US ITER Test Blanket Module (TBM) Program:

US Participation in ITER TBM is essential for a credible US fusion energy program strategy

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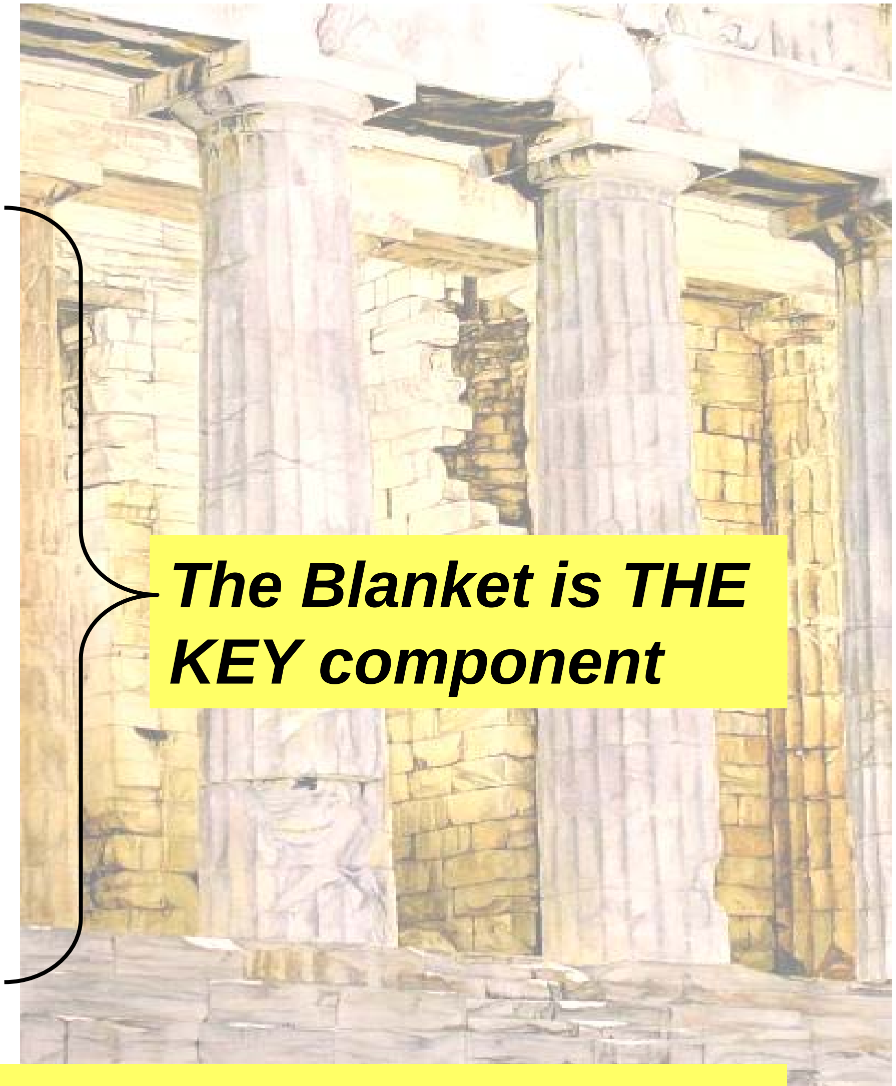
for the US ITER TBM Team

Fusion Energy Sciences Advisory Committee Meeting
Gaithersburg, Maryland
March 1-2, 2007

Pillars of a Fusion Energy System

1. ***Confined and Controlled Burning Plasma (feasibility)***
2. ***Tritium Fuel Self-Sufficiency (feasibility)***
3. ***Efficient Heat Extraction and Conversion (attractiveness)***
4. ***Safe and Environmentally Advantageous (feasibility/attractiveness)***
5. ***Reliable System Operation (attractiveness)***



The Blanket is THE KEY component

Yet, No fusion blanket has ever been built or tested!

Performing integrated breeding blanket experiments has been a principal objective of ITER since its inception

- ***"ITER should test design concepts of tritium breeding blankets relevant to a reactor. The tests foreseen in modules include the demonstration of a breeding capability that would lead to tritium self sufficiency in a reactor, the extraction of high-grade heat, and electricity generation."***

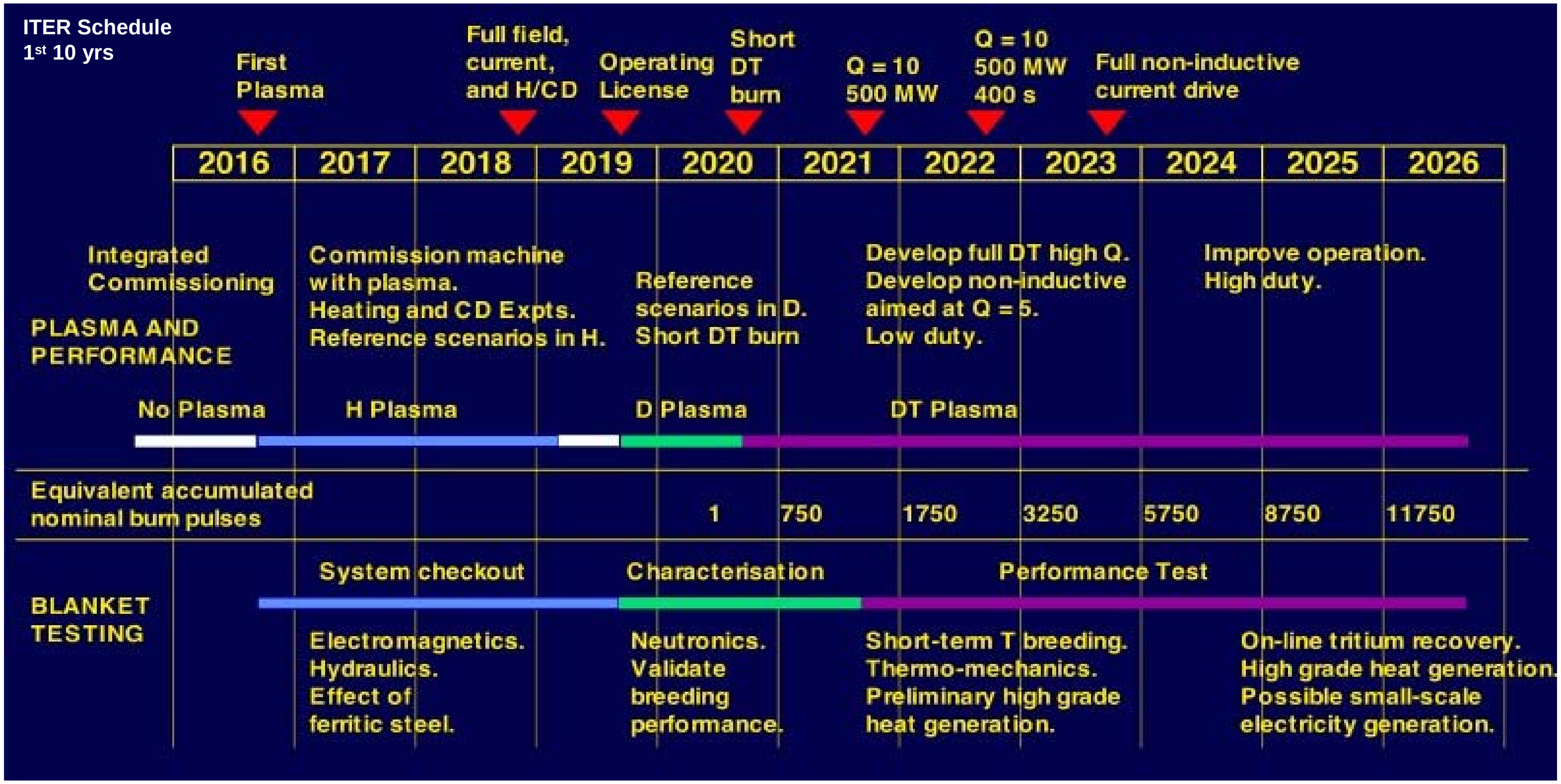
  SWG1, reaffirmed by ITER Council, IC-7 Records (14–15 December, 1994), and stated again in forming the Test Blanket Working Group (TBWG).

