Introduction - Presenter

Richard Nygren

- **Hanford Eng. Dev. Lab** <1981 — radiation damage, **LMFBRs**, fusion
- **Oak Ridge NL** 1979-81 — materials in Fusion Eng. Device (pre-ITER)
- **Argonne NL** 1981-85 — FW-Blanket-Shield Program Director
- **DOE/OFES** 1986 — Spec. Ass't. to Dir. US Fusion Program
- **UCLA** 1987-88 — PSI experiments, PISCES (now at UCSD)

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

  Distinguished Member, Technical Staff

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

  Manager, Fusion Technology Dept.

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

- US Virtual Laboratory for Technology, *Deputy Director*
- USBPO Research Committee, *Chair of Engineering Sciences Topical Group*

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HHFC designs & constraints in a reactor environment

Richard Nygren
Sandia National Laboratories

Sources:
1. **ARIES Workshop on HHFC - UCSD (Raffray et al.)**
   international participation, multi-disciplinary, DEMO divertors
2. **ReNeW** (Research Needs Workshop, US national effort)
3. **ITER first wall design** - revised in 2010, CDR Feb 2010

- **High heat flux components –** readiness to proceed from near term fusion systems to power plants, Raffray, Nygren, Whyte, Abdel-Khalik, Doerner, Escourbiac, et al., FED 85 (2010) p93-108
- **DEMO Divertor Development**, Nygren, Norajitra, Suzuki, Malang, Raffray, Youchison, (oral ISFNT9, no paper)
- **Making Tungsten Work**, Nygren, Raffray, … oral presentation at ICFRM14, JNM paper

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Outline

High Heat Flux Components (HHFCs)

Introduction

- ***which HHFC, what FNSF, whose DEMO***
- ***integration and the development path for HHFCs***
- ***importance of ITER HHFCs***
- ***what ITER will not do***

Brief review of actively-cooled PFCs

- ***concepts***
- ***PFC technology***

Perspective on development of robust HHFCs

- ***some key concerns***

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Which HHFC? What FNSF/CTF? Whose DEMO?

- **Tokamak/AT**

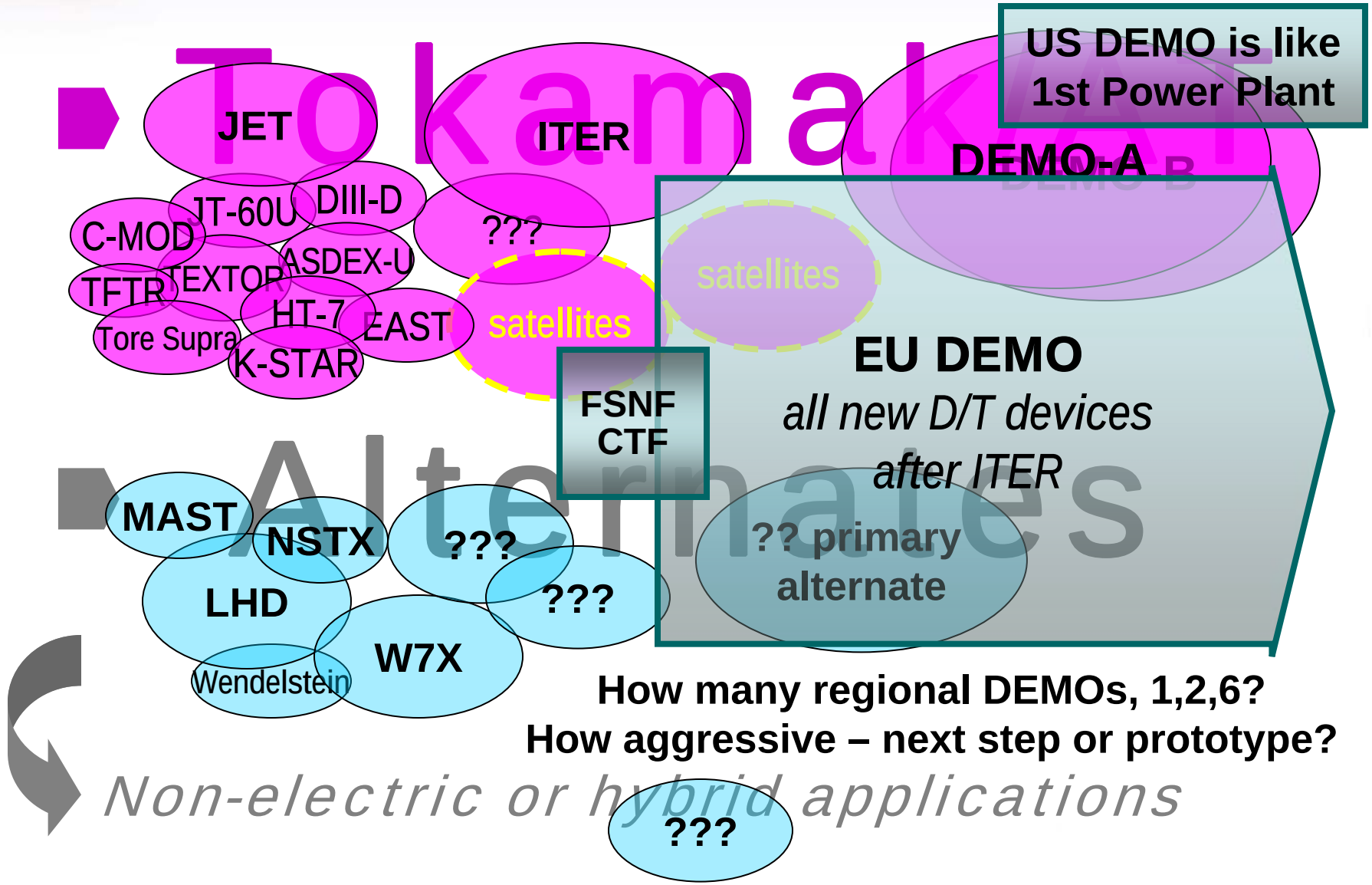
  Focus: 1. tokamaks
  2. solid surface PFCs

