Major Conclusions of the MFE Study

1. Why a burning plasma	Navratil
2. Burning plasma options	Baker
3. Assessment of contributions of the options	Van Dam
4. Assessment of the feasibility of the options	Taylor
5. Assessment of fusion development paths	Taylor
6. Relation to the national program	Prager

CONCLUSION 1

The study of burning plasmas, in which self-heating from fusion reactions dominates plasma behavior, is at the frontier of magnetic fusion energy science.

The next major step in magnetic fusion research should be a burning plasma program, which is essential to the science focus and energy goal of fusion research.

BURNING PLASMAS IS A CRUCIAL ELEMENT IN THE PROGRAM

- **Study of burning plasmas is a crucial and missing element in the fusion energy sciences program.**

- **The capability to study burning plasmas will take us a large step forward in demonstrating magnetic fusion as a source of practical fusion energy.**

WE ARE READY TO TAKE A BURNING PLASMA STEP

- The tokamak is now at the stage of scientific maturity that we are ready to undertake the essential step of burning plasma research.

- Present experiments cannot achieve the conditions necessary for a burning plasma.

- A new experimental facility is required to address the important scientific issues in the burning plasma regime.

- The conditions needed to study the key physics phenomena expected in the burning plasma state have been identified.

BURNING PLASMAS AFFORD UNIQUE OPPORTUNITY FOR DISCOVERY

- Burning plasmas afford unique opportunities to explore, for the first time, high-temperature-plasma behavior in the regime of strong self-heating in the laboratory.

- Production of a strongly, self-heated fusion plasma will allow the discovery and study of a number of new phenomena. These include the effects of:
  - Energetic, fusion-produced alpha particles on plasma stability and turbulence.
  - The strong, nonlinear coupling that will occur between fusion alpha particles, the pressure driven current, turbulent transport, MHD stability, and boundary-plasma behavior.
  - Stability, control, and propagation of the fusion burn and fusion ignition transient phenomena.

ADVANCED TOKAMAK (*AT*) RESEARCH CAPABILITY IS HIGHLY DESIRABLE IN ANY BURNING PLASMA EXPERIMENT

- Recent physics advances in tokamak research, aimed at steady-state and high performance, demonstrate the potential to significantly increase the economic attractiveness of the tokamak. Therefore, Advanced Tokamak (AT) research capability is highly desirable in any burning plasma experiment option.

A BURNING PLASMA WILL MAKE IMPORTANT CONTRIBUTIONS TO THE FUSION PROGRAM

- **Physics and technology learned in a tokamak-based burning plasma would be transferable to other configurations**

- **Scientific flexibility, excellent diagnostics, and close coupling to theory and simulation are critical features of a program in burning plasmas. Such a program would contribute significantly to the physics basis for fusion energy systems based on the tokamak- and other toroidal magnetic configurations.**

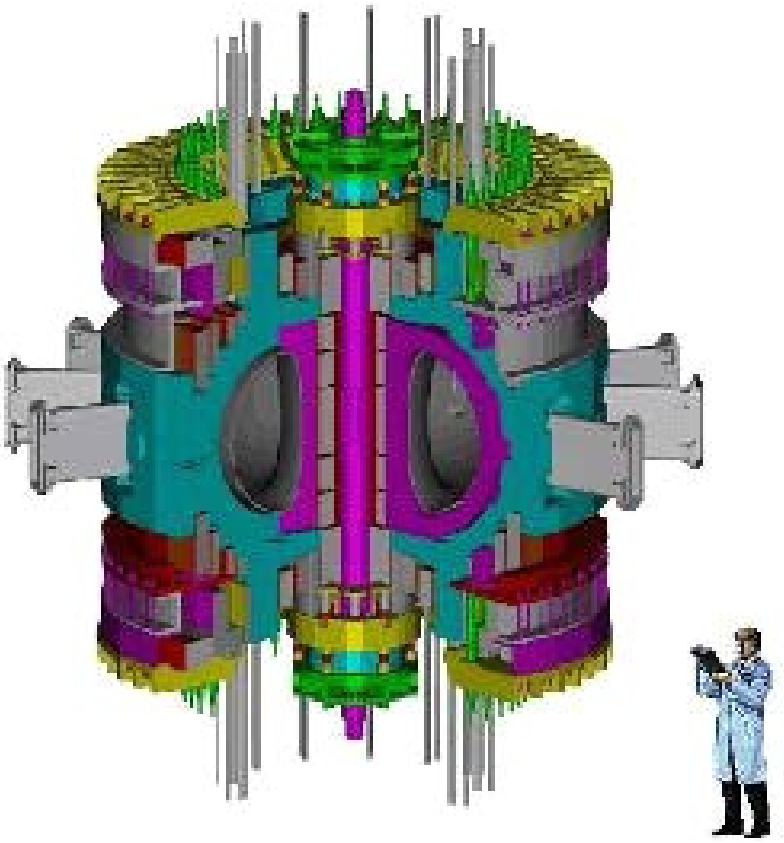
- **The experience gained in burning plasma diagnostics, essential to obtaining data to advance fusion plasma science, will be highly applicable to burning plasmas in other magnetic configurations.**

