IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 55, January, 2024. Invited presentation given at IREF 23, November 13, 2023, Arona, Italy

EUROfusion

Overview on the research and development of HTS conductors and irradiation studies within the EU-DEMO project

Valentina Corato – ENEA (Italy)

G. Anniballi, P. Bruzzone, N. Bykovskiy, G. Celentano, I. Duran, M. Eisterer, M. Jirsa, F. Laviano, L. Muzzi, A. Nijhuis, M. Rames, K. Sedlak and D. Torsello

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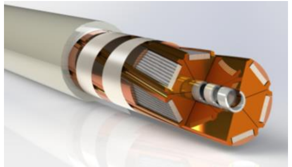
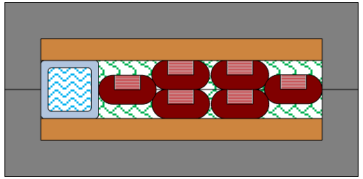
Outline

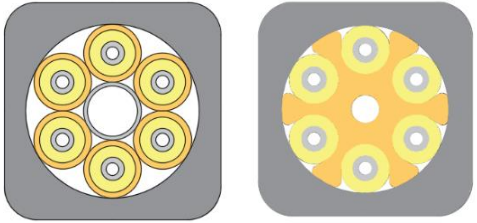
- **Introducion on EU DEMO tokamak**
- **HTS conductors for the hybrid Central Solenoid**
  - SECtor ASsembled CICC (SECAS)



  - Aligned Stacks Transposed in Roebel Arrangement (ASTRA)



  - CORC-like conductors developed by ASIPP



- **Irradiation activities**

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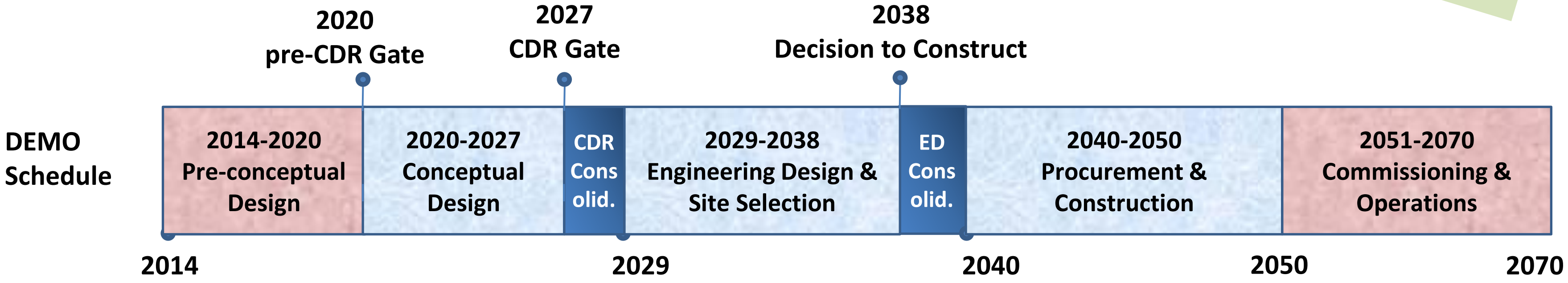
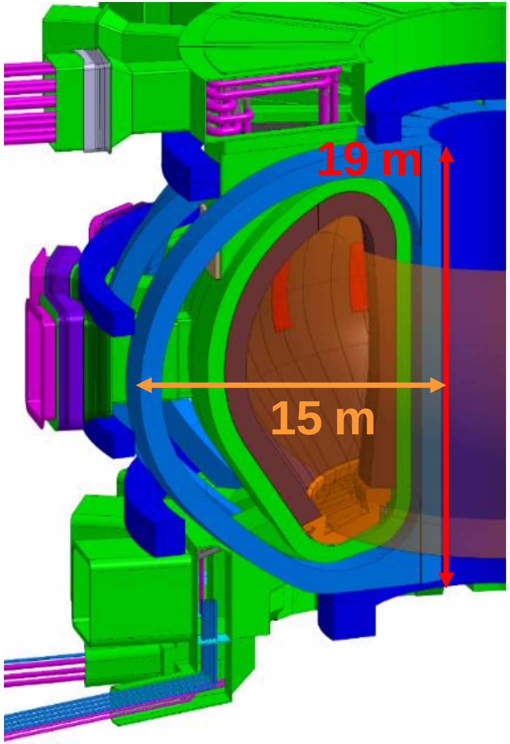
EU Fusion Energy Roadmap

- EU-DEMO reactor is designed for demonstrating net production of electricity and operation with a closed fuel cycle (TBR>1)
- The intermediate step between ITER and a commercial Fusion Power Plant (FPP)
- DEMO: 500 MW net electric power, and supply to the grid
- The DEMO staged-design approach relies on a progressive flow of validation input from ITER prior to start the DEMO construction (2040).
- Allow extrapolation to a Fusion Power Plant



Main parameters of the DEMO Baseline 2018

16 TF coils (B_{peak}= 12T, E_{total} = 150GJ)
5 CS coils (B_{peak}= 15.8 T, E_{total} = 15GJ)
6 PF coils (B_{peak}= 8 T, E_{total} = 21GJ)



Parameters	Symbol	EU-DEMO
Major radius	R_0 (m)	**9**
Minor radius	a (m)	2.9
Aspect ratio	A	3.1
Plasma current	Ip (MA)	18
Safety factor	q	3.6
Plasma elongation	k_{95}	1.6
Triangularity	δ_{95}	0.33
Av. electron density	$\langle n_{e,vol} \rangle$ ($10^{20}m^{-3}$)	0.73
Eff. ionic charge	Z_{eff}	2.2
Confinement enhancement	H	1.1
Burn Time	t_{burn} (hrs)	**2**
Bootstrap fraction	f_{bs} (%)	37
Fusion Power	P_{fus} (MW)	2000
Net electric power	$P_{e,net}$ (MW)	**500**
Divertor configuration		Single null

DEMO CS WP: Hybrid variant

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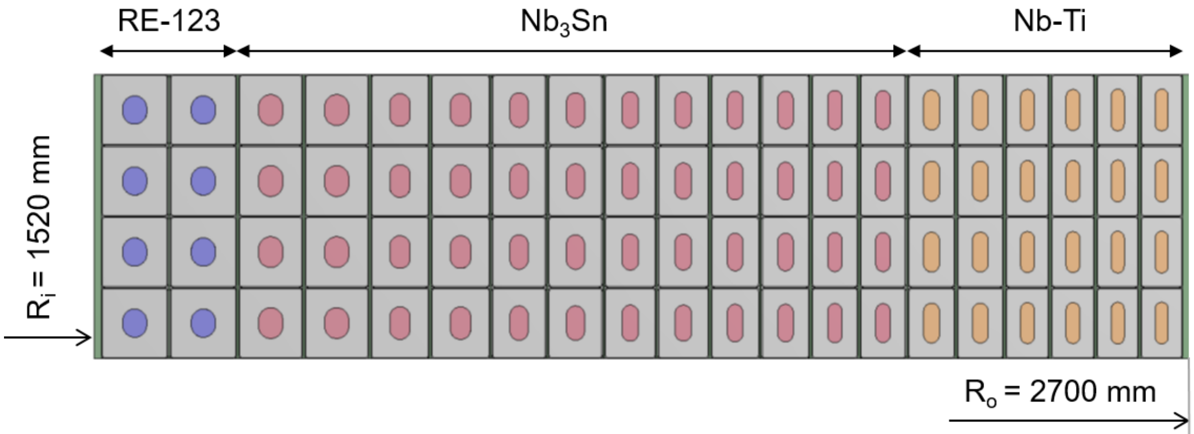
Design		Hybrid variant
Total current [MAt]		72.2
Cond current [kA]		46.3
R_i [mm]		1520
R_o [mm]		2700
Max B [T]		15.8
Mag flux [Wb]	Only CS	218.5
	CS+PF	239
σ_{hoop} [MPa]		295.4

5 modules CS (with a central double one)

The hybrid variant allows the **Increase of the magnetic flux** wrt the ITER-like design of 13%.
Layer winding with **grading on superconductor and stainless-steel**



Need to study HTS conductors suitable for the EU-DEMO central solenoid

Target for HTS CICCs

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European-Chinese collaboration with ASIPP for manufacturing, testing and modelling HTS cables and testing the BEST hybrid CS module.

