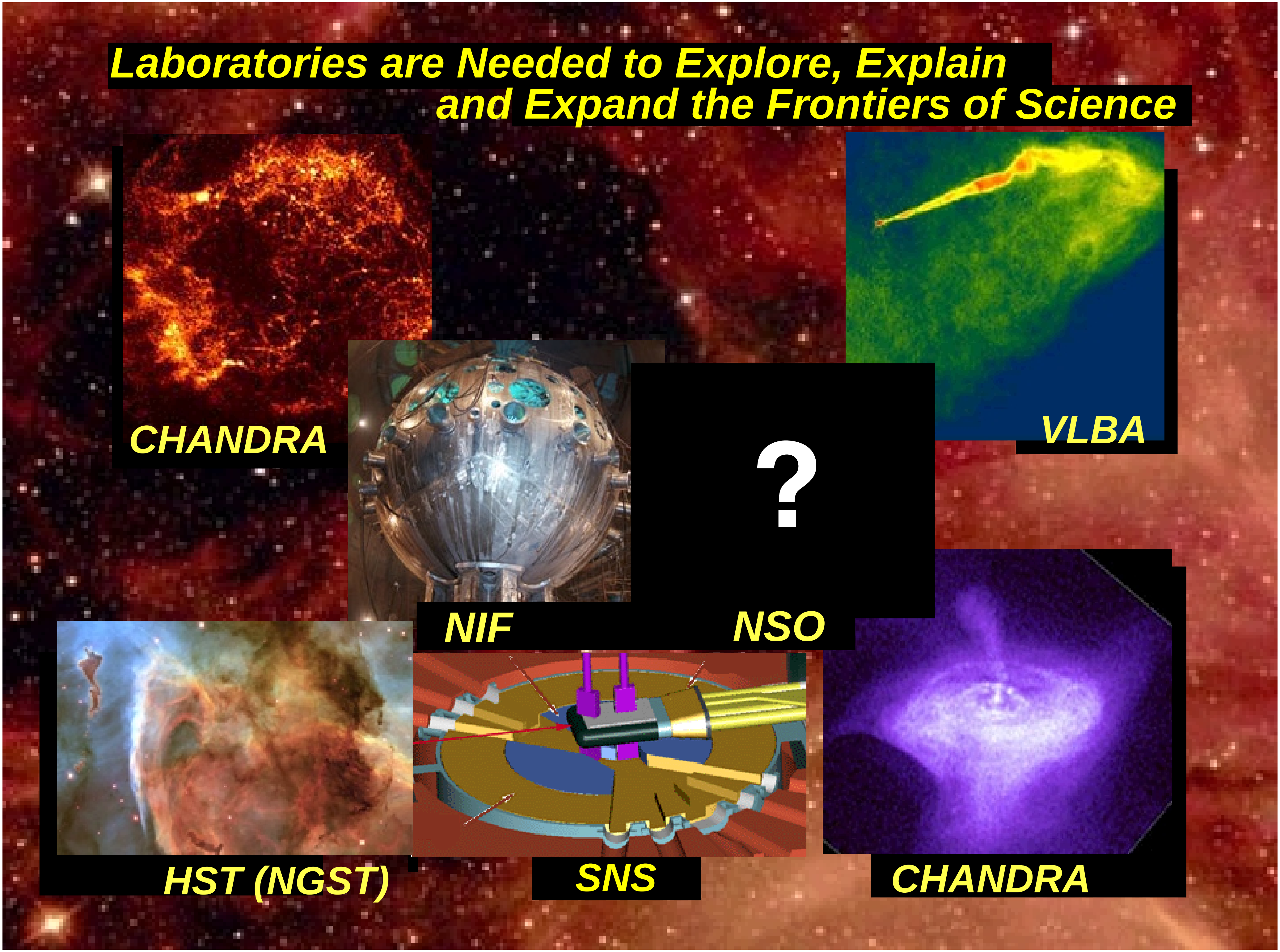

Laboratories are Needed to Explore, Explain
and Expand the Frontiers of Science
CHANDRA
VLBA
?
NIF
NSO
HST (NGST)
SNS
CHANDRA

