Goals, present status and future prospects for the Fusion Simulation Project (FSP)

D. B. Batchelor

Oak Ridge National Laboratory

PSIF Meeting 2005

- **History**
- **What is the concept of the FSP?**
- **Where we are today**

From Charge to the Fusion Energy Sciences Advisory Committee (FESAC, 2002)

Develop a roadmap for a joint initiative with the Office of Advanced Scientific Computing Research (OASCR) – James F. Decker, Acting Director, Office of Science

- Previously adopted 10-year objective for the fusion program: "…develop fully integrated capability for predicting the performance of externally-controlled systems including turbulent transport, macroscopic stability, wave-particle physics, and multi-phase interfaces."
- "The initiative should be planned as a 5-6 year program"
- "Rough estimates are that an integrated simulation initiative would require a total funding level of about $20 million per year, with funding for the plasma scientists provided by OFES and funding for the applied mathematicians, computer scientists, and computational resources provided by OASCR."

Fusion Simulation Project (FSP) Timeline (Calendar Year)

02 03 04 05 06

ISOFS FESAC subcommittee (Decker, Hazeltine)

Donald Batchelor
Randall Bramley
James Corones
Jill Dahlburg
Martin Greenwald
Stephen Jardin
Sergei Krasheninnikov
Alan Laub
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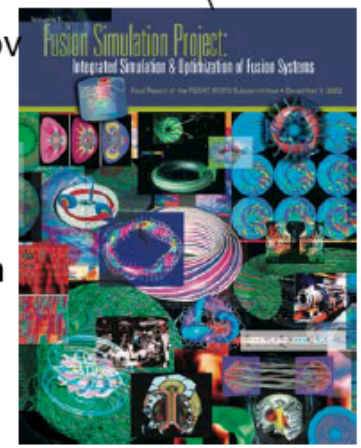

Final Report: December 02

FSP Steering Committee (Willis)

Don Batchelor
Randy Bramley
John Cary
Ronald Cohen
Phil Colella
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Doug Post

Steve Eckstrand
Arnold Kritz

Final Report: September 04

Call for proposals: SciDAC – Fusion Simulation Prototype Centers ~ $2M/yr

Start of project

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A FESAC subcomittee (J. Dahlburg, chair) that a major simulation initiative be undertaken:

Ultimate (~ 15yr) objective is to predict reliably the behavior of plasma discharges in a toroidal magnetic fusion device on all relevant time and space scales → Fusion Simulation Project (FSP)

This is in essence the capability for carrying out "virtual experiments" of a burning magnetically confined plasma, implying predictive capability over many energy-confinement times, faithful representations of the salient physical processes of the plasma, and the interaction with the external world (sources, control systems and bounding surfaces).

The initiative should be structured to add capability incrementally and should adopt near and intermediate term objectives of: supporting basic theoretical research; supporting the understanding, interpretation, and planning of ongoing fusion experiments; exploration of new confinement concepts to improve the prospects for economical fusion power; and predicting the performance of future fusion devices.

Fundamental challenges to fusion simulation

- **Extreme range of time scales – wall equilibration/electron cyclotron O(10^{14})**
- **Extreme range of spatial scales – machine radius/electron gyroradius O(10^{4})**
- **Extreme anisotropy – mean free path in magnetic field parallel/perp O(10^{8})**
- **Non-linearity**
- **Sensitivity to geometric details**
- **High dimensionality – basic object of plasma is 7D → *f*(x, v, t), described by non-linear Boltzman equation**

$$\frac{\partial f}{\partial t} + \mathrm{v} \cdot \nabla f + \frac{q}{m}\left[E + \mathrm{v} \times B\right] \cdot \nabla_{\mathrm{v}} f = C(f)$$

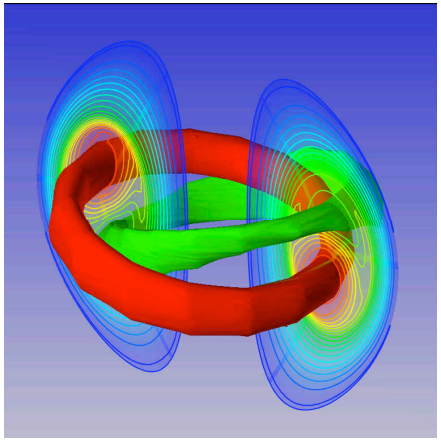
convection | **convection in velocity space** | **Collisional relaxation toward Maxwellian in velocity space**