- **Alternates**

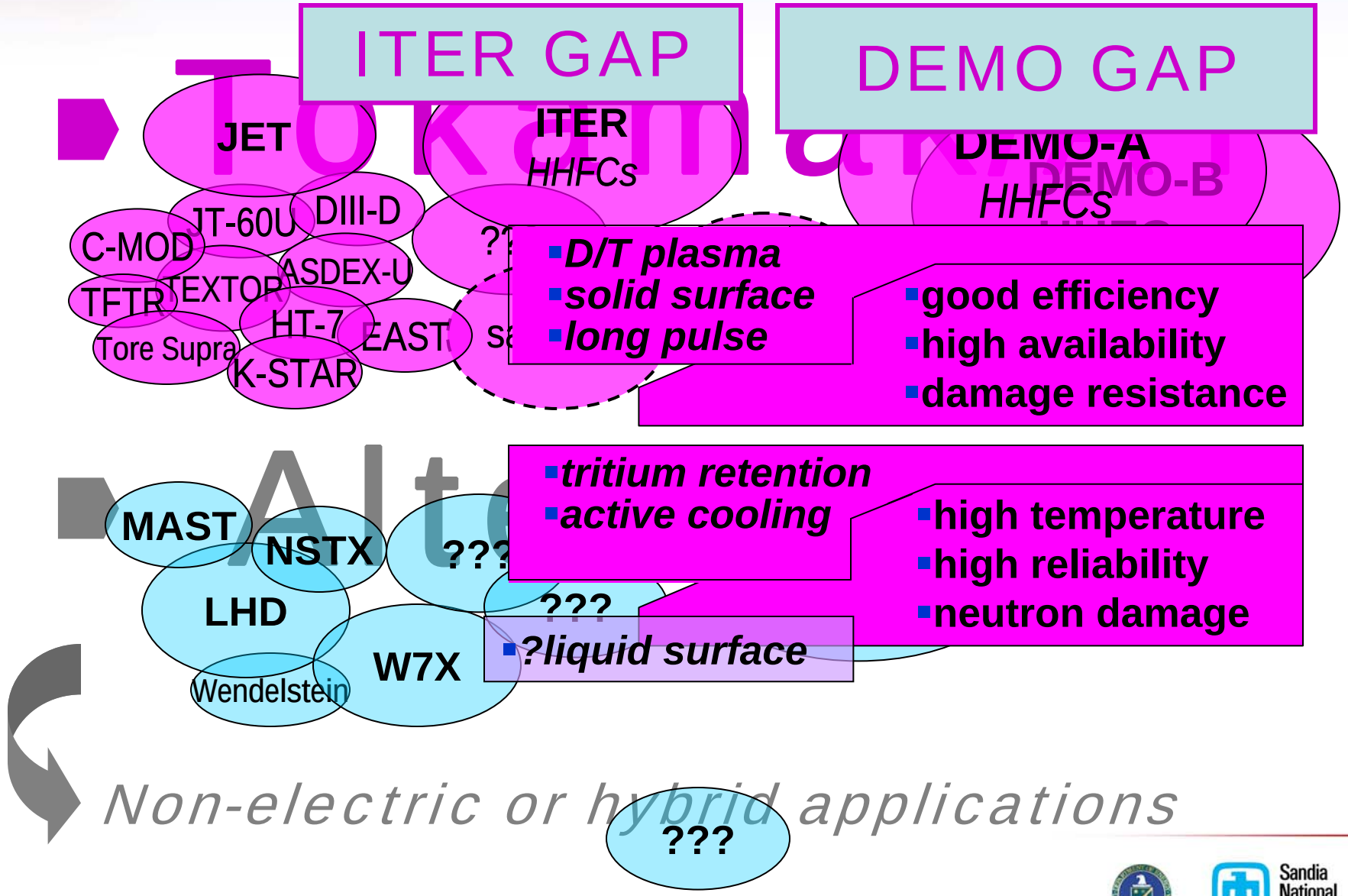
  Other: 3. alternates
  4. liquid surface
  5. other fusion pathways

Non-electric or hybrid applications

Which HHFC? What FNSF/CTF? Whose DEMO?



In ReNeW we asked where are the gaps?



ITER is our 1st large fusion nuclear system.

What will a successful ITER not do in advancing HHFCs?

ITER:

- **Pulsed**
- **Water** (150 C) **coolant**
- **C, Be, W** (mixed mat'l)

DEMO:

- **Steady-state**
- **Hot coolant** (~600 C)
- **Refractory metals**
- **Neutron irradiation** (up to 100 dpa)

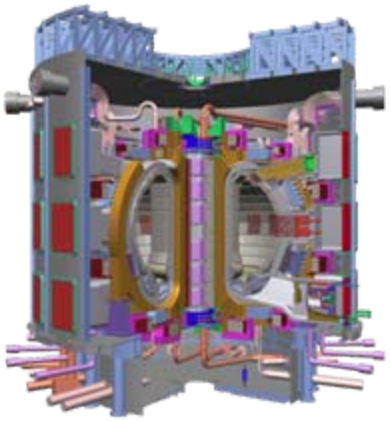
Present tokamaks and PMI experiments cannot access these parameters.

Parameters in the ITER divertor

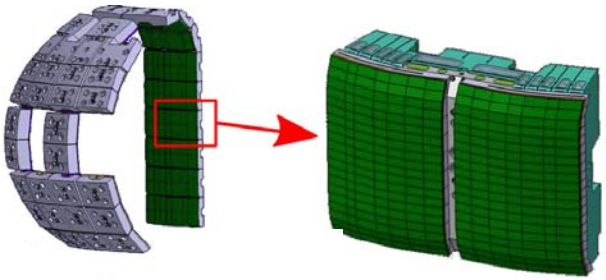
- $n_e = 10^{21}$ m^{-3}
- T_e = 1-10 eV
- $\Gamma_{D,T} = 10^{24}$ m^{-2}-s
- q_{div} = 10 MW/m^2

Similar in DEMO

Design has remained fairly unchanged.



ITER



Significant evolution of FW design and heat loads – *more later*

ITER TBMs can provide some experience with modular blanket systems. The loads and position of a TBM FW are still being evaluated.

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What will successful ITER HHFCs not do?

ITER will not address most PSI/PFC issues.

- **PSI is complex non-linear feedback to the plasma.**
- **Experiments integrate effects.**
- **New PFCs/mat'ls are threats to machine operation.**

ITER:

- **Pulsed**
- **Water** (150 C) **coolant**
- **C, Be, W** (mixed mat'l)

DEMO:

- **Steady-state**
- **Hot coolant** (~600 C)
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- **Neutron irradiation** (up to 100 dpa)

Present tokamaks and PMI experiments cannot access these parameters.

- **heat removal**
- **transient loads**
- **neutron damage**
- **erosion**
- **tritium retention**

Each is "worse" in ITER than present devices and worse yet in DEMO (quantity & quality), and

pushes our knowledge of PSI up against and past our current limits.

