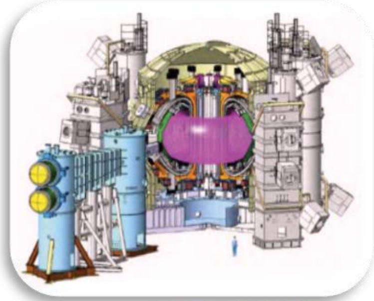
cea irfm



JT-60SA
Advanced Superconducting Tokamak
BA-Satellite Tokamak Program

EUROfusion

TS Title: 2024 TF and EF Thermohydraulic models

TS Ref. Nr: SA-SE.CM.OP.06-T002

Technical Specification: TF and EF Thermohydraulic models including casing-winding pack (WP) exchanges and pulsed PF operation.

Deliverable SA-SE.CM.OP.06-T002-D002: Deliverable title EF STREAM model prediction for heat loads deposition

Benchmark with a reference case on EF and CS during plasma scenario with IC database by consolidating AC
losses calculation in FAOW-STREAM with Loop 2 cryogenics input

Extend predictions on selected cases on EF and CS during plasmascenario and assess their risk level (DT margin
and potential reduced helium mass flow) and identify their repetition rate. Explore edge configurations/scenarii.

S. Nicollet, CEA / DRF/ IRFM: 2 pm

→ **Partly (1 pm) upgrade of TFC Fast Discharge studies with FAOW-STREAM (final paper of MT28),**

Thermohydraulical Analysis and Fast Assessment of Operating Windows for JT-60SA TFC Commissioning, August 2024,IEEE Transactions on Applied Superconductivity PP(99):1-6, August 2024, PP(99):1-6, DOI:10.1109/TASC.2024.3393894

→ **Partly (1 pm) STAM Model still to be developed and applied to CS3 pulsed Operation (Part of EUROFusion Trainee of 6 months, beginning 01/09/2024)**

1. JT-60SA TFC FAOW-STREAM Model for Current Discharge

FAOW-STREAM: Fast Assessment of Operating Windows- Superconductors Thermohydraulical &Resistive Electrical Analytical Model

TFC FAOW-STREAM MODEL & CALCULATION STATUS:

→ 2023 Tasks and Deliverable: FAOW-STREAM Model developed → 2024 Tasks and Deliverable: Updated Results

→ Partly (1 pm) upgrade of TFC Fast Discharge studies with FAOW-STREAM (final version of MT28 paper),

Thermohydraulical Analysis and Fast Assessment of Operating Windows for JT-60SA TFC Commissioning, August 2024,IEEE Transactions on Applied Superconductivity PP(99):1-6, August 2024, PP(99):1-6, DOI:10.1109/TASC.2024.3393894

