Issues and Paths to Magnetic Confinement Fusion Energy

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Symposium on Worldwide Progress Toward Fusion Energy
AAAS Annual Meeting
Boston
16 February 2013

PPPL

Issues and Paths to MFE: Outline

- International context
- Scientific & technical challenges
- U.S. next-step planning

Context: MFE in Transition

ITER: Landmark accomplishments by the world MFE community:

✓Established ITER's scientific & technical (S&T) basis.

✓Developed the design.

✓Formed an international project.

✓Started construction.

With ITER, MFE has crossed a threshold to a phase of the program increasingly focused on fusion energy generation.

Making ITER succeed is the first task for this new phase.

Several countries are planning major facilities and next steps beyond ITER on the path to DEMO.

EFDA
EUROPEAN FUSION DEVELOPMENT AGREEMENT

EU Roadmap in a ...

Europe’s new fusion roadmap:

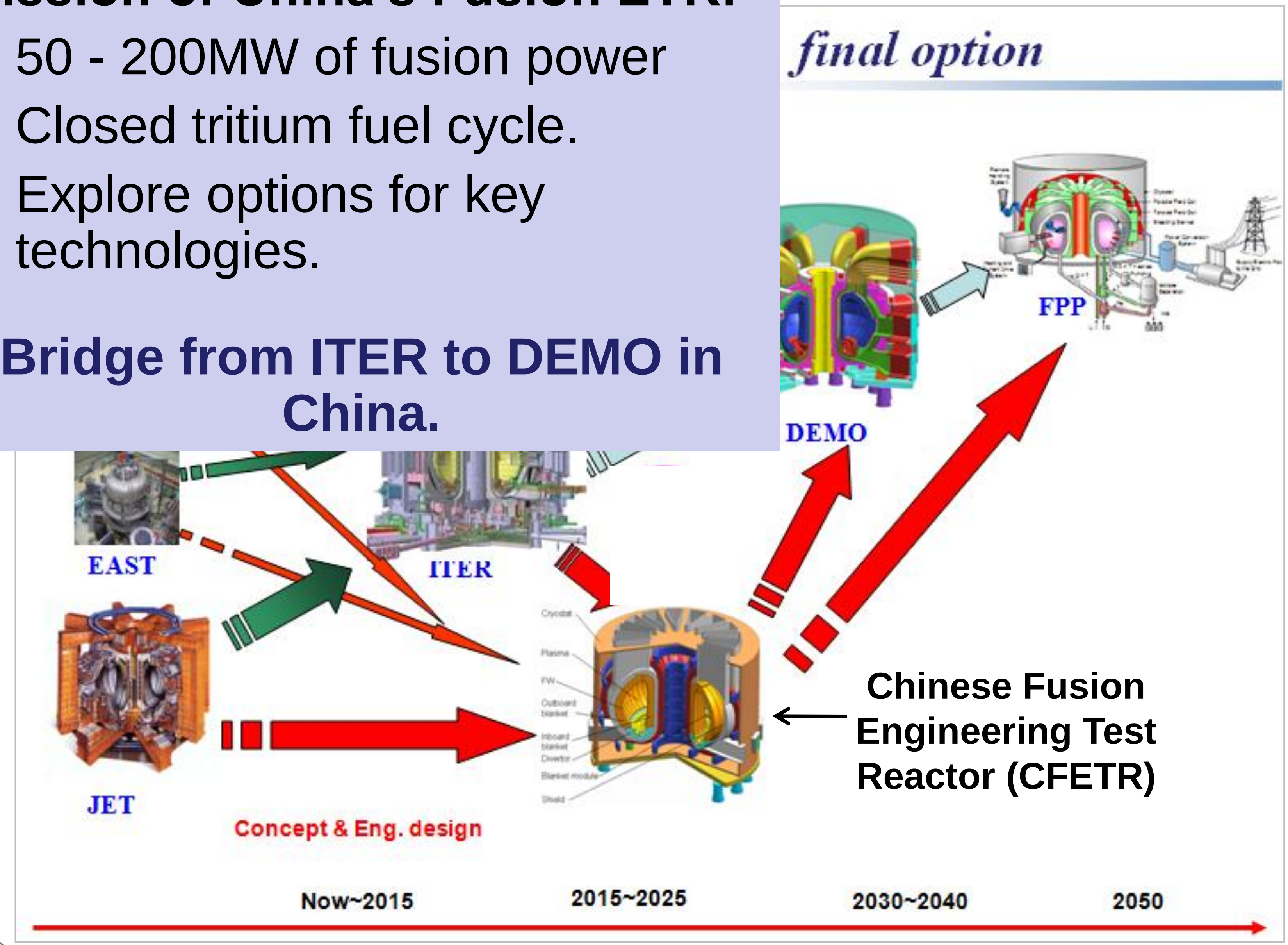
- Eight strategic missions.
- International collaboration.
- Large fusion nuclear machine (“DEMO”) starting construction in ~2030.
- One critical path: ITER → DEMO → electricity.
- Fusion electricity in the mid-40’s

1. Plasma operation
2. Heat exhaust
3. Materials
4. Tritium breeding
5. Safety
6. DEMO
7. Low cost
8. Stellarator

Mission of China's Fusion ETR:

- 50 - 200MW of fusion power
- Closed tritium fuel cycle.
- Explore options for key technologies.

Bridge from ITER to DEMO in China.

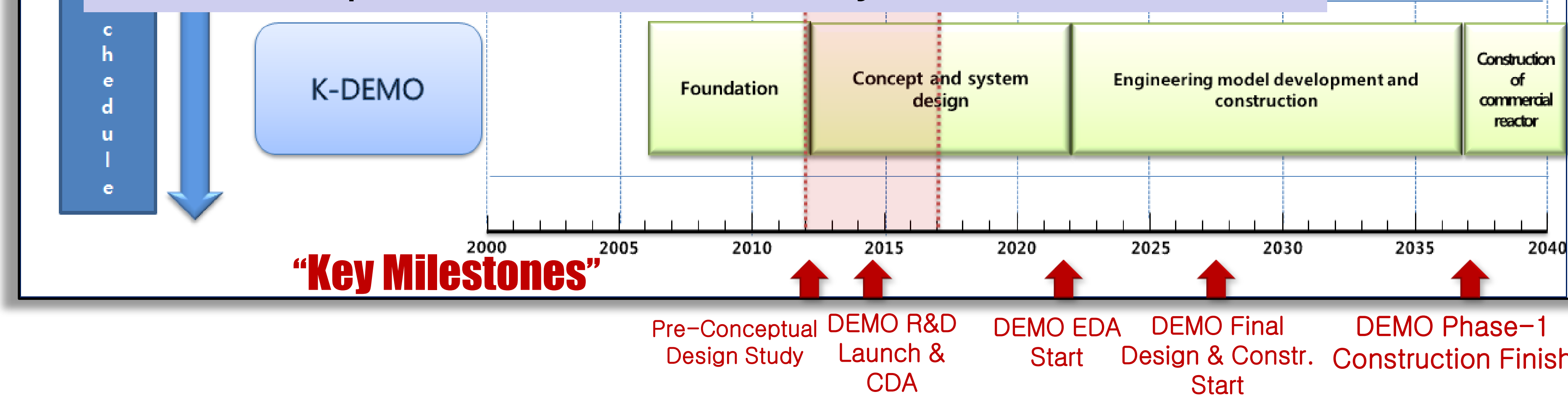


Chinese Fusion Engineering Test Reactor (CFETR)

Korean Fusion Energy Development Roadmap

Mission of S. Korea's K-DEMO

- Technology representative of the commercial plant.
- Phase I: Component testing, demonstration of…
  - Net electricity generation
  - Closed tritium cycle.
- Phase II: (after internal component upgrade):
  - Advanced component testing
  - Net electricity >450 MWe.
  - Availability >70%
  - Competitive cost of electricity.



