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ICC POP Contributions to Fusion Energy Development

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Executive Summary

The U.S. Fusion Energy Sciences program has adopted a multiple path strategy for optimizing fusion energy development. Central to this strategy is the “portfolio approach”, where multiple plasma confinement configurations advance, in parallel, through varying stages of development. The portfolio approach provides an excellent vehicle for program innovation and a means for broadening the scientific and technical basis for fusion energy with a view to developing the best fusion energy sources. Its success, however, is very dependent on the coherent integration of the portfolio’s scientific and technical contributions to fusion energy development. This integration must be pursued at all stages of a concept’s development.

The fusion development stages have been discussed in other reports and are summarized here for completeness. In order of increasing technical maturity, the first three stages are “Concept Exploration”, “Proof-of-Principle”, and “Performance Extension”. Concept Exploration experiments are relatively low-cost experiments that investigate the basic plasma characteristics of a confinement concept. The Proof-of-Principle stage is intended to develop an integrated understanding of the basic science of a concept. Performance Extension programs explore the physics of the concept at or near fusion-relevant regimes.

Success in these first three stages should then, in principle, lead to the “Fusion Energy Development” and “Fusion Energy Demonstration” stages. The Fusion energy Development stage, such as a burning plasma experiment (BPX), is intended to develop the technical basis for advancing a concept to the power plant level in a fusion environment. However, the large cost and development time associated with these last two stages will most likely preclude pursuing concepts in parallel. Hence, it is likely that there will only be one BPX class facility in the near future based on the tokamak. The Fusion Energy Demonstration (DEMO) step that follows the BPX could have better reactor attributes than a standard tokamak, by taking advantage of improvements that would be available from a mature portfolio. To make this possible, the portfolio must continue to advance in both maturity and breadth. In addition, the BPX must be

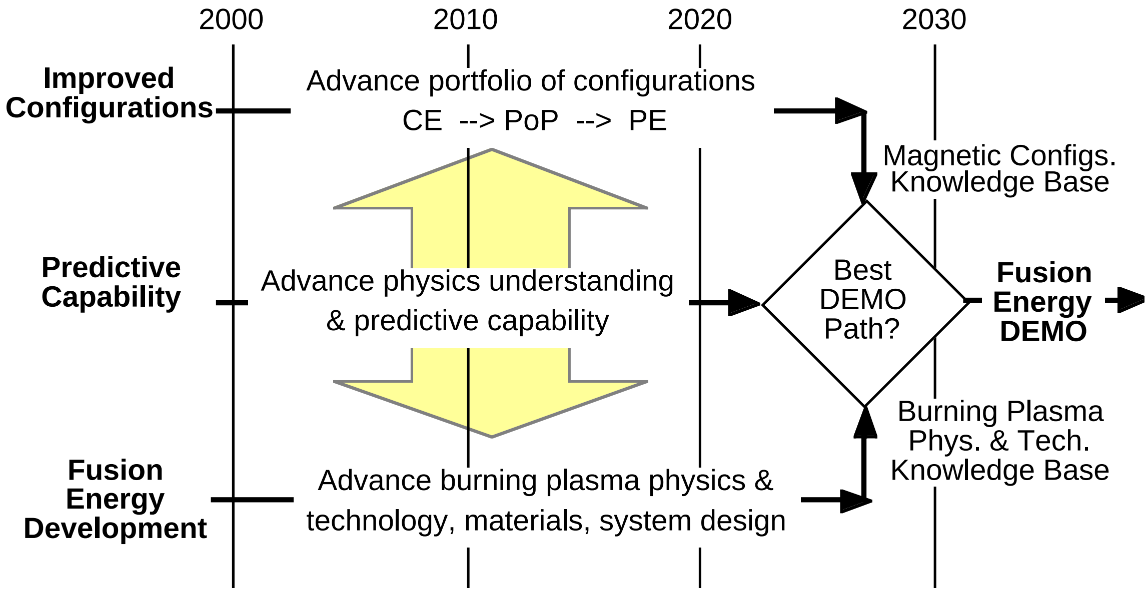

Fig. 1. Program for Developing a Practical Magnetic Fusion Energy

designed and planned to deliver generic benefits, and a reliable predictive capability must be developed based on understanding and tested models that span the range of configurations.