CONCLUSION 2

The three experiments proposed to achieve burning plasma operation range from compact, high field, copper magnet devices to a reactor-scale superconducting-magnet device. These approaches address a spectrum of both physics and fusion technology, and vary widely in overall mission, schedule and cost.

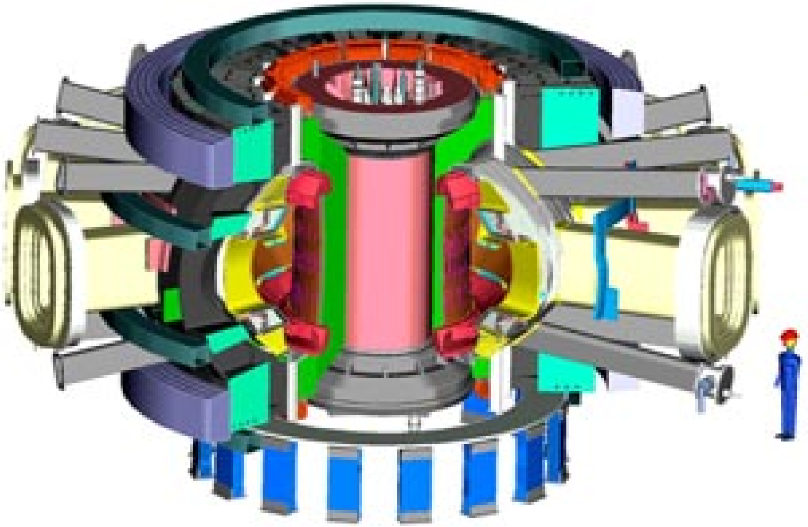
MISSION STATEMENT PROVIDED BY THE IGNITOR TEAM

- IGNITOR is a facility whose mission is to achieve fusion ignition conditions in deuterium-tritium plasmas for a duration that exceeds the intrinsic plasma physics time scales. It utilizes high-field copper magnets to achieve a self-heated plasma for pulse lengths comparable to the current redistribution time. IGNITOR will study the physics of the ignition process and alpha particle confinement as well as the heating and control of a burning plasma subject to thermonuclear instabilities.



