

Reflections on Fusion Chamber Technology and SiC/SiC Applications

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The Region Immediately Surrounding the Plasma Divertor / First Wall / Blanket / Vacuum Vessel / Shield

Names

Fusion Nuclear Technology (FNT)

Fusion Power Technology

Reactor Core

Plasma Exterior

In-Vessel System (components)

- FNT embodies a majority of the most challenging issues in development of an attractive fusion energy source
- Despite Meager Resources for FNT R&D, remarkable progress has been made (witness this conference)

What Have We Learned?

Realizing the fusion promise of an attractive energy source for future generations requires, among other top priorities, advances in engineering sciences and innovative research to develop advanced fusion nuclear technology

Functional Requirements of Chamber Technology

- 1) Provision of VACUUM environment
- 2) EXHAUST of plasma burn products
- 3) POWER EXTRACTION from plasma particles and radiation (surface heat loads)
- 4) POWER EXTRACTION from energy deposition of neutrons and secondary gamma rays
- 5) TRITIUM BREEDING at the rate required to satisfy tritium self sufficiency
- 6) TRITIUM EXTRACTION and processing
- 7) RADIATION PROTECTION

General Criteria for Attractiveness of (Fusion) Energy System

1. ECONOMICS

- a) Cost per unit thermal power
- b) Thermal conversion efficiency
- c) Mean time between failure (MTBF)
- d) Mean time to repair (MTTR)
- e) Lifetime

2. SAFETY

- a) Chemical reactivity
- b) Decay heat
- c) Tritium inventory and tritium permeation
- d) Off-site dose
- e) Biological hazard potential
- f) Radioactive inventory of volatile materials
- g) Etc.

3. ENVIRONMENTAL

- a) Waste disposal
- b) Routine releases (e.g. tritium)
- c) Material resources utilization
- d) Etc.

Economics Principles motivated our Chamber Technology Goals



Need High Power Density/Physics-Technology Partnership

- High-Performance Plasma
- Chamber Technology Capabilities

Need Low Failure Rate

$$COE = \frac{C \cdot i + \text{replacement cost}}{P_{fusion} \cdot \text{Availability} \cdot M \cdot h_{th}} + O \& M$$

Energy Multiplication

Need High Temp. Energy Extraction

Need High Availability / Simpler Technological and Material Constraints

(1 / failure rate)

1 / failure rate + replacement time

- **Need Low Failure Rate:**
 - Innovative Chamber Technology
- **Need Short Maintenance Time:**
 - Simple Configuration Confinement
 - Easier to Maintain Chamber Technology

Power Density and Heat Flux in Fission Reactors Compared to Fusion with Traditional Evolutionary Concepts

	PWR	BWR	HTGR	LMFBR	ITER-Type
Equivalent Core Diameter (m)	3.6	4.6	8.4	2.1	30
Core Length (m)	3.8	3.8	6.3	0.9	15
Average Core Power Density (MW/m³)	96	56	9	240	1.2
Peak-to-Average Heat Flux at Coolant	2.8	2.6	12.8	1.43	50

