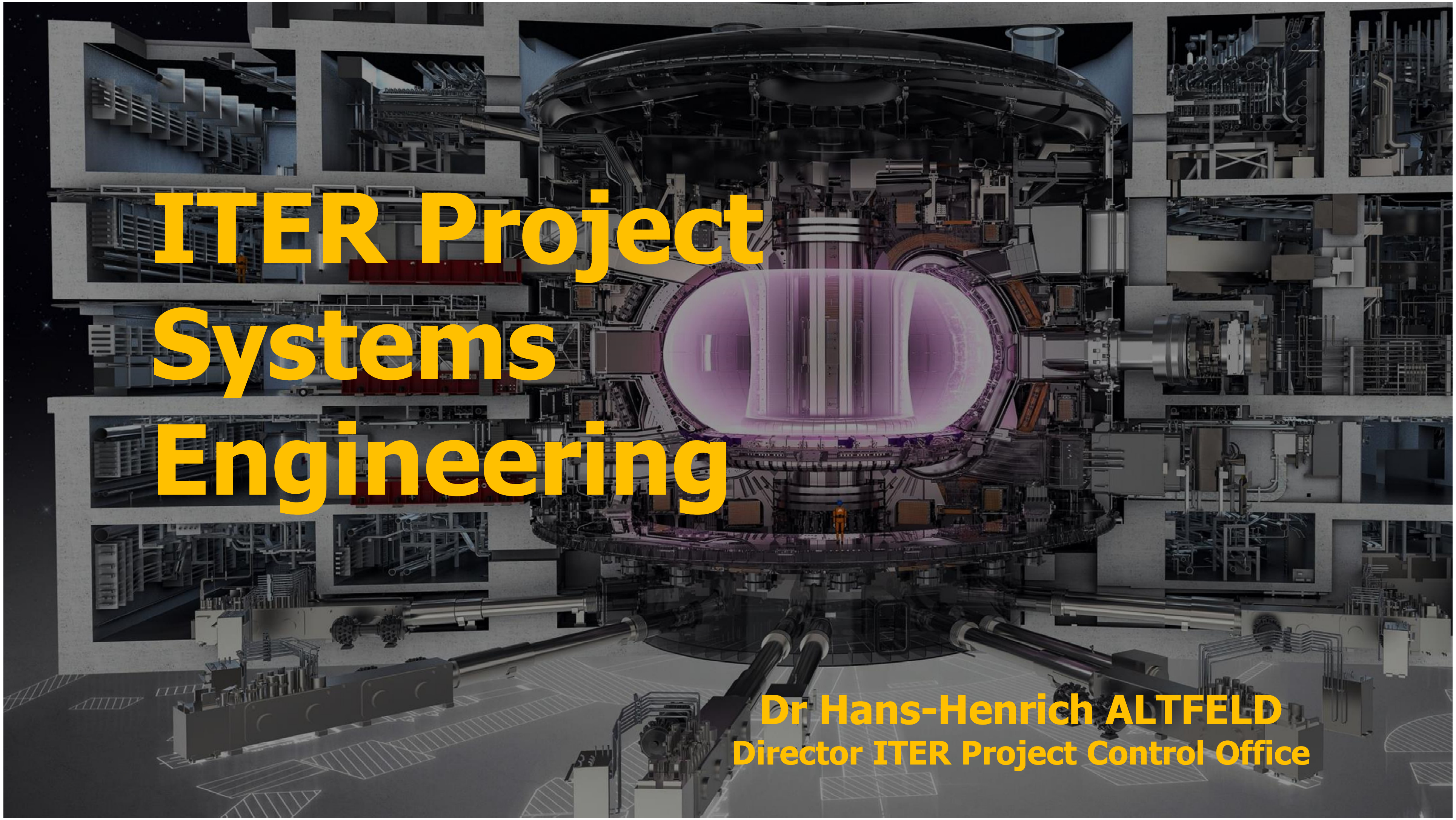


# ITER Project Systems Engineering

**Dr Hans-Henrich ALTFELD**
**Director ITER Project Control Office**

# ITER: What is it?

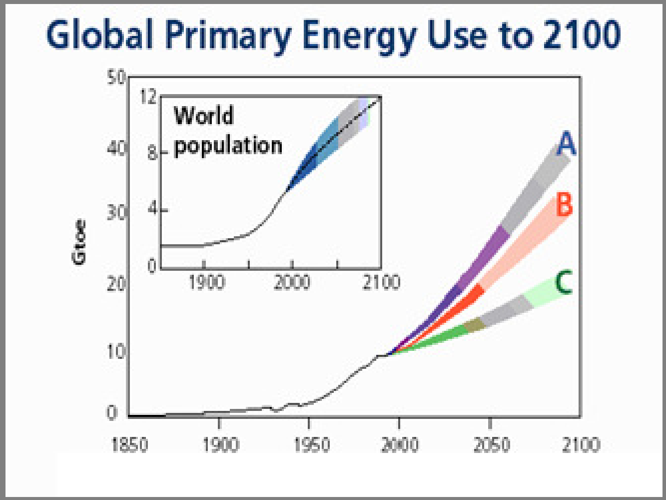
- ITER (International Thermonuclear Experimental Reactor) is the world's largest project attempting to generate energy out of fusion of atomic nuclei
- The idea for ITER was born at an US-USSR summit in Geneva in 1985, when presidents Reagan and Gorbatchev proposed a project to develop fusion energy …"as an unlimited source of energy for the benefit of mankind".
- China, Europe, India, Japan, Korea, Russia and the US signed the ITER Agreement on November 21st 2006 in the Elysee Palace in Paris

# Table of Contents

# Table of Contents

# Why Fusion Energy

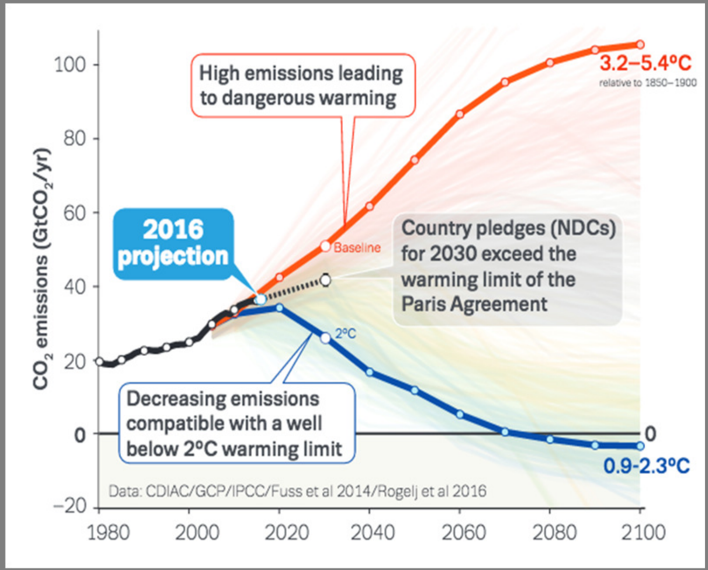
- About 1.2 billion people (>17% of world population) live without electricity.
- Electricity consumption will double by 2060 – essential for improvement of quality of life




➡ Climate change, limited resources

# Why Fusion Energy

- ❑ Paris Climate accord is excellent starting point, but pledges insufficient to meet 1.5°C goal
- ❑ Total greenhouse emission budget at 92% in 2016 for 1.5°C goal
- ❑ Today, across all energy sources, 64% generated from fossil fuels
- ❑ Even with renewables expanding rapidly, fossil fuels will still account for majority of energy generation



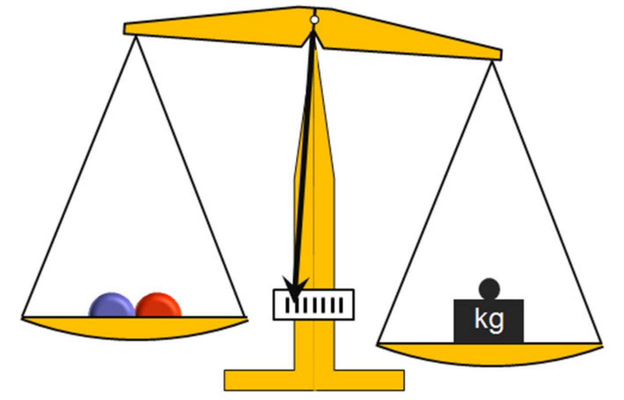

➡ **Fossil fuels must be phased out by 2050 to achieve goal**

# Table of Contents

# Fusion Physics

## The Mass Defect

- When atomic nucleons of low mass number are fused together, they lose mass (Δm)
- According to Einstein, this Δmass is equivalent to a huge amount o 'binding energy', which gets released
- This binding energy has also to be invested in order to separate the nucleons

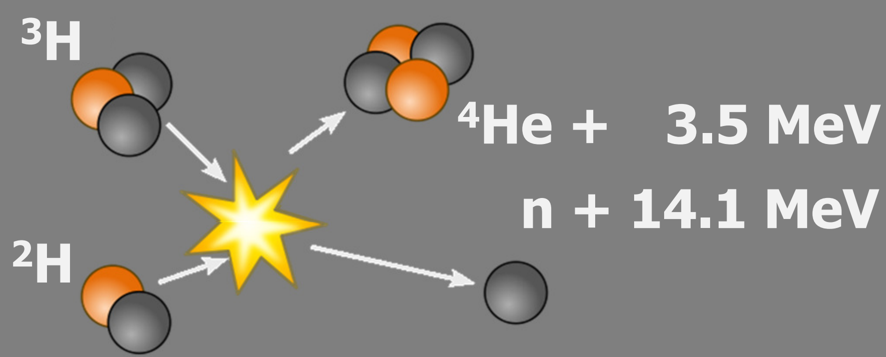


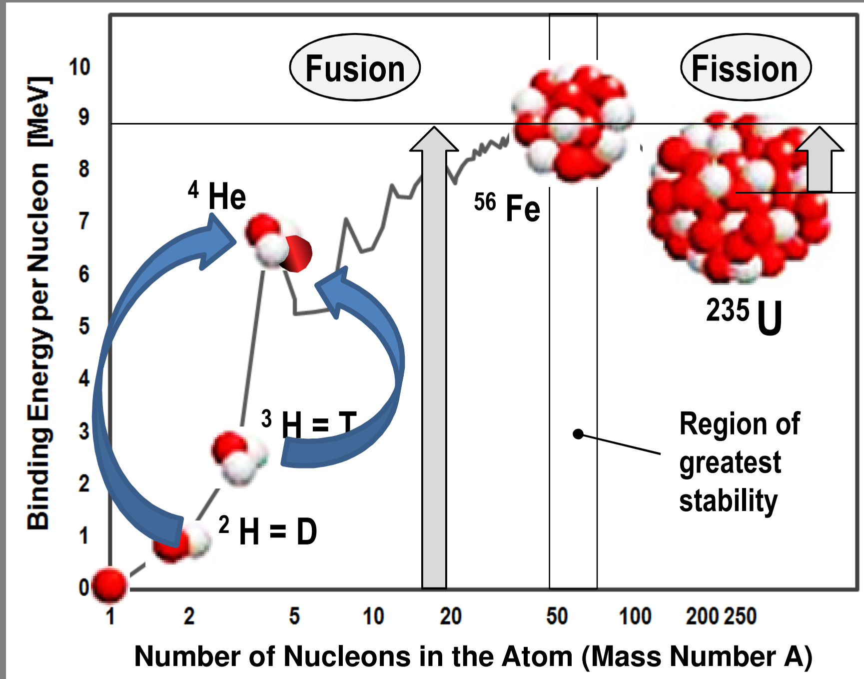

$$\Delta E = \Delta mc^2$$

# Fusion Physics

## The Binding Energy

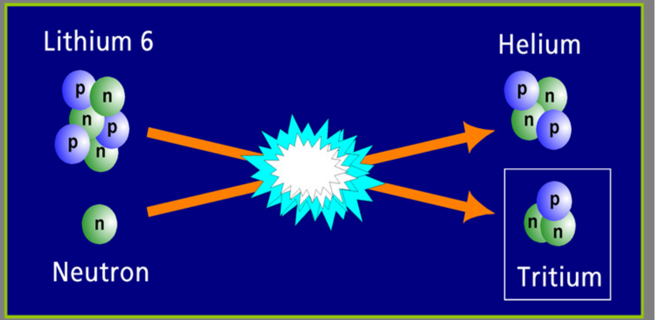
| | Δm | Joule | MeV | MeV/A |
|---|---|---|---|---|
| $1\cdot {}^{1}_{1}p + 1\cdot {}^{1}_{0}n = 1\cdot {}^{2}_{1}H + 0\cdot {}^{1}_{0}n$ | 0.09% | 2.7E-13 | 1.71 | 0.86 |
| $1\cdot {}^{1}_{1}p + 2\cdot {}^{1}_{0}n = 1\cdot {}^{3}_{1}H + 0\cdot {}^{1}_{0}n$ | 0.28% | 1.3E-12 | 7.97 | 2.66 |
| $2\cdot {}^{1}_{1}p + 2\cdot {}^{1}_{0}n = 1\cdot {}^{4}_{2}He + 0\cdot {}^{1}_{0}n$ | 0.73% | 4.4E-12 | 27.28 | 6.82 |
| $1\cdot {}^{2}_{1}H + 1\cdot {}^{3}_{1}H = 1\cdot {}^{4}_{2}He + 1\cdot {}^{1}_{0}n$ | 0.38% | 2.8E-12 | 17.59 | 3.52 |



# Fusion Physics
## The Fusion Raw Materials

- ❑ Enough Deuterium in sea water for millions of years (0.015%)
- ❑ Tritium is not available naturally on Earth, but there is a solution ⇨ Tritium breeding from Lithium
- ❑ Conservative estimates call for available Lithium resources for thousands of years
- ❑ Tritium is radioactive with a half-life of 12.3 years




⇨ **The raw materials for fusion are Deuterium and Lithium**

# Fusion Physics

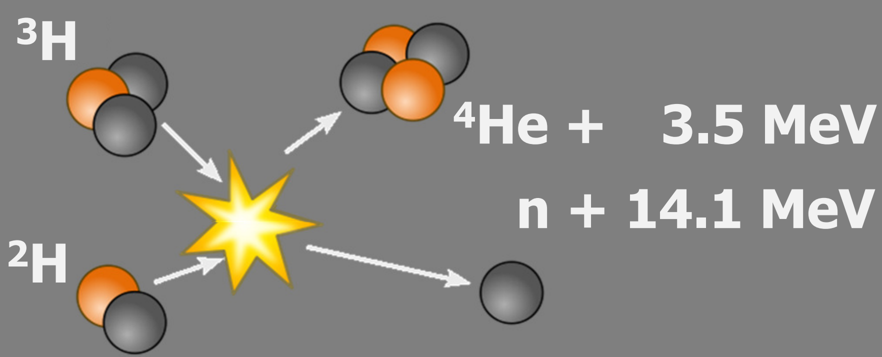
## The Promise of Fusion

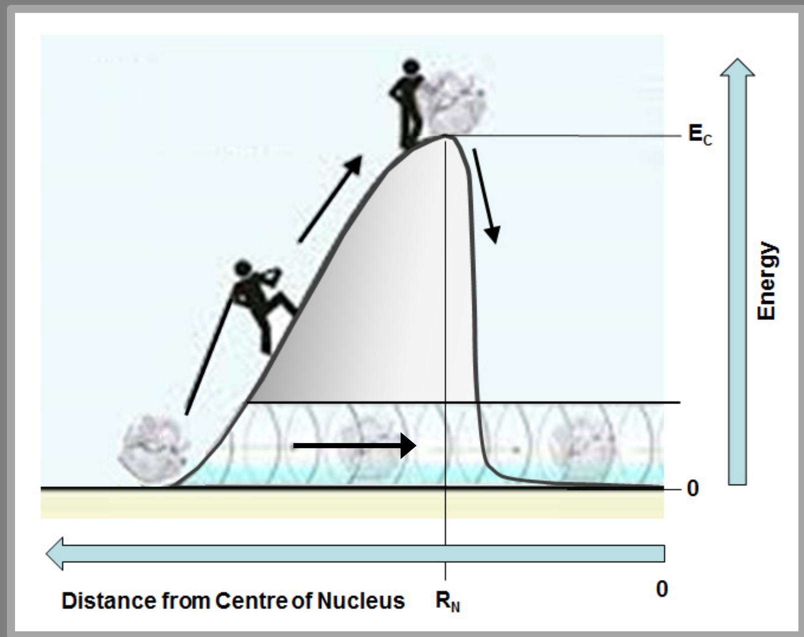
- 48 GJ/13 000 kWh of electricity can be generated from 2 litres of water and 250 g of lithium-containing ore
- This is equivalent to the energy content of 1 ton of oil and sufficient for a 4 person household for 1 year

# Fusion Physics

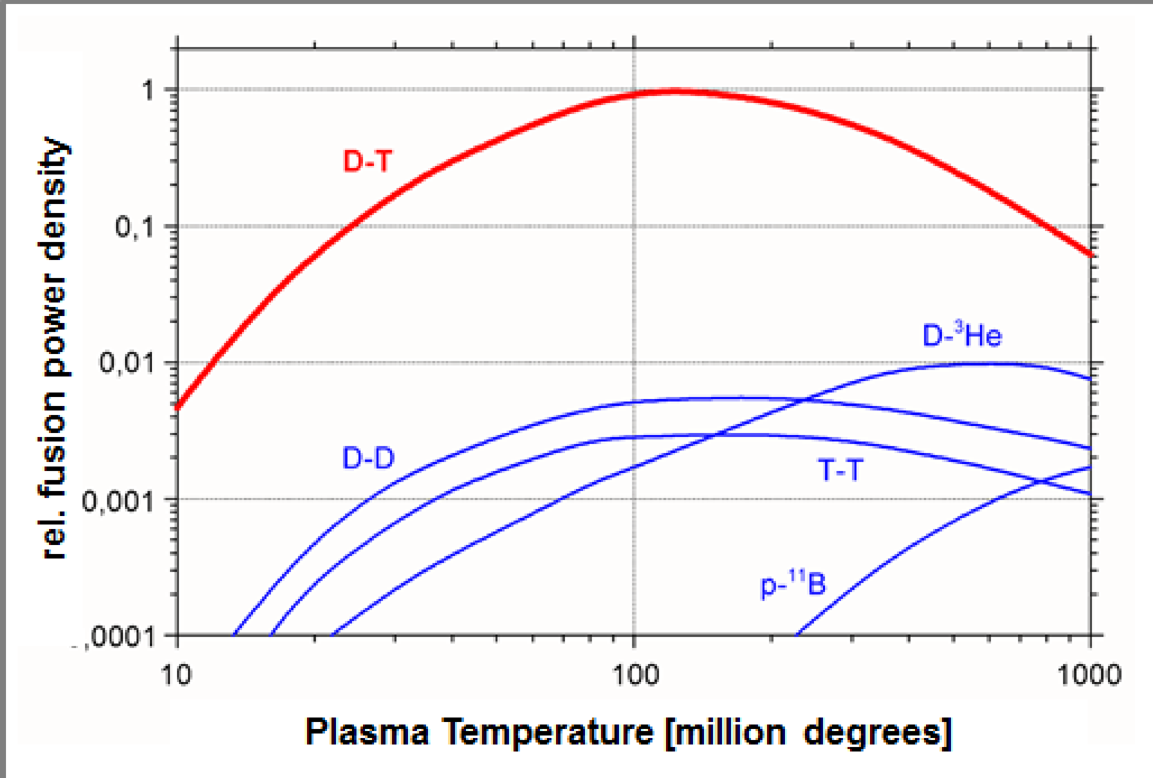
## The Coulomb Barrier

| $E_C$ [MeV] | $E_C$ [MK] | Probability |
|---|---|---|
| 0.400 | 5,000 | 1:1 |
| 0.012 | 150 | $10^5$:1 |



