USTC SNST 2014 Autumn Semester Lecture Series

Title: Introduction to Tokamak Fusion Energy Nuclear Science and Technology Research and Development (R&D)

L2: Which R & D parameters (drivers) really matter to magnetic fusion energy – a matter of high leverage?

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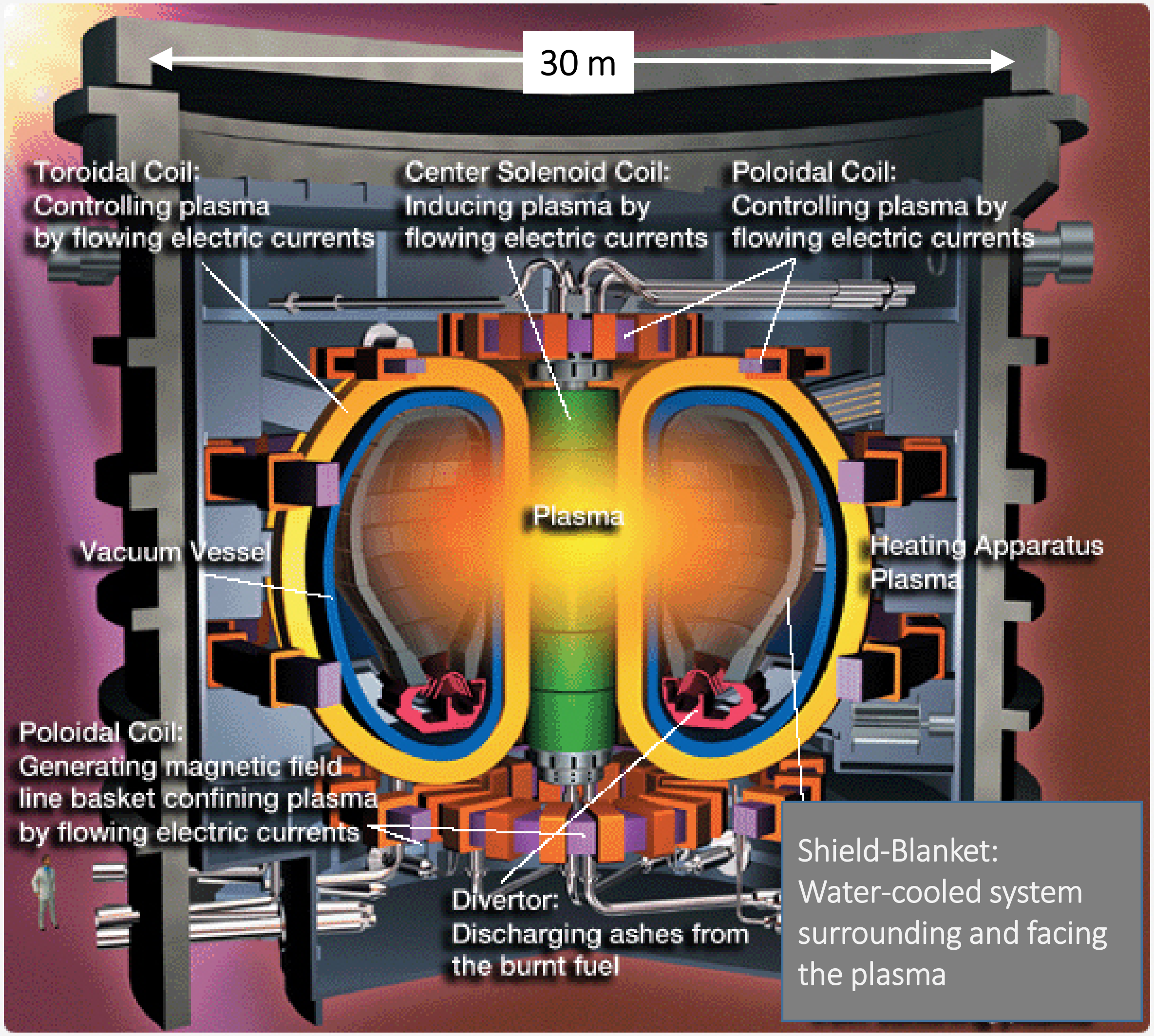
Room 1617, 930-1130, November 22, 2014

What to Carry with You?

