Snowmass
Fusion Technology Working Group

Summary

Presented by
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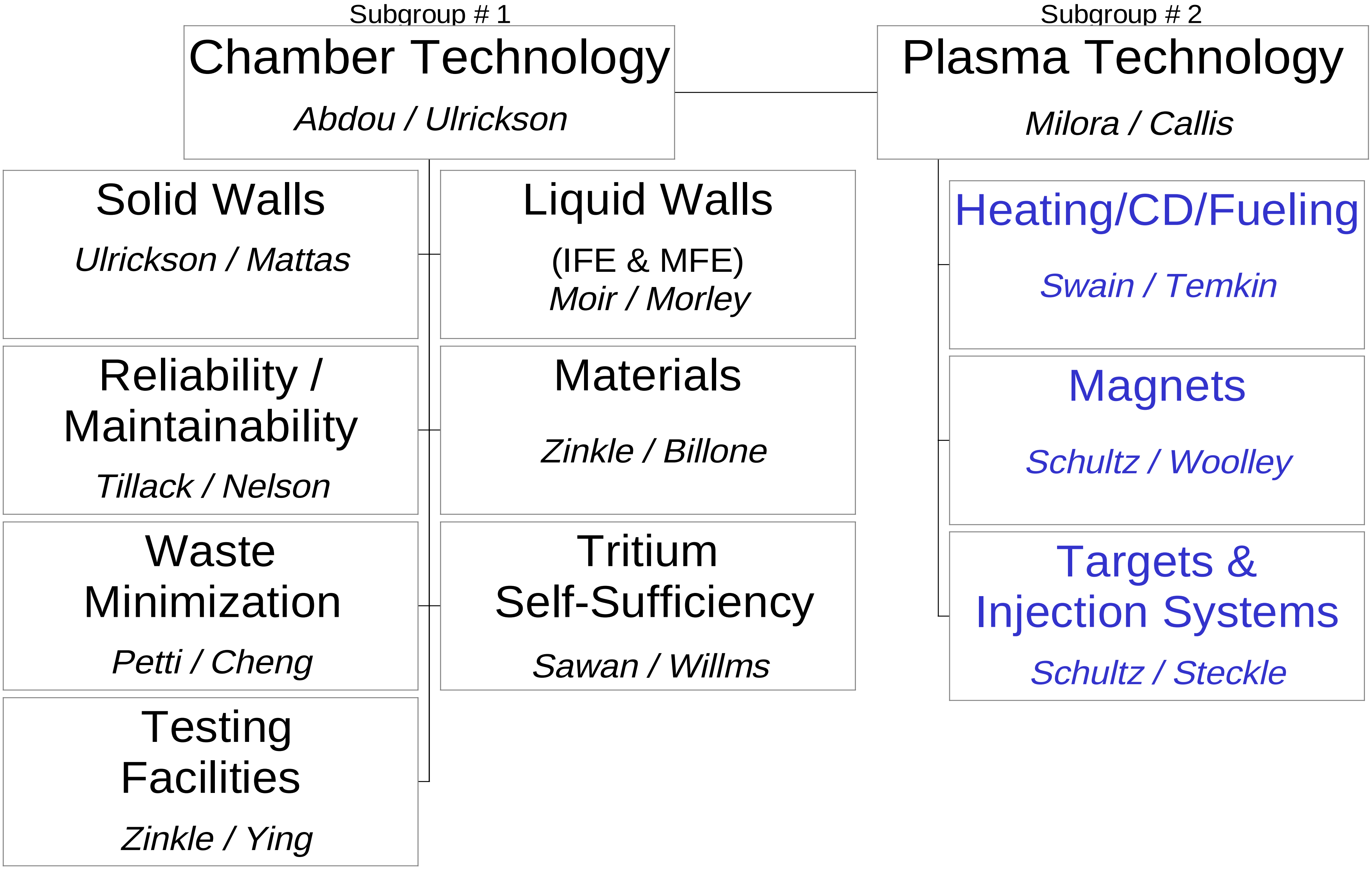
Snowmass
July 23, 1999

Technology Working Group



Subgroup # 1

Chamber Technology

Abdou / Ulrickson

Subgroup # 2

Plasma Technology

Milora / Callis

Solid Walls

Ulrickson / Mattas

Liquid Walls

(IFE & MFE)
Moir / Morley

Reliability / Maintainability

Tillack / Nelson

Materials

Zinkle / Billone

Waste Minimization

Petti / Cheng

Tritium Self-Sufficiency

Sawan / Willms

Testing Facilities

Zinkle / Ying

Heating/CD/Fueling

Swain / Temkin

Magnets

Schultz / Woolley

Targets & Injection Systems

Schultz / Steckle

Outline

- ❑ Vision for Technology Research
- ❑ Chamber Technology
- ❑ Plasma Support Technology

Note

- ➢ **The presentation DOES NOT cover all key points from the Snowmass sessions, only Selected Highlights**

- ➢ **The Draft Summary, being prepared, will cover all the key points**

Exciting Opportunities for Fusion Technology Research in the Next Decade

Partnership with Fusion Plasma Research to Provide Essential Contributions to:

I. Creating an Improved Vision for an Attractive and Competitive Fusion Product and a Cost-effective Path for Fusion Development

II. Enabling Near-Term Fusion Progress

III. Advancing Science

Creating Improved Vision through Performance Enhancement, Cost and Complexity Reduction

