SAND2011-0600P

FNS Pathways Core Group
UCLA -- Jan. 24-25, 2011

Plasma Facing Components

- Divertors
- First Wall
- In-vessel Components
  - *- RF launchers, armor*
  - *- RF mirrrors*
  - *- large probes (mat'ls, calorimetry, ..)*

Presented by Dennis Youchison (Sandia)

prepared by Richard Nygren (Sandia)
based on past input from many people

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.

Plasma Facing Components (FNS Pathway)

Outline

1. **Status of US PFC program**
2. **Views of gaps and issues**
3. **Importance of sequence in the FNS Pathway**
4. **Brief overviews:**
   - liquid surface PFCs
   - modeling
5. **Example of R&D program for W PFCs**
   - nature of the "bits" or elements in the FNS Pathway

Main theme today:

What kinds of elements and sequences will we use to construct our pathway?

3. Importance of sequence in the FNS Pathway

5. Example of R&D program for W PFCs
(elements in the FNS Pathway)

Historical Perspective on PFC/PMI Development

1980 — 1990 — 2000 — 2010

limiters
isolated core
radiation loss
sputtering

more power in plasma
conditioned/coated wall
erosion-consequence
[CX neutrals, Maxwellian tail]

diverted plasmas
[more core isolation]
[radiative, detached div.]
importance of plasma edge

large D/T devices
- *exhausted power*
- *stored energy*

?FNSF/DEMO div.

DT Mat'l Physics Group
tritium in TFTR

PFC Facilities Review

limiters → divertors → active cooling
power → impurities

prominence of ITER
tritium retention

- **some issues, C**
- **JET uses Be**
- **PFC options for ITER**

- **Hot walls**
- **Shaped FW**
- **?super-X**

PISCES --------- **PISCES** --
(Conn/Goebel, UCLA) (Doerner, UCSD) Be upgrade

TPX (Causey)--- **TPE** ---------------------- **STAR** -----------------
SNL (tritium PISCES) @ LANL @ INL

Codep (Hsu)
Conditioning (Wilson)
[LAMPE/Penning, STOX]

DiMES (DIII-D) --
SSS (C-MOD)

lab PSI probes ---
SNL, ANL ANL → Purdue, UofI, DIONYSIS (MIT)

ESURF **PMTF** ---
FELIX (EM)

Upgraded & new capabilities

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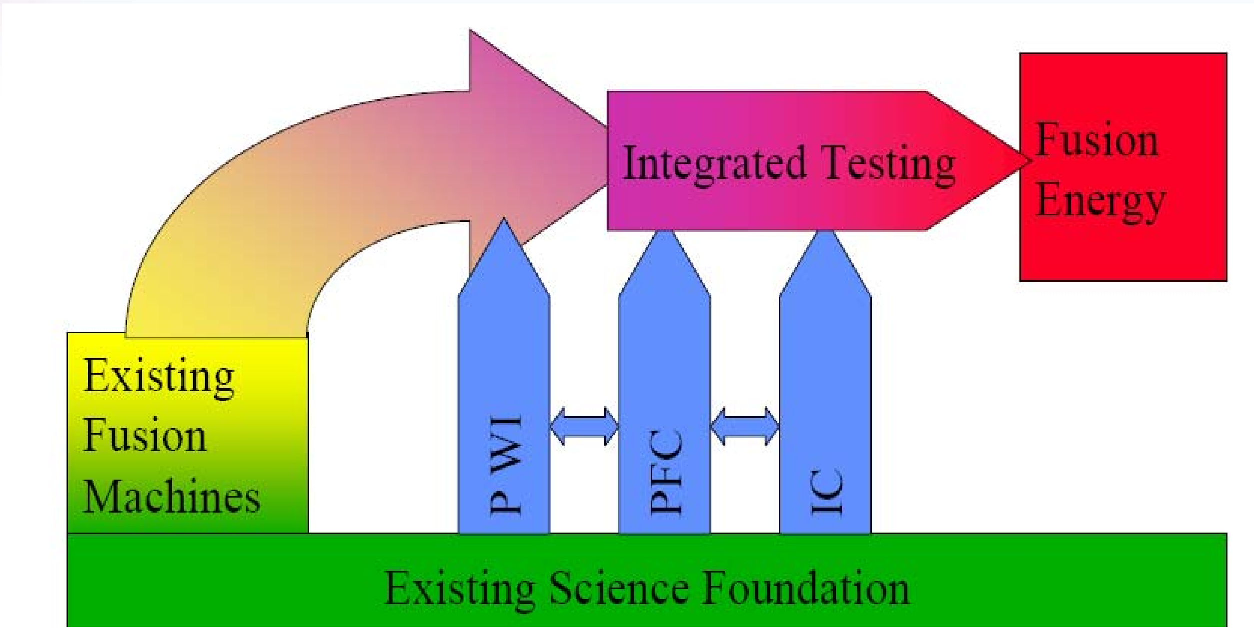
PFC-PSI Development & Integration

PFC program elements



Upper portion of figure by Ulrickson from ReNeW

Program elements added by Nygren

Modeling edge-PFC-materials

Probes & Tiles plasma edge

Lab Experiments *PSI studies*

PFCs Operating *physics*

PFC Development HHF tests

Materials Development properties, fab

Modeling Components PFCs, etc

Modeling Integration DEMO, reactor

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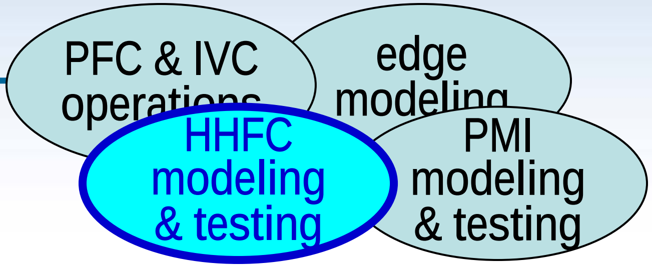
Status of HHFC Program

Excluding PMI and edge programs



#1 Support ITER PFC design & R&D and develop component fabrication processes, QA, and operation.

excellent relations with IPO, IP, DAs;
US R&D & testing** (for all DAs) **ongoing;
US role in design expanding; valuable insight into design/machine interfaces

<u>gap</u>: test capabilities (old & frail);
design integration & interfaces;
participation in divertor R&D

2. Support physics missions of existing, upgraded and new US confinement experiments.

needs but limited R&D, some testing for C-MOD and DIII-D
(NSTX Liquid Li divertor and DiMES are really PMI)

<u>gap</u>: program organization;
integration with machines;
test capabilities (He, probes, disruption simulation)

3. Develop and prove robust PFCs for future confinement devices.

limited but sustained work on He cooled W and on liquid surfaces

gap: expanded test capabilities; stronger integrated modeling;
test capabilities (He, liq. met.)

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"Greenwald" Panel Report

Recommendation 4. .... nine major initiatives.

I-1. .. predictive plasma modeling and validation ..,

I-2. Extensions to ITER AT capabilities .. burning AT regimes

I-3. Integrated advanced burning physics …facility .. dedicated

I-5. .. disruption-free concepts .. performance extension device ..

I-4. Integrated experiment for PWI/PFCs .. steady-state .. non-DT

I-6. .. advanced computer modeling and laboratory testing .. single-effects science for major fusion technology issues,

I-8. Component development/testing program … multi-effect issues in critical technology .. breeding/blanket .. first wall

I-7 Materials qualification facility … (IFMIF).

I-9. Component qualification facility.. high availability.. heat flux .. neutron fluence .. DT device .... (CTF).

FNSTF Core Group Homework: **List of Generic FNST R&D**

Richard Nygren and Stan Milora 8 sep 2010

Refs:
1. Presentation by Rajesh Maingi at PMI Test Stand Workshop, ORNL, Aug 30 – Sep 2, 2010
2. Draft "Generic FNST R&D – VLT, August 2010" (developed by R. Maingi and M. Peng, Aug 2010)
3. Draft "ReNeW: Technology Content, Thrusts 1-18" (developed by R. Nygren, 4 june 2009

All thrusts target elements in PWI, PFC, and IC

9. Unfolding the physics on the boundary layer plasma
   – SOL, divertor, private flux, pedestal; innovative divertors
   – Develop predictive capability, new diagnostics

10. Decode and advance the science and technology of plasma surface interactions
   – Well-controlled and well-diagnosed dedicated facilities

11. Improved power handling through engineering innovations
   – New solid and liquid concepts; innovative heat sinks

Input developed in fall for FNS Pathways

12. Demonstrate an integrated solution for plasma-material interfaces compatible with an optimized core plasma
   – Integrated test of PFC and IC components + PMI modeling
   – Low activation environment with improved diagnostics

13. ~ "Fusion nuclear science" (paraphrased)

14. ~ "Materials science" (paraphrased)

Several "lists" of R&D topics for FNST have been developed and distributed to a limited group. To start the FNSF Core Group, this list was developed from the references above. The flow follows that of an excellent presentation (Ref. 1) with pages 4, 6, 8, 9 and 11 from Ref. 2 added to give more specifics. Some final comments (p13) are also added based on Ref. 3.

