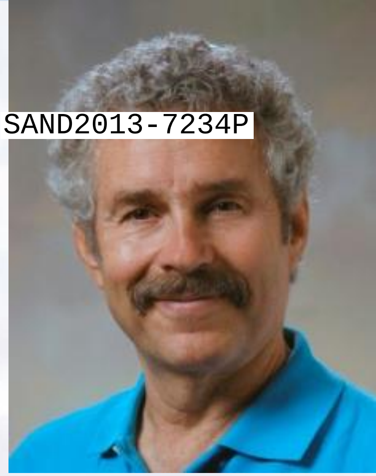
Introduction - Presenter
Richard Nygren



▪ **Hanford Engineering and Development Lab**	radiation damage, **LMFBRs**, fusion
▪ **Oak Ridge Nat. Lab**	materials in Fusion Engineering Device
▪ **Argonne Nat. Lab**	Director, FW-Blanket-Shield Program
▪ **DOE/FES**	Spec. Ass't. to AD US Fusion Program
▪ **UCLA**	Plasma materials interactions (PISCES now at UCSD)

▪ **Sandia National Laboratories** **(since 1989)**

Distinguished Member Technical Staff (DMTS)

TEXTOR *He pumping,* ***Tore Supra*** *water-cooled pump limiter,* ***ITER***

Manager, Fusion Technology Dept. Until April 2012

Plasma Materials Test Facility: High heat flux testing; water, He, liquid metal coolants; ITER R&D; Liquid Lithium Divertor for NSTX

DMTS again

Richard Nygren
Sandia National Laboratories
Analytical Materials Science Department

Fusion Technology & Future Opportunities

Diagnostics and Materials in Extreme Environments

Future Opportunities for Sandia in Magnetic Fusion

themes/opportunities

- **Diagnostics, instrumentation**
- **Component development**
- **Materials & fabrication**

aspects of fusion technology

- ***plasma, plasma edge***
- ***in-vessel components***
- ***damage***
- ***power handling***
- ***fluid physics***
- ***materials applications***
- ***fabrication***

Sandia National Laboratories is a multi program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.
.

Path for presentation

- **Diagnostics** [diagnostics$_{fusion}$ ≡ plasma diagnostics]

diagnostics (plasma, plasma edge)

instrumentation (components)

control (operations)

components

- integrated wall-breeder module (solid or liquid breeders)
- heat removal (fluid physics)

plasma edge & materials

- solid walls (tungsten, ?ferritics)
- materials damage
- liquid walls (lithium, molten salt)
- PFC solutions (configuration)
- near term experiments
- long term development

