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Issues and Decisions (Trade-offs) for Plasma Facing Components

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Outline

Brief looks at the following:*

1. ITER, power, PFCs and our future
2. Power Handling and Linkage to Configuration

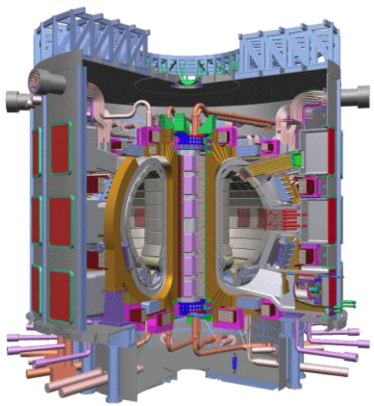
   -- High Level Decisions–
   - solid or liquid walls?
   - no disruptions, no tokamaks?
   - what is our "cost" for use of low-activation materials
3. Concepts and Some Issues for Refractory PFCs
4. Concepts and Some Issues for Liquid Walls
5. Final Comments

**Review important decisions, skip details about underlying issues. Many here know many of the issues.*

ITER - fusion's 1st large nuclear system

ITER integrates active-cooling, a D/T plasma and a W PFC.
We are learning a tremendous amount about PFCs and design integration.

One strong driver is our lack of knowledge in the physics of how power is exhausted at the edge of the plasma.



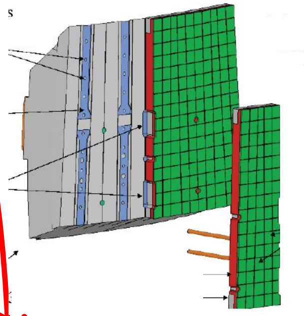
Mike Ulrickson *(Sandia)* is the technical leader of US design and R&D for the FWS and also is the ITER coordinator for the Blanket Integration Product Team

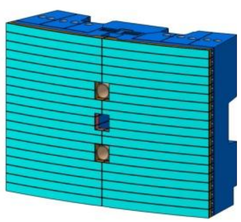
Big changes:

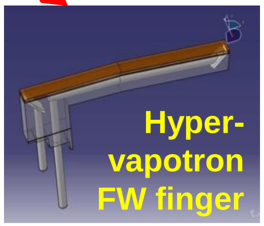
1. Plasma contacting FW
   ⇒ halo currents,
   Total redesign of FW

2. Disruption path
   ⇒ 10X higher transient heat loads
   Enhanced Heat Load Modules
   - hypervapotron cooling
   - strongly shaped FW panels

No vertical fingers

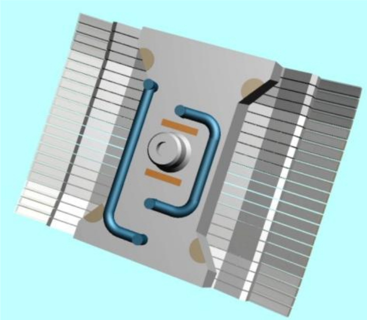


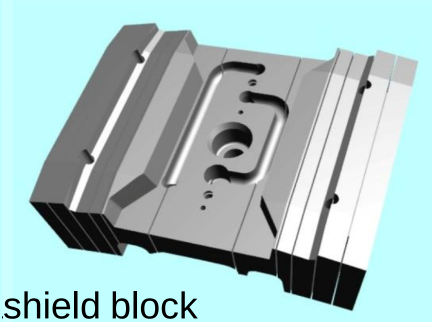




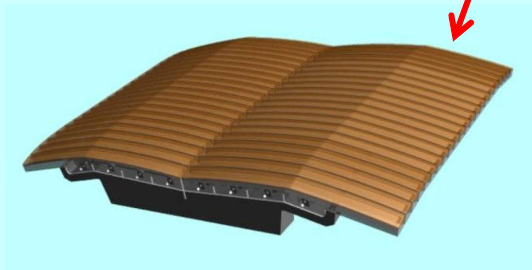
5 MW/m^2 peak

Current ITER design for typical FWS module





shield block



First wall panel for Enhanced Heat Load Module

PFCs, ITER, power and our future

To handle power from the plasma we need:

1. an approach to distribute the heat, e.g., radiating power from the edge, configurations that permit flux expansion in the divertor, etc.; and
2. heat loads that we can accommodate with realistic engineering solutions for the design, e.g. cooling, materials, fabrication, etc.

