Fusion Simulation Project

Final report of the FESAC ISOFS Subcommittee

ISOFS (Integrated Simulation & Optimization of Fusion Systems)
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Final Report Major Conclusion

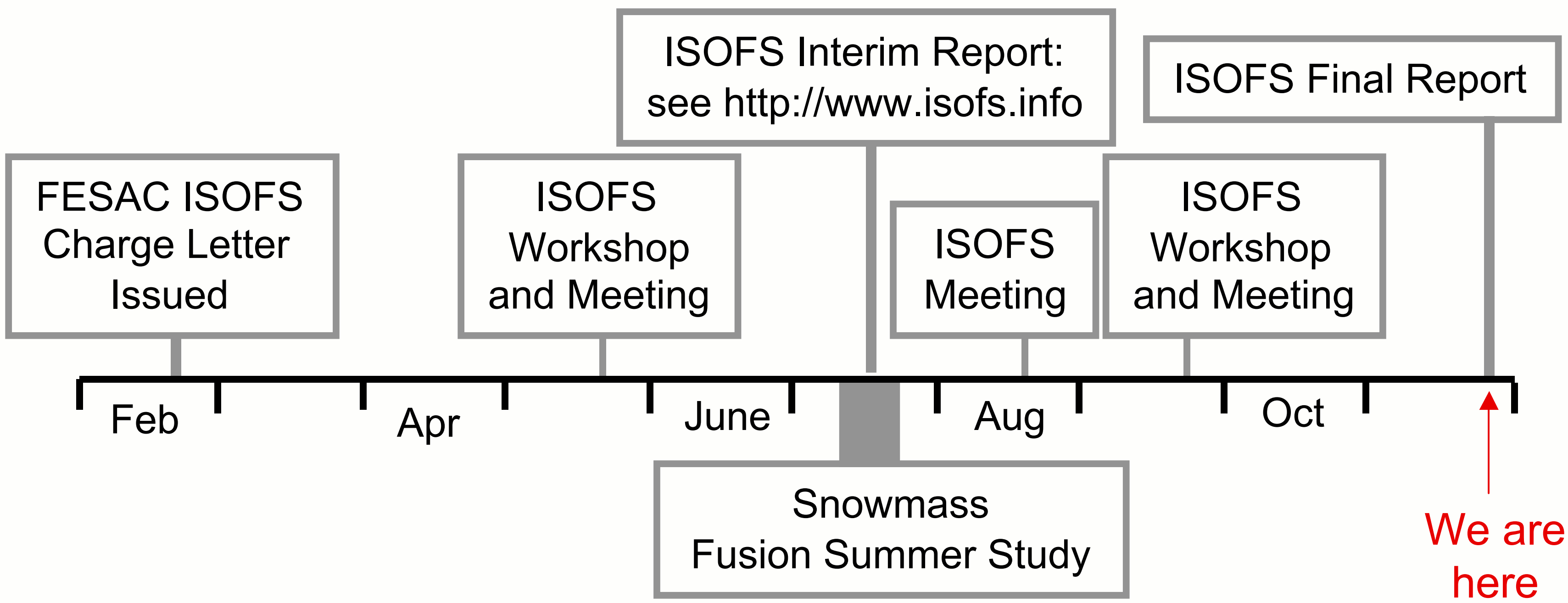
The ISOFS Subcommittee recommends that a major initiative be undertaken, referred to here as the Fusion Simulation Project (FSP).

The purpose of the initiative is to make a significant advance within five years toward the ultimate objective of fusion simulation: to predict reliably the behavior of plasma discharges in a toroidal magnetic fusion device on all relevant time and space scales.

The long-term [15 year] goal 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 physics processes of the plasma, and inclusion of the interactions with the external world (sources, control systems and bounding surfaces).

By its very nature of enabling more comprehensive modeling, the FSP will lead to a wealth of insights not realizable previously, with new understanding in areas as diverse as wall interaction phenomena, the effects of turbulence on long time confinement, and implications of burning plasma self heating in advanced tokamak operating regimes.