Fusion Plasma Science and NSO

Scientific Benefits and Readiness for a Burning Plasma Experiment

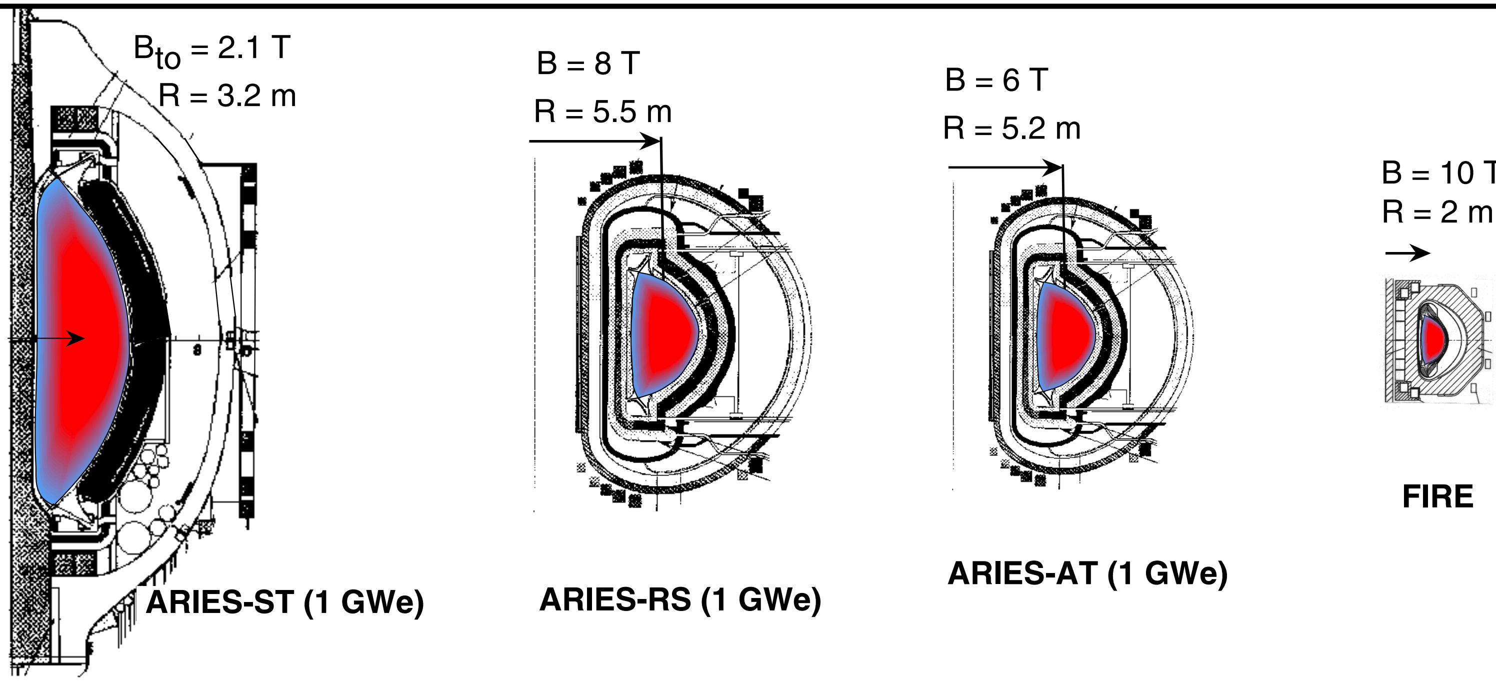
Dale M. Meade
National FIRE Design Study Team

Next Step Options Program Advisory Committee Meeting
General Atomics, San Diego, CA.

July 20, 2000

http://fire.pppl.gov

The Tokamak has the Potential to be an Attractive Fusion Reactor.



Fusion Metrics	ARIES-ST	ARIES-RS	ARIES-AT*	FIRE
Plasma Volume (m^3)	810	350	330	18
Plasma Surface (m^2)	580	440	426	60
Plasma Current (MA)	30	11	13	6.5
Fusion Power (MW)	3000	2200	1755	200
Fusion Power Density(MW/m^3)	3.7	6.2	5.3	12
Neutron Wall Load (MW/m^2)	4	4	3.5	3
COE Projected (mils/kWh)	81	76	≈55	

* 6/14/2000

NSO/FIRE Community Discussions

A Proactive NSO/FIRE Outreach Program has been undertaken to solicit comments and suggestions from the community on the next step in magnetic fusion.