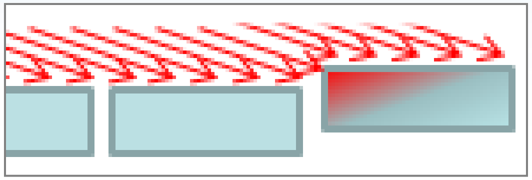
Our understanding of heat loads for future PFCs has improved, but the basis for predicting heat loads has big uncertainties.

- Peak heat loads for a given operating regime are proportional to the width (λ_q) of the zone at plasma edge, i.e. "near" SOL (scrape-off layer) that convects most of the power to the wall. But projections of λ_q and **how λ_q scales with power** are uncertain. [Maybe $\lambda_q \propto$ 1/power] *[Example for R&D at MIT; also R&D at GA and many other institutions]*
- Transients (ELMs, disruptions) set **maximum transient heat loads**.
- There is significant convected power **beyond the near SOL of the plasma** and **this power will reach the wall**. *[Examples, ITER.]*

How do we align PFCs?
-- and what are the implications --

Well known "Leading Edge Problem"

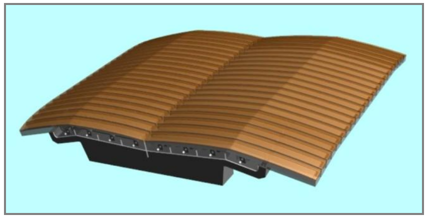
A protrusion (e.g., misaligned edge of a PFC) into the plasma edge will intercept a huge parallel heat flux.



ITER

FW joined to shield blocks suspended from VV, removed from front.

- *In this build-out, alignment of adjacent PFC surfaces on two sectors depends on the tolerance of these cantilevered structures and how they and the vessel are affected by heating cycles and EM transients.*



- *Mitteau analyzed the alignment needed for Enhanced Heat Load Modules. The plasma-wetted area on the strongly shaped EHLMs is ~50% of the frontal area, so the steady state heat load is increased by 2X.*

FNSF/DEMO

Integral FW-blanket units (breeding neutronics) removed from rear or top.

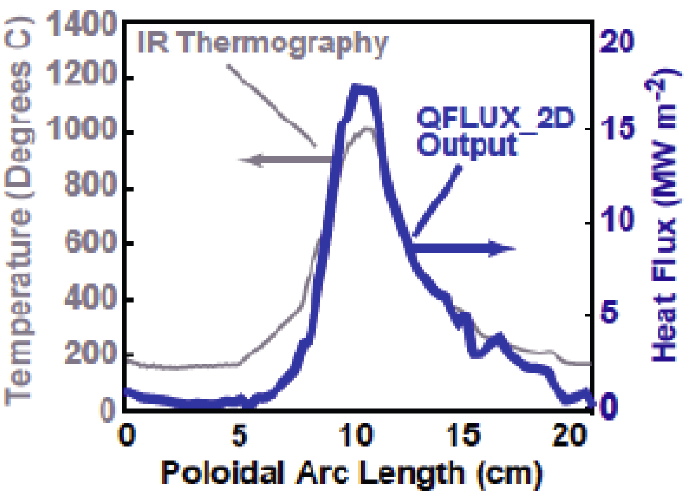
- *Uncertainties faced by ITER will be unacceptable in future (FNSF or DEMO).*
- *Build-out To Be Determined – but will be welded at port. What requirement do we face? We will have to know more about the plasma edge than we do now.*