Time line and major events for ISOFS subcommittee

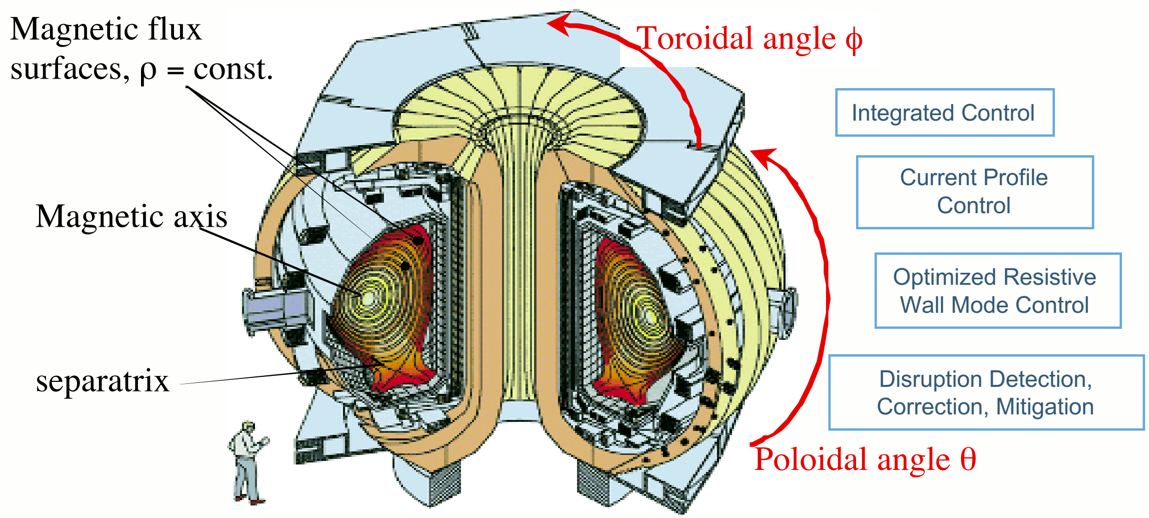


Questions posed in the February 22 charge letter from J. Decker

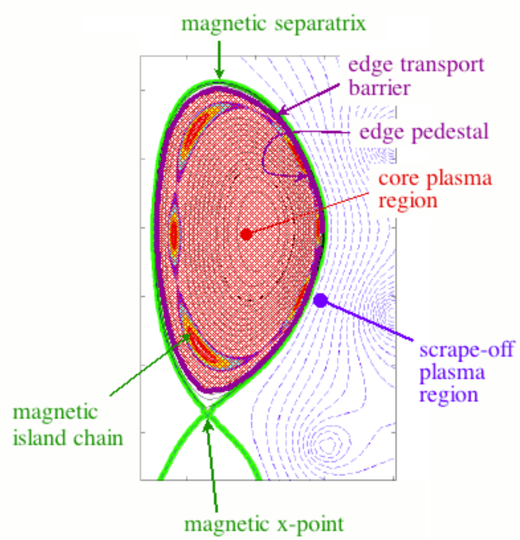
- What is the current status of integrated computational modeling and simulation?
- What should be the vision for integrated simulation of toroidal confinement fusion systems?
- What new theory and applied mathematics are required for simulation and optimization of fusion systems?
- What computer science is required for simulation and optimization of fusion systems?
- What are the computational infrastructure needs for integrated simulation of fusion systems?
- How should integrated simulation codes be validated, and how can they best be used to enable new scientific insights?