Need Revolutionary Concepts with High Power Density Capability

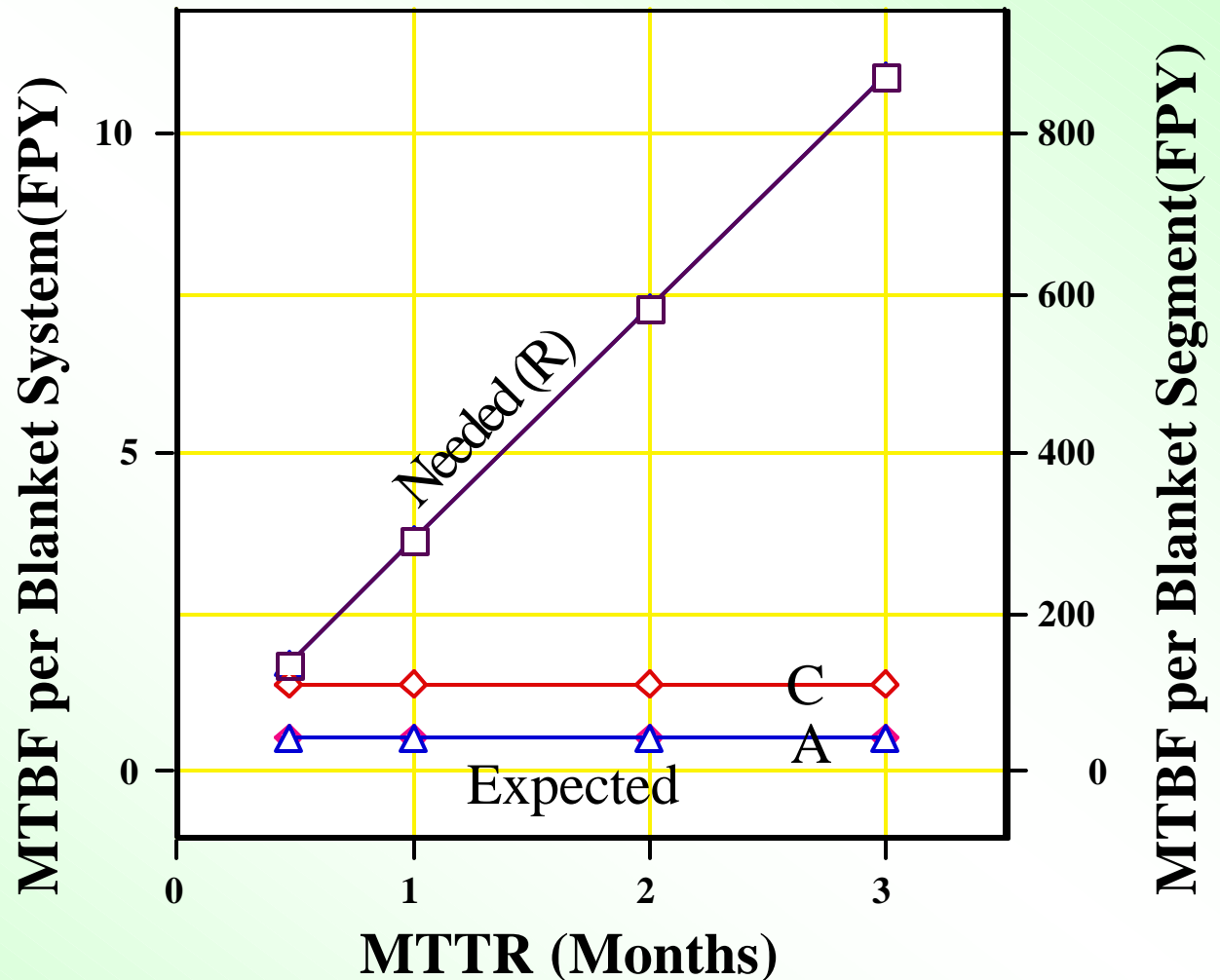
**i.e. concepts capable of handling both
high plasma heat flux and neutron wall load**

Current FW/B Design Concepts are NOT Capable of Meeting the Challenging Reliability Requirements

R = Required

A = Expected with
extensive R&D
(based on mature
technology and no
fusion-specific
failure modes)

C = Potential
improvements with
aggressive R&D



Challenging Fusion Nuclear Technology Issues

- 1. Heat Removal at High Temperature and Power Density*
- 2. Tritium Fuel Self-Sufficiency*
- 3. Failure Rate*
- 4. Time to Recover from a Failure*

Heat Extraction Issue

Suggested Future Directions

Aggressively Promote Creativity and Innovation to Stimulate NEW DESIGN CONCEPTS for First Wall / Blanket / Divertor / Shield (In-Vessel System) that Have

- **Less Constraints**
- **Higher Power Density Capability**
- **Larger Design Margin**
- **Better Breeding Capability**

SiC/SiC for Fusion Applications

Major Advantages

- Low Long-Term Radioactivity
 - Enhances the environmental attractiveness of fusion energy
- “Potentially” High Temperature Capability

Applications in Fusion

- Strong interest in using SiC composites in fusion first wall / blankets started in the early 80's in the US.
- Several reactor design studies have explored the utilization of SiC/SiC. These studies served to understand the benefits and identify the issues in the use of SiC.

Challenges in Utilization of SiC/SiC in Fusion Applications

- Low Thermal Conductivity
Limits High Power Density Capability
- Typical Problems of Ceramics
(e.g. embrittlement/fracture toughness, particularly when they are irradiated, joining, hermiticity, etc.)
- Do Not know yet how to design first wall/structure with SiC/SiC (e.g. no design criteria exists yet in the fusion environment)

How to Resolve These Challenges?

Key Points as Elements in a Strategy for Enhancing the Potential of SiC/SiC in Fusion Applications

Near-Term Applications

- Focus on utilizing SiC for suitable applications such as inserts (for electric insulation), and deeper regions of the blanket.