ITER will not have:

- **Hot walls & divertor**
  right physical chemistry
  thermal management
  high thermal cycles
- **High neutron dose**
- **Integration with blanket and open fuel cycle**
- **Power recovery**
- **High availability**
- **… other (FNST)**

ReNeW: Understanding and Developing PMI Science and Technology
Thrust 10 [Hillis and Doerner et al.]

presentation by Whyte*: Fusion Science Advisory Committee, National Academy of Science*

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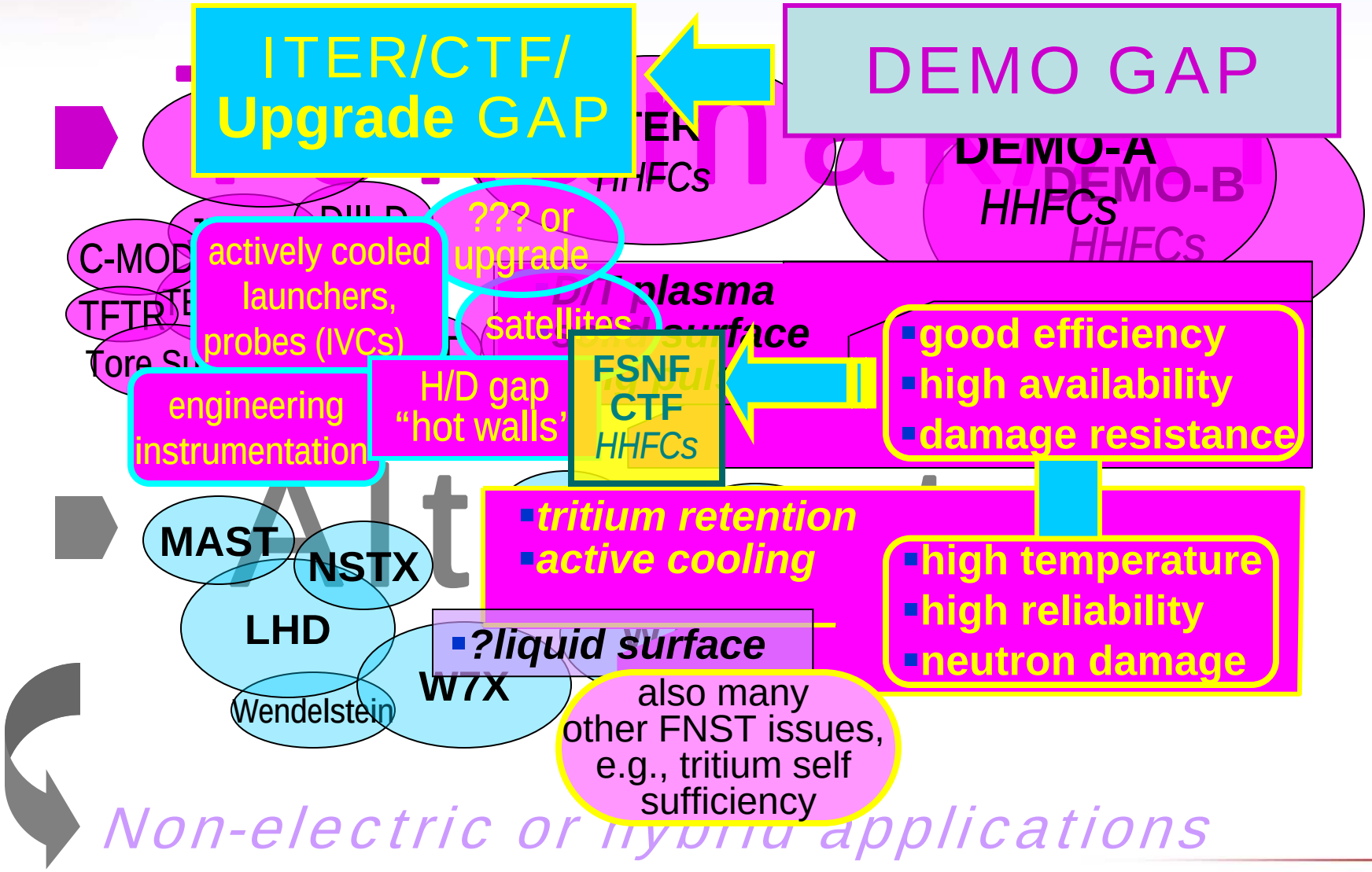
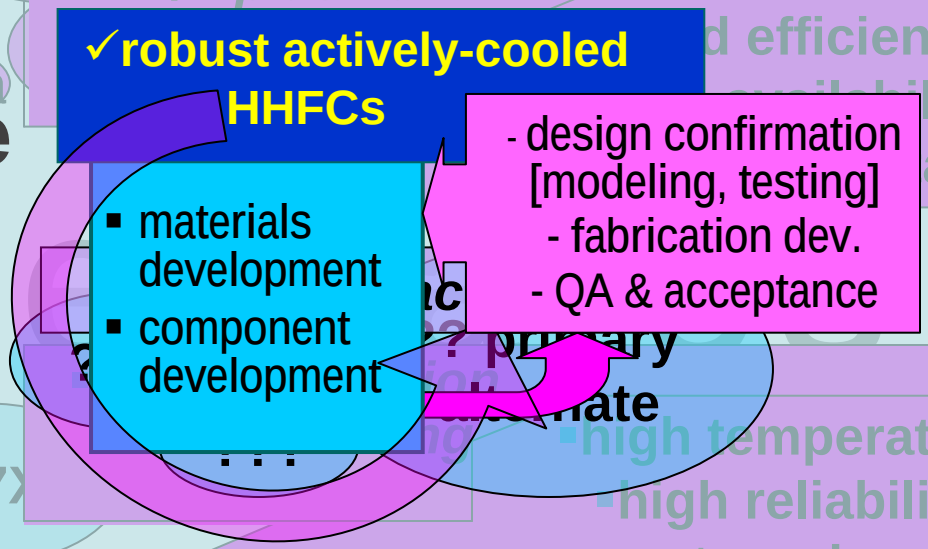
In ReNeW we asked where are the gaps?



Two key changes for HHFCs with FNSF:

#1 Add CTF/FNSF with robust damage-resistant hot walls.

#2 Develop adequate HHFCs (and ICs)



Realistic operating conditions and workable materials

Development & Integration Paths

Physics in all metal devices

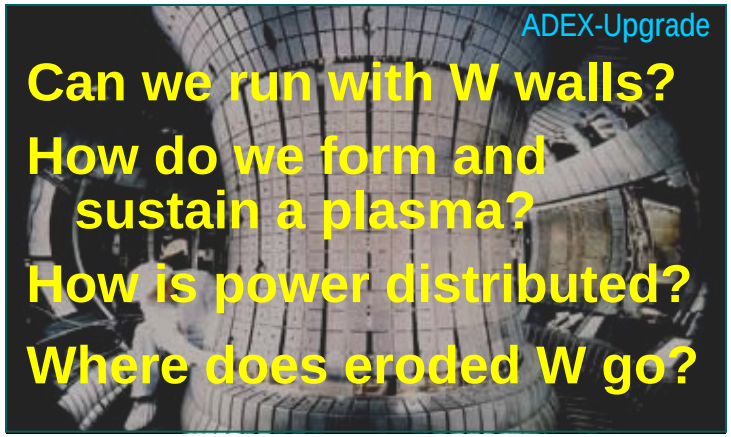
- **ASDEX-U** (divertor)
- **Alcator C-MOD** (divertor)
- **Others: TRIAM-U** (limiter)
- **JET with "ITER-like" divertor**

