Road Map for a Modular Magnetic Fusion Program

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During the past several decades magnetic fusion has made outstanding progress in understanding the science of fusion plasmas, the achievement of actual fusion plasmas and the development of key fusion technologies. Magnetic fusion is now technically ready to take the next step: the study of high gain fusion plasmas, the optimization of fusion plasmas and the continued development and integration of fusion technology. However, each of these objectives requires significant resources since the tests are now being done at the energy production scale. This paper describes a modular approach that addresses these objectives in specialized facilities that reduces the technical risk and lowers cost for near term facilities needed to address critical issues.

Ignition the Litmus Test for Fusion

The focal point of the modular strategy is to address the key credibility test for fusion, the achievement of high-gain fusion plasmas in the laboratory. This would constitute a proof of magnetic fusion, the analog of the Wright brother's flight for aviation or Fermi's first self-sustained reactions in nuclear fission. Ignition is the litmus test for fusion, and until high-gain plasmas can be produced in the laboratory, the world fusion community will not be able to explore, understand and then optimize the physics of a fusion plasma needed for a fusion power plant.

The Lawson Diagram - A Topographical Map for Fusion

The physics requirements for a burning plasma were described in John Lawson’s original paper[1] describing the conditions for energy production in a thermonuclear plasma. Lawson defined the criteria for ignition and energy gain (Q), which can be illustrated by plot of $n\tau_E T$ versus temperature (Fig. 1). This is the topolographical map for fusion showing the elevations marked by the Q values. This is the roadmap that the world fusion community has used to measure progress starting with the Russian tokamak, T-3, in 1969, through PLT in 1980 and now up to the larger tokamaks (TFTR, JET and JT-60U) which have produced near break-even conditions in the 1990s. There is still roughly an order of magnitude increase remaining in $n\tau$ to achieve ignition since temperatures exceeding 10keV have been achieved. This logarithmic plot is somewhat deceiving because it gives the impression 80 to 90% of the goal has been accomplished. On the contrary, only 10% of the goal has been accomplished and 90% remains to achieve the confinement needed for a magnetic fusion power plant. This is the challenge facing fusion, since the cost of taking this last step will be larger than the preceding step.

Toroidal Magnetic Configurations have many common physics issues.

The approaches to magnetic fusion are all based on toroidal magnetic confinement and have a common physics basis regarding magnetic instabilities that limit the maximum plasma pressure, microinstabilities that limit the plasma energy confinement and fast particle-plasma wave interactions that determine the efficiency of current drive and plasma heating. The tokamak is the most advanced magnetic configuration in developing the physics basis for all toroidal configurations and has proceeded the most rapidly and cost-effectively along the road to ignition. The alternate (non-tokamak) magnetic configurations are at various stages of development, and are following the path laid down by the tokamak on the Lawson diagram. The second generation stellarator experiment, W-7AS, has achieved the performance of comparably sized tokamaks in 1980. A third generation stellarator, LHD, has just begun operation and is expected to have about an order of magnitude less performance at steady-state than that achieved by the third generation large pulsed tokamaks of comparable construction cost. The spherical tokamak experiment, START, at the Culham Laboratory in England has achieved performance approaching that attained on T-3 in 1969. A second generation in the development of spherical tokamaks, NSTX and MAST, are projected to achieve near PLT-type parameters in ~2001. The key question for NSTX and MAST will be to determine the confinement scaling in spherical tokamaks so that the reactor possibilities of the spherical tokamak configuration can be assessed.

Minimizing the Cost of the Next Step in Fusion R&D

TFTR and JET have produced fusion plasmas and were able to measure alpha heating at low gain, $Q < 1$. The next step is to study plasmas with dominant alpha heating. A high-gain plasma with $Q \sim 10$ would have alpha heating twice the externally applied heating, and would require a plasma system with an $n\tau$ about ten times larger than the TFTR/JET D-T experiments. During the period from 1988 to 1991, the U.S. proposed a number of compact high-field copper-coil tokamak experiments (CIT and BPX) with a focused objective of studying high-gain burning plasmas. In 1990, concerns about these devices attaining the required confinement led to an increase in their size and to an escalation of the construction cost, which eventually led to their cancellation. As discussed below, tokamak experiments carried out during the 1990s have validated the original design assumptions.