# Fusion Physics

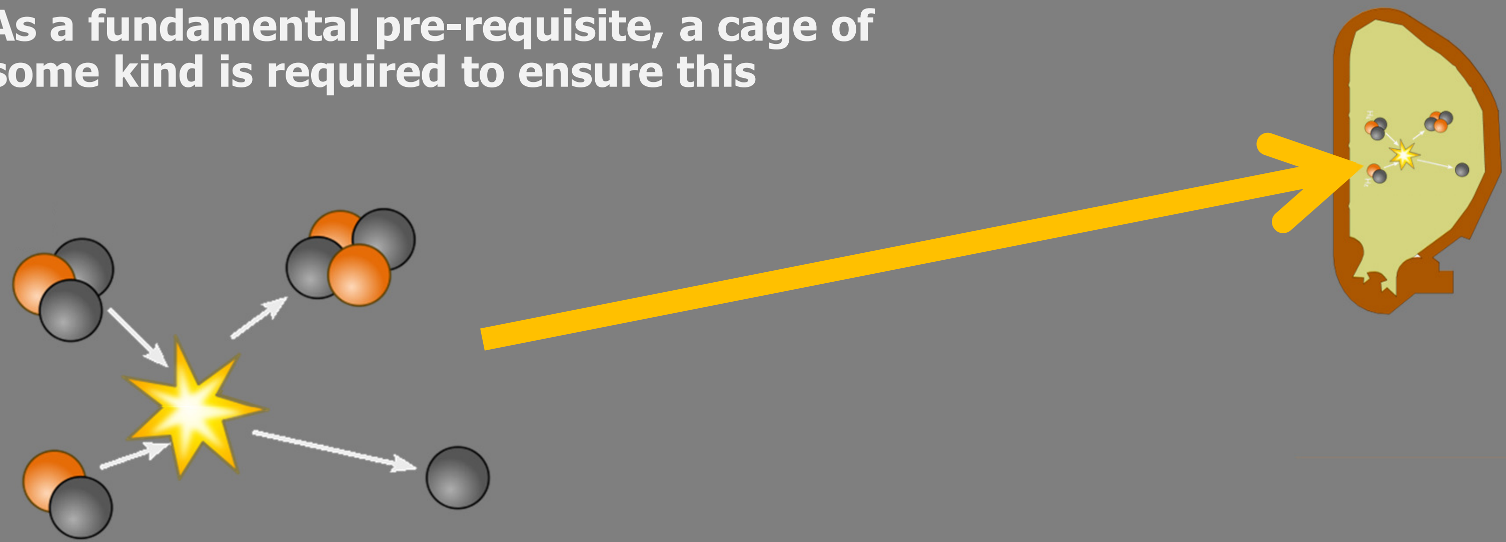


# Table of Contents

# The ITER Machine

## Fundamental Engineering Concepts

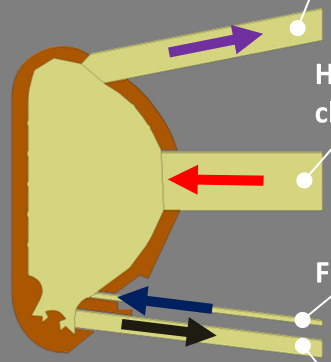
- First of all, what is required is a protected environment for D and T to fuse
- As a fundamental pre-requisite, a cage of some kind is required to ensure this



# The ITER Machine

## Fundamental Engineering Concepts

- The cage must have ports in order to
  - create a vacuum
  - feed the fuel (D and T) into it
  - deliver the required heat to overcome Coulomb barrier
  - Take out the ash of the reaction (i.e. $^4He$)

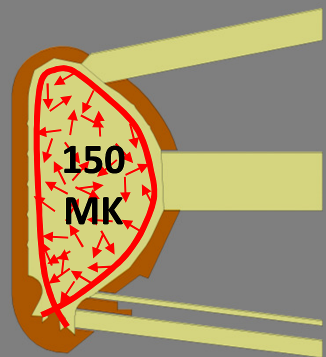



➡ **Major Systems challenges**

# The ITER Machine

## Fundamental Engineering Concepts

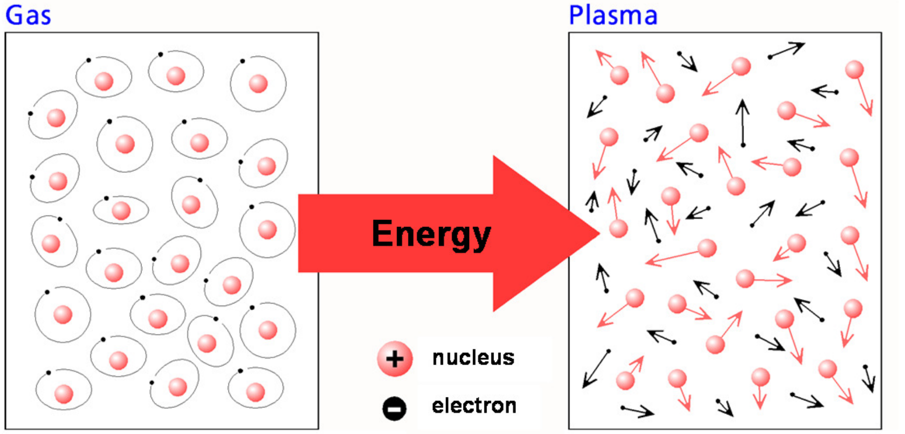
- **At the high temperature required for fusion:**
  - **the inner walls of the cage would immediately melt away**
  - **matter is in the state of a plasma, i.e. the electrons (-) and nuclei (+) do no longer form atoms, but move around arbitrarily**



# The ITER Machine

## Fundamental Engineering Concepts

- At the high temp
  - the inner wa immediately
  - matter is in electrons (-) form atoms,




**Temperature 20 C**

Electrons and ions are bound

Neutral atoms

**Temperature > 100.000 C**

Electrons and ions have dissociated

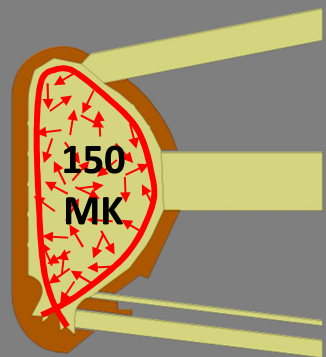
Electrically charged particles


Aurora borealis
Flame
Sun
Lightening
NEWS
Neon light

# The ITER Machine

## Fundamental Engineering Concepts

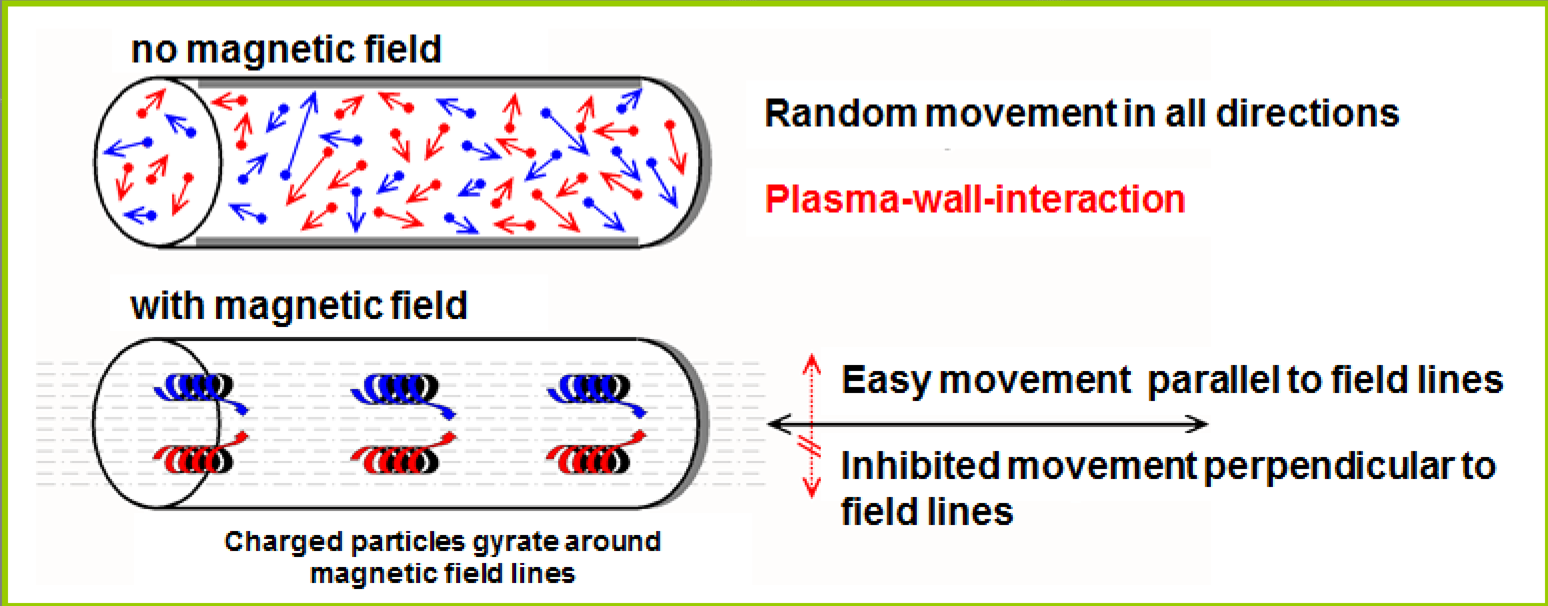
- At the high temperature required for fusion:
  - the inner walls of the cage would immediately melt away
  - matter is in the state of a plasma, i.e. the electrons (-) and nuclei (+) do no longer form atoms, but move around arbitrarily




➡ **Magnets could provide confinement**

# The ITER Machine

## Fundamental Engineering Concepts

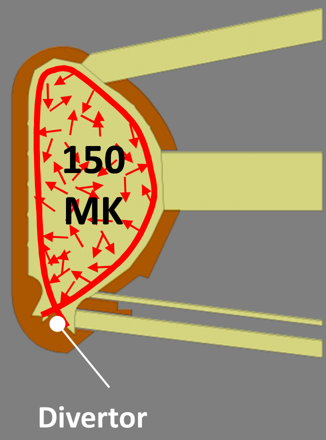



➡ Magnets could provide confinement

# The ITER Machine

## Fundamental Engineering Concepts

- Magnetic confinement can be used to
  - provide D and T particles with the required time to fuse
  - avoid charged D, T and $^{4}He$ particles to hit the First Wall
  - concentrate the ash to the divertor for disposal

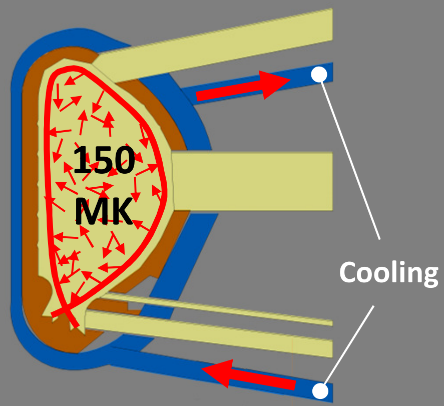



⇒ Magnets need to be installed

# The ITER Machine

## Fundamental Engineering Concepts

- ❑ **Neutrons do not carry any electric charge and can, thus, not be confined by magnets.**
- ❑ **As they carry the far majority of the created fusion energy, they heat up the inner 'First Wall' of the cage through impact**
- ❑ **The wall needs to be cooled (e.g. by a water cooling system)**
- ❑ **At the same time, heating up the coolant is the (classical) way to capture the neutron's energy to eventually generate electricity**

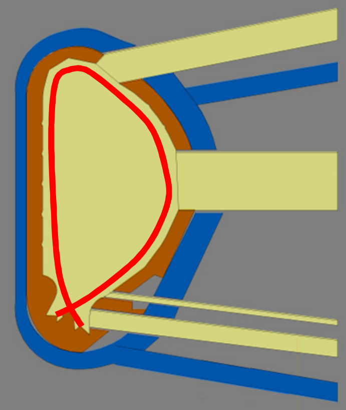



➡ **The First Wall and Cooling System are crucial for energy conversion**

# The ITER Machine

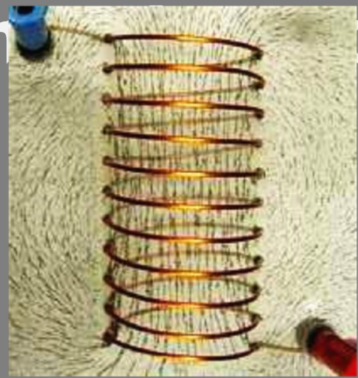
## Fundamental Engineering Concepts

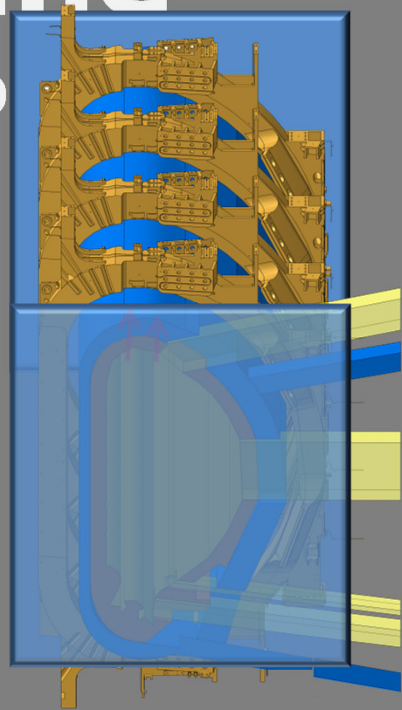
- What would be a suitable form for a 3D cage with installed magnets?



# The ITER Machine

## Fundamental Engin…





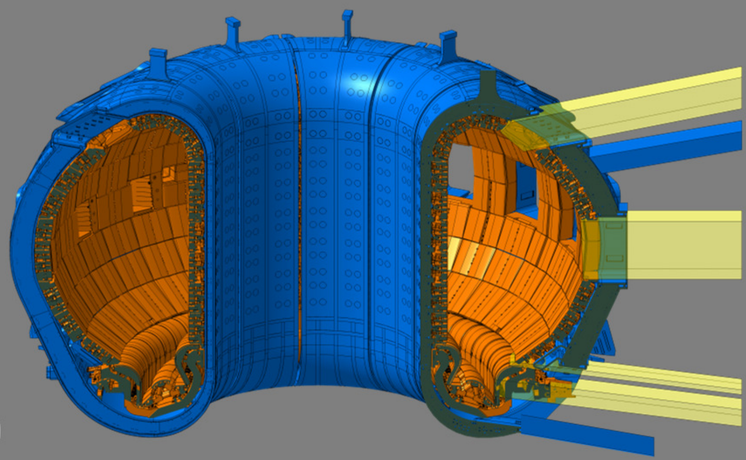
- ❑ **What would be a suitable form for a 3D cage with installed magnets?**
  - **Option (A): A cylindrical shape**
    - **easy principle**
    - **many repetitive components**
    - **BUT: would require magnetic mirrors at each end**

**➡ No practical solutions available today**

# The ITER Machine

## Fundamental Engineering Concepts

- What would be a suitable form for a 3D cage with installed magnets?
  - Option (B): A toroidal shape
    - endless field lines
    - BUT: fast drift to low field region as there is stronger magnetic field inboard (no equilibrium)

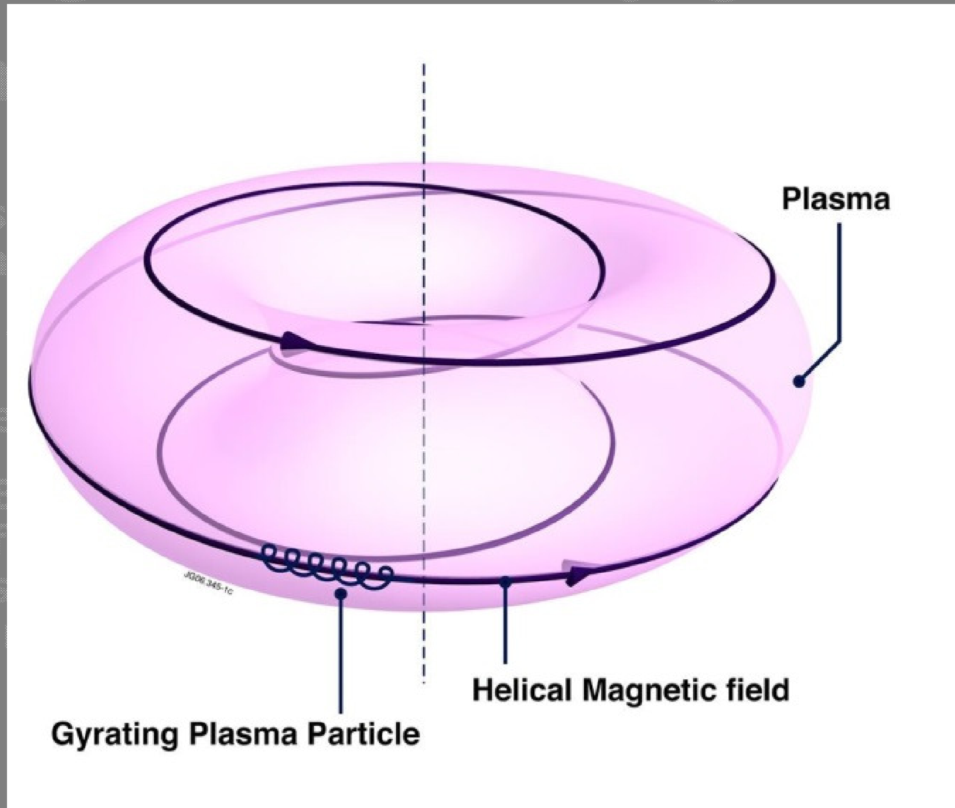


➡ **Three different types of magnets required!**

# The ITER Machine

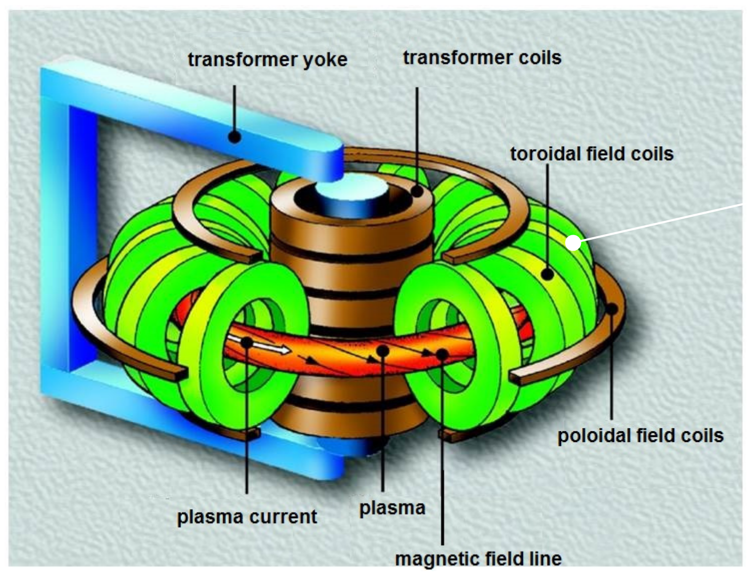
## Funda... ...epts

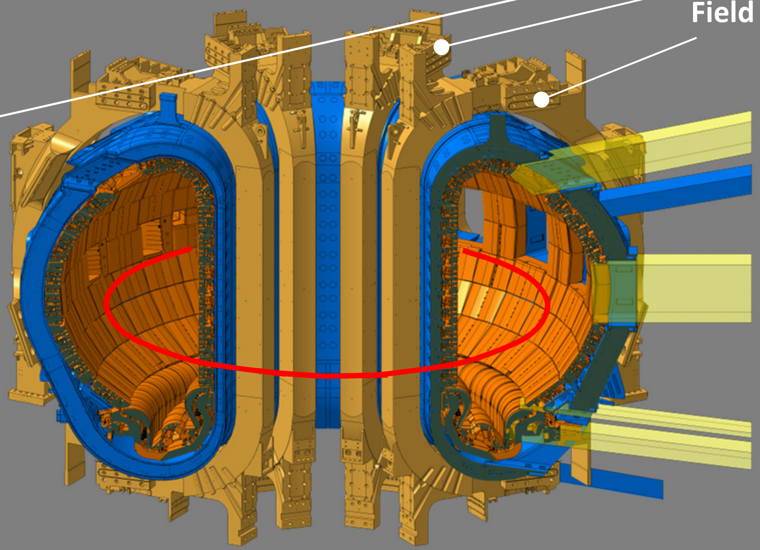
- What would be a s... 3D cage with insta...
  - Option (B): A ...
    - e...
    - E... f... s... i...



