

# Pulsed field stability and AC loss of Nb<sub>3</sub>Sn CICC; modeling and experiments

A. Nijhuis<sup>1</sup>, T. Bagni<sup>1</sup>, M. Dijkstra<sup>1</sup>, A. Devred<sup>2</sup>

<sup>1</sup> University of Twente, Enschede, The Netherlands

<sup>2</sup> ITER International Organization, Saint-Paul-lez-Durance, France

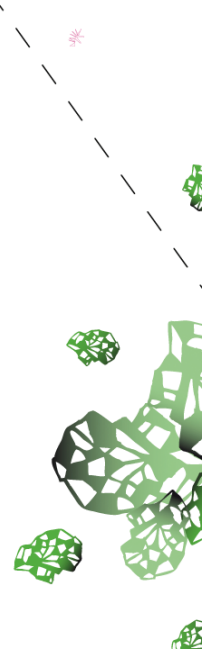


# Outline

---

- JackPot-ACDC model validation; AC loss & Temperature
- Minimum Quench Energy; experiment & modeling
- 15 MA Plasma Scenario modeling

Aim JackPot-model stability analysis: see if we can find some general criterion for CICC that can serve as a quantitative quench threshold (E-P-max-ave).

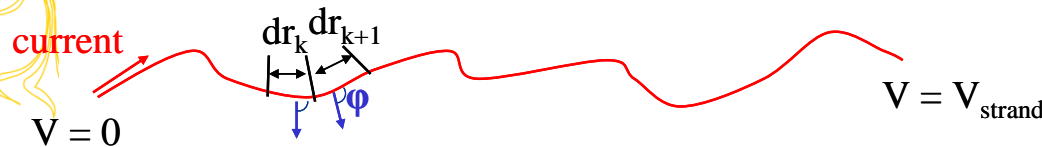


Pulsed field stability of ITER CICCs is experimentally tested with a truncated fast sinewave pulse, but how is stability during a plasma scenario with lower dB/dt, larger amplitude and longer duration?

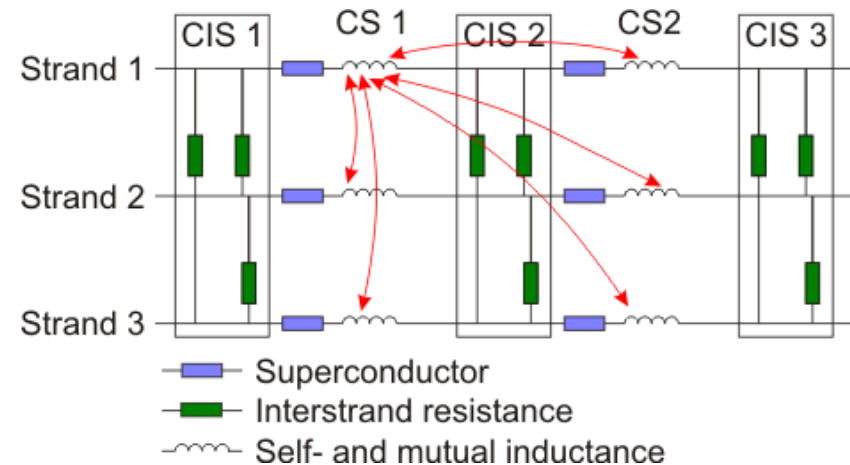
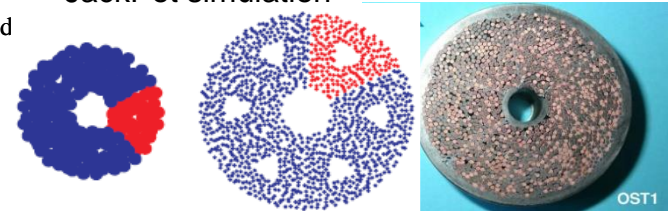
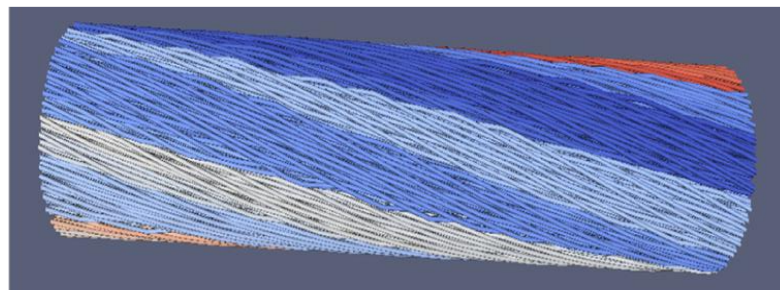
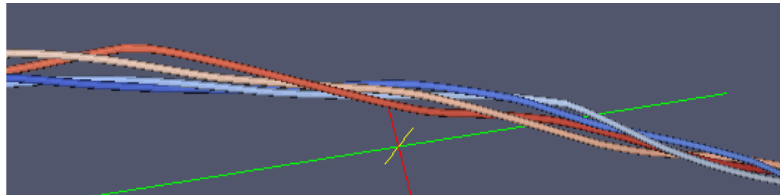
# JackPot-ACDC CICC cable model



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



- interstrand contact resistance distribution from IS contact area
- strand's inductances
- coupling with self- & background field
- strand's properties scaling law  $I_c(B, T, \epsilon)$



Electrical network,

# JackPot ACDC - AC loss

Inter-strand resistivity parameters  $\rho_{is}$  are derived from short sample measurements under applied cyclic load and SULTAN AC loss measurements.

