The ITER Project - Fusion Research towards a Burning Plasma

SULI 2020 class, Princeton, NJ


ITER site, Feb 2019

iter
china eu india japan korea russia usa

F. M. Laggner

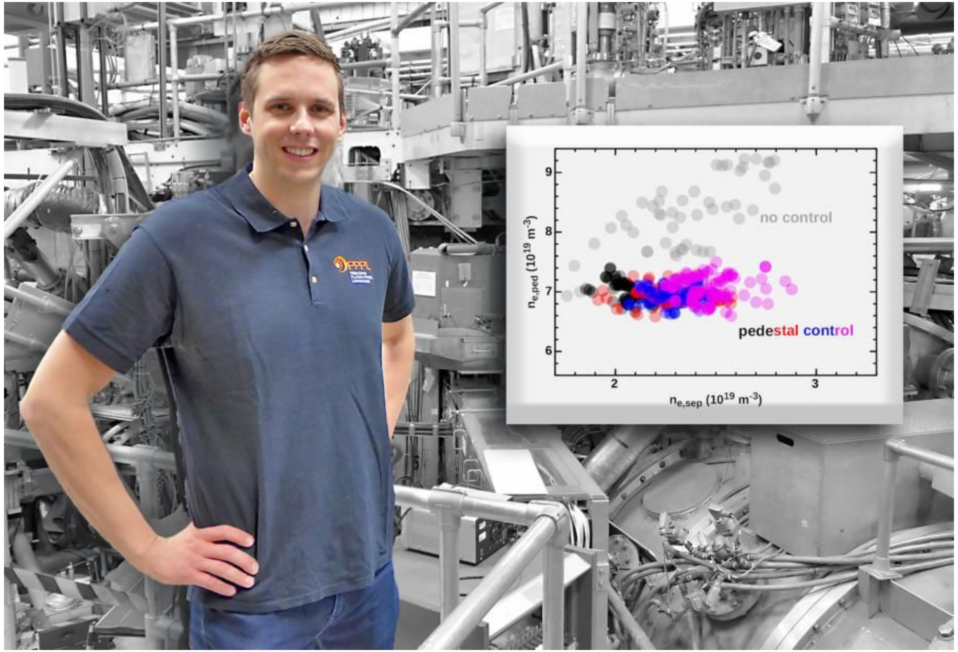
June 18, 2020

PPPL PRINCETON PLASMA PHYSICS LABORATORY
U.S. DEPARTMENT OF ENERGY
PRINCETON UNIVERSITY


http://www.iter.org

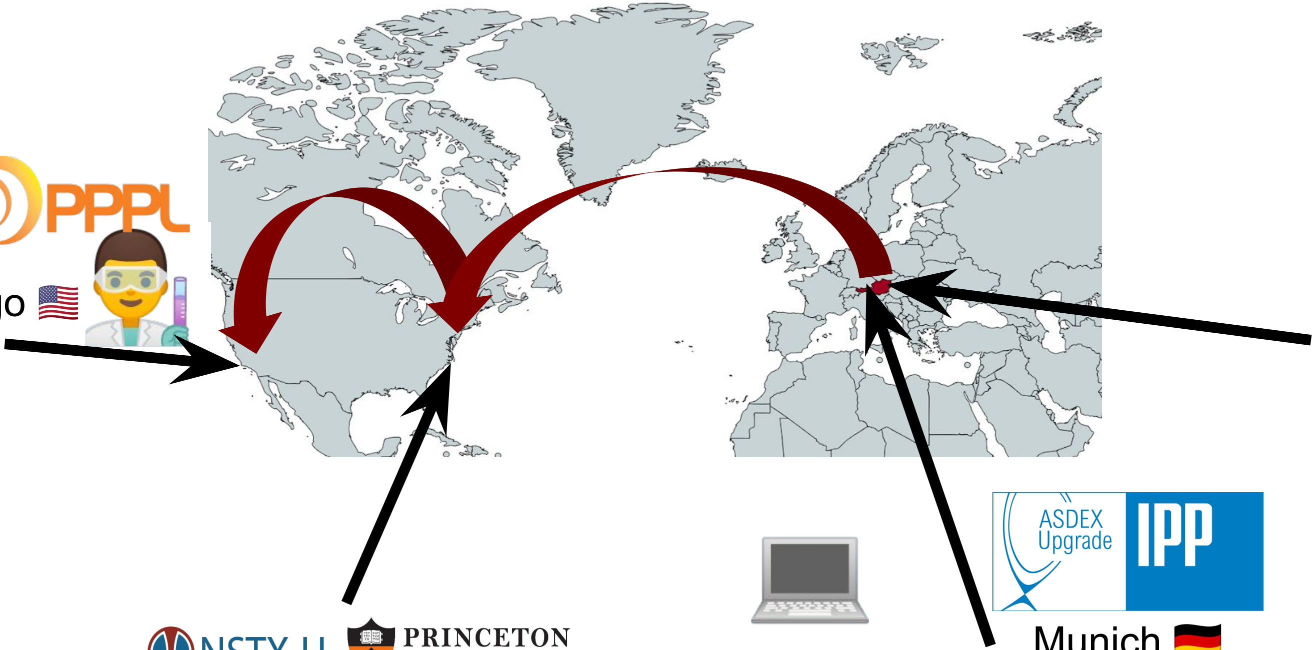
About me: Where do I come from? Austria (≠ Australia😉)

About me: A picture is worth a thousand words…



www.pppl.gov

My path: From Europe to the U.S.



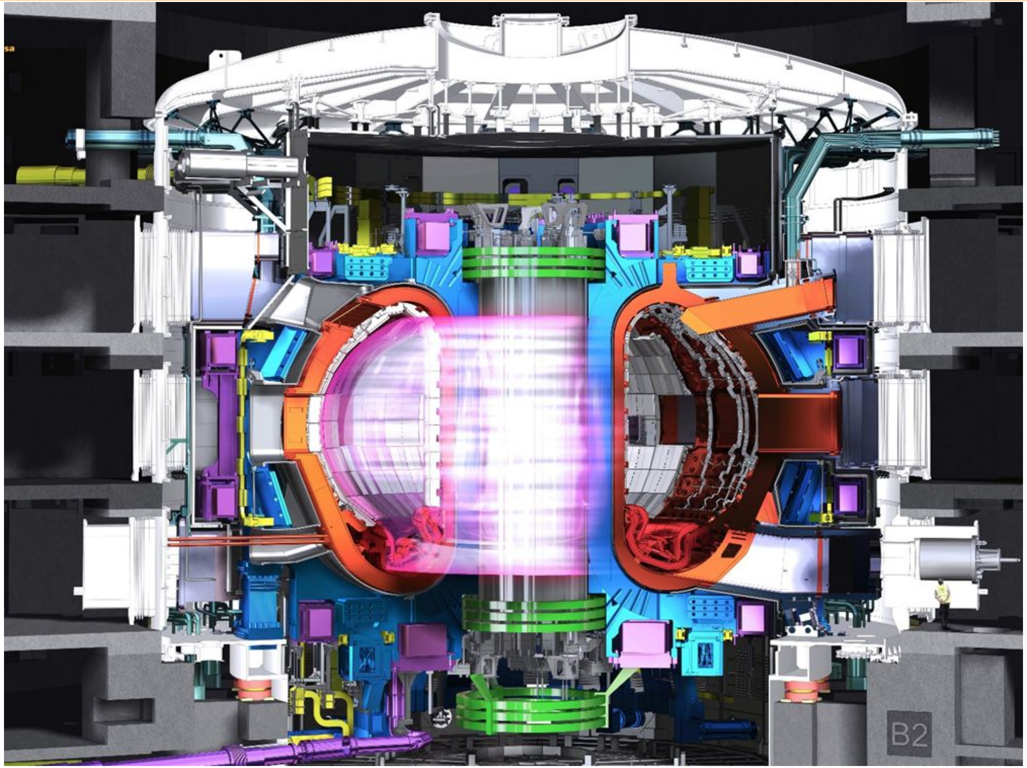
Today’s topic: The ITER project

iter

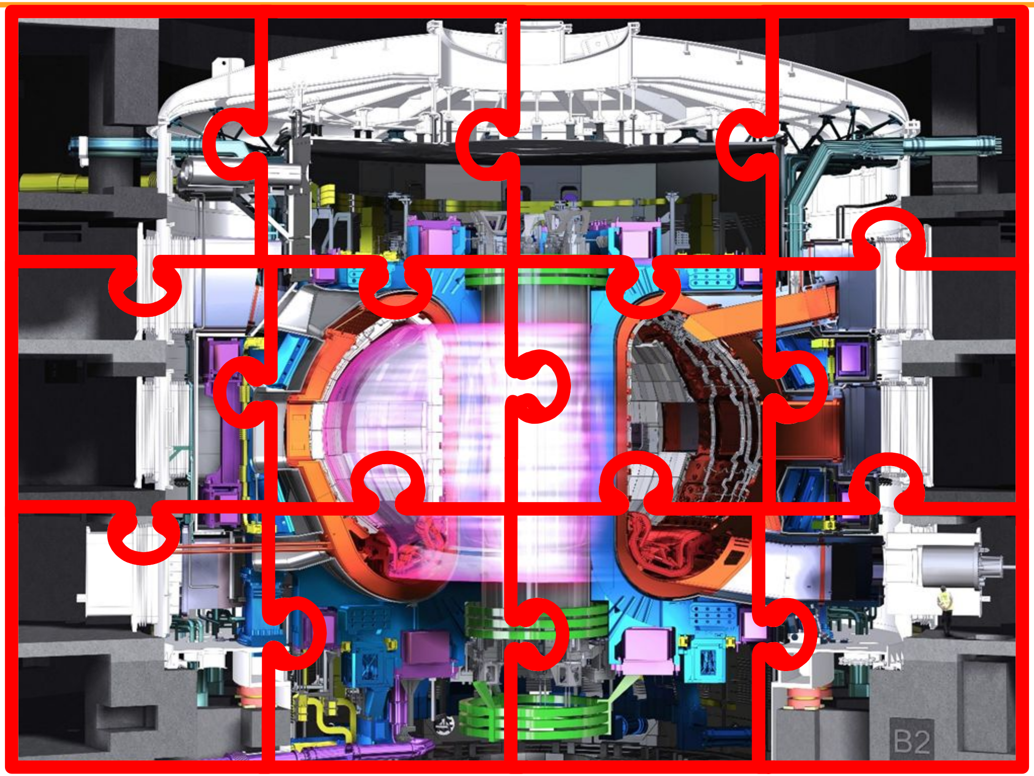
china eu india japan korea russia usa

Saint-Paul-lès-Durance 🇫🇷

Takeaway: Building a fusion reactor …



… is a complex puzzle.



… is a complex puzzle. BUT ‘we’ are getting there!

Why? Fusion efficiency trumps fossil fuel

11 million times more energy per gram material!