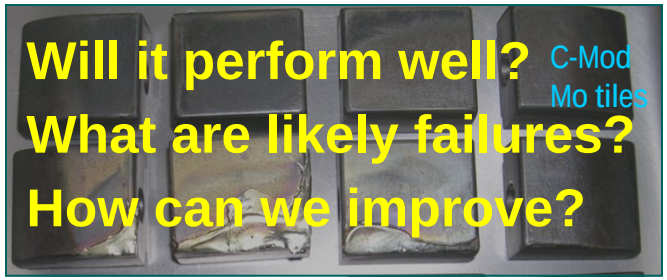
R&D on W PFCs

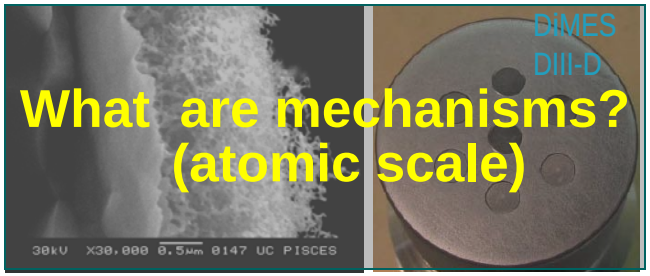
- **JET ITER-like divertor**
  (W monoblocks & coatings)
- **Coatings in ASDEX-U**
- **W limiters in TEXTOR, HT-7**
- **Fabrication development**

- **Probe/tiles measurements** *PSI*
  - **W erosion in DIII-D and C-MOD**
  - **D or He damage in TRIAM, LHD**

Nature of inquiry







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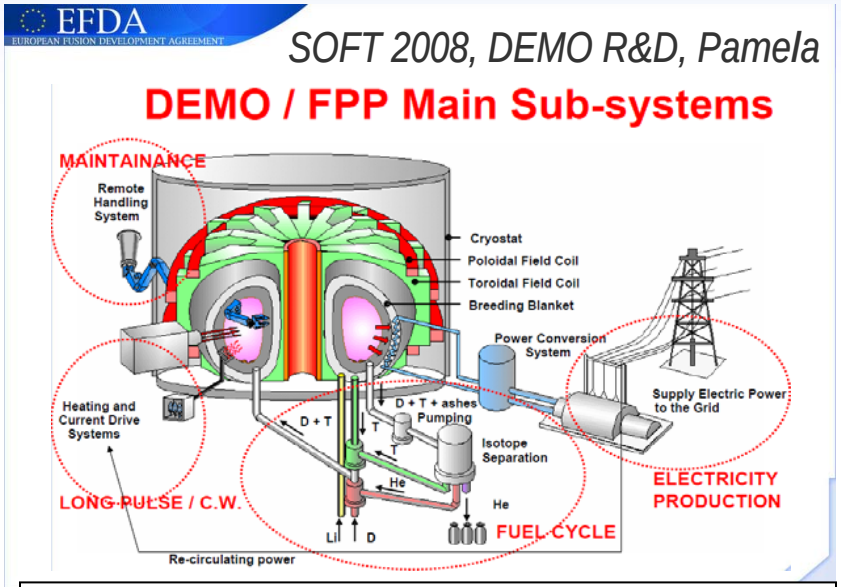
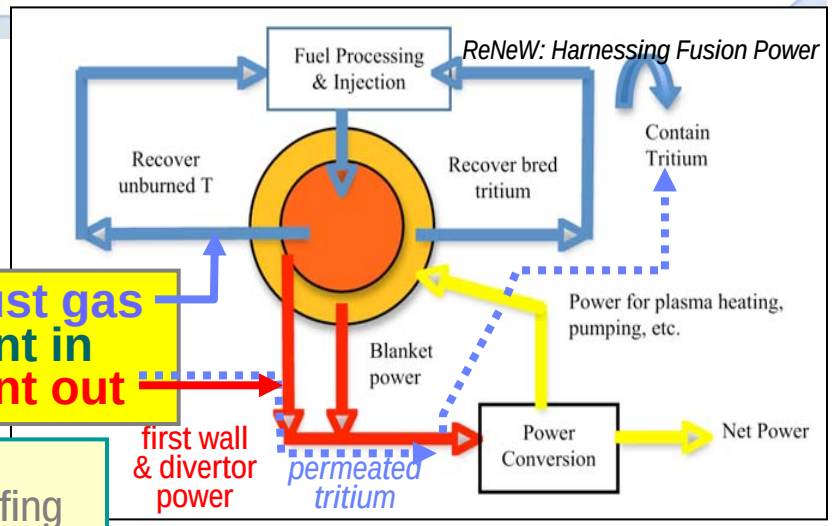
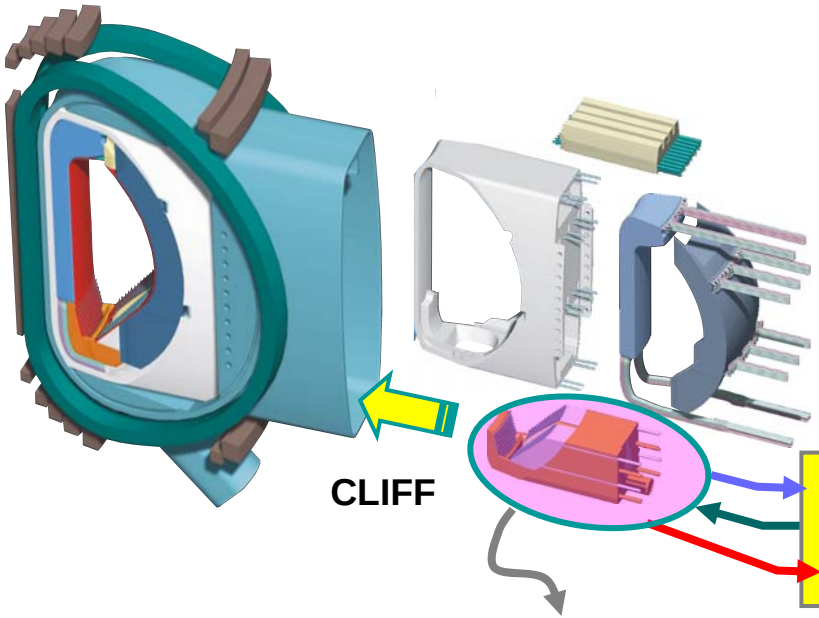
The Divertor - a complex heat removal system

To produce energy efficiently, we must use the (20%) power going to the divertor; so the **divertor must be integrated with heat removal from the first wall and blanket.**







exhaust gas
coolant in
coolant out

radiation shielding
sensors
vacuum boundary
leak monitoring

?gas puffing
seal welds
etc., etc.