The requirement for a mature portfolio can be satisfied by continuing to follow the development strategy established in recent years. Configurations that are now at the proof-of-principle stage, namely the spherical torus (ST), compact stellarator (CS), and reversed-field pinch (RFP) are closely related to the tokamak and in the next 5-15 years are natural candidates for promotion to performance extension, joining the advanced tokamak (AT) and the stellarator (S). A substantial performance extension knowledge base for these configurations can be made available by the time DEMO decisions need to be made, about 25-30 years from now. In the same period, some configurations now at the exploratory stage will most likely advance to proof-of-principle, and the opportunity to introduce new ideas for study at the concept exploration stage will be continuously maintained. This strategy provides opportunity for configurations that are less closely related to the tokamak, but have the potential for more dramatic improvements, to contribute to decisions on fusion development beyond the burning plasma experiment.

The requirement for coherent integration across elements in the fusion program drives each element to develop a level of understanding and predictive capability such that knowledge transfer across magnetic configurations becomes possible. In this sense, developing a predictive capability for ultimately designing the best fusion reactor system becomes the integrating principle across program elements as illustrated in Figure 1. For example, knowledge-based integration allows for "transferring" scientific discoveries from innovative confinement concepts (ICCs) to tokamaks with the goal of improved tokamak performance. Conversely, a tokamak BPX that had the flexibility in design, operation, and diagnostics to address a broad range of physics and technology issues could impact the development path of ICCs as well. There exists commonality across the portfolio in major development issues such as macrostability, transport and turbulence, wave-particle interactions, plasma-material interactions and boundary physics Incorporating this broad physics based in our predictive tools will provide the capability to transfer knowledge across concepts.

From the portfolio perspective, the role of a tokamak BPX is to address, in as broad a way as possible, burning plasma science (i.e. alpha particle physics) and technology (i.e. superconducting magnets, power and particle exhaust, fueling, tritium, remote maintenance, etc.). In addition, the BPX will afford the opportunity to study effects related to device scale and performance such as the ratio of plasma size to gyroradius, wall loading, and pulse length. The degree of transferability of BPX physics understanding to other ICC concepts is both concept specific and issue specific. For example, if tokamaks and quasi-symmetric stellarators have a high degree of commonality in their physics, then the understanding of burning-plasma physics effects, obtained in a tokamak BPX, should transfer readily to stellarators for integration with the three-dimensional plasma effects. Similar transferability is expected for the spherical torus for integration with the effects of order-unity β and strong shaping. With respect to the reversed field pinch (RFP), there is also the possibility for commonality in basic physics. Recent developments in reducing magnetic-driven transport in RFPs, by means of profile control, enables the examination of limiting transport mechanisms and their relation to those seen on tokamaks, spherical tori, and stellarators. If underlying RFP transport is similar, then the predictive understanding developed for the full compliment of toroidal plasma research, including a tokamak BPX, will impact the RFP development path as well.

In summary, a burning plasma experiment can make substantial contributions to the development of magnetic fusion energy, if properly planned and executed. Although it will use a tokamak to confine the plasma, the BPX needs to support the goal of improving the vision of a magnetic fusion reactor, so it must deliver benefits that are generic to a range of magnetic fusion concepts. A burning plasma experiment can take a major step in the integration of fusion technologies in a realistic environment. The production of hundreds of megawatts of fusion power for hundreds of seconds from a high-gain plasma will be a success for plasma physics models and will demonstrate substantial progress in understanding of the design, construction, and operation of a major fusion system. Beyond that, achieving levels of availability approaching those required for a fusion reactor would demonstrate that magnetic fusion could be practical. Accomplishing these objectives in a burning plasma experiment will involve advances over the next twenty-five years or so that are generic to a range of magnetic fusion concepts. Examples include MHD modes driven by energetic alphas, neoclassical tearing modes at large ratio of gyroradius to system size, steady-state heat removal and helium exhaust, magnetics, diagnostics, heating and fueling, and maintenance. Thus, the value of a tokamak burning plasma experiment to the goal of attractive fusion will depend on how successful we are in generalizing and integrating the knowledge gained from the BPX to other concepts. In particular, the integration of the knowledge base from a BPX with the portfolio of ICC experiments up to the Performance Extension stage will be required to achieve the predictive capabilities needed to determine the designs of the best fusion energy sources for power production.