Magnets	• Reduce cost (factor of 2) and reduce size
Plasma Profile Control	• Develop high power density, efficient heating and current drive systems
PFC/ Solid Walls	• Extend capabilities of solid wall concepts • Develop reliable, long-life plasma facing materials capable up to 50 MW/m^2 with low tritium retention
Availability	• Increase emphasis on maintainability and reliability in design studies and as a metric for confinement and technology concepts

Creating Improved Vision through Innovative Solutions

Safety and Environmental	• **Develop new rad-waste management strategy that minimizes both volume and hazard**
Liquid Walls	• **Develop liquid wall concepts for both MFE and IFE**
Materials	• **Increase performance limits for low activation materials** • **Expand scope to include high performance refractory alloys**
Tritium	• **Explore ways to ensure tritium supplies for future needs (Develop breeding technology on burning plasma devices?)**

Enabling Near Term Fusion Progress

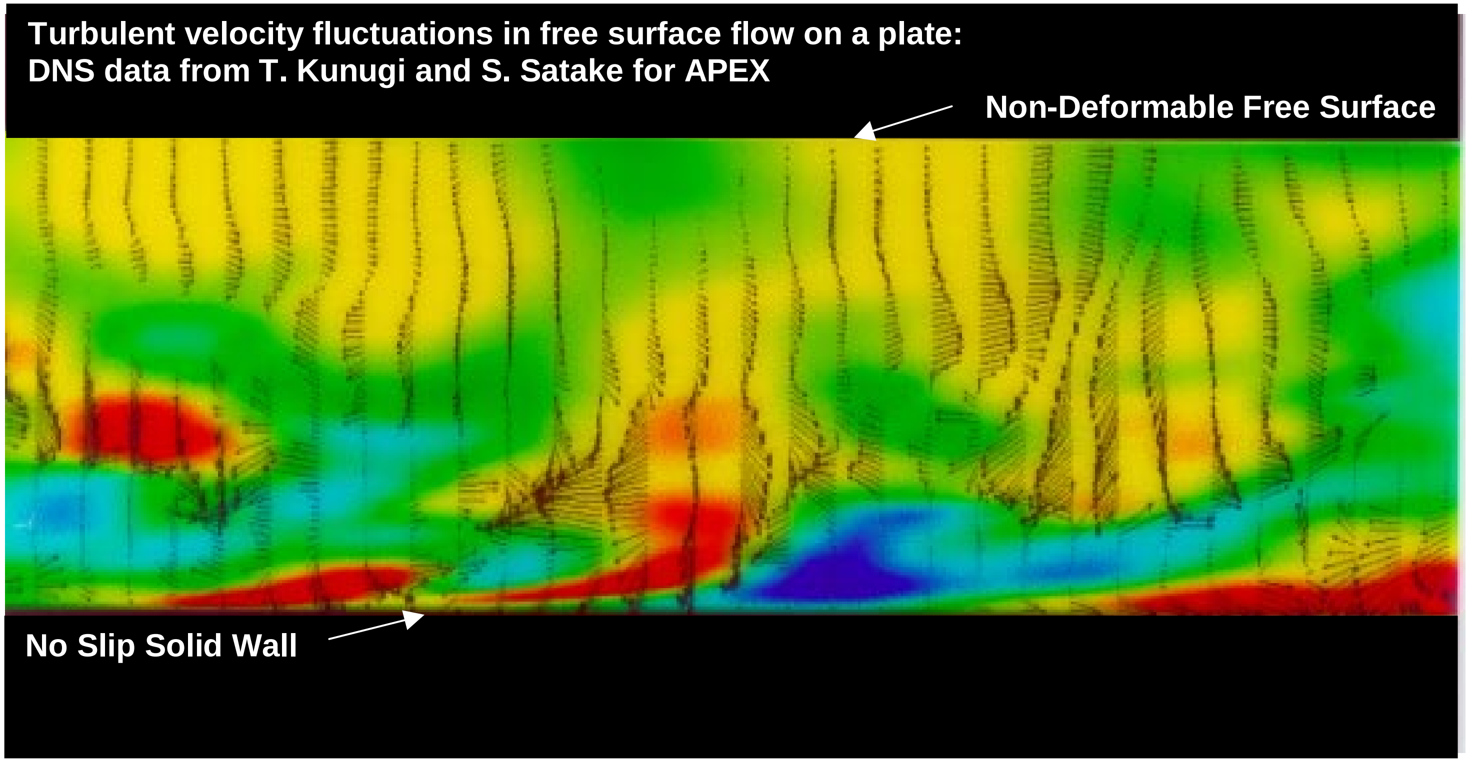
- ☐ Develop tools to locally optimize and sustain plasma profiles
- ☐ Develop disruption avoidance and mitigation techniques
- ☐ For PFC: Apply new refractory alloys with improved thermal shock and radiation damage resistance
- ☐ Develop targets for IFE/IRE including fabrication, injection and tracking.
- ☐ Utilize existing facilities and construct new non-neutron test facilities for chamber technology exploration. Assess neutron source options and recommend strategy and priorities

Advancing Science

Technology Research will continue to offer excellent opportunities for advancing science by:

- ♦ **Enabling Plasma Science**
- ♦ **Advancing Engineering Sciences**

Example: Turbulent interaction with free liquid



Turbulent velocity fluctuations in free surface flow on a plate:
DNS data from T. Kunugi and S. Satake for APEX