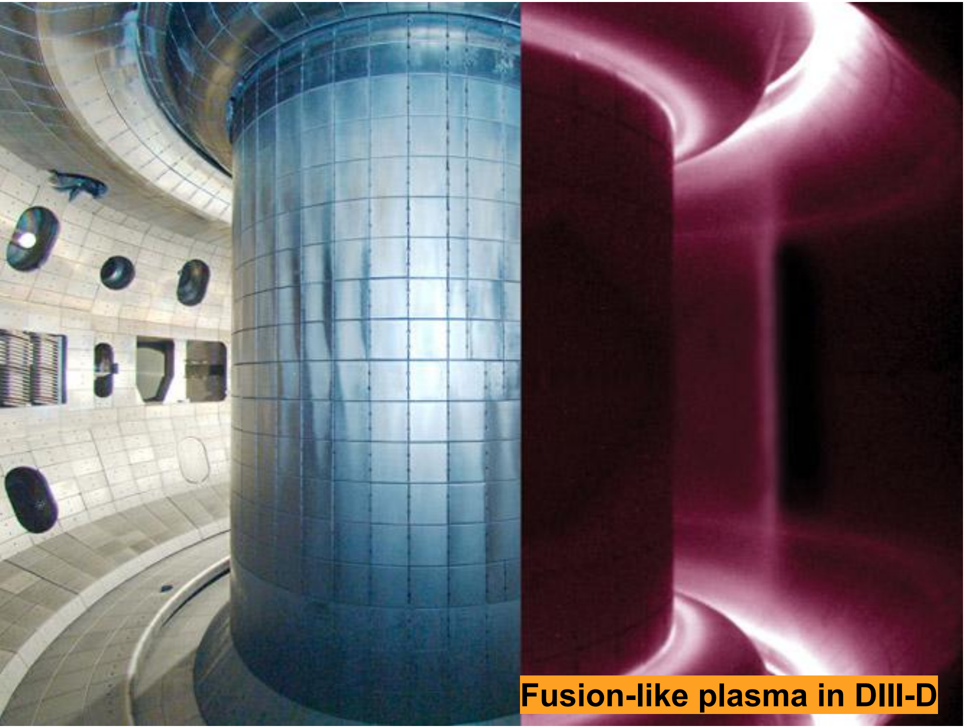
1 tablespoon
liquid Deuterium-Tritium (2.5 grams)

1 railway car of coal (28 tonnes)

Why? Fusion's Advantages

- Massive, continuous, baseload energy
- Safe, no meltdown possible
- No CO_2 or other greenhouse gases
- No long-lived high-activity radioactive waste
- Unlimited fuel from water and Lithium for millions of years

Why? Fusion's Advantages



Fusion-like plasma in DIII-D

- Massive, continuous, baseload energy
- Safe, no meltdown possible
- No CO_2 or other greenhouse gases
- No long-lived high-activity radioactive waste
- Unlimited fuel from water and Lithium for millions of years

Global challenge, global response

- June 2005: Members agree to build ITER in France
- November 2006: ITER Agreement signed in Paris

More than 50% of world population, 85% of global GDP

China EU India Japan Korea Russia USA

An integrated project - Intellectual Property shared by all

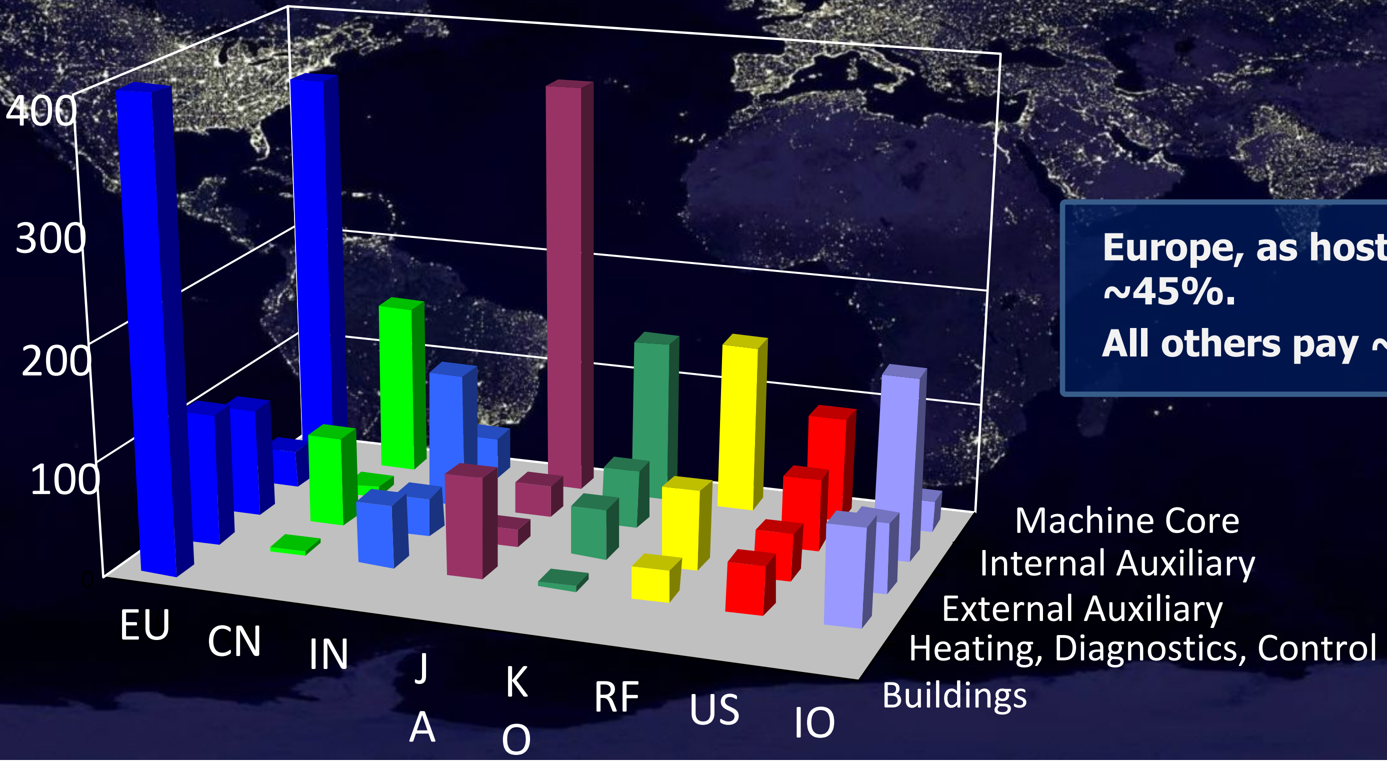
Project Structure

- 1 Central Team - ITER organization (IO)
- 7 Domestic Agencies

Financial support:

- 80-90% in-kind
  - Lots of Hardware!
- 10-20% in-cash

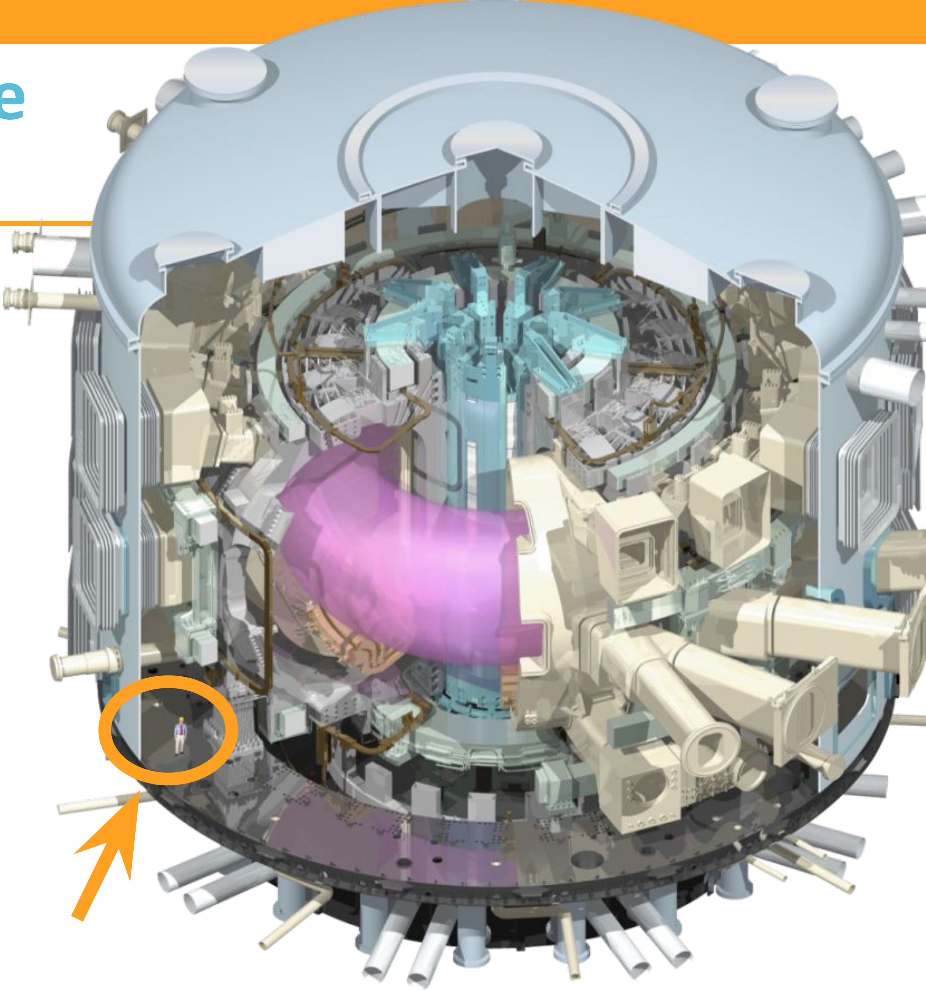
A unique cost share...



Europe, as host, pays ~45%.
All others pay ~9%.

