Chamber Technology Goals Used in APEX to Calibrate New Ideas and Measure Progress

1. High Power Density Capability

    Average/Peak Neutron Wall Load ~ 7 / 10 MW/m^2

    Average/Peak Heat Flux ~ 1.4 / 2 MW/m^2

    (80% of the Alpha Power Radiated to First Wall to ease divertor loading)

2. High Power Conversion Efficiency (>40%)

3. High Availability (MTBF>43 MTTR)

4. Simpler Technological and Material Constraints

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* “APEX will explore concepts with lower power density capabilities if they provide significant improvement in power conversion efficiency or other major features.”

Technological limits for “conventional concepts” have been documented in several papers; see for example APEX paper in Fusion Engineering & Design, vol. 54, pp 145-167 (1999)

APEX "Idea Formulation" Phase Identified Two Classes of Promising Concepts:

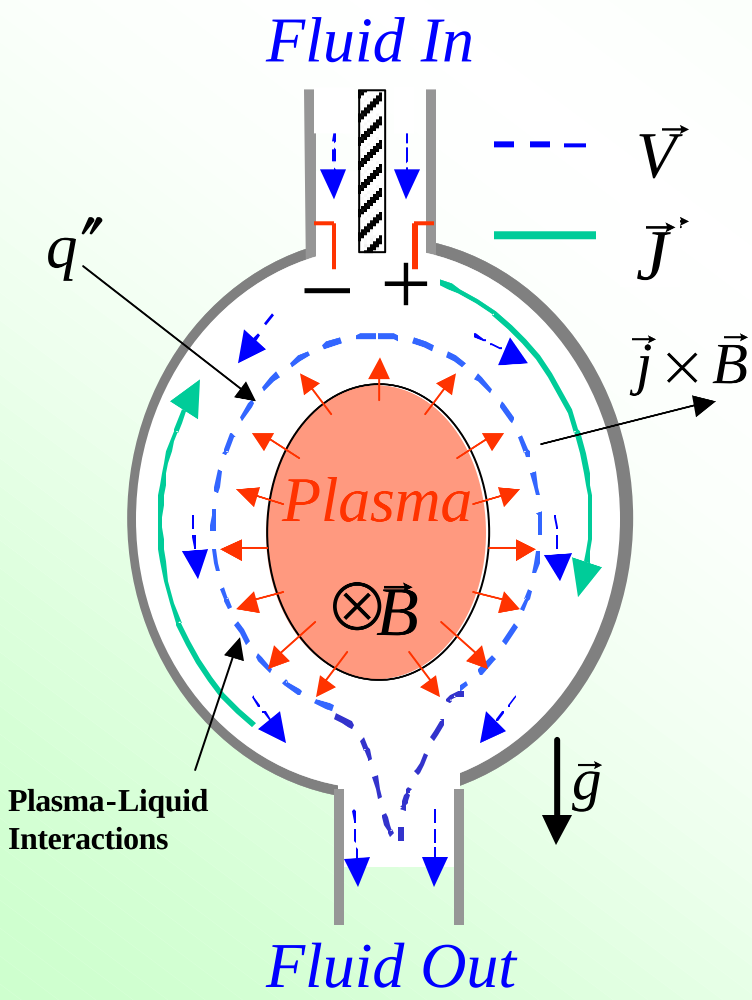
1. Liquid Walls   2. EVOLVE

- "Idea Formulation Phase": Many ideas proposed and screened based on analysis with "existing tools"
- Liquid Walls and EVOLVE (W alloy, vaporization of Li) were selected to proceed to the "Concept Exploration" Phase
- The "Concept Exploration" Phase involves extending modeling tools, small experiments, and analysis of key physics and engineering issues
- APEX remains open to new ideas