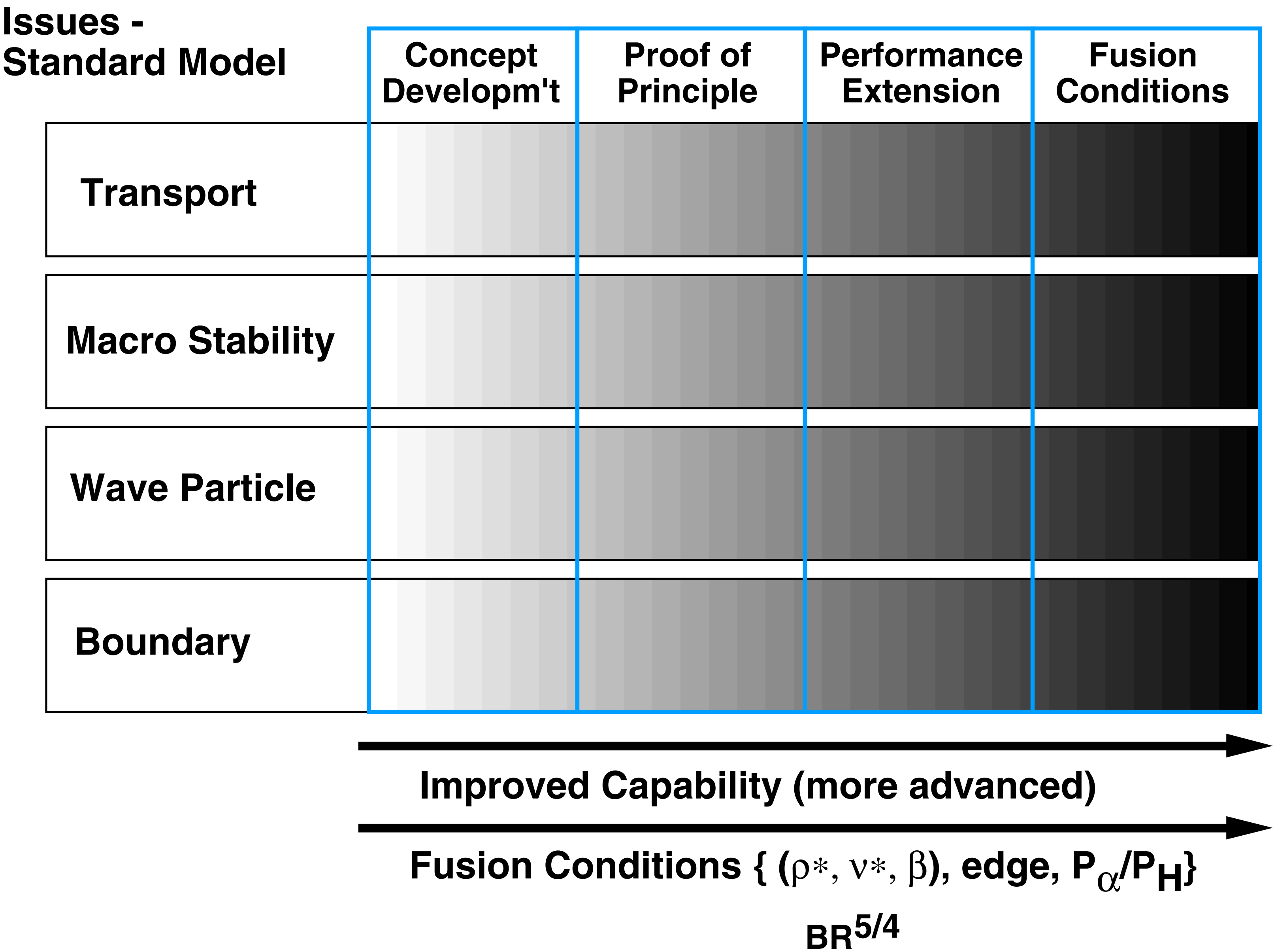
- Presentations have been made and comments received from:

SOFT/Fr	**Sep 98**	**IAEA/Ja**	**Oct 98**
APS-DPP	**Nov 98**	**FPA**	**Jan 99**
APEX/UCLA	**Feb 99**	**APS Cent**	**Mar 99**
IGNITOR	**May 99**	**NRC**	**May 99**
GA	**May 99**	**LLNL**	**May 99**
VLT-PAC	**Jun 99**	**MIT PSFC**	**Jul 99**
Snowmass	**Jul 99**	**PPPL/SFG**	**Aug 99**
U. Rochester	**Aug 99**	**NYU**	**Oct 99**
U. Wis	**Oct 99**	**FPA**	**Oct 99**
SOFE	**Oct 99**	**APS-DPP**	**Nov 99**
U. MD	**Dec 99**	**DOE/OFES**	**Dec 99**
VLT PAC	**Dec 99**	**Dartmouth**	**Jan 00**
Harvey Mudd	**Jan 00**	**FESAC**	**Feb 00**
ORNL	**Feb 00**	**Northwest'n**	**Feb00**
U. Hawaii	**Feb 00**	**Geo Tech**	**Mar 00**
U. Georgia	**Mar 00**	**PPPL**	**Mar 00**
Naval Postgrad S	**Mar 00**	**U. Wis**	**Mar 00/Apr00**
EPS/Budapest	**Jun 00**	**IPP/Garching**	**Jun 00**
CEA/Cadarache	**Jun 00**	**JET-EFDA**	**Jun 00**

- **The FIRE web site has been developed to make information on FIRE and fusion science accessible and up to date. A steady stream of about 150 visitors per week log on to the FIRE web site since the site was initiated in early July, 1999.**

Magnetic Fusion Science

Part I



Requirements for Fusion Plasma Science

Study Physics of Fusion Plasmas (transport, pressure limits, etc.)

