Stellarator Paths to DEMO

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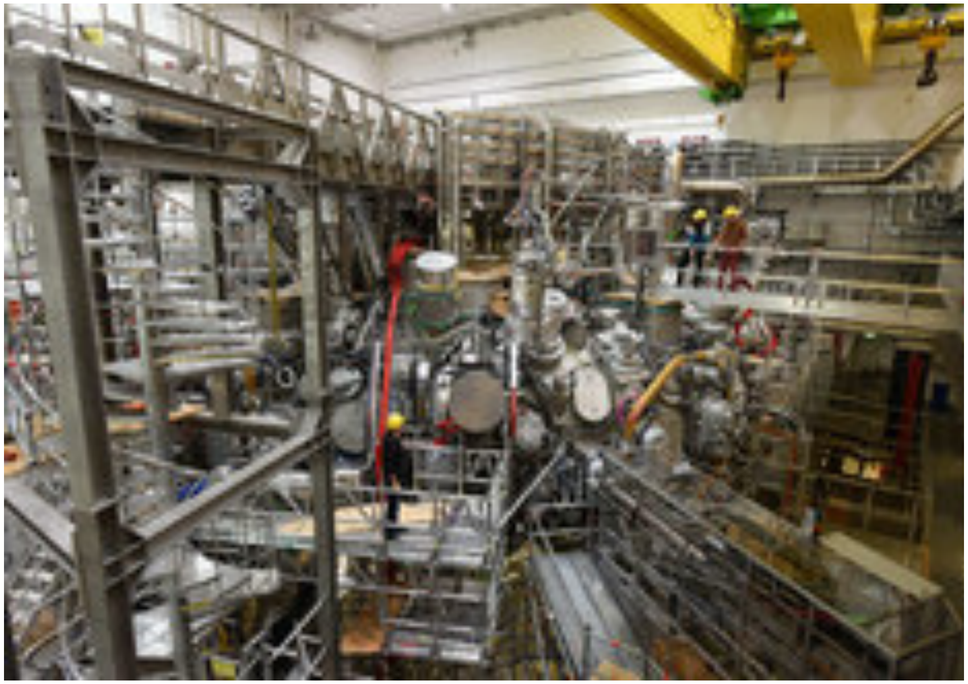
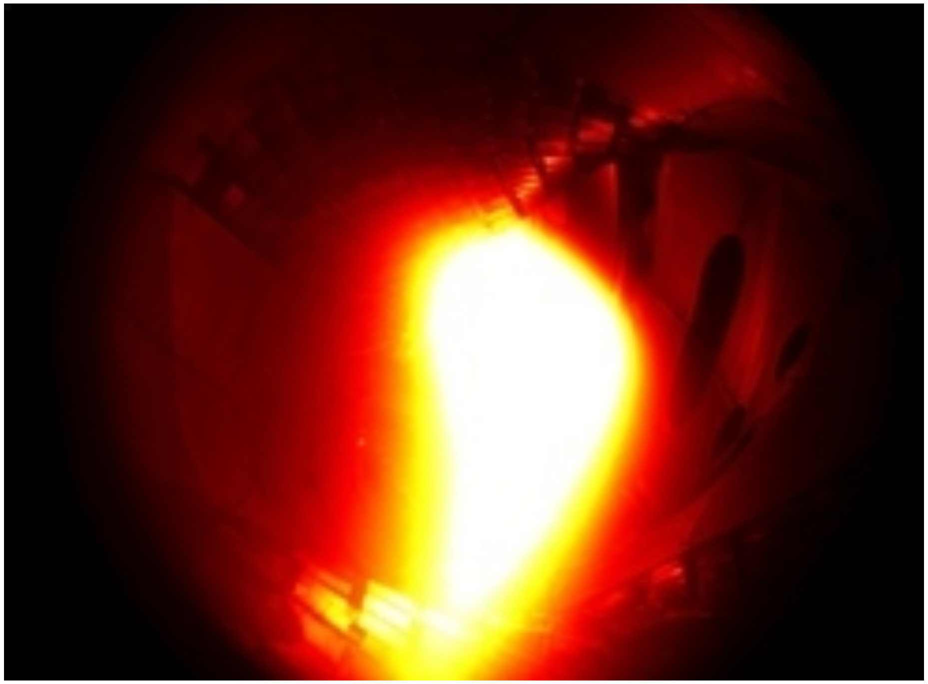
Wendelstein 7-X First Plasma!





