

The ITER Project - Fusion Research towards a Burning Plasma



SULI 2020 class, Princeton, NJ

ITER site, Feb 2019

F. M. Laggner

June 18, 2020

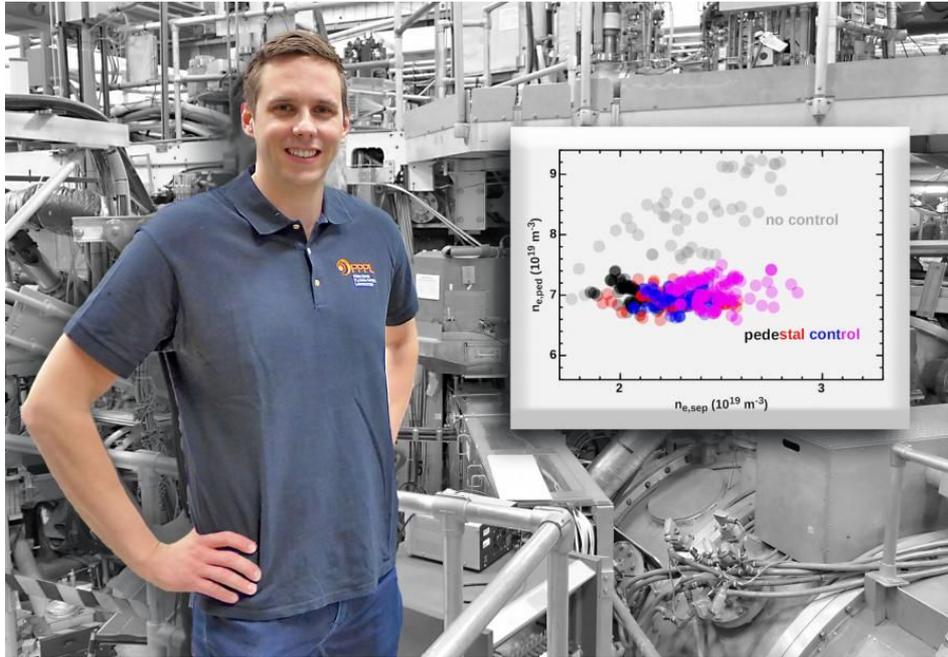




About me: Where do I come from? Austria (≠ Australia 😊)



About me: A picture is worth a thousand words...

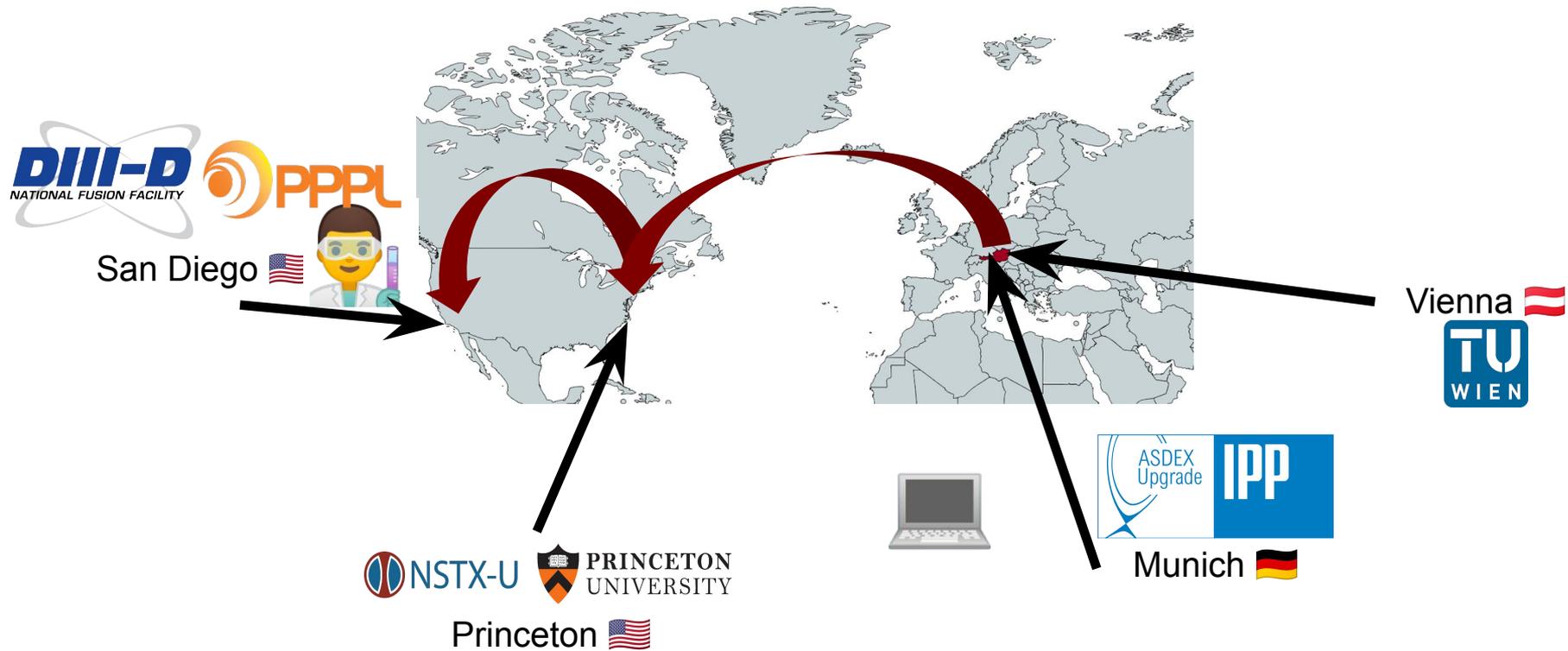


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My path: From Europe to the U.S.



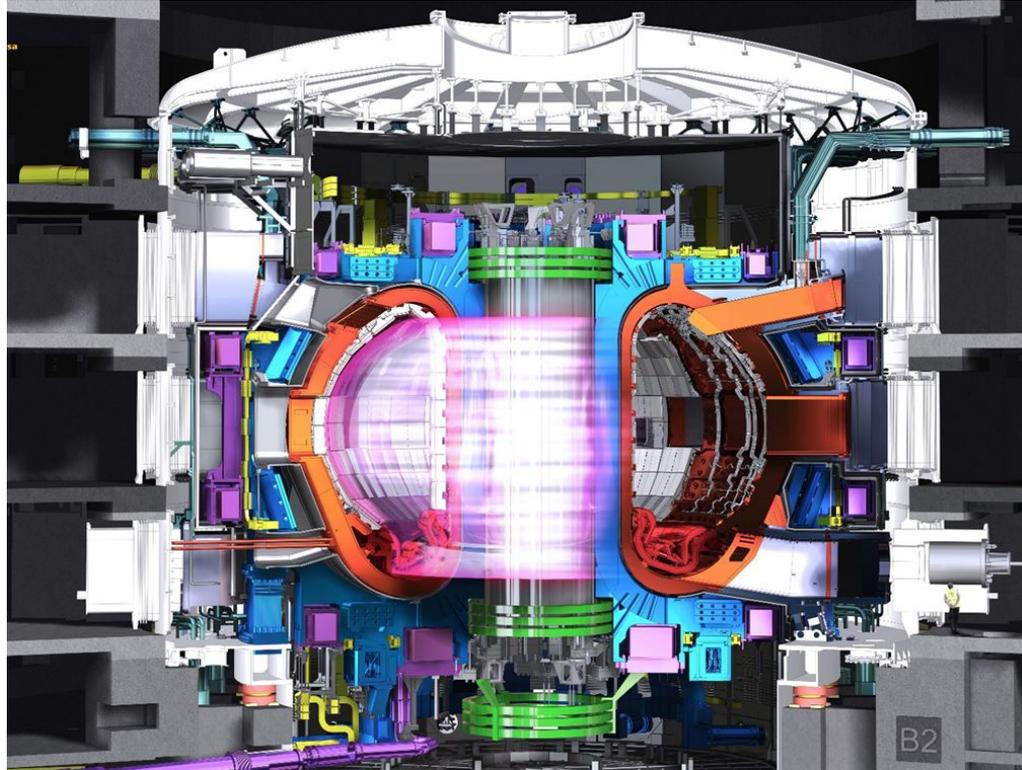
Today's topic: The ITER project



china eu india japan korea russia usa
Saint-Paul-lès-Durance 



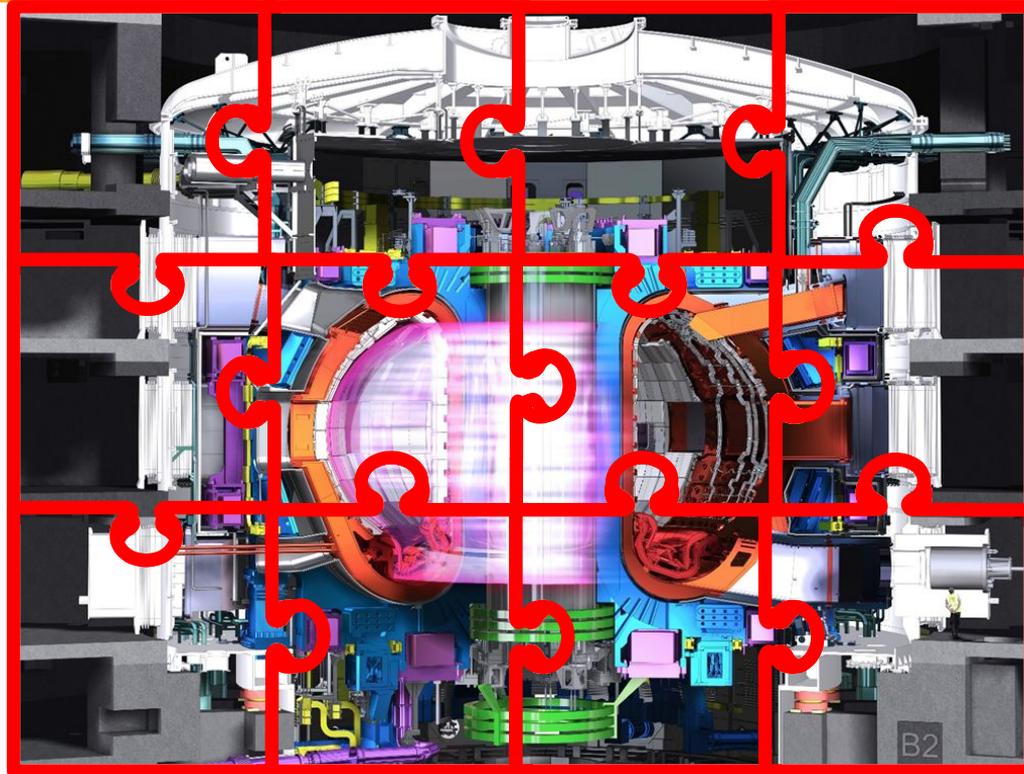
Takeaway: Building a fusion reactor ...