- **Same plasma physics if $\rho^* = \rho/a$, $\nu^* = \nu_c / \nu_b$ and β are equal**

  Requires $BR^{5/4}$ to be equal to that of a fusion plasma

Study Physics of Burning Plasmas (alpha confinement, self heating, etc)

- **Alpha particle confinement requires $Ip(R/a) \geq 9$, $Ip(R/a) \sim BR(R/a)$**

- **Alpha heating dominant, $f_\alpha = P_\alpha/P_{heat} = Q/(Q+5) > 0.5$**

  $f_\alpha = n\tau_E T \,/\, (n\tau_E T)_{Ignition}$ for $P_\alpha >> P_{brem}$

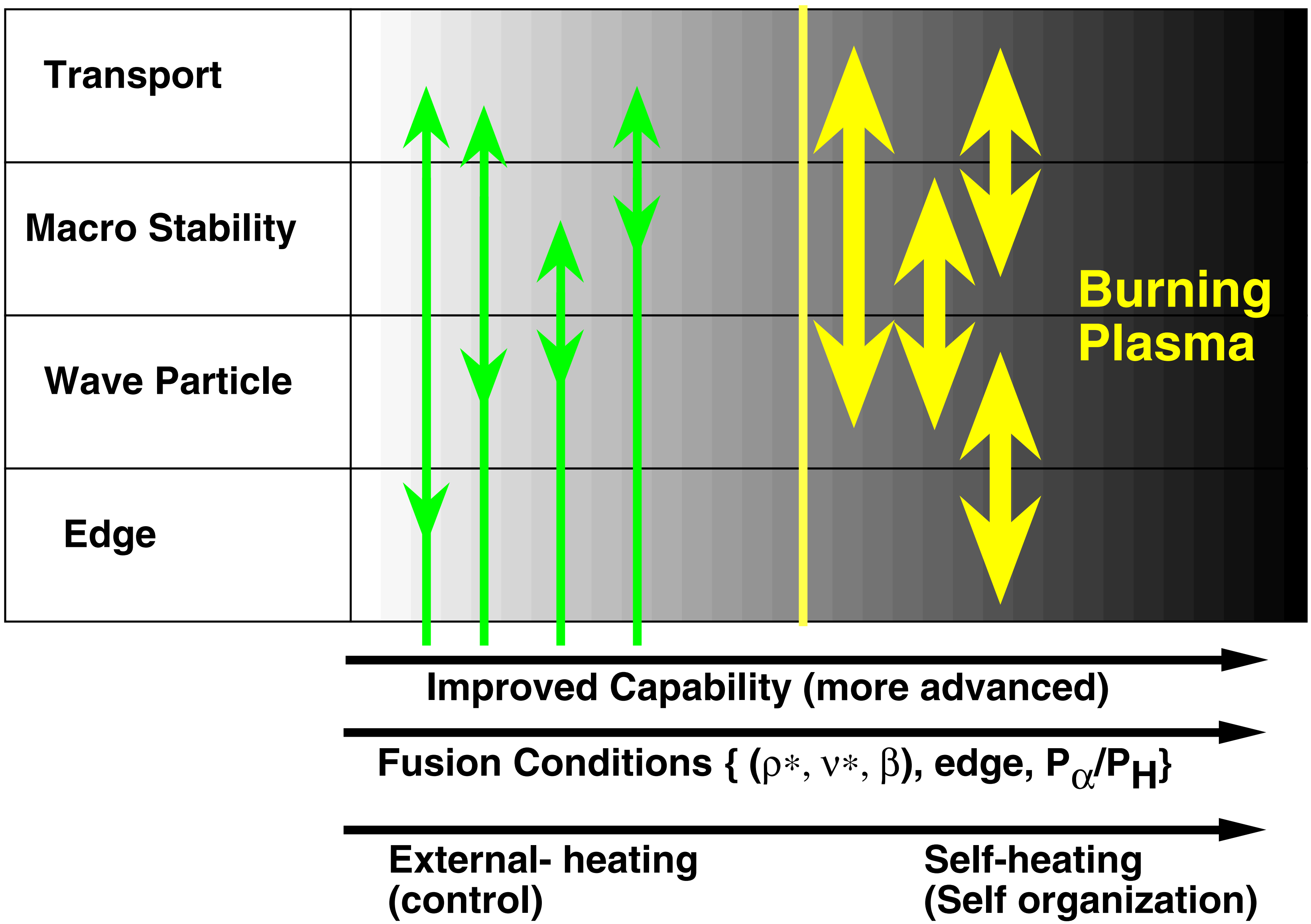
  $n\tau_E T = B \times \text{function}(\rho^*, \nu^*, \beta)$ in general