Long-Term Applications

- Explore fusion designs that can keep the “surface heat flux” away from a SiC/SiC first wall.

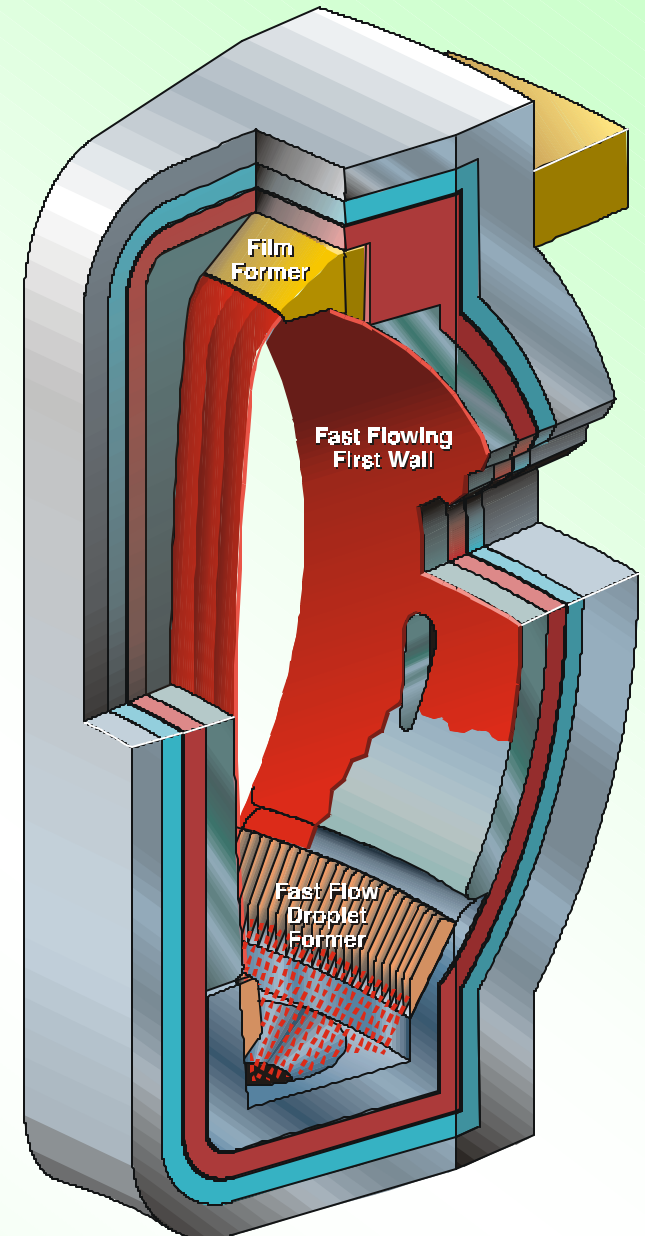
Example: Thin Liquid Wall

- 1-2 cm liquid on the plasma side of SiC first wall will remove the surface heat flux.
 - mitigates problems of low thermal conductivity, high stresses, etc.
 - allows SiC to be considered for high density, high temperature attractive fusion applications

THIN Liquid Wall

Use thin (1-2 cm) liquid layer to remove surface heat flux and peak nuclear heating in First Wall & Divertor

- a) Provide High Power Density Capability
 - eliminate thermal stress and erosion as limiting factors in the first wall and divertor
 - results in smaller and lower cost system
- b) Make the structural wall thermomechanics & other material issues more tractable
- c) Tolerate Disruptions
- d) Realize almost all the potential benefits of LM's in improving plasma performance