# The ITER Machine

## Fundamental Engineering Concepts

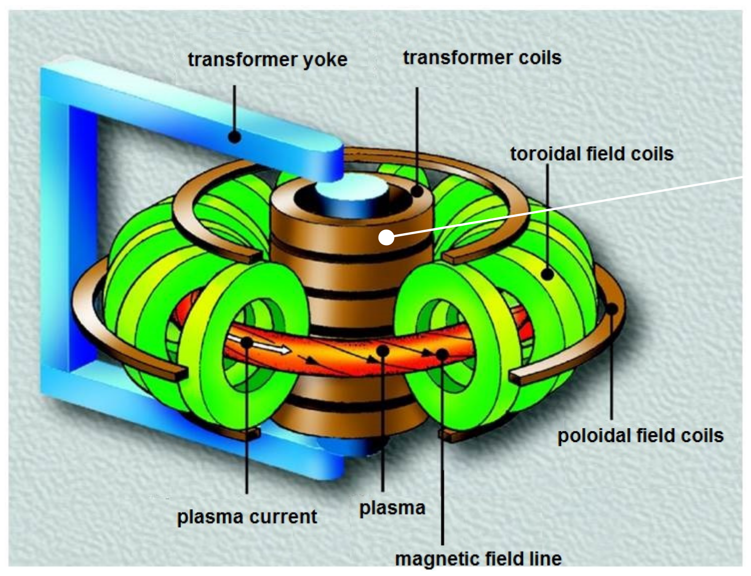


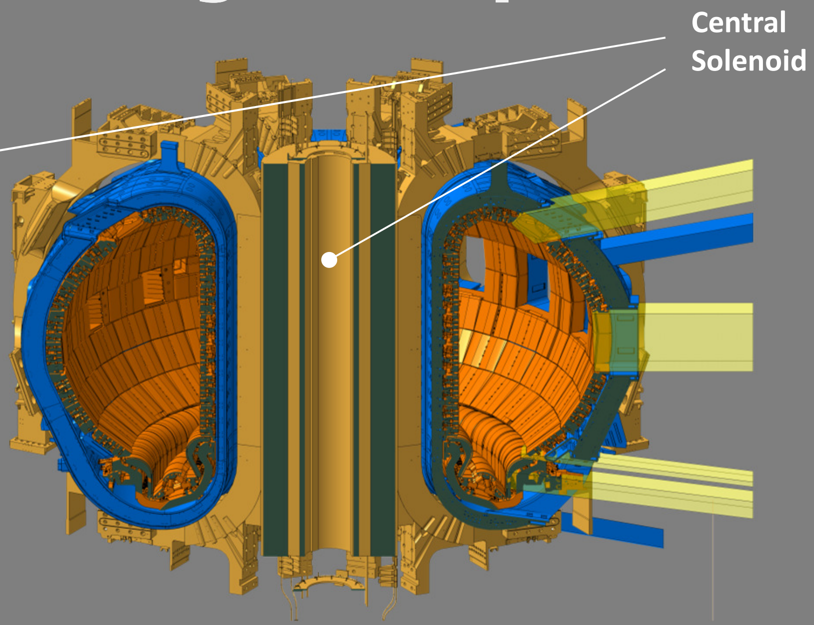




➡ **Toroidial Field Coils**

# The ITER Machine

## Fundamental Engineering Concepts

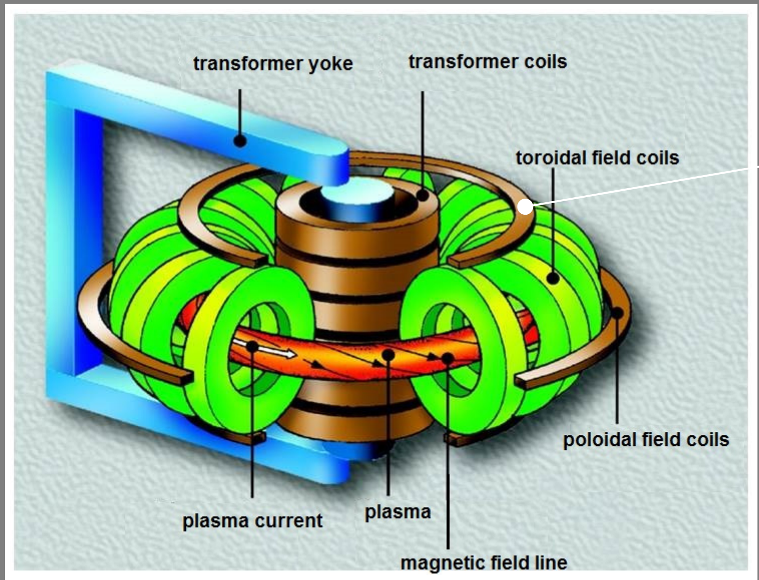


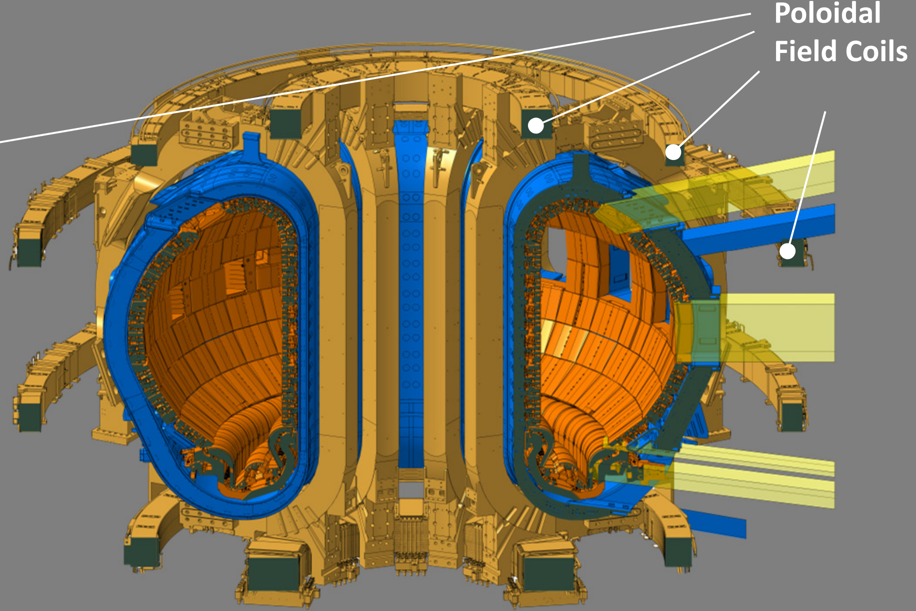




➡ Central Solenoid

# The ITER Machine

## Fundamental Engineering Concepts



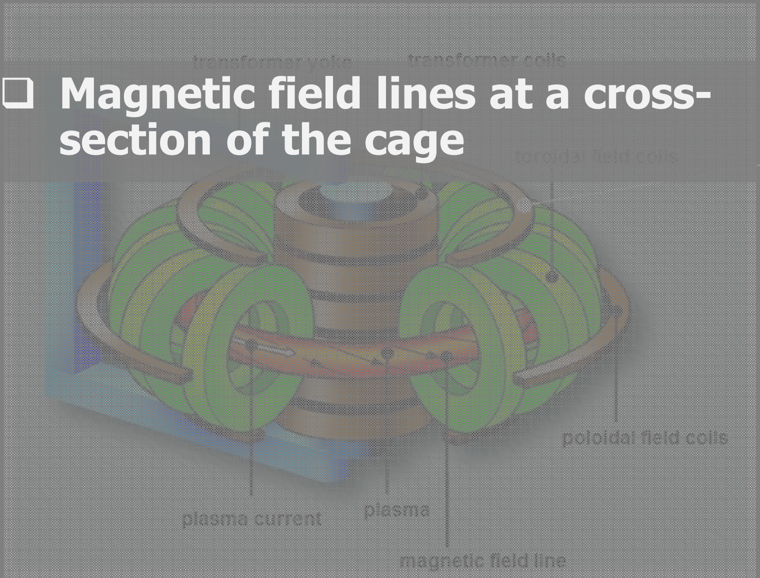



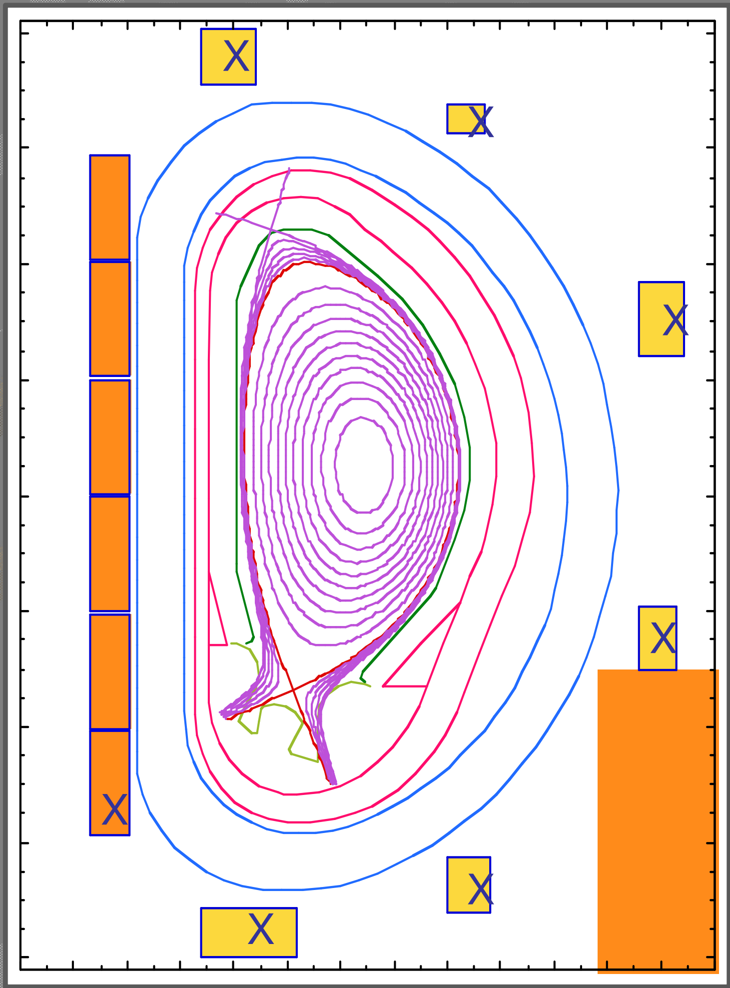

**➡ Poloidial Field Coils**

# The ITER M…

## Fundamental Engi…

- Magnetic field lines at a cross-section of the cage



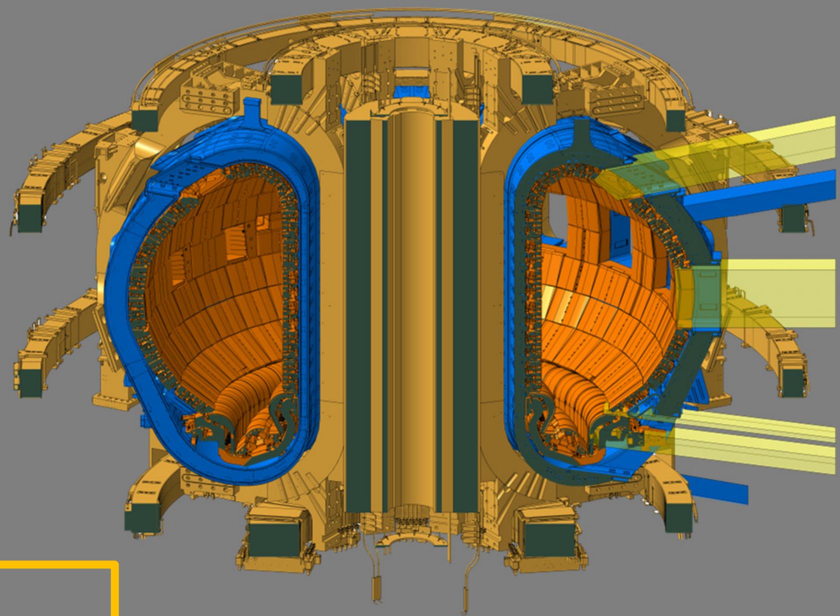



➡ Poloidial Field Coils

# The ITER Machine

## Fundamental Engineering Concepts

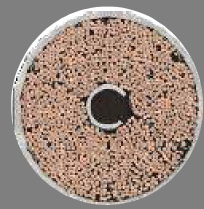
- Toroidal chambers with magnetic coils for fusion applications have been invented in the former USSR in the late 1960s
- The term "tokamak" comes from a Russian acronym that stands for "toroidal chamber with magnetic coil."