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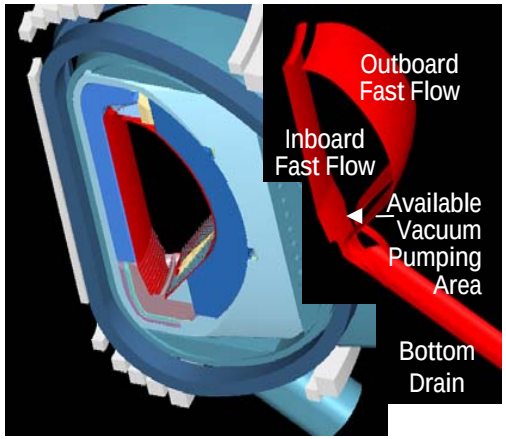
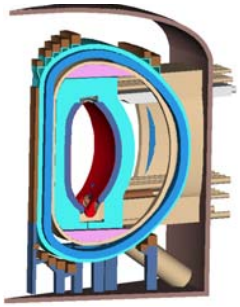
Concepts and Designs for Divertors

DEMO or Power Plant



CLIFF (above)
- Flowing FLiBe

EU PPCS
- Cases A-D

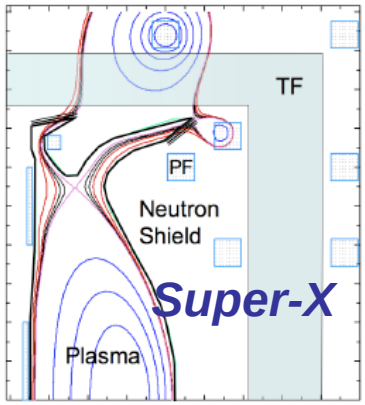


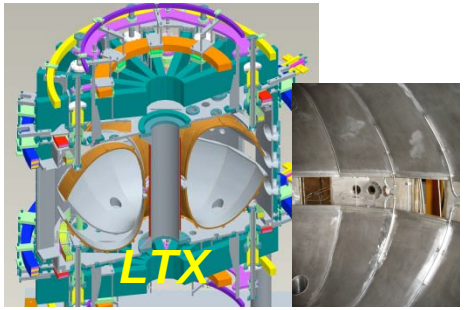
ARIES
- Advanced Tokamak
- Compact Stellerator

Large Stellerator (J), others

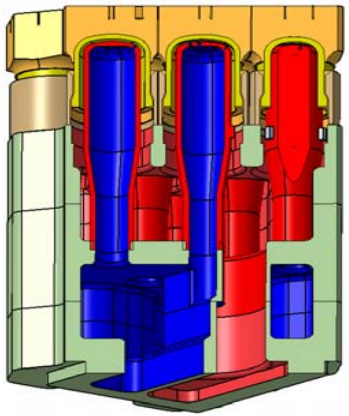
Review of Stellerator Design Issues Toward MFE DEMO, Sagara I03-A1, ISFNT9

Divertor Configuration





Technology for Heat & Particles



He-cooled W PFCs
- **T-Tube**
- **HEFM** (Norijitra+, FZK) ongoing hardware R&D

Liquid surfaces
- **Li limiter** (T-11M, FTU, CDXU/LTX)
- **Liquid Li divertor** (NSTX)

Initial Results ... LTX
Majeski I07-A2, ISFNT9

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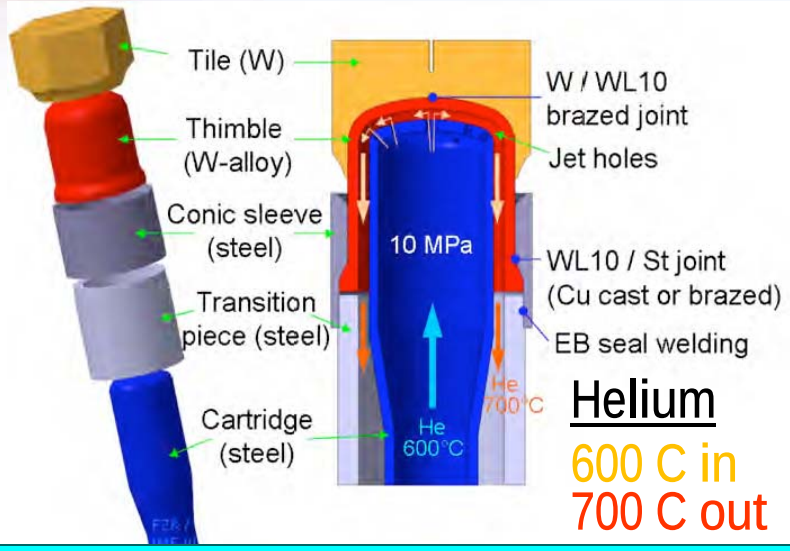
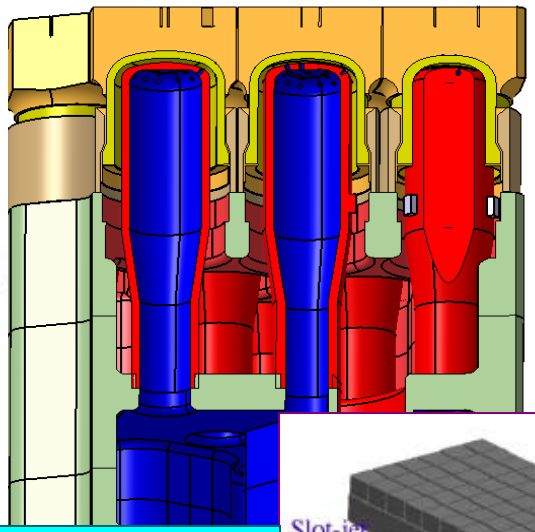
Fusion DEMO Options – He jet-cooled W