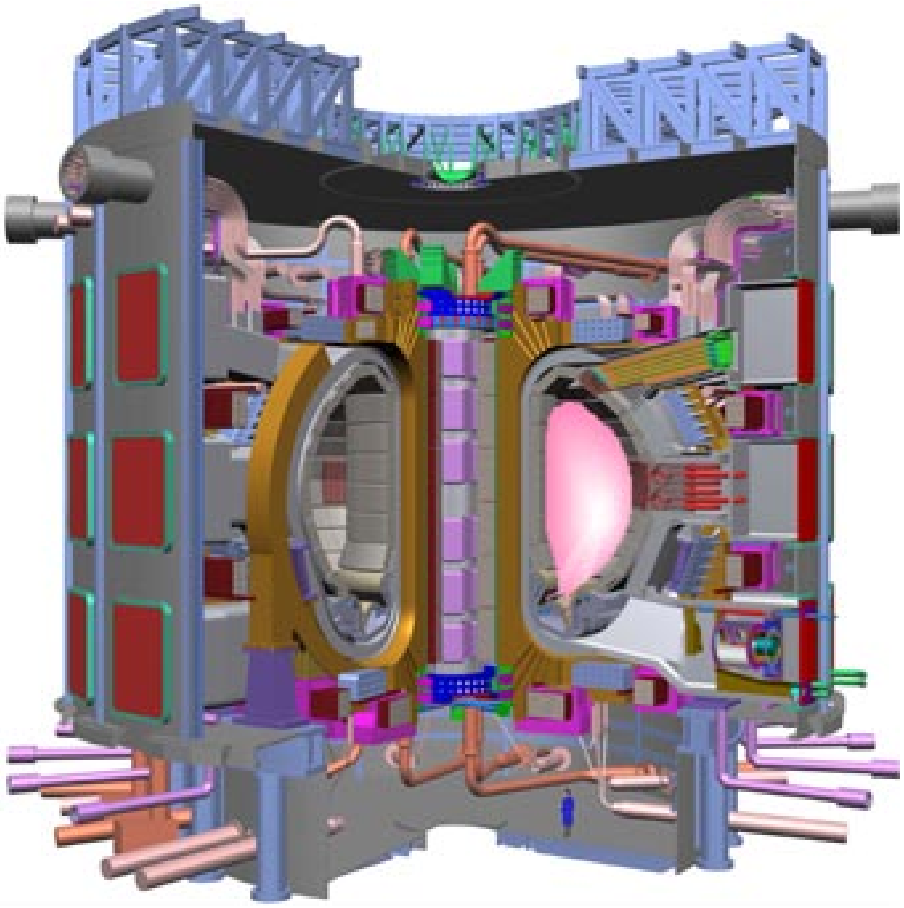
MISSION STATEMENT PROVIDED BY THE FIRE TEAM

- FIRE is a facility whose mission is to attain, explore, understand and optimize magnetically-confined fusion-dominated plasmas. FIRE would study burning plasma physics in conventional regimes with Q of about 10 and high-beta advanced tokamak regimes with Q of about 5 under quasi-stationary conditions. FIRE employs a plasma configuration with strong plasma shaping, double null poloidal divertors, reactor level plasma exhaust power densities and pulsed cryogenically cooled copper coils as a reduced cost approach to achieve this mission.



MISSION STATEMENT PROVIDED BY THE ITER TEAM

- The overall objective of ITER is to demonstrate the scientific and technological flexibility of fusion energy. ITER would accomplish this objective be demonstrating controlled ignition and extended burn of deuterium-tritium plasmas, with steady-state as an ultimate goal, by demonstrating technologies essential to a reactor in an integrated system, and by performing integrated testing of the high heat flux and nuclear components required to utilize fusion energy for practical purposes.



CONSTRUCTION SCHEDULES FOR THE THREE OPTIONS

- Construction schedules were reported as 5 years for IGNITOR, 6 years for FIRE, and 9 years for ITER.

- FIRE is not at the same level of readiness as ITER and IGNITOR and will require some additional time to be ready for construction.

- ITER must complete international negotiations and agreement before construction can commence.

COST OF THE THREE OPTIONS

Cost information was obtained from the ITER and FIRE teams and was assessed within the limited resources available for the Snowmass work. All costs were converted to 2002-US dollars. ITER assumes an international cost-sharing approach while FIRE costs are estimated as a US project.

COST ASSESSMENT OF ITER

- The purpose of the ITER cost information is to provide accurate relative estimates of the “value” of all the tasks necessary for construction to facilitate international negotiations on task sharing. The cost information is based on a large engineering effort (about 1000 PPY) and a large R&D effort (about $900M) with prototypes of all key components. Also, the ITER cost information (about 85 procurement packages) is based on input from the industries in all the parties. The estimate of the ITER total “value”, when converted to 2002 US dollars, is about $5 billion. The actual cost estimate is to be developed by each party using their own procedures, including the use of contingency. Thus, the ITER cost information does not included explicit contingency.

- The US will need to carefully estimate the cost of any potential contributions to ITER. These estimates should include adequate contingency and any additional required R&D to mitigate against potential cost increases.

COST ASSESSMENT OF FIRE

- The estimate for FIRE is about $1.2 B including about a 25% contingency. It is based on an advanced pre-conceptual design using in-house and some vendor estimates. However, substantial further engineering is needed as well as some supporting R&D.