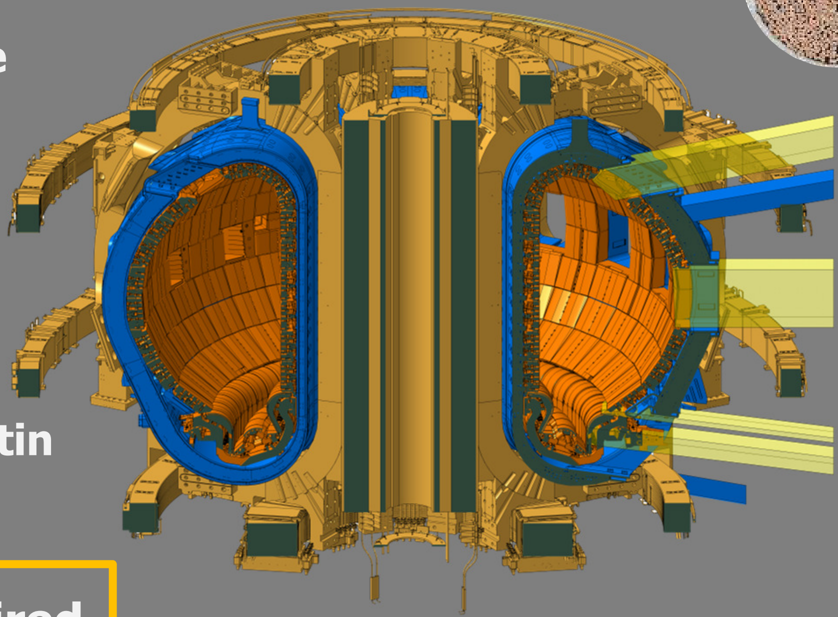
➡ ITER machine = Tokamak

# The ITER Machine

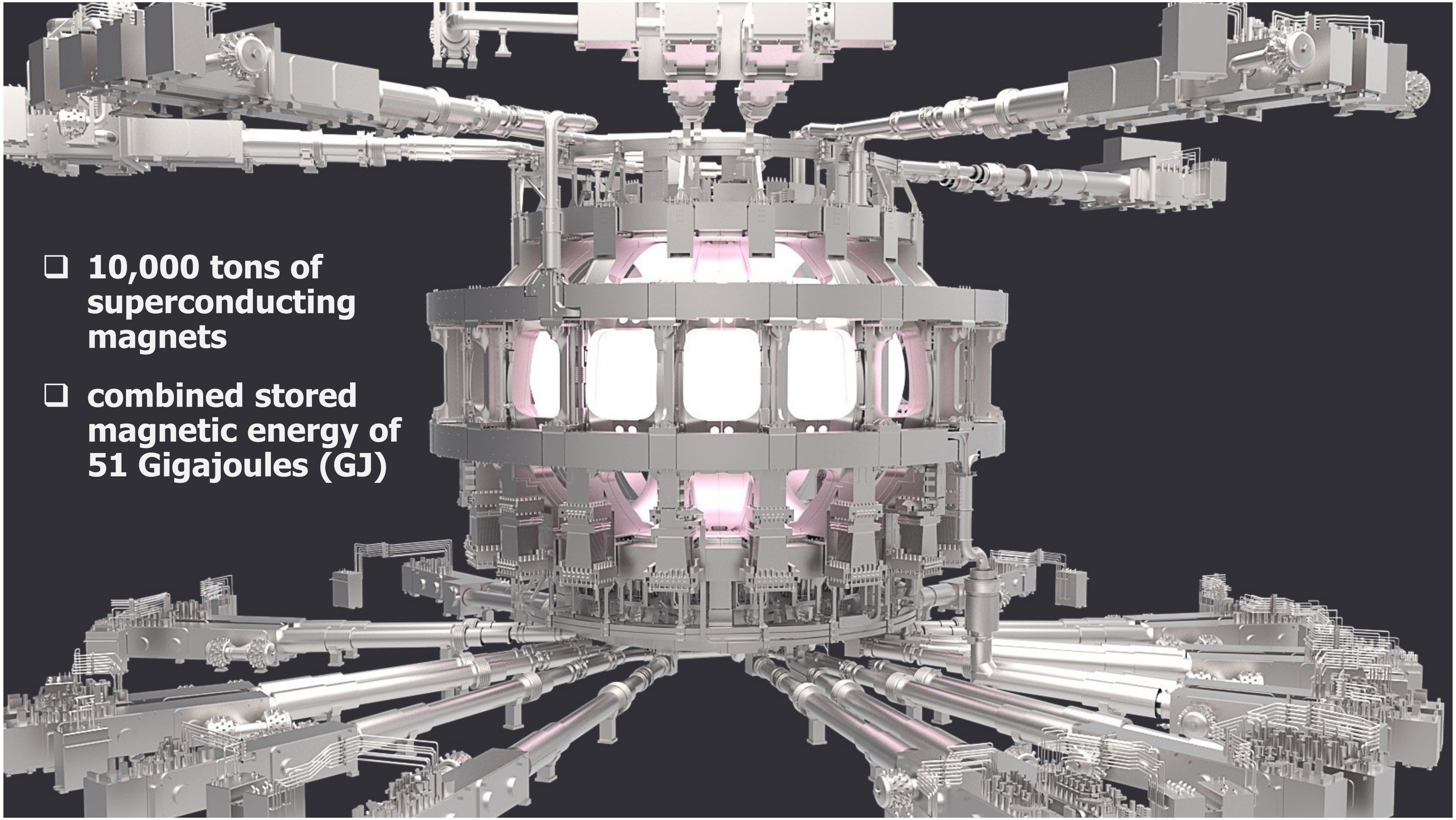
## Fundamental Engineering Concepts

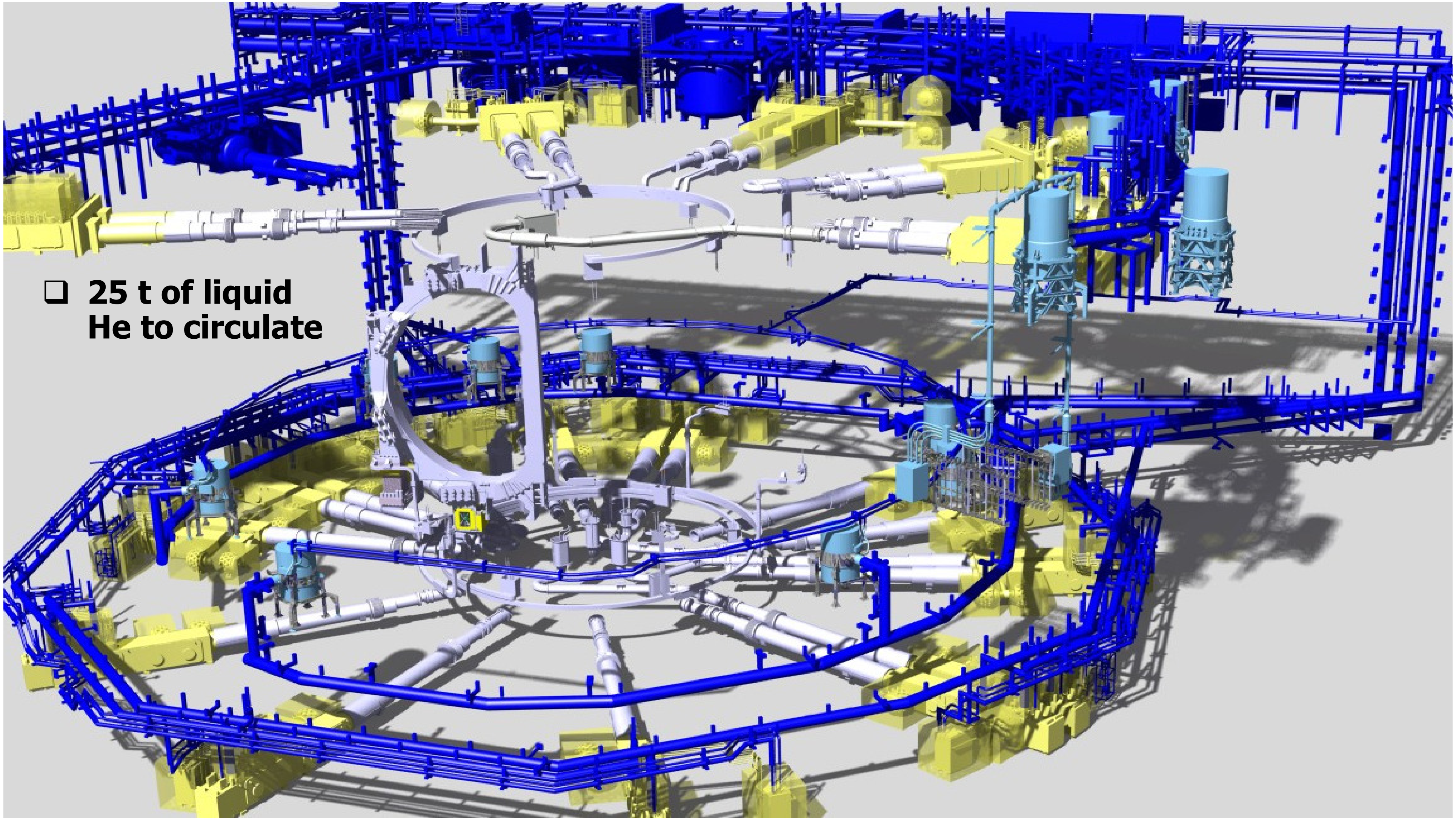


- To improve efficiency, all magnets are superconducting in order to
  - carry higher current
  - produce stronger magnetic fields
  - consume less power
  - operate cheaper
- They are manufactured from niobium-tin ($Nb_3Sn$) or niobium-titanium (NbTi)



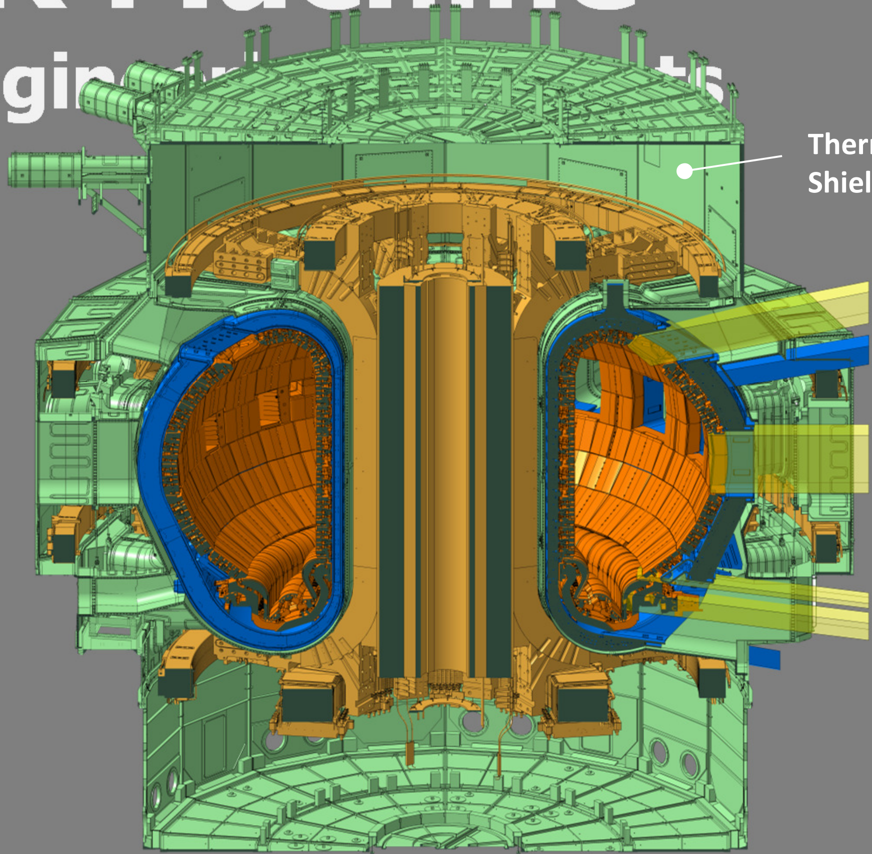
➡ **He-cooling at 4K (-269C) required**


❑ 10,000 tons of superconducting magnets
❑ combined stored magnetic energy of 51 Gigajoules (GJ)


❑ 25 t of liquid
He to circulate

# The ITER Machine

## Fundamental Engin ... ts

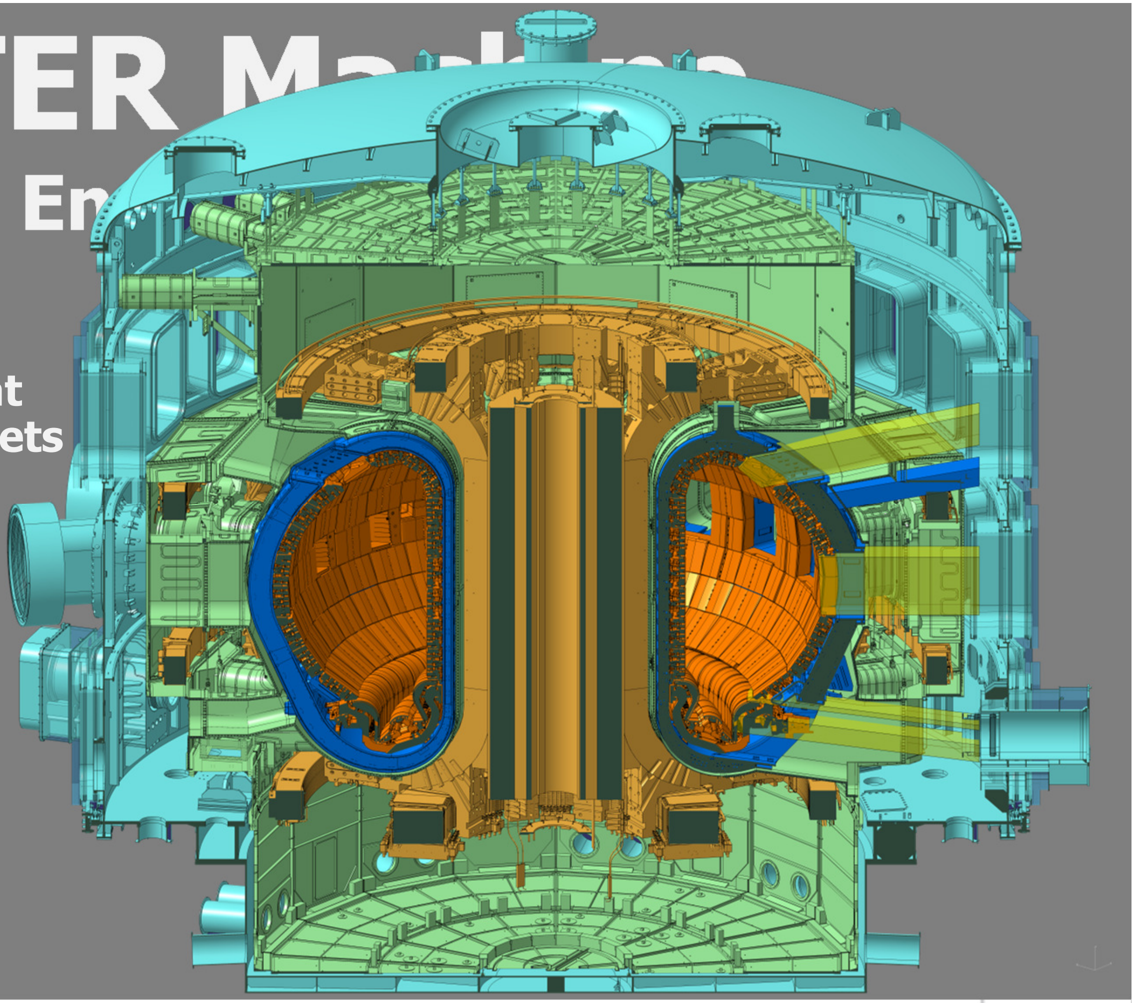



- ❑ But superconductivity requires massive measures to avoid heat loads penetrating to the magnets through
  - Conduction
  - Convection
  - Radiation
- ❑ The cryostat consists of a

➡ **Thermal Shield**

# The ITER Ma

## Fundamental En



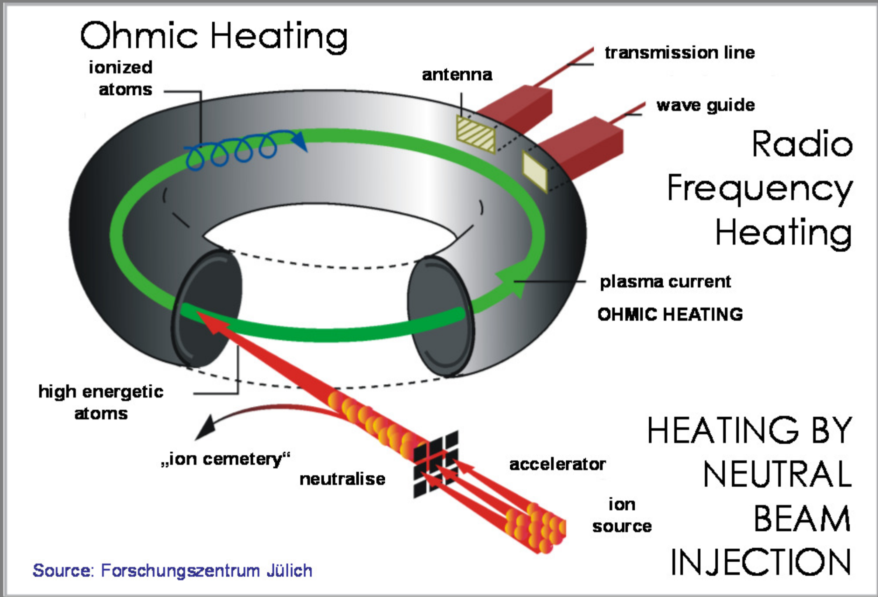
- But superconductivity requires massive measures to avoid heat loads penetrating  to the magnets through
  - Conduction
  - Convection
  - Radiation
- The cryostat consists of a
  - Thermal Shield and a

