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# Analysis of stability margins with JackPot-ACDC of four ITER Central Solenoid conductor designs during a 15 MA plasma scenario

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# Content

- Intro – CS optimisation
- DC & AC performance results
- Simulation inner turn CS Coil & comparison to Tcs tests
- Transient stability
- Conclusions

Aim: explore temperature and current stability margins for ITER Central Solenoid inner turn at 15 MA Plasma Scenario conditions for different CSIO cable options.

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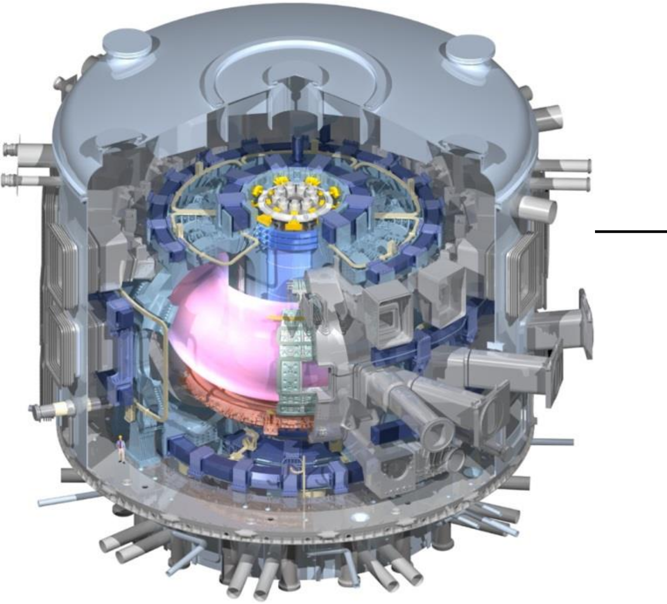
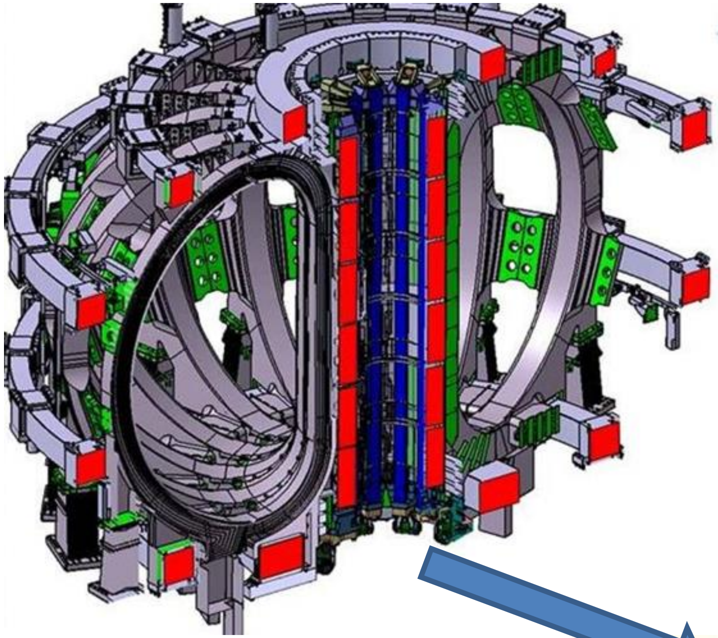
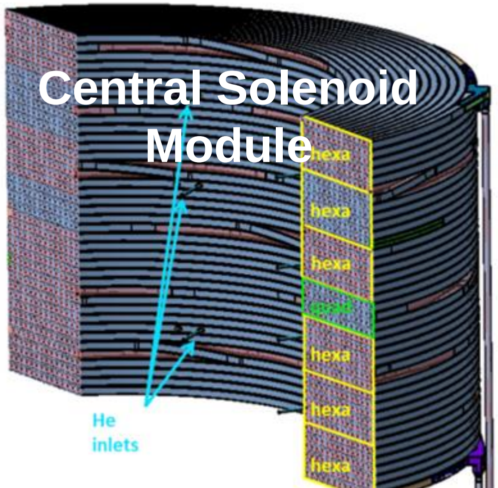
china eu india japan korea russia usa

# ITER CS Coils

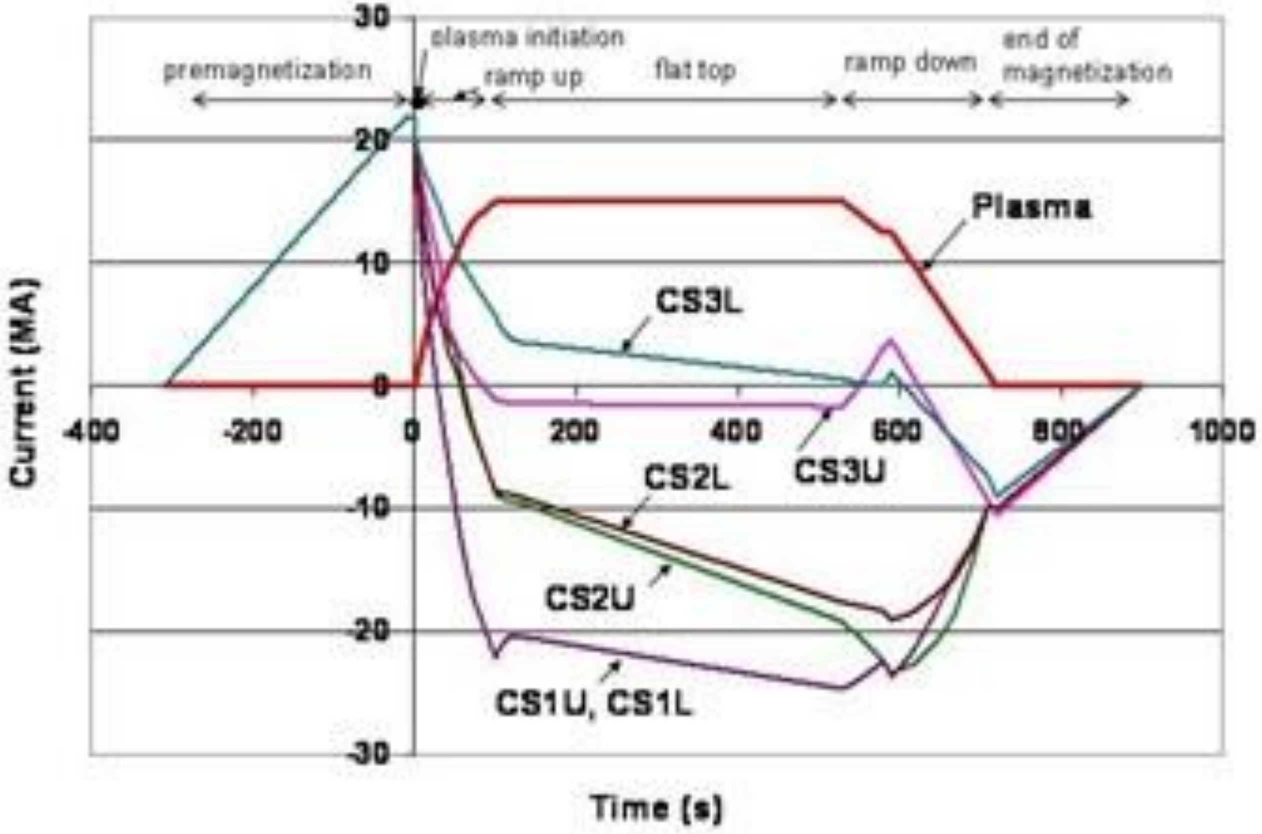






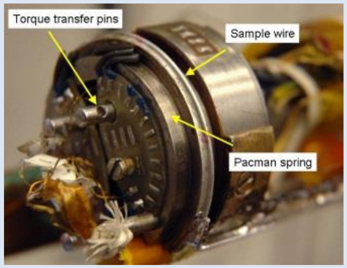
ITER Central Solenoid (CS) - diameter 4,3 m, height 13 m, 1000 tons, Imax=46 kA, Bmax=13 T. Stored magnetic energy 6,4 GJ to initiate and sustain a plasma current of 15 MA for 300-500 s

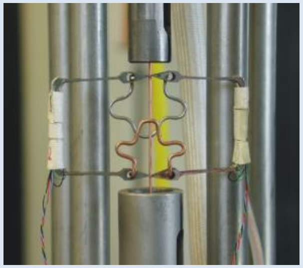
# ITER CS Coils current ramps



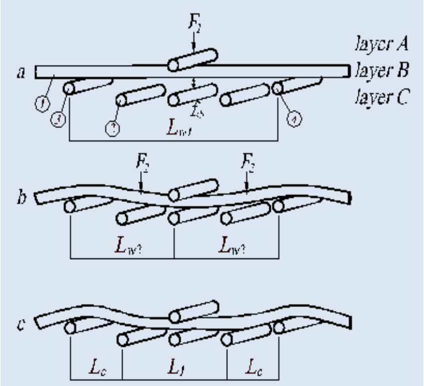
The CS modules will be magnetized together, and then discharged according to individual current profiles to initiate and sustain the ITER plasma (shown in red).
30,000 plasma pulses are foreseen for the ITER experimental campaign, fast ramping at SOD

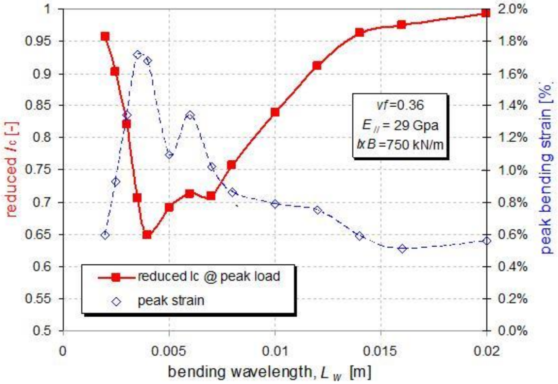
# TEMLOP prediction 2006 / validation 2007

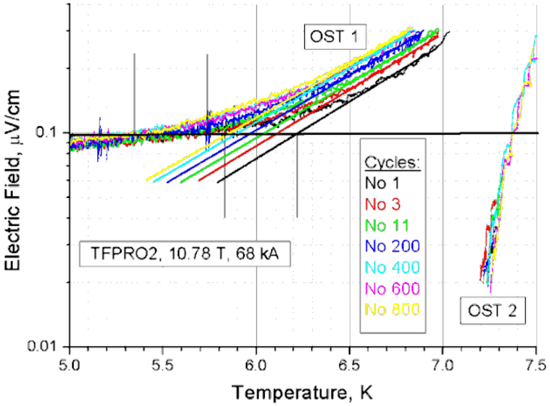




Input parameters all experimentally determined (strand & cable loads)







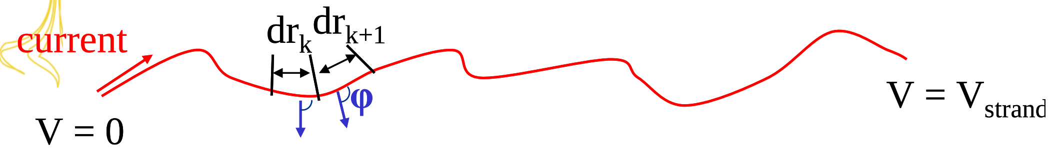
Long / short twist pitch, lower void fraction, high strand stiffness enhances strand support and reduces transverse load degradation

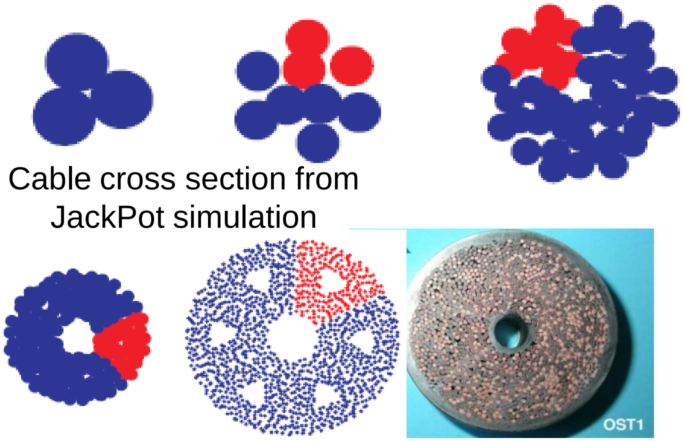
Evidence that cabling pattern is important to control EM and Thermal cyclic **degradation**

At the same time, cable pattern determines **interstrand coupling** loss: → **optimisation!**

# JackPot-ACDC CICC cable model

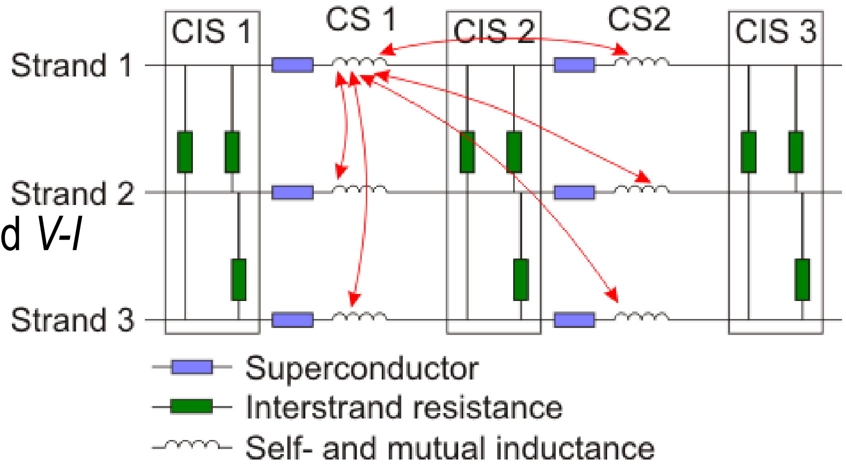
Cable / joint model accurately describing *all* (>1000) strand trajectories in CICC (>10 m); including compaction steps.