Presently all manufactured conductors use REBCO tapes

DEMO CS target

Inlet Temperature = **4.5 K**

Peak field = **18 T**

Operating current = **60 kA**

Minimum bending radius = **1.5 m**

BEST CS target

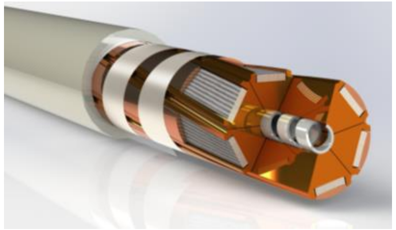
Inlet Temperature = **4.5 K**

Peak field = **20 T**

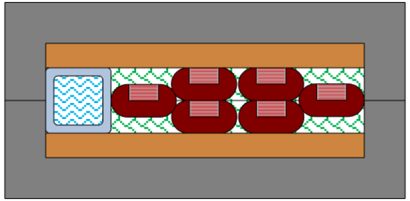
Operating current = **46.5 kA**

Minimum bending radius = **0.5 m**

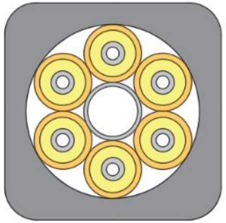
SECAS



ASTRA



Option 1



Option 2

SECAS conductor development

BRAided STack & SECtor ASsembled cable:

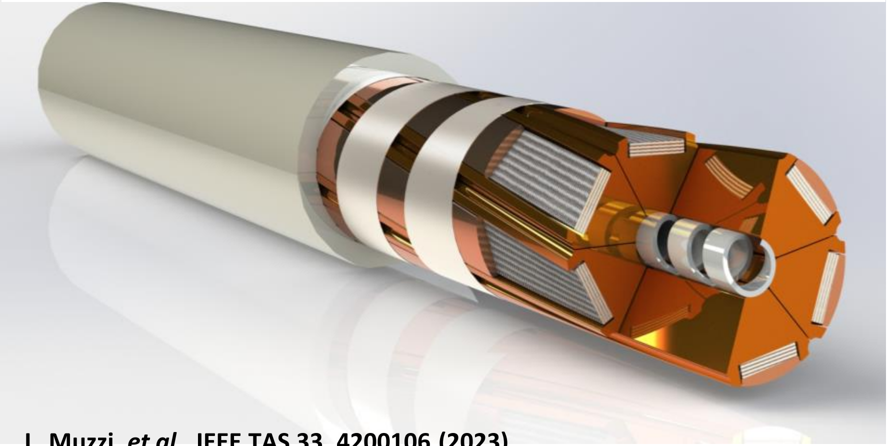
HTS stack sub-unit + new cable layout/concept

BRAided STAcks ***(BRAST)*** of REBCO tapes

BRAST Features

Flexible
Compact
Easy to handle

SECtor ASsembled ***(SECAS)*** CICC concept



L. Muzzi, *et al.*, IEEE TAS 33, 4200106 (2023)

Multi-stage cable processing approach

SULTAN sample in preparation: test in 2024

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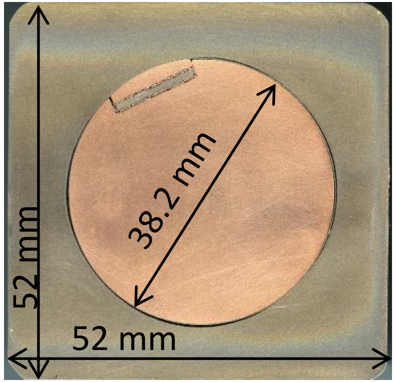
BRAST mechanical assessment: twisting and compaction

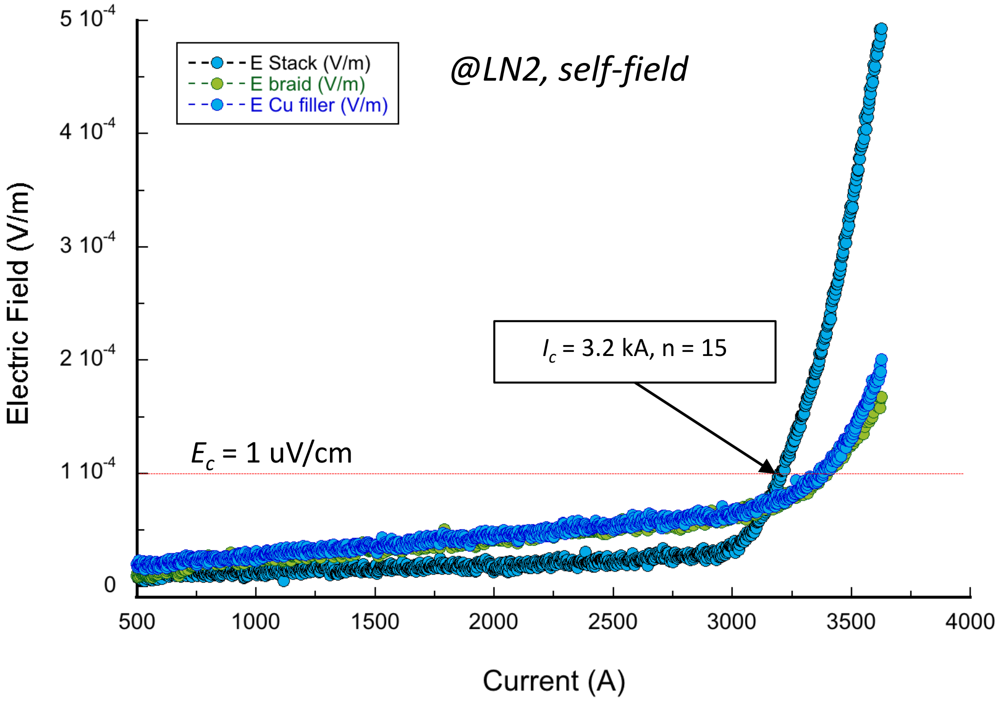
Core: Cu tube, dia. 38 mm, with machined spiral slot (Twist Pitch 1.2 m)
HTS strand: BRAST 10 tapes (SuperOx Jp, 12 mm x 0.08 um), Braid: 144 Cu wires, dia. 0.15 mm
Jacket: Circle-in-square SS tube (PF ITER cable), 54 x 54 mm, compacted with a 4 rolls mill **@CRIOTEC Impianti (Italy)**



SECAS sub-cable: electric performances

In line with calculated cable critical current by FEM model

De Marzi, et al., SuST 34 (2021)