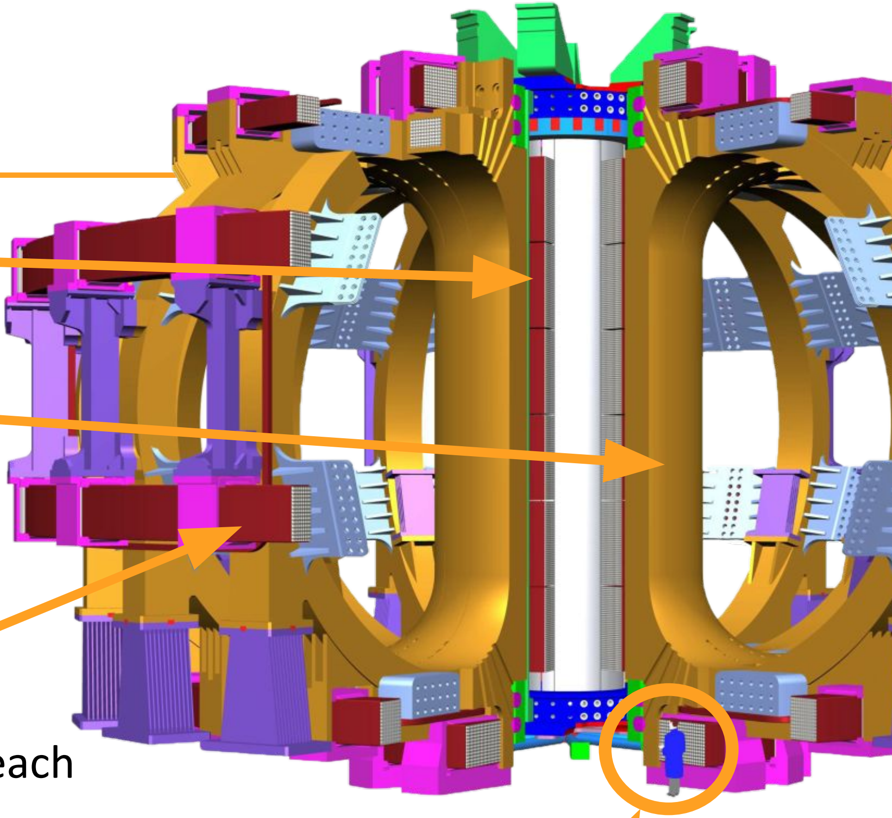
ITER's Mission - Demonstrate fusion at industrial-scale

- Produce a plasma with dominant heating of alpha particles
  - Study a "burning plasma"
- 500 MW fusion power (Q≥10)
- Extend pulse duration
  - Non-inductive current drive
- Test Fuel technology
  - Tritium breeding
- Costs: $ 20 billion



A giant magnetic cage

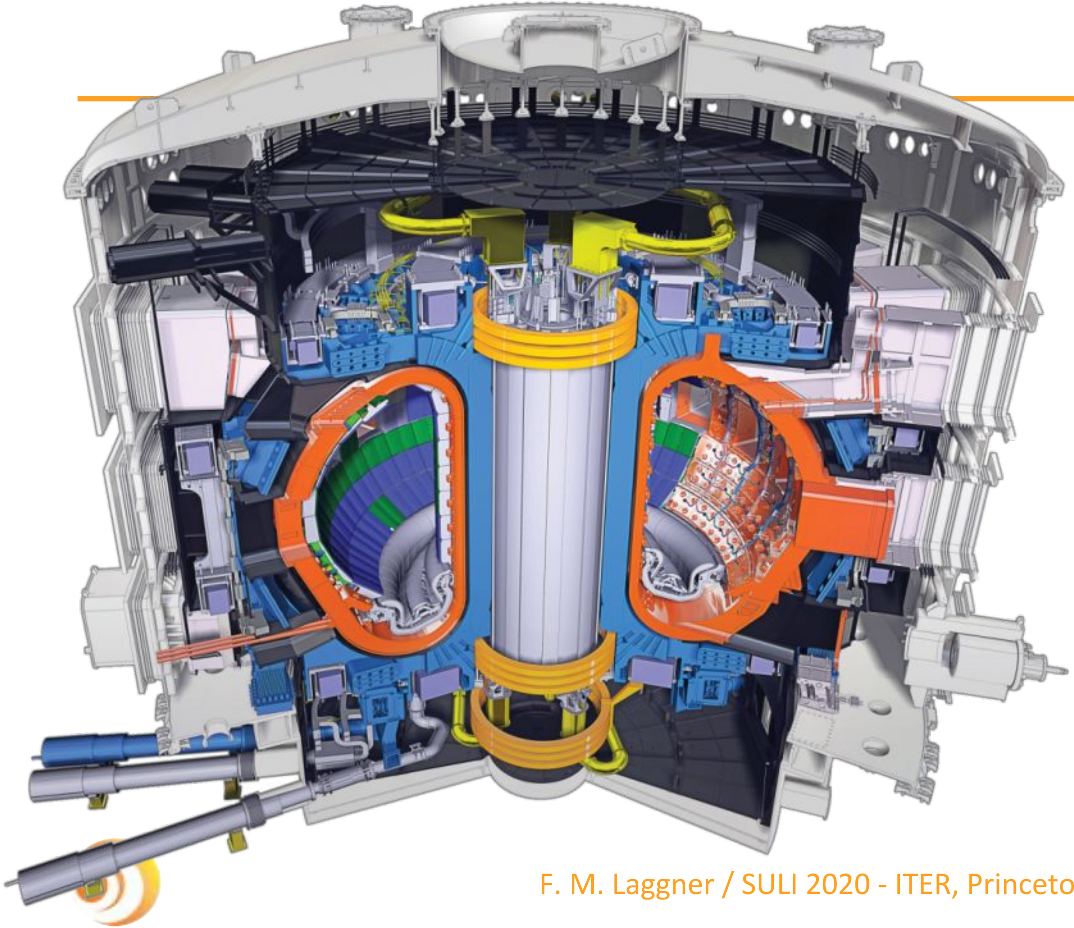
- 1 central solenoid (Nb3Sn)
  - 13 m high, 1,000 tonnes
- 18 toroidal magnets (Nb3Sn)
  - 17 m high, 360 tonnes each
  - Magnetic axis to be positioned with a precision below 0.5 mm
- 6 poloidal magnets (Nb-Ti)
  - 8 to 24 m diametre, 200 to 400 tonnes each



"Tokamak": Russian acronym for "Toroidal Chamber, Magnetic Coils"

Day 4
Batta-
glia

The ITER Tokamak - Massive Components



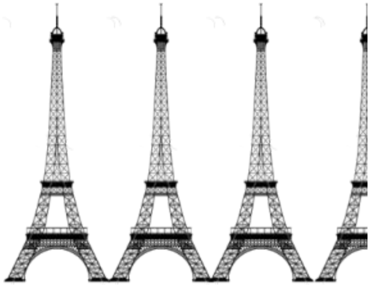
Vacuum Vessel: ~ 8 000 t

TF Coils: ~ 18 x 360 t

Central solenoid: ~ 1 000 t

Radius: 6.2 m

Total ~ 23 000 tonnes



3.5 Eiffel Towers

Reminder: Performance of Fusion Plasmas

- Temperature - T_i: 1-2 × 10^8 K (10-20 keV)
  - ~10 × temperature of sun's core
- Density - n_i: 1 × 10^{20} m^{-3}
  - 10^{-6} of atmospheric particle density
- Energy confinement time - τ_E: few seconds
  - $\propto$ plasma current × radius^2
- Plasma pulse duration: ~1000 s

Fusion power amplification:

$$Q = \frac{\text{Fusion Power}}{\text{Input Power}} \sim n_i T_i \tau_E$$

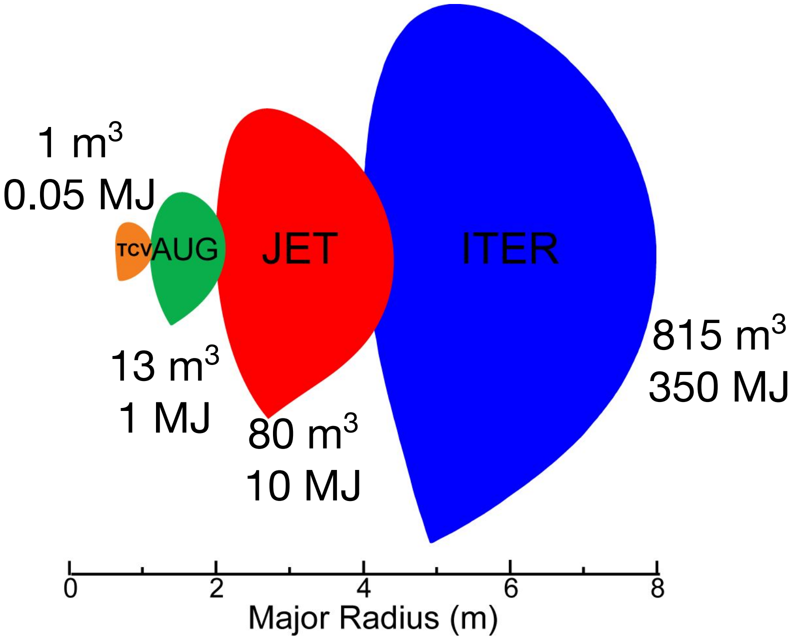
⇒ Present devices: Q ≤ 1

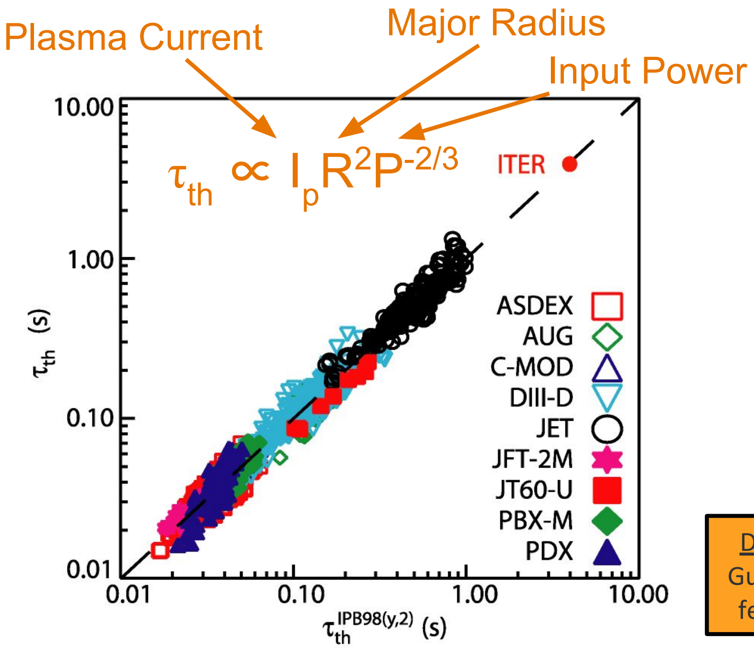
⇒ ITER: Q ≥ 10

⇒ 'Controlled ignition': Q ≥ 30

Day 1 Cowley

Why bigger? How big should ITER be?
Confinement scaling studies provide robust approach





Day 7 Guttenfelder

Detailed design rely on numerical codes combining engineering and physics constraints

