USTC SNST 2015 Autumn Semester Lecture Series

Title: Introduction to Research and Development in Tokamak Fusion Energy Science and Technology

Room 1617, 930-1130, **Saturday** October17, 2015

L3: Challenges and Opportunities of Tokamak Magnetic Fusion Energy Research and Development, Continued

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Class assistant: 徐国梁
Webpage assistant: 王伸吉

Class Dates and Plans for This Special Lecture Series

1. To work around national holidays and USTC activities

Please raise hands to confirm dates!

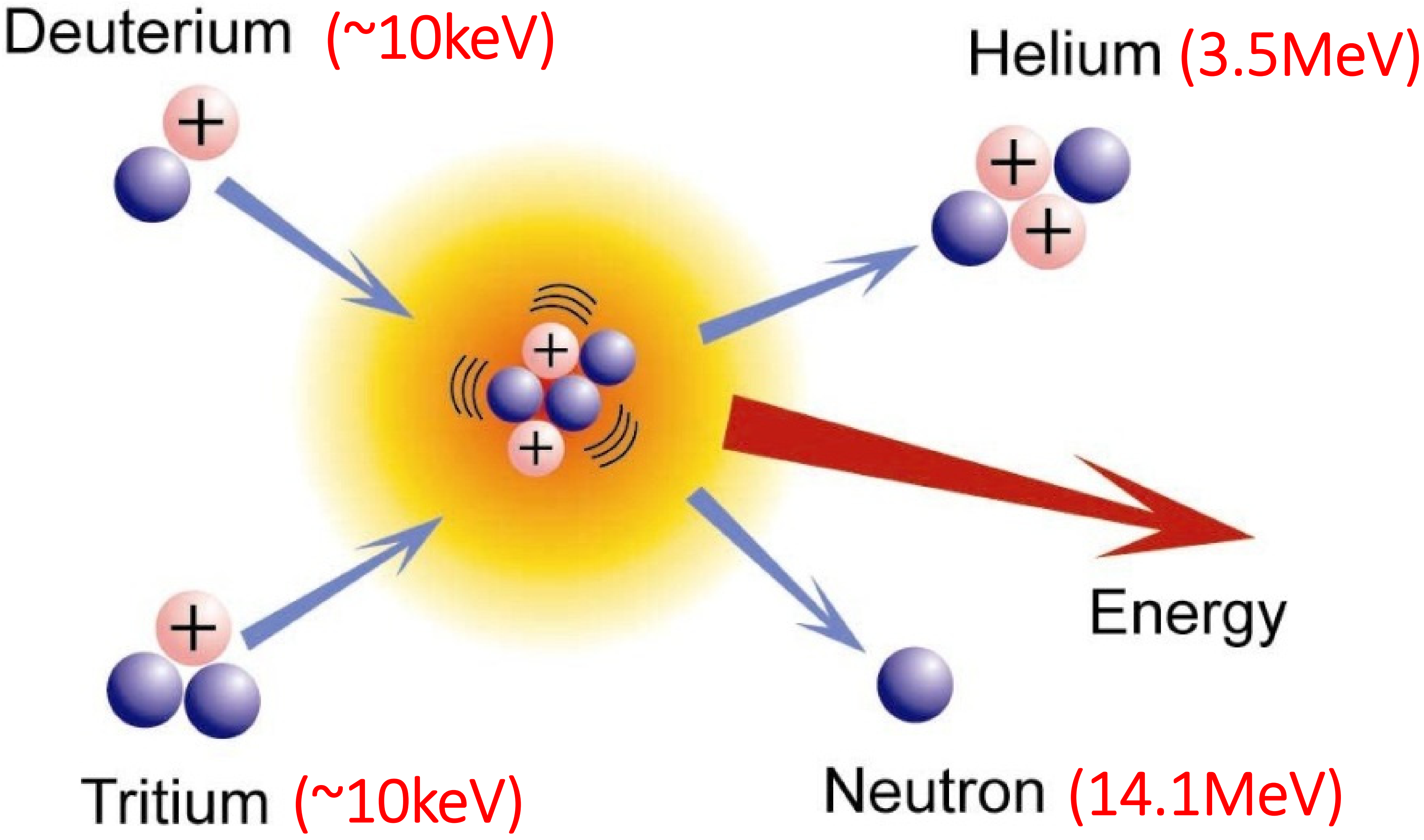
√	1) 09/12: Philosophy and approach of these lectures
√	2) 09/19: Where fusion plasma meets the material world
√	3) 10/17: Where fusion plasma meets the material world, cont.
	4) 10/24: Zone III, H-mode plasma pedestal, behind the “frontline”
	5) 11/21: Frontline: SOL, PMI, and PFC
	6) 11/28: 2nd-line: neutron irradiation on the materials
	7) 12/12: 2nd-line: neutron irradiation on the materials, cont.
	8) 12/19: 3rd-line: tritium, tritium, everywhere
	9) 01/09: 3rd-line: tritium, tritium, not here
	10) 01/23: Semester conclusion, discussion, and feedback

Great challenges of magnetic fusion energy bring great opportunities in science and technology advancement

- Why is magnetic fusion energy attractive?
- Scientific and technical features of tokamak fusion, the ITER example
- **Plasma fusion core** properties is adequately understood for ITER project
- Present focus of R&D
  - Plasma-material interface – divertor, first wall, interface for heating and diagnostic systems, the **“frontline”**
  - Power conversion system – fusion nuclear blankets, the **“2nd line”**
  - Tritium self-sufficiency – tritium production & recovery, the **“3rd line”**
- Potentials beyond deuterium-tritium fusion

Opportunities abound in developing the knowledge and know-how to make fusion energy available to help enable a sustainable world.

Most Popular Fusion Process in Magnetic Fusion Energy R&D Today



What does this mean, potentially?

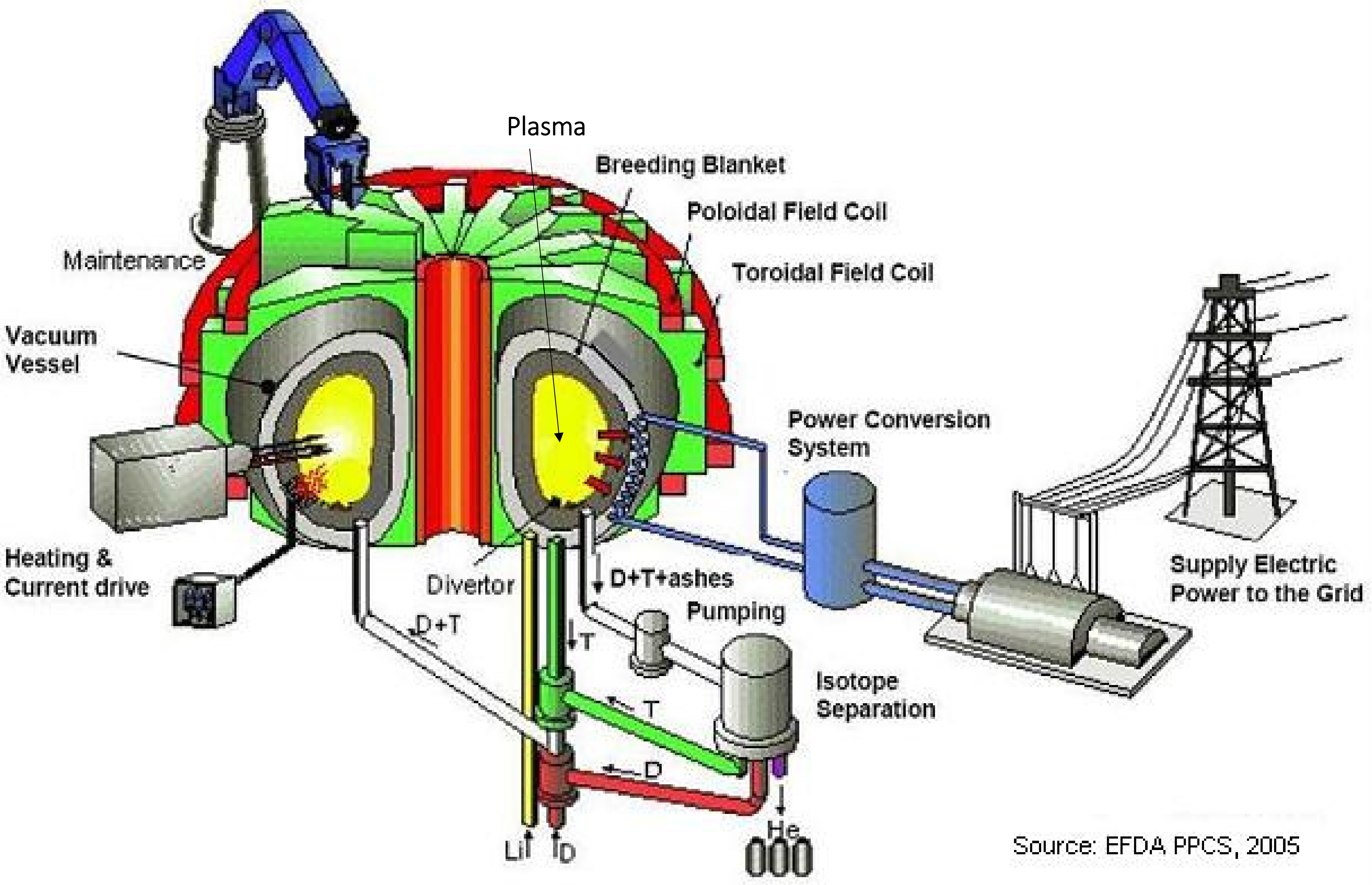
- D-T cycle: ^{2}H (10keV) + ^{3}H (10keV) $\rightarrow$ n (14.1MeV) + ^{4}He (3.5MeV)
- One gram of D-T fuel $\Rightarrow$ 90 MW-hour in energy

  One pound of D-T fuel $\Rightarrow$ 5 thousand tons of coal in energy
- D-T fusion ash is non-radioactive helium
- D-T fusion neutrons transmute wall and blanket materials making them radioactive – so develop and use low-activation materials
- D-T fusion nuclear environment introduces new challenges and opportunities compared to fission nuclear environment
- Ultimately, other more challenging fusion cycles, such as p-^{11}B:

  ^{1}H (30keV) + ^{11}B (30keV) $\rightarrow$ 3^{4}He (8.7MeV), produces no radioactivity!

The world deserves a sustainable energy future; and fusion energy can be a big part of it

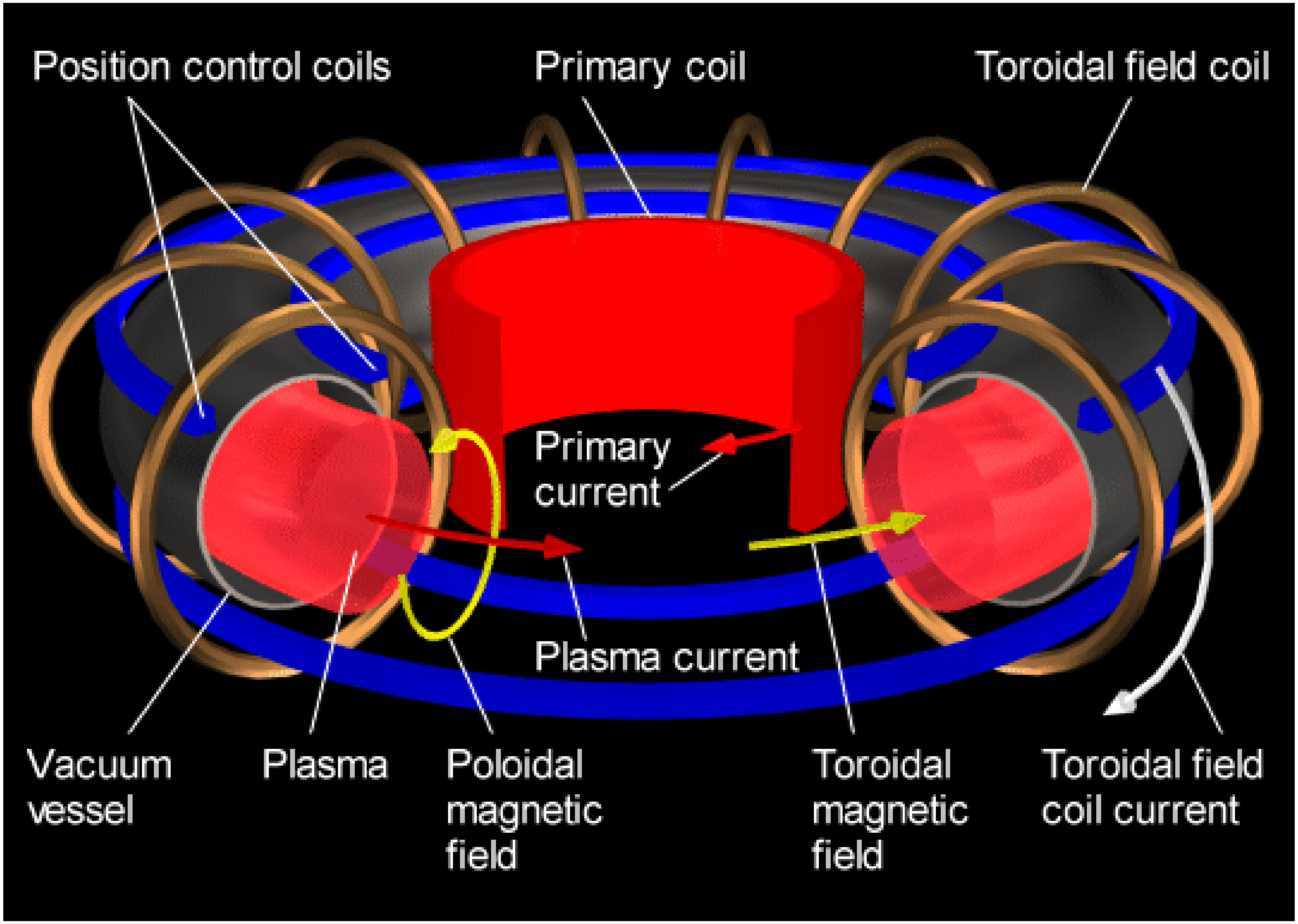
A Basic Concept of Future Tokamak Fusion Power Plant