The need to test breeding blankets in ITER has been recognized many times in the US planning efforts for ITER

- "Deliver to ITER for testing the blanket test modules needed to demonstrate the feasibility of extracting high-temperature heat from burning plasmas and for a self-sufficient fuel cycle (2013)" A Strategic Program Plan for Fusion Energy Sciences. http://www.ofes.fusion.doe.gov/News/FusionStrategicPlan.pdf

- "Participate in the [ITER] test blanket module program", and "Deploy, operate and study test blanket modules", Planning for U.S. Fusion Community Participation in the ITER Program, US BPO Energy Policy Act Task Group, 2006

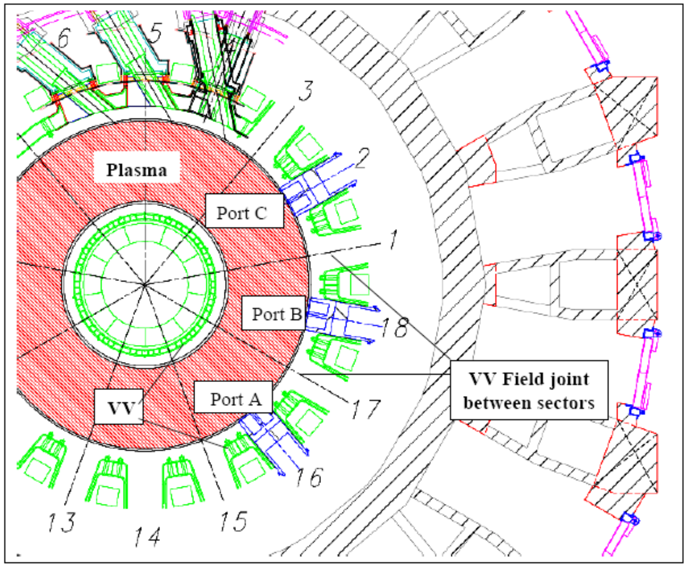
TBM is an integral part of ITER Schedule, Safety, and Licensing



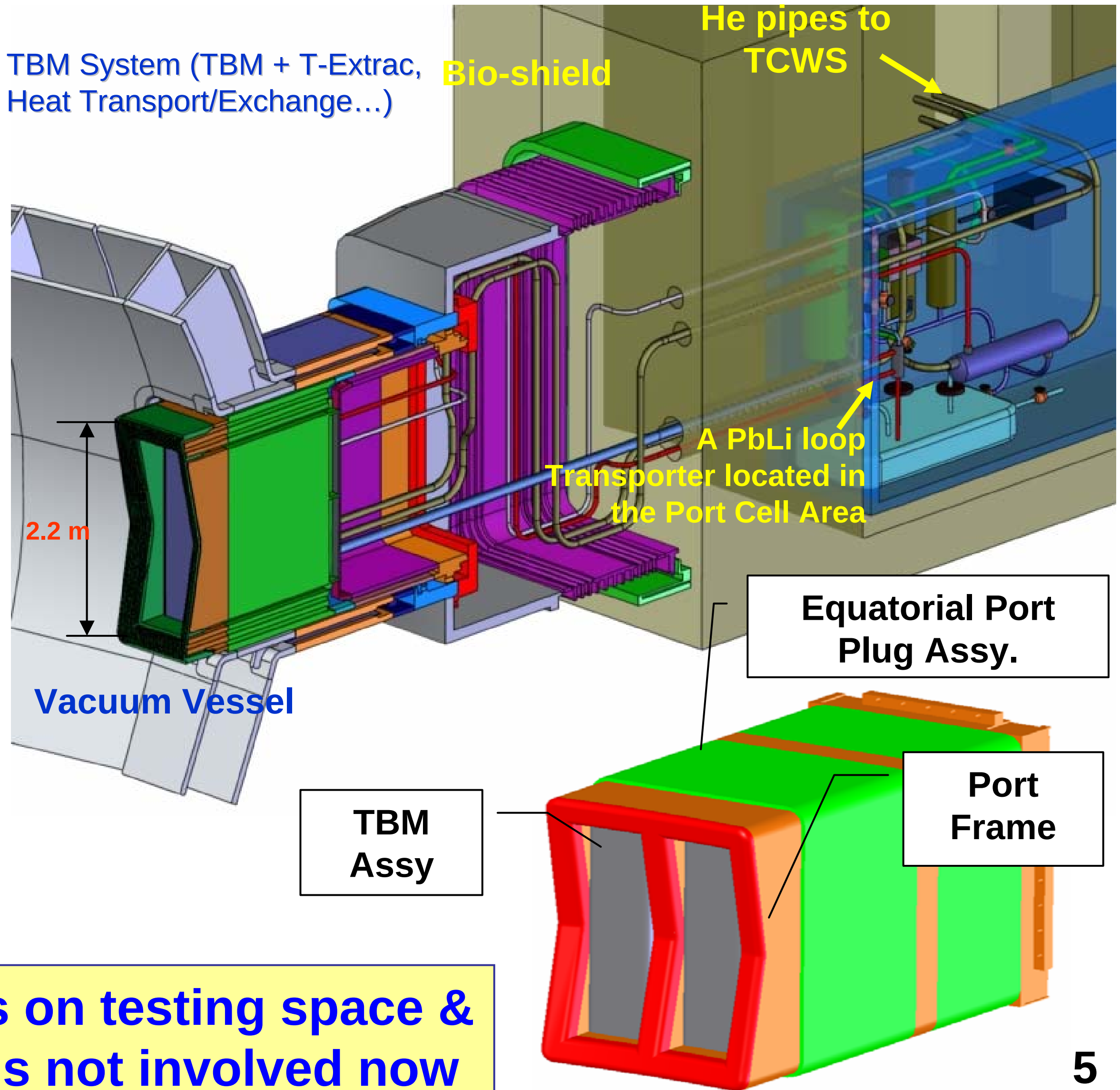
Early H-H Phase TBM Testing is mandated by ITER IO and licensing team:

1. Optimize plasma control in the presence of Ferritic Steel TBMs
2. Qualify port integration and remote handling procedures
3. License ITER with experimental TBMs for D-T operation