ITER Physics Basis, NF 1998

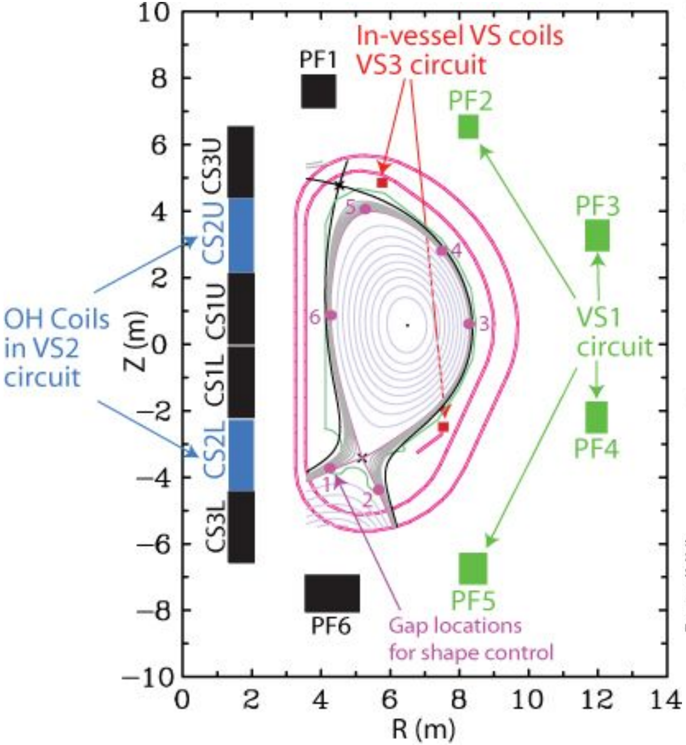
ITER Baseline Plasma Scenarios for Fusion Power Operation (Deuterium-Tritium D-T)

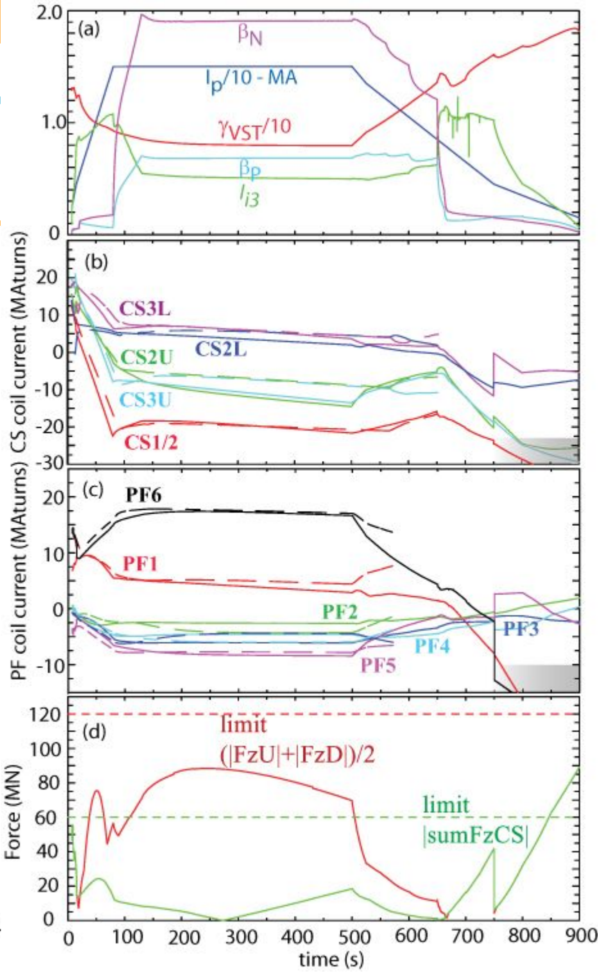
Parameter	Inductive Operation	Hybrid Operation	Non-inductive Operation
Plasma Current, I_p (MA) Safety Factor, q_{95}	15 3.0	13.8 3.3	9 5.3
Confinement Time, τ_E (s)	3.4	2.7	3.1
Fusion Power, P_{fus} (MW) Power Multiplication, Q	500 10	400 5.4	360 6
Burn time (s)	300 – 500	1000	3000

A range of non-active (H, He) and D plasma scenarios must be supported for commissioning purposes to support rapid transition to DT operation

Simulation of a ITER plasma Discharge - Control will be Key to Achieve Mission

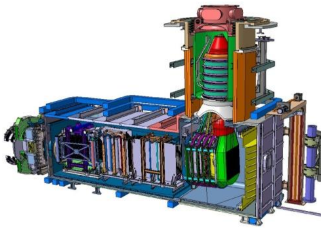
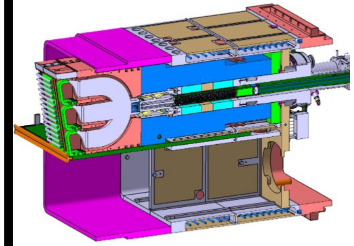
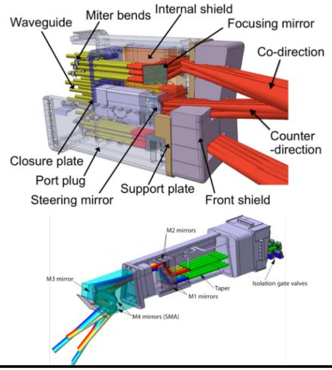
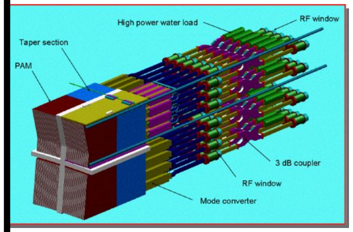
- Central Solenoid (CS) induces the plasma current (I_p)
- Poloidal field (PF) coils control the vertical stability
- Both coil sets are used control the plasma boundary





T. Casper, *et al* NF 2014

Heating and Current Drive Systems

<table>
<tr><th>NB</th><th>IC</th><th>EC</th><th>LH</th></tr>
<tr><td>Neutral Beam
- 1 MeV</td><td>Ion Cyclotron
40-55MHz</td><td>Electron Cyclotron
170GHz</td><td>Lower Hybrid
~5 GHz</td></tr>
<tr><td></td><td></td><td>
</td><td>
</td></tr>
<tr><td>33MW*
+16.5MW#</td><td>20MW*
+20MW#</td><td>20MW*
+20MW#</td><td>0MW*
+40MW#</td></tr>
<tr><td>Bulk current drive limited modulation</td><td>Sawtooth control modulation < 1 kHz</td><td>NTM/sawtooth control modulation up to 5 kHz</td><td>Off-axis bulk current drive</td></tr>
</table>

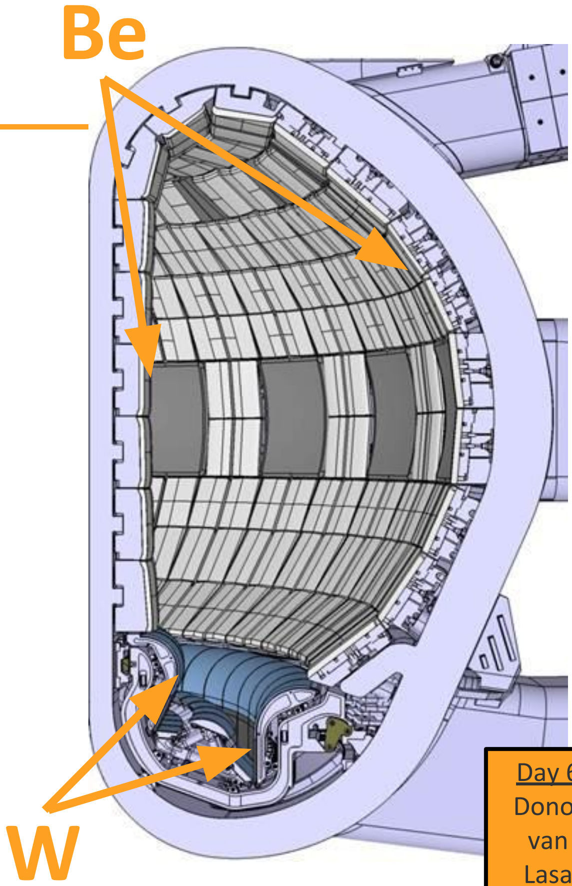
Day 5
Pinsker

*Baseline Power

#Possible Upgrade

All-Metal Plasma Facing Components

- **Beryllium (Be) first wall (~700m²):**
  - low-Z limits plasma impurity contamination
  - low neutron activation
  - low melting point – plasma transients!
  - erosion/ redeposition ⇒ fuel retention
  - dust production
- **Tungsten (W) divertor (~150m²):**
  - resistant to sputtering
  - limits fuel retention (Be dominates)
  - W concentration in core must be below ~ 2.5×10^{-5}
  - melting during plasma transients

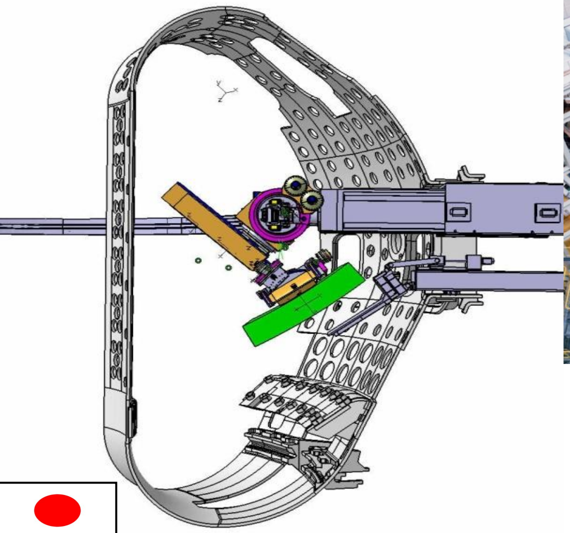


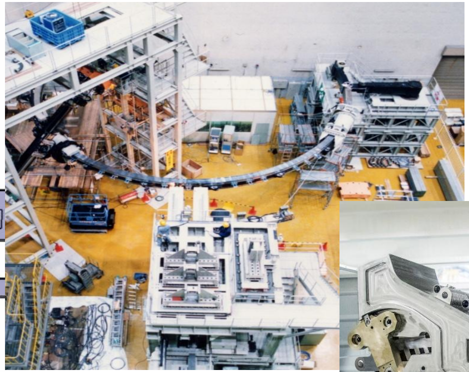
Day 6 Dono-van Lasa

Remote Handling - Challenging to repair & replace complex & heavy components in a nuclear environment