materials & fabrication

- He or CO2 cooling of PFC
- enhanced heat transfer
- development path

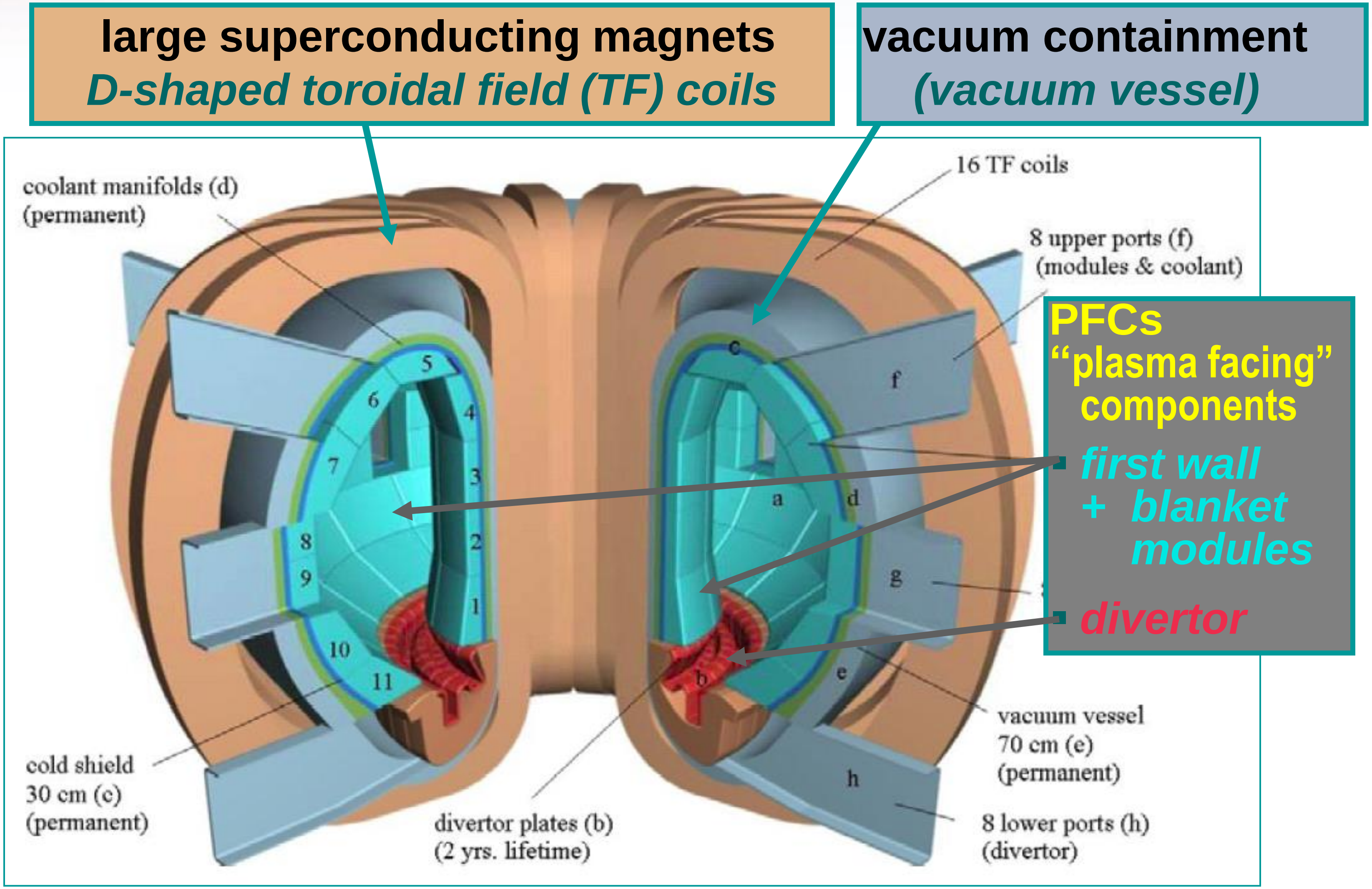
1. ITER

2. FNSF

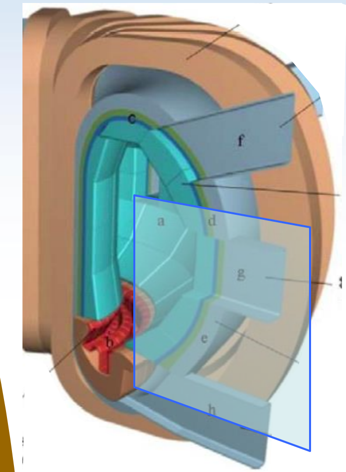
Comp. Test

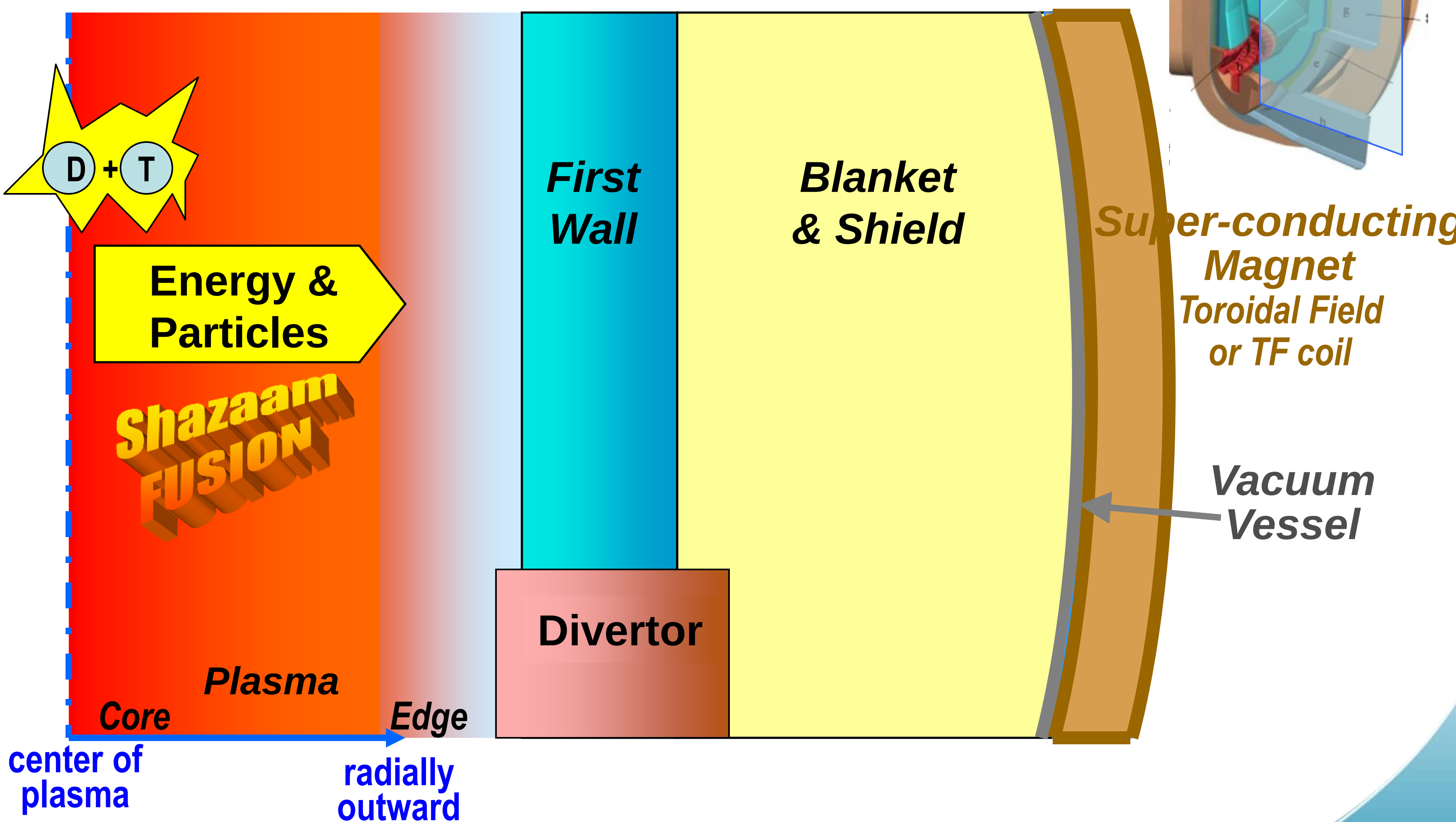
3. DEMO

DEMO Fusion Reactor

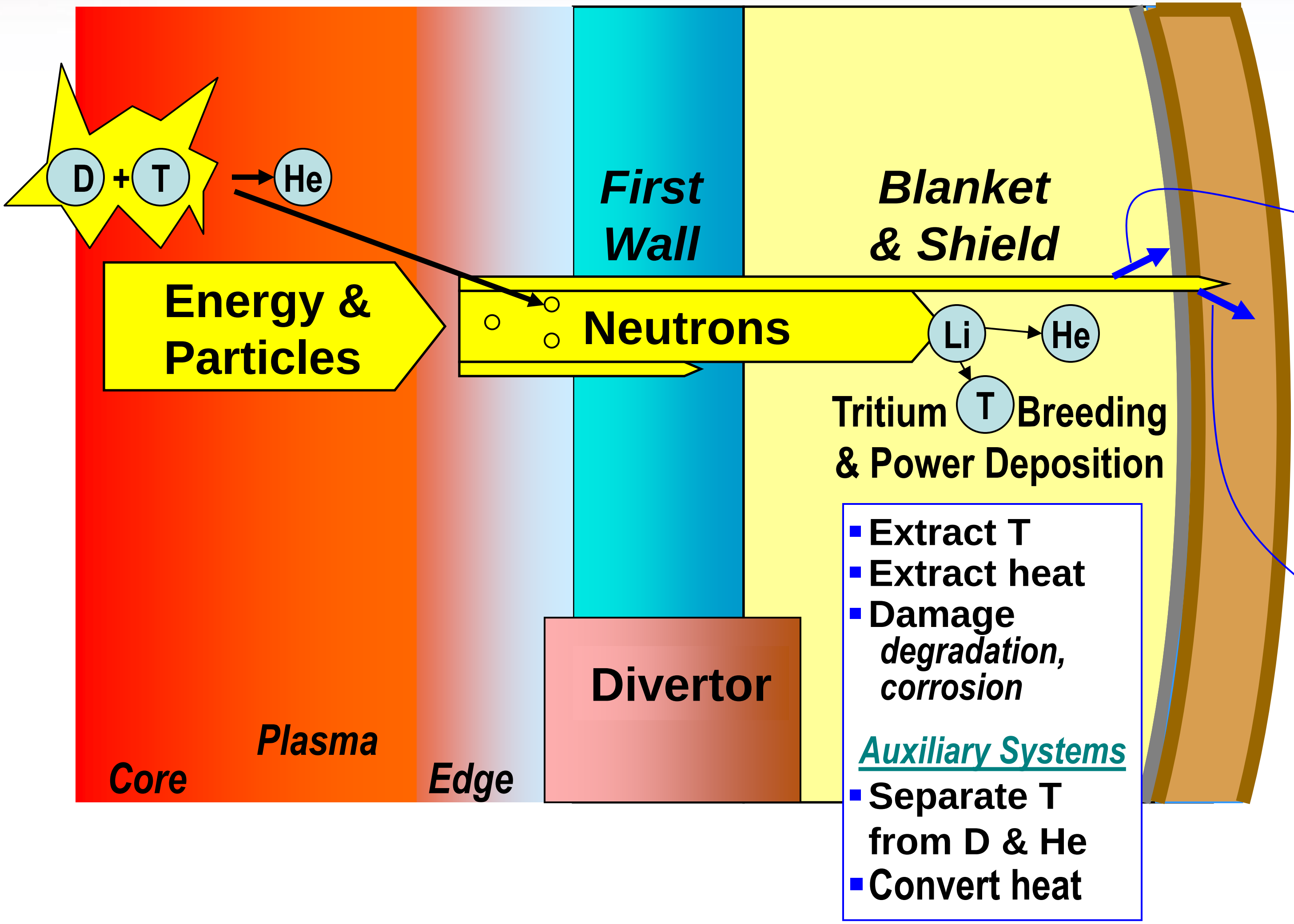


2-D view - components





Blanket technology, design studies



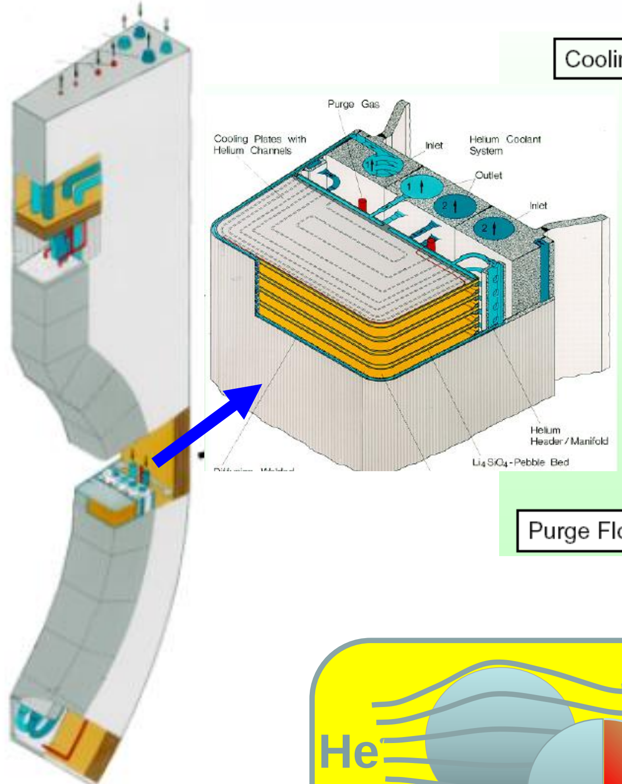
Shield
- large mass
- cost

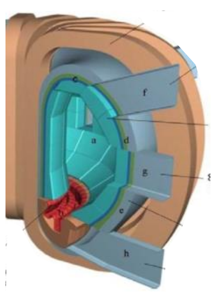
Protect Vessel
- Activation
  remote maint., disposal
- Damage
  degradation, corrosion, weldability

Protect Magnets
- Heating
  bulk heating
- Damage
  Cu→Ne
  critical J,B

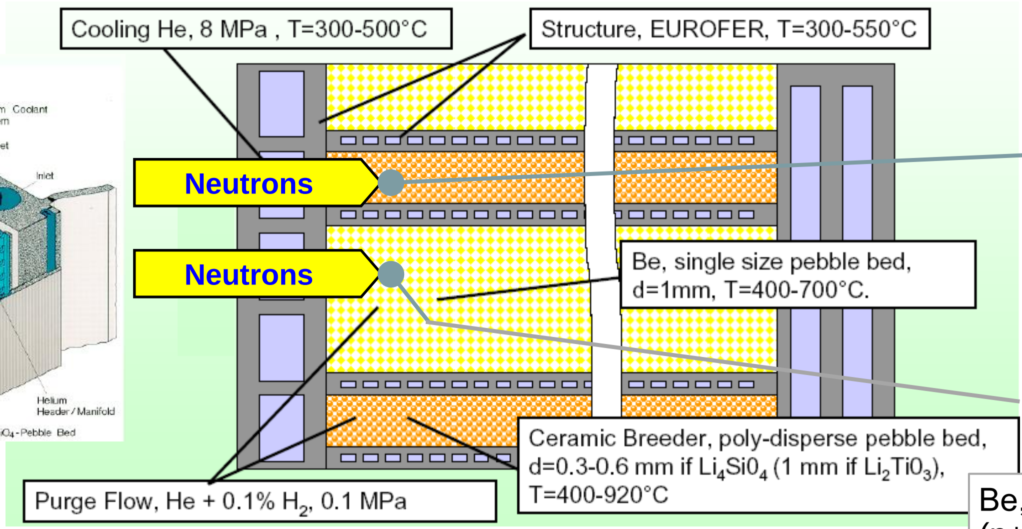
Blanket technology, design studies

First Wall – Blanket – Shield

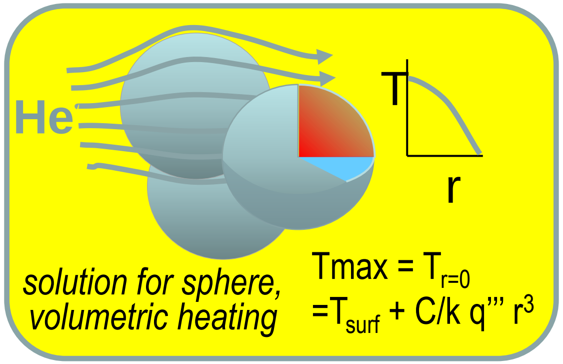




Solid (Ceramic) Breeder Li_4SiO_4



Be, a "neutron multiplier" (n+^{9}Be $\rightarrow$ ^{8}Be+2n), makes more neutrons available for breeding (n+^{7}Li $\rightarrow$ He+^{3}H).



