# Recent EFDA work on pulsed DEMO

T N Todd
Culham Centre for Fusion Energy, Oxfordshire

## Contents

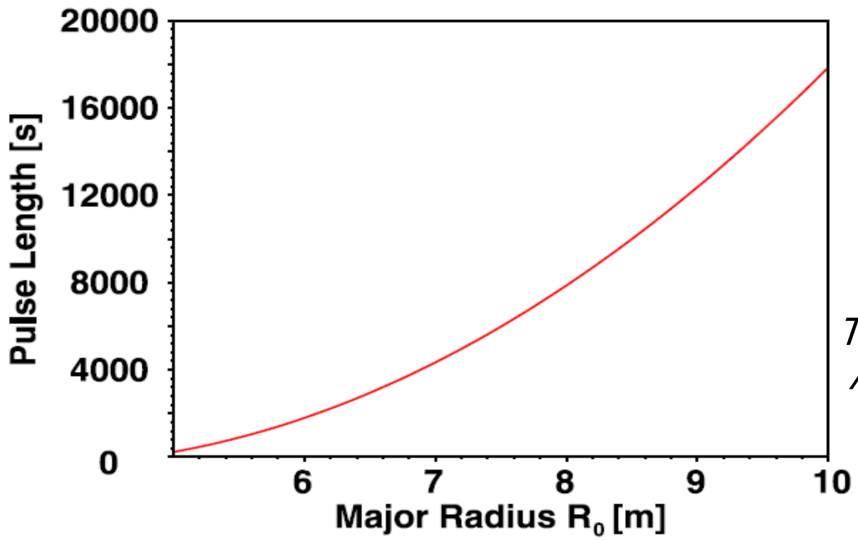


The UK fusion research programme is funded jointly by the Engineering and Physical Sciences Research Council and by the European Communities under the contract of Association between EURATOM and UKAEA.

# Literature review - Minimum size

*F.P. Orsitto, ENEA Frascati*

- Minimum size depends on choice of steady state or pulsed operation.
- Steady state (recirculating power fraction $F_R$ up to 30%) - ~3 $GW_{th}$
- Pulsed ~1 $GW_{th}$, permits low $F_R$ but pulse is short, < 3hours.



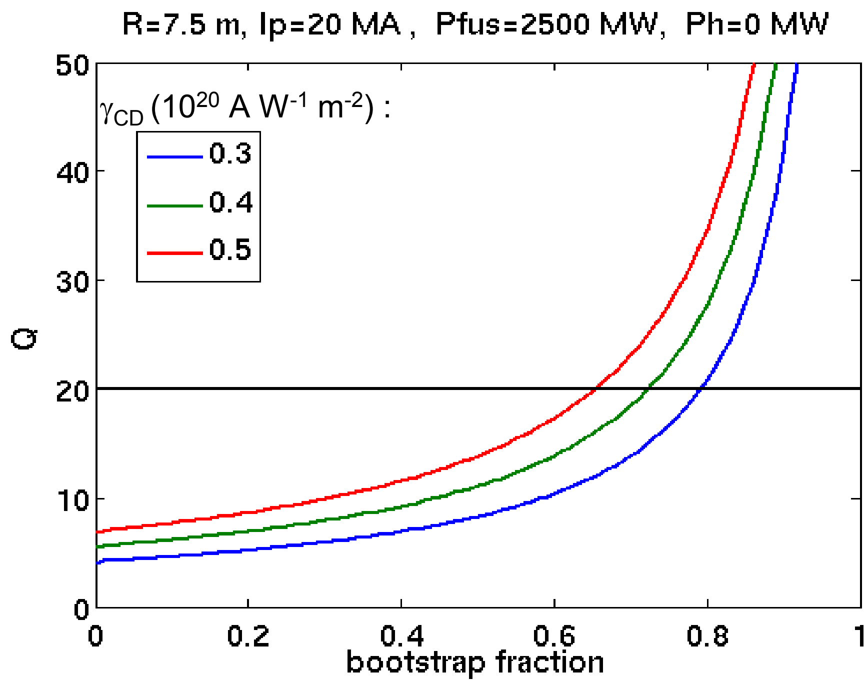

*T-pulse vs R for ITER-like machine with A=4, B=7.4T, $\beta_N$=2.6 and $f_{CD}$ =0 (Zohm)*

- Good experimental demonstrations of simultaneous HH, $\beta_N$ etc...
- But is ITB OK in DEMO (sustainable)?
- Alpha confinement in ITB plasmas (hollow j(r))?
- Self-organising effects at high Q?
- Burn control issues (diagnostics, actuators) at high Q?

# Literature review – Physics issues

## Analysis of DEMO scenarios (J Garcia)

For realistic Current Drive efficiencies ($\gamma_{CD}$≈0.3-0.4 $10^{20}$ A $W^{-1}$ $m^{-2}$), a high bootstrap fraction is required, $f_{BS}$≥0.7-0.8, to suit the ~110MW power available.




In the PPCS papers a more optimistic $\gamma_{CD}$≈0.7 $10^{20}$ A $W^{-1}$ $10^{20}$ $m^{-2}$, is assumed.

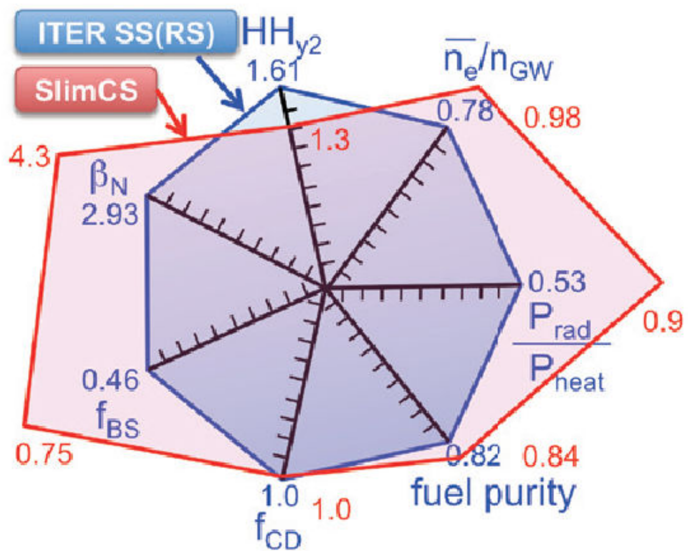
*We also need to consider the "wall-plug efficiency" of Watts delivered to the plasma per Watt taken from the mains connection , perhaps ~45% for negative ion neutral beams.*

# Literature review – Physics issues

The critical issues for SS DEMO were analyzed by Y Sakamoto *et al* 2010.

**It is noted that the ITER steady-state scenario assumes parameters ($HH_{ipby2}$=1.61, $\beta_N$=2.93, $f_{BS}$=0.46, $n/n_G$=0.78) not yet demonstrated simultaneously in present devices.**

**SLIM CS, an R=5.5m SS DEMO, is even more demanding:**



# First wall heating and erosion

*Y. Igitkhanov, KIT*

## Power and Particle loads

### Steady state normal operation:

Blanket armour (FW)

- Power flux ~ 0.5 MW/m2
- Particles flux ~ 2 10E21 m-2
- Temperature ~ 100-500 eV

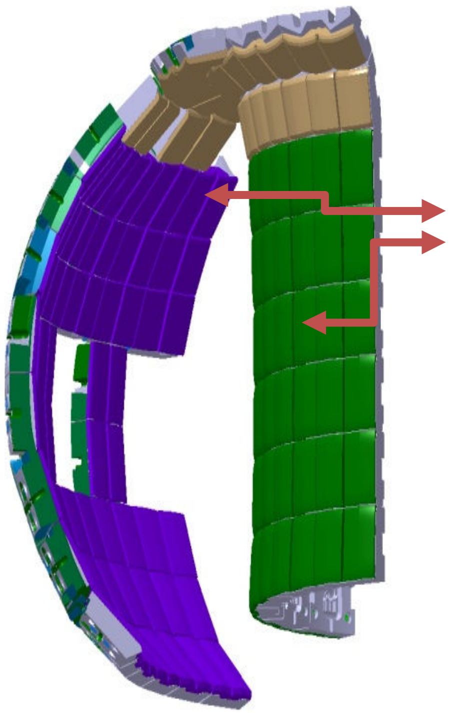
Divertor plates

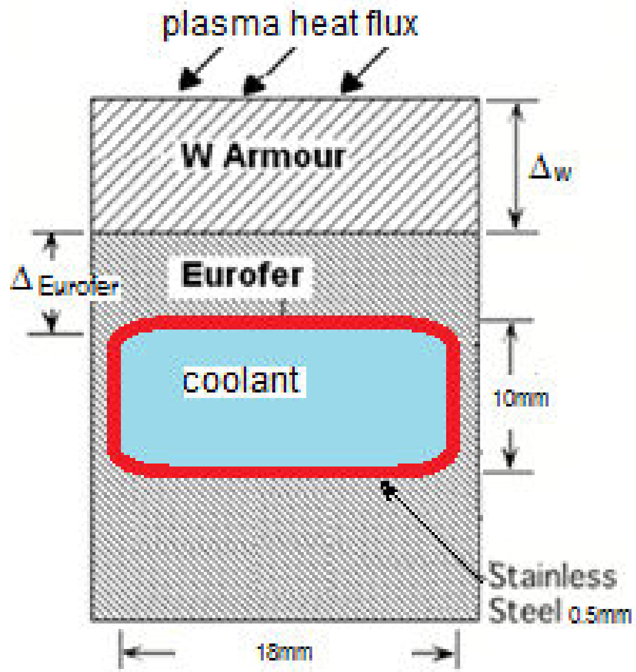
- Power flux ~ 10-20MW/m2
- Particles flux ~ 5 10E21 m-2
- Temperature ~ 500-1000eV

### Operation with off-normal events

Blanket armour (FW)

- Hot VDE ~ 50/100 MW/m2 ~ 1sec
- Cold VDE ~30-50 MW/m2 ~ 0.3-1sec
- RE ~100 MW/m2 ~ 0.05-0.3sec



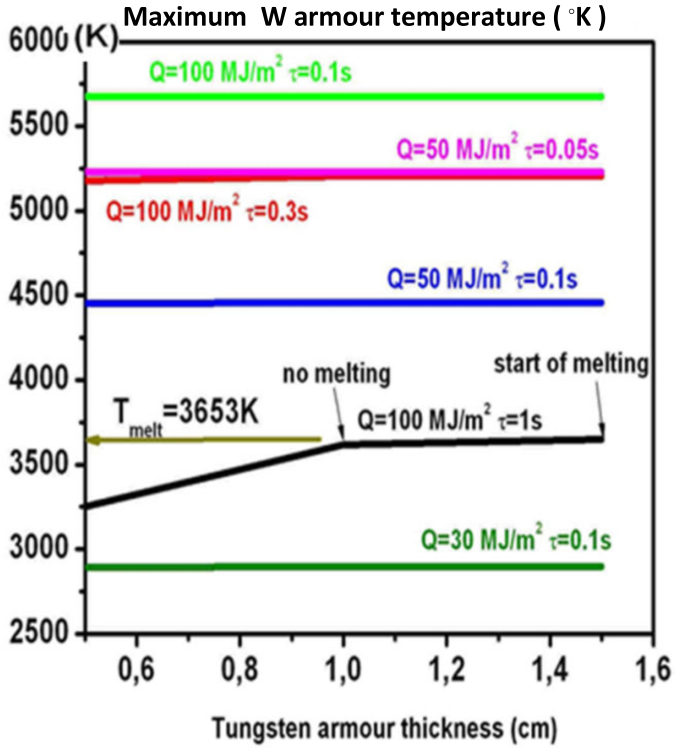


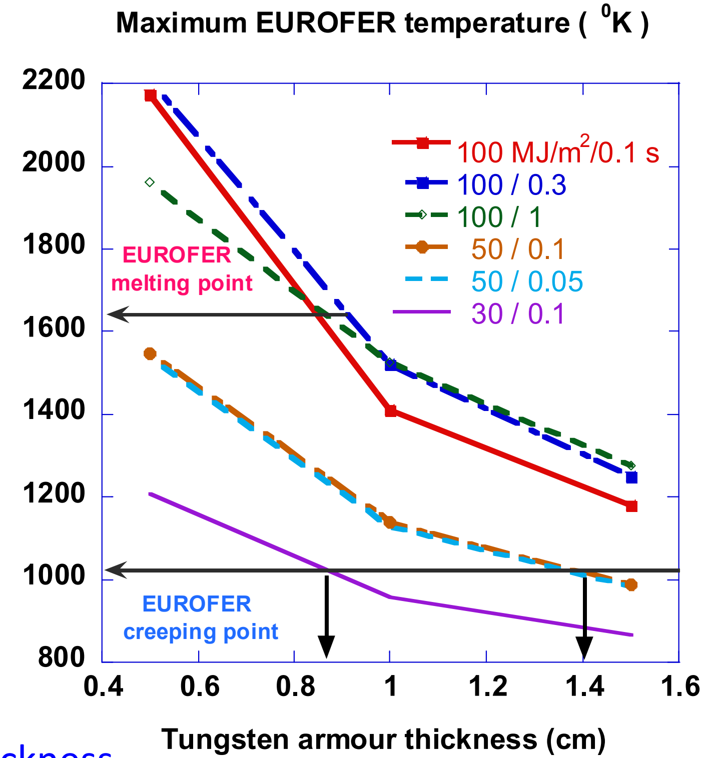

**Sandwich type FW blanket module; heat flux into coolant ($H_2O$) remains (as in ITER) under the CHF, ~ 9MW/m², $T_{wall}$~280°C , $T_{water}$~150°C, P~3.6MPa, v ~ 3.4m/s**

Disruptions must be very rare but nevertheless must be accommodated in DEMO-1.
All these off-normal events are “difficult”! Must try to keep the Eurofer below 550°C.
REs: we can stop the Eurofer from softening by thickening the W to 14mm, but then the W melts.