To deal with this there have been developed several classes of sub-discipline in fusion physics each with related simulation codes

There are great many processes simultaneously at work in fusion plasmas

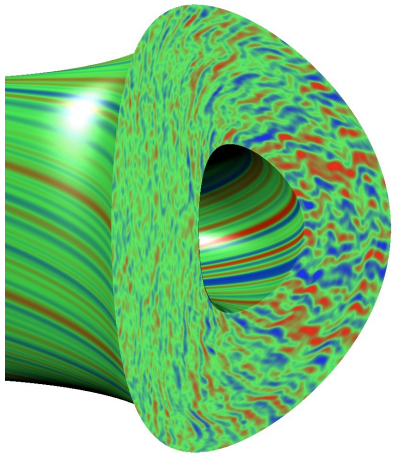
Hydromagnetic force balance of plasma pressure supported by J×B force

- MHD equilbrium
- Macroscopic fluid instability
- Current and magnetic field evolution



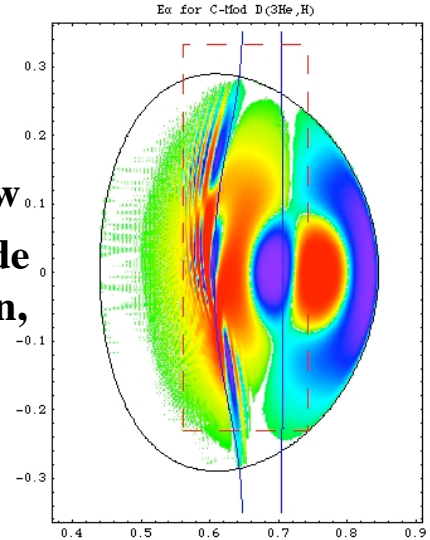
Kinetic stability and transport

- Micro-stability
- Turbulence and turbulent transport
- Long mean-free-path collisional transport
- Fusion heating



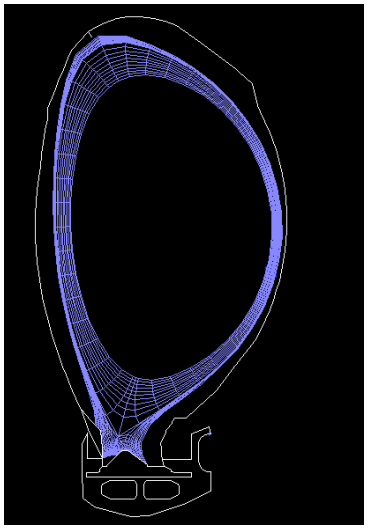
Injection of high-power waves or particle beams, magnetic flux

- Plasma heating
- Externally driven current or plasma flow
- Wave processes – mode conversion, absorption, reflection
- Non-Maxwellian particle distributions