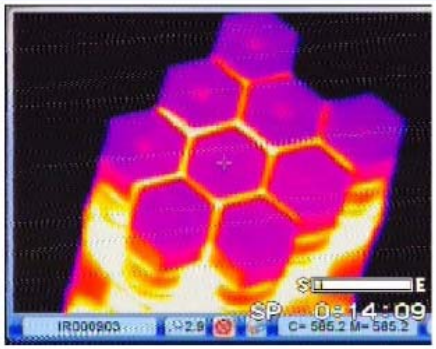


Helium

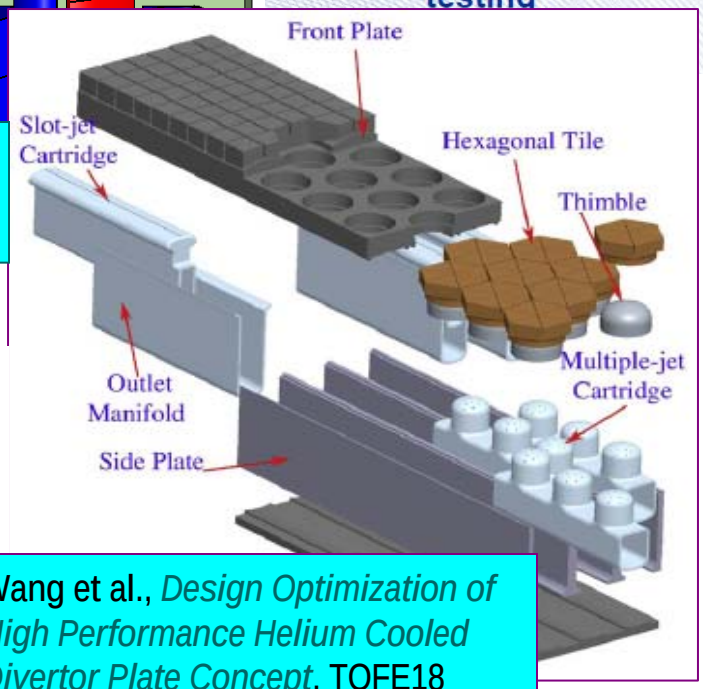
600 C in

700 C out





Infra-Red Image during testing

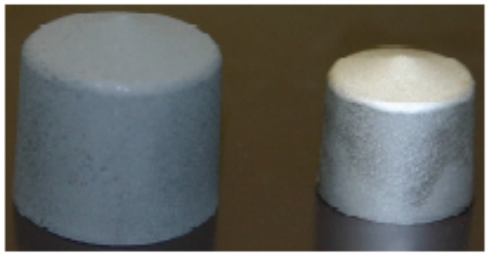


Helium-cooled Divertor for DEMO, Norijitra P03-029, ISFNT9

Norajitra et al., *Divertor conceptual designs for a fusion power plant*, FED 83 (7–9) (2008) 893–902.

Metal Injection Moulded Tungsten Components for Fusion Application

Jan Opschoor (Phillips Lighting), Jaan van der Laan (NGR Petten)

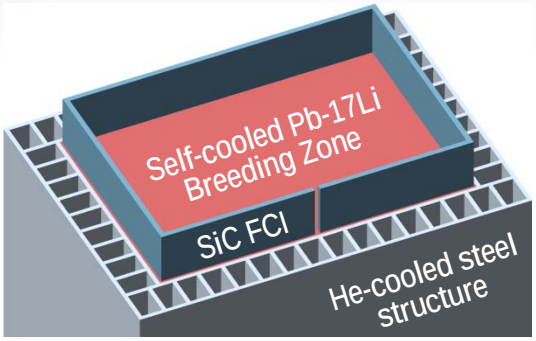


Green & as sintered thimble for HEMJ divertor design

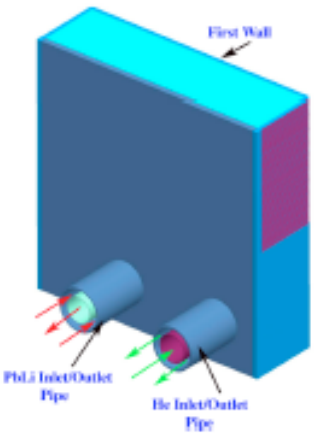
Wang et al., *Design Optimization of High Performance Helium Cooled Divertor Plate Concept*, TOFE18

More information: *Reith et al., … EFDA Programme on Tungsten Materials Technology and Science ICFRM-14*

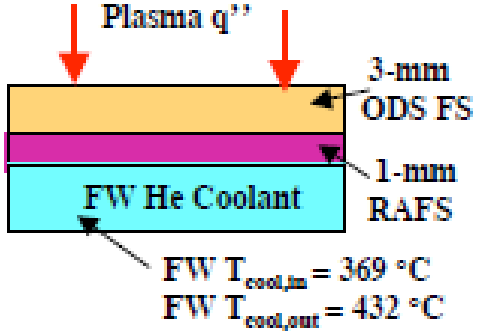
Typically a solid FW is part of the blanket.



LM Option - DCLL Typical Unit Cell with SiC flow channel insert

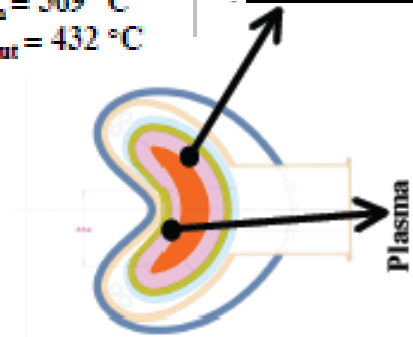


- 10 MPa He to cool FW toroidally and box
- Slow flowing (<10 cm/s) Pb-17Li in inner channels
- RAFS everywhere (T_{max}<550°C)
- Additional layer of ODS-FS on FW (T_{max}<700°C)

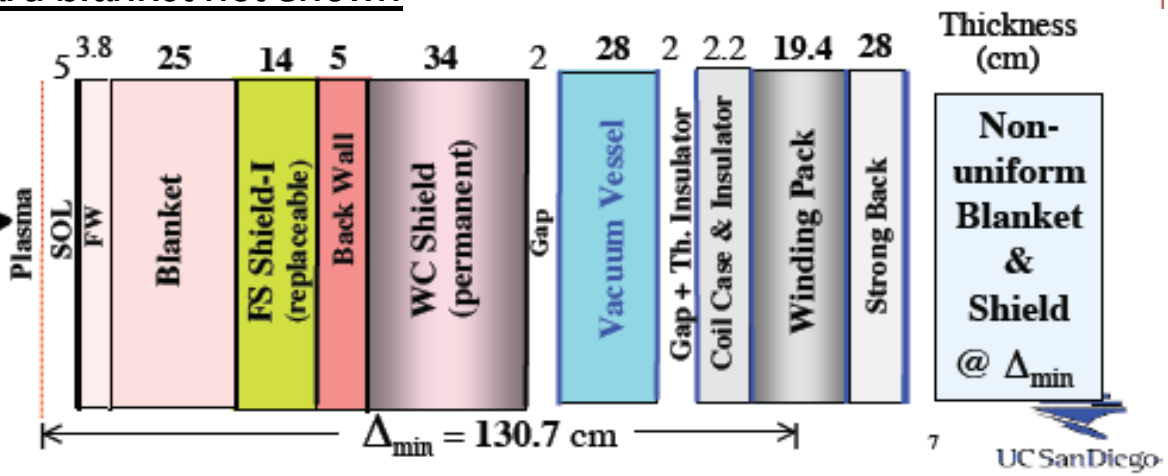


Optimization of DC Blanket Coupled to Brayton Cycle assuming a FS/Pb-17Li Compatibility Limit of 500°C

figures from ARIES-CS study.