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... is a complex puzzle.



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... 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)



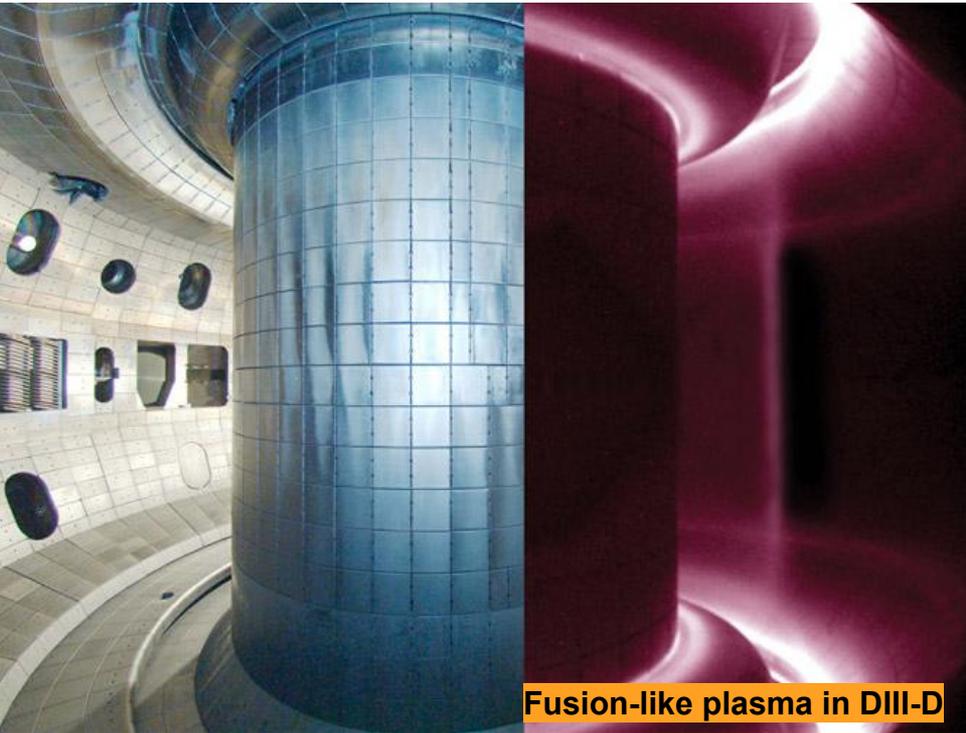
Why? Fusion's Advantages



- Massive, continuous, baseload energy
- Safe, no meltdown possible
- No CO₂ 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 CO₂ 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

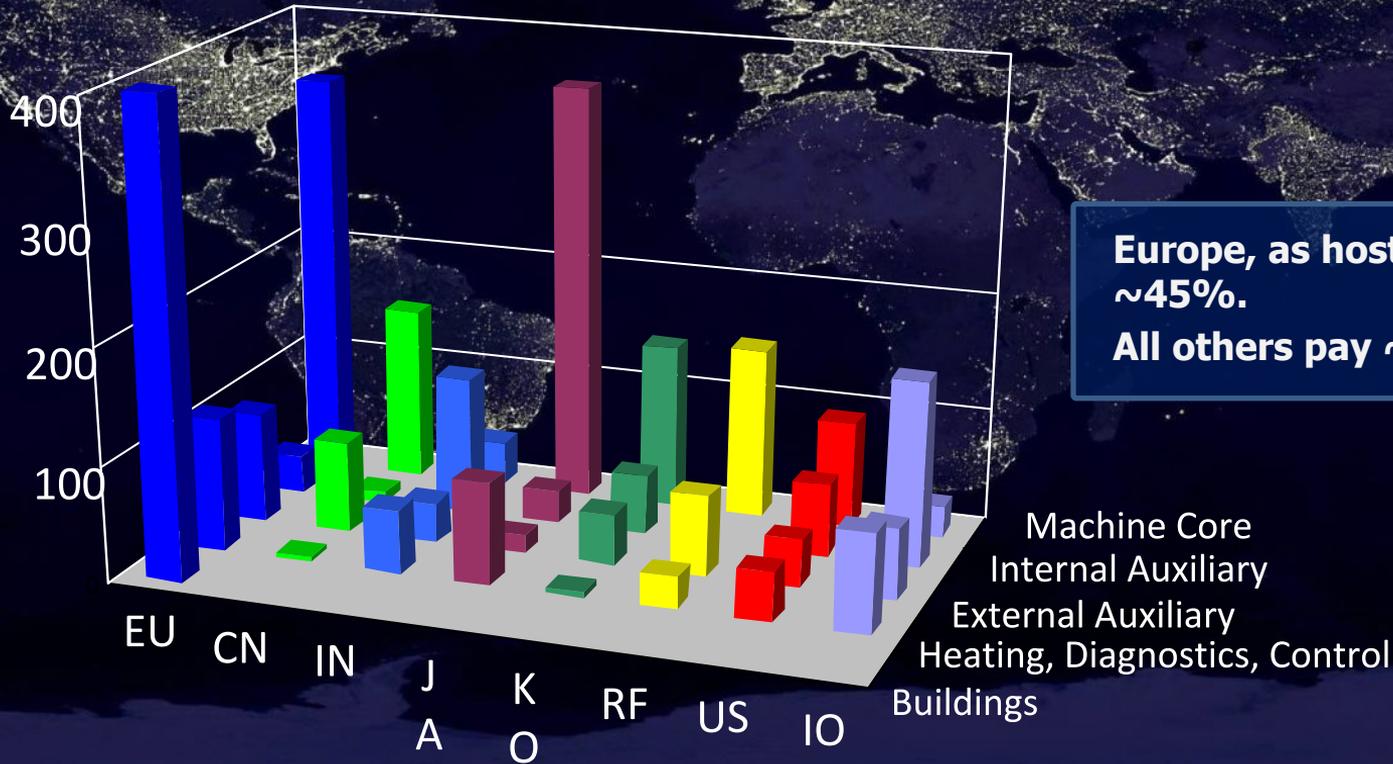
- 1 Central Team - ITER organization (IO)
- 7 Domestic Agencies

Financial support:

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



A unique cost share...