Fusion Science and Technology also Contribute to Near-Term National Goals

- **For example, in the areas of:**
  - plasma processing and surface modification
  - advanced plasma thrusters for spacecraft
  - next generation lithography for microelectronics

Helicon plasma sources

for plasma processing and space propulsion

- **Such applications increase the value of the fusion program as perceived by the public**

- **A balanced level of research in these areas can also contribute new ideas to help advance fusion research**

Chamber Technology

Re-Structuring has Resulted in major Changes in Chamber Technology

Research Focus

1. **Emphasize Scientific EXPLORATION of INNOVATIVE concepts with more promising potential**
2. **Establish US Leadership in Advanced Chamber Technology Concepts**
3. **Enhance Collaboration with International Programs by focusing on areas of unique US capabilities**

The Snowmass Discussions have Reinforced this new focus.

Environmental Concerns: Radioactive Waste

Current Waste Management Strategy

All activated materials should qualify for shallow land burial (Class C)

Approach: Minimize hazard via the use of low activation materials

Issues

1. **Radwaste volume is very large**
   - **Fusion waste volume is 3 to 10 x that of fission**
2. **Will the shallow land burial be practical for radwaste from fusion?**

Opportunities For Better Environmental Impact

Consider New Strategies for Waste Management:

Minimize both volume and hazard, i.e.,

- Limit activation in large volume components so that they can be cleared or recycled for re-use
- Minimize activated material that cannot be cleared or recycled

Technological innovations can reduce volume of waste:

- High power density designs (e.g. liquid walls; refractory materials)
- Re-optimize existing designs; reduce radial build and volume

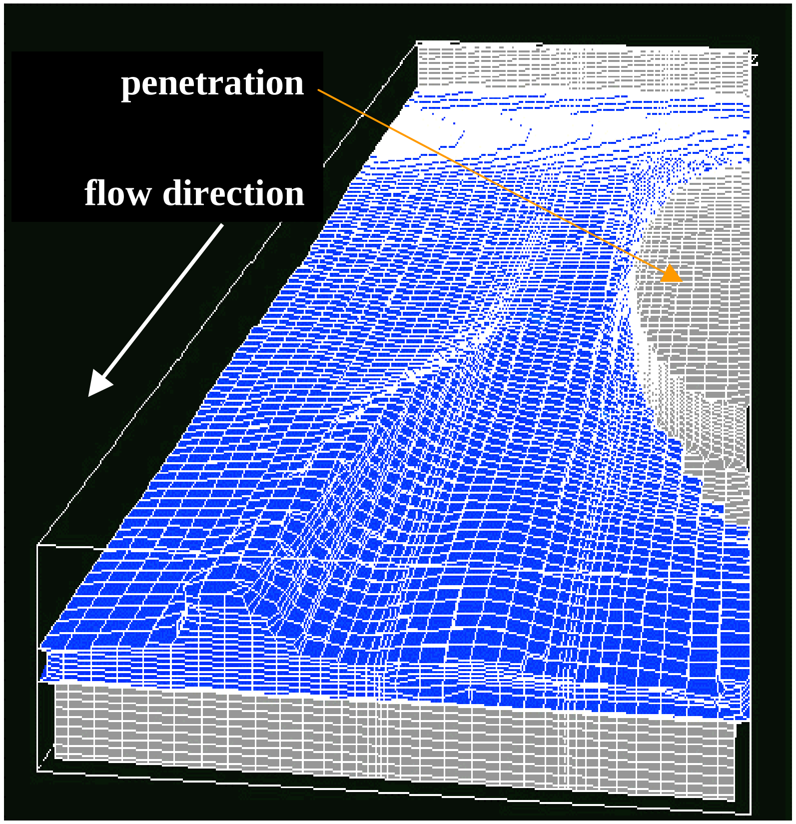
Recycling/reuse minimize waste volume. Low activation allows for multiple recycling

What Happened in the Liquid Wall Discussions at Snowmass?

- Themes of improved vision, reduced development cost, enabled physics regimes, and physics/technology, MFE/IFE synergy were evident

- Many configurations and concepts using the liquid wall idea were presented. The area is very concept-rich

- Facility needs and R&D pathway were discussed



3D-CFD calculation of liquid Flibe flow past an elliptically-shaped penetration.

Why Develop Liquid Walls?

- Liquid walls have the potential to lead to an **improved fusion energy reactor product**. Examples:
  - High power density, impulse loading, and disruption handling capability
  - Enabling high β, stable physics regimes
  - Reduction in volume and hazard of radioactive waste
- Liquid walls have the potential to **reduce MFE/IFE development costs**. Examples:
  - More tractable materials development and testing issues
  - Liquid wall proof-of-principle without neutrons
  - Near-term HHF technology for long-pulse physics experiments

Opportunities for Liquid Wall Research in the Next Decade

- Liquid Walls are **now entering into concept exploration**.
  - **Quantify the potential benefits** and identify trade-offs
  - **Explore concept variations** that utilize the LW idea
  - **Explore generic critical issues** in hydrodynamics, plasma transport, surface composition, sputtering, *etc*.