- December 10, 2015
- Largest stellarator in world, R=5.5m   a=0.5m, B_{max} = 2.5 T
- Numerically optimized for transport and MHD stability
- Superconducting. Expected max. heating pulse 30 min.

March 2015 Workshop on Stellarator/Heliotron Strategy

- Organized and hosted by NIFS (Japan)
- Attended by researchers from Australia, Germany, Japan, Russia, Spain, Ukraine, US

- Research status and strategies for stellarator approaches to fusion
  - Large and small experiments

- National strategies for DEMO, and the path to a stellarator DEMO

Motivation for Stellarator Approach

- No disruptions
- No current drive, low recirculating power

  Higher fusion gain
- Steady-state magnetic fields and plasma
- Sustained high pressure ($\beta \geq 5\%$)

These characteristics may be necessary for commercial viability.

- Requires configuration optimization
- Smaller database of experimental results & model validation

EU and Japan include Stellarators in Plans for DEMO

- Both have large, superconducting experiments
  - LHD (Japan), operating since 1998
  - Wendelstein 7X (Germany), just starting operation
- Reactor design studies
- Reactor technology programs

Japanese Strategy for DEMO

- Develop tokamak and stellarator/heliotron in parallel

- Including: experiments, technology development, integrated modeling, and DEMO designs