- Allowable Tmax in pellet determines size.
- Size sets surface area for given volume.
- Surface area $\Rightarrow$ drag
- What is pressure drop?
- Ergun equation, for flow in packed beds.

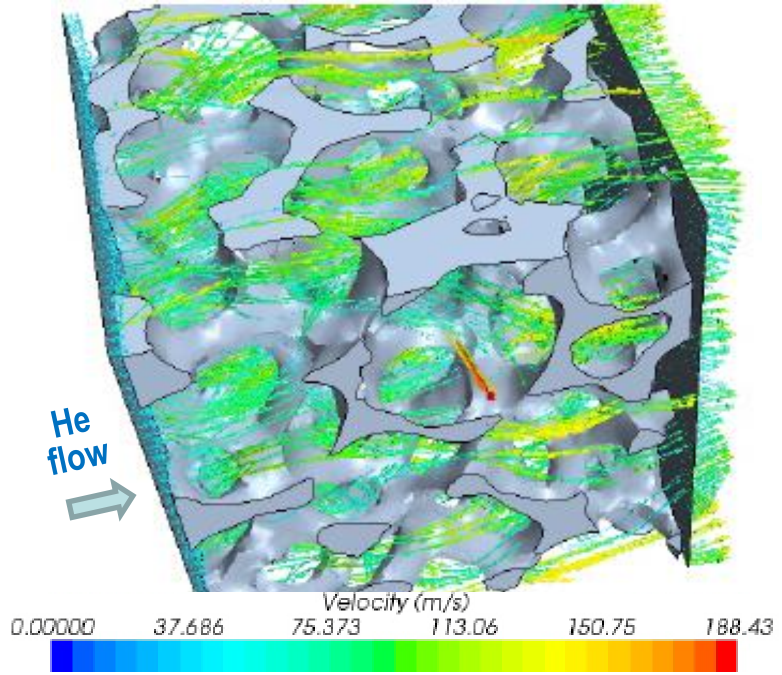
"Breakthrough analysis" of flow in porous media for fusion applications

Dennis Youchison
DMTS at Sandia

Evaluation of Heat Transfer in High-Temp. Refractory Foam HXs using CFD
Int. Conf. on Emerging Energy Systems, San Francisco 2010

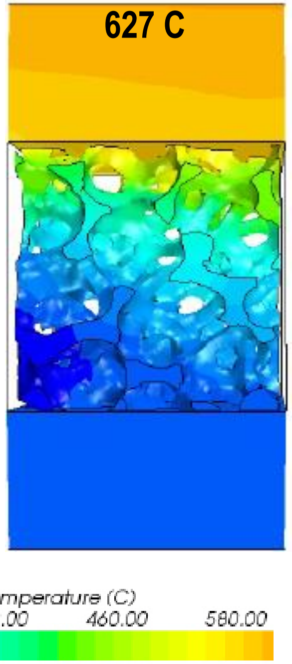
Early work for helium-cooled fusion heat sinks used correlations (Ergun equation) to predict heat transfer in porous media.

New approach combines accurate and irregular geometry and full fluid physics of boundary layers and turbulence to model fluid flow and heat transfer.



2x2 mm volume from model
65 ppi, 10% dense Mo foam

Use computerized X-ray microtomography to image foam* and then translate data to format for solid models.

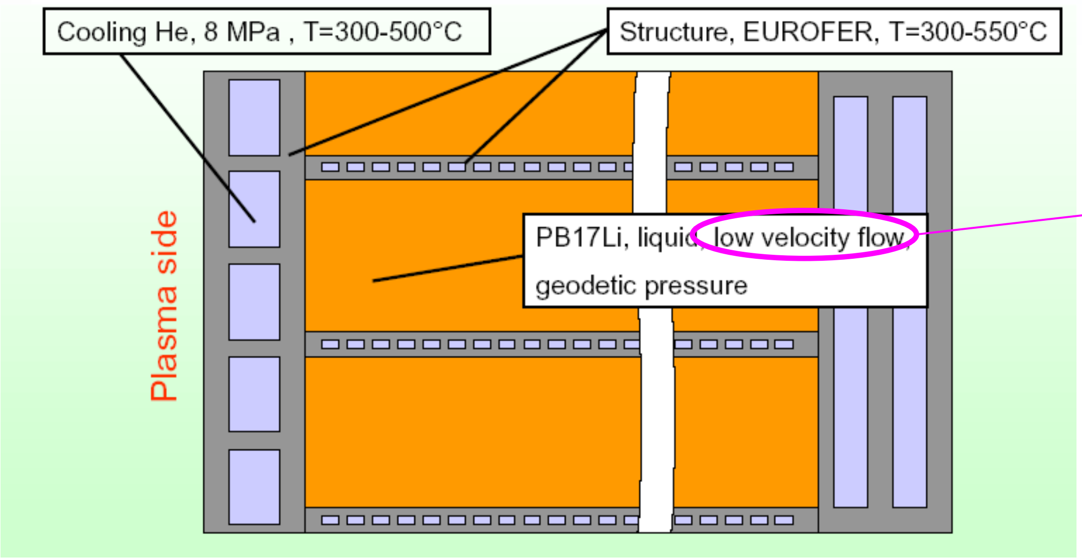


*carbon foam made by Ultramet, Inc. (Pacoima CA)

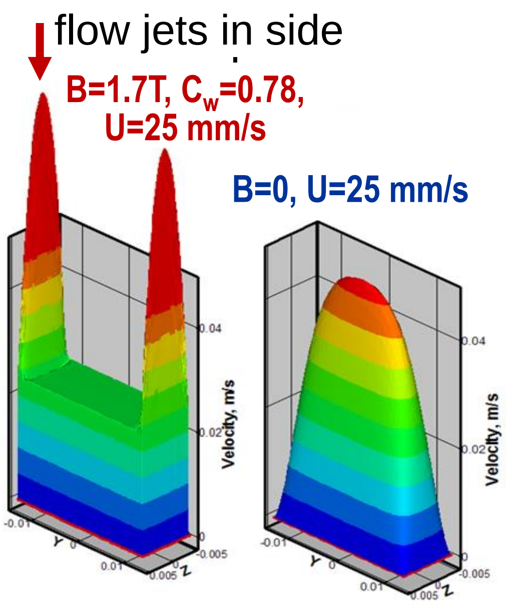
Analysis reveals turbulent mixing and fin effect created by foam.