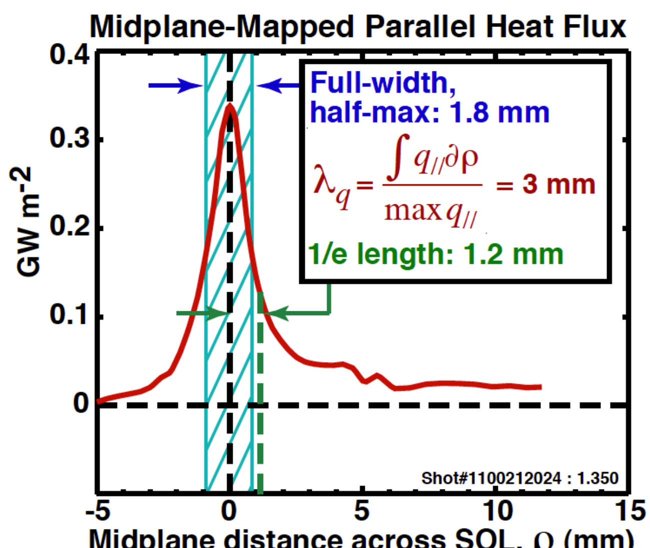
PFCs, ITER, power and our future

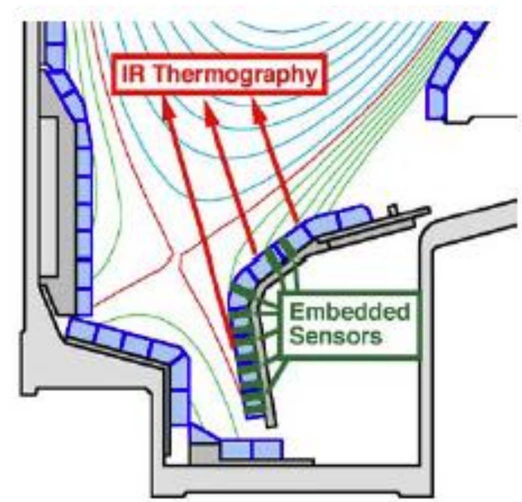
There is very limited understanding of λ_q despite this being critical in predicting wall heat fluxes.

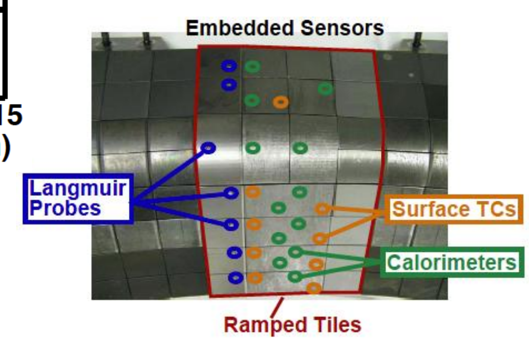
G.M. Wright, The Alcator C-Mod Team, The PSI Science Center Team
Plasma Science & Fusion Center, MIT, US PFC Meeting, ORNL, Aug 2010

MIT is using new diagnostics in C-Mod to investigate heat loads.









[Kirnev, *et al.*, PPCF 49 (2007) 689]

$$\lambda_q \propto P_{SOL}^{-0.5} B_\phi^{-1} q_{95} n_{e,u}^{0.25} R^2$$

Prediction: Integral λ_q ~ 0.7 mm

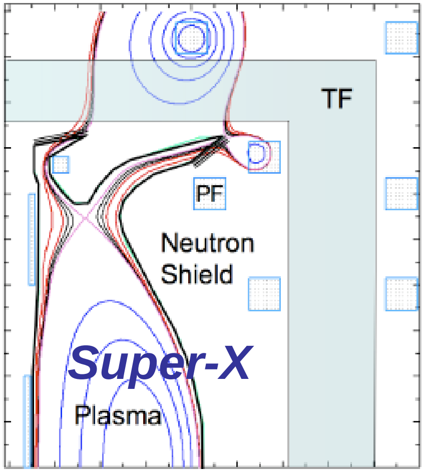
[Loarte, *et al.*, JNM 266-269 (1999) 587]

$$\lambda_q \propto P_{div}^{0.44} B_\phi^{-0.45} q_{95}^{0.57}$$

Prediction: Integral λ_q ~ 5 mm

What are our innovative ideas for design?