Dependence of resistance on magnetic field is taken into account.

Simulations:

$$B_{dc} = 2 \text{ T and } I_T = 0 \text{ A}$$

$$\rho_{is} = 1,0 \cdot 10^{-5} \mu\Omega \cdot \text{m}^2$$

$$B_{dc} = 9 \text{ T and } I_T = 0 \text{ A}$$

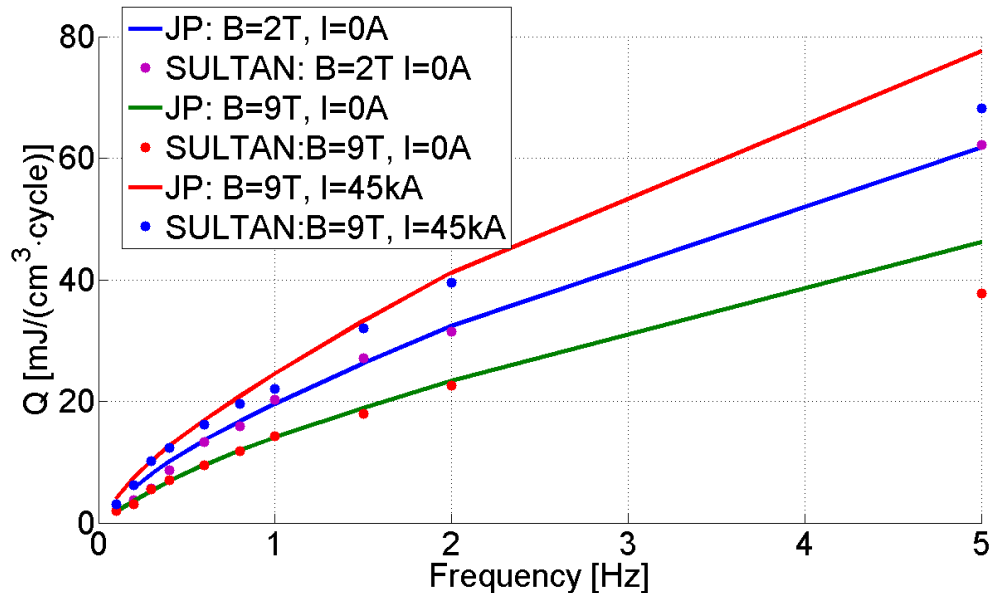
$$\rho_{is} = 1,7 \cdot 10^{-5} \mu\Omega \cdot \text{m}^2$$

$$B_{dc} = 9 \text{ T and } I_T = 45,1 \text{ kA}$$

$$\rho_{is} = 0,7 \cdot 10^{-5} \mu\Omega \cdot \text{m}^2$$

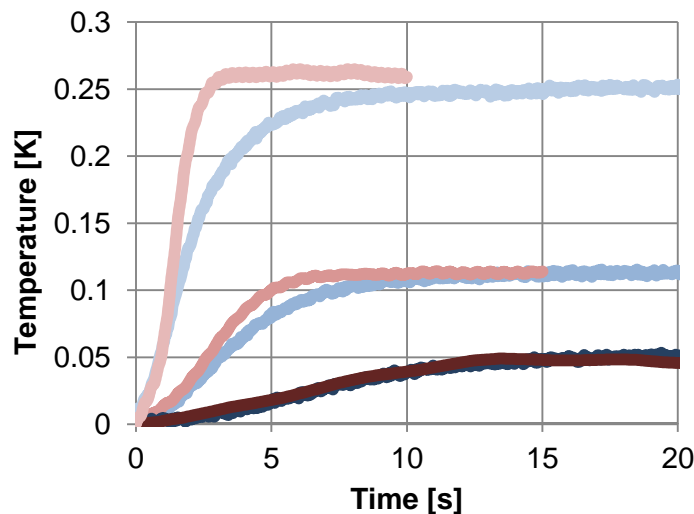
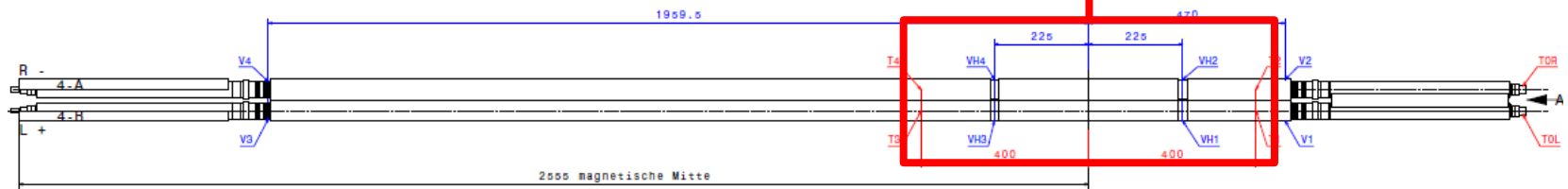
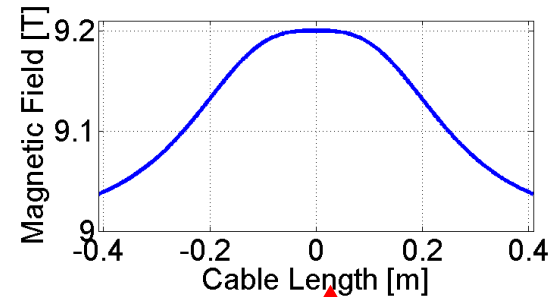
AC losses versus frequency  
w/o  $I_T$  and  $B_{dc}$   
(for  $f \geq 5 \text{ Hz}$ , experimental  
values less accurate)

Hysteresis loss subtracted  
for comparison.