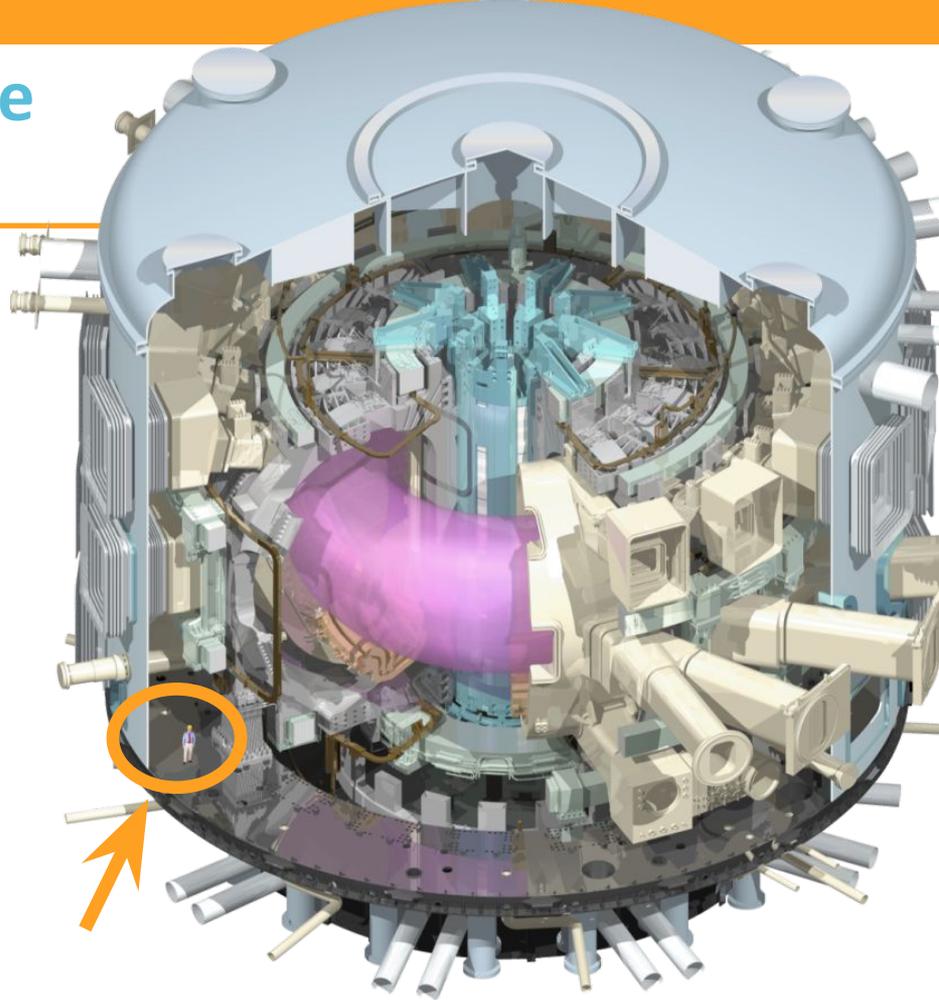


**Europe, as host, pays ~45%.
All others pay ~9%.**



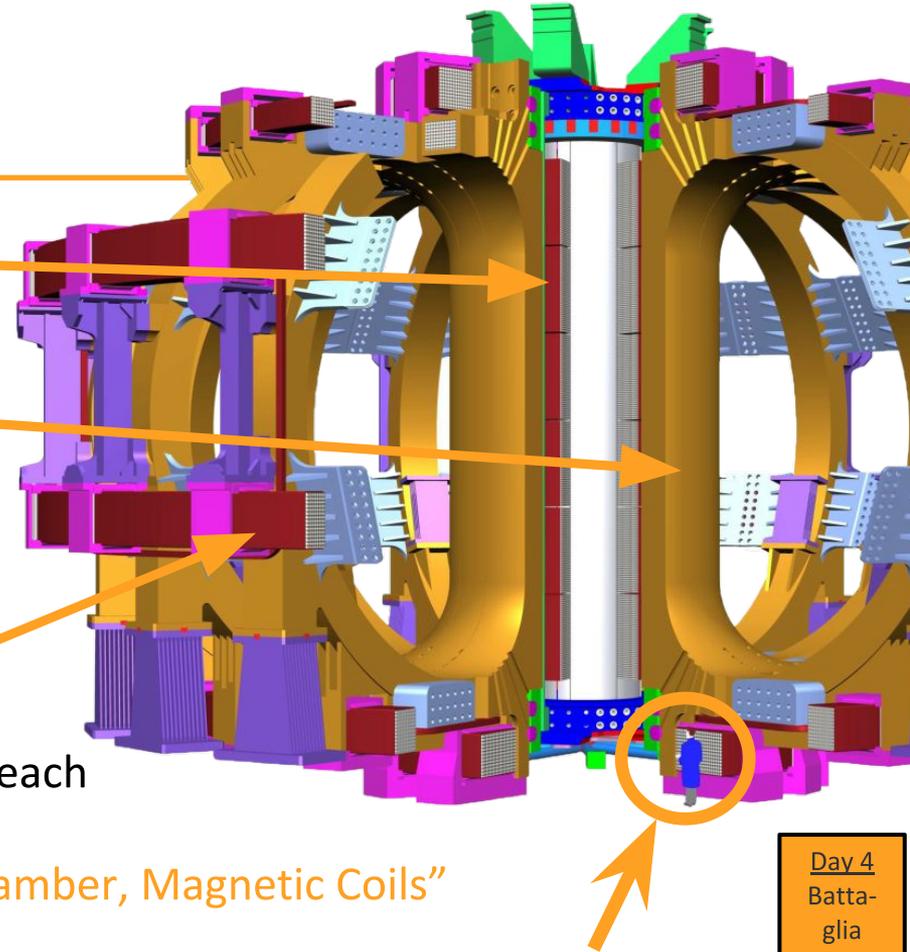
ITER's Mission - Demonstrate fusion at industrial-scale

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



A giant magnetic cage

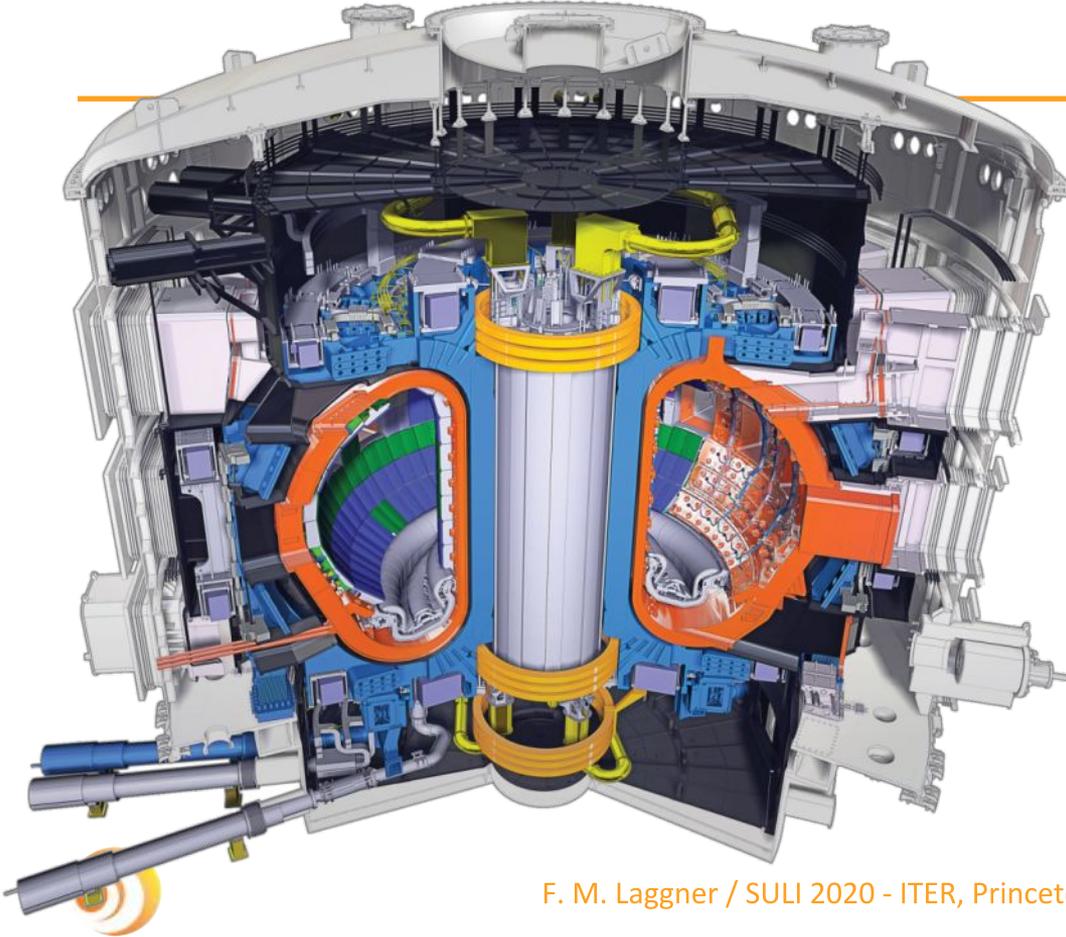
- 1 central solenoid (Nb₃Sn)
 - 13 m high, 1,000 tonnes
- 18 toroidal magnets (Nb₃Sn)
 - 17 m high, 360 tonnes each
 - Magnetic axis to be positioned with a precision below 0.5 mm
- 6 poloidal magnets (Nb-Ti)
 - 8 to 24 m diameter, 200 to 400 tonnes each



“Tokamak”: Russian acronym for “Toroidal Chamber, Magnetic Coils”



The ITER Tokamak - Massive Components



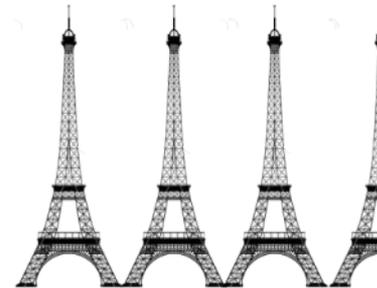
Vacuum Vessel: $\sim 8\,000$ t

TF Coils: $\sim 18 \times 360$ t

Central solenoid: $\sim 1\,000$ t

Radius: 6.2 m

Total $\sim 23\,000$ tonnes



**3.5 Eiffel
Towers**

Reminder: Performance of Fusion Plasmas

- Temperature - T_i : $1-2 \times 10^8$ K (10-20 keV)
 - $\sim 10 \times$ 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 \times radius²
- Plasma pulse duration: ~ 1000 s

Fusion power amplification:

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

\Rightarrow Present devices: $Q \leq 1$

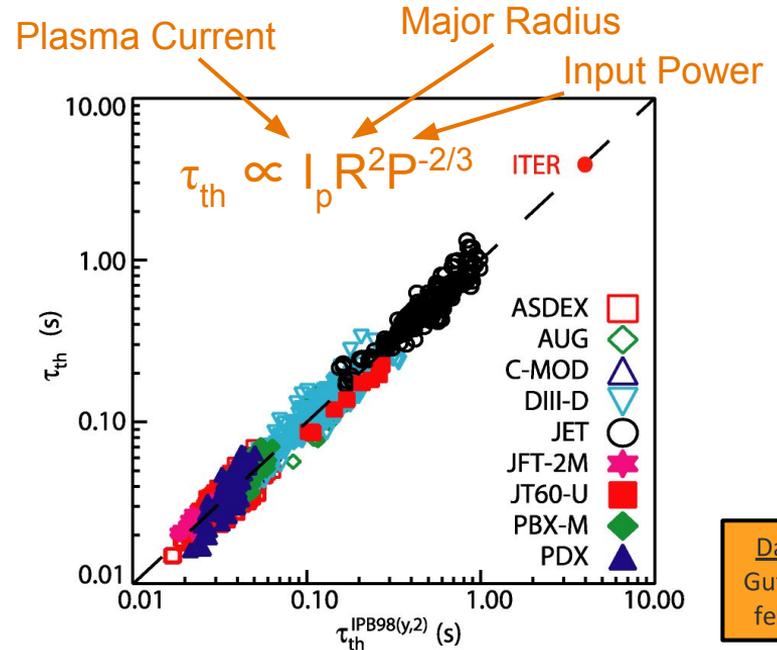
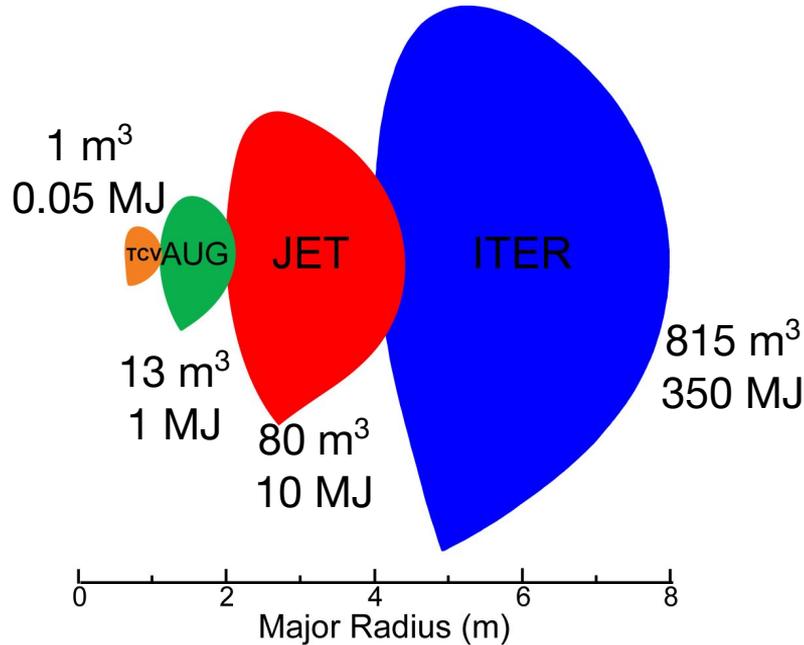
\Rightarrow ITER: $Q \geq 10$

