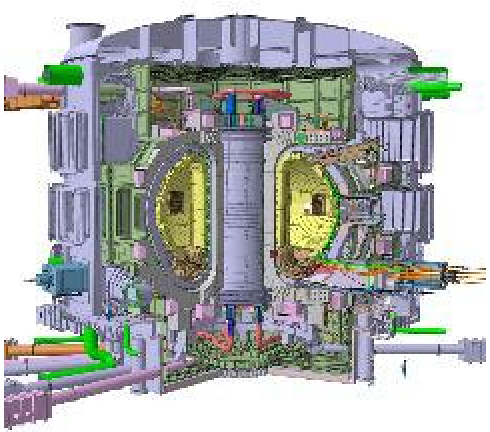
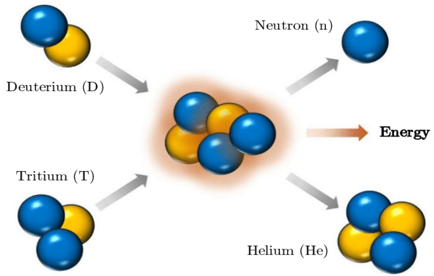
Plasma Technology and ITER Project

Amro Bader





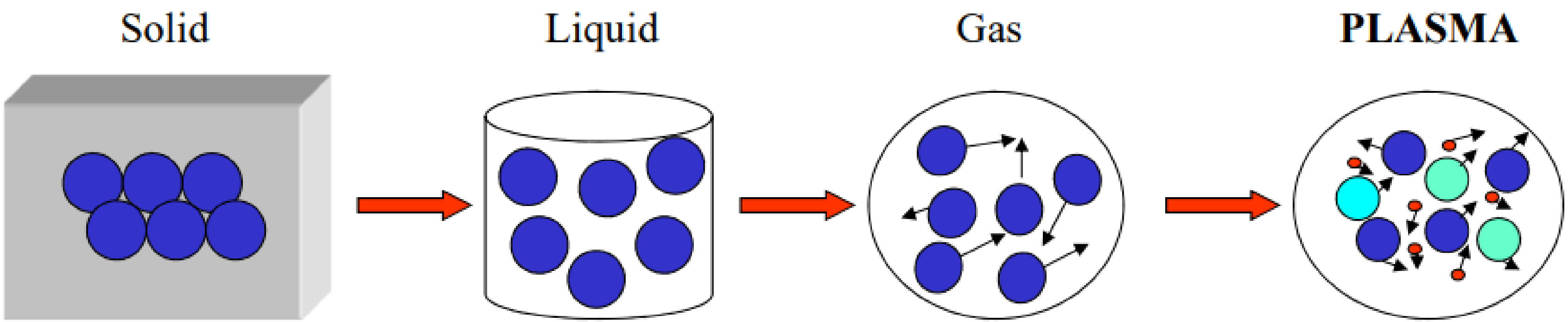
(Views and opinions expressed here do not necessarily represent those of ITER Organization).

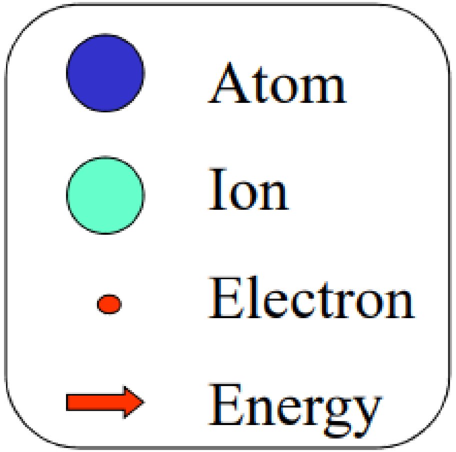
Disclaimer: some slides/pictures in this presentations have been copied or quoted from presentations made by the following scientists, for the PPPL summer school 2020 version:

Dr. Florian Laggner; Dr. Tammy Ma; Prof. Jose Lopez

Prologue: Plasma Technology

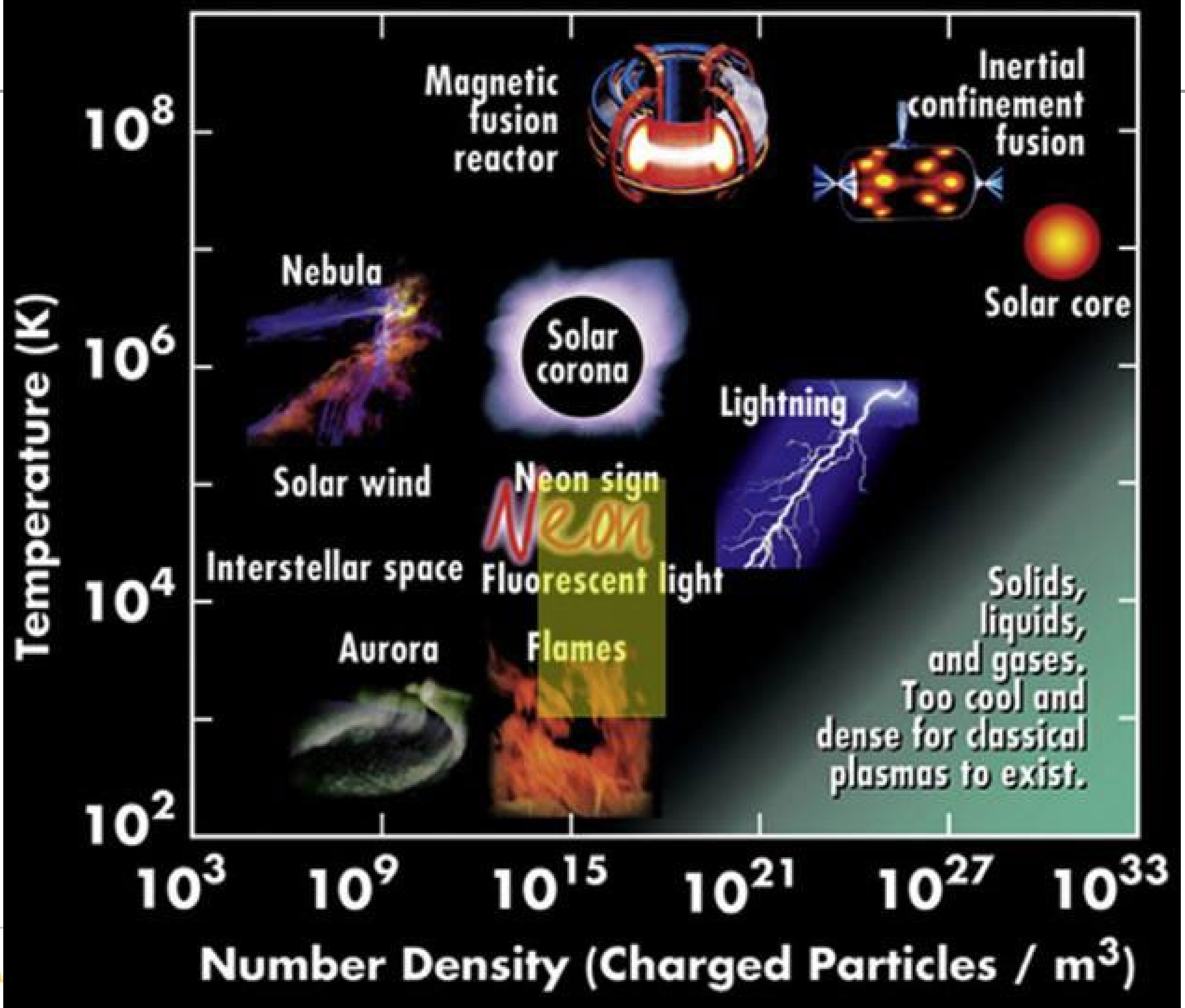
The *Plasma* state is 'The Fourth State of Matter' (99%)





A *Plasma* is a collection of neutrals, ions, and electrons characterized by a *collective behavior*.

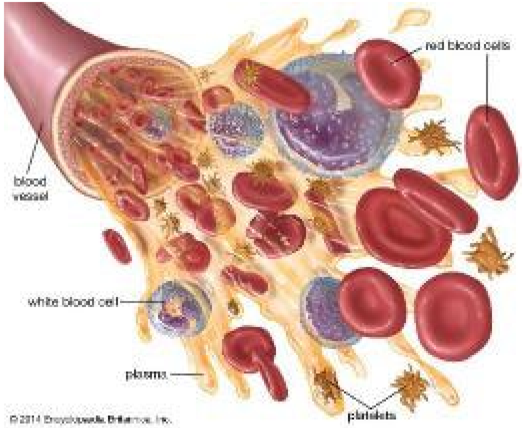
S. Eliezer and Y. Eliezer. *The Fourth State of Matter: An Introduction to Plasma Science*. Bristol, UK: IOP Publishing (2001)

