3.1.3.4. Development Path

The development path to realize fusion power as a practical energy source includes four major scientific elements:

- Fundamental understanding of the underlying science and technology;
- Plasma physics research in a burning plasma experiment;
- Configuration optimization such as high performance, steady-state operation;
- Development of low-activation materials and fusion technologies

A diversified and integrated portfolio consisting of advanced tokamak, ICCs, and theory/simulation is needed to achieve the necessary predictive capability. BPX should be flexible & well-diagnosed in order to provide fundamental understanding.

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.

An international tokamak research program centered around ITER and including 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 for fusion.

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.

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 portfolio supporting ITER-based or FIRE-based development scenarios.

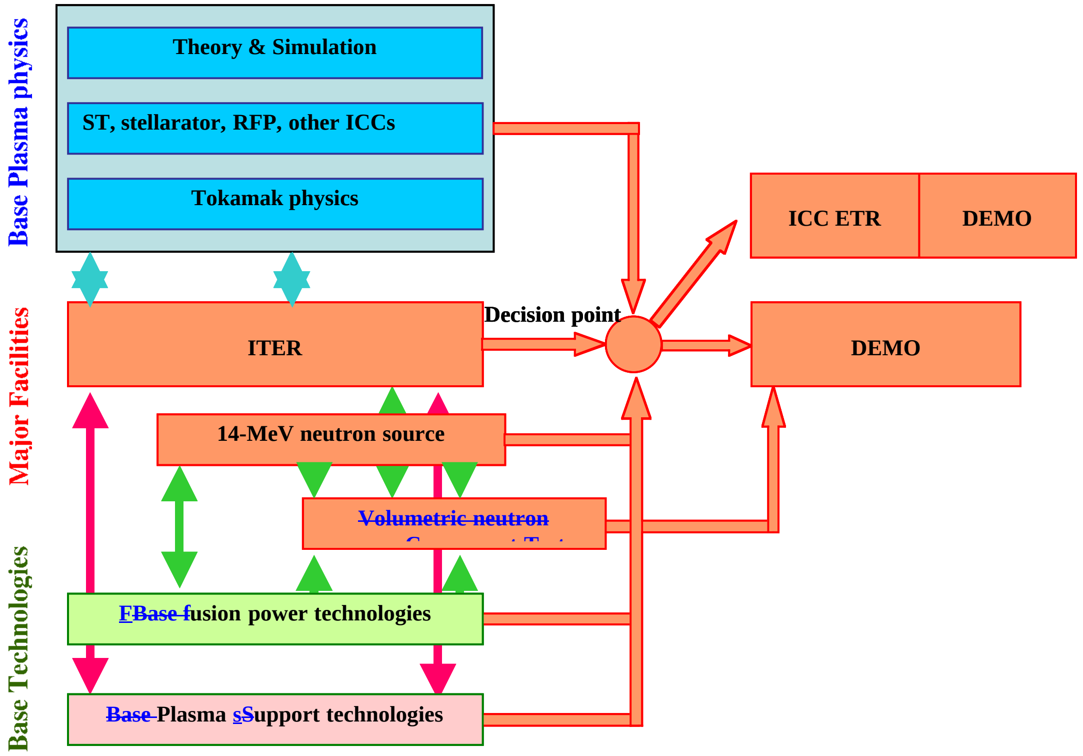

Fig.3.1.4.1. Schematic of development path based on ITER-class burning plasma experiment.