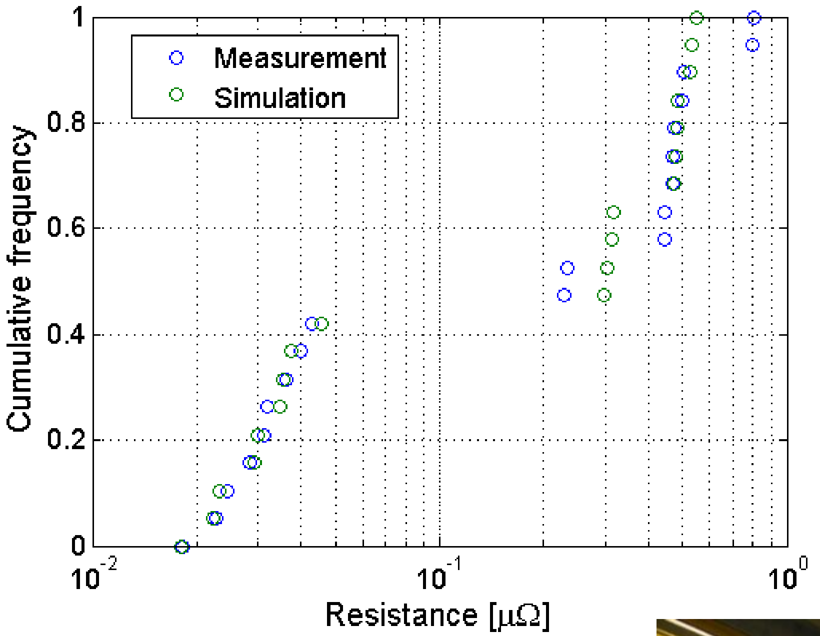
Cable cross section from JackPot simulation

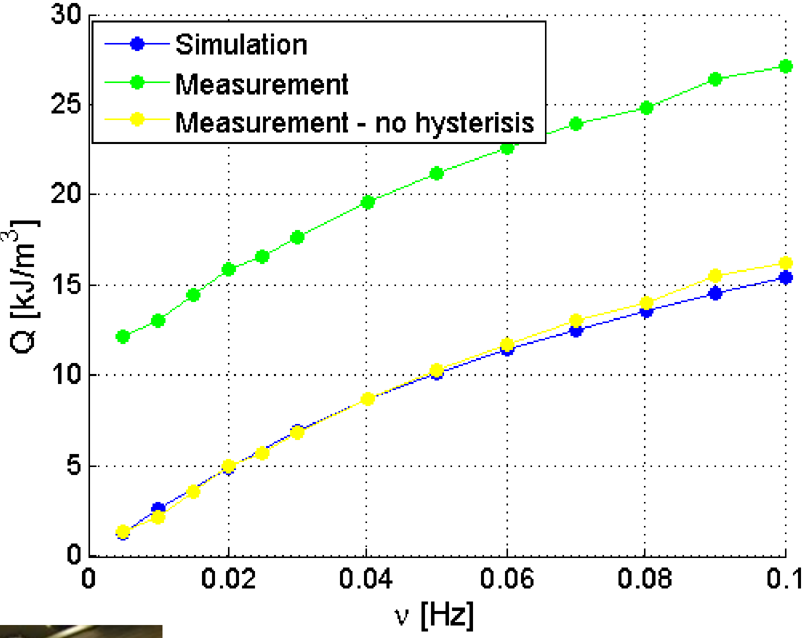
- Simulated strand trajectories used to:
  - calculate interstrand contact resistance distribution;
  - calculate mutual inductances
  - coupling with self- & background field
- Strand's properties scaling law $I_c(B,T,\varepsilon)$ and $V$-$I$
- Copper magneto-resistance
- Suitable for any cable pattern
- 7 channel coupled thermo-hydraulic model (central channel and 6 petals)



Electrical network

# JackPot AC Loss: validation



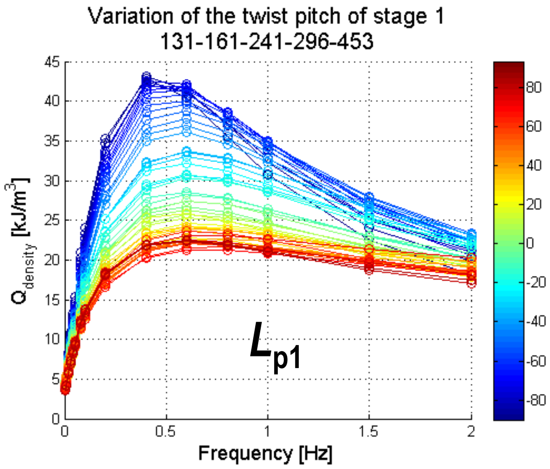


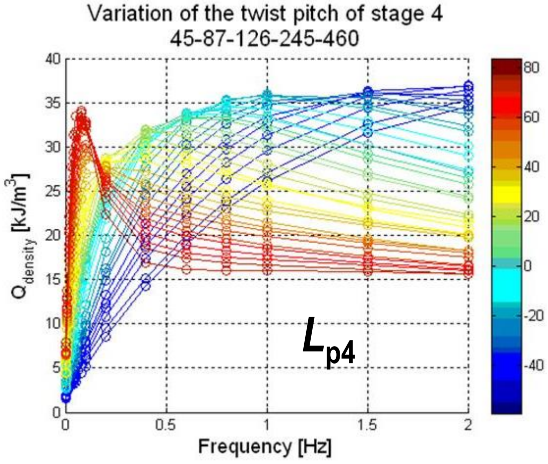
TFJA5-JASTEC sample interstrand resistance cumulative distribution measured from different cable stages in the Twente Press and its fit by JackPot.

AC loss measurement and JackPot prediction based on the interstrand resistance measurements (hysteresis loss subtracted).

**Good match!**
**JackPot suitable for prediction**

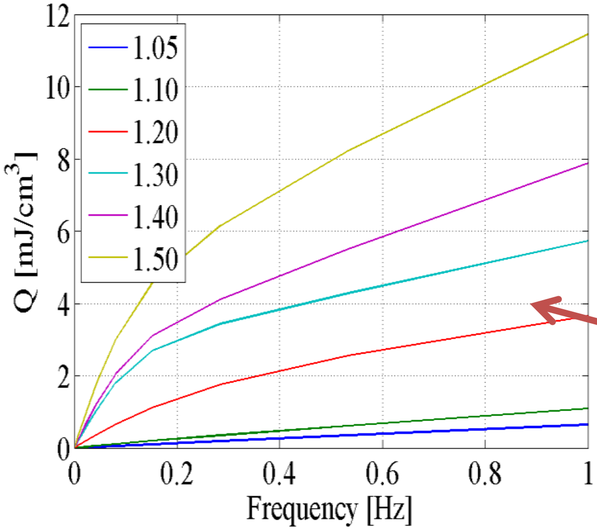
# JackPot ACDC: interstrand coupling loss





Increase $L_{p1}$ leads to lower coupling loss

Increase $L_{p4}$ leads to an increase in loss



Extensive parametric study with twist pitch variations.

"β" = ratio in cabling twist length ($L_p$) sequence from one cable stage to the next:
$L_{p2} = \beta * L_{p1}$, $L_{p3} = \beta * L_{p2}$ etc,
$\beta$ varied from 1.05 to 1.50 and $L_{p1}$=100 mm

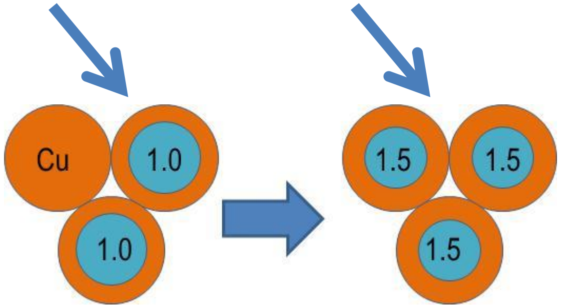
**Minimum coupling loss for $\beta \approx 1$**

# JackPot-ACDC CS design option LTP

Aim: design for <u>low AC </u>loss with minimum sensitivity to <u>EM forces</u>.
IO constraint: void fraction > 30 %

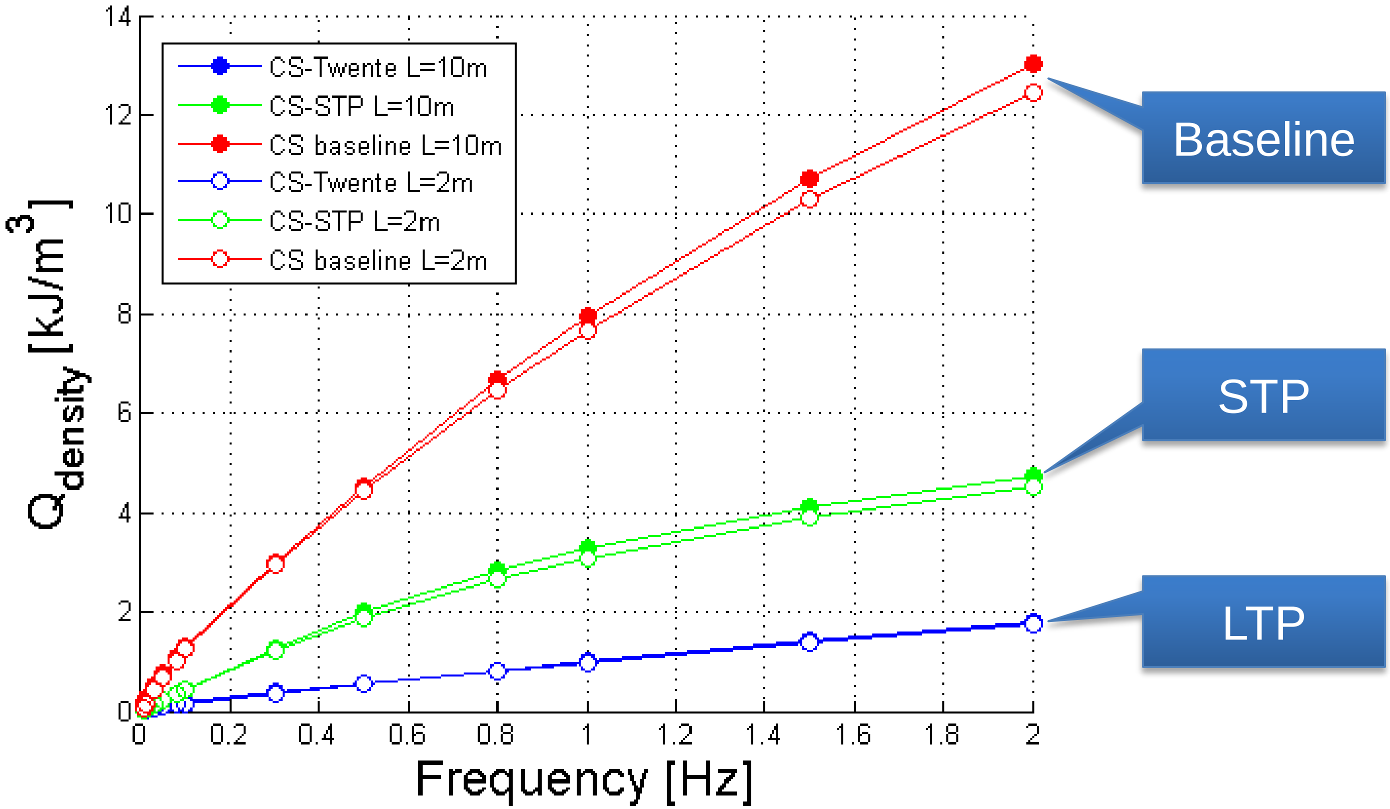
| Twist pitches [mm] | CSIO-2sc baseline | CSIO-3SC (Cu:nCu-1.5) | CS-Twente Long TP | CSIO-Short Twist Pitch |
|---|---|---|---|---|
| Lp-ratio β | 1.8 | 1.8 | 1.1 | 2.0 |
| Lp1 | 45 | 45 | 110 | 20 |
| Lp2 | 83 | 83 | 118 | 44 |
| Lp3 | 141 | 141 | 126 | 78 |
| Lp4 | 252 | 252 | 140 | 156 |
| Lp5 (petal) | 423 | 423 | 352 | 423 |
| Petal coverage [%] | 70 | 70 | 70 | 70 |
| Void fraction [%] | 33 | 33 | 30 | 30 |

Cabled according to the CS (2sc + 1Cu) x 3 x 4 x 4 x 6 configuration.