Source: EFDA PPCS, 2005

The Most Popular Fusion Device Configuration Today

Tokamak



Present-Day Tokamak Experiment Is Complex

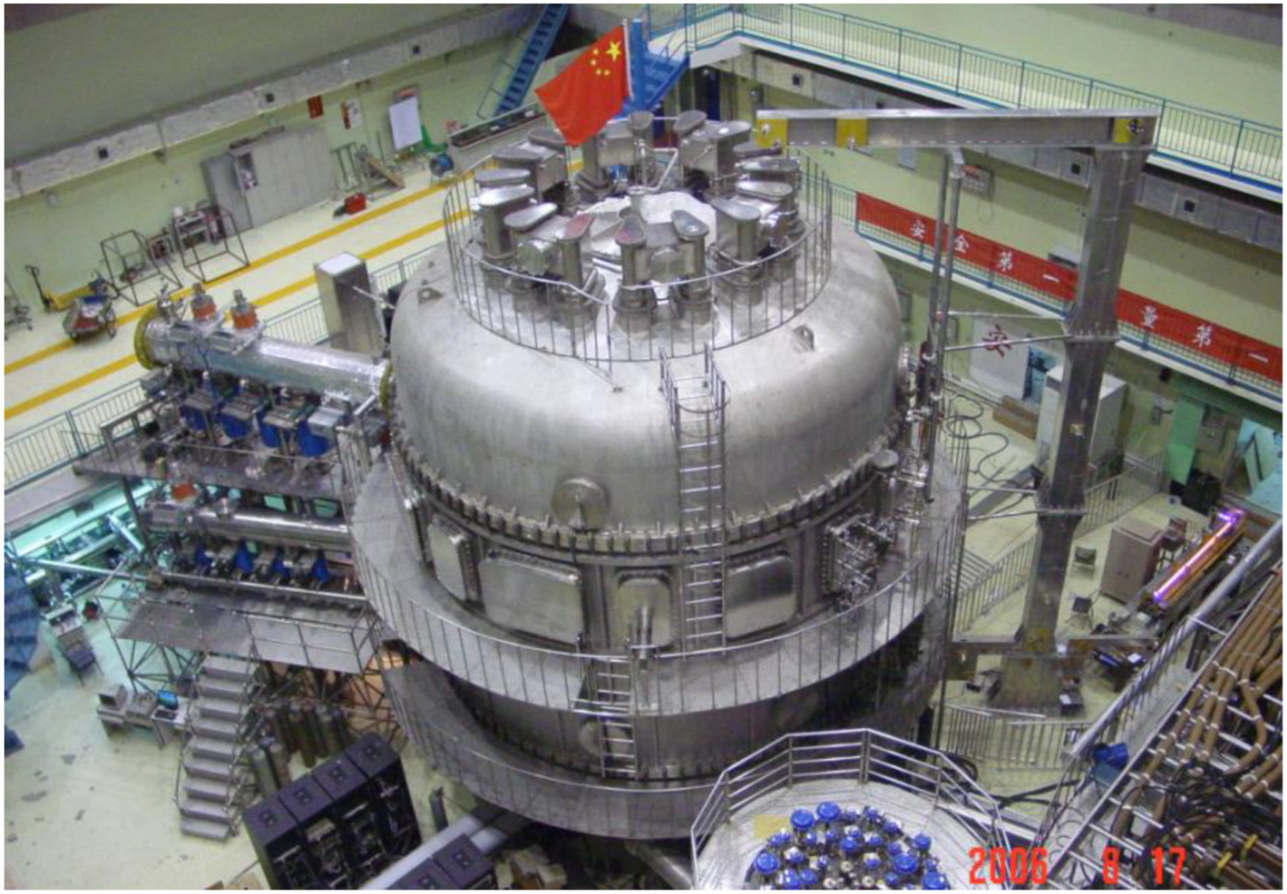
Early Picture of EAST Superconducting Coil Tokamak, ASIPP

Main Parameters of the EAST

	Nominal	**Upgrade**
B_o	3.5 T	4.0 T
I_P	1 MA	1.5 MA
R_o	1.7 m	1.7 m
a	0.4 m	0.4 m
R/a	4.25	4.25
K_x	1.2-1.5	1.5-2
δ_x	0.2-0.3	0.3-0.5
Heating and Driving:		
ICRH	3 MW	6 MW
LHCD	3.5 MW	8 MW
ECRH		2 MW
NBI		8 MW
Pulse length	1000 s	

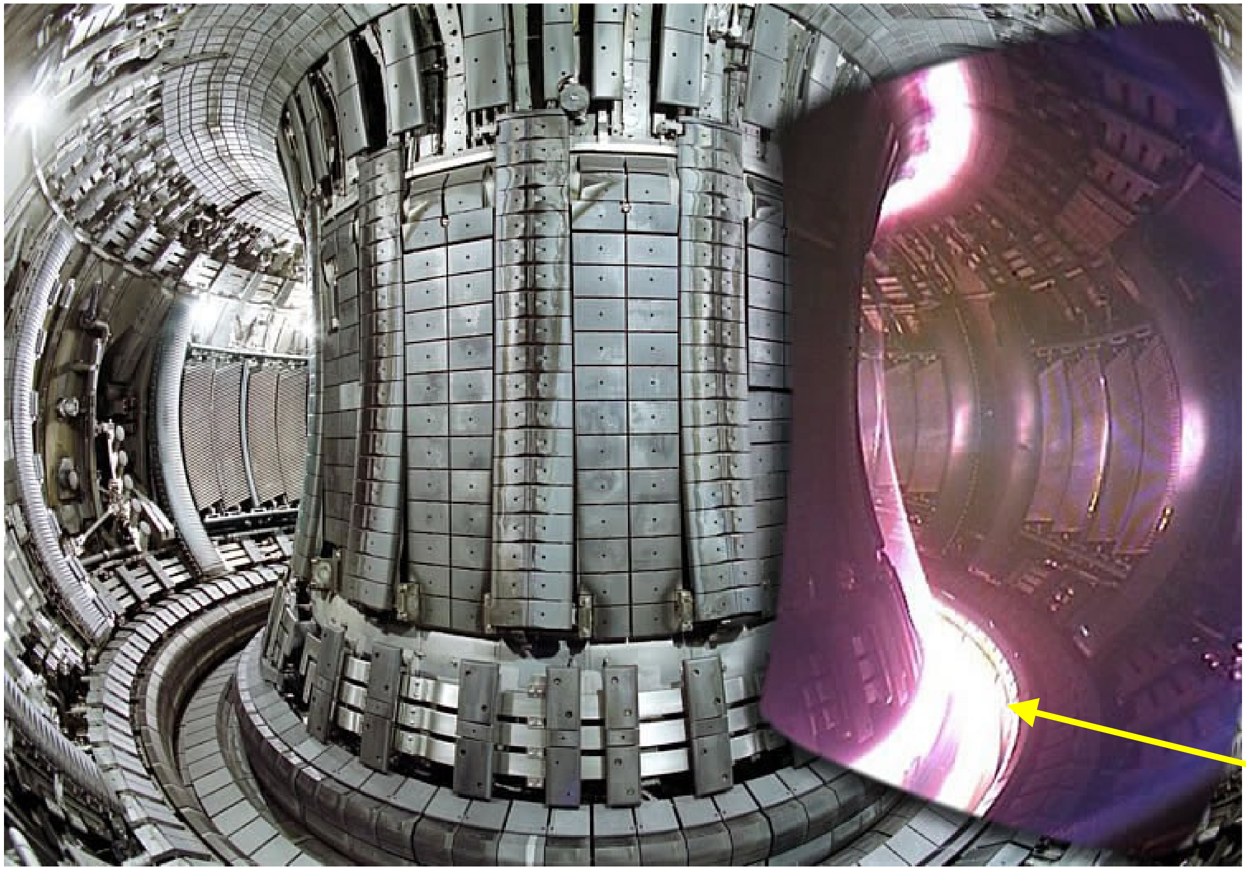
Configuration:

Double-null divertor
Single-null divertor

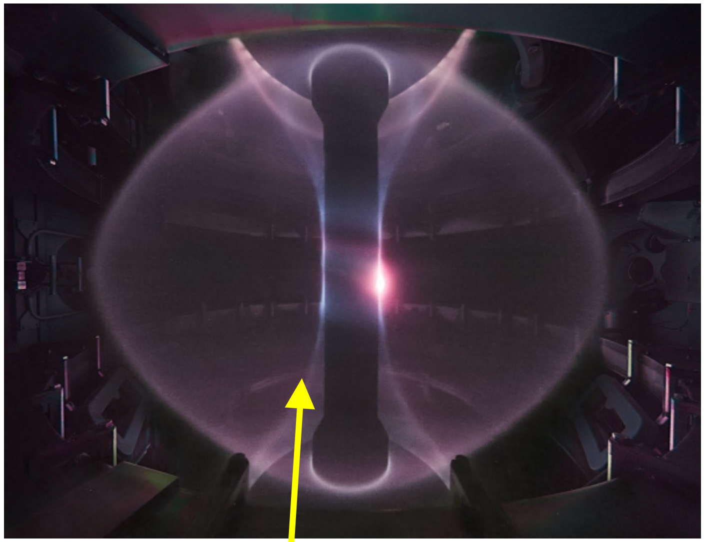


High Temperature High Density plasmas are Produced Routinely

Joint European Torus (JET)



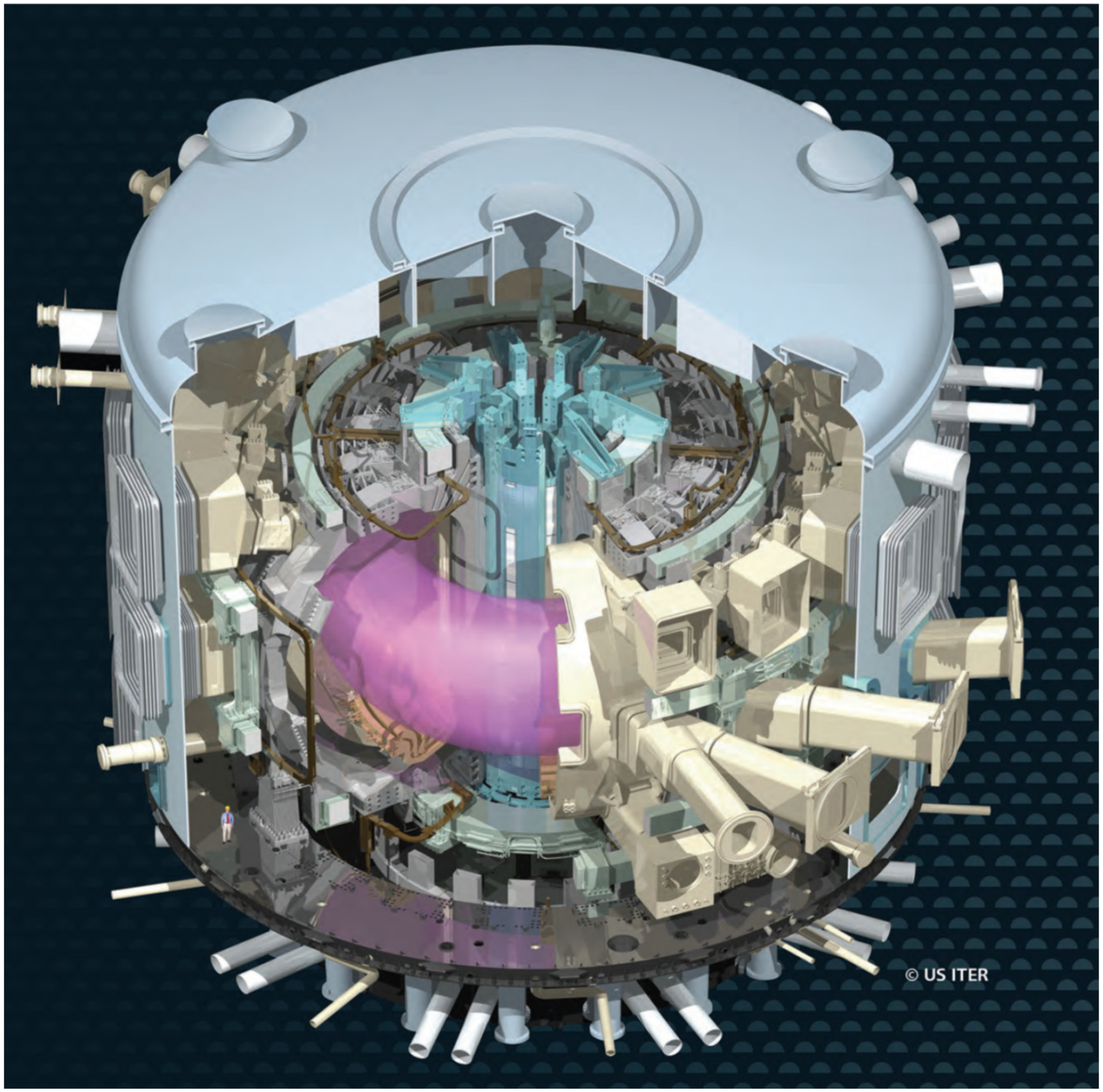
MAST (UK)