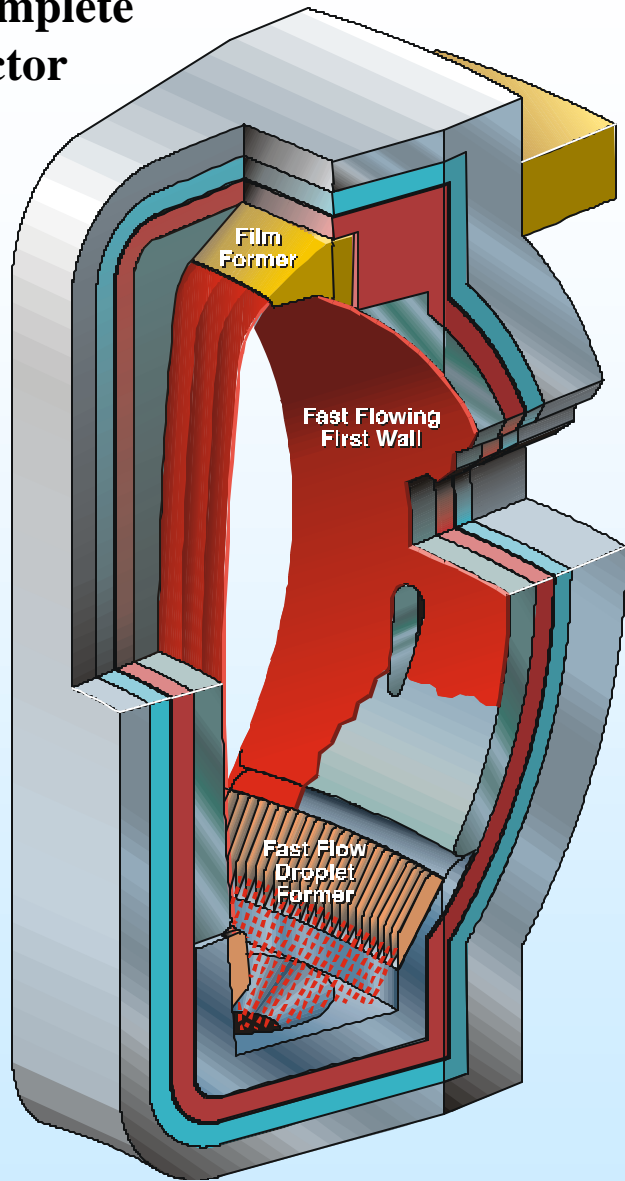
CLiFF - Convective Liquid Flow Firstwall

Potential Benefits if we can develop good liquid walls:

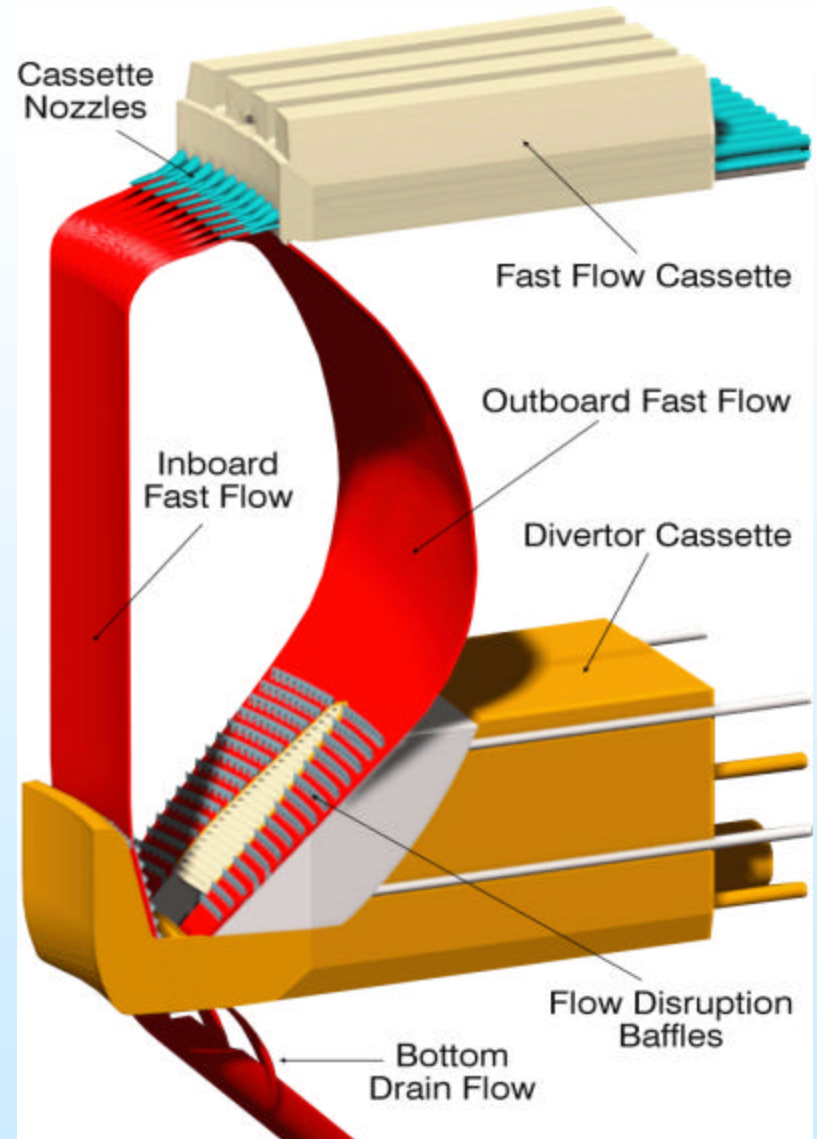
- Improvements in **Plasma Stability and Confinement**
 - Enable high β , stable physics regimes if liquid metals are used
- High Power Density Capability
 - Eliminate thermal stress and erosion as limiting factors in the first wall and divertor
 - Results in smaller and lower cost components
- Increased 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