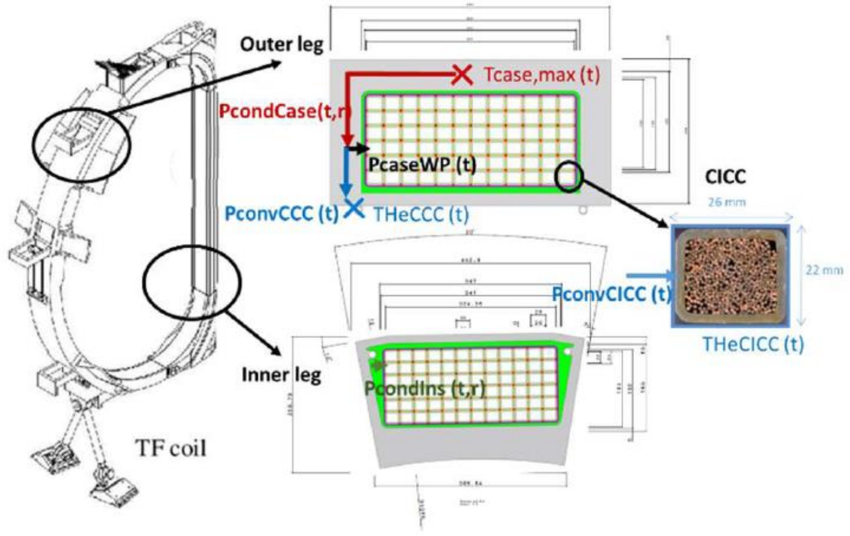


Fig. 2. JT-60SA TF Coil, Winding Pack, case and CICC

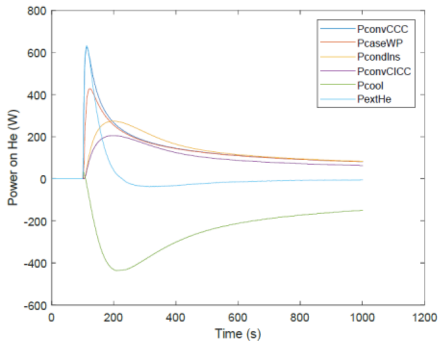


Fig. 6. TFC 18 kA current discharge: Casing Cooling Channel convective power PconvCCC, transferred power from case to WP PcaseWP, conductive transfer power in insulation PcondIns, convective power in CICC PconvCICC, cooling power Pcool, and external power to helium PextHe.

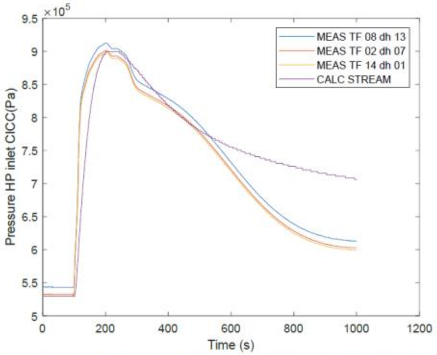


Fig. 7. TFC 18 kA current discharge helium pressure (Low Pressure side at outlet of CICC) Measurements and FAOW-STREAM Calculated Results.

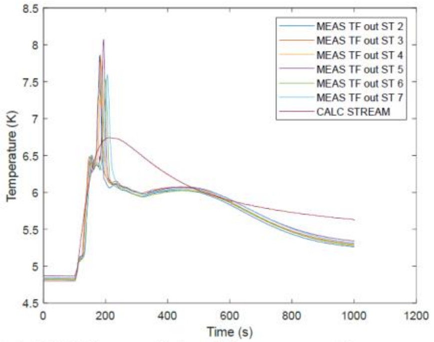


Fig. 8. TFC 18 kA current discharge helium temperature Measurements and FAOW-STREAM Calculated Results.

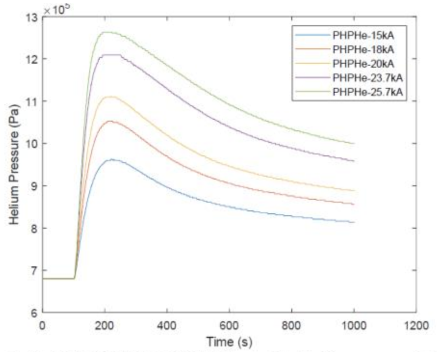


Fig. 9. JT-60SA TFC FAOW-STREAM calculated helium pressure (at high pressure side) for current discharge at 15, 18, 20, 23.7 and 25.7 kA.

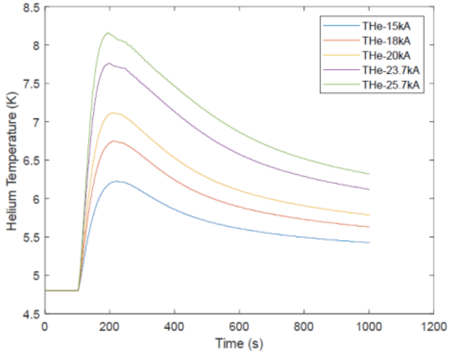


Fig. 10. JT-60SA TFC FAOW-STREAM calculated helium temperature for current discharge at 15, 18, 20, 23.7 and 25.7 kA.