# Effect of Off-Normal Events on DEMO First Wall

| Event | Energy density, $MJm^{-2}$/deposition time, sec | Deposited area, $m^2$ | Max. Eurofer temperature, K | Molten Layer Thickness (mm) W | Evaporated Thickness(mm) W | Max. W armour temperature, K |
|---|---|---|---|---|---|---|
| Hot VDE | ~50-100/1 | 24 | ~1610 | ~0.85 | 0.011* | $T<T_m$ for $\Delta w<1$cm |
| Cold VDE | ~30-50/0.3-1 | 24 | ~1260 | ~0.740 | 0.009* | $< T_m$ |
| RE | 50~100/0.05-0.3 | 0.8 | ~1500 | ~1.8 | ~0.035 | $>> T_m$ |



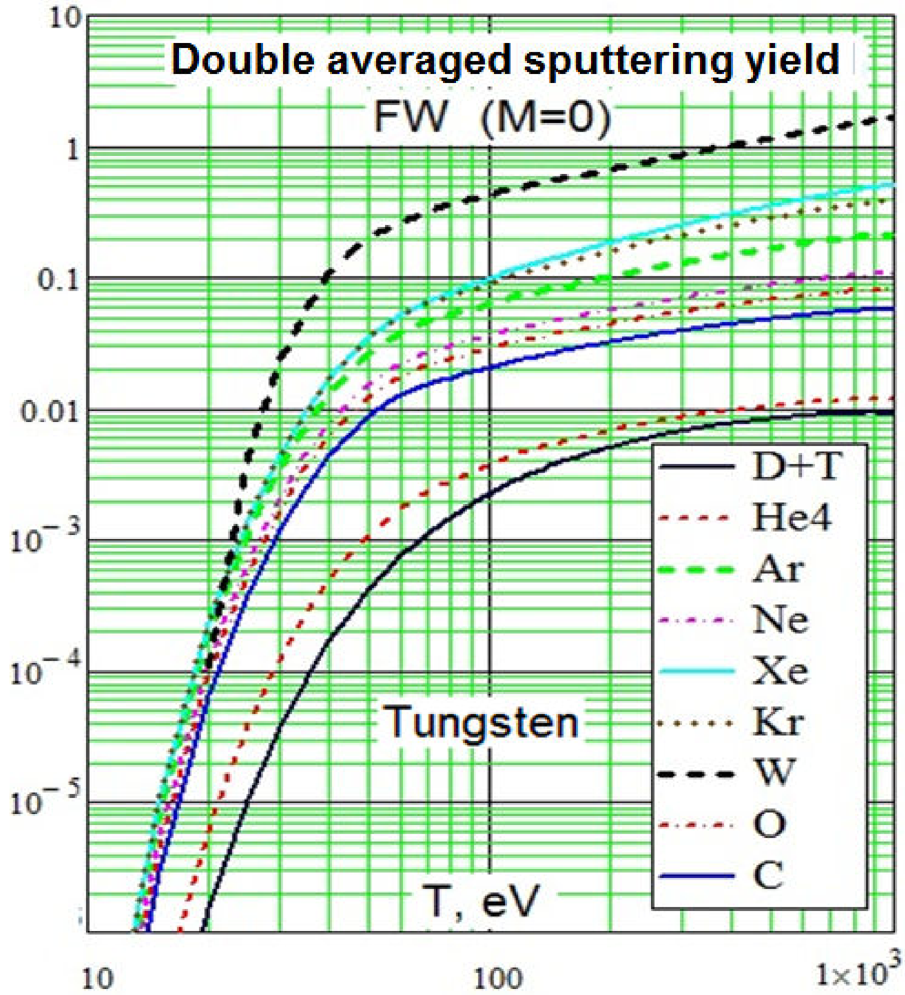




- The EUROFER creep point limits the minimum W thickness (as indicated by vertical arrows for 30 and 50MJ/m2, τ=0.1s); the case of RE and hot VDE

# First Wall heating and erosion

## Impurities greatly aggravate erosion

- Impurities exacerbate sputtering due to their high mass
- If ionised, as in the divertor, they fall through the sheath drop of several $kT_e/e$ with a multiple charge state and gain considerable energy
- However, if that is not a large perpendicular acceleration...

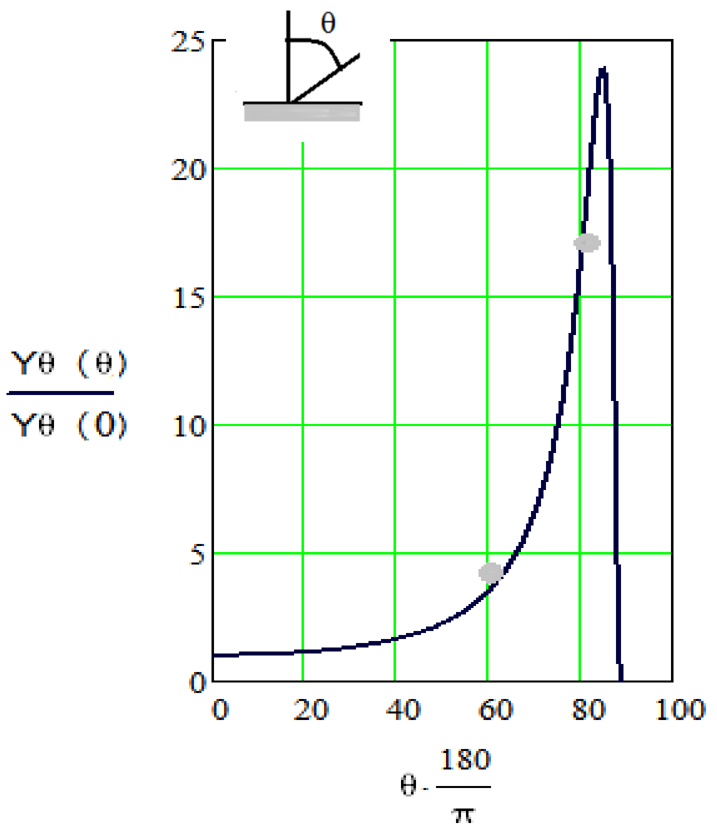


# First Wall heating and erosion

*Yuri Igitkhanov, KIT*

## Angular dependence of sputtering yield

H+ impacting W,  E=4keV:




Yamamura Y., Itikava Y., N. Itoh: IPPJ-AM-26, Nagoya (1983)

Assuming normal incidence will underestimate the rate of erosion, especially near grazing incidence as in the divertor.

Total sputtering erosion of W armour by charge-exchange neutrals is ~1mm in one year of steady-state operation.

*Dust implications…*

*But if the W is made many mm thick, more neutrons are scattered into the divertor region, reducing the tritium breeding ratio.*

*J.L. Duchateau, P. Hertout, CEA/DSM/IRFM*

## Parameter selection for HELIOS -based systems code studies

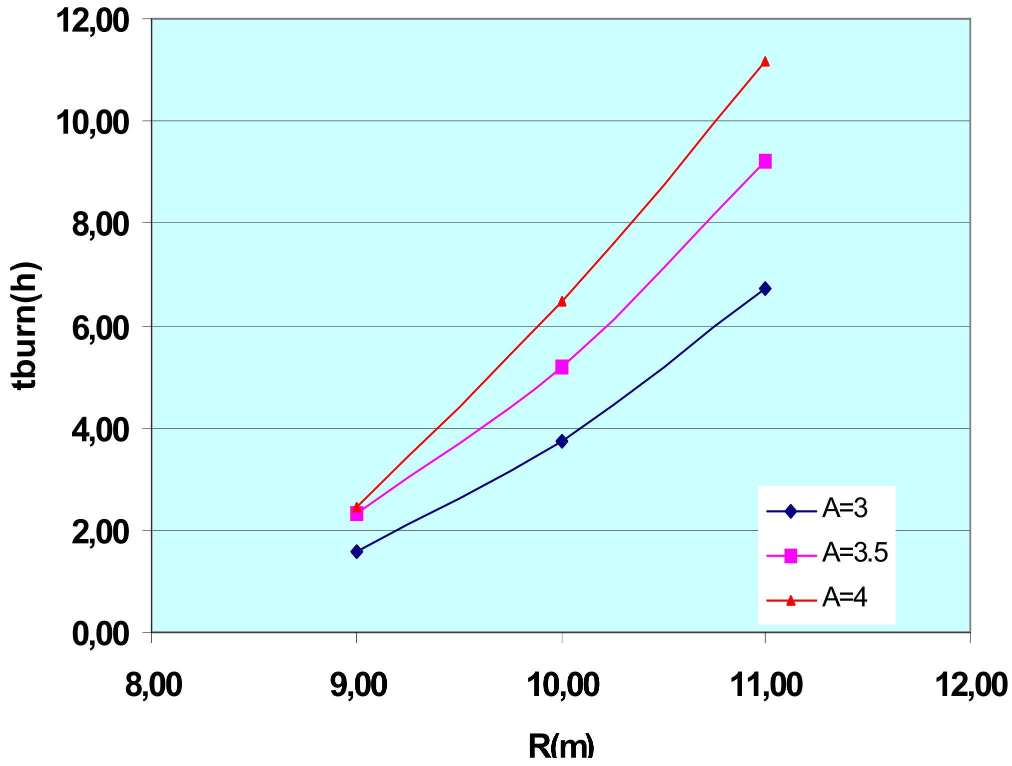
- Only 1 GW of fusion power
- Only 4.8 T central toroidal field
- 1.9m of efficient neutron shielding
- Very conservative superconductor loads:
  - only 50W/m$^3$ nuclear heating, 2K margin, <12T max
- No plasma current drive at all.

- No suitable plasma current drive technology or magnet cable design is available at present to build a "standard" 3 GW, 7.45 T machine

- ⇒ This is a reasonable near-term (pulsed) demonstration machine.

# Systems code studies

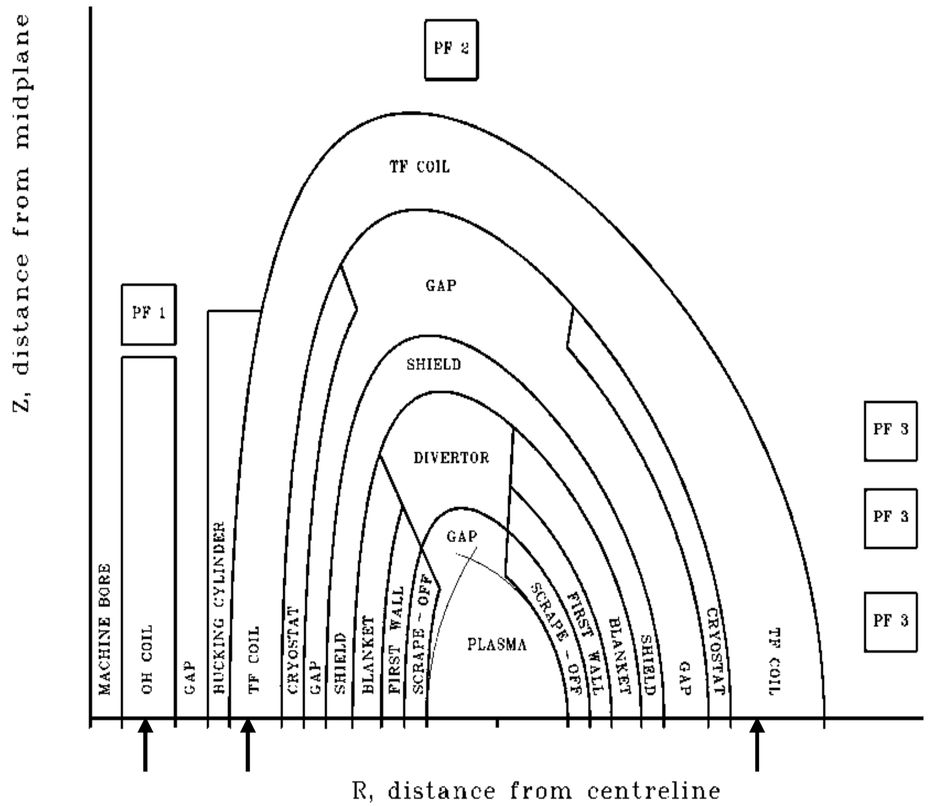
- Burn duration explored for various R and A.
- $T_{burn}$ only ~3 hours for major radius of ~9 m (as in DJ Ward reference case for these 2011 pulsed DEMO studies).
- Recirculating power is small because there is no current drive.
- Need heating during start-up to reduce the resistance and therefore the flux consumption during ramp-up.