COST ASSESSMENT OF IGNITOR

- **As an Italian project, IGNITOR has been designed in detail with supporting R&D. It has a detailed cost estimate which is confidential for business purposes and was not made available to the assessment team.**

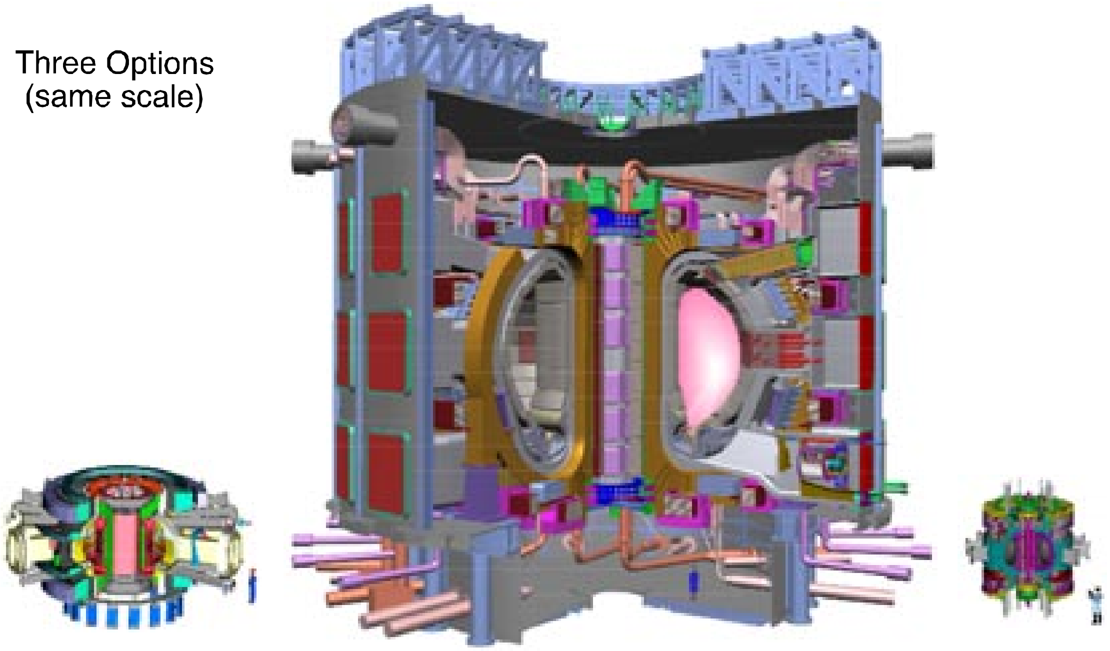
Conclusion 3

IGNITOR, FIRE, and ITER would enable studies of the physics of burning plasma, advance fusion technology, and contribute to the development of fusion energy. The contributions of the three approaches would differ considerably.

- **IGNITOR offers an opportunity for the early study of non-stationary burning plasmas aiming at ignition.**
- **FIRE offers an opportunity for the study of burning plasma physics in conventional and advanced tokamak configurations under quasi-stationary conditions and would contribute to plasma technology.**
- **ITER offers an opportunity for the study of burning plasma physics in conventional and advanced tokamak configurations for long durations with steady state as the ultimate goal, and would contribute to the development and integration of plasma and fusion technology.**

The contributions of the three approaches would differ considerably.

For the three candidate burning plasma devices, we will list **key benefits**: i.e., *the capabilities for studies of the physics and technology of burning plasmas* (assuming that each facility will achieve its proposed performance).


Three Options
(same scale)

Common benefits from all three candidate devices

PHYSICS

1. Strongly-coupled physics issues of equilibrium, stability, transport, wave-particle interactions, fast ion physics, and boundary physics in the regime of dominant self-heating.

TECHNOLOGY

2. Plasma support technologies (heating, fuel delivery, exhaust, plasma-facing components, and magnets) will benefit most because parameters and plasma conditions will be close to those required for power production.
3. Nuclear technologies (remote handling, vacuum vessel, blankets, safety and materials) will advance as a result of the experience of operating in a nuclear environment. The level of benefit will depend on tritium inventory, pulse length, duty factor, and lifetime fluence.

Key benefits from IGNITOR

PHYSICS

1. Capability to address the science of self-heated plasmas in a reactor-relevant regime of small ρ^* (many Larmor orbits) for globally MHD-stable plasmas at low β_N (normalized plasma pressure).
2. Capability to study sawtooth stability at low beta with isotropic alpha particles and self-consistent pressure profile determined by dominant alpha heating.