From FNSP Summary of ReNeW Themes 9-14

Nygren, Milora, Peng

T9: Unfolding the physics on the boundary layer plasma

- **Develop and deploy new diagnostics in existing devices for** comprehensive bound... ...lasma flow, density, temperature, ...acteristics, and neutral density in at le... ...ropriate, in 3 ... ...ver the controlling

T11: Improved power handling through engineering innovations

- **Design, fabricate and test refractory heat sinks with advanced cooling** techniques for high temperature operation (>600C) and deploy liquid metal PFC experiments in plasma devices
- **Develop fabrication processes and better joining techniques** using reduced activation refractory alloys for both PFCs and internal components, e.g. RF launchers
- **Construct/upgrade new lab facilities for synergistic testing including** cyclic high-heat-flux, irradiation/permeation, and liquid metal performance; and improve models of thermal performance, irradiation damage and tritium transport in PFCs
- **Provide improved PFCs for qualification on existing or new confinement** experiments
- **Develop more robust PFCs for transient events with higher design** margins and improved reliability and maintainability. Include engineering diagnostics to monitor PFC performance and provide data for lifetime prediction models.

T10: Decode and advance th... science and technology of plasma surface interactions (in well-diagnosed dedicated facilities)

- **Upgrade existing laboratory facilities capable of extend...** parameters closer to conditio... the capability to handle tritiu... *(first principles models for Th...*
- **Build large-size test stands... tests** and design validations
- **Develop and improve first p...** plasma coupling for future fu... experimental data
- Invest in **surface material di...** and evolution
- Develop and test **new surfac... materials to improve performance** margins *(connect to Thrust 14)*

Input developed in fall for FNS Pathways

From FNSP Summary of ReNeW Themes 9-14

Nygren, Milora, Peng

T14: Materials Science and Technology Needed to Harness Fusion Power

- Improve the performance of existing and near-term materials, while also developing the next gene[…]rials with revolutionary properties.

[…] resistance to cracking.

[…]ength.

T13: Establish the Science and Technology for Fusion Power Extraction and Tritium Sustainability

[…]rm **fundamental research to establish the scientific parameters** [nec]**essary to** address the issues. An example activity is the exploration of [...]m chemistry, heat transfer, and magnetic field interactions in lithium-[...]ing liquid metal coolants.

[…] **combined impact of** […] typical of a fusion […] burning plasma as a test […]xtraction experiments […] designs, and operating

[…]omplete effect of fusion […]**uld be construction** […] **(FNSF) to perform** […] from the effects of […]me in concert with all

[…]**odels necessary to** […] collect reliability and

T12: Demonstrate an integrated solution for plasma-material interfaces compatible with an optimized core plasma

- **Develop design options for a new moderate-scale facility with a DEMO relevant** boundary, to assess core-edge interaction issues and solutions. Key desired features include **high power density, sufficient pulse length and duty cycle, elevated wall temperature, as well as steady-state control of an optimized core plasma. Design for a hydrogen and deuterium fuel** environment, to assure flexibility in changing boundary components as well as access for comprehensive measurements to fully characterize the boundary plasma and plasma-facing surfaces. The balance and sequencing of hydrogen and deuterium operation should be part of the design optimization. **Develop an accurate cost and schedule for this facility, and construct it.**
- Extend and validate transient heat flux control from Thrust 2, plasma control and sustainment from Thrust 5, boundary plasma models from Thrust 9, plasma-material interaction science from Thrust 10 and plasma-facing component technology from Thrust 11 with the new research from this facility, thereby demonstrating a viable solution to the very challenging core edge integration problem for DEMO.

Input developed in fall for FNS Pathways

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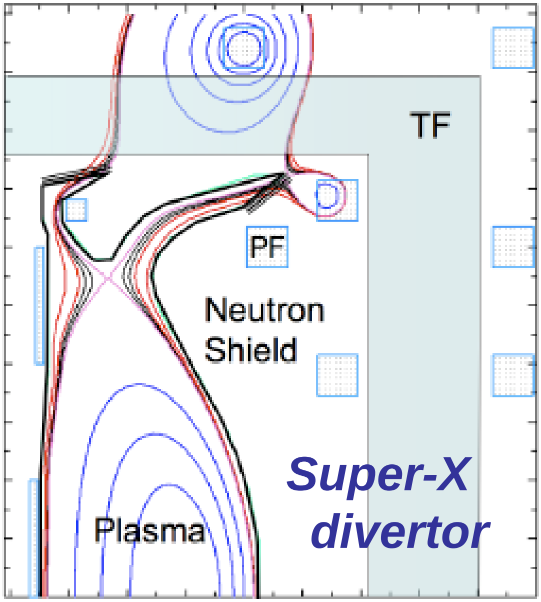
Some concerns for HHFCs

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 path 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.]

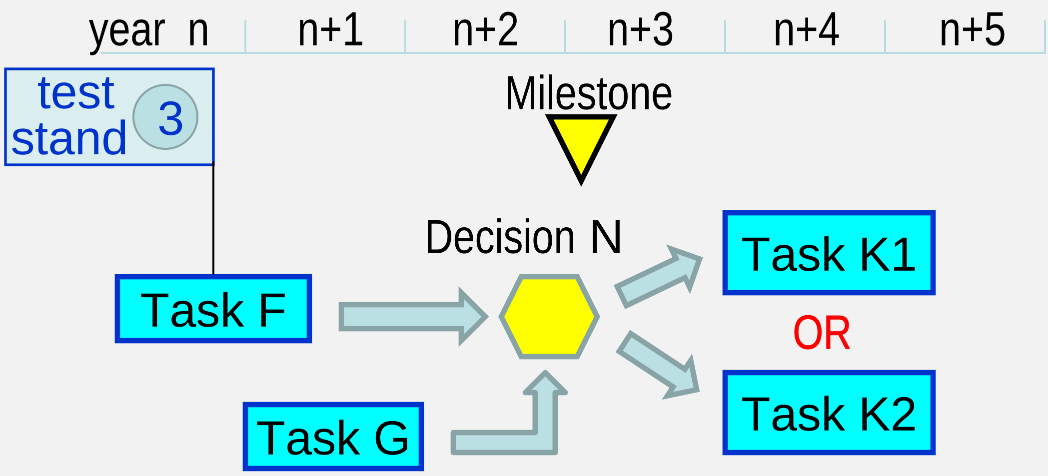
We want to address the high level gaps and issues with some suite of options for tasks, sequences and required facilities.

At what level of detail should we be working now?

What supporting detail is needed in the future to confirm the credibility of the pathway analysis?

Main point:

What kinds of elements and sequences will we use to construct our pathway?