Planning the Roadmap to Fusion Energy

The international discussion of scientific and technical needs has broadened in recent years:

IOP Publishing and International Atomic Energy Agency — Nuclear Fusion
Nucl. Fusion 52 (2012) 047001 (11pp) — doi:10.1088/0029-5515/52/4/047001

CONFERENCE REPORT

Summary of the International Workshop on Magnetic Fusion Energy (MFE) Roadmapping in the ITER Era; 7–10 September 2011, Princeton, NJ, USA

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Abstract
With the ITER project now well under way, the countries engaged in fusion research are planning, with renewed intensity, the research and major facilities needed to develop the science and technology for harnessing fusion energy. The Workshop on MFE Roadmapping in the ITER Era was organized to provide a timely forum for an international exchange of technical information and strategic perspectives on how best to tackle the remaining challenges leading to a magnetic fusion DEMO, a nuclear fusion device or devices with a level of physics and technology integration necessary to cover the essential elements of a commercial fusion power plant. Presentations addressed issues under four topics: (1) Perspectives on DEMO and the roadmap to DEMO; (2) Technology; (3) Physics-Technology integration and optimization; and (4) Major facilities on the path to DEMO. Participants identified a set of technical issues of high strategic importance, where the development strategy strongly influences the overall roadmap, and where there are divergent understandings in the world community, namely (1) the assumptions used in fusion design codes, (2) the strategy for fusion materials development, (3) the strategy for blanket development, (4) the strategy for plasma exhaust solution development and (5) the requirements and state of readiness for next-step facility options. It was concluded that there is a need to continue and to focus the international discussion concerning the scientific and technical issues that determine the fusion roadmap, and it was suggested that an international activity be organized under appropriate auspices to foster international cooperation on these issues.

1. Introduction

With the ITER project now launched on its mission to achieve, for the first time, a magnetically confined burning fusion plasma on a power-plant scale, the countries engaged in fusion research are planning, with renewed intensity, the research and major facilities needed to develop the fusion nuclear science and technology for harnessing fusion energy. The Workshop on MFE Roadmapping in the ITER Era was organized to provide a timely forum for an international exchange of technical information and strategic perspectives on how best to tackle the remaining challenges leading to a magnetic fusion DEMO, a nuclear fusion device or devices with a level of physics and technology integration necessary to cover the essential elements of a commercial fusion power plant. Sixty-five researchers from 10 countries, including all the ITER partners, attended the workshop, which was held 7–10 September 2011 at Princeton University. The level of international participation reflected a widely felt sense of

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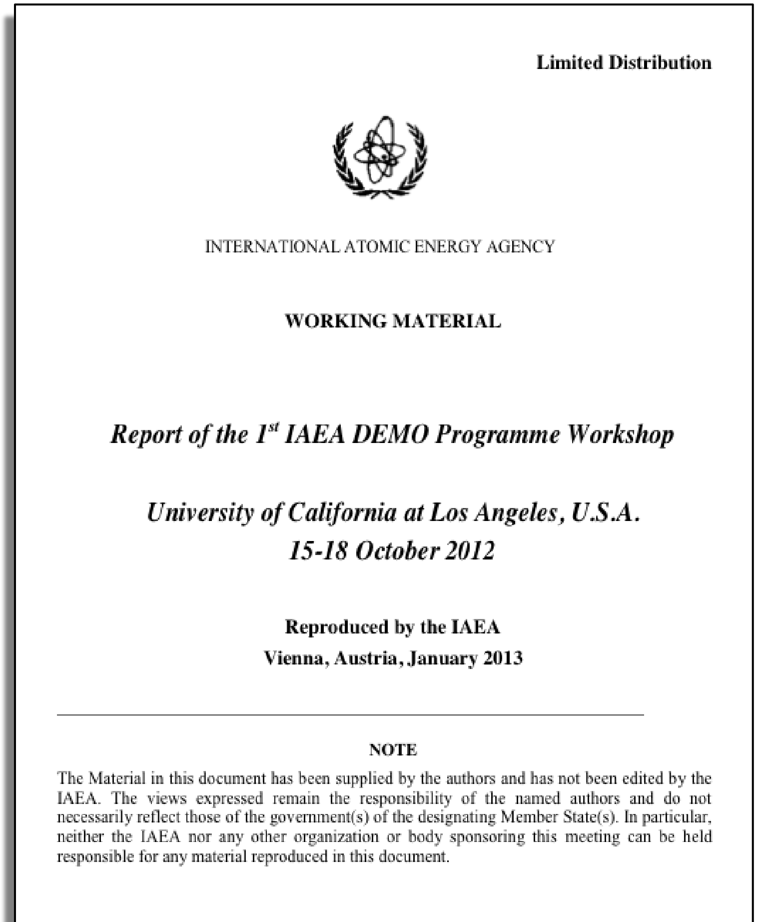


Limited Distribution

INTERNATIONAL ATOMIC ENERGY AGENCY

WORKING MATERIAL

Report of the 1st IAEA DEMO Programme Workshop

University of California at Los Angeles, U.S.A.
15-18 October 2012

Reproduced by the IAEA
Vienna, Austria, January 2013

NOTE

International Perspective on the Roadmap

Fusion development is approached from many directions, e.g. from fundamental science, from energy technology, etc.

The diversity of approaches is an asset- we can benefit from each other's programs.

The characteristics of the world's DEMO program are emerging and will become clearer as government decisions are made to implement major next-step facilities.

Meanwhile, there is general agreement on basic points:

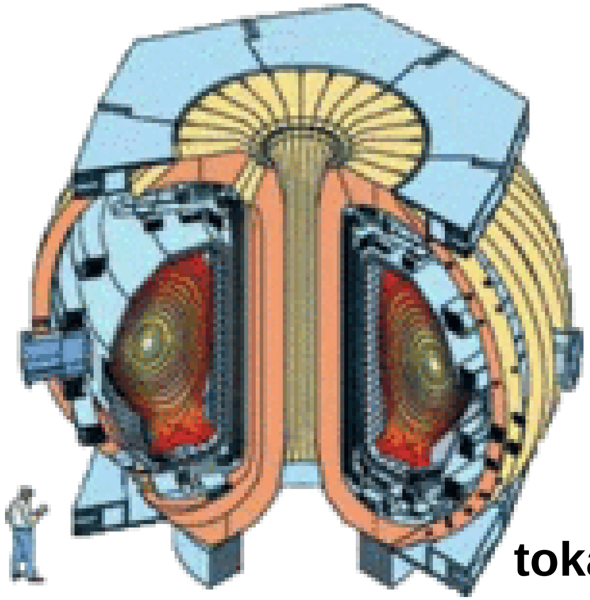
- **The central importance of ITER.**
- **The main outstanding scientific and technical challenges**
- **The continuing importance of international collaboration.**

Key Scientific and Technical Challenges

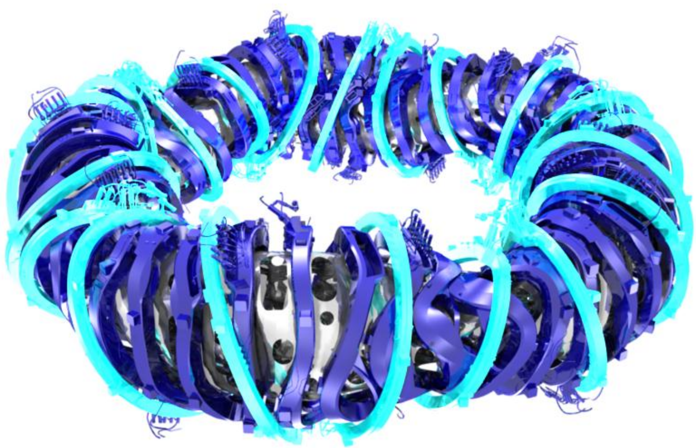
1. Plasma confinement and control.
2. Plasma exhaust
3. Power extraction and tritium self-sufficiency.
4. Availability

Research on these issues constitutes a world *DEMO Program*.