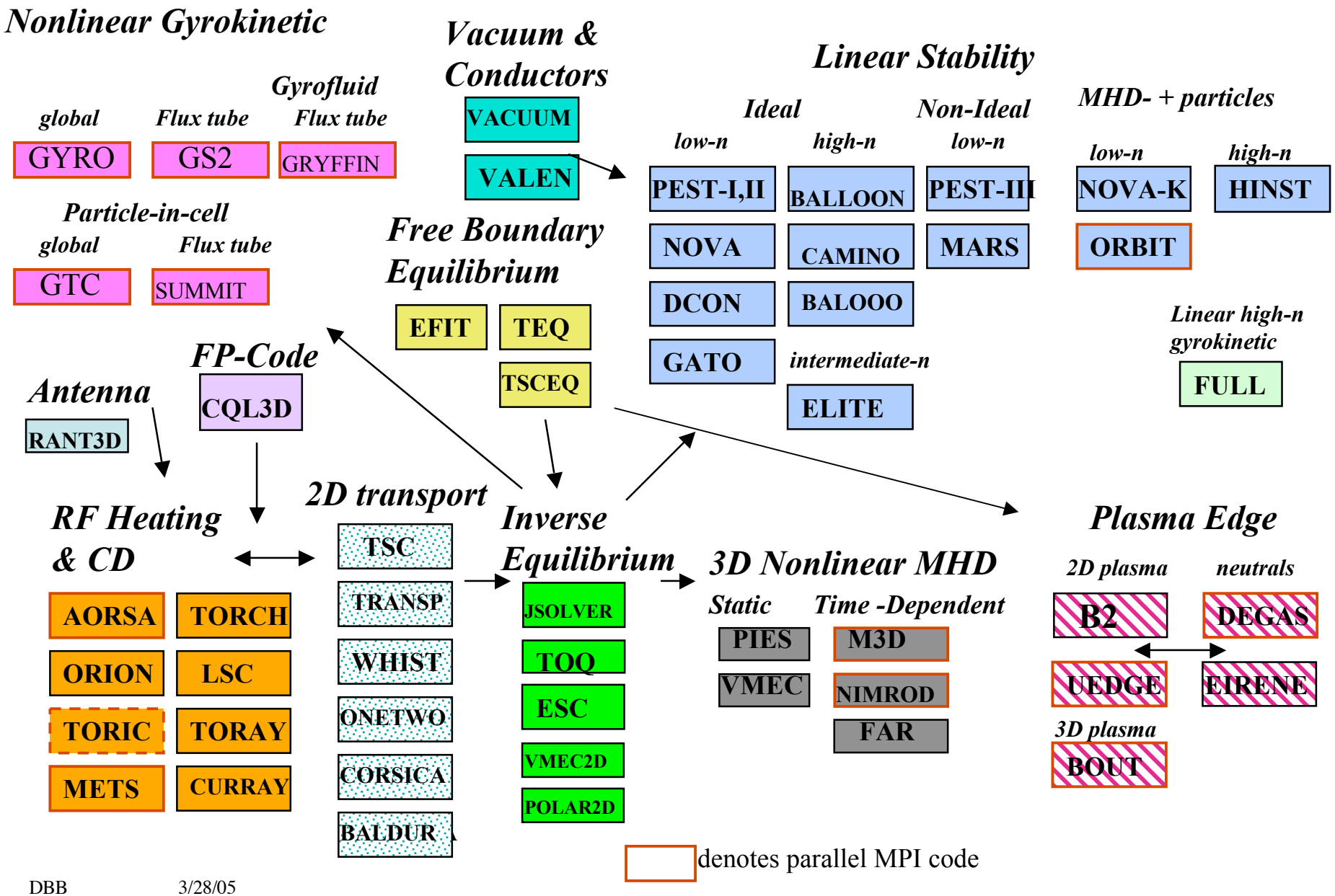


Plasma/edge interactions

- Atomic physics processes
- Transition closed → open flux surfaces
- Transport on open field lines
- Turbulence
- Plasma/material interactions