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

Complete Sector

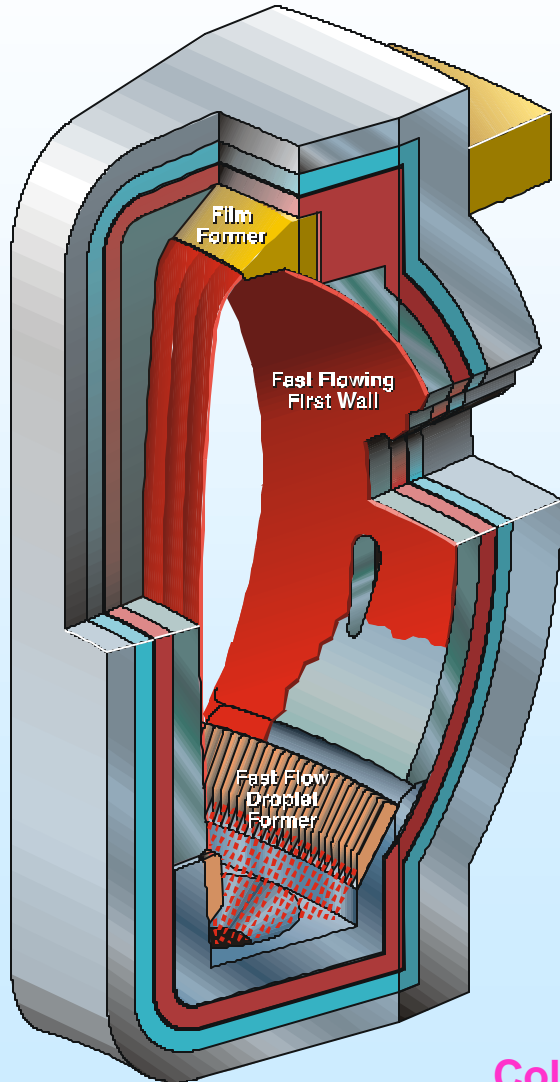


Liquid Wall Components

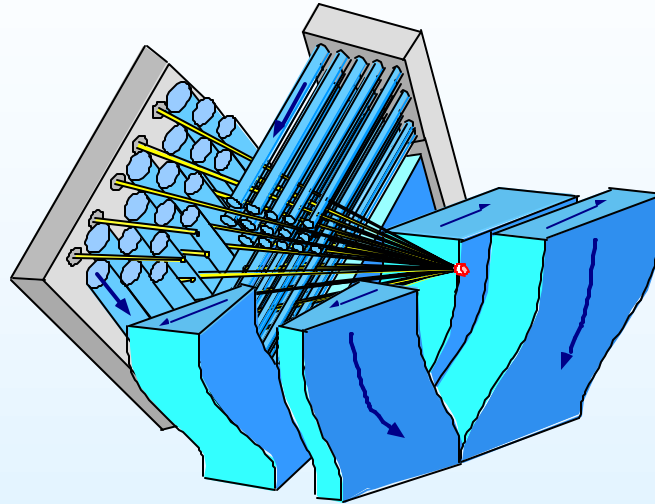


Thin Liquid Wall Concept

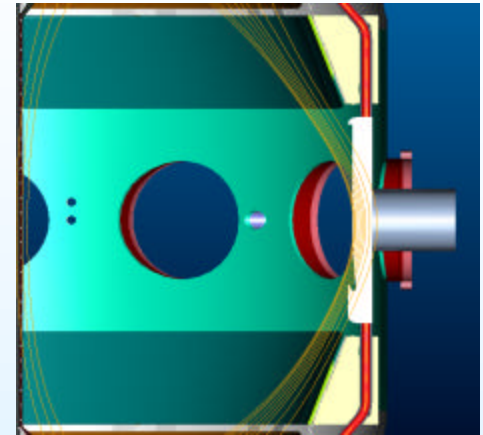
Liquid Wall Science & Technology are being Advanced in Several MFE & IFE Research Programs