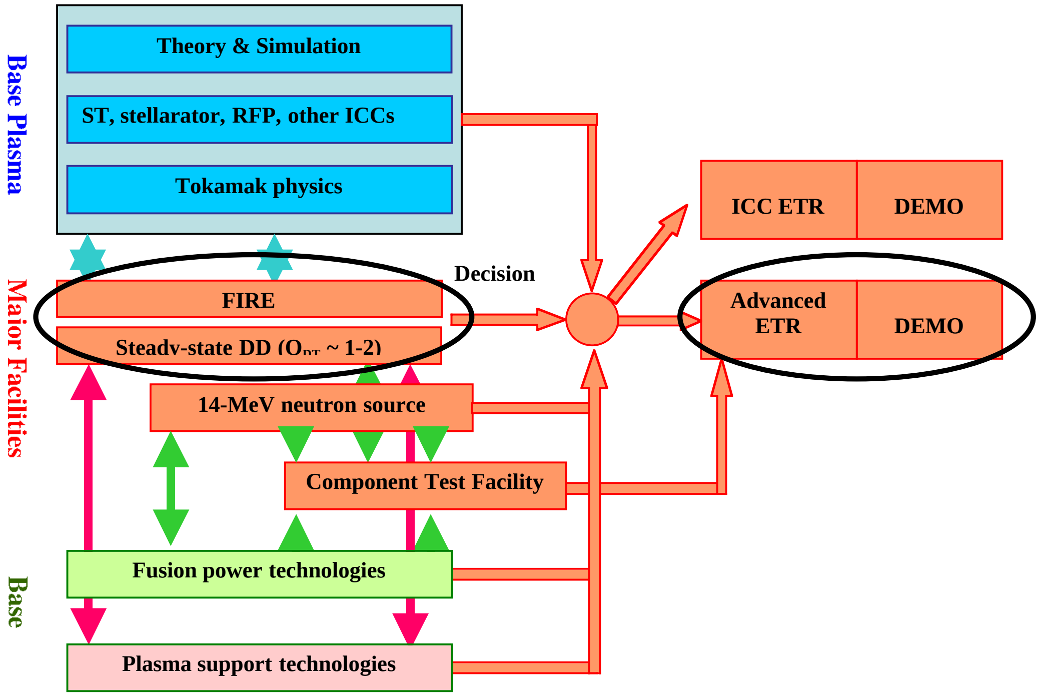

Fig. 3.1.4.2. Schematic of development path based on FIRE-class burning plasma experiment.

3.2 MFE Development Paths

The development path to realize fusion as a practical energy source must include three additional essential elements:

- Fundamental understanding of the underlying science and technology;
- Plasma physics research in a burning plasma experiment;
- Configuration optimization such as high performance, steady-state operation;
- Development of low-activation materials and fusion technologies

Burning plasma physics and configuration optimization: A diversified and integrated portfolio consisting of burning plasma experiment(s), steady-state DD tokamak experiments, ICCs, and theory/simulation is needed to develop the necessary predictive capability in burning plasma physics and high-performance state operation and concept operation. The BPX should be flexible and well diagnosed in order to provide fundamental understanding and physics and technology data for the entire toroidal concept portfolio.

Plasma Support Technologies: A strong program in plasma support technologies (fueling, magnets, heating, PFC) including experiments on test stands is necessary to develop advanced technologies necessary for power plants. Experience on present and future high performance and steady state device as well as the BPX will provide a wealth of data on individual technologies. Among the proposed BPX experiments, ITER will provide valuable data on integration of power-plant relevant plasma support technologies.

Low-activation material and fusion power technologies: All scenarios considered require development of low activation material and fusion power technologies for integration at a subsequent device to BPX. Fusion power technologies are in their infancy and are probably a pace setting element of fusion development. Development of fusion power technologies require:

- A strong technology research program including testing of components in non-nuclear environment as well as fission reactors.
- A materials program including an intense neutron source to develop and qualify low-activation material. International Fusion Material Irradiation Facility (IFMIF) is an example of such a material test facility and has been included in fusion development plan worldwide.
- A Component Test Facility (CTF) which is sometimes referred to as a volume neutron source (VNS) for integration and test of power technologies in a fusion environment with a high duty factor. Such a device should test and integrate fusion power technologies under proto-typical power and neutron flux and fluence conditions and should address reliability of components in a power-plant environment.

3.2.1.1. Fusion development scenario based on ITER-class burning plasma experiment

Burning plasma physics and configuration optimization: It is highly unlikely that an ITER-class experiment would be the only large tokamak experiment in the world. National or regional programs will include performance-extension tokamak devices. These devices are needed to ensure continuation and growth of national expertise and capabilities. More importantly, physics investigations on these performance-extension devices will allow optimum utilization of ITER-class experiment. Smaller devices would allow thorough investigation of individual physics phenomena and act as a test bed for ideas, which can be tested in an integrated manner in ITER. As such, an international tokamak research program centered around ITER and including these national performance-extension devices have the highest chance of success in thorough examination of burning plasma physics in advanced tokamak modes.

Non-tokamak facilities to extend physics understanding, and to develop and test the innovations for improving toroidal magnetic configurations are an essential part of the magnetic fusion program. Diversified facilities at various stages of scientific exploration are needed to carry this fusion program forward, and thus to provide assurance that an adequate magnetic configuration is available at the time of the DEMO decision point.