In conclusion, with a well planned and integrated program, there is an excellent chance of advancing the physics and technology of fusion energy as well as substantially improving the vision of magnetic fusion energy. Such a program will maximize the value of a tokamak burning plasma experiment and the opportunity for much more attractive next steps thereafter. The key program requirements are:

1. Developing physics solutions to improved reactor attractiveness by advancing a portfolio of concepts through their development stages based on merit.
2. A burning plasma experiment aimed at developing a deep understanding of the physics and technology of burning plasmas. It must have good flexibility, capable diagnostics, and a strong theory and modeling component.

3. Advancing the understanding and predictive capability for fusion plasma physics in a way that integrates the portfolio, such that knowledge gained from one concept can be readily transferred to others for the ultimate purpose of developing the best fusion energy system.

Introduction

In 1999, the Fusion Energy Sciences Advisory Committee (FESAC) adopted three major goals for the development of fusion energy in the United States.

- Advance plasma science in the pursuit of national science and technology goals.
- Develop fusion science, technology, and plasma confinement innovations as the central thee of the domestic program.
- Pursue fusion energy science and technology as a partner in the international effort.

To attain these goals, the fusion program adopted a development structure comprised of a "portfolio" of fusion approaches, where each approach has the chance to advance through a series of stages of experimental development. The principal stages were identified as "concept exploration", proof-of-principle", "performance extension", "fusion energy development", and "fusion energy demonstration". At each stage of development, the opportunities increase for developing the building blocks of a fusion energy system and for increasing scientific understanding. The facilities associated with each higher development stage have a greater range of capabilities for exploring reactor relevant plasma conditions and are more demanding on technology requirements.

A burning plasma experiment (BPX) is at the "fusion energy development" level. At this level, the facility and infrastructure requirements are costly. It is very likely that the national or even international fusion energy effort will only be able to afford a single BPX within the next twenty years. Hence, within the integrated fusion energy (FE) development plan, it is important to assess the mutual benefits of a BPX to other elements of the "portfolio" and visa versa.

The ICC E4 subgroup is proceeding with this initial assessment using the proof-of-principle (PoP) concepts for the simple reason that they are the most advanced ICC concepts to date.).

This strategy in no way precludes other ICC concepts from making similar assessments. At present, the family of PoP concepts includes the Stellarator, Spherical Torus, and Reversed Field Pinch (RFP). With respect to these PoP concepts, we have focused on answering two basic questions.

- What will a given concept contribute to the development of fusion energy over the next 20 years? (Included should be an assessment of potential contributions to physics understanding, reactor attractiveness, and technology & materials.)

- What are our expectations for a BPX in terms of:
  - Advancing attractive fusion energy development in general?
  - Advancing the science and technology of fusion common to the development of this ICC concept?

A summary of our findings to date follows.

Stellarator

The stellarator is an important component of the magnetic concepts portfolio and a major research thrust of the world fusion program. A billion-dollar-class stellarator is operating in Japan, another is under construction in Germany, and the U.S. has launched an initiative to construct a new proof-of-principle experiment, the NCSX, as the center of a national program to develop the physics of compact stellarators. Thus, substantial contributions are expected over the next 20 years.

Stellarator Contributions to Physics Understanding

Stellarators contribute to advancing the understanding and predictive capability in fusion plasma physics, one of the main goals of the U.S. Fusion Energy Sciences program. Their role is to provide tested models and benchmarked theoretical tools for three-dimensional plasma effects important to toroidal magnetic configurations generally, putting the theory on a firmer foundation for extrapolation to new areas. Compact stellarator research will explore the role of quasi-symmetry in extending our knowledge base to low-aspect ratio stellarators that use bootstrap current to generate part of the rotational transform. It will provide answers to important questions in all areas of fusion plasma physics:

Macrostability:

- What are the beta limits and limiting mechanisms in a low aspect-ratio stellarator?
- Can pulse-length-limiting instabilities, such as external kinks and neoclassical tearing modes, be stabilized by external transform and 3D shaping?
- How do externally generated transform and 3D shaping affect disruptions and their occurrence?

Transport and Turbulence:

- Can the collisionless orbit losses typically associated with 3D magnetic fields be reduced by designing the magnetic field to be quasi-symmetric? Is flow damping reduced? Is the resulting transport and confinement similar to actually axisymmetric systems?
- How does the transport scale in a compact stellarator?
- Do anomalous transport control and reduction mechanisms that work in tokamaks transfer to quasi-axisymmetric stellarators? Do zonal flows saturate turbulent transport in a quasi-axisymmetric stellarator at levels similar to tokamaks?