- Assessment in 2027 of progress

  Decision ~2030 on DEMO approach & construction

LHD: Deuterium Experiments

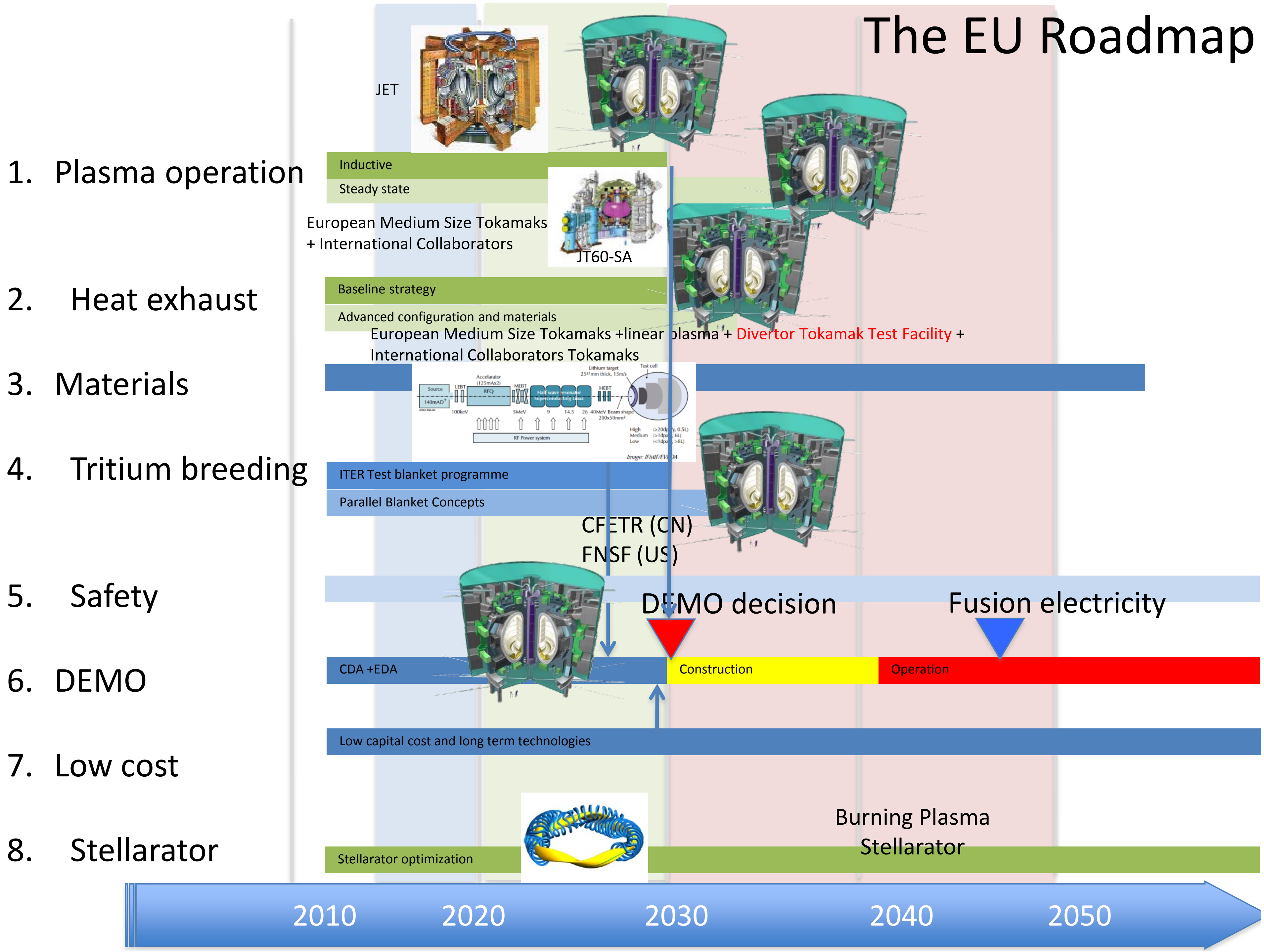
- Deuterium starting Feb. 2017
  - Installing upgrades: NBI, ECH, ICRF, diagnostics
- Goals
  - Maximize confinement performance, $nT\tau_E$
  - Study isotope effects on plasma confinement
  - Demonstrate confinement of high-energy ions
  - Validation of modeling for extrapolation
- Additional research
  - MHD stability at high-β and low collisionality
  - Divertor optimization & plasma-wall interactions
  - ICRF heating

LHD Progress and Goals

- High temperatures (at low density)
  - $T_i(0)$ = 8.1 keV Goal: 10 keV
  - $T_e(0)$ = 10 keV