# JackPot ACDC - Thermal Validation

Magnetic field ( $B_a$ ) profile used to simulate Sultan AC loss and MQE simulations



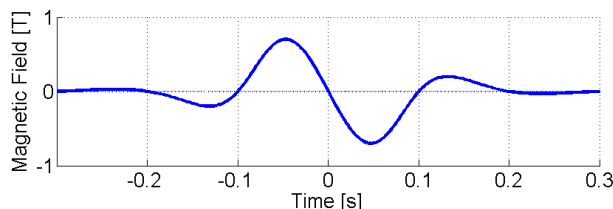
- Sultan 1Hz -  $I=0A$
- JP sim 1Hz -  $I=0A$
- Sultan 0,4Hz -  $I=0A$
- JP sim 0,4Hz -  $I=0A$
- Sultan 2Hz -  $I=45kA$
- JP Sim 2Hz -  $I=45kA$

$T(t)$  comparison between JackPot simulations and Sultan measurements for sinusoidal  $B_a$  based on identified  $\rho_{is}$

Diffusion time cable-jacket not taken into account

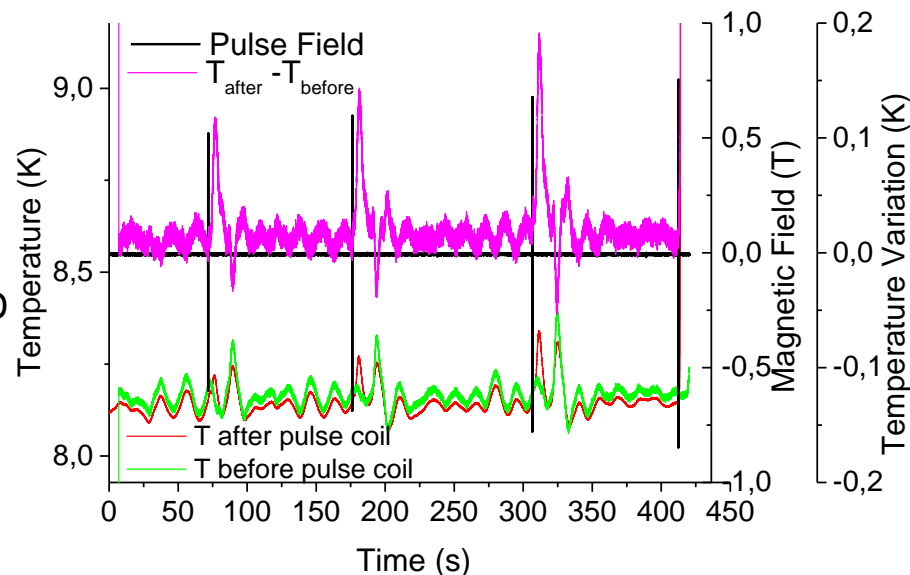
# Sultan Facility - CSK01 - MQE tests

One single sine-wave pulse for MQE.



$\Delta T = T$  before and behind AC coil, taking into account flow rate (phase shift) and subtract oscillation.

$T$  increase  $\rightarrow$  energy deposited in cable during pulse.