Blanket technology, design studies

***Liquid Metal Breeder* Pb-17Li**

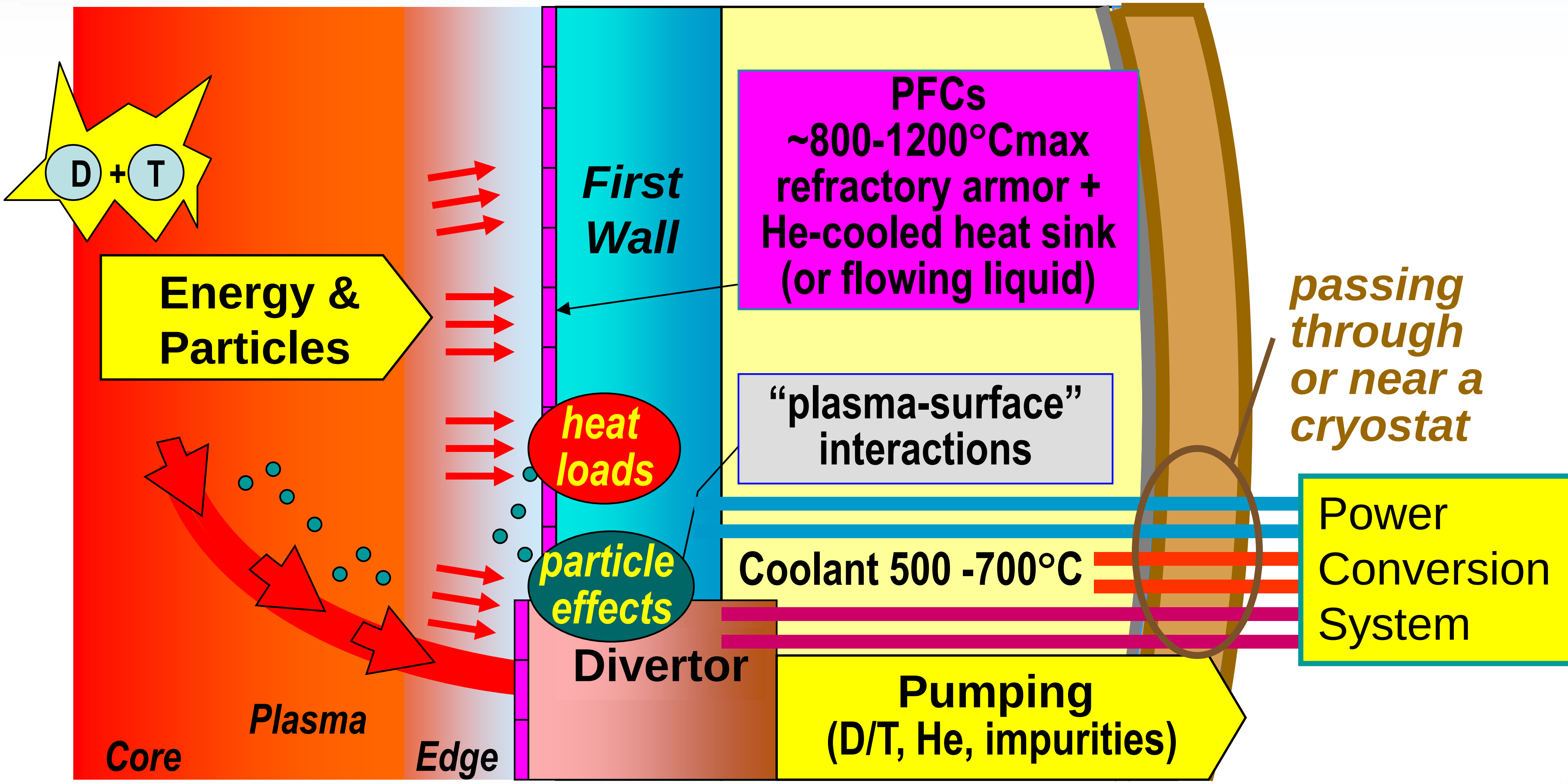


Low velocity flow reduces MHD effects that otherwise dominate flow and heat transfer.



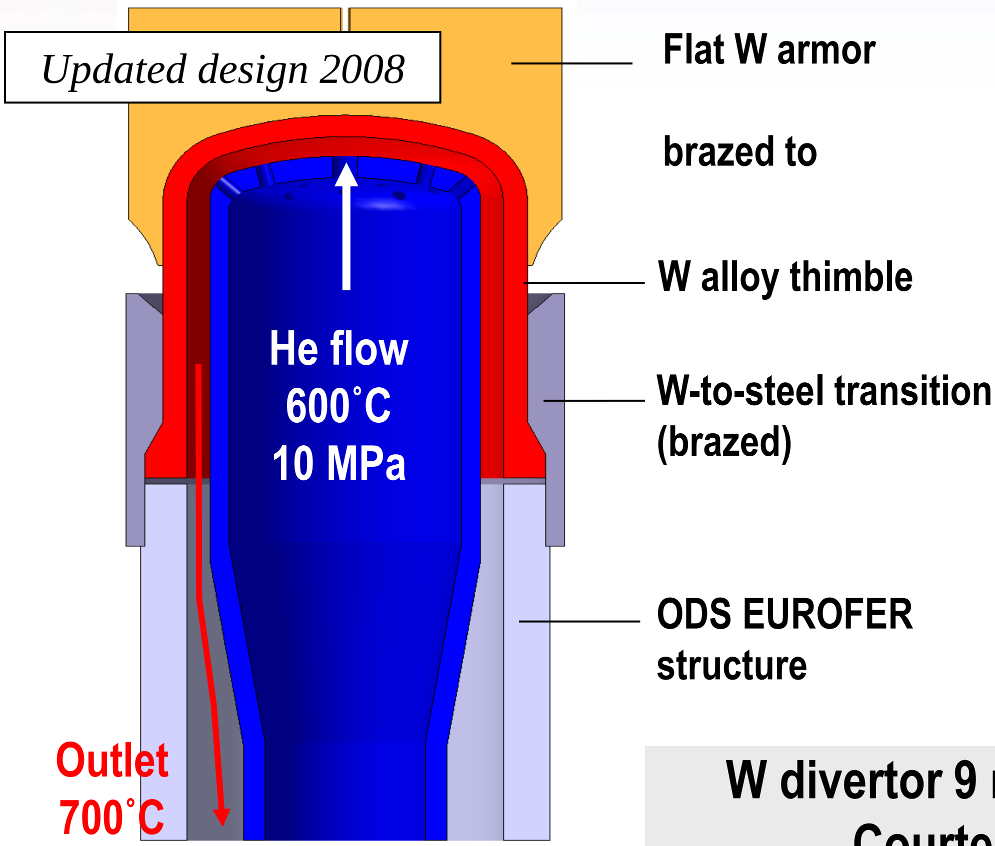
- At high magnetic fields (high Hartmann numbers), MHD effects dominate flow.
- Classic solutions in simple channels have been available, but complications such as gradients, bends, constriction and manifolds make the computational problem difficult.
- Insights into the nature of the flow, as in the examples shown, have aided our understanding.

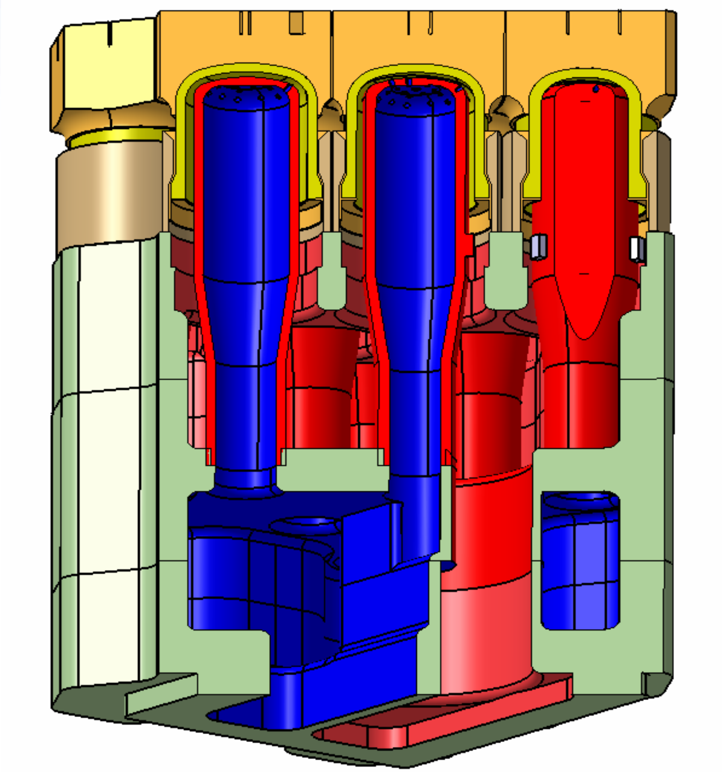
HOT STUFF - PFC Materials & Testing



And we need robust and reliable components that can resistant damage from ions and neutron irradiation.

Fusion DEMO Options – He-cooled W





W divertor 9 module array with transition joints.
Courtesy of Prachai Norajitra, FZK .

In tests at the Efremov Institute, a single module mockup with a WL-10 thimble survived a heat load of 11.6 MW/m^2 with He (inlet) at 500°C.

Personal Observations

The acceptance/use of materials is a cycle of "materials development" and experience in application.

This is challenging, time-consuming and needs strong coordination with plasma devices on interfaces and with industrial suppliers on fabrication development, QA and acceptance. e.g., Tore Supra and ITER.