ITER Provides Substantial Hardware Capabilities for Testing of Blanket System

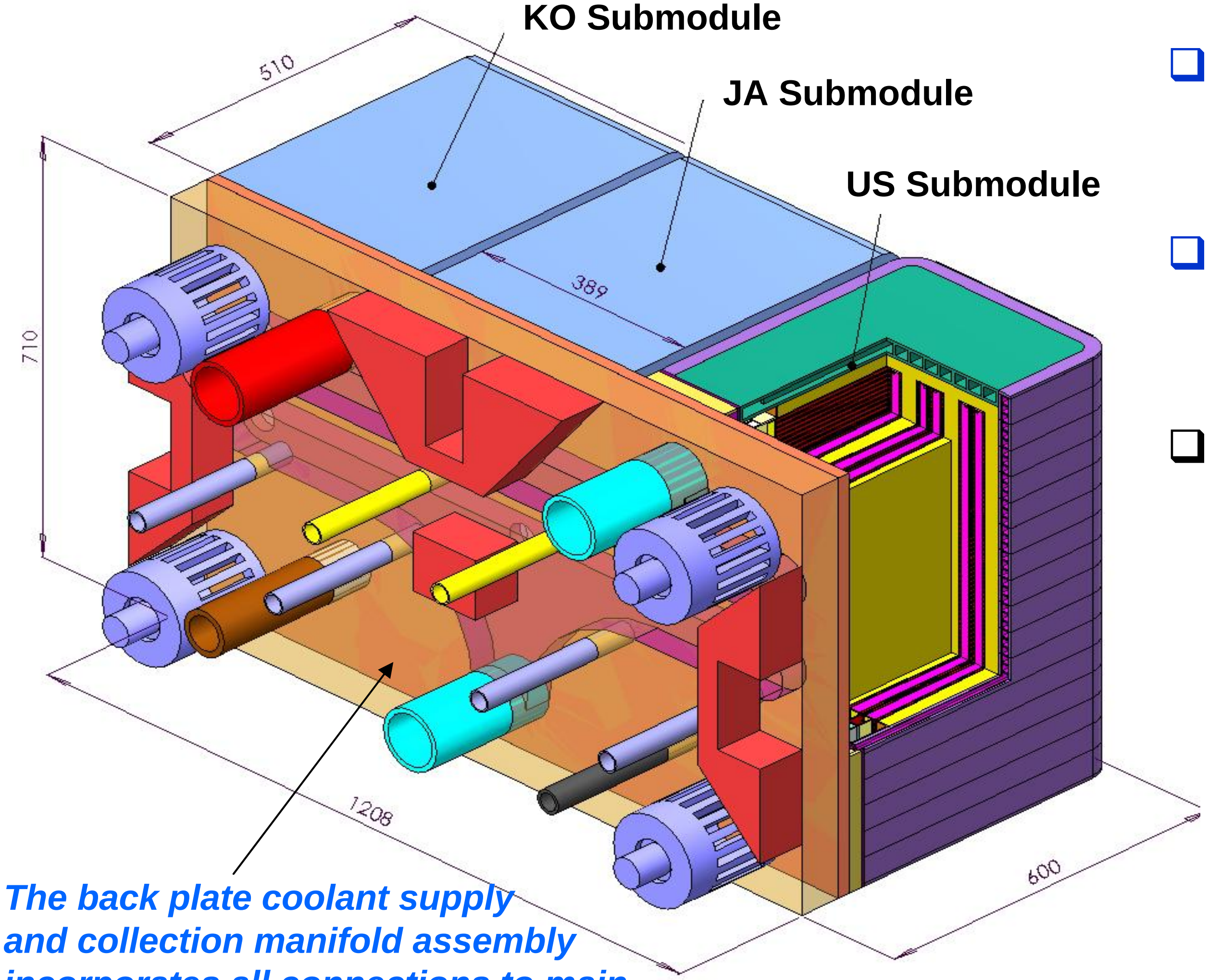


- ITER has allocated **3 ITER equatorial ports** (1.75 x 2.2 m^2) for TBM testing
- Each port can accommodate only 2 Modules **(i.e. 6 TBMs max)**
- But, 12 modules are proposed by the parties
  - ***Aggressive competition for Space***



US rights to and claims on testing space & time can be lost if US is not involved now

US advanced Ideas to Solve the TBM testing-space problem in ITER, while improving effectiveness of the tests



The back plate coolant supply and collection manifold assembly incorporates all connections to main support systems. A "Lead Party" takes responsibility for back plate and sub-module integration

- ***US experiments can focus on niche areas of US interest and expertise,***
- ***While benefiting from world resources and testing results***

- **Different sub-modules can be tailored to address the many different:**
  - **design configurations**
  - **material options**
  - **operating conditions (such as flow rates, temperatures, stresses)**
  - **diagnostics and experimental focus**

The US can benefit greatly from timely international collaboration with ITER partners

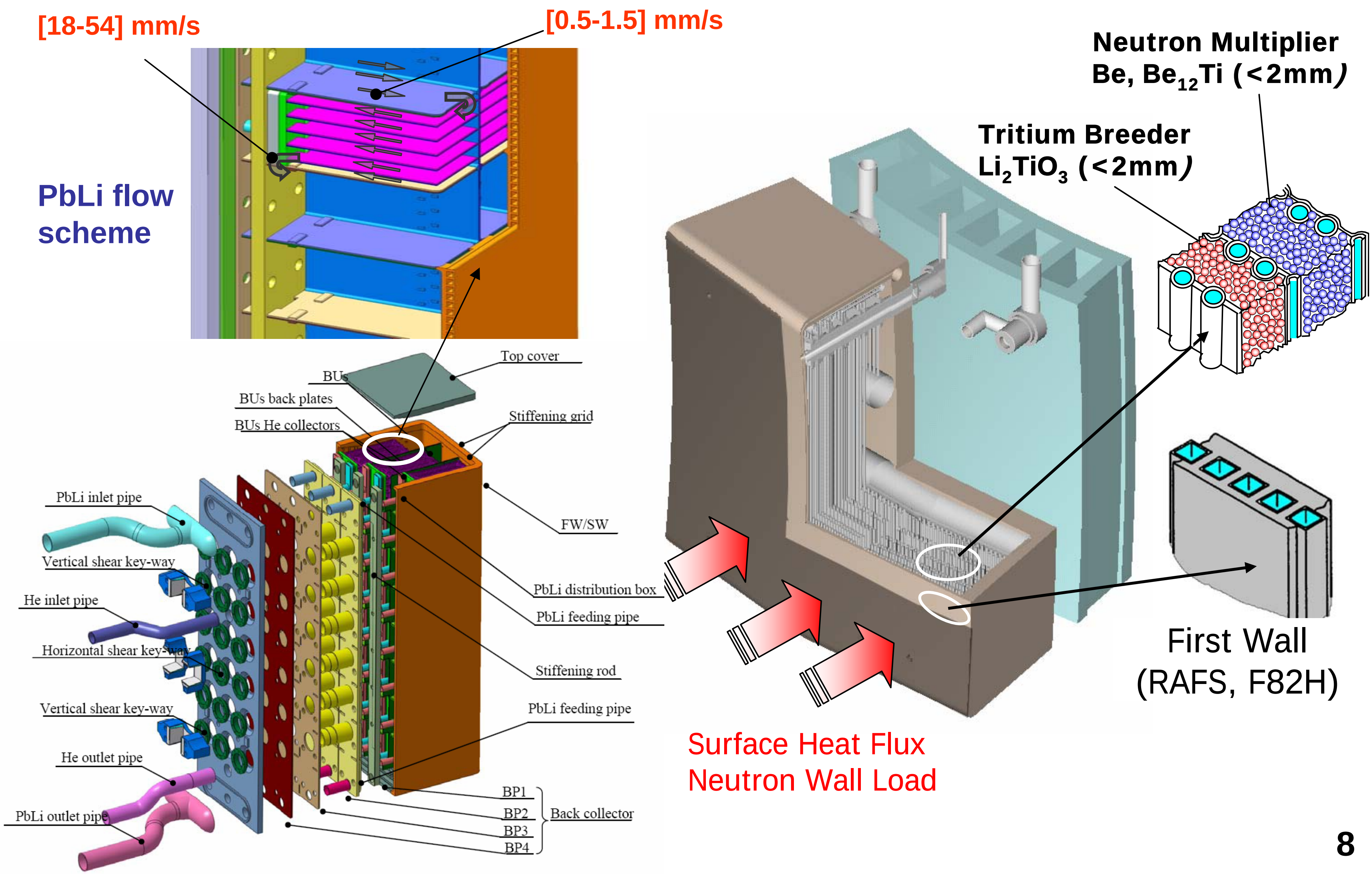
- US ingenuity, innovation, and leadership on Fusion Nuclear Technology have strongly influenced the world program over the past 35 years
  - ***Many parties have been continuously investing R&D resources in concepts the US invented and which are still of US interest***

- Other ITER parties are already committing significant resources to their TBM programs.
  - But these parties won't share their critical preparatory R&D, testing facilities, and TBM experiment results, unless reciprocated

- All ITER parties have a strong interest to collaborate with the US,
  - But are concerned about the delay of an official US position and commitment to Test Blanket experiments in ITER

An early signal of US commitment and intention of continued leadership will enable negotiating international agreements that best serve US strategic interests

Blanket systems are complex and have many integrated functions, materials, and interfaces