Dedicated, state-of-the art systems for both Blanket and Divertor

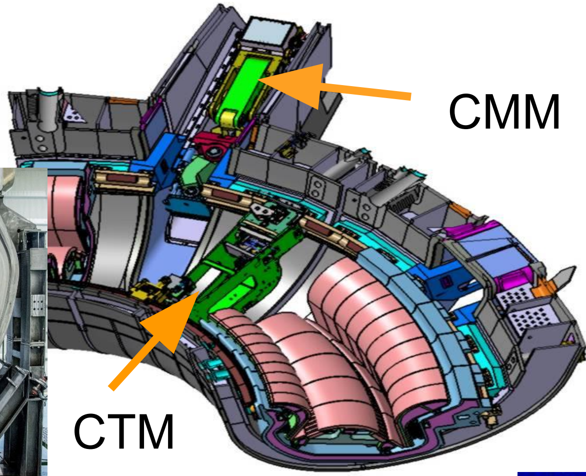
Blanket RH procured by JA





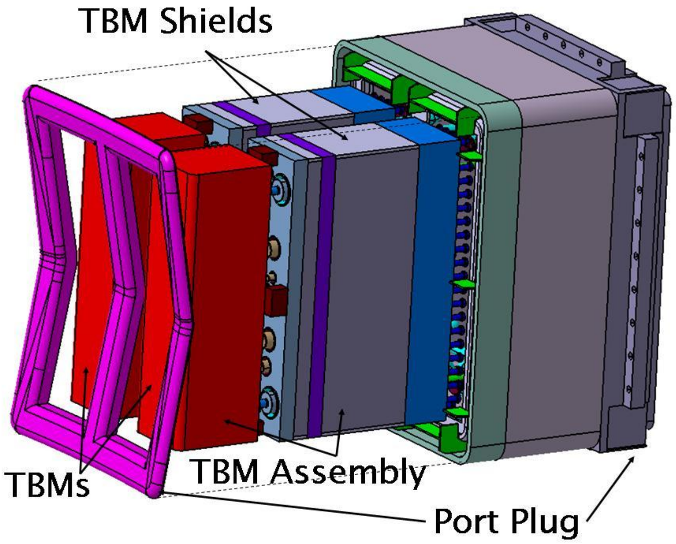
Divertor RH procured by EU

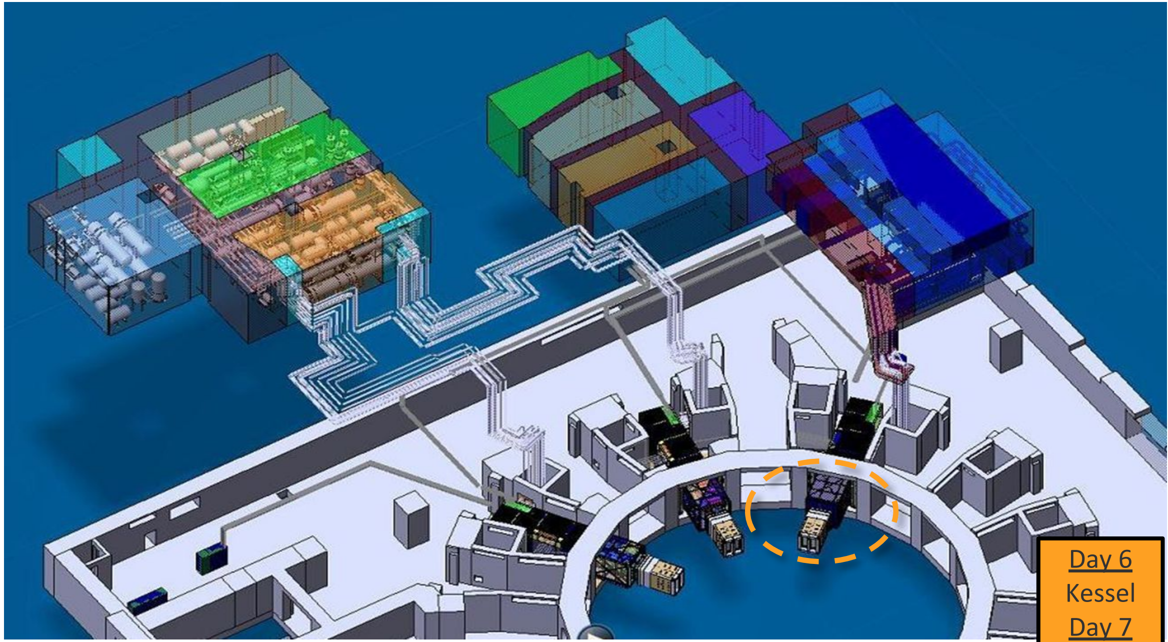
Divertor Cassette Prototype



Test Blanket Modules - Tritium fuel cycle is major challenge for all D-T fusion devices

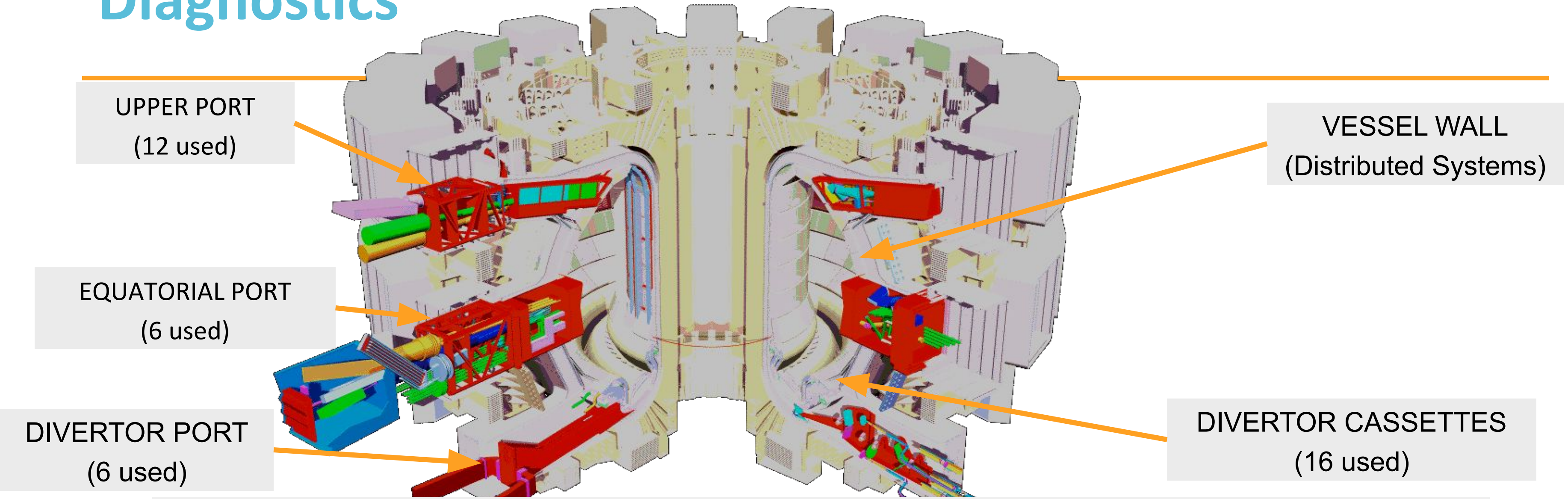
ITER will test concepts: 6 modules with different designs





Day 6
Kessel
Day 7
Xiao

Analyzing the Plasma - ITER Diagnostics



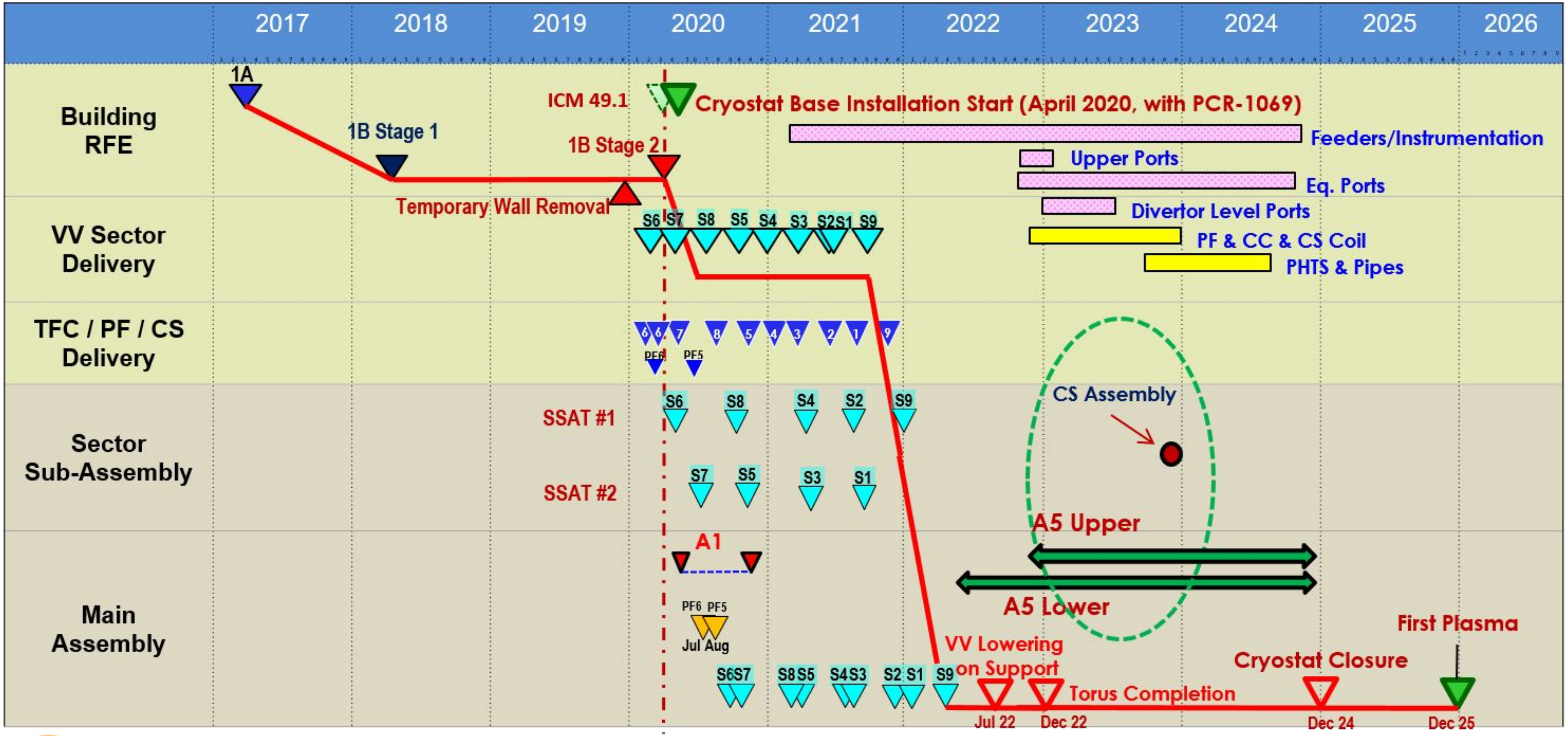
- About 40 large scale diagnostic systems are foreseen:
  - Diagnostics required for protection, control and physics studies
  - Measurements from DC to γ-rays, neutrons, α-particles, plasma species
  - Diagnostic Neutral Beam for active spectroscopy (CXRS, MSE ....)