Divertor Configuration



physics missions that need new technology

Liquid surfaces

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

DEMO or Power Plant

ARIES

- Compact Stellerator
- Advanced Tokamak

EU Power Plant Studies

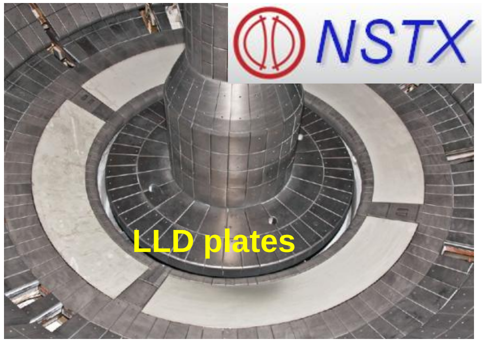
- Cases A-D

Large Stellerator

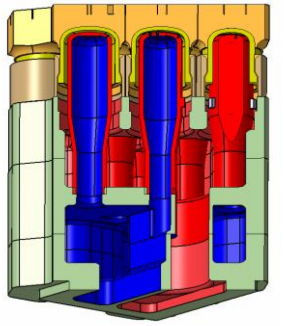
- Japan, EU

CLIFF

- Flowing FLiBe



Technology for Heat & Particles



He-cooled W PFCs

- T-Tube
- HEFM (Norijitra+, FZK) ongoing hardware R&D
- ARIES optimizations

Moving liquid surfaces

- EM-driven
- EM & thermo-electric
- Capillary systems

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1. PFCs, ITER, power and our future
2. **Power Handling and Linkage to Configuration**

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   - **no disruptions, no tokamaks?**
   - **what is our "cost" for use of low-activation materials?**
3. Concepts and Some Issues for Refractory PFCs
4. Concepts and Some Issues for Liquid Walls
5. Final Comments

Power Handling and Configuration

-- Some High Level Decisions --

solid or liquid walls?

- **Each system has tremendous challenges to resolve. Less is understood about how to integrate liquid surface systems.**
- **No designs yet based on a new view of the plasma edge.**
- **Need better understanding of physics in plasma edge.**
- **We need "push back" from fusion technology experts to specify what is acceptable to manage power reliably for a DEMO or FNSF.**
- **We are investigating tungsten-based PFCs even as we recognize the challenges such as improving ductility and understanding the evolution of microstructure in a DEMO.**
- **Liquid PFCs have issues regarding the control of the free surfaces and successfully integrating such systems, and our knowledge base is quite limited.**
- **There is interest in both the beneficial effects of lithium at the edge of the plasma, and for liquid walls as the "default path" for development in parallel with solid walls.**

Power Handling and Configuration

-- Some High Level Decisions --

Disruptions and large ELMs?

- **Decision to build [FNSF or a DEMO] with goal of reliable, repeatable operation and high availability has earlier needs**
  - *demonstrated solution for mitigating disruptions* ***yes/no***
  - *demonstrated solution for excluding large ELMS* ***yes/no***

Tokamak Path:	**YES/YES**	**⇒ OK for these criteria**
	YES/NO	**⇒ another path**
	NO/YES	**⇒ another path**

- **No designs yet based on a new view of the plasma edge.**
- **Need better understanding of physics in plasma edge.**
- **We need "push back" from fusion technology experts to specify what is acceptable to manage power reliably for a DEMO or FNSF.**
- **"Default path" of liquid surfaces for development in parallel with solid walls.**

Power Handling and Configuration

-- Some High Level Decisions --

Low activation materials?

- **Fusion has promised an attractive plant with materials that can be recycled.**
- **Low activation is an important part of the public perception of fusion and of the attractiveness of fusion to the power industry and governments.**

Hypothesis: ***Some compromise away low activation materials would reduce the resources and time needed to develop materials.***

Can/should we consider such a trade-off? If so, then …

- What are the "costs" in terms of attractiveness to public, industry and governments?

- What are the benefits in an accelerated schedule and less investment for R&D?

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3. **Concepts and Some Issues for Refractory PFCs**

4. Concepts and Some Issues for Liquid Walls

5. Final Comments

Solid Walls - refractory + ferritic?