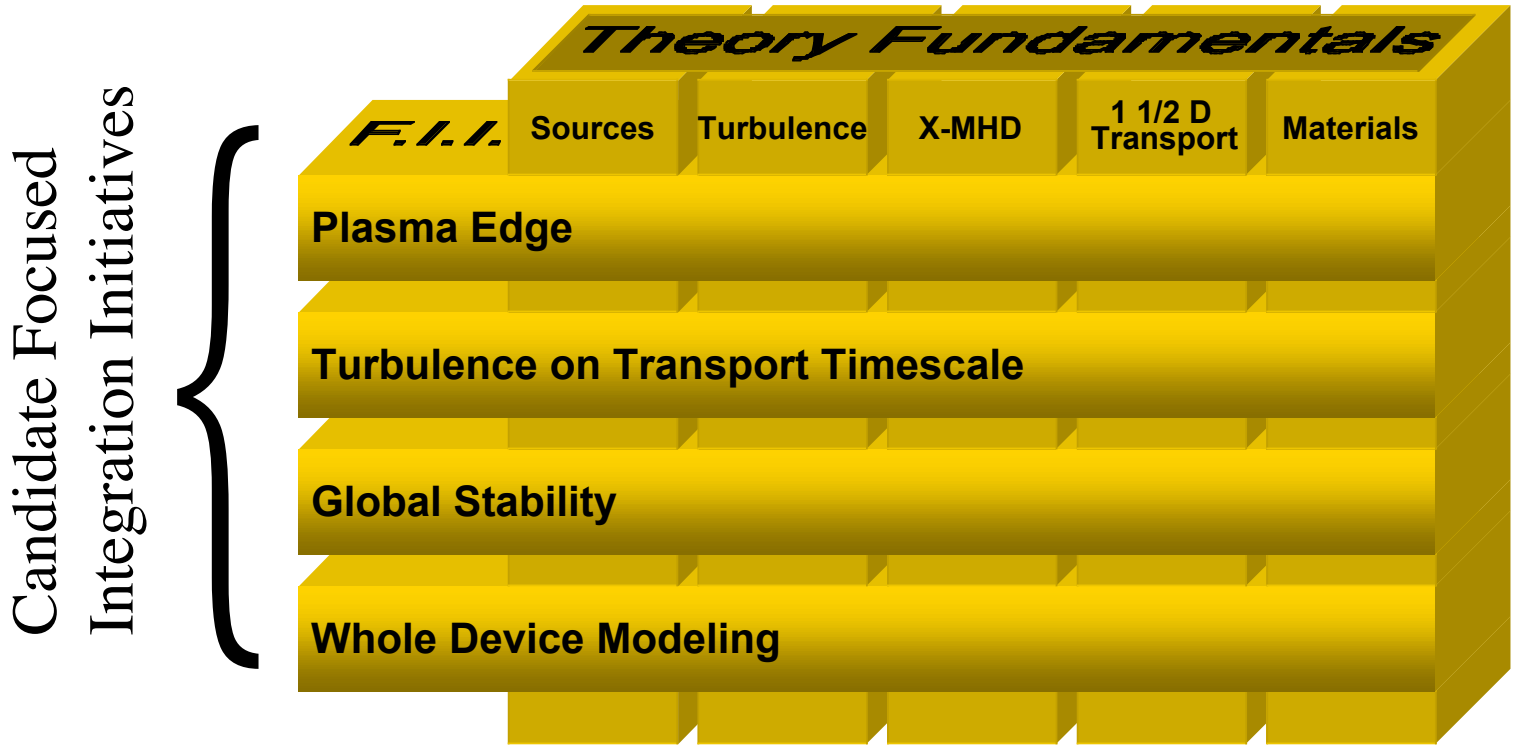


Fusion research involves a tremendous amount of computing
Major US fusion codes ⇒ there is no "THE" fusion code (YET!)



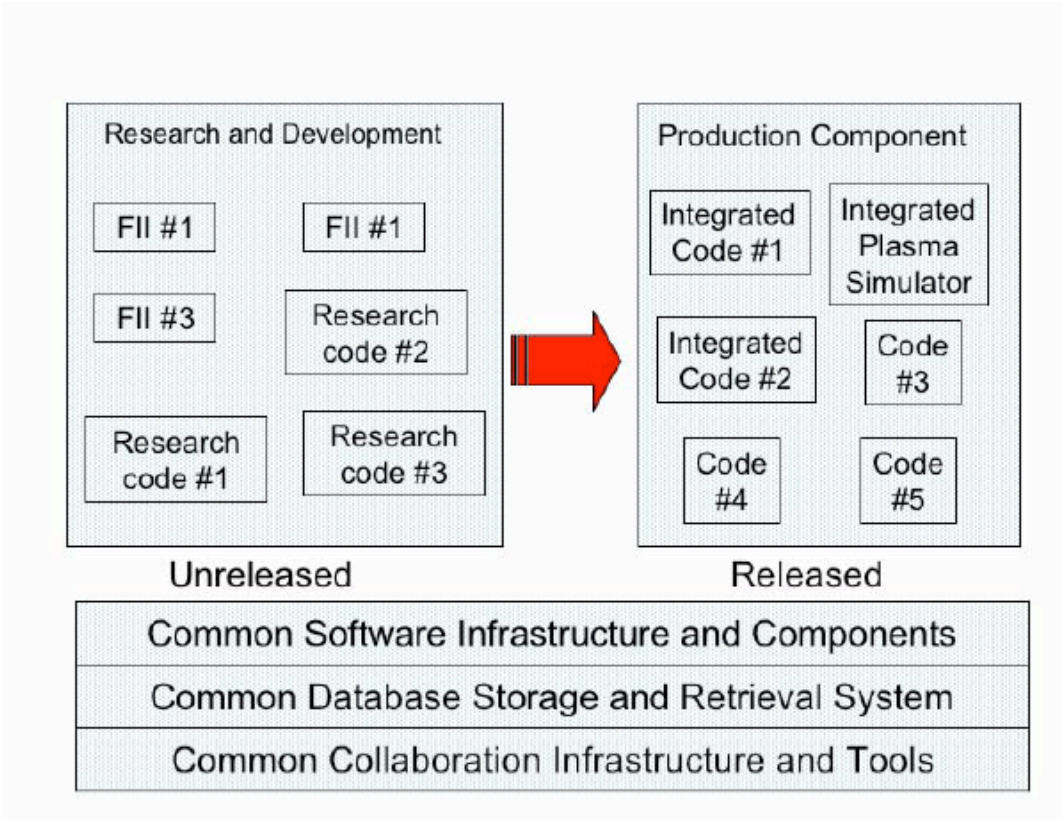
Approach – start simple, pairwise physics couplings "Focused Integration Initiatives" (FIIs), first ~5 years