- Tokamak fusion test reactors and power plants are multidisciplinary, multi-physics, interactive, complex systems.
- The “道” of tokamak fusion power: Basis for plasma, material, engineering, and nuclear sciences – plus interactions among them.
- The “德”: Engineering and technology of the tools (“know-how”) being used and developed to push to the conditions of a fusion system, which allow more light to shine on these aspects of “道”.
- The R & D now also includes “德” of fusion, *i.e.*, add CFETR to ITER.
- New R & D goal: to enable CFETR to achieve its mission, which in turn is to help enable practical tokamak fusion power plant.
- New R & D drivers impact most components and systems: tritium self-sufficiency in full cycle; continuous operation; high duty cycle; large divertor heat & particle fluence (time-integrated flux); large neutron fluence through FW & blanket; strong nuclear effects on materials in components; …

Let's start with the largest tokamak under construction,
A multidisciplinary, multi-physics, interacting, complex device

ITER Tokamak



- Plasma: 20 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
- Toroidal magnets: maintain field condition for plasma, removes heat at <4°K, keeps it out
- Etc.

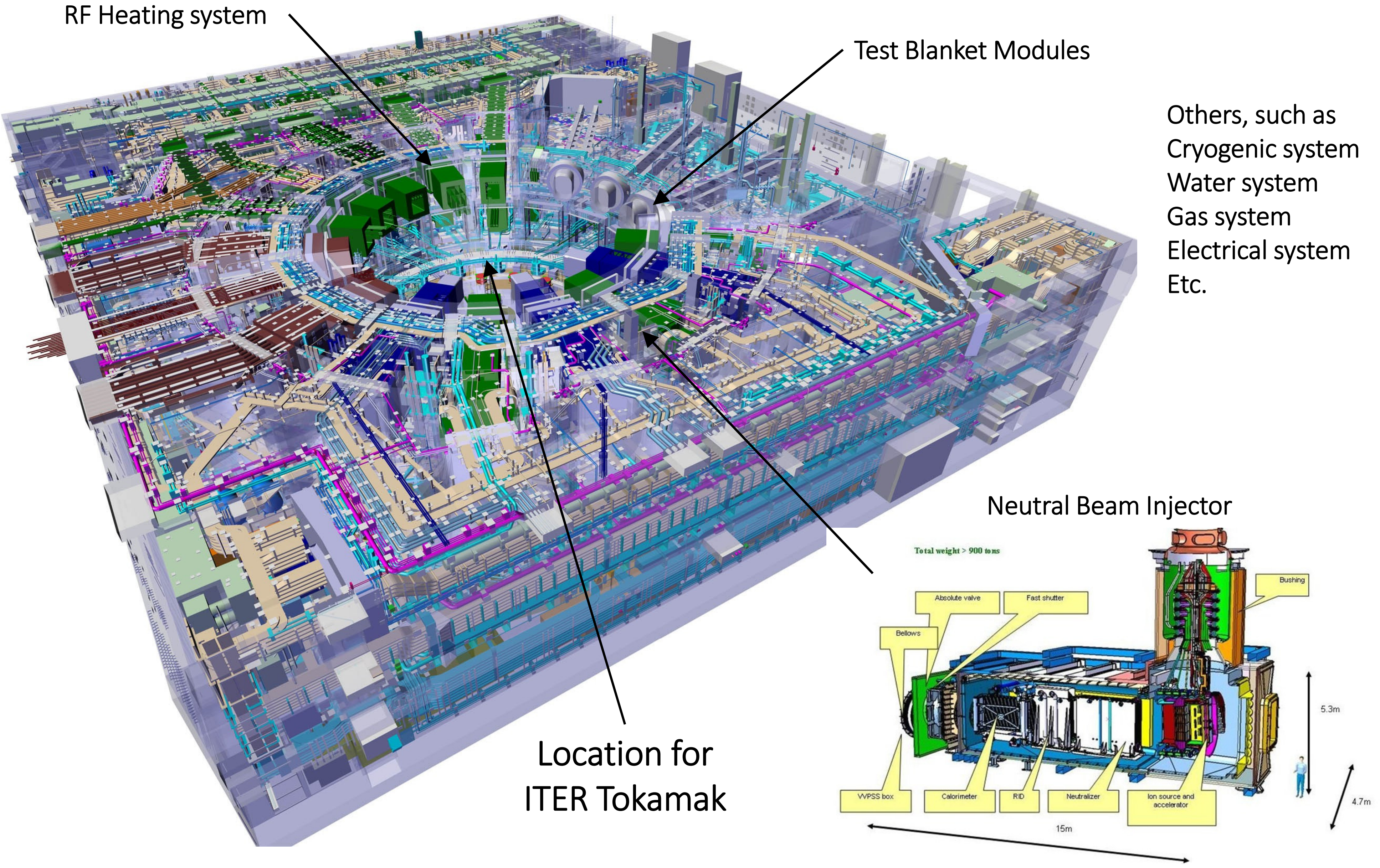
A matrix of interactions of ITER tokamak