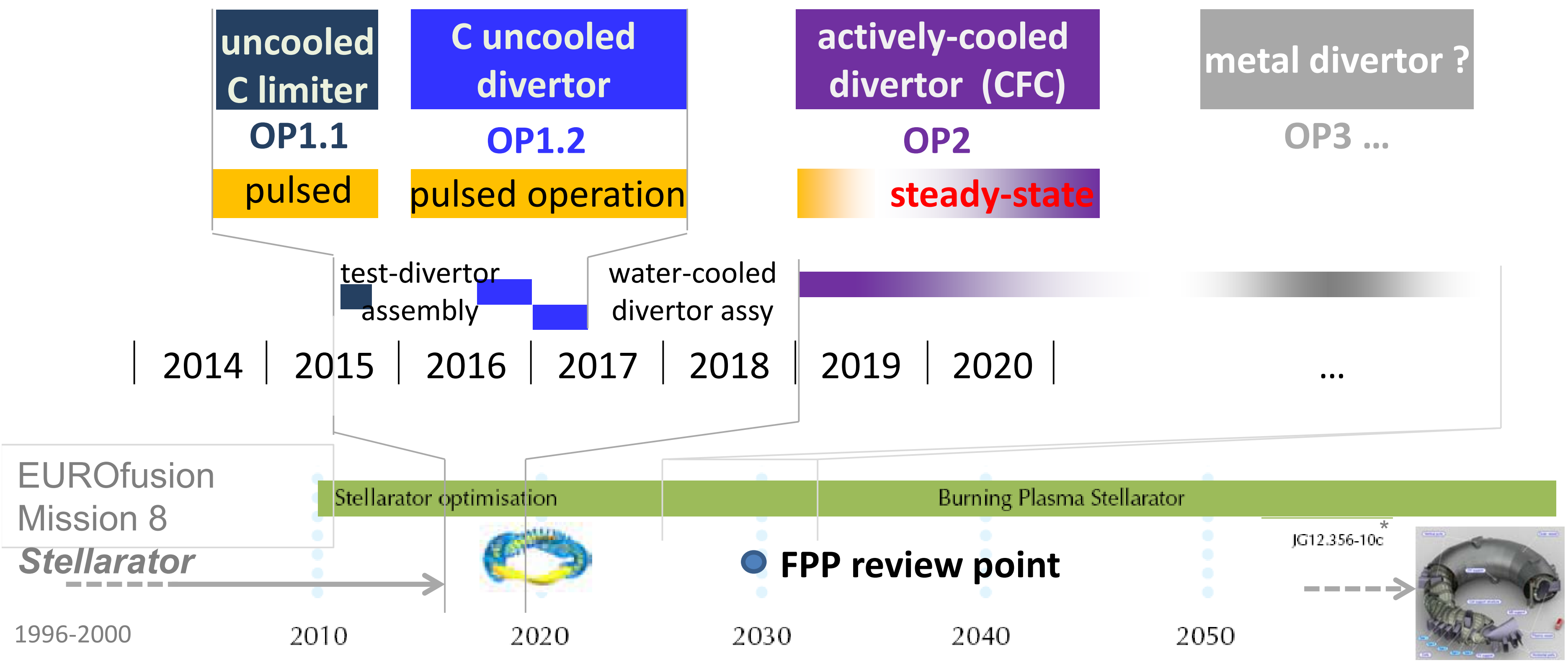
- High β (norm. pressure)
  - 5.1% at 0.425 T Goal: 5% at ≥1 T
  - 4.1% at 1T

- Sustained operation
  - 48 min at 1.2 MW, 2keV Goal: 60 min at 3 MW
  - 54 min at 0.5 MW, 1keV


The EU Roadmap
1. Plasma operation
2. Heat exhaust
3. Materials
4. Tritium breeding
5. Safety
6. DEMO
7. Low cost
8. Stellarator
JET
Inductive
Steady state
European Medium Size Tokamaks
+ International Collaborators
JT60-SA
Baseline strategy
Advanced configuration and materials
European Medium Size Tokamaks +linear plasma + Divertor Tokamak Test Facility +
International Collaborators Tokamaks
ITER Test blanket programme
Parallel Blanket Concepts
CFETR (CN)
FNSF (US)
DEMO decision
Fusion electricity
CDA +EDA
Construction
Operation
Low capital cost and long term technologies
Burning Plasma
Stellarator
Stellarator optimization
2010
2020
2030
2040
2050

W7X Timeline

PFC-technology structures the way to reliable, steady-state, high –$nT\tau_E$ *operation*



- Develop the basis for a W7X-like fusion power plant (FPP)
- Scenario development and demonstration
- Validation of models and design approach
- Development and demonstration of steady-state divertor: 10MW for 30 min.

