Response to the NAS Committee for a Strategic Plan for U.S. Burning Plasma Research

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Presented to:
National Academies Committee for a Strategic Plan for U.S. Burning Plasma Research
August 29, 2017

What is the US Virtual Laboratory for Technology (VLT)?

- Formed in 1998 to provide a single entity with central leadership for the US fusion technology program
  - Provide advocacy for the technology program
  - Provide representation among the fusion program leaders
  - Build consensus within the program
  - Program management, guidance, and direction remains with FES
- Largely dormant from 2013-2016 (Milora retirement)
- New director named in May 2016
- Currently 18 institutions
  - 8 universities, 1 private company, 9 national labs
  - ~8% of US non-ITER budget

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Topics to be addressed by the VLT

- The *importance of U.S. burning plasma research* to the development of fusion energy
- The *scientific and technical developments since the 2004 report* of the NAS Burning Plasma Assessment Committee
- *Current status of U.S. research* that supports burning plasma science and advances fusion energy technologies
- Strategic *elements that might strengthen or accelerate* U.S. burning plasma research

All of these with a technology emphasis…

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"Experimental investigation of a burning plasma remains a grand challenge for plasma physics and a necessary step in the development of fusion energy"

National Research Council. 2004. Burning Plasma: Bringing a Star to Earth. Washington, DC: The National Academies Press

- *As true now as it was in 2004*
  - Strong consensus on this point, including among the technology programs

- ***"The creation of such plasmas is a necessary but not sufficient condition for the development of a practical energy-producing magnetic fusion power plant"***
  - Also from the 2004 report, and also still true
  - Important questions for fusion nuclear science from burning plasmas that must be answered

Near unanimous opinion that burning plasma science is among the most important, *or the most important*, topic in fusion energy research.

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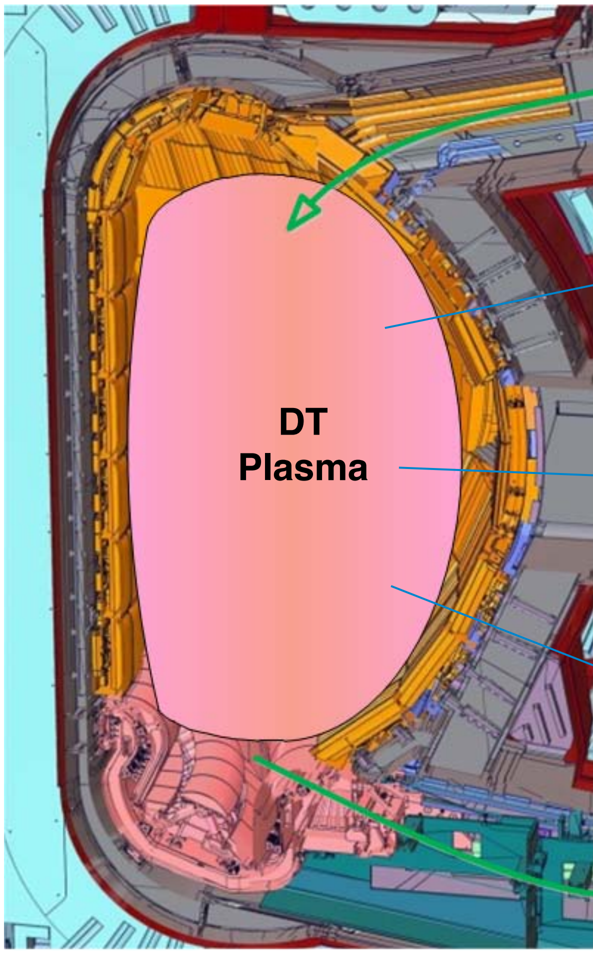
The 2004 report anticipated participation in ITER driving technology advancements in several areas

- From the 2004 report, fusion technology advances from burning plasma experiments were expected to include:
  - Breeding blanket development
  - Tritium processing
  - Magnet technology
  - High-heat-flux component development
  - Remote handling technology
- ITER has driven progress in each of these areas, ***as well as***:
  - Radiation transport
  - Disruption mitigation
- Additional areas of progress (from the base program) includes:
  - Fusion materials
  - Plasma-materials interactions (PMI)

A project approach like ITER drives a holistic approach to the fusion fuel cycle

Characteristics of magnetic fusion		Technology needs
	Magnetic plasma resists injection of replacement fuel	*Fueling*
	He "ash" and impurity build-up quenches fusion reaction	*Tritium Processing*
	Tritium is radioactive and expensive Only a fraction (~1%) of the fuel burns per pass	Drives all *Fuel Cycle* technology, including need for tritium self-sufficiency
	Vacuum must be maintained around plasma	*Vacuum* requires tritium handling

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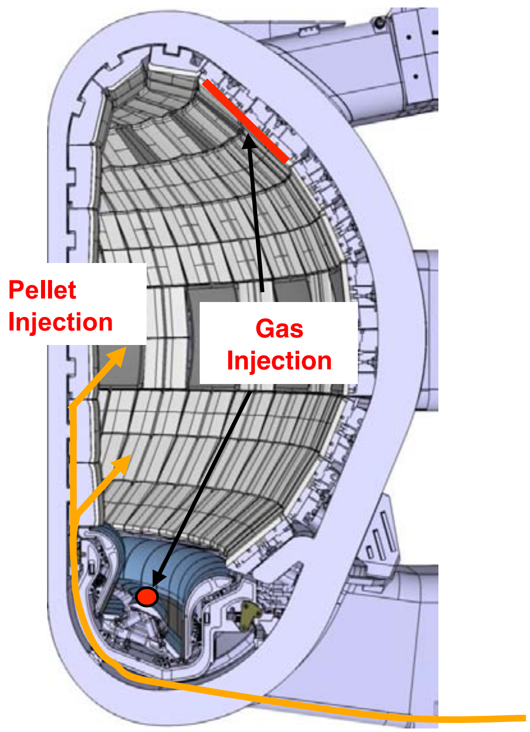
ITER Fueling Needs are Significant:
Cryogenic Pellet Injection is the Solution



ITER Cross Section

- ITER plasma volume is 840 m^3 and scrape-off layer is ~30 cm thick. This compares to 20 m^3 and ~ 5 cm for DIII-D.
- ITER is designed to operate at high density (> 1x 10^{20} m^{-3}) in order to optimize Q.
- NBI fueling to be negligible (< 2 x 10^{20} atoms/s or < 3 torr-L/s).
- Inboard pellet injection planned for deep fueling and high efficiency. Reliability must be very high.
- ITER will require significant fueling capability to operate at high density for long durations
  - ⇨ Gas fuelling will be limited by poor neutral penetration

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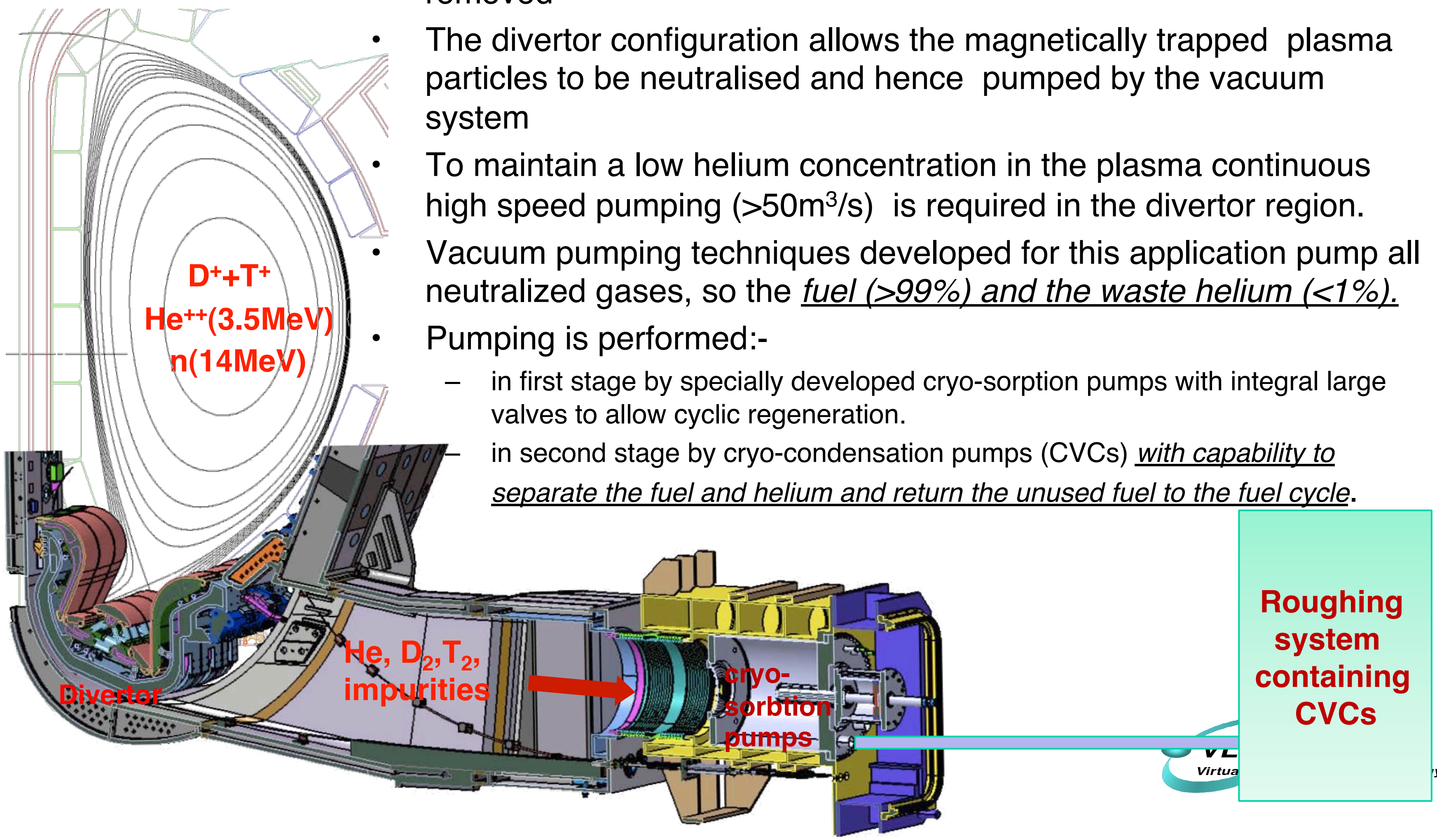
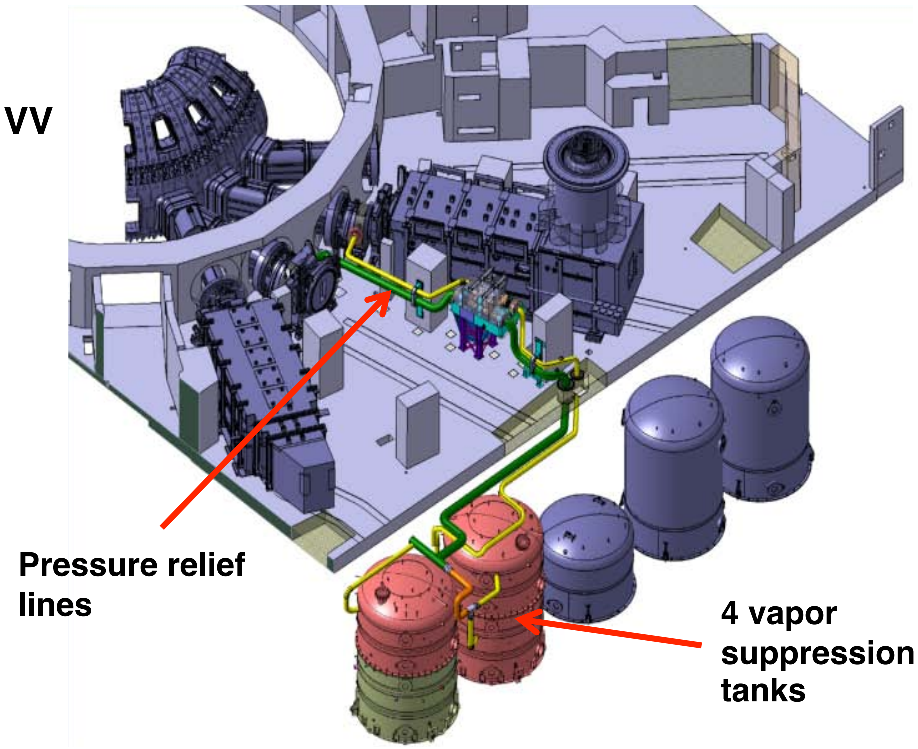
ITER needs have driven advances in vacuum technology