Fusion environment is unique and complex: multi-component fields with gradients

- *Neutrons (fluence, spectrum, temporal and spatial gradients)*
  - *Radiation Effects (at relevant temperatures, stresses, loading conditions)*
  - *Bulk Heating*
  - *Tritium Production*
  - *Activation*
- *Heat Sources (magnitude, gradient)*
  - *Bulk (from neutrons and gammas)*
  - *Surface*
- *Synergistic Effects*
  - *Combined environmental loading conditions*
  - *Interactions among physical elements of components*
- *Particle Flux (energy and density, gradients)*
- *Magnetic Field (3-component with gradients)*
  - *Steady Field*
  - *Time-Varying Field*
- *Mechanical Forces*
  - *Normal/Off-Normal*
- *Thermal/Chemical/Mechanical/ Electrical/Magnetic Interactions*

Multi-function blanket in multi-component field environment leads to:

- ***Multi-Physics, Multi-Scale Phenomena*** ⇨ ***Rich Science to Study***

- **Synergistic effects** that cannot be anticipated from simulations & separate effects tests. *Even some key separate effects in the blanket can not be produced in non-fusion facilities (e.g. volumetric heating with gradients)*

A true fusion environment is ESSENTIAL to Activate mechanisms that cause prototypical coupled phenomena and integrated behavior

It is important to precisely understand the state-of-the-art in blanket and material research, and the role of ITER

- Over the past 30 years the fusion nuclear technology and materials programs have spent much effort on developing theories and models of phenomena and behavior.
  - *But, these are for idealized conditions based on understanding of single effects. There has never been a single experiment in a fusion environment!*

  Are they scientifically valid?

- ITER will provide the 1st opportunity to test these theories and models in a real fusion environment.

Only the Parties who will do successful, effective TBM experiments in ITER will have the experimentally-validated scientific basis to embark on the engineering development of tritium breeding blankets

The US Follows a Science-Based Approach for Understanding Complex Blanket Systems and Fostering Innovation

- Understand and Predict important underlying phenomena at all relevant scales
- Provide the basis for large-scale computational simulations of integrated behavior
- Utilize grounded scientific understanding to foster **innovation** in design towards resolving feasibility issues and improving performance, safety, and reliability of blanket systems

The World TBM Program will be more successful with the US scientific approach and leadership

One Example of Innovation

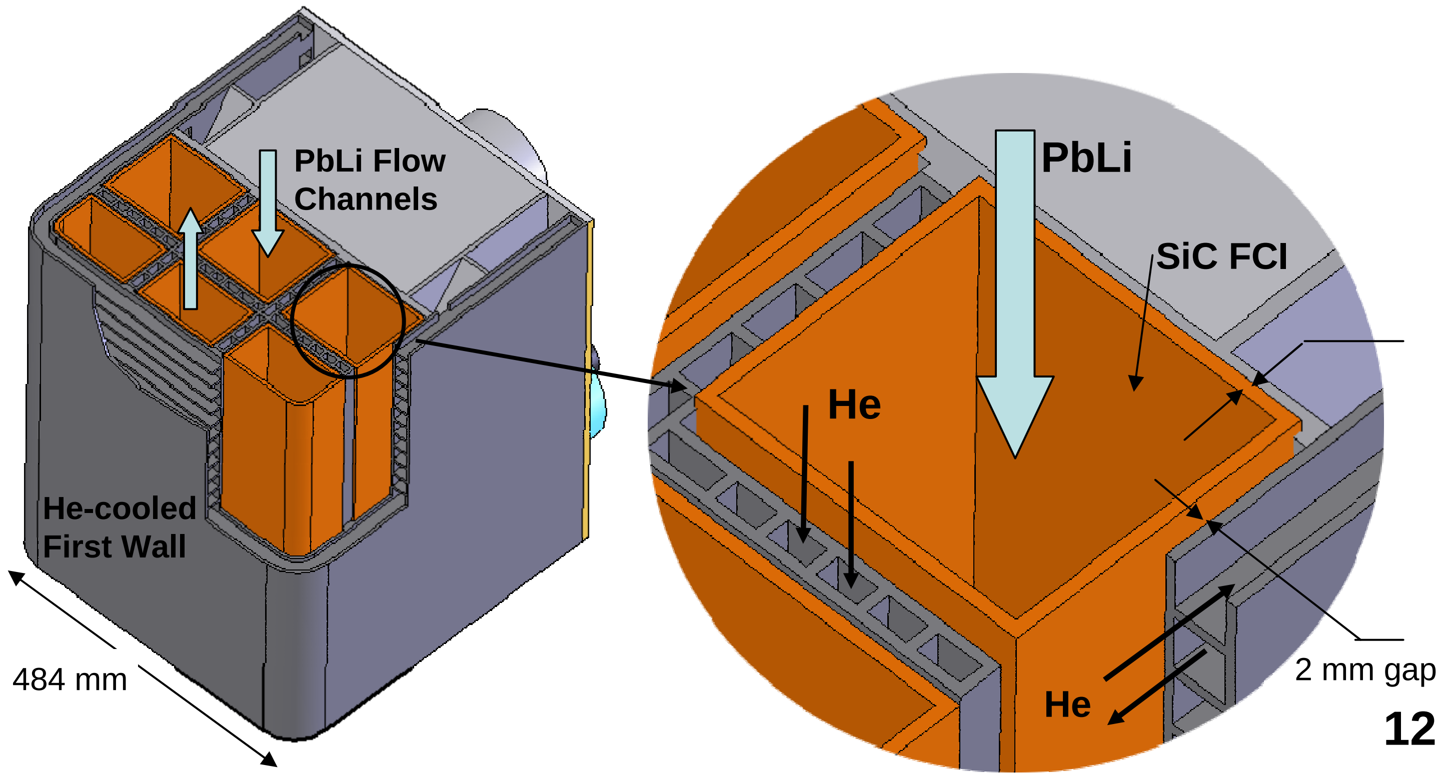
The US-Selected Dual Coolant Lead Lithium (DCLL) TBM Concept provides a pathway to high outlet temperature with current generation structural materials :

- Use RAFS with He cooling for structure, but SiC Flow Channel Inserts (FCI) to thermally and electrically isolate PbLi breeder/coolant
- Result is High outlet temperature PbLi flow for improved thermal efficiency, while making best use of both RAFS and SiC

DCLL Evolution:

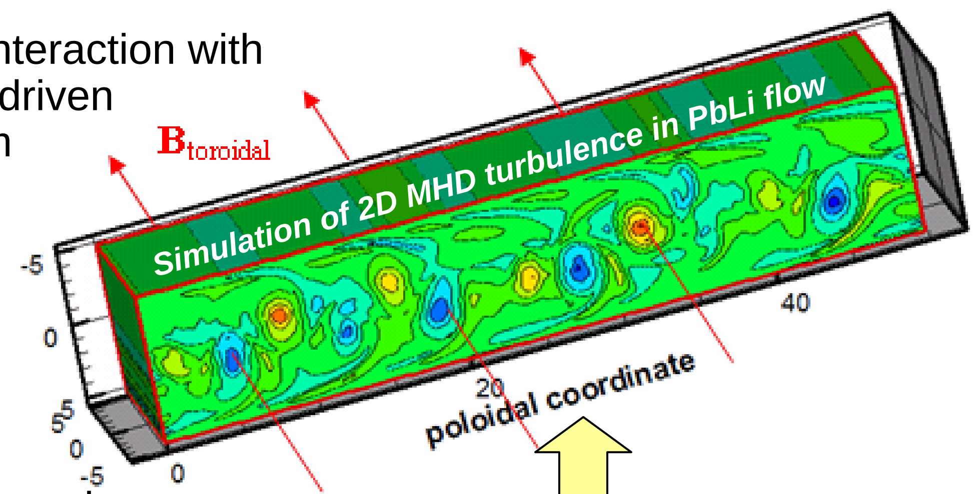
- ***Developed in ARIES-ST ,US-APEX and in the EU-PPS***
- ***Adopted for ARIES-CS***
- ***Similar concept considered in US-IFE-HAPL program***