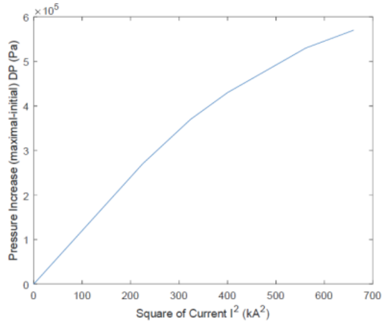


Fig. 11. JT-60SA TFC current discharge helium pressure increase (maximal-initial) as a function of the square of current

2. JT-60SA CS/EF STAM Model for Operation

STAM Model: Superconductors Thermohydraulical Analytical Model FOR OPERATION

Inputs: CICC AC losses Coupling (nTau ?) + Hysteresis (deff ?)

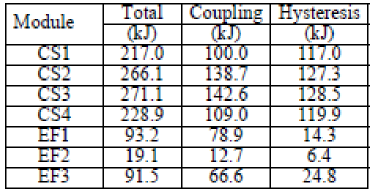
$$Q_{cl}(x,t) = \frac{n.\tau.S_{st}}{\mu_0}.\int\left(\frac{dB_{mod}(x,t)}{dt}\right)^2.dx$$

Sst = superconducting strands cross section
$\mu_0=4*\pi*10^{-7}$ Hm^{-1}
example : n.τ = 150 ms

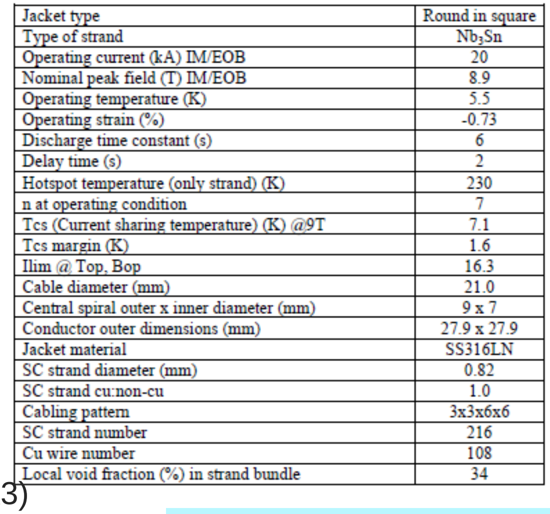
Example : deff= 5 µm
Sноncu = 74.5 10-6 m²
JnonCu (T,B) : Current critical density in Superconductor

$$Q_h(x,t) = \frac{2}{3.\pi}.d_{eff}.S_{nonCu}.\int J_{nonCu}.\frac{dB_{mod}(x,t)}{dt}.dx$$

Table 4.3-1 AC loss energy of whole module



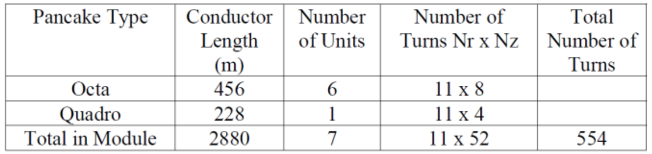
Module	Total (kJ)	Coupling (kJ)	Hysteresis (kJ)
CS1	217.0	100.0	117.0
CS2	266.1	138.7	127.3
CS3	271.1	142.6	128.5
CS4	228.9	109.0	119.9
EF1	93.2	78.9	14.3
EF2	19.1	12.7	6.4
EF3	91.5	66.6	24.8



Jacket type	Round in square
Type of strand	Nb_3Sn
Operating current (kA) IM/EOB	20
Nominal peak field (T) IM/EOB	8.9
Operating temperature (K)	5.5
Operating strain (%)	-0.73
Discharge time constant (s)	6
Delay time (s)	2
Hotspot temperature (only strand) (K)	230
n at operating condition	7
Tcs (Current sharing temperature) (K) @9T	7.1
Tcs margin (K)	1.6
Ilim @ Top, Bop	16.3
Cable diameter (mm)	21.0
Central spiral outer x inner diameter (mm)	9 x 7
Conductor outer dimensions (mm)	27.9 x 27.9
Jacket material	SS316LN
SC strand diameter (mm)	0.82
SC strand cu:non-cu	1.0
Cabling pattern	3x3x6x6
SC strand number	216
Cu wire number	108
Local void fraction (%) in strand bundle	34