- DT fuel is fused in the plasma and turned into Helium ash.
- Helium dilutes the plasma reducing the fusion efficiency if not removed
- The divertor configuration allows the magnetically trapped plasma particles to be neutralised and hence pumped by the vacuum system
- To maintain a low helium concentration in the plasma continuous high speed pumping (>50m^3/s) is required in the divertor region.
- Vacuum pumping techniques developed for this application pump all neutralized gases, so the *fuel (>99%) and the waste helium (<1%).*
- Pumping is performed:-
  - in first stage by specially developed cryo-sorption pumps with integral large valves to allow cyclic regeneration.
  - in second stage by cryo-condensation pumps (CVCs) *with capability to separate the fuel and helium and return the unused fuel to the fuel cycle*.



ITER Vacuum Vessel Pressure Suppression System addresses design basis accident scenarios

- Prevent the pressure in VV to exceed 1.5 bar(abs) for all design basis accidents following an Ingress of Coolant Event
- Keep the VV below atmospheric pressure (dynamic confinement) for all high probability in-VV accidental events: Loss of Coolant Accidents combined or not with air ingress accidents



<u>Key features and technological challenges</u>:

- **Fast sub-atmospheric steam condensation with variable fraction of non-condensable gases over wide range of flow rates**
- **In-line management of the hazard posed by presence of flammable Hydrogen-air mixtures in large varieties of concentrations**

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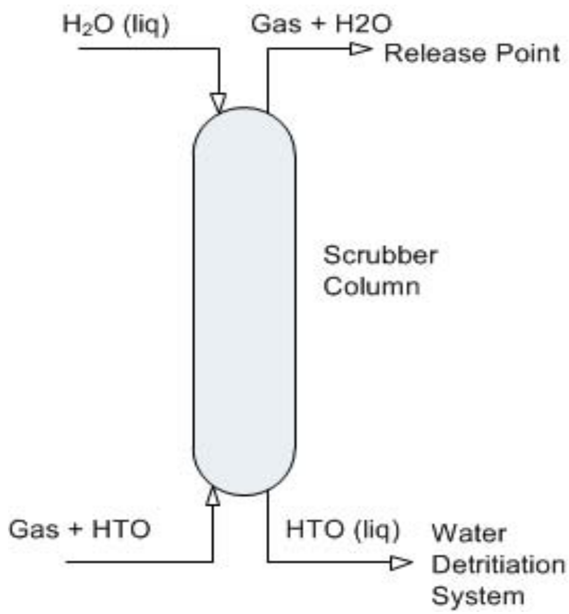
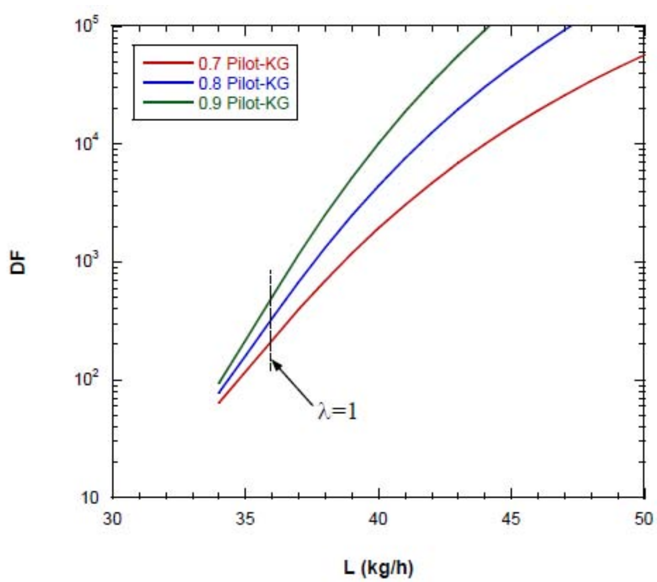
Example: Scrubber column technology developed for ITER-scale gas detritiation



***Concept:** Clean water trickles down on rising tritiated gas stream and "scrubs" tritium out though isotopic exchange*

***Construction:** Uses industrial column packing to promote liquid-gas contact*



***Performance:** Detritiation factor sufficient for safe facility performance and can be increased by raising liquid water flow (λ=1 at equimolar liquid and vapor water flow)*

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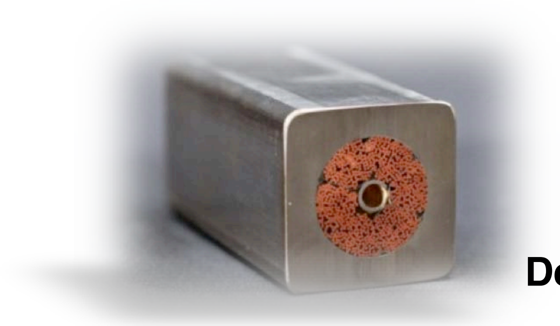
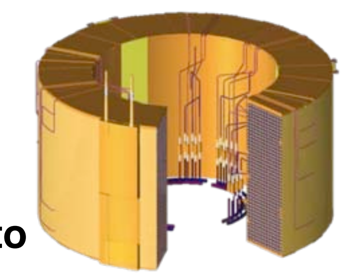
General Atomics Works with International Partners to Manufacture the ITER Central Solenoid

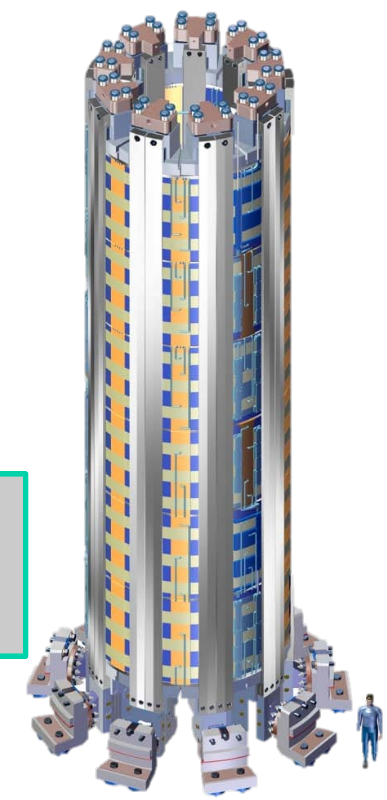
- Nb_3Sn CICC Conductor supplied by JAEA in 900 m lengths
- 7 modules wound, cured, insulated, and tested at GA
- 6 of these assembled at ITER (1 spare)



Delivered to GA



Delivered to Cadarache

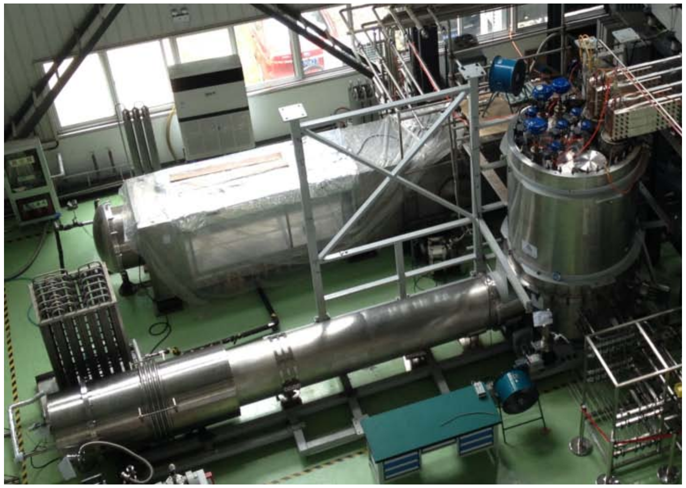


Completed module weighs 250,000 pounds has 560 turns (4 miles of conductor)

Design and manufacturing assisted via discussions with Koreans, Japanese, Italians, Chinese

ITER Central Solenoid

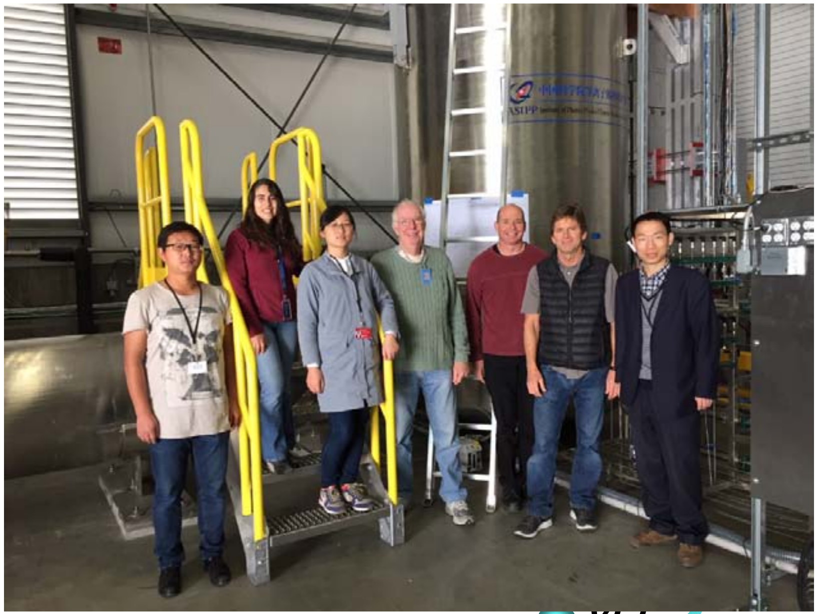
Collaboration between GA and ASIPP for ITER CS Final Test System Feeder



Feeder under test at ASIPP

- CS Feeder system designed and built at ASIPP based on ITER feeders
- Testing of feeders performed at ASIPP with GA assistance
- Installation performed at GA as collaboration
- Operational testing with balance of CS Final Test System performed by joint GA/ASIPP team