(This is only part of the tokamak device!)

	Plasma	Divertor	Shield-blanket	Vacuum vessel	TF magnets	PF magnets	Central solenoid
Plasma		√	√	√	√	√	√
Divertor				√		√	√
Shield-blanket				√		√	√
Vacuum vessel					√	√	√
TF magnets						√	√
PF magnets							√
Central solenoid							

What support systems are connected to the ITER tokamak?

(Only showing tokamak building mid-plane and below.)



RF Heating system

Test Blanket Modules

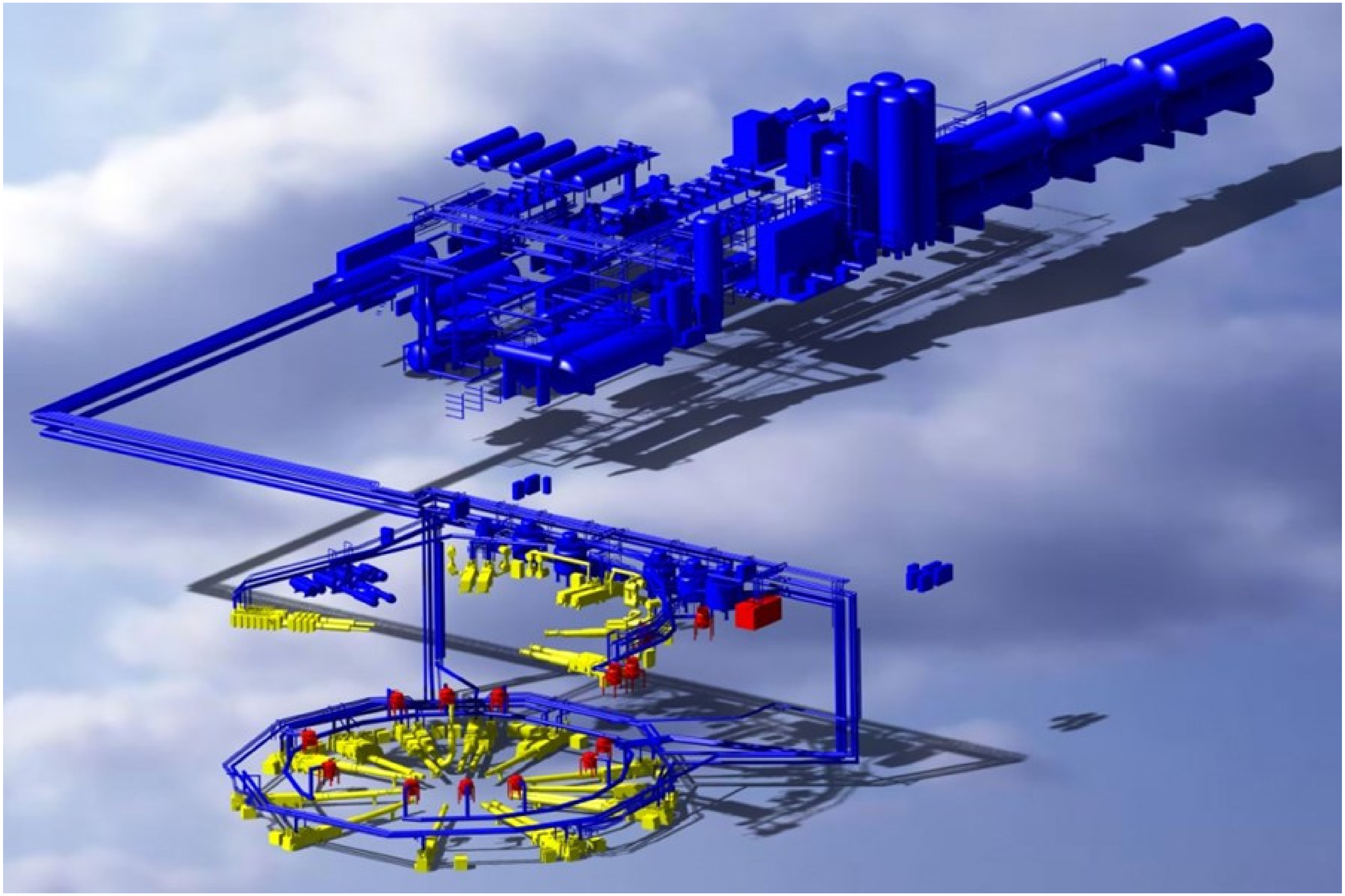
Others, such as
Cryogenic system
Water system
Gas system
Electrical system
Etc.