Plasma Support Technologies: Because of its size, its relatively high duty factor, and its neutron flux and fluence, ITER will provide valuable data on integration of power-plant relevant plasma support technologies.

Low-Activation Material and Fusion Power Technologies: A unique aspect of an ITER-class burning plasma is the capability for limited testing of fusion power technologies. However, because of the low base-line fluence of 0.3 MW.yr/m^2 and relatively low neutron flux, there would be a high risk to proceed to an electricity producing device solely based on ITER testing program. As described above, a strong base program, an intense neutron source facility and a CTF/VNS is necessary before proceeding with the DEMO. ITER capability in testing fusion power technologies as well as the ITER experience on integration and operation of a variety of fusion technologies are valuable to CTF/VNS operation.

Decision Point: An ITER-class BPX allows leapfrog in fusion development path by combination three areas of burning plasma physics, advanced tokamak modes, and plasma support technologies. Successful completion of ITER experimental program (demonstration of high-performance AT burning plasma) will allow tokamak concept to move to fusion power demonstration (DEMO) leading to the shortest development time for fusion. Here DEMO is defined as a device which incorporates all physics and technologies necessary for an attractive commercial power plant. Alternatively, the tokamak configuration may be replaced by an alternative configuration. The technology integration within the ITER program will allow significant acceleration of alternative configurations at this stage.

3.2.1.2. Fusion development scenario based on FIRE-class burning plasma experiment (Diversified International Portfolio Pathway)

Burning plasma physics and configuration optimization: The major next step plasma physics facilities in the International Portfolio Approach are:

<u>Advanced tokamak physics facilities</u> to address the high-b, high-bootstrap and non-burning plasma physics issues needed for attractive power plants. The programs planned for KSTAR, now under construction in South Korea, and JT-60SC under design in would be sufficient to address these issues in a non-burning plasma. The larger of these facilities would have advanced tokamak performance capability sufficient to achieve equivalent Q_{DT} ~ 1 – 2 while operating in

deuterium. Very limited DT experiments might also be carried out. These facilities would also address the integration of plasma technologies in DD plasmas.

Burning plasma facility(s) to address the burning plasma physics issues expected in power plants. The most expeditious way to do this is to incorporate the results from the advanced tokamak facilities into the later phases of the burning plasma experiment. The FIRE experiment, being designed in the US with a construction cost of ≈ $1.2B, has adopted strong plasma shaping, geometry and other advanced features identified by ARIES power plant studies.

Fusion Plasma Simulator to contain comprehensive coupled self-consistent models of all important plasma phenomena that would be used to guide experiments and be updated with ongoing experimental results.

Non-tokamak facilities to extend physics understanding, and to develop and test the innovations to improve the toroidal magnetic configuration are an essential part of the magnetic fusion program. Diversified facilities at various stages of scientific exploration are needed to carry this fusion program forward, and thus to provide assurance that an adequate magnetic configuration is available at the time of the DEMO decision point.

Plasma Support Technologies: Experience on present and future high performance and steady state device as well as FIRE will provide a wealth data on individual technologies. Complete integration with burning plasmas is deferred to the follow-up step.

Low-Activation Material and Fusion Power Technologies: As described above, a strong base program, an intense neutron source facility and a CTF/VNS is necessary before proceeding with the DEMO.

Decision Point: Integration of Program Elements is needed to provide the technical basis for the decision on an Advanced Engineering Test Reactor (ETR). FIRE in combination with non-burning KSTAR and JT-60 SC and a strong burning plasma simulation program would provide the integrated physics basis (advanced confinement, high power plasma exhaust and burning plasma) needed for the Decision on proceeding with a tokamak based Advanced ETR. The integration of technology from the CTF/VNS with the superconducting long-pulse advanced tokamak and the advanced burning plasma tokamak would provide the technology basis for the decision on a tokamak Advanced ETR. During the initial operating phase of the advanced ETR the integration of the physics and technologies would be validated, and the facility would evolve into the DEMO. Alternatively, the tokamak configuration may be replaced by an alternative configuration which has been developed within the configuration optimization program.

3.2.1.3. Fusion development scenario based on IGNITOR burning plasma experiment

The major advantage of IGNITOR is demonstration of fusion burn, a major milestone for fusion energy development, at earliest date and at the lowest cost. Because of its short pulse length, IGNITOR cannot thoroughly investigate burn control and/or advanced tokamak modes.