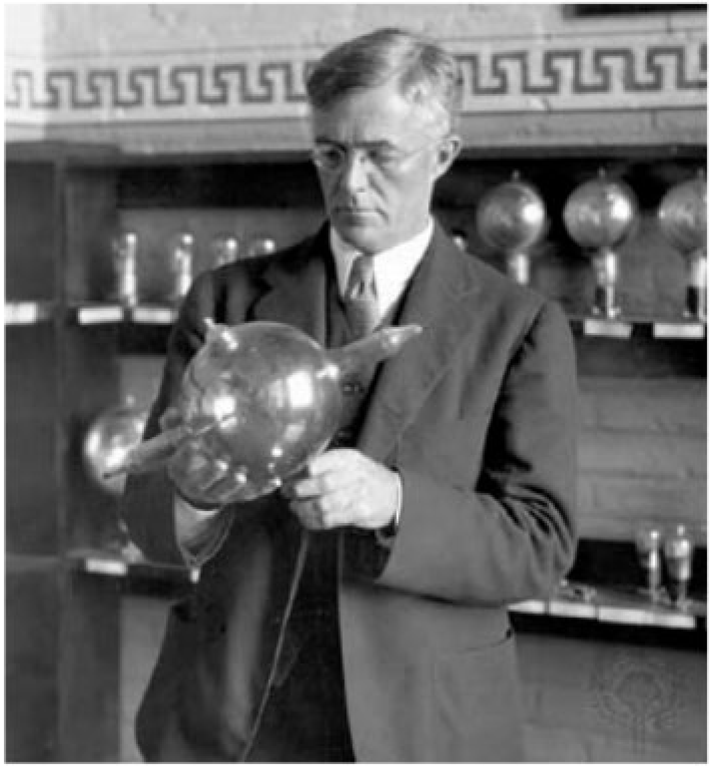


Magnetic fusion reactor
Inertial confinement fusion
Solar core
Nebula
Solar corona
Lightning
Solar wind
Neon sign
Neon
Interstellar space
Fluorescent light
Aurora
Flames
Solids, liquids, and gases. Too cool and dense for classical plasmas to exist.
Temperature (K)
10^8
10^6
10^4
10^2
10^3
10^9
10^{15}
10^{21}
10^{27}
10^{33}
Number Density (Charged Particles / m^3)

Plasma

Irving Langmuir was one of the first scientists to work on plasmas and the first to refer to this 4th state of matter as ***plasmas***, because their similarity to blood plasma





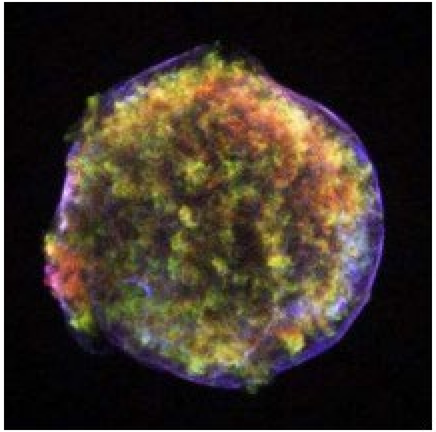
Irving Langmuir

The Sun

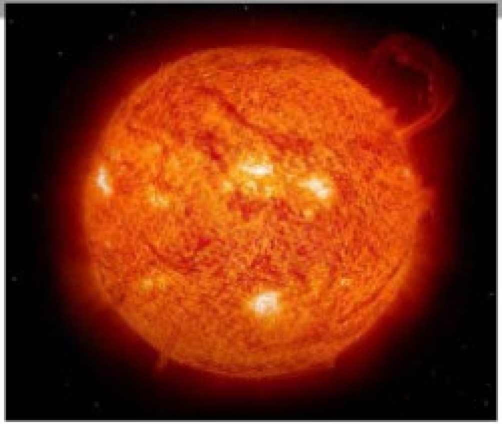
Aurora

Lightning

The Comet



Supernova



Sun

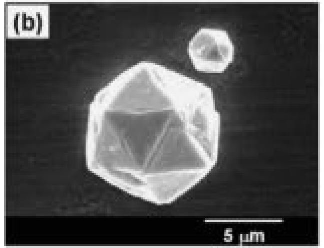
Aurora Borealis (Northern Lights)

Lightning

Fluorescent Lamps

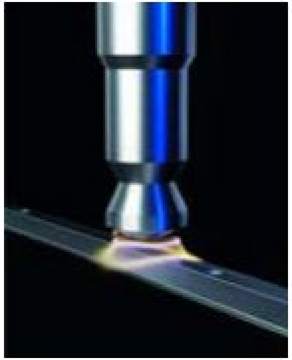
Plasma Display Televisions

Material Synthesis



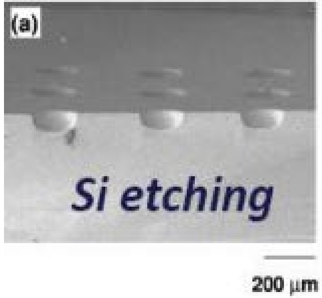
Plasma display

Surface Treatment



Lighting

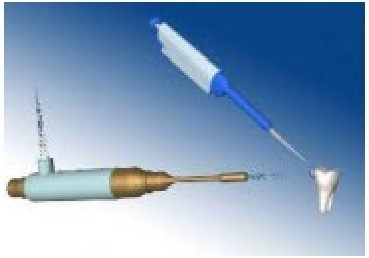
Material processing



Ozone generation for water cleaning

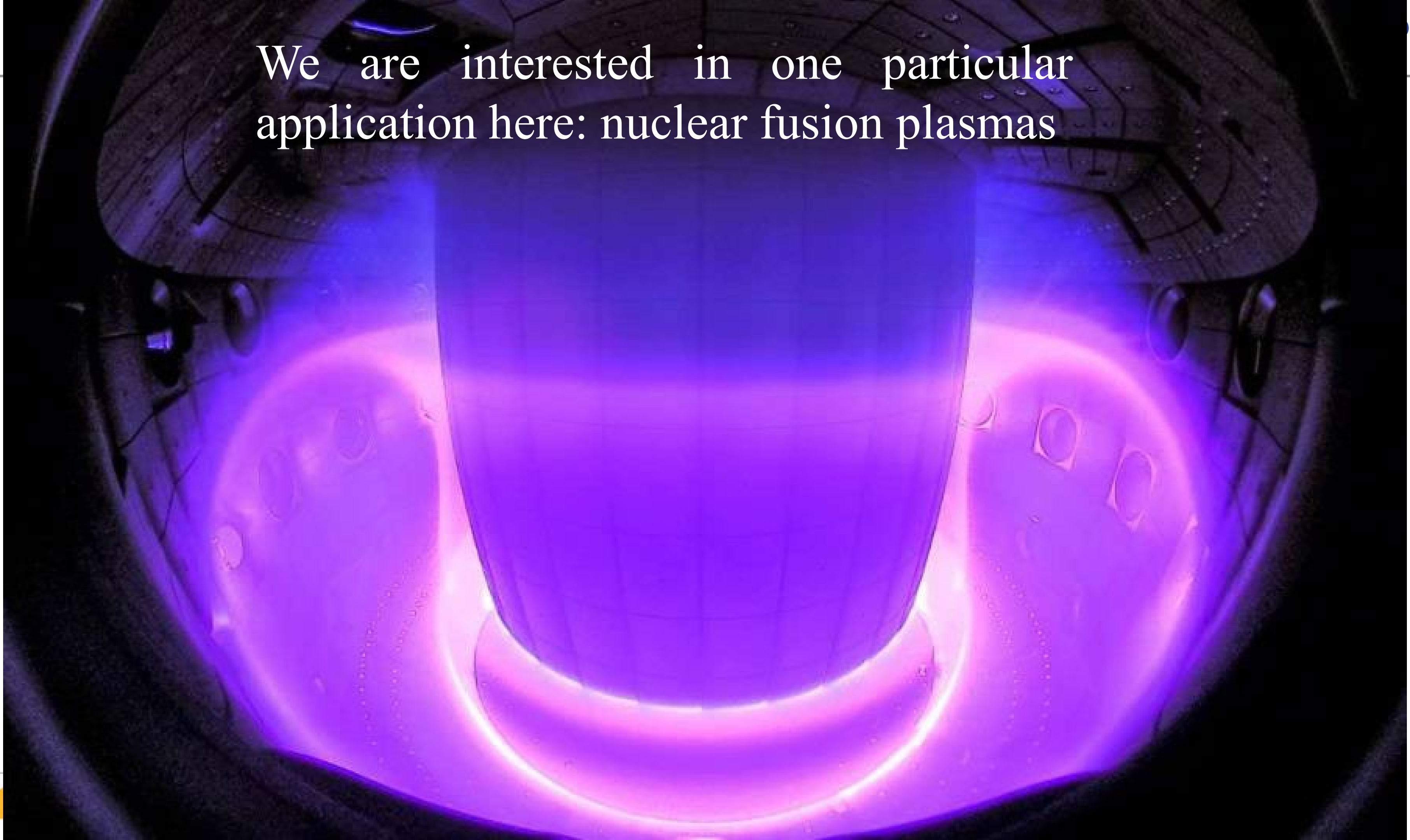
Bio-application

Dental application



and Many more…

We are interested in one particular application here: nuclear fusion plasmas

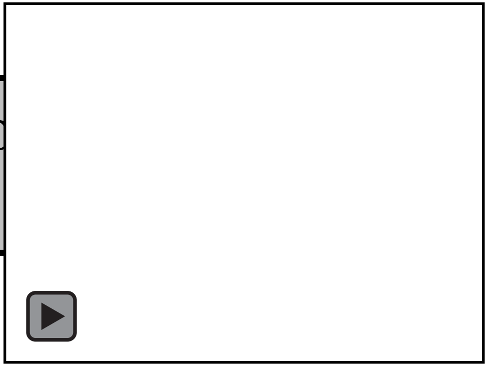


1. Energy Landscape

Why should we care about Nuclear Fusion?

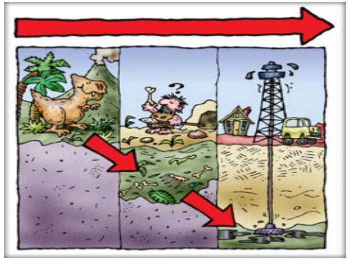
Pollution

More than **80%** of our glo
comes from fossil fuels



Supply shortage

200,000,000 years



100 years?

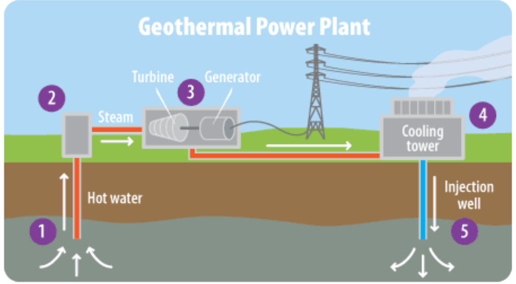
Why should we care about Nuclear Fusion?