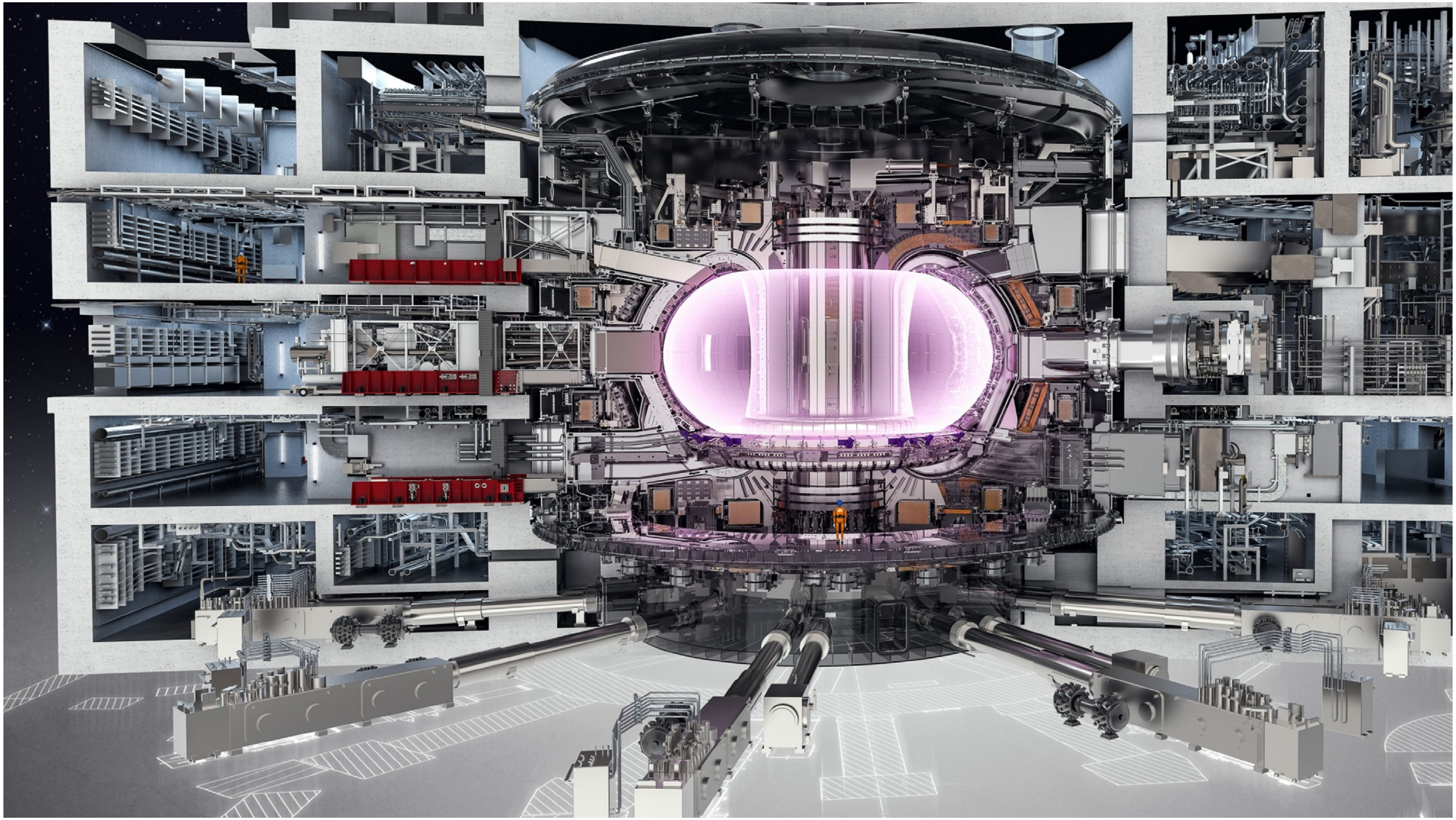
➡ **Vacuum Chamber**

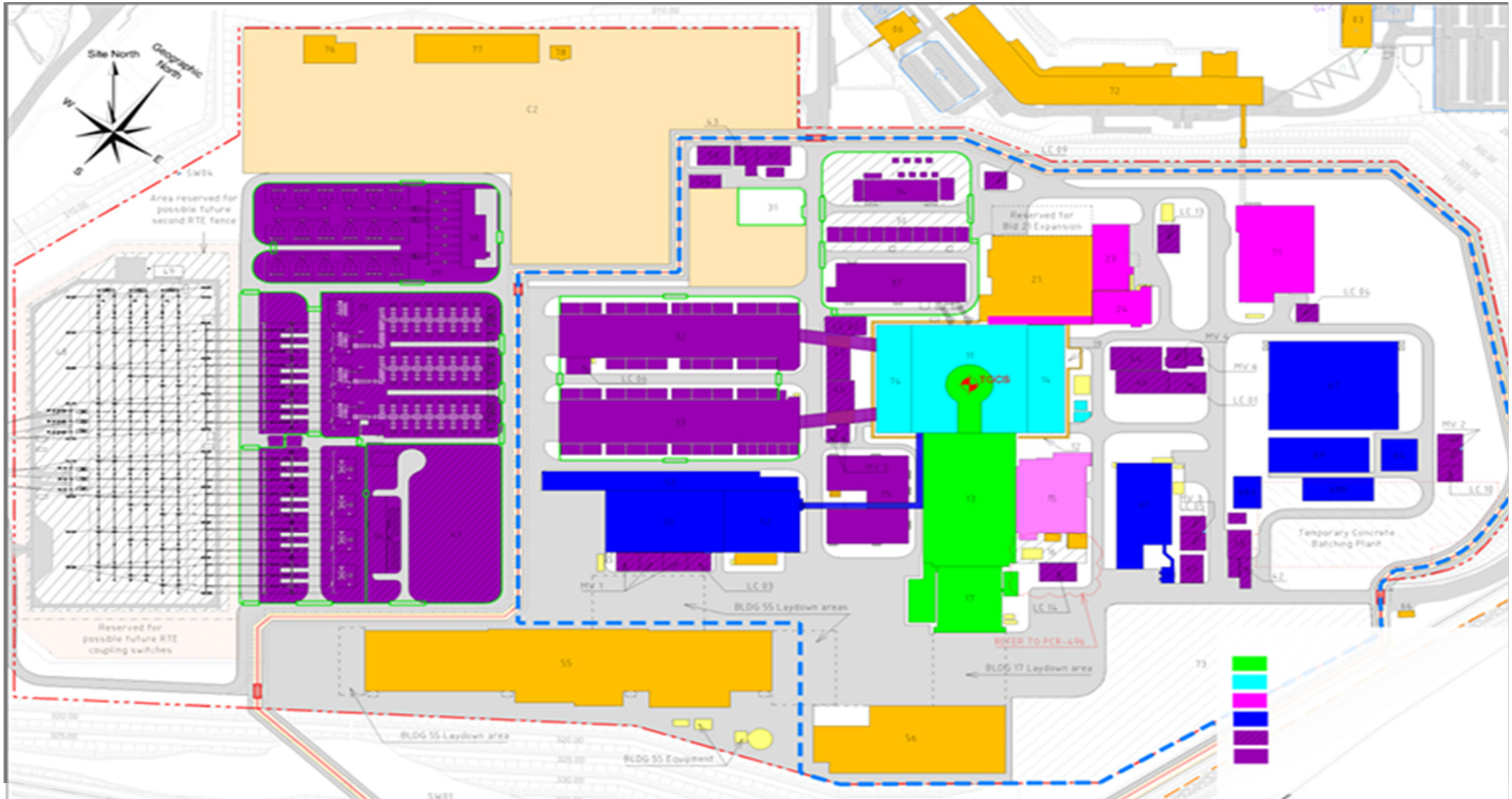
# The ITER Machine

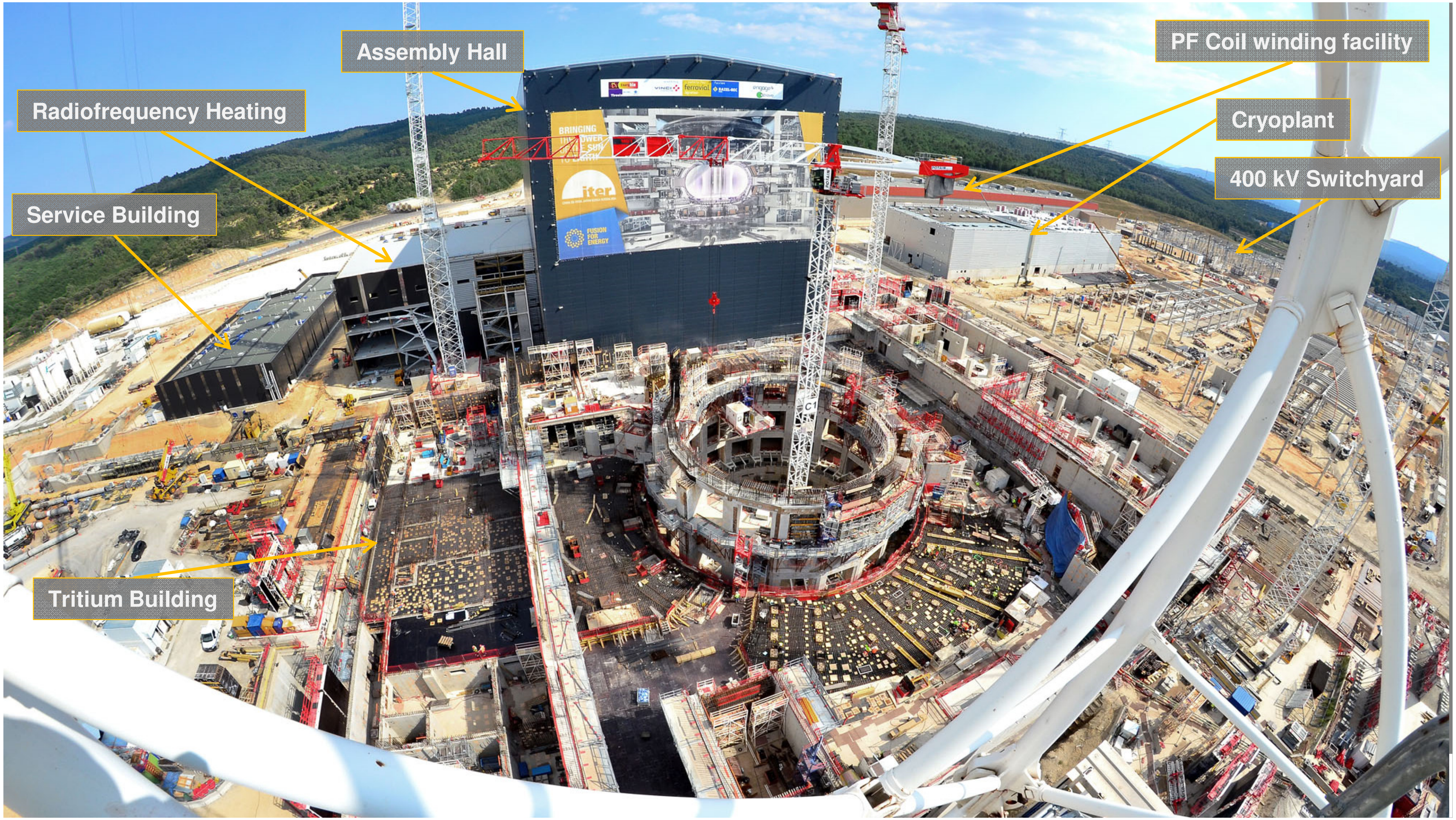
## Fundamental Engineering Concepts

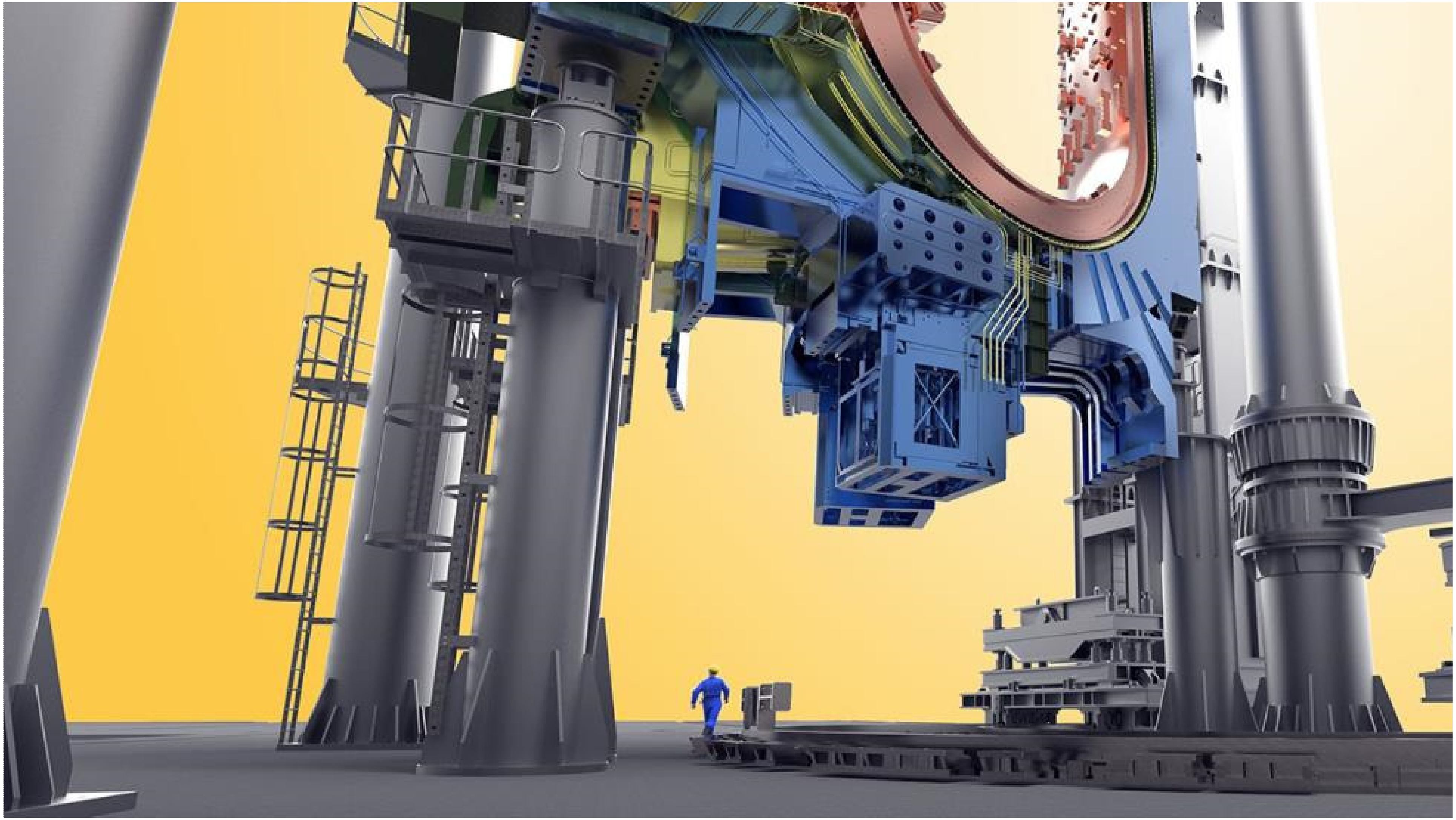
- **Heating concepts:**
  - **Ohmic heating (plasma resistivity) – only useful for 'low' plasma temperatures**
  - **Radio Frequency heating for electrons and ions – works well for all temperature range**
  - **Neutral beam injection – for higher temperature ranges and for fueling**






Site North
Geographic North
TOCS

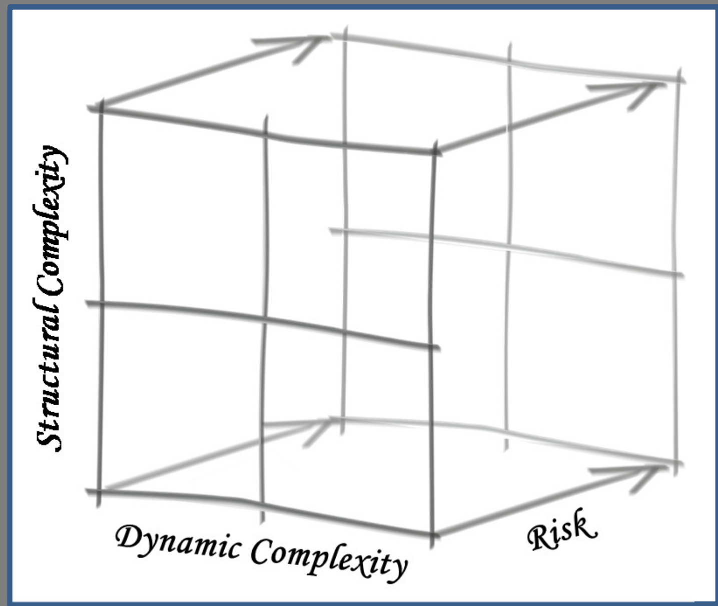

Assembly Hall
PF Coil winding facility
Radiofrequency Heating
Cryoplant
400 kV Switchyard
Service Building
Tritium Building



# Table of Contents

# ITER Systems Engineering
## Project Complexity

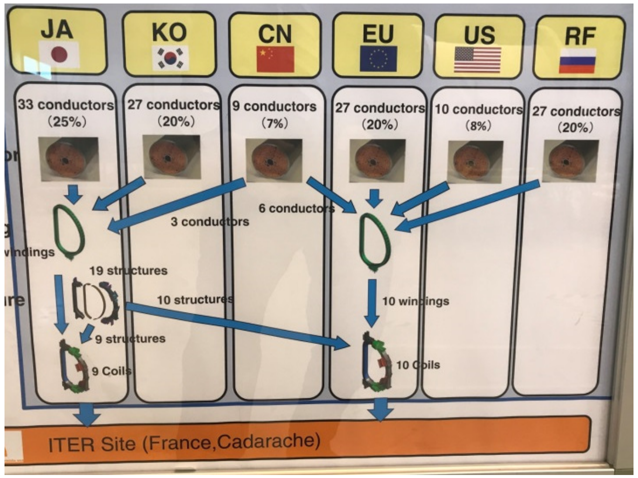
- ❑ Structural Complexity
- ❑ Dynamic Complexity
- ❑ Risk