Test chamber and feeder installed at GA



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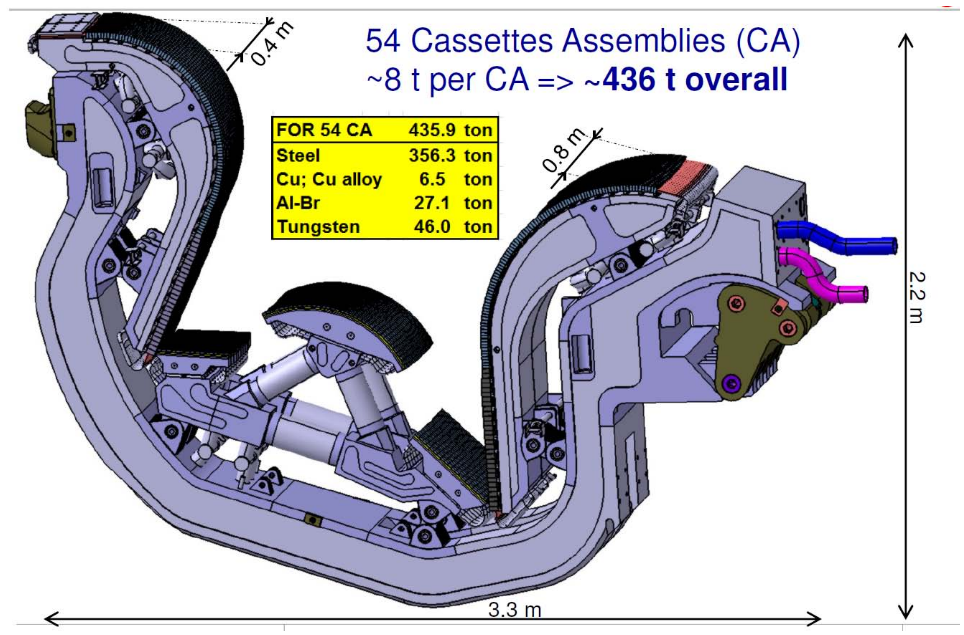
Design of high heat flux components have matured significantly as a result of ITER

- Design reviews and schedule drive engineered systems that meet fusion energy challenges
  - Cooling for high heat flux
  - Remote handling for replacement
  - No leading edges
- Result is a design that meets specifications and can be constructed
  - ~2 m X 3 m structure
  - ~8 tons per cassette
  - Provides neutron shielding for vacuum vessel
  - Joining of dissimilar metals has been thought through
  - Alignment and adjustment has been considered



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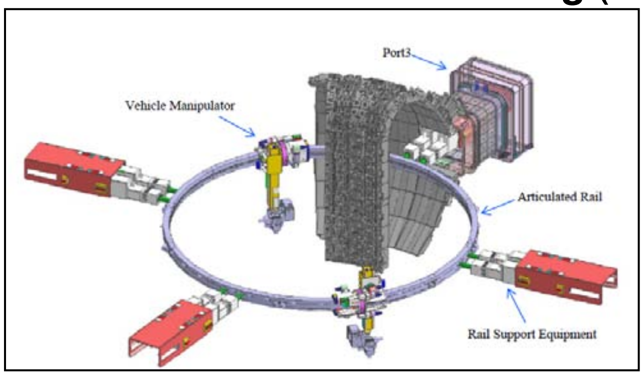
Remote Handling Technology Development for ITER

<u>In-vessel component handling devices</u>

One of the main challenges specific to Remote Handling in ITER is the *<u>precise (millimetric) handling</u>* of very large in-vessel components (weighing *<u>several tons</u>*) within radiation fields of *<u>up to 500 Grays/hour</u>*. To develop and demonstrate the technologies necessary to undertake this task, in the context of ITER, *<u>full scale prototype devices have been built and tested</u>* in relation to both blanket and divertor remote handling.

Blanket Remote Handling (Japan)

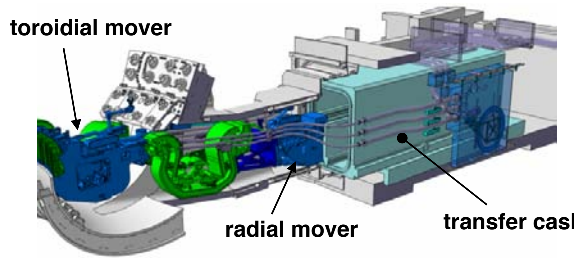


Overview of the ITER Blanket RH System.

Blanket module handling trials using the prototype In-Vessel Transporter (IVT) hosted by the Japanese Domestic Agency in Naka, Japan.

(ITER Blanket module weight is approx. 4 tons).

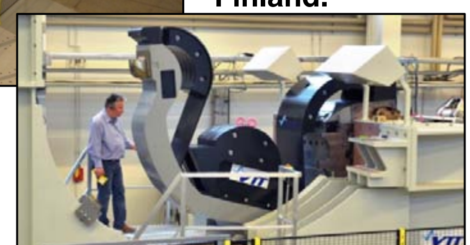
Divertor Remote Handling (EU, Finland)



Overview of the ITER divertor remote handling process.

Divertor cassette handling trials in the ITER Divertor Test Platform created by the European Domestic Agency in Tampere, Finland.

(ITER divertor cassette weight is approx. 10 tons).



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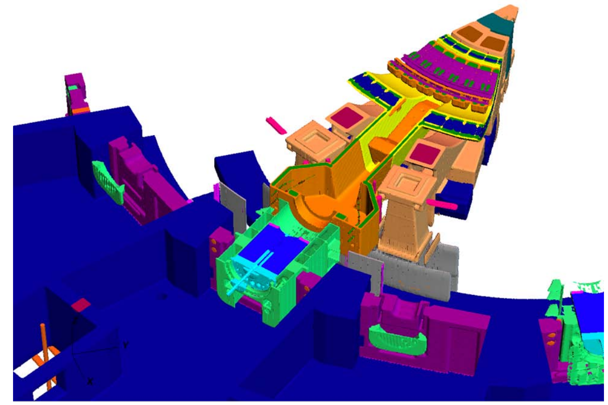
ITER-driven advances in radiation transport methods development makes solutions possible

- **New software** provides major algorithmic and shared memory implementation improvements to the MCNP code. Improvements were ***absolutely necessary*** to simulate transport on ITER-released models with ***useful speed and fidelity***.

- Significant enhancements of **hybrid MC-deterministic methods** (ADVANTG) specifically to ***visualize and generate MC variance reduction parameters*** for ITER transport models.

- **Shutdown dose rate analysis toolset** (MSX/NAGSS) created with bottleneck removal and parallelism in mind. Toolset was built around the ORIGEN activation solver for the largest ITER models and formally validated for ITER fusion neutronics applications.

- **CAD-to-MC model conversion and integration process**. Includes ITER-preferred model conversion technology coupled with automated tools developed for integration of different radiation transport models.



Massive models (hundreds of thousands of unique geometry cells) of the ITER tokamak integrated into full building models with detailed representations of important equipment.

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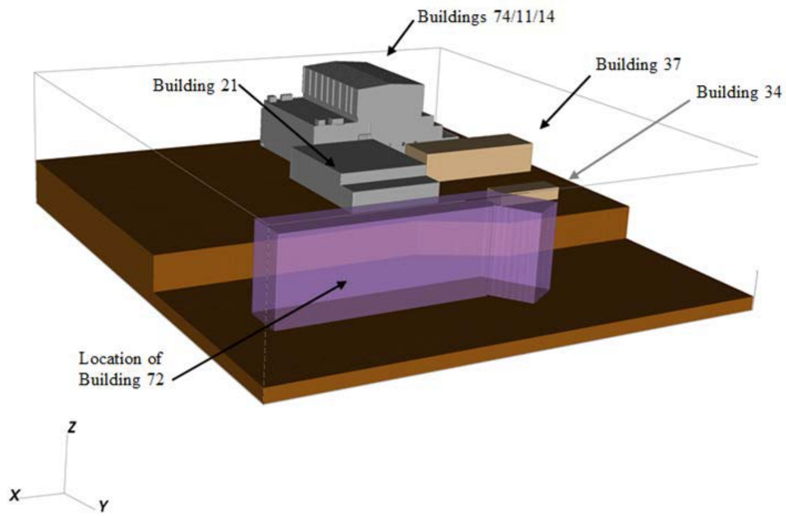
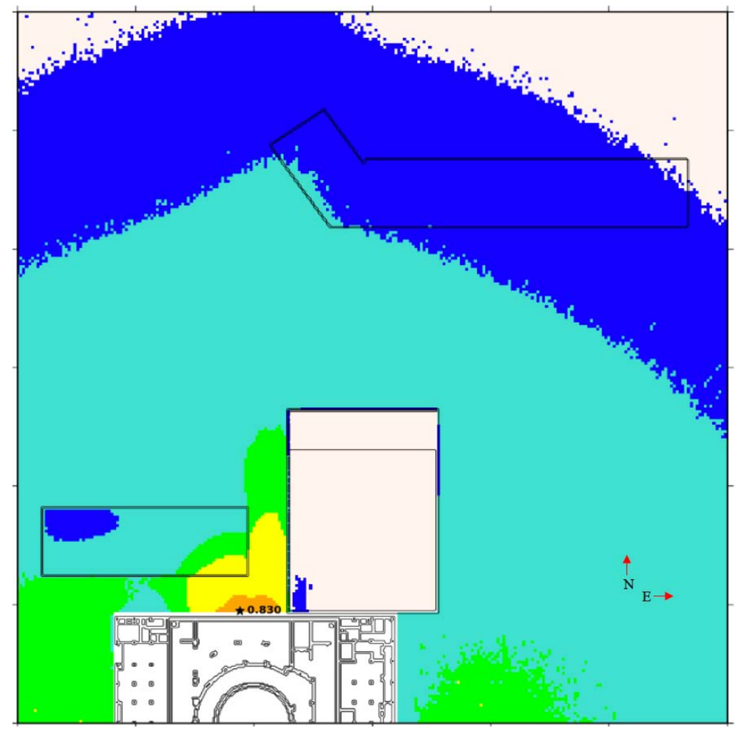
World-leading hybrid methods allow radiation challenges to be addressed



Models developed to represent the entire nuclear platform of the the ITER facility with high fidelity dose rate solutions to determine whether personnel safety criteria are met hundreds of meters away.