**\Rightarrow 'Controlled ignition':
 $Q \geq 30$**



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

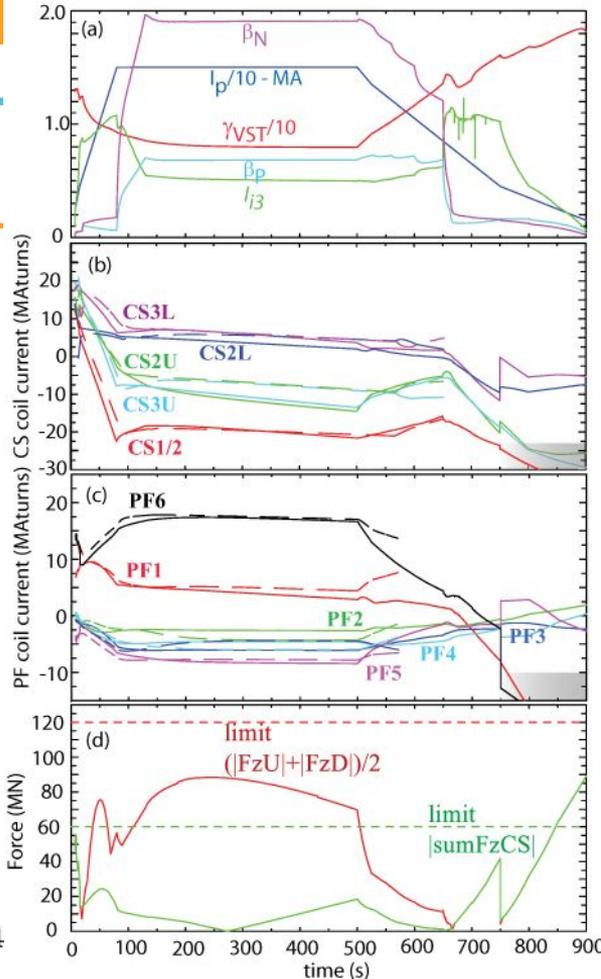
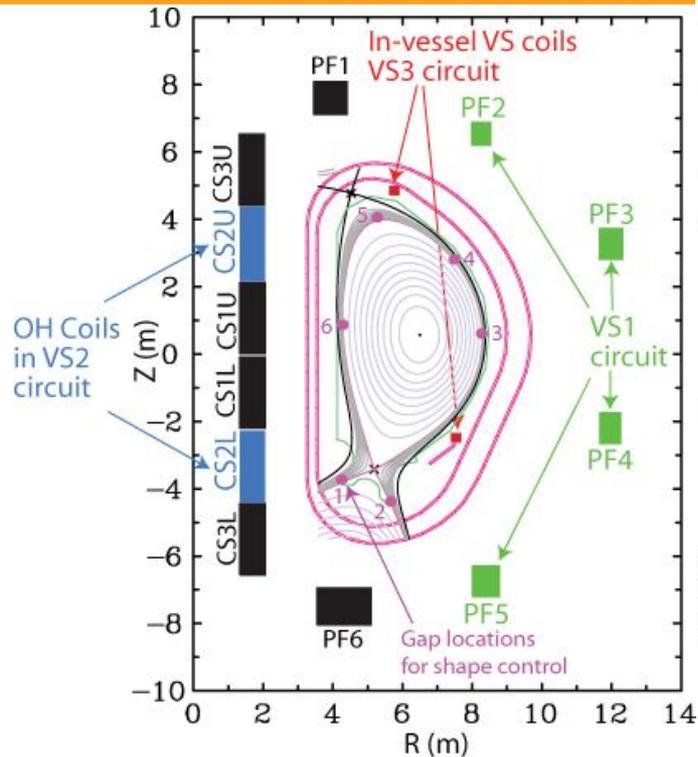
Parameter	Inductive Operation	Hybrid Operation	Non-inductive Operation
Plasma Current, I_p (MA)	15	13.8	9
Safety Factor, q_{95}	3.0	3.3	5.3
Confinement Time, τ_E (s)	3.4	2.7	3.1
Fusion Power, P_{fus} (MW)	500	400	360
Power Multiplication, Q	10	5.4	6
Burn time (s)	300 – 500	1000	3000

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

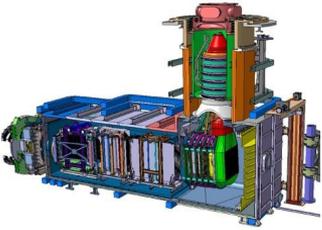
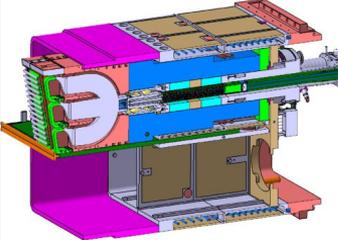
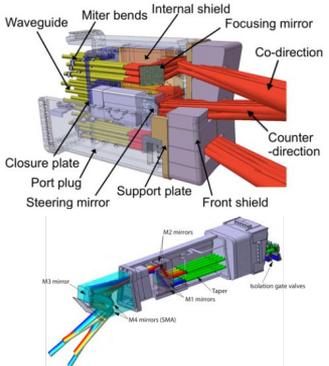
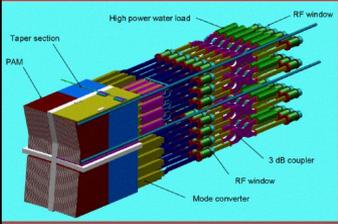


Simulation of a ITER plasma Discharge - Control will be Key to Achieve Mission

- 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



Heating and Current Drive Systems

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



* Baseline Power

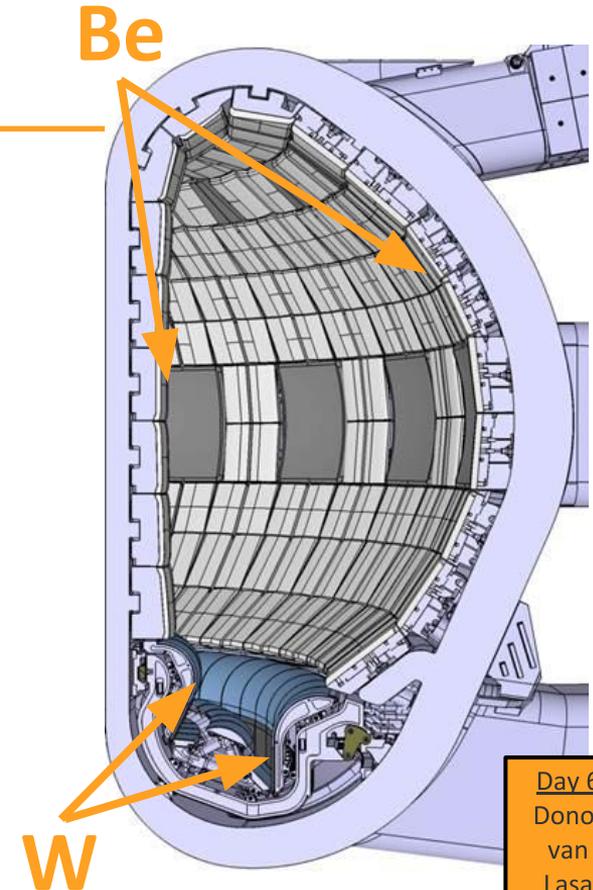
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Possible Upgrade

Day 5
Pinsker

All-Metal Plasma Facing Components

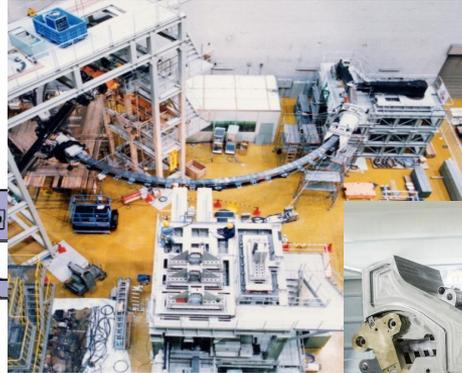
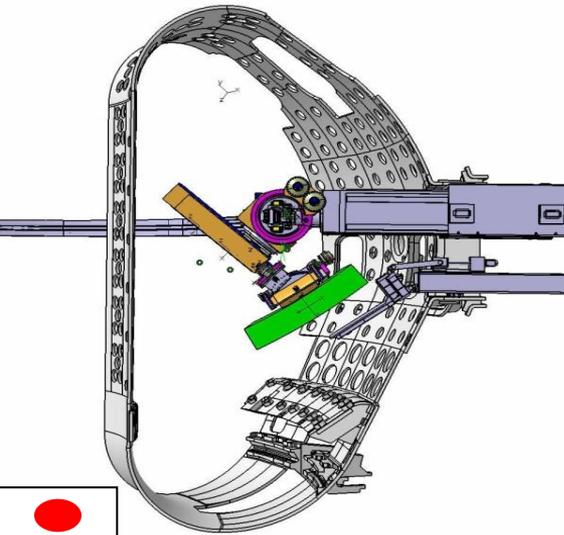
- **Beryllium (Be) first wall (~700m²):**
 - low-Z limits plasma impurity contamination
 - low neutron activation
 - low melting point – plasma transients!
 - erosion/ redeposition ⇒ fuel retention
 - dust production
- **Tungsten (W) divertor (~150m²):**
 - resistant to sputtering
 - limits fuel retention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



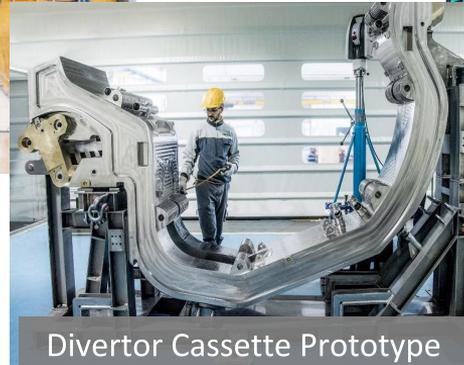
Remote Handling - Challenging to repair & replace complex & heavy components in a nuclear environment