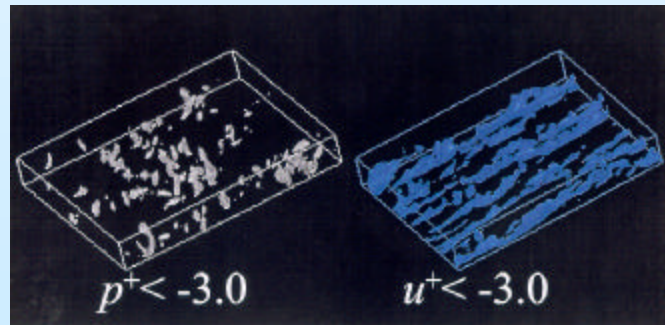
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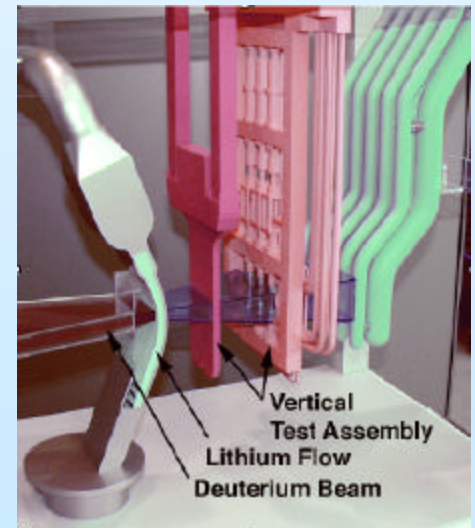
HYLIFE-II



ALPS/APEX NSTX Li module



DNS Free Surface Simulation
Collaboration with non-fusion scientists
US-Japan Collaboration

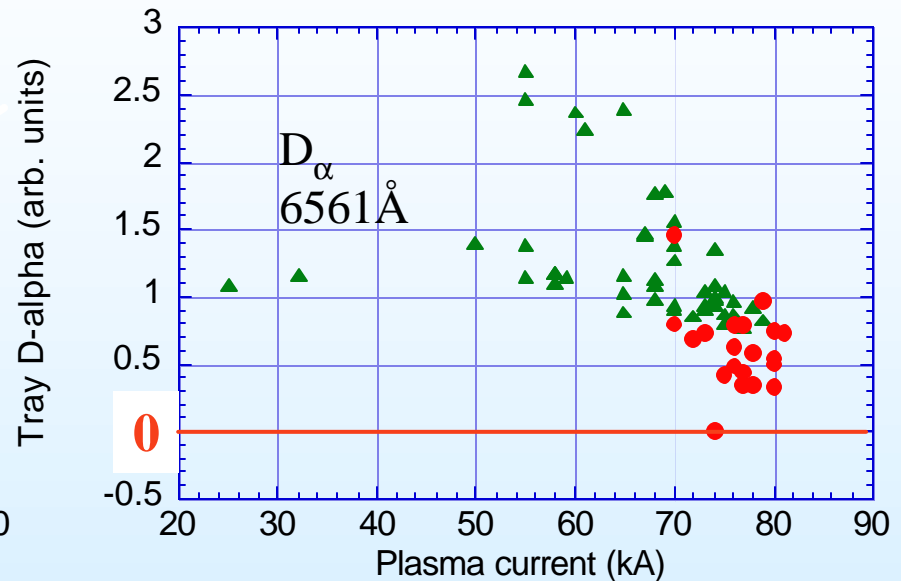
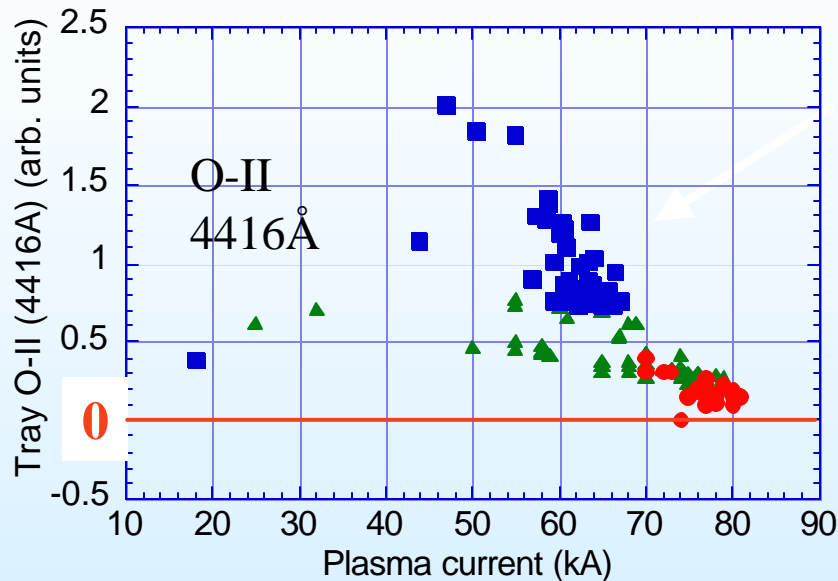