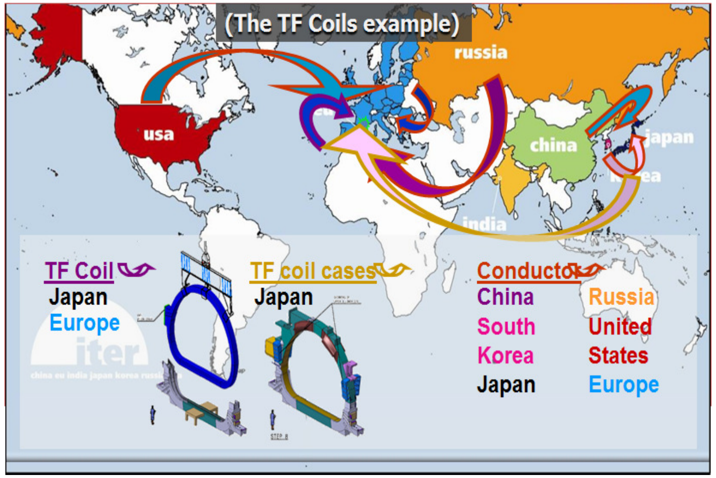


# ITER Systems Engineering

## Structural Complexity

**Global Supply Chain**



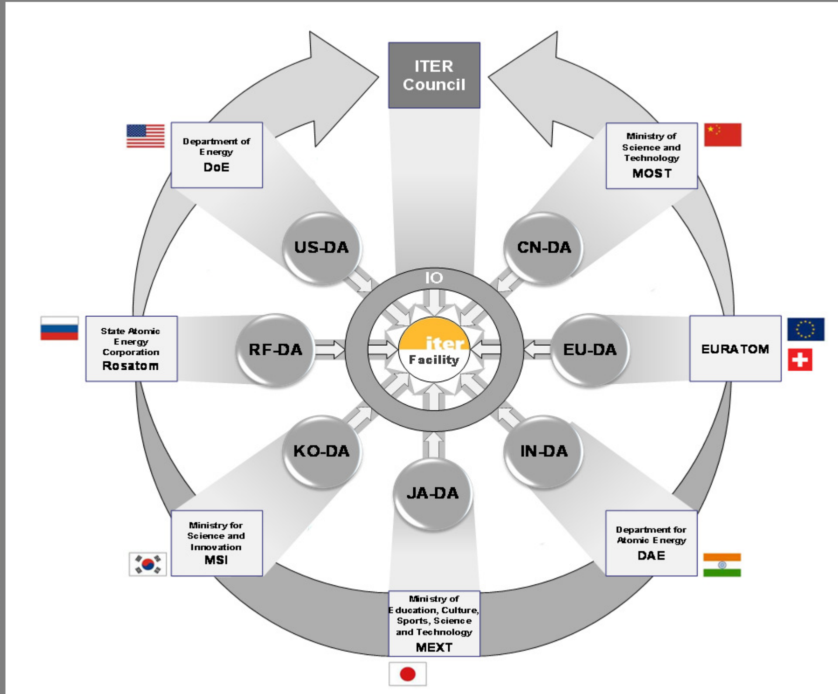



# ITER Systems Engineering

## Structural Complexity

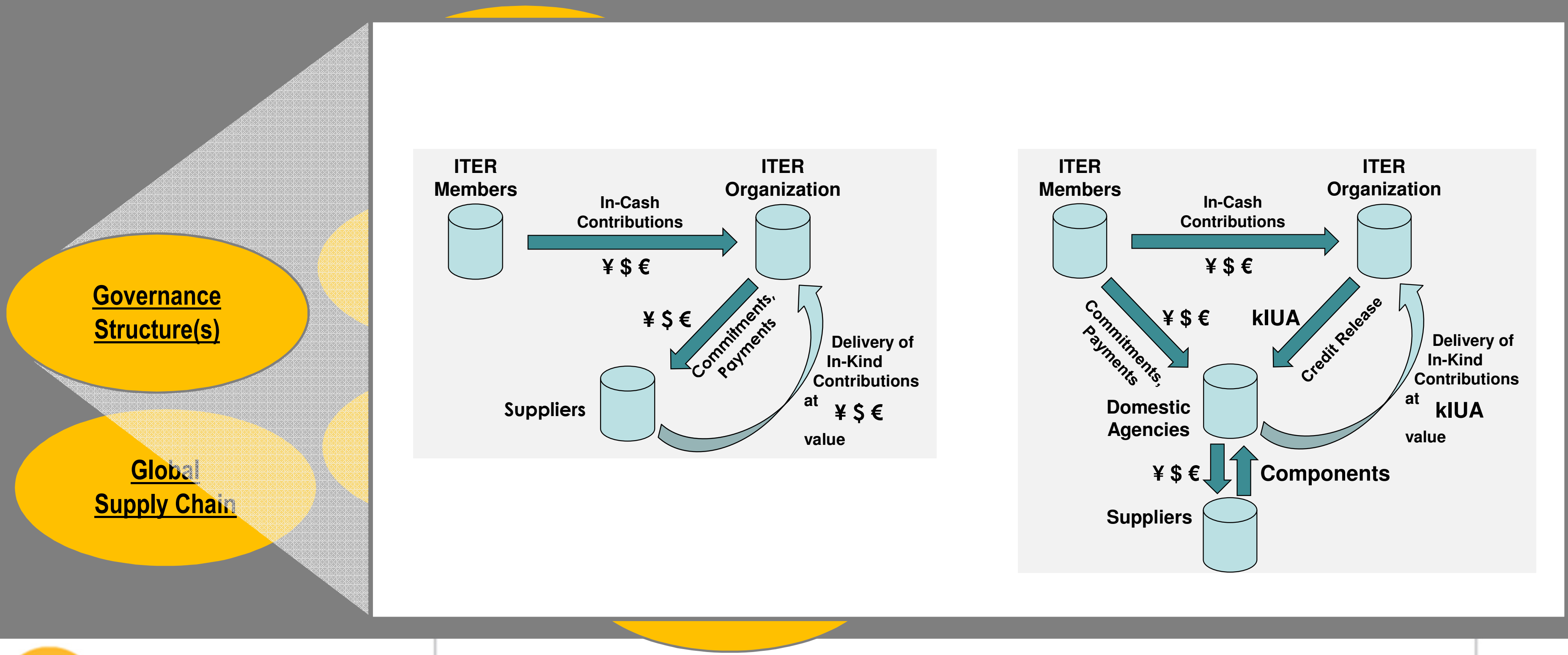
**Governance Structure(s)**

**Global Supply Chain**




### ITER Agreement

# ITER Systems Engineering
## Structural Complexity



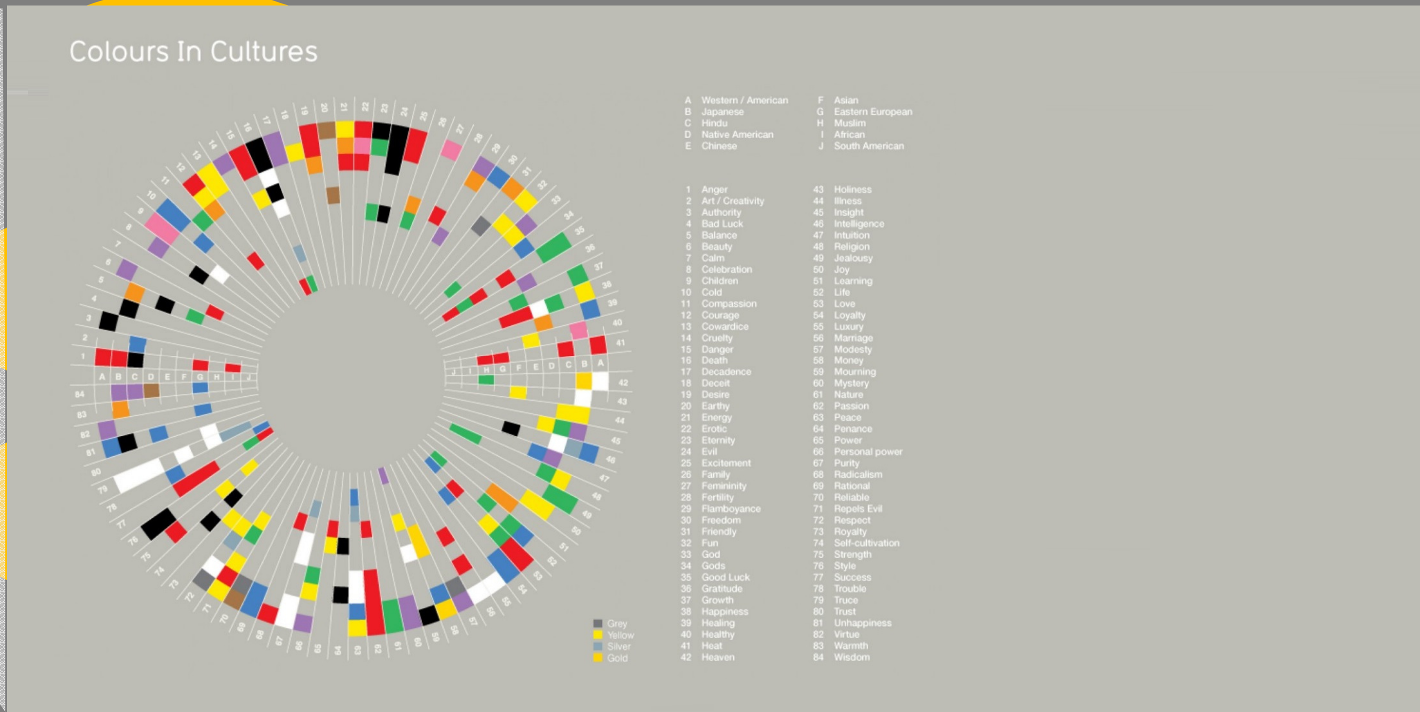
# ITER Systems Engineering

## Structural Complexity

**Cultures:**
A380: 1 Member
ISS: 5 Members
ITER: 7 Members

**Governance Structure(s)**

**Global Supply Chain**



# ITER Systems Engineering

## Structural Complexity

**Cultures:**
A380: 1 Member
ISS: 5 Members
ITER: 7 Members

**Drawings:**
A380: 79,000
ITER: 250,000

**Governance Structure(s)**

**Cost of Development**
ISS: 100 €bn
ITER: 20 €bn

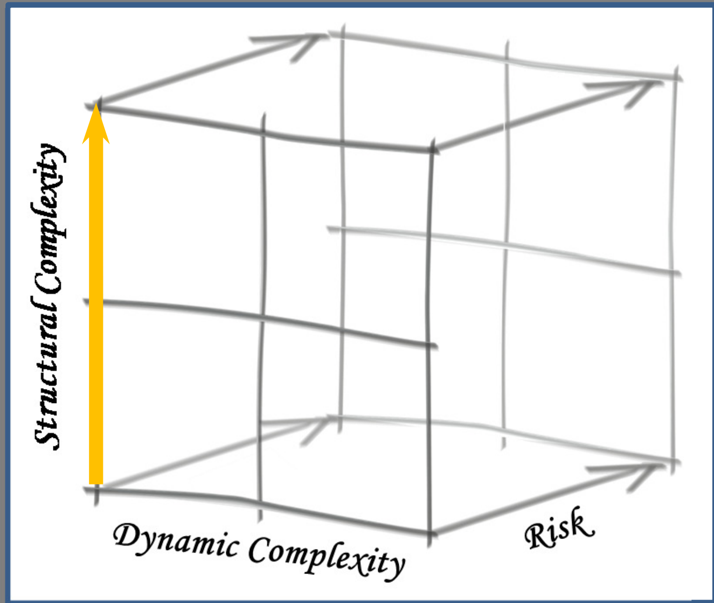
**Project FTEs:**
A380: 6,000
ITER: 3,000

**Global Supply Chain**

**Parts:**
747: $5 \cdot 10^6$
ITER: $10 \cdot 10^6$

**System of Systems**

**Interface Challenges and Systems**



# ITER Systems Engineering

## Dynamic Complexity

Technology Changes

Product Changes

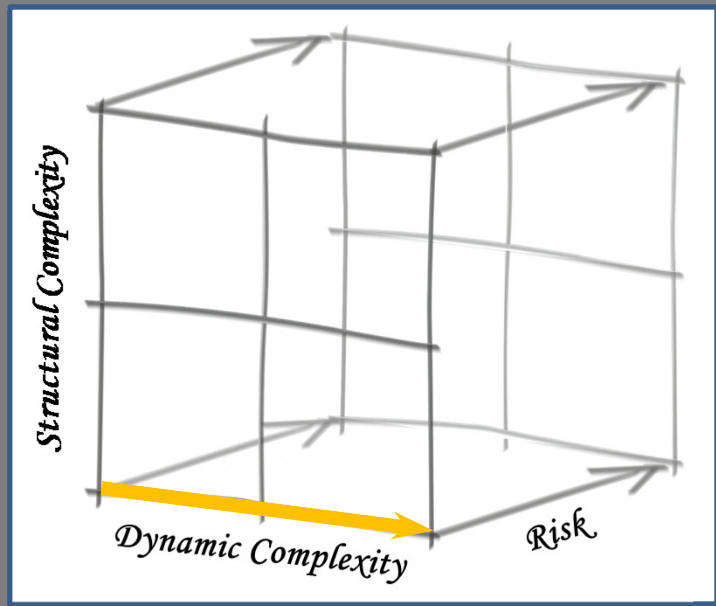
Financing Changes

Objectives Changes

Process Changes

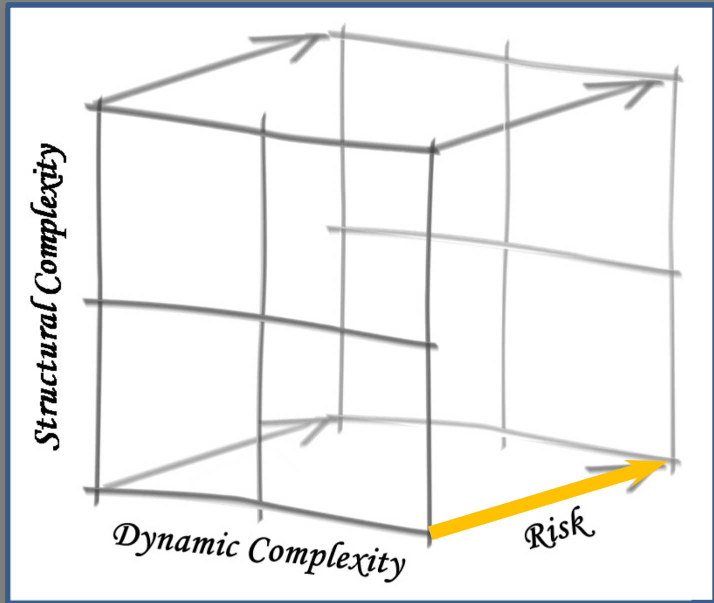
People Changes

Organization Changes



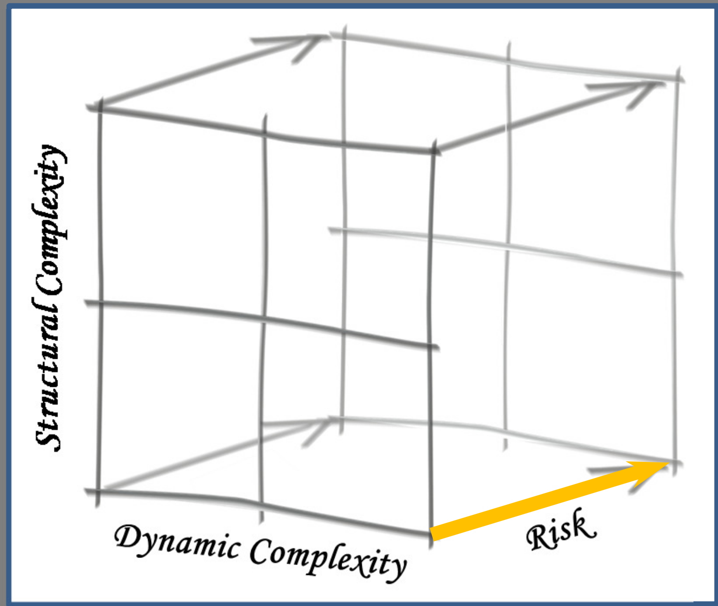
# ITER Systems Engineering
## Risk

- A Risk represents a future Issue which may occur with a certain probability (i.e., 0% < p < 100%).
- An Issue represents an adverse deviation from the program baseline(s) (e.g. scope, time, costs), which has already occurred (i.e., it always occurs at a probability of 100%).
- An Opportunity represents a chance to improve the program conditions which can be implemented with a certain probability (i.e., 0% < p ≤ 100%).



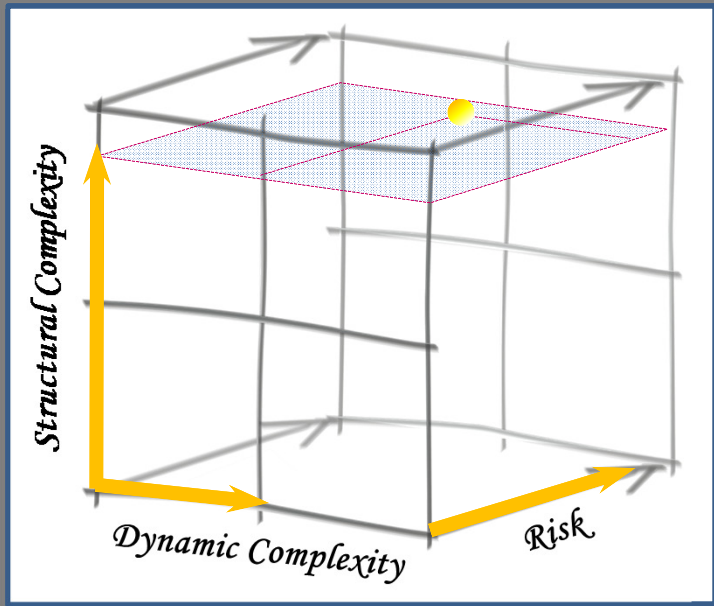
# ITER Systems Engineering

## Risk



# ITER Systems Engineering
## Project Complexity

- High Structural Complexity
- Medium Dynamic Complexity
- More than medium Risk

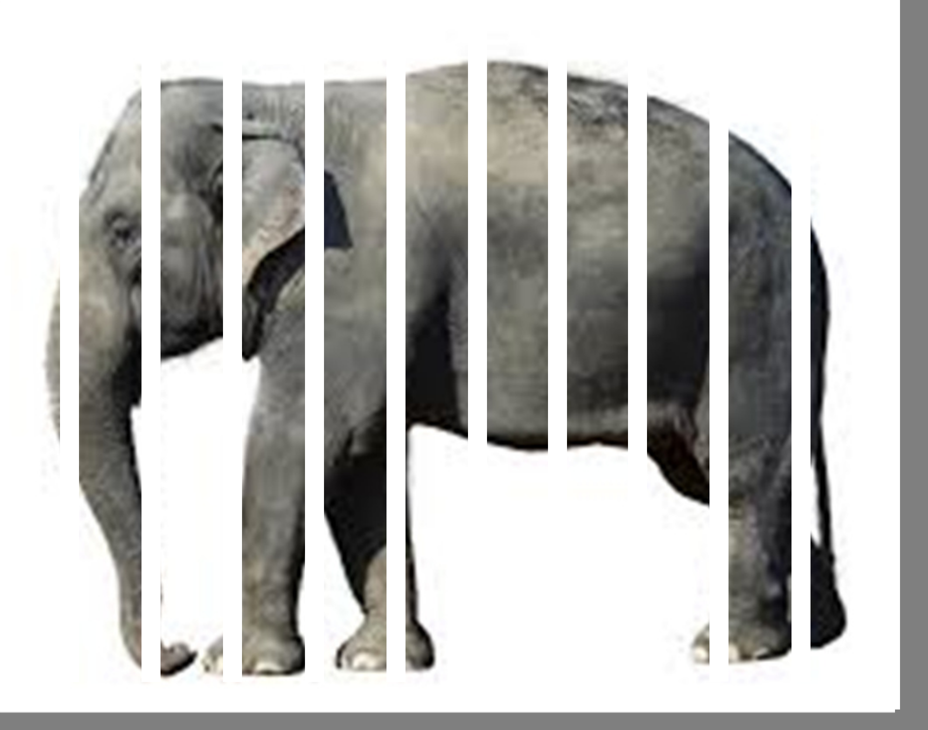



⇨ **A Project of significant Complexity!**

# ITER Systems Engineering

## Addressing Structural Complexity

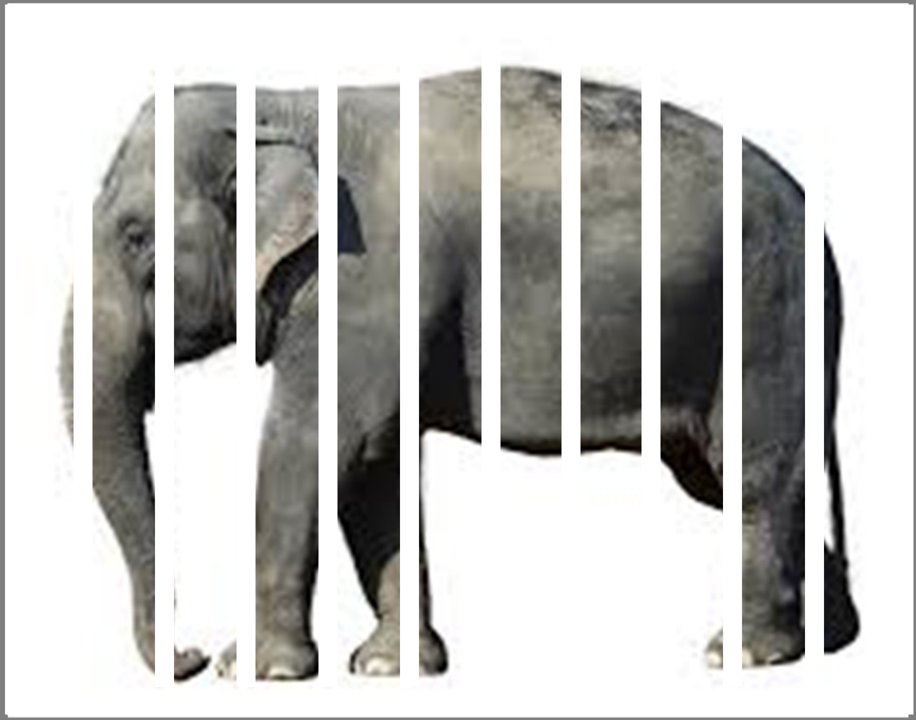
➡ **Slicing the Elephant**



# ITER Systems Engineering

## Addressing Structural Complexity

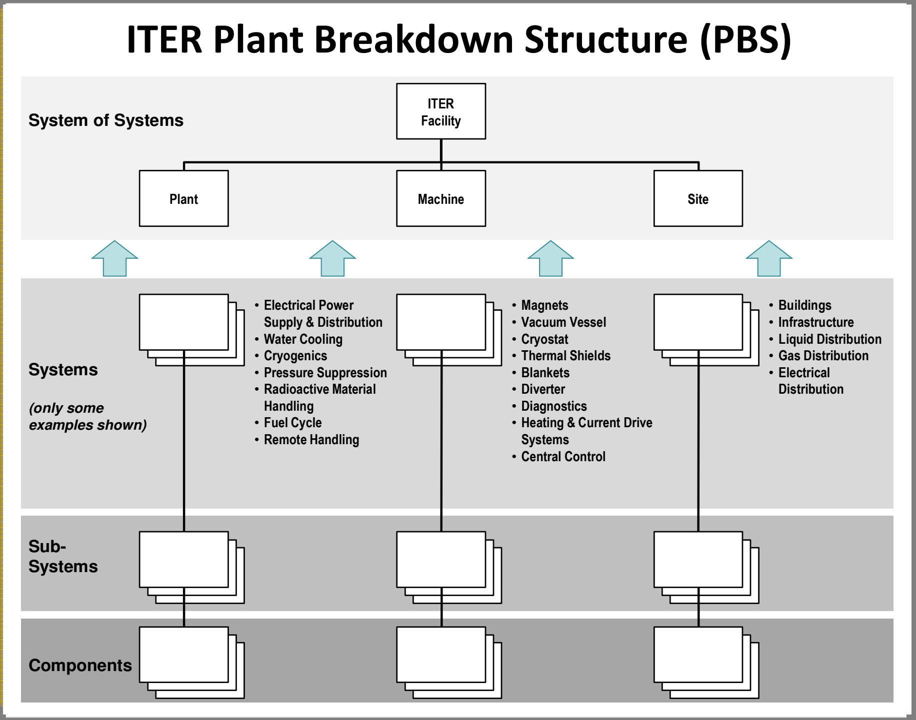
- Break down of content along different dimensions, e.g.
  - System
  - Work
  - Requirements / V&V
  - Schedule
  - Site
  - Organization