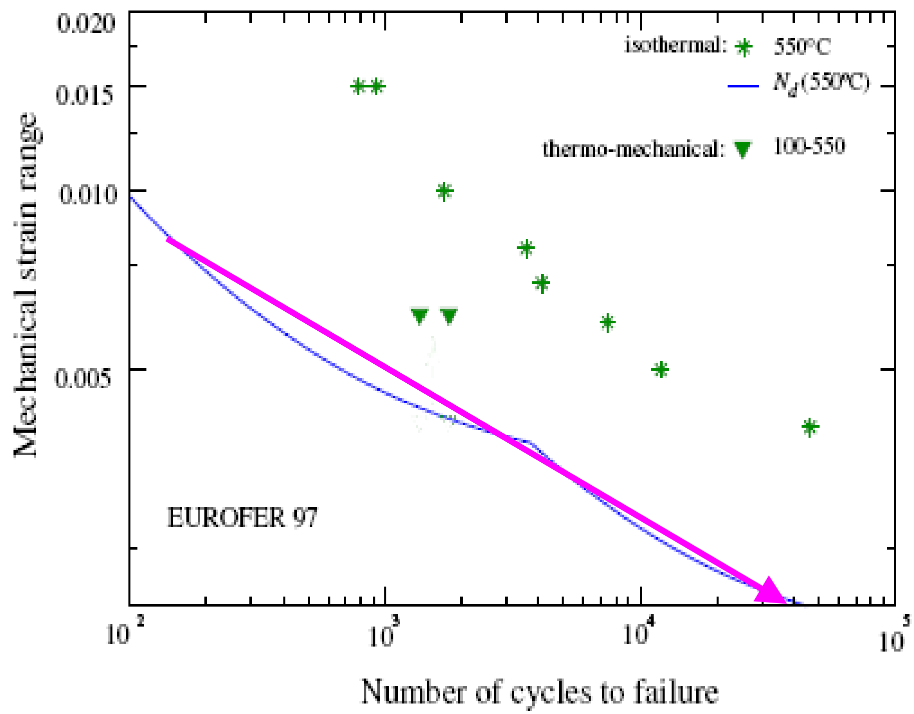


# Fatigue in the Central Solenoid and TF Coil

- Typical fatigue S-N curves for Eurofer and similar alloys: maximum allowable stress needs factor of 3 reduction for pulsed operation (~50k cycles instead of ~150 for SS).
- But no room to expand radial build!

*W. Han, CCFE*




*Aktaa et al*

# Fatigue in the Central Solenoid and TF Coil

*W. Han, CCFE*

- Fatigue data was`gathered for a wide range of high performance alloys, but they only offer a ~20% gain in allowable stress at 40,000 cycles, compared to EUROFER.
- In any case, we need much more data on creep fatigue and the effect of fast neutron irradiation for structures near the First Wall.
- Since PROCESS assumptions are not specific about engineering design, two cases were developed assuming that the usual PROCESS radial build would suit ~40k pulses.
- Iteration permitted a close match of net $P_e$ etc, with the solenoid enlarged to increase pulse length.
- And the predicted cost of electricity was the same!

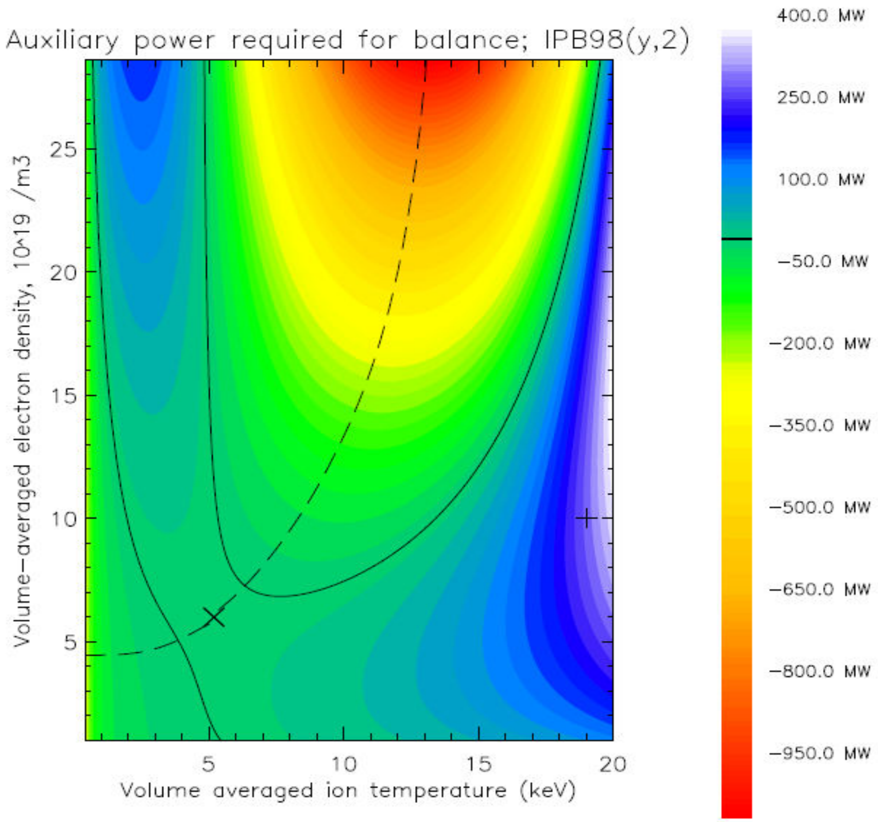
Comparison of reference and enlarged-solenoid reactor designs explored by PROCESS

| Parameter | Referenc e | Enlarged solenoid |
|---|---|---|
| Available flux swing (Wb) | 873 | 1058 |
| Pulse length (s) | 12890 | 19040 |
| Major Radius (m) | 9.58 | 9.88 |
| Minor Radius (m) | 2.395 | 2.41 |
| Aspect Ratio | 4.0 | 4.1 |
| TF on axis (T) | 7.45 | 7.45 |
| Plasma Current (MA) | 18.0 | 17.6 |
| Average Temperature (keV) | 19 | 19 |
| Average Density ($10^{20}m^{-3}$) | 1.0 | 1.0 |
| Confinement time (s) | 3.94 | 3.90 |
| Net heating power MW) | 412 | 434 |
| Fusion Power (GW) | 2.70 | 2.82 |
| Thermal Power (GW) | 3.25 | 3.39 |
| Net Electric Power (GW) | 1.03 | 1.08 |
| COE (m$/kWh) | 151 | 149 |

# Start-up power requirements, energy storage strategy

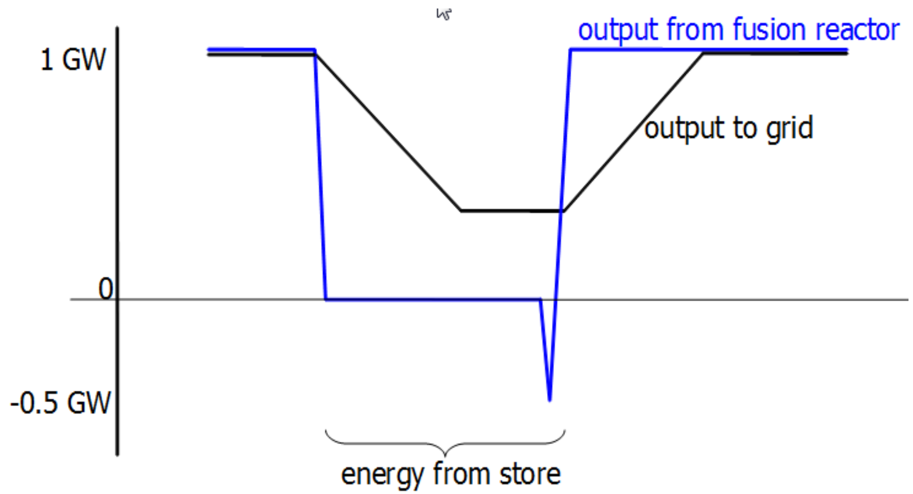
*W. Han, P.J. Knight, CCFE*

PROCESS runs determined the PF coil power supply demands & the required P-aux, checked by a POPCON code.




*"H-mode everywhere" test case*

*Stylised form of output indicating need for energy storage*



# Energy Storage

*R. Clarke, CCFE*

- Energy storage – three options:
  - To make up for some or all of the missing electric power output during the dwell time, and to supply power for pulse start-up. Could be off-site;
  - To supply power for start-up only;
  - To stretch out the ramp-up and ramp-down periods at the beginning and end of each pulse (to meet national grid rules). Must be on-site!
  - *NB whichever of these is chosen, it will be idle >90% of the time, so the function could be sold in real-time (at some risk of unintended fusion breaks).*
- The last two options might be met by adding thermal inertia to the fusion plant steam drum, avoiding duplication of generators.
- UK National Grid "rules" in 2010:
  - Max Infrequent Infeed Loss 1320 MW – very large, *but...*
  - Max Capacity change rate (routine) 50 MW/minute (120MW/min in Europe).
- However the grid rules will be different in 2080 (renewables, super-grid links, storage facilities, electric vehicles, embedded generation...).

# Potential Storage Technologies

- Reference CIEMAT Report *Energy Storage Systems for a Pulse DEMO* (EFDA ref TW5-TRP-007), updated:

| *Type* | *Description* | *Efficiency, speed* | *Comment* |
|---|---|---|---|
| Pumped storage | Mountain, \$1k/kW | 75%, 15s, GWs | Benchmark, grid |
| Thermal - cycle | HPump \$35/MWh | 75%, ?s, MWs | Distributed, grid |
| Compressed air | Mine, comp/xpandr | 35%, fast, MWs | Grid |
| Cryogenic | Dewar, cx, \$1k/kW | 50-70%, ?s, MWs | Grid or <u>site</u> w heat |
| Flywheel | Disc-in-vac, ?cost | 85%, 15min, 2MW | UPS w no battery |
| SMES | ScMag, | 95%, fast, 100MW | HiTc promising |
| Steam drum | V.dP | See DLR work | Couple w melting |
| Salt storage | Molten, \$50/kWh | 50%, 15min, 1GW | <u>Onsite</u>, size, plug |
| Hydrogen | FC tech, expensive | 30%, fast, small | Small scale/wind |
| U-capacitors | Dbl layer, falling | 95%, fast, MW+ | Cost, size falling |

# Pumped hydro-electric storage

More than 100 GW of generation capacity worldwide, for example...