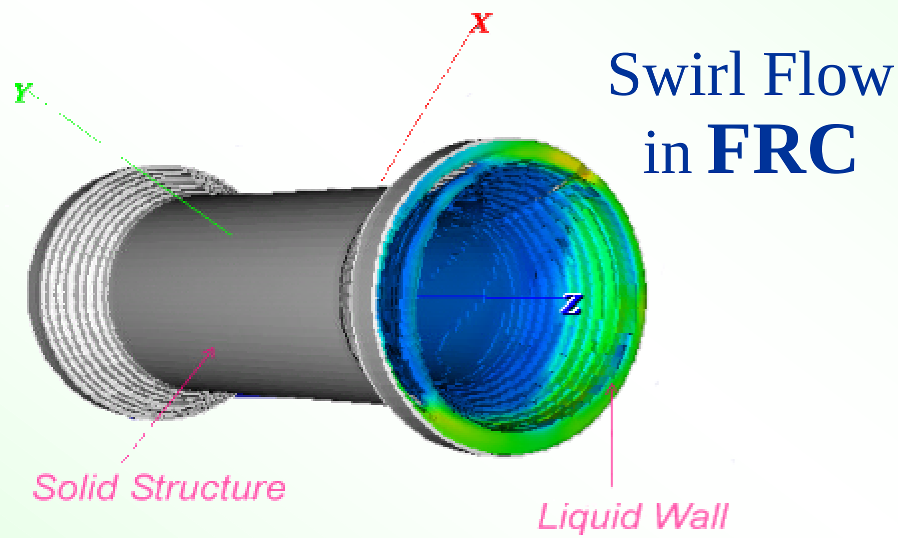
- Results of the "Idea Formulation" phase are fully documented on the website and in many journal publications
- An Interim Report (> 600 pages) fully documents all details:

  "On the Exploration of Innovative Concepts for Fusion Chamber Technology", APEX Interim Report, UCLA-ENG-99-206 (November 1999).

“Liquid Walls” Emerged as one of the Two Most Promising Classes of Concepts to proceed to “Concept Exploration”



- **The Liquid Wall idea is “Concept Rich”**
  - a) Working fluid: Liquid Metal, low conductivity fluid
  - b) Liquid Thickness
    - thin to remove surface heat flux
    - thick to also attenuate the neutrons
  - c) Type of restraining force/flow control
    - passive flow control (centrifugal force)
    - active flow control (applied current)
- **We identified many common and many widely different merits and issues for these concepts**



Motivation for Liquid Wall Research

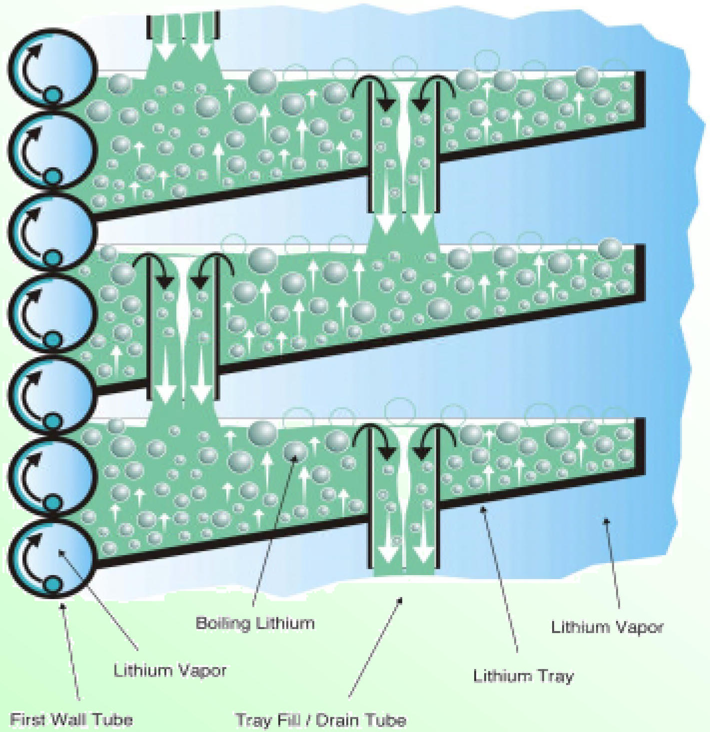
What may be realized if we can develop good liquid walls:

- Improvements in Plasma Stability and Confinement
  Enable high ß, stable physics regimes if liquid metals are used
- High Power Density Capability
- Increased Potential for Disruption Survivability
- Reduced Volume of Radioactive Waste
- Reduced Radiation Damage in Structural Materials
  -Makes difficult structural materials problems more tractable
- Potential for Higher Availability
  -Increased lifetime and reduced failure rates
  -Faster maintenance

No single LW concept may simultaneously realize all these benefits, but realizing even a subset will be remarkable progress for fusion

Innovative concepts proposed by APEX can extend the capabilities and attractiveness of solid walls

- Structural material is key to extending capabilities of solid walls
  - High-Temperature Refractory Alloys evaluated: W-alloy selected
- Helium cooling and Li boiling evaluated



EVOLVE

- Novel Concept based on use of high temperature refractory alloy (e.g. tungsten) with innovative heat transfer/transport scheme for vaporization of lithium
- Low pressure, small temperature variations greatly reduce primary and thermal stresses
- Low velocity, MHD insulator may not be required
- High Power Density, High Temperature (high efficiency) Capabilities

- SiC/SiC-LiPb limits are being evaluated

  SiC may allow high temperature, but power density may be limited

APEX "Concept Exploration" of Liquid Walls and EVOLVE is emphasizing Science and Innovation

- Deeper understanding of phenomena and issues
- Advancing the underlying engineering science
- Extending the best available tools through pioneering model development and carefully planned small laboratory experiments
- Proposing, advancing, and verifying an impressive list of Innovative Solutions to key physics and engineering issues

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Concept Exploration Phase is the current phase (it started in November 1999).
A fully detailed technical plan is posted on the web.

The Framework for APEX Concept Exploration was guided by community deliberations that identified Chamber 5-Year Objectives

Liquid Walls:

1. Fundamental understanding of free surface fluid flow phenomena and plasma-liquid interactions verified by theory and experiments.

2. Operate flowing liquid walls in a major experimental physics device (e.g. NSTX)

3. Begin construction of an integrated Thermofluid Research Facility to simulate flowing liquid walls for both IFE and MFE.

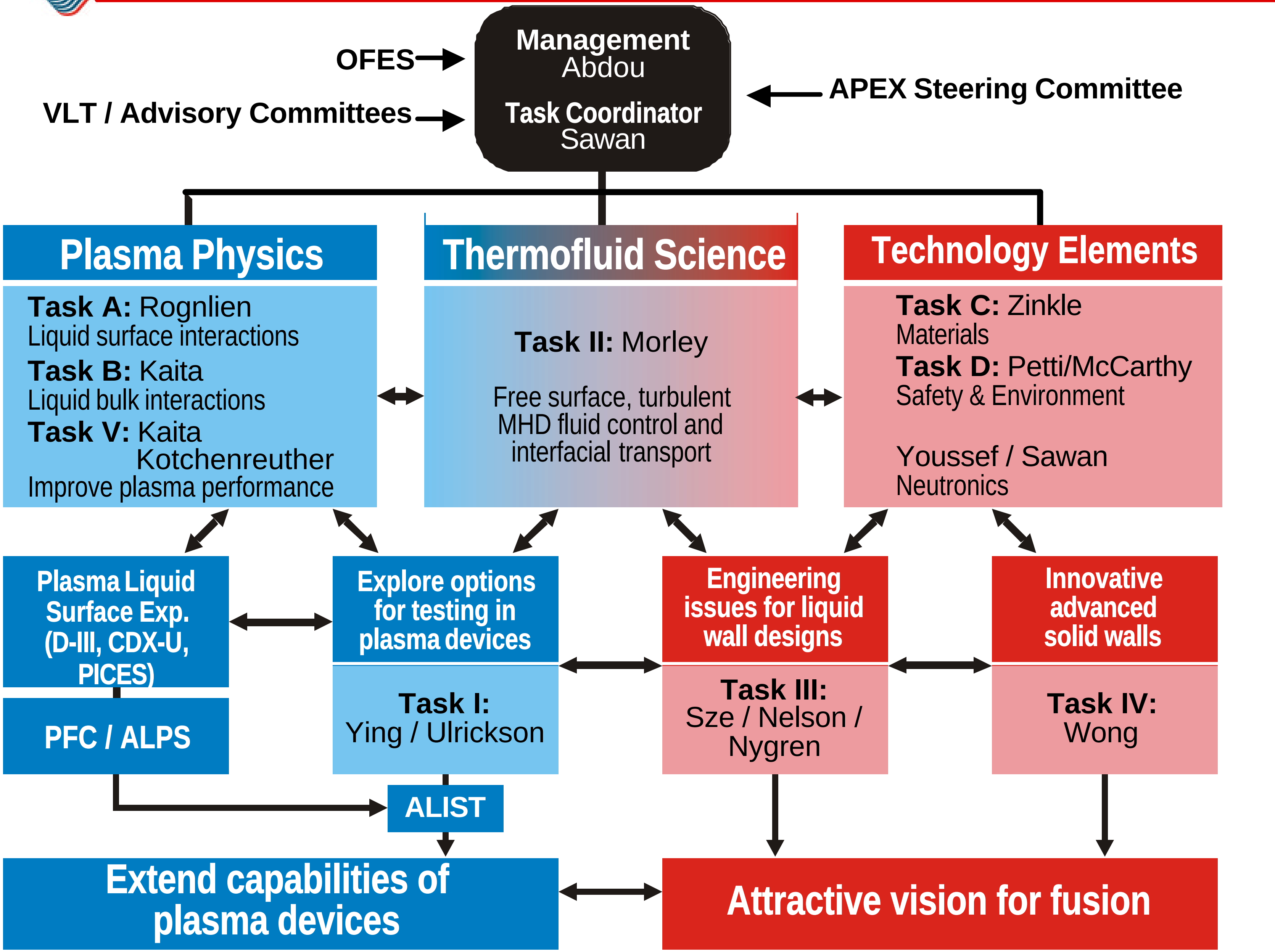
4. Understand advantages & implications of using LW's in fusion energy systems.