As an element of a national base program, IGNITOR would support ITER-based or FIRE-based development scenarios.

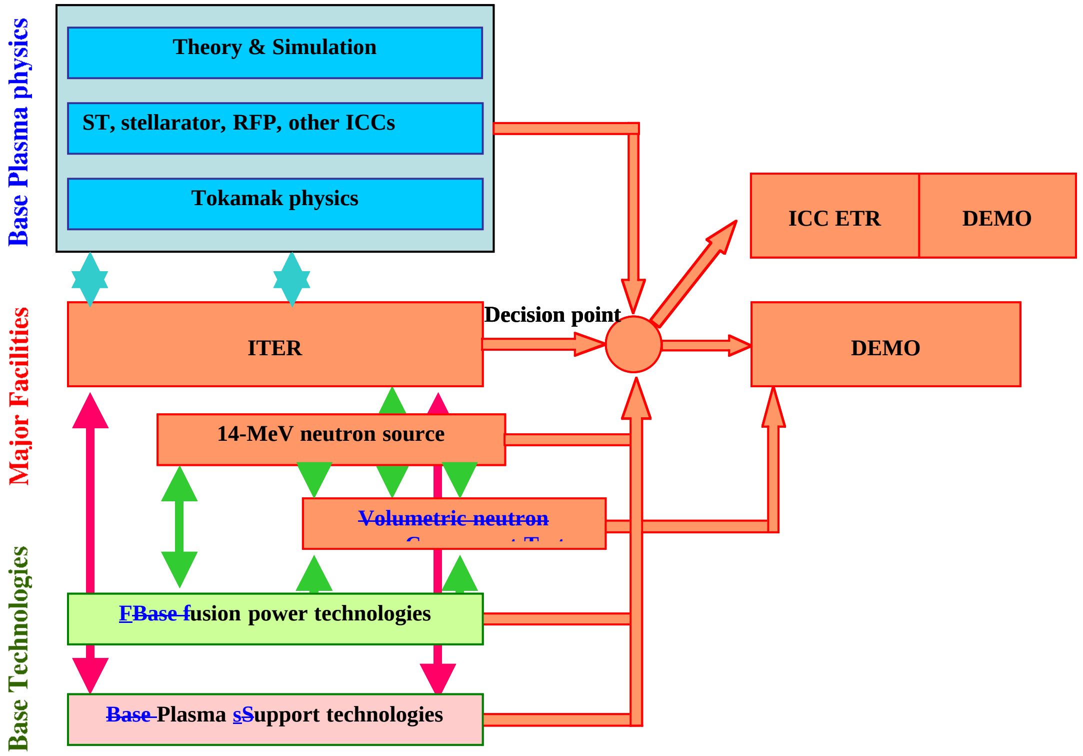

Fig 3.2.1.1. Schematic of development path based on ITER-class burning plasma experiment.