# ITER Systems Engineering

## Addressing Structural Complexity

- ❑ Break down of content along different dimensions, e.g.
  - ❑ **System**

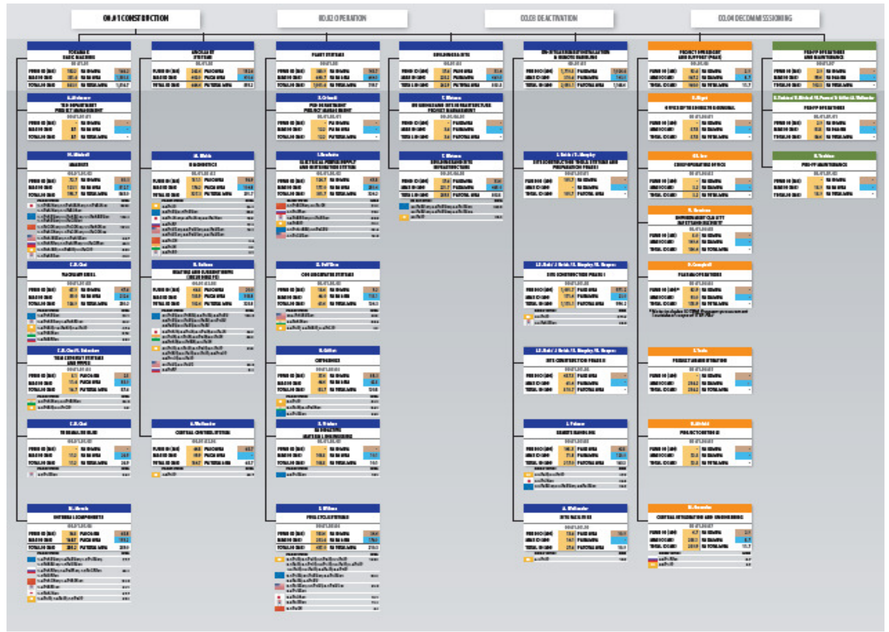


# ITER Systems Engineering

## Addressing Structural Complexity

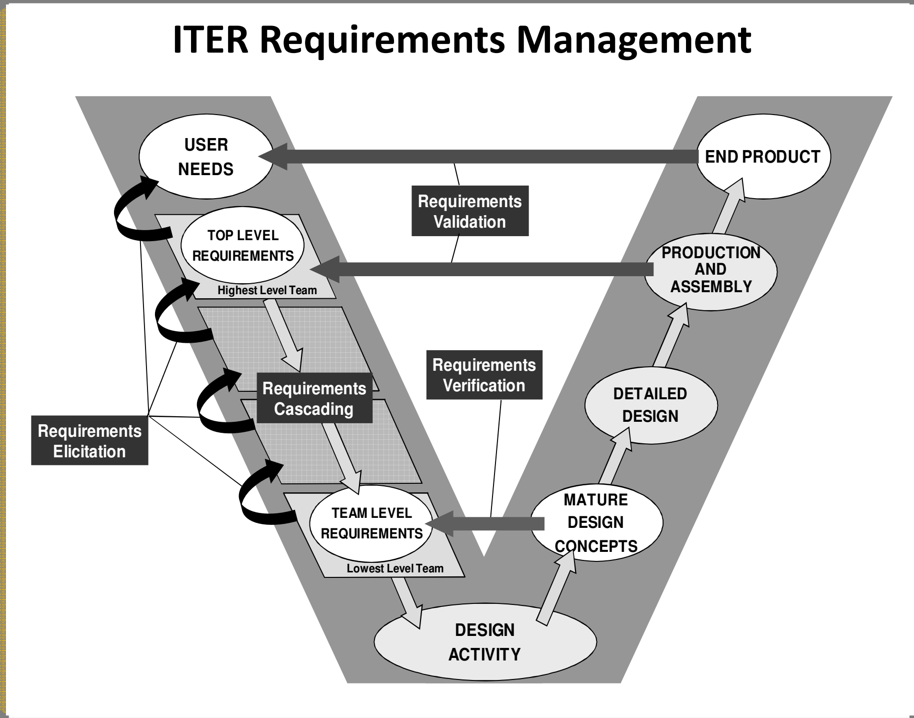
- ❑ Break down of content along different dimensions, e.g.
  - ❑ System
  - ❑ **Work**

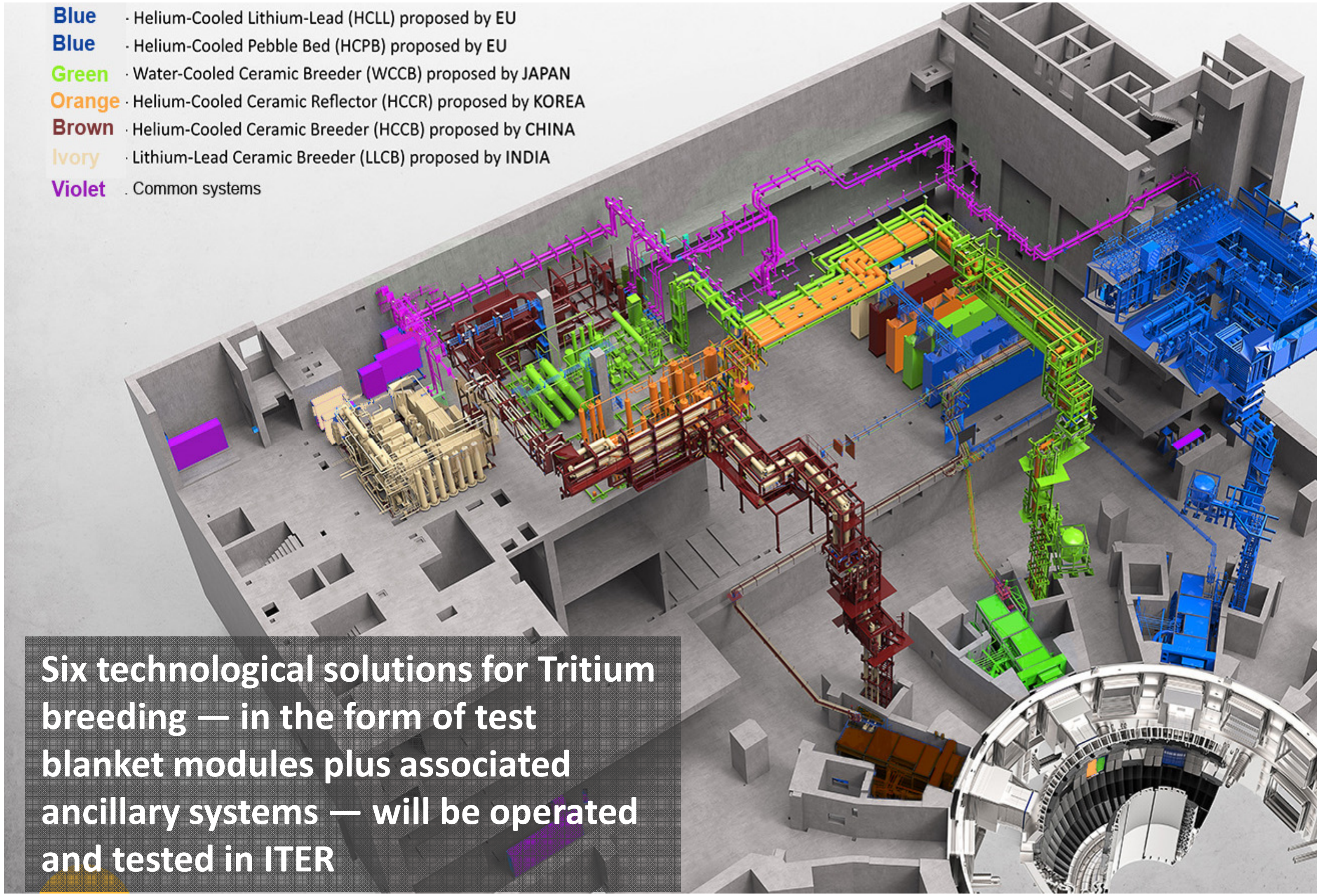
ITER Work Breakdown Structure (WBS)

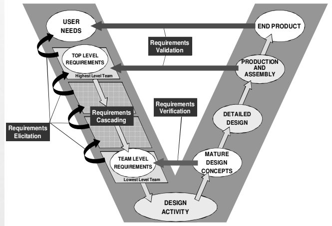


# ITER Systems Engineering
## Addressing Structural Complexity

- ❑ Break down of content along different dimensions, e.g.
  - ❑ System
  - ❑ Work
  - ❑ **Requirements**

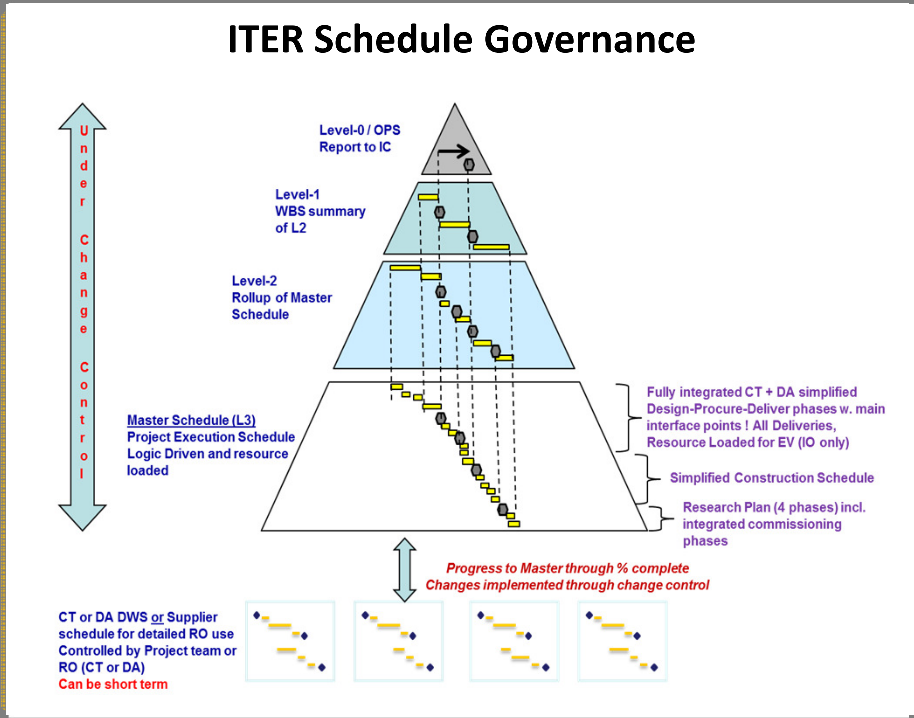



Blue · Helium-Cooled Lithium-Lead (HCLL) proposed by EU
Blue · Helium-Cooled Pebble Bed (HCPB) proposed by EU
Green · Water-Cooled Ceramic Breeder (WCCB) proposed by JAPAN
Orange · Helium-Cooled Ceramic Reflector (HCCR) proposed by KOREA
Brown · Helium-Cooled Ceramic Breeder (HCCB) proposed by CHINA
Ivory · Lithium-Lead Ceramic Breeder (LLCB) proposed by INDIA
Violet . Common systems
Six technological solutions for Tritium breeding — in the form of test blanket modules plus associated ancillary systems — will be operated and tested in ITER


USER NEEDS
END PRODUCT
Requirements Validation
TOP LEVEL REQUIREMENTS
Highest Level Team
PRODUCTION AND ASSEMBLY
Requirements Cascading
Requirements Verification
Requirements Elicitation
DETAILED DESIGN
TEAM LEVEL REQUIREMENTS
Lowest Level Team
MATURE DESIGN CONCEPTS
DESIGN ACTIVITY

# ITER Systems Engineering
## Addressing Structural Complexity

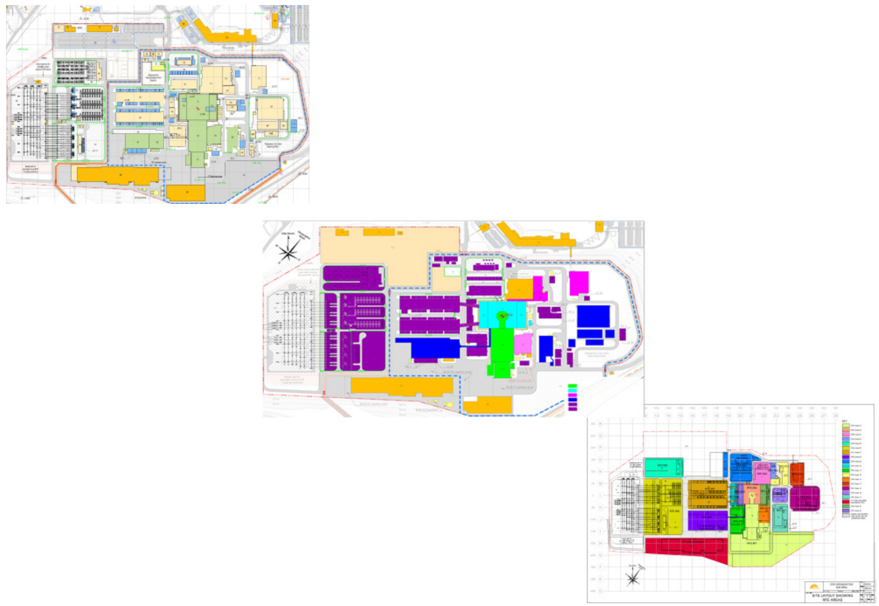
- ❑ Break down of content along different dimensions, e.g.
  - ❑ System
  - ❑ Work
  - ❑ Requirements
  - ❑ **Schedule**



# ITER Systems Engineering
## Addressing Structural Complexity

- Break down of content along different dimensions, e.g.
  - System
  - Work
  - Requirements
  - Schedule
  - **Site**

**ITER Geographic Breakdown Structure (GBS)**

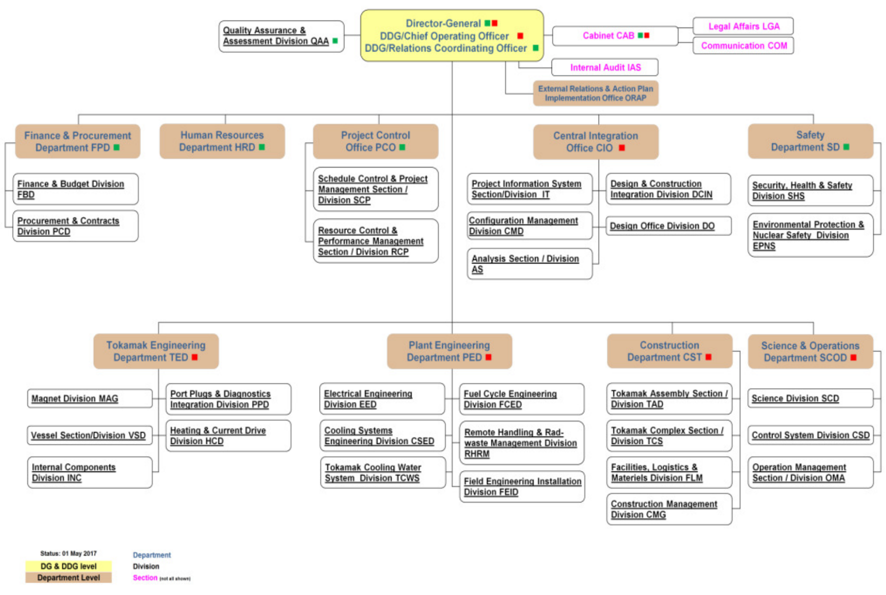


# ITER Systems Engineering

## Addressing Structural Complexity

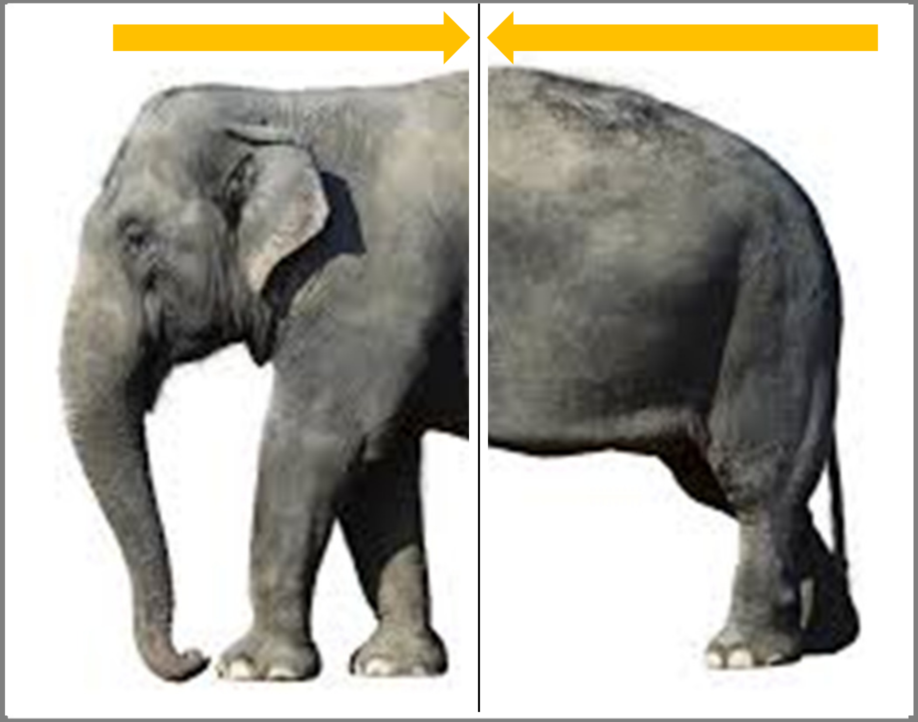
- ❑ Break down of content along different dimensions, e.g.
  - ❑ System
  - ❑ Work
  - ❑ Requirements
  - ❑ Schedule
  - ❑ Site
  - ❑ **Organization**

### ITER Organization Breakdown Structure (OBS)



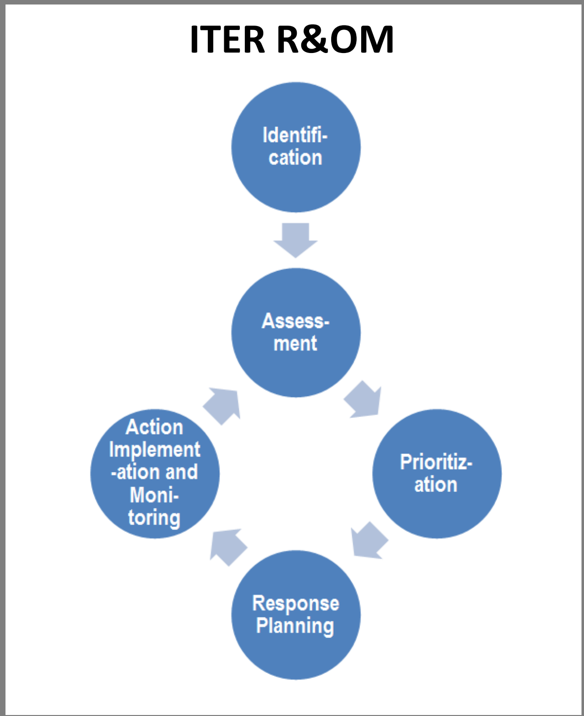
# ITER Systems Engineering
## Addressing Structural Complexity

- 'Slicing the Elephant' requires tight management and control of $I^3$
  - Interfaces
  - Interdependencies
  - Interchangeabilities



# ITER Systems Engineering
## Addressing Risk

- ❑ ITER Project Baseline comes without any initial contingencies for cost and schedule
- ❑ The Project has to identify and generate opportunities to manage issues and risks




➡ **Professional, but classical R&OM**

# ITER Systems Engineering
## Addressing Dynamic Complexity

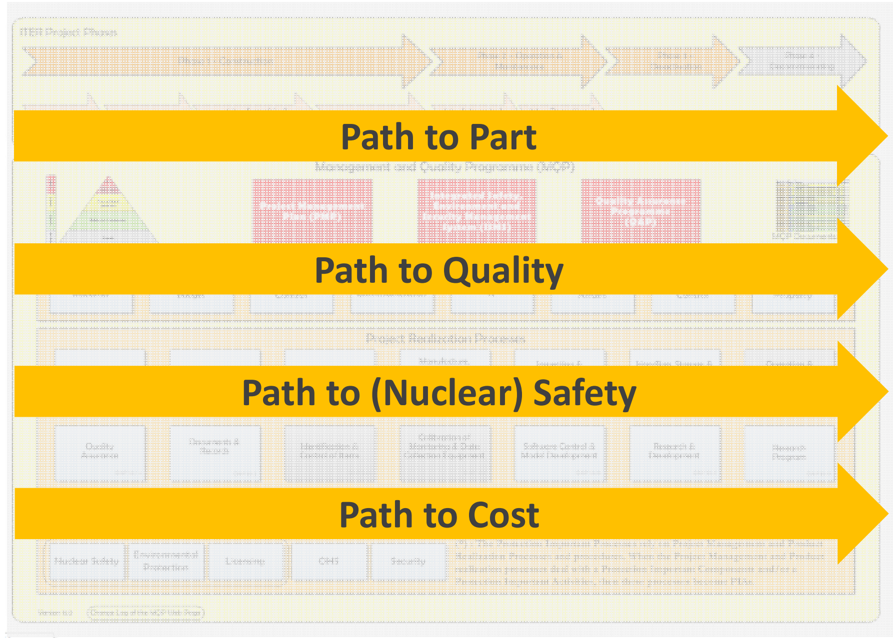
- Addressing Dynamic Complexity is all about responding to change in a controlled, yet agile manner