Wave-particle interactions:

- How do the Alfvénic-eigenmode spectrum and stability of a quasi-symmetric stellarator differ from those of a tokamak or a non-symmetric stellarator?

Plasma boundary and plasma-material interactions:

- How do stellarator field characteristics such as islands and stochasticity affect the boundary plasma and plasma-material interactions? Are 3D methods for controlling particle and power exhaust compatible with good core confinement?

Stellarator Contributions to Reactor Attractiveness

The attractiveness of the stellarator as a reactor concept lies in its potential to eliminate disruptions and operate steady-state with minimal recirculating power. The compact stellarator, one of the innovative magnetic confinement configurations being investigated by the U.S. Fusion Energy Sciences Program, uses magnetic quasi-symmetry to combine these stellarator advantages with the compactness, high-beta, and good confinement of a tokamak. Its goals are to:

- Demonstrate conditions for high-beta disruption-free operation, compatible with bootstrap current and external transform in a compact stellarator configuration.
- Understand beta and aspect-ratio limits, and the limiting mechanisms, in low-aspect-ratio, current-carrying stellarators.
- Understand reduction of neoclassical transport and flow damping by quasi-symmetric design.
- Understand confinement scaling and reduction of anomalous transport by flow-shear control.
- Understand equilibrium islands and stabilization of neoclassical tearing-modes by choice of magnetic shear.
- Understand compatibility between power and particle exhaust methods and good core performance in a compact stellarator.

These gains in physics understanding will make it possible to quantify compact stellarator benefits and costs and ultimately assess its attractiveness as a concept for magnetic fusion.

Stellarator Contributions to Technology

Stellarators have led the way in the optimization of magnetic confinement system designs to realize specific physics and engineering objectives. Flexible stellarator experiments are designed to achieve desired physics properties (e.g., stability to various MHD modes; quasi-symmetry in the helical, axial, or poloidal direction; low aspect ratio) within the constraints (e.g., coil radius of curvature and spacing) of a given engineering concept. The same approach, with the appropriate set of optimization objectives, is used to design stellarator reactors. These advances in optimized design, which are an interesting application of advanced computing to fusion problems, are an important contribution of the stellarator to fusion technology. As a deliverable, optimized power plant designs will be developed as part of the stellarator proof-of-principle program.

Spherical Torus

The spherical torus (ST) is a toroidal plasma confinement configuration in which the aspect ratio (major radius/minor radius) is reduced toward 1 (so far 1.05 - 1.5 in the designs of existing ST experiments) while maintaining a high safety factor (q, the ratio of the field line rotations in the toroidal direction over the poloidal direction). Like a tokamak, the ST is an axisymmetric torus with similar or higher safety factor, and plasma currents that can be driven externally via induction and momentum input and internally via pressure gradient (the so-called "bootstrap" current). Unlike a tokamak, its magnetic field in the small major radius region wraps tightly around a slender center column, giving strong good curvature to ensure stability of the plasma at high toroidal beta (β_T, average plasma pressure over the applied toroidal field pressure) and order unity local central beta (β_0, local plasma pressure over the local magnetic field pressure at the magnetic axis). The squeeze by the externally applied vertical fields from the outboard and the limited space toward the inboard of the plasma cross-section gives a naturally large plasma elongation (vertical height over the radial width) in the range of 1.5 to 3. Such elongations further strengthen plasma stability at very high beta, which scientifically approach other high beta concepts such as Reversed field Pinch (RFP), Spheromak and Field Reversed Configuration (FRC). The new approaches in device design and operation to produce high quality toroidal plasmas of very low aspect ratios have been key to the ST innovative confinement concept (ICC).

Potential Over Next 20 Years

The potential contributions of the ST program to the development of fusion energy are expected to result from the attractive and new plasma properties stemming from the strong good curvature of the magnetic field and the very high beta. The physics principles and the scientific boundaries of the ST plasma are currently under investigation worldwide at the Proof of Principle (PoP) level (NSTX/US; MAST/UK; GLOBUS-M/RF with Ip ~ 0.5 - 2 MA, R ~ 0.5 - 0.8 m, Bt ~ 0.5 T) and the Concept Exploration (CE) level (PEGASUS, HIT-II, CDX-U/US; TST-2, TS-3, TS-4, HIST/Japan; ETE/Brazil with Ip ~ 0.1 - 0.3 MA, R ~ 0.4 m, Bt ~ 0.3 T). Other CE level experiments include SUNIST being built in PRC and PROTO-SPHERA being designed in Italy.