Plasma Confinement and Control



tokamak



stellarator

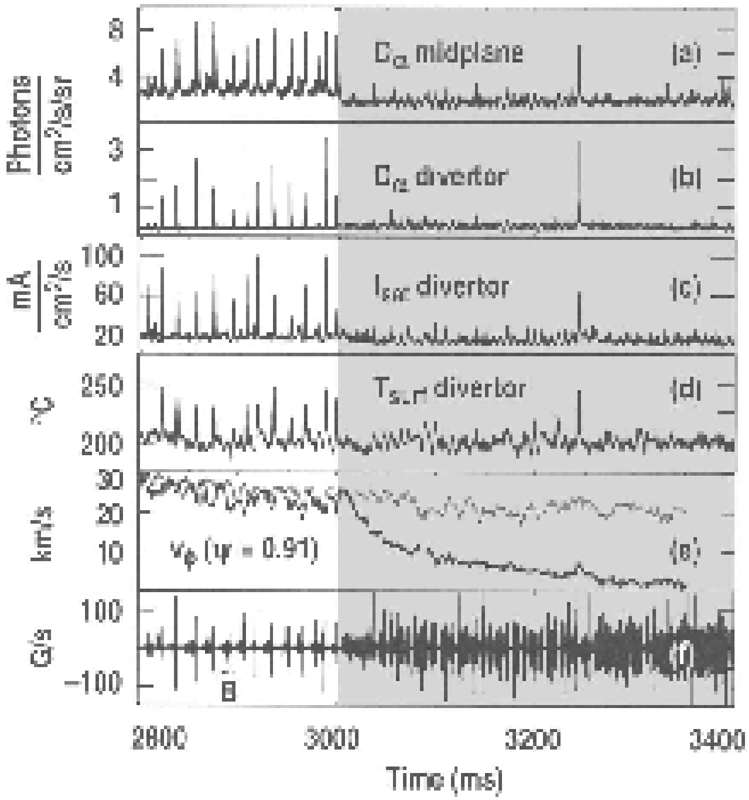
To recap from A. Hubbard…

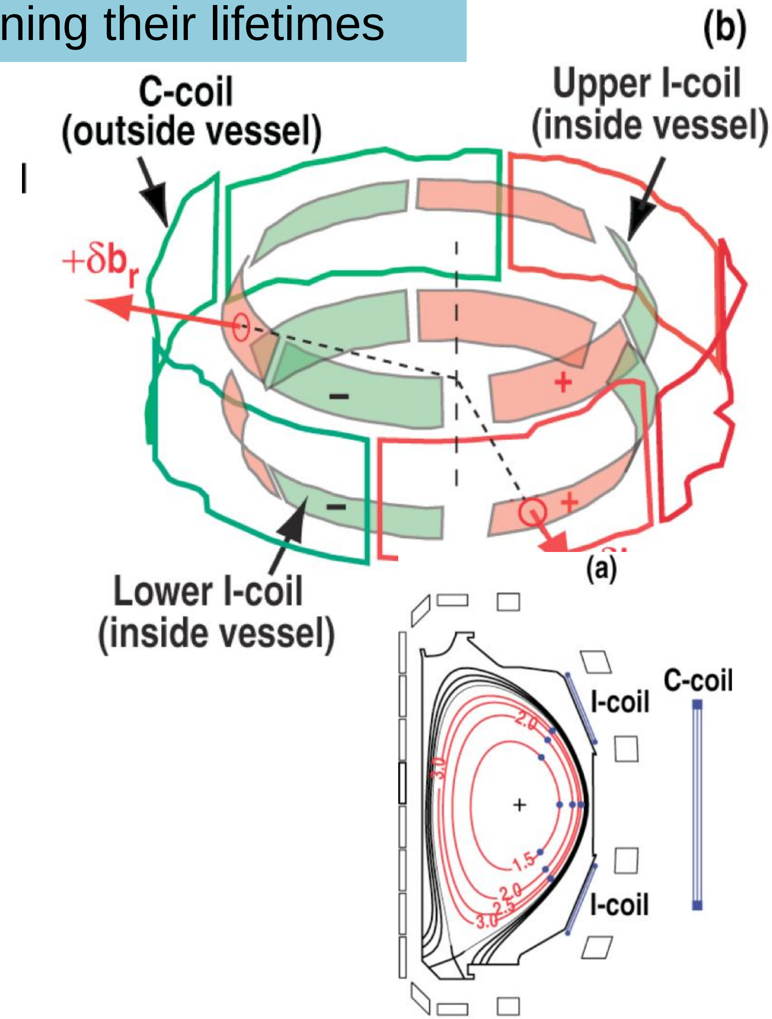
Today's fusion experiments are addressing plasma questions for ITER and future machines:

- What are the best control strategies for plasmas operating close to stability boundaries?
- How is plasma behavior affected by material choices for plasma-facing surfaces?
- How can we improve on the basic toroidal magnetic confinement configuration?
  - Application of non-axisymmetric fields.
  - Optimized edge configuration.

Edge-Localized Instabilities Are Suppressed by Application of 3D Magnetic Fields

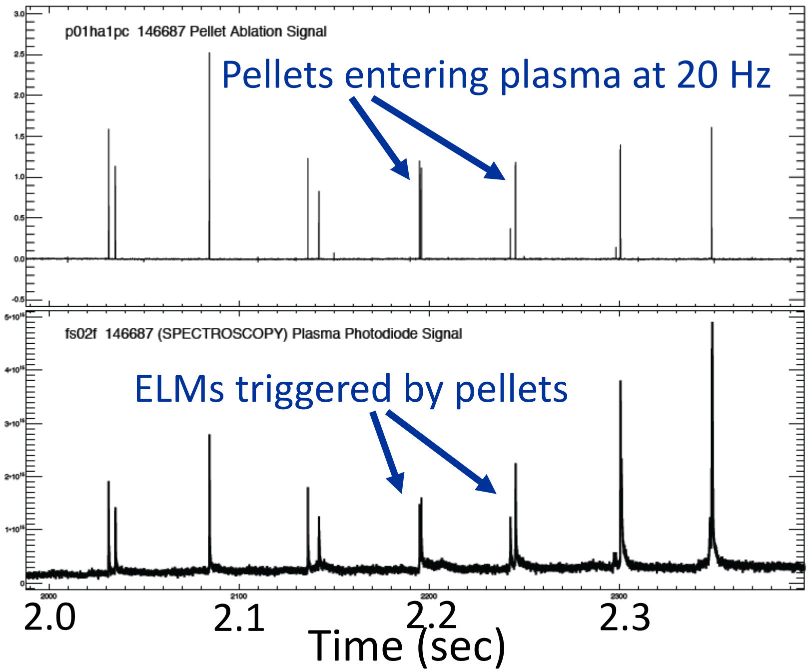
Plasma energy released in bursts can erode internal component, shortening their lifetimes

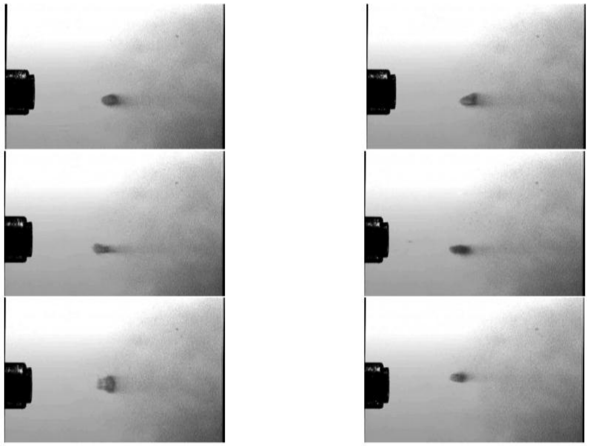




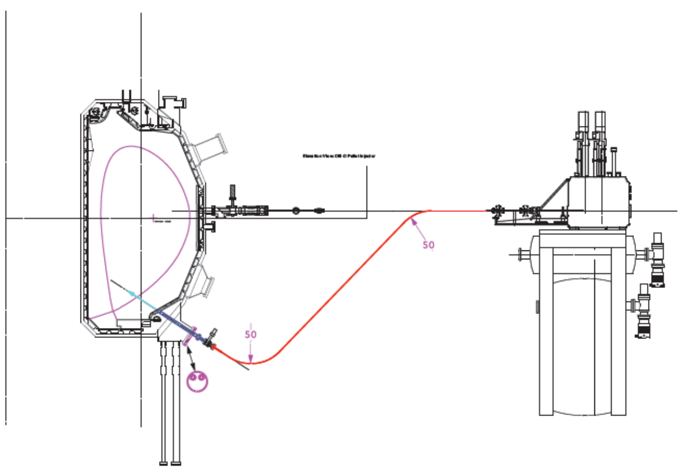
Bursts suppressed when 3D fields are applied

Inject Fuel Pellets to Trigger the Instability at a Lower Threshold and Release Energy in Smaller Bursts



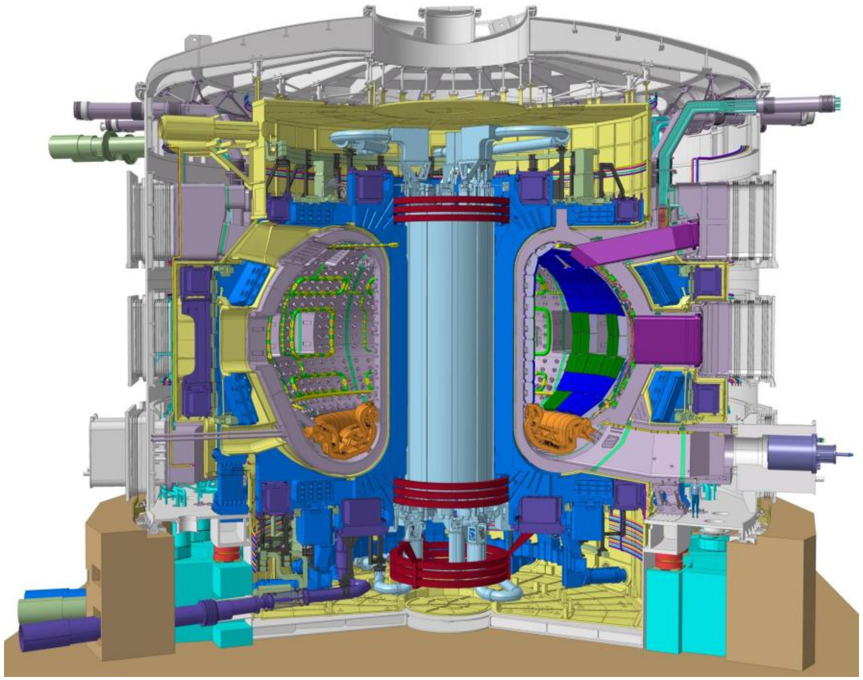


Pellets leaving gun barrel.