- What are the alternative energy sources
  - Wind power
    - ☺ Cheap, proven
    - ☹ Weather dependent

  - Solar power (voltaic and thermal)
    - ☺ Modular, proven
    - ☹ Weather dependent

Why should we care about Nuclear Fusion?

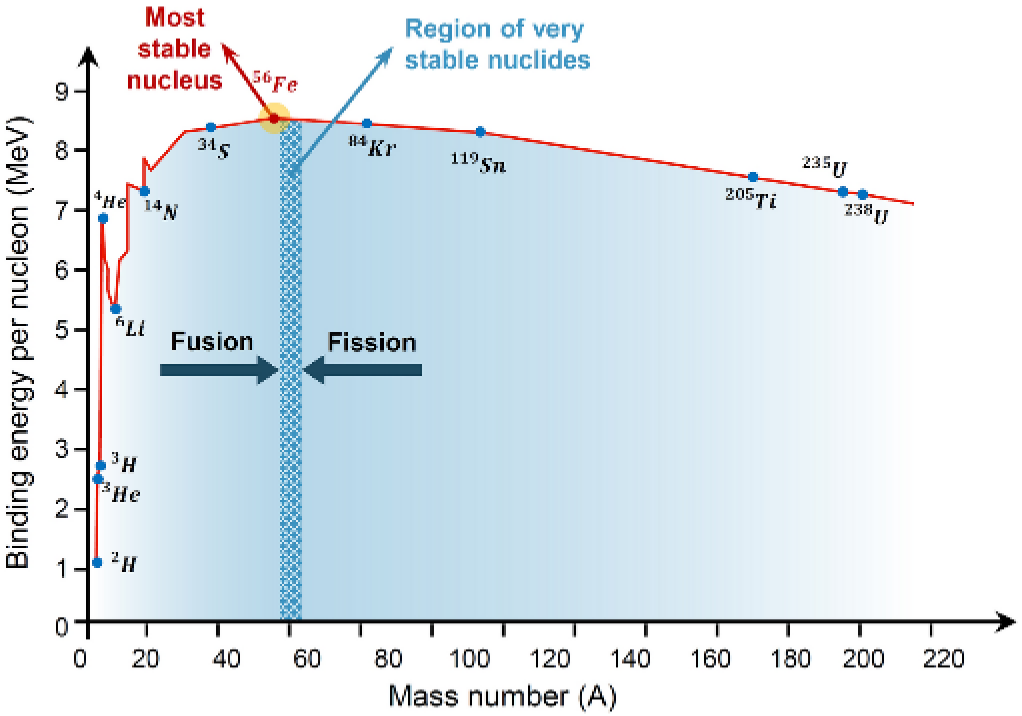
- What are the alternative energy sources
  - Geothermal power
    - ☺ Cheap, proven
    - ☹ Geography dependent
  - Hydro-electric power
    - ☺ Proven
    - ☹ Geography dependent
  - Nuclear Fission
    - ☺ Proven
    - ☹ Safety concerns

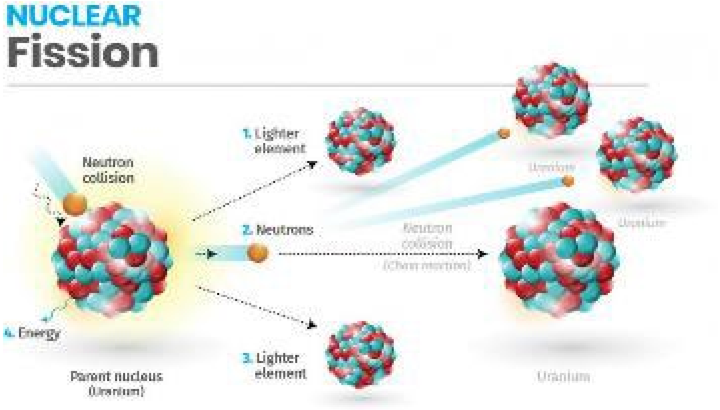


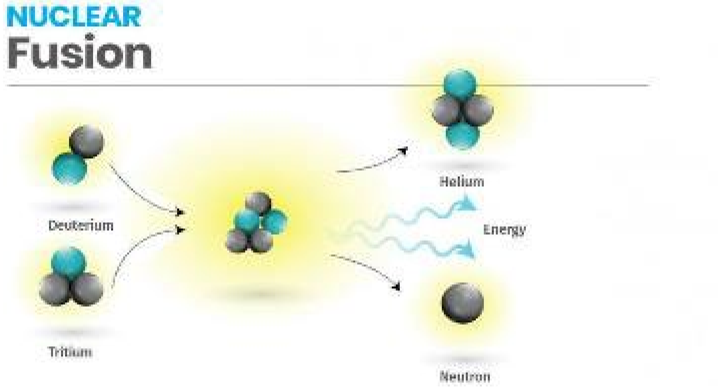
➡ All have merits and challenges …

2. What is Fusion?

What is Fusion





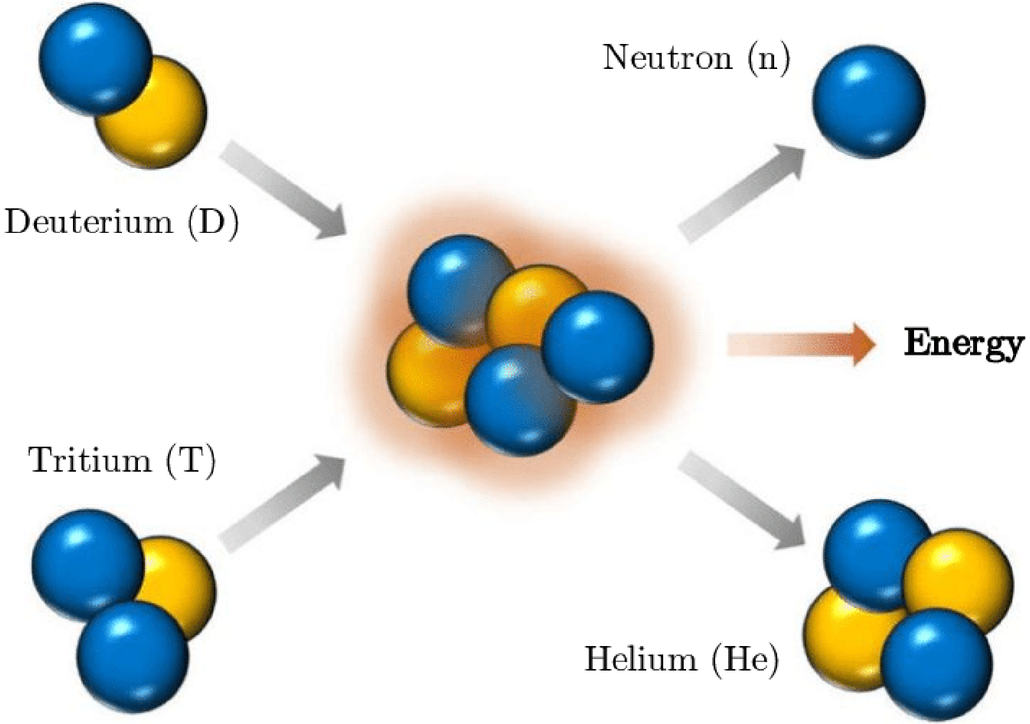


What is Fusion?

A **nuclear reaction** between **Hydrogen isotopes**, releasing tremendous energy

Low temperatures:

High temperatures:



Take aways

- Fission is the process of breaking large nuclei into smaller ones, fusion is the opposite

- Fusion produces 4 times more energy per reaction as fission

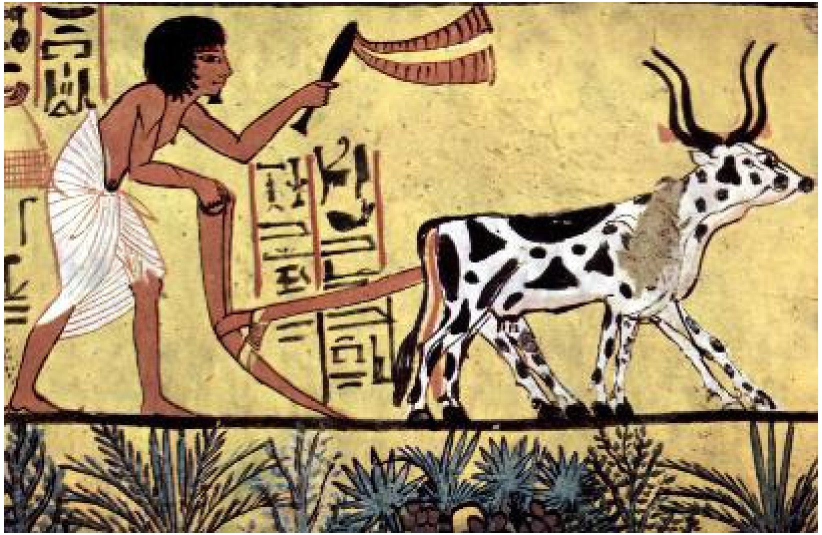
- There are many fusion fuel candidates, with Deuterium-Tritium being the most commonly assumed in fusion energy applications

3. Fusion energy: why bother?

1. Virtually unlimited fuel resources

Deuterium and Tritium are available to meet the world's demand are enough for:

A few hundred-thousands to millions of years

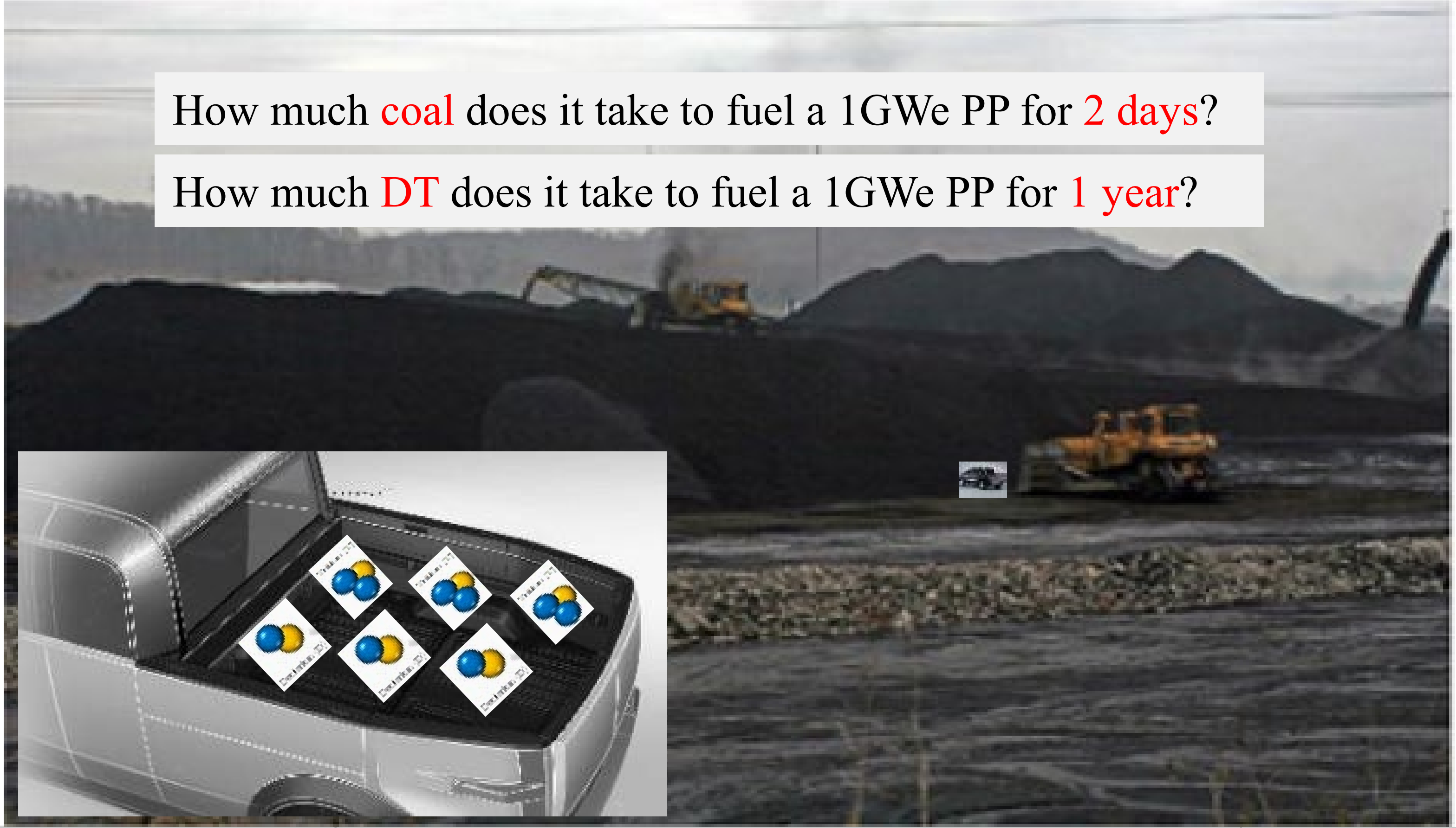


Earliest human civilizations date to as far as **10 thousand years** ago

2. Most energy-dense fuel

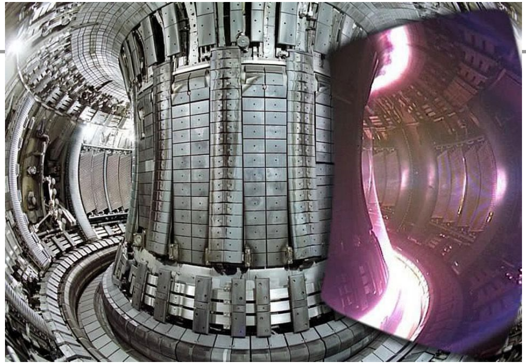
How much coal does it take to fuel a 1GWe PP for 2 days?

How much DT does it take to fuel a 1GWe PP for 1 year?



3. Environment and Safety

- No greenhouse gases emitted
- Inherently safe (unlike nuclear fission)

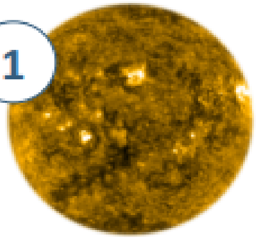


- Virtually unlimited fuel
- Stable baseload source
- Geography independent
- Highest energy density
- No green-house gases
- Inherently safe

4. Fusion energy: how?

Fusion: how?

There are at least three ways to achieve nuclear fusion

1 

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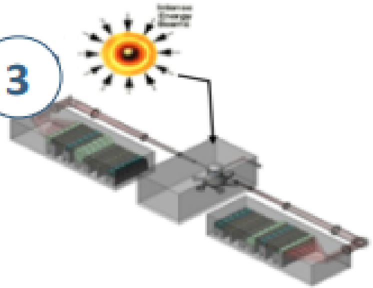
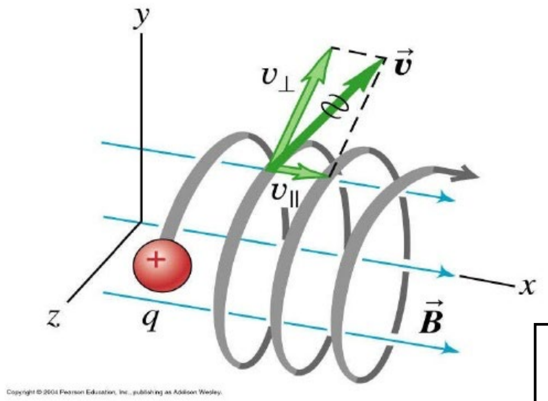
3 

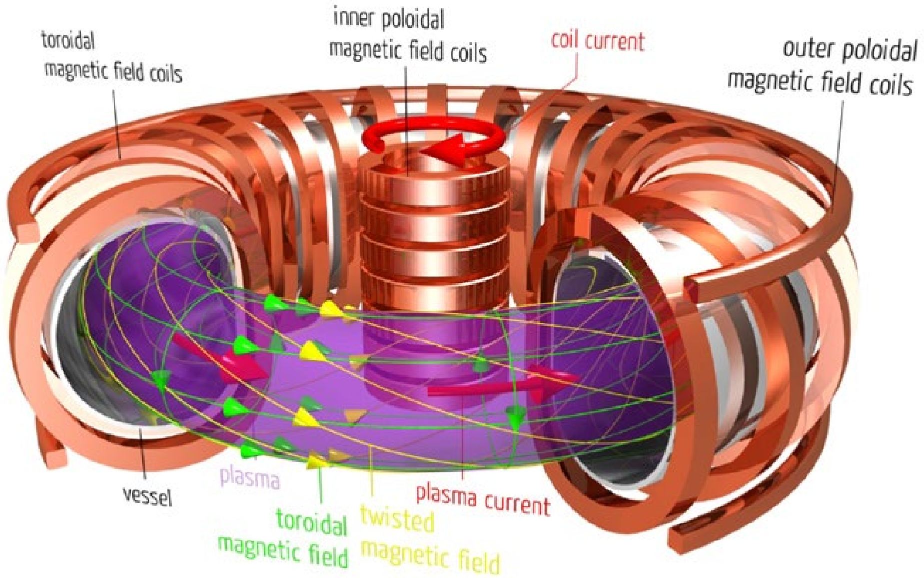
	Gravitational Confinement	Magnetic Confinement	Inertial Confinement
Density	10^4 x solid	solid / 10^8	10^3 x solid
Temperature	1 keV	10 keV	10 keV
Confinement time	10^5 years	seconds	10^{-10} seconds

Fusion: how?

Magnetic confinement: apply magnetic fields to trap the ultra-hot plasma at 200 million degrees

Motion of charged particles in a magnetic field





4. Initiatives to realize Fusion energy

4.1 ITER Project

ITER: “the way” for a new energy source

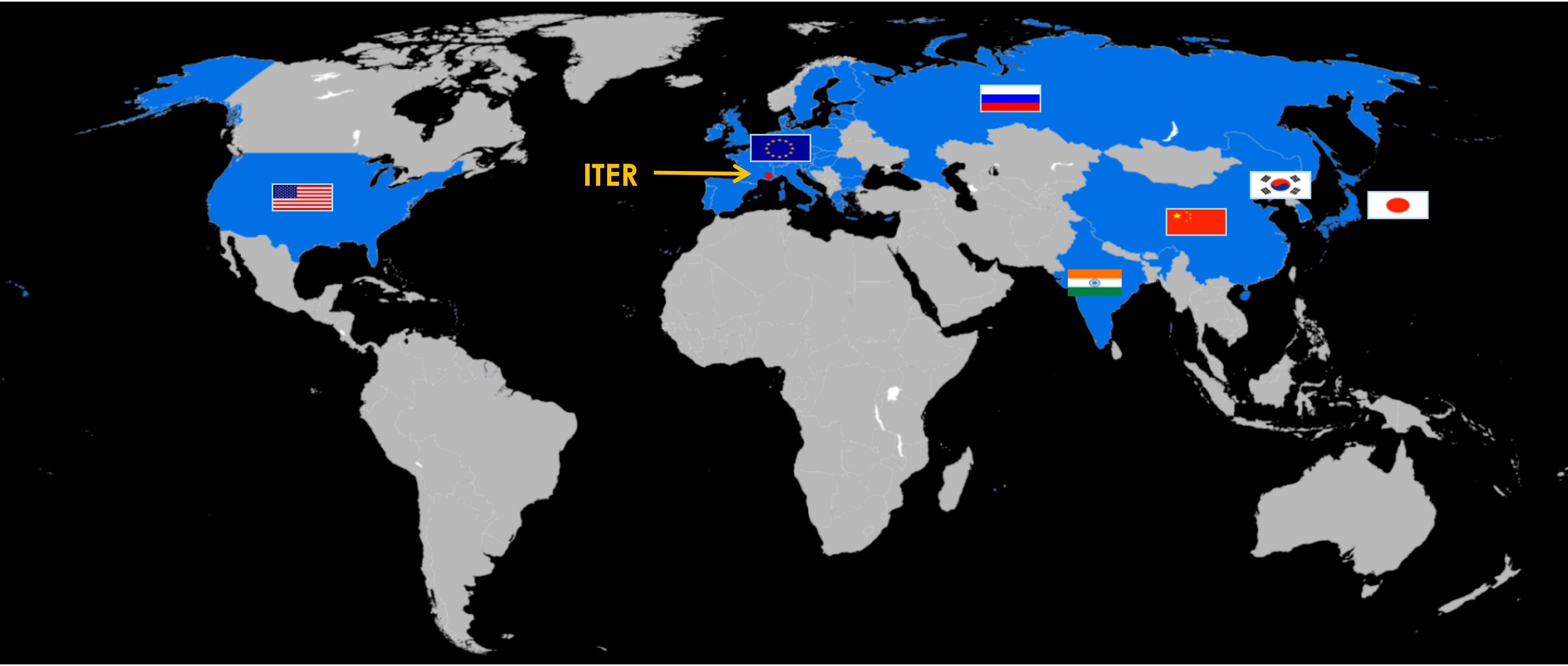
International Fusion energy mega-project of 35 countries