Neutral Beam Injector

Location for
ITER Tokamak

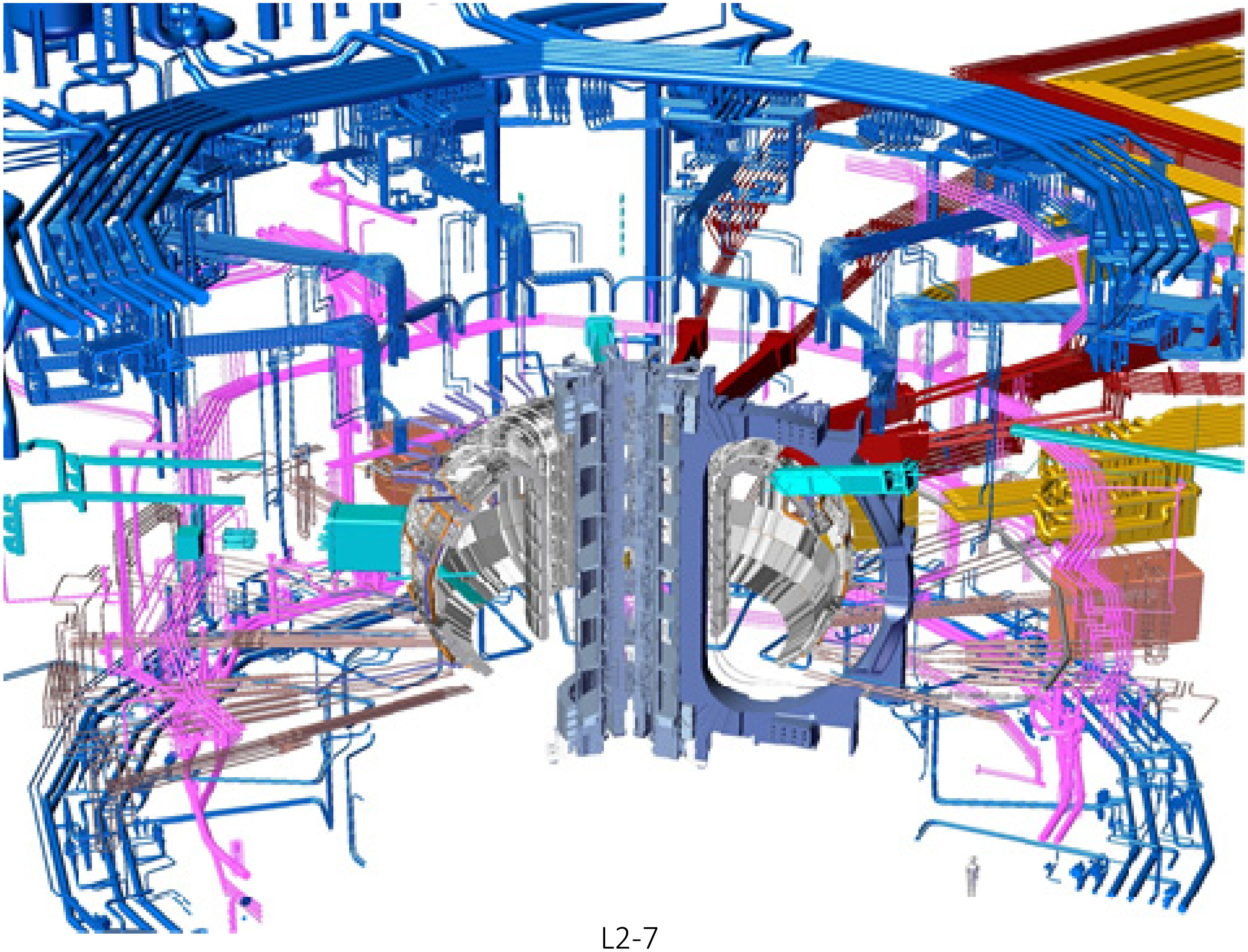
Where is the cryogenic system?