- **Solid walls + high-temperature coolant $\Rightarrow$ refractory materials**
  (for goal of high-efficiency in generation of electricity)
- **Divertors** in most recent US and EU design studies for DEMOs or power plants utilize **W armor and He-cooled W-alloy heat sinks**.
- W-based metals are attractive if we develop materials to operate in a **reasonable temperature range** and **severe conditions**. (irradiation, etc.)
- Possible **approaches:**
  1. ***Limit W parts (e.g. armor tiles or coatings or graded materials).***
  2. ***Limit loading conditions to permit robust performance of these parts.***
  3. ***Use armor or coatings supported on robust ductile materials.***
- A **W-armored FW** would have lower heat loads than a divertor but is also **integral with the blanket**. Two main issues:
  1. ***What is the underlying structure, e.g. an advanced ferritic alloy? (NO)***
  2. ***What type of plasma facing material for a FW is appropriate? Pure W only? Can coatings and graded structures be considered?***

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Conditions: Heat loads and materials

1. *Does tungsten work?*

2. *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**.

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

small | ?20C film drop | 500C (in FW)

q" = 5 MW/m²

Wall ΔT = 450C

t_{wall} = 3 mm, ***k_{wall}*** *= 33 W/m-K,* ***q'''*** *= 6 MW/m³* $\Rightarrow$ $\Delta T \cong \frac{30°C}{mm * MW / m^2}$

***$k_{ave\text{-}F82H}$ is 33 W/m-K (20-700°C)**

Thermophysical and Mechanical Properties of Fe-(8-9)%Cr Reduced Activation Steels, Zinkle, Robertson, Kleuh (ORNL)

3. *What are other choices?*

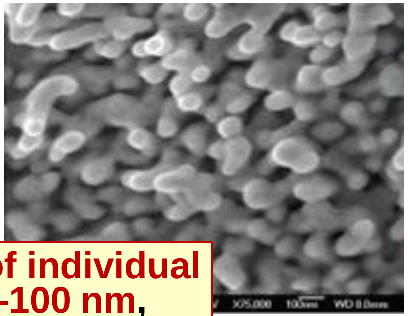
$\Rightarrow$ **liquid walls, other confinement schemes**

Materials Issues for W PFCs

Data for
- **Alloy selection**
- **Safety analyses,** ***credible accidents, "off normal" events (strong drivers)***

What improvements can we deliver?

- Lower DBTT
- Better machineability
- Mitigation of some neutron & ion damage
  - PSI (including evolution of microstructure), oxidation, dust…
- *Reduced cost*
- *Weight*



W tendrils from probe in C_MOD

Thickness of individual tendril is 50-100 nm, which is thicker than tendrils grown in linear devices (20-30 nm).

What are intrinsic limitations?

- Defects frozen in cascades "black spots"
- **Cracking**
  - *base material*
  - *evolving structure*
  - *melt layer*
- ?Other

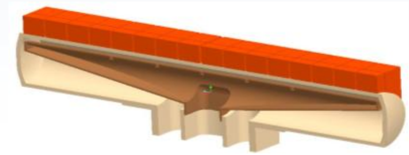
manageable → **YES - operate**

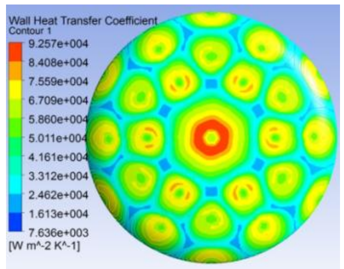
manageable → **NO – replace/repair**

Recent Work in ARIES

Pushing limits with design improvements

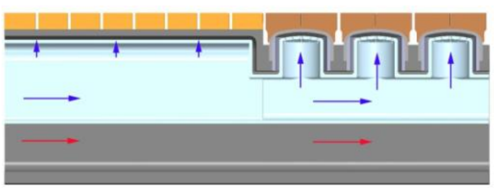
1. Tapered T-tube divertor
2. Modified divertor finger
3. W-pin first wall concept
4. Heat transfer enhancement with jets + fins
5. External transition joints
6. Fingers-in-plate design
7. External transition joints