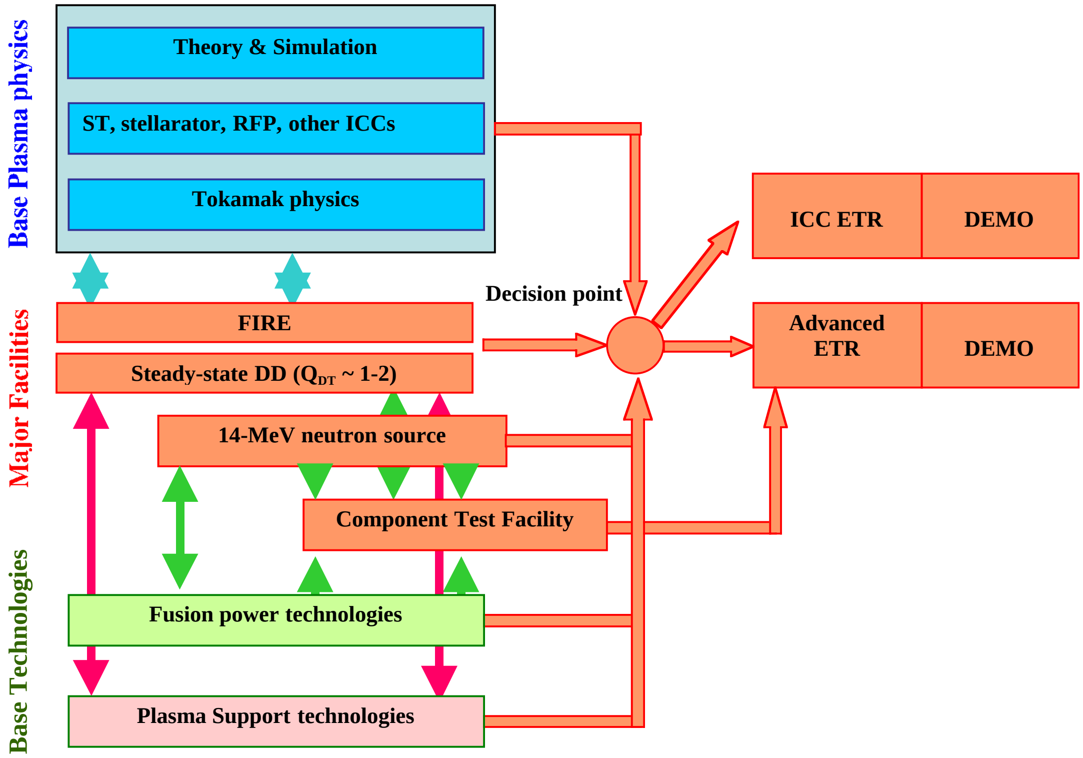

Fig. 3.2.1.2. Schematic of development path based on FIRE-class burning plasma experiment.

3.1.2.4. Relationship between the MFE innovative confinement concepts (ICCs) and tokamak burning plasmas (science and technology)

The Innovative Confinement Concepts are a core part of the U.S. base Fusion Energy Sciences Program, along with the Advanced Tokamak (AT) program and the theory and computational modeling program. The ICC program responses to Goal 2 of the Integrated Program Planning Activity:

> ***Resolve outstanding scientific issues and establish reduced-cost paths to more attractive fusion energy systems by investigating a broad range of innovative magnetic confinement configurations.***

The ICC experiments address several programmatic and fusion energy science objectives by:

- Working within a broad range of plasma and fusion energy sciences, including cross fertilization with other fields of plasma science;
- Seeking concepts and innovations that work better or change the paradigm for fusion energy;
- Broadening the physics of toroidal magnetic confinement by operating in parameter regimes inaccessible by the tokamak;
- Strengthening university plasma science and technology programs, engaging faculty by providing opportunities to contribute to plasma and fusion science with small-to-medium size experiments; and
- Attracting bright, young talent with the vision of unlimited energy for mankind while providing the opportunity to participate in experiments they can “get their hands around.”

The contribution to development of fusion energy by the PoP ICCs is discussed above in terms of the U.S. multiple path strategy and in the Appendix. Generally, we envision a progression through the PE phase in parallel with the tokamak, coupled through the predictive science knowledge base to the BPX physics, as shown in Fig. 3.1.2.3. Assuming progress on one or more of the ICCs, at the appropriate time a decision will be made as to the best DEMO. A reactor based on these concepts is anticipated to look much like one based on the tokamak, although obviously with differences arising from operating in a different part of toroidal-physics parameter space. A reactor based on the toroidal CEs may follow a similar path, although these configurations are expected to pass through the PoP stage before becoming a PE.

There are, in addition, possible reactor scenarios for several of the CEs which would result in a very different reactor implementation. Preliminary concepts have been explored for a spheromak reactor including a conventional (tokamak-like) device using coaxial helicity injection; a steady state, flowing liquid wall reactor; a pulsed, liquid wall reactor; and a reactor driven by multiple, merging spheromaks. For any of these to become viable will require a better understanding of the physics than we have today. The FRC is considering rotational magnetic field current drive and may take advantage of the ability to move the plasma from one vacuum chamber into another in order to separate the formation and burn phases. Magnetized target fusion is examining reaching pulsed burn by the compression of a ST, FRC, spheromak, z-pinch, or other plasma. At the extreme, concepts like Inertial Electrostatic Confinement will generate small, net power in each of many cells, perhaps using no magnetic field; the assembly into a reactor looks much more like a fission assembly than a tokamak. Such ideas move the fusion power options far from the tokamak burning plasma and in some cases have as much or more in common with the IFE ideas than MFE.