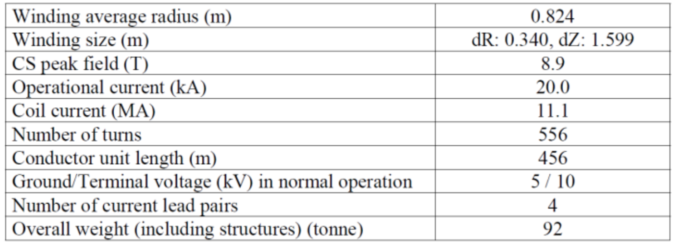
Inputs: CS3 CICC application, (Magnetic Field ?, Current evolution in time ?, Jc Law ?) INPUTS

Table 2.4.2 Winding configuration for each CS Module



Pancake Type	Conductor Length (m)	Number of Units	Number of Turns Nr x Nz	Total Number of Turns
Octa	456	6	11 x 8	
Quadro	228	1	11 x 4	
Total in Module	2880	7	11 x 52	554

Table 2.4.1 Parameters for CS



Winding average radius (m)	0.824
Winding size (m)	dR: 0.340, dZ: 1.599
CS peak field (T)	8.9
Operational current (kA)	20.0
Coil current (MA)	11.1
Number of turns	556
Conductor unit length (m)	456
Ground/Terminal voltage (kV) in normal operation	5 / 10
Number of current lead pairs	4
Overall weight (including structures) (tonne)	92

MODEL STAM

MF(t,x1) →

(MF(t,x3)-MF(t,x1))*Cp(t,x2)*THe(t,x2)=Pheat=Pcl+Ph

MHe(t,x2)*Cv(t,x2)*(PHe(t+dt,x2)-PHe(t,x2))=Pheat=Pcl+Ph

(PHe(t,x1)-PHe(t,x2))/dx=(fb*ά²*MF(t,x1)²)/(2*ρ*Dhb*Ab²)=(fh*(1-ά)²*MF(t,x1)²)/(2*ρ*Dhh*Ah²)=(feq*MF(t,x1)²)/(2*ρ*Dheq*Aeq²)

MF(t,x3) →

Ultimate goal :
+ FAST + MODULAR

STAM Outputs - RESULTS:
- → *Verification and crosscheck of heat loads (AC losses) & Evolution in time and space of the helium (P,T,mt) (Pressure, Temperature, Total mass flow, alpha)*
- → *Comparison to Current sharing temperature Tcs (from Jc law) &Validation of the temperature margin*

***CS STAM MODEL & CALCULATION STATUS:* → Partly (1 pm) STAM Model still to be developed and applied to CS3 Pulsed Operation (Part of EUROFusion Trainee of 6 months, 01/09/2024, Matthieu Sutcliffe, from Cambridge University)**