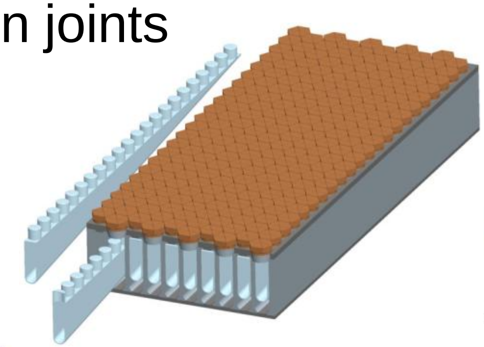


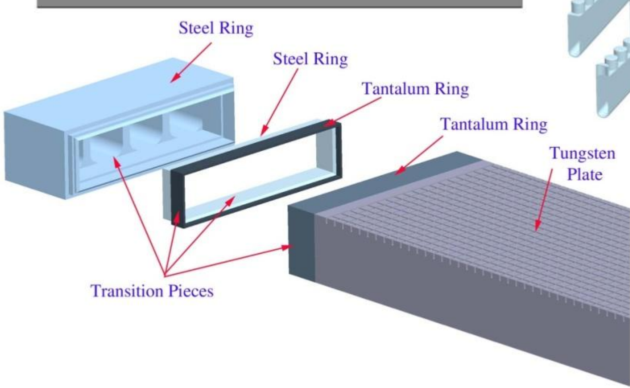


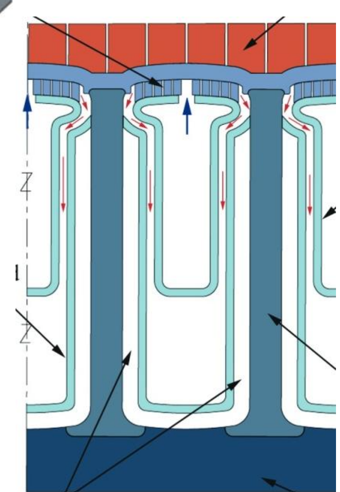
8. 3D elastic-plastic analysis with thermal stress relaxation (*yield*)
9. Application of accumulated strain limit
10. **Birth-to-death** modeling
    Fabrication steps, operating scenarios, off-normal events

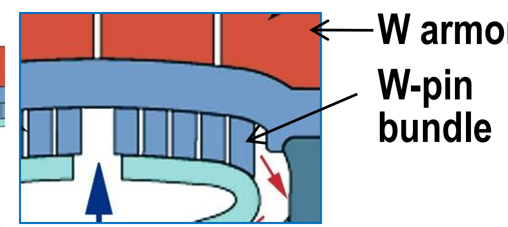
__Future work__: Thermal and irradiation creep, crack growth and low-cycle fatigue, irradiation damage effects











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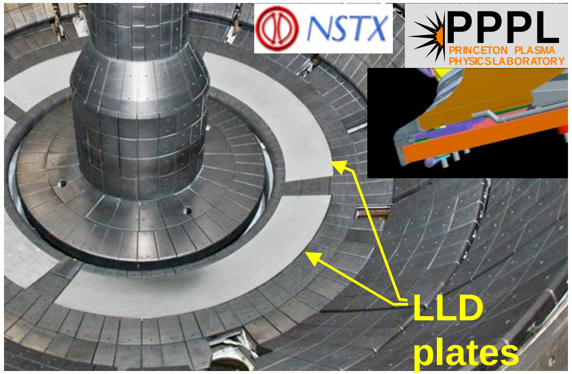
Liquid Surfaces

Divertor/FW

Experiments in
T-11M, CDXU/LTX

Li limiter in FTU



Liquid surfaces (for pumping)