Solid Walls:

5. Advance novel concepts that can extend the capabilities and attractiveness of solid walls.

6. Contribute to international effort on key feasibility issues for evolutionary concepts in selected areas of unique expertise

APEX is organized as a partnership between plasma physics and all elements of science & technology



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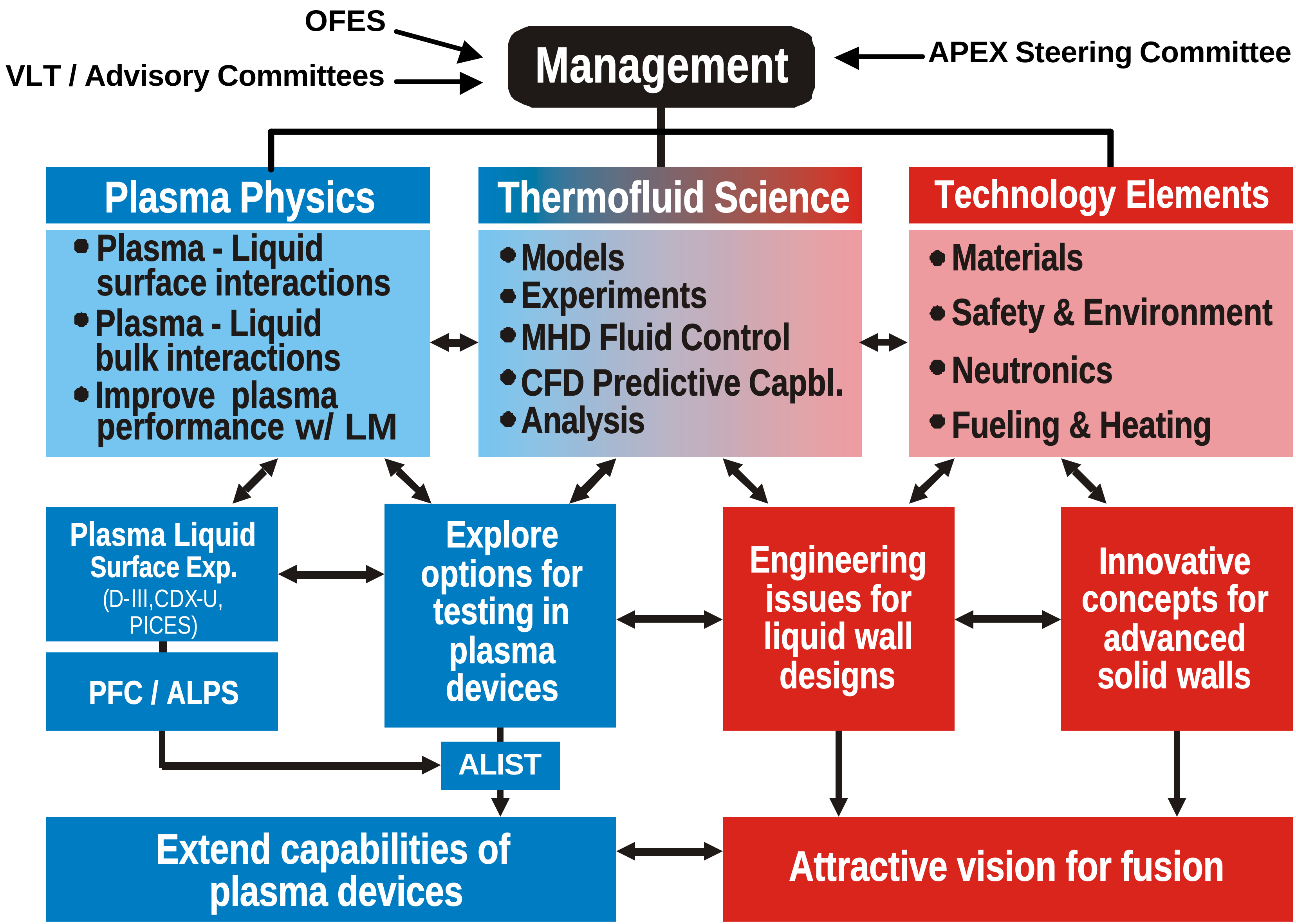


Scientific Issues for Liquid Walls

1. Thermofluid Issues

- Interfacial Transport and Turbulence Modifications at Free-Surface
- Hydrodynamic Control of Free-Surface Flow in Complex Geometries, including Penetrations, Submerged Walls, Inverted Surfaces, etc
- MHD Effects on Free-Surface Flow for Low- and High-Conductivity Fluids

2. Bulk Plasma-Liquid Interactions

Effects of Liquid Wall on Core Plasma including:

- Discharge Evolution (startup, fueling, transport, beneficial effects of low recycling
- Plasma stability including beneficial effects of conducting shell and flow

3. Plasma-Liquid Surface Interactions

- Limits on operating temperature for liquid surface

Liquid Walls Sparked Great Interest in the Community

LW Research in the US is well Coordinated

APEX

1. Thermofluid Issues

- Modeling (APEX: UCLA, PPPL, SBIR)