Glow from ionizing deuterium

International Tokamak Experimental Reactor (ITER) Project

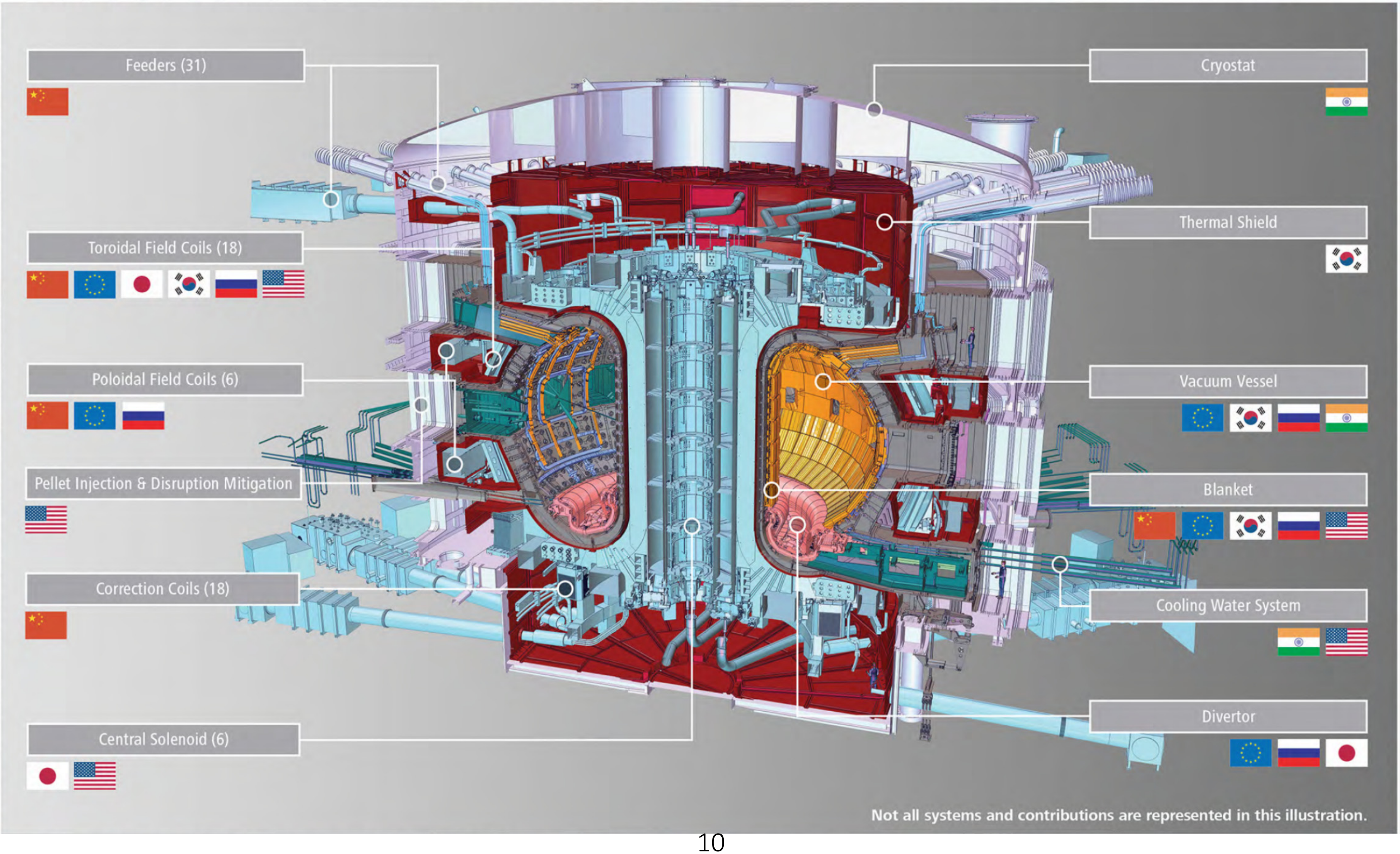
World’s most powerful fusion device under construction


© US ITER

Height	30 m
Diameter	30 m
Plasma Volume	840 m^3
Plasma Temp	$1.5x10^8$
Fusion Power	500 MW
Weight	23 kton

International Tokamak Experimental Reactor (ITER) Project – cont.

Being carried out by seven countries/union

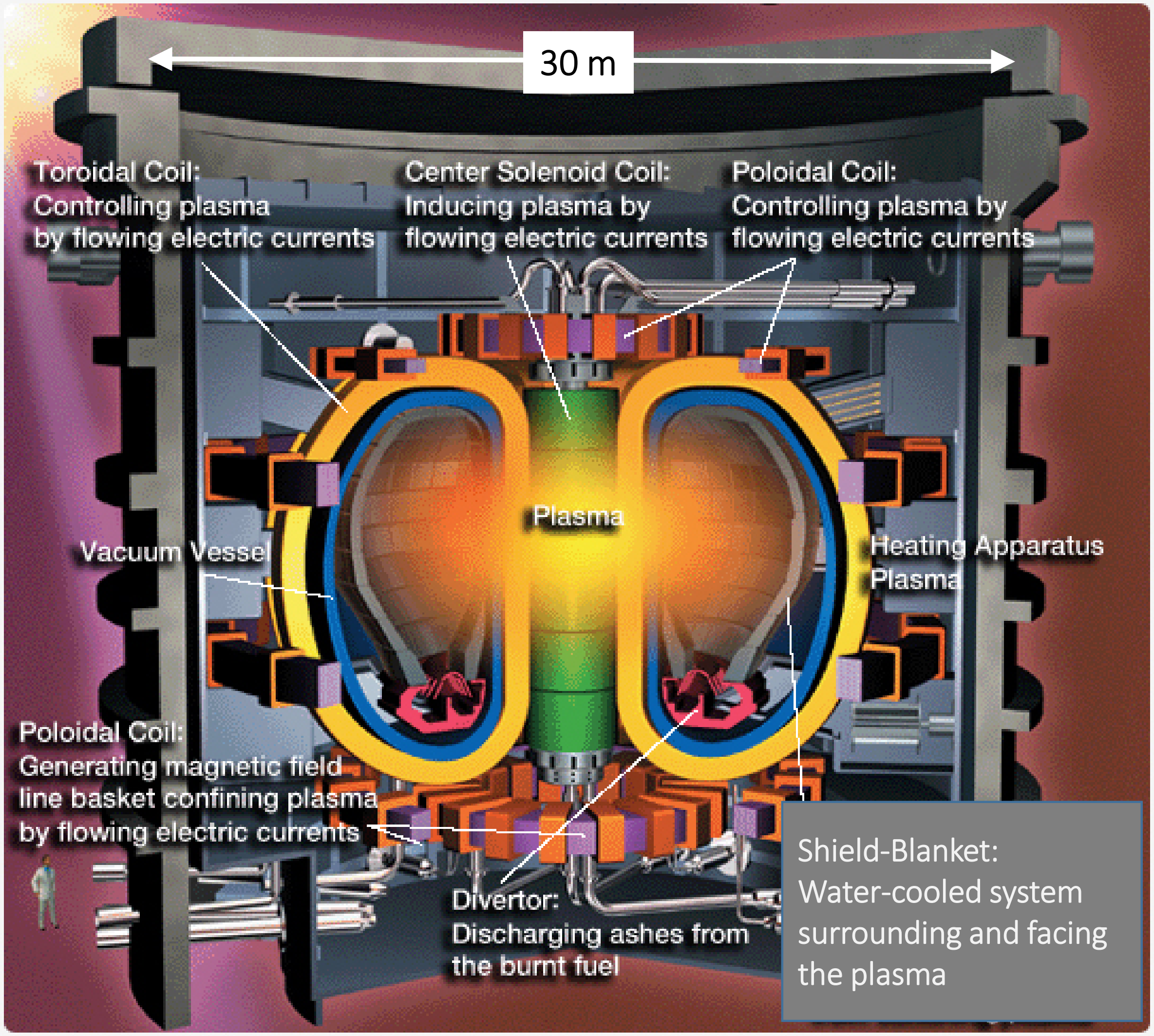


Not all systems and contributions are represented in this illustration.

Let’s start with the ITER tokamak,

A multidisciplinary, multi-physics, interacting, complex system

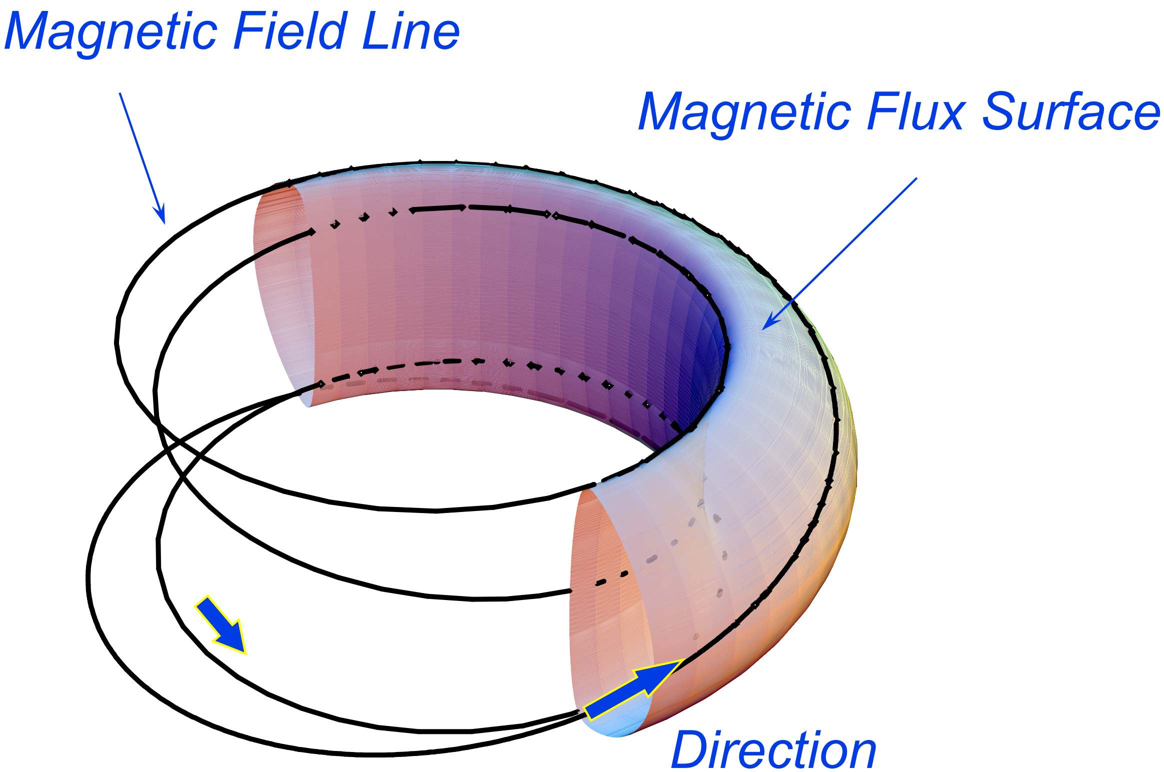
ITER Tokamak



- Plasma: 200 million °C, emits heat, particles, neutrons; receives heating, fueling, impurities
- Divertor: W, Cu, high surface temperature and erosion, receives and removes high heat & particle fluxes, suffers neuron damage
- Shield-blanket: steel, water, receives & removes heat, receives particles and erosion, suffers neutron damage
- Magnets: maintain field for plasma, removes heat at <4°K, keeps it out
- Etc.