TECHNOLOGY

3. Development of high-field copper magnets with advanced structural features, including bucking & wedging and magnetic press.
4. Development of high-frequency RF antennas for wave heating in a burning plasma environment.

Key benefits from FIRE

PHYSICS

1. Capability to address the science of self-heated plasmas in reactor-relevant regimes of small ρ^* (many Larmor orbits) and high β_N (normalized plasma pressure) with a large fraction of non-inductive current sustained for up to a few current relaxation times.
2. Exploration of high self-driven current regimes with strong shaping and active MHD stability control.
3. Study of removal of helium ash and impurities with exhaust pumping.

TECHNOLOGY

4. Development of electrical insulation for high-field pulsed copper magnets in high neutron fluence environment.
5. Development of high heat flux plasma-facing components with steady-state heat removal capability (tungsten/beryllium).

Key benefits from ITER

PHYSICS

1. Capability to address the science of self-heated plasmas in reactor-relevant regimes of small ρ^* (many Larmor orbits) and high β_N (plasma pressure), and with the capability of full non-inductive current drive sustained in near steady state conditions.
2. Exploration of high self-driven current regimes with a flexible array of heating, current drive, and rotational drive systems.
3. Exploration of alpha particle-driven instabilities in a reactor-relevant range of temperatures.
4. Investigation of temperature control and removal of helium ash and impurities with strong exhaust pumping.

TECHNOLOGY

5. Integration of steady-state reactor-relevant fusion technology: large-scale high-field superconducting magnets; long-pulse high-heat-load plasma-facing components; control systems; heating systems.
6. Testing of blanket modules for breeding tritium.

CONCLUSION 4
Feasibility Assessment

- There are no outstanding engineering-feasibility issues to prevent the successful design and fabrication of any of the three options.
- However, the three approaches are at different levels of design and R&D.
- There is confidence that ITER and FIRE will achieve burning plasma performance in H–mode based on an extensive experimental database.
- IGNITOR would achieve similar performance if it either obtains H–mode confinement or an enhancement over the standard tokamak L–mode.
- However, the likelihood of achieving these enhancements remains an unresolved issue between the assessors and the IGNITOR team.

The three options are at very different stages of engineering development

- ITER and IGNITOR have well-developed engineering designs.
- ITER has been supported by a comprehensive R&D program. Also, ITER has demonstrated full-scale prototypes for all major components of the fusion core and their maintenance.
- FIRE is at the advanced pre-conceptual design level. It has benefited from previous R&D for CIT/BPX and, most recently, from ITER R&D.
- IGNITOR has carried out R&D and built full-size prototypes on all key components.

Projections for the three options are based on present understanding of tokamak physics

- Based on 0D and 1.5D modeling, all three devices have baseline scenarios which appear capable of reaching $Q = 5 – 15$ with the advocates' assumptions. ITER and FIRE scenarios are based on standard ELMing H–mode and are reasonable extrapolations from the existing database.
- IGNITOR's baseline scenarios, based on cold edged L–mode, depend on a combination of enhanced energy confinement and/or density peaking for which a firm basis has not been established. An unresolved issue arose as to whether an adequate database exists (proposers) or does not exist (assessors) for assessing confinement projections in the proposed IGNITOR operational modes: L–mode limiter or H–mode with x-point(s) near the wall. Further research and demonstration discharges are recommended.
- More accurate prediction of fusion performance of the three devices is not currently possible due to known uncertainties in the transport models. An ongoing effort within the base fusion science program is underway to improve the projections through increased understanding of transport.

A number of issues have been identified

Some Examples

- ITER and FIRE: the predicted ELM-power loads are at the upper boundary of acceptable energy deposition; ELM-control and amelioration is needed.

- FIRE: control of the neoclassical tearing mode by lower hybrid current drive is not sufficiently validated.

- FIRE: radiation damage of magnet insulators.

- ITER: tritium retention is a concern with carbon-based divertor materials.

These issues are the subjects of continuing R&D.