It is hidden below the tokamak building mid-plane.

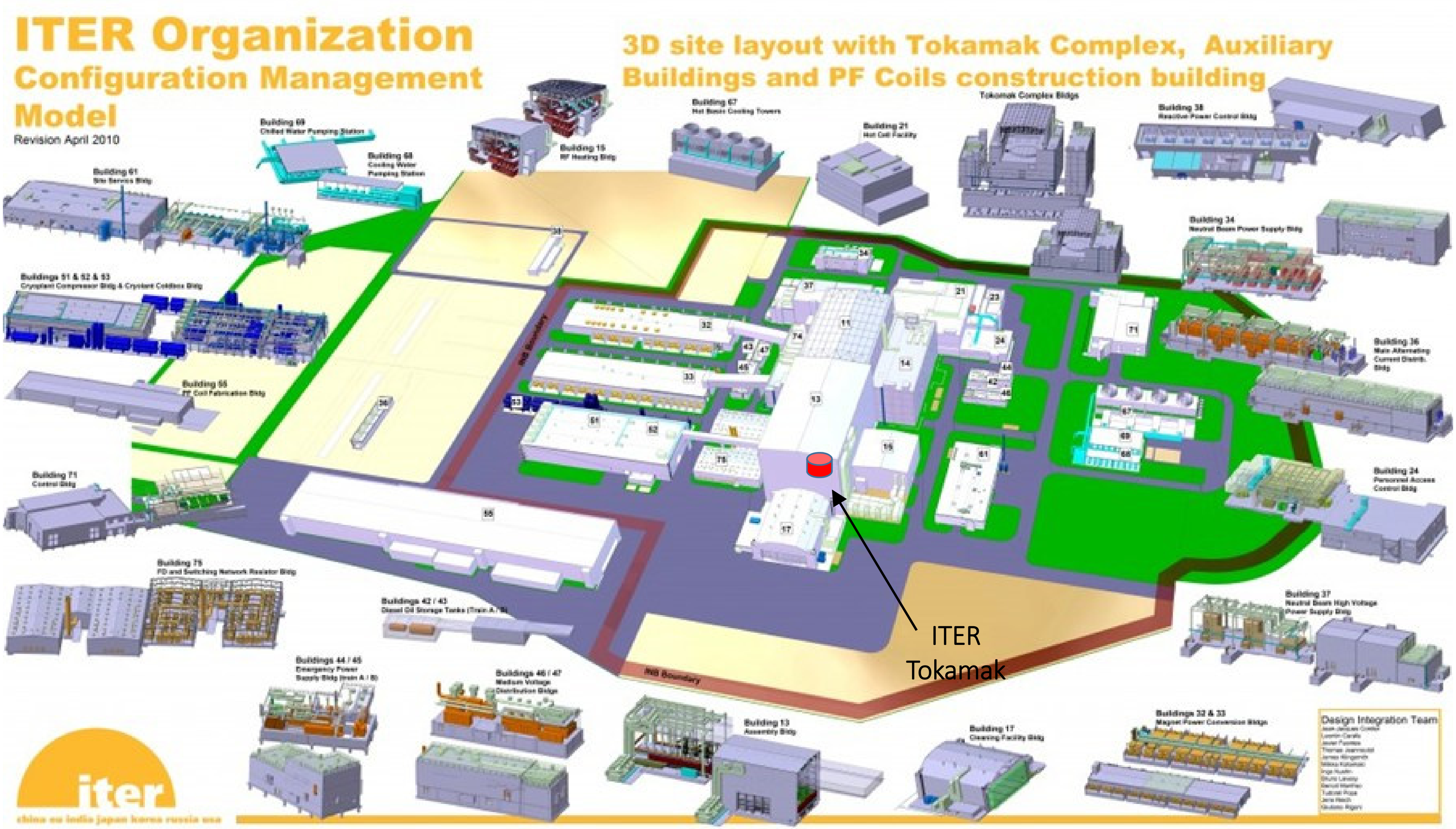


More examples of systems that support ITER tokamak

Cooling, Diagnostics, Plasma Heating, Fueling and Exhaust Systems (Tritium), Electrical Network, S/C Magnets (2011 drawing)



ITER support facilities support the tokamak support systems



So, why are we doing all these?

ITER mission and technical objectives (ITER Org., 2009)

Mission: to demonstrate the feasibility of fusion power, and prove that it can work without negative impact. The project *aims to* (*i.e.*, technical objectives)

(regarding *"道" of fusion burning plasma physics*)

- To momentarily produce ten times more thermal energy from fusion heating than is supplied by auxiliary heating (a *Q* value equals 10).
- To produce a steady-state plasma with a *Q* value greater than 5.
- To maintain a fusion pulse for up to 480 seconds.
- To ignite a 'burning' (self-sustaining) plasma.

(regarding *some "德" of fusion power*)

- To develop technologies and processes needed for a fusion power plant — including superconducting magnets and remote handling (maintenance by robot).
- To verify tritium breeding concepts.
- To refine neutron shield/heat conversion technology (most of the energy in the D+T fusion reaction is released in the form of fast neutrons).

Relationship between mission and technical objectives of a project

Mission (任务,使命)	Technical Objectives (技術性的目标)
Fundamental vision and motivation of the Project	Present information-based conditions to be obtained, in order to achieve the mission
Qualitative, the big picture	Quantitative, actionable, measurable
Usually single in number	Multiple in number
Driver for the technical objectives	Drivers for detailed plans (design, construction, schedule, R&D, etc.) of Project
Does not change	Can be updated due to progress in information, experience, cost-risk tradeoffs, and even options in tokamak and confinement configurations

What can we say about ITER?