A single magnetic field line in a magnetic surface of tokamak

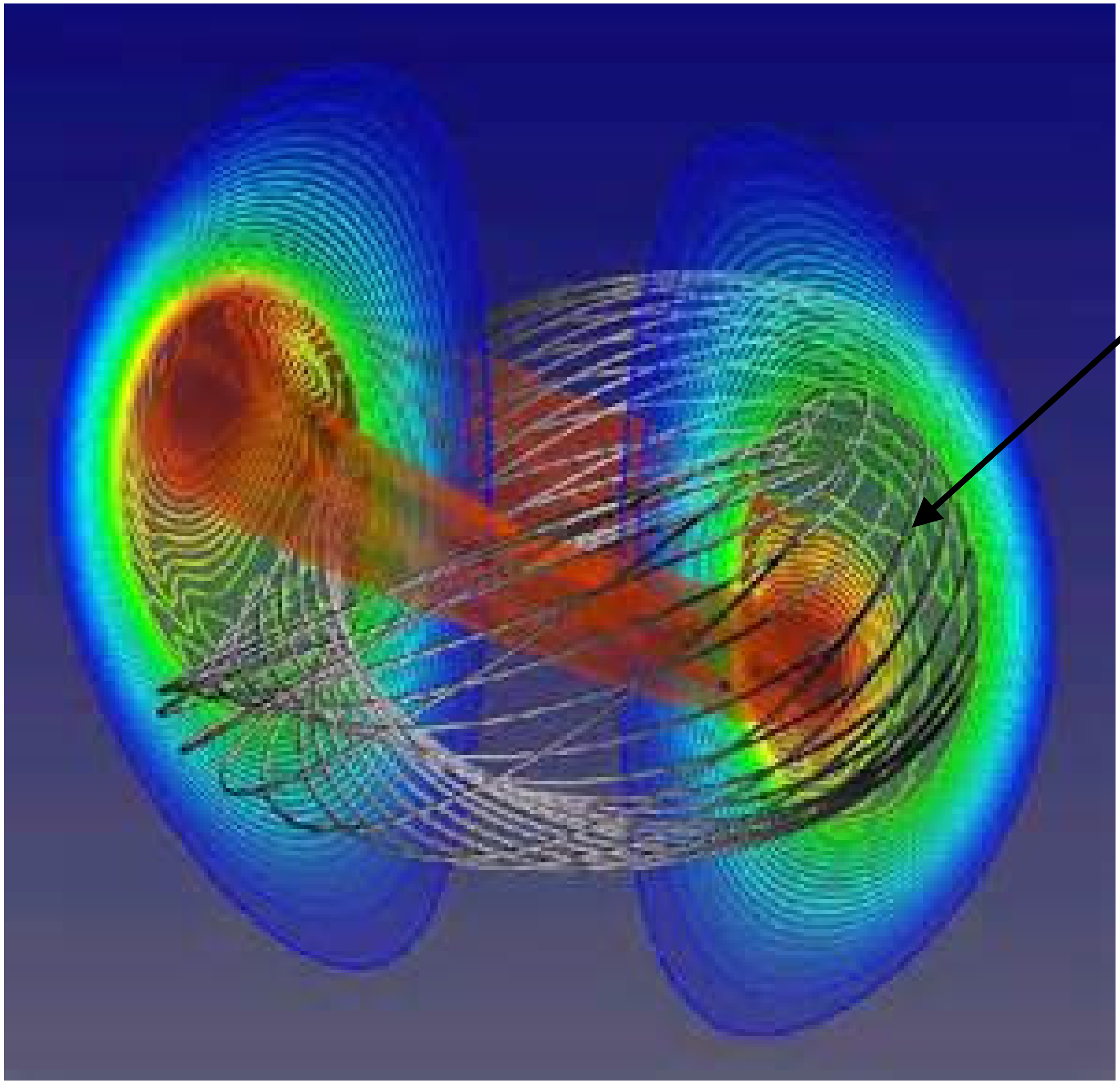
- Magnetic flux surface is formed by sweeping field line toroidally



Tokamak Plasma

Plasma Is Confined by Nested Magnetic Field Lines

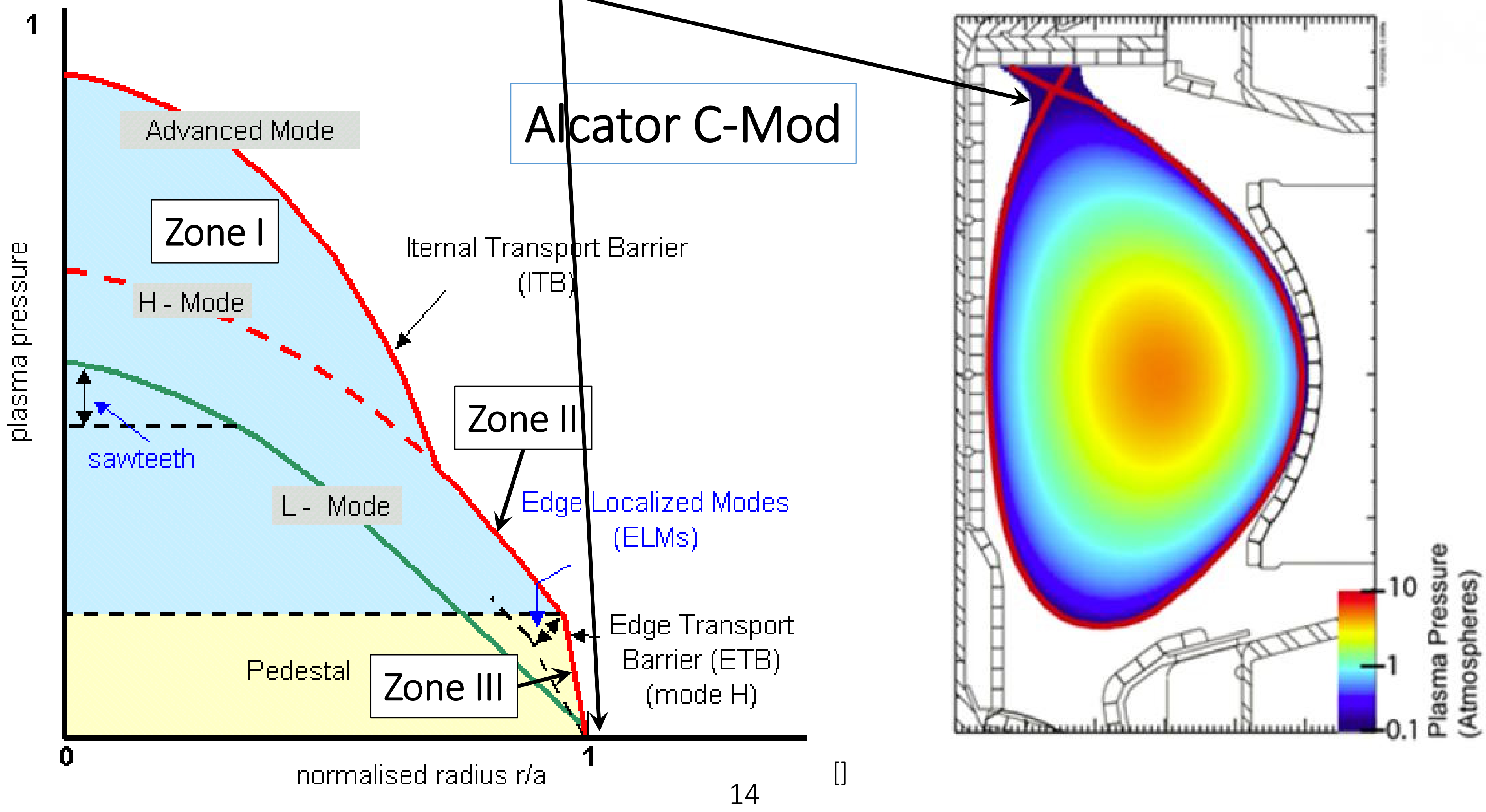
Even with plasma dynamics that can bend the lines



Magnetic Field Line

Present fusion plasma core model contains four zones (H-Mode)

- Zone I: Internal transport barrier
- Zone II: normal transport layer
- Zone III: edge transport barrier “pedestal” *(behind the frontline)*
- The Scrape-Off Layer bridges to the PFC (Zone IV, *frontline)*



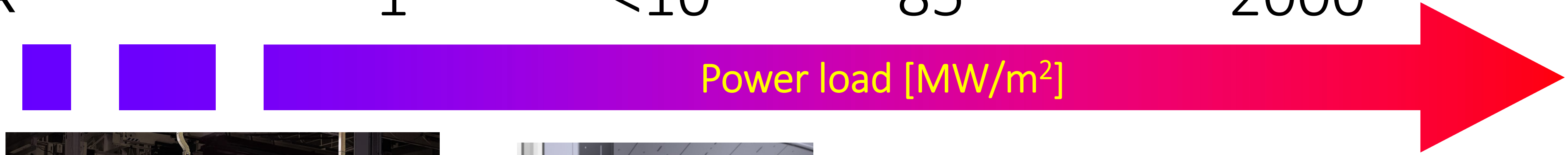
The world of thermal loads *(frontline)*

PWR

Re-entry vehicle

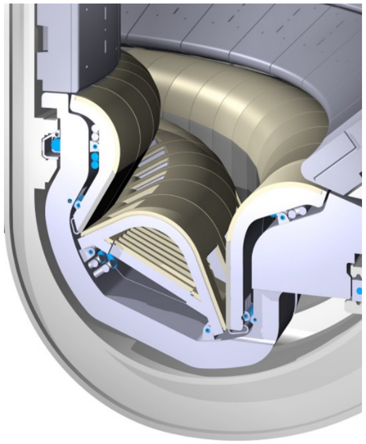
Space Shuttle rocket nozzle

~1 <10 85 2000



Power load [MW/m^2]

GE90-115B



Outer divertor:

1200 C

Inner divertor:

800 C

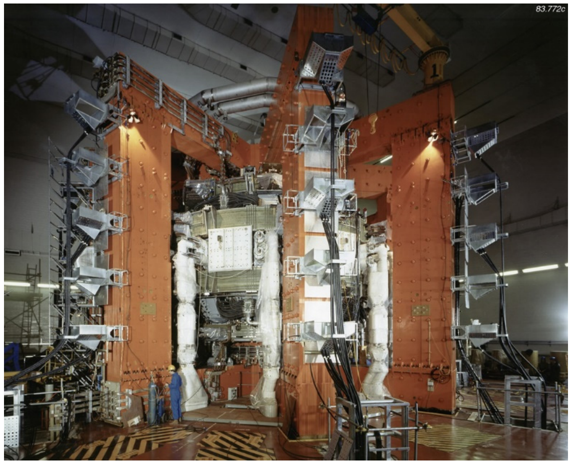
ITER steady-state

ITER transients, welding

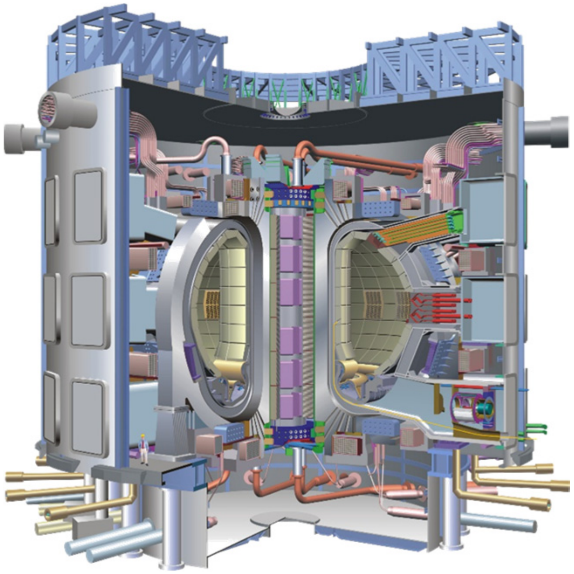
(1ms lifetime)