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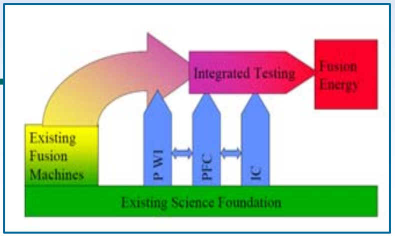
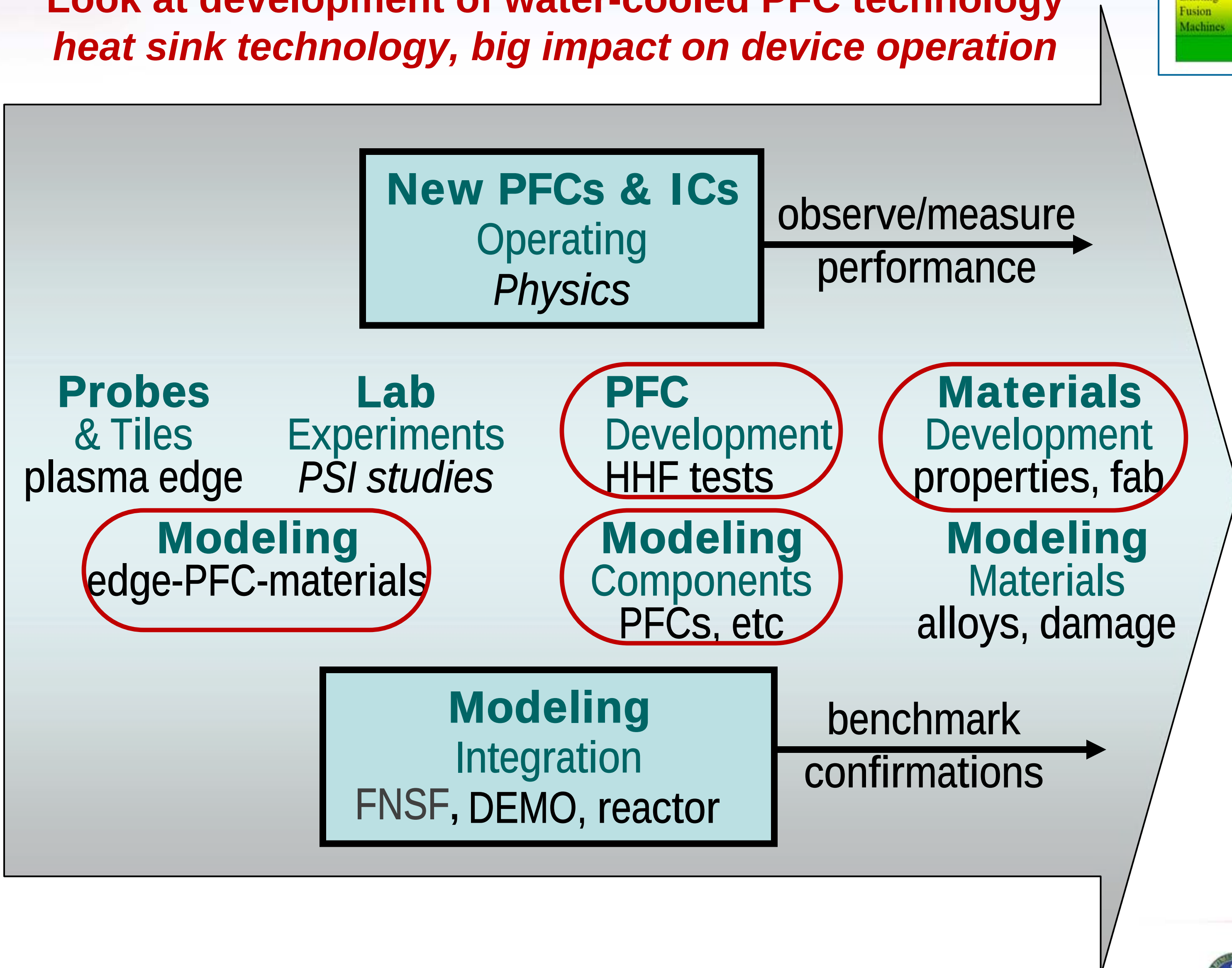
PFC-PSI Development & Integration



Look at development of water-cooled PFC technology
heat sink technology, big impact on device operation



FUSION

ENERGY

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Tore Supra *CIEL configuration* (since2002)

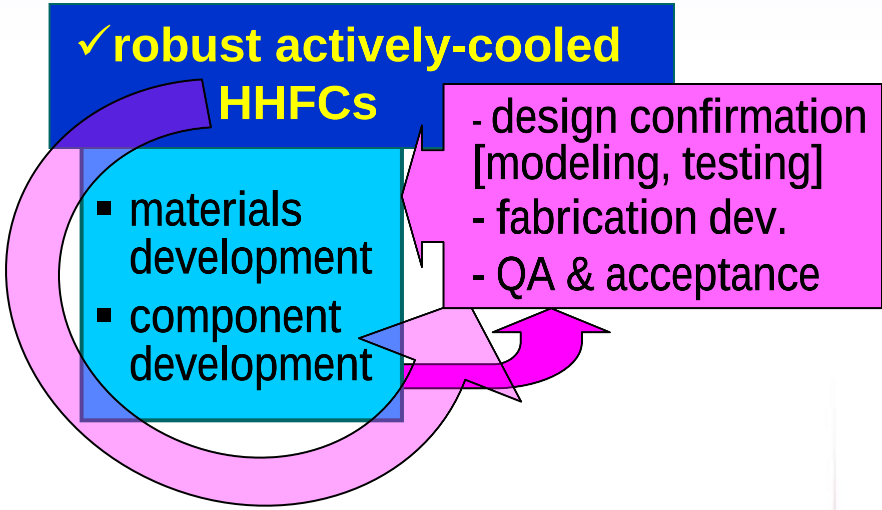
CEA was major player in developing and deploying water-cooled PFCs in Tore Supra (limiter). This is an example of the introduction of new PFC technology.

TPL leading edge and neutraliser fingers,
pumping throat
(4 Pam³s⁻¹)

Specific fingers with slot for traversing Laser Beam

Development of water-cooled PFCs

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**



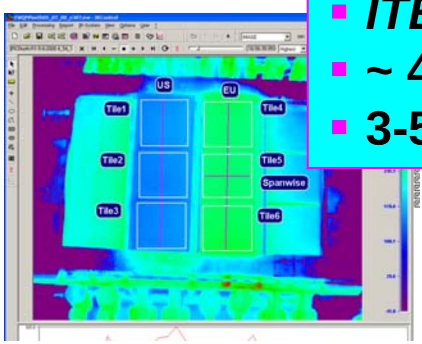
Basic process cycle in development

Fundamental Point

HHFC R&D is challenging & time-consuming.
It requires strong coordination with confinement projects on interfaces and with industrial suppliers on fabrication development, QA and acceptance.

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

FWQM Testing Status
US & EU Mockups
Date: End of May 8, 2008
Cycles Completed: 3447



Development of He-cooled PFCs

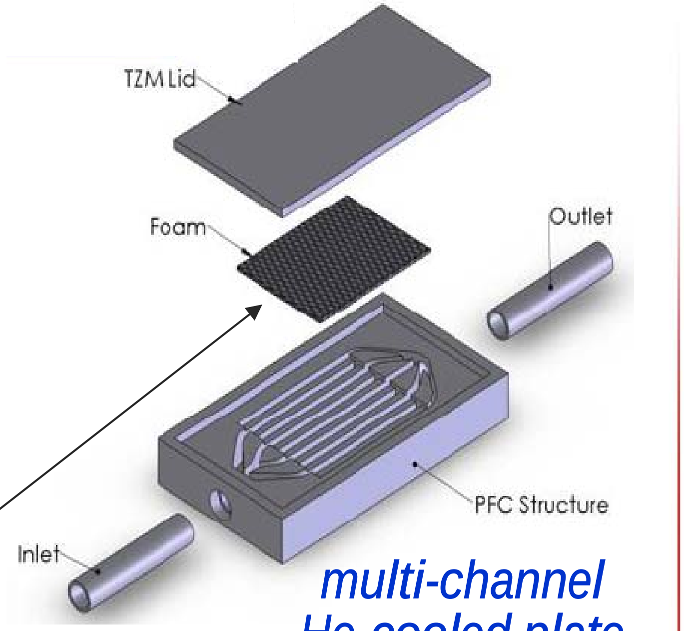
Start: Deploy He-cooled probes or guards for longer pulse operation.
Room temperature He is easier adaption of the technology (high density, mat = SS)

A strong well integrated HHFC program (near term) could enable new PFCs and IVCs for longer shots, higher power or hot walls in upgrades of current devices.

The technologies for heat pipes and for helium cooling have both progressed significantly in the last decade.

W foam

US He-cooled PFC target >20MW/m^2



multi-channel He-cooled plate

New PFCs as Enabling Tech.

.. enabling R&D on current devices and upgrades that must precede an FNSF.

PFC-1 Enabling Tech.

HHF In-Vessel Comp'ts (IVCs)
- RF launchers, armor
- RF mirrors
- Probes (mat'l, calorimeter, ..)

HHFC, divertor targets
- Strike point targets
- Li pumping/edge
- Pre-prototype deployment

"Hot wall" PFCs
(heaters tough, as better)
- Protoype wall panel
- Hot divertor tiles
- Full wall/div deployment

Liquid Surface PFCs
- Pumping panels, LLD/LTX
- Divertor targets (heat load)
- Liq. walls (plumbing, MHD)

Solid Surface R&D

Liquid Surface R&D

PFC-2 for FNFS/DEMO

Solid high temp. PFCs
- Divertor (integrated system)
- FW integral with blanket
- Probes (mat., calorimeter, ..)

HHF IVCs - 2

? AND/OR ?