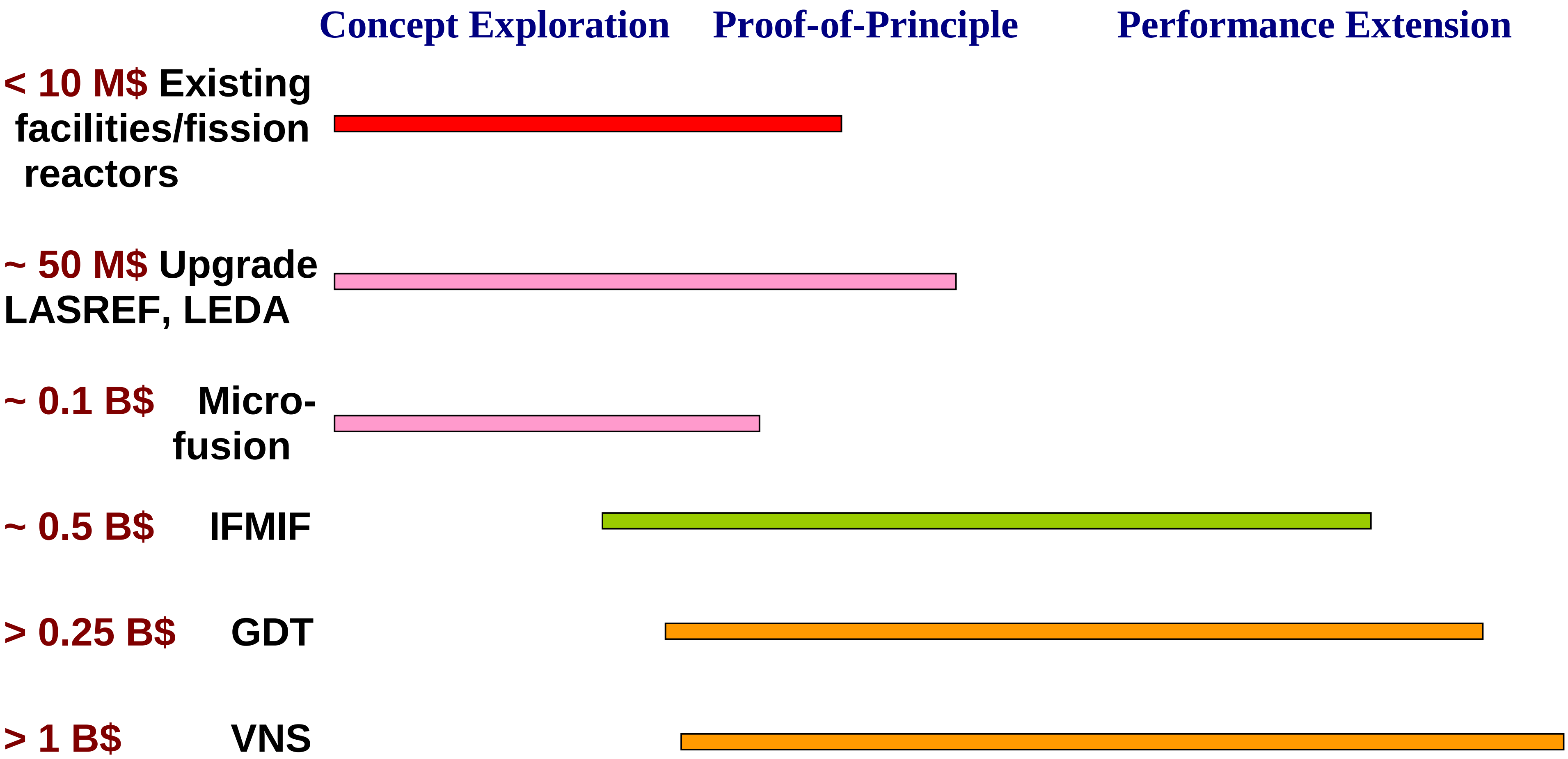
- **Generic facility needs** have been identified:
  - LM-MHD/Free Surface Flow in Tokamak-like B-Fields
  - Thermal-Fluid Flibe Simulant Flow and Flibe Handling
  - Laser/HI Beam Propagation in Vapor and Droplet Mists
  - HHF, Sputtering, and Plasma Interaction Experiments

- Testing in tokamaks should initially focus on divertor, but full potential will require all-liquid wall plasma experiments

Facility Opportunities for Chamber Technology Issues

- **Develop Non-Irradiation Test Facilities (e.g., Thermal-fluid facility for IFE/MFE Liquid Walls) < 10 M$**
- **Assess Neutron Source Options and Recommend Strategy and Priorities**

Neutron Source Options



Concept Exploration **Proof-of-Principle** **Performance Extension**

< 10 M$ Existing facilities/fission reactors

~ 50 M$ Upgrade LASREF, LEDA

~ 0.1 B$ Micro-fusion

~ 0.5 B$ IFMIF

> 0.25 B$ GDT

> 1 B$ VNS

MATERIALS ADVANCES

- **Major Opportunities**
  - **NEW high-performance and waste-minimization strategies have opened the door for the consideration of NEW structural and plasma facing materials**
  - **Near-term, cost-effective materials R&D using non-nuclear and low-dose fission-reactor test facilities, along with modeling, to address key concept feasibility issues**
  - **Integration of materials R&D to improve advances in fusion technology (heating, confinement, PFC, blanket, etc.)**
- **Examples of Anticipated Advances**
  - **Increased T_{max} and ΔT for structural materials (Fe-, V-, W-alloys, etc.)**
  - **Increased surface heat flux capabilities for PFC materials**
  - **Improved performance & cost for optical, heating and magnet materials**