Outcome from these experiments in the next several years will potentially provide the database and advance the plasma science needed to design and build a more powerful ST experiment at the Performance Extension (PE) level (Ip ~ 5 - 10 MA, R ~ 1.5 m, Bt ~ 1 - 2 T) at manageable cost and schedule. This PE level experiment would be used in the second decade to test attractive plasma properties and operation scenarios at the fusion levels (T ~ 10 keV, n ~ 10^{20} /m^3) for varying durations and currents. Continued progress in ST research could further establish database for an Energy Development (ED) level volume neutron source (Ip ~ 7 MA, R ~ 1 m, Bt ~ 1.5 T) for operation during the third decade. The ED level experiment would be free of a central solenoid to enable tests at high neutron fluence of nuclear components for fusion energy applications in steady state. The potential contributions from such experiments, combined with the results from a tokamak burning plasma experiment (such as FIRE or the first phase of ITER) in the second decade and the results from an integrated engineering test (such as the second phase of ITER), would expand and strengthen the science and technology bases for an attractive Demonstration Power Plant to follow.

Spherical Torus Contributions to Physics Understanding

The ST program contributes to advancing the understanding and predictive capability in fusion plasma physics by producing and studying high-temperature high-density plasmas of order-unity beta in strongly curved magnetic fields. This research builds on the large body of tokamak physics understanding and tools, and owing to the high q, contributes to strengthening them by adding data from physics regimes so far attainable only in the ST. Examples of these contributions in key topical areas are provided below.

Magnetohydrodynamics

Theoretical calculations have suggested that $\beta_T \sim 40\%$ and $\beta_0 \sim 100\%$ can be achieved in NSTX if the resistive wall mode can be stabilized. Without active stabilization, $\beta_T \sim 30\%$ plasmas have already been sustained for several resistive wall times in NSTX. As the central plasma beta approaches unity, the effects of plasma pressure begin to compete with those of magnetic field pressure in determining the macroscopic stability of the plasma. The diamagnetic (gradient-driven) flow of the plasma can become a substantial fraction of the Alfvén velocity and begin to modify the force balanced "equilibrium" of the plasma from the static equilibrium, which has been very successful in modeling the tokamak properties. Momentum input from injection of energetic neutral atoms further drives the plasma flows to Mach and Alfvén Mach numbers toward unity. The modest field used in the ST devices naturally increases the significance of kinetic and finite gyroradius effects. ST research can therefore make important contributions by addressing the following questions:

- What are the effects of large Alfvén Mach numbers on the force-balance equilibrium with strong plasma flows, and how do these affect the macroscopic stability of the toroidal plasma?
- What are the effects of large ion gyroradii ($1/\rho^* \sim 30$, $1/\rho_{NE}^* \sim 6$) on the equilibrium and stability of such plasmas, such as the neoclassical tearing modes?

- What are the effects of large diamagnetic and externally driven plasma flows and flow shear (~10^6 /s) on the stability of the resistive wall modes in such plasmas with strong field line curvatures?
- The ST research also contributes to the physics understanding of reconnection and self-organization, at high magnetic Reynold's numbers, in testing current startup and sustainment using coaxial helicity injection (CHI) in forming and maintaining nearly closed magnetic flux surfaces.

Turbulence and Transport

The strong flow shearing rates and competition between the thermal kinetic and the magnetic free energies anticipated in the ST plasma provide new opportunities to test and understand the possibility of suppression of long-wavelength (electrostatic) turbulence and short-wavelength (electromagnetic) turbulence in high beta plasmas. Recent neutral beam and rf heating experiments on NSTX and MAST have produced plasmas covering a wide range of T_i/T_e (2 _ 0.2), which theoretically alters the intrinsic virulence of micro-instabilities driven by the ion and electron temperature gradients. The large flow, flow (or ExB) shear, ρ^*, ρ_{NE}^*, in-out asymmetry, and B_p/B_t (~1) in the outboard region of the plasma are expected to affect strongly the formation of transport barriers in the plasma core and near the edge (H-modes). Large central beta also creates an absolute magnetic well (~30% in magnitude from the outer plasma edge) in the plasma core and alters the strongly curved magnetic geometry of the ST. These further are expected to modify substantially the neoclassical mechanisms where the plasma diffusivities are not dominated by turbulence mechanisms. ST research can therefore make important contributions by addressing the following questions:

- What are the effects of the above ST plasma features on the mechanisms responsible for turbulence driven ion and electron thermal diffusivities? Can the long-wavelength and short-wavelength micro-instabilities be reduced or even suppressed simultaneously in such plasmas?
- How do these ST plasma features (e.g., large ρ^* and B_p/B_t~1) alter the mechanisms determining the formation of transport barriers, with large externally driven or internallydriven shearing rates?
- What are the effects of order-unity local beta and large magnetic well in strongly curved magnetic fields on neoclassical diffusivities and viscosities of the plasma?