*Seneca Pumped Hydro Station near Warren Pennsylvania, USA; 435MW, 4GWh*

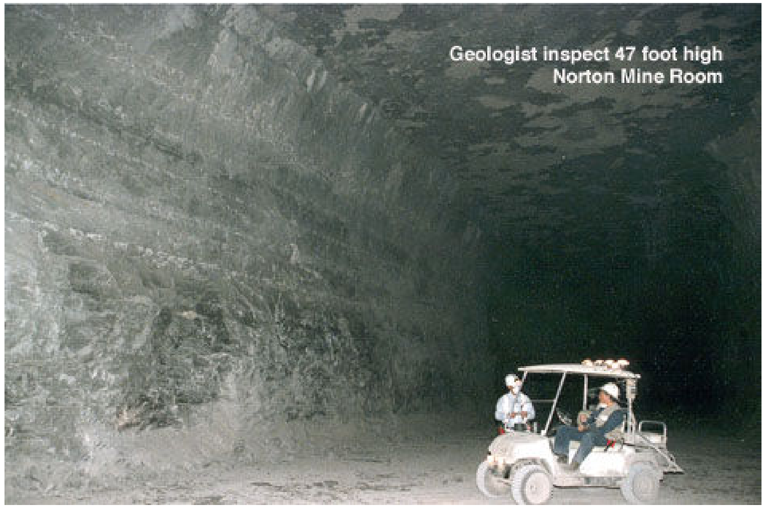
*Żarnowiec pumped storage system, Poland; 720MW, 4GWh*

*Dinorwig pumped storage system (1984), Wales; 1.7GW, 8GWh*

# Alternative "COTS" energy storage schemes

## Compressed air energy storage

*Norton (Ohio) project,*
*eventually 2.7GW, 43 GWh*




## Molten salt storage

*Andasol-1, Spain;*
*50MW, 0.35GWh*

Valle 1 and Valle 2 plants soon in Spain:
Similar to Andasol x 2

Capital costs \$50 to \$100 per kWh (??)
Storage for 0.5 GWe start-up power: \$(12.5-25)M

# Molten salt (nitrates) energy storage

- **Driven by needs of Solar Energy...**

Sun → Collector → Heat
'Therminol' max 370°C
Oil → Steam
$\eta_{RANKINE}$ ~37%

- **How to use Solar Energy at night?**

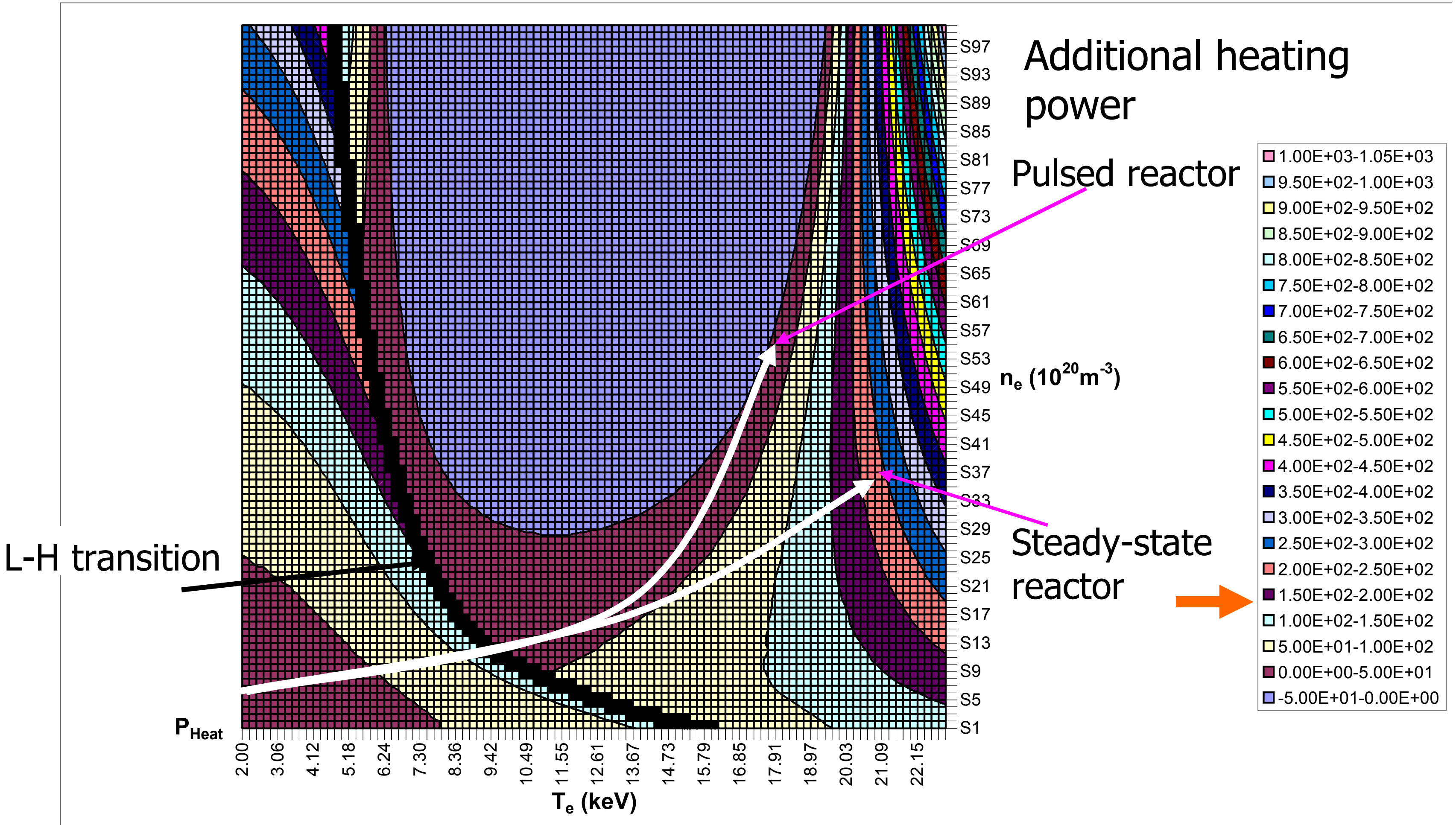
Demand and supply are separated by hours
Seek better employment of capital, better $\eta_{RANKINE}$
K/Na nitrate/nitrite eutectic ("HTS") heat store
 - 142°C (m.p.) to 550°C (instability)
 - 1750 kg/m$^3$ and 1550 J/kg°C
Need to keep it molten, and clean

*Andasol-1, Spain*

# Heating requirements for plasma startup

*W. Han and P. Knight, CCFE*

## POpCon plot assuming L to H transition on $P_{threshold}$ contour



# Use of start-up heating power for burn-phase CD

- Start-up P-aux is chosen at 150MW from POPCON analyses.
- Then effective "gamma" was varied and pulse length calculated assuming that only the start-up P-aux was used for burn-phase CD.
- Hence a reduced number of stress cycles to be accommodated.
- E.g. 48k cycles drops to 14.9k (if Paux was NBH/CD: much less reduction if RF).

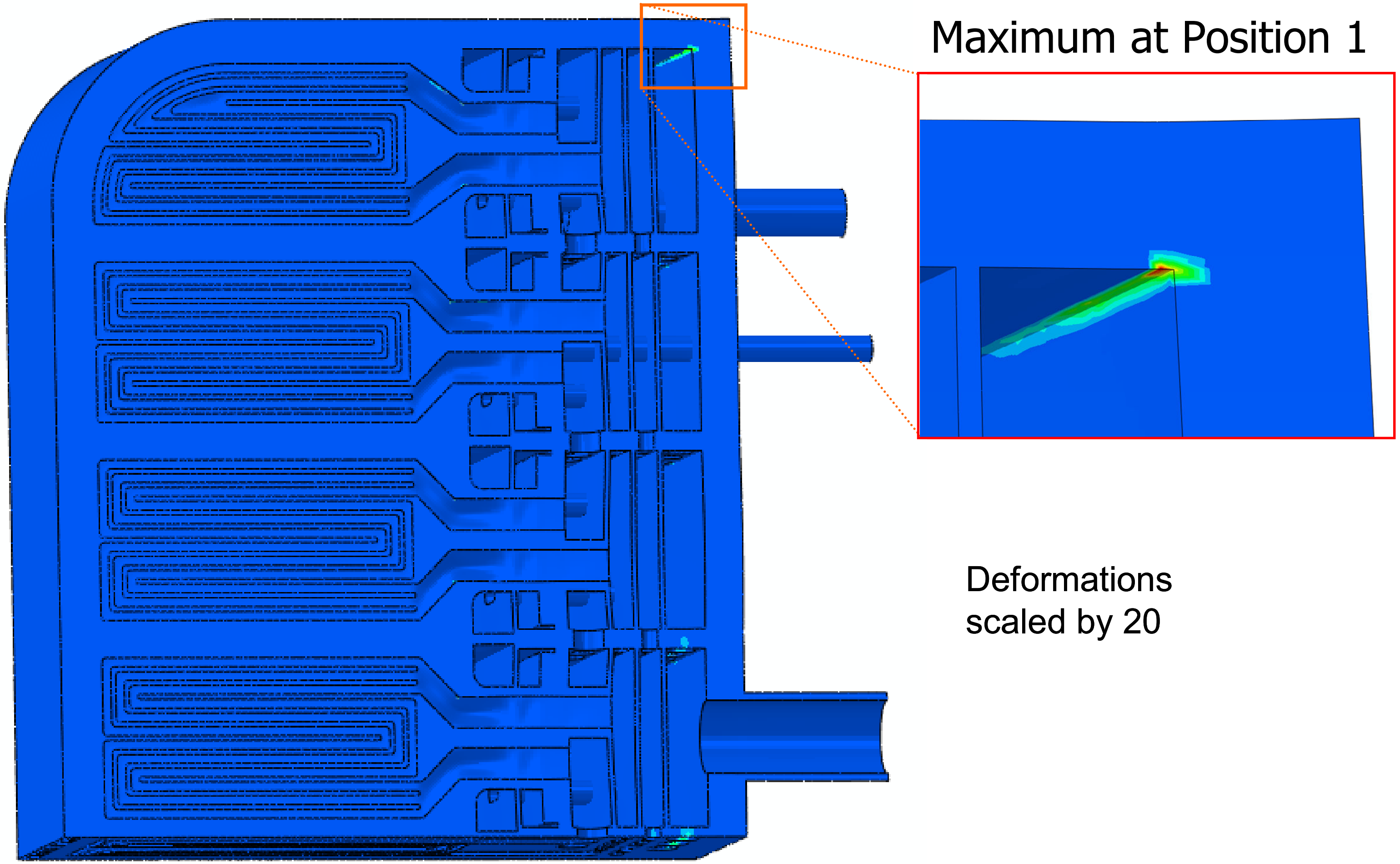
*Parameters determining the level of current-drive and reduction in the number of lifetime pulses achievable with a 150 MW NBI system. These results are obtained by scaling the value of $\gamma$.*

| | | RUN 66 | Additional CD | | |
|---|---|---|---|---|---|
| Constant | Ip (A) | 1.8000E+07 | 1.8000E+07 | 1.8000E+07 | 1.8000E+07 |
| | Vs-burn | 4.0610E+02 | 4.0610E+02 | 4.0610E+02 | 4.0610E+02 |
| | n ($10^{20}m^{-3}$) | 1.0000E+00 | 1.0000E+00 | 1.0000E+00 | 1.0000E+00 |
| | R (m) | 9.5800E+00 | 9.5800E+00 | 9.5800E+00 | 9.5800E+00 |
| | rplas (ohm) | 2.8520E-09 | 2.8520E-09 | 2.8520E-09 | 2.8520E-09 |
| | bootipf | 3.8300E-01 | 3.8300E-01 | 3.8300E-01 | 3.8300E-01 |
| Variable | $P_{CD}$ (W) | 9.3820E+07 | 1.5000E+08 | 1.5000E+08 | 1.5000E+08 |
| | gamma | 4.5500E-01 | 2.0000E-01 | 3.0000E-01 | 4.5500E-01 |
| | $I_{CD}$-available | 4.4560E+06 | 3.1315E+06 | 4.6973E+06 | 7.1242E+06 |
| | $I_{CD}$ (A) | 0.0000E+00 | 3.1315E+06 | 4.6973E+06 | 7.1242E+06 |
| | facoh | 6.1700E-01 | 4.4303E-01 | 3.5604E-01 | 2.2121E-01 |
| | faccd | 0.0000E+00 | 1.7397E-01 | 2.6096E-01 | 3.9579E-01 |
| | fvsbrnni | 3.8300E-01 | 5.5697E-01 | 6.4396E-01 | 7.7879E-01 |
| | V-loop (V) | 3.1674E-02 | 2.2743E-02 | 1.8278E-02 | 1.1356E-02 |
| | tburn (s) | 1.2821E+04 | 1.7856E+04 | 2.2218E+04 | 3.5761E+04 |
| | No. pulses | 5.5343E+04 | 3.9738E+04 | 3.1936E+04 | 1.9842E+04 |

| | | RUN 50 | Additional CD | | |
|---|---|---|---|---|---|
| Constant | Ip (A) | 1.7999E+07 | 1.7999E+07 | 1.7999E+07 | 1.7999E+07 |
| | Vs-burn | 4.2090E+02 | 4.2090E+02 | 4.2090E+02 | 4.2090E+02 |
| | n ($10^{20}m^{-3}$) | 1.0000E+00 | 1.0000E+00 | 1.0000E+00 | 1.0000E+00 |
| | R (m) | 9.5800E+00 | 9.5800E+00 | 9.5800E+00 | 9.5800E+00 |
| | rplas (ohm) | 2.6410E-09 | 2.6410E-09 | 2.6410E-09 | 2.6410E-09 |
| | bootipf | 4.0000E-01 | 4.0000E-01 | 4.0000E-01 | 4.0000E-01 |
| Variable | $P_{CD}$ (W) | 1.5740E+08 | 1.5000E+08 | 1.5000E+08 | 1.5000E+08 |
| | gamma | 4.7550E-01 | 2.0000E-01 | 3.0000E-01 | 4.7550E-01 |
| | $I_{CD}$-available | 7.8125E+06 | 3.1315E+06 | 4.6973E+06 | 7.4452E+06 |
| | $I_{CD}$ (A) | 0.0000E+00 | 3.1315E+06 | 4.6973E+06 | 7.4452E+06 |
| | facoh | 6.0000E-01 | 4.2602E-01 | 3.3903E-01 | 1.8635E-01 |
| | faccd | 0.0000E+00 | 1.7398E-01 | 2.6097E-01 | 4.1365E-01 |
| | fvsbrnni | 4.0000E-01 | 5.7398E-01 | 6.6097E-01 | 8.1365E-01 |
| | V-loop (V) | 2.8521E-02 | 2.0251E-02 | 1.6116E-02 | 8.8584E-03 |
| | tburn (s) | 1.4757E+04 | 2.0784E+04 | 2.6117E+04 | 4.7514E+04 |
| | No. pulses | 4.8082E+04 | 3.4139E+04 | 2.7168E+04 | 1.4934E+04 |