## Boundary conditions:

Initial  $T = 8,1$  K

$B_{dc} = 9$  T

Pulse period = 0,128 s

$I_T = 45,1$  kA

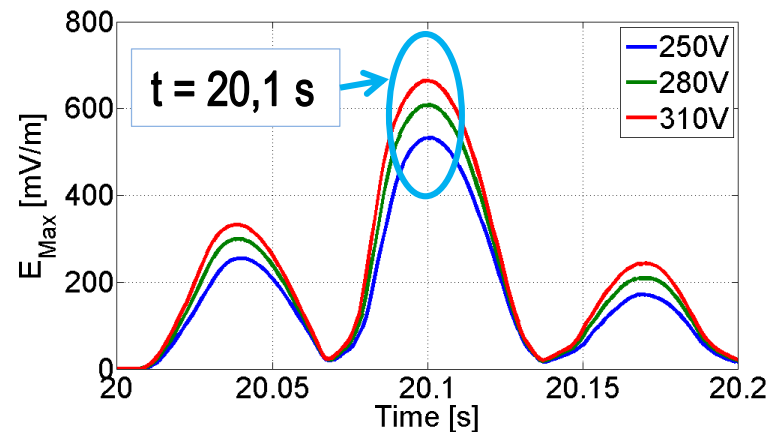
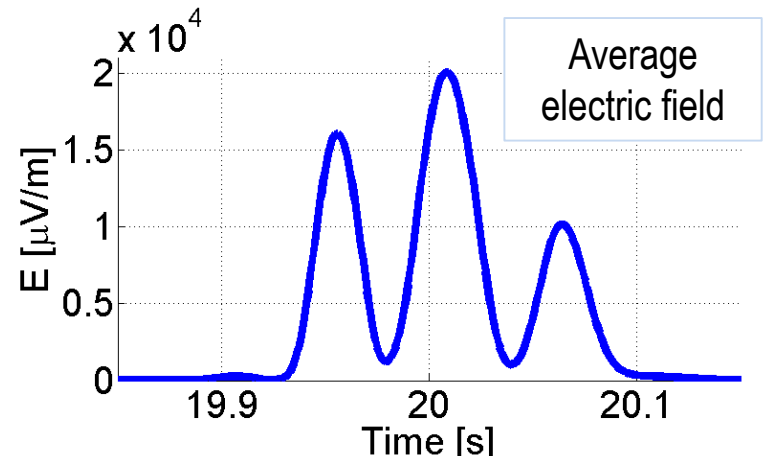
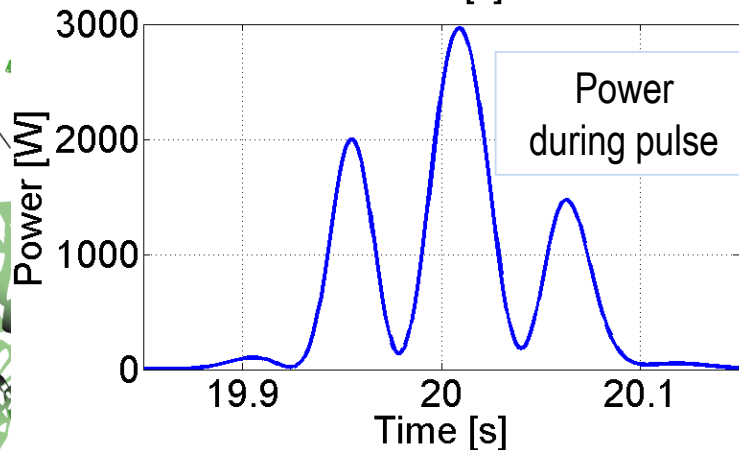
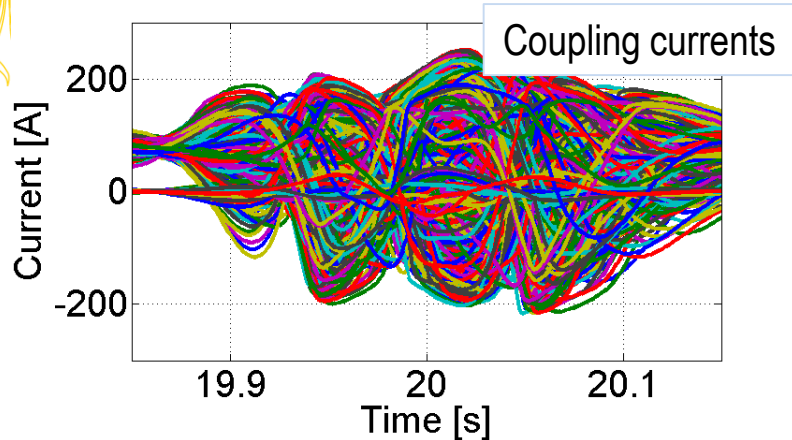
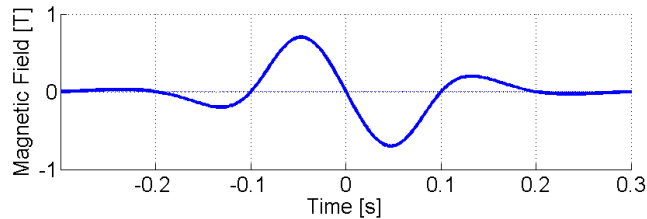
He mass flow = 3,3 g/s

Pulse amplitude = 220/250/280/310Q V

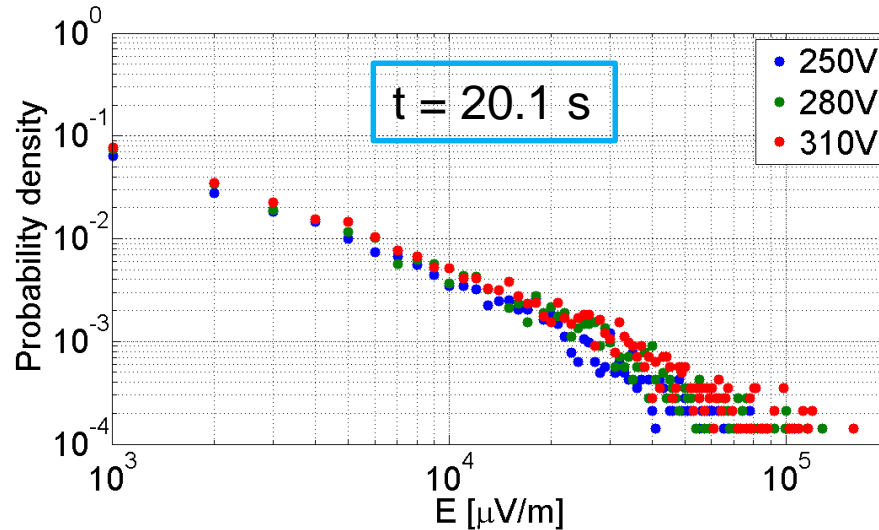
V-pulse	$\text{Int}(T \cdot dt)$	$B_a$	$dB/dt_{\text{max}}$
[V]	[K·s]	[T]	[T/s]
220	0,76	0,56	17,5
250	0,87	0,64	20,0
280	1,14	0,73	22,8
310Q	##	0,80	25,0