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

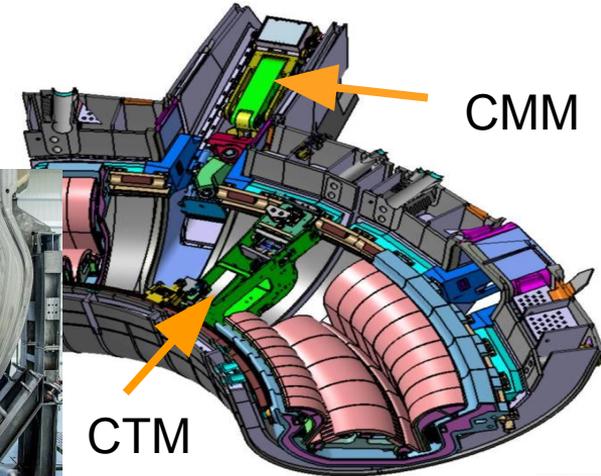
Blanket RH procured by JA



Divertor RH procured by EU

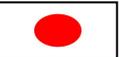


Divertor Cassette Prototype



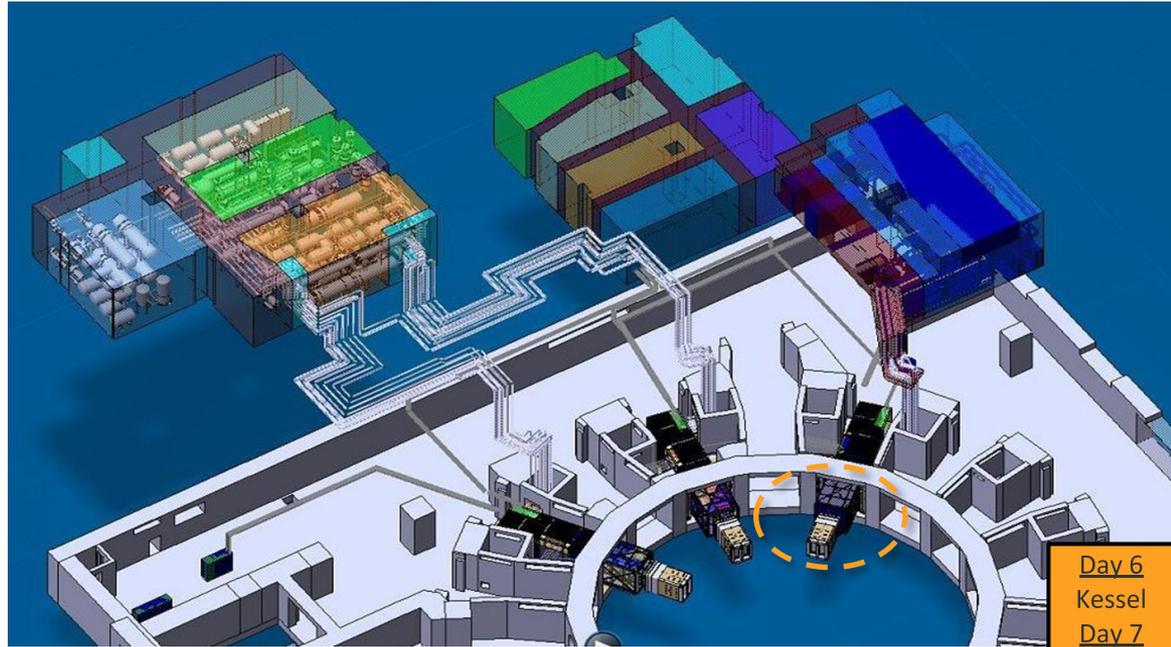
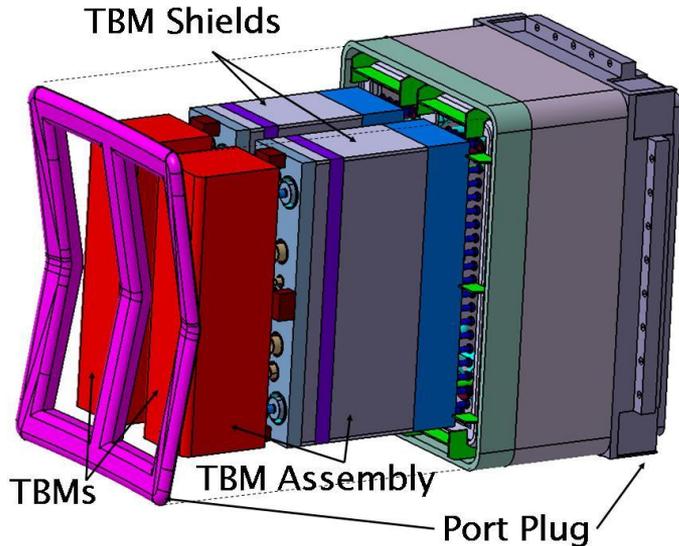
CMM

CTM



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

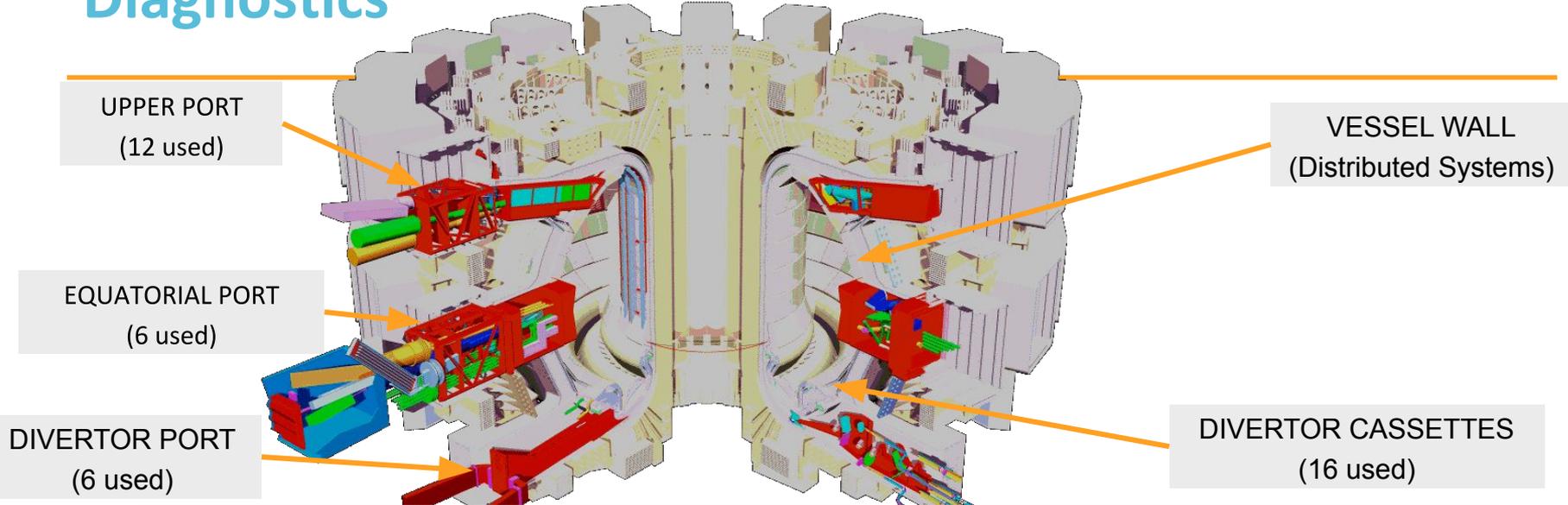
ITER will test concepts: 6 modules with different designs



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)



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

Jan 2009



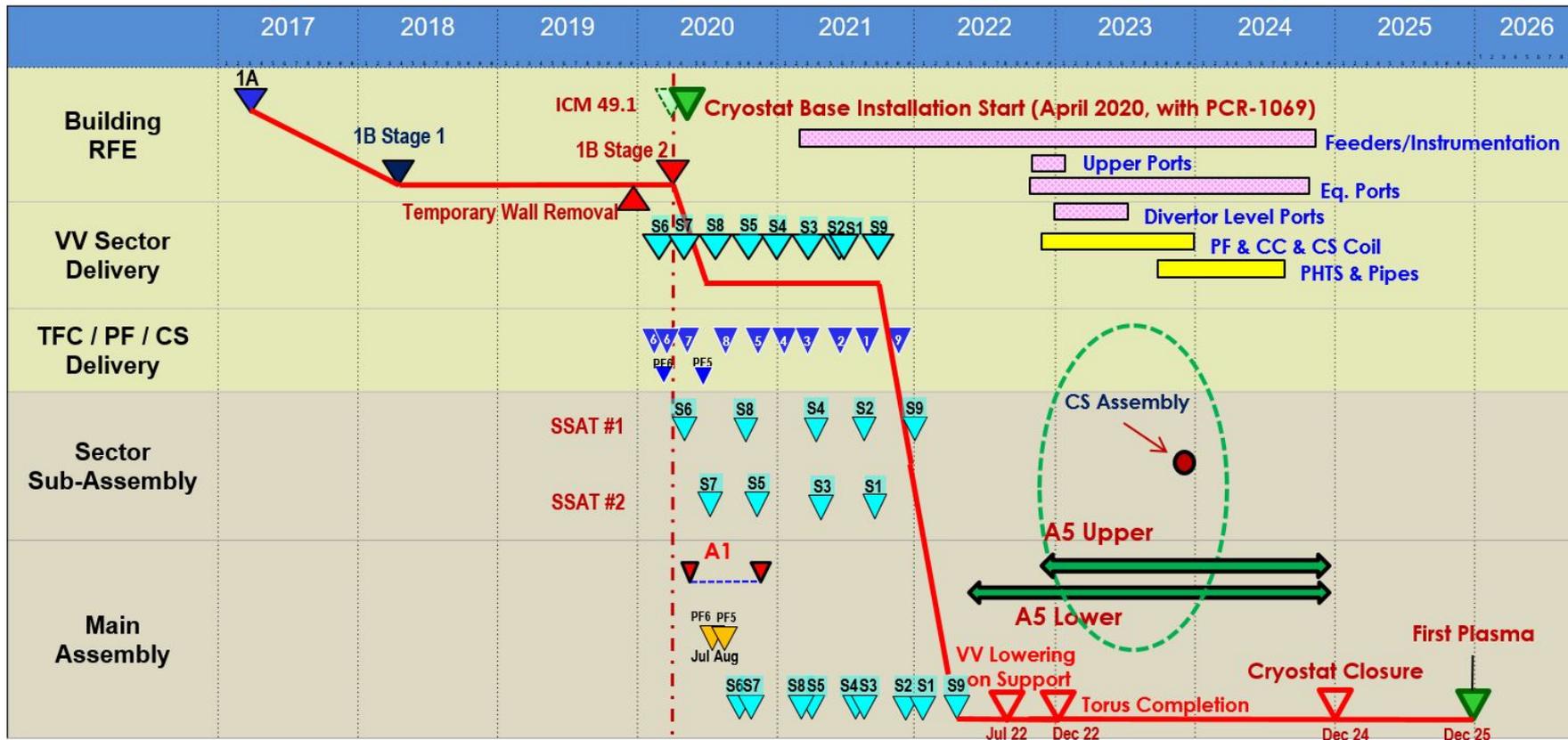
Significant onsite progress - ITER is HAPPENING