Sample TEST in LN2 @ the ENEA 20kA test facility

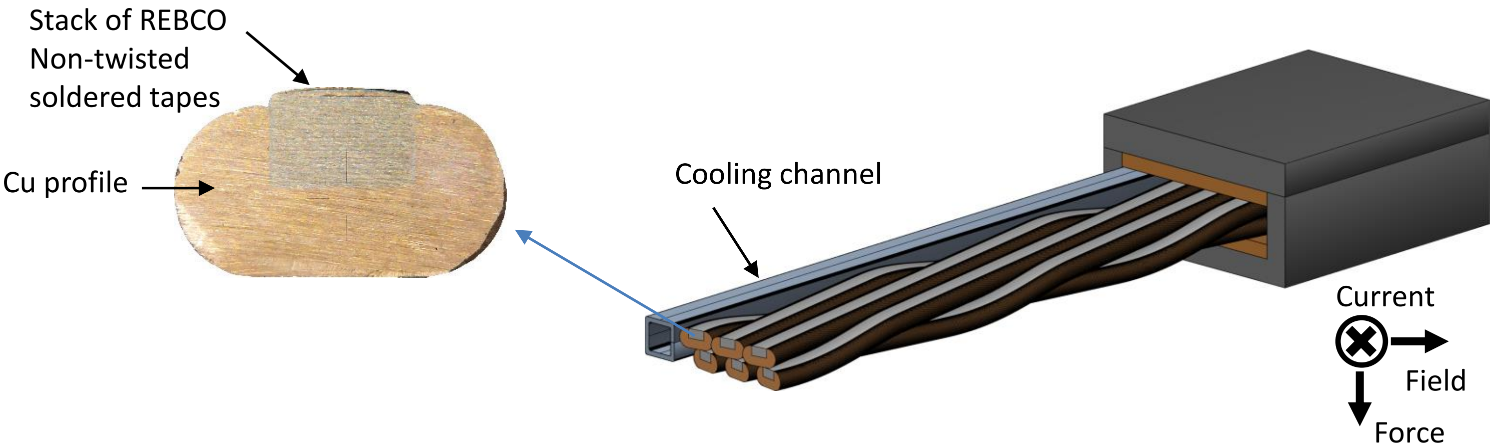
Next steps:

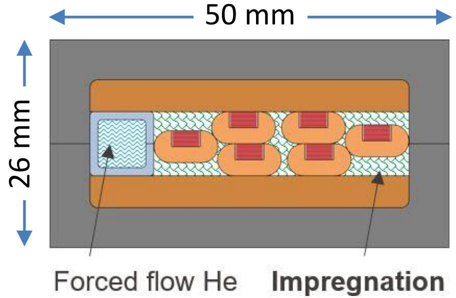
- Bending of the sample on a bending radius of 1.5 m
- Electric test to check if there is a degradation of the performance

ASTRA Conductor prototype: layout

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE | SWISS PLASMA CENTER

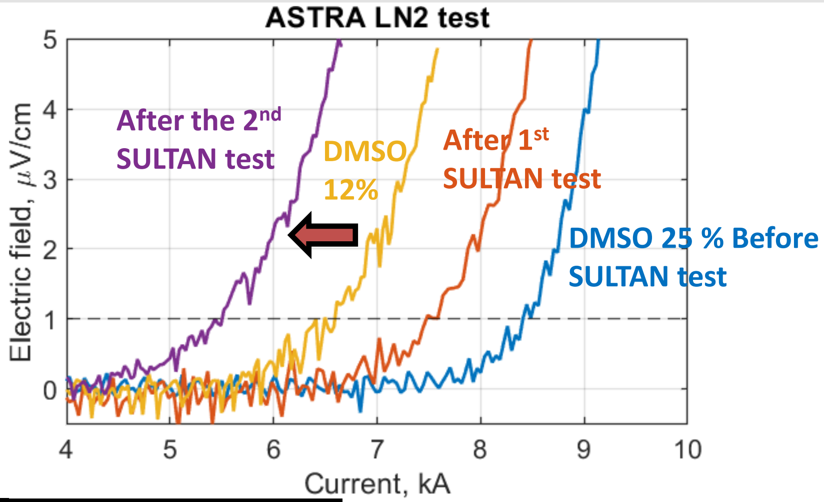
Aligned Stacks Transposed in Roebel Arrangement (ASTRA)

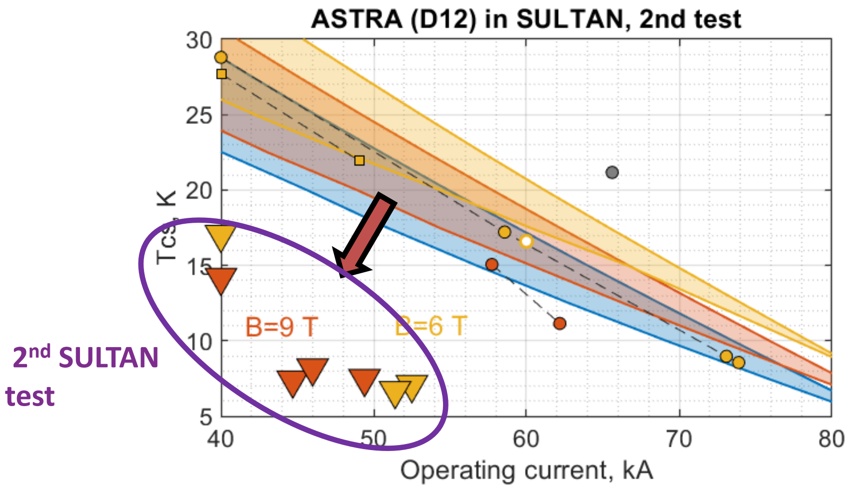


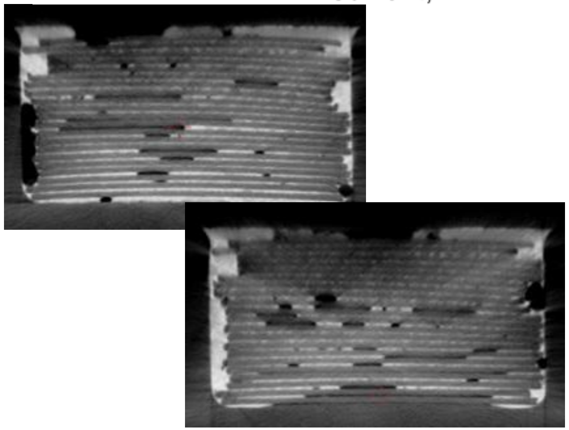


- 3.3 mm SST tapes, 21-tape **soldered stacks**
- 6 **transposed** strands (L~0.75 m) → reduce AC losses
- Aqueous DMSO (Dimethyl Sulfoxide) **impregnation** (for mechanical support)
- **Tight cooling channel** → conduction cooling
- Operation in **parallel background magnetic field** → reduce # tapes

ASTRA Conductor prototype: test results



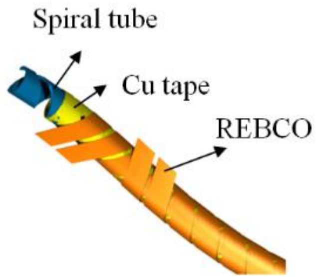




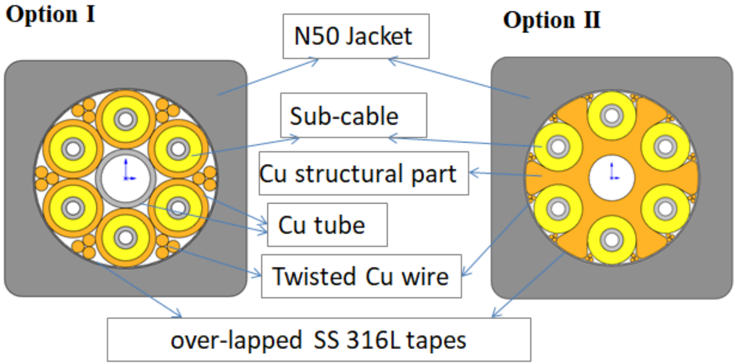
- Initial DC performance in-line with expectations both from LN2 bath and SULTAN testing.
- Strong performance reduction by EM load (at 9 T, 63 kA ~570 kN/m) and thermal stresses by frozen aqueous DMSO due to its thermal expansion
- Voids in soldered stack might be the root cause, thus strand manufacturing is being revised trying either to improve soldering or avoid using it (using BRAST strands).