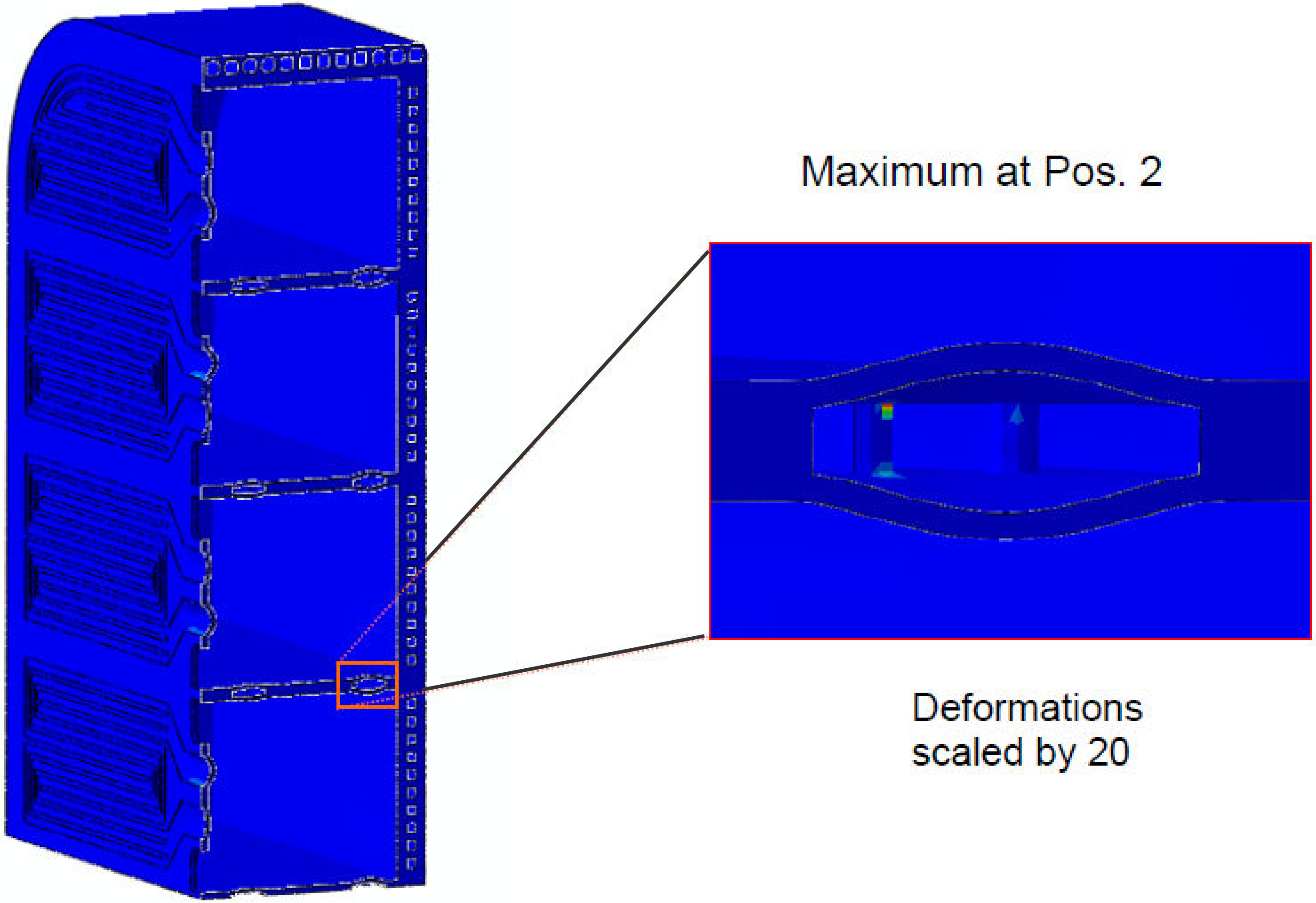
# Fatigue and creep-fatigue in blanket (TBM)

*J. Aktaa, KIT*



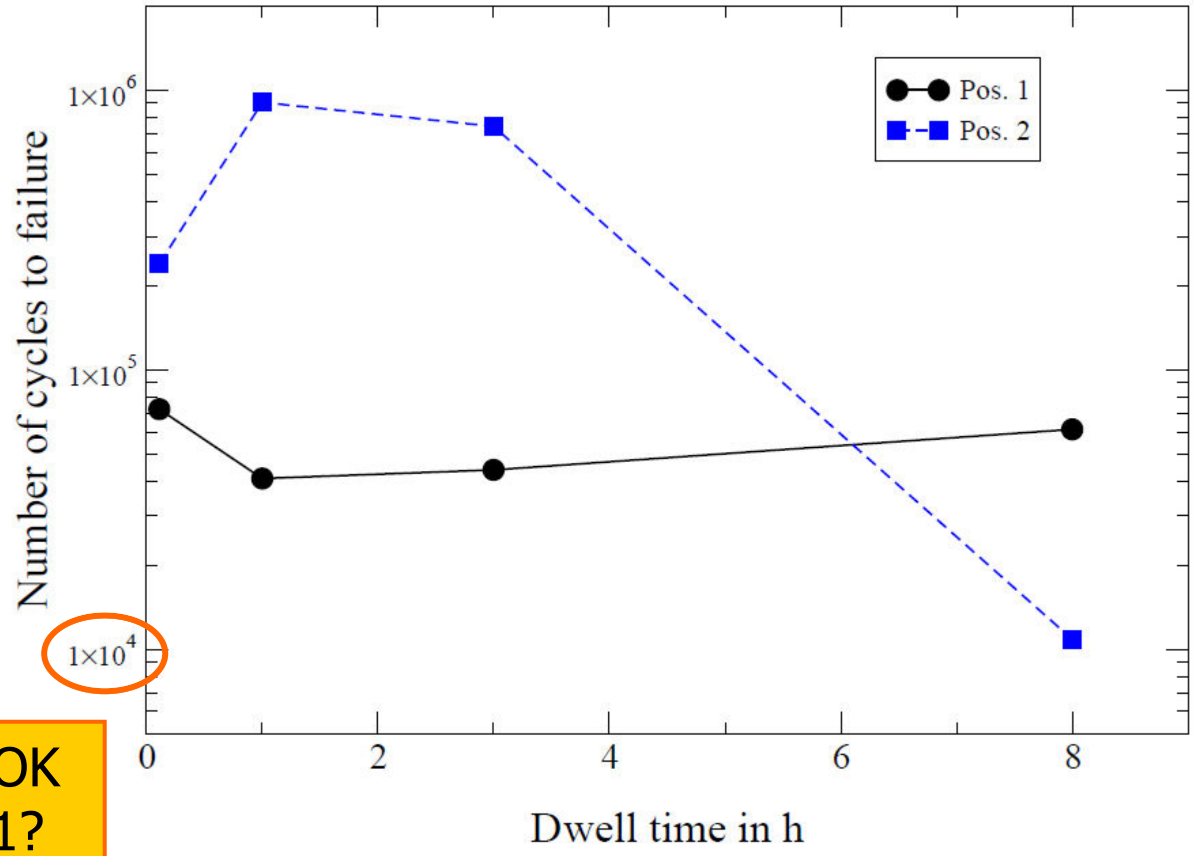

Distribution of “damage” due to fatigue and creep-fatigue in helium-cooled pebble bed test blanket module after 1st pulse with 400 sec dwell time.

# Fatigue and creep-fatigue in blanket (TBM)




With 8 hours dwell time, position of maximum damage is **different.**

# Fatigue and creep-fatigue in blanket (TBM)




10k cycles OK
For DEMO-1?

Estimated numbers of cycles to failure for Position 1 and Pos. 2 and different dwell times: <u>behaviour is different for different positions.</u>

# Fatigue and creep-fatigue in first wall

*Z Vizvary, CCFE*

Generic first wall model developed from the literature:

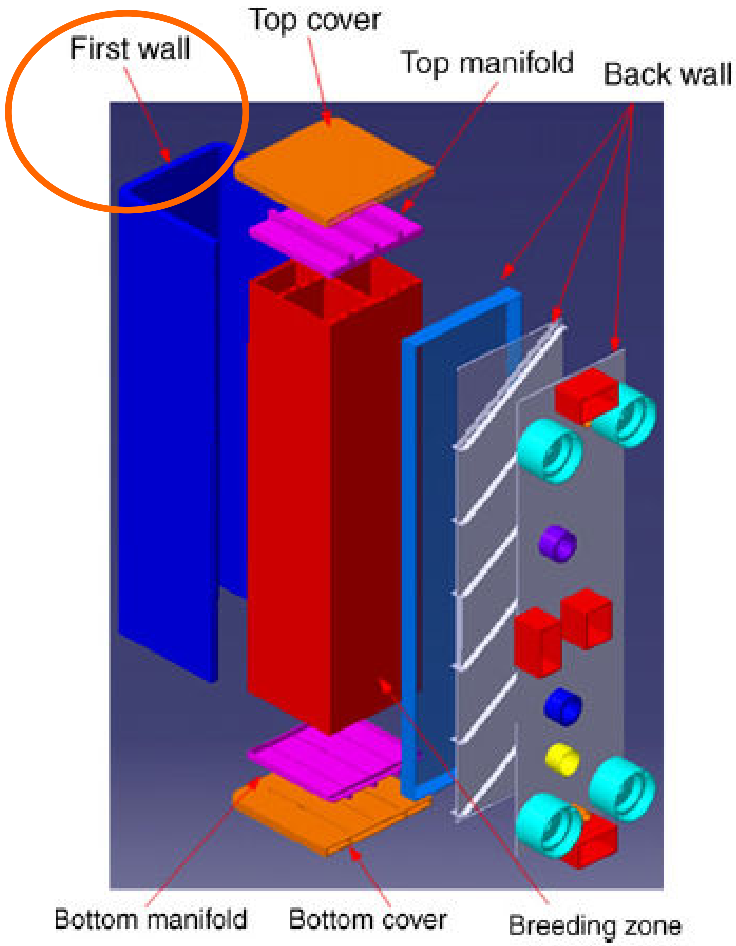
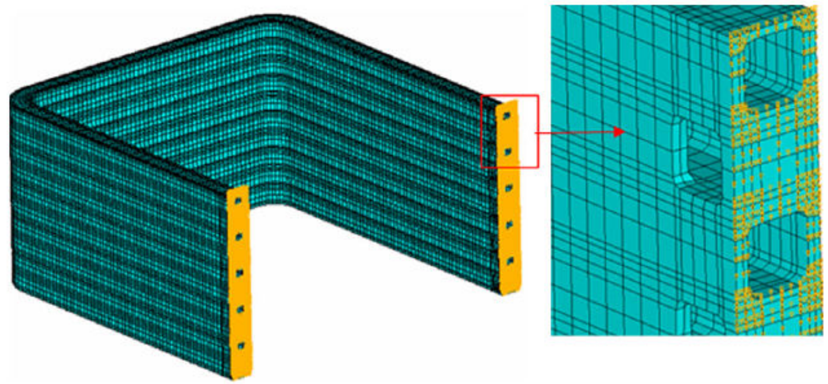
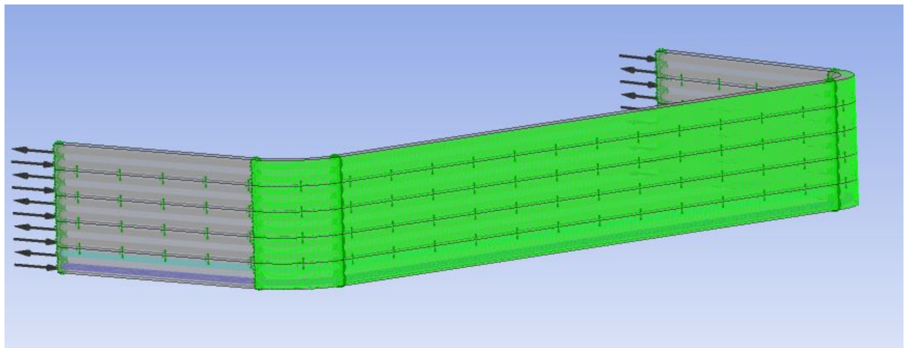



Fig. 3. The 3D model of HCML TBM.