✓robust actively-cooled PFCs

- materials development
- component development
- test instru-mentation

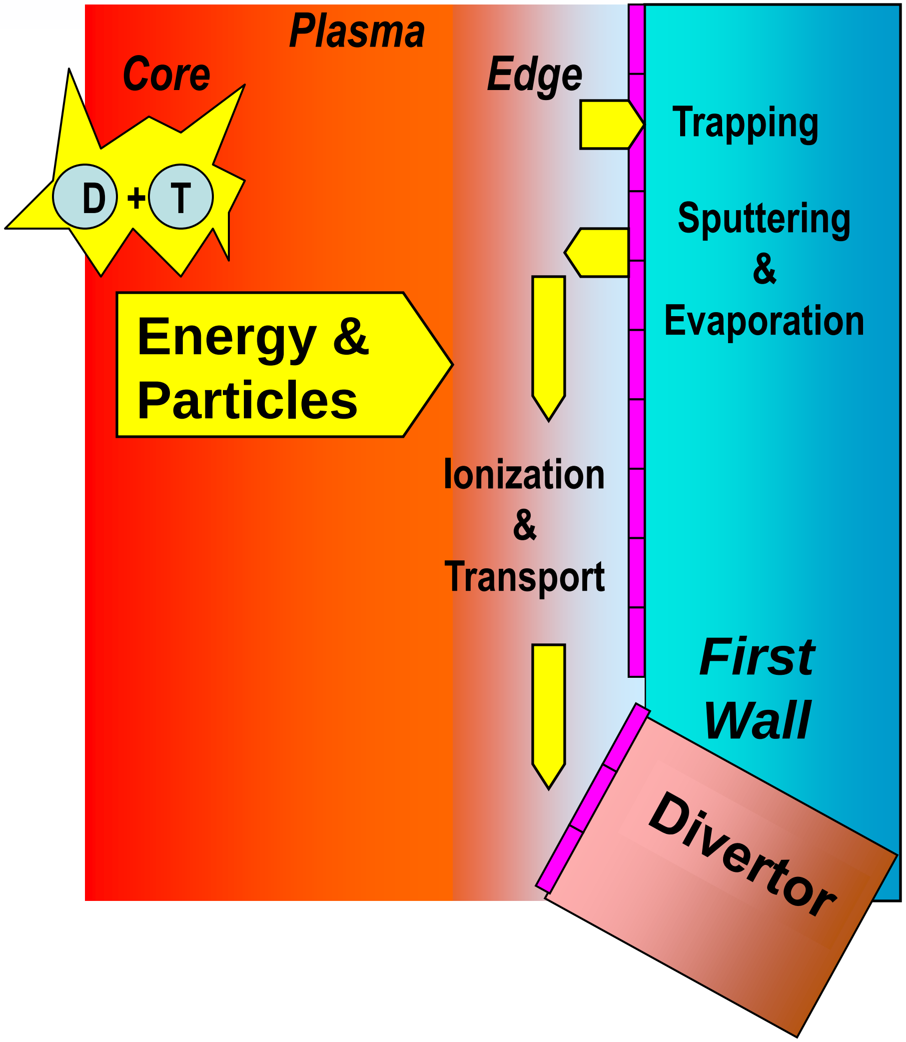
- design confirmation [modeling, testing]
- fabrication dev.
- QA & acceptance

Tore Supra water cooled PFCs
- modular limiters in 1990s failed
- very good history working closely with Plansee on fabrication
- yet still had quality problems
- rebuilt PFCs - CIEL completed 2002

- ~25y - fusion-specific water-cooled PFCs
- ~15y - ITER PFC R&D
- ~10y detailed R&D
- ITER design changing
- ~ 4y FWQ mockups
- vendors engaged
- 3-5y final design to fab

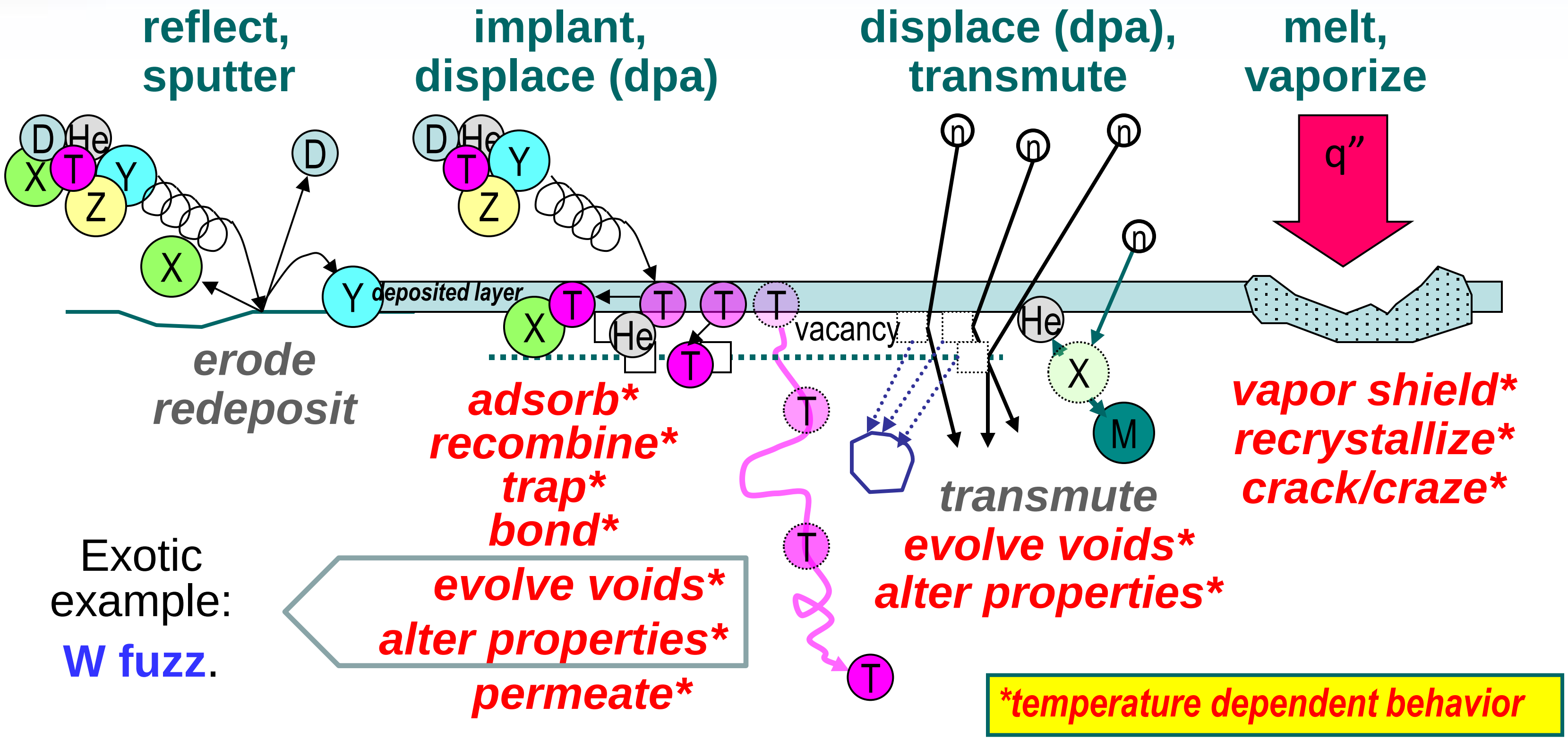
Sandia National Laboratories

Plasma Wall Interactions



- High heat flux, high particle flux.
- Key issues: trapping of D & T, erosion, and thermal fatigue.
- Ions move along field lines. Exposed edge gets huge heat load.
- PFC surfaces are smooth.
- Magnetic fields are designed to direct plasma flow onto a narrow stripe around the machine at the "divertor", which gets very high heat and particle loads.

Plasma Wall Interactions (PWI)

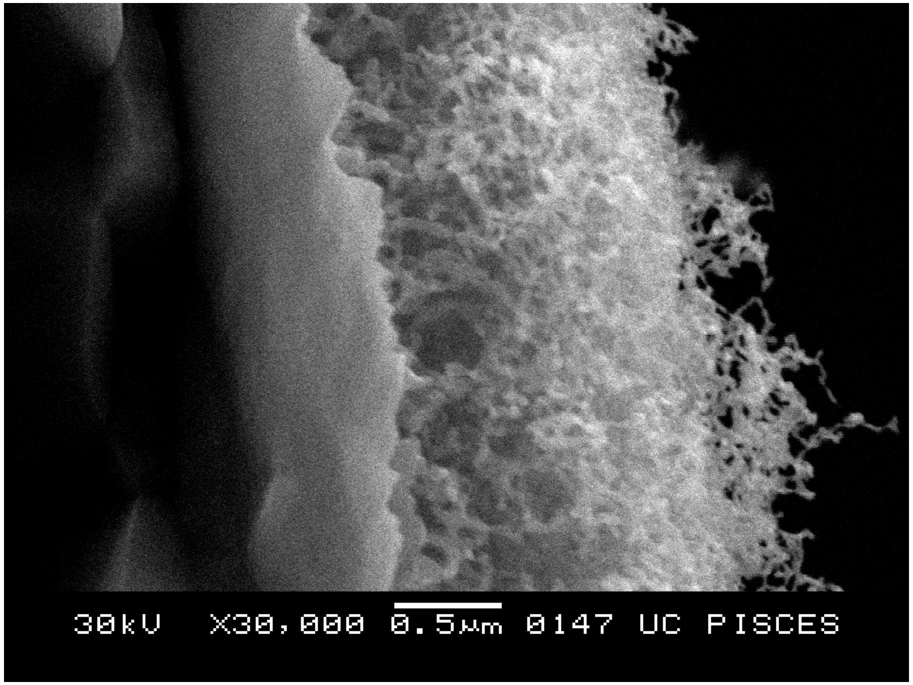


The physical chemistry of PWI processes on high temperature walls will determine the strong interaction between wall and plasma in DEMO (or FNSF).