PFC-3 for FNFS/DEMO

Liquid Surface PFCs
- Strike point targets
- Li pumping/edge
- Pre-prototype deployment

HHF IVCs - 3

R&D on solid surface PFCs and liquid surface PFCs are somewhat independent pathways.

Both are important because we do not have a confirmed solution for FNSF and DEMO PFCs.

Solid Surface R&D

The next section gives a brief overview of liquid surfaces and modeling (short to save time).

The last section uses development of W PFCs as an example to illustrate some questions about pathways.

Liquid Surface R&D

New PFCs as Enabling Tech.

… enabling R&D on current devices and upgrades that must precede an FNSF.

PFC-1 Enabling Tech.

HHF In-Vessel Comp'ts (IVCs)
- RF launchers, antenn…
- RF mirrors
- Probes (mat'l, calorimeter, ..)

HHFC, divertor targets
- Strike point targets
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(heaters tough, as better)
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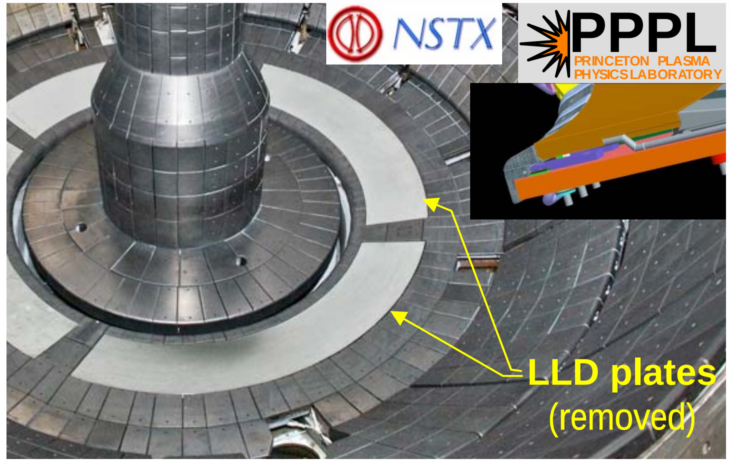
Liquid Surfaces *Divertor/FW*

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

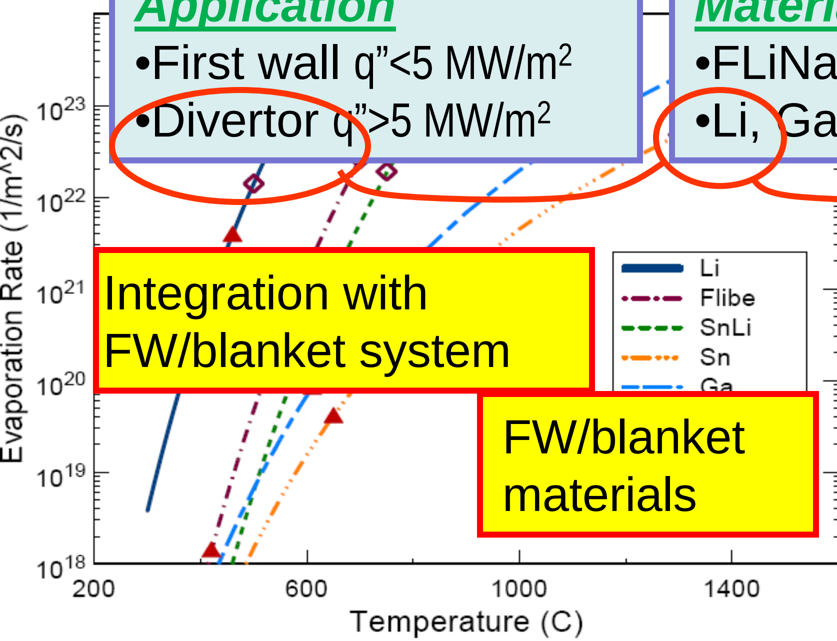
- **capillary-supplied Li**
- **flowing Li** (modified edge)
- **Sn, Ga, …**

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!
(unless there is some new regime)

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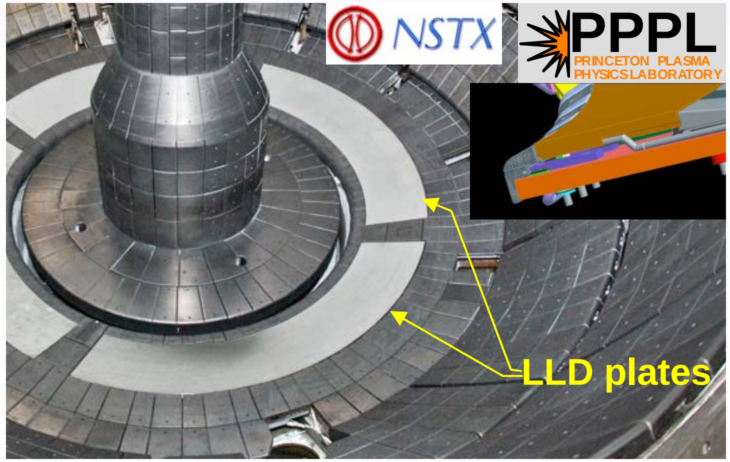
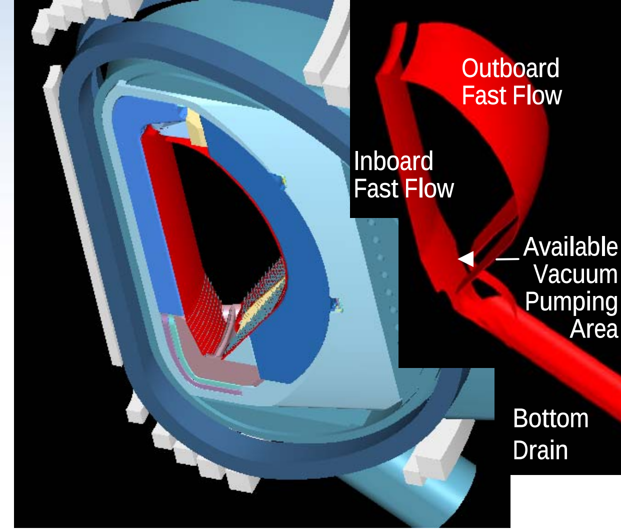
Liquid Surfaces *Divertor/FW*

Experiments in
T-11M, CDXU/LTX

Li limiter in FTU





CLIFF (Flowing FLiBe)

APEX design study
Prof. Abdou, UCLA , leader

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

Material
- FLiNaBe
- Li, Ga

Function
- Cooling
- Pumping

Speed/cooling
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Integration with FW/blanket system

FW/blanket materials

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

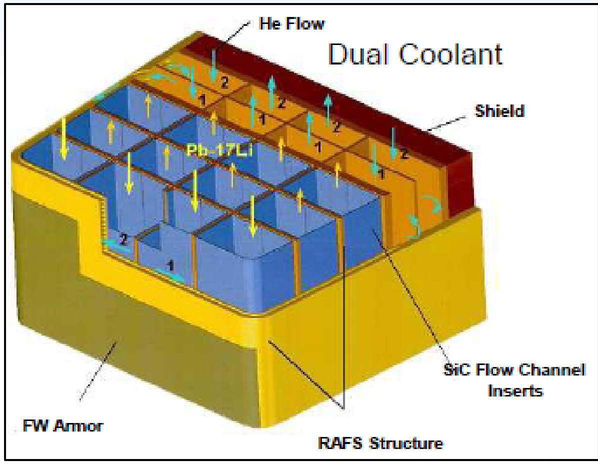
High speed flow difficult to achieve, predict and control