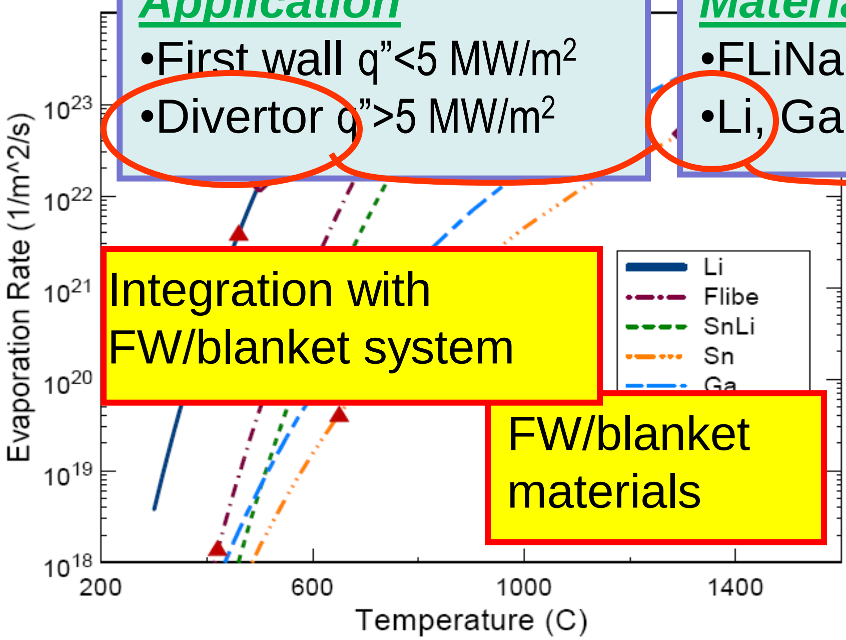
- **Li limiter (T-11M, FTU, CDXU/LTX)**
- **Liquid Li divertor (NSTX)**

Other ideas proposed

- **EM and TE driven flows capillary-supplied Li**
- **flowing Li (modified edge)**
- **Sn, Ga, …**

We can look at the systems quickly with the "decision boxes" below.

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

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

This set of choices gives ..

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

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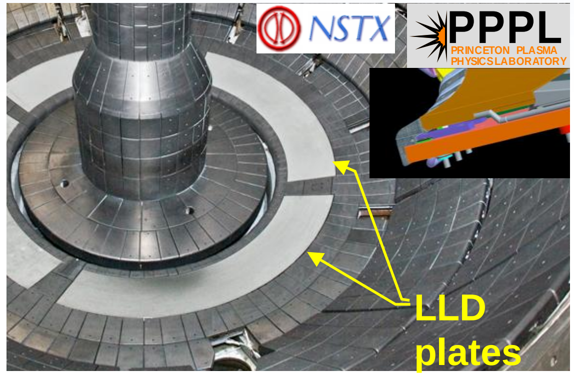
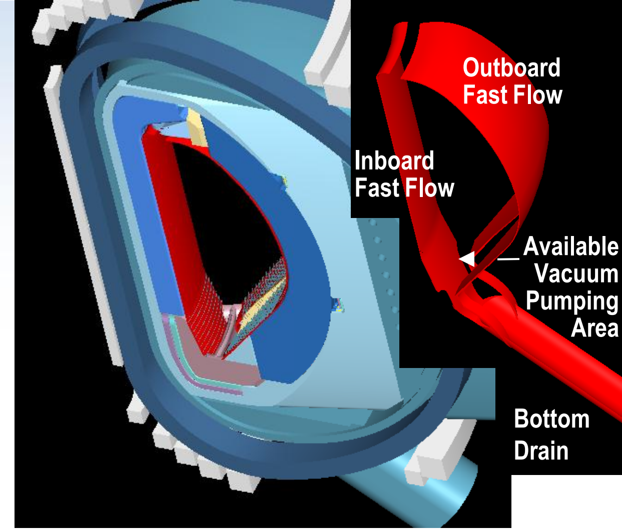
Liquid Surfaces
Divertor/FW

Experiments in
T-11M, CDXU/LTX

Li limiter in FTU





CLIFF (Flowing FLiBe)
APEX study, Prof. Abdou, UCLA lead

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Integration with FW/blanket system

FW/blanket materials

<u>coolant system</u>
LM MHD flows
pumping power
draining
corrosion
<u>pumping</u> *??Ga*
exhaust ducts

This set of choices gives ..