ASIPP CICC specimen tested at Sultan

◆ HTS CICC under developing at ASIPP (Design and manufactured at ASIPP)



CORC®-like sub-cable concept and cabling



Item	Parameter
Tape No.	210
Cable OD	31.75±0.15mm
Twist Pitch	500±50 mm
Conductor OD	41.1±0.15mm
Conductor length	2.77 m

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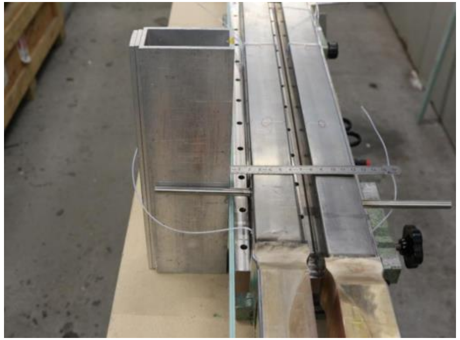
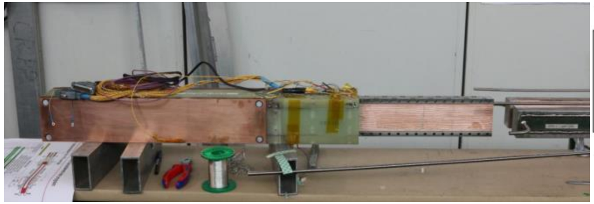
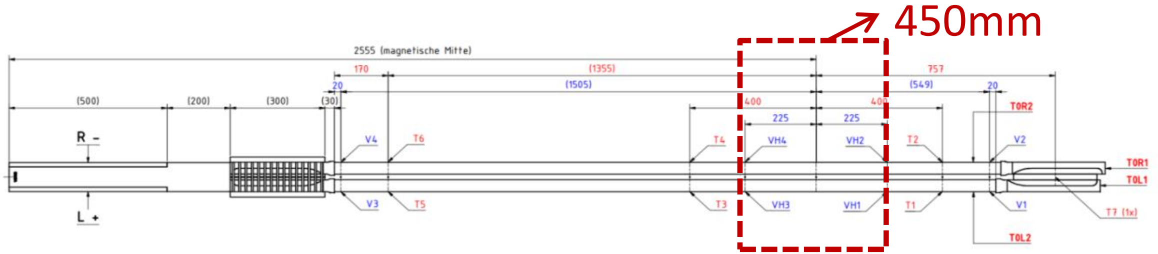
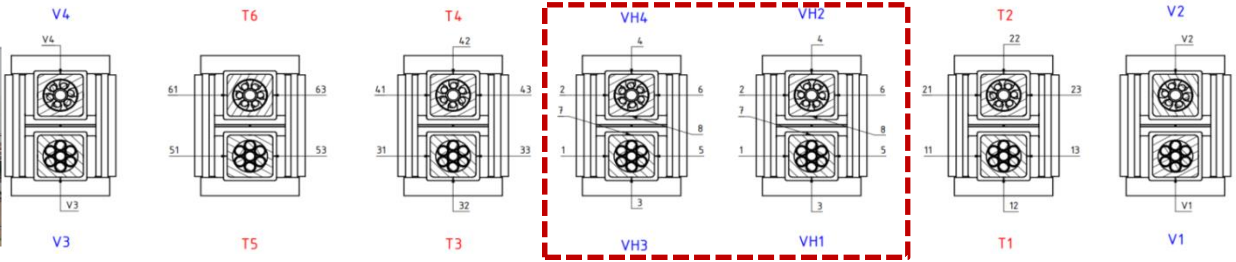
◆ Specimen and instrumentation assembly finished at SULTAN lab



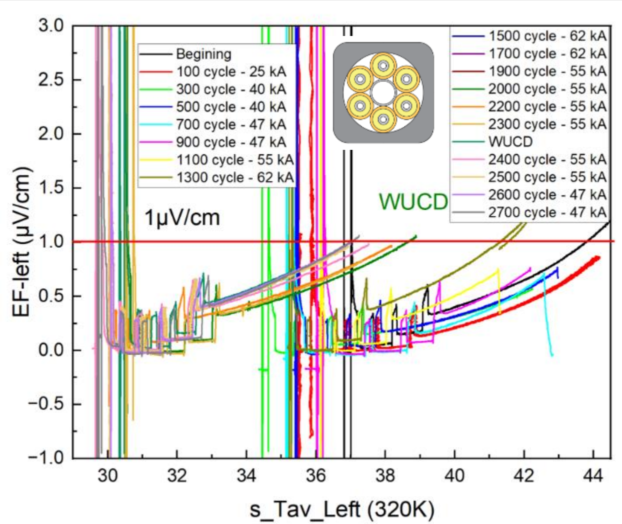


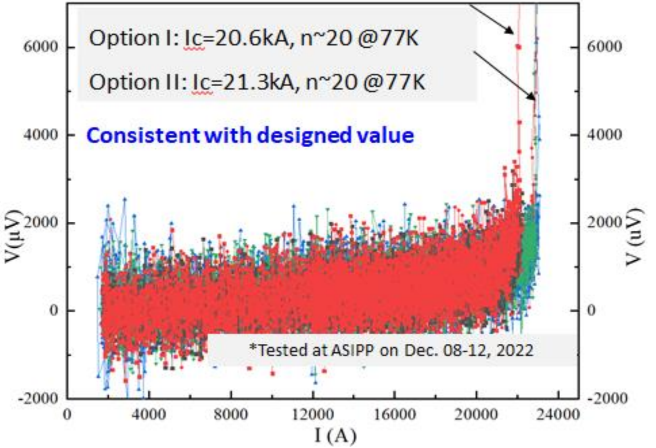




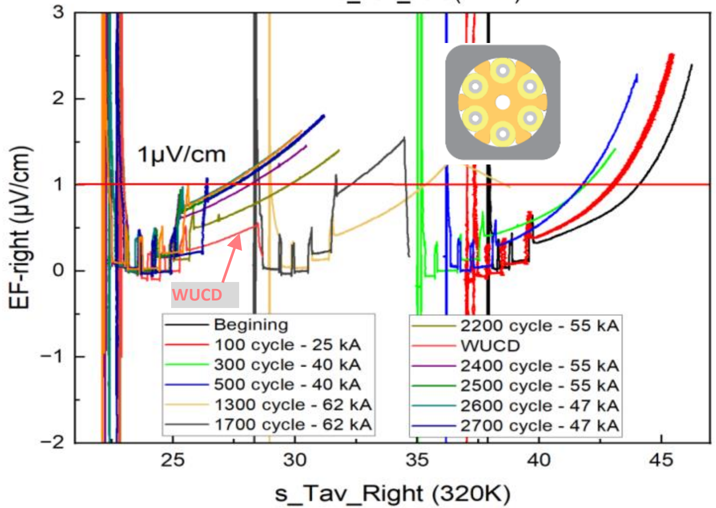
DC test results of ASIPP sample

- Critical current are around 21 kA @77 K self-field (Tested at ASIPP);
- the predicted Tcs at 25kA,10.8T is around 43K.
- Totally 2700 EM cycle with current from 25 kA to 62 kA @ 10.8T were carried out;
- The sample shows stable performance with EM cycling when the current ≤ 47kA (option I) and 25 kA (option II). Progressive degradation is observed for higher currents;