Day 5
Reinke

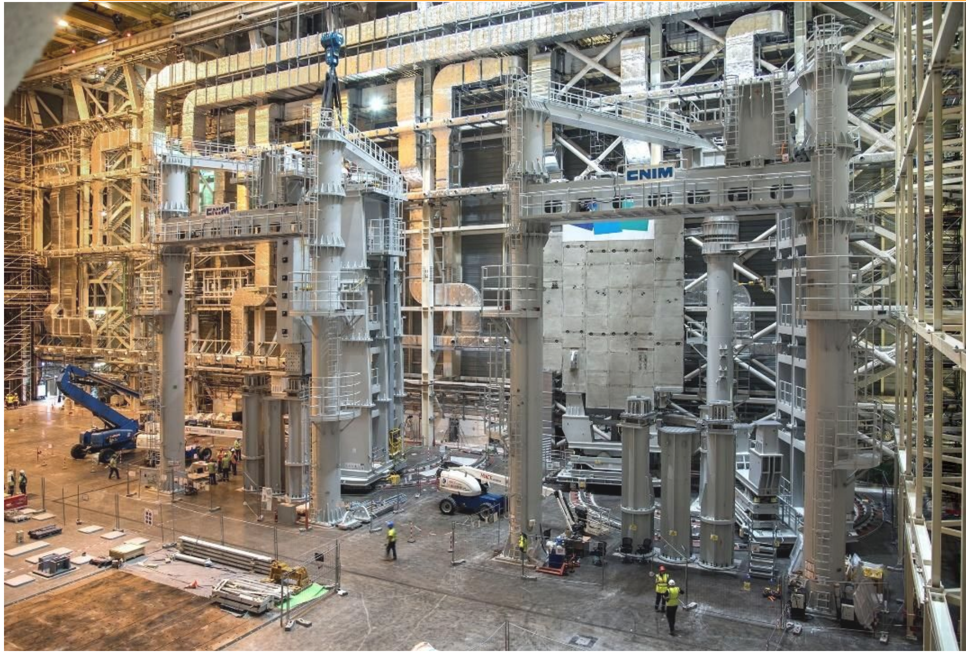
Always take a look back - before looking ahead...

Significant onsite progress - ITER is HAPPENING
Optimism for the next 10 years

Construction Strategy and Staging (Baseline 2016)

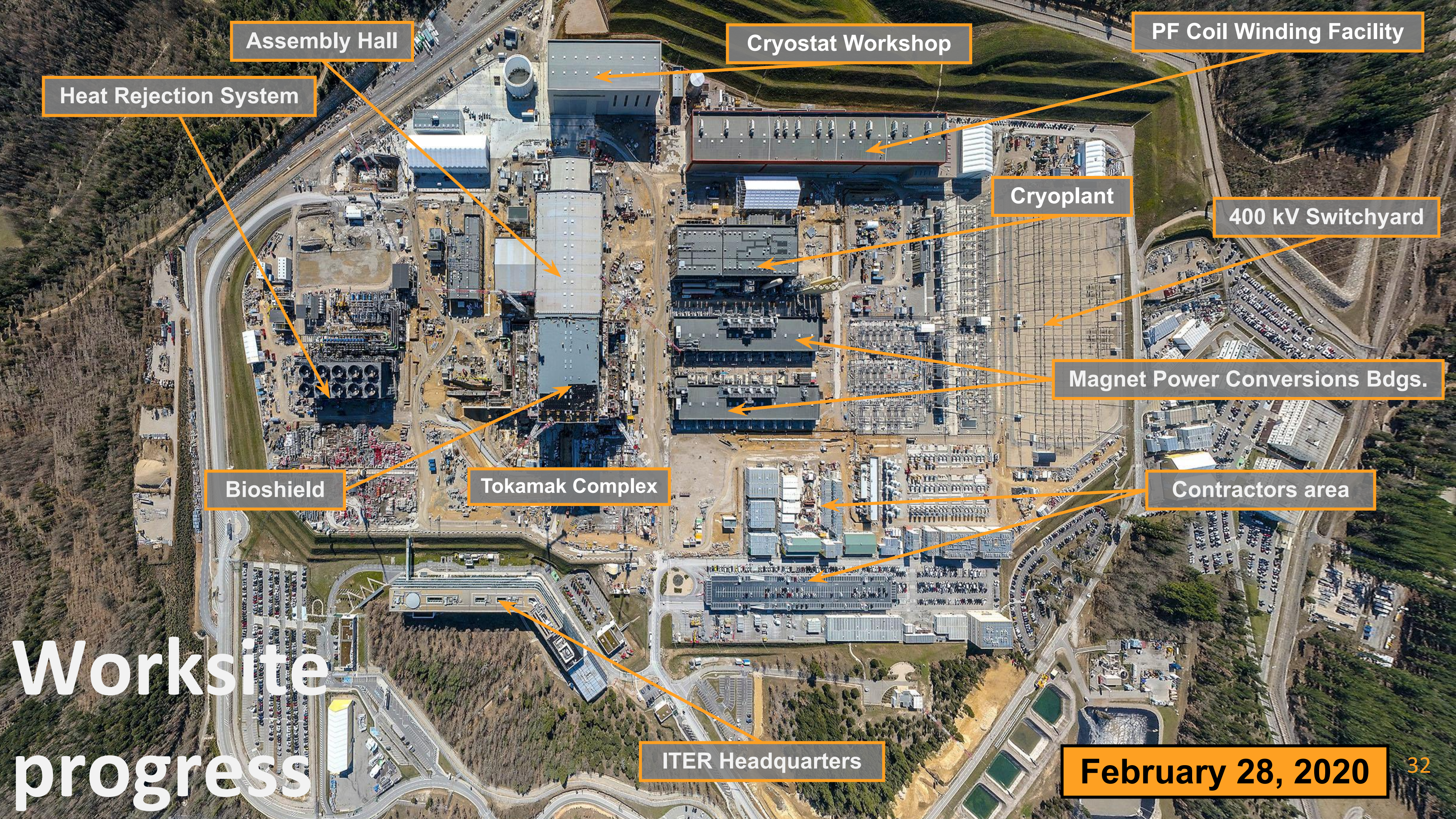


Challenge: Naval construction sized components with watch-like precision



ITER Assembly Hall, giant tools will handle components up to ~1500 tonnes

Insertion of a 300-tonne toroidal field magnet into its case with tolerances of 0.2 millimeters


Assembly Hall
Cryostat Workshop
PF Coil Winding Facility
Heat Rejection System
Cryoplant
400 kV Switchyard
Magnet Power Conversions Bdgs.
Bioshield
Tokamak Complex
Contractors area
Worksite progress
ITER Headquarters
February 28, 2020

Buildings and manufacturing onsite - Plant Systems

Heat removal system

Power Supply (switchyard and magnet power conversion)

Cryogenic Plant

Inside the Magnet Power Conversion buildings

Buildings and manufacturing onsite - Poloidal Field Coils

Poloidal Field Coil #5 nearing completion, April 2020

PF Coil #2 in fabrication, April 2020

Buildings and manufacturing onsite - First two Toroidal Field magnets arrived

TF Coil #09, arrived from Italy,
April 17, 2020

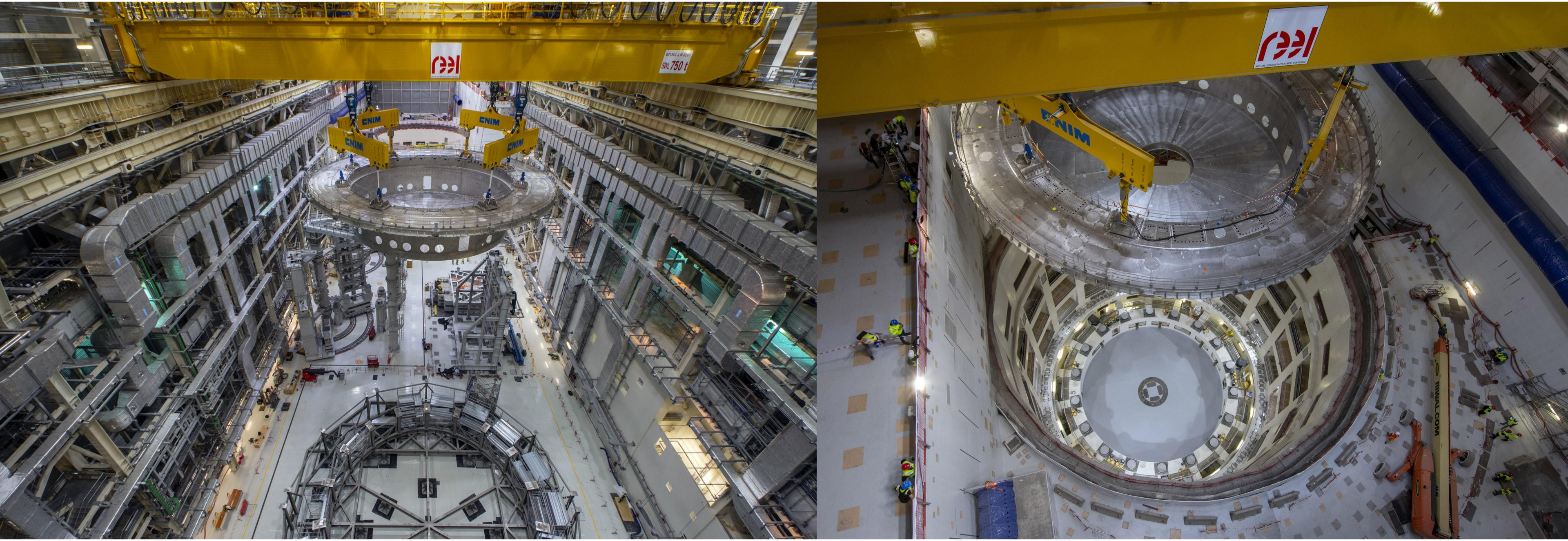
TF Coil #12, arrived from Japan
April 25, 2020