IFMIF

Remarkable Progress on Liquid Wall Research in the Past 3 years

- New **Design** Ideas for Liquid Walls in MFE Have Evolved
(Elaborate Liquid Wall Designs for IFE have long existed)
- Key Technical **Issues** Identified & Characterized
- **R&D** Effort on Top Issues Initiated: Significant Progress
 - ◆ **Modeling**
 - Plasma Physics Edge & Core
 - Fluid Mechanics, MHD, Heat Transfer
 - ◆ **Experiments**
 - Laboratory Experiments on Thermofluids (w/ & w/o MHD)
 - Laboratory Experiments on Sputtering & Particle Trapping, etc.
 - Tokamak Experiments: Liquid Lithium in Actual Plasma Devices

Best CDX-U Plasmas Achieved with Liquid Lithium Limiter

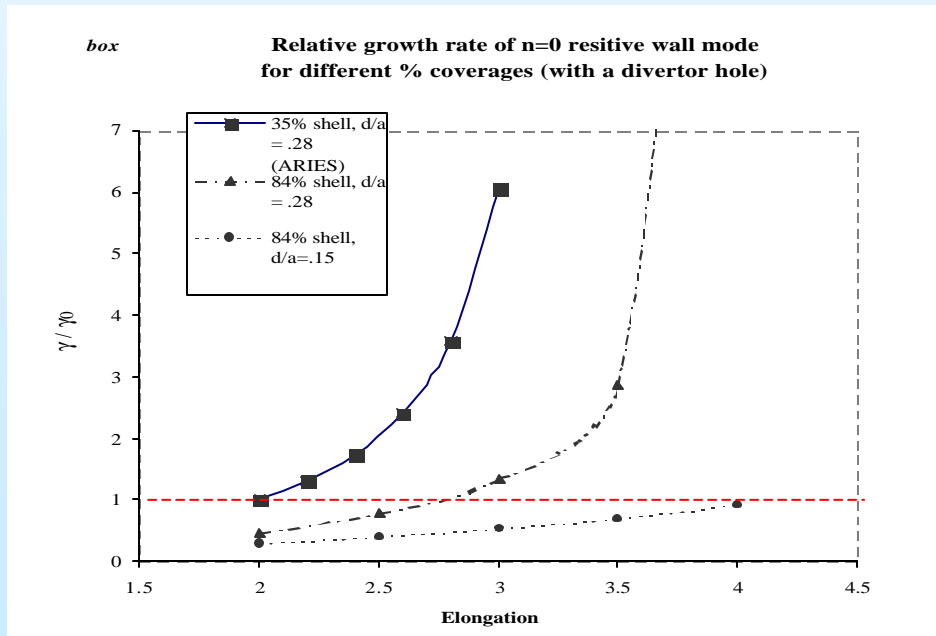


■ Bare SS tray limiter ▲ Cold lithium limiter ● Liquid lithium limiter (250° C)

- Highest plasma currents and lowest impurity emission ever obtained in CDX-U were achieved with liquid lithium in the tray limiter
- Plasma recycling is very low on liquid lithium
 - Possible that the recycling coefficient is zero

Utilization of Liquid Metals for a Conducting Shell May Allow Higher Power Density Tokamak Plasma

- Initial results from **new WALLCODE resistive MHD code**: **Stable** highly elongated plasmas possible with appropriately shaped conducting shell
- Liquid metals may be used for the conducting shell
- **Implications for fusion:**
 - High power density plasma (plus power extraction capability)
 - Overcome physics-engineering conflicting requirements that reactor designers have struggled with for decades