A toroidal fusion experiment

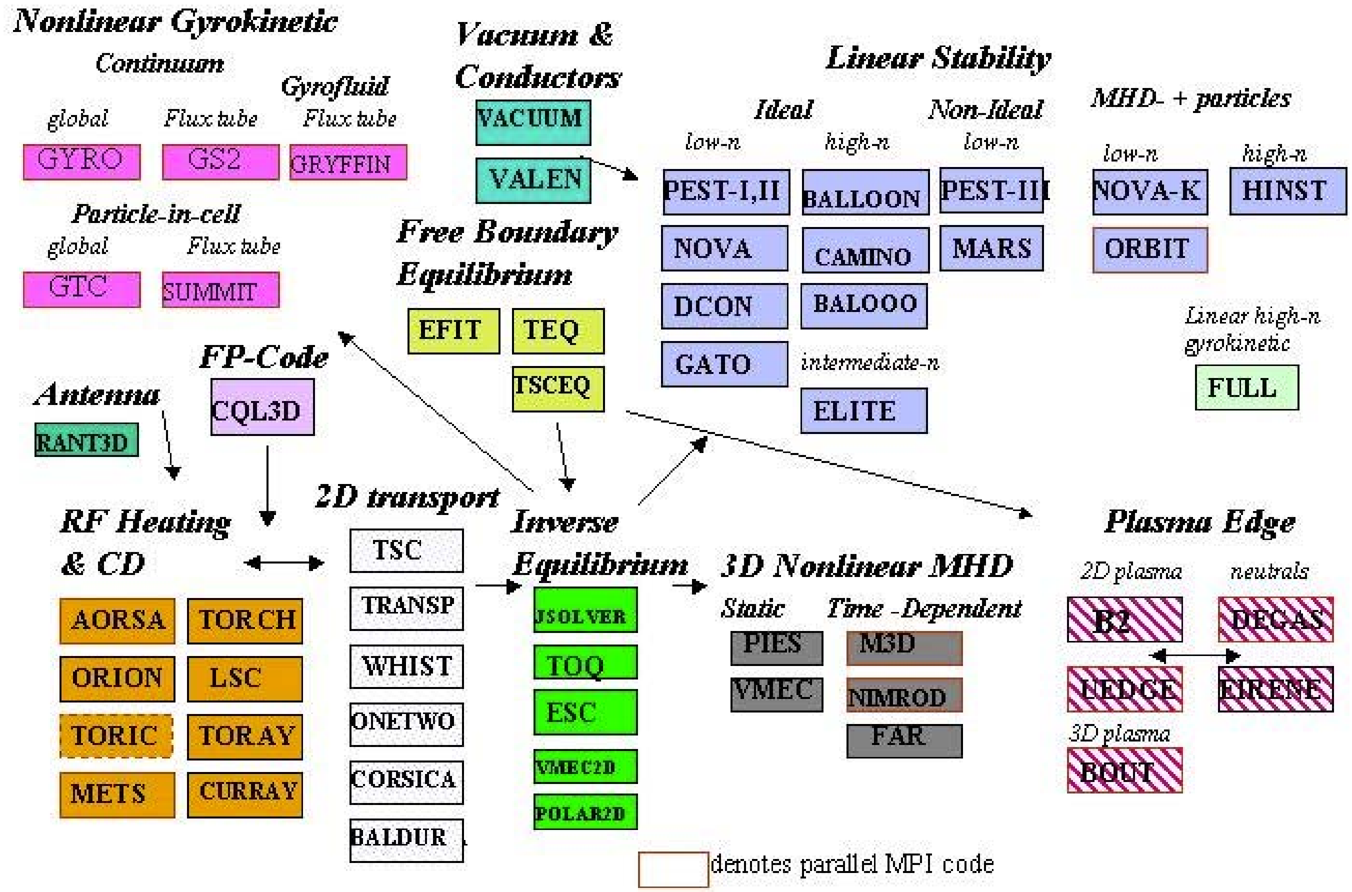
Cutaway view of an advanced tokamak (DIII-D)



Key plasma and magnetic regions of a typical tokamak plasma, shown as a computed cross-section