General to tokamak, stellarator and IFE



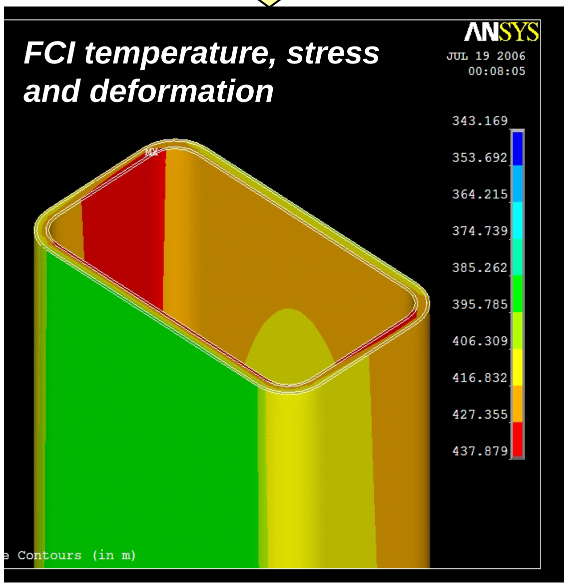
Example: Interaction between MHD flow and FCI behavior are highly coupled and require fusion environment

- PbLi flow is strongly influenced by **MHD** interaction with plasma confinement field and **buoyancy**-driven convection driven by spatially non-uniform volumetric **nuclear heating**



- **Temperature** and thermal **stress** of SiC FCI are determined by this MHD flow and convective heat transport processes

- **Deformation** and **cracking** of the FCI depend on FCI temperature and thermal stress coupled with early-life radiation damage effects in ceramics



- Cracking and movement of the FCIs will strongly influence **MHD** flow behavior by opening up new conduction paths that **change** electric **current** profiles

Similarly, coupled phenomena in tritium permeation, corrosion, ceramic breeder thermomechanics, and many other blanket and material behaviors

ITER TBM is the Necessary First Step to enable future Engineering Development

Role of ITER TBM

Stage I	Stage II	Stage III	
Fusion "Break-in" & Scientific Exploration	**Engineering Feasibility & Performance Verification**	**Component Engineering Development & Reliability Growth**	**DEMO**
~ 0.3 ***MW-y/m²***	1 - 3 ***MW-y/m²***	> 2 - 4 ***MW-y/m²***	
Sub-Modules/ Modules Size Tests	**Module Size Tests**	**Module / Sectors Size Tests**	

Stage I

- Initial exploration of **coupled phenomena** in a fusion environment
- Uncover unexpected synergistic effects, Calibrate non-fusion tests
- Impact of rapid property changes in early life
- Integrated environmental data for model improvement and simulation benchmarking
- Develop experimental techniques and test instrumentation
- Screen and narrow the many material combinations, design choices, and blanket design concepts

Stage II

- Uncover unexpected synergistic effects coupled to radiation interactions in materials, interfaces, and configurations
- Verify performance beyond beginning of life and until changes in properties become small (changes are substantial up to ~ 1-2 MW · y/m^2)
- Initial data on failure modes & effects
- Establish **engineering feasibility** of blankets (satisfy basic functions & performance, up to 10 to 20 % of lifetime)
- Select 2 or 3 concepts for further development

Stage III

- Identify lifetime limiting failure modes and effects based on full environment coupled interactions
- Failure rate data: Develop a data base sufficient to predict mean-time-between-failure with confidence
- Iterative design / test / fail / analyze / improve programs aimed at **reliability growth** and safety
- Obtain data to predict mean-time-to-replace (MTTR) for both planned outage and random failure
- Develop a data base to predict overall availability of FNT components in DEMO

Tritium breeding capabilities are needed for the continued operation of successful ITER and fusion development

Tritium Consumption in Fusion is HUGE! Unprecedented!

55.8 kg per 1000 MW fusion power per year

Production & Cost:

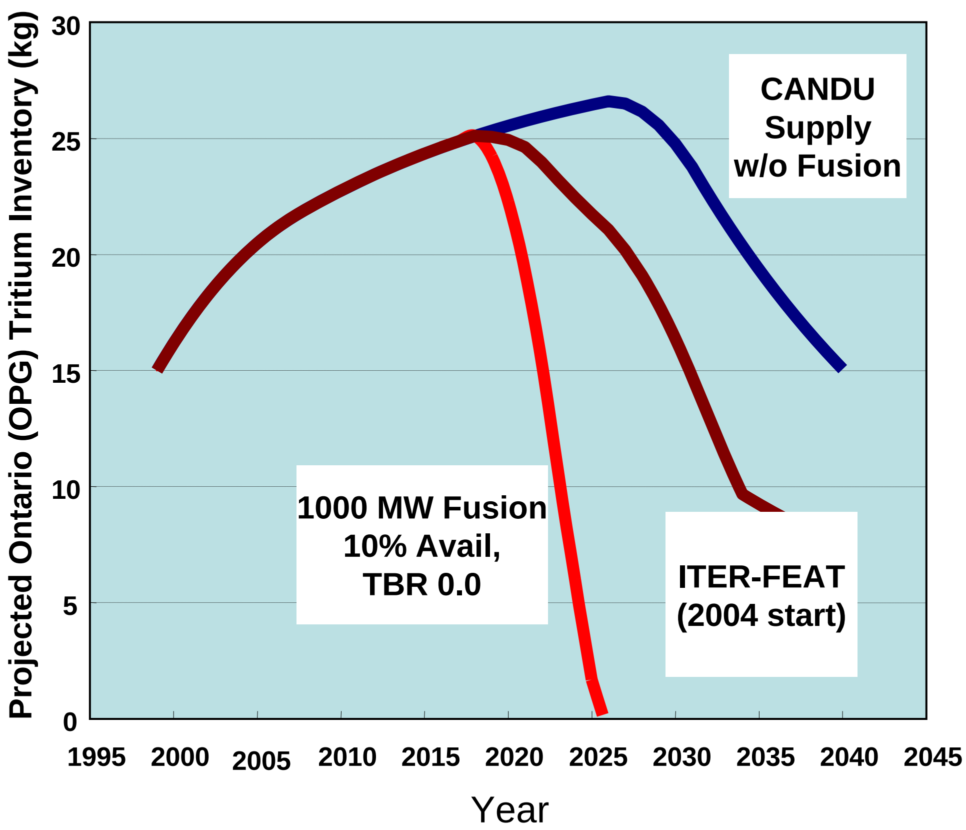
CANDU Reactors: 27 kg from over 40 years, $30M/kg (current)

Fission reactors: 2–3 kg/year/reactor,

$84M-$130M/kg (per DOE Inspector General*)