Particle fluxes and fluence *(frontline)*

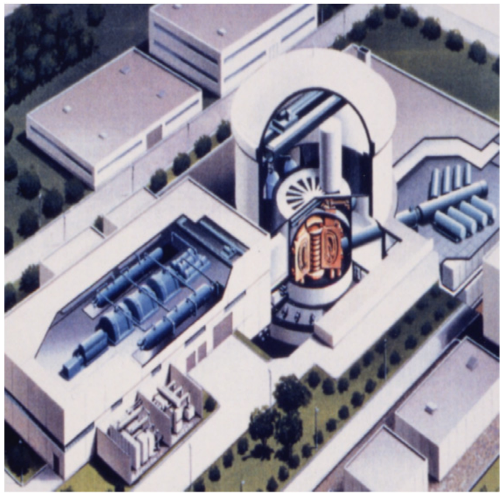
JET



ITER



Fusion Reactor



50 x higher ion fluxes

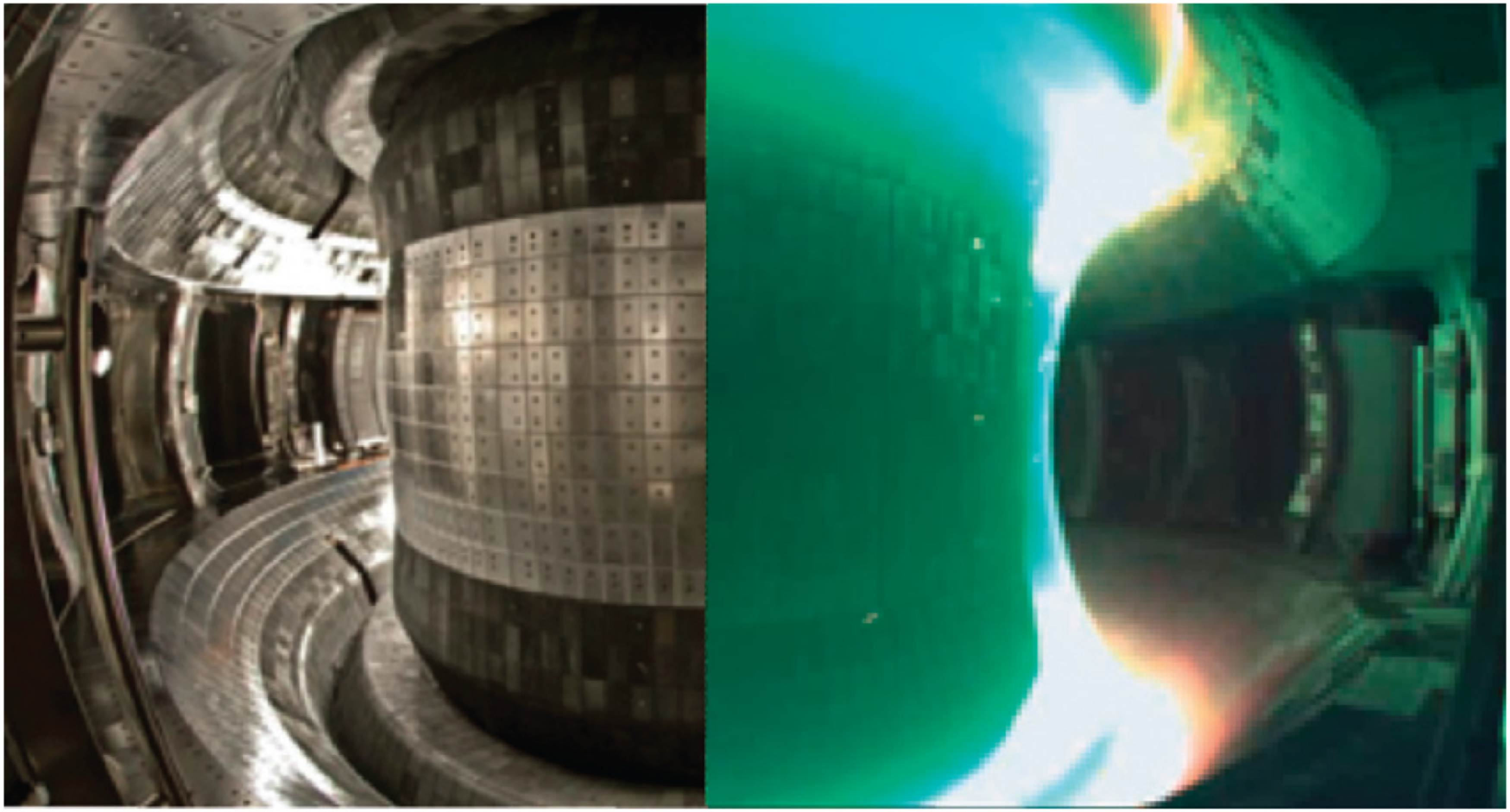
5000 x higher ion fluence

10^6 x higher neutron fluence (~1dpa)

up to 5 x higher ion fluence

100 x higher neutron fluence (~150 dpa)

Long-pulse tokamak operation will face the challenge of keeping the plasma core free of debilitating levels of impurity *(frontline)*



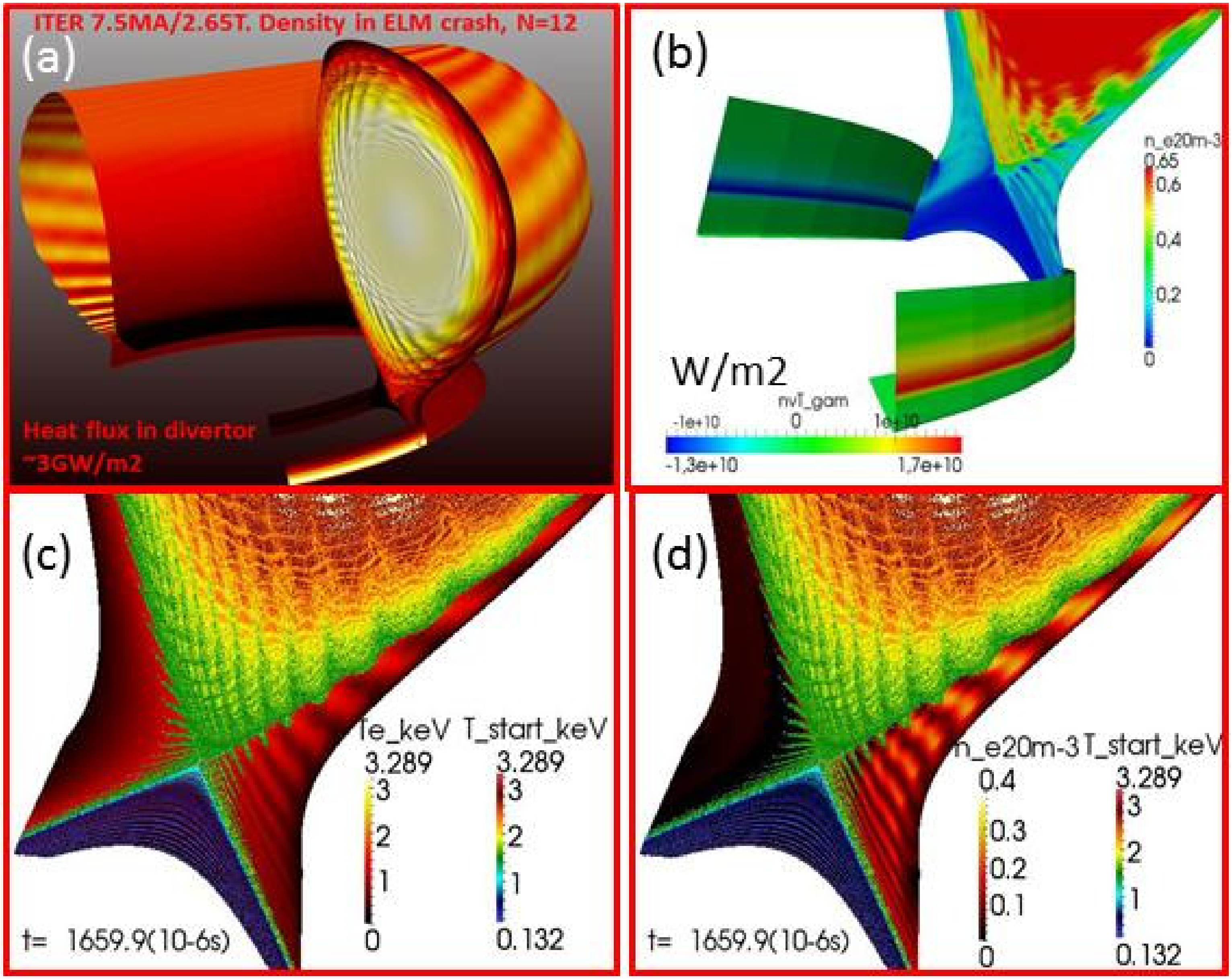
EAST Tokamak Vessel and photo of a long pulse plasma

[2013-Li-Nature Phys-v9-p817]

What do you see from this photo of plasma?

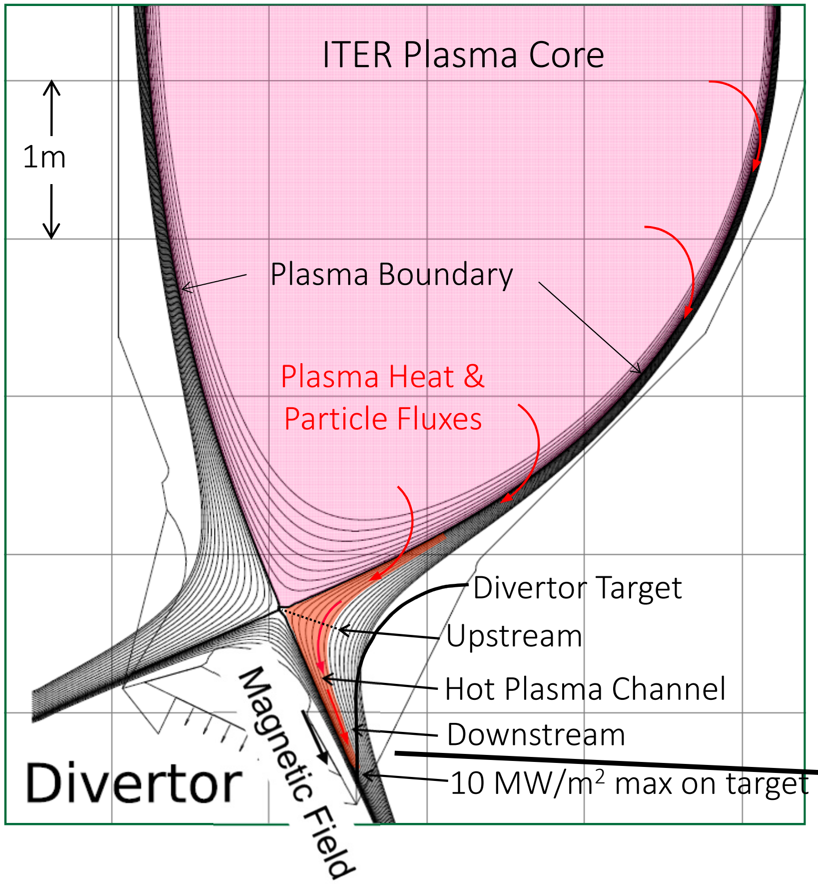
Divertor faces high frequency pulsed heat and particle fluxes *(frontline)*

(http://irfm.cea.fr/Phocea/Vie_des_labos/Ast/ast.php?t=fait_marquant&id_ast=372)



Strongly coupled plasma-material interaction (PMI) occur at the interface of plasma and divertor target surface *(frontline)*

ITER plasma core, to edge, to interface plasma, to divertor

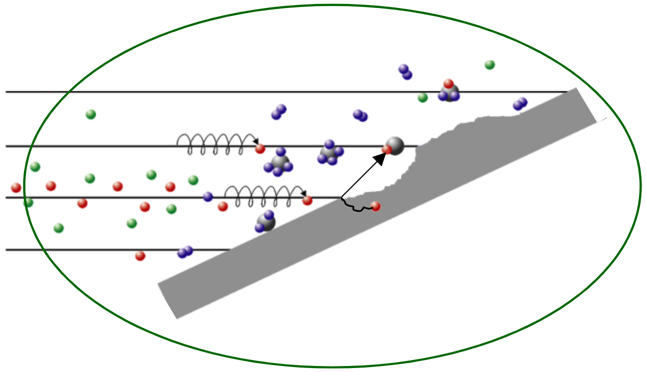


Even when target temperature is maintained, how fast would

- Material surface be eroded?
- Dust accumulate, and where?
- Bulk material properties change?
- Impurities invade the plasma core?
- And lead to failure of divertor & plasma