  $n\tau_E T = B \times (BR^{5/4})^{4/3}$, if τ_E scales as Bohm

  $= B \times (BR^{5/4})^2$, if τ_E scales as gyroBohm

Magnetic Fusion Science

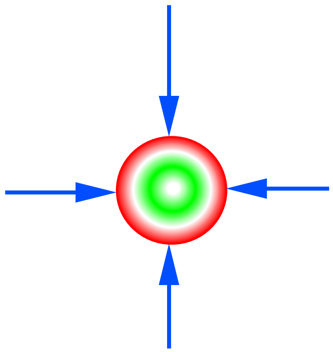
Issues - Strongly Coupled in a Fusion (Burning) Plasma

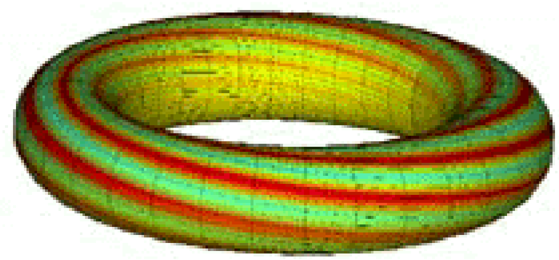


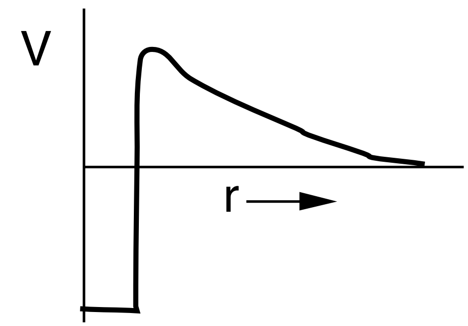
Burning Plasma Physics is Widely Accepted as the Primary Objective for a Next Step in Fusion Research

- Grunder Panel and Madison Forum endorsed Burning Plasmas as next step.
- NRC Interim Report identified "integrated physics of a self-heated plasma" as one of the critical unresolved fusion science issues.
- The Snowmass Fusion Summer Study endorsed the burning plasma physics objective, and that the tokamak was technically ready for high-gain experiment.
- R. Pellat, Chair of the CCE-FU has stated that "the demonstration of a sustained burning plasma is the next goal" for the European Fusion Program.
- SEAB noted that "There is general agreement that the next large machine should, at least, be one that allows the scientific exploration of burning plasmas" and if Japan and Europe do not proceed with ITER "the U. S. should pursue a less ambitious machine that will allow the exploration of the relevant science at lower cost." "In any event the preliminary planning for such a machine should proceed now so as to allow the prompt pursuit of this option."

There are Three Principal Fusion Concepts







Spherical Inertial

gravitational

transient compression

- drive (laser-D/I, beam)
- radial profile
- time profile

electrostatic

Toroidal Magnetic

surface of helical B lines

- twist of helix
- twist profile
- plasma profile
- toroidal symmetry

Reactivity Enhancement

muon catalysis

polarized nuclei

others?

Generic Benefits of Tokamak Experiments

1. There are many examples of how results, understanding and models for tokamaks have been transferred to studies of other magnetic configurations.

transport	stability
wave particle	edge

2. How do we expect burning plasma experiments to help advance understanding of burning plasmas in other magnetic configurations?