Proving the feasibility of fusion energy generation

Costs around **25 Billion USD**

Who is with ITER?

- The world's most industrialized nations



Who is with ITER?

An integrated project - Intellectual Property shared by all

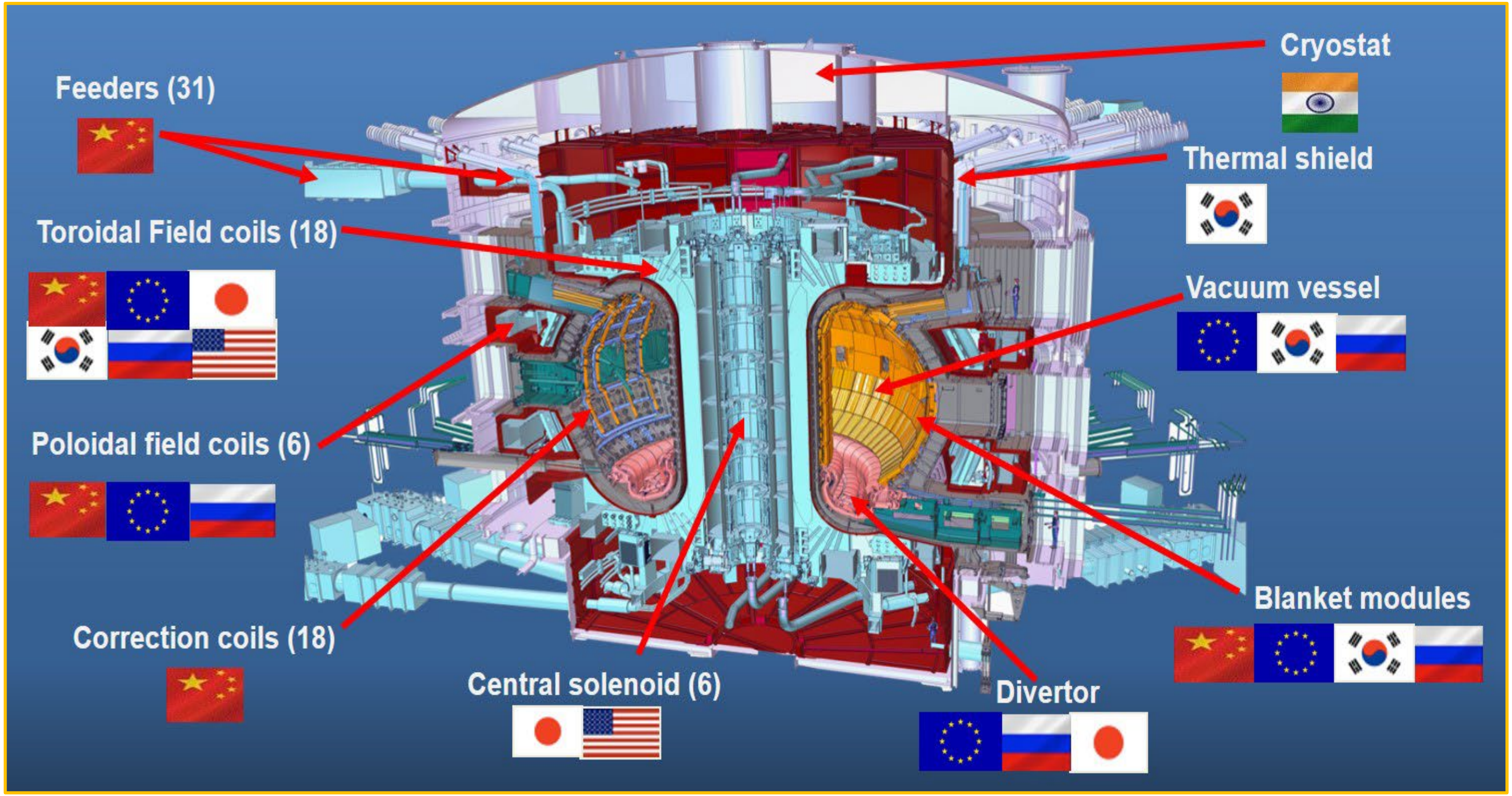
Project Structure

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

Financial support:

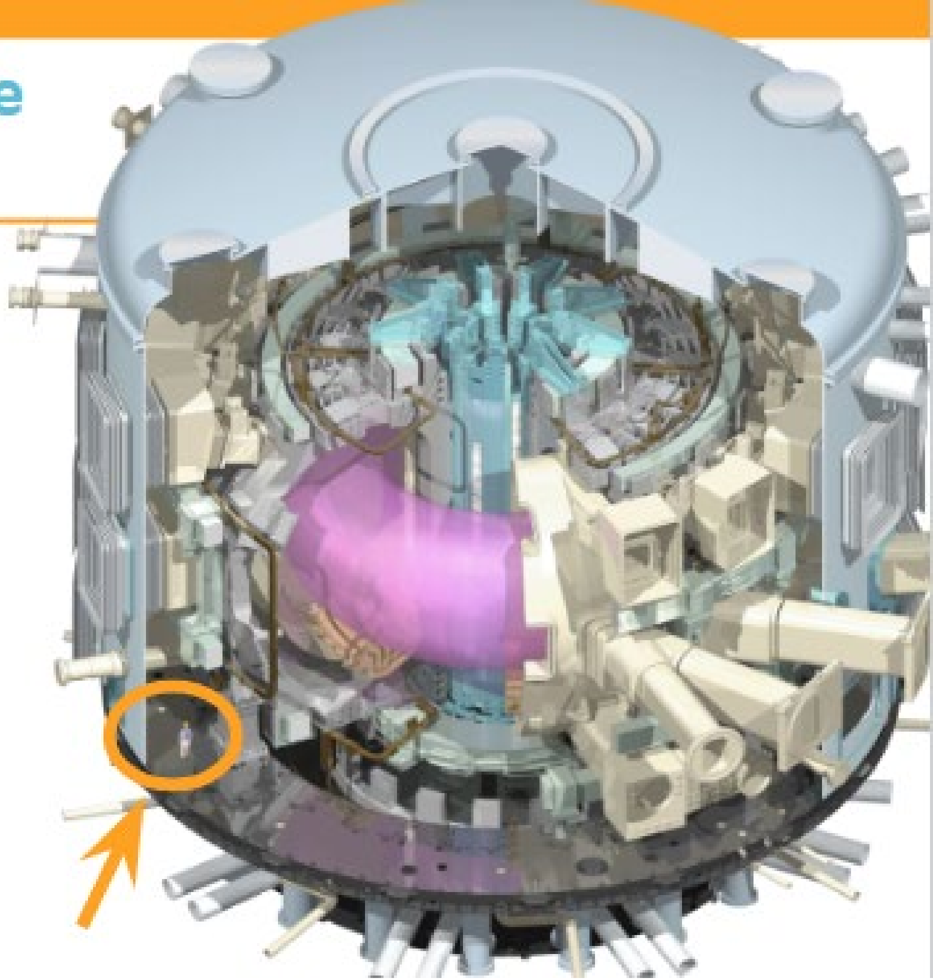
- 80-90% in-kind
  - Lots of Hardware!
- 10-20% in-cash

Who manufactures what?



