- TECH Summary -

Dr M. Gorley, Chief Technologist, UKAEA.
TECH area oral summary

ITER 9 Talks
- Completion of component constrictions: field coils, heating and current dive systems.
- Plasma control and protection
- Test Blanket Models.

DEMO & Advance Technology 7 Talks
- Overview of DEMO progress (J-DEMO)
- Remote handling
- Systems codes and conceptual designs
- Superconducting advancements

Divertor and Heating 10 Talks
- Fantastic EU, Japan divertor overview
- Divertor component representative testing
- New manufacturing methods
- Advanced Heating and current drive tests

Materials and material systems 6 Talks
- IFMIF/EVEDA
- Neutron irradiation test results (Steels)
- Handbooks, strategy
- Plasma materials interactions
- Multi-physics modelling

Related OV talks:
Bernard Bigot, Preparation for Assembly and Commissioning of ITER.
Yutaka Kamada, Completion of JT-60SA Construction and Contribution to ITER.
Jerome Bucalossi, Operating a full tungsten actively cooled tokamak: overview of WEST first phase of operation
ITER construction has made enormous progress since IAEA FEC 2018 despite the challenges due to the pandemic and many FoAK.

Challenges remain ahead to complete assembly, commissioning, demonstrate First Plasma and go on executing the Research Plan.

Support of ITER Members fusion communities is essential to success.
Overview – TECH Summary

Long pulse discharges with duration 30 s – 1 min routinely performed in Phase I

- 9 MW of combined ICRF/LHCD power coupled, without W accumulation
- Wall monitoring system for RT metallic PFC protection implemented
- No failure on ITER-grade PFU prototypes (from CN, EU and JPN) but evidence of damages after several hours of plasma at moderate heat fluxes:
  - Optical hot spot observed for the first time as predicted by modeling
  - Cracks and local melting observed at moderate heat flux on misaligned PFUs from 0.3mm - 0.8mm → crucial issues for safe operation in ITER and divertor lifetime

Phase II with the full ITER-grade divertor aiming at 1000s plasmas to start in summer 2021

- 456 PFUs manufactured and reception tests competed → assembly ongoing
- Main thrusts for phase 2:
  - Combined high heat flux/high particle fluences studies
  - Towards steady-state H-mode operation in full W device

Welding of a 30 degree-sector of divertor composed of 38 ITER-grade PFUs
Overview – TECH Summary

OV. Yutaka Kamada

Tokamak Construction: completed in March 2020
All main components: Manufacture and assembly satisfied requirements.
Heating, Diagnostics: also going well
Operation control systems: completed

Integrated Commissioning (IC) started:
Vacuum pumping => Cool-down => Coil excitation
Super-conducting state: confirmed for all TF, EF, CS
TF coil current reached 25.7kA (nominal)

IC suspended by EF1 Incident:
Analyses under way for recovery.

Importance of JT-60SA plasma research:
confirmed with advanced plasma modellings

JT-60SA contributes to ITER and enhances international collaborations
Precision engineering at it’s finest. Near current limits? – DEMO beware
ITER – TECH Summary

ITER is construction and plasma preparations. Yet ITER also advance our TECH knowledge and system for DEMOs.
Japan & Russia gyrotrons have passed the performance tests and are readying for ITER First Plasma
Disruption mitigation a key to ITER operations. Designing for ITER → testing in leading experimental tokomaks
ITER TBM testing represent critical validation testing for our fusion futures. They are foundation of ITER to DEMO bridge.
DEMO & Advance Technology – TECH Summary

1. Steady and stable power generation beyond several 100 MW
   - Primary heat transfer system
     - PWR: 15.5MPa, 290~325°C
     - Electric output: 254 MWe
   - Turbine system
     - Thermal efficiency: 34.4%
     - Tritium release: 318 Ci/y/loop

It is less than the restricted amount of T disposal for PWR in JA.

2. Overall tritium breeding to fulfil self-sufficiency of fuels
   Breeding blanket was developed to meet the target overall TBR (> 1.05) in the condition of the pressure tightness against in-box LOCA.

Holistic DEMO design highlight issues, and find solutions!
Architecture can dominate remote handling methodology
MODULAR INTEGRATED REACTOR ANALYSIS (MIRA)

- Reactor Integration into Plant System
  - Integral plant power balance
  - Reactor pulse characterization
- Reactor Magnetics
  - 3D magnetostatics
  - Magnetic field, force, energy
  - Toroidal field ripple
  - Conductor design
- Reactor Neutronics
  - 2D n-p plasma chamber
  - 1D n-p reactor
  - TBR, nuclear heating
  - Neutron shielding, dpa
- Reactor Architecture
  - 2D geometric construction
  - Blanket material composition
  - Coil cable technology
- Magnetic Equilibrium & Core/SOL Physics
  - 2D free-boundary equilibrium
  - Plasma power, particle, current integral balance

BLUEMIRA – an optimised start point for all future fusion reactor designs?
DEMO & Advance Technology – TECH Summary

TECH-2/4. Jonathan Menard
Overview of US FPP.
Nice adaptations prepossessed such as Li in divertors