PSI Processes – Oh fuzz and blisters! (in W)

PISCES-B: pure He plasma

T_s = 1200 K, Δt = 4290 s,
Fluence = 2×10^{26} He^+/m^2, E_i = 25 eV

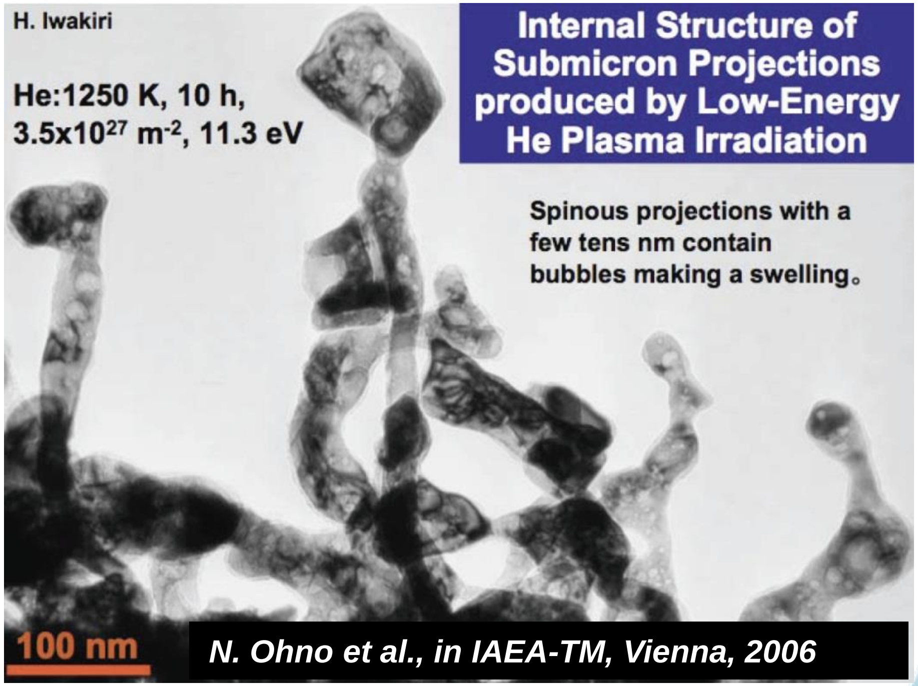


Scanning electron microscope (SEM)

Baldwin, Nishijima, Doerner, et. al, courtesy of Center for Energy Research, UCSD, *La Jolla, CA*

NAGDIS-II: pure He plasma

T_s = 1250 K, Δt = 36,000 s,
Fluence = 3.5×10^{27} He^+/m^2, E_i = 11 eV



Transmission electron microscope (TEM) in Kyushu Univ.

Basic requirements in fusion systems

BURNING PLASMA
- Configure
- Confine
- Sustain

HEAT power handling
- Exhaust
- Harvest
- Convert

neutron damage

TRITIUM self-sufficiency
- Produce
- Harvest
- Contain

HANDLE/HARVEST HEAT **and** ***BREED/PROCESS/TRACK TRITIUM***

PROTECT the PLASMA

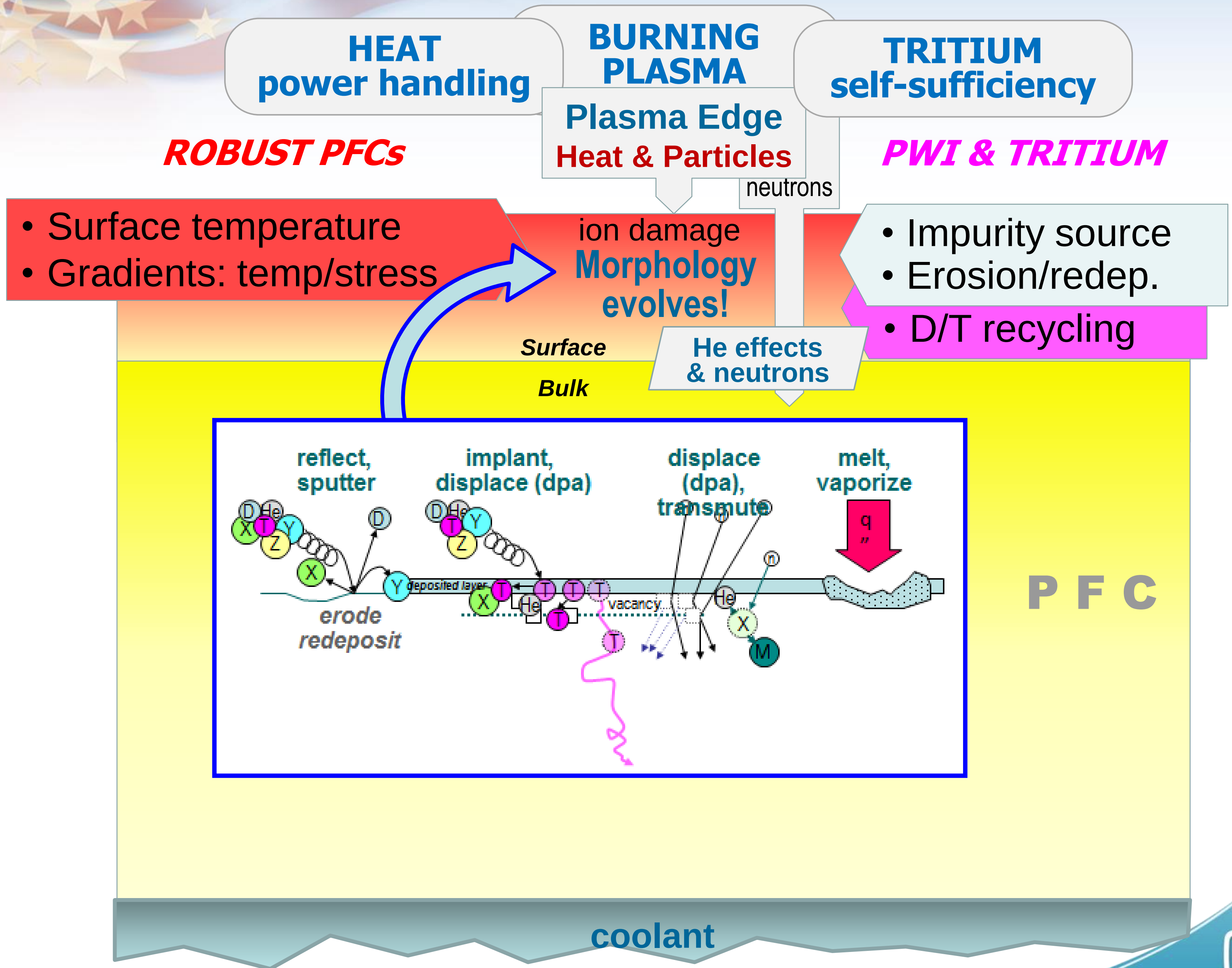
ROBUST PLASMA FACING COMPONENTS
- Mitigate ion & radiation damage
- Develop suitable materials*
- Develop workable cooling systems*
- Understand/predict system behavior including plasma-wall interactions*

ROBUST PFCs

VIABLE BREEDING BLANKETs
- Demonstrated tritium breeding
- Develop suitable materials*
- Viable integrated systems*
- Understand/predict system behavior including tritium migration/retention*

PWI & TRITIUM

****Solutions are the focus of Sandia's research for OFES.***


HEAT
power handling
BURNING
PLASMA
TRITIUM
self-sufficiency
Plasma Edge
Heat & Particles
ROBUST PFCs
PWI & TRITIUM
neutrons
• Surface temperature
• Gradients: temp/stress
ion damage
Morphology
evolves!
• Impurity source
• Erosion/redep.
• D/T recycling
Surface
Bulk
He effects
& neutrons
reflect,
sputter
implant,
displace (dpa)
displace
(dpa),
transmute
melt,
vaporize
erode
redeposit
deposited layer
vacancy
P F C
coolant

HEAT
power handling

BURNING PLASMA

TRITIUM
self-sufficiency

Plasma Edge
Heat & Particles

neutrons

ROBUST PFCs

- Surface temperature
- Gradients: temp/stress

PWI & TRITIUM

- Impurity source
- Erosion/redep.
- D/T recycling

ion damage
Morphology evolves!

Surface

He effects & neutrons

Bulk

- Material damage & modification
- T retention
- T permeation

understanding of PWI, including:

- ***erosion & redeposition***
- ***damage & trapping***
- ***evolution - microstructure***

P F C

HEAT
power handling

BURNING
PLASMA

TRITIUM
self-sufficiency

Plasma Edge
Heat & Particles

neutrons

ROBUST PFCs

- Surface temperature
- Gradients: temp/stress

PWI & TRITIUM

- Impurity source
- Erosion/redep.
- D/T recycling

ion damage
Morphology evolves!

Surface

He effects
& neutrons

Bulk

- Material damage & modification
- T retention
- T permeation

- Cooling
- Pressure
- Thermal-hydraulics
- Thermal stress
- Cracking/failure
- Fab – Joining etc.

P F C

PMI
SNL R&D

We design, build and use probes and analyze tiles. We collaborate on plasma edge experiments.

With various facilities, we investigate trapping of D/T/He; permeation of D/T and growth of W fuzz.

Sandia National Laboratories

HEAT
power handling

BURNING
PLASMA

TRITIUM
self-sufficiency

Plasma Edge
Heat & Particles

ROBUST PFCs

PWI & TRITIUM

neutrons

- Surface temperature
- Gradients: temp/stress

ion damage

Morphology evolves!

