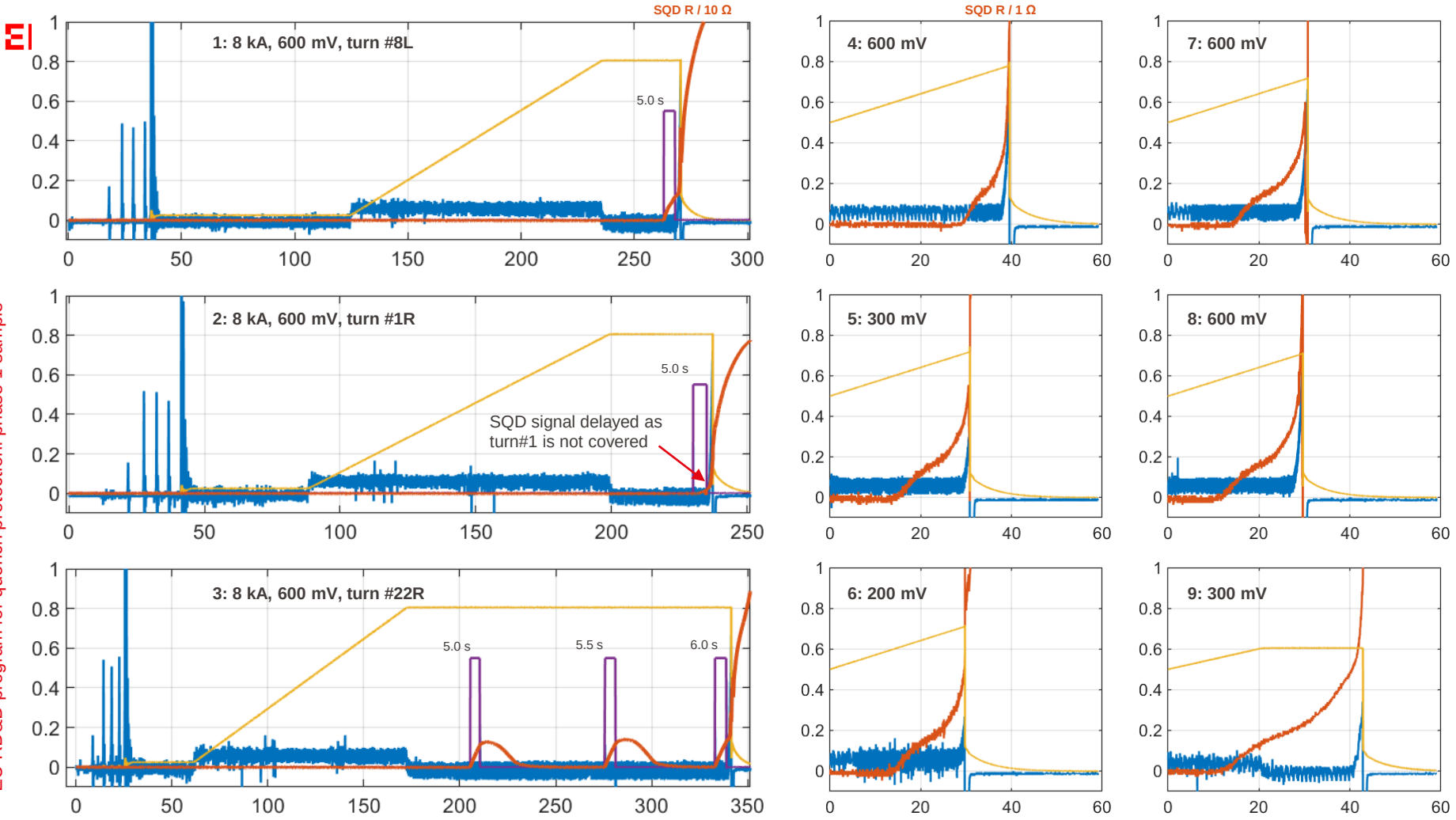
File	I Target	dI/dt	T Start	FI1003	V Th (0.5)	V Th tot	t delay	Heater
	kA	A/s	K	mbar	mV	mV	s	label
Quench_q250901	6	50	10	135	5	[10]	not used	S8 L, S22 R
Quench_q250902								
Quench_q250903					17	[35]	1 at 1.6 mV	B8 L
Quench_q250904					33	[67]		
Quench_q250905							not used	
Quench_q250906					67	[135]		B22 R
Quench_q250907								B1 R
Quench_q250908		70			67	[135]		
Quench_q260909		50				400		B8 L
Quench_q260910	8	70	10	135	not used	600		
Quench_q260911								B1 R
Quench_q260912								B22 R



DC Test after Quench

File	I Target	dI/dt	T Start	FI1003	V Th (0.5)	V Th tot	t delay	Heater
	kA	A/s	K	mbar	mV	mV	s	label
DC_d260903	10	70	10	135		600		
DC_d260904						300		
DC_d260905						200		
DC_d260906						600		
DC_d260907								
DC_d260908	6	50				300		



How did SQD react?

Nikolay Bykovskiy