“Locked strands” high compaction

# JackPot coupling loss 2 & 10 m cable



A priori prediction: comparison between coupling loss of 2 m and 10 m long cable, for three different cable twist pitch layouts. Assumption: all same void fraction & similar ISCR.
Not sensitive to length increase from 2 to 10 m.

# Strand lateral support & petal wraps

CS-Short Twist Pitches

CS Baseline pattern

CS-Twente LTP design

Petals before and after wrapping 70 – 80 % coverage.

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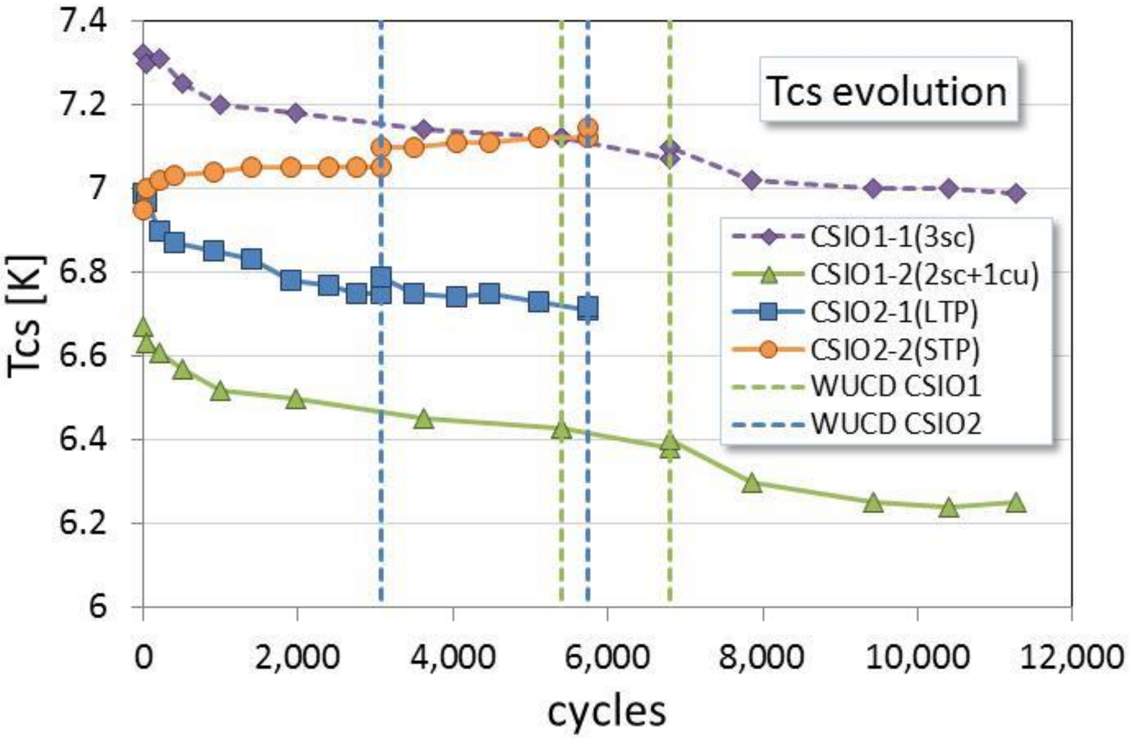
# Sultan results: Tcs versus cycling

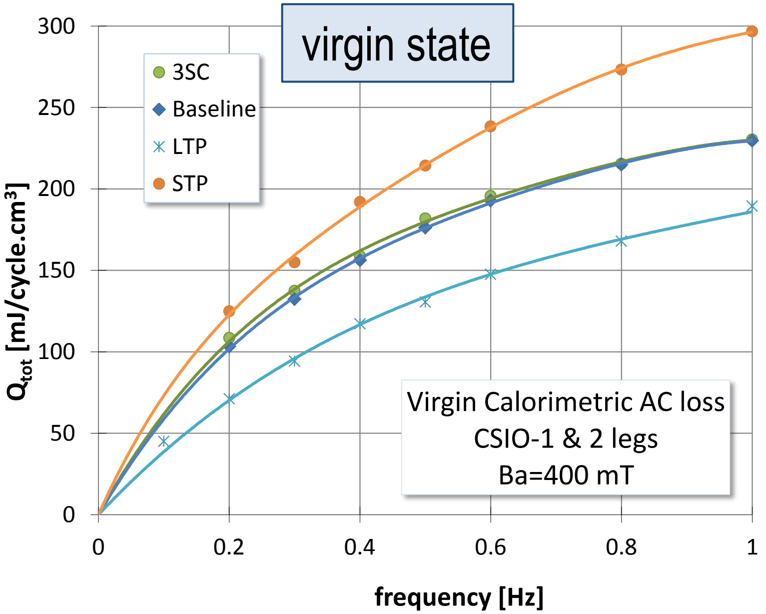


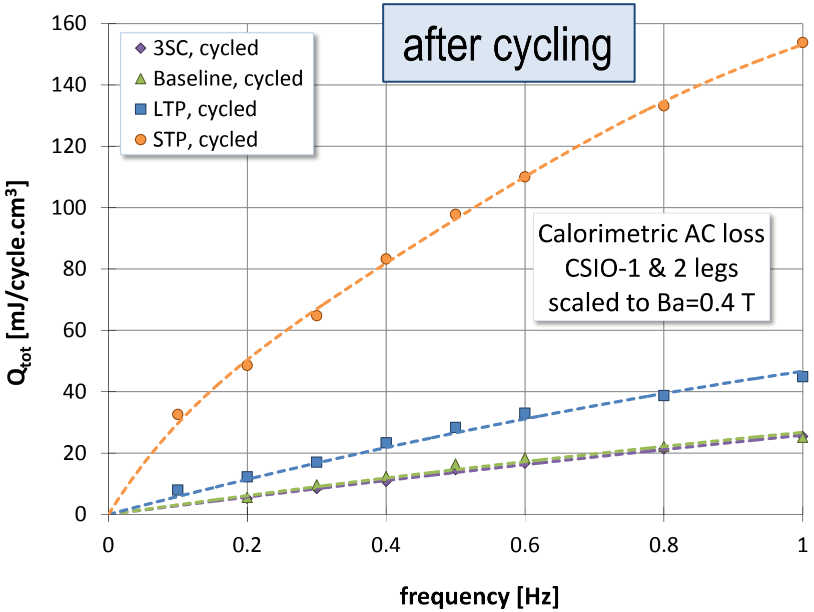
Tcs degrades with cycling, except STP (dashed lines mark WUCD).

HT witness strand showed cable with 3 sc strands in triplet leads to higher overall Ic

| strand | Ic strand, 12 T, 4.2K [A] | Ic-triplet [A] | $T_{cs}$ [K] | $\varepsilon_{eff}$ [%] |
|---|---|---|---|---|
| Cu:nonCu=1.0 | 248 | 496 | 7.00 | -0.60 |
| Cu:nonCu=1.5 | 216 | 649 | 7.55 | -0.60 |
|  | factor triplet Ic | 1.31 |  |  |

# Test results: virgin & cycled coupling loss





Coupling loss according to prediction, when accounting for influence lower void fraction STP & LTP: coupling loss for STP remains high.

| cable | virgin nτ | nτ after cycling | # cycles |
|---|---|---|---|
| Baseline | 350 | 10 | 11,000 |
| 3SC | 360 | 10 | 11,000 |
| LTP | 170 | 20 | 6,000 |
| STP | 550 | 200 | 6,000 |

*A. Nijhuis, et al, 'Impact of void fraction on mechanical properties and the evolution of coupling loss in ITER Nb3Sn conductors under cyclic transverse loading', IEEE Trans Appl Supercond 15, 2005, 1633-1636*

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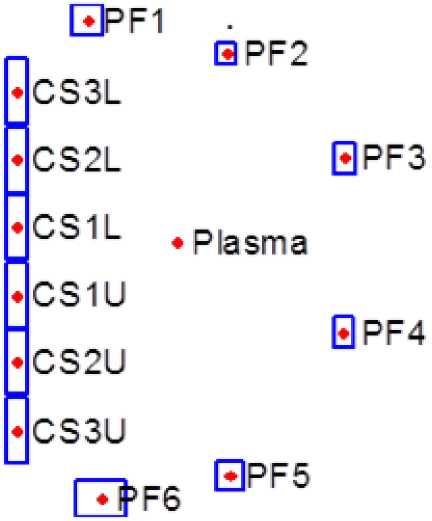
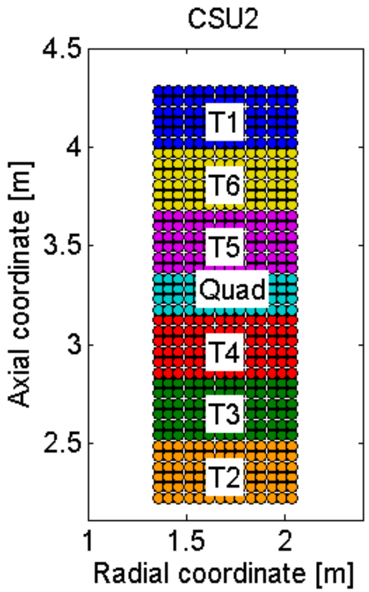
# Magnetic field

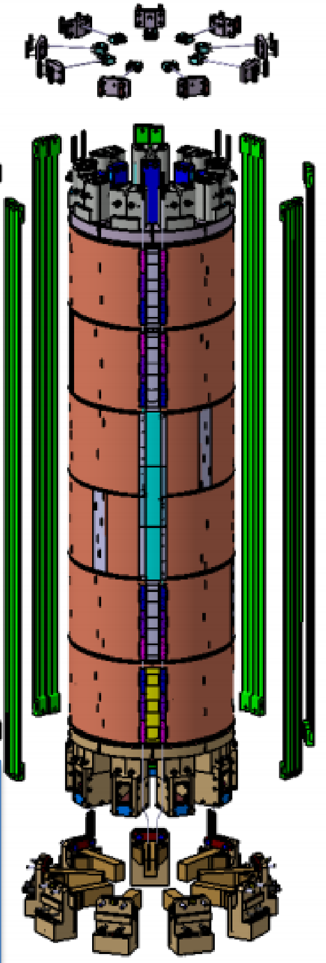
**Field model**

- Coils are approximated by their current centre lines
- Field produced by the analysed CS module is calculated with a higher accuracy, taking the position of all its windings into account

- 6 CS modules, each consisting of 6 hexa + 1 quad pancakes
- 40 turns in the axial direction and 14 in the radial one
- The magnetic field varies over the windings of each module



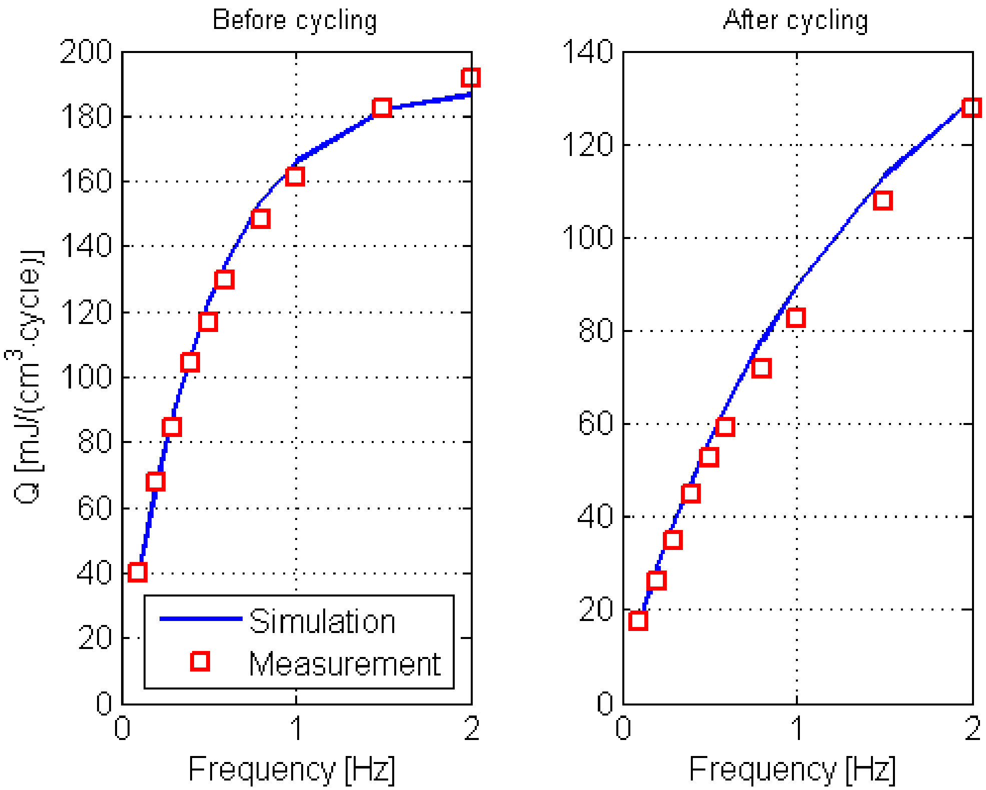




Worst field conditions at inner radius of quad pancake of the CS2U and CS2L modules