# JackPot CSK01 - MQE simulations (1)



# JackPot – CSKO1 - MQE simulations (2)



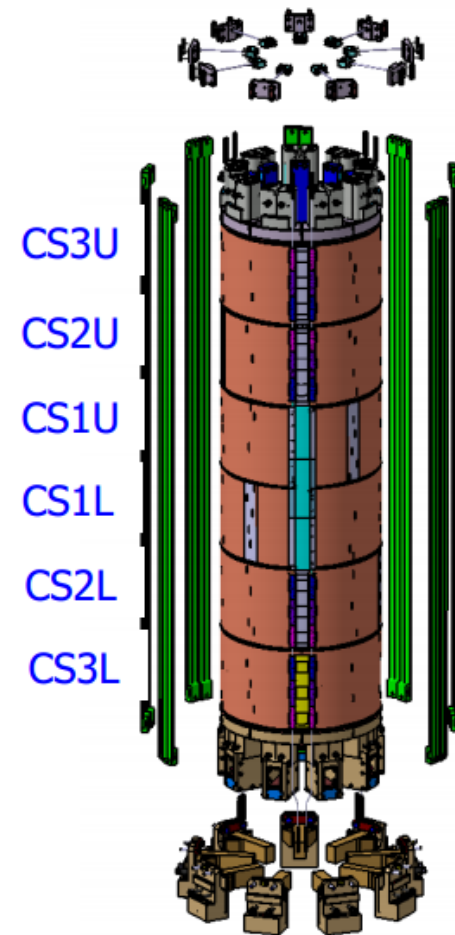
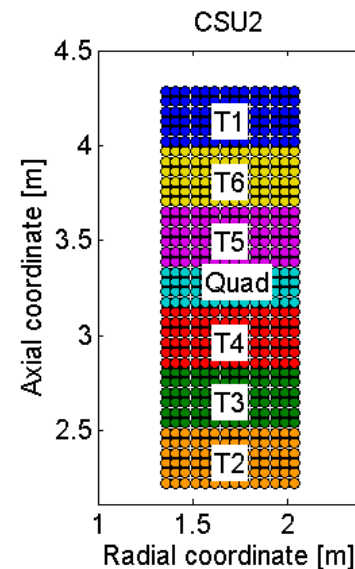
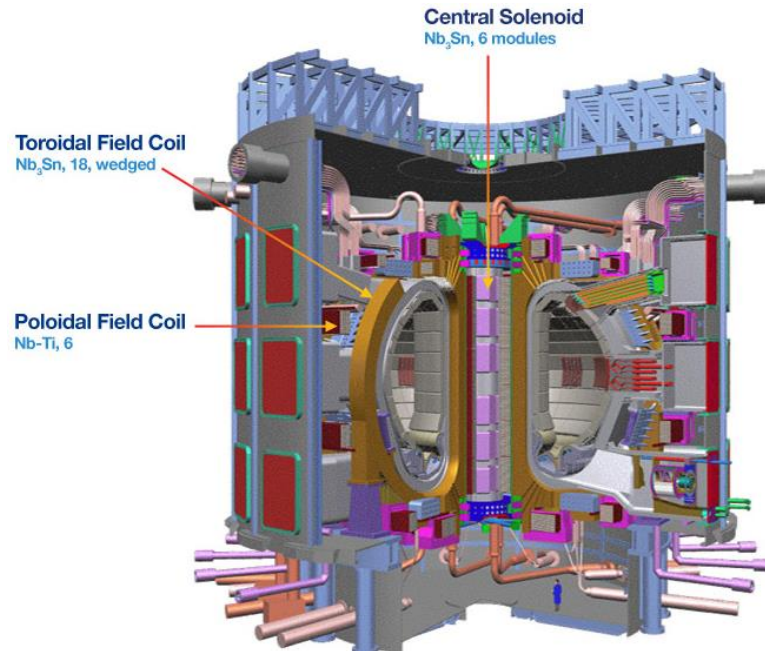
Probability density of  $E_z$  for different pulse amplitudes.

Pulse	JackPot <sub>sim</sub>	Sultan
[V]	[K·s]	[K·s]
250	0,99	0,87
280	1,25	1,14
310Q	1,47	##

Integral  $T \cdot dt$  values close to Sultan results ( $\sim 10\%$  difference).