US Activities in modeling PFCs

***plasma edge modeling** (Rognlien)*

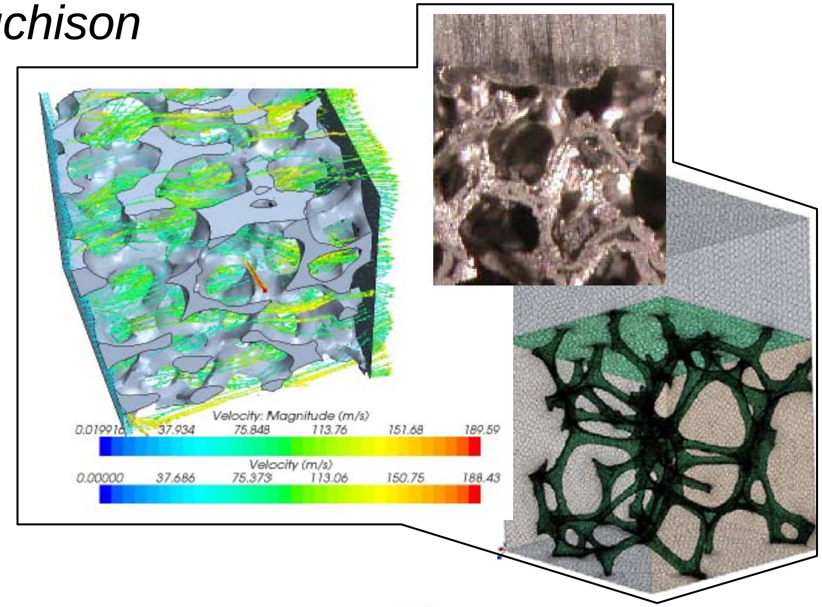
PFCs

- **All Metal ITER (IAEA paper) -** *Brooks et al.*
- ***APEX studies*** – *Abdou and APEX Team*
- **ARIES design studies –** *ARIES Team*
- **ITER TBM and TITAN activities** – *UCLA/GA/others*
- **Integrated Blanket Systems** – *Ying, Narula, Wang*
- **Thermal performance models of mockups** – *Youchison, Sharafat, Raffray*
- **Response to EM loads** – *Ulrickson, Youchison*
- **He flow through porous media (CFD)** – *Youchison*



PSI – *covered elsewhere*

- **Tritium retention in neutron damaged W** – *Wampler et al.*
- **Conditions for formation and erosion of tungsten "fuzz"** – *Doerner et al.*
- **Erosion and redeposition** – *Brooks et al.*
- **Erosion and vapor shielding of W PFCs** – *Hassanein*
- **Hydrogen on the surface of W –** *Kolasinski*
- **Hydrogen permeation in W** – *Causey et al.*
- **Other work …..**



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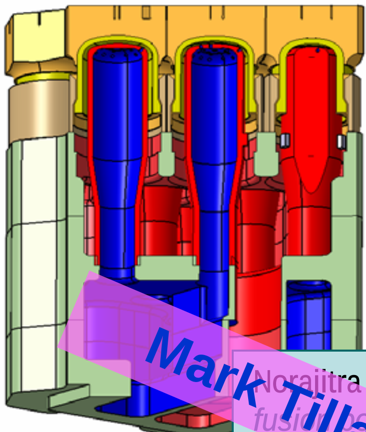
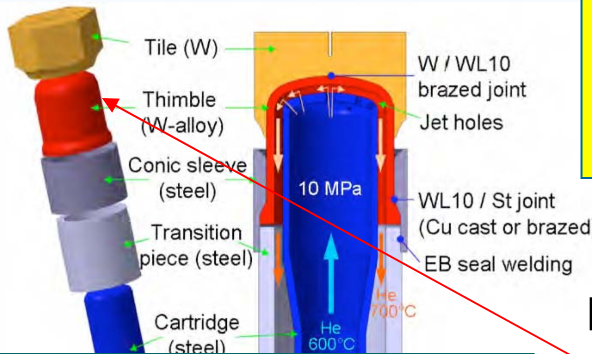
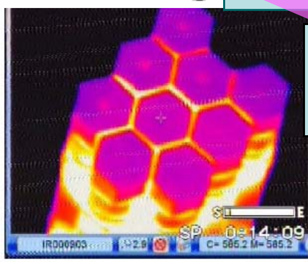
W PFC research – He-cooled W, e.g., HEJM in by EU

HEMJ – component dev. aspects
- design iterations, high heat flux tests
- fabrication development
- commercial mat'ls + innovations



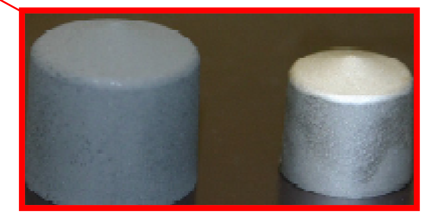


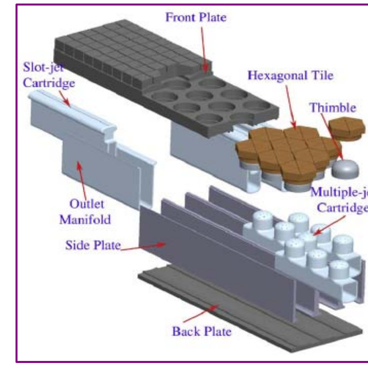
P. Norajitra et al., *Divertor conceptual designs for a fusion power plant*, FED 83 (7–9) (2008) 893–902.



IR imaging during testing, *P. Norajitra et al., FZK*

HEMJ Thimbles

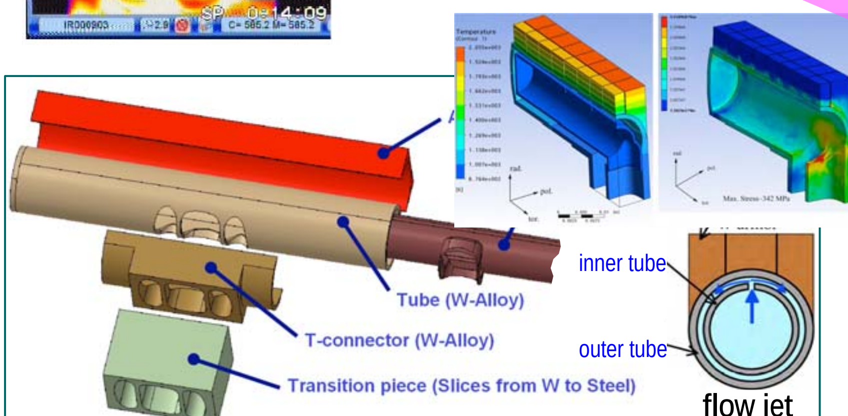




Mark Tillack will present more information on these designs.

- Deep drawing is suitable for mass production. Grain orientation of the W follows the contour.
- Dry machining does not contaminate surfaces for subsequent brazing and takes 1/4 work time.
- Finishing with a CBN grinding wheel (rather than EDM) eliminates fine surface cracking.

Reiser et al., Development of a He-cooled Divertor: Technological Studies of Tungsten Machining, SOFT08



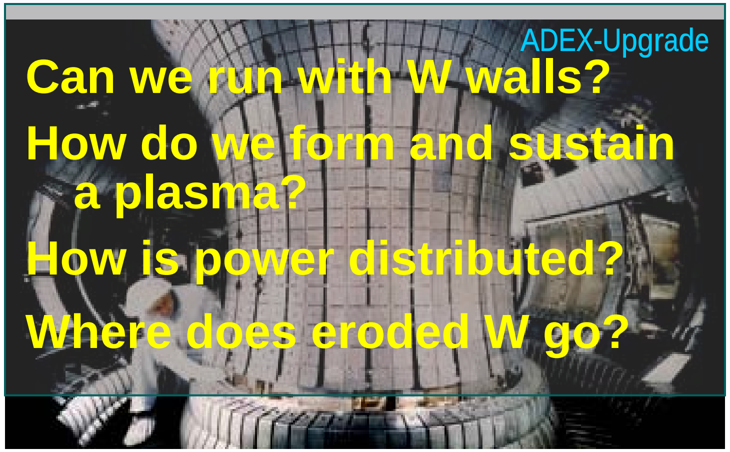
T-tube in ARIES-CS divertor - nice idea

PFC-PSI Development & Integration for W PFC

Nature of inquiry

Physics in all metal devices

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



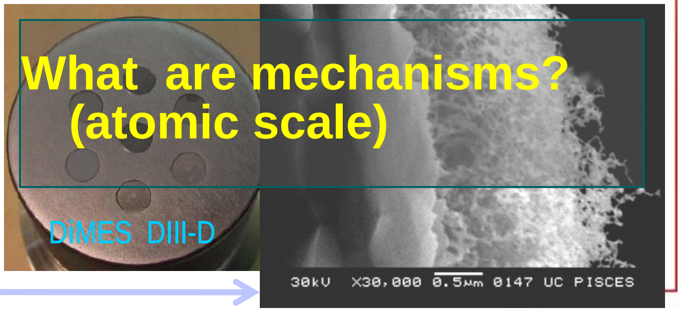
R&D on W PFCs

- **JET ITER-like divertor**
  (W monoblocks & coatings)
- **Performance of Mo & W tiles in C-MOD** →
- **Coatings in ASDEX-U**
- **W limiters in TEXTOR, HT-7**
- **Fabrication development**