Following the cancellation of the U.S. burning plasma design initiatives in 1991, the burning plasma experimental physics mission elements were added to the objectives of ITER, a large integration facility to demonstrate the scientific and technological feasibility of fusion (Fig. 2). Since data from a prior burning plasma experiment is not available, ITER must be designed conservatively and this has increased the cost and risk of the next step in magnetic fusion. The total projected cost of ITER ~ $10B exceeds the cost of existing power plants and none of the four ITER partners has committed to construction during the Engineering design Activity from 1992 to 1998. This is similar to the Mountain of Death described by PCAST-1997 [2] where the cost of the next-step in the development of a technology becomes so high it can not be taken. In order for the magnetic fusion program to move forward, this large multi-mission barrier must be broken into several smaller size steps that will address key issues and will be small enough to be fundable. These smaller parallel steps will also reduce the technical risk as described previously. This is the essence of the Modular Strategy. Fortunately, research on tokamaks during the past eight years has confirmed that physics assumptions of the original designs. This new information has revived interest in low cost approaches to studying the physics of high-gain burning plasmas.

Design Constraints for an Affordable Next Step.

The cost of a magnetic fusion burning plasma experiment is a strong function of the total magnetic energy and the plasma current (Fig. 3) that must be provided. Existing experiments like TFTR and JET have roughly 1.5 giga-joules (GJ) of magnetic energy and 3 to 5 mega-amps (MA) of plasma current while the ITER design has 21 MA and ~120 GJ of magnetic energy. A typical tokamak with aspect ratio (R/a) ~ 3 needs about 3 MA to confine the alpha particles. If microinstabilities did not degrade plasma confinement in a tokamak, then a plasma current of only ~3 MA would be sufficient to confine the plasma due to neoclassical diffusion. So the fact that tokamak designs have plasma currents much larger than 3 MA represents the penalty we're paying because we don't understand transport and can't reduce transport to the neoclassical limit. This is exactly analogous to the situation faced in inertial fusion. If ICF didn't have Raleigh-Taylor instabilities, the driver energy in ICF could be reduced significantly. A difficulty is that ITER is projected to cost over $10B which is larger than the projected $4B capital cost for a fusion power plant. Note that the cost of various magnetic fusion power plant designs based on the tokamak, stellarator and spherical tokamak carried out by the ARIES design studies all have about the same magnetic energy and similar capital costs and cost of electricity. So the different magnetic configurations not only have a common physics basis, but similar technological requirements leads to nearly identical power plant prospects. The costs of TFTR and JET facilities are in the range of ~ $0.5B. Therefore, an ignition machine must have magnetic energy <10GJ and plasmas currents < 10 MA (modestly larger than TFTR and JET) if it is to be affordable (<$1B).

The High Density Road to an Affordable Ignition Experiment

The path to an affordable ignition experiment becomes clearer when the Lawson diagram is plotted in the original format of $n\tau$ versus T. Fig 4 shows the high-temperature moderate-density path and high-density high-field approach, which has historically produced the highest confinement ($n\tau$). For example, TFTR, with the pellet injection systems from Oak Ridge, achieved $n\tau$'s about 70% of that required for ignition but at the lower temperature of 1.5 keV. This second higher-density path holds the key to a lower cost approach to ignited plasmas as previously studied by IGNITOR, CIT, and BPX. There are many of advantages to this approach and B. Coppi [3] deserves credit for being an advocate of this approach. Since this is an experiment and not a commercial prototype, copper coils can be used allowing the elimination of the shield required for the superconducting coils which significantly reduces the size and cost. These compact higher-field, higher-density operating regimes have larger margins with respect to confinement, beta limit, density limit, impurities and fast particle instabilities, and provide plasmas that are of interest for the future. Previous studies of compact high field copper tokamaks with major radii < 2.1m had cost estimates significantly less than $1B.