Pellet injection configuration on tokamak.

Control of a Burning Plasma: ITER

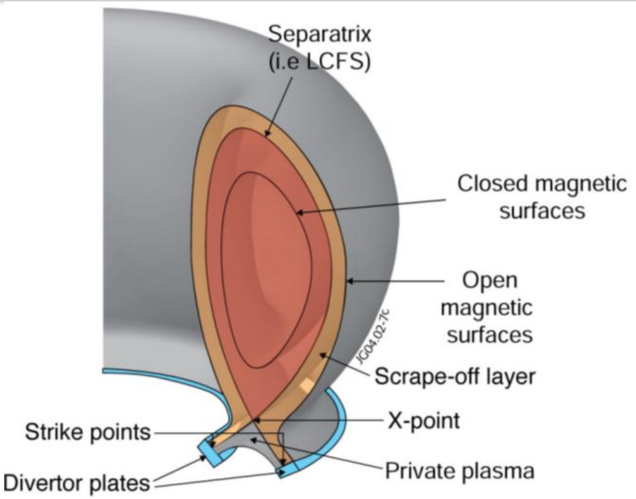


To recap from R. Hawryluk, with ITER we will learn:

- Performance and behavior of a plasma dominated by alpha-particle self-heating.
- Test of plasma control strategies under burning conditions at reactor scale.
- Advances in fusion machine technology and engineering.

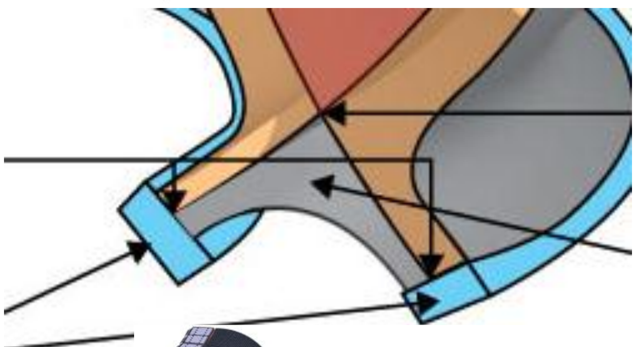
ITER is the burning plasma step for all MFE approaches.

Plasma Exhaust Handling

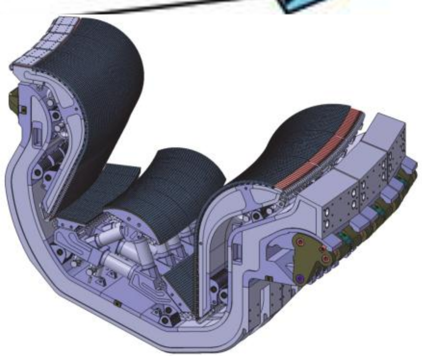


- DEMO exhaust power per unit length (P/R) is **4xITER's.**

  New solutions are needed!

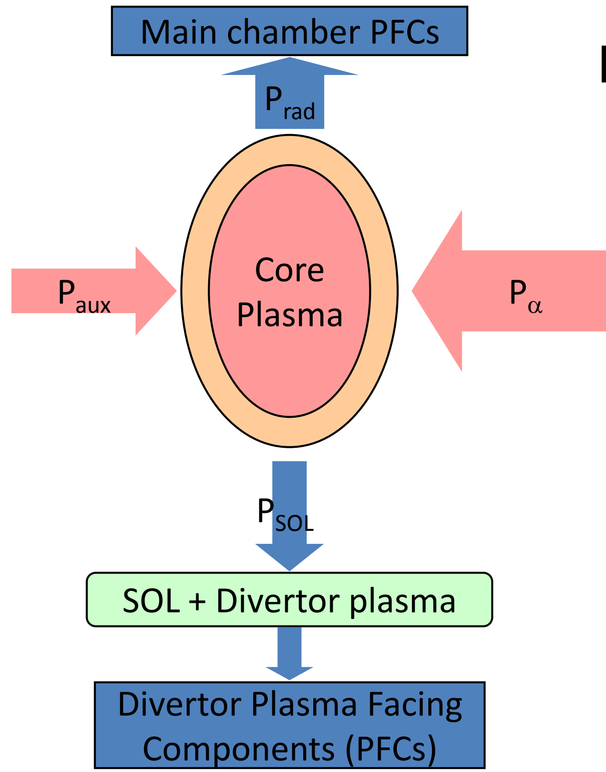


Divertor



Divertor PFCs

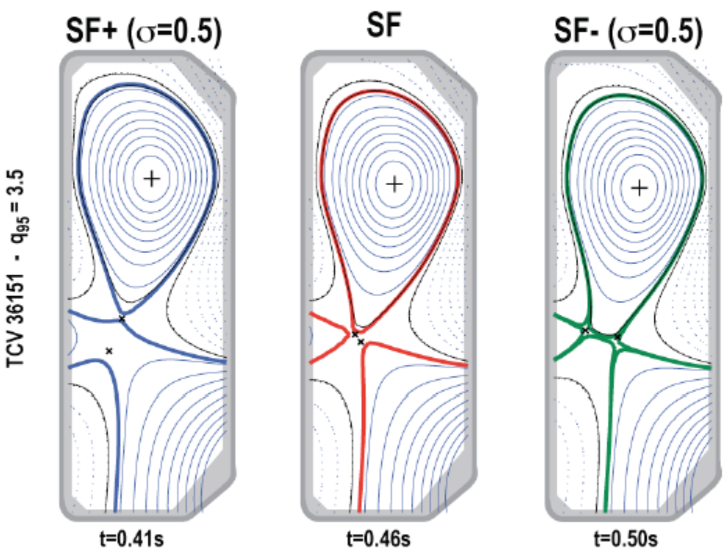
Power Flow



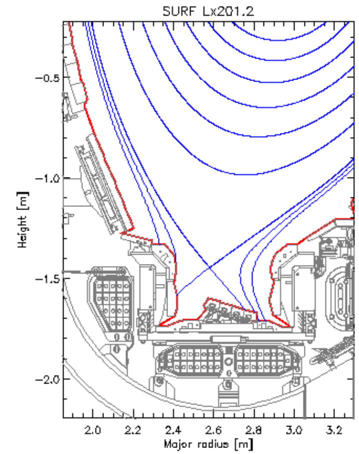
Plasma Exhaust: Configuration Solutions

Snowflake

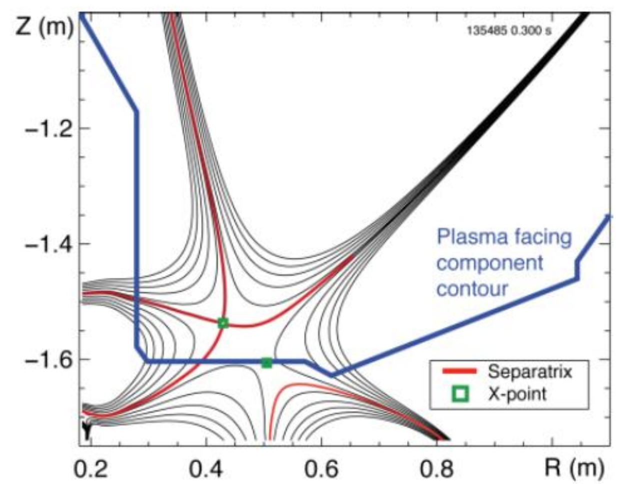
Use a high-order null (*vs.* a simple X-point) to spread the divertor field lines over a wider surface area. → Lower peak heat flux to target.