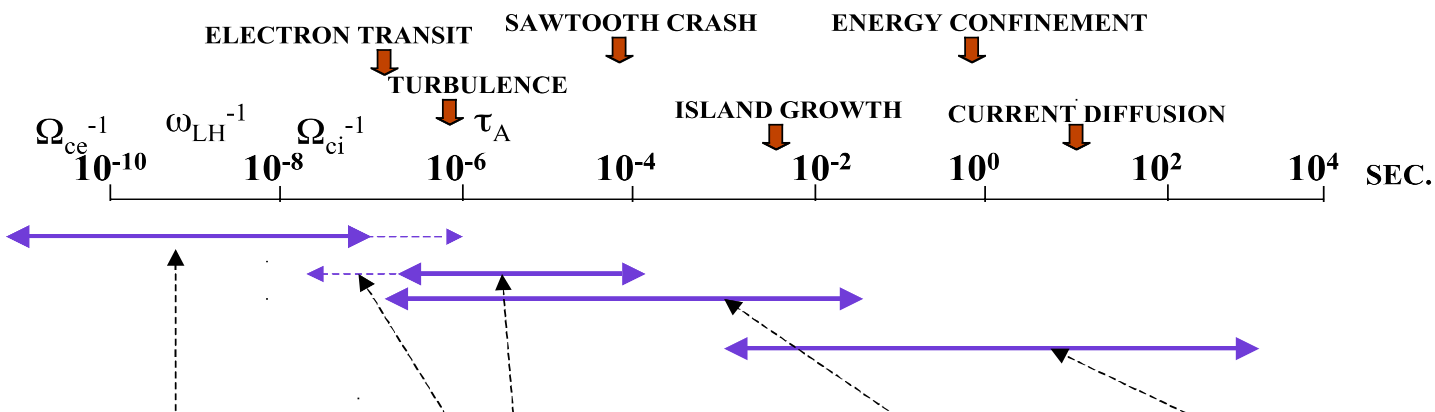


Major US toroidal physics design and analysis codes used by plasma physics community



Numerical modeling has played a vital role in fusion for more than four decades.

Summary of the four major fusion code groups and the time scales being addressed



Single frequency and prescribed plasma background	Neglect displacement current, average over gyroangle, (some) with electrons	Neglect displacement current, integrate over velocity space, neglect electron inertia	Neglect displacement current, integrate over velocity space, average over surfaces, neglect ion & electron inertia
RF Codes	Gyrokinetics Codes	Extended MHD Codes	Transport Codes
wave-heating and current-drive	turbulent transport	device scale stability	discharge time-scale

Full predictive modeling of fusion plasmas will require cross coupling of a variety of physical processes and solution over many space and time scales.

Success of the FSP will require coordinated and focused advances in:

Fusion Physics

to further develop the underlying models, elucidate their mathematical basis,

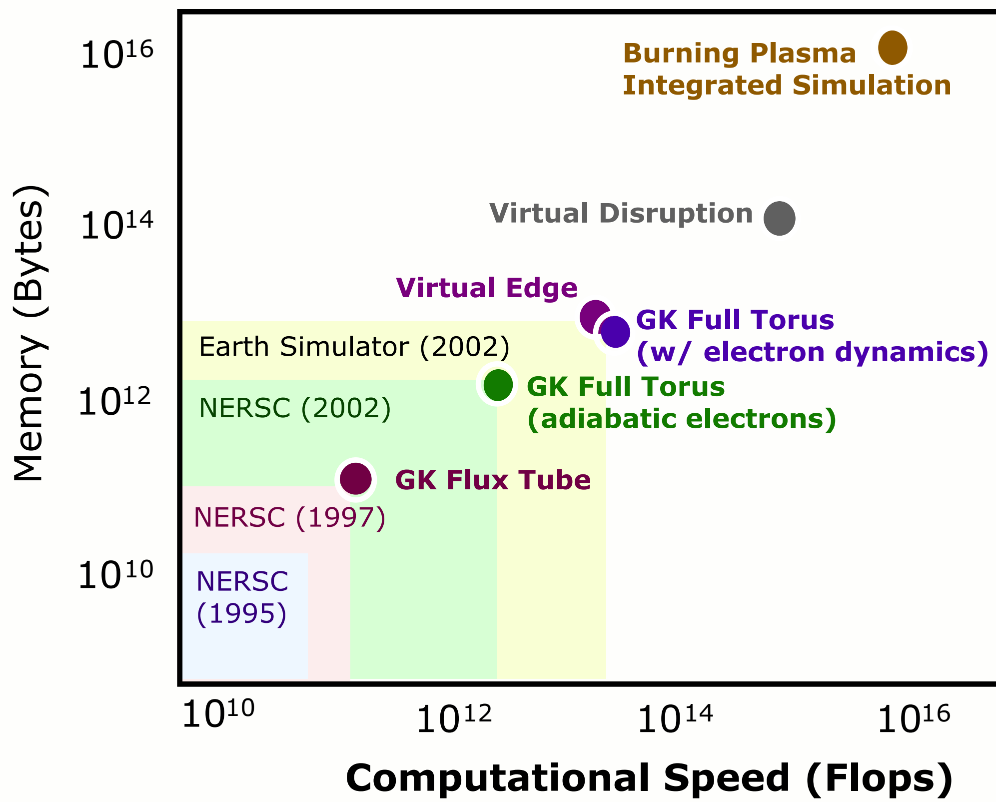
Applied Mathematics

to further develop suitable algorithms for solving the mathematical models on the appropriate computer architecture, and to define frameworks within which these algorithms may be easily assembled and tested, and

Computer Science

to provide an architecture for integrated code development and use, and to provide analysis and communication tools appropriate for remote collaboration.

Computational requirements for fusion simulations



The FSP will require significant improvements in computational and network infrastructure, including enhancements to shared and topical resources.

Core expertise for the FSP is resident in the DOE Office of Science

* ongoing fusion experimental and theoretical research and development activities within OFES,
* applied mathematics development activities in OASCR
* recently developed SciDAC initiative, and
* materials sciences research in OBES

Because this initiative rests entirely on a progressing science base

-- and will for successful execution attract and retain junior researchers committed to the goals of fusion energy sciences --

it is paramount that FSP funding (~ $20M/year for each of five years) be new rather than redirected from present, critical areas.

To realize integration from the beginning, the FSP should commence with FSP subsets: Focused Integration Initiatives (FIIs)

The goal of each FII team is the solution of a compelling problem in fusion science physics that requires integrated simulation.

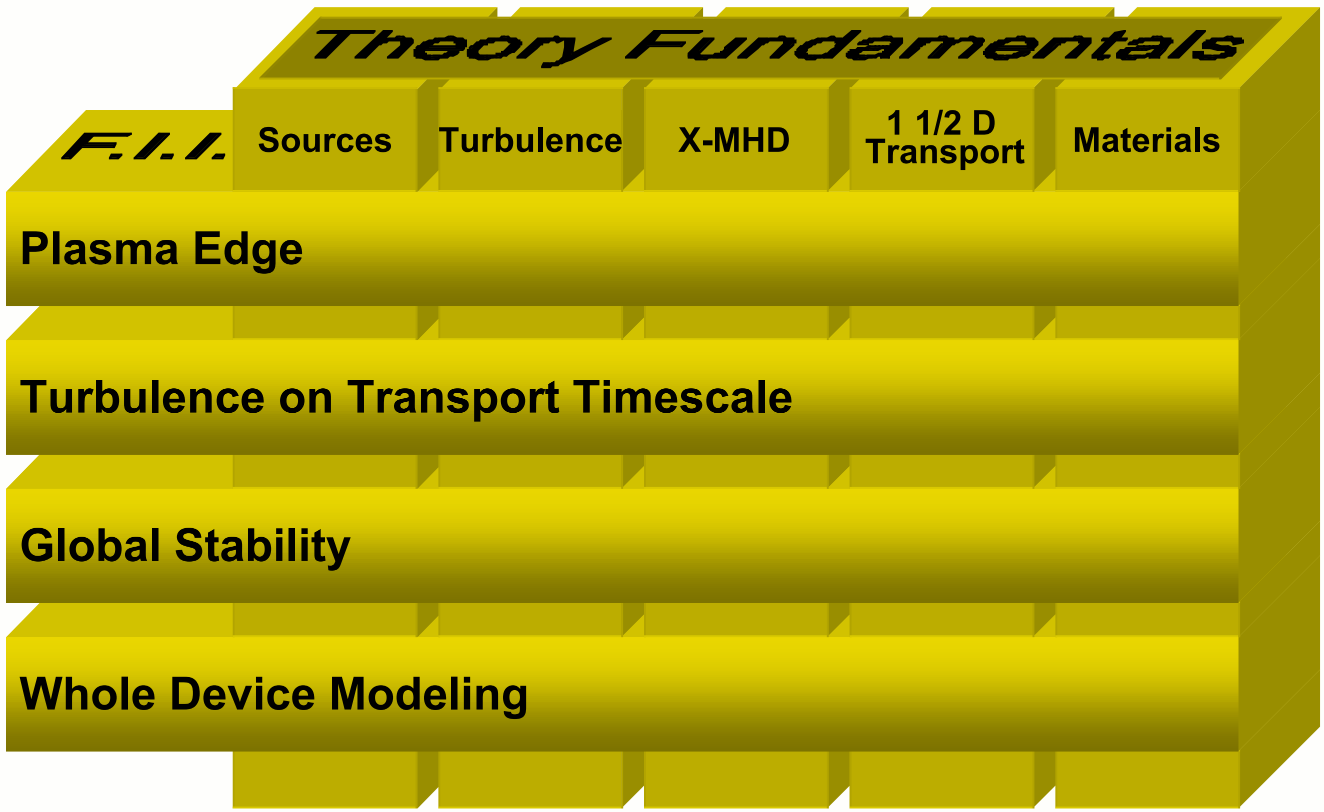
FIIs should be multi-disciplinary, multi-institutional, and should integrate subsets of fusion fundamentals using interoperable software.