High speed flow difficult to achieve, predict and control

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5. **Final Comments: example of integration in R&D on PFCs**

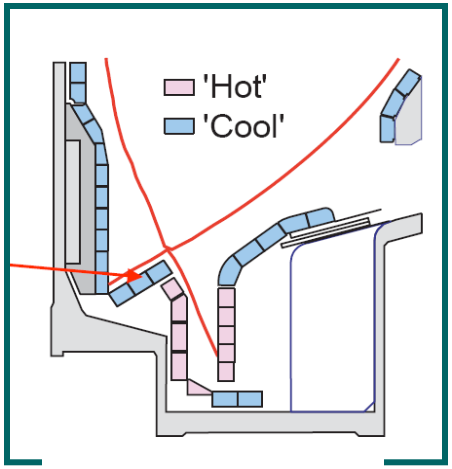
Example of R&D Step: Hot Wall Experiment

-- large area of hot PFCs --

gas-heated refractory heat sinks, tungsten armor

(control of wall temperature separate from power, no electrical heaters)

What are the commitments?.



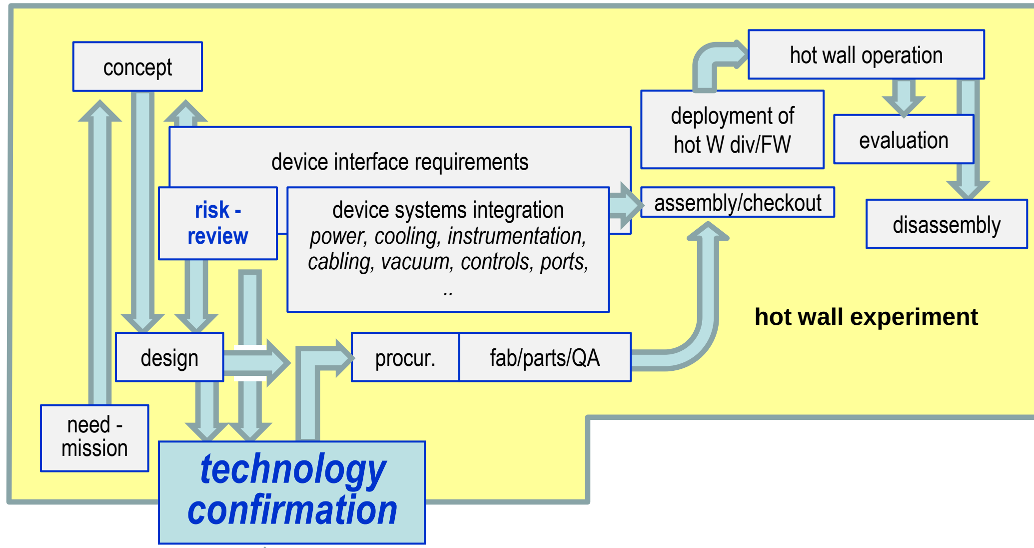
C-MOD hot tiles

Many/diverse experts

Significant hardware

Many years

earlier experiments and R&D

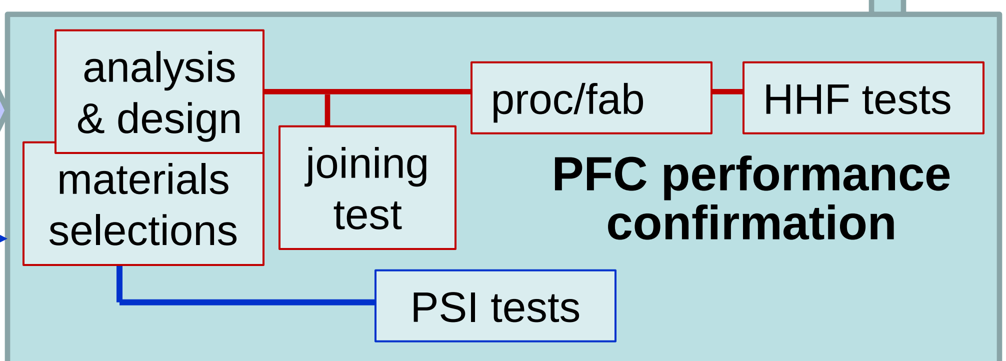


?2-5 years

?2-3 years

Mat. Dev.

?2-5 y



?2-5 years

How do we define the basic elements of our pathway and their sequence?

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Thank you