Potential for Achieving Tritium Self-Sufficiency

Major critical issues:

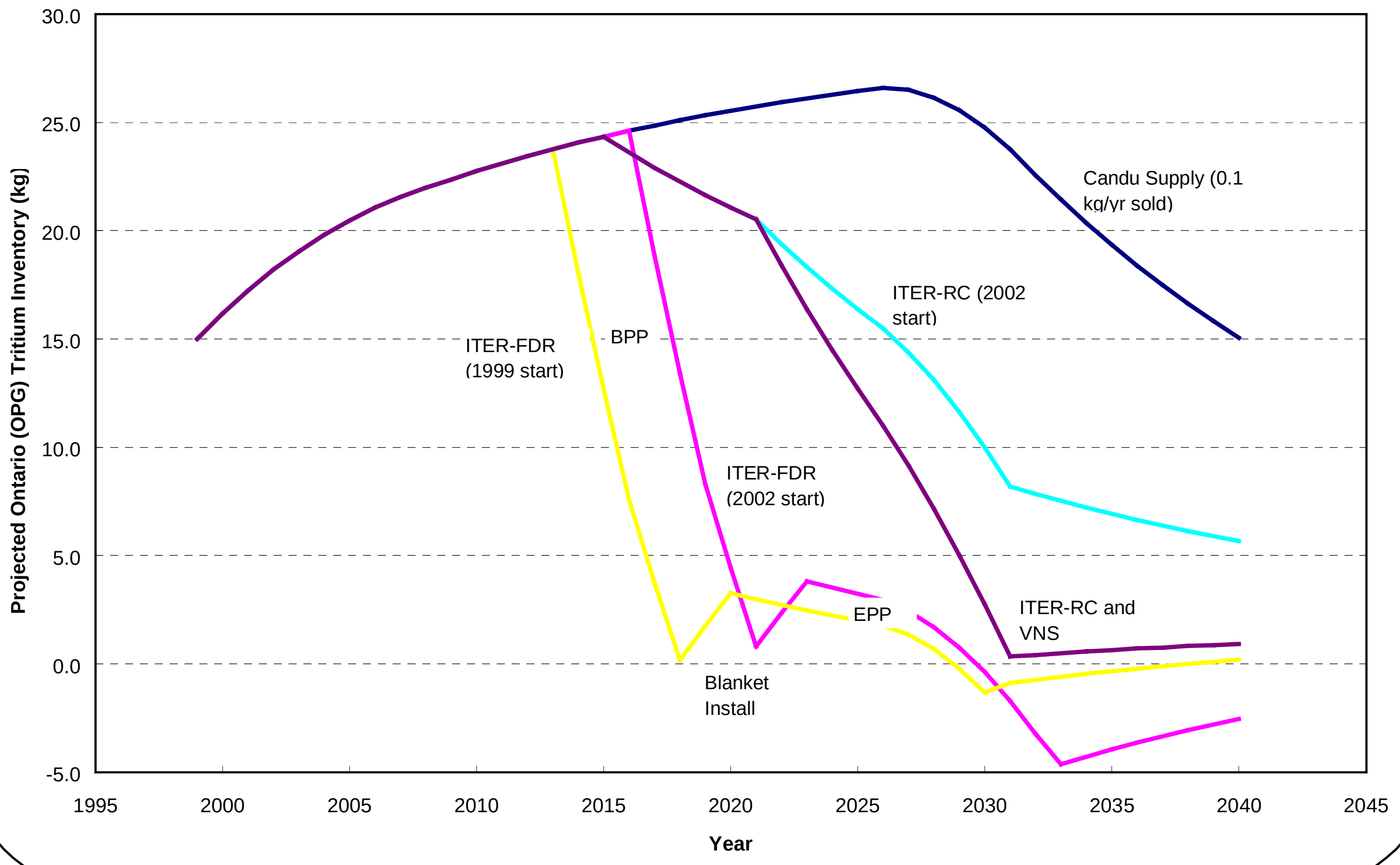
- Tritium supply is currently marginal and diminishes rapidly after 2025.
- Tritium self-sufficiency in DT fusion power plants can not be assured unless specific plasma and technology conditions are met.

Opportunities:

- Aggressive tritium breeding technology should start without delay.
- Near-term DT burning devices (e.g. ITER-like) should provide for testing breeding technology and have their own breeding capability.

- Definitive demonstration of tritium self-sufficiency can be performed only in a DT fusion facility. These tests do not require long operating time.

Tritium available for D-T fusion development for various scenarios



Solid Wall

- Success Story: A ten fold increase in heat removal capability of PFCs.
- Extended performance of solid walls can lead to high performance with disruption avoidance
- Key Opportunities
  - Apply new refractory alloys that have improved thermal shock and possible radiation damage resistance
  - Take advantage of existing disruption facility to test new materials for both MFE and IFE
  - Leverage access to international research with work on conventional systems

Reliability, Availability, Maintainability, Inspectability (RAMI)

- **We *assume* 75% availability for an attractive reactor,**

  …..but none of our effort is applied to this goal

- **Both *reliability* and *maintainability* are important:**

Availability = MTBF/(MTBF+MTTR)

- **Both should be raised to a high level of importance**

  …..in next step options, reactor studies, and emerging concepts

- -

- **Availability improvement depends on physics *and* technology**

Technology: **Vigorously pursue inovation, inside & outside fusion program**
Develop RAMI metrics