Buildings and manufacturing onsite - Cryostat installation begins

Cryostat Base moving into Assembly Hall, April 2020

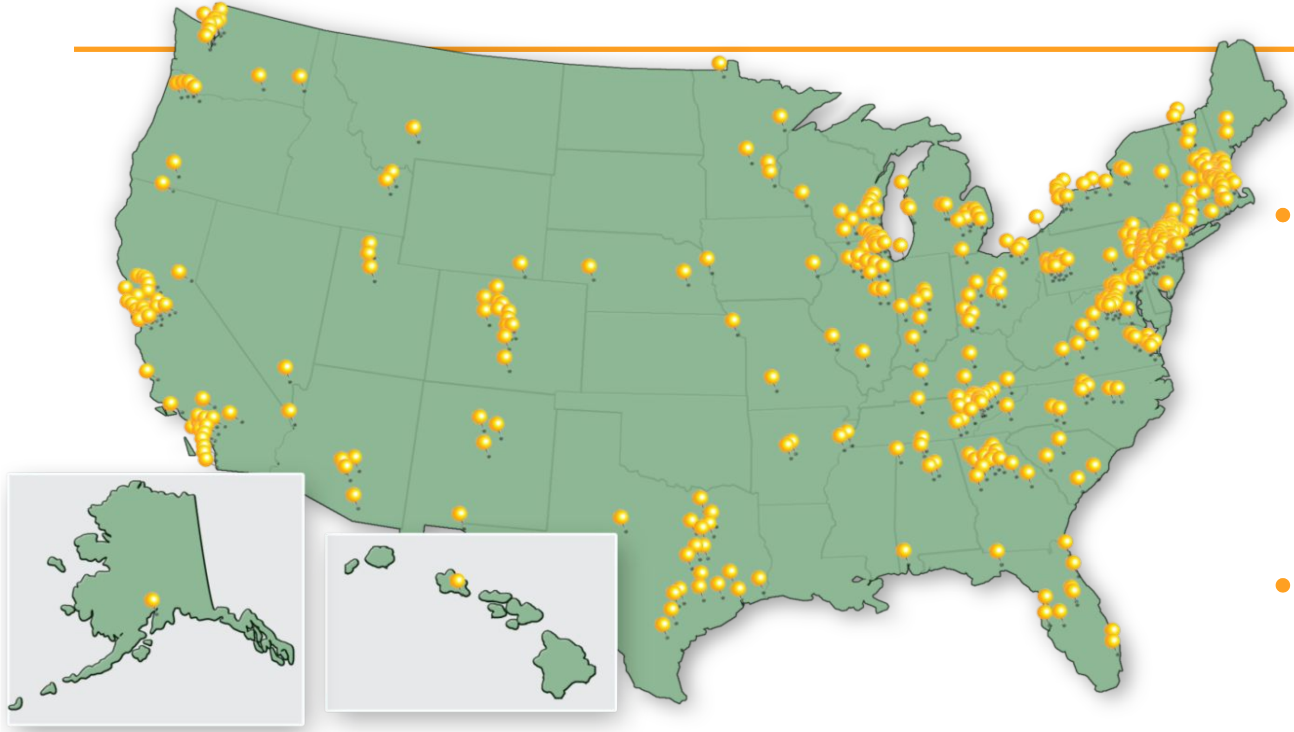
Tokamak pit lid removal, April 2020

Buildings and manufacturing onsite - Recent milestone: Cryostat base plate installed (May-30)



https://www.youtube.com/watch?v=QsToHk2aBx8

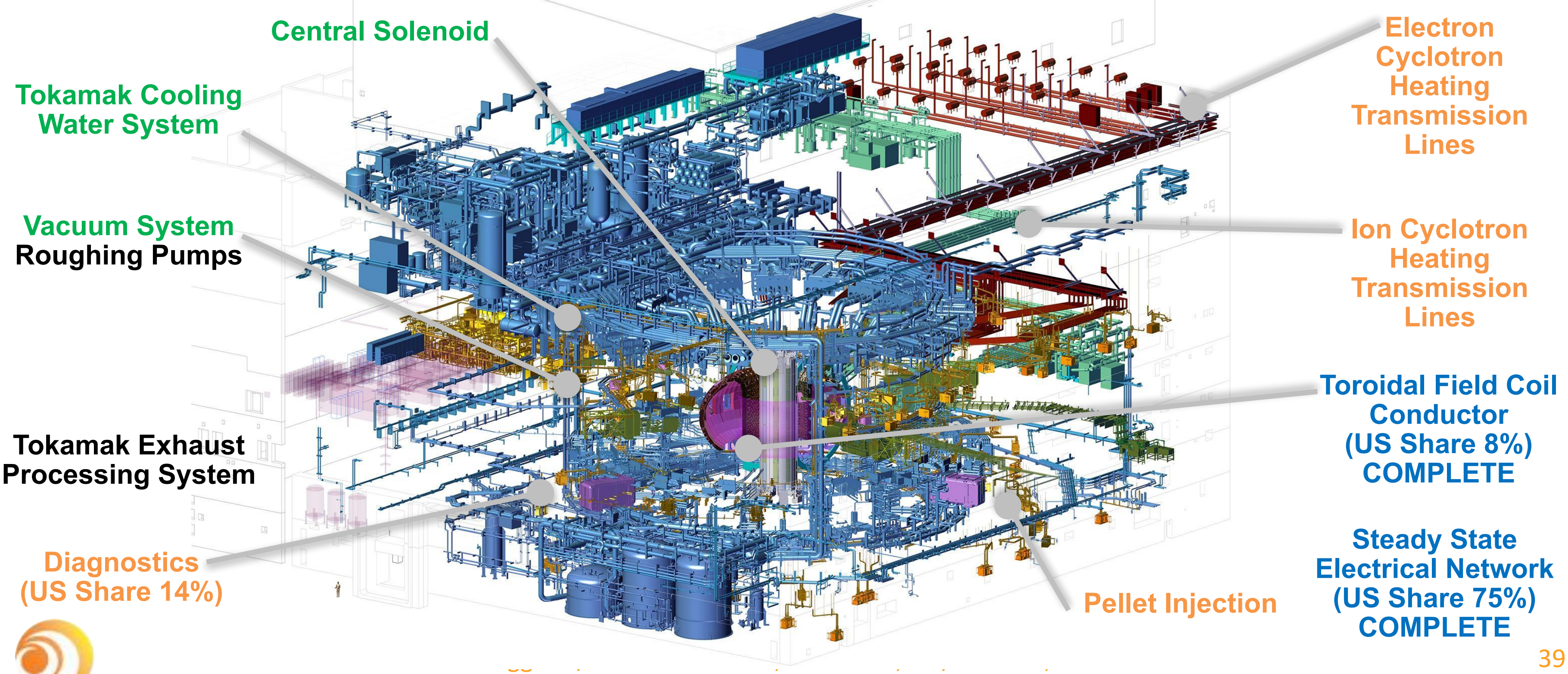
The ITER Project in the U.S.



- Highly Leveraged:
  - U.S. pays 9%
  - U.S. gets 100% access to the science & technology
- Most U.S. ITER funding goes to U.S. companies:
  - >$1 billion since 2007

US ITER hardware scope

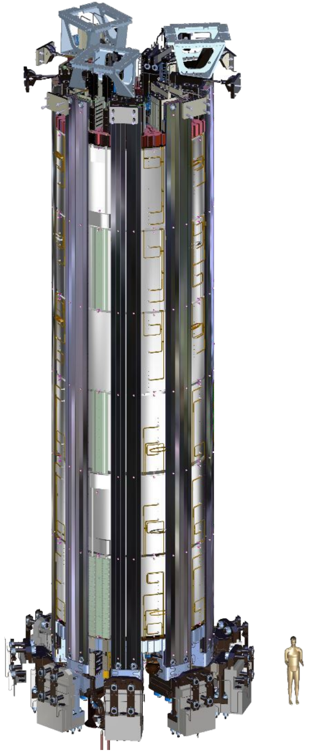
Key: Finished • Hardware in fabrication • Prototypes in fabrication • In design



US ITER manufacturing examples

36 km of nuclear piping

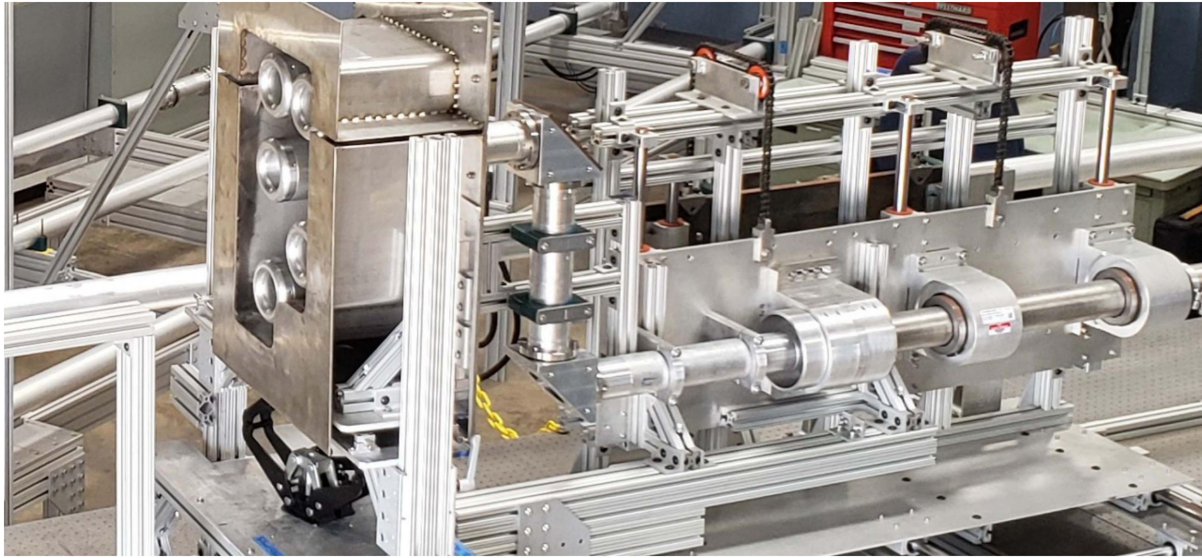
Roots pump testing



5 of 7 CS modules are in fabrication

US ITER Diagnostic Example - Low Field Side Reflectometer will measure the Electron Density

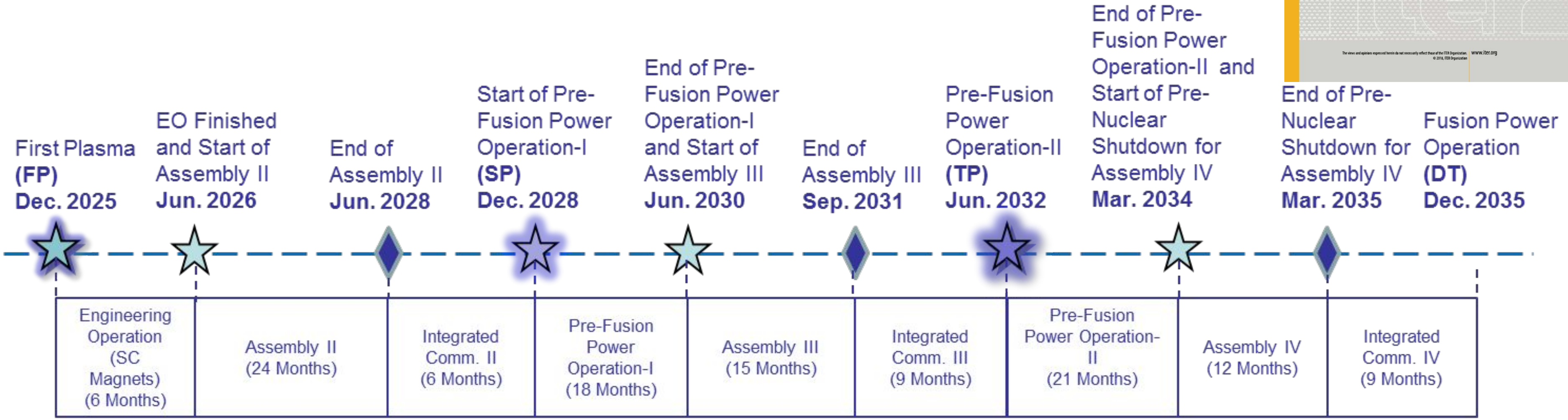
- Reflectometer is basically a radar system
- Launches frequency-modulated (FM) microwaves and measures the reflected signal from the plasma