Optimism for the next 10 years

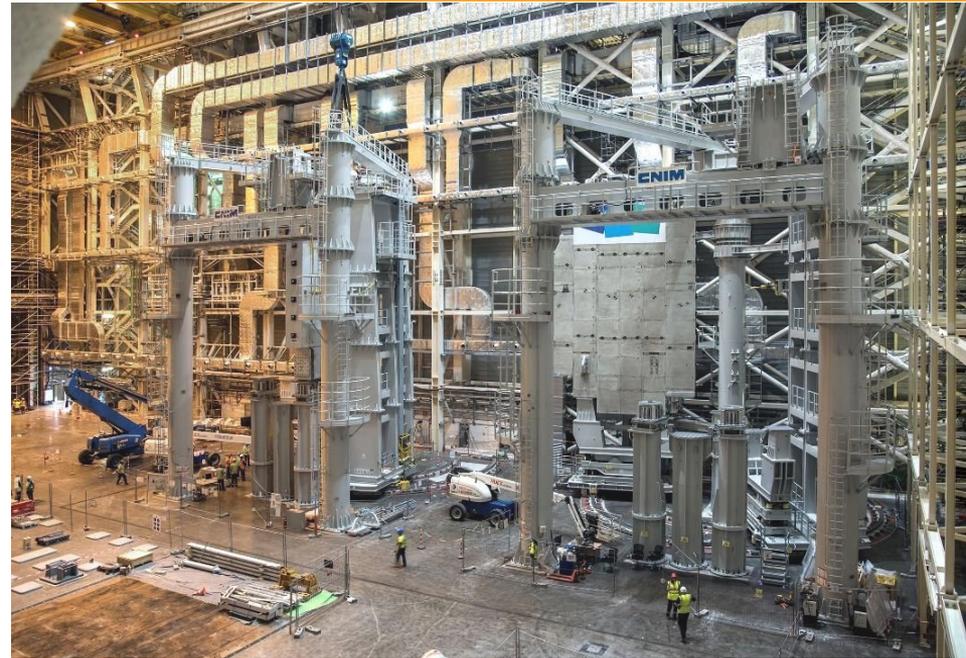
Mar 2020



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

Heat Rejection System

Cryostat Workshop

PF Coil Winding Facility

Cryoplant

400 kV Switchyard

Magnet Power Conversions Bldgs.

Bioshield

Tokamak Complex

Contractors area

ITER Headquarters

February 28, 2020

Worksite
progress

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



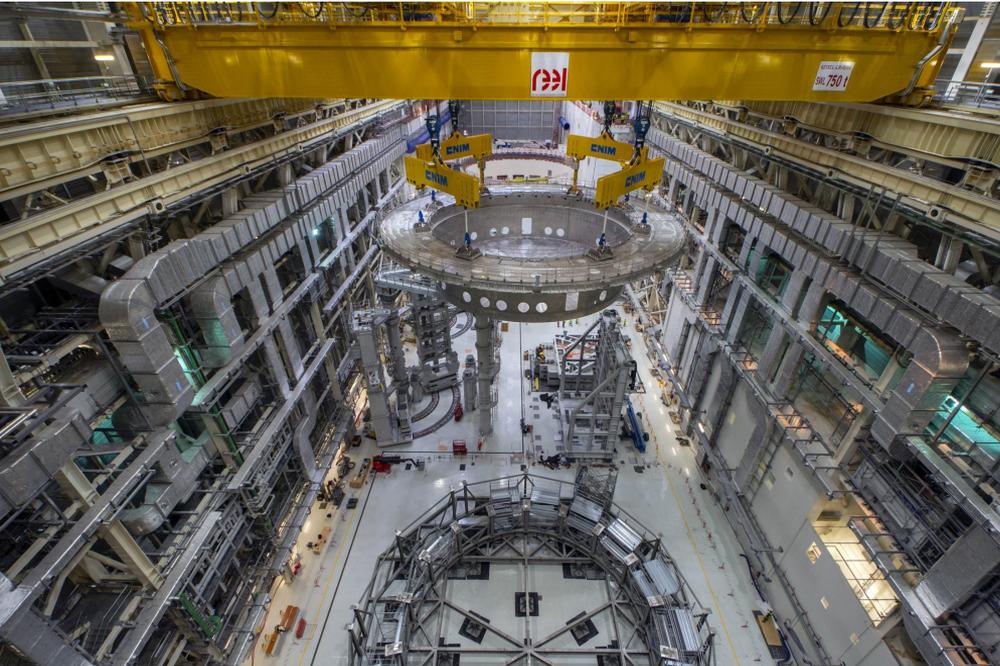
Cryostat Base moving into Assembly Hall, April 2020



Tokamak pit lid removal, April 2020



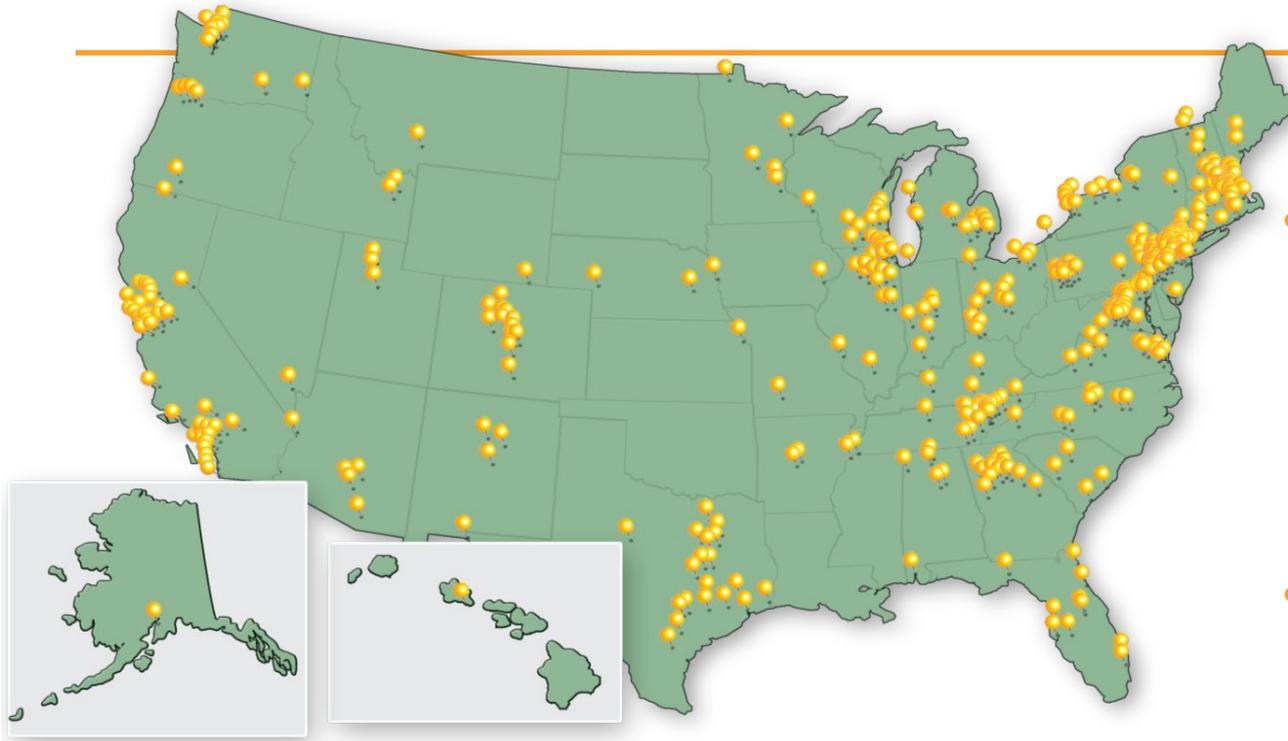
Buildings and manufacturing onsite - Recent milestone: Cryostat base plate installed (May-30)



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



The ITER Project in the U.S.