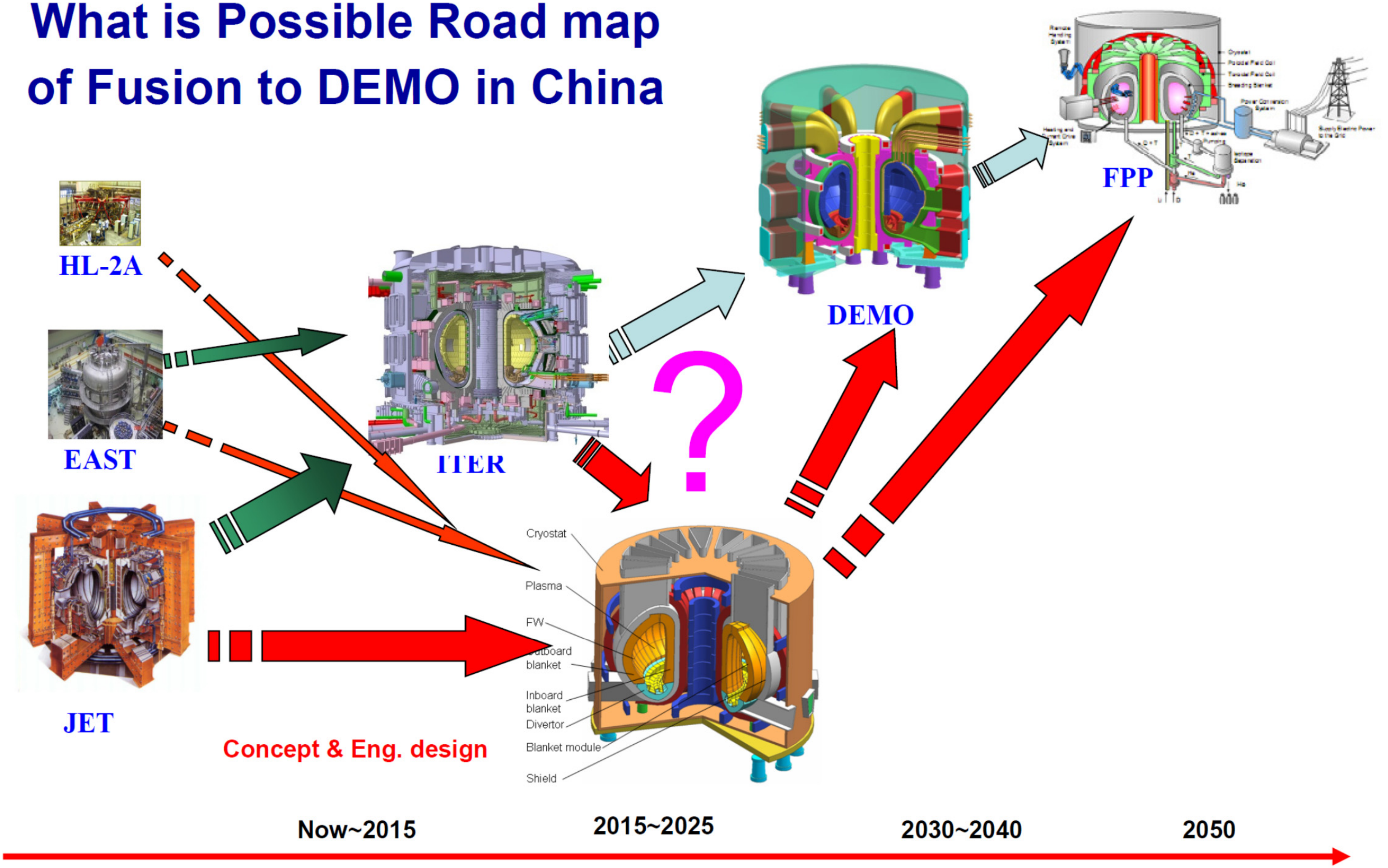
- The ITER Project is a multidisciplinary, multi-physics, interactive, complex system.
- The “道” of the ITER Project has been selected, and its “德” has been chosen and is being implemented.
- Achieving the ITER objectives will create the new conditions that
  a) Shed new light on the “道” that demonstrate the feasibility of fusion power, and
  b) Advance fusion engineering and technology (“德”) toward fusion power, in three topical areas.

How should the remaining “德” of fusion power be advanced?

What are the R & D drivers (high-leverage parameters)?

Under discussion (March, 2013)

What is Possible Road map of Fusion to DEMO in China



Mission of CFETR (Prof. Wan, March 2013)

(Patterned after the style of ITER mission, for the sake of discussion in class)

Mission: A good complement with ITER (*in R&D toward fusion DEMO*)

Project technical objectives:

- Demonstrate fusion energy production at a minimum of

  $P_f = 50 \sim 200$MW; *(Note: ITER has no Pf objective!)*

- Long pulse or steady-state operation with

  a time duty cycle $\geq 0.3 \sim 0.5$;

- Demonstrate full, self-sustained T cycle with TBR ≥ 1.2;
- Rely on existing ITER physics ($k<1.8$, $q>3$, $H \sim 1$) and technical bases;

  (The "道" and "德" of the ITER Project)

- Exploring options for DEMO blanket & divertor with a easy changeable core by RH.