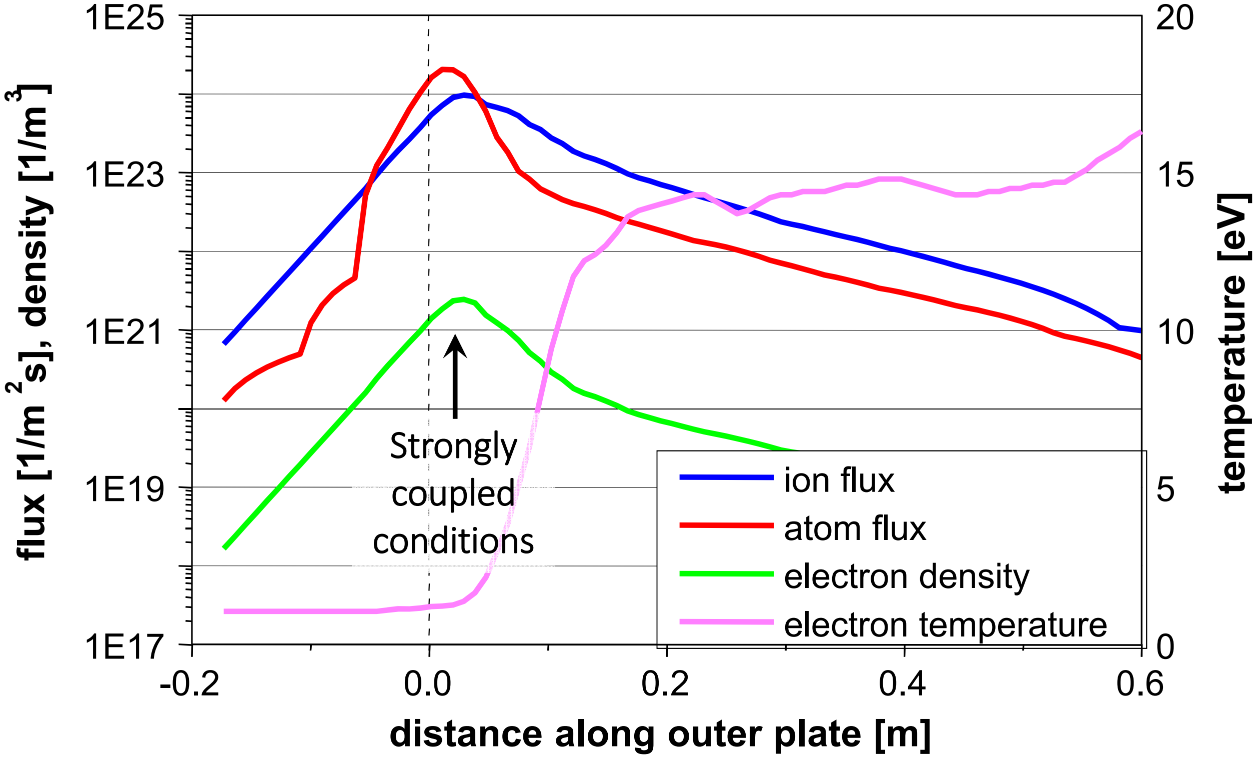
Area of much R&D opportunities

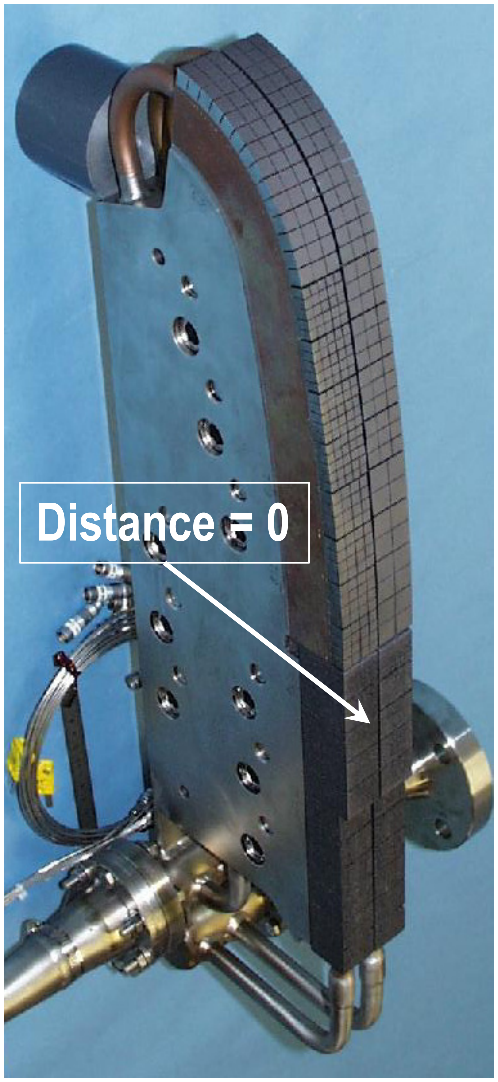
High-recycling, strongly coupled PMI



ITER divertor is to survive for 400 – 3000s at a time, under conditions of extremely high heat and particle fluxes *(frontline)*

B2-Eirene simulation for the ITER outer divertor, including impurities (A.S. Kukushkin)

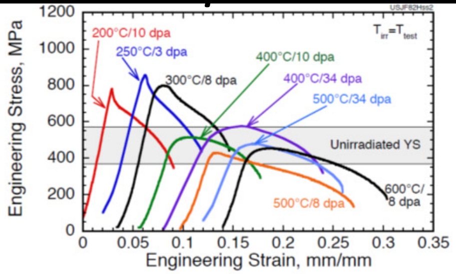




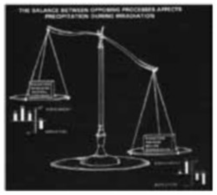
- $n_e = 3 \times 10^{21}$ m^{-3}; $T_e = 1 – 10$ eV
- $\Gamma_{D,T} = 10^{24}$ m^{-2} s^{-1}; fluence = 10^{30} m^{-2} (ITER life)
- q_{div} = 10 MW m^{-2}; fluence = 10^7 MJ m^{-2}
- Surface temperature (up to 1600 °K)
- Fusion neutron fluence = 0.1 MW-yr/m^2 (~ 1 dpa)

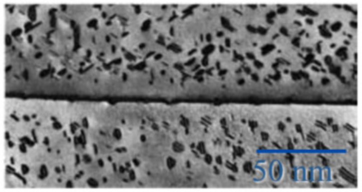
Radiation damage can produce large changes in structure materials *(2nd line), achievable when the "frontline" survives to provide the dpa*

- **Radiation hardening and embrittlement (<0.4 T_M, >0.1 dpa)**



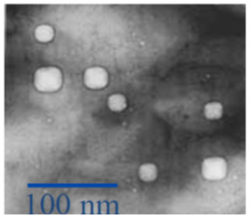
- **Phase instabilities from radiation-induced precipitation (0.3-0.6 T_M, >10 dpa)**



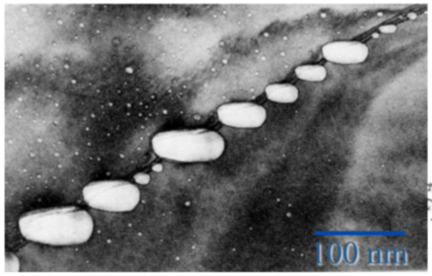


- **Irradiation creep (<0.45 T_M, >10 dpa)**

- **Volumetric swelling from void formation (0.3-0.6 T_M, >10 dpa)**

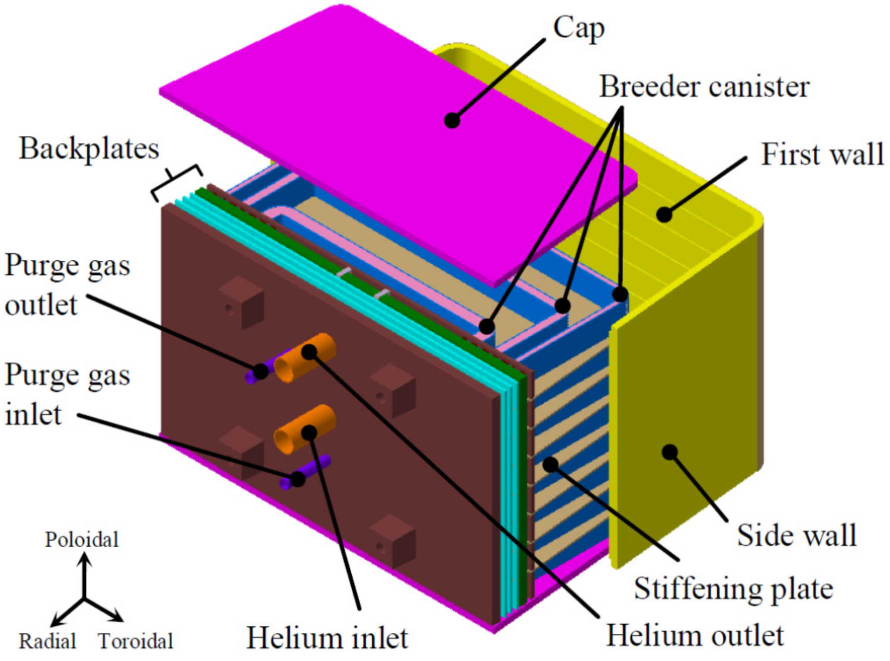


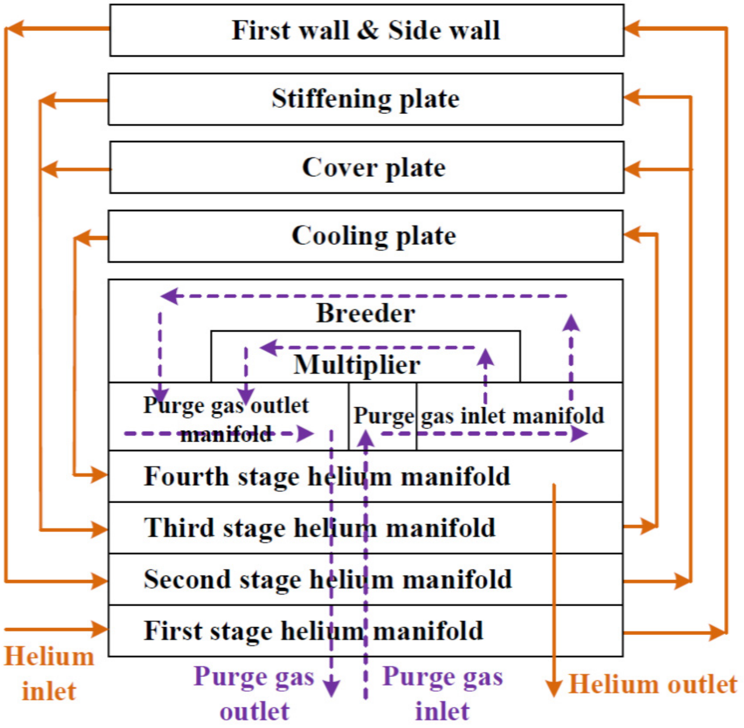
- **High temperature He embrittlement (>0.5 T_M, >10 dpa)**

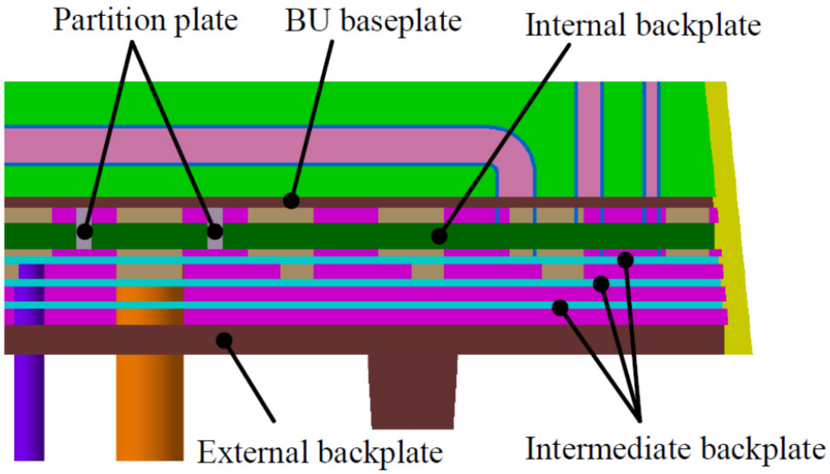


S.J. Zinkle, Phys. Plasmas 12 (2005) 058101; Zinkle & Busby, Mater. Today 12 (2009) 12