# ITER Systems Engineering

## Addressing Dynamic Complexity

- ❑ **Addressing Dynamic Complexity is all about responding to change in a controlled, yet agile manner.**
  - ❑ **Processes**

**ITER Management & Quality Program (MQP)**



# ITER Systems Engineering
## Addressing Dynamic Complexity

- ❑ **Addressing Dynamic Complexity is all about responding to change in a controlled, yet agile manner.**
  - ❑ **Processes**
  - ❑ **Adherence to Processes**

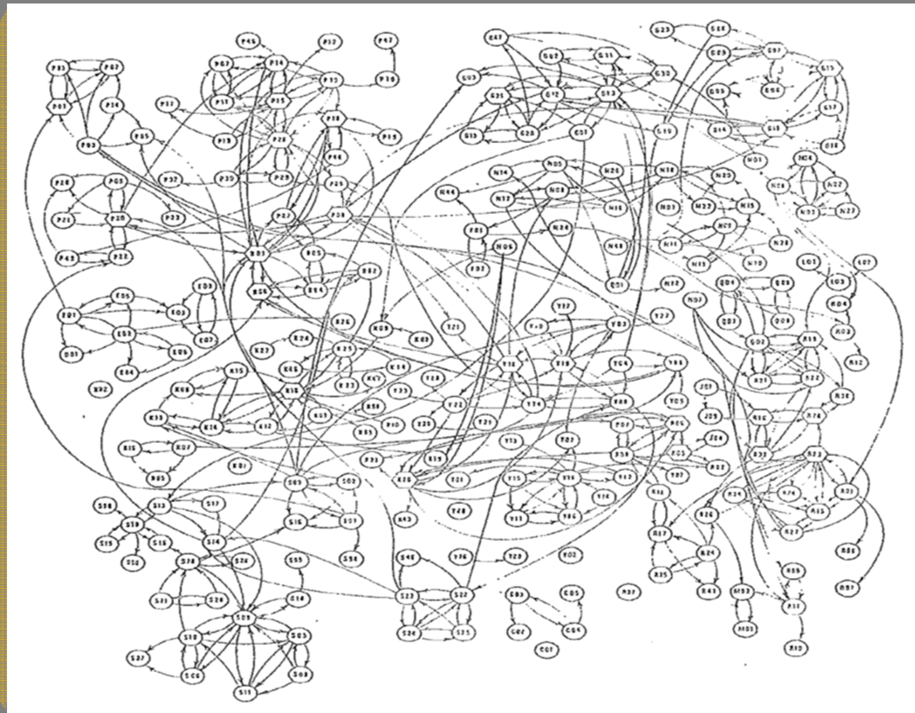
**Adhering to Processes …**

**… requires Team-Discipline and Self-Discipline!**

# ITER Systems Engineering

## Addressing Dynamic Complexity

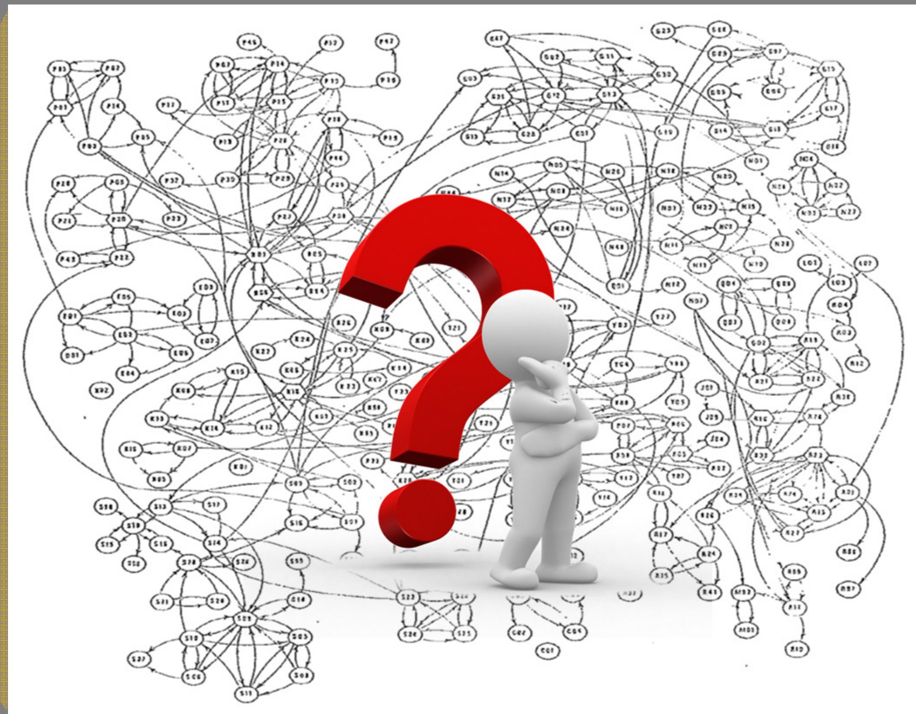
- ❑ **Addressing Dynamic Complexity is all about responding to change in a controlled, yet agile manner.**
  - ❑ **Processes**
  - ❑ **Adherence to Processes**
  - ❑ **Effective Communication**



# ITER Systems Engineering

## Addressing Dynamic Complexity

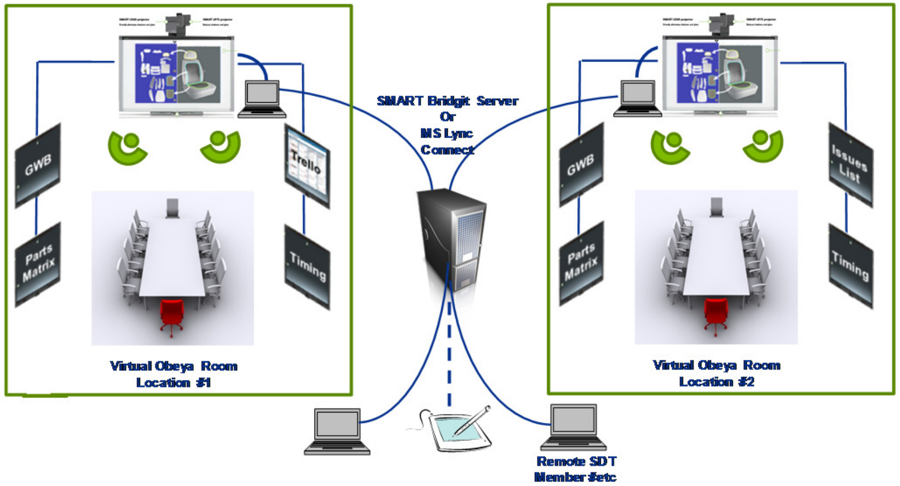
- ❑ **Addressing Dynamic Complexity is all about responding to change in a controlled, yet agile manner.**
  - ❑ **Processes**
  - ❑ **Adherence to Processes**
  - ❑ **Effective Communication**



# ITER Systems Engineering
## Addressing Dynamic Complexity

- ❑ **Addressing Dynamic Complexity is all about responding to change in a controlled, yet agile manner.**
  - ❑ **Processes**
  - ❑ **Adherence to Processes**
  - ❑ **Effective Communication**

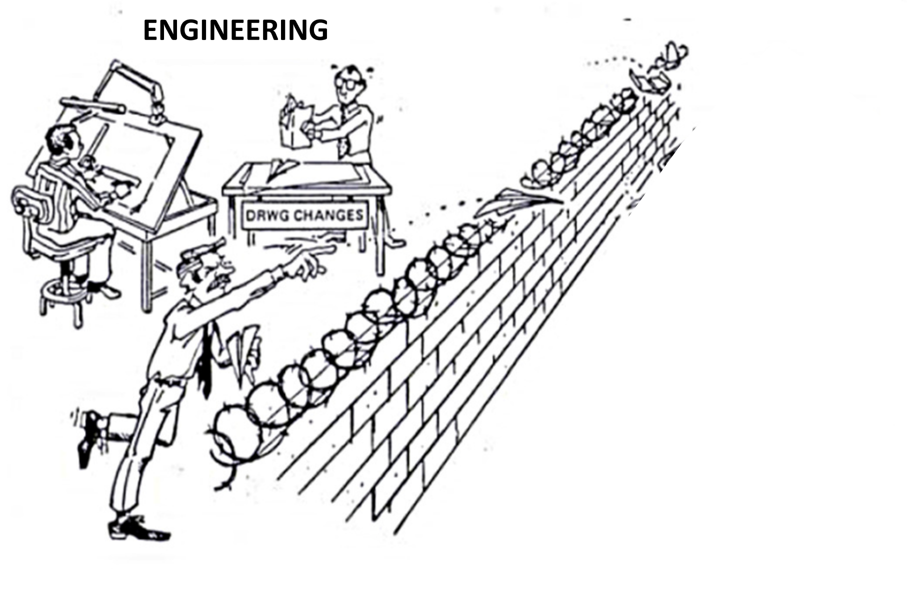
**(1) Worldwide Connectivity**



# ITER Systems Engineering
## Addressing Dynamic Complexity

- ❑ **Addressing Dynamic Complexity is all about responding to change in a controlled, yet agile manner.**
  - ❑ **Processes**
  - ❑ **Adherence to Processes**
  - ❑ **Effective Communication**

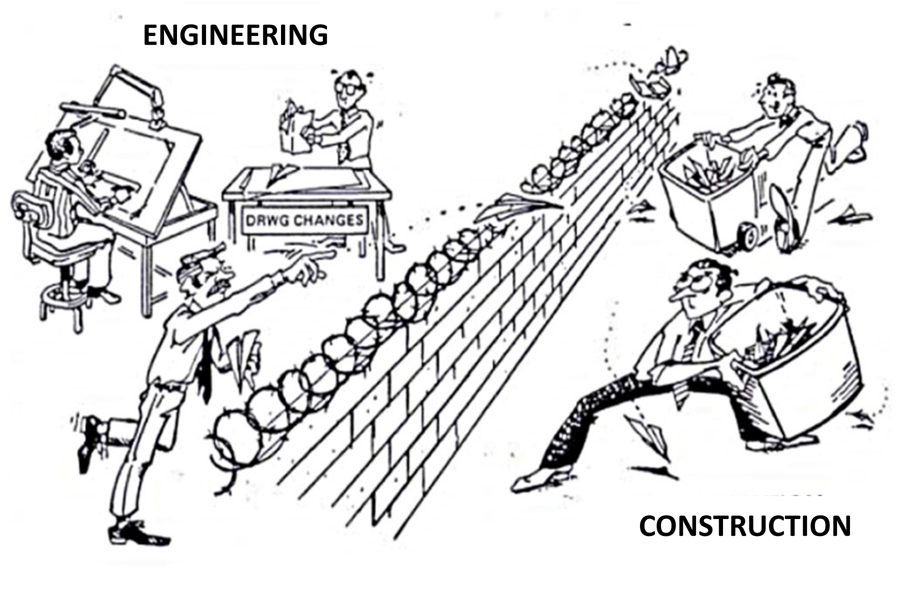
**(2) Integrated Project Teams**



# ITER Systems Engineering
## Addressing Dynamic Complexity

- ❑ **Addressing Dynamic Complexity is all about responding to change in a controlled, yet agile manner.**
  - ❑ **Processes**
  - ❑ **Adherence to Processes**
  - ❑ **Effective Communication**

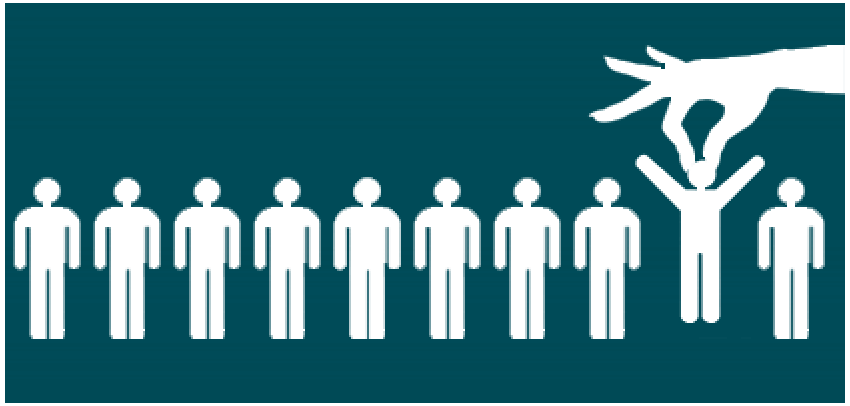
**(2) Integrated Project Teams**



# ITER Systems Engineering
## Addressing Dynamic Complexity

- ❑ **Addressing Dynamic Complexity is all about responding to change in a controlled, yet agile manner.**
  - ❑ **Processes**
  - ❑ **Adherence to Processes**
  - ❑ **Effective Communication**
  - ❑ **Competences of People**

**(1) Experience-based People Selection**



# ITER Systems Engineering
## Addressing Dynamic Complexity

- ❑ Addressing Dynamic Complexity is all about responding to change in a controlled, yet agile manner.
  - ❑ Processes
  - ❑ Adherence to Processes
  - ❑ Effective Communication
  - ❑ **Competences of People**

(2) ITER Academy

# ITER Systems Engineering
## Addressing Dynamic Complexity

- Addressing Dynamic Complexity is all about responding to change in a controlled, yet agile manner.
  - Processes
  - Adherence to Processes
  - Effective Communication
  - **Competences of People**

**(3) Annual Performance Assessment**

# ITER Systems Engineering

## Addressing Dynamic Complexity

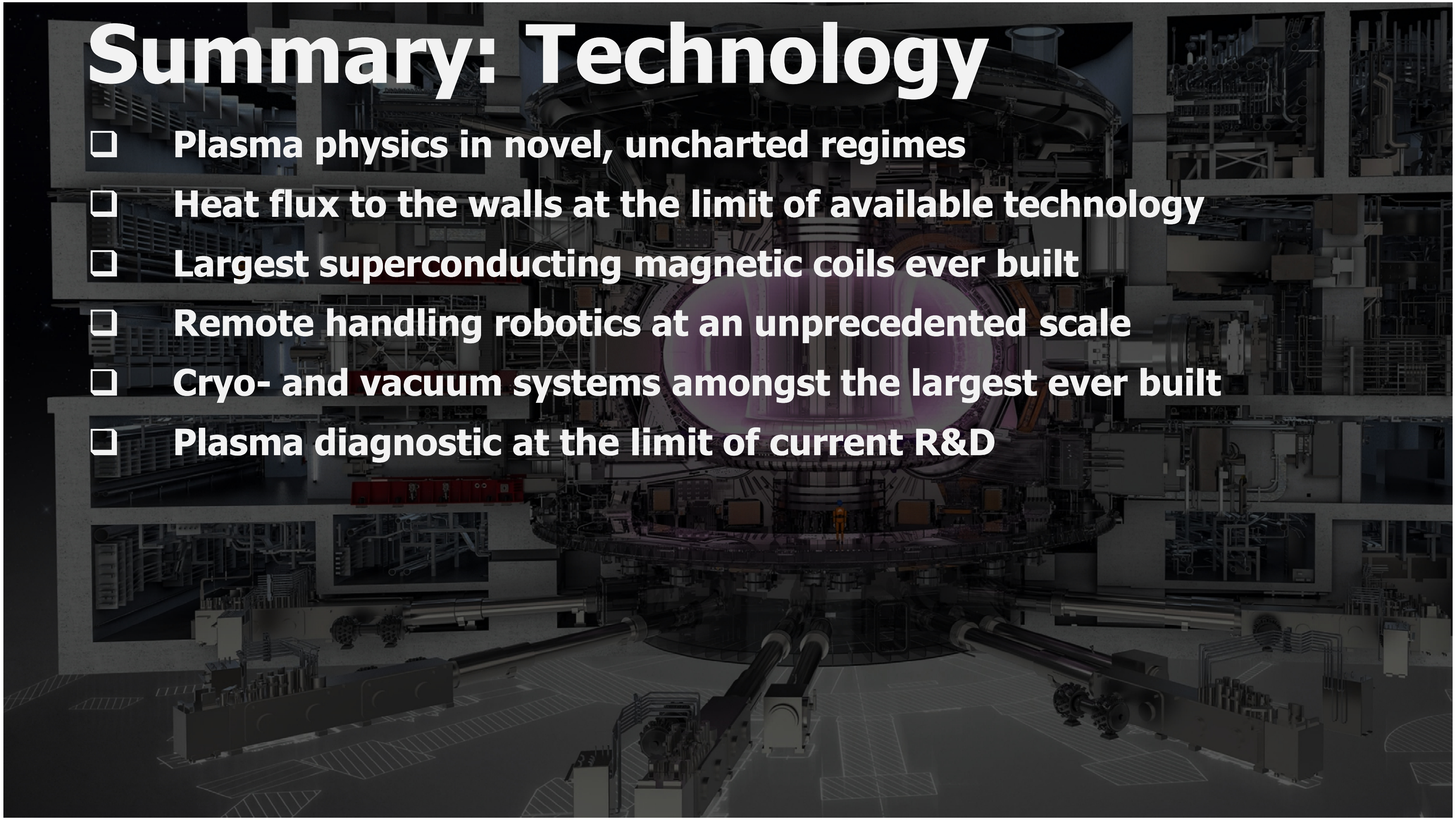
- ❑ **Addressing Dynamic Complexity is all about responding to change in a controlled, yet agile manner.**
  - ❑ **Processes**
  - ❑ **Adherence to Processes**
  - ❑ **Effective Communication**
  - ❑ **Competences of People**


**➡ Effective Communication and People Competences for ITER**

# Table of Contents

# Summary: Fusion Energy

- Nuclear fusion is the power source of the universe – source of light and heat for the sun and stars
- Fusion has the potential to be a nearly inexhaustible source of energy in the future
- Fusion is carbon neutral, comparatively ‘clean’ and safe
- No risk of nuclear accidents (e.g. core melt in Fukushima Daiichi, explosion in Tschernobyl)
- Fusion does not produce long lived radioactive waste, for which the timescale is manageable
- Reactor contains only fuel for a few seconds



# Summary: Technology

- Plasma physics in novel, uncharted regimes
- Heat flux to the walls at the limit of available technology
- Largest superconducting magnetic coils ever built
- Remote handling robotics at an unprecedented scale
- Cryo- and vacuum systems amongst the largest ever built
- Plasma diagnostic at the limit of current R&D

# Summary: Systems Engineering

- ITER Systems Engineering is all about addressing the project's Structural Complexity, Dynamic Complexity and Risk
- 'Slicing the Elephant' is the classical response to Structural Complexity, also applied at ITER
- Addressing Risks is done using classical methodologies, too
- Addressing Dynamic Complexity, however, still requires significant effort beyond the classical thinking

➡ ITER: one of the most exciting projects to be on!


Thank You!
www.iter.org