The traditional modeling elements that structure our understanding of fusion plasmas include: plasma sources; turbulence; extended MHD; 1.5D (one and one-half dimensional) transport; and fusion materials.

Each FII should cut across and integrate two or more of these traditional elements, to provide physics integration both spatially and temporally, with a guiding focus of a single overarching scientific question or topic that satisfies the criterion of importance to the fusion program.

Focused Integration Initiatives

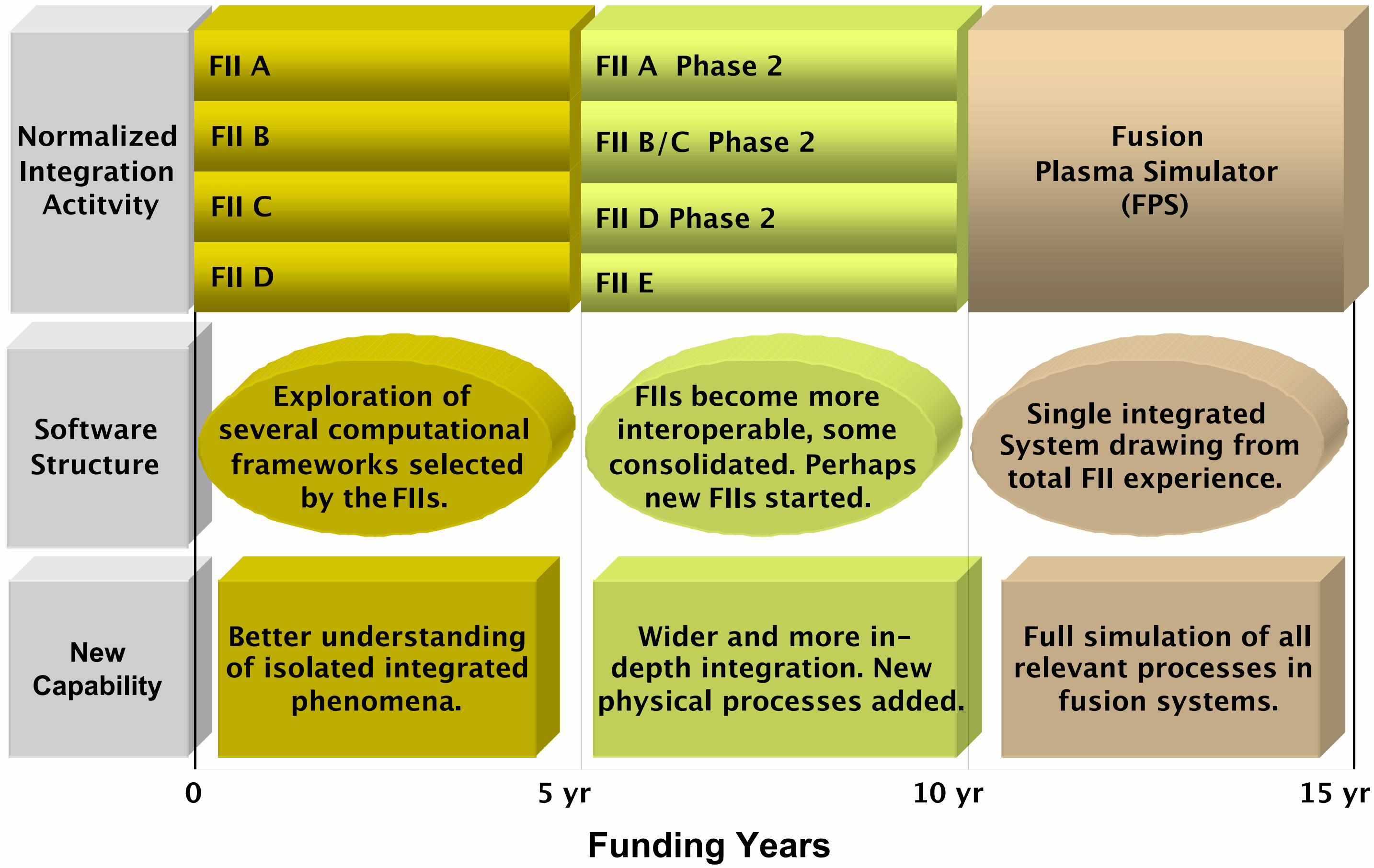
Focused Integration Initiatives are built from Fundamentals of varying complexity with selected algorithms using interoperable software