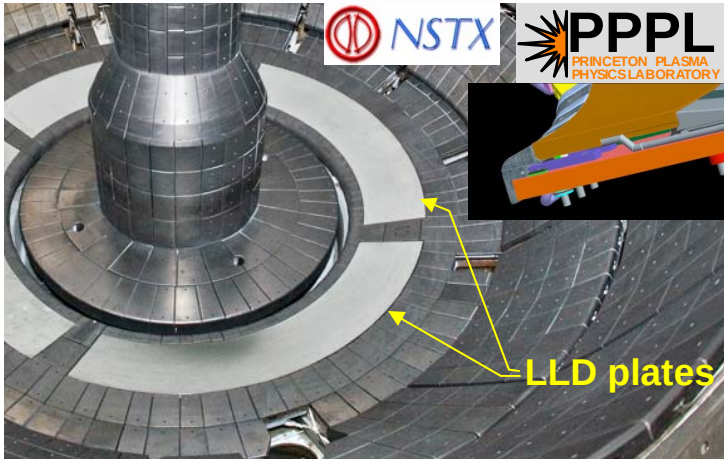
Outboard blanket not shown



Liquid Surfaces
Divertor/FW

Experiments in
T-11M, CDXU/LTX

Li limiter in FTU



Liquid surfaces

- **Li limiter** (T-11M, FTU, CDXU/LTX)
- **Liquid Li divertor** (NSTX)
  mostly tests for pumping

Other ideas proposed

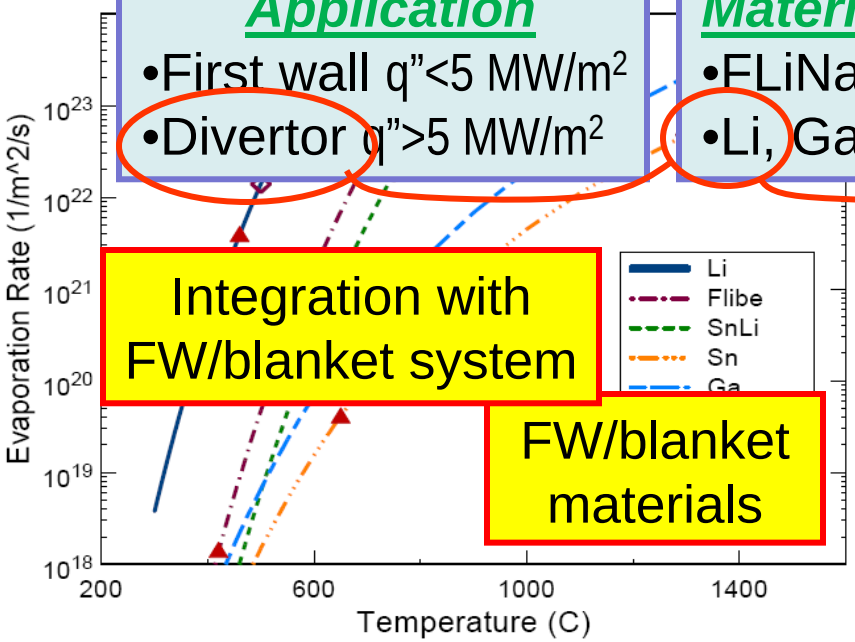
- **capillary-supplied Li**
- **flowing Li** (modified edge)
- **Sn, Ga, …**

Application
- First wall q"<5 MW/m^2
- Divertor q">5 MW/m^2

Material
- FLiNaBe
- Li, Ga

Function
- Cooling
- Pumping

Speed/cooling
- fast, self cooled
- slow, on heat sink



Integration with FW/blanket system

FW/blanket materials

heat sink
He-cooled
⇒ ***high P***
(?same for FW)
pumping
??control

$T_{Li\text{-}surface} - T_{coolant}$ too large
Excessive evaporation!

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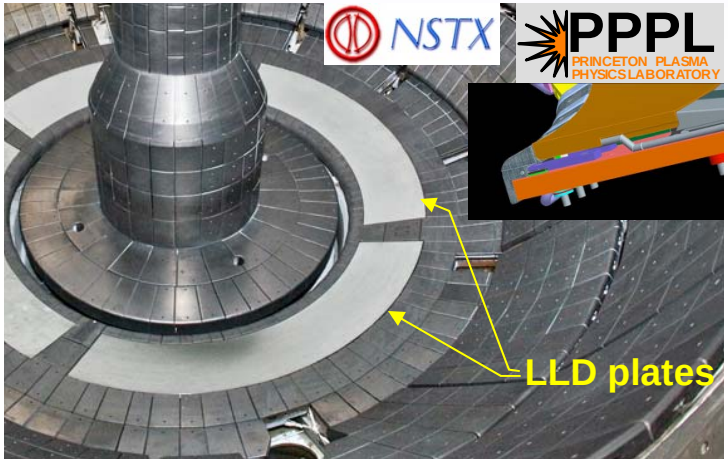
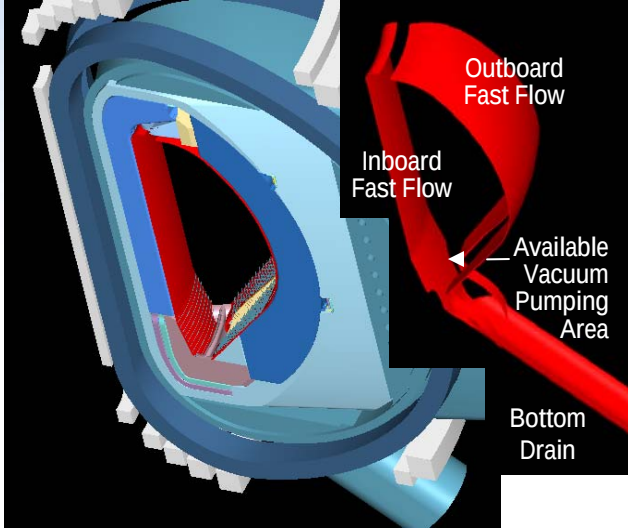
Liquid Surfaces
Divertor/FW

Experiments in
T-11M, CDXU/LTX

Li limiter in FTU





CLIFF (Flowing FLiBe)

APEX design study
Prof. Abdou, UCLA lead

Application	***Material***	***Function***	***Speed/cooling***
•First wall q"<5 MW/m^2	•FLiNaBe	•Cooling	•fast, self cooled
•Divertor q"<5 MW/m^2	•Li, Ga	•Pumping	•slow, on heat sink

Integration with FW/blanket system

FW/blanket materials

coolant system
LM MHD flows
pumping power
draining
corrosion
pumping *??Ga*
exhaust ducts

High speed flow difficult to achieve, predict and control

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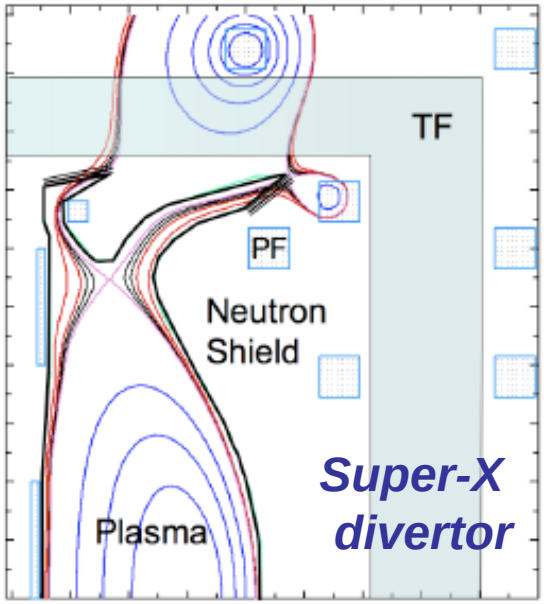
Some concerns for HHFCs

Richard's Rules

1. **Manageable heat loads based on**
   a) **reasonable physics, including startup, shutdown and plasma transients and**
   b) **sound engineering practices.**
2. **Credible integration of systems.**
3. **Recognition of <u>credible</u> development paths and recommendations on which must be taken.**



(for example, engineer's view of Super-X)

Idea is intriguing; need experiments, e.g., MAST.