Wave-Particle Interactions and Energetic Particle Effects

High beta and density in an ST introduces a high dielectric constant ($\omega_{pe}^2/\omega_{ce}^2 \sim 100$ in NSTX) and strong diffraction of radiofrequency plasma waves. This opens up new opportunities for strong wave-plasma interactions in the ranges of high multiples of the ion cyclotron frequencies and low multiples of the electron cyclotron frequencies (such as the Electron Bernstein Waves). The modest field in ST devices ($B_t \sim$ 3-6 kG) also leads to low Alfvén velocities in the plasma core so that the energetic ions from neutral beams would be strongly supra-Alfvénic in speed ($V_{fast}/V_{Alfvén} \sim 4$). This, together with the tendency for high beta plasmas to support magnetosonic oscillations, have led to the observation of broad spectra of Compressional Alfven Eigenmodes (CAE's) between cyclotron resonances. A similar condition is expected for fusion _-particles in larger ST devices with B_t up to 2 T. ST research can therefore make important contributions by addressing the following questions:

- What are the effects of very high dielectric constant in a high beta plasma on the mechanisms responsible for RF heating and momentum transfer (current drive), in the ion cyclotron and the electron cyclotron frequency ranges?
- How does the presence of supra-Alfvénic fast ions alter the stability properties of the Alfvén waves, particularly the compressional branches, in view of the competition between the thermal and magnetic pressures in high beta plasmas?
- How do non-harmonic compressional Alfvén oscillations and waves interact and possibly alter the diffusivities of the energetic and the thermal components of such plasmas?

Boundary Physics

The large in-out asymmetry of the ST plasma edge and scrape-off layer (SOL) regions leads to large magnetic mirror ratios (~ 2 for double-null divertor SOL, ~4 for inboard limited SOL, and ~ 4 the edge region within the last closed flux surfaces). Because of the near proximity of an higher order poloidal magnetic field null along the machine axis to the plasma edge of an inboard limited plasma, a substantial fraction of the SOL could be *naturally* diverted without the presence of externally imposed "x-points" at the plasma edge. ST research can therefore make important contributions by addressing the following questions:

- What are the effects of the strong mirror ratios on the mechanisms that determines the rates at which plasma energy and particles are exhausted from the plasma edge and through the SOL? In particular, how are the exhaust fluxes partitioned between the inboard and outboard sides of a diverted ST plasma?

- What are the effects of a nearby higher order field null on the mechanisms that determines the rates at which plasma energy and particles are exhausted from the plasma edge, first through the inboard limited portion of the SOL, and finally through the naturally diverted SOL?
- How are the amplitude and width of the edge pedestals in plasma pressure and temperature altered in these differing edge-SOL configurations?
- How do these differing edge-SOL configurations alter the influence of the plasma edge on the plasma core and on the properties of the high beta plasma core?

Spherical Torus Contributions to Reactor Attractiveness

The attractiveness of the spherical torus as a reactor concept stems from the potential of the ST plasmas to enable fusion energy producing devices with the following attractive features:

- Simplified magnets and device configuration via solenoid-free startup and sustainment of the plasma current. RF and CHI techniques are being tested in ST experiments to determine the physics basis and possible implementation in future ST devices.
- Lowered magnet and device costs via macroscopic stability at high β_T and order-unity β_0.
- Reduced unit size for sustained fusion burn via reduced turbulence and improved energy containment efficiencies at high beta and with strong toroidicity.
- More efficient fusion α and RF heating and current drive via strong wave-energetic particle-plasma interactions in plasmas of high dielectric constant and high beta.
- Survivable plasma facing components via dispersed plasma heat and particle fluxes over large areas in the presence of large magnetic mirror ratios and a nearby higher order field null.

The combination of these device features, if the physics basis for them is proven to be achievable, are expected to enable fusion energy devices of reduces cost and size, including the PE and ED level experiments and future power producing reactors.