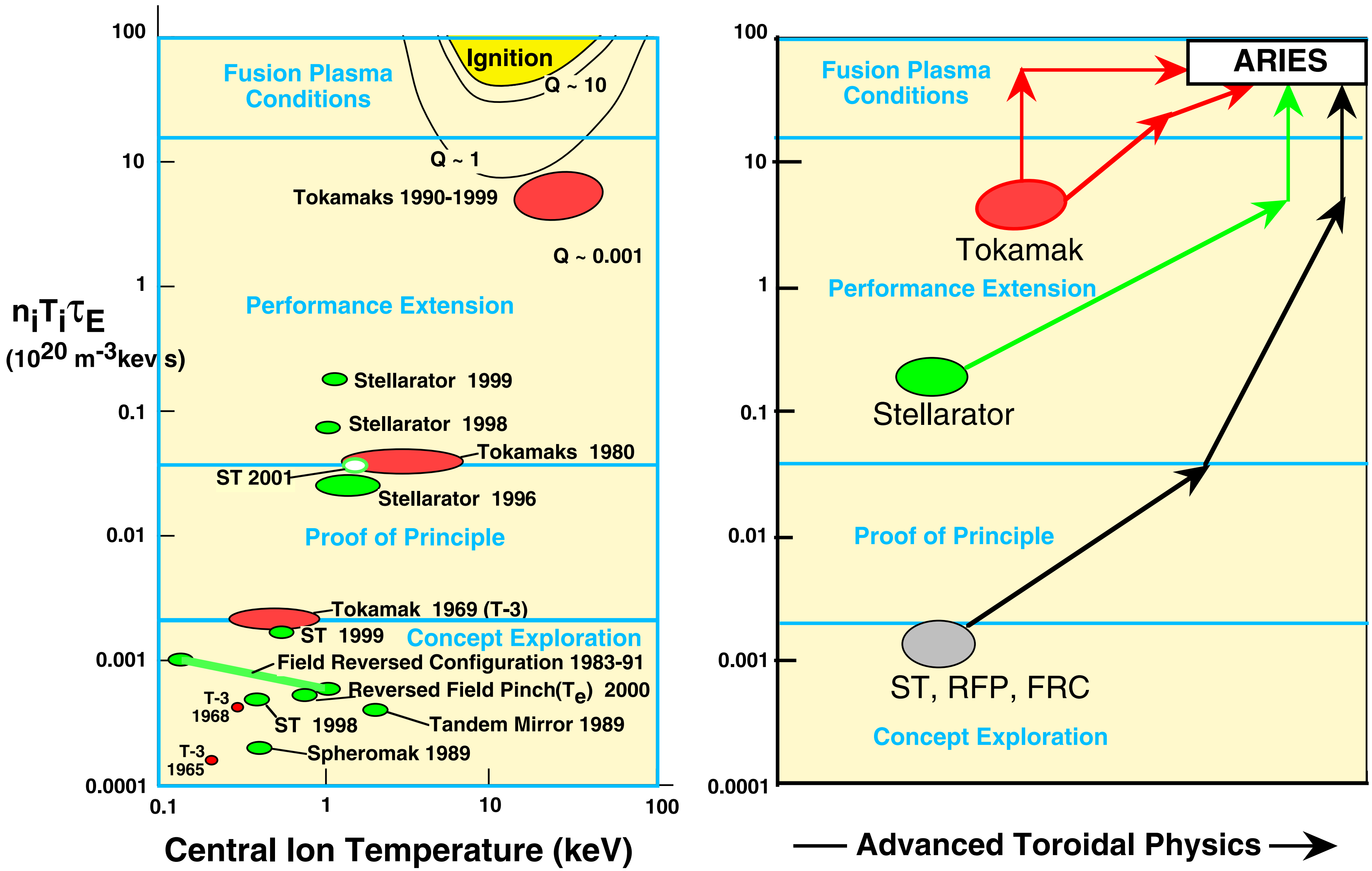
   spherical torus (tokamak)