Physics: **Use RAMI as a discriminator in confinement concept development**

Plasma Support Technologies

Continuing the Partnership that Enables Progress on Fusion Devices

R. Callis, S. Milora, co-conveners

Sub-Topic Group Leaders

J. Schultz, K. Schultz, W. Steckle ,D. Swain, R.Temkin
R. Woolley

“Plasma Support Technologies” Are Needed for the Vision of a Lower Cost, Attractive Fusion Product

Achieve and Sustain Advanced Plasma Performance:

Fusion power density: $p_f \sim \langle\beta^2\rangle B^4$

Burn condition: $nT\tau \sim (\beta/\chi)\, a^2 B^2$

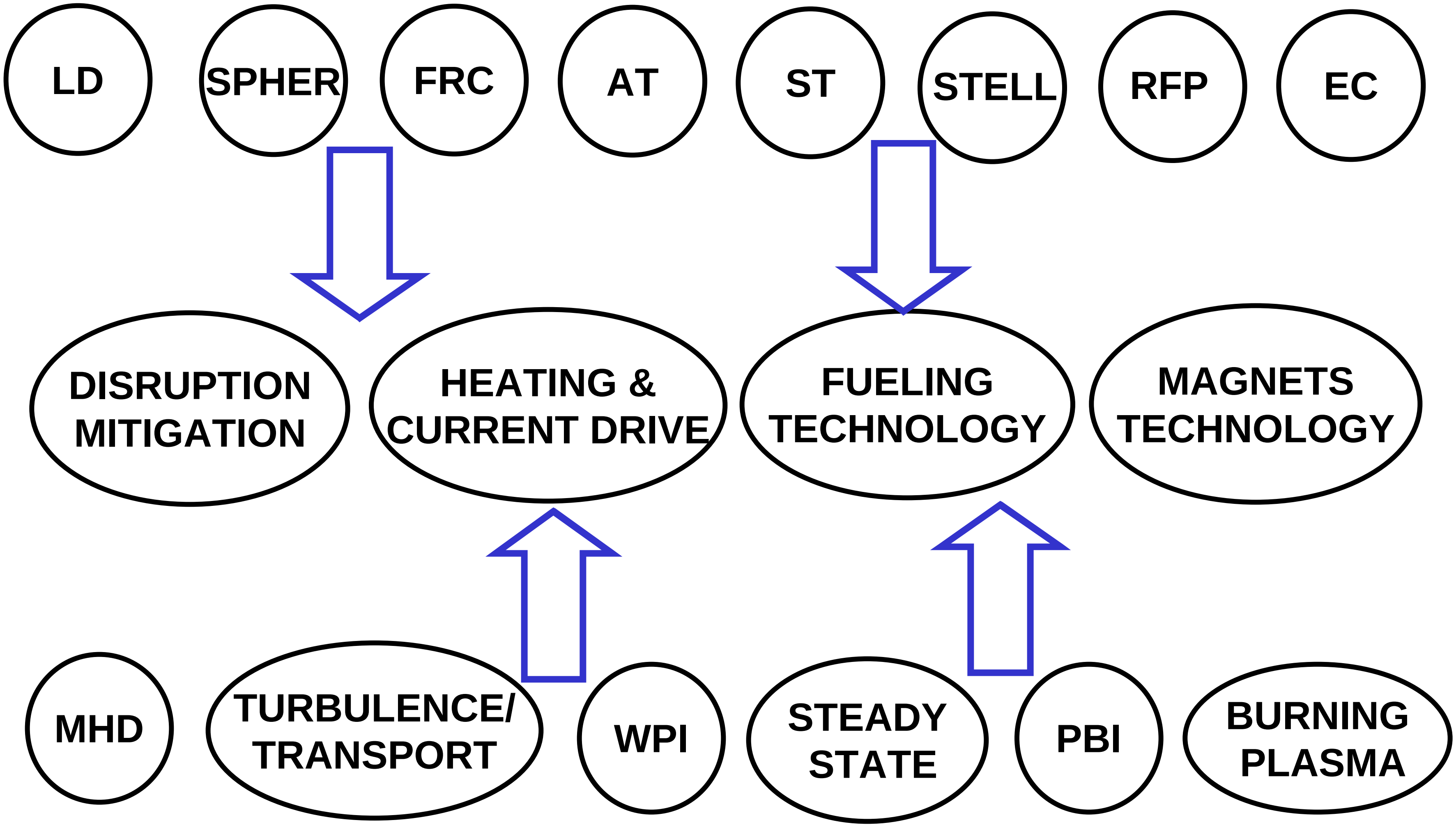
- **Profile Control Technologies:**
- Heating/current drive/fueling:
  - Increase β and β limits
  - Reduce χ, generate ITB

- **Disruption Mitigation/Control Technology:**
- Pellet/gas/liquid injection:
  - Enable operation near ultimate β potential

- **Magnet Technology:**
- High performance/low cost:
  - Improved strand, insulation, structural materials, thermal isolation, quench protection, joints

- **IFE Target Technology:**
- Low cost mass produced targets
  - 500,000/day @ < 30 cents
- Injection and tracking systems to deliver targets to precise location (in hostile environment?)