The community will define overarching FII themes via proposals.
Suggestions are shown in the schematic.

FSP Roadmap

We expect a 15 year timeline is required to produce the FPS



A fifteen year timeline, with specific milestones at the end of five and ten years. The full extent of the 15-year project is expected to require on the order of $0.4B.

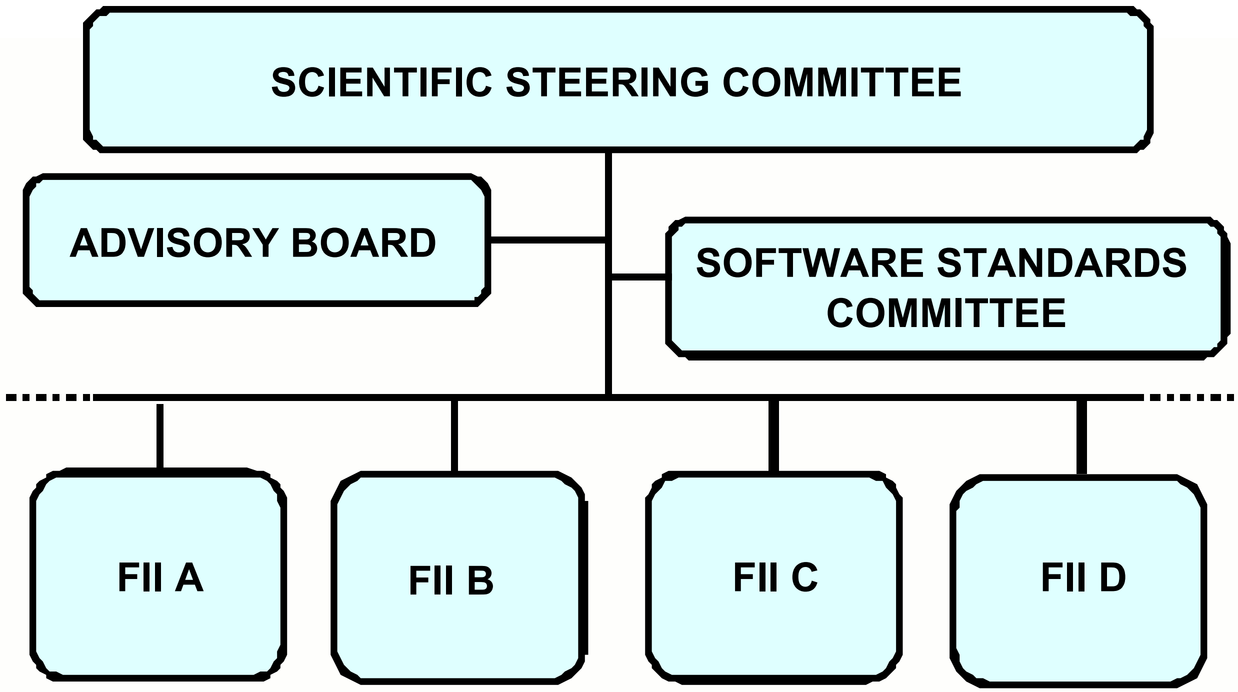
Fifteen-year goal: Fusion Plasma Simulator (FPS)