# ITER - Central Solenoid



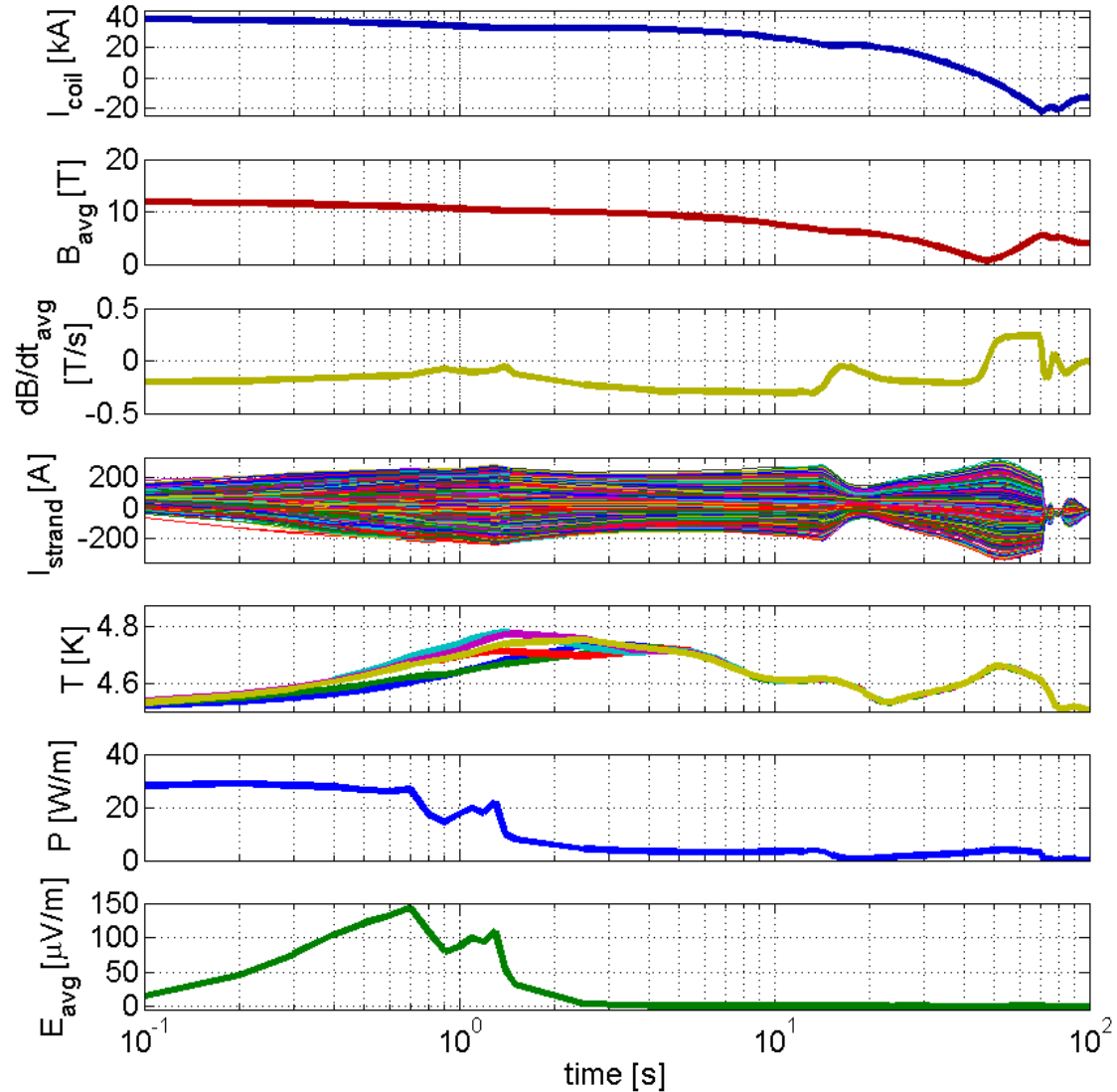
## Field model:

- The field produced by the analysed CS module is calculated with a high accuracy, taking the position of all its windings into account
- Other coils are approximated by their current centre lines

# JackPot - CSK01 – 15 MA Plasma scen. (1)

Simulation for ITER CS 15 MA Plasma Scenario conditions.