Advanced operating regimes are pursued on each option

- Each device presents a reasonable set of advanced scenarios based on present understanding. ITER and FIRE have moderate and strong shaping respectively and the control tool set needed to address the issues of high beta and steady-state related to Advanced Tokamak regimes. FIRE has the capability to sustain these regimes for 1 – 3 current redistribution times, while ITER’s capability to operate for up to 3000 s allows near steady-state operation. IGNITOR presents credible advanced performance scenarios using current ramps and intense heating to produce internal transport barriers on a transient basis.

CONCLUSION 5.
Fusion Development Path

- **The development path to realize fusion as a practical energy source includes four major scientific elements:**
  1) Fundamental understanding of the underlying science and technology and optimization of magnetic configuration
  2) Burning plasma physics
  3) High performance, steady-state operation
  4) Development of low-activation materials and fusion technologies

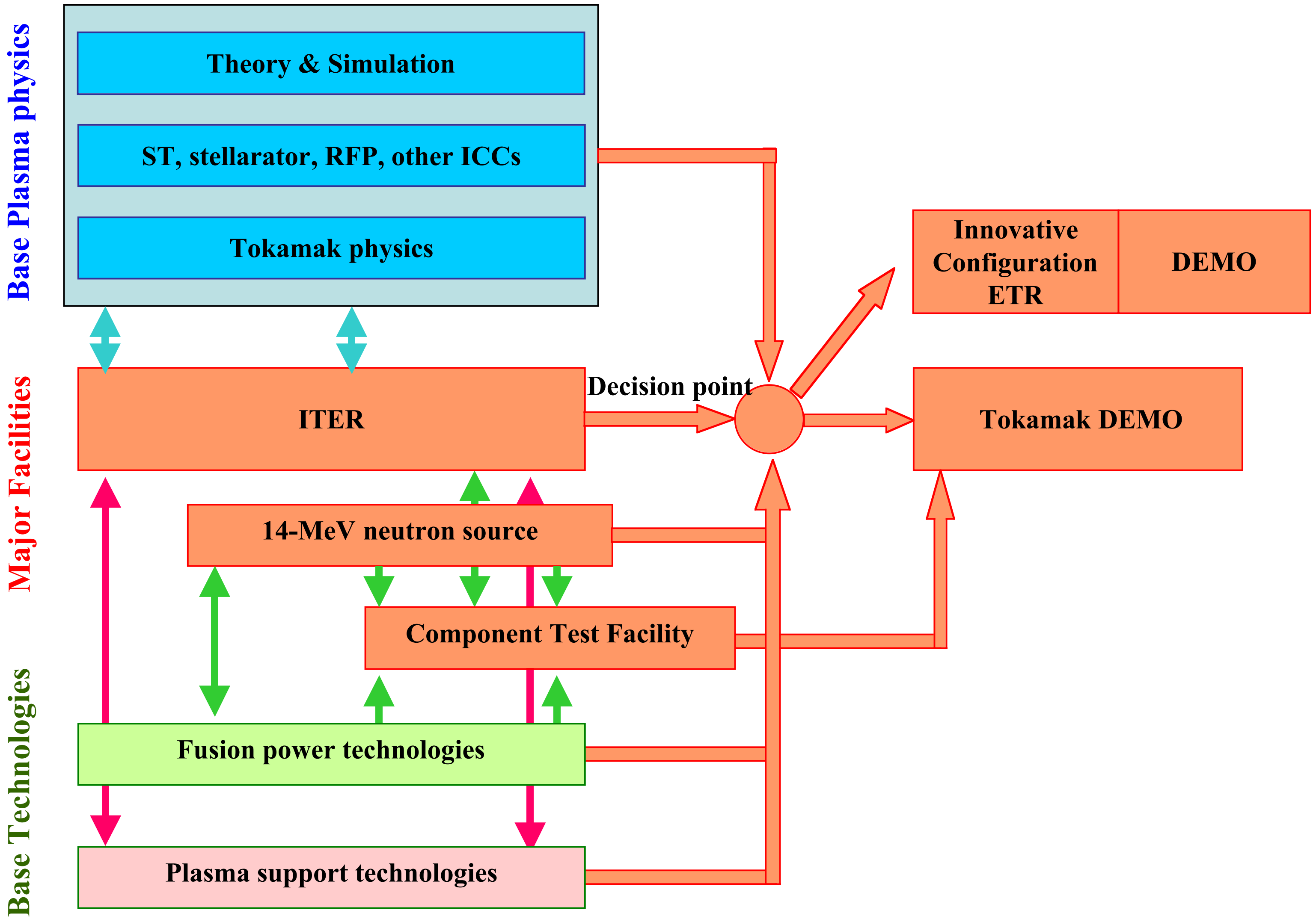
Low Activation Materials and Fusion Technologies Are Needed for Fusion Development