- Experiments (APEX: UCLA, PPPL, ORNL, SNL, Univ. of IL)

2. Bulk Plasma-Liquid Interactions

- Modeling (APEX: PPPL, U. Texas, ORNL)
- Experiments (Science Division/OFES: Univ. of Wisconsin)

3. Plasma-Liquid Surface Interactions

- Modeling (Joint APEX/ALPS: ANL, LLNL, others)
- Experiments (ALPS: CDX-U, DIII-D, PISCES, SNL, Univ of IL)

4. Li Test Module on NSTX (and C-MOD): (APEX, PFC, Physics)

*** Important Note: All the Plasma-Liquid Surface Interaction Experiments are funded under ALPS, which is under the PFC Program. ALPS' Budget is much larger than APEX's. ALPS is not part of this Chamber Review.**

LW Thermofluid Modeling aimed at understanding and predicting flow behavior and interfacial transport

APEX LW Modeling effort strives to:

- balance design-focused engineering analyses with tool development for greater scientific understanding and improved predictive capabilities
- utilize and extend state-of-the-art modeling tools - both those developed in fusion and by other applications
- fill the void in predictive capabilities where none have previously existed
- establish connections to and collaboration with scientists in other fields nationally and internationally
- share knowledge with SBIR participants for the commercial development of modeling tools useful for fusion