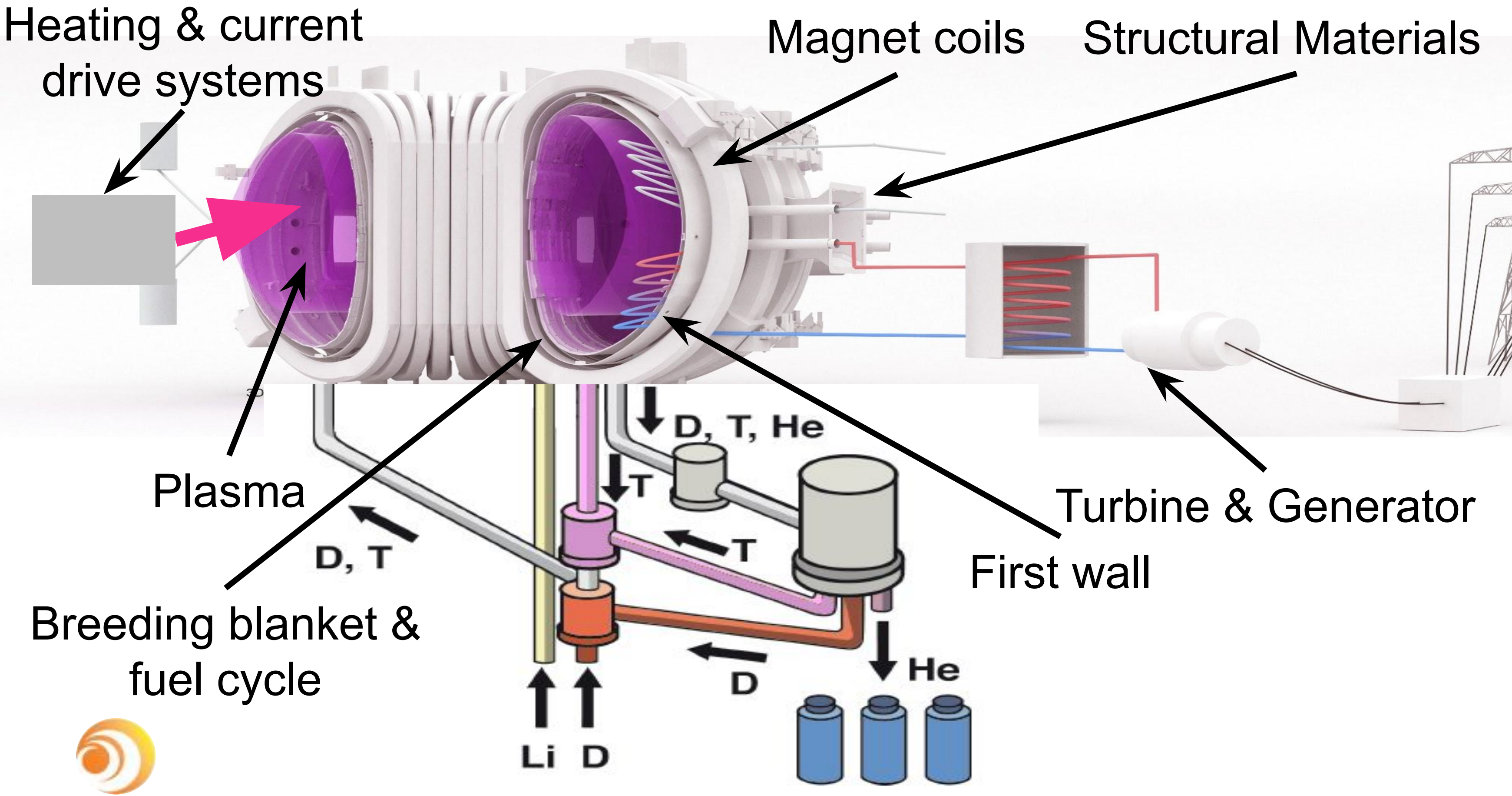
Low field side reflectometer test stand with antennae (left) and waveguides (right)
www.usiter.org

The ITER research plan - A Staged Approach to D-T Fusion

- Series of Assembly and Operation phases between First Plasma and start of DT Full Fusion operation.

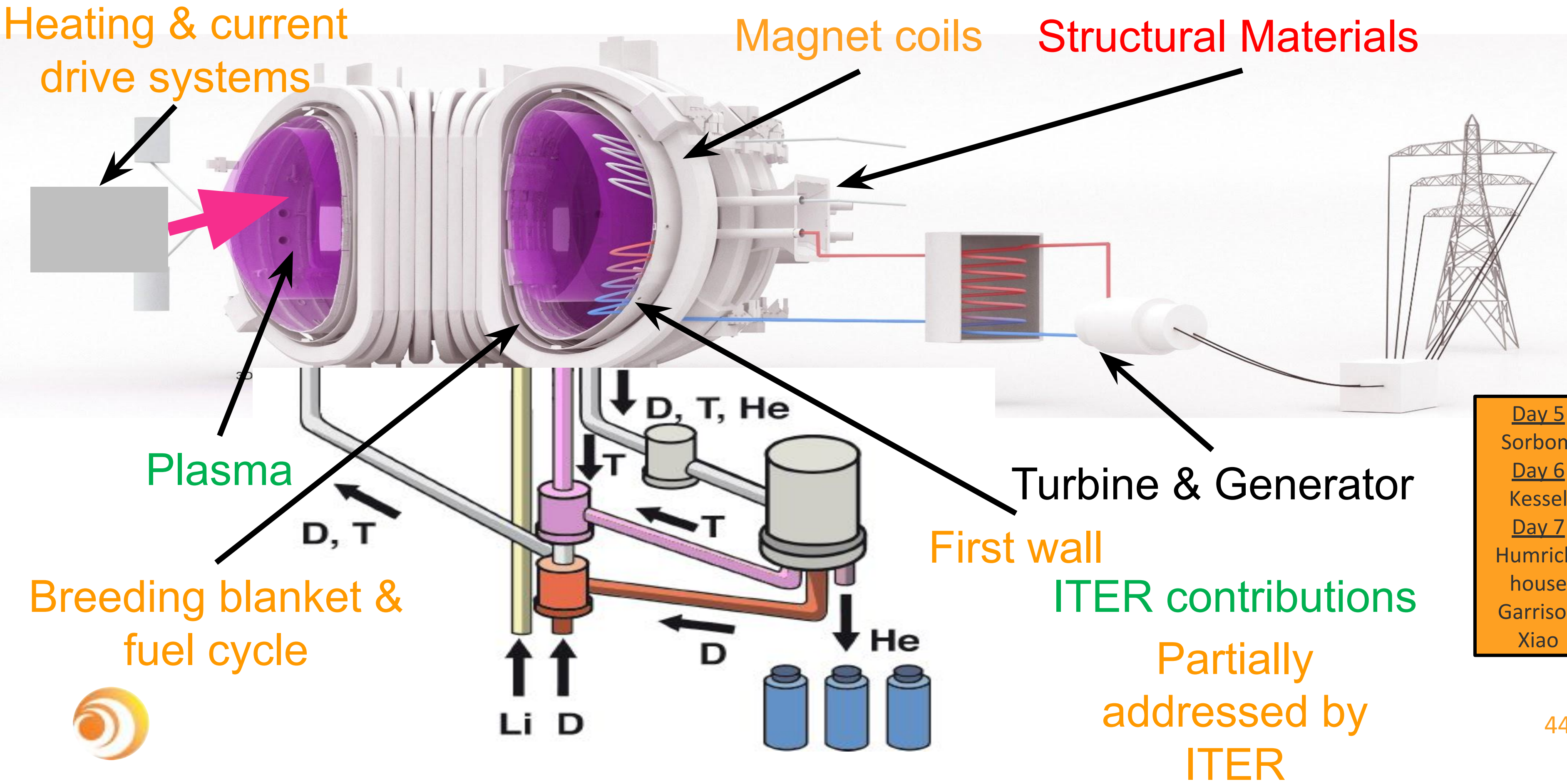


Towards a fusion power plant...



Day 5
Sorbom
Day 6
Kessel
Day 7
Humrick-house
Garrison
Xiao

Towards a fusion power plant...



Day 5
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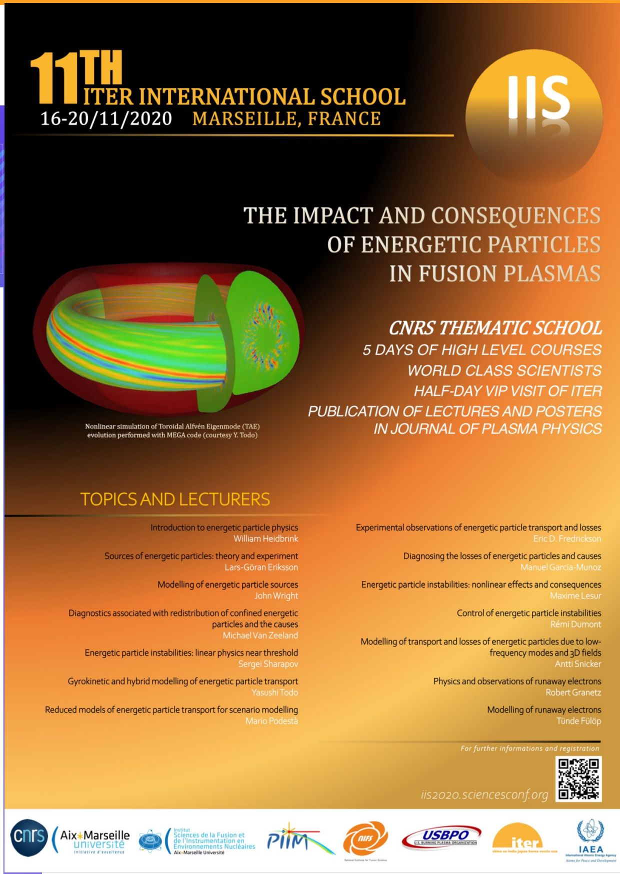
ITER International school (2020 Marseille)

- Since 2007
- On selected topics of ITER research
  - 2020 on 'Energetic Particles'
- Targets graduate students and postdocs
- Support Scholarships through USBPO



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Who manufactures what?