PSI

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

PSI R&D in labs *(PISCES, NAGDIS, IBL, TPE ...)* →



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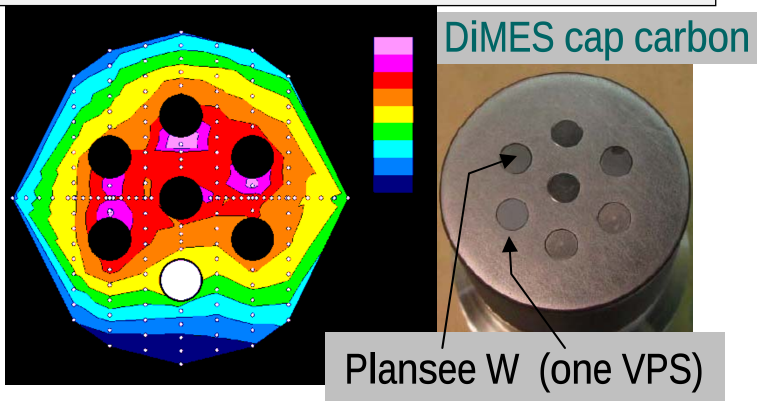
US Activities with W PFCs - erosion

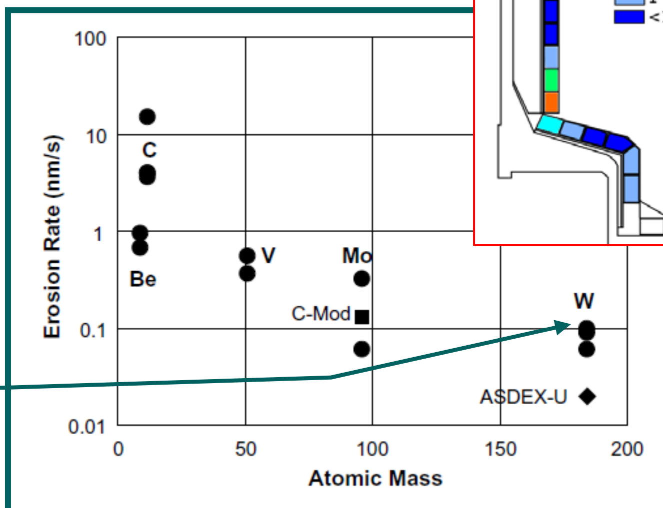
W redeposition, DiMES div. probe

Courtesy of DIII-D (General Atomics) & DiMES Team



- RBS measurements (pre/post)
- W deposits mainly near source
- Average net W erosion rate 0.13 nm/s

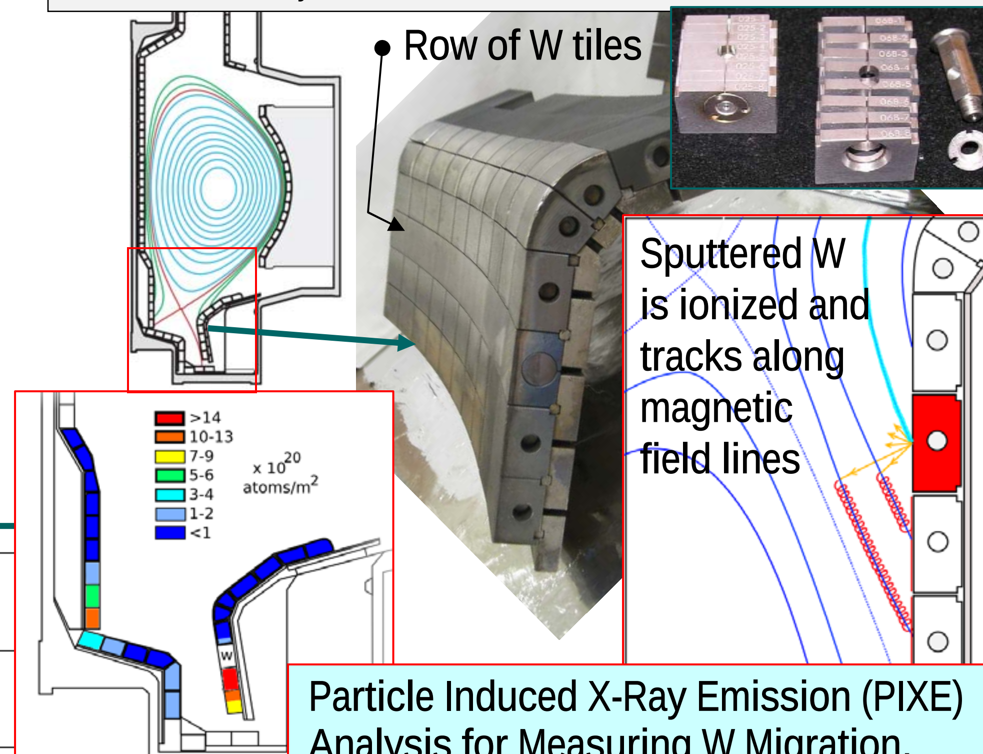
Fit with earlier measurements



W. Wampler, *Nucl. Instr. & Meth. in Phys. Res. B 219–220 (2004)*

Section of Alcator C-Mod outer divertor

Courtesy of MIT Plasma Fusion Science Center



Particle Induced X-Ray Emission (PIXE) Analysis for Measuring W Migration, Barnard, Lipschultz, Whyte, Sainct

PFC Mtg MIT July 2009

Extensive studies in ASDEX-Upgrade

All Metal ITER

(IAEA paper) J. Brooks et al.

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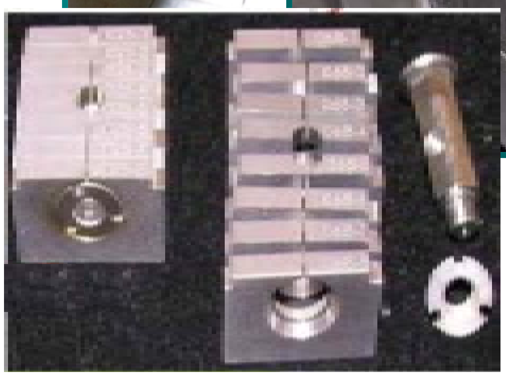
US Activities with W PFCs – R&D on W tiles

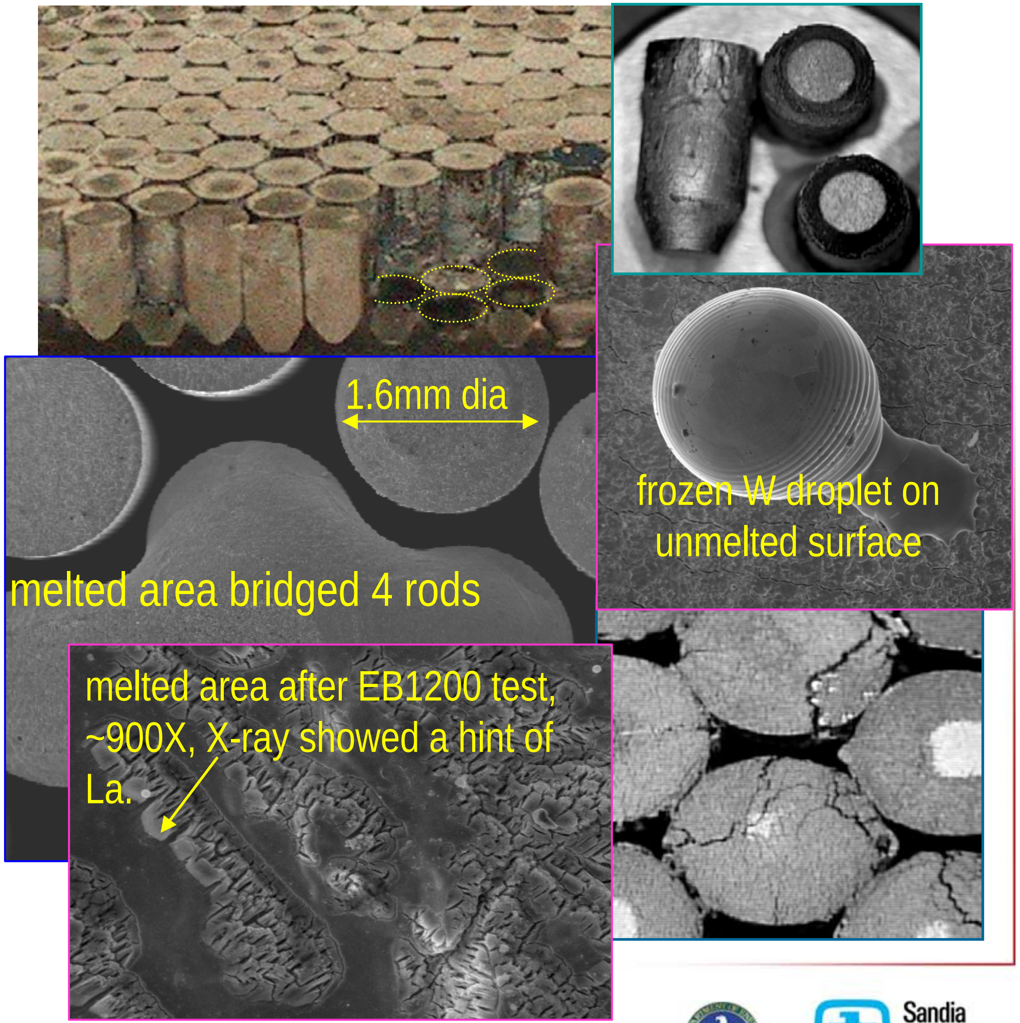
Alcator C-MOD tokamak at MIT's Plasma Fusion Science Center



W lamellar plate tiles

Sandia-Boeing ITER W rod mockup

- rods in PS Cu bed
- bed HIPPed to CuCrZr
- method did not work.