* Envisioned to be an integrated research tool that contains comprehensive coupled self-consistent models of all important plasma phenomena that would be used to guide experiments and be updated with ongoing results.
* Would serve as an intellectual integrator of physics phenomena in advanced tokamak configurations, advanced stellarators and tokamak burning plasma experiments.
* Would integrate the underlying fusion plasma science with the Innovative Confinement Concepts, thereby accelerating progress.

The ISOFS FSP is a first five-year stage of the ultimate FPS.

This need is recognized in the preliminary report of the FESAC Development Path Subcommittee charged with identifying the requirements for the start of operation of a fusion energy demonstration power plant in 35 years.

FSP Governance



- Multi-institutional
- Multi-disciplinary
- Balance between intellectual independence and goal-driven activity
- Must involve both OFES and OASCR

Need to continue the planning process

The FSP planning process should continue during 2003.

Examples of planning activities:

- Focused technical workshops that continue to broaden participation among fusion physicists and applied mathematicians and computer scientists;
- Small working groups that begin to clarify and define the software architecture, including documenting requirements;
- Venues for the clarification of needed collaborative tools;
- Continued integration of the outputs of the above by the ISOFS Subcommittee -- or whichever future organization DOE decides to enfranchise in this role -- into a detailed planning document that will lead to a suitable FSP proposal call;
- As technical planning becomes more refined, activities that provide more accurate budget estimates for the duration of the FSP; and,
- Attention to new and ongoing international activities in these areas with a goal of fostering collaboration where feasible.

Summary

- Achieving the goals of the FSP will require significant collaborative advances in physics, applied mathematics and computer science:
  - The wide range of temporal and spatial scales, extreme anisotropies and complex geometry, make this problem among the most challenging in computational physics.
  - Will require qualitative improvements, innovations and strong collaborations.
  - Disciplinary integration will be an essential element of the project.
  - The FSP must develop software methodologies and frameworks for designing, building, maintaining, and validating the simulation software.
  - Computer science issues raised by this initiative include: the choice of an architecture for interconnecting code modules; data models; performance monitoring and optimization; provision for flexibility and extensibility; and, tools for enabling human collaborations over long distances.
- Verification, and validation:
  - A central feature of this initiative must be an intensive and continual close coupling between the simulations efforts, theory and experiments.
- The FSP will require significant improvements in infrastructure:
  - Advances at major computational facilities
  - Deployment and enhancements to local or topical computing centers.
  - Investments in advanced storage systems at all levels.
  - Timely upgrades to the communication network and local infrastructure will be required.
- New insights (in multi-time and -space scales):
  - Wall interaction phenomena
  - Effects of turbulence on long time confinement
  - Implications of burning plasma self-heating in advanced tokamak operating regimes
  - ...

Thanks to the fusion and computation communities for providing essential input for the FSP initiative planning

particularly, for the technical contributions:
in the computational science sections of the report, by David Brown and David Keyes; and,
in the fusion sections, by Jeff Candy, Ron Cohen, Nasr Ghoniem, Greg Hammett, Wayne Houlberg, David Humphreys, William Nevins, Ron Stambaugh, and Ron Waltz.