- **Address one or a few of the fundamental issues for physics integration** (wide range of time scales, range of space scales, extreme anisotropy, non-linearity, models of different dimensionality)
- **Address problems of immediate programmatic importance**
- **Test several different approaches to computational framework/code integration that might ultimately lead to a basis for complete simulation**



The FSP Steering Committee (D. Post – 2004) came up with a slightly different model

1. A production component
2. A Research and Integration Component
3. A Software Infrastructure Component



Highlights from the call for SciDAC proposals (LAB 05-11)

The SciDAC Program, the Office of Fusion Energy Sciences (OFES) and the Office of Advanced Scientific Computing Research (OASCR) of the Office of Science (SC), U.S. Department of Energy (DOE), hereby announce their interest in receiving cooperative agreement applications for the **development of specific scientific simulation codes that can become components of an integrated fusion plasma simulation. These integrated fusion plasma simulation prototype codes should focus on the development of new capabilities that couple together a wider range of physical phenomena in an integrated package of simulation codes (or code suite) than is currently being done**.

As a first step toward the initiation of the FSP, SciDAC, OFES and OASCR **are seeking focused integration initiatives in topical areas that are particularly important to ITER**. The goal of each initiative is to **develop an integrated predictive modeling capability for a specific topical area while, at the same time, dealing with the integration issues that will be faced by the FSP**.

1) An integrated simulation of the edge/boundary region of a fusion plasma:

A specific topic…is the self-consistent simulation of a full Edge Localized Mode (ELM) cycle and its effect on the pedestal formation, dynamic evolution and characteristics…

Should address all relevant physical processes on all spatiotemporal scales, except for interactions with material walls.

The formalism should be valid for the expected range of collisionality in present and next-generation experiments …

2) An integrated understanding of how electromagnetic waves affect plasma profiles and plasma stability:

…The primary goal of this focused integration initiative is to understand how electromagnetic waves affect MHD stability of a fusion plasma and how these effects can be used to optimize the performance of a burning plasma.

A specific product of this focused integration initiative would be a suite of simulation codes that self-consistently couples the time evolution of the plasma equilibrium with the wave-driven modifications of the current, temperature, and flow profiles and includes the analysis of stability limits.…

…**it is expected that the software and algorithm development environment and the code framework will be flexible enough to facilitate recombining of software components into new code capabilities as additional physics is added to the mathematical models.**

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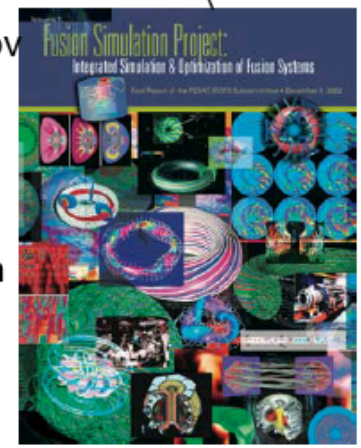

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Proposals due tomorrow

Start of project

Full FSP ?

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Concluding remarks

- **I'm still a believer**
- **This is a way to get started in the real world**
- **Full predictive modeling of fusion plasmas will require cross-coupling of many complex physics processes and solution over many space and time scales – this will be interesting**
- **"Full" simulations of burning plasma experiments could be possible in the 10 year to 15 year time frame if an aggressive program is launched in this area**
- **A fusion simulator would have significant benefits to the fusion sciences program and to a "burning" plasma experiment – a cost effective way to ensure that the US has a significant science role in ITER**