Courtesy of Qin



Twente CICC Model of ASIPP sample

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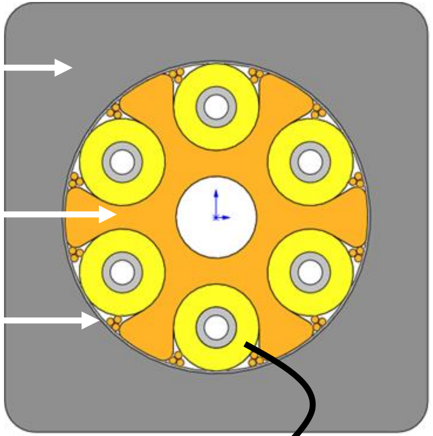
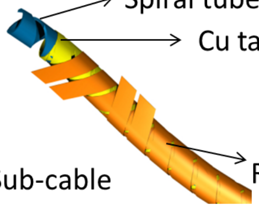
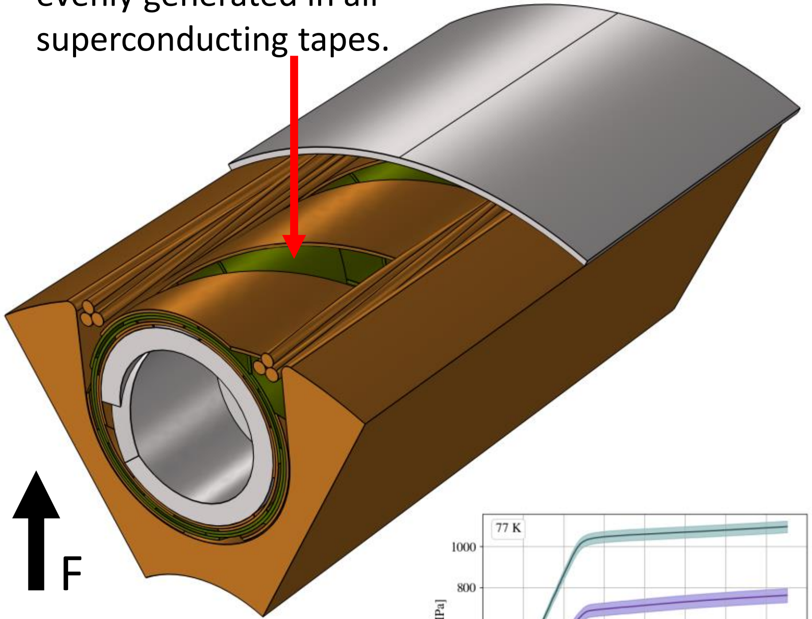


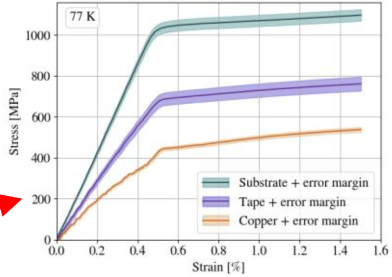


Sub-cable parameters	
Tape manufacturer	Fujikura
# SC Tapes	36
# Cu Tapes	7
# Layers	16 (3 Cu)
# Simulated Layers	3 (3 Cu)
Tape width	4[mm]
Tape thickness	110 [μm]
Substrate thickness	50 [μm]
Copper thickness	23 [μm]
Spacing	1.3/1.6 [mm]
Core	SS Spiral
Spiral Thickness	0.8 [mm]
Strain window	[-1.3 %, 0.29 %]

EM-load simulated as body load, evenly generated in all superconducting tapes.



Axial stress-strain curves measured at Twente for use as model input parameter.



EM load is equal to nominal one.

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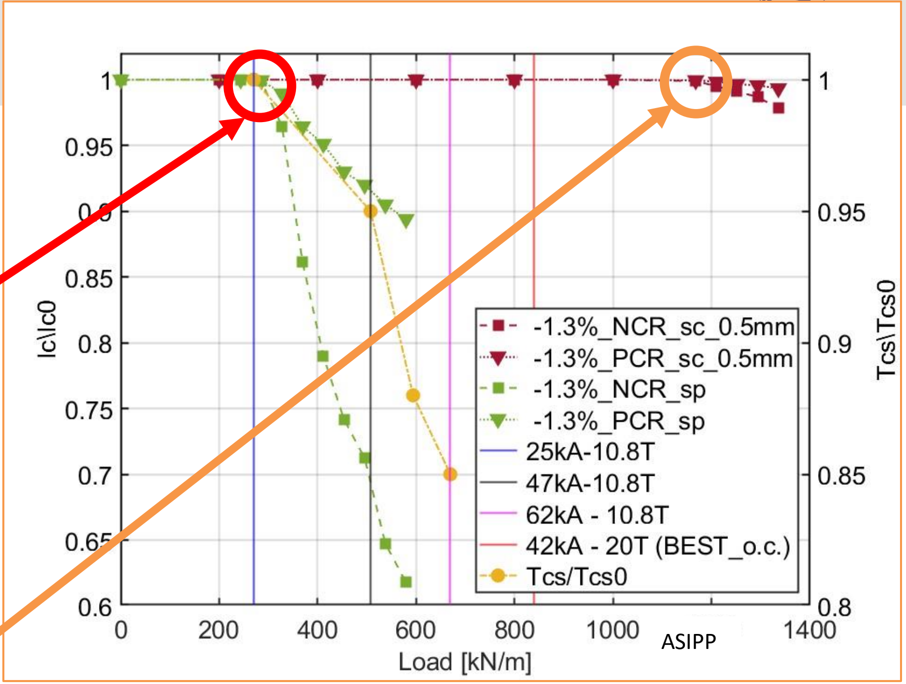
Model & Sultan sample results

	I [kA]	B [T]	F [kN/m]
SULTAN (max)	100	10.8	1080
BEST CS	42	20	840
EU-DEMO CS	60	18	1080



Irreversibility starts @ ~ 300 kN/m (27 kA/10.8 T). Model prediction of first damage & SULTAN T_{cs} reduction coincide.

Damaged volume fraction ReBCO ~ 1.5% at 47 kA / 10.8 T Sultan *IxB* condition.

Proposed optimization:
Reducing gap from 1 mm to 0.5 mm leads to sufficient improvement.

- _sp = with spiral and 1 mm tape gap spacing (actual ASIPP sample)
- _sc_0.5mm =with solid core & 0.5 mm tape gap spacing
- NCR = no current sharing between tapes.
- PCR = perfect current sharing between tapes.
- Vertical lines: Sultan testing load levels (*IxB*).
- ASIPP o.c. = ASIPP CS coil operating condition.