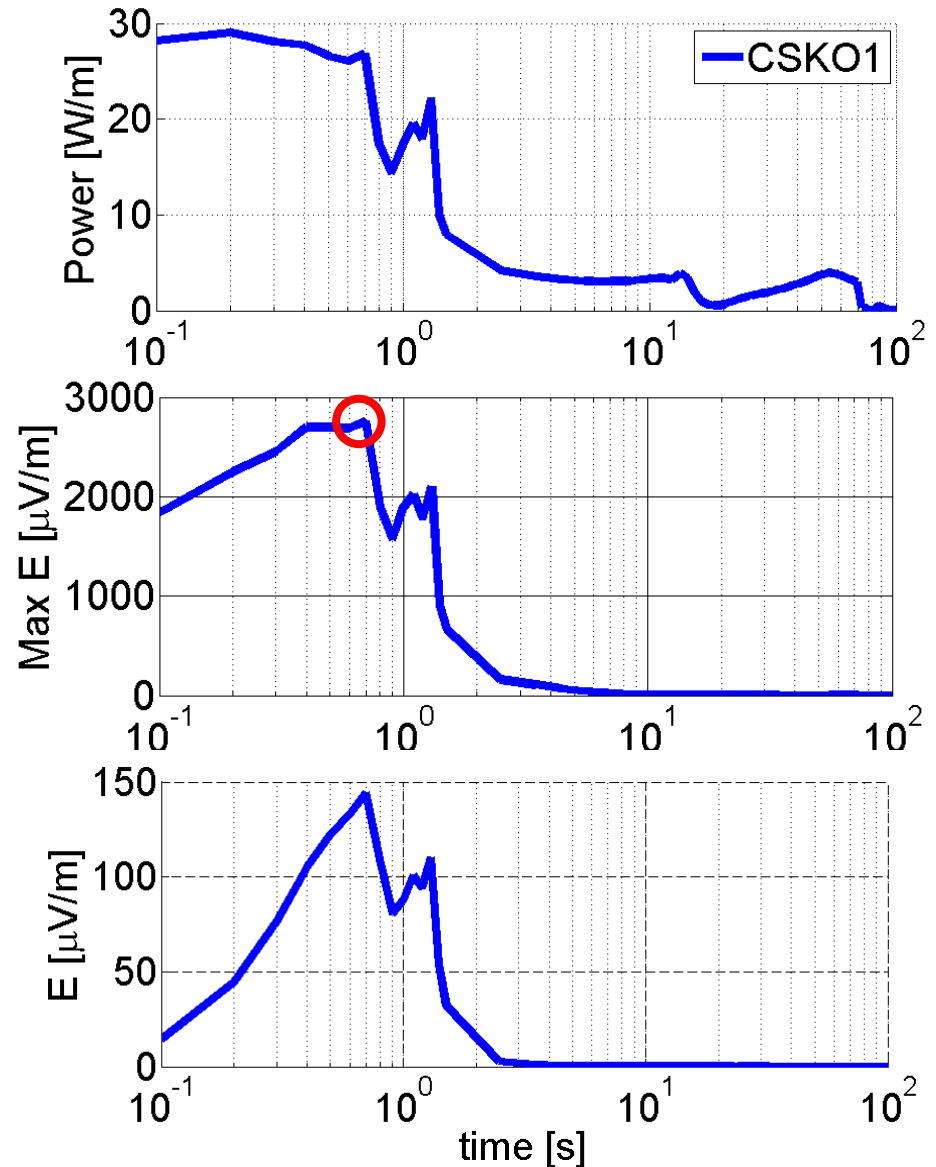
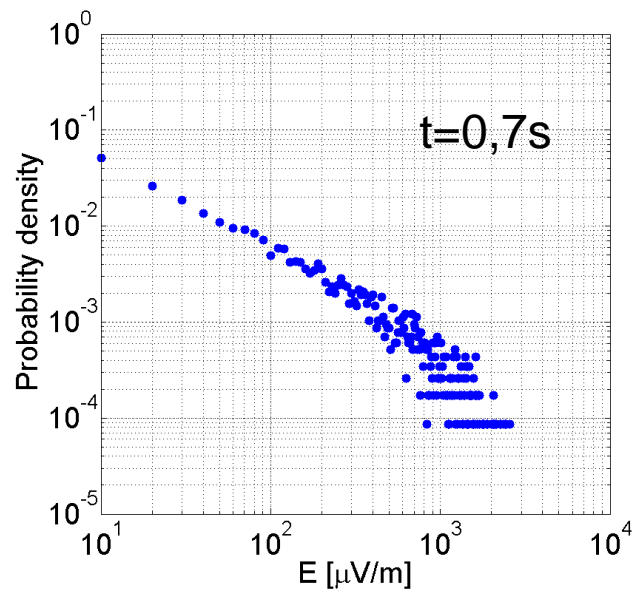
Worst condition, in pulsed operation, are in the turns at inner radius of pancakes from CSU2 and CSL2 modules.



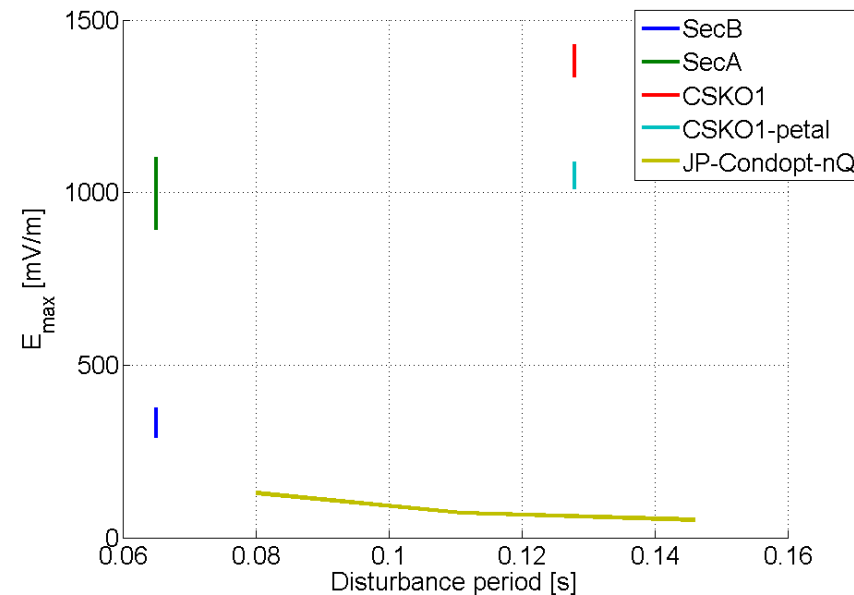
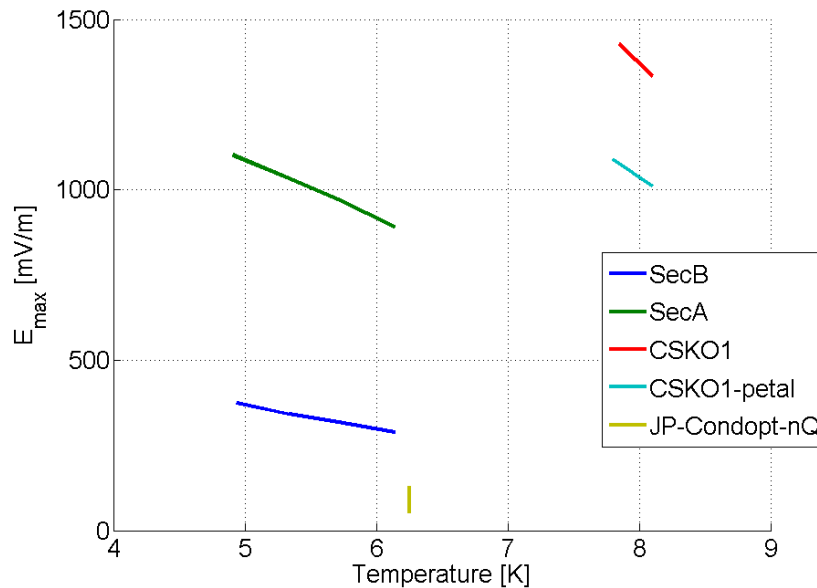
# JackPot - CSKO1 – 15 MA Plasma scen. (2)