3. ANNEXES

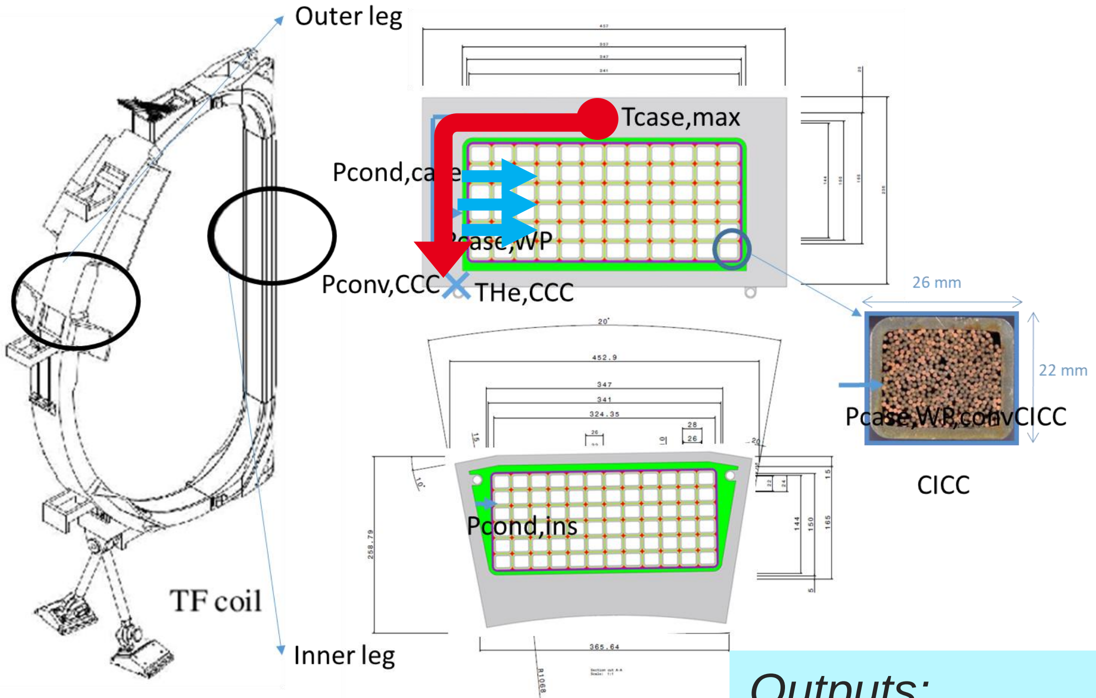
3.1. JT-60SA TFC FAOW-STREAM Model for Current Discharge

Tcase adiabatic longest length to CCC Thermal Path

FAOW Conduction and Inertia Process in Structures

Main FAOW module consists:

- → **Adiabatic boundary condition (at Tcase,max)** in radial direction (r)
- → **Conduction power** Pcond,case,r (1) and **inertia power** (2) with Cp specific heat, **in stainless steel case**, with source deposited Power Pcase,r.
- → **Convective heat transfer power to casing cooling channels** Pcase,conv,CCC (3) determined from Nusselt (4) number and convective heat exchange coefficient (5) in CCC.
- → **Remaining conductive power from case to Winding Pack (WP)** Pcase,WP (6), at the interface of the stainless steel case and ground insulation determined **by difference.**
- → **Conductive power** Pcond,ins,r (7) **and inertia effect** (8) **in insulation**
- → **Additional CICC smoothed deposited convective power** PcaseWP,conv,CICC (9) (coming from radial heat transfer with time delay)



$Pcond,case,r = \lambda case *$Scase/drcase*(Tcase,r-Tcase,r+dr) (1) $Pcond,case,r + Pcase,r - Pcond,case,r + dr = Mass,case * Cp,case * dTcase,r/dt$ (2)

$Pcase,conv,CCC = Hconv,CCC * UwCCC * LCCC * (Tcase,rmax - THe,CCC)$ (3)

$Nu,CCC = 0.023 * REHe,CCC^{0.8} * PrHe,CCC^{0.4}$ (4) $Hconv,CCC = Nu,CCC * \lambda He,CCC/Dh,CCC$ (5) $PcaseWP = Pcond,case,rmax - Pcase,conv,CCC$ (6)

$Pcond,ins,r = \lambda ins *$Sins/drins*(Tins,r-Tins,,r+dr) (7) $Pcond,ins,r - Pcond,ins,r + dr = Mass,ins * Cp,ins * dTins,r/dt$ (8)

$PcaseWP,conv,CICC = Hconv,CICC * Sconv,CICC * (Tins,rmax - THe,CICC)$ (9)

Outputs:
Heat flux to CCC & CICC,
T solid

- → ***FAOW-STREAM Main Interest is execution time duration and upgrade capabilities.***
- → ***Work useful for performances analyses: operation (NH), slow (cool down) or rapid transients (current discharge, quench)***
- → ***In view to recommend their use in ITER or EU-DEMO, with possibility of real-time feed-forward calculations/control.***