*www.ig.energy.gov/documents/CalendarYear2003/ig-0632.pdf

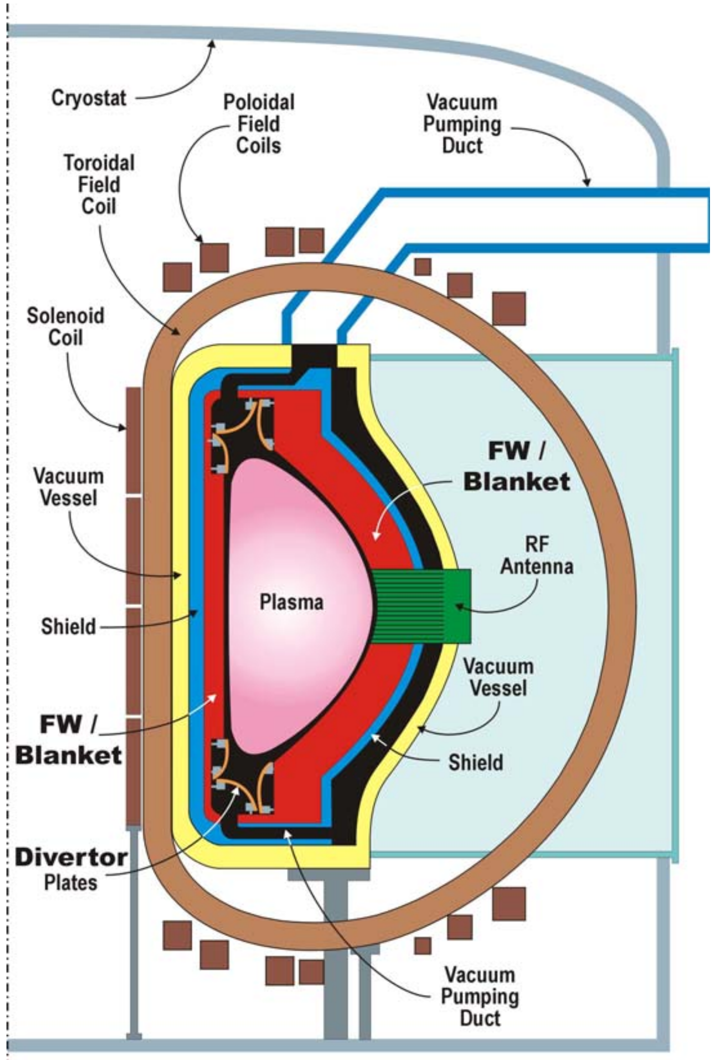
- A Successful ITER will exhaust most of the world supply of tritium
- ITER extended performance phase and any future long pulse burning plasma will need tritium breeding technology
- TBMs are critical to establishing the knowledge base needed to develop even this first generation of breeding capability



TBM helps solve the Tritium Supply Issue for fusion development (at a fraction of the cost of purchasing tritium from fission reactor sources!)

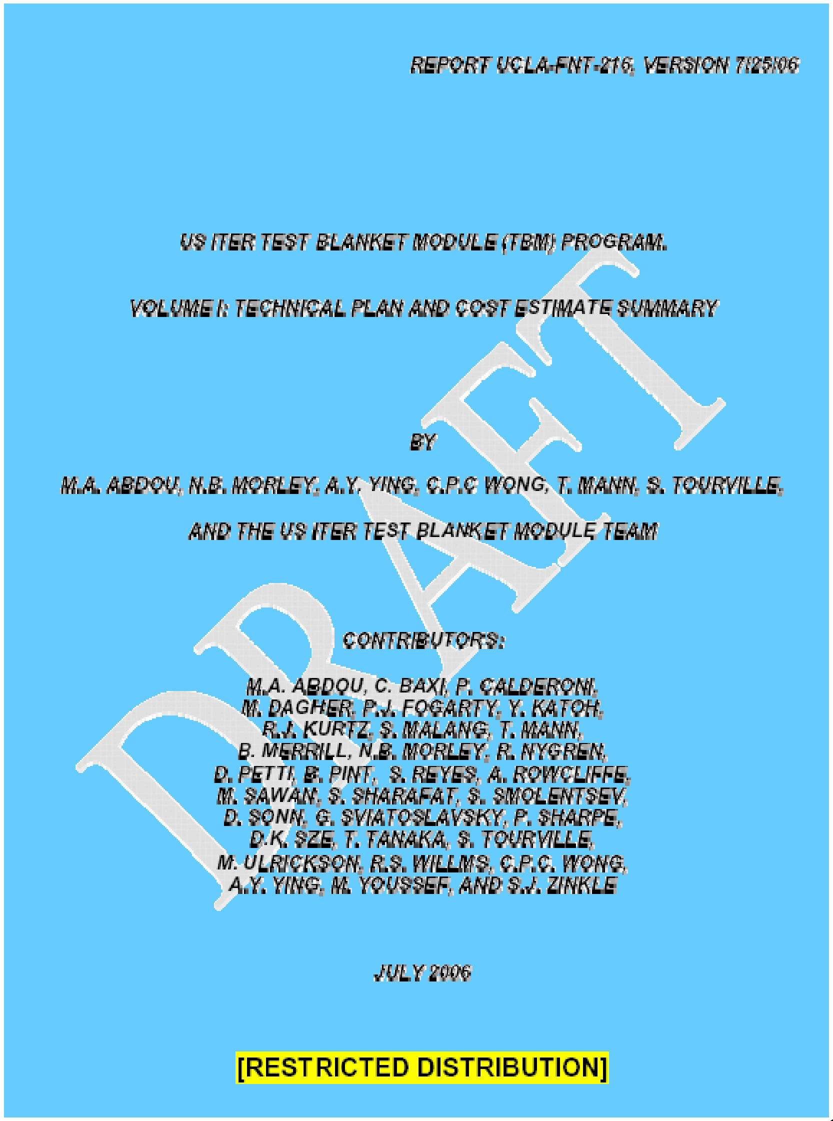
Blanket systems and plasma confinement and control are highly interactive and must be advanced together

- Blankets are INSIDE the vacuum vessel, with the LARGEST plasma facing surface of any PFC.
  - blankets affect overall physical environment of the plasma, *e.g.* a single coolant leak from the blanket will require plasma shutdown and lengthy blanket replacement
- Blankets can be highly conductive, ferromagnetic, and can even generate current via MHD effects of moving liquid metal breeders
  - *e.g.* ITER requires blanket testing during H-H phase in order to determine plasma control procedures in the presence of blanket TBMs
- Blankets are the components that produce tritium and enable closure of the fuel cycle. **Blanket research** contributes concepts and requirements that will **shape the evolution of plasma physics** research
  - *e.g.* allowable tritium fractional burn-up in the plasma will be strongly influenced by blanket tritium production and extraction characteristics
  - *e.g.* the requirement for steady-state plasma and non-inductive current drive originated from conclusions concerning FW/blanket cyclic fatigue.



A US TBM Technical Plan and Cost Estimate have been developed and favorably reviewed

- A technical plan for US ITER TBM has already been developed.
  - A good cost estimate was generated through the combined efforts of the technical experts from Plasma Chamber, Materials, PFC, and Safety Programs, plus costing & management professionals
- An external review by US DOE technical and project experts found the cost and plan "complete and credible" and *strongly recommended the program move forward with committing to collaborations in the US interests*
- *A significant fraction of the manpower, facilities, codes and other important resources needed already exist in the US base program*
- The incremental costs are modest and depend strongly on the:
  - Level of international collaboration and degree of integration among ITER Parties
  - Desired US flexibility and leadership role


REPORT UCLA-FNT-216, VERSION 7/25/06

US ITER TEST BLANKET MODULE (TBM) PROGRAM,

VOLUME I: TECHNICAL PLAN AND COST ESTIMATE SUMMARY

DRAFT

BY

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JULY 2006

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SUMMARY
Strong US Participation in the ITER TBM will...