Snowflake test in TCV (Switzerland)



Standard X-point Divertor (JET)

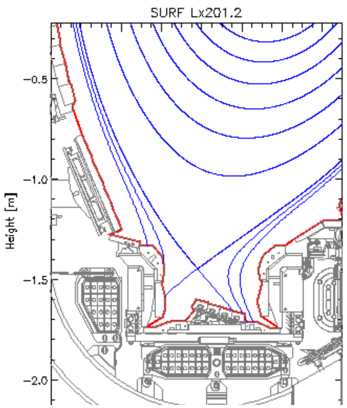


Snowflake test in NSTX (U.S.)

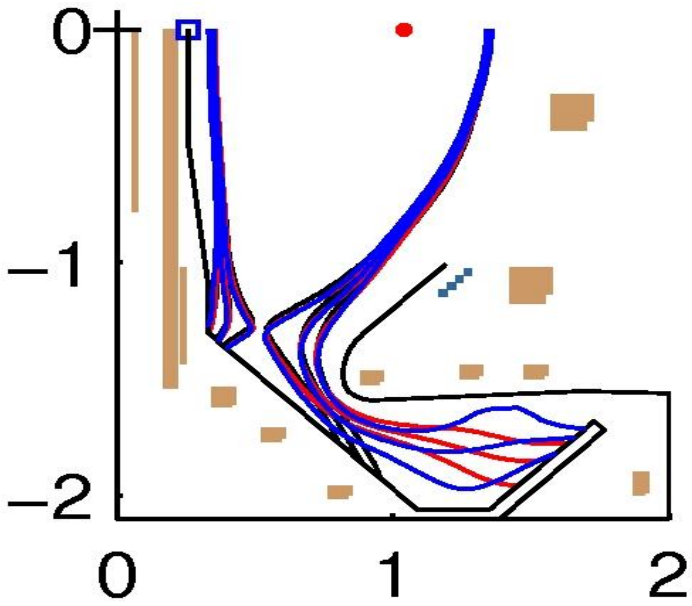
Plasma Exhaust: Configuration Solutions

Super-X

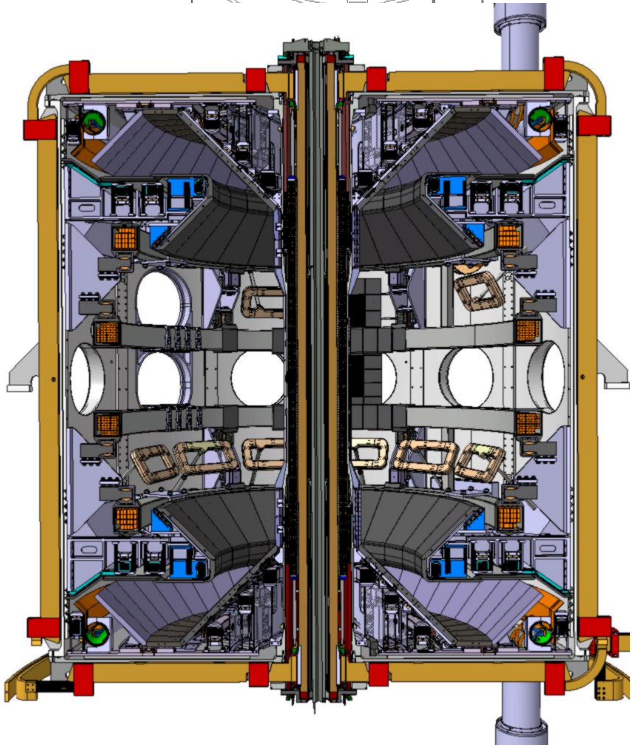
Channel the diverted field lines to larger radius to spread heat loads, and increase isolation from main chamber.



Standard X-point Divertor (JET)



Super-X design for MAST-Upgrade (U.K.)

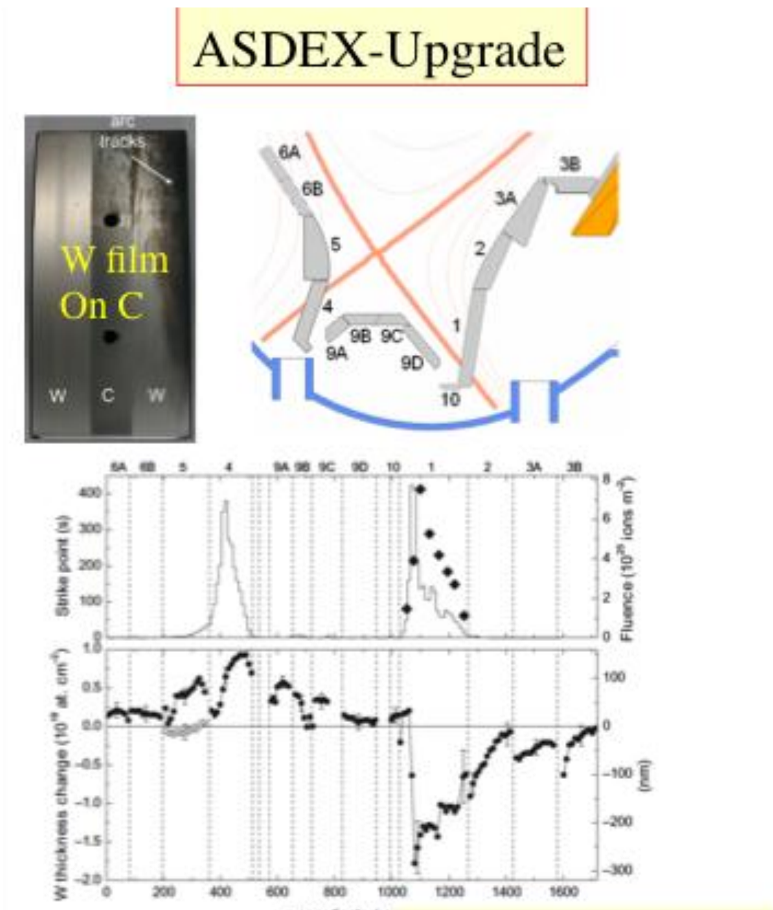


MAST-Upgrade

Plasma Exhaust: Material Solutions

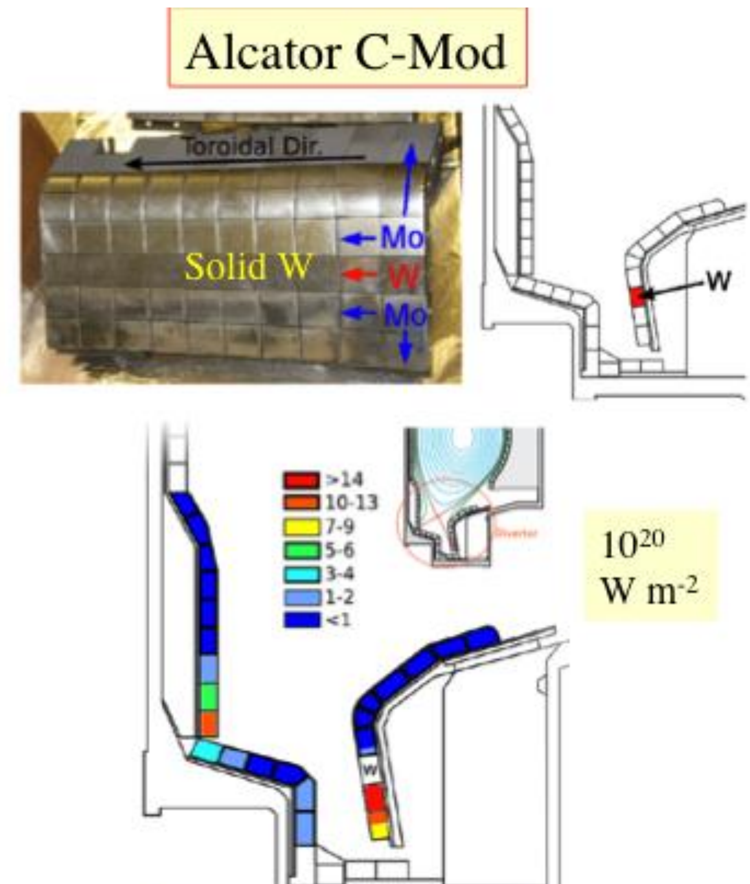
Tungsten

- **Favored for erosion control due to low sputtering yield.**
- **Plasma-tungsten compatibility is studied in several machines.**