- Impurity source
- Erosion/redep.
- D/T recycling

Surface

He effects & neutrons

Bulk

- Material damage & modification
- T retention
- T permeation

development of plasma facing components (PFCs), including:

- ***fluid flow physics, CFD***
- ***heat transfer***
- ***thermal stresses***
- ***high heat flux testing***
- ***experiments in plasma devices***

- Cooling
- Pressure
- Thermal-hydraulics
- Thermal stress
- Cracking/failure
- Fab – Joining etc.

P F C

Sandia National Laboratories

HEAT
power handling

BURNING PLASMA

TRITIUM
self-sufficiency

Plasma Edge
Heat & Particles

neutrons

ROBUST PFCs

- Surface temperature
- Gradients: temp/stress

PWI & TRITIUM

- Impurity source
- Erosion/redep.
- D/T recycling

ion damage
Morphology evolves!

Surface

He effects & neutrons

Bulk

- Material damage & modification
- T retention
- T permeation

- Cooling
- Pressure
- Thermal-hydraulics
- Thermal stress
- Cracking/failure
- Fab – Joining etc.

P F C

PFC
SNL R&D

We analyze and test PFCs.

We have designed, built and deployed PFCs.

And we develop fundamental data in the Engineering Sciences on fluids and heat transfer.

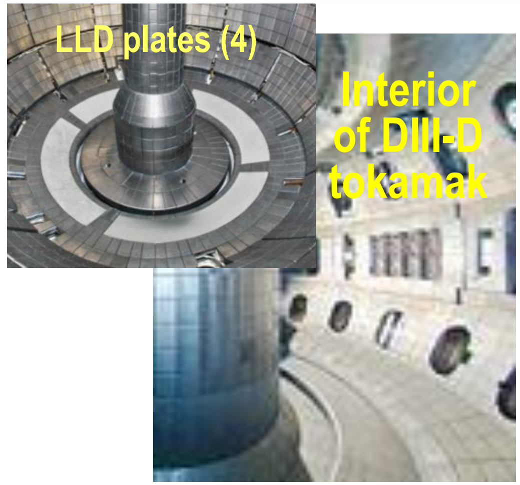
HEAT power handling | **BURNING PLASMA** | **TRITIUM self-sufficiency**

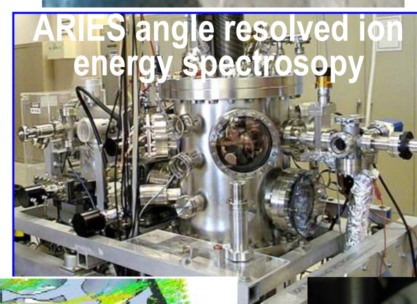
Plasma Edge
Heat & Particles

ROBUST PFCs | ***PWI & TRITIUM***

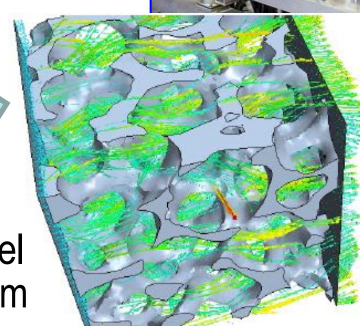
SNL PFC R&D

- **Design/build PFCs**
  - Liq. Li Div (NSTX)
  - Limiters (Tore Supra)
  - Alt-I&II (TEXTOR)
  - First wall (ITER)
- **Test/analyze PFCs**
- **Engineering Science**
  - EM/Thermal/TH models
  - Fundamental testing & benchmarking
    - fluid physics, gas flow in porous media
    - 2-phase flow in hypervaportron
    - post-CHF behavior





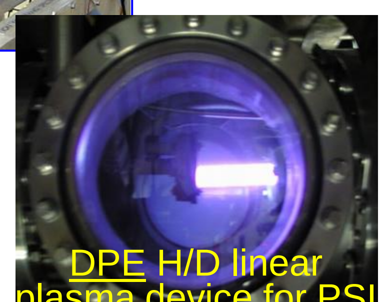
He flow



2x2 mm volume from model
65 ppi, 10% dense Mo foam

SNL Plasma & PMI R&D

- **Edge probes**
  - DIII-D divertor probes & fast thermocouples
  - DiMES collaboration
  - Coupons/tiles (DIII-D, C-MOD, NSTX, EAST, ...)
- **Experiments**
  - T permeation (TPE)
  - D trap/perm. (DPE, IBL)
  - D trapping (ARIES)
  - Li emissivity (@Purdue)
  - CT injection (@UC-Davis)
  - W fuzz (DPE/UCSD)



Sandia has a unique set of capabilities that support our PFC research.

Surface analysis for Plasma Wall Interactions

- Plasma sources for tritium PSI studies: Deuterium Plasma Experiment (DEP) and TPE, now at INL in Idaho.
- Low-energy ion beam probes for LEIS, DRS & SIMS
- MeV ion beam analysis of surface modification and T trapping.
- Traditional surface analysis (Auger, Raman AFM, and XPS).

Modeling and testing for PFC Development

- Modeling/Codes:
  - computational fluid dynamics
  - steady and transient magnetic fields
  - thermal & stress distributions
- Large sample SEM
- High Heat Flux Facility
  - EB60 - ready for restart
  - EB1200 - cold standby
  - High T & P water, He loops
  - IR, pyrometers, TCs, calorimetry
  - Beryllium handling

and others we can utilize

- Rad-hard electronics
- Materials
  - extreme environments
  - failure and damage
- Advanced manufacturing
- .... others

Sandia National Laboratories

Path for presentation

components

- integrated wall-breeder module (solid or liquid breeders)
- heat removal (fluid physics)

plasma edge & materials

- solid walls (**tungsten**, ?ferritics)
- materials **damage**
- liquid walls (lithium, molten salt)
- PFC solutions (configuration)
- near term experiments
- **long term** development

materials & fabrication

- He cooling (or CO2)
- enhanced heat transfer
- development path

1. **ITER**
2. **FNSF**
   Comp. Test
3. **DEMO**

Sandia National Laboratories

Path for presentation

components

- integrated wall-breeder module (solid or liquid breeders)
- heat removal (fluid physics)

plasma edge & materials

- solid walls (**tungsten**, ?ferritics)
- materials **damage**
- liquid walls (lithium, molten salt)

materials & fabrication

- He cooling (or CO2)
- enhanced heat transfer
- **development path**

DEVELOPMENT PATH

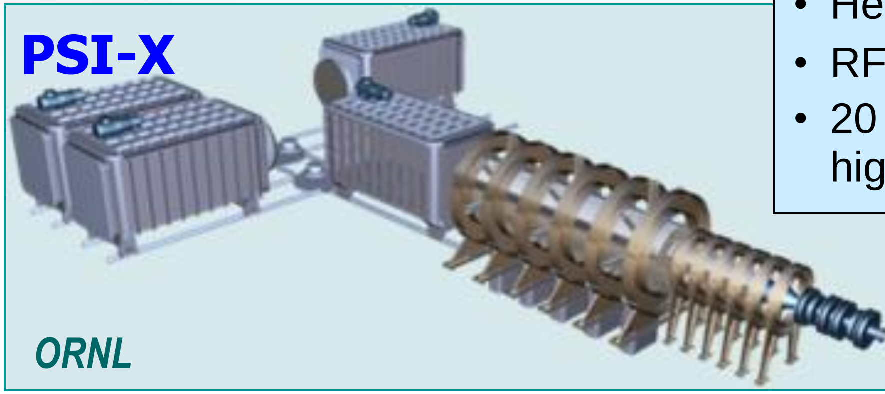
- **New form of W or W alloy**
- **Low DBTT, radiation resistant**
- **Fabrication enabling micro-features**
- **Integral structure with FW and blanket**

SANDIA CONNECTIONS

- Materials
- Advanced manufacturing
- Hydrogen/Tritium in metals
- Design – fluid flow (next)

- **Enhanced heat transfer required**
- Need for refractory; high sputtering threshold
- Base metal: brittle BCC material; need new form of W

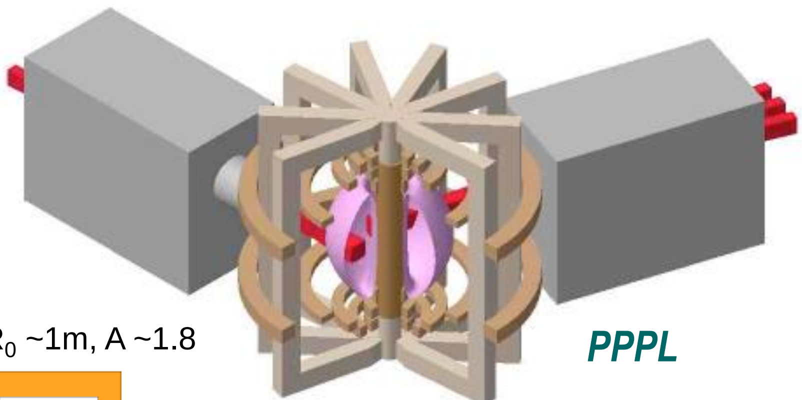
Proposed non-fusion facilities for PFC development



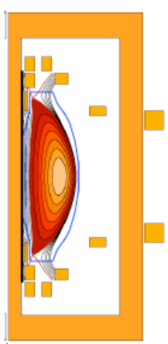
- Helicon and magnetic mirror (1.5m, 1T)
- RF heating, ~100 eV plasma (~100 cm^2)
- 20 MW/m^2 on target, $10^{23\text{-}24}$ $/m^2s$ under high recycling conditions

SATs satellites

- Upgrades and new devices likely in future, e.g., Chinese superconducting tokamak EAST, ?EU SAT later
- US-ST (PPPL)?