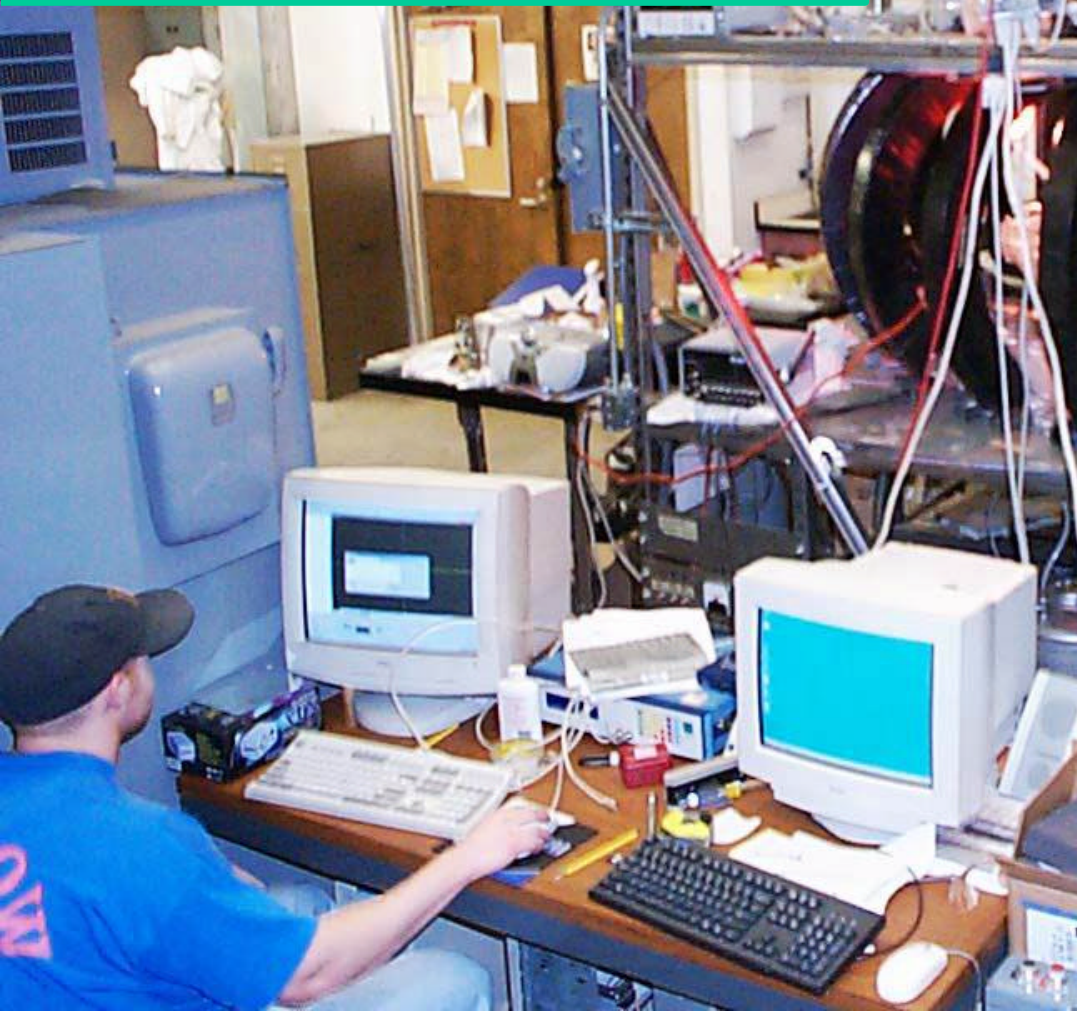


Beta Limits for high elongation (example of initial results)

k	b*
2	7.6 %
3	15.8 %
4	21.8 %

Magnetic TOROIDAL Facility (MTOR) has been constructed

Multiple MHD experiments currently underway



- 24 electromagnets:
600KW, 130 KJ stored energy
- $B_{\max} = 0.6 \text{ T}$ ($>1.0 \text{ T}$ with magnetic flux concentrators)
- 15L room-temp Ga-alloy flowloop



HEAT TRANSFER - EDGE PLASMA MODELING FOR FLINABE FW SHOWS HIGH HEAT LOAD CAPABILITIES

Flinabe

- Melting Point = 240 - 310 C
Inlet T ~ 350 C
- From Plasma-edge modeling
T (allowable) = 480 C - FW
= 700 C - Divertor
- Turbulent FLINABE layer
can tolerate high heat fluxes:
FW: 1.4 MW/m^2 (averaged)
Divertor: 30 MW/m^2 (peak)
(accounting for B effect with
no flow mixing)
- Further improvements are
possible through, for
example, mixing the liquid
right before the divertor
inlet