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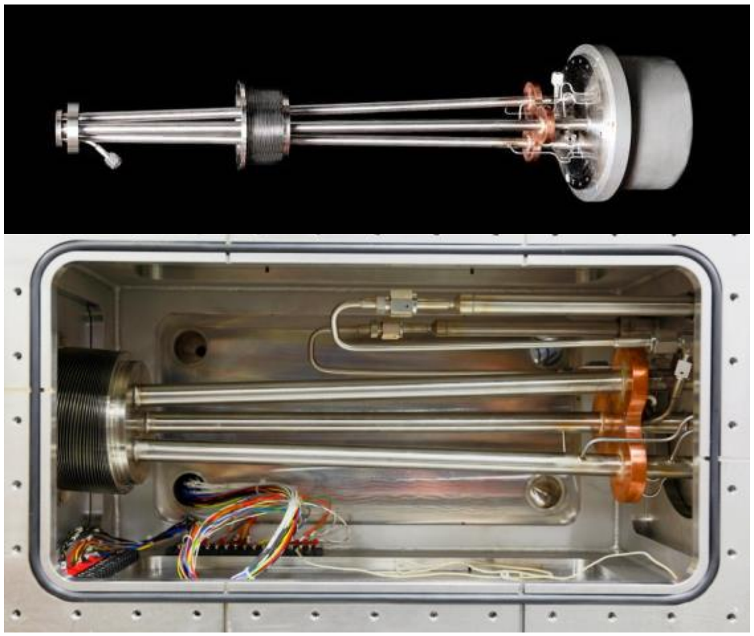
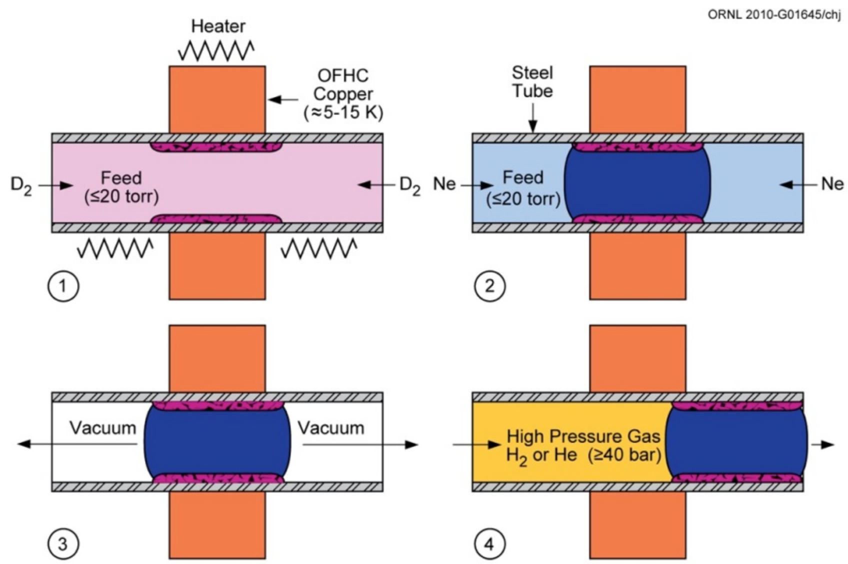
Shattered pellet disruption mitigation systems have become reliable and robust through development and engineering support





Barrel inner diameter increased to 24.4 mm (from 16 mm diameter) in order to study scaling of D2 and neon pellet formation/ acceleration.

Ice forming process in pipe gun injector

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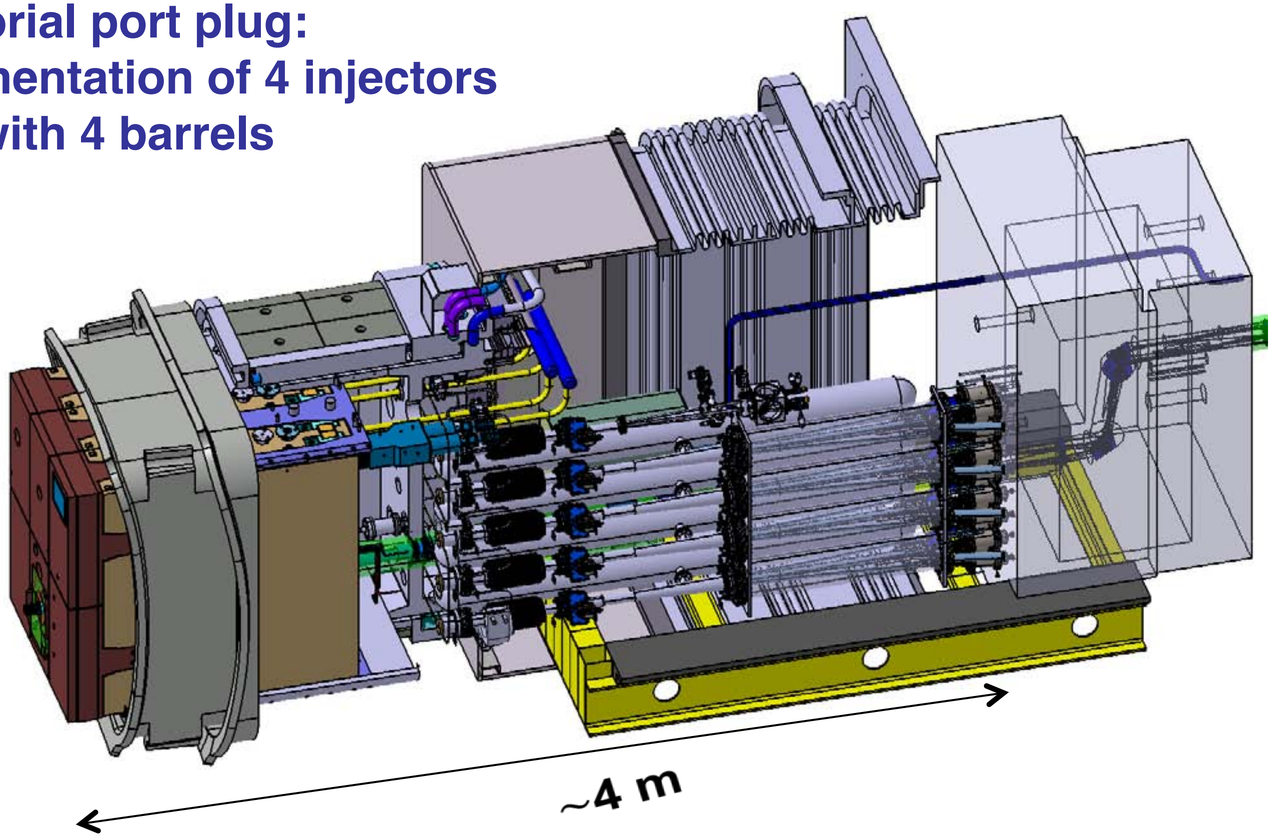
Integrating any pellet system into a nuclear device is a complex engineering challenge, and ITER has risen to that challenge

Equatorial port plug:
Implementation of 4 injectors
Each with 4 barrels



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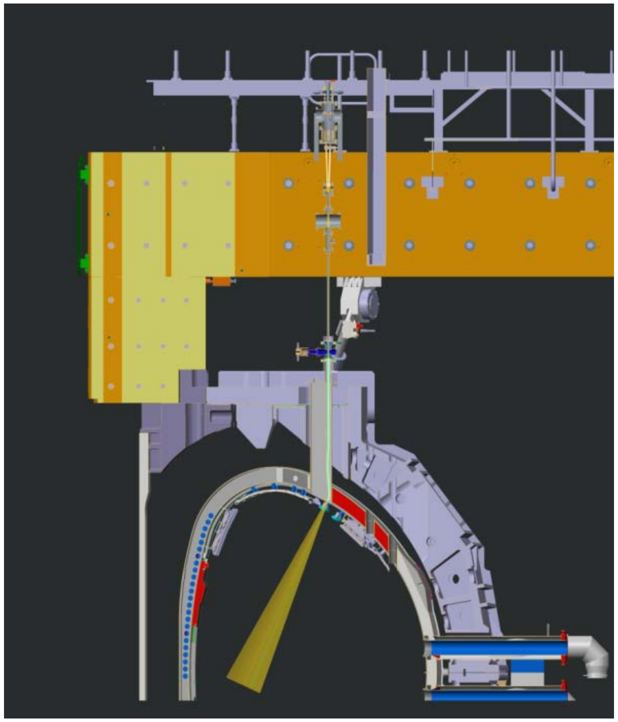
Shattered Pellet Injector DMS experiments on JET under ITER/JET/US collaboration expands our existing knowledge on scalability towards fusion energy

- Framework agreement has been signed by IO-CT, *USIPO, ORNL, US DoE, EUROfusion* and *CCFE*
- Testing SPI at JET is of high priority for the following reasons:
  - More energetic and larger target plasmas and larger RE beam cross-section than in DIII-D
  - JET could not demonstrate RE mitigation with MGI into a full-blown beam
  - Impact of Be/W ITER-like wall on disruption behaviour
  - Gain experience in operating SPI in a much more stringent environment (RAMI)
- Installation of a 3-barrel SPI, prototypical for that planned for ITER, on a top port at JET



SPI shatter tube fits inside vertical injection line with bend just before entering the plasma.

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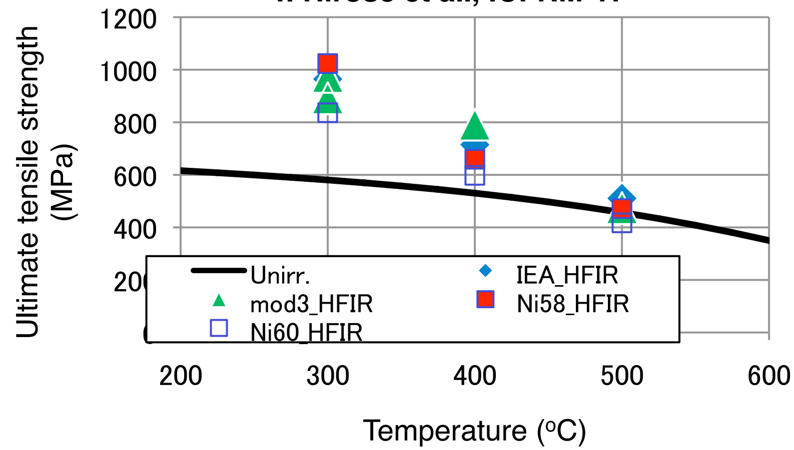
Fusion materials studies have made great advances since 2004

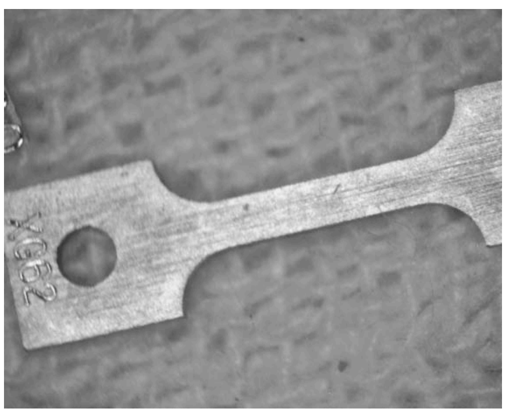
- RAFM steels: high dose (>80 dpa) irradiation effects positively addressed; qualification for use in early DEMO blanket in progress
  - Most of recent and planned high dose neutron irradiation studies are in US in international collaborations.
- Advanced steels: CNA emerged as the new generation, computationally designed alloys; ODS steels achieved progress in alloy design, understanding properties, fusion environment effects
  - US leadership in computational alloy design and development of advanced steels
- SiC/SiC: achieved rapid progress as an industrial material and nuclear structural material; on track toward the first code-qualified low-activation structural material
  - US leadership in all aspects of SiC/SiC technology for nuclear; from materials development to code qualification
- Tungsten: transitioning from poorly understood to material with basic properties and fusion environment effects being understood
  - Future directions of tungsten-based PFM development becoming clear
  - Case for tungsten sets a model of multi-angle evaluation of candidate/emerging PFMs
- Emerging materials: high entropy alloys, bulk metallic glasses, MAX phases, ultra-high temperature ceramics, high entropy ceramics, etc. – initial studies presented promises
  - Bridge design window gaps for conventional materials
  - Enable novel component designs and reactor concepts
- Advanced manufacturing: rapid progress over last decade (outside fusion program)
  - Opens routes to develop novel materials that were inaccessible with conventional manufacturing techniques; beyond rapid prototyping and complex net-shaping

High dose irradiation effects addressed for reduced-activation ferritic/martensitic steels

	JP-28	JP29
Start	April, 2005	Jan., 2005
Finish	July, 2013	July, 2013
Temperature (^oC)	300/400/500	300/400/500
Max dose (dpa)	87	87
# of reactor cycles	46	46

T. Hirose et al., ICFRM-17





300 °C irradiated (JP29 #13)