ASIPP CICC; Gap ~ 1 mm and ~ 0.5 mm

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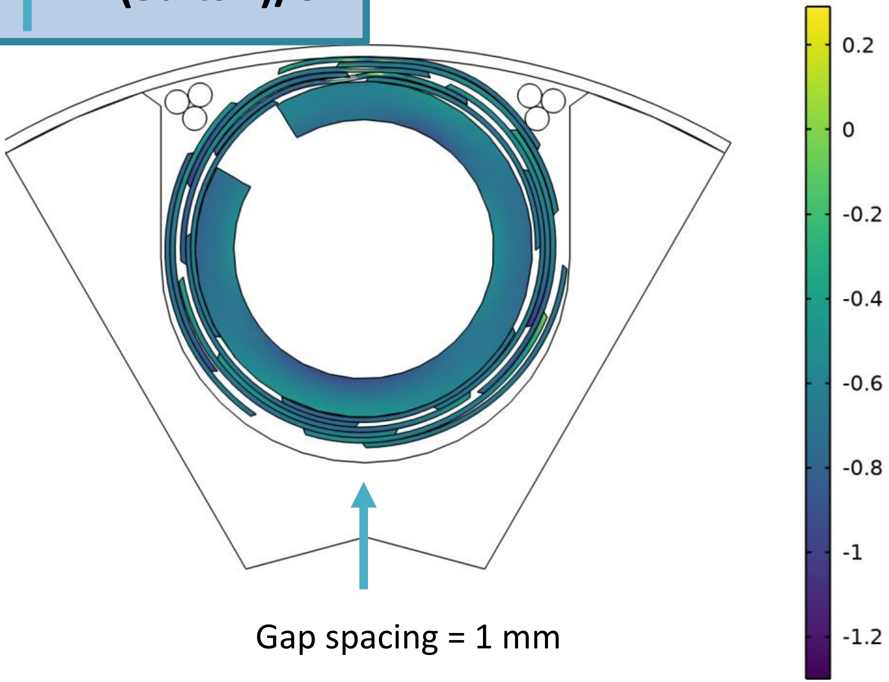
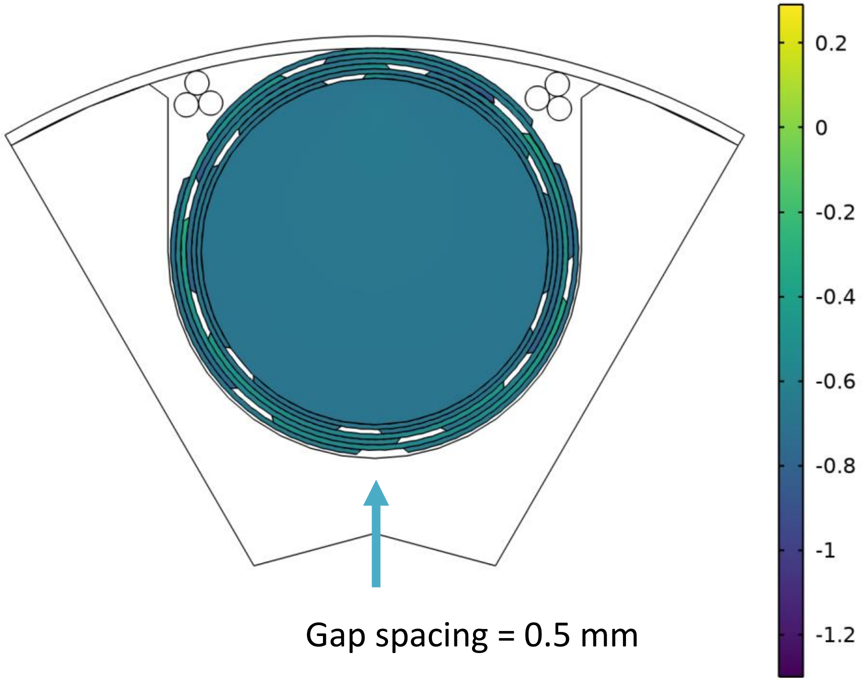
F=F(Sultan)/6

GAP= spiralling spacing between tapes from the same layer



Gap spacing = 1 mm



Gap spacing = 0.5 mm

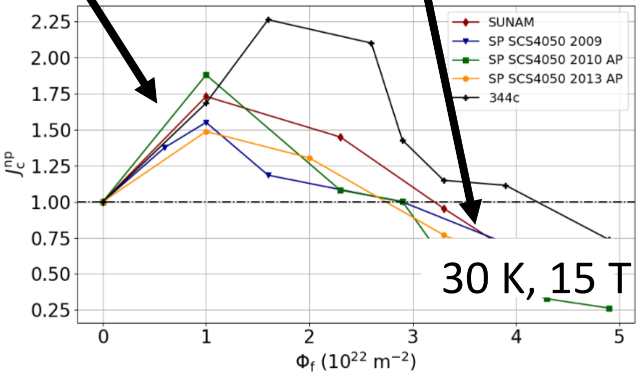
Reducing gap from ~ 1 to ~ 0.5 mm reduces voids and bending and significantly improves performance.

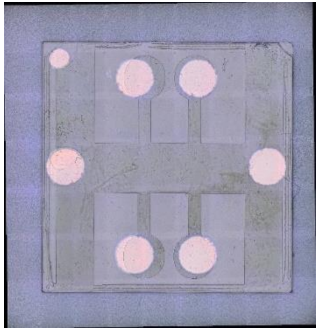
Irradiation activities: TU Wien

- Irradiation and characterization of coated conductors from commercial suppliers (SuNAM, SuperOx, SuperPower, Theva, D-nano)
- Understanding the reasons for the degradation at high fluences