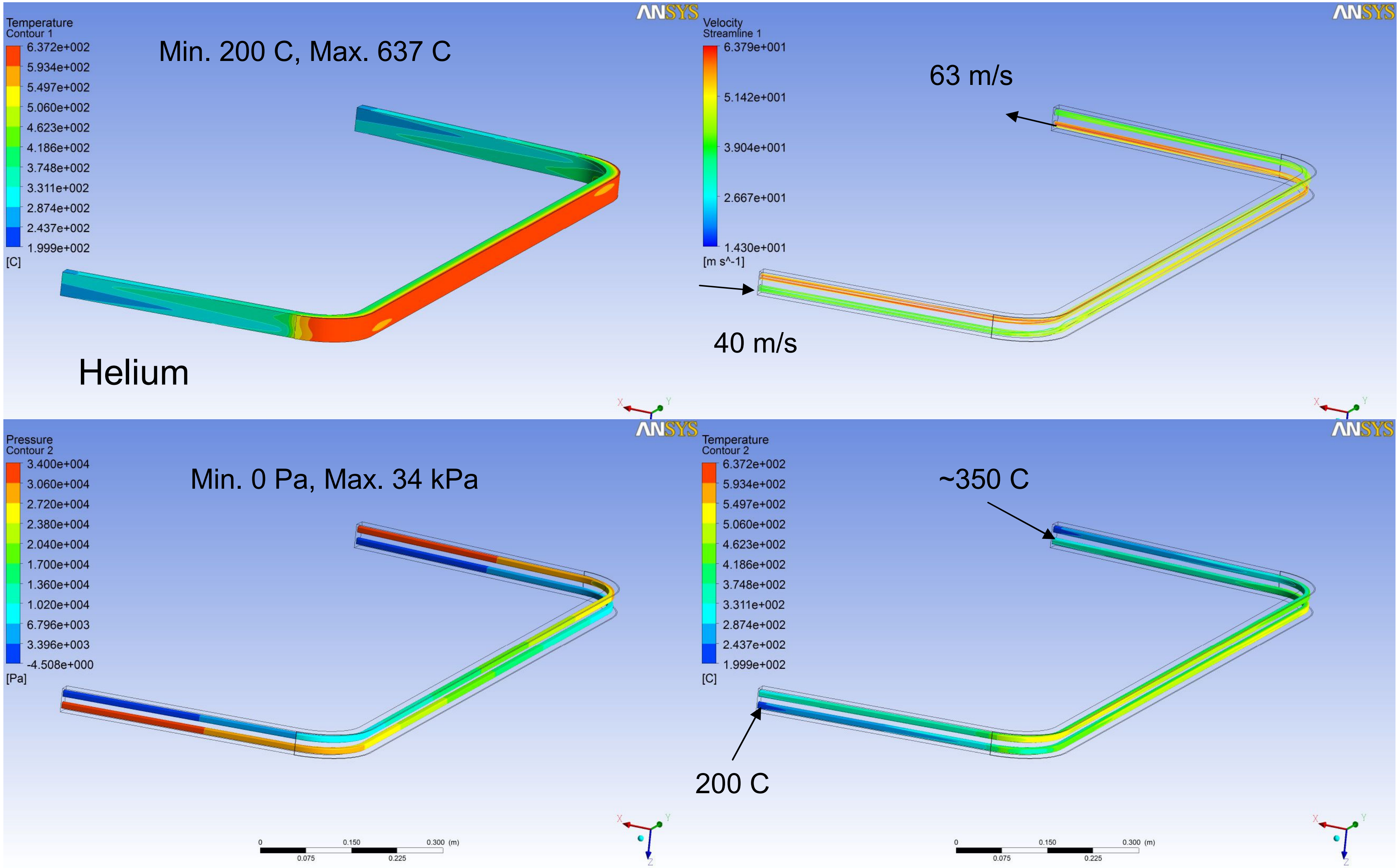


*P. Chaudhuri,Fusion Engineering and Design 84 (2009) 573-577.*

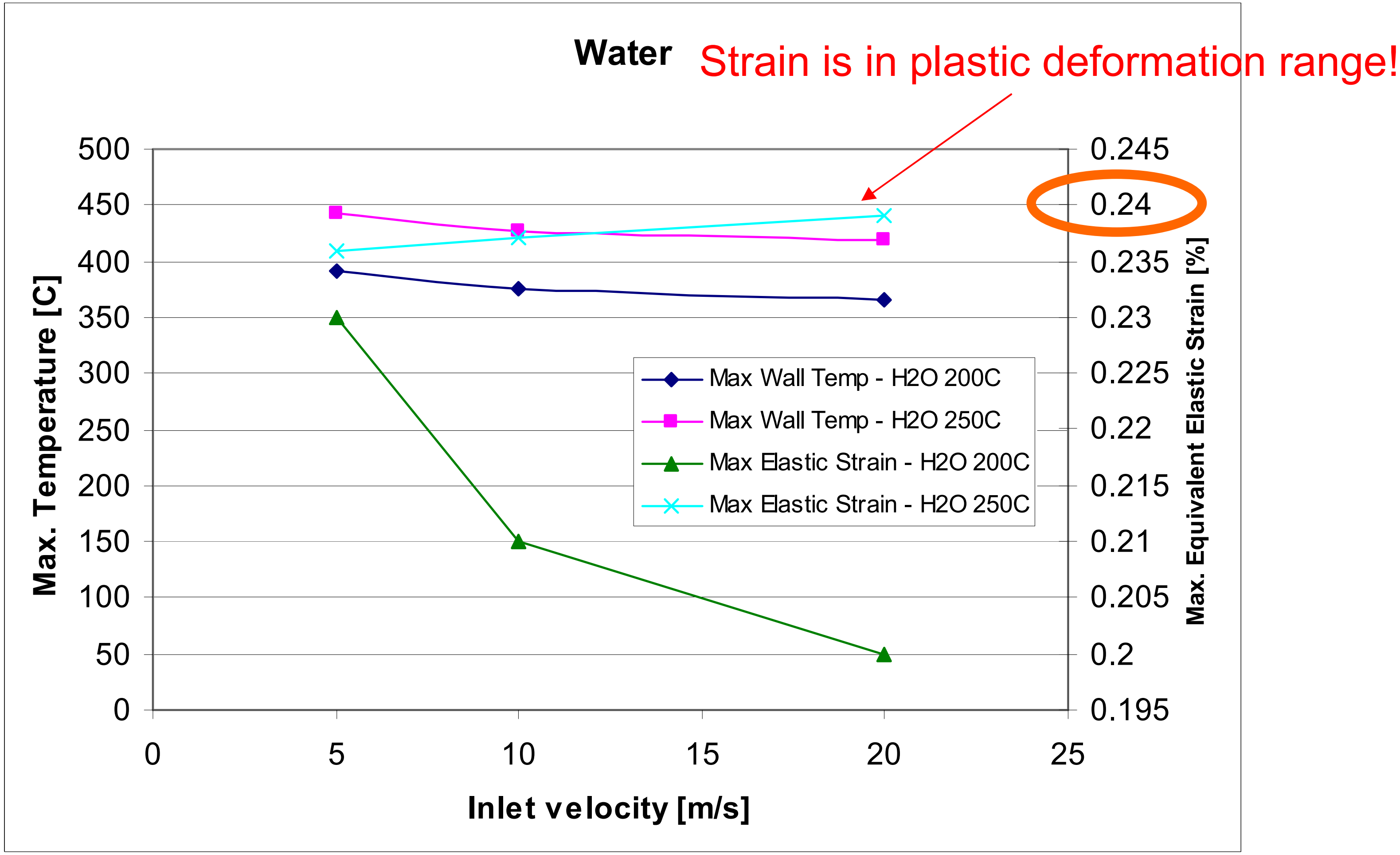


The ZV model had 5 pairs of cooling channels, the coolant flowing in the opposite direction in a pair.