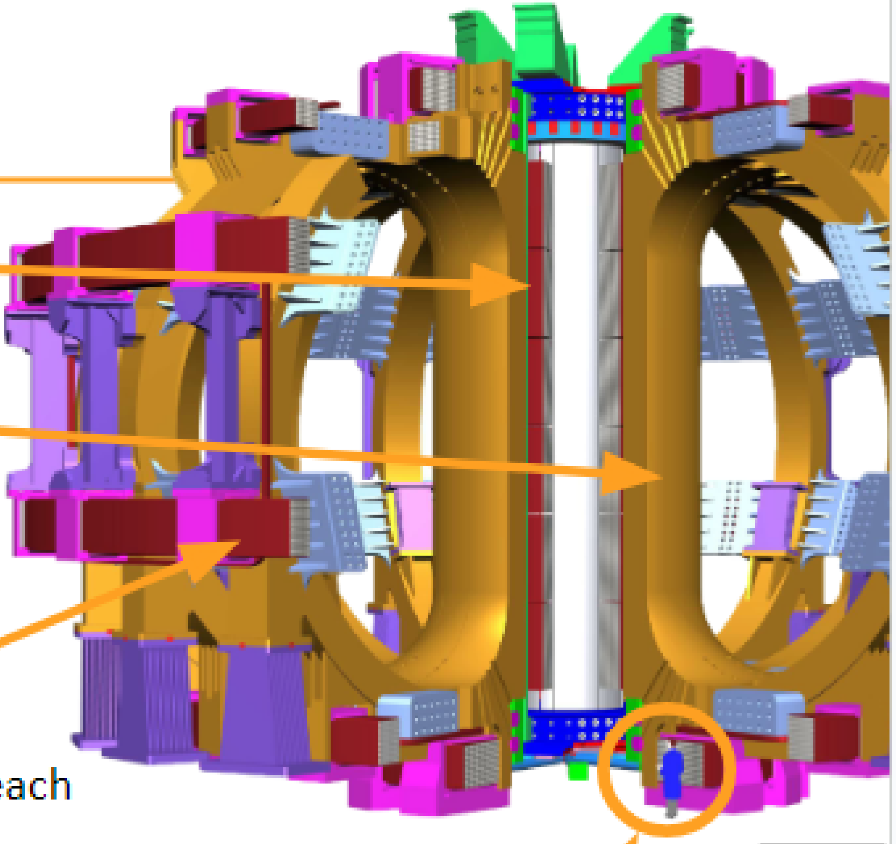
ITER's Mission - Demonstrate fusion at industrial-scale

- 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

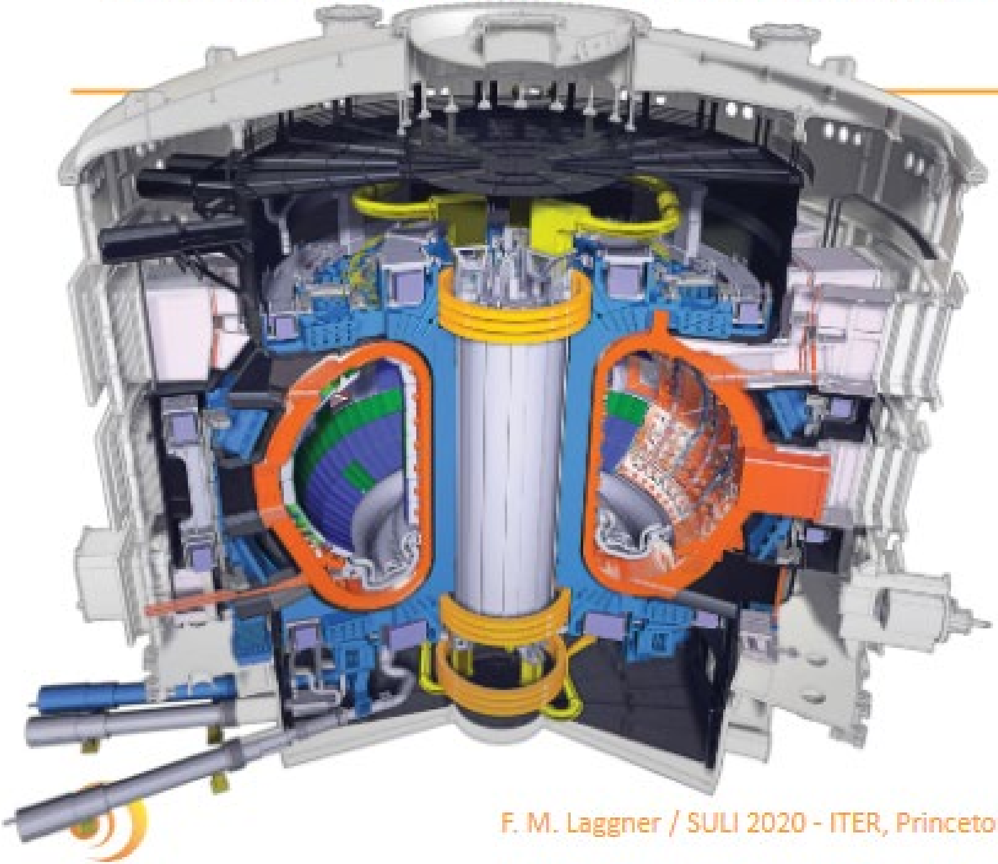
- 1 central solenoid (Nb3Sn)
  - 13 m high, 1,000 tonnes
- 18 toroidal magnets (Nb3Sn)
  - 17 m high, 360 tonnes each
  - Magnetic axis to be positioned with a precision below 0.5 mm
- 6 poloidal magnets (Nb-Ti)
  - 8 to 24 m diametre, 200 to 400 tonnes each



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

Day 4 Batta-

The ITER Tokamak - Massive Components



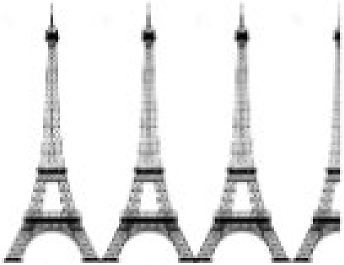
Vacuum Vessel: ~ 8 000 t

TF Coils: ~ 18 x 360 t

Central solenoid: ~ 1 000 t

Radius: 6.2 m

Total ~ 23 000 tonnes



3.5 Eiffel Towers

F. M. Laggner / SULI 2020 - ITER, Princeton, NJ / June 18, 2020

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
  - ∝plasma current × radius^2
- Plasma pulse duration: ~1000 s

Fusion power amplification:

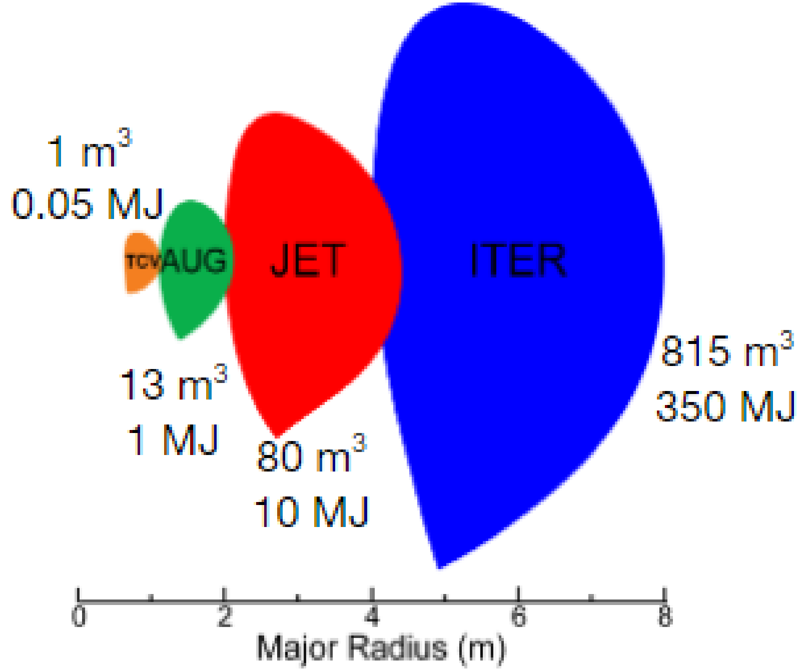
$$Q = \frac{\text{Fusion Power}}{\text{Input Power}} \sim n_i T_i \tau_E$$

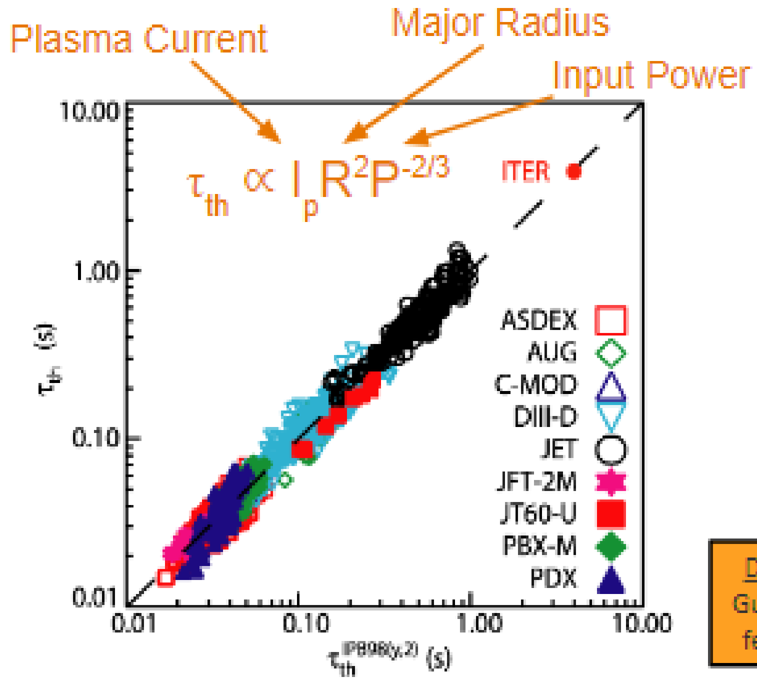
⇒ **Present devices: Q ≤ 1**

⇒ **ITER: Q ≥ 10**

⇒ **'Controlled ignition': Q ≥ 30**

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

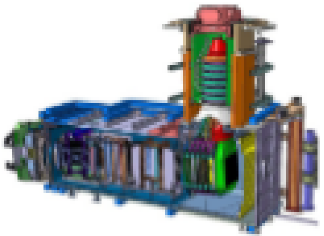
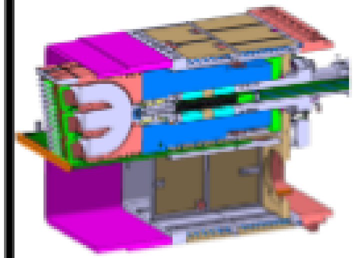
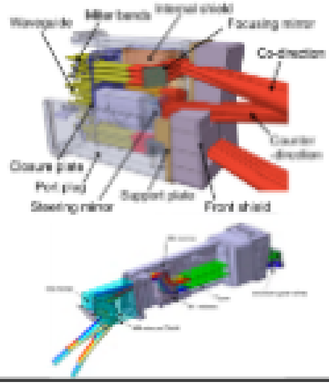
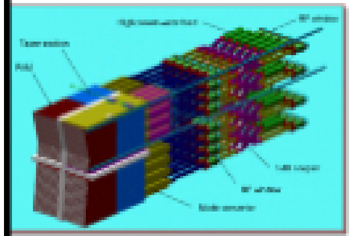