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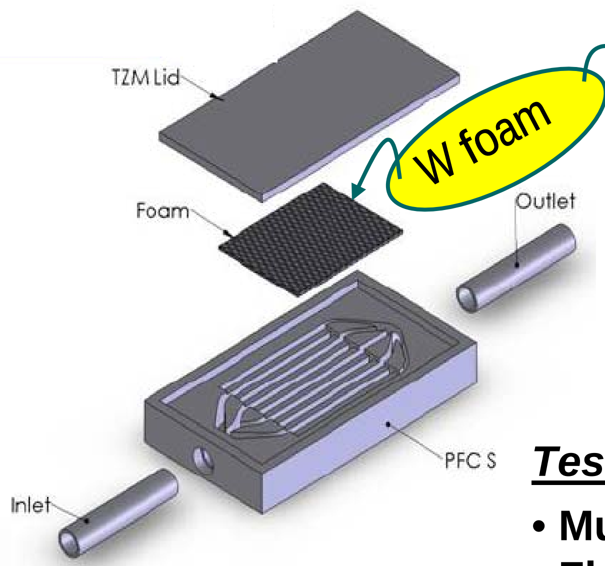
US Activities - He-cooled W mockups

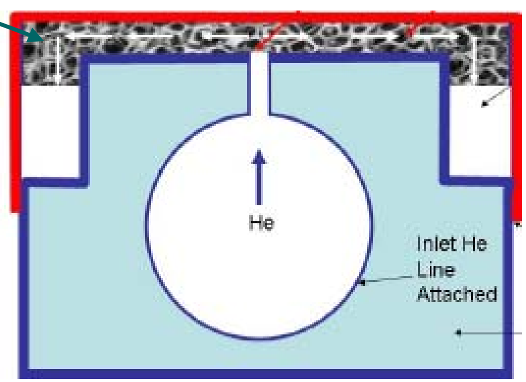
Sandia tested He-cooled heat sinks since the 1990's.

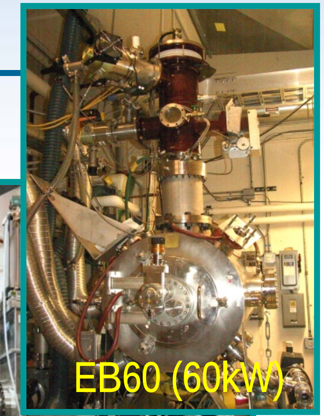
In more recent tests:

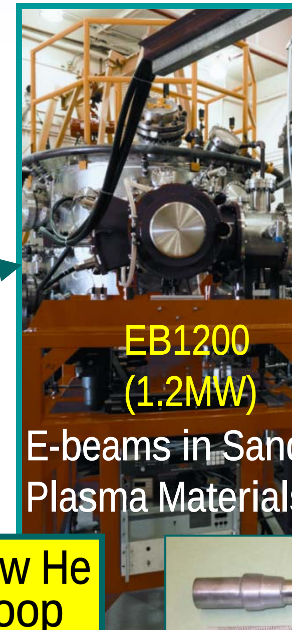
- dual-channel He-cooled W heat sink, **Thermacore***, **34.6 MW/m²** *(study channel-to-channel flow instability)*
- 15-mm-diameter tubes with porous medium, integral structure by **Ultramet*** with CVD W, **22.4 MW/m²**

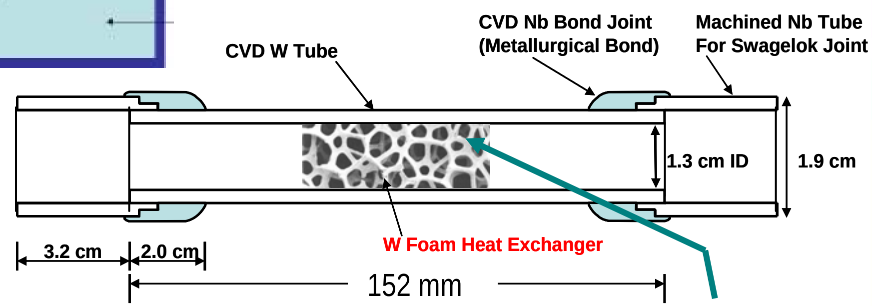
**done under DOE grants for Small Business Innovative Research*











carbonization of open-celled foam then W CVD coating

Test in coming year

- **Multiple channel (4)**
- **Flat surface**
  All refractory
  Short flow paths
  600 C inlet temps

Investigate:

- **Larger heated areas**
- **Flow instabilities**

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Basic Elements for W PFC Development*

Development of W-based materials, including production, fab, joining and neutron damage

Investigation of PMI issues

Measurements of the plasma edge

Development and deployment of PFCs (confirmation of design, goals for performance, QA, high heat flux testing, ..)

Experiments with large areas of W PFCs; operation with hot walls.

Modeling of materials and the evolution and effects of damage

Modeling of the plasma edge

Benchmarking of edge and materials models

Modeling of component performance and integrated testing

Benchmarking of predictive performance models that integrate plasma edge, materials evolution and component performance

***Making Tungsten Work**
R Nygren ICFRM-14 (2009)

We can list basic tasks.

This is one way to summarize activities in a pathway.

But a list has no sequence implied.

And the tasks here cut across several of our topical areas.

Basic Elements for W PFC Development

	Topical Area (Phys/PSI/PFC/MAT)			
	Physics	PSI	PFC	MAT
Development of W-based materials, including production, fab, joining and neutron damage			PFC	MAT
Investigation of PMI issues		PSI		
Measurements of the plasma edge	Physics	PSI		
Development and deployment of PFCs (confirmation of design, goals for performance, QA, high heat flux testing, ..)			PFC	MAT
Experiments with large areas of W PFCs; operation with hot walls.	Physics	PSI	PFC	
Modeling of materials and the evolution and effects of damage		PSI		MAT
Modeling of the plasma edge	Physics	PSI		
Benchmarking of edge and materials models	Physics	PSI		MAT
Modeling of component performance and integrated testing		PSI	PFC	
Benchmarking of predictive performance models that integrate plasma edge, materials evolution and component performance	Physics	PSI	PFC	MAT

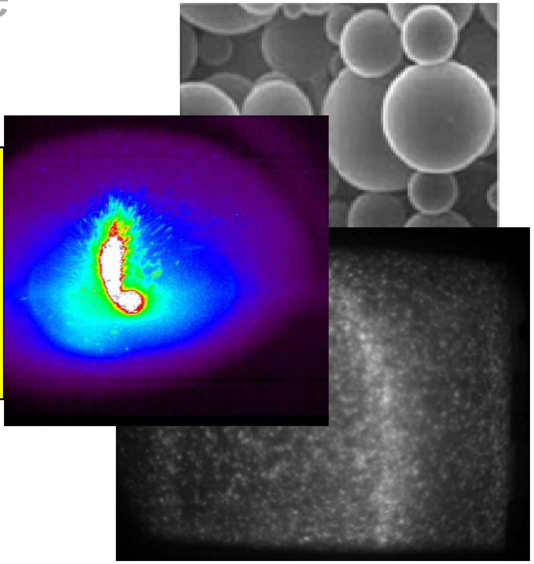
Materials Issues for W PFCs

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

What improvements can we deliver?

- Lower DBTT
- Better machinability
- Mitigation of some neutron & ion damage
- PSI , oxidation, …
- *Reduced cost*
- *Weight*

Rudikov (General Atomics), Dust Study: loose dust mobilized (? electrical charging) and prevented discharge. *MIT PFC Meeting, 2009*



What are intrinsic limitations?