Proof of physics will include information about how T_e and T_i decrease from X-point to divertor.
[Important for PSI effects along lengthy throat.]

What about requirements on plasma control, restoring position promptly, etc?

Will an adequate blanket fit with a super-X divertor?
[You do not know until you do detailed engineering.]

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Some critical concerns about requirements

divertor heat removal

Highly efficient energy conversion with a **Brayton cycle** and **He cooling** requires a **refractory structure** for the divertor,

OR .. another approach, such as a **liquid surface**,

AND compatible integration with the first wall and blanket.

first wall & blanket

A **solid first wall** and **blanket** typically have a common coolant and integrated structure.

Past DEMO designs with solid walls have a "**conforming FW**." But this approach failed for ITER.

- **Do FNSF & DEMO need shaped FW panels?**

Heat loads on some of the ITER FW increased drastically.

- **New DEMO designs must re-evaluate FW heat loads and determine which materials (e.g., ferritics) are adequate.**

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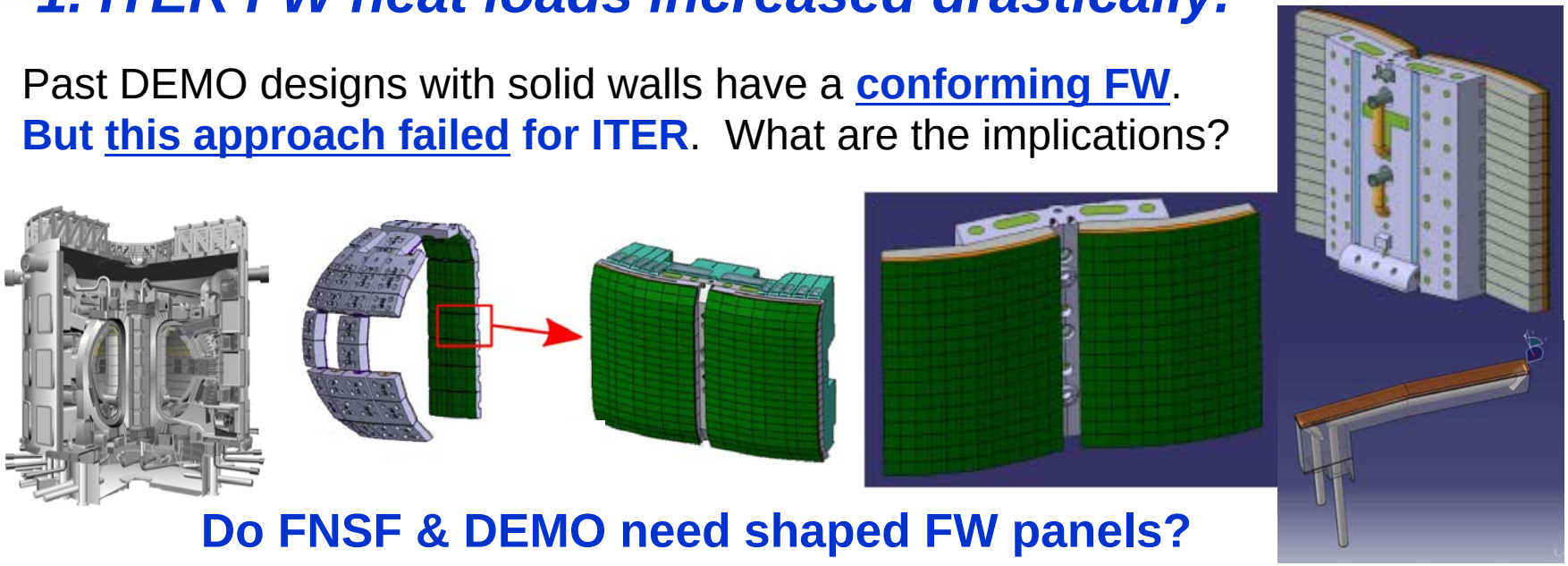
Conditions: Heat loads and plasma edge

1. ITER FW heat loads increased drastically.

Past DEMO designs with solid walls have a **conforming FW**.
But this approach failed for ITER. What are the implications?



Do FNSF & DEMO need shaped FW panels?

2. **"The uncertainties in the SOL have driven the ITER design to the edge of the possible."**

What is possible for FNST and DEMO?

ReNeW:
Taming the Plasma Interface
Theme 3 Ulrickson & Miangi

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Conditions: Heat loads and materials

1. How can we use ferritic alloys for structure?

ITER FW heat loads have increased drastically - 0.5 ('95) to 1.3 ('02) to **5MW/m²**.

The desire for permanent structure and concerns about cost, fabrication and compatibility have favored iron-based alloys, e.g., **advanced ferritics**.
But, iron-based alloys may not have **adequate thermal conductivity**.

$$T_{surface} = \frac{q'' t_{wall}}{k_{wall}} + \frac{q''' t_{wall}^2}{2k_{wall}} + (q'' + q''' t_{wall})h + T_{coolant}$$

Wall ΔT = **450C**

small

?20C film drop

500C (in FW)

$$\Delta T \cong \frac{30°C}{\frac{MW}{m^2} * mm}$$

t_{wall} = 3 mm
k_{wall} = 33 W/m-K*
q'' = 5 MW/m²
q''' = 6 MW/m³

2. Does tungsten work?

3. What are other choices?

*$k_{ave\text{-}F82H}$ is 33 W/m-K (20-700°C)
Thermophysical and Mechanical Properties of Fe-(8-9)%Cr Reduced Activation Steels – Zinkle, Robertson, Kleuh (ORNL)

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The importance of tungsten for fusion

1. We want our kids to see and use fusion plants.

2. Our DEMO divertor must be robust.

It will have terrible heat and mechanical loads,
plus ion and neutron damage,

and …

we are seriously proposing

what is today a brittle material.

Our visions for DEMO PFCs carry a huge implicit commitment to make tungsten work.

This will take a strong dedicated effort, as is beginning now in the EU but not elsewhere.

From Nygren et al., Making tungsten work, ICFRM14

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Conclusions and Comments

- **Interdisciplinary teams are essential in identifying and recommending the appropriate path(s) for developing HHFCs -- AND –**

  in defining the missions and requirements for FNSF/CTF and DEMO.
- **ITER is giving us some valuable lessons, e.g., issues with heat load and plasma edge.**
- **We must press hard to evaluate the real potential (and technical barriers) of how we can remove heat effectively from fusion plasmas. For example, should issues with tokamaks or tungsten force us to look harder at alternatives for DEMO?**

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Thank You