An Example of a Compact High-Density Burning Plasma Experiment

BPX-AT, shown in Fig. 5, incorporates recent innovations and advances made in magnetic fusion after previous studies of compact high-field cryogenically cooled copper tokamaks. The mission of BPX-AT is a research experiment to extend the frontier of fusion plasmas to explore the relevant burning plasma phenomena. The objective is to use today's knowledge about tokamak performance to achieve Q ~ 10 in regimes for the first studies of confinement, beta limits and other operational limits in a strongly burning plasma where alpha heating dominates the plasma dynamics. In later phases of the experiment, advanced toroidal physics similar to that envisioned for ARIES would be incorporated. This experiment would have a magnetic field of 10 tesla (T) similar to the 8T field in ARIES-RS. Using today's knowledge base for plasma confinement, 6.3 MA would be sufficient with slightly peaked density profiles produced using pellet injection of deuterium-tritium fuel. The fusion power produced would be in the range of 150 to 200 MW with a 10 second burn time. The fusion power density in the plasma would be ~ 10 MWm^{-3} and the neutron wall loading would be ~ 3 MWm^{-2}.which are in the range desired for an attractive fusion power plant. A Q = 10 burning plasma producing 150 MW for 10 seconds would be a spectacularly interesting plasma to explore burning plasma physics and interest in MFE would be revived. In addition, if devices such as this are built, they should incorporate technological innovations such as low activation materials, advanced techniques to remove the fusion heat and advanced remote handling techniques.

Confinement is the critical issue for achieving burning plasmas since Q is very sensitive to confinement at high gain. A curve of Q versus the confinement enhancement factor based on a standard scaling relation used to predict ITER D-T performance (Fig. 6) illustrates how Q increases as confinement is improved. The Alcator C-Mod tokamak is a prototype of this type of experiment and has achieved confinement enhancement factors comparable to those needed for high gain in BPX-AT. One of the key features of a copper coils system is that the pulse length can be increased significantly as the field is reduced. Fig. 7 shows the number of current redistribution times of the plasma current times versus the confinement improvement factor needed to keep Q = 10. At the nominal ITER design point of H = 0.85, the burn time of 11 seconds is ~ 15 energy confinement times so that the dynamics and control of the plasma pressure and temperature evolution can be studied. In addition, this pulse length would also allow the buildup of helium ash to be studied. This pulse length is about one skin time so one could begin to investigate the effect of alpha particle heating on the bootstrap current profile. If the confinement to achieve Q = 10 can be improved ~ 20% into the range of C-MOD experimental data, then the magnetic field could be reduced from 10T to 8T. This would allow the pulse length to be increased to ~33 seconds thereby providing the capability to explore advanced toroidal physics in a strongly burning plasma.

The Modular Strategy - a Cost Effective Way to Develop Fusion

There are a large number of the elements of Fig. 1 that can be addressed in a billion-dollar class compact burning plasma experiment as illustrated in Fig. 8. In fact, this was the strategy for the U. S. MFE program in the mid-‘80’s prior to ITER which was initiated by the desire to have a US-USSR collaboration to help ease tensions during the Cold War. The Modular Plan developed during the Technical Planning Activity [4] of the mid-1980s was a sound plan and has been advocated by PCAST-1995 [5] and others [6, 7]. All long-range high technology R&D programs are approached in a modular fashion with integration only occurring after the modules have reached their final objectives or when integration is required to accomplish the goal of a specific module. The present plan advocated for Inertial Fusion energy is a modular plan as shown in Fig. 9. The IFE plan has an ignition machine as the main element with the development of advanced drivers with high repetition rate and efficiency and target chambers as additional elements. The is very similar to the modular plan advocated for MFE which would have an ignition machine as the main element with advanced confinement and long-pulse/high-duty cycle confinement systems integration and nuclear technology and materials development. In both IFE and MFE, the step integrating burning plasmas, high-duty cycle and nuclear technology would occur after each had been demonstrated individually. This is in contrast to the ITER plan in which all these elements are developed and integrated simultaneously on a single facility. The ITER approach has very high technical risk since all of these elements are concentrated in a single facility which has increased the price to >$10B. A modular program for MFE of the type described in Fig. 9 reduces the technical risk, allows innovations to be introduced earlier, allows individual steps to be taken since they are smaller and therefore more likely to be fundable. The ultimate product will be more attractive and likely to be achieved sooner than the present one step to DEMO ITER plan.