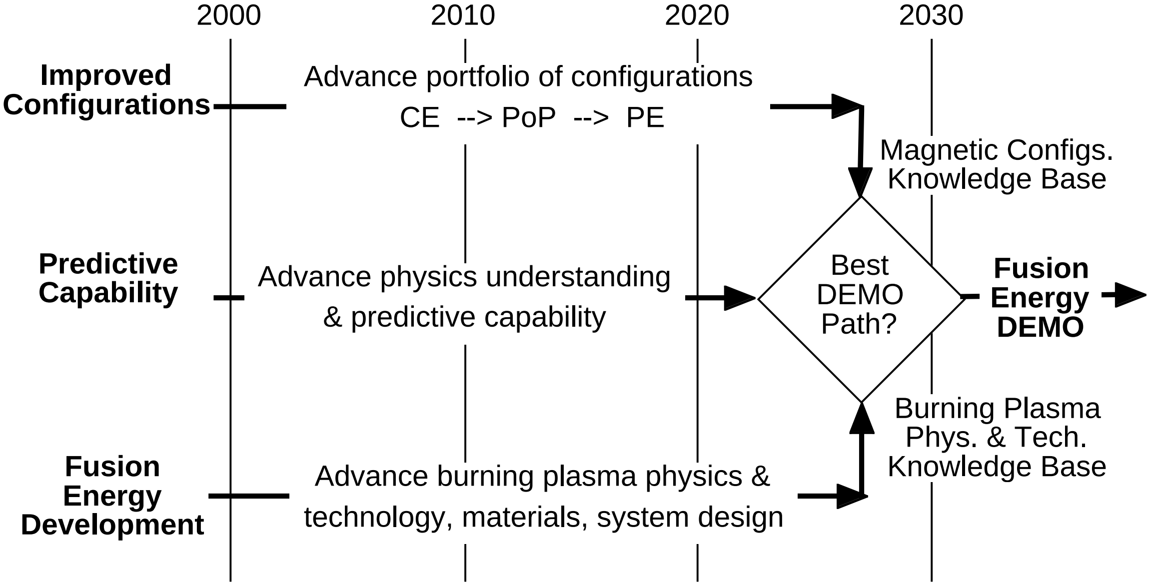

Fig.3.1.2.3. Integrating burning plasma physics with an advanced portfolio of configurations. The decision on the best DEMO path will include consideration of the need for a burning plasma experiment for a candidate advanced configuration in the context of the predictive science base developed from the BPX and the toroidal ICCs.

To couple effectively the BPX and the ICCs, it will be essential to develop and focus on the science. To see this, it is useful to consider some examples from the 3 Proof-of-Principle (PoP) and almost 30 Concept Exploration (CE) experiments. Consider first two toroidal concepts:

Spherical Torus (ST): The ST, a PoP-level experiment, is a tokamak squeezed to the lower limit of aspect ratio, resulting in strong fieldline curvature, a low outboard toroidal magnetic field, high toroidal beta with a central value ~ 1, and a strong diamagnetic well (~ 30%). There is a strong overlap with tokamak burning physics, allowing application of the lessons learned therein to STs ranging from the PoP level to a burning plasma. However, several differences will broaden contributions to and from the ST. As in the BPX, alpha-generated pressure may impact operation at high beta, MHD stability, and control of the discharge; however, the strong diamagnetic effects and deep magnetic well will modify the response of the ST plasma in ways that will be clear only through experimentation and deep scientific understanding. Energy confinement may retain substantial features of electrostatic turbulence, but the relatively large ion gyroradii man result in strong magnetic effects on the turbulence. Stability and waves will be affected by the large Alfvén Mach number (~ 4) particles and the large dielectric constant (~ 100). Plasma-boundary interactions will require a divertor or other means of handling high power, but the large mirror-ratio may modify plasma boundary physics.

Spheromak: The spheromak, a toroidal CE-level experiment, operates in a very different regime from the tokamak, with $q \leq 1$, transport driven by magnetic turbulence (at least in present experiments), and a singly connected volume with no central column to generate a vacuum magnetic field or inductive current drive. BP physics will, however, carry over by enhancing understanding of MHD equilibria and stability, the effects of self-consistent pressure profiles from fusion products, alpha particle drive for Alfvén and other modes, and high-power plasma-wall interactions. The spheromak may also be considered as the limit in which the ST vacuum toroidal magnetic field reaches zero, thus benefiting from applications to the ST but extending toroidal physics beyond the ST regime.