# Fatigue and creep-fatigue in first wall

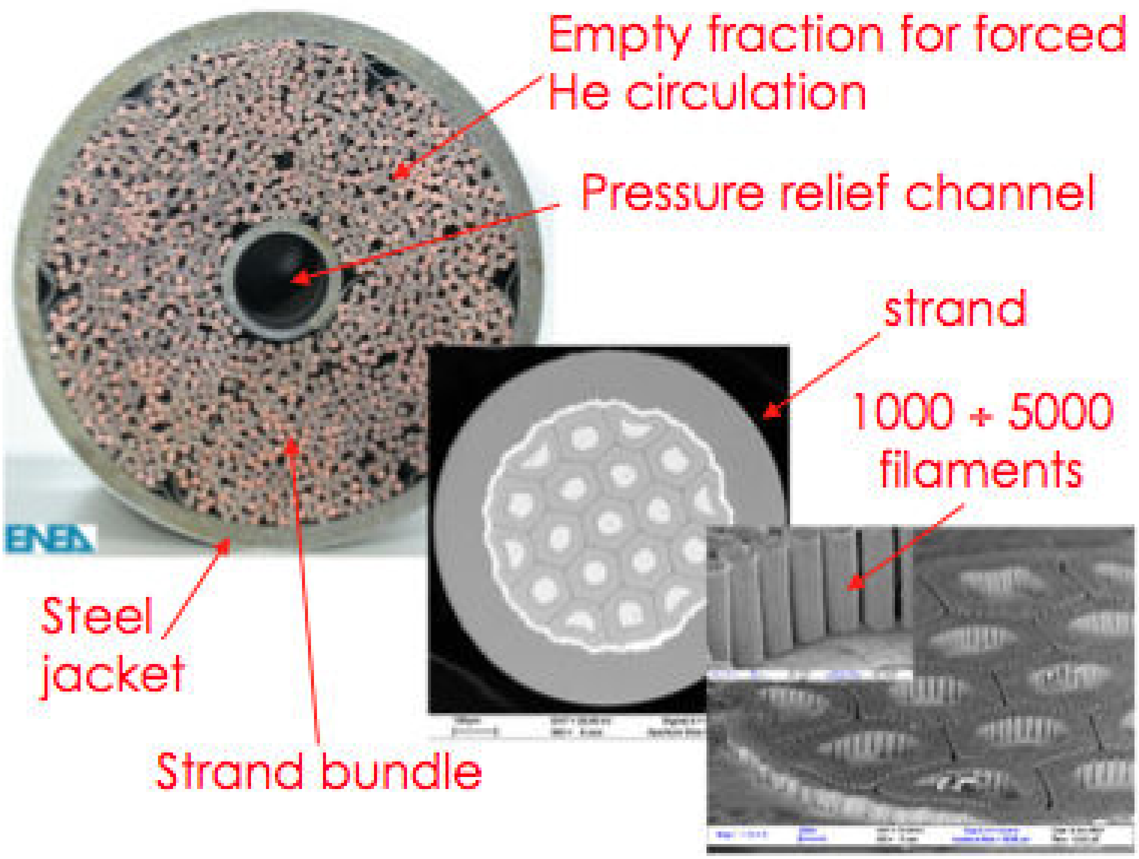


# Fatigue and creep-fatigue in first wall



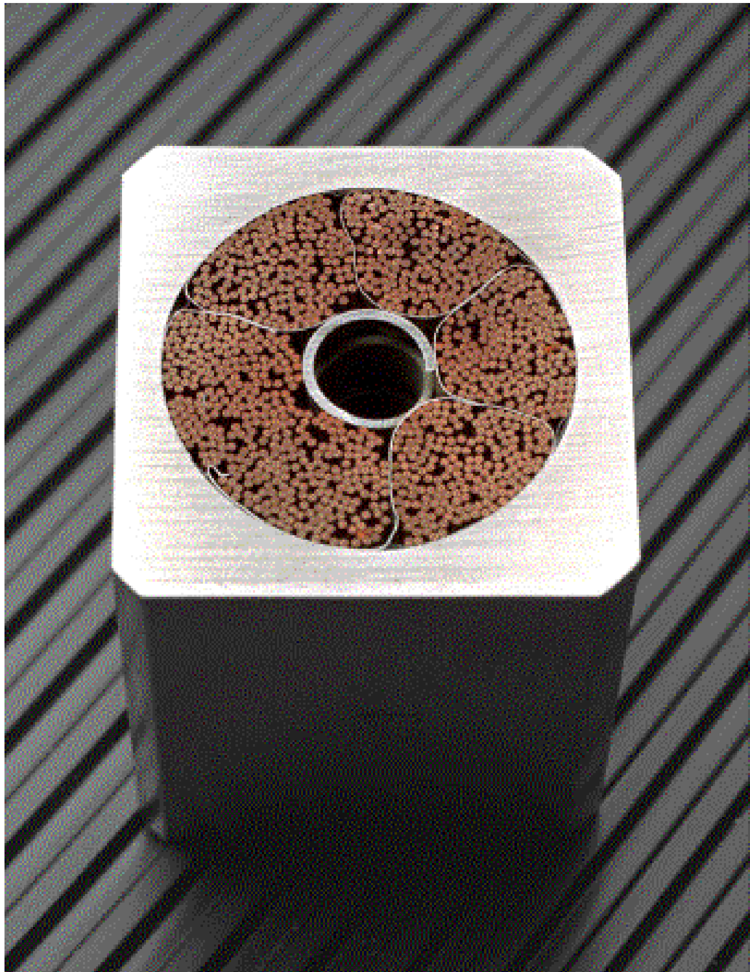
# Improved $Nb_3Sn$ conductor designs

*Pierluigi Bruzzone – Swiss Association, B.L. Muzzi and G.M. Polli, ENEA*




Typical construction of Cable in Conduit Conductor

# Improved $Nb_3Sn$ conductor designs



Superconducting cable for ITER Central Solenoid Model Coil
51 mm x 51 mmm 40 kA 13 T

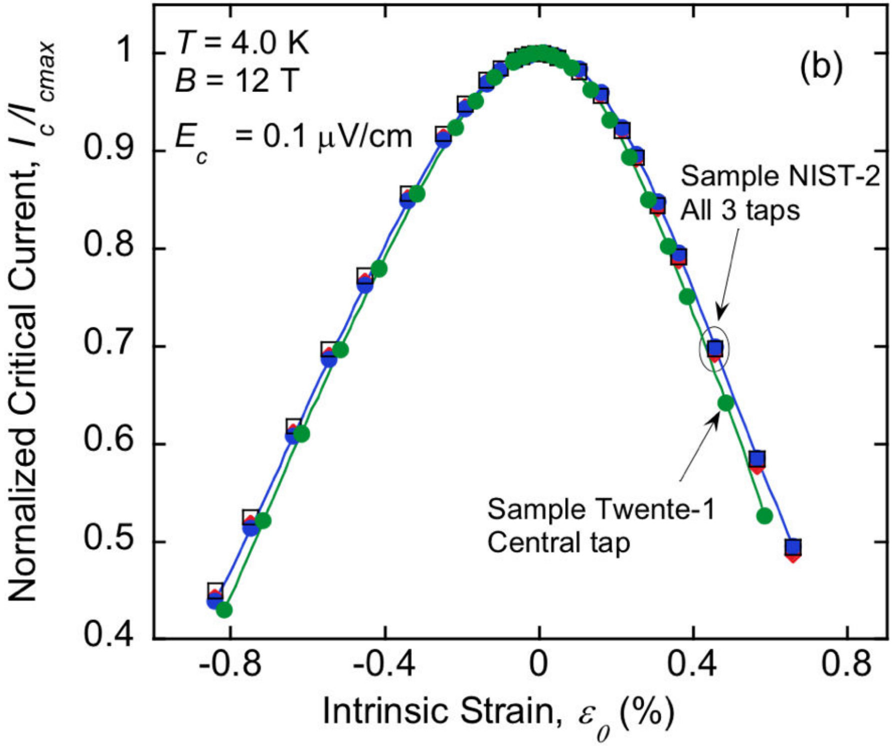
Superconducting cable for ITER Toroidal Field Model Coil
Φ 40,7mm, 80 kA, 9.7 T

# Improved $Nb_3Sn$ conductor designs

- $Nb_3Sn$ exhibits strong sensitivity to strain;
- Filament cracking → irreversibility.

**$Nb_3Sn$-based CICC:**

$Nb_3Sn$ inside CICC is subject to **various strain components** due to the mismatch of heat expansion coefficient with respect to the structural steel material, between 650 °C (reaction heat treatment) and 4.2K (operating Temp.) **($\varepsilon_{axial}$ ~ - 0.7% ÷ - 0.4%)**.



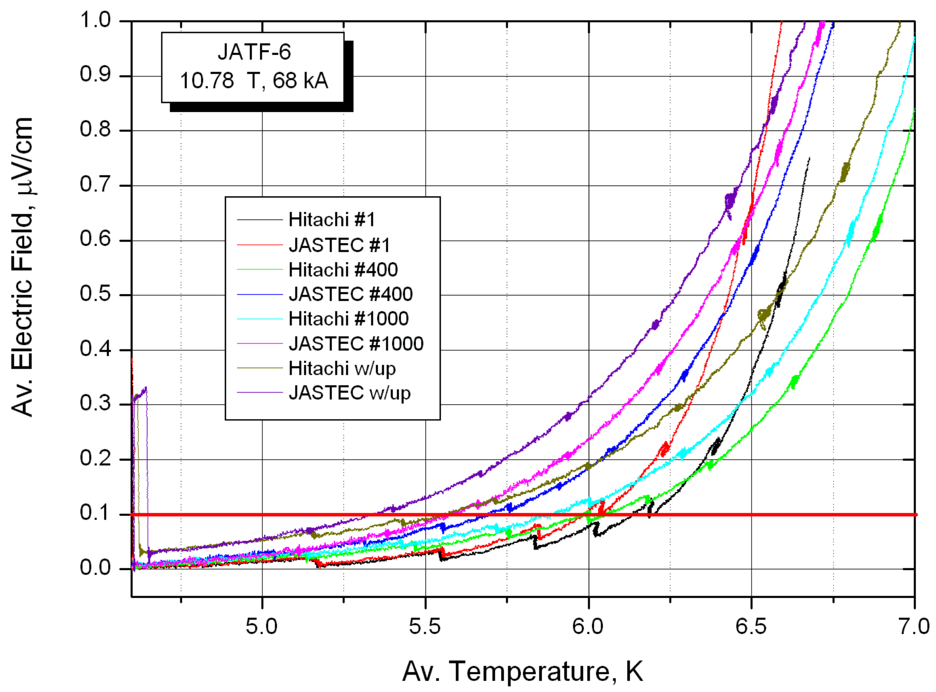

→ only about **50% ÷ 80%** of the current carrying capability of the material is actually available ***– before any degradation***

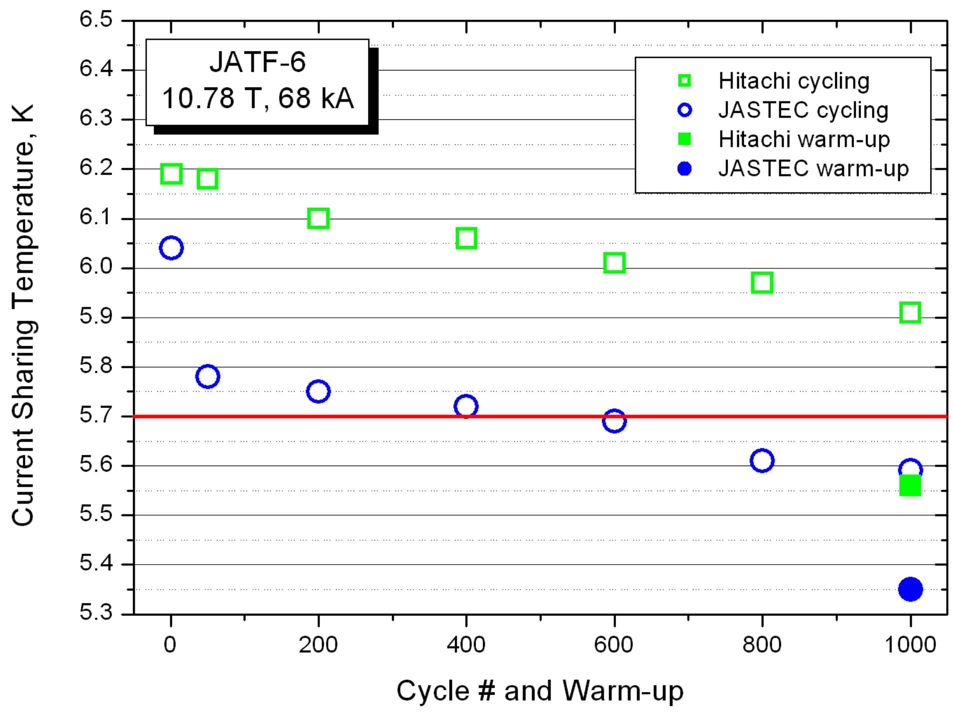
# Improved $Nb_3Sn$ conductor designs

## Typical TF conductor test results

The degradation of the $T_{cs}$ performance is observed upon ***cyclic load*** (current up and down in constant background field) and ***thermal cycle*** (warm-up / cool-down). The degradation always shows up as *broadening of the transition* (lower n-index).

The degradation rate decreases from the start of the test, but is >0 at 1000 cycles.



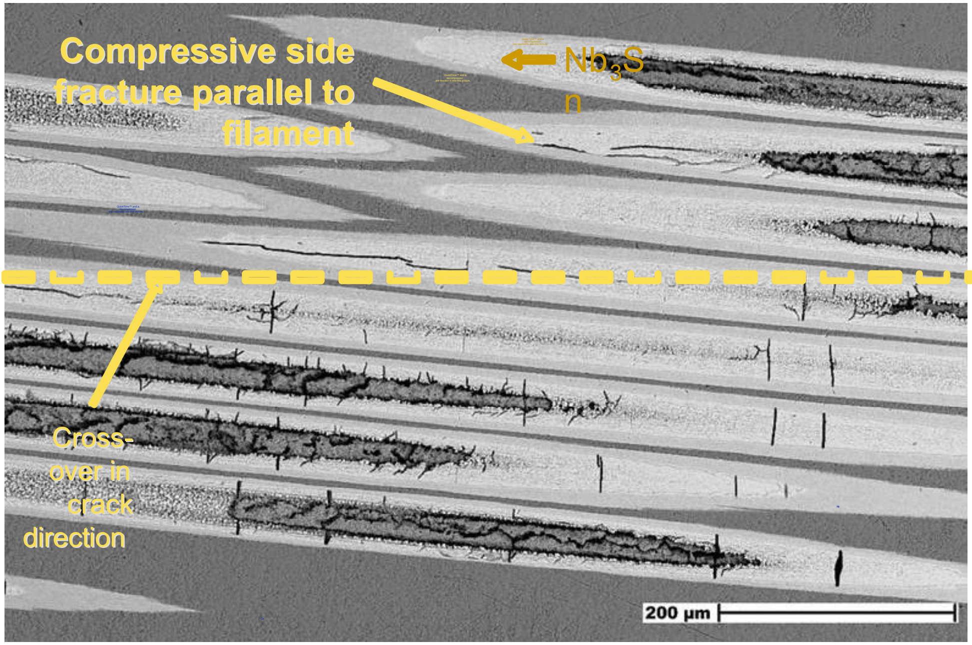
# Improved $Nb_3Sn$ conductor designs

Cyclic loading tests have revealed problems…

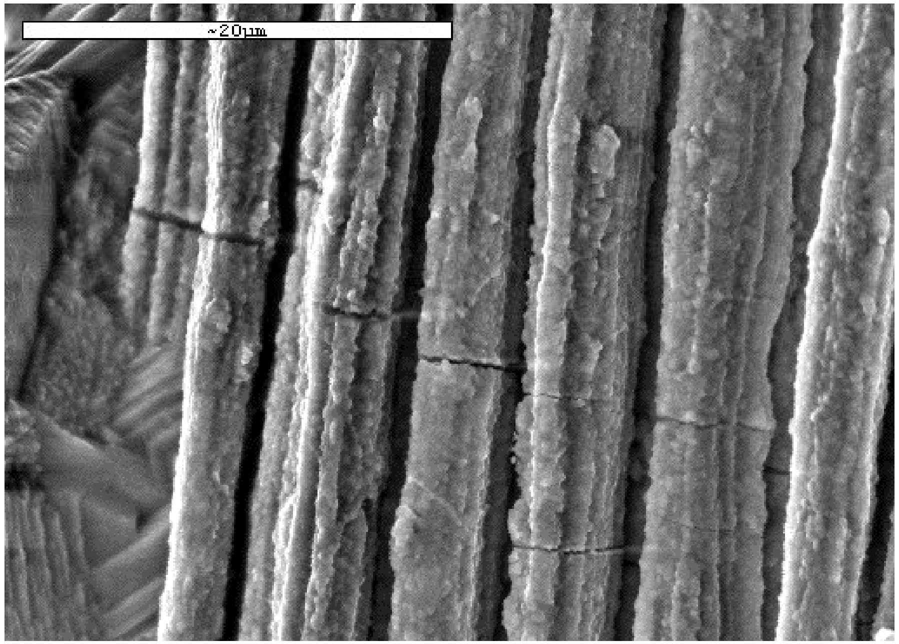
- Some laboratories are able to apply and cycle the full magnetic field
- Most testing to date only to 1000 cycles.
- Tests of the ITER CS conductor in 2010-2011:
  - Performance degradation does **not** stop after few hundred cycles
  - Degradation continues without saturation to over 15000 cycles.
  - The lifetime of the 2011 ITER CICC is found to be only ~ few thousand load cycles ∴ N/A for pulsed DEMO…
- Need better cable
- A few suggestions:
  - improve strand support with much lower conductor void fraction,
  - longer cable twist pitches (despite higher AC losses)
  - rectangular cross-section (thin direction bent in winding)
  - layer (grade) the coil windings