- Fission neutron irradiation effects were addressed in US/Japan HFIR JP-28/29 experiment to <u>maximum dose of 87 dpa</u> (*more than 8 years of irradiation)*
- Hardening and ductility degradation appeared significant and unsaturated at 300°C
- *<u>Helium effects on mechanical properties appeared insignificant</u>* as studied by Ni isotope tailoring

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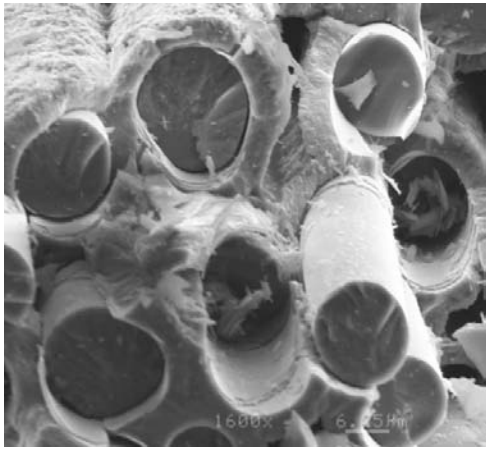
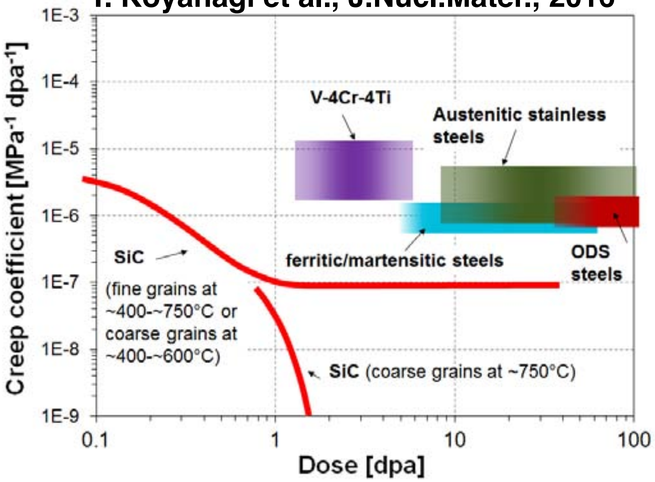
Silicon carbide composite developed from low TRL into industrialized nuclear structural material

- Nuclear grade SiC/SiC developed in fusion program in early 2000's
- Proved to be *<u>highly radiation-stable in broad temperature/ dose ranges</u>*
- *<u>Radiation-tolerant joining technologies</u>* were successfully developed in fusion program
- Rapid technology development driven by interest from aircraft engine and fission energy R&D communities

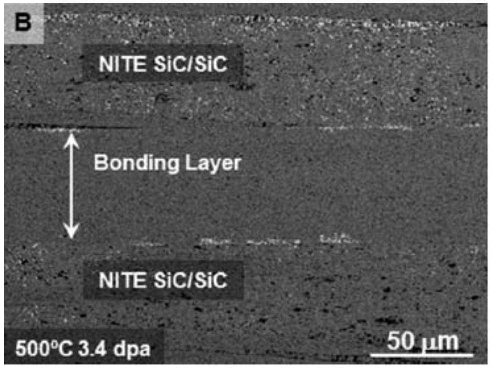


T. Koyanagi et al., J.Nucl.Mater., 2016



Exceptional irradiation creep resistance for SiC

Y. Katoh et al., J.Nucl.Mater., 2014



Radiation-tolerant joining for SiC/SiC

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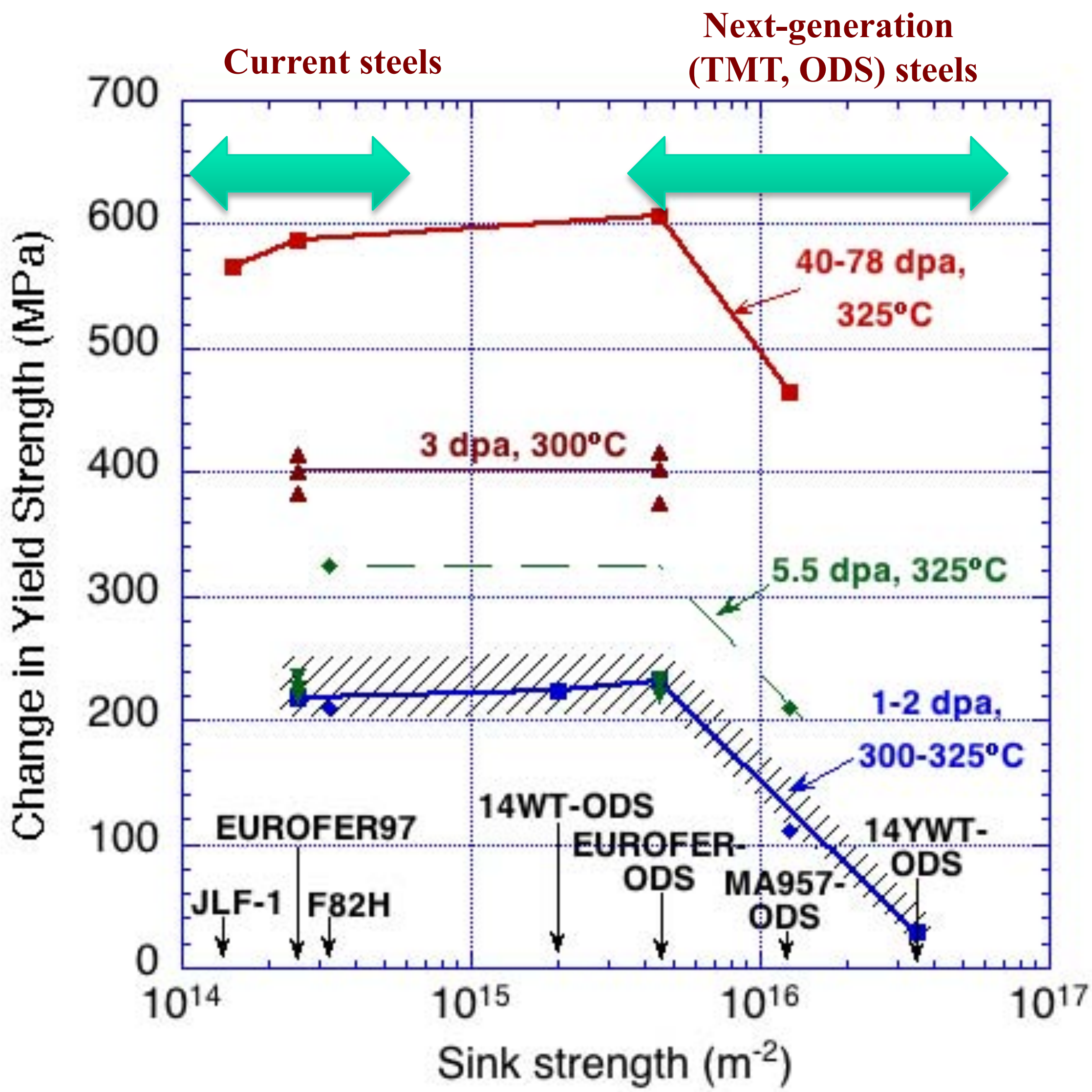
Progress has been made on understanding radiation hardening of ferritic/martensitic steels



Dramatic reduction in radiation hardening occurs when average spacing between defect cluster nuclei (dislocation loops, etc.) is much greater than average spacing between defect sinks

$N_{loop}^{-1/3} \gg S_{tot}^{-1/2}$

or equivalently,

$S_{tot} \gg S_{rad\ defects}$

S.J. Zinkle and L.L. Snead, Ann Rev. Mat. Res., 44 (2014) 241

S.J. Zinkle et al., Nucl. Fusion 57 (2017) 092005

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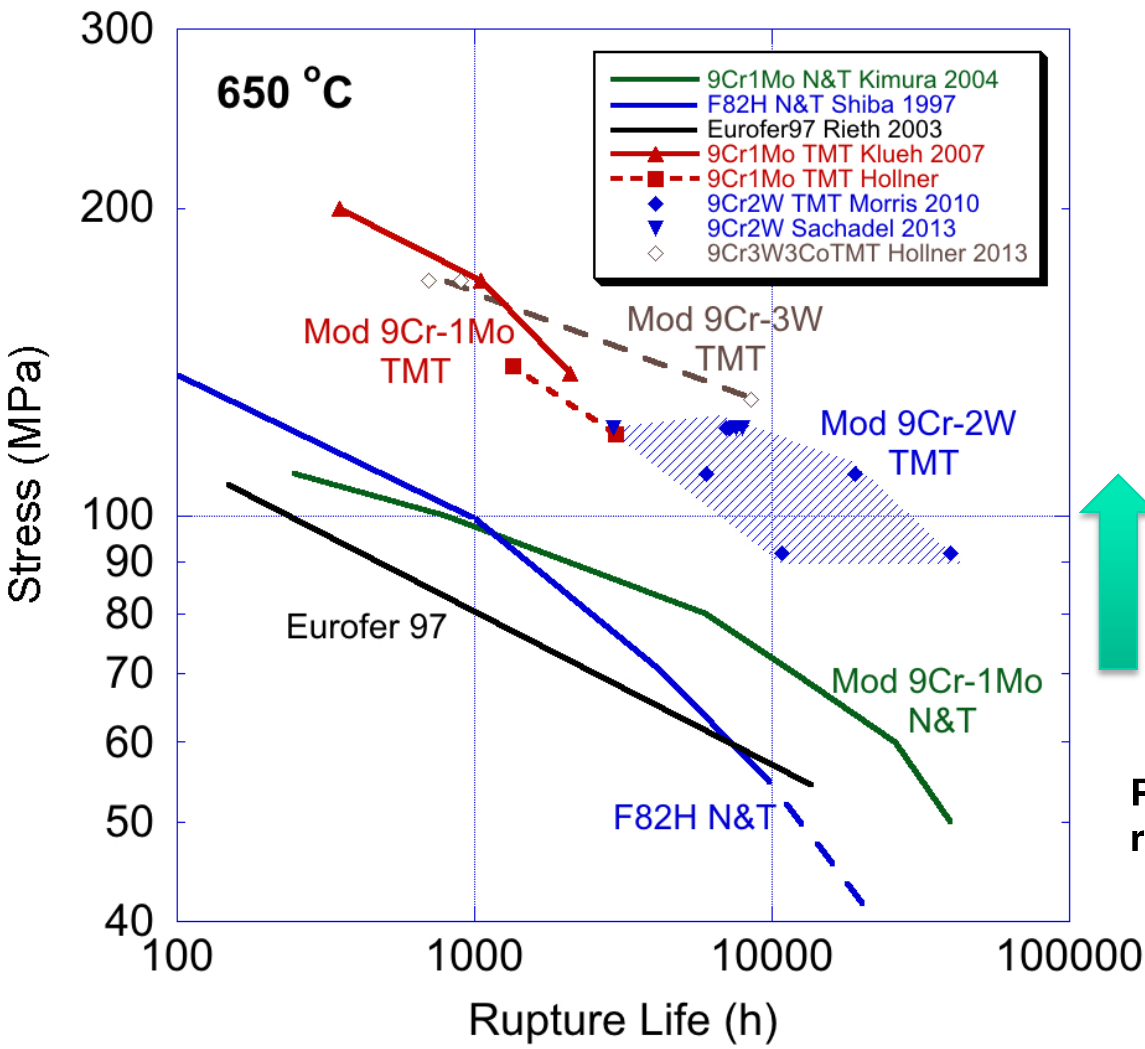
Thermomechanical treatment improves creep rupture behavior over conventional 9Cr steels