Toroidal physics in these and other ICCs thus occupies a broader parameter space than in the tokamak alone. The reversed-field pinch (RFP) operates with a weak magnetic field and thus $q < 1$ and large shear; the plasma current consequently plays a more dominant role in it than in the tokamak, and the reversal of the safety factor, q, opens parameter space not accessible to the spheromak. Compact stellarators will test the physics of quasi-symmetric magnetic fields, extending the axisymmetric physics of the tokamak without requiring plasma toroidal current. The quasi-axisymmetric stellarator, which does make modest use of bootstrap currents, will clarify the trade-offs between poloidal fields generated by external coils and by internal currents, and offers a fusion opportunity that combines features of the tokamak with those of other stellarator configurations. The compact stellarators will also test neoclassical transport levels, plasma stability, and accessibility of enhanced confinement regimes. The Electric Tokamak (ET) has a large aspect ratio and low magnetic field and the goal of reaching unit beta; the study of this part of toroidal parameter space will significantly extend the tokamak operating space and may lead to interesting energy options. The Field-Reversed Configuration (FRC) and levitated dipole experiment (LDX) extend the toroidal operating space to zero toroidal magnetic field. Both are anticipated to operate at high beta but with the plasma current ranging from dominant and perpendicular to the magnetic field in the FRC to negligible in the LDX.

Thus, the synergistic combination of the tokamak burning plasma, the advanced tokamak, and the toroidal ICCs will generate a much broader scientific understanding of toroidal physics than would be obtained by operating tokamaks, leading to a better optimization of the toroidal confinement concept. This understanding will support the ICCs in their scientific and energy missions and are likely to contribute to broadening the scientific options available to the BPX, plasma-based test facilities, and DEMO.

Successful coupling through a predictive science base will require outstanding diagnostics both in the BPX and the ICCs. However, measurements will be very difficult in the intense radiation environment of the BPX, and the resources available to the CEs require them to focus on a narrow set of issues. Most AT experiments are very well diagnosed, so they and the PoP ICCs can provide a bridge between the BPX and the CE ICCs, helping to unify the program by providing an opportunity to explore physics to a detailed and integrated manner. The ATs can also test new physics generated in the ICCs and from science experiments focused on narrow physics issues such as magnetic reconnection. In doing this, it can help guide experiments on the BPX and strengthen the coupling of results to theory and simulation.

Much of the knowledge determined from a tokamak BPX will be encapsulated in computational models. Because of the cost of a BPX, successful ICCs will need to take advantage of this knowledge to minimize the cost of their bp step by making it more focused, taking a more aggressive step, possibly leap-frogging the BPX step. In the process of doing this, they will contribute to this vertical integration of modeling across the concepts, complementing the horizontal physics goals of existing integrated simulation codes. This will strengthen our modeling and simulation capabilities, providing a tool to develop and enhance the toroidal physics discussed above.

Technology transfer between the BPX and the ICCs will be as important as physics transfer. The BPX will develop operating experience and improve availability in a real fusion environment for key magnetic fusion technologies, most of which are applicable to one or more ICCs. Technologies developed by the ICCs may be applicable to the BPX as well:

- Magnetic coils – Superconducting coils will be needed for most steady-state devices, although resistive coils may be acceptable if the plasma beta is high.
- Heating and current drive technologies – These technologies are applicable to many ICCs; also, new current drive techniques such as helicity injection and rotating magnetic fields are being developed in the ICCs and may find application to a BPX.
- Fueling technologies – Gas puffing or pellet injection are sufficiently flexible to be adapted to most toroidal ICCs. Compact toroid injection is an advanced option which arises from research on the spheromak and FRC and may be used in BPX.
- Plasma facing components – Toroidal ICCs have similar or greater wall power and particle handling issues as the tokamak, so this may be one of the most important spin-offs from the BPX to the ICCs.
- Remote handling – Development of and experience with remote handling will be of major utility to eventual burning plasma ICCs.
- Fusion Power Technologies – Breeder materials tests and blanket designs will be applicable to many ICC concepts.

There are thus significant couplings between the BPX and the ICCs which promise benefits to both. To achieve these couplings, the chosen burning plasma experiment must be capable of exploring a broad range of physics parameters, have good access for diagnostics and a well thought-out diagnostic plan, and be supported by a strong theoretical and computation modeling and simulation effort coupled especially to the toroidal ICC physics experiments.