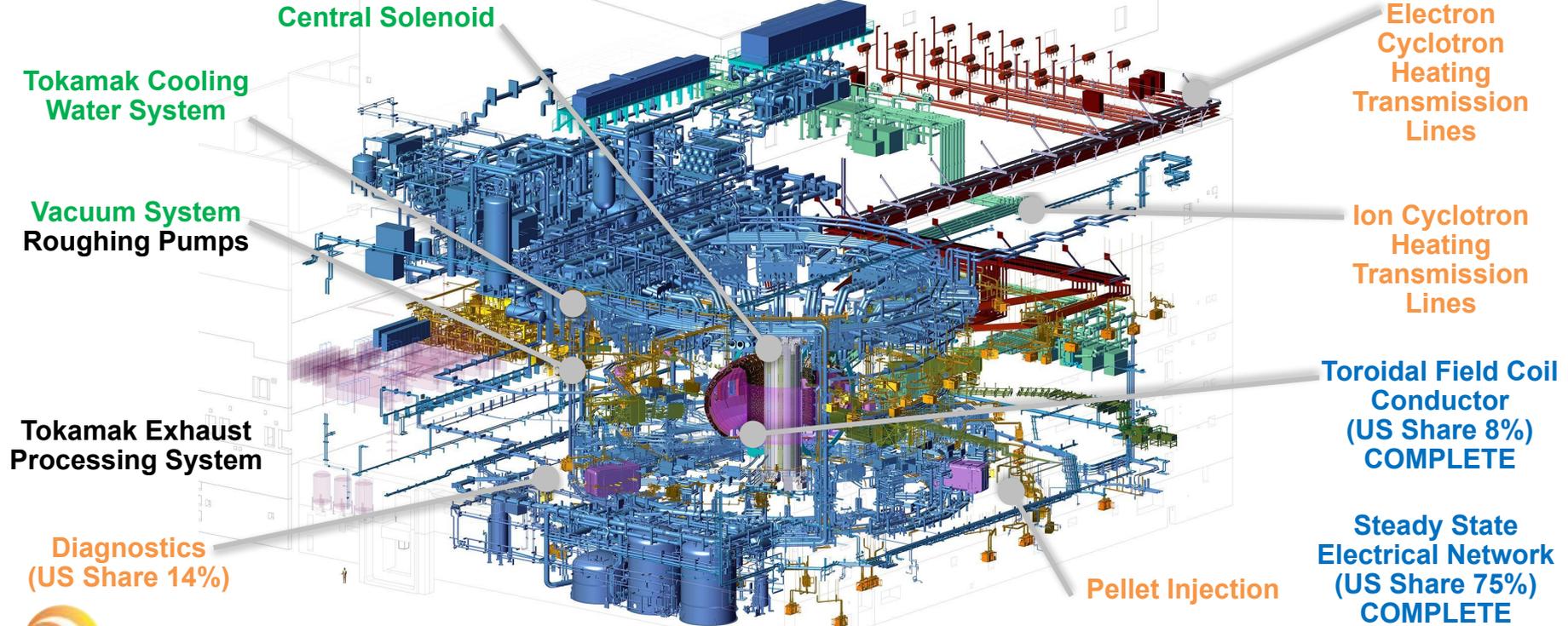
- Highly Leveraged:
 - U.S. pays 9%
 - U.S. gets 100% access to the science & technology
- Most U.S. ITER funding goes to U.S. companies:
 - >\$1 billion since 2007



US ITER hardware scope



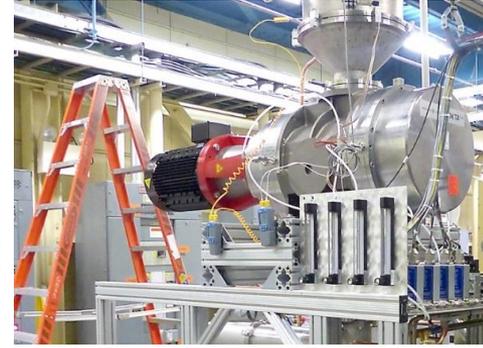
Key: **Finished** • **Hardware in fabrication** • **Prototypes in fabrication** • **In design**



US ITER manufacturing examples



36 km of
nuclear
piping



Roots
pump
testing

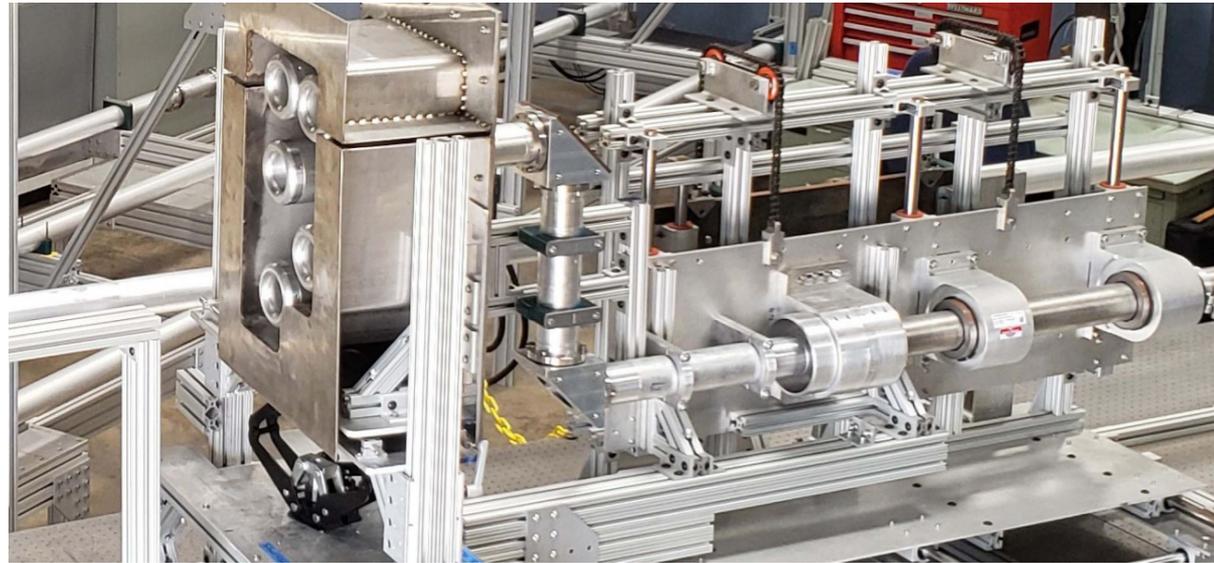


5 of 7 CS
modules are
in fabrication



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



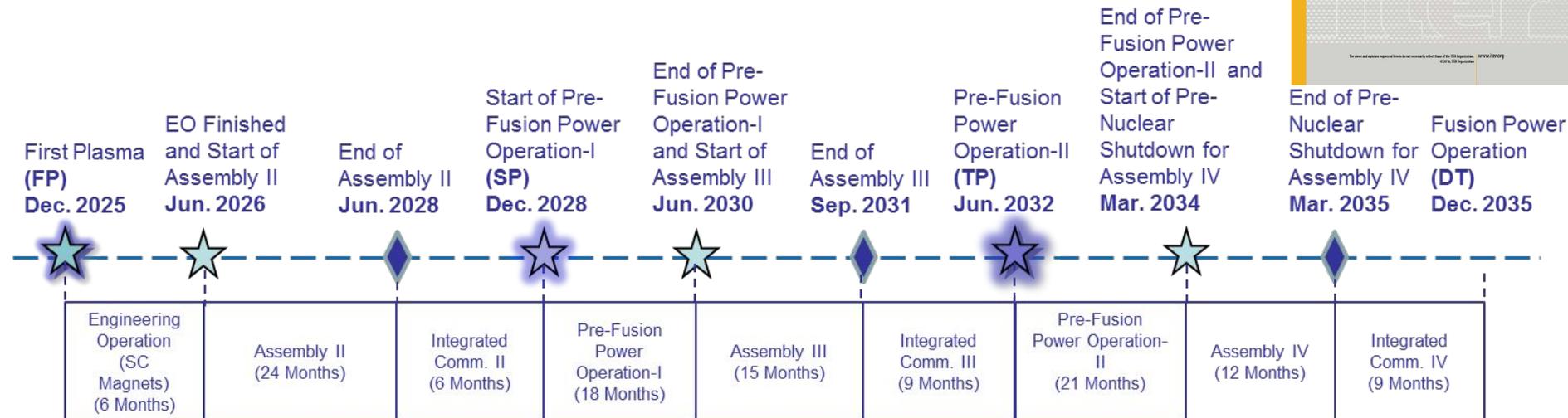
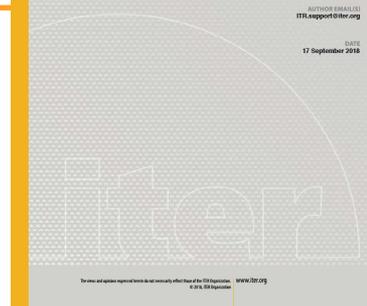
Low field side reflectometer test stand with antennae (left) and waveguides (right)

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.

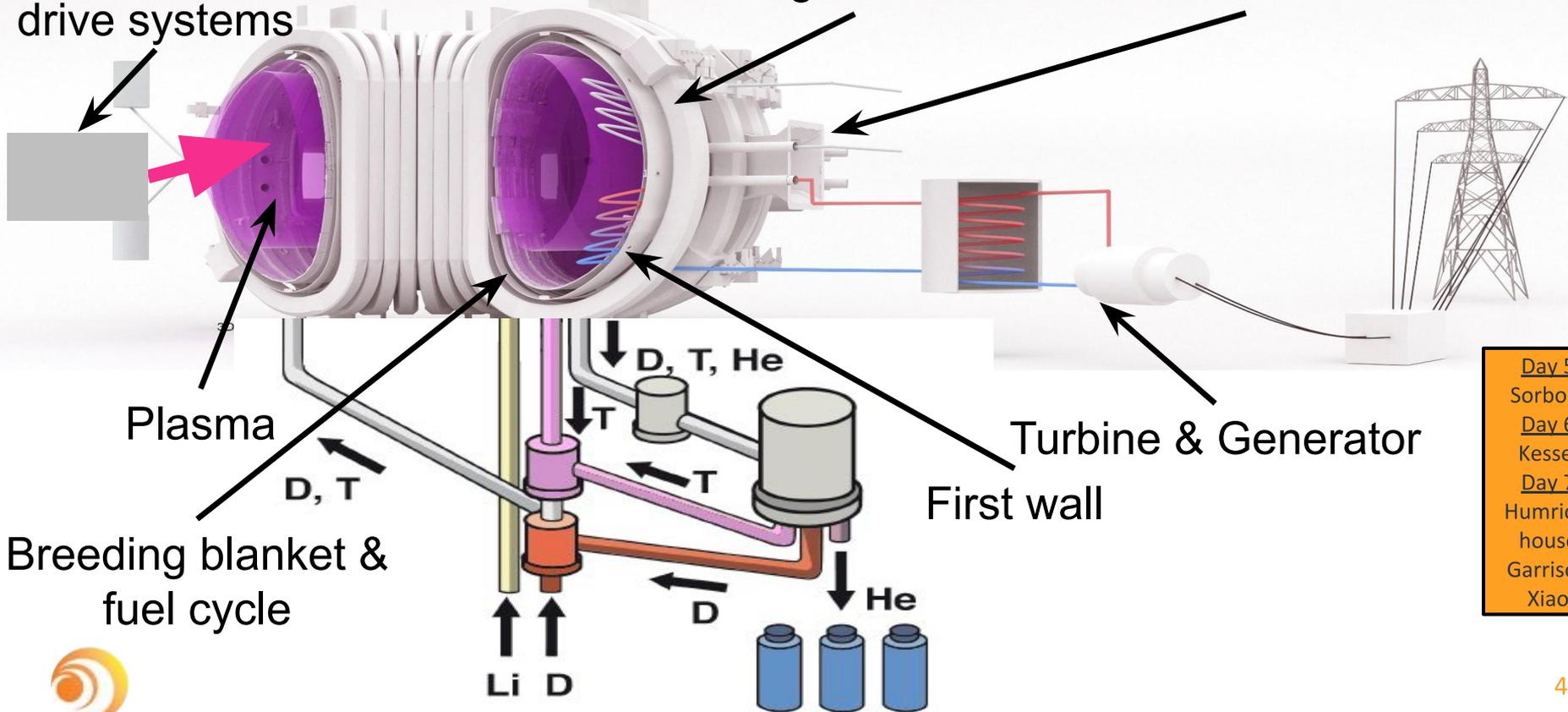


Towards a fusion power plant...