50-100% improvement in creep rupture strength for newly designed reduced activation steels

Predicted improvement in radiation resistance as well

S.J. Zinkle et al., Nucl. Fusion 57 (2017) 092005

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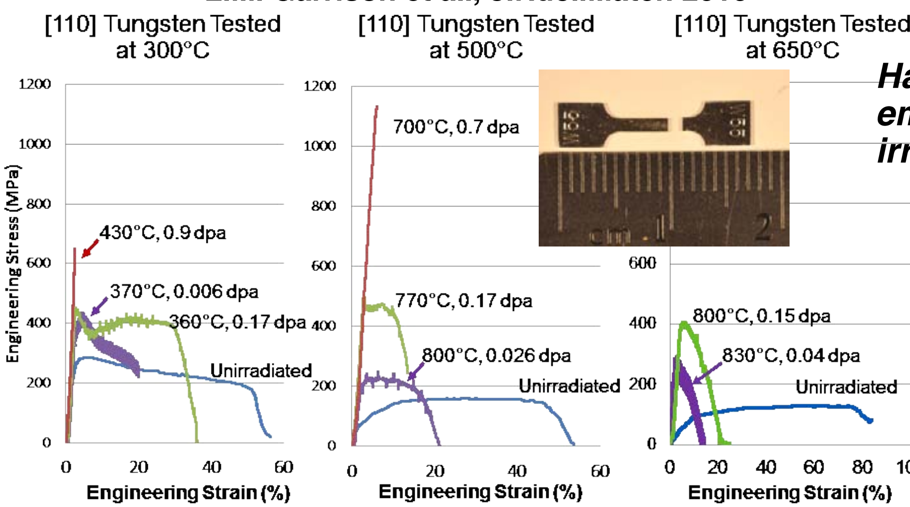
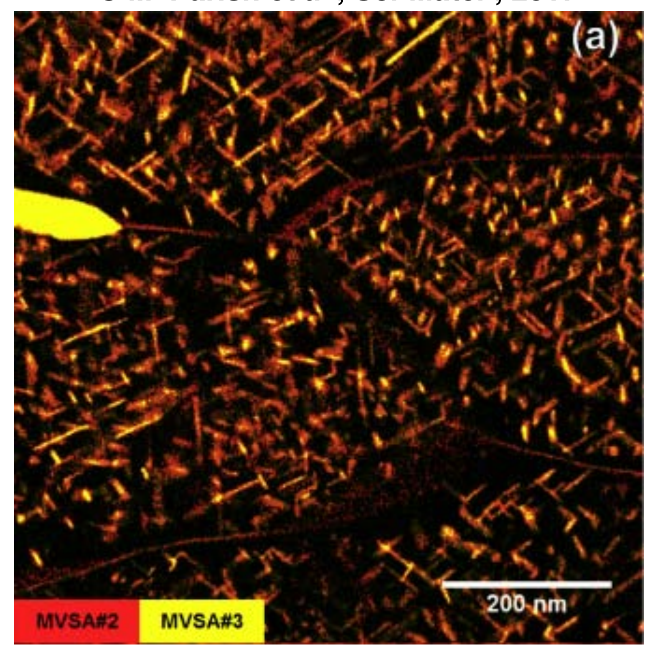
Behavior of tungsten in an irradiation and plasma environment is being understood

L.M. Garrison et al., J.Nucl.Mater. 2016



Hardening and severe embrittlement in irradiated tungsten

C.M. Parish et al., Scr.Mater., 2017



Re (red) and Os (yellow) in irradiated W revealing detailed precipitation features

- Complex radiation effects in tungsten are finally getting clarified in a systematic manner
- Provides information on thermo-mechanical performance envelopes for PFCs
- Important implications to design space for tungsten-based composite materials
- “Case for tungsten” useful in exploring and assessing emerging materials

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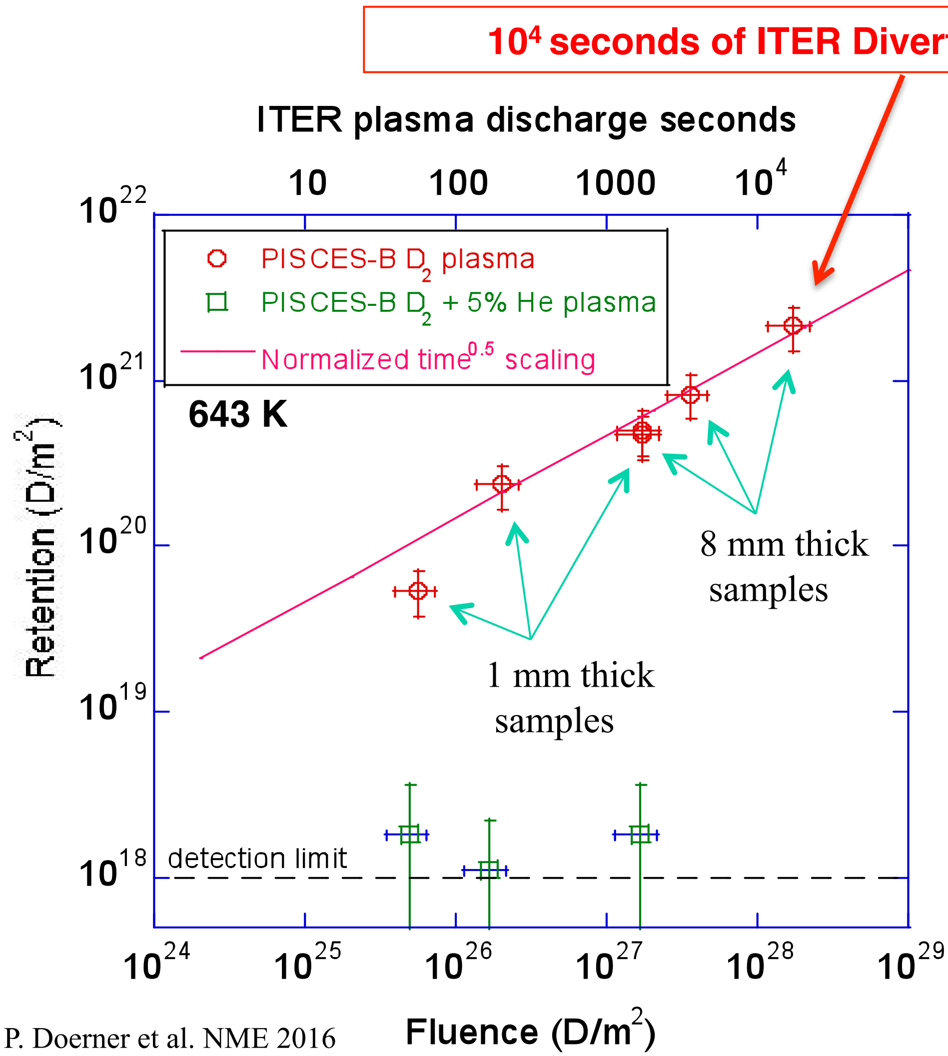
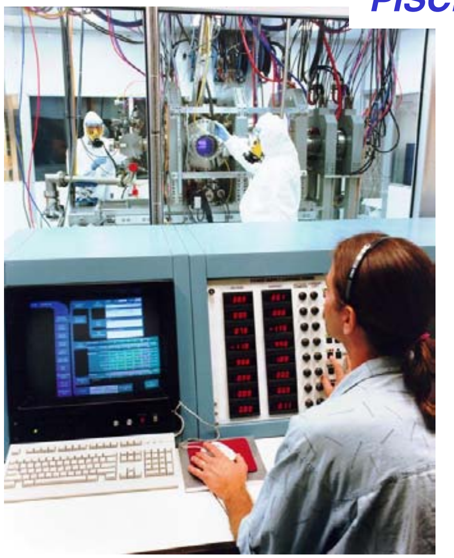
Linear devices have developed to the point of providing ITER relevant fluxes/fluences for PMI studies

PISCES





- **No saturation in D retention** in W with high-fluence deuterium plasma exposure
- **5% He^+ flux during deuterium plasma exposure drastically reduces D retention** in W at 643 K

R. P. Doerner et al. NME 2016
http//dx.doi.org/10.1016/j.nme.2016.04.008.

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Fusion Nuclear Science has been identified for more than a decade as an important program element

- 2005 FESAC "Scientific Challenges, Opportunities and Priorities for the US Fusion Energy Sciences Program"
  - Identifies key thrusts including fusion materials, systems engineering, fueling, etc.
- 2007 FESAC "Priorities, Gaps and Opportunities: Towards a Long-Range Strategic Plan for Magnetic Fusion Energy"
  - Identifies predictive modeling, transients, magnet technology, etc.
- 2009 Research needs for Magnetic Fusion Energy Sciences
  - Major thrust of "Harnessing Fusion Power" includes fuel cycle, power extraction, materials science, etc.
- 2014 FESAC Strategic Planning and Program Priorities Report
  - Identified fusion nuclear science among four high priority areas
- 2015 FES Community workshops focused on three areas with wide community support
  - Transients, whole device modeling, & plasma-materials interface

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So where are we now?

- Fusion nuclear science and technology exists as a stable part of the US program
  - ~8% of the FES budget has gone into the FNS&T program for the last 3 years
    - An energy program will require additional investment
  - Program is highly leveraged where possible (NE, BES, University investment, Lab investment, etc.)
  - There are fusion specific challenges that are not funded external to the program (fusion specific, e.g., tritium retention in PFCs, etc.)
- Fusion nuclear science covers many topics
  - The US can't and shouldn't do everything; there is not enough time or budget
  - International collaboration will play a vital role in FNS&T
- Three areas of prime opportunity are *<u>fusion materials</u>*, *<u>fusion fuel cycle</u>*, and *<u>power handling</u>*
  - Other opportunities, like liquid metals and HTS, will be discussed briefly

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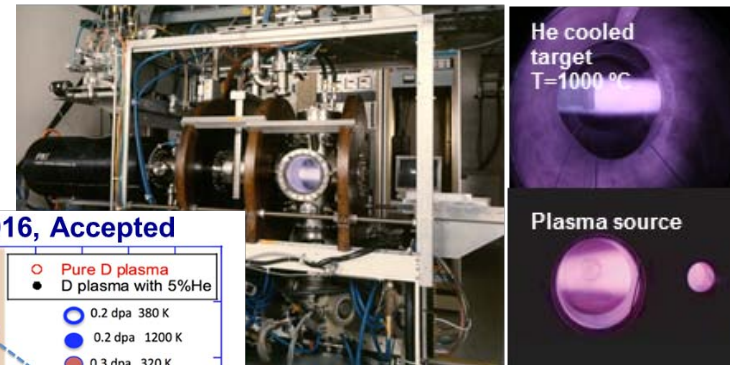
Fusion materials leadership is strong