- Allow the US to define the “phase-space” of plasma, nuclear and technological conditions in which tritium self-sufficiency / high temperature heat extraction / safe & reliable operation can be attained
- Capitalize on the substantial resources invested by the Parties, and influence their tritium breeding technology programs
- Maximize the US return on investment in ITER – including the major capabilities for TBM testing (worth billions of dollars)
- Provide a source of tritium for continued fusion development in the US
- Support the American Competitiveness Initiative and the Office of Science mission
- Answer critics of fusion who argue that “the time to realize fusion is 40 years away and expanding”
- ***“help Congress understand whether ITER is promoting progress toward fusion as a reliable and affordable source of power”***
  - Rep. Judy Biggert's Remarks on Fusion to the Fusion Power Associates Annual Symposium - 2006

BACKUP SLIDES

Mohamed Abdou
for the US ITER TBM Team

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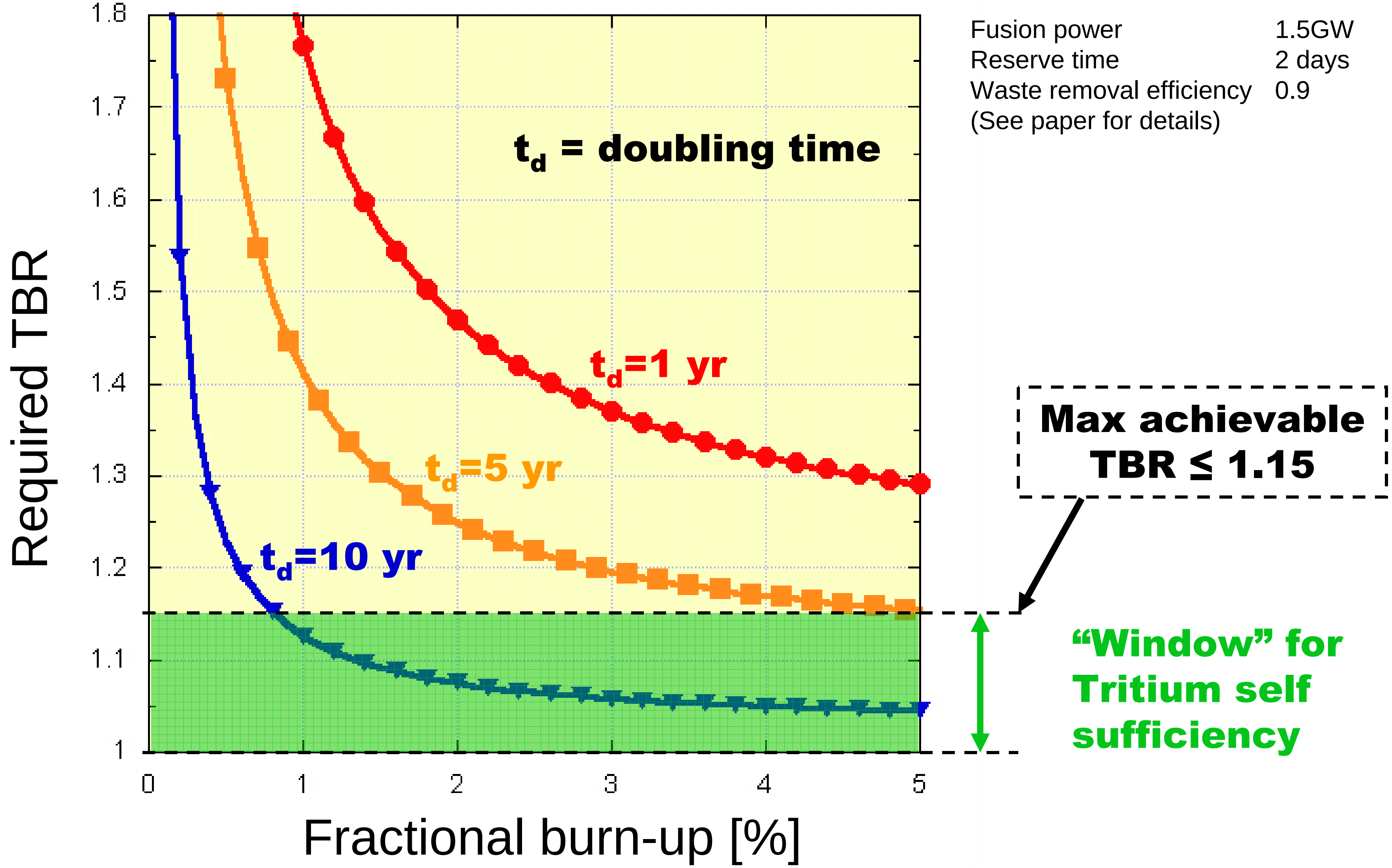
Current physics and technology concepts lead to a "narrow window" for attaining Tritium self-sufficiency



Fusion power	1.5GW
Reserve time	2 days
Waste removal efficiency	0.9

(See paper for details)

Tritium Consumption in ITER

- Here is from a summary of the final design report. Link is:

  http://fusion.gat.com/iter/iter-ga/images/pdfs/cost_estimates.pdf

- ***9.4.3 Fuel Costs***
  The ITER plant must be operated, taking into account the available tritium externally supplied. The net tritium consumption is 0.4 g/plasma pulse at 500 MW burn with a flat top of 400 s
- "The total tritium received on site during the first 10 years of operation, amounts to **6.7 kg**."
- "whereas the total consumption of tritium during the plant life time may be up to **16 kg** to provide a fluence of 0.3 MWa/m2 in average on the first wall"
- "This corresponds, due to tritium decay, to a purchase of about **17.5** kg of tritium. This will be well within, for instance, the available Canadian reserves."

ITER TBM is also of great benefit to CTF/VNS

- Exactly the same R&D and qualification testing for ITER TBM will be needed for CTF
  - Ferritic steel, Ceramic FCI and Breeder, Be development
  - MHD flow and heat transfer simulation capabilities
  - Tritium permeation and control technologies
  - Other safety, fabrication, and instrumentation R&D

But in ITER costs can be shared with international partners

- **ITER should be used for Concept screening and fusion environment break-in**
  - Spending years doing screening in CTF will cost hundreds of millions in operation. ITER operation costs are already paid for, and shared internationally
  - CTF should be used for engineering development and reliability growth on the one or two concepts that look most promising following screening in ITER

- TBM tests in ITER will have prototypical Interactions between the FW/Blanket and Plasma, thus complementing tests in CTF (if CTF plasma and environment are not exactly prototypical, e.g. highly driven with different sensitivity to field ripple, low outboard field with different gradients)

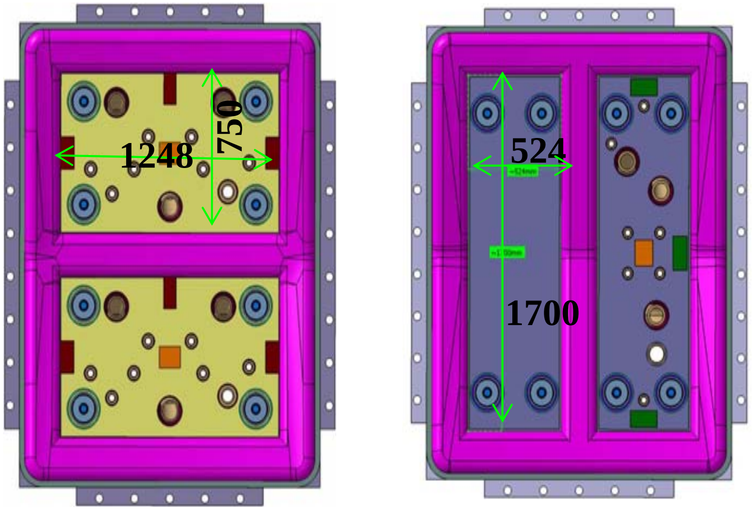
Structure of TBM collaboration*

- Each 1/2 of a port is dedicated to testing of one TB concept design (one module or several connected sub-modules).
- Each Concept design is tested by a partnership of a TB concept leader + supporting partners
- One of the two TB leaders occupying the same port must play a role of the Port master – responsible for integration of the given port
- **Port Master has main responsibility of integration of 2 concepts in the same port frame and preparation of the integrated testing program (replacement strategy) for the port**

List of TBM Design Proposals for day-one
(DDDs completed by Parties)

☞ Helium-cooled Lithium-Lead TBM (2 designs)
☞ Dual-coolant (He+Lithium-Lead) TBM (2 designs)
☞ He-cooled Ceramic Breeder/Beryllium multiplier TBM (4 designs)
☞ Water-cooled Ceramic Breeder/Beryllium multiplier TBM (1 design)
☞ He-cooled Liquid Lithium TBM (1 design)
☞Self-cooled Liquid Lithium TBM (1 design)

ITER has only 3 ports ➔ Only 6 TBMs can be tested



Horizontal Vertical

Each Port can hold two vertically or horizontally oriented half-port size integrated TBMs