# Inter-strand resistance

Inter-strand resistivity parameters are deduced from SULTAN AC loss measurements before and after cycling with JackPot

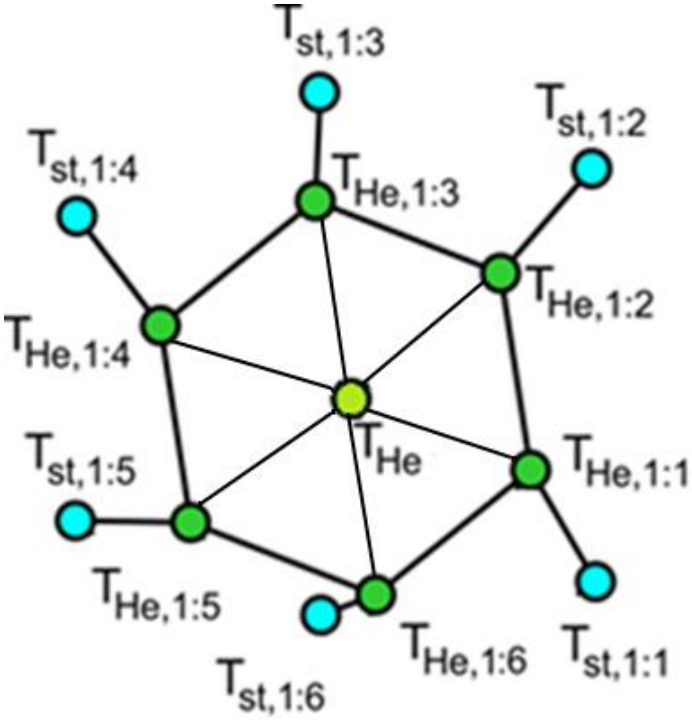


For the fit, hysteresis loss is subtracted from measured values

The inter-strand resistance increases with cycling of the conductor

In plasma scenario simulation, the dependence of resistance on magnetic field is taken into account

# JackPot Thermal model



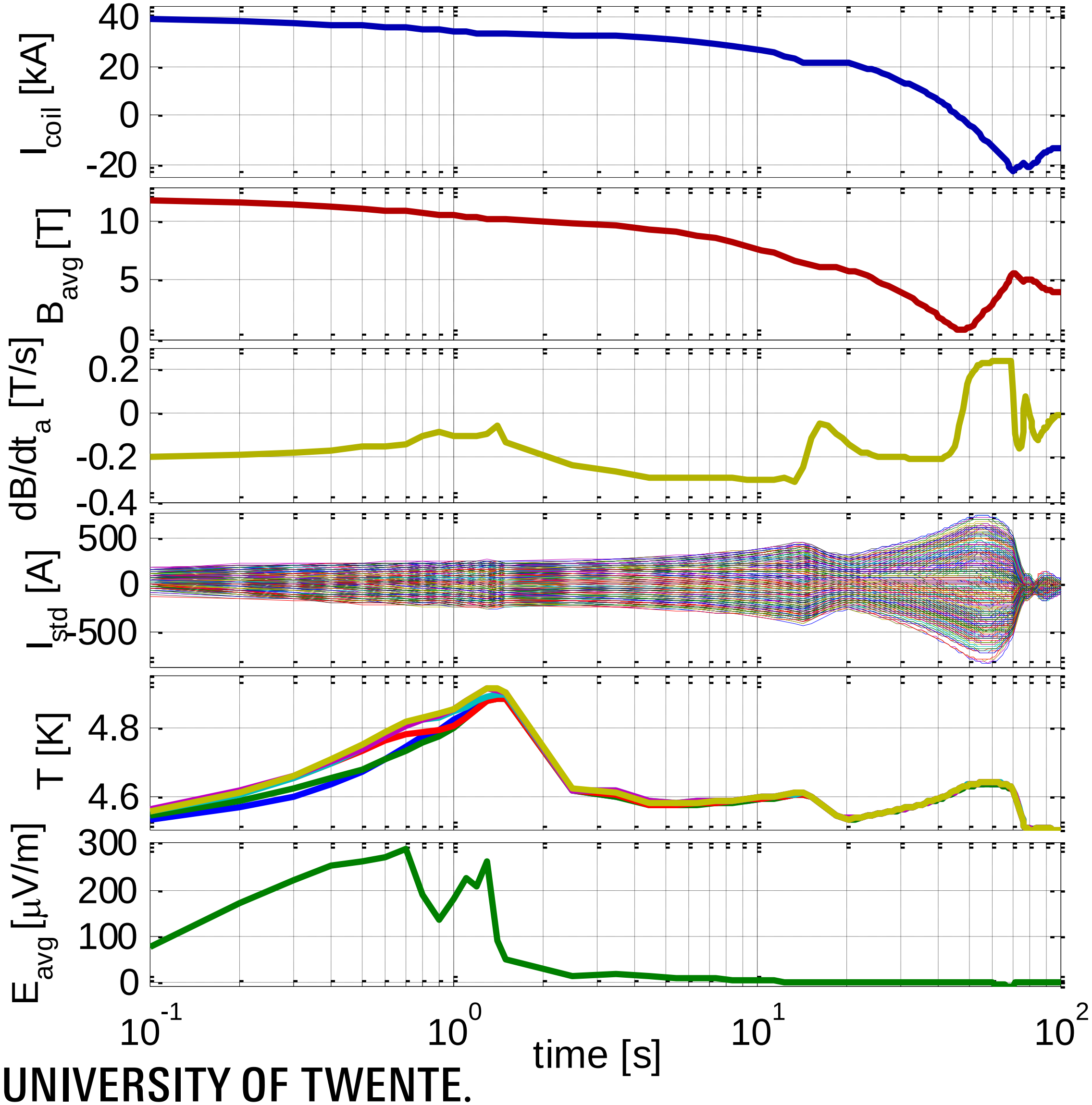
Calculate temperature distribution

1. coupling losses
2. magnetic field at strand locations
3. critical current saturation (resistive)
4. hysteresis loss

The temperature distribution is calculated along the conductor for:

- Last stage sub-cables (petals)
- Helium in the petals
- Helium in the central channel

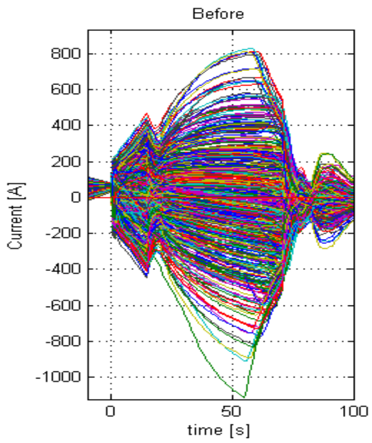
# 15 MA scenario with SOD



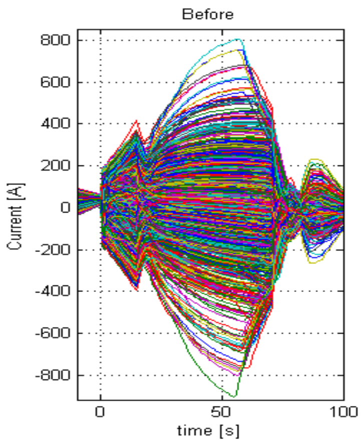
Example of the:

- Coil current
- Average B on CICC
- Average dB/dt
- Coupling + transport currents in strands
- T in petals
- Average E in strands inner winding of CS coil