IAEA Demo Workshop Whyte Oct. 2012

Mayer Phys. Scr. ***T138*** *(2009)*



Barnard JNM ***415*** *(2011)*

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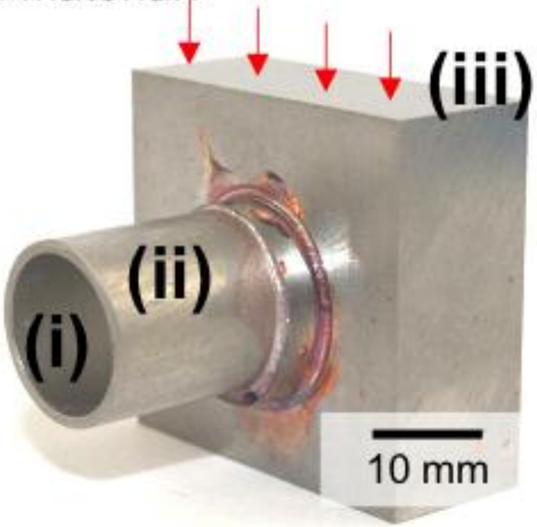
Plasma Exhaust: Technology Solutions

Technology Challenge:

- Definition of the divertor: pipe, surrounded by tungsten
  - (i): type of coolant?
  - (ii): structural material for the pipe?
  - (iii): armour material? → tungsten
- Question: What amount of heat can we remove with a specific combination of (i) coolant and (ii) structural material?

picture: PLANSEE SE



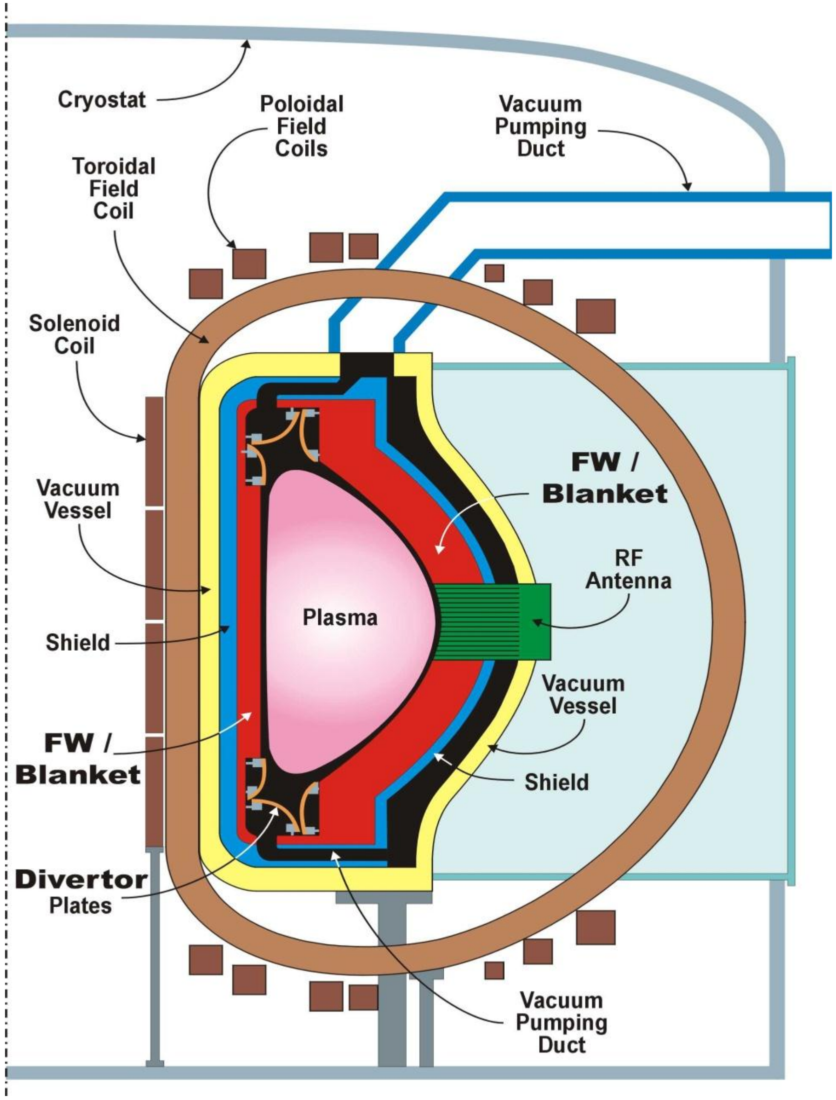
Fusion Power Extraction and Tritium Breeding

Functions of the Blanket–First Wall (FW) system

A. Nuclear and Plasma Power Absorption and Extraction

B. Tritium Breeding and Recovery

C. Radiation Shielding of the Vacuum Vessel and Magnets

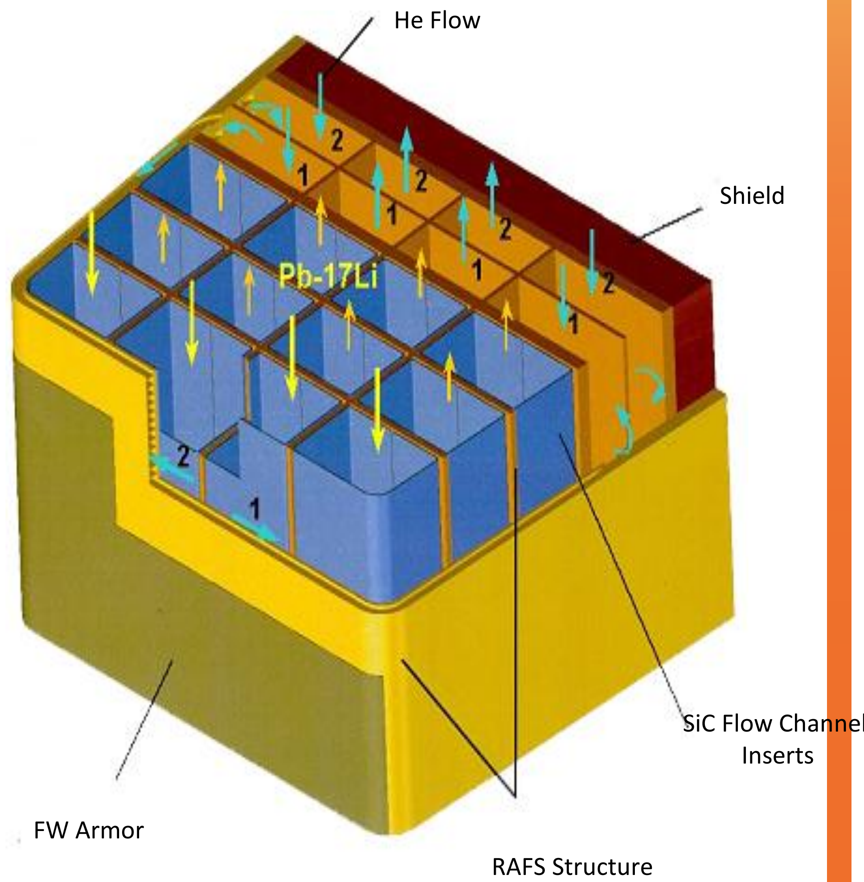


Blanket Designs

Liquid breeder: Dual-Coolant Lead Lithium (DCLL)

Basic Features

- Flowing lead-lithium breeder/coolant in large parallel channels
- Flow channel inserts (silicon carbide) for MHD pressure drop control and thermal insulation
- Reduced-activation ferritic steel (RAFS) first wall and structure cooled by helium

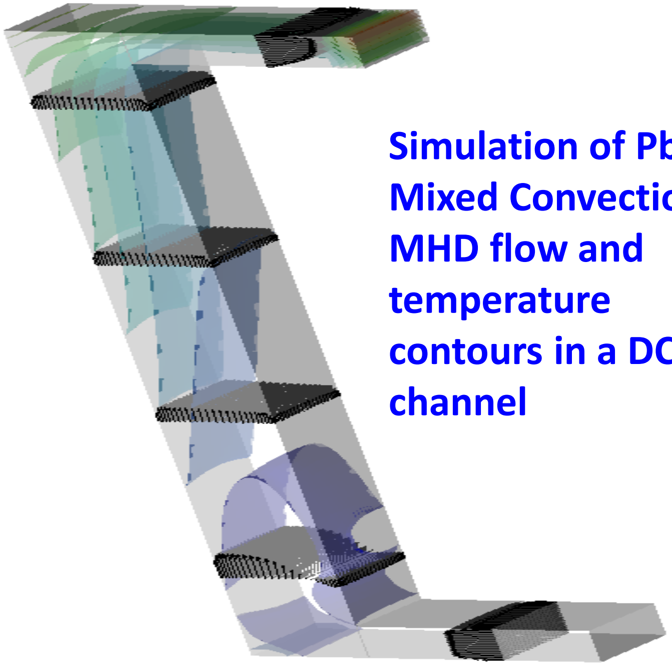


Possible Advanced features

- Potential for high temperature operation with high temperature tritium and heat extraction