Reversed Field Pinch (RFP)

The reversed field pinch (RFP) represents toroidal plasma confinement in the limit where the externally imposed magnetic field is very small. Like a tokamak, the RFP is an axisymmetric plasma torus. Unlike a tokamak, its magnetic field is produced almost entirely by currents flowing inside the plasma, not externally imposed. Its strength as a fusion concept stems from its simple magnet system, especially the small demands on the toroidal magnet. Some of these strengths are (1) non-superconducting construction, (2) small forces at the magnet location, (3) naturally high plasma beta and fusion power density, (4) simple assembly, and (5) possibility for Ohmic ignition. On the other hand, the weak imposed magnetic field permits greater susceptibility to plasma motion, so magnetic turbulence is generally a bigger problem than for tokamaks and stellarators. A controlled reduction of this turbulence has been the main thrust of recent RFP research, resulting in confinement quality in RFP plasmas that is now comparable to tokamak plasmas. This development followed from a mature understanding of MHD turbulence associated with magnetic relaxation. Since magnetic relaxation occurring in RFP plasmas is similar to that seen in astrophysical settings, the RFP is an important terrestrial laboratory for understanding basic physical processes occurring in stars, planets, and galaxies. Such connections between fusion plasma physics and astrophysics have been underutilized to date. An important goal of the RFP program is to strengthen these ties.

The worldwide RFP research program is very much smaller than the tokamak and stellarator programs, both in the scale of devices and funding. Three medium sized devices (a~0.5 m) currently operate in the US, Italy, and Japan (MST, RFX, and TPE-RX respectively). Smaller devices operate in Sweden (Extrap-T2R, a~0.2 m) and Japan (several, a<0.01 m). The US program has been reviewed favorably for “proof-of-principle” status. The PoP plan for the MST experiment adds new plasma control tools (rf current drive and heating, neutral beam heating, Ohmic power supply modifications) plus crucial profile diagnostics. A major goal is to demonstrate near-tokamak confinement in plasmas sustainable by reasonable means. This sets the foundation for the discussion of next-step experiments which could begin operation well within the next 20 years timeframe. A major justification for an RFP next step will be the promise of a simpler magnetic configuration which adequately confines a high beta (_>15%) plasma. Because the worldwide RFP program is small, greater reliance on physics understanding will be essential, rather than empirical scaling.

RFP Contributions to Physics

A sampling of the RFP program’s physics contributions are listed below. A recurrent theme is the direct or indirect consequence of small imposed toroidal magnetic field on various physical processes that occur in toroidal plasmas.

Magnetohydrodynamics

Standard inductively driven RFP plasmas operate with strong nonlinear resistive MHD processes involving multiple tearing modes. Although famous for their consequences represented in magnetic relaxation and dynamo, tearing modes cause the field to become stochastic and enhance transport. Current profile control tools are being developed to combat this problem. In addition to these resistive MHD effects, a separate set of nonresonant (ideal) MHD modes also appear, stabilized by a conducting shell in experiments. These develop into resistive wall modes in the long pulse limit and must be actively controlled. Sample anticipated contributions to MHD physics include:

- Understand the mechanisms and consequences of magnetic relaxation (magnetic reconnection, dynamo, anomalous ion heating, magnetic transport of heat, particles, and momentum)
- Control of tearing instability (and magnetic transport) through profile optimization.
- Active control of resistive wall modes.
- Determination of the beta limit in a toroidal magnetic geometry with everywhere bad curvature but large stabilizing magnetic shear.

Transport Physics

The RFP's small safety factor permits many possible resonant surfaces on which magnetic islands can form. The dominant transport mechanism in standard RFP plasmas is particle streaming in a stochastic magnetic field generated when these islands overlap. Using tearing-control techniques, the amplitude of these islands can be reduced to control magnetic stochasticity. Presumably a weaker electrostatic turbulent transport mechanism masked by the larger magnetic transport will be revealed. Sample anticipated contributions to transport physics include:

- Understand the transition from stochastic to non-stochastic transport, including partially stochastic intermediate regimes (e.g., nearly overlapping magnetic islands).
- Identify electrostatic transport mechanism(s) in low safety factor toroidal plasmas with large, reversed magnetic shear and large _*. Comparison with transport in other configurations will test general understanding of anomalous transport in toroidal plasmas.
- Possible demonstration of classical confinement (banana widths in the RFP are ~_$_{i}$).