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

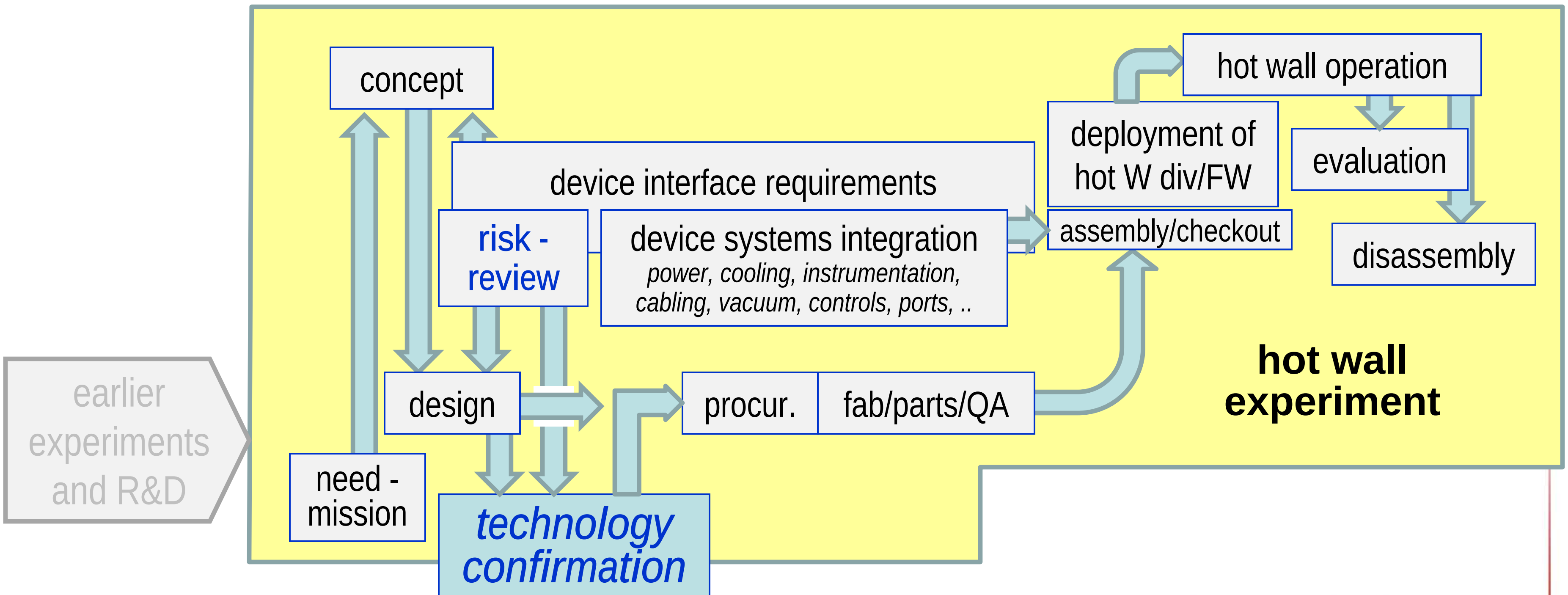
→ manageable → **YES - operate**

↓ **NO – replace/repair**

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)



How do we define the basic elements of our pathway?

Hot Wall Experiment – large area of hot PFCs

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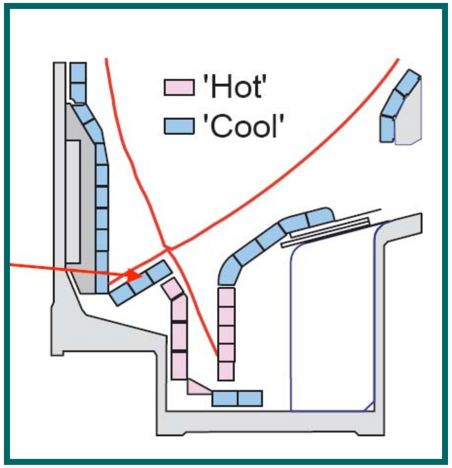
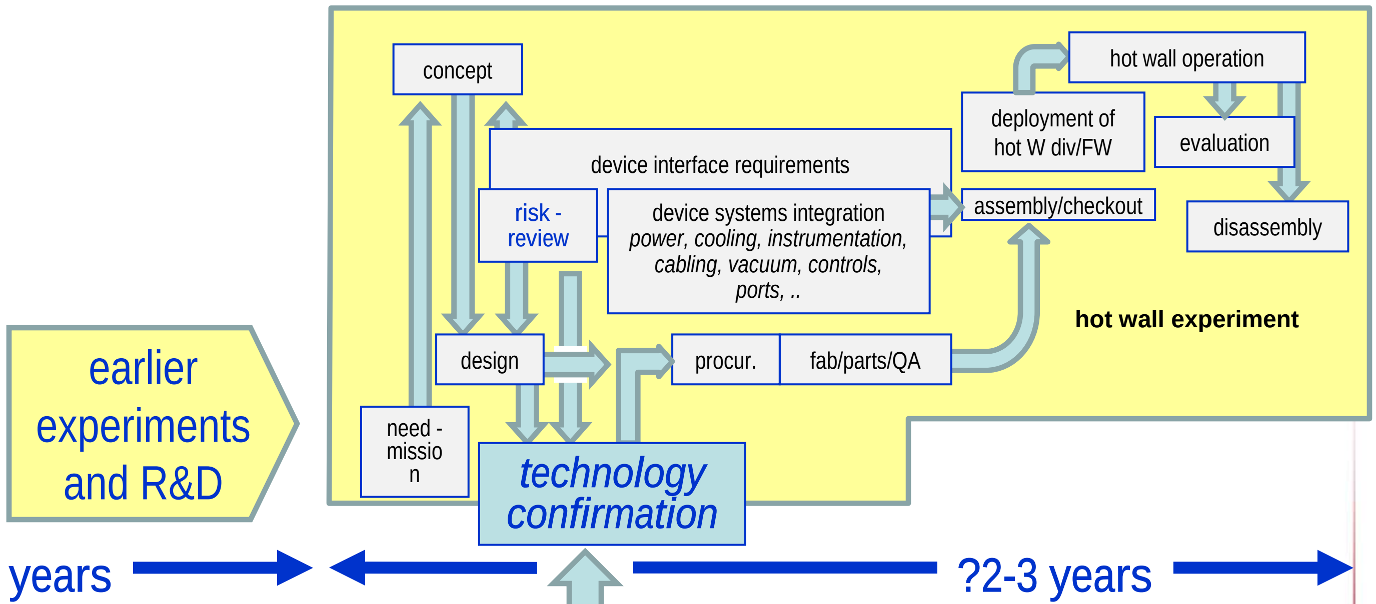
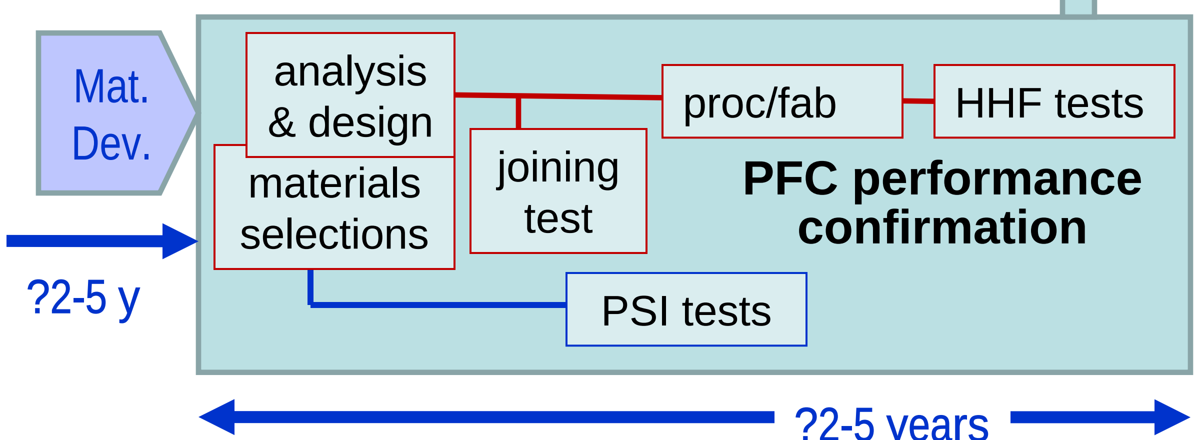


C-MOD hot tiles





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

Nygren/Youchison PFC Development, FNSP Core Group Meeting – Jan 24-25, 2011 UCLA

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

E ND