TECH-2/5. Shishir Deshpande
Studies on spherical tokamak
Baseline info coming from work on ITER

TECH-2/6. Alexander Molodyk
Development in HT superconductors
Importantly worked from industrial developments
1. W Mock-up chain exposed to combined plasma and up to $10^6$ ELM-like (laser) pulses in Magnum-PSI

2. Comparing to similar e-beam data indicates additional effects due to plasma (surface modifications, “rounded” roughened surfaces)

3. Increasing surface base temperature leads to a decrease in resistance to fatigue cracking

4. Seeding impurities increase surface roughening compared to pure H discharges

5. Results indicate importance of plasma effects on fatigue damage of W

Established teams, established facilities, constantly upgrading → supporting our progressive fusion path.
Divertor and Heating– TECH Summary

- EU and JA BA-DDA study covers common aspects of divertor physics and engineering design: water-cooled single-null divertor and appropriate geometry for plasma detachment.
- Both concepts handle similar thermal heating power ($P_{\text{heat}}$), and require large total radiation fraction ($f_{\text{rad}} = P_{\text{rad}}/P_{\text{heat}} \geq 80\%$) in order to reduce the peak heat load ($\leq 10 \text{ MWm}^{-2}$):

  **Divertor power handling is determined by requirements of $f_{\text{rad}}^{\text{main}}$ and the plasma performance.**

  **JA DEMO challenge (steady-state operation):**
  Lower $I_p$ and higher HH with ITER-level $f_{\text{rad}}^{\text{main}}$ ⇒ Large divertor power handling: $P_{\text{sep}}/R \sim 30\text{ MWm}^{-1}$

  **EU DEMO challenge (pulse operation):**
  Higher $I_p$ and ITER-level HH with large $f_{\text{rad}}^{\text{main}}$ by high-Z seeding ⇒ ITER-level $P_{\text{sep}}/R = 17\text{ MWm}^{-1}$

- Same leg length (1.6 m: longer than ITER) but different geometry (JA: ITER-like closer baffle, EU: rather open without dome and baffle) were proposed as baseline designs.

Steady state and pulsed operation. Divergent regimes, but co-learning from developing solutions.
Advanced manufacturing, opening the design space for DEMOs
100 seconds negative ion accelerations for JT-60SA negative-ion based NBI

Requirement:
This is performed after restoration of JT-60SA NBI.

Present achievement:
500 keV, 154 A/m², 118 s.

Deuterium beam (D) since 2017, D power was 1/3 – 1/2 of H power, which was lower than expected value (mass ratio: \( \sqrt{m_H/m_D} = 1/1.4 \)).

Challenge for long pulse

Extracted electrons with D beam become larger than that with H beam.
- Breakdowns at extraction gap
- Damage on Extraction Grid (EG)
Divertor and Heating – TECH Summary

Travelling Wave Array antenna

- TWA proposed to be tested on WEST as demonstrator for a fusion reactor relevant actuator

- Design extrapolated to DEMO and fully integrated in the blanket

- First stage with a high power (2 MW) mock-up successfully completed in TITAN facility

TECH-3/5. Julien Hillairet & Riccardo Ragona

Ion-Cyclotron Resonance Heating System
Additive manufacturing enables monolithic printing of complex RF structures.

Laser welding results in 450 MPa UTS, smooth top and bottom surfaces.

Heat treatment selects tensile properties:
- As Printed: Yield=500 MPa, UTS=740 MPa
- 450°C 3h: HT, Yield=790 MPa, UTS=970 MPa

Additive manufacturing opening design options
Most roadmaps for fusion power necessitate experimental materials damage from fusion irradiation spectrum. We must realise these facilities soon or change our roadmaps.
### Material, PMI, and Neutron Source – TECH Summary

- Target dose of **2.5 dpa ± 0.38 dpa**

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<thead>
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<th>E</th>
<th>H</th>
<th>I</th>
<th>P</th>
<th>J</th>
<th>K</th>
<th>L</th>
<th>O</th>
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</thead>
<tbody>
<tr>
<td>EUROFER 97/2</td>
<td>Low C</td>
<td>Low Mn</td>
<td>Low Mn</td>
<td>Low Mn</td>
<td>Low C</td>
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<td>High V</td>
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<tr>
<td>TMT + Technological HT (980°C + slow AC)</td>
<td>1150°C/1h 8 steps of HR down to 900°C + WQ</td>
<td>1250°C/1h 6 steps of HR down to 850°C + AC</td>
<td>TMT 1000°C/1h + HR at 650°C With 40% reduction</td>
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<tr>
<td>980°C 0.5h</td>
<td>1000°C 0.5h</td>
<td>1000°C 0.5h</td>
<td>1000°C 0.5h</td>
<td>880°C 0.5h</td>
<td>1050°C 15min</td>
<td>1150°C 0.5h</td>
<td></td>
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<tr>
<td>+ AQ</td>
<td>+ WQ</td>
<td>+ WQ</td>
<td>+ WQ</td>
<td>+ WQ</td>
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<tr>
<td>+ 760°C</td>
<td>+ 820°C</td>
<td>+ 820°C</td>
<td>+ 820°C</td>
<td>+ 750°C 2h</td>
<td>+ 675°C 1.5h</td>
<td>+ 700°C 1h</td>
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<tr>
<td>+ AC</td>
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</tbody>
</table>