Day 7
Gutten-
felder

Detailed design rely on numerical codes combining engineering and physics constraints

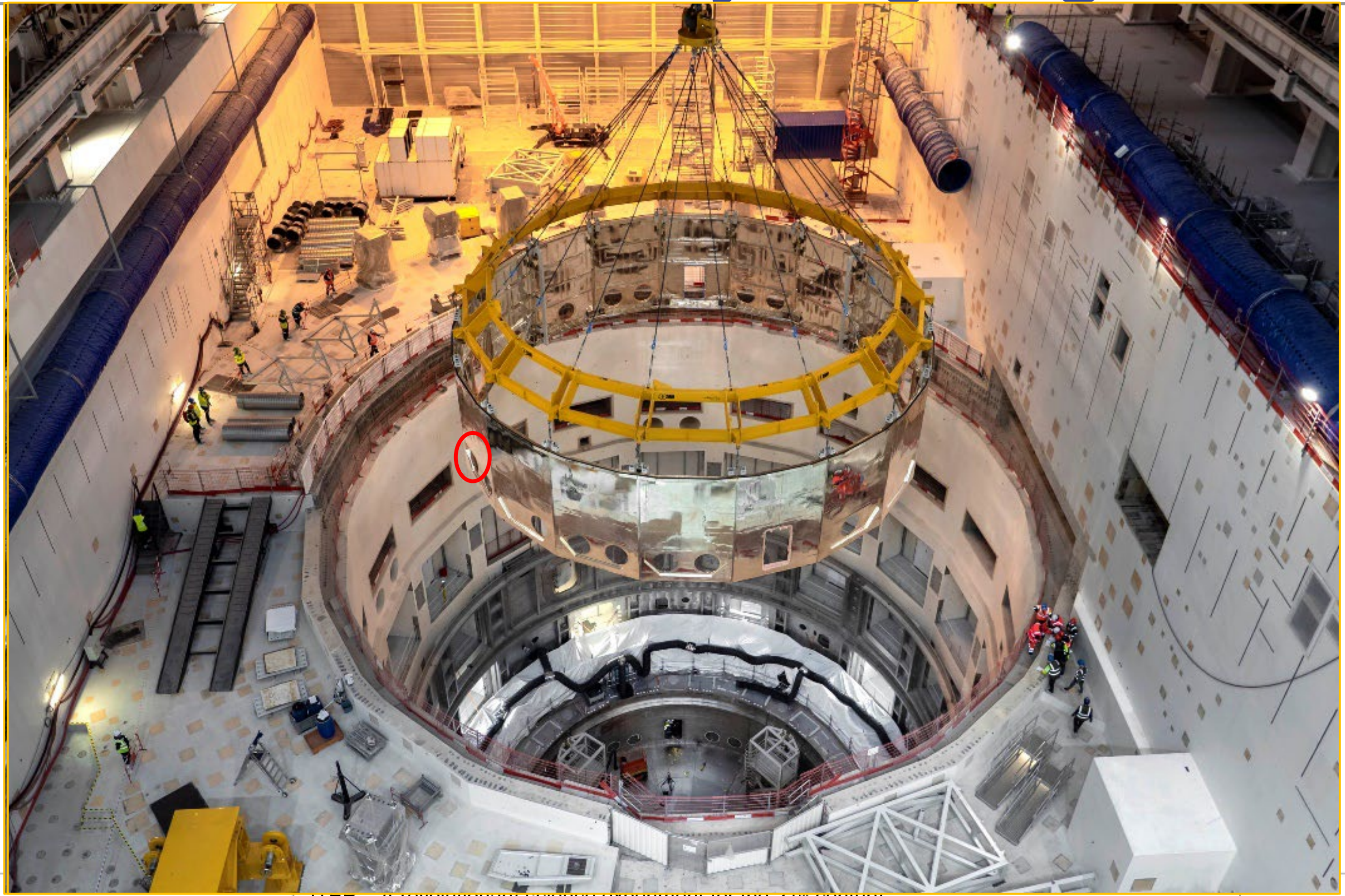
Heating and Current Drive Systems

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

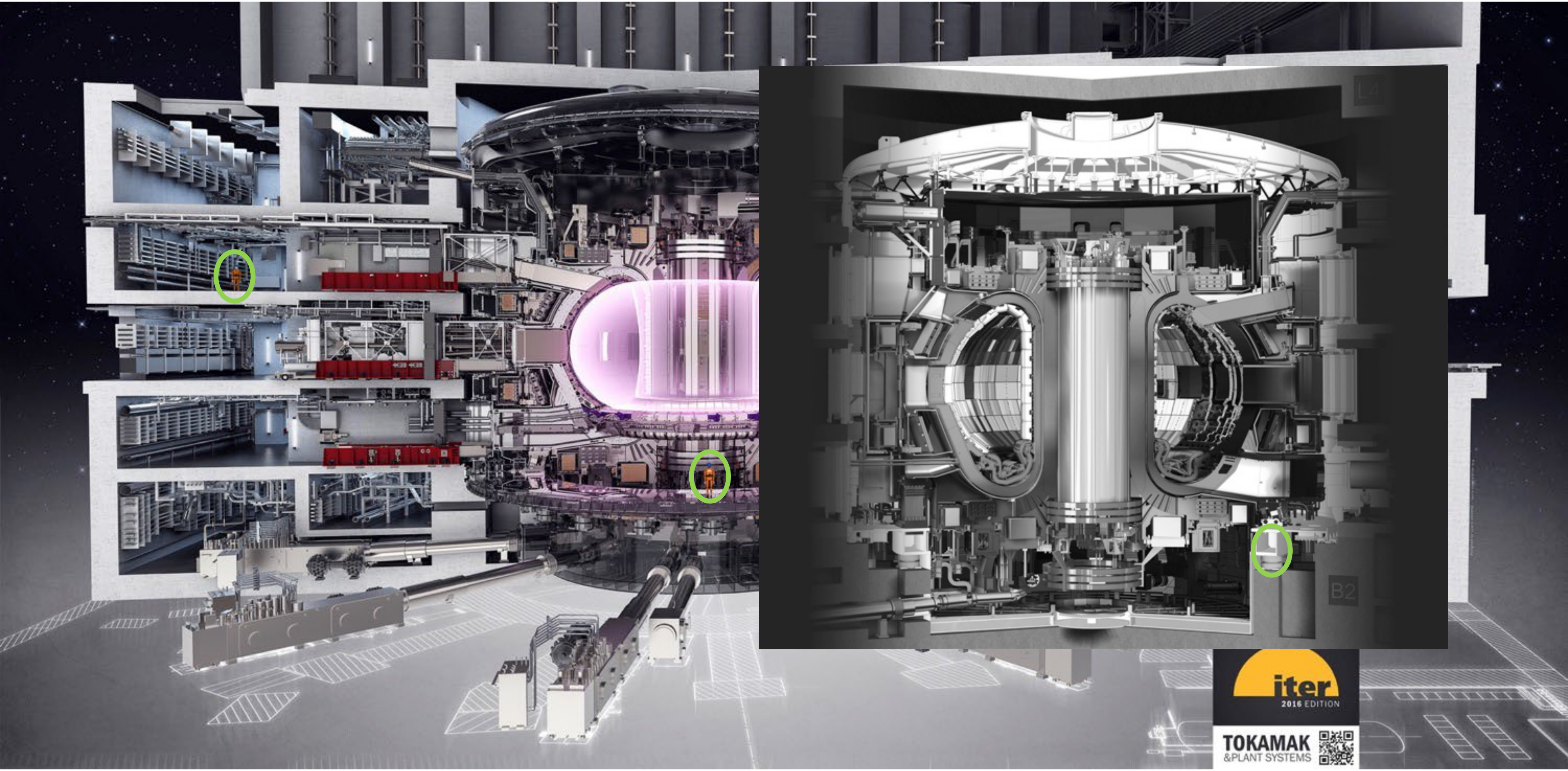
Day 5

Who manufactures what?