- Fusion power technologies are a pace setting element of fusion development. Development of fusion power technologies requires:
  - Strong base program including testing of components in non-nuclear environment as well as fission reactors.
  - Material program including an intense neutron source to develop and qualify low-activation material.
  - A Component Test Facility for integration and test of power technologies in fusion environment.

ITER-Based Development Path

- An international tokamak research program centered around ITER and including these national performance-extension devices have the highest chance of success in exploring burning plasma physics in steady state.
- ITER will provide valuable data on integration of power-plant relevant plasma support technologies.
- Assuming successful outcome (demonstration of high-performance AT burning plasma), an ITER-based development path would lead to the shortest development time to a demonstration power plant.

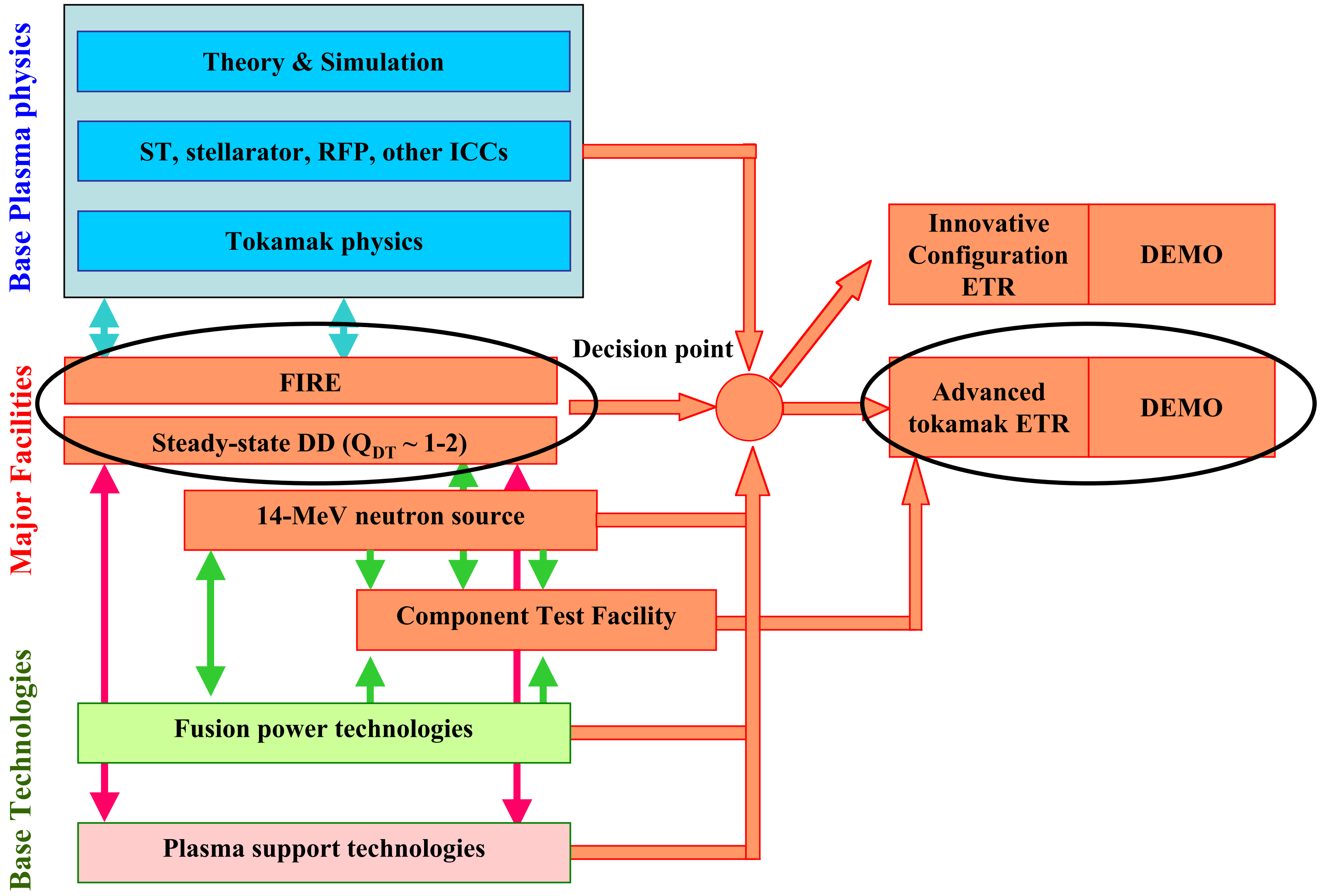
ITER-Based Development Path



FIRE-Based Development Path

- FIRE-based development plan reduces initial facility investment costs and allows optimization of experiments for separable missions.
- It is a lower risk option as it requires “smaller” extrapolation in physics and technology basis.
- Assuming successful outcome, a FIRE-based development path provides further optimization before integration steps, allowing a more advanced and/or less costly integration step to follow.

FIRE-Based Development Path



Role of IGNITOR in Fusion Development

- IGNITOR allows early demonstration of an important fusion milestone, burning plasmas.
- IGNITOR has a low initial facility investment cost.
- Because of its short pulse length, IGNITOR cannot thoroughly investigate burn control and/or advanced tokamak modes.
- **IGNITOR could be an element of a portfolio of experiments supporting ITER-based or FIRE-based development scenarios.**

Principal Advantages of Different Development Scenarios

- **ITER:**
  - Early exploration and optimization of integrated burning plasma, steady state (AT) operation, and plasma support technologies.
  - Minimizes number of steps (and time) to tokamak-based fusion power.
- **FIRE:**
  - Reduces initial facility investment costs and allows optimization of experiments for separable missions.
  - Provides further optimization before integration steps.
- **IGNITOR:**
  - Early demonstration of an important fusion milestone, burning plasmas.
  - Low initial facility investment cost.
- **Fusion Power technologies are the pace setting element of fusion development. Their development requires:**
  - Strong base program including testing of components in non-nuclear environment as well as fission reactors.