Example: helium cooled solid breeder blanket – thermal hydraulics *(2nd line)*







Goals: to optimize

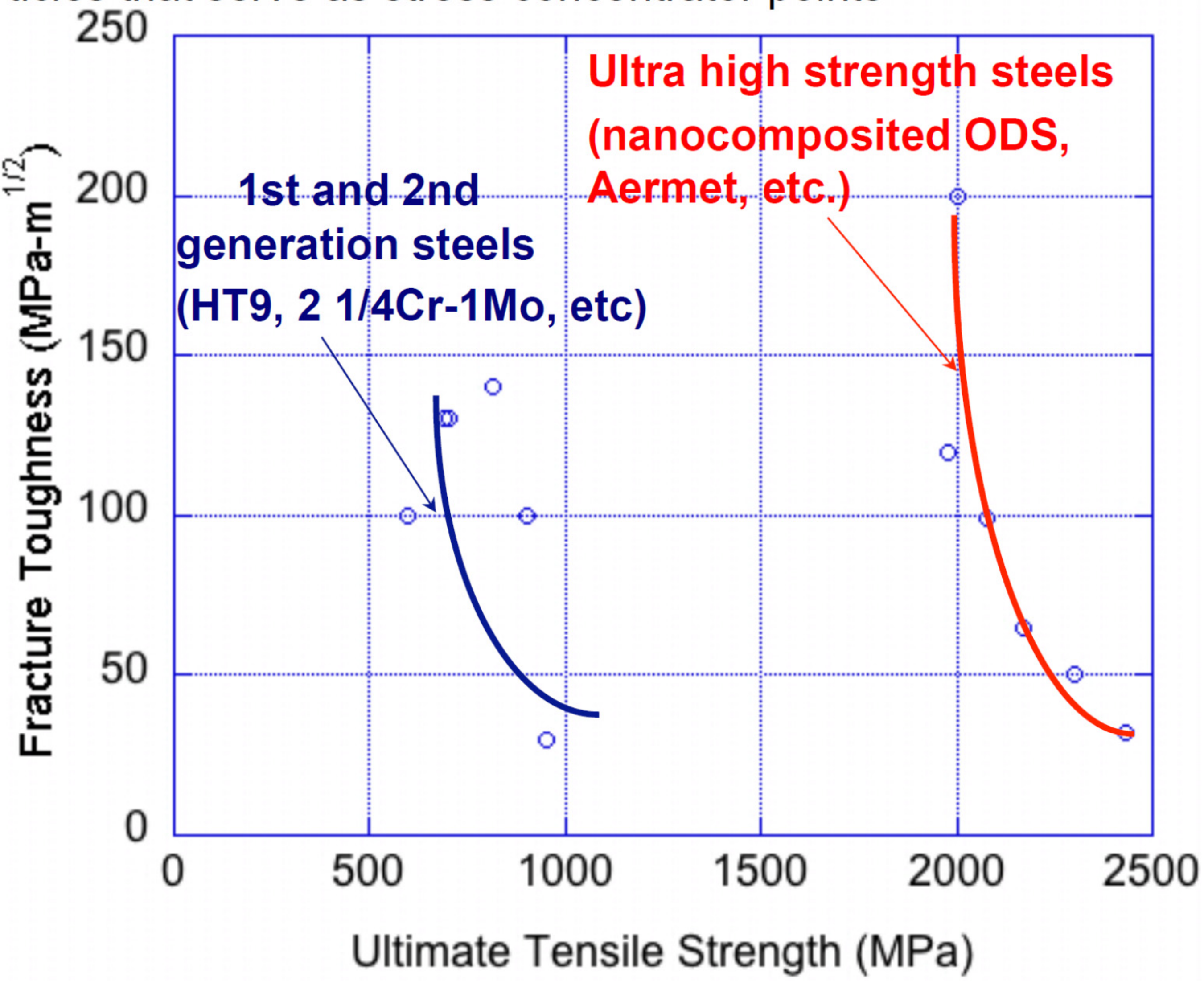
- Tritium breeding ratio
- Energy conversion

How to minimize tritium loss?

- Additional helium “flush”?
- Reduced permeation surfaces?

Recent progress in developing high-strength steels that retain high-toughness has been remarkable

- Generally obtained by producing high density of nanoscale precipitates and elimination of coarse particles that serve as stress concentrator points



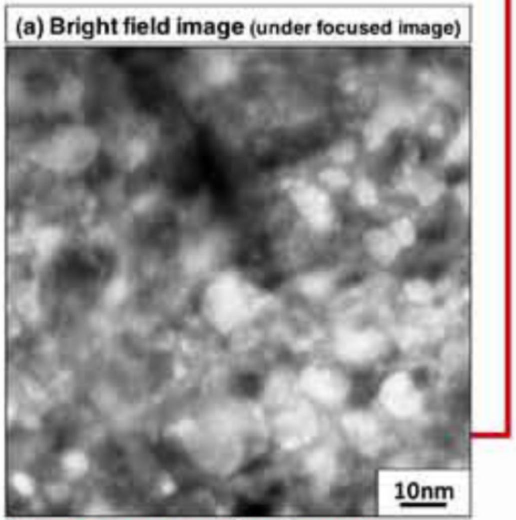
S.J. Zinkle & J.T. Busby, Mater. Today 12 (2009) 12

W Temperature & PMI are coupled

~ 600 - 700 K

~ 900 – 1900 K

> 2000 K


(a) Bright field image (under focused image)

PISCES-A: D_2-He plasma

M. Miyamoto et al. NF (2009) 065035

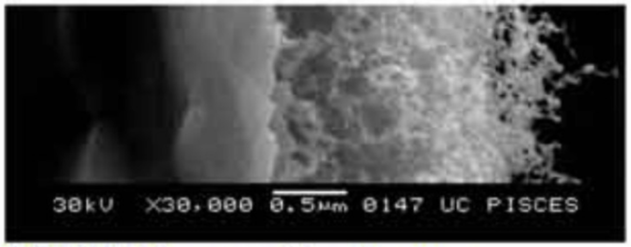
600 K, 1000 s, 2.0x10^{24} He^+/m^2, 55 eV He^+

- Little morphology
- He nanobubbles form
- Occasional blisters

PISCES-B: mixed D-He plasma

M.J. Baldwin et al, NF 48 (2008) 035001

1200 K, 4290 s, 2x10^{26} He^+/m^2, 25 eV He^+



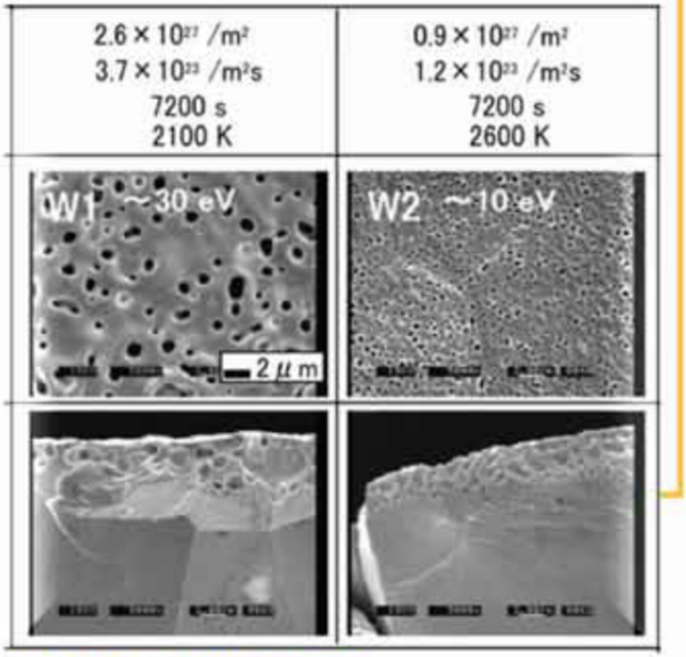
NAGDIS-II: pure He plasma

N. Ohno et al., in IAEA-TM, Vienna, 2006

1250 K, 36000 s, 3.5x10^{27} He^+/m^2, 11 eV He^+


100 nm (VPS W on C) (TEM)

- Surface morphology
- Evolving surface
- Nano-scale 'fuzz'



2.6 × 10^{27} /m^2 3.7 × 10^{23} /m^{2}s 7200 s 2100 K	0.9 × 10^{27} /m^2 1.2 × 10^{23} /m^{2}s 7200 s 2600 K

NAGDIS-II: He plasma

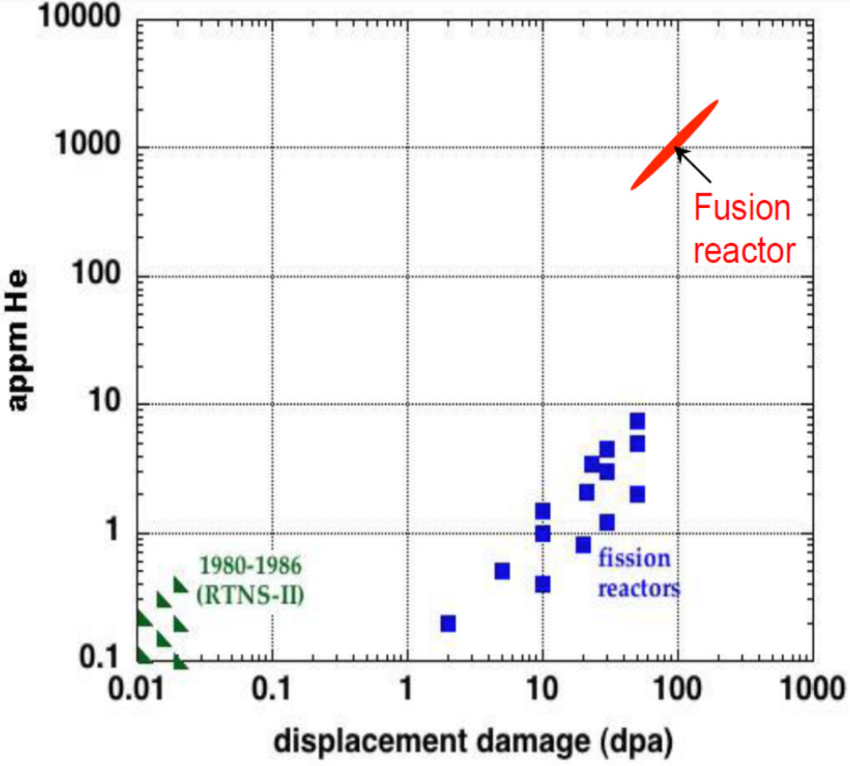
D. Nishijima et al. JNM (2004) 329-333 1029

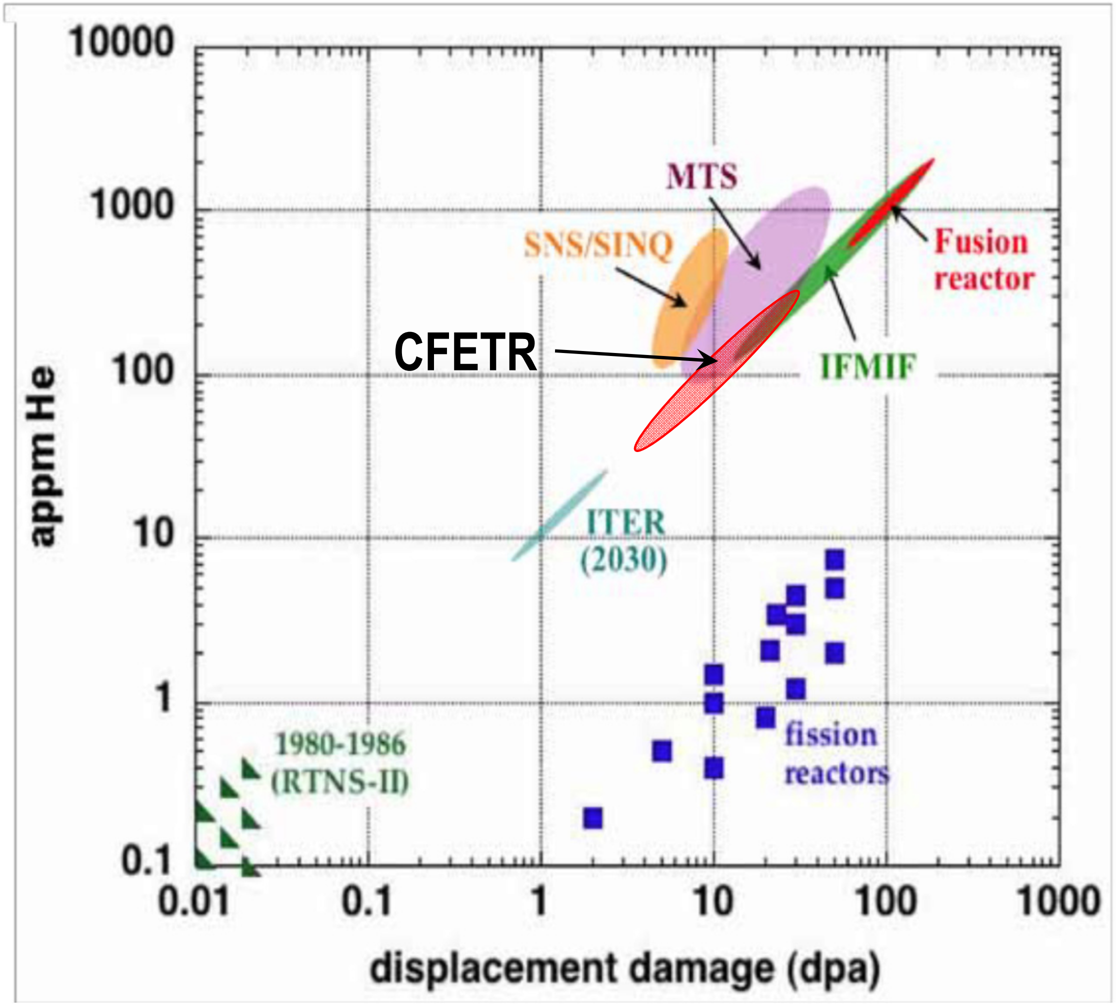
- Surface morphology
- Shallow depth
- Micro-scale