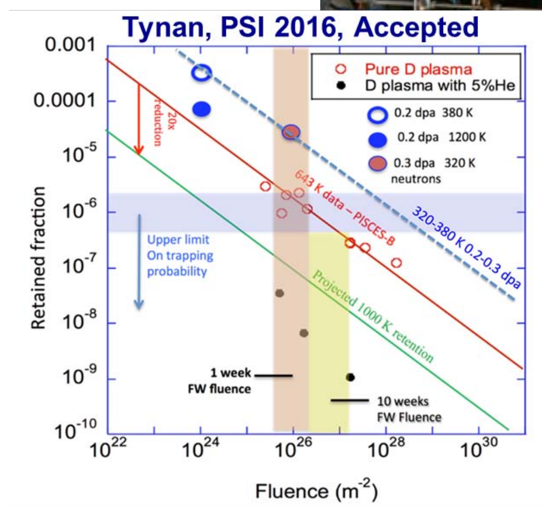
- The US is a leader among the international fusion materials program
  - US-Japan collaboration is more than three decades strong, and continues to make key contributions (current PHENIX collaboration)
  - US is executing a structural materials irradiation and PIE for the EUROfusion program (Europe is outsourcing work and recognizing US expertise)
  - Consistent request for review participation by US program members
- However, resources are limited
  - With existing budget, prime focus is structural materials and existing materials
  - Not much effort on blanket materials or materials development
  - Even PMI science is not a large program in the US
- Opportunities for leadership include:
  - PMI, fusion relevant neutron source, and modeling & simulation

Three PMI facilities would position the US uniquely to address challenges

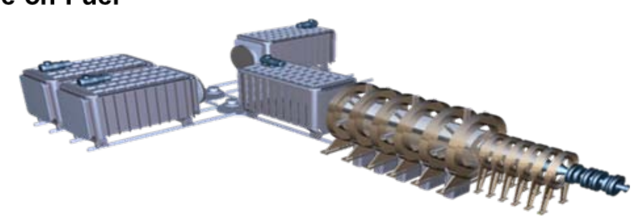
- TPE addresses *tritium retention* in damaged samples
- PISCES is a high fluence facility with *beryllium capabilities* to address ITER challenges
- MPEX will be a DEMO-level fluence device with *tilted target & neutron irradiated capabilities*

TPE & new external control center





Effect of Radiation damage on Fuel Retention



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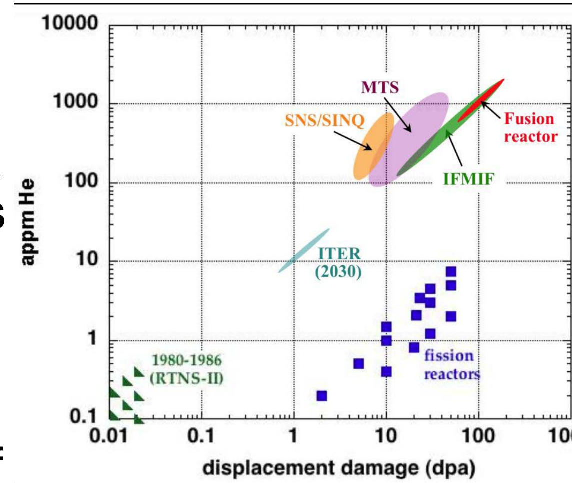
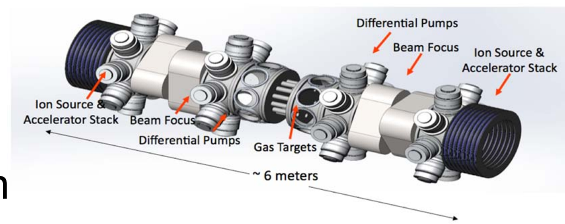
A fusion relevant neutron source is an international need, and a US opportunity

- High displacement rate irradiations have been carried out in HFIR for decades
- A neutron source with the *correct energy spectrum, producing gas synergistically* with displacements, is needed for material qualification
- IFMIF has been discussed for decades
- DONES is the latest version, with reduced scope (30-40 dpa vs 150 dpa) but still costing hundreds of millions of dollars
- It is time to consider nearer term, lower cost options with reduced performance compared to DONES
  - Phoenix Nuclear Labs has a proposal for a DT neutron generator
  - A Gas Dynamic Trap proposal has been mentioned
  - Spallation sources can provide low displacement data
    - Transmutations become an issue as total displacements rise





Phoenix Nuclear Labs neutron generator concept

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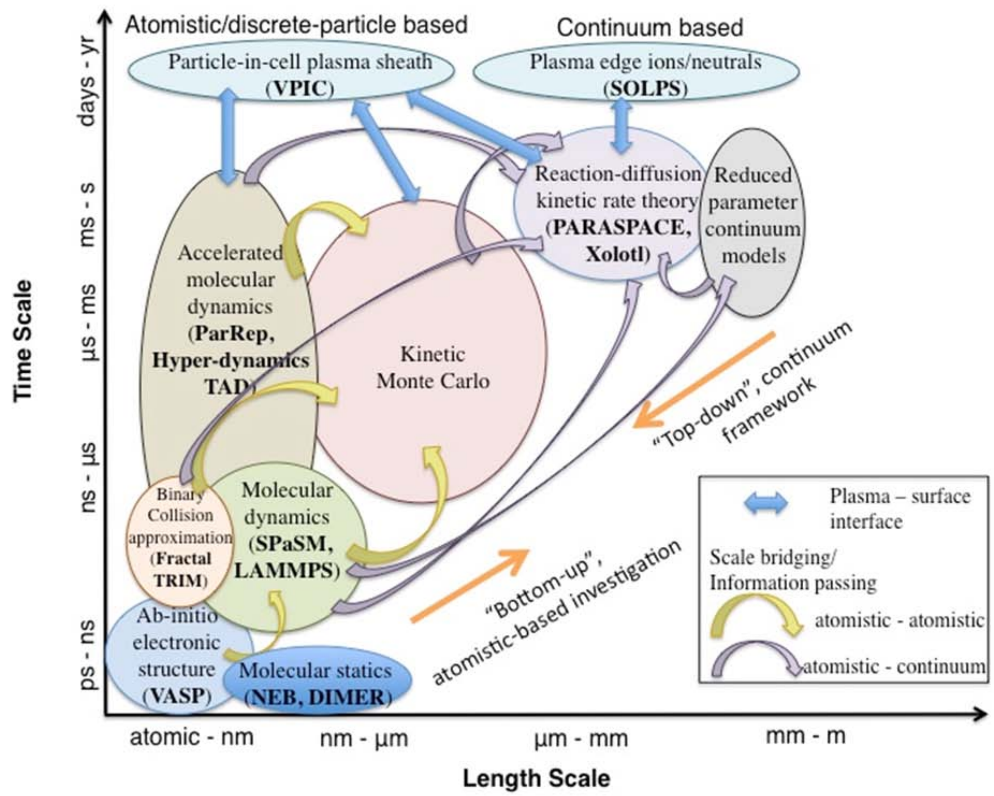
Modeling is a critical part of addressing the materials challenge

- Experiments help us understand the physics, so we can accurately model a wide range of scenarios
- The PSI SciDAC is making progress on modeling materials challenges from first principles to macroscopic effects, over large length and time scales
- Leverages ASCR/HPC and NE investments



BD Wirth, K.D. Hammond, S.I. Krashenninikov, and D. Maroudas, *Journal of Nuclear Materials* 463 (2015) 30-38.

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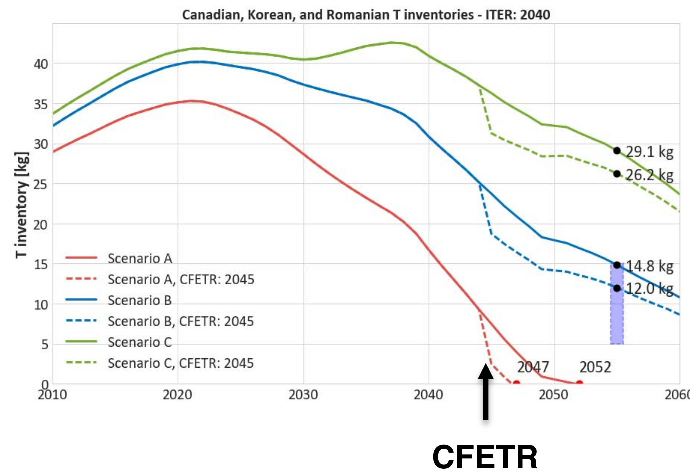
Closing the fuel cycle is a critical part of fusion energy

- Analysis shows there is likely enough tritium for ITER and possibly one DEMO (startup=5-15 kg)
  - Control of production and consumption is largely outside of fusion community control
    - Korvai, et al, Nuclear Fusion (in press); Federici, SOFE 2017 presentation
  - Without a closed fuel cycle, we need tritium production from fission power plants
    - Why have additional complexity of fusion power plants if fission plants are required?
- We must close the fuel cycle for any fusion energy system
    - ***Must actually do better than that to start additional plants in the future***



Scenario A:
- Romania does not extract their T
- All HWRs finish their lives ~30y and some HWRs are refurbished +25y
Scenario B:
- Romania extracts their T
- Several refurbishments
Scenario C:
- All known refurbishments go ahead and then some more!
- Romania builds two new CANDUs in the mid-2020s (and refurbishes them)

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Tritium inventory & release are significant issues for fusion energy

- Fission power reactors (typical annual tritium discharges of 100-800 Ci/ GW_e; ~10% of production) are drawing increasing scrutiny for tritium release
- 1 GW_e fusion plant will produce ~10^9 Ci/yr; historic assumed allowed releases are ~0.3 to $1x10^5$Ci/yr (<0.01% of production)
  - Public concern about tritium release from *fission plants* suggests actual release may be limited to ~100 Ci/yr (10^{-7} of production)
  - Can fusion achieve 10^6 times better tritium control than operating fission plants?
- Tritium inventory and release pathways in fusion plants are poorly understood
  - Nanoscale cavity formation may lead to significant trapping of hydrogen isotopes in the blanket structure (tritium inventory issue)
  - Tritium trapping efficacy of precipitates, nanoscale solute clusters and radiation defect clusters (blanket & piping) is poorly understood from a fundamental perspective

Leadership opportunities in fuel cycle research exist

- US has leadership in tritium science and handling due to the activities at defense/nuclear labs (LANL, SRNL, & INL)
- Efficient tritium handling, including extraction in flowing liquids and safety, is a challenge where the US can lead
- Tritium breeding blankets are among the lowest TRLs in fusion energy
  - US (UCLA) strength in liquid metal modeling and experiments
  - Several international collaborations in blankets
- US leadership in pellet fueling
  - Current discussions/plans for installations on W7-X and MAST-U

Demonstration of Direct LiT Electrolysis using an Immersion Cell

Scientific Achievement

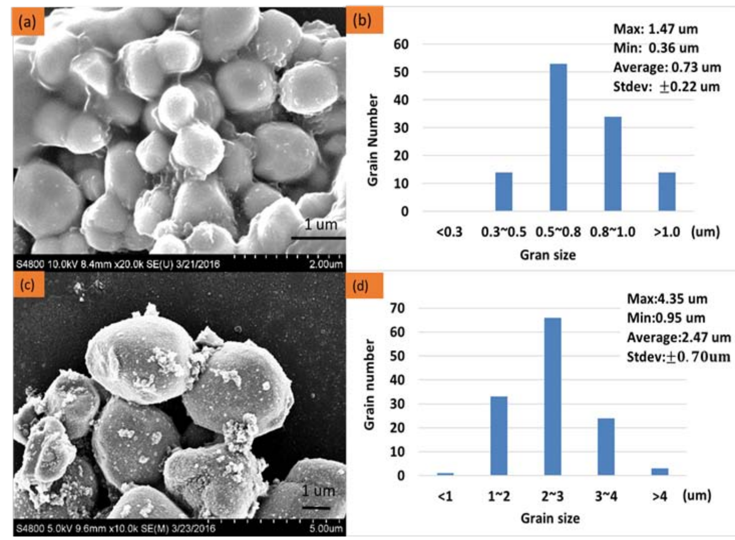
- Direct LiT electrolysis has the opportunity to simplify tritium recovery from a liquid lithium cooling blanket
- Improvement of the conductivity and structural integrity of the solid lithium ion conducting materials is critical to creating a viable direct LiT electrolysis process.