- The surface operation temperature could be extended from 550 °C (this is the maximum for EUROFER) to 650 °C (for 100 heat flux pulses of 2 minutes and for additional 7 cycles of 2 hours each, heat flux of 0.9 MW/m², simple helium cooling without flow promoters).
- Extremely robust and crack-resistant HIP joining process for the EUROFER/ODS-steel plating demonstrated and industrial-scale fabrication processes with very high tolerances against manufacturing imperfections for advanced blanket first wall proven.
- Production route of 100 kg ODS steel powder and plate fabrication verified. Up-scaling to the several 10-ton ranges is feasible.
Material, PMI, and Neutron Source – TECH Summary

**Status and challenges in development of MPH**

<table>
<thead>
<tr>
<th>Physical Properties</th>
<th>Non-irradiated</th>
<th>Reactor irradiation (T_m = 300, 400, 500°C)</th>
<th>14MeV neutron irradiation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 dpa</td>
<td>~5 dpa (N=1-3)</td>
<td>~80 dpa (N=1-3)</td>
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<tr>
<td></td>
<td></td>
<td>~20 dpa (N=10)</td>
<td>~20 dpa and more (N=10)</td>
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<tr>
<td>Thermal expansivity</td>
<td>(green)</td>
<td>(green)</td>
<td>(red)</td>
</tr>
<tr>
<td>Young's modulus</td>
<td>(green)</td>
<td>(orange)</td>
<td>(white)</td>
</tr>
<tr>
<td>Poisson's ratio</td>
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<td>(orange)</td>
<td>(white)</td>
</tr>
<tr>
<td>Density</td>
<td>(green)</td>
<td>(orange)</td>
<td>(blue)</td>
</tr>
<tr>
<td>Thermal conductivity</td>
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<td>(white)</td>
</tr>
<tr>
<td>Electrical resistivity</td>
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<td>(white)</td>
<td>(white)</td>
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<tr>
<td>Swelling</td>
<td>n/a</td>
<td>(white)</td>
<td>(white)</td>
</tr>
<tr>
<td>Tensile</td>
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<td>(orange)</td>
<td>(blue)</td>
</tr>
<tr>
<td>Fatigue</td>
<td>(green)</td>
<td>(orange)</td>
<td>(white)</td>
</tr>
<tr>
<td>Creep</td>
<td>(green)</td>
<td>n/a</td>
<td>(white)</td>
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<tr>
<td>Fatigue-creep</td>
<td>(blue)</td>
<td>n/a</td>
<td>(blue)</td>
</tr>
<tr>
<td>Ratchet</td>
<td>(green)</td>
<td>(white)</td>
<td>(blue)</td>
</tr>
<tr>
<td>Impact properties</td>
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<td>(white)</td>
<td>(blue)</td>
</tr>
<tr>
<td>Irradiation creep</td>
<td>n/a</td>
<td>(white)</td>
<td>(blue)</td>
</tr>
</tbody>
</table>

(*) color code:
- White (blank) for properties not addressed, lack of data
- Black : potential showstopper identified
- Red : lack of data and potentially challenging
- Blue : lack of data, NOT challenging
- Orange : data available, results not good enough, further optimization needed
- Green : data available, results are good, concept is mature
- n/a : not applicable, N: number of valid data

**TECH-4/3. Takashi Nozawa**

Important to find criticality of irradiation effects on all properties → they may be “showstoppers”
Entering the delivery era for fusion, our materials models must blend near term approximations with these long term developments to support DEMOs.
Many thanks for 107 fantastic poster contributions in TECH area


Personal highlights: 633, Nawal Prinja & 708, Fumito Okino.

Special note: 1346, Zahoor Ahmad. 1348, Leopoldo Soto. 624, Salah El-Din El-Morshedy. 1132, Igor Sokolov.
Conclusions

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Closing Thoughts

• ITER is so challenging, yet progressing every day. The lessons learned from ITER construction are key to fusion power, we must capture and use for DEMO.

• We have ITER and increased funding on many DEMOs. This bring industrialist interests in our the work. The community must learn to send out our challenges and let industries solve them, and not try to lead on everything in DEMO designs.

• Recent years have seen increasing work in private fusion companies. Established programmes and experienced staff should help these endeavours so there, often disruptive, developments can support our global efforts.

• I hope our next FEC TECH talks can see: Great TBM progress, more industrialist talks, more private fusion talks and more talks on representative scale testing in facilities like MITICA (NBI) and CHIMERA (In-vessel component testing).
We strive to realise a humankind changing endeavour - fusion power. Summarising FEC2020 TECH area was a privilege.

Many Thanks to all for your dedicated work and see you at 29th FEC!

Mike Gorley, May 2021