Wave-Particle Interactions and Energetic Particle Effects

No significant rf or neutral beam power has been injected into an RFP plasma to date. Motivated as tools for manipulating the plasma, significant power of both types are planned for existing experiments. Expected results related to wave and energetic particle physics include:

- Demonstration of rf heating and current drive in high beta, high dielectric plasmas.
- Understanding the confinement of fast particles in stochastic magnetic fields (perhaps modified by finite larmor radius averaging).

Boundary Physics

All but a few RFP experiments have been conducted in (circular cross-section) limiter geometries. Since the poloidal magnetic field is dominant at the edge, poloidal divertor configurations as developed for the tokamak will not transfer to the RFP unmodified. Although not included in any existing experiment's plan, different boundary geometries must be investigated. Example solutions could be:

- Development of highly radiating plasma mantles in non-diverted smooth wall geometries with "vented pump limiters."
- Development of toroidal divertor configurations.

RFP Contributions to Technology

The benefits of a compact, high power density fusion core with small toroidal magnetic field were largely verified in the 1980's TITAN system study based on the RFP configuration. This design achieved one of the highest mass-power densities in system studies to date; demonstrating the advantage of pushing upper limits to heat and neutron fluxes. The RFP and other high beta configurations continue to play an important role in defining paths that could lead to smaller, and thereby cheaper, fusion reactor cores. In particular, pulsed reactor scenarios could be optimized for a non-tokamak configuration in which the various cycling stresses might be smaller. It is crucial that sufficient resources be available to re-examine, update, and optimize RFP system studies using modern tools and methods. This is important both to verify reactor potential and to guide experimental research at all stages of development.

ICC Expectations for a Burning Plasma Experiment

There is little doubt that a burning plasma experiment, if properly planned and executed, can make substantial contributions to the development of magnetic fusion energy. . Although it will use a tokamak to confine the plasma, the BPX needs to support the goal of improving the vision of a magnetic fusion reactor, so it must deliver benefits that are generic to a range of magnetic fusion concepts. A burning plasma experiment can take a major step in the integration of fusion technologies in a realistic environment. The production, even once, of hundreds of megawatts of fusion power for hundreds of seconds from a high-gain plasma will be a success for plasma physics models and will demonstrate substantial progress in understanding of the design, construction, and operation of a major fusion system. Beyond that, achieving levels of availability approaching those required for a fusion reactor will demonstrate that magnetic fusion can be practical.

Achieving the BPX objectives will involve advances over the next several decades that are generic to a range of magnetic fusion concepts in a number of areas. For example MHD modes driven by energetic alphas, neoclassical tearing modes at large ratio of gyroradius to system size, steady-state heat removal and helium exhaust, magnetics, diagnostics, heating and fueling, and maintenance. Thus, a goal of our base physics and technology programs must be to develop a reliable knowledge transfer capability, at least among concepts closely related to the tokamak, namely the advanced tokamak, spherical torus, and stellarator, such that any of these showing sufficient promise could carry the next step after a successful tokamak burning plasma experiment.

The definition and assessment of realistic BPX goals are crucial to the success of its mission. The “base case” must be a solid tokamak design (only a tokamak configuration is under consideration) that has very high probability of confining burning plasma and surviving that environment. Note that such a design implies flexibility, since the extrapolations from present-day experiments to a BPX are not made completely on well-understood physics and technology. It also follows that the plasma must be well diagnosed, at least to the standards of present-day fusion research, including characterization of anomalous processes. When this next generation plasma does not behave exactly as predicted, crucial data must be available to assess the problem. It also follows that the design should accommodate reasonable modifications to address specific issues as they arise.

In summary, with a well planned and integrated program, there is an excellent chance of advancing the physics and technology of fusion energy as well as substantially improving the vision of magnetic fusion energy. Such a program will maximize the value of a tokamak burning plasma experiment and the opportunity for much more attractive next steps thereafter. The key program requirements are:

1. Developing physics solutions to improved reactor attractiveness by advancing a portfolio of concepts through their development stages based on merit.

2. A burning plasma experiment aimed at developing a deep understanding of the physics and technology of burning plasmas. It must have good flexibility, capable diagnostics, and a strong theory and modeling component.
3. Advancing the understanding and predictive capability for fusion plasma physics in a way that integrates the portfolio, such that knowledge gained from one concept can be readily transferred to others.