Fusion LW Researchers are Contributing to the Resolution of GRAND CHALLENGEs in Fluid Dynamics

Liquid Walls: many interacting phenomena

SCALAR TRANSPORT

$$?C_p\left[\frac{\partial T}{\partial t} + (\vec{V}\cdot\nabla)T\right] = k\Delta T$$

$$\frac{\partial C}{\partial t} + (\vec{V}\cdot\nabla)C = D\Delta C$$

FREE SURFACE PHENOMENA

$$\frac{\partial j}{\partial t} + (\vec{V}\cdot\nabla)j = 0$$

- Turbulence redistributions at free surface
- Turbulence-MHD interactions
- Mean flow and surface stability MHD effects
- Influence of turbulence and surface waves on interfacial transport and surface renewal

MHD

$$\frac{\partial \vec{B}}{\partial t} = \frac{1}{s\mu_0} ?\vec{B} + \nabla\times(\vec{V}\times\vec{B});$$

$$\vec{j} = \frac{1}{\mu_0}\nabla\times\vec{B} \qquad \nabla\cdot\vec{B} = 0$$

TURBULENCE

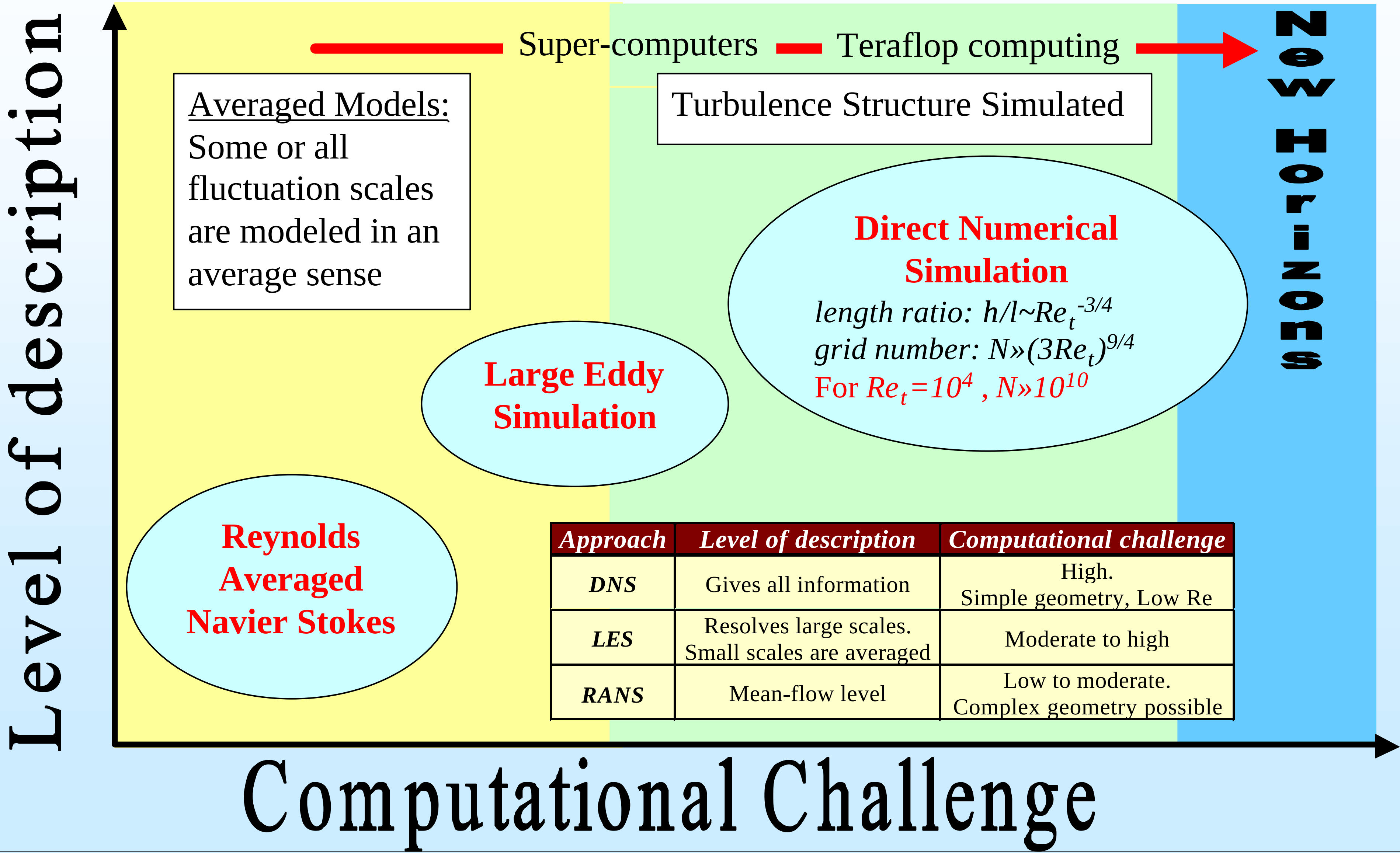
$$\frac{\partial \vec{V}}{\partial t} + (\vec{V}\cdot\nabla)\vec{V} = -\frac{1}{?}\nabla p$$