(Note: no high-Q objective for CFETR!)

Complementarity of ITER and CFETR mission & objectives

	ITER Project (2009)	CFETR Proposal (2013)
Mission	• Demonstrate fusion power feasibility • Prove it can be done without negative impact	• Good complement to ITER (*in R&D toward DEMO)*
Fusion gain (Q)	• Q = 10 (short pulse); 5 (steady state) • Ignite and maintain burn for 480 s • Pf & duty cycle not specified	• Pf = 50 ~ 200 MW, Q not specified • Steady state operation • Duty cycle = 0.3 ~ 0.5
Burning plasma condition & techniques	• To be experimentally tested in ITER	• Rely on ITER plasma physics (k<1.8, q>3,H~1) & techniques
Fusion core technology	• S/C magnets • Remote handling (RH)	• Rely on ITER • Easy RH change-out of blanket and divertor
Tritium fuel	• Verify breeding concept	• Demonstrate full self-sustained cycle with TBR ≥ 1.2
Neutron shield & heat conversion	• Refine techniques	• Explore DEMO blanket options

These complement ITER

ITER Project provides basis for CFETR design, modified to achieve the complementary objectives ⇒ R&D drivers!

- Divertor and blanket options
  a) Survive steady-state operation of high duty cycle and neutron fluence
  b) Be configured for easy RH change-out and installation
  c) Include techniques to reduce material surface erosion (dust!) and possibly reduce heat and particle fluxes to allow high fluence
  d) More stringent tritium containment and accountability
  e) Apply these also to all other plasma facing components
- Plasma facing components include
  a) Radiofrequency (RF) heating in-vessel components
  b) Diagnostic components (mirrors, windows, photon sensors, ...)
  c) Dust control and removal from in-vessel surfaces

ITER Project provides basis for CFETR design, modified to achieve the complementary objectives ⇒ R&D drivers! – cont.

- Remote handling systems
  a) Large mass of modules?
  b) 3D metrology of modules to fit in core, during transit, and in hot cells?
  c) Different layout (arrangement) of reactor hall to accommodate such RH requirements
  d) How much, when and where to allow “hands-on” activities
  e) Stringent personnel safety and environment protection
- Tritium involved systems
  a) Continuous operation in high duty cycle (collection, recovery, purification, storage, refueling, etc.)
  b) Containment in all connected vacuum and tritium recovery systems!
  c) Including pumping, fueling, heating, divertor, and most diagnostics systems
  d) Tritium in-vessel inventory build-up during continuous operation

ITER Project provides basis for CFETR design, modified to achieve the complementary objectives ⇒ R&D drivers! – cont.

- Blanket options
  - a) Compatibility among blanket options:
    - Helium cooled solid breeder
    - Lithium-lead cooled liquid breeder
    - Supercritical water cooled solid breeder!
  - b) Blanket in-vessel coverage
- Neutron loss through other in-vessel access
  - a) Divertor
  - b) Heating
  - c) Diagnostics
  - d) Pumping
  - e) Can these be partially recouped through breeding at low energy?

ITER Project provides basis for CFETR design, modified to achieve the complementary objectives ⇒ R&D drivers! – cont.

- Materials in in-vessel components (high-fluence neutron damage and degradation)

  a) Ferritic-martensitic steel

    - Fission neutron damage data to 10 dpa (displacement per atom)
    - Fusion neutrons have higher helium co-production ratio than fission neutrons

  b) Cu alloys

  c) Tungsten

  d) Ceramics

  e) Insulator

  f) Joining & coating materials (brazing, tritium barrier, coolant tube coating, etc.)

  g) Tritium retention associated with the damage

CFETR complementary mission ⇒ objectives ⇒ new R&D drivers for most components and systems

- Divertor
- Other plasma facing components
- Remote handling systems
- Tritium-involved systems
- Blanket options
- Neutron loss through other in-vessel access
- Materials in in-vessel components (neutron damage and degradation)

These new R & D topics are beginning to be identified, analyzed, and researched

R & D drivers are derived from CFETR mission and objectives, and impact the design of most components and systems

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L3 on December 6, 2014, same time & place