  - Material program including an intense neutron source to develop and qualify low-activation material.
  - A Component Test Facility for integration and test of power technologies in fusion environment.

Conclusion 6

A strong base science and technology program is needed to advance essential fusion science and technology, and to participate effectively in, and to benefit from, the burning plasma effort. In particular, the development path for innovative confinement configurations would benefit from research on a tokamak-based burning plasma experiment

A strong base science and technology program is needed to advance essential fusion science and technology

- An accepted premise of the fusion program

- The base program includes all the key, fundamental science and technology issues other than burning plasma science

- It is critical to advance the base program in the presence of a burning plasma experiment

A strong base program is needed to participate effectively in, and to benefit from, the burning plasma effort

for participation, we need

- the full spectrum of physicists and engineers to participate in the BPX
- Training of new fusion scientists
- Tokamak experiments to contribute to the database supporting a BPX

to receive benefits, we need

- Theorists to generalize the BPX results
- A configuration optimization program so that BPX results can be used to accelerate concept development

The development path for innovative confinement configurations would benefit from research on a tokamak-based burning plasma experiment

Research in innovative confinement configurations aims to advance fusion plasma physics and to evolve attractive approaches to fusion energy

Transferability of information enhances the utility of a burning plasma experiment

Sample list of configurations

- Nonaxisymmmetric: stellarator family
- q > 1axisymmetric: tokamak family
  AT, ST
- q < 1 axisymmetric: RFP, spheromak, FRC

Key issues and transferability

- α - generated instabilities:physics of spectra, excitation, damping extend to other configurations; geometric details differ
- α - effects on existing instabilities: drift-precession effects transferable
- Fluctuation-driven α transport: effect on electrostatic fluctuations, sawteeth transferable
- RF wave interactions with α particles : interaction physics transferable
- Burn control, nonlinear coupling: some control aspects transferable
- The unknown: ??

- Transferability requires understanding at a fundamental level, through experiment, theory, computation

- Nearly all past tokamak results have influenced other configurations

BPX technology is strongly transferable

e.g.,

- magnets
- diagnostics
- plasma facing components
- heating sources
- fueling
- blankets
- remote handling