Significance and Impact

A direct LiT electrolysis process can eliminate the need to use molten salts for LiT recovery and can eliminate the need for centrifugal separators used in the Maroni process for LiT recovery

Research Details

- A sol-gel method was developed for LLZO synthesis that enabled a reduction in grain size to between 0.5 and 0.8 microns as opposed to 2-3 microns for the solid state reaction pathway
- The ionic conductivity of the electrolyte is a function of a number of variables, including grain size. The reduction in the LLZO grain size should enable increased conductivity.



Grain size reduction for Lithium Lanthanum Zirconate (LLZO) achieved by using a sol-gel method of synthesis as compared to a solid-state reaction method

Savannah River National Laboratory™

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Dealing with power exhaust from a fusion energy device is a recognized challenge

- The US is not currently world leading in this area from a fusion nuclear science point of view
- We should leverage our strengths to address this challenge
  - *New materials* may provide a solution to the power exhaust challenge, and the US is a world leader in materials
  - *Additive manufacturing* may change the game, and the US is among the world leaders in additive manufacturing

Addressing Power Handling Challenges Can Involve New Materials

Achievement

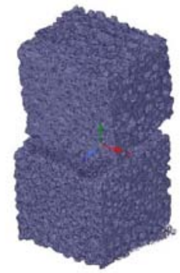
- Demonstrated that a *nearly isotropic high-conductivity, low-Z plasma facing material* is possible by combining pyrolytic graphitic ligaments with an isotropic-engineered microstructure

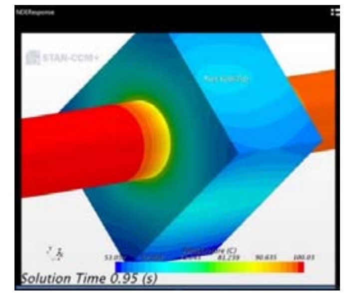
Significance and Impact

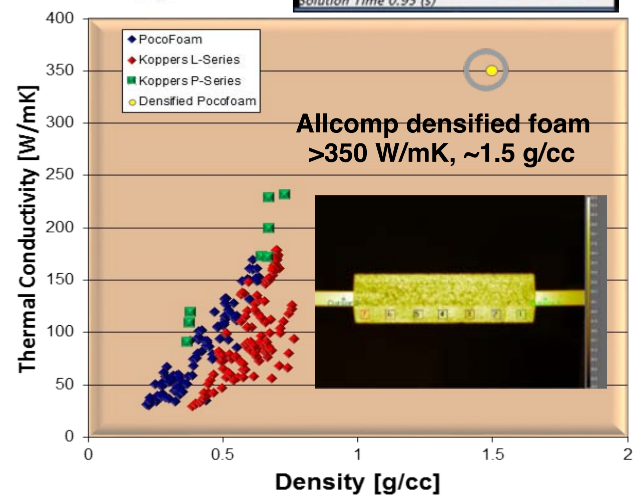
- For the first time, the thermal efficiency of low-Z armor is *comparable to the copper heatsink*
- Max Planck IPP interested in fielding the monoblock in the *W7-X stellarator for potential* use in divertor scraper element

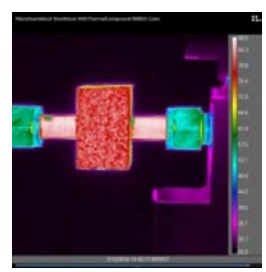
Research Details

- Densified graphitic foam and mock-ups produced
- Thermal properties measured, *k=265 W/mK to date*, expect 350 W/mK
- *Robust braze joint* obtained on CuCrZr tubes
- Hot water IR thermography showed that using no braze joint actually delivers best thermal performance
- Thermal modeling and tomography of microstructure is in progress









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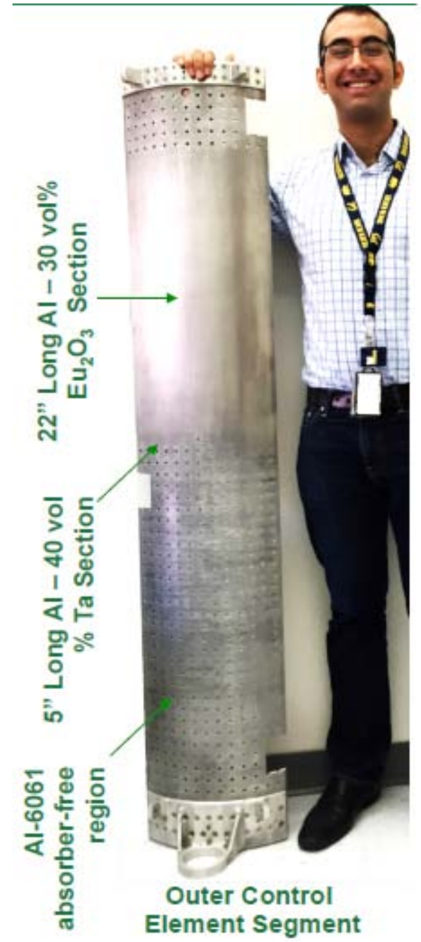
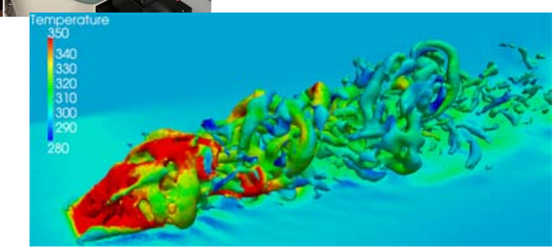
Advanced manufacturing has been demonstrated on nuclear components

- HFIR annular control plates used 1960s technology based on the original design
  - Costly, low yield to meet specifications
- A joint project between the nuclear fuel materials group, HFIR staff, and the Manufacturing Demonstration Facility at ORNL was initiated in 2014
- Multiple techniques were tested
  - The cost was less than we initially thought, and was more successful than we could have imagined



Advanced manufacturing coupled with HPC can lead to innovative solutions for power handling

- Additive manufactured parts for HHF testing can be produced and tested
- Positron emission particle tracking (PEPT) is used to experimentally validate computational tools
  - Remove large conservatism from average heat transfer coefficients
- After validating computational tools, HPC can be used to scan a vast array of geometries for additive manufacture
  - Optimize the heat transfer capabilities without human bias
- Test the new components



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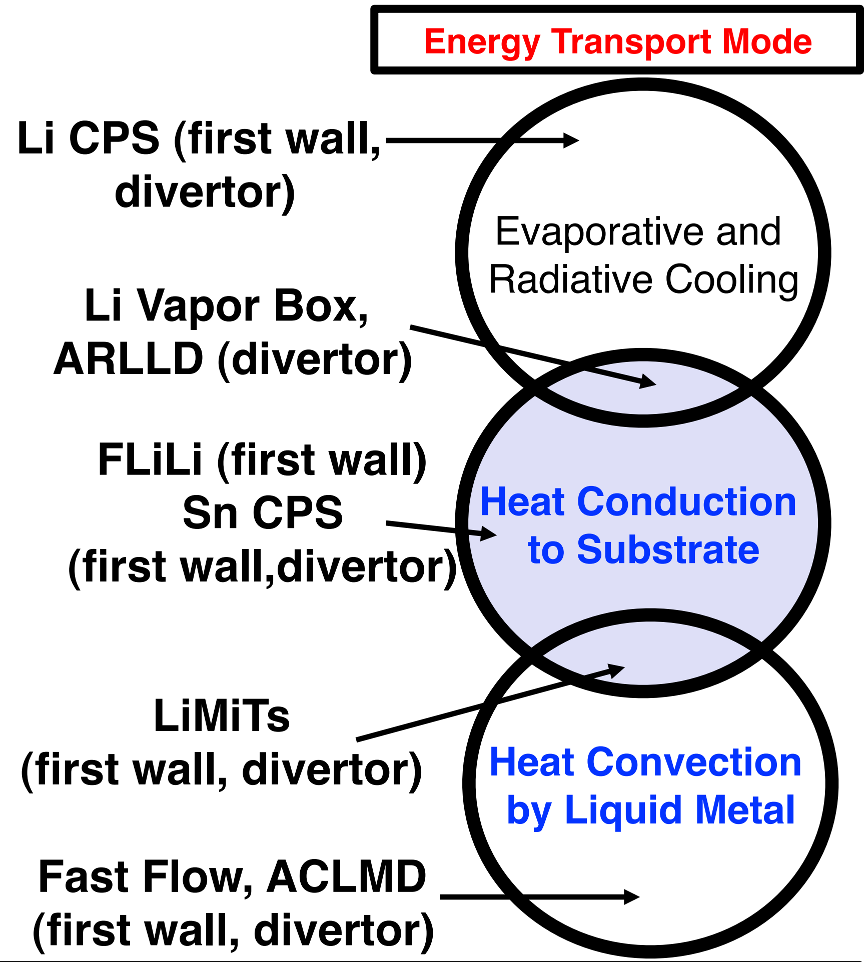
Liquid metals are a potential PFC solution for power reactors

- Liquid metals (LMs) provide a self-healing and renewable plasma-facing material
- LMs eliminate long-time constants associated with plasma-induced wall evolution
- LMs separate neutron damage effects from plasma-material interactions
- LMs add additional methods for power-exhaust
  - **Lithium vapor divertor and fast-flow concepts can both greatly exceed current technological limits**



See also: M.A. Jaworski, et al., "Breaking through to Reactor Solutions with a Focused, Liquid Metal Program" white paper submitted to the USMFRSD workshop

High temperature superconductors may provide an opportunity for fusion energy development

- High-field, high-temperature superconductors (HTS) may enable a new generation of compact fusion experiments and power plants, dramatically speeding up the development path and improving the overall attractiveness of fusion energy
- The advantages of HTS are that they can operate at very high magnetic field, high cryogenic temperature, high current densities, and larger mechanical stresses and strains
- HTS can significantly enhance the performance and feasibility of almost any type of magnetic confinement device, including:
  - Tokamaks
  - 3D shaped devices such as stellarators and other helical configurations
  - STs
  - FRCs
  - gas dynamic traps
  - magnetic mirrors
  - levitating dipoles

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Summary

- Burning plasma research is recognized as a key element in the development of fusion energy
  - There are technology implications beyond the physics questions that must be answered
- Tremendous advances have been made in fusion nuclear science & technology since the 2004 report
  - Advances beyond those predicted in 2004 have been achieved
  - Many of these advances have been driven by ITER and the need for design solutions
- Fusion nuclear science is an identified need, and an opportunity for world leadership for the US program
- A growing fusion nuclear science program is needed to prepare the US for the next step toward fusion energy
- Fusion materials is already an area of leadership, but offers opportunities
  - PMI, blanket materials, fusion relevant neutron source
- Fuel cycle is also a strength and offers opportunities
  - Tritium handling, safety, breeding, and fueling
- Power handling is a challenge where we are not world leading, but can be by applying our strengths
  - New materials, advanced manufacturing, and HPC