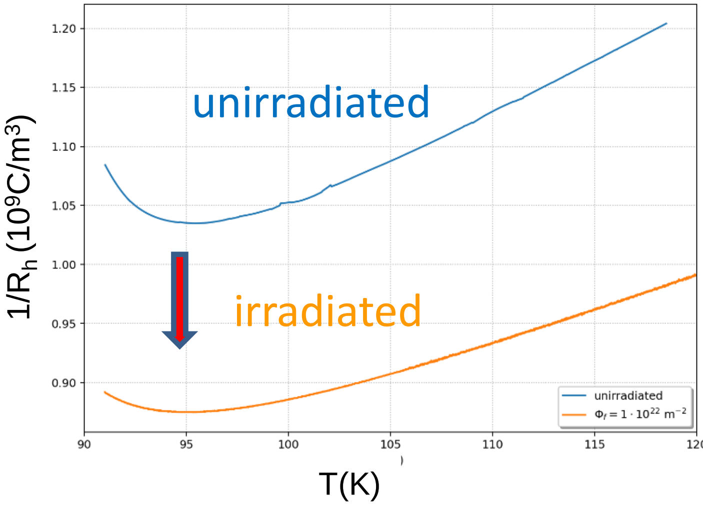
Large defects → Improved flux pinning

Small defects → Reduced superfluid density





1 µm YBCO (PLD) on 10mm x 10mm MgO substrate

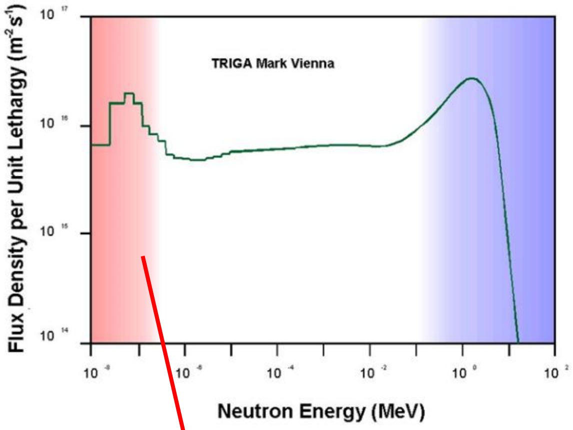


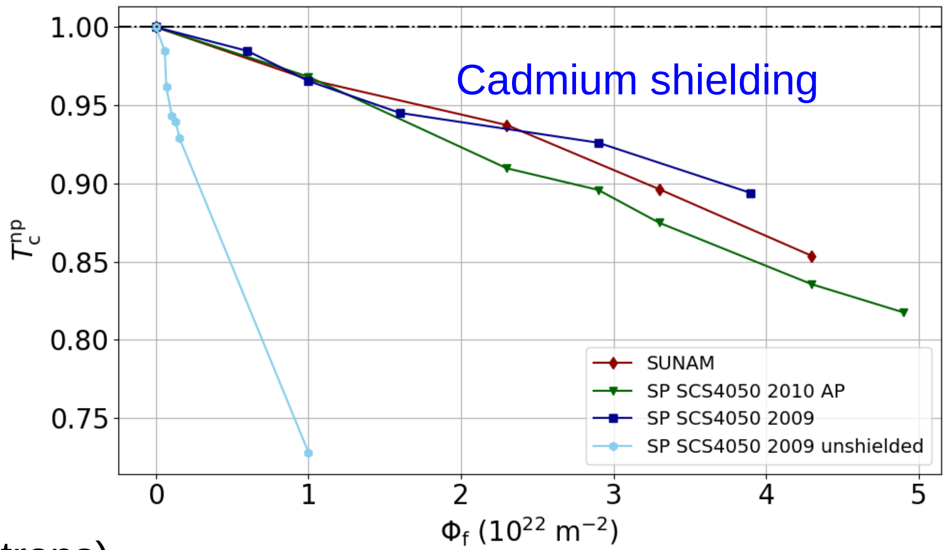
Hall resistivity is indirectly proportional to charge carrier density.

Irradiated samples have reduced # of charge carrier → Reduced Superfluid density

Irradiation activities: TU Wien

Understanding the reasons for the degradation at high fluences: Role of small defects





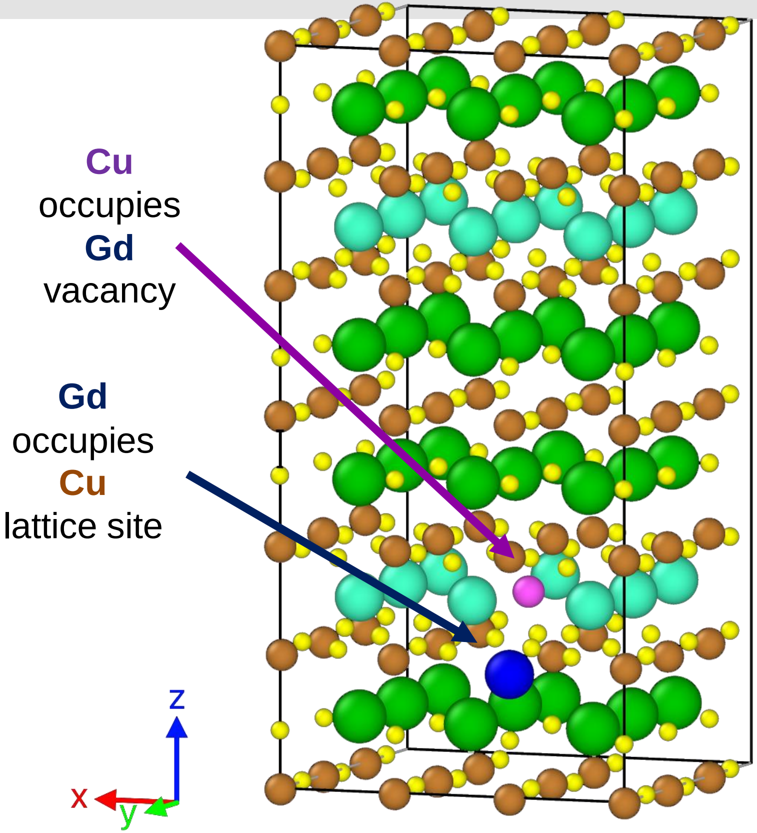
Neutron capture reactions (low energy neutrons)

^{157}Gd + n → ^{158}Gd + γ (σ ~ 2x10^5 barn)

Recoil energy: ~ 30 eV → single displaced atom

Why are these defects so efficient in degrading the superconductor?

Irradiation activities: Tu Wien/PoliTO



Defects in the Cu-O planes!

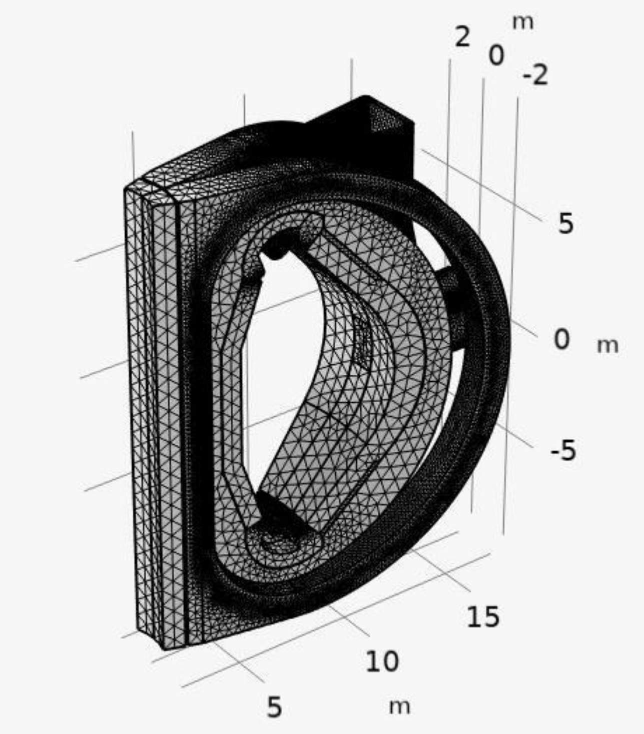
- Picture shows one of the potential defects
- Distortion in the Oxygen lattice very localized
- Very stable distortions of the lattice

Collaboration with
Davide Gambino (Linköping University)
Francesco Laviano and Daniele Torsello
(Politecnico of Turin)

See the presentation of Raphael Unterrainer on Wednesday h. 9:00.