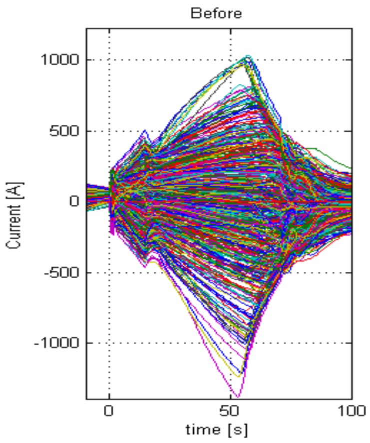
# Strand currents SOD-15 MA scenario



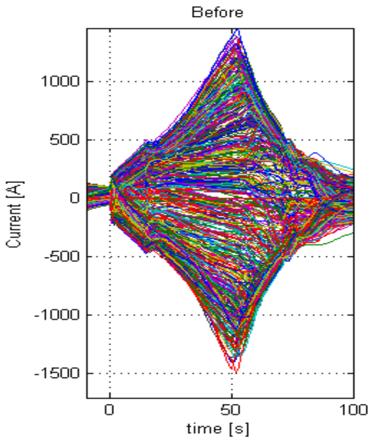
**Baseline**



**3SC**

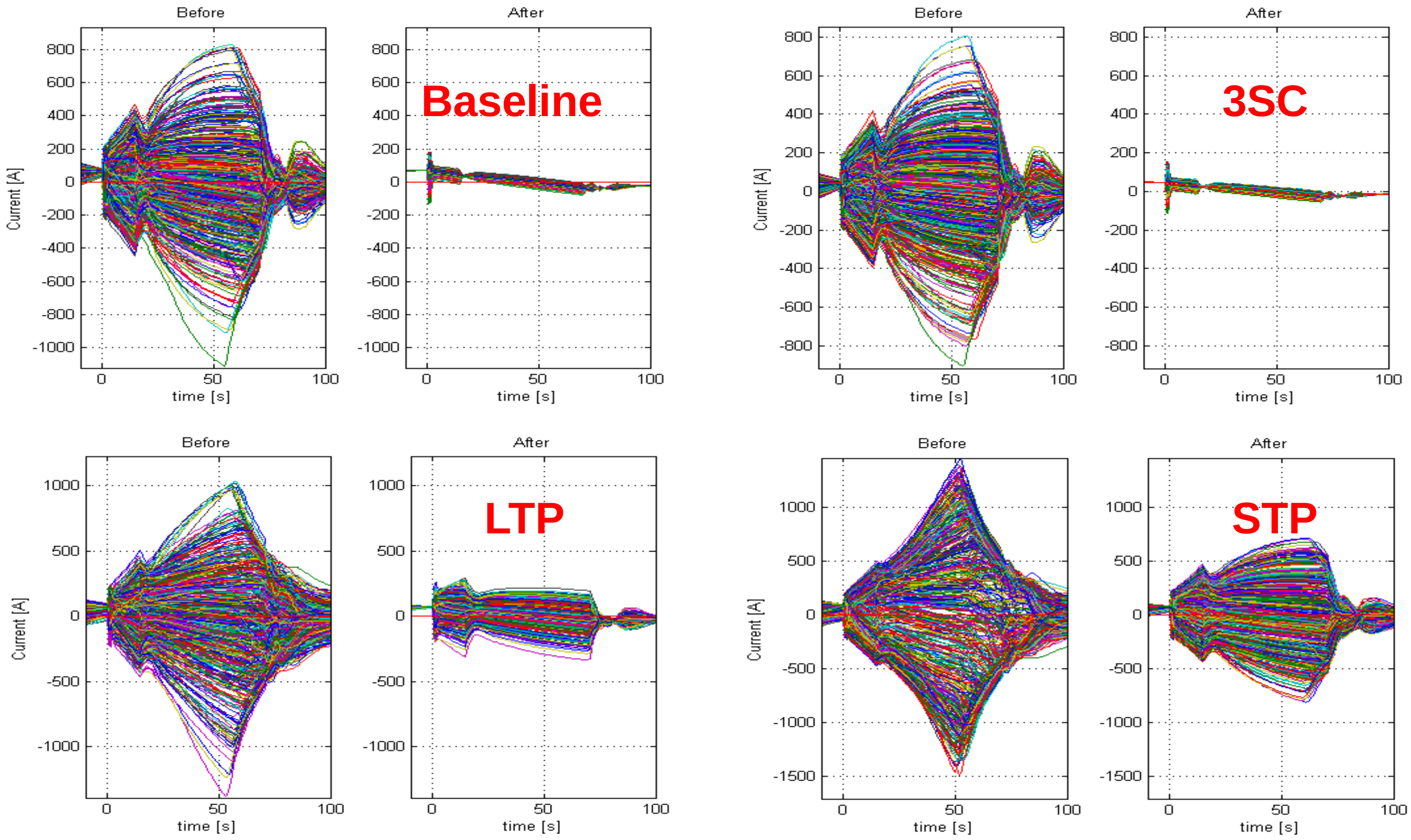


**LTP**



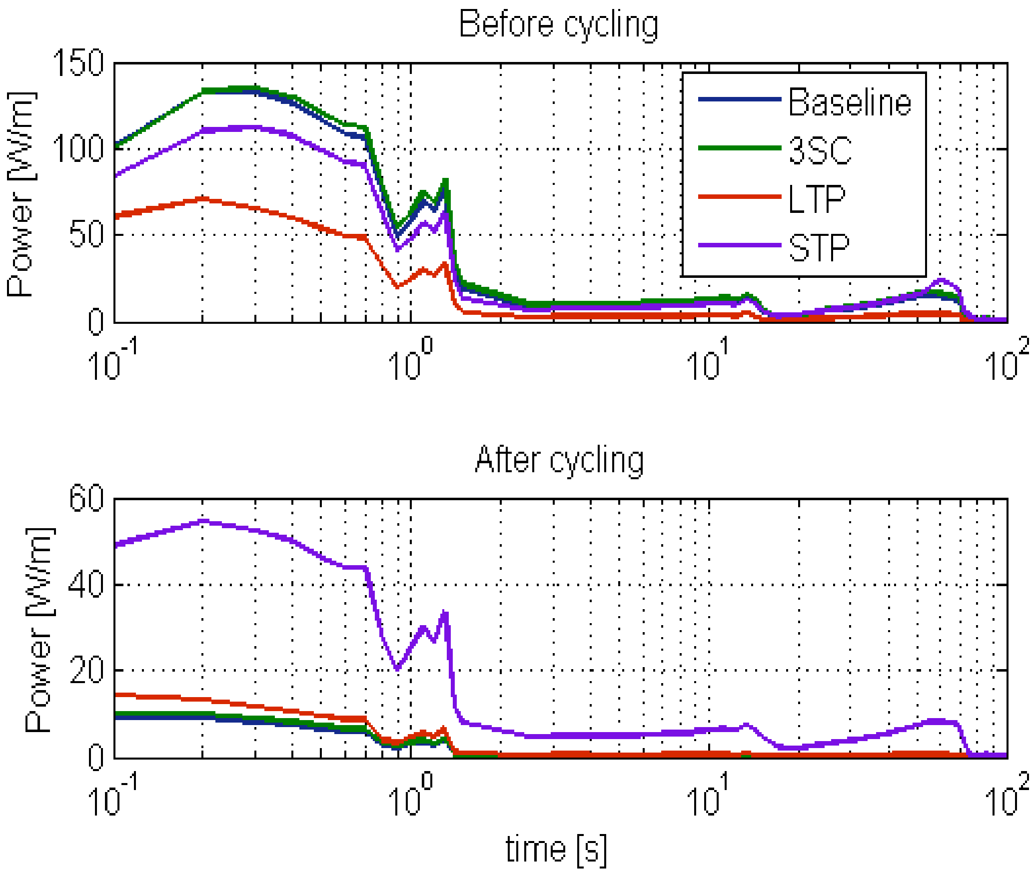
**STP**

# Strand currents SOD-15 MA scenario



Before cycling: LTP lowest coupling losses, some strands with peak currents
After cycling: STP high dissipation due to small increase inter-strand resistance with cycling

# Coupling currents & loss (SOD-15 MA)



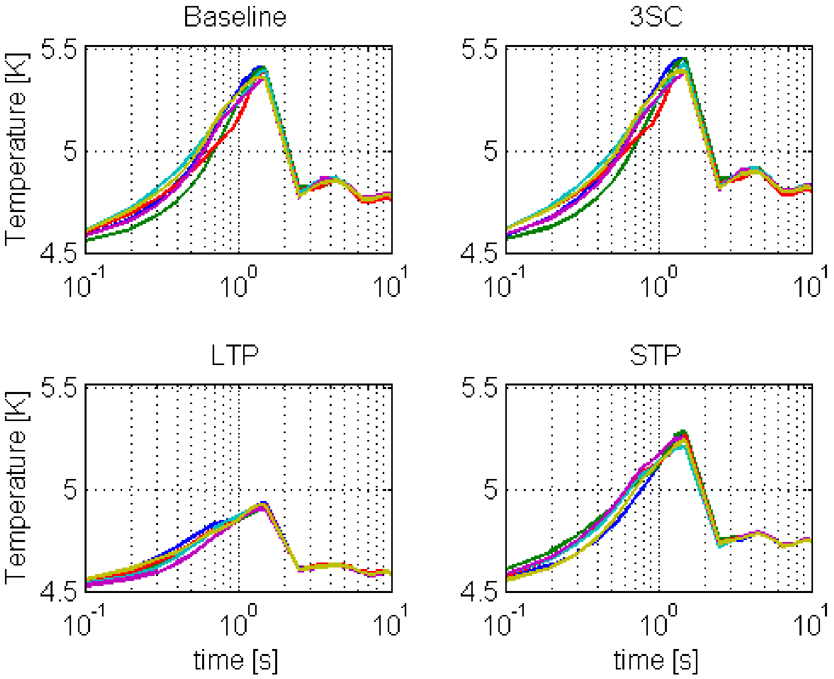
Before cycling: LTP lowest coupling losses
After cycling: STP high dissipation due to restricted increase inter-strand resistance with cycling

Baseline & 3SC ~11,000 load cycles
LTP & STP ~6,000 load cycles

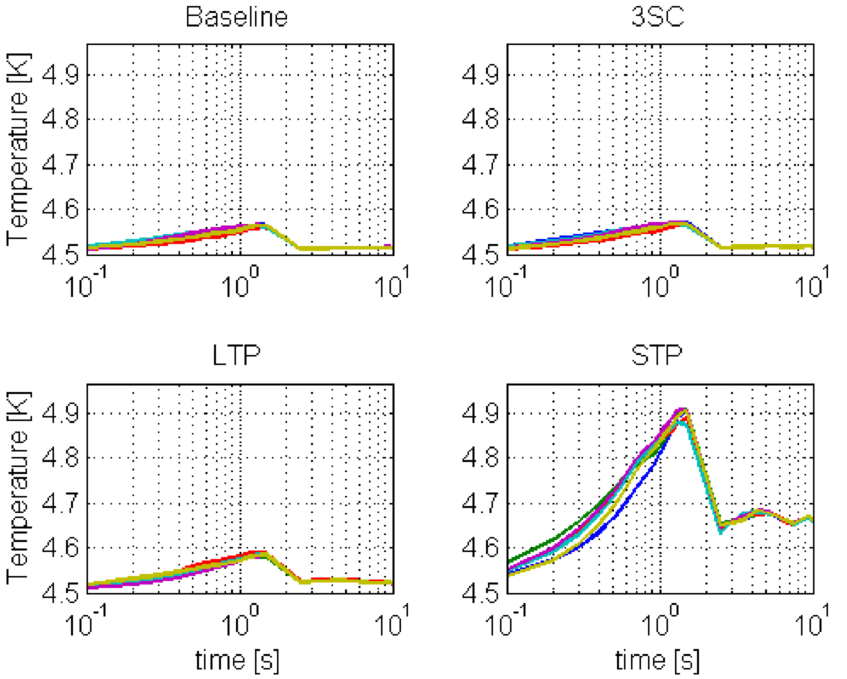
# Temperature during 15 MA scenario (SOD)

Temperature evolution for each cable pattern before and after cycling (inner turn CS coil)

**Before cycling**



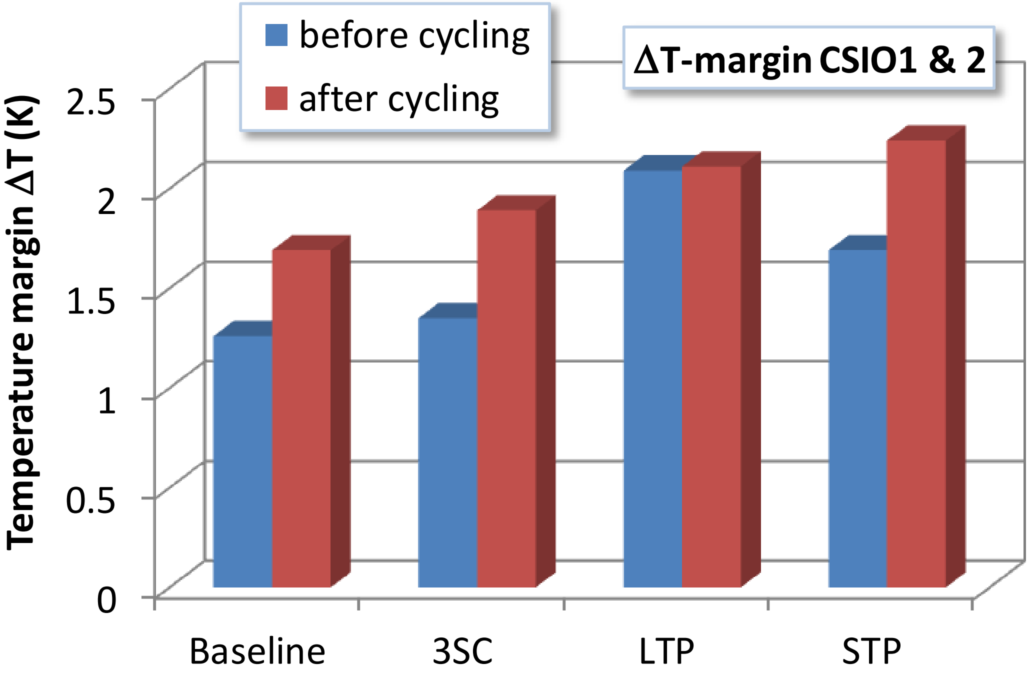
**After cycling**



**After cycling: high dissipation (coupling loss) in STP initiates - average petal - peak temperature increase, with a maximum value of 4.9 K**

# Temperature margin (15 MA scenario, SOD)

Temperature margin of CSIO types before / after cycling, based on *T*-average petal:
$T_{margin}$ = measured $T_{cs}$ Sultan from DC test minus computed JackPot *T*-max during 15 MA scenario



$T_{margin}$ high for all, LTP highest before cycling (3SC corrected for higher strand $I_c$)
After cycling (6,000) $T_{margin}$ of LTP and STP practically similar, in spite of different $T_{cs}$ evolution with cycling. DC test sufficient as criterion for pulsed coil?

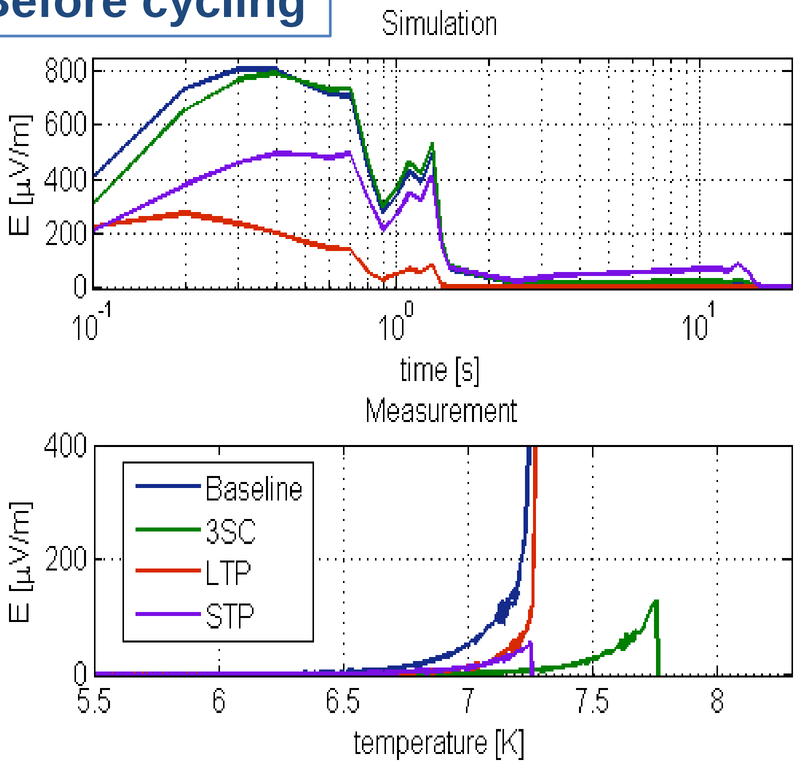
# Electric field during 15 MA scenario

Sultan *E*-quench in range 100 µV/m before, and 200 µV/m after cycling (quasi steady state)