# Improved $Nb_3Sn$ conductor designs

## Forensic evidence of irreversible damage

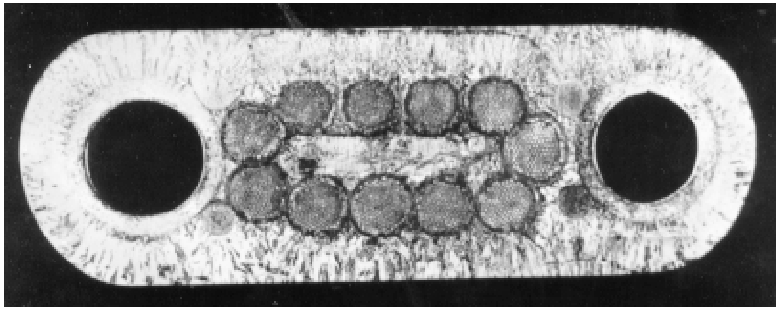



Longitudinal section of a bent strand, highlighting cracks in the tensile region.

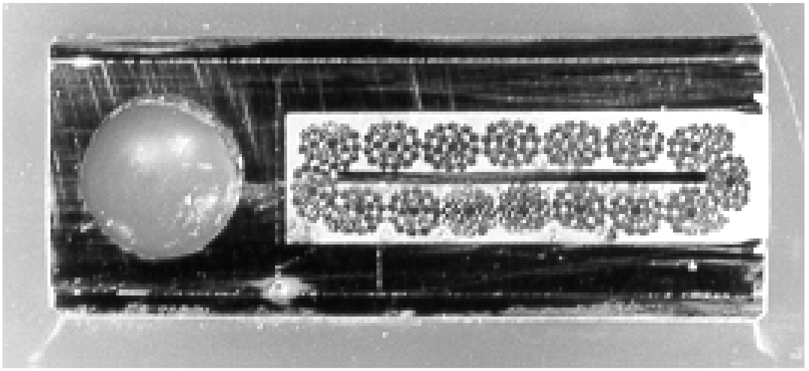



Scanning microscope image of etched filaments with crack propagation

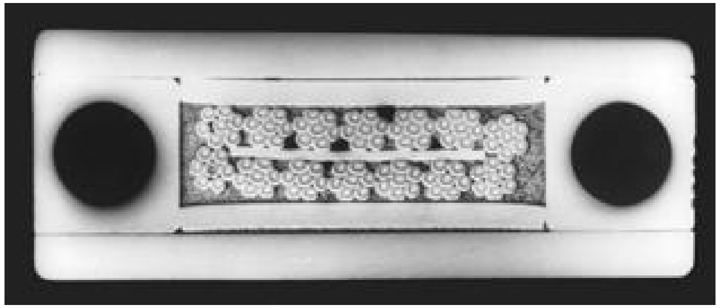
# Improved $Nb_3Sn$ conductor designs



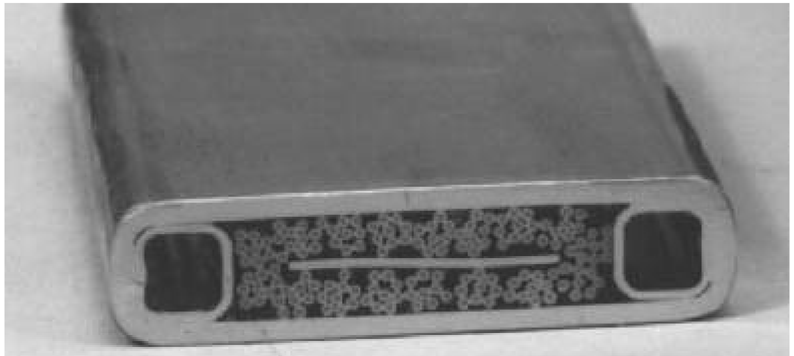
T15 (single stage, flat cable assembled by electro-plating to two copper pipes)



SULTAN 12T (2-stage flat cable, soldered to a brazed copper/steel stabilizer and pipe)



SULTAN 9T (2-stage flat cable, soldered to copper stabilizer, pipes and steel strips)



DPC-EX (2-stage flat cable, encased into a welded steel conduit and pipes)

The strands are usually *soldered* in place – unlike in ITER

CCFE CULHAM CENTRE FOR FUSION ENERGY

# Conclusions

- Literature review – R>9m required for pulsed DEMO; physics issues e.g. control of $P_{rad}$ and of burn, especially at very high Q; CD efficiency.
- First Wall heating and erosion: severe problems; melting W and creeping Eurofer!
- Systems code studies – $P_{fusion}$ ~1GW is OK in pulsed machine, but $T_{Pulse}$<3h
- Fatigue in the central solenoid and TF coil – swapping large solenoid with "thin" structure for small solenoid with "thick" structure does not alter CoE
- Start-up power requirements – many x 100MW but solenoid and $P_{Aux}$ can be separated in time; energy storage strategy – choice of type; choice of on-site or off-site; consider use between site reactor needs.
- Energy storage systems available and in development: off-site = pumped hydro or air; on-site = molten salt or SMES
- TBM and First Wall fatigue assessments: "work in progress"; non-linear creep-fatigue damage model shows points of concern shifting; need more irradiated material creep-fatigue data!
- Improved $NB_3Sn$ conductor designs: 2011 ITER conductor not suitable for pulsed DEMO, several $Nb_3Sn$ alternatives emerging (and "watch" HTSC development). Next few years = paper studies, or prototype trials?
- Future work plan: 2012 "DAS-PLS" work is more focussed and distributed amongst SS DEMO studies.

# End

# Fatigue and creep-fatigue in blanket & first wall

Future work on first wall and blanket fatigue should include:

- The effect of irradiation
- Creep and creep fatigue
- Non-zero mean stress
- Consistency with DEMO requirements for flow rate, pressure drop, inlet temperature etc.
- Derive simple parametric formulae, suitable for system codes, for estimating the lifetime of the blanket.

# Future work plan

In the 2012 PPPT DAS work, there are no tasks specifically for pulsed DEMO, but several issues from the “2011” work will be addressed in the context of the Steady State DAS tasks to be launched in 2012. Some key points are as follows:

Energy storage (choice of maintaining $1GW_e$ net output, only avoiding grid loading during start-up, or merely softening rates of change – new package)

Wall erosion (impurity effects, angles of incidence, realistic particle fluxes - PEX)

Systems code development and benchmarking (including burn control and design options with ultra-low nuclear heating of the superconductors - SYS)

Generically applicable wall and divertor fatigue criteria (if possible! - IVC)

Superconducting conductor development, possibly considering “high temperature” superconductors (new package)

*Conductor R&D – experts seem very relaxed regarding time-scales cf others' thoughts! Need to understand degradation effects better, hence need prototype trials asap.*

*Extract from "* **Proposals for Initial PPPT H&CD Assessments** *", D J Ward May 2011*

## Inductive DEMO

| Parameter | Value |
|---|---|
| R, a (m) | 9.6, 2.4 |
| Plasma Current (MA) | 18 |
| Elongation (95) | 1.66 |
| Triangularity (95) | 0.33 |
| Toroidal field (T) | 7.45 |
| Safety factor | 3.0 |
| BetaN (thermal) | 2.6 |
| <n> ($10^{20}m^{-3}$) | 1.0 |
| <T> (keV) | 19 |
| Zeff | 1.95 |
| Fusion Power (MW) | 2700 |
| Bootstrap fraction | 0.38 |
| H factor | 1.2 |
| Peak divertor heat flux ($MW/m^2$) | <10 |
| Pulse Time (hours) | 6 |
| n peaking factor | 0.1 |
| T peaking factor | 1.5 |

# Comparison of CEA device with parameters from D. Ward

| | David Ward | CEA study |
|---|---|---|
| R, $B_t$ | 9.6 m, 7.45 T | 9.6 m, 7.45 T |
| $\beta_N$, $\kappa_{95}$ | 2.6, 1.7 | 2.6, 1.7 |
| A | 4 | 4 |
| $n_e/n_G$ | 1. | 1. |
| $q_{95}$ | 3 | 3 |
| $T_i/T_e$ | 1. | 1 |
| Pfus | 2700 MW | 2705 MW |
| $I_p$ | 18 MA | 18.1 MA |
| $T_e$ | 19. keV | 19.17 keV |
| $n_e$ | 10 $10^{19}$ /m$^3$ | 9.68 $10^{19}$ /m$^3$ |
| Q | | 1000 |
| H | 1.2 | 1.2 |
| $Z_{eff}$ | 1.95 | 1.95 |

# Comparison between various DEMO models

| | | EUROPE (Power Plant Conceptual Study) | | USA | JAPAN | RUSSIA |
|---|---|---|---|---|---|---|
| | ITER (SS) | Mod - A | Mod - B | ARIES-AT | DEMO - slim CS | DEMO-S |
| $P_{thermal}$=1.18· $P_{fus}$ (GW) | 0.36 | 5.9 | 4.2 | 1.9 | 3.6 | 2.9 |
| $P_{el,net}$ (GW) | 0 | 1.5 | | 1 | 1 | 0.7 |
| $\eta_{th}$ (%) | == | 25 | 36 | **53** | 28 | 24 |
| $R_0$ (m) | 6.2 | 9.5 | 8.6 | 5.2 | 5.5 | 7.8 |
| A | 3.1 | 3 | | 4 | **2.6** | **5.2** |
| b/a | 1.7 | 1.7 | 1.7 | **2.2** | 2 | **1.85** |
| $B_T$ (T) | 5.3 | 7 | 6.9 | 5.3 | 6 | 7.7 |
| $I_p$ (MA) | 9 | 30 | 28 | 12.8 | 16.6 | 11.2 |
| $f_{GW}$ | 0.75 | **1.2** | **1.2** | **1.1** | 0.98 | 0.98 |
| $H_H$ | **1.5 (ITB)** | **1.2** | **1.2** | **1.4** | **1.3** | 1 |
| $\beta_{N.th}$ | 2.9 | 2.8 | 2.7 | **5.4** | **>3.5** | **4.7** |
| $I_{bs}/I_p$ | 0.5 | 0.45 | 0.43 | **0.91** | **0.77** | **0.59** |
| $q_{div,ref}/q_{ITER}$ (at $P_{rad}$=80%) | 1 (eq. to 4.8 MW/m$^2$) | **4.6** | **4.3** | **3.3** | **5.7** | **3.1** |
| $P_{heat}/R_0$(MW/m) | 22.5 | **130** | **115** | 68 | **121** | **78** |
| $P_{aux}$ (MW) | 33+40 | 246 | 270 | 35 | 60 | 117 |

**NOTE :**
**EU PPCS is NOT a DEMO study is only a guideline.**
Aggressive scenarios exist also for EU PPCS, but not given here

**Highlighted are the 'strong' extrapolations as compared to EU**

*11-16/10/2009 - ISFNT-9 – DALIAN - CHINA* *V. Pericoli Ridolfini – DEMO R&D Challenges*

F P Orsitto ENEA

DAS PLC IRM 15 dec 2011

# Costs of energy storage systems