   stellarator

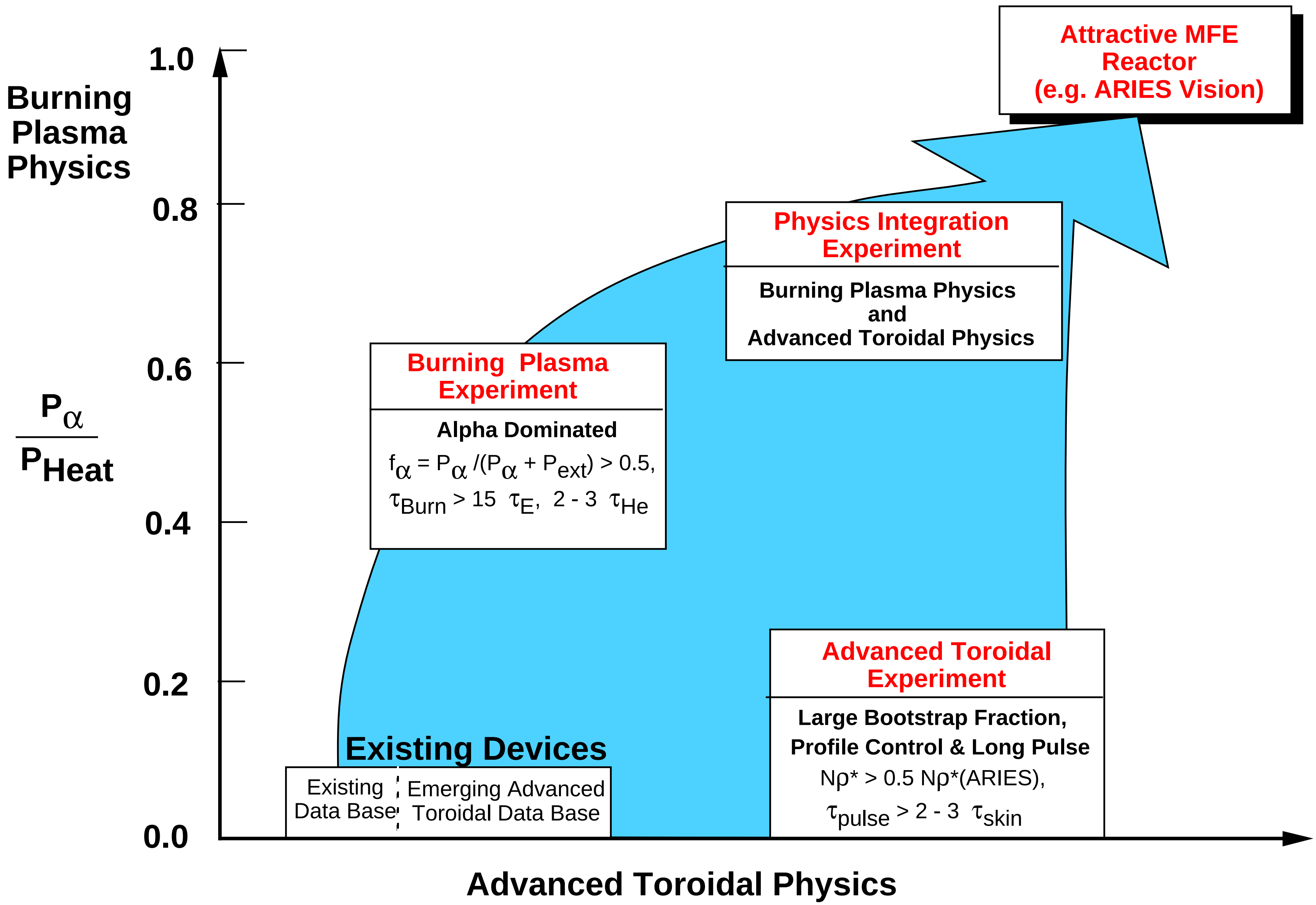
   RFP, Spheromaks, FRCs,

Good discussion of this in Snowmass Burning Plasma Physics Report

Is the Tokamak Ready to Explore the Science of Fusion Plasmas?



Stepping Stones for Resolving the Critical Fusion Plasma Science Issues for an Attractive MFE Reactor



The "Old Paradigm" required three separate devices, the "New Paradigm" could utilize one facility operating in three modes or phases.

Purpose of the Next Step

Status - physics understanding and predictive capability is improving but uncertainties will always remain that must be tested in a “real” fusion plasma.

The purpose of NSO is to extend both physics understanding and performance

it is not to demonstrate that present understanding is correct.

Size of the extrapolation (risk) must be chosen to maximize the information in the critical areas for a fusion reactor.

At the same time, the cost constraints will force one toward a minimum size step.

Fusion Science Objectives for a Major Next Step Experiment (e.g., FIRE)

- Explore and understand the physics of alpha-dominated fusion plasmas:
  - Energy and particle transport (extend confinement predictability)
  - Macroscopic stability (β-limit, wall stabilization, NTMs)
  - Wave-particle interactions (fast alpha driven effects)
  - Plasma boundary (density limit, power and particle flow)
  - Strong coupling of previous issues due to self-heating(self-organization?)
- Test techniques to control and optimize alpha-dominated plasmas.
- Sustain alpha-dominated plasmas - high-power-density exhaust of plasma particles and energy, alpha ash exhaust, study effects of profile evolution due to alpha heating on macro stability, transport barriers and energetic particle modes.
- Explore and understand some advanced operating modes and configurations that have the potential to lead to attractive fusion applications.

see also ITER Physics Basis Report Nuclear Fusion

Optimizing a Tokamak Next Step Experiment

- Utilize existing experimental, modeling and theoretical activities to extend the understanding of present plasma regimes with enhanced performance