Fusion Energy Science Advances in a Partnership between Science and Technology



LD

SPHER

FRC

AT

ST

STELL

RFP

EC

DISRUPTION MITIGATION

HEATING & CURRENT DRIVE

FUELING TECHNOLOGY

MAGNETS TECHNOLOGY

MHD

TURBULENCE/ TRANSPORT

WPI

STEADY STATE

PBI

BURNING PLASMA

The Need for Improved Profile Control Technologies was Identified by Several Magnetic Fusion Concept and Science Cross Cutting Subgroups

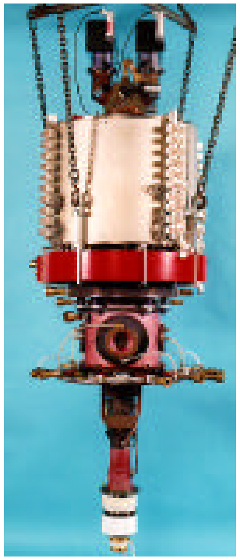
- MFE transport - control turbulence and transport/optimize confinement
  - Sharpen up current drive, heating, flow drive, and fueling tools
  - Tokamak, ST, RFP, Spheromak, ET
- MHD - avoid/mitigate disruptions and control tearing modes
  - profile control, current drive, RF stabilization
- Steady State - continuously sustainable high performance fusion plasma
  - Equilibrium, MHD, profile control
    - IBW/ EBW(ITB), HHFW/OFCD/LH/EC(CD), SC magnets
- Burning plasmas
  - Fueling (for burn control), current drive, disruption amelioration

The Need for Improved Profile Control Technologies was Identified by Several Magnetic Fusion Concept and Science Cross Cutting Subgroups

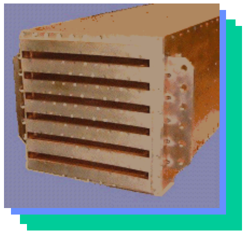
- Integration and Performance Measures
  - AT
    - Disruption mitigation, profile control(equilibrium)
  - ST
    - Non-inductive current ramp and sustainment, profile control(equilibrium)
  - RFP
    - Efficient sustainment of current

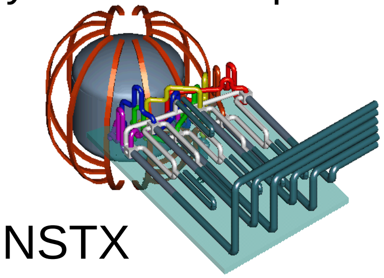
- Wave Particle Physics
  - Develop reliable rf plasma control techniques for j(r) control
  - P(r) control by localized heating and fueling
  - IBW for shear flow has great potential for ITB if developed

Heating and Current Drive Major Opportunities - Localized Power and Current Deposition

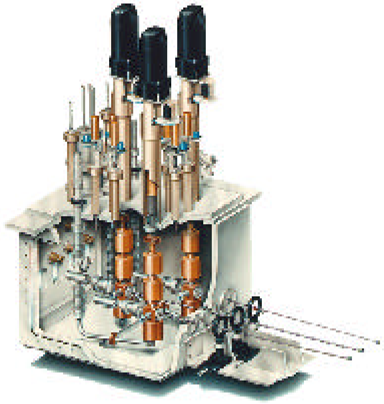


- Electron Cyclotron Heating (ECH)
  - Develop gyrotrons with increased reliability and lifetime
  - Increase gyrotron power (x2, 1MW → 2 MW)
    - Develop long pulse launcher
  - Increase gyrotron efficiency (x2, 35% → 70%)
    - Decrease system cost
- Ion Cyclotron Heating (ICH)
  - Develop reliable, flexible systems
    - Handle changing plasma conditions with dynamic CD capability
  - Increase launcher power density (x2)
    - Understand voltage limits
    - Develop and test new launcher concepts



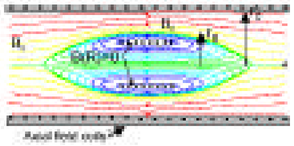


Fueling Opportunities - Density Profile Peaking



- Pellet Injection
  - Develop High Field Side launch technology and fueling physics scaling for advanced fueling scenarios.
  - Increase pellet speed by x2 to fully exploit HFS launch potential for strong profile peaking.

- CT Injection - accelerated FRC
  - FRCs may be more effective(higher density) than CT injection
  - CE experiments needed on a plasma facility to demonstrate trapping, disassembly and fuel deposition mechanism, and effects on plasma parameters.



Disruption Mitigation and Control - Enable Safe High β Operation

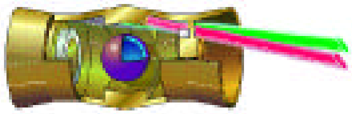
- Recent tests with high Z pellets (C-MOD, DIII-D) and high pressure He gas (DIII-D) have demonstrated ability to “soften” thermal quench and vessel forces during VDE disruptions

- Develop low-Z mitigation techniques (i.e. massive gas-puff, liquid jet injector, etc.).

- Integrate detection and mitigation systems into the control system of an existing tokamak to test and demonstrate reliability.

IFE Target Fabrication and Injection Technology
Near Term Opportunities

- Before IRE is approved, a credible pathway to low cost, high quality target fabrication and accurate target injection and tracking must be demonstrated.
  - IFE target materials (foam capsules and hohlraums)
  - Accurate mass production (~500,000/day) fabrication techniques (microencapsulation, fluidized bed coating,…)
  - Projection to acceptable fabrication costs
  - Injection and tracking in a surrogate chamber



- The IFE IRE (PoP) will require rep. rated (~5 Hz) surrogate target fabrication, injection and tracking

Magnet Technology Opportunities
Low Cost High Performance

- Improve magnet cost / performance by a factor of ~2
  - for MFE: through materials / component improvements;
  - for IFE: through prototype development
- Undertake concept exploration development for low and high temperature superconductors. Potential cable cost reduction of 3-10.
- Details:
  - Small concept exploration facility for SC cables needed.
  - Insulation with >10 x improvement in radiation dose.
  - Improvements in manufacturing and assembly, especially joints.