$$+ \nabla\cdot\mathbf{t} + \vec{g} + \frac{1}{?}\vec{j}\times\vec{B}$$

$$\nabla\cdot\vec{V} = 0$$

Teraflop Computer Simulation

We are Extending Computationally Challenging Turbulence Models to Free Surface, MHD Flows

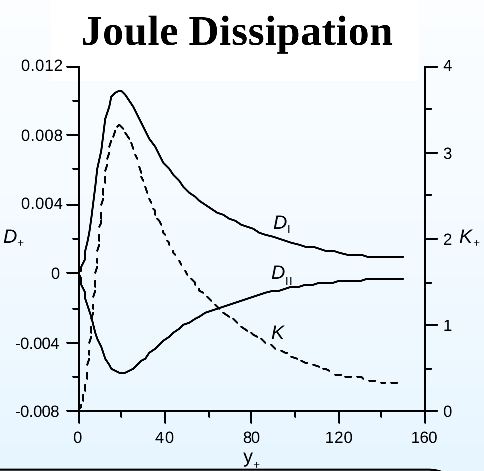


Approach	*Level of description*	*Computational challenge*
DNS	Gives all information	High. Simple geometry, Low Re
LES	Resolves large scales. Small scales are averaged	Moderate to high
RANS	Mean-flow level	Low to moderate. Complex geometry possible

Our Science-based CFD Modeling and Experiments are Utilized to Develop Engineering Tools for LW Applications

D N S

for free surface MHD flows developed as a part of collab-oration between UCLA and Japanese Profs Kunugi and Satake



DNS and Experimental data are used at UCLA for characterizing free surface MHD turbulence phenomena and developing closures in RANS models

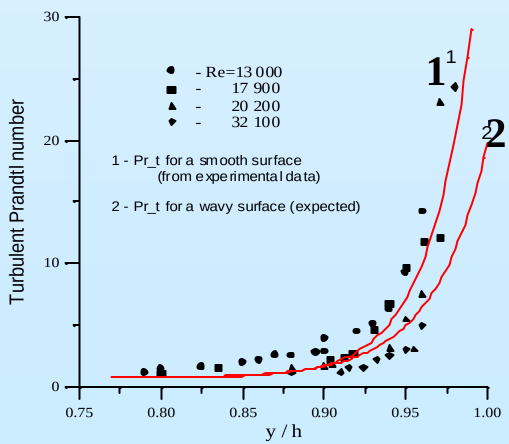
Extend RANS Turbulence Models for MHD, Free Surface Flows

•K-epsilon

•RST model

EXPERIMENTS

underway at UCLA for near surface turbulence and interfacial transport measurements



Turbulent Prandtl Number

Curve1: Available Experimental Data

- Missing 0.95-1 and restricted to smooth surface, non-MHD flows

Curve2: “Expected” for wavy surface