*** Initial result of TBWG DH meeting, 18-19 July 2006**

The US planning effort evaluated several scenarios and recommended a compromise between cost and risk that best supports US scientific approach

In evaluating possible US testing plans, it was recognized that:

- The assumed level of international collaboration has a larger impact on overall program costs than uncertainty in other areas – but usually at increased risk
- The best strategy pursues two different concepts with dramatically different operational feasibility issues, but synergism in structural material fabrication development

Higher Cost Range / Lower Risk Range Scenario

- Consists of an independent US testing of both the DCLL and Ceramic breeder based systems while taking advantage of existing complementary R&D efforts in the international program.
- Similar to EU, Japan, and most other parties in independently testing their concepts

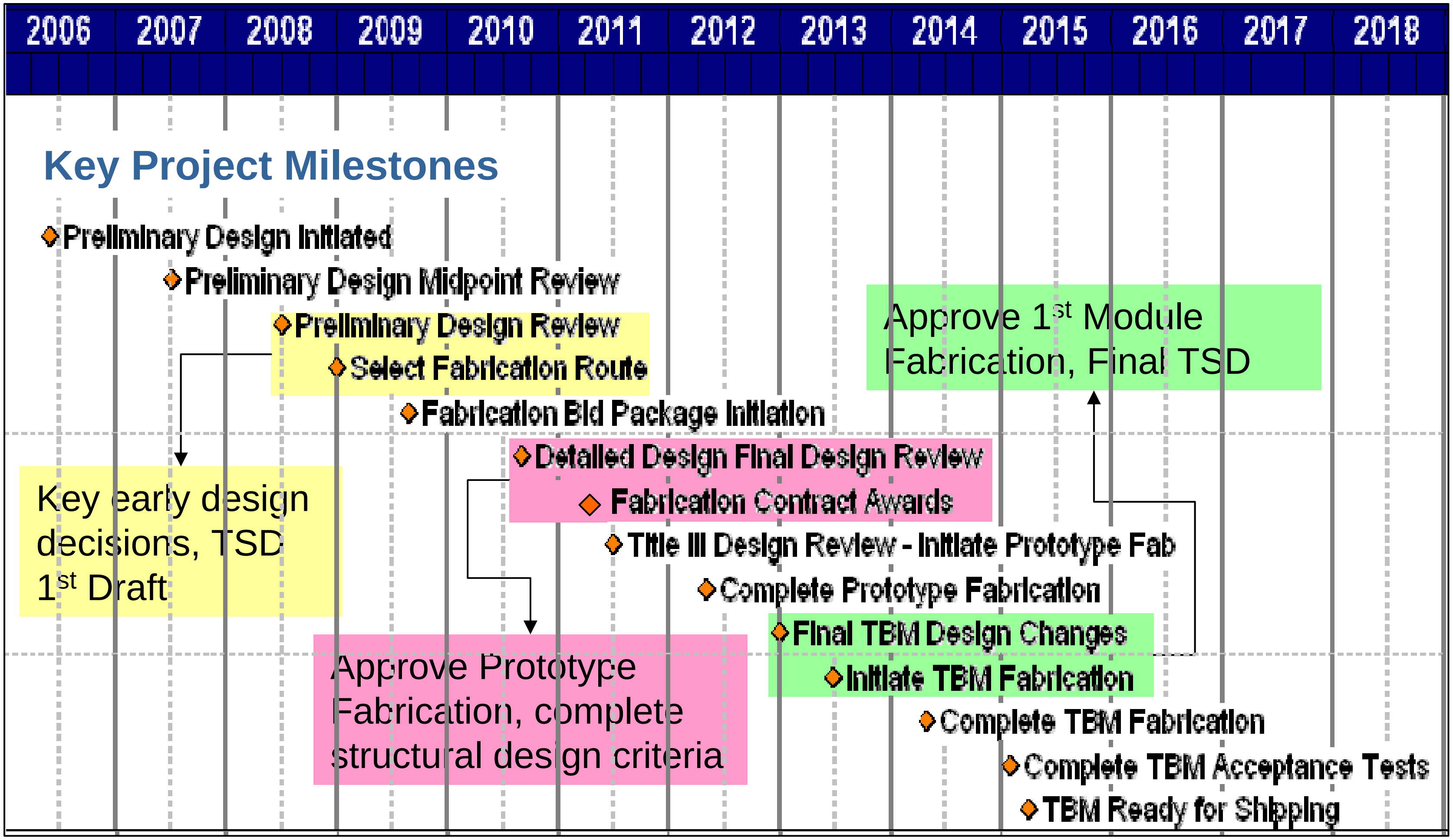
Recommended Scenario

- Consists of largely independent US DCLL testing effort while taking advantage of existing complementary R&D efforts in the international program.
- A supporting partnership with other Party(ies) (e.g. Japan, EU, KO) on the Ceramic Breeder TBMs, providing only a portion of the R&D and a smaller size sub-modules

Lower Cost Range/ Higher Risk Range Scenario

- Consists of a leading international partnership (with one or more ITER Parties) on the DCLL testing and a supporting partnership on the Ceramic Breeder testing.
- Collaborates/shares the preparatory R&D and hardware costs among all partners

R&D, Design, Fabrication and Qualification for TBMs must proceed Similar to all ITER components



- TBMs must not affect ITER availability
- TBM systems make up part of the "Safety" boundary
- TBMs must be part of the ITER licensing for HH and DT operation

To be sure that test blanket modules are compatible with tokamak operation, 1st test module must be installed as early as possible before beginning of the DT operation.

From Dr. Chuyanov's IT presentation at TBWG-15, July, 2005

- There are several issues from the ITER perspective, which must be investigated at the H-H stage:
  - operation of test modules and supplementary equipment in strong magnetic field,
  - Forces acting on test modules during disruptions ,
  - sputtering of the bare steel surface of the test module's first wall and necessity to use a Beryllium protective layer,
  - interference of the test modules with plasma confinement,
  - thermal loads on the test module's first wall.
- Moreover, most TBMs will be made of a martensitic/ferritic steel. Their magnetization in the ITER field will generate "error fields" - small perturbations of the axial symmetry of the poloidal magnetic field.
  - Even small error fields ($\sim 10^{-4}$ of toroidal field) can induce in the plasma locked (i.e. non-rotating) modes, and influence confinement of fast particles and change heat load on the test modules themselves.
  - There are also other sources of the error fields like TF or PF coil misalignment creating error fields of a similar amplitude but , probably , with different phases.
  - **The ITER magnet system is designed to compensate these error fields.**
- Estimates show that the amount of ferritic steel in the current design is so high that the amplitude of the error fields created by test modules is close to limits for compensation.
  - Taking in account uncertainties in prediction of the total error field and in tolerance of the ITER plasma to error fields ITER does not request to change the design of test modules to-day and to limit the amount of ferritic steel.
  - If the experiments during the hydrogen phase will show that the level of the error fields is unacceptable, test modules designers must be ready to respond to such a request.

Will the US Utilize ITER to Strengthen its Leadership?

- The US has been the world's intellectual leader of Fusion Nuclear Technology Development and has invested considerable resources over the past 35 years
- The US, together with EU and Japan, spent over 30 billion dollars over the past 35 years to enable construction of ITER.
- The US is already paying for ITER Design and Construction – including major capabilities for TBM testing (worth billions of dollars).
- US ingenuity and innovation have strongly influenced the world program, now the US can benefit from the capabilities and resources being invested by ITER partners
- Strong US TBM program supports the American Competitiveness initiative

<u>OR</u> Will the US, by not participating in TBM, surrender?

- Fail to fully capitalize on its significant investment in ITER
- Effectively let "*Other Countries*" each pay <$100M to utilize ITER to develop DEMO Blanket Technology.
- Render the US INCAPABLE of building a DEMO and INCAPABLE of competing with other countries.
- Allow other countries to develop tritium production capabilities, superior to the US ("strategic concern")