A Stronger Effort is Required to Meet the Increased Needs of the Fusion Program

- Cutting edge R&D at the dedicated development facilities within the program. Build selected new facilities at ~ $1M level.
- Early application of technology advances on existing and planned domestic experimental facilities to advance the state-of- the art (feedback).
- International collaboration and deployment of technologies on foreign facilities to pursue issues of long pulse, high power density and energy-producing plasmas, leveraging the international program's investment in large performance extension facilities.

Technology Development is Needed to Meet Requirements from Physics Groups for Future Experiments

Tools	Development needed	To get to
Heating & Current Drive	Better gyrotrons Better ion cyclotron launchers and control	Steady-state/ Advanced Performance/ Burning Plasma
Fueling	Faster inside-launch pellets Compact torus injection tests	
Magnets	Increased B-field/$ Improved innovative superconductor cable	
Disruption Mitigation	Fast, reliable disruption detection Fast low-Z liquid/gas injection system	
IFE Target Fab./Injection	Lower target cost 5-Hz rep. rate	Integrated Research Experiment(s)

MFE Plasma Support Technology Opportunities

Heating & Current Drive, Fueling, Magnets, Disruption Control

	AT or Profile Control	ICH	ECH	Helicity & CT Injection	Pellet Injection	NBI	Lower Hybrid	Magnets	Disruption Control	Divertor
C-Mod 3-5 s	√	ICRH FWCD MCCD IBW upgrade	170 GHz ECCD upgrade				LHCD	Sliding joints		PMI
NSTX 5 s	√	HHFW H&CD IBW waveguide	EBW ECH upgrade	Coaxial HI	upgrade				Passive plates	Coaxial HI
DIII-D 5-10 s 20 s	√	Faraday shield upgrade	ECCD 10 MW upgrade		Inside launch			Steady-state Coil upgrade	Killer pellet Gas puff Liquid jet upgrade	Vanadium-Upper PMI DIMES
NCSX 1 s	√	HHFW IBW Electron heating preferred	ECH Startup ECHeating upgrade		?	Long pulse upgrade	Upgrade?	LN-cooled Cu or SSC cable or HTS		upgrade
KSTAR* 20-300 s	√	FWCD	ECCD upgrade		?	√ 8-20 MW	LHCD	Nb_3Sn NbTi		Steady-state materials
JET* 20 s ?	√	Reliability Antenna upgrade			Inside launch upgrade					PMI?
LHD* CW	√	IBW Steady-state	CW gyrotrons	CT	Repeating		?	Data from NbTi		Local Island Divertor

MAIN THEMES

Flexible Profile and Shape Control

Transport Barriers

High- β with Disruption Avoidance

Steady-state Capability

*US Technology International Collaboration Opportunities

MFE Plasma Support Technology Opportunities

Heating & Current Drive, Fueling, Magnets, Disruption Control

	AT or Profile Control	**ICH**	**ECH**	**Helicity & CT Injection**	**Pellet Injection**	**NBI**	**Lower Hybrid**	**Magnets**	**Disruption Control**	**Divertor**
Tore Supra* 100 s	√?	FWCD			Repeating		LHCD	Superfluid NbTi		PMI
W7-X*	√	ICRH	CW Gyrotrons		Repeating			NbTi		
MST				Oscillating field CD Rotomak						
CDX	√	IBW 0.5MHz HHFW 10 MHz	ECH startup 2.45 GHz EBW 10 GHz?	Rotomak edge CD			1 MHz Alfven			Lithium Target divertor
FIRE		ICRH			High velocity inside launch			LN-cooled Cu SC-PF upgrade		
LDX			Multi-frequency					Nb_3Sn, NbTi and H_2O Cu and HTS		
LAPD	RF/Wave Diagnostics & Basic Science	Alpha Channeling IBW	ECH Startup ECHeating upgrade							
Pegasus	√	EBW Steady-state								Liquid walls?
JFT-2M*				Rotomak?						

MAIN THEMES

Flexible Profile and Shape Control

Transport Barriers

High- β with Disruption Avoidance

Steady-state Capability

*US Technology International Collaboration Opportunities

IFE Support Technology Opportunities

Magnets, Pellets, Chamber wall

	AT or Profile Control	ICH	ECH	Helicity & CT Injection	Pellet Injection	NBI	Lower Hybrid	Magnets	Pulsed Power	Chamber First wall
Electra KrF								NbTi LTS or HTS		Materials
HCTE Heavy Ion								NbTi LTS or HTS		Materials
HIFD Heavy Ion IRE						Li O2/C Li/SS LiAlO2/SiC PbLi/SiC		NbTi LTS Nb_3Sn LTS or HTS		Materials
IFE Generic					High precision Low cost				Rep-rate Cost	Materials
MTF								H_2O Cu		

MAIN THEMES

- **Low cost magnet assemblies**
- **High precision and low cost pellets**
- **First wall materials**
- **High rep rate pulsed power**