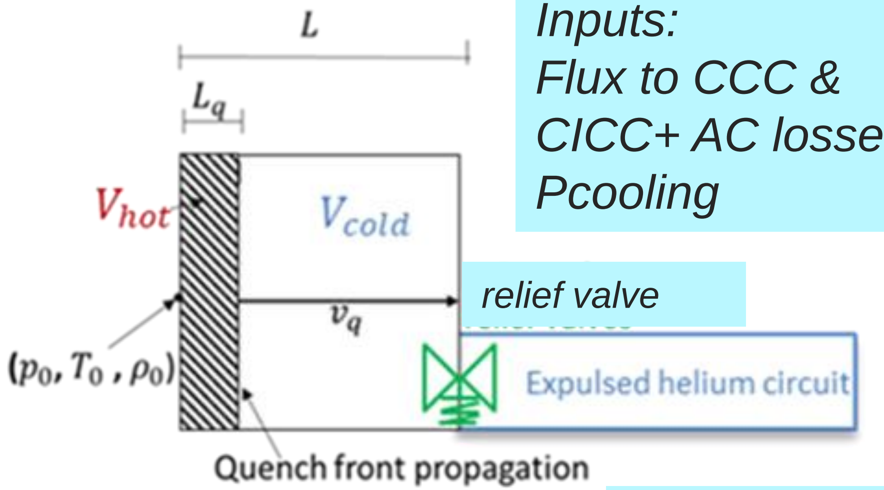
3.2. JT-60SA TFC FAOW-STREAM Model for Current Discharge

STREAM Model for Current Discharge

without Electrical model

STREAM [6] comprises two following sequences:

- → **first phase (thermal and thermodynamical) is the evolution (from initial state) of helium pressure and temperature in a closed volume.** The heated volume (V_h in which the external and Joule energy is deposited) induces an isentropic compression of the other cold volume (V_c) which remains adiabatic (no energy inside).
- → **second phase (hydraulical) describes the helium mass flow expulsion, from a given pressure drop threshold,** through relief pipes and valves with the limitation at atmospheric pressure or Mach number equal to 1.



STREAM General Scheme (from [6]): the hot volume is heated by AC losses or power transferred to CCC and CICC (instead of Joule power with quenched length Lq in [6])

relief valve

Inputs:
Flux to CCC &
CICC+ AC losses+
Pcooling

General He model
HP/CICC/LP=Loop 1

[6] S. Nicollet, A. Torre, B. Lacroix, A. Louzguiti, Q. Gorit and WEST Team, Superconductor Thermohydraulical and Resistive Electrical Analytical Model (STREAM) applied to WEST TF Coil Quench Analysis, Cryogenics 125 (2022) 103493

[7] S. Nicollet et al., JT-60SA TFC Integrated Commissioning Current Discharge Thermohydraulical Analyses with FAOW-STREAM and SuperMagnet, to be published in Cryogenics (2023).

For JT-60SA TFC Current Discharge and WP CICC & case cooled in series:

Closed Loop 1 initial total helium volume (before valves open) with one heated "hot" part , and the other not heated "cold" part volumes.

Aditionnal average cooling power PcoolAv (10) ***with ideal heat exchanger*** imposing a constant outlet temperature of 4.5 K.

Loop1 considered in 0-D for thermohydraulical evolution (helium pressure and temperature) ***with total external heating power Pext,He,Tot*** (11)

Directly deposited in helium (from FAOW model and results), with supposed coupling & hysteresis losses immediately deposited (CICC large wetted perimeter).
If relief safety valves open (pressure threshold of 1.2 MPa), helium mass flow expulsed through exhaust circuit, discretised in space (exhaust valves and pipes).

$$PcoolAv = MF,He * (hout(PHP,Tbath) - hin(PHP,THe,calc)) \qquad (10)$$

$$\boldsymbol{Pext,He,Tot = Pcoup + Physt + Pcase,conv,CCC + PcaseWP,convCICC - PcoolAv} \qquad \mathbf{(11)}$$

Ultimate goal :
+ FAST + MODULAR