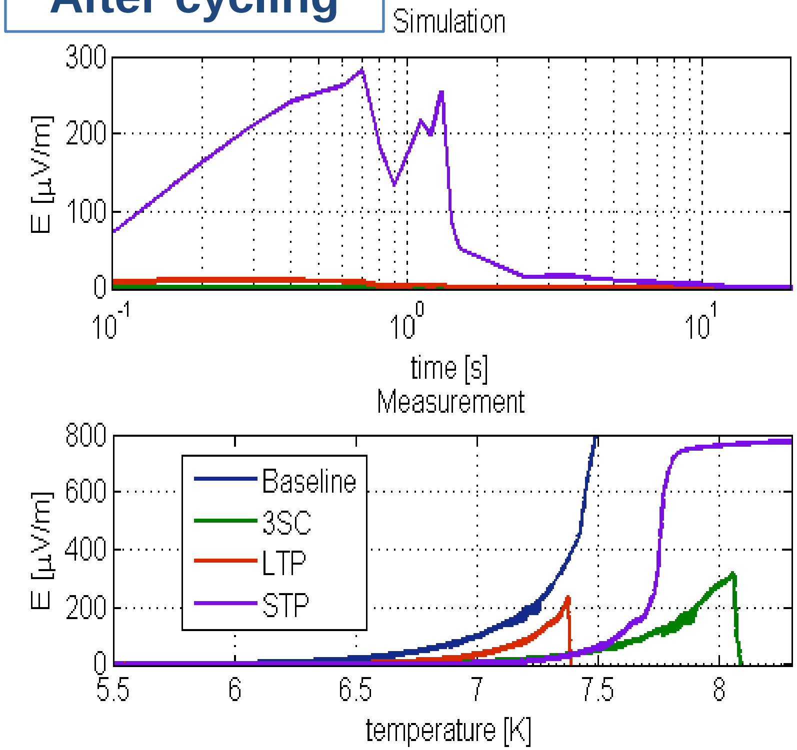
JackPot computation (CS-15 MA):

- before cycling: average *E*(JackPot) exceeds *E*-quench(Sultan) at SOD for all 4 designs,
- after cycling: STP exceeds *E*-quench(Sultan), Baseline, 3SC and LTP < Sultan E-quench

**Before cycling**



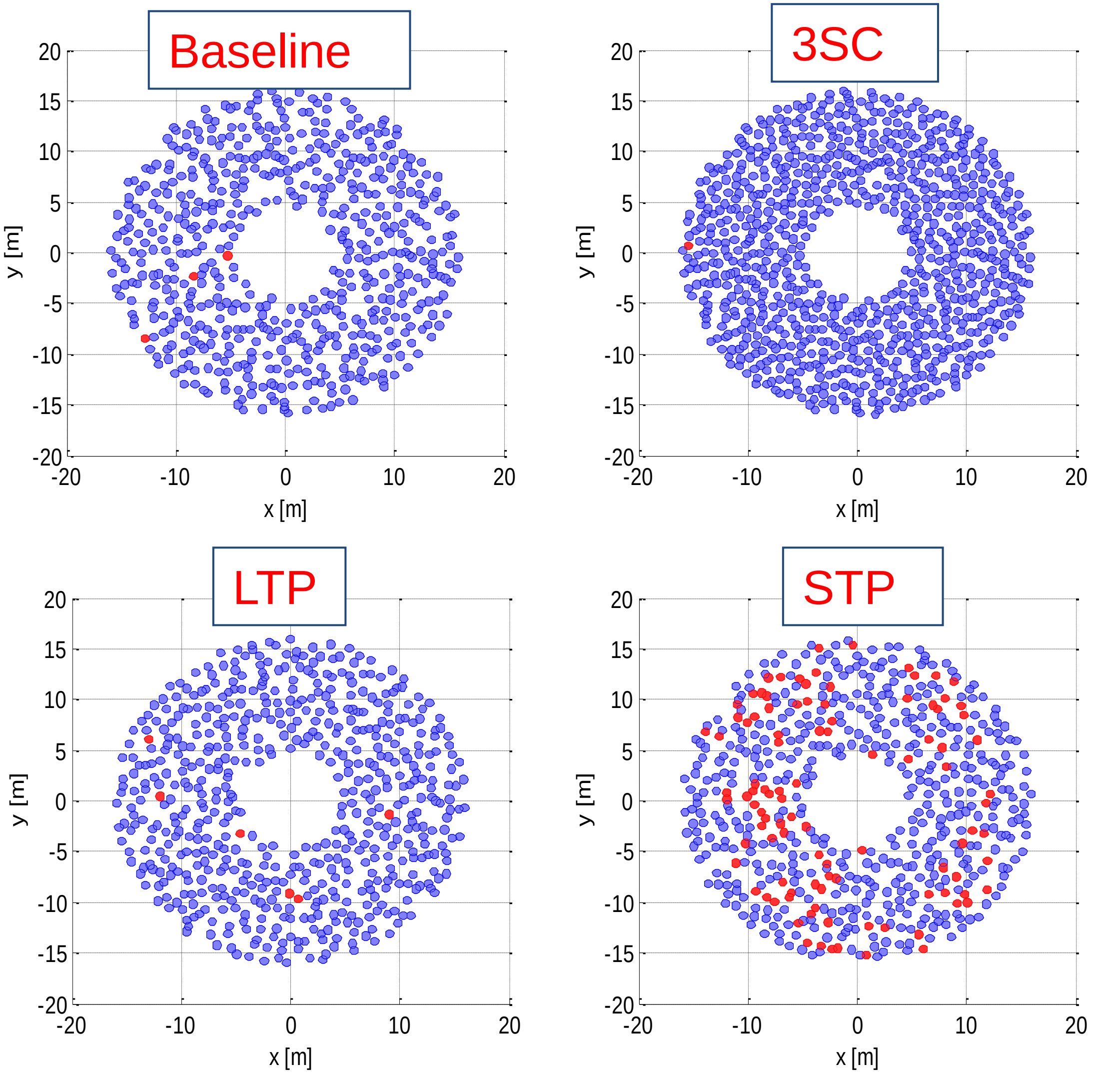
**After cycling**



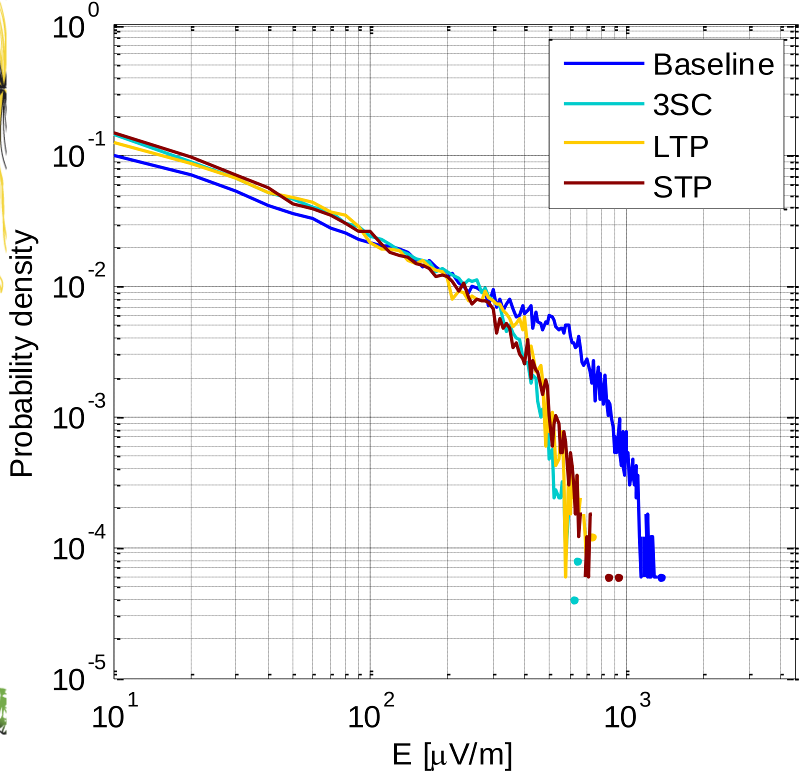
# $E_z$ distribution at SOD after cycling in coil

Number of strands exceeding **$E_q$=200 μV/m in red**, representing the quench E level **after** cycling

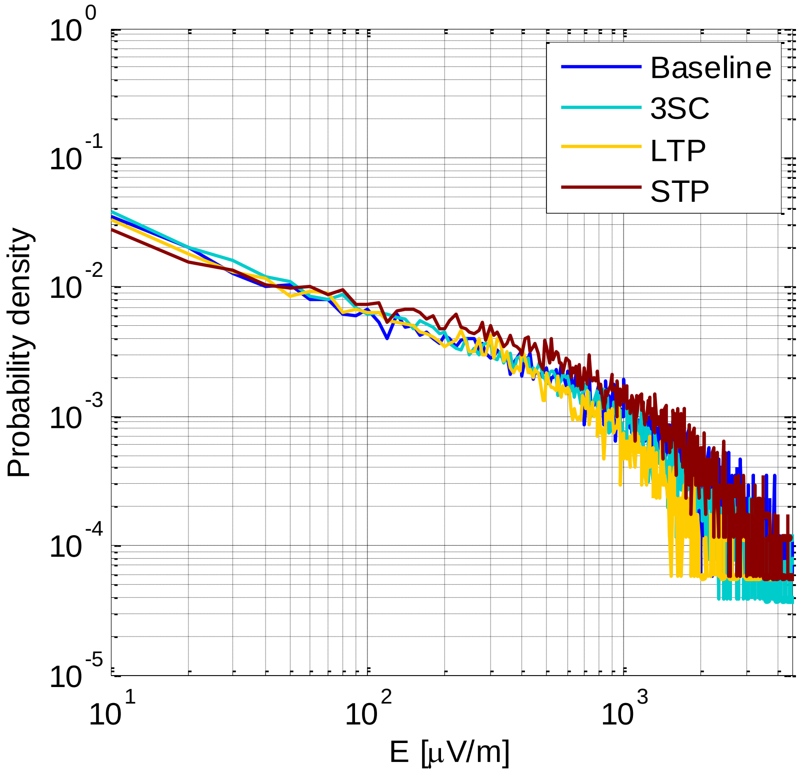
STP contains the largest number and highest density of strands exceeding $E_q$



# $E_z$ probability distribution (JackPot-ACDC)



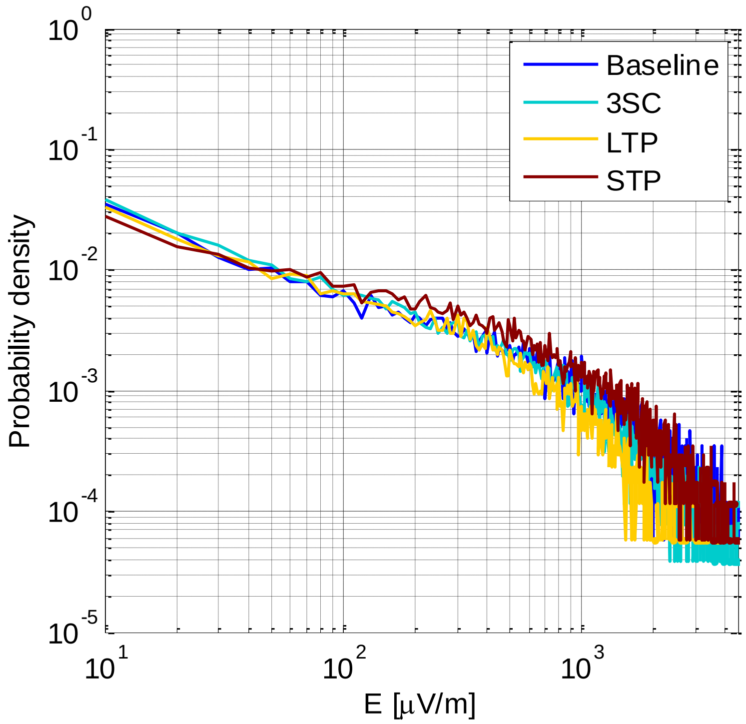
Sultan test DC probability distribution of $E_z$ at quench



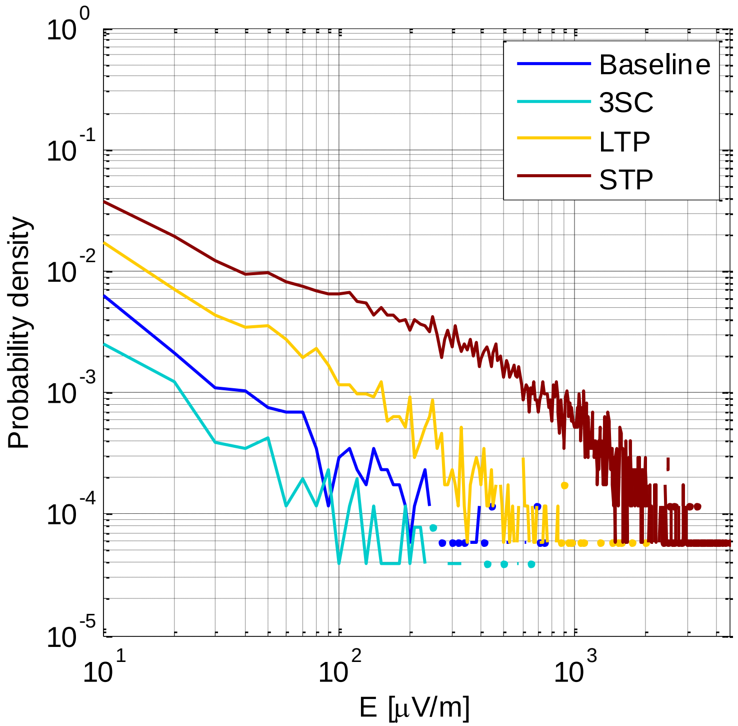
**CS-Coil 15 MA** @ SOD probability distribution of $E_z$ before cycling