Heating & current drive systems

Magnet coils

Structural Materials



- [Day 5](#)
- [Sorbom](#)
- [Day 6](#)
- [Kessel](#)
- [Day 7](#)
- [Humrick-house](#)
- [Garrison](#)
- [Xiao](#)

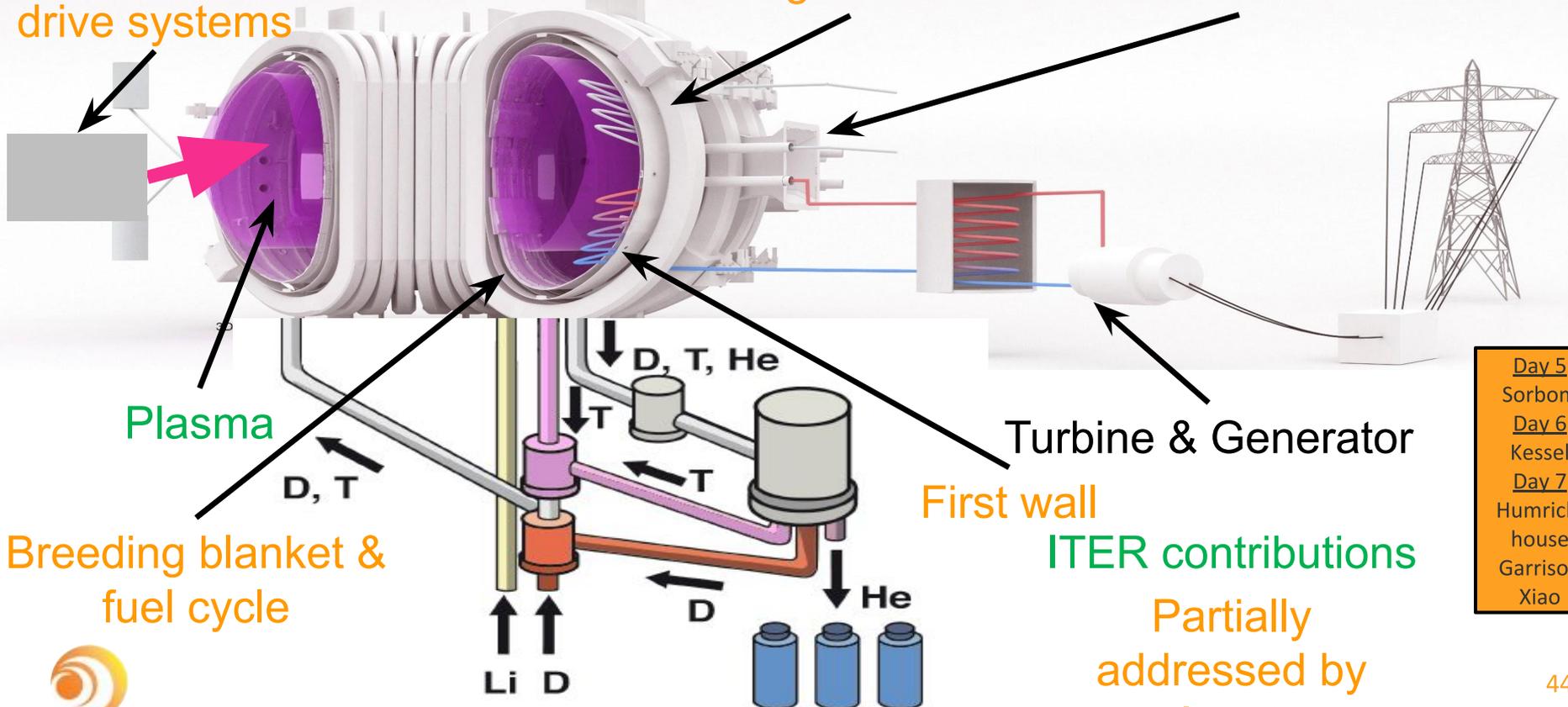


Towards a fusion power plant...

Heating & current drive systems

Magnet coils

Structural Materials



Plasma

Breeding blanket & fuel cycle

Turbine & Generator

First wall

ITER contributions

Partially addressed by ITER

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



ITER International school (2020 Marseille)

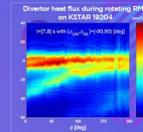
- Since 2007
- On selected topics of ITER research
 - 2020 on 'Energetic Particles'
- Targets graduate students and postdocs
- Support Scholarships through USBPO

10th ITER International School 2019

The physics and technology of power flux handling in tokamaks

21st (MON)-25th (FRI) January 2019

Korea Advanced Institute of Science and Technology (KAIST), Daejeon, South Korea
www.itschool2019.kr



	MONDAY 21-1-2019	TUESDAY 22-1-2019	WEDNESDAY 23-1-2019	THURSDAY 24-1-2019	FRIDAY 25-1-2019
Topic	Introduction	Physics of stationary power dissipation	Physics of transient power fluxes in H-mode plasmas scenarios (L-H/HL/ELMs)	Plasma Facing Component Technology	Plasma Facing Component Technology
9:00-9:30	Welcome and Introduction to KAIST W. Choe	Power Exhaust in ITER - I R. Pitts	ELM suppression by 3-D fields Y. In	ITER Plasma Facing Components M. Marola	Plasma facing components beyond ITER - solid materials F. Maviglia
9:30-10:20	Introduction to ITER A. Loarte	Coffee Break	Coffee Break	Coffee Break	Coffee Break
10:20-10:40	Coffee Break	Coffee Break	Coffee Break	Coffee Break	Coffee Break
10:40-11:20	Introduction to KSTAR S.W. Yoon	Power Exhaust in ITER - II R. Pitts	Active control of ELMs and small-ELM/E-Mless regimes M. Farnstamacher	Shape design of plasma facing components for stationary and transient power fluxes J. Gunn	Plasma facing components beyond ITER - liquid materials D. Andruzyk
11:20-12:00	Korean contributions to ITER H.G. Lee	Lunch Break	Lunch Break	Lunch Break	Lunch Break
12:00-12:30	Overview of the K-COASD programme Y.S. Hwang	Lunch Break	Lunch Break	Lunch Break	Lunch Break
12:30-13:30	Coffee Break	Coffee Break	Coffee Break	Coffee Break	Best Poster Prize
13:30-15:00	Basic Boundary Physics D. Reiter	Physics of divertor power exhaust beyond ITER controlled divertors and high core radiation regimes H. Zohm	Power Fluxes in suppressed/controlled ELM H-mode plasma scenarios O. Schmitz	Technology and Manufacturing of Plasma Facing Components K. Ezato	Closing Session
15:00-15:20	Coffee Break	Coffee Break	Coffee Break	Coffee Break	Coffee Break
15:20-16:50	Introduction to H-mode plasmas: LH transition, pedestal, ELMs and stationary and transient power fluxes R. Mengi	Poster Session - I	Discussion	Discussion	Poster Session - II
16:50-18:00	Discussions	Discussions	Discussions	Discussions	Discussions
		18:30	Banquet		

NOTE: The registration will be available at the beginning of December 2018 in our website.
(www.itschool2019.kr)

11TH
ITER INTERNATIONAL SCHOOL
16-20/11/2020 MARSEILLE, FRANCE



THE IMPACT AND CONSEQUENCES
OF ENERGETIC PARTICLES
IN FUSION PLASMAS



Nonlinear simulation of Toroidal Alfvén Eigenmode (TAE) evolution performed with MEGA code (courtesy Y. Totsu)

CNRS THEMATIC SCHOOL

5 DAYS OF HIGH LEVEL COURSES

WORLD CLASS SCIENTISTS

HALF-DAY VIP VISIT OF ITER

PUBLICATION OF LECTURES AND POSTERS

IN JOURNAL OF PLASMA PHYSICS

TOPICS AND LECTURERS

Introduction to energetic particle physics William Heidbrink	Experimental observations of energetic particle transport and losses Eric D. Fredrickson
Sources of energetic particles: theory and experiment Lars-Göran Eriksson	Diagnosing the losses of energetic particles and causes Manuel Garcia-Moniz
Modelling of energetic particle sources Jon Wright	Energetic particle instabilities: nonlinear effects and consequences Thomas Ernst
Diagnostics associated with redistribution of confined energetic particles and the causes Michael Van Zeeland	Control of energetic particle instabilities Boris Dumort
Energetic particle instabilities: linear physics near threshold Sergei Sharapov	Modelling of transport and losses of energetic particles due to low-frequency modes and 3D fields Arnt Snicker
Gyrokinetic and hybrid modelling of energetic particle transport Yoshiki Totsu	Physics and observations of runaway electrons Robert Granetz
Reduced models of energetic particle transport for scenario modelling Marco Pascazio	Modelling of runaway electrons Thomas Filipp

For further informations and registration

its2020.sciencesconf.org



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<https://www.usiter.org>

<https://www.burningplasma.org>



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[@ITERorganization](https://www.facebook.com/ITERorganization)



[ITER Organization](https://www.linkedin.com/company/ITER-Organization)



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Who manufactures what?