R. P. Doerner, VLT Call, Jan. 17, 2011

How to bridge the gap in appm He and dpa? *(2nd line)*

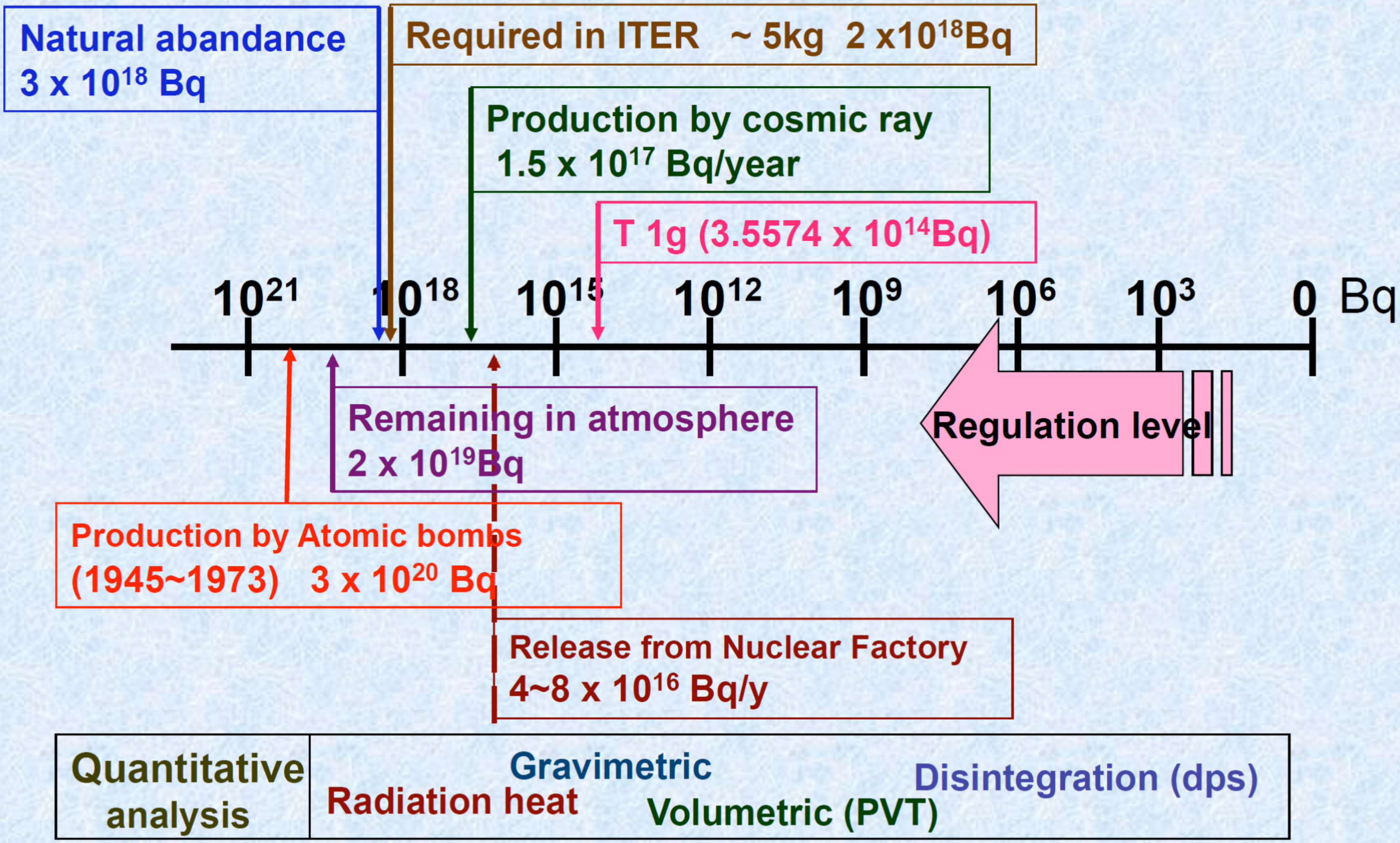
Current knowledge base on ferritic steels





Assuming the survival of the "frontline" & the 3rd line

Tritium Abundance
(limited resources and regulation for safety)



Natural abandance
3×10^{18} Bq

Required in ITER ~ 5kg 2×10^{18}Bq

Production by cosmic ray
1.5×10^{17} Bq/year

T 1g (3.5574×10^{14}Bq)

Remaining in atmosphere
2×10^{19}Bq

Regulation level

Production by Atomic bombs
(1945~1973) 3×10^{20} Bq

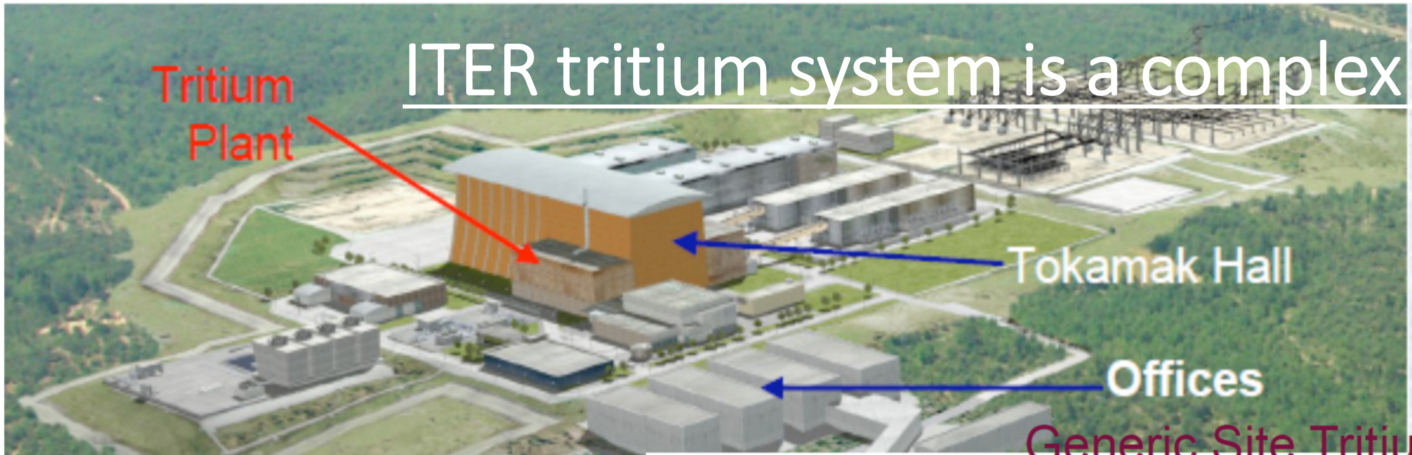
Release from Nuclear Factory
4~8 $\times 10^{16}$ Bq/y

Quantitative analysis

Gravimetric
Radiation heat
Volumetric (PVT)
Disintegration (dps)

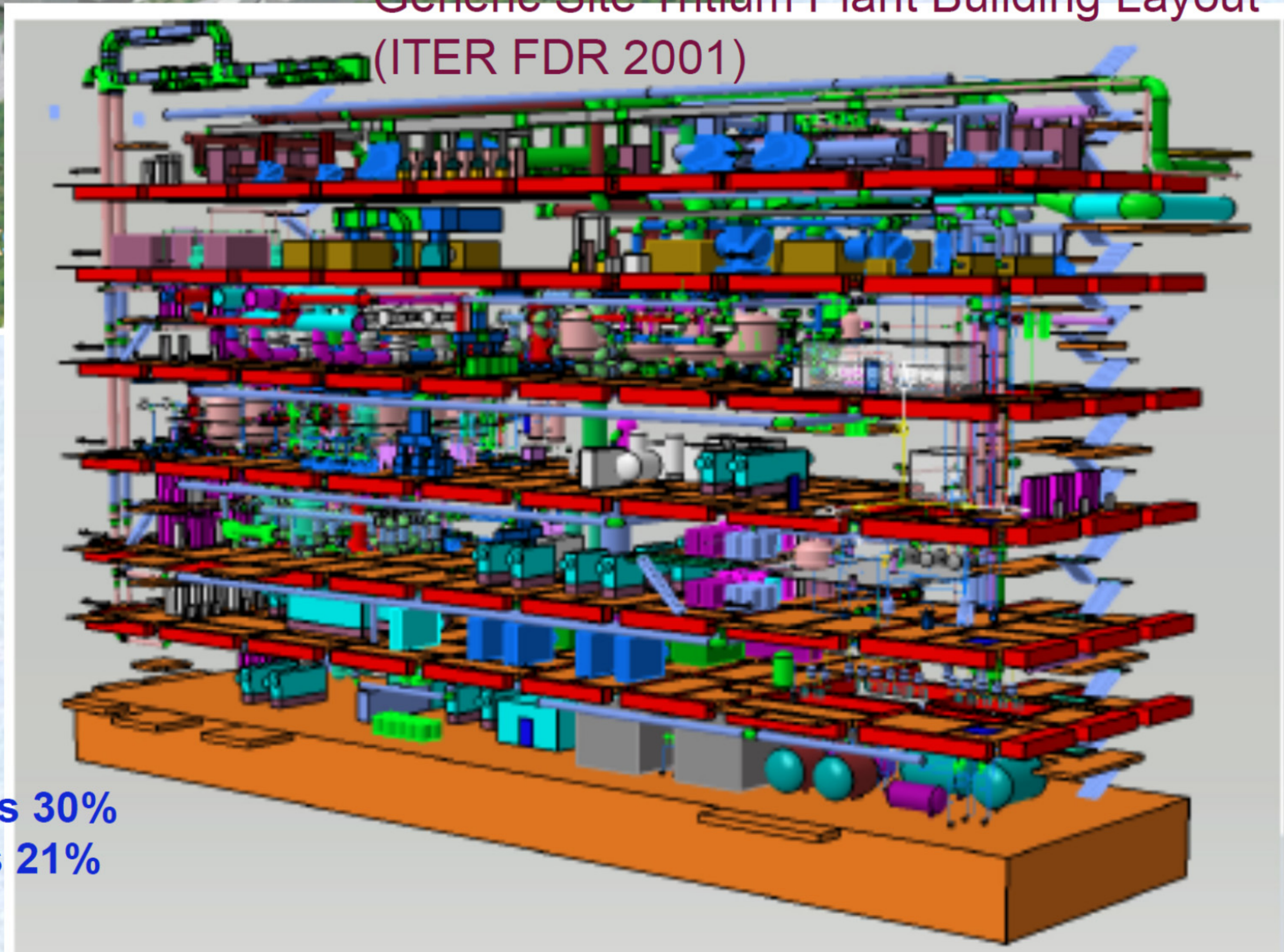
No single method can cover the whole range.
Poor resolution inhibits cross-check.

ITER tritium system is a complex chemical plant *(3rd line)*



- **Dimensions**
  - Length: 79 m
    Width: 20 m
    Height: 34 m
- **Space occupation**
  - HVAC: 18%
  - Detritiation systems 16%
  - Tritium processing systems 30%
  - Non Tritium Plant systems 21%
  - Non process areas 15%

Generic Site Tritium Plant Building Layout (ITER FDR 2001)



Manfred Glugla, JAES Meeting, Osaka University, Japan, March 28, 2008

Great challenges of magnetic fusion energy bring great opportunities in science and technology advancement

- Fusion energy is potentially attractive
- Scientific and technical features of tokamak fusion is very complex
- D-T fusion plasma core are adequately known for use in ITER project
- Present focus of R&D – *"Front Lines of mutual survival"*
  - "Frontline": plasma-material interface at high heat and particle fluxes – divertor, first wall, interface for heating and diagnostic systems
  - "2nd Line": neutron power conversion – fusion nuclear blankets
  - "3rd Line": fuel self-sufficiency – tritium production & recovery
- Reminder: beyond D-T fusion: p-^{11}B cycle potentially may simplify the last two at the risk of making the first two more challenging.

Opportunities abound in developing the knowledge and know-how to make fusion energy available.

2015 / 2016 Major Public Holiday Calendar

Name	Date	Legal Holidays	2015	2016
New Year's Day	Jan. 1	1 day	Jan. 1 - 3 off	**Jan. 1 - 3 off**
Chinese New Year	subject to lunation	3 days	Feb. 19 (Feb. 18 - 24 off)	**Feb. 8 (Feb. 7 - 13 off)**
Qingming	Apr. 4 or 5	1 day	Apr. 5 (Apr. 4 - 6 off)	**Apr. 4 (Apr. 2 - 4 off)**
May Day	May 1	1 day	May 1 - 3 off	**Apr. 30 - May 2 off**
Dragon Boat	5th of 5th lunar month	1 day	Jun. 20 (Jun. 20 - 22 off)	Jun. 9 (Jun. 9 - 11 off)
Victory Day	Sep. 3	1 day	Sep. 3 (70th Anniversary of Victory over Japan)	Sep. 3 (no holiday)
Mid-Autumn Day	Aug. 15 of lunar calendar	1 day	**Sep. 27 (Sep. 26 - 27 off)**	Sep. 15 (Sep. 15 - 17 off)
National Day	Oct. 1	3 days (Oct. 1 - 3)	**Oct. 1 - 7**	Oct. 1 - 7