**Distribution of electric fields among strand elements from JackPot computations in same range for Sultan quench test level and at 15 MA CS Coil scenario.**

# $E_z$ probability distribution: CS-Coil @ SOD



JackPot AC probability distribution of *E* before cycling



JackPot AC probability distribution of *E* after cycling; density for STP remains high

**After cycling, the coupling currents remain at high *E*-level for STP with reduced values for the others (order of magnitude)**

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# Energy dissipation & transient stability

Quasi steady-state quench conditions (Sultan Tcs test) may differ significantly from pulsed ones (SeCRETS transient stability experiment under fast pulses)

The sub-size SeCRETS-A CICC is comparable to a single CS petal

| | **Secret A** |
|---|---|
| Cable pattern | 3x3x4x4 |
| N. of SC strand | 144 |
| Cu:nonCu ratio | 1.5 |
| Lp1 [mm] | 51 |
| Lp2 [mm] | 76 |
| Lp3 [mm] | 136 |
| Lp4 [mm] | 167 |
| Void fraction [%] | 36.8 |

Transient stability test conditions

- ~ 320 mm conductor exposed to pulsed field
- $T_{background}$ = 9.71 T
- Single sinusoidal field pulse (T = 65 ms)
- Pulse amplitude increased until quench
- I = 12 kA
- He mass flow rate = 3.5 g/s

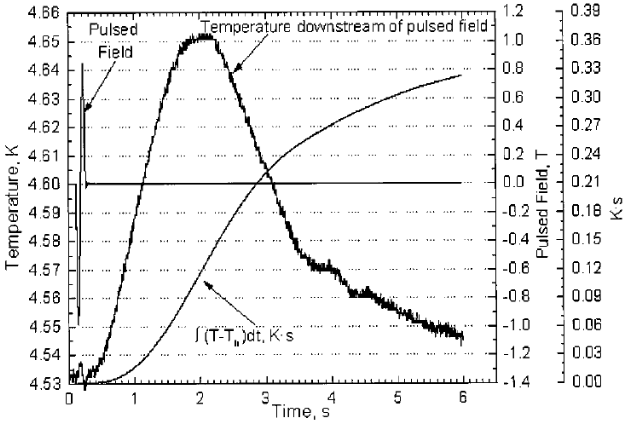
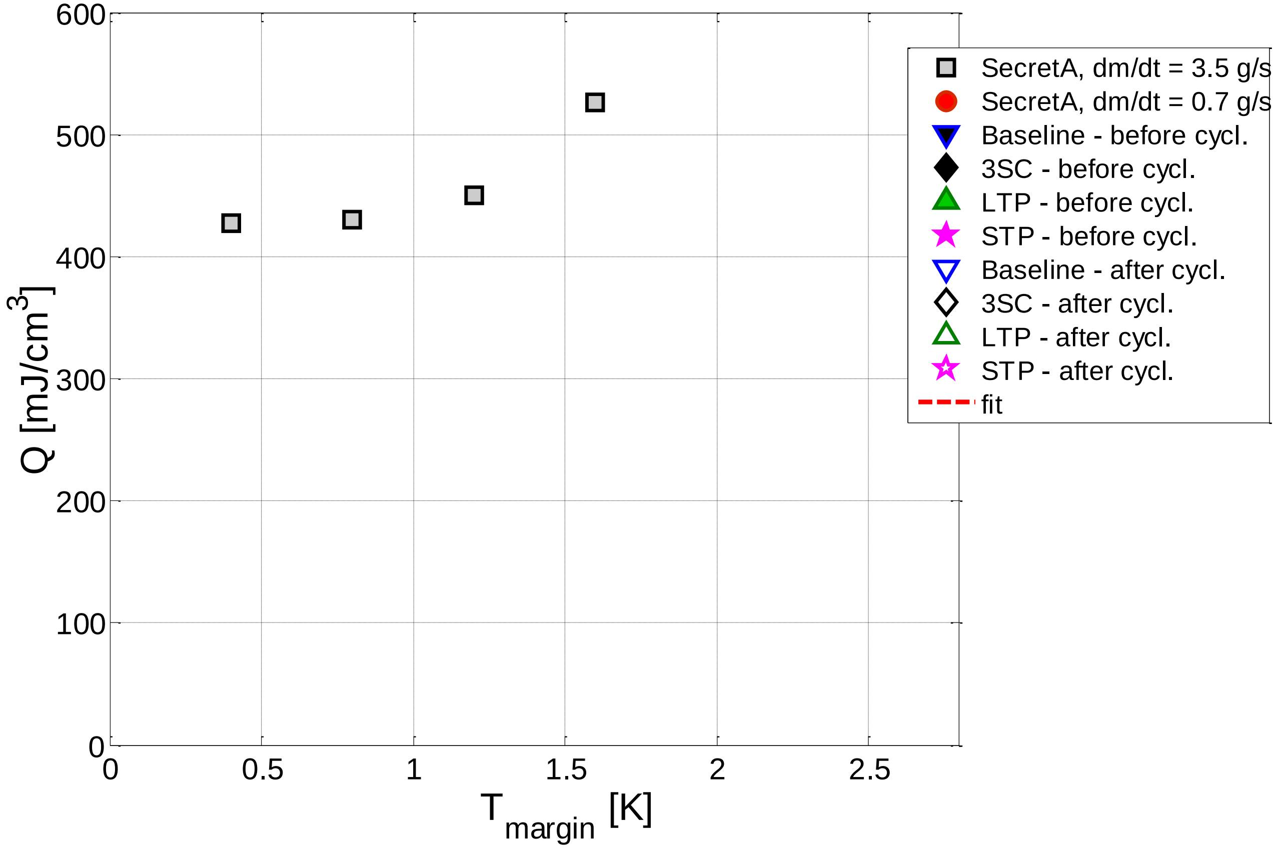


Fig. 1. Assessment of the deposited energy during a field transient by heat slug calorimetry ($I = 0$, $B_{dc} = 10$ T, $dm/dt = 2$ g/s).

P. Bruzzone, A.M. Fuchs, B. Stepanov, G. Vecsey, E. Zapretilina, Test Results of SeCRETS, a Stability Experiment about Segregated Copper in CICC, IEEE Trans Appl Supercond 11, 2001, pp 2018

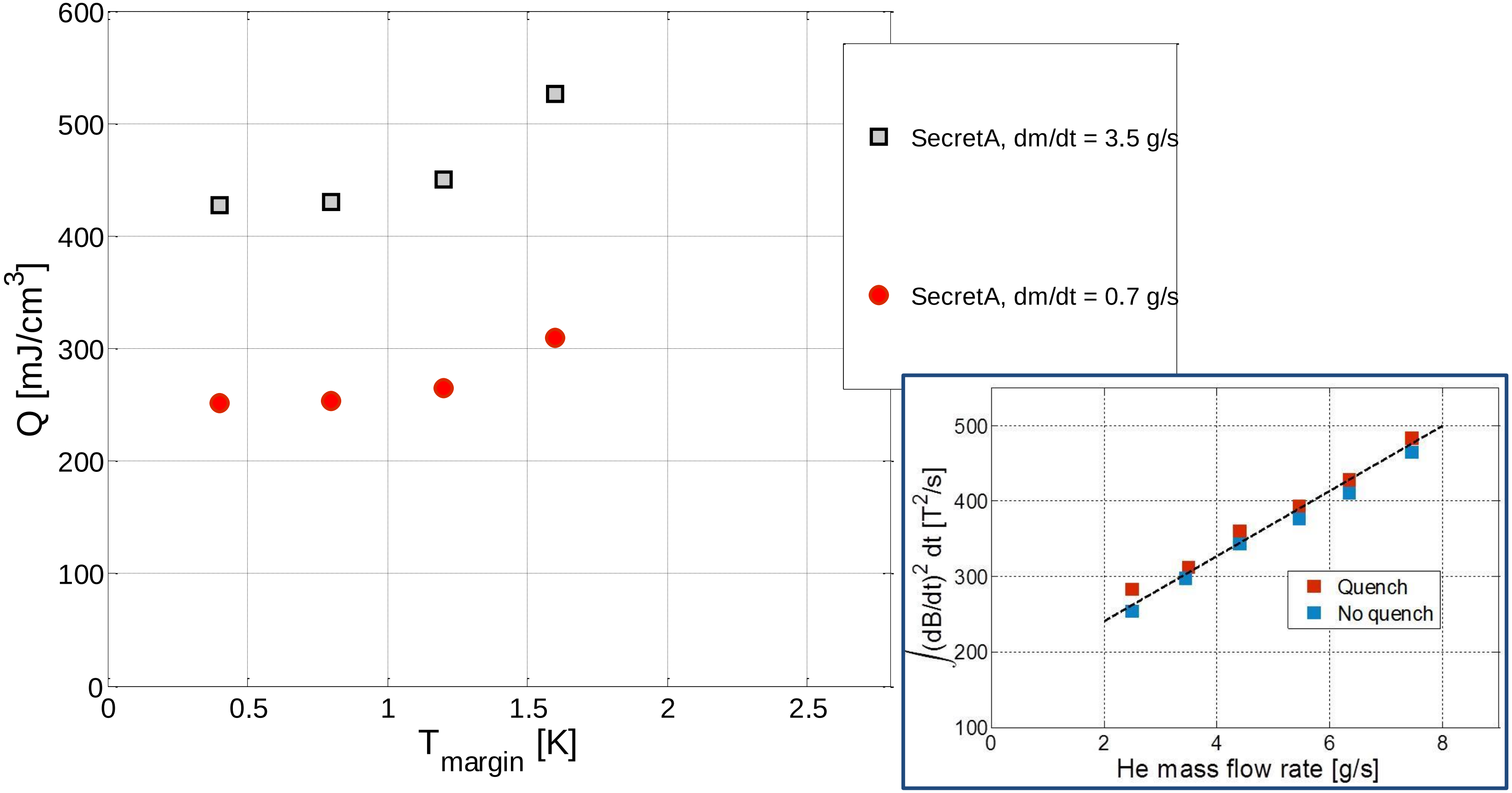
# CSIO1 & 2, SeCRETS Transient Stability



Quench energy (absorbed) per SC volume vs $T_{margin}$ of the SeCRETS CICC during a transient fast sinewave pulse (65 ms) computed by JackPot based on coupling loss data

$E_{quench}$ = dissipation SC strands, inter-strand contacts and inter-filament coupling

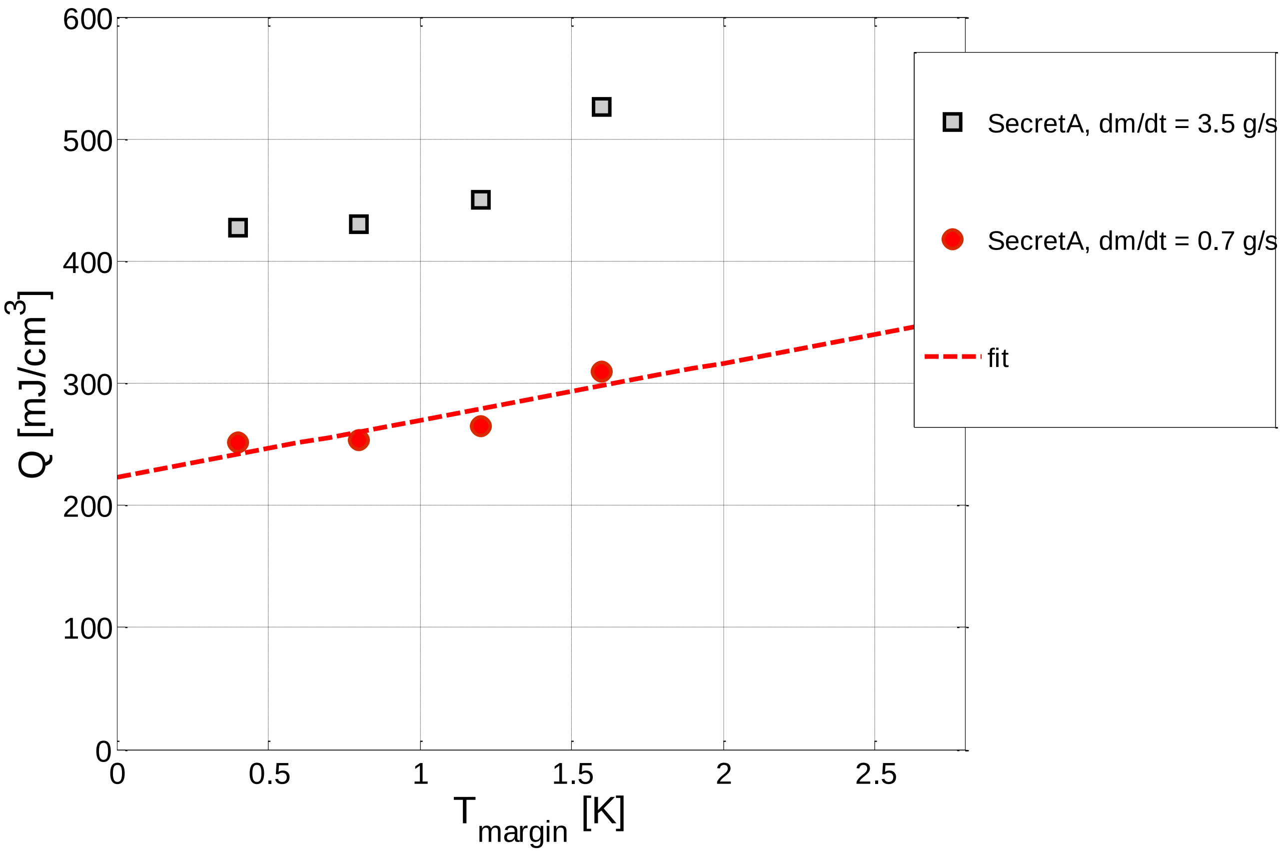
# CSIO1 & 2, SeCRETS Transient Stability