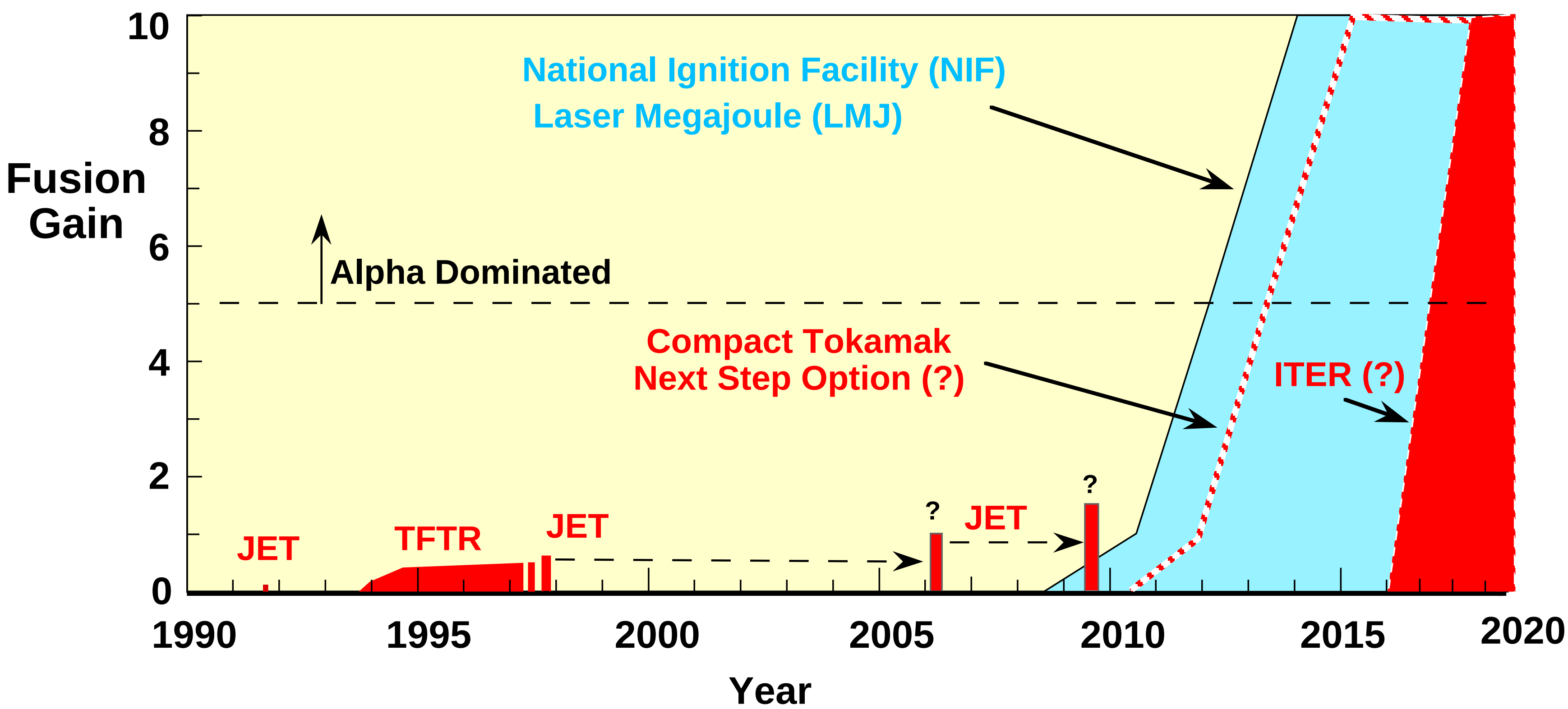
  - revitalize the science issue expert groups, participate in the international effort, develop the physics basis for incorporating some AT features or flexibility into a Next Step experiment.

- Take advantage of the growing resources becoming available in various computer simulation initiatives to extend the capability of existing magnetic fusion simulation codes.

- Exploit this improved capability to refine/improve/optimize the design of a Next Step experiment to that it is able to test the essential physics issues and extend the physics understanding to fusion plasma conditions.

- Use a similar philosophy on the engineering issues to optimize the design.

Timetable for Burning Plasma Experiments



- Even with ITER, the magnetic fusion program will be unable to address the alpha-dominated burning plasma issues for ≥ 15 years.
- Compact High-Field Tokamak Burning Plasma Experiment(s) would be a natural extension of the ongoing "advanced" tokamak program and could begin alpha-dominated experiments by ~ 10 years.
- More than one high gain burning plasma facility is needed in the world program.
- The information "exists now" to make a technical assessment, and decision on a magnetic fusion burning plasma experiment(s) for the next decade.

Critical Issues for NSO and Magnetic Fusion

The critical physics and engineering issues for NSO are the same as those for fusion, the goal of NSO is to help resolve these issues for magnetic fusion. The issues and questions listed below need to be addressed in the near future.

- Physics
  - confinement - H-mode threshold, edge pedestal, enhanced H-mode, AT-modes
  - stability - NTMs, RWM, disruptions: conducting wall? feedback coils? VDE(DN)?
  - heating and current drive - ICRF is baseline: NBI & LHCD as upgrades?
  - boundary - detached divertor operation, impurity levels, confinement
  - self-heating - fast alpha physics and profile effects of alpha heating

  Development of self-consistent self-heated AT modes with external controls

- Engineering
  - divertor and first wall power handling (normal operation and disruptions)
  - divertor, first wall and vacuum vessel for long pulse AT modes
  - evaluate low inventory tritium handling scenarios, higher fluence TF insulator
  - complete many engineering details identified in FIRE Engineering Report
  - evaluate potential sites for Next Step MFE experiment
  - complete cost estimate for baseline, identify areas for cost reduction

Summary

- Exploration, understanding and optimization of alpha-dominated (high-gain) burning plasmas are critical issues for all approaches to fusion.
- The advanced tokamak has the potential to be an attractive fusion reactor.
- A Next Step Experiment capable of accessing fusion plasma conditions is needed to explore and understand critical science issues to provide the basis for an attractive tokamak reactor.
- The Next Step Experiment should have the capability/flexibility be a “stepping stone” between the physics accessible with present experiments and the physics required for the ARIES vision of magnetic fusion energy.