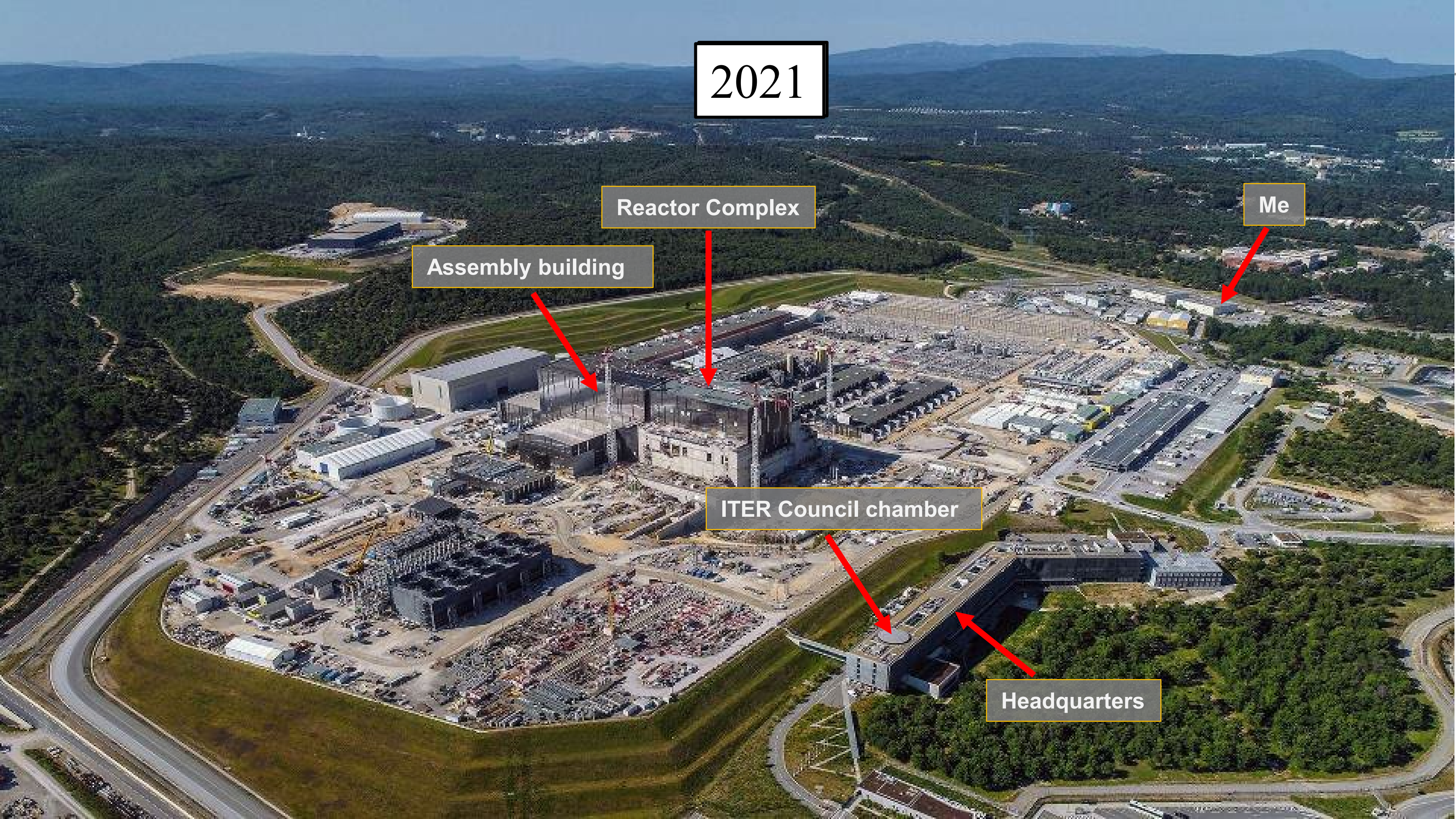
ITER reactor assembly ongoing



What will ITER look like?



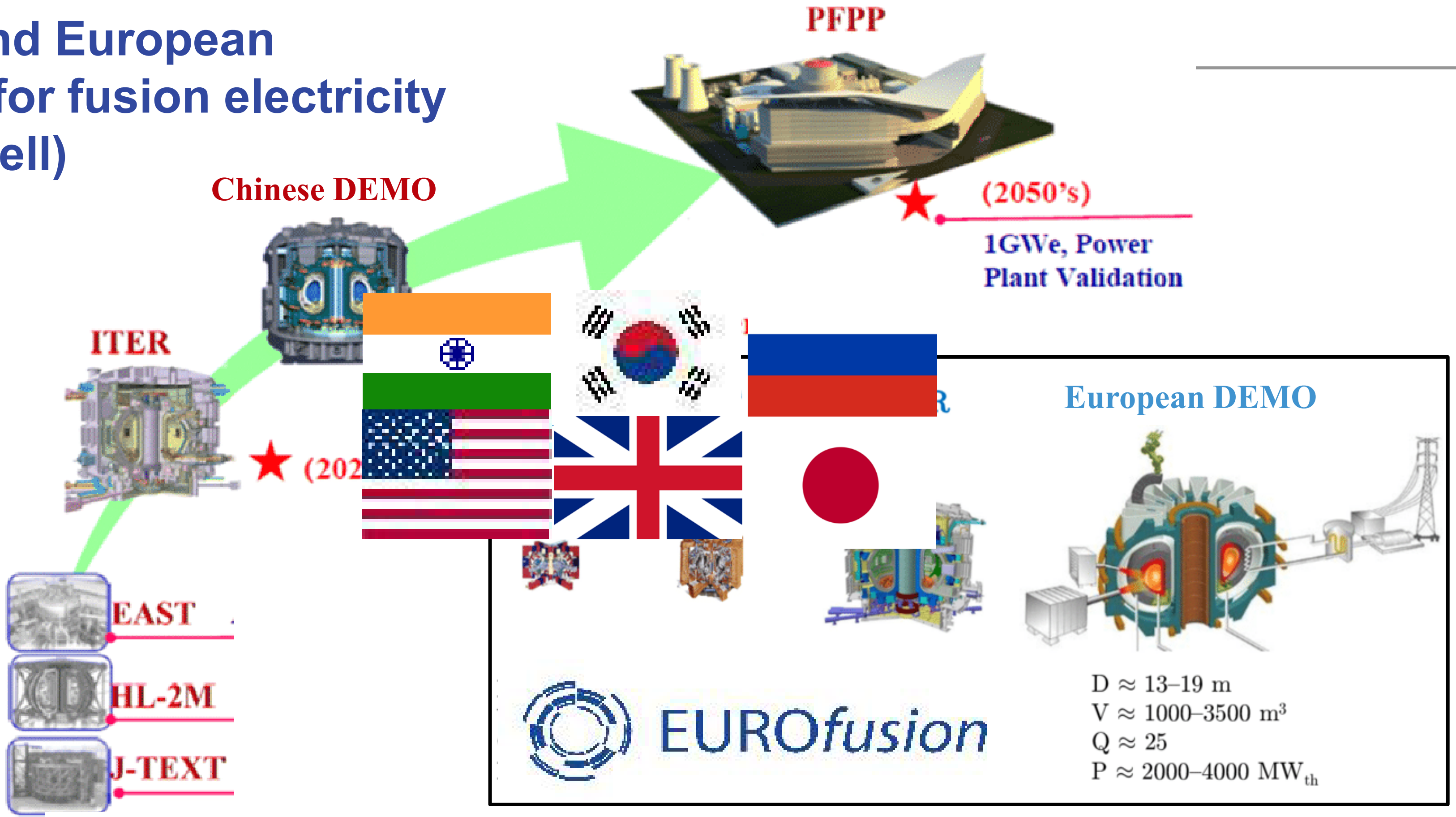
Buildings and manufacturing onsite - Recent milestone: Cryostat base plate installed (May-30)


2021
Reactor Complex
Me
Assembly building
ITER Council chamber
Headquarters

ITER Council, the highest authority in ITER

4.2 Continental & State initiatives

Chinese and European programs for fusion electricity (in a nutshell)



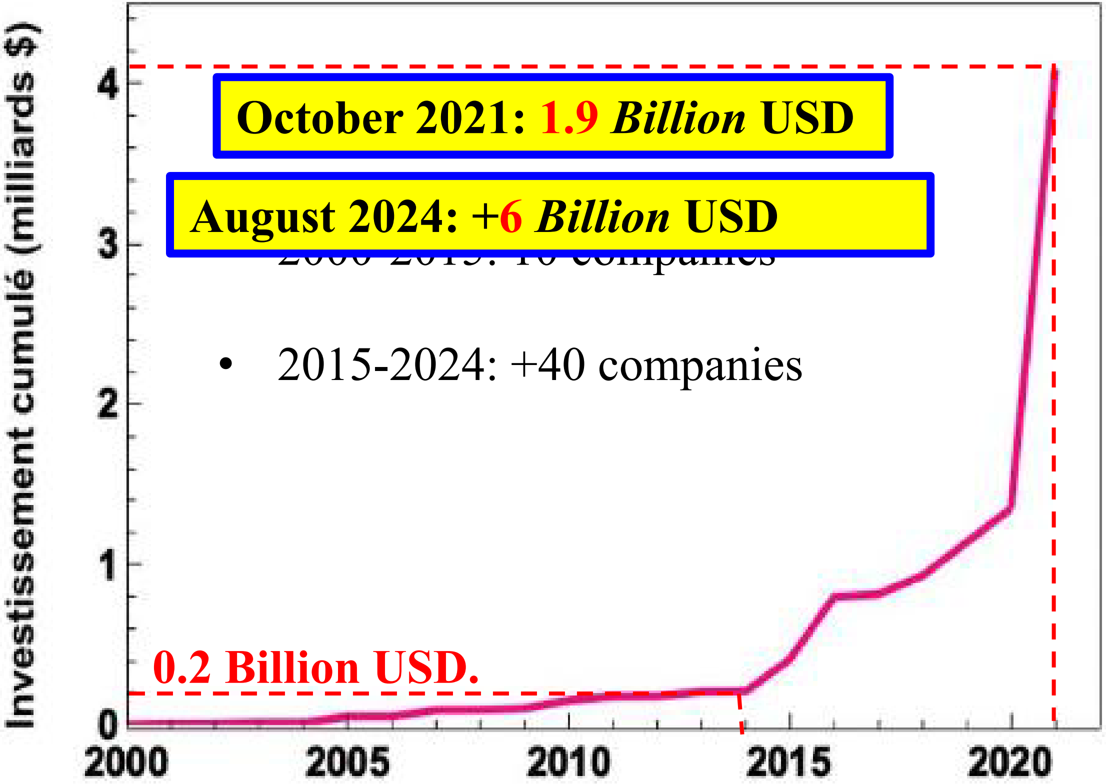
Figures from EUROfusion

4.3 Private initiatives

Private fusion companies

Google

Private funding for fusion has exploded since 2015



October 2021: 1.9 *Billion* USD

August 2024: +6 *Billion* USD

- 2015-2024: +40 companies

Figure by Greg De Temmerman

5. Conclusions

What do we take from all this?

iter (china eu india japan korea russia usa)	**2035**	**Inter-Continental initiative**
EUROfusion	**2040-2050**	**Continental initiative**
	2040-2050	**State initiatives**
FUSION INDUSTRY ASSOCIATION	**2030's**	**Private initiatives**

→ **Fusion Renaissance**