$E_{\max}$  of CSKO1 during Plasma Scenario is  $\approx 200$  X, and  $E_{\text{ave}}$  100 X, lower than during MQE simulation with truncated sine wave pulse

But duration is longer

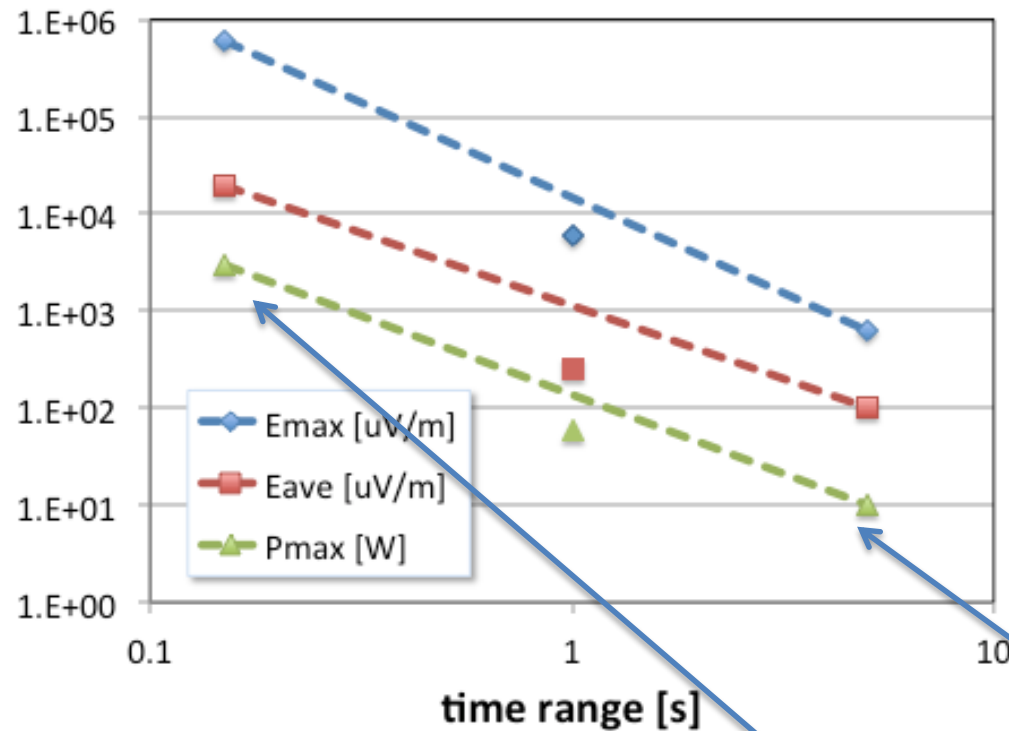


# $E_{\max}$ different conductors - fast pulse



- Local  $E_{\max}$ , during quench, is similar for SecA and CSKO1 in spite of different size, twist pitch and void fraction.
- SecB and Condopt, with 6 SC around 1 Cu, quenches at order of magnitude lower  $E_{\max}$ .
- Suggestion: **local  $E_{\max}$  of  $\approx 1$  V/m serves as quench threshold during fast pulse** (for roughly same helium mass flow rate).

# Quench: $E_{\max}$ , $E_{\text{ave}}$ & $P_{\max}$ vs time scales



Time scale for pulses are different: for fast sine-wave pulse (0.1 s), 15 MA (1 s),  $T_{\text{cs}}$  test (5 s). When simply assuming quasi DC  $T_{\text{cs}}$  test as 5 s range and connecting experimental points (power law fit), stable performance is predicted for 15 MA scenario.

□ 15 MA scenario stability: experiments in proper time range needed.



# Conclusion

---

- JackPot calculation of  $T$  based on AC losses consistent with experimental data.
- Analysis suggests a local strand peak  $E$  level as a critical threshold for quench during very fast pulse (0.1 s range).
- Clean MQE experiments on CICC scarce; more fast pulses and eventually pulse time closer to 1 s range (time scale plasma discharge) needed.