R_0 ~1m, A ~1.8



PPPL/NHTX concept:

US H/D spherical torus, flexible configuration for Super-X or LM divertors – high input power, long pulse

What we need:

Develop/deploy actively-cooled PFCs.

Facility for “hot wall” experiments.

Benefit depends on cost and feasibility of new devices and access and opportunity for PFC experiments.

Path for presentation

components

- integrated wall-breeder module (solid or liquid breeders)
- heat removal (fluid physics)

plasma edge & materials

- **solid walls** (tungsten, ?ferritics)
- materials **damage**
- **liquid walls** (lithium, molten salt)
- PFC solutions (configuration)
- near term experiments
- **long term** development

materials & fabrication

- He cooling (or CO2)
- enhanced heat transfer
- development path

1. **ITER**
2. **FNSF**
3. **DEMO**

INTEGRATED FW & BLANKET

- Real estate requires thin blanket with attached first wall
- Divertor must use same coolant, otherwise too complicated
- Tritium breeding and management not yet demonstrated
- ITER will have some modules but not integrated system.
- Need for component development and testing (FNSF+..)

Path for presentation

components

- integrated wall-breeder module (solid or liquid breeders)
- heat removal (fluid physics)

plasma edge & materials

- **solid walls** (tungsten, ?ferritics)
- materials **damage**
- **liquid walls** (lithium, molten salt)
- PFC solutions (configuration)

materials & fabrication

- He cooling (or CO2)
- enhanced heat transfer
- development path

DEVELOPMENT PATH

- **Improved designs, e.g. porous media in blanket and micro-features in FW**
- **Design verification**
- **Component testing**
- **Systems integration**
- **Deployment (PFCs, diagnostics)**
- **Partnerships**

SANDIA CONNECTIONS

- Design – CFD, EM, TH
- HHF testing
- Systems engineering
- Prototype development
- Design-development partners

grated system.

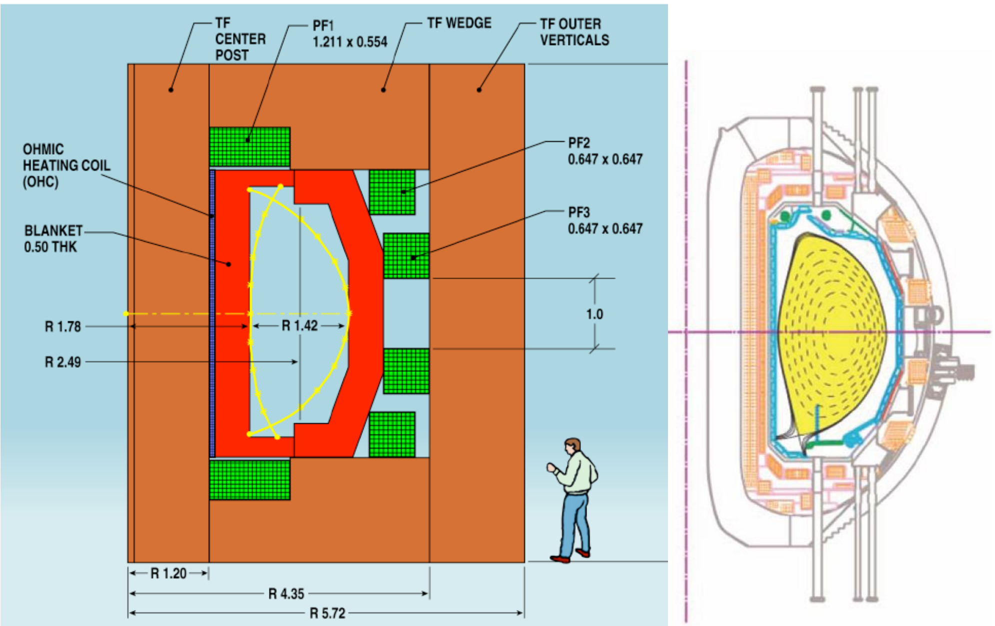
- Need for component development and testing (FNSF+..)

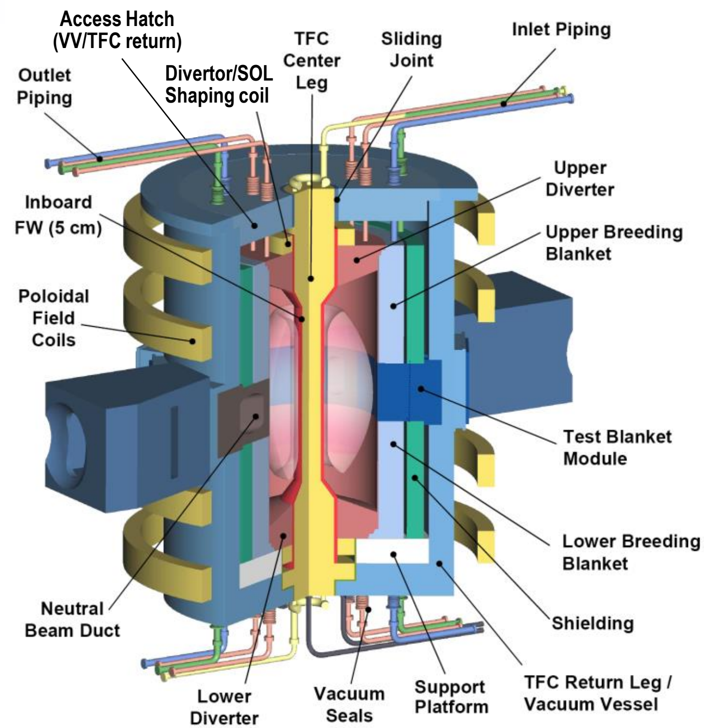
TWO classes of Design Options are proposed for FNSF

Both options satisfy FNST testing requirements

Standard Aspect Ratio, 2.8-4

Small Aspect Ratio, ~1.5, kappa 3





FNSF/FDF GA Design

high elongation & triangularity

Demountable TF coils, double null for high gain

$\mathbf{P_{fusion}}$ **125 MW at** $\mathbf{P_{NW}}$ **of 1 MW/m²**

FNSF/ST ORNL design

Cu center post & TF coils

$\mathbf{P_{fusion}}$ **76MW at** $\mathbf{P_{NW}}$ **of 1 MW/m²**

Differences are in the physics, configuration, TF Coil resistive power.

Engineering Instrumentation for Future Fusion Devices

R.E. Nygren
Fusion Technology Department
Sandia National Laboratories

Viewpoint on safety

We have a significant investment in our cars. Diagnostics warn us when the operating system is functioning outside its prescribed ranges.

We make adjustment or do maintenance.

The same philosophy applies in ITER or DEMO.

We identify conditions of interest and design diagnostics based on common sense and some insight from instrumentation used in other systems.

We need to learn how to do this and show that we can.

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company,
for the United States Department of Energy's National Nuclear Security Administration
under contract DE-AC04-94AL85000.

Viewpoint on safety

Information desired from engineering diagnostics (instrumentation) would likely include at minimum confirmation that FW/blanket were functioning OK.

Example: data on coolant flow and local temperature confirm that short term failure by distortion and cracking due to overheating of some section of the first wall or blanket is unlikely.

While the FW may be visible to an IR camera, this is not true for shield modules and mounting structure.

ITER can accept a risk for its FW and divertor, but may be interested in some instrumentation to confirm the design.

Examples from other systems

Preliminary examples, work in progress

- Fission plants: Operators monitor core temperature with thermocouples, identify hot channels (diagnose low coolant flow), monitor inlet & outlet temperature of core coolant.
- PWR steam generators: Operators monitor inlet and outlet coolant temperatures, pressure, water level & water chemistry. They also use acoustic measurements to monitor mechanical noise that might arise from vibration of tubes, action of the check valve in the return flow channel or rattling of loose hardware.
- MHD Generators: Experimenters monitor measure voltage (electrically isolated probes), pressure and chemistry (impurity level).

Sandia National Laboratories

Path for presentation

- **Diagnostics** **[diagnostics$_{fusion}$ ≡ plasma diagnostics]**

diagnostics (plasma, plasma edge)

instrumentation (components)

control (operations)

components

DEVELOPMENT PATH

- **New designs, e.g. "smart tiles" that transmit data (light rather than wires)**
- **Damage resistant, actively-cooled mirrors and probes**
- **Radiation-resistant electronics**
- **Prototype development**
- **Tritium monitoring**
- **Deployment**
- **Partnerships**

SANDIA CONNECTIONS

- Design – CFD, EM, TH
- HHF testing
- Rad-hard electronics
- Prototype development
- Design-development partners

End

THANKS