Roadmap

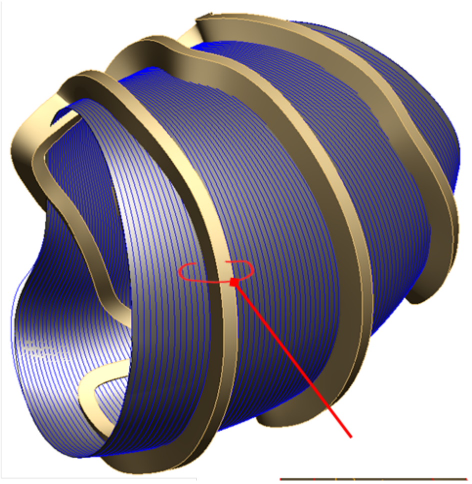
AUG → JET → ITER
Significant α–heating
Test of DEMO technologies → DEMO
Pulsed?
T-self sufficiency → Commercial fusion

W7-X
verify physics of concept → HELIAS-ITER
Significant α-heating
Technology test → (Use DEMO technology) → Commercial fusion

2015 Start of operation
2019 Full steady-state capability

US Stellarator Research

- Experiments on basic physics
  - HSX: physics of quasi-symmetry
  - CTH: physics of disruptions stabilization
  - Collaborations with LHD and W7X, 3D-tokamaks
- Improve numerical modeling & validation of 3D physics understanding

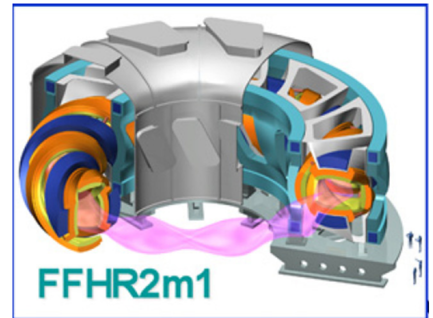


- Improved 3D optimization
  - Turbulence optimization by 3D shaping
  - Simpler coils for maintenance
- Stellarator pilot plants, FNSF scoping studies
  - Use stellarator capabilities to <u>simplify overall fusion system</u>

Stellarator Reactor Designs Based on Experiment Designs

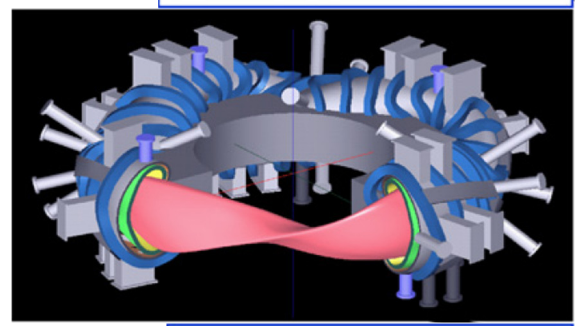
- FFHR-2ml (Japan), LHD-like

  R=14m, a=1.73m, B=6.2T, P_{fusion}=1.9GW



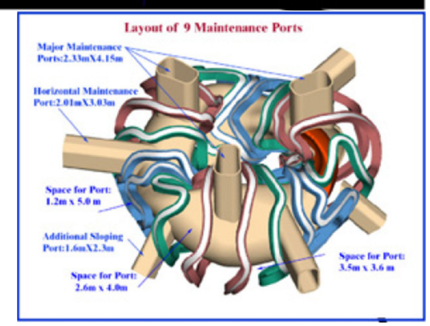
- HSR (Germany), W7X-like

  R=20m, a=1.6m, B=5T, P_{fusion}~3GW



- Aries-CS (US), NCSX-like

  R=7.75m, a=1.7m, B=5.7T, Pfusion=2.44



Designs differ due to different optimization strategies. Innovations will evolve designs.

Is Stellarator DT-step Required?

- Extensive discussion at Workshop
- DT Stellarator would reduce risk, but add step

- Can it be mitigated, by validating integrated models using ITER and non-DT large experiments?

- General feeling was that a stellarator DT step may be needed (as in EU plan). Decision will depend on research advances.

Summary

- Stellarators are making substantial progress towards goals
  - Start of W7X research. Deuterium experiments on LHD
- Stellarator development is integrated into the EU and Japanese plans for DEMO
- Stellarators characteristics solve current challenges and may be needed for a viable, steady-state commercial energy system
- Key question for future: is there a separate DT stellarator step?