For SeCRETS relatively strong dependence on helium mass flow rate

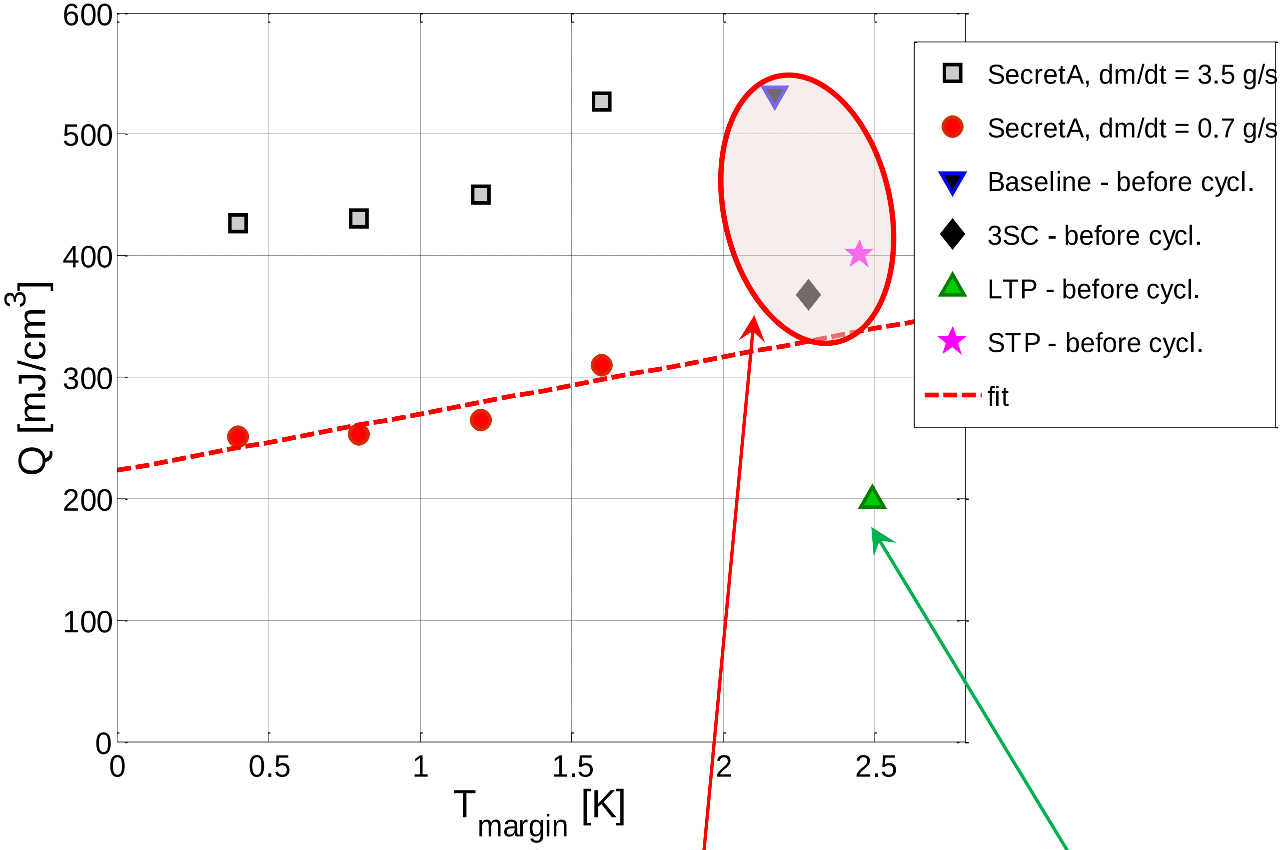
$Q_{quench}$ Secret-A corrected for CS petal mass flow (~0.7 g/s)

# CSIO1 & 2, SeCRETS Transient Stability



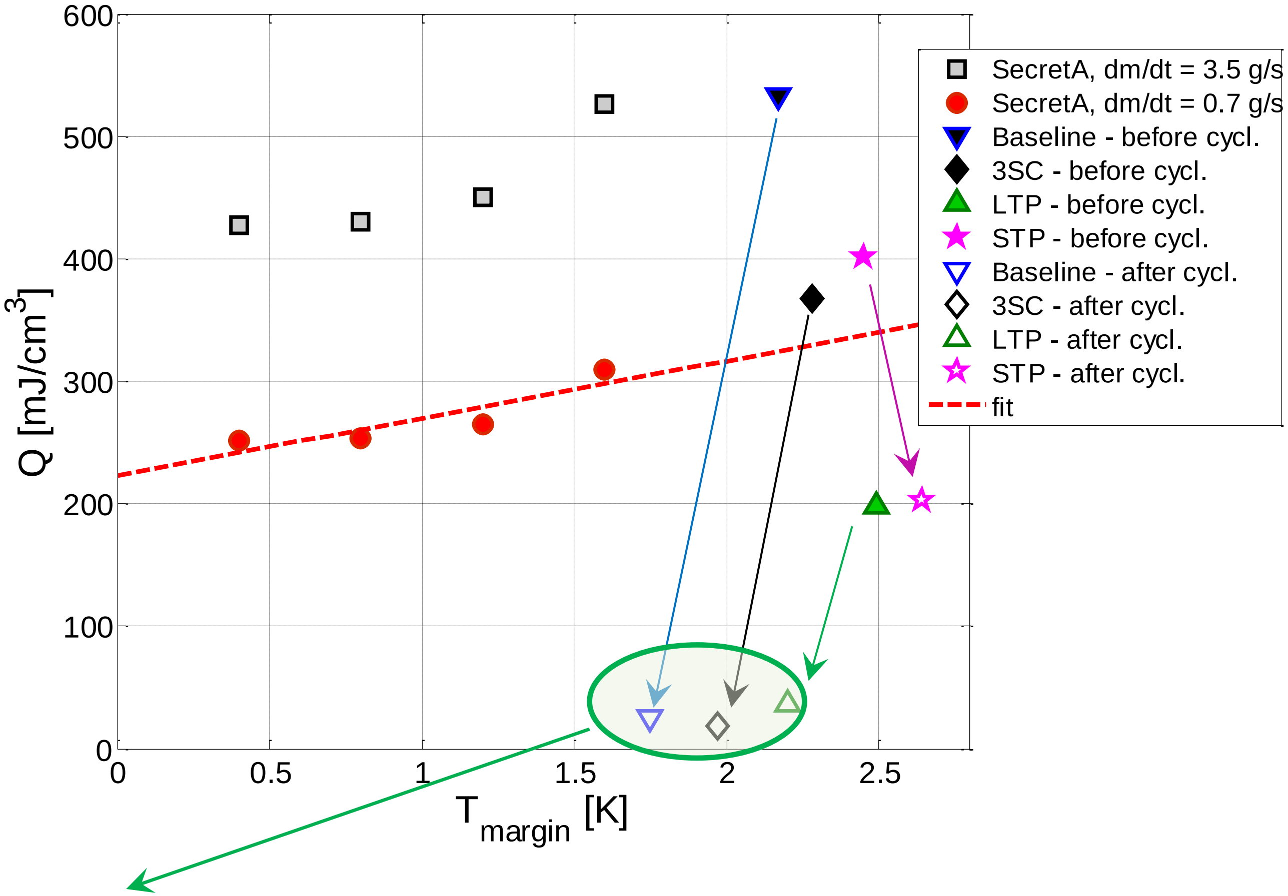
Red line is fit through quench energy points for 0.7 g/s helium flow rate (threshold).

# CSIO1 & 2, SeCRETS Transient Stability



Dissipated energy (SC strands) during first 2 s of 15 MA scenario in virgin state of Baseline, 3SC & STP in critical range (possibly unstable), LTP seems stable (virgin state)

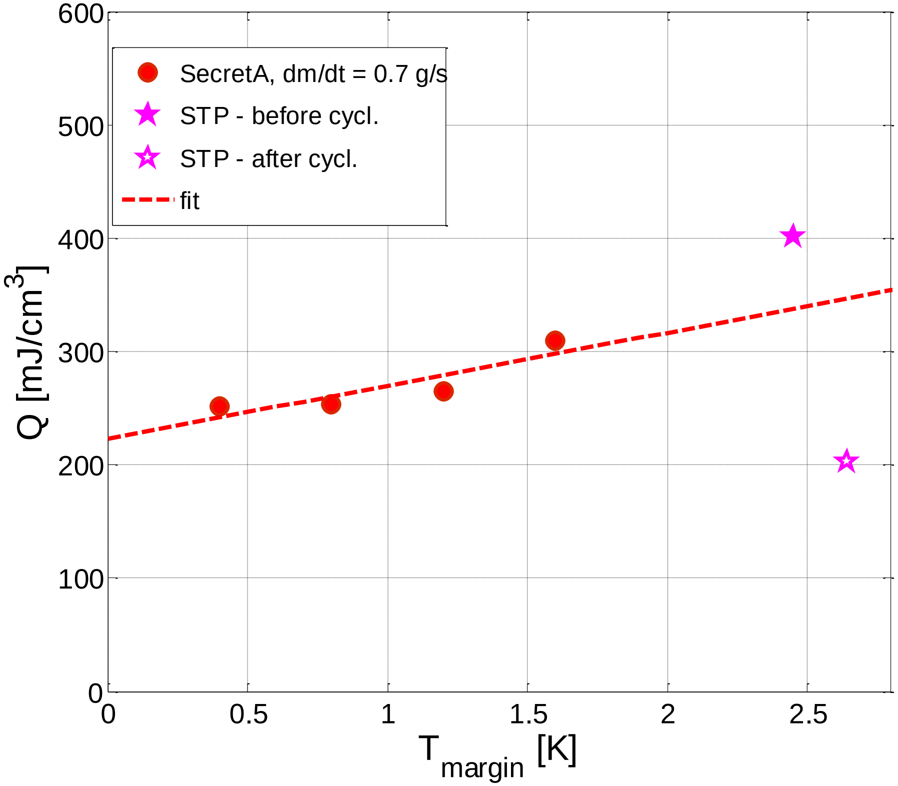
# CSIO1 & 2, SeCRETS Transient Stability



**Stable** after cycling: Baseline, 3SC & LTP, low energy during first 2 s of 15 MA scenario.
STP also below SeCRETS transient fast sinewave pulse (65 ms) during 15 MA

# CSIO1 & 2, SeCRETS Transient Stability

Large energy margin between Secret-A transient $E_{quench}$ and plasma scenario dissipation of Baseline, 3SC and LTP conductors after cycling. How about STP?



- ✓ Experimental error bar (~10% ??)
- ✓ Simulation based on resistivities obtained without EM load underestimates plasma scenario dissipation
- ✓ Other (unquantifiable) factors: disturbance duration and shape. Initial dissipation phase of plasma scenario is longer (~1.5 s) than 65 ms pulse used in stability test (can lead to not negligible variations of heat transfer coefficient
- ✓ $Q_{quench}$ may increase with $T_{margin}$

# CSKO1 MQE Stability test

Qualification Test of CSKO1 now ongoing in Sultan

Stability test (next week) only allowed after Qualification program, after cycling and AC loss test:

- B=9 T, I=45.1 kA
- Sine wave pulse 128 ms
- Two helium flow rates: 1.0 and 2.5 g/s
- MQE investigated as a function of Tq-ΔT, with ΔT from 0.1 K to 1.5 K

Pulse is actually too fast (coupling currents not fully developed) compared to 15 MA plasma scenario.

# Conclusions

- After cycling: effective temperature margin LTP ≈ STP
- AC Loss: JackPot prediction long pitches and “close-to-one” $\beta$-ratio pitch sequence experimentally confirmed, lowest virgin AC loss LTP
- High coupling loss in STP
- When quasi steady-state quench electric field ($E_q$) is taken as a measure for stability → electric field in unstable operation regime at virgin condition  
  → safe $E_q$ levels after cycling, except STP?
- Transient stability: stable operation also possible for STP after cycling (Differences in pulse shape / duration between Sultan test and 15 MA plasma scenario and extra dissipation with EM load, give uncertainty (critical?)
- To be continued…. (CSKO1 etc).