A Comprehensive Technical Assessment of Fusion is Needed

Achieving controlled fusion by either magnetic or inertial fusion is a daunting technical task and neither the MFE nor the IFE program is in sound health at the moment. A thorough technical assessment of both MFE and IFE is needed to develop a common set of quantitative metrics, which can be used to determine the present status, evaluate the ultimate potential and to measure progress toward that potential. The results of this comprehensive technical assessment are needed to develop a plan for the optimal path for fusion R&D.

Acknowledgement

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References

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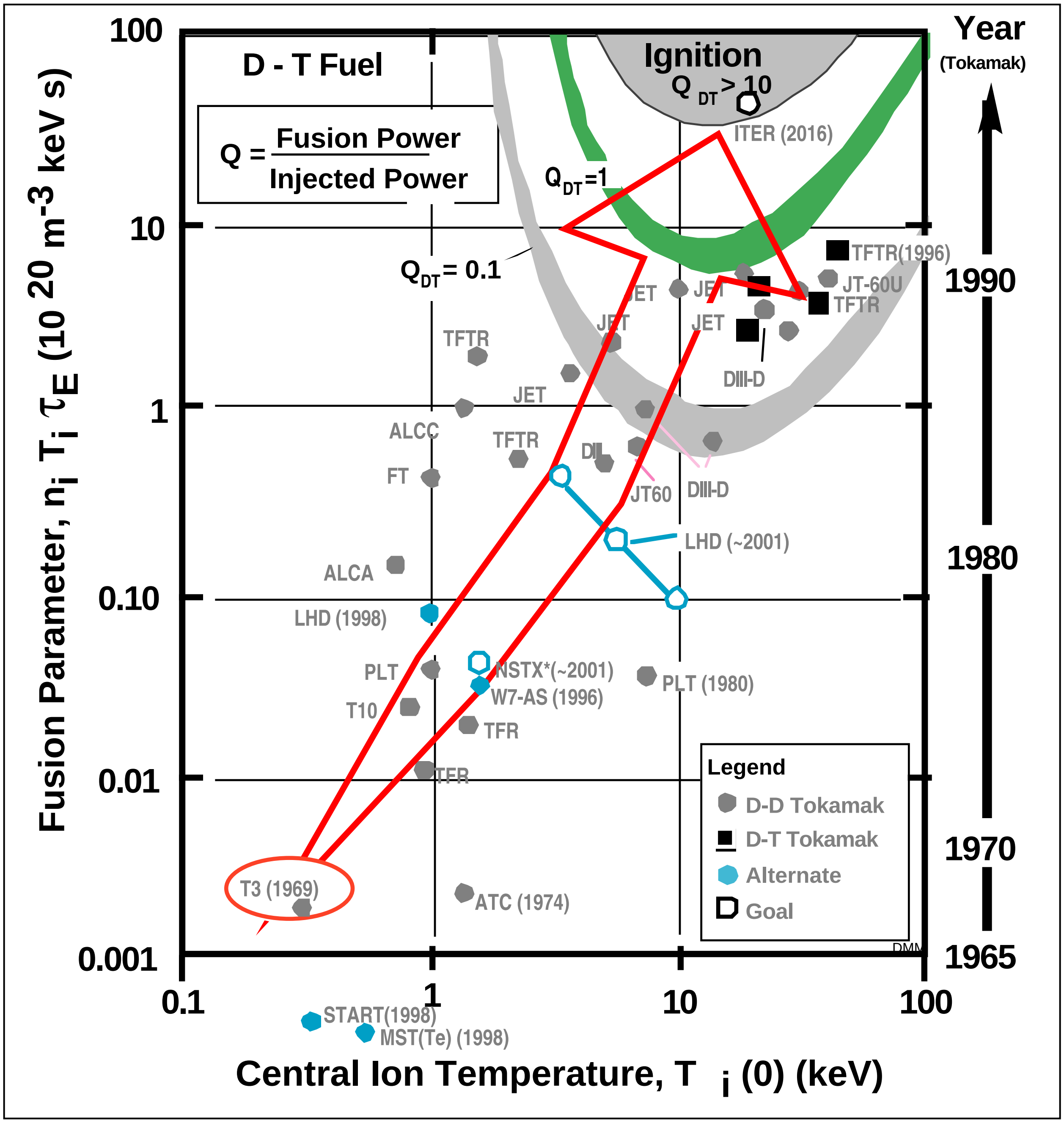