Blanket Materials Engineering Challenges

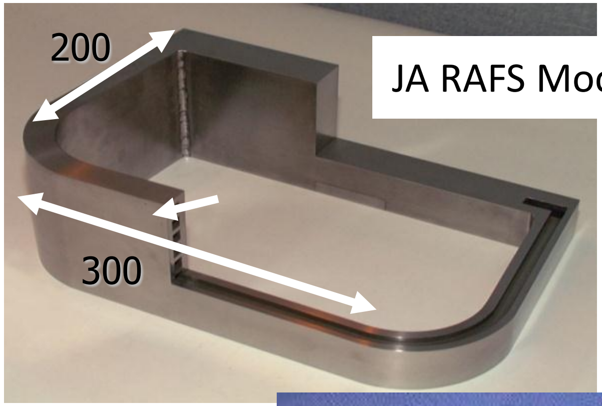
Functional Materials

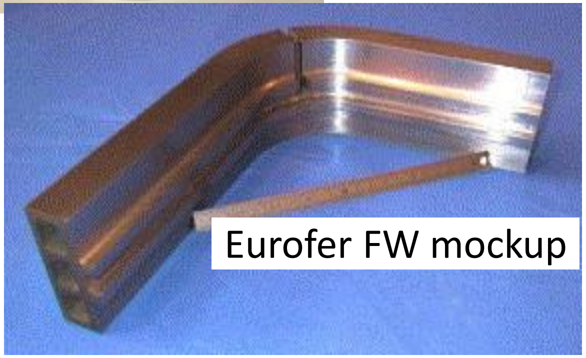


Simulation of PbLi Mixed Convection MHD flow and temperature contours in a DCLL channel

- Liquid metal thermofluid-MHD.
- Corrosion.
- Transport & extraction of tritium in PbLi.
- PbLi fabrication; chemistry control.

Structural Materials



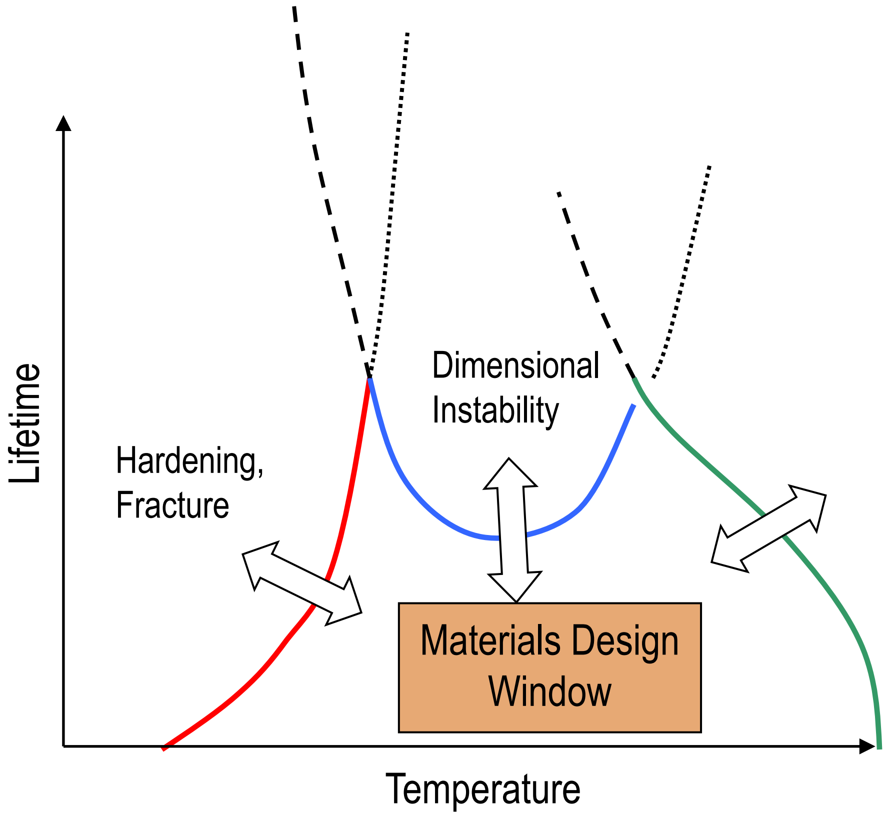


- Fabrication & joining.
- Heat transfer
- Reliability and failure modes.
- Material property changes in service.

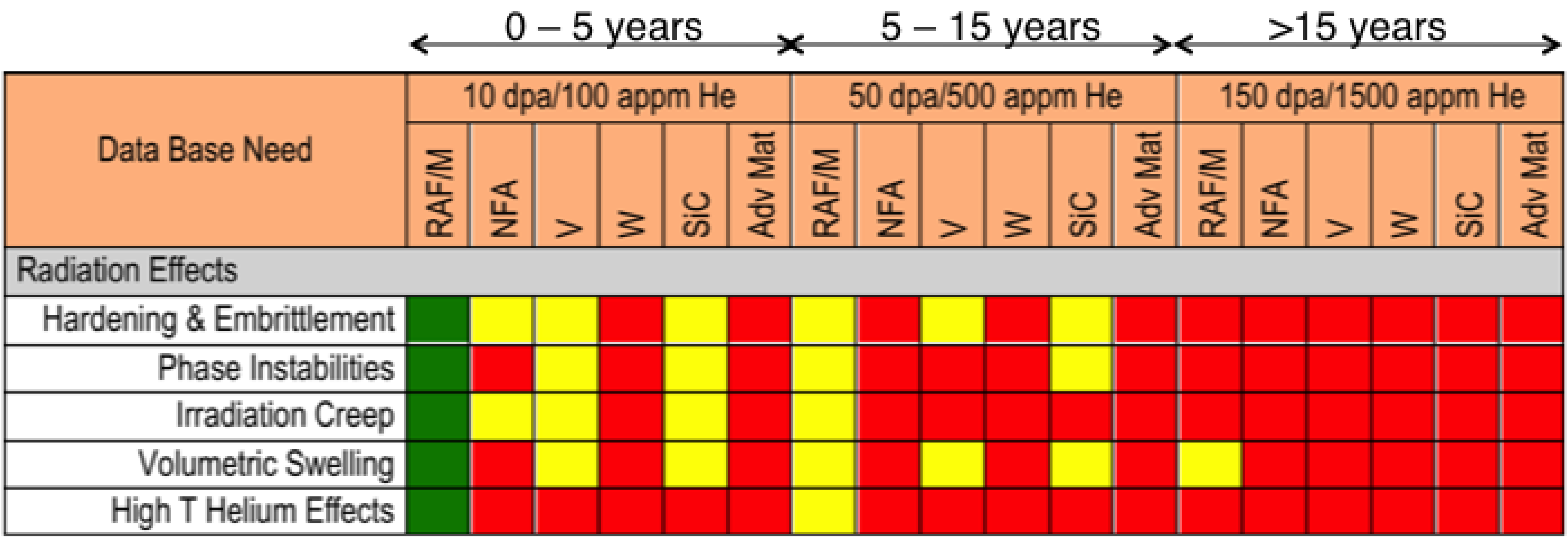
Materials in the Fusion Environment

Unique to fusion: microstructure and property changes due to coupled effects of displacement damage (displacements per atom or dpa) and Helium.

- Low temperatures
  - Hardening + He embrittlement
  - Loss of ductility
  - Loss of fracture resistance
- Intermediate temperatures
  - Swelling + He
  - Irradiation creep + He
- High temperatures
  - Thermal creep
  - He embrittlement (> 10 dpa)
  - Fatigue and creep-fatigue, crack growth
  - Corrosion, oxidation and impurity embrittlement



Structural Materials Maturity for Fusion Neutron Irradiation Effects.



Planning for next-step fusion nuclear facilities currently focuses on ~20 dpa (2 MW-yr./m^2 neutron exposure) for first-generation components.