Irradiation activities: PoliTO

- Monte Carlo calculations of neutron fluxes and spectra on SC cables of TF coils for **DEMO design**



- Detailed estimation of dpa in TF coils and also in HTS of CS coils will give an updated picture

reactor	total flux at TFC ($cm^{-2}s^{-1}$)	nuclear power at TFC	dpa at 10 Full Power Year
DEMO [1]	$5{\cdot}10^9$	80 W/m^3	$3{\cdot}10^{-4}$
ARC-like [2]	$1.28 \cdot 10^{13}$	32 kW/m^3	0.22

[1] P. Pereslavtsev et al., Fusion Engineering and Design 89 (2014) 1979–1983
[2] F. Ledda et al., submitted

Irradiation activities: IPP.CR

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Fast neutrons	Energy (0.1 MeV, 20 MeV)	Gradual fluence (10^{22} m^{-2})				
		Step 1	Step 2	Step 3	Step 4	Step 5
		0.6	0.16	3.0	0.57	1.83

Sample set	Cumulative fluence (10^{22} m^{-2})				
	Step1	Step2	Step3	Step4	Step5
1	0.6	0.76	3.76	4.33	6.16
2	n.a.	n.a.	3.0	3.57	5.4
3	n.a.	n.a.	n.a.	0.57	2.4

The last irradiation was done in another channel of the reactor, closer to the neutron source, at much higher irradiation speed (about 20 times)

→ Intense irradiation heating by neutrons and gamma rays

→ Insufficient sample cooling

→ **Degradation of HTS tapes due to overheating**

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Irradiation activities: IPP.CR

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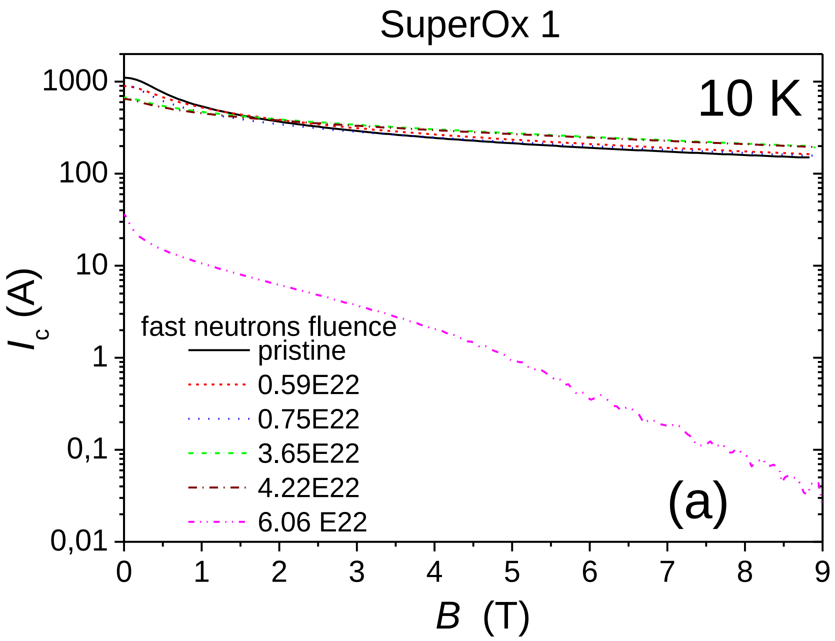
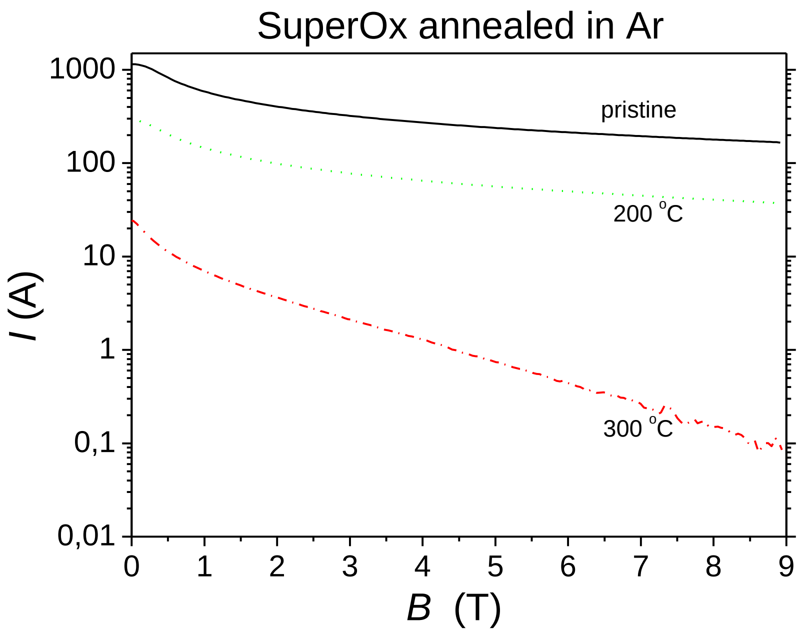
Modelling the effect of samples overheating by annealing samples at high temperatures





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Irradiation activities: IPP.CR

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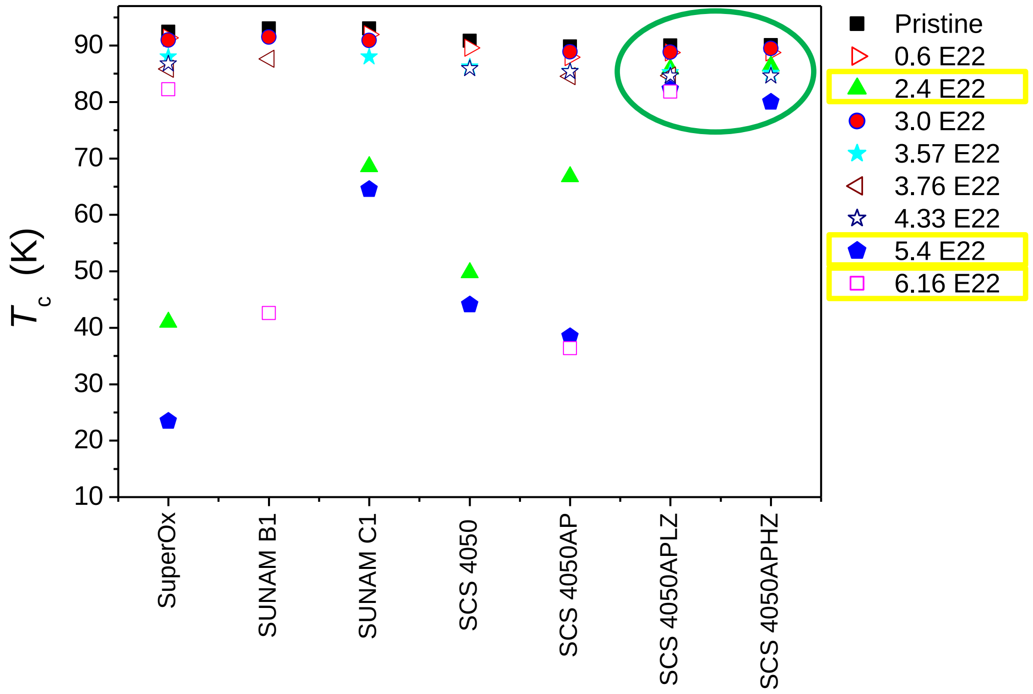

1. Limiting temperature of the tape handling is about 200 °C.
2. The tapes doped by Zr possess much higher thermal stability than others. It originates from a more stable crystalline structure of $ZrBO_3$ (TEM).
3. For further irradiation experiments, the thermal contact of samples with the glass envelope cooled from outside to 55 °C must be improved.

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Conclusions

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- All HTS conductor prototypes have initial performances in line with expectations
- The degradation of the performances of HTS full-scale conductors with electromagnetic cycles requires improved technical solutions
- Irradiation experiments indicate that:

1) degradation at high fluences are due to small defects that reduce superfluid density
2) Intense Irradiation heating, causing a sample overheating above 200 °C, can degrade the HTS tapes (but Zr-doped samples are more robust)

Thanks for your attention