Availability

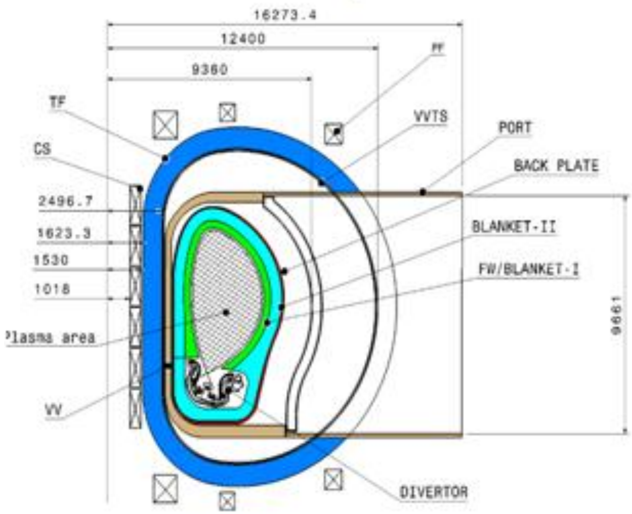
Availability is a key challenge for fusion, now receiving more attention.

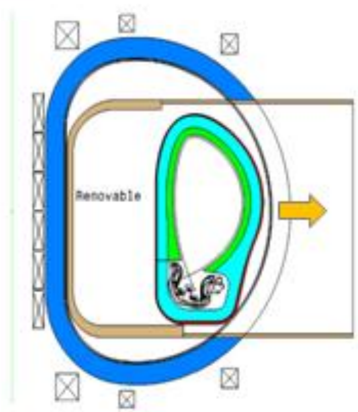
Rapid replacement of major components, using remote handling technology, is a concept-level design driver.

Reliability and maintainability must be prominent in the design of all components.

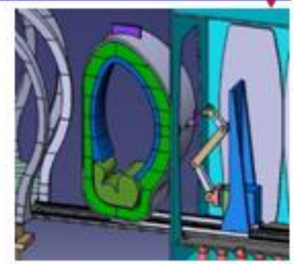
Studies for Chinese Fusion Engineering Test Reactor: Remote Handling concept for "big window" style strategy

All of the in-vessel components can be moved out in one time.

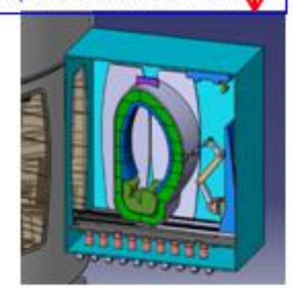




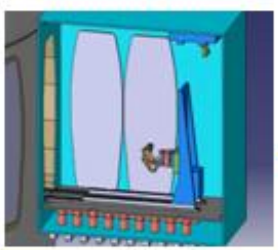
4.Move back the wheels with the blanket, by gear system



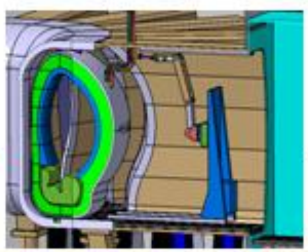
5. Use remote handing and guide rail to keep the blanket balance



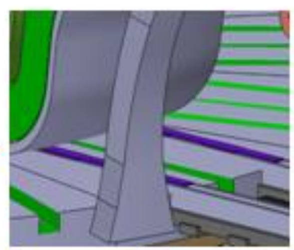
Maintenance process:



1. Dismantle the window's flange



2. Cut the cooling pipe and other connection things by remote handing



3. Inset wheels assemble under the blanket and lifting the blanket

6.Close the window's flange and move the CASK to hot cell for repair

U.S. Next-Step Planning Focuses on a Fusion Nuclear Science Facility (FNSF)

- The FNSF mission space is wide:

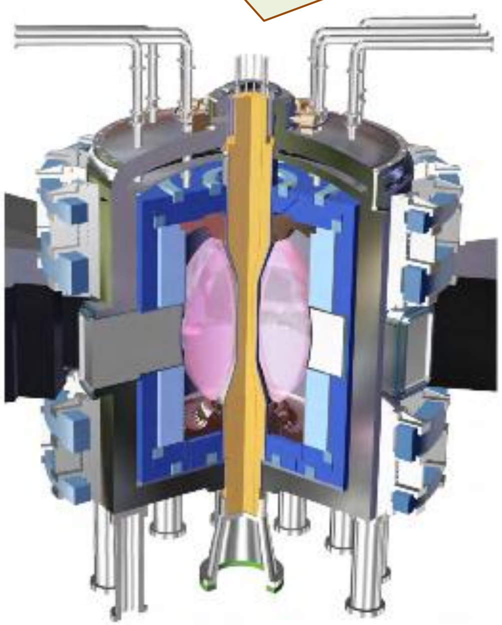
Materials research → Component Testing → Tritium Self-Sufficiency → Reliability/ Maintainability → Net Electricity

Increasing System Integration

- Basic FNF mission requirements (typ.):
  - Steady-state / high duty-cycle DT plasma.
  - Tritium self-sufficiency.
  - Neutron wall loads (NWL) challenging to internal components: 1-2 MW/m^2.
  - Neutron exposure challenging reliability and lifetime limits: ≥ 2-3 MW-yr./m^2.
  - Accommodation for test blanket modules.
- Optional extras:
  - Prototype reactor design and maintenance.
  - Generate (net) electricity.
  - Achieve high availability.

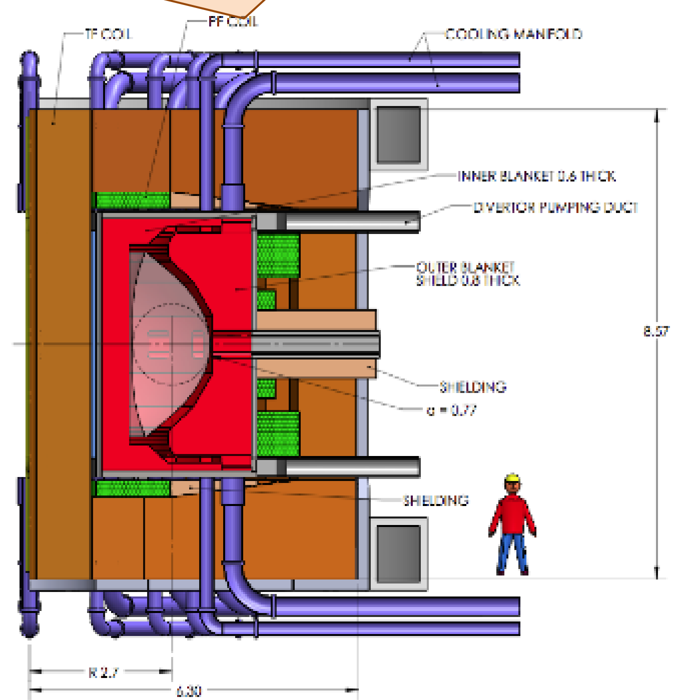
U.S. Fusion Nuclear Science Facility Designs

Materials research — Component Testing — Tritium Self-Sufficiency — Reliability/ Maintainability — Net Electricity



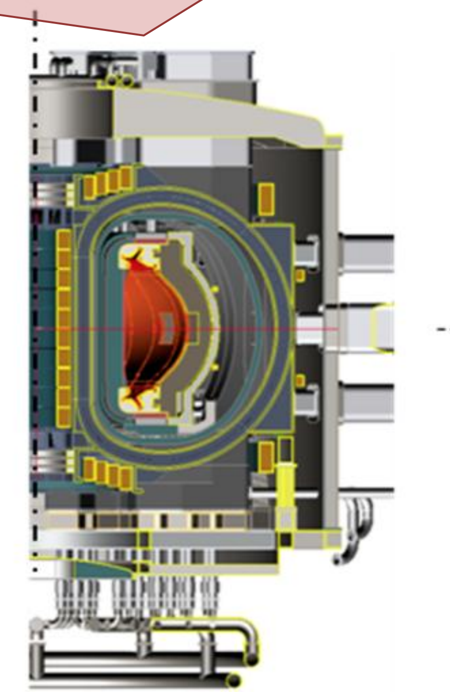
FNSF-ST– ORNL

Peng, *et al.*, F.S.&T. **60** (2011)



FNSF-AT – GA

Stambaugh, *et al.*, F.S.&T. **59** (2011)



Pilot Plant – PPPL

Menard, *et al.*, NF **51** (2011)

Summary

- A new phase of Magnetic Fusion R&D has begun.
- Succeeding with ITER is the first imperative.
- In parallel, nations are planning roadmaps to DEMO, moving ahead on DEMO R&D, and planning integrated fusion nuclear facilities.
- A range of next-step missions and design options are studied in the U.S.
- There are multiple approaches to fusion development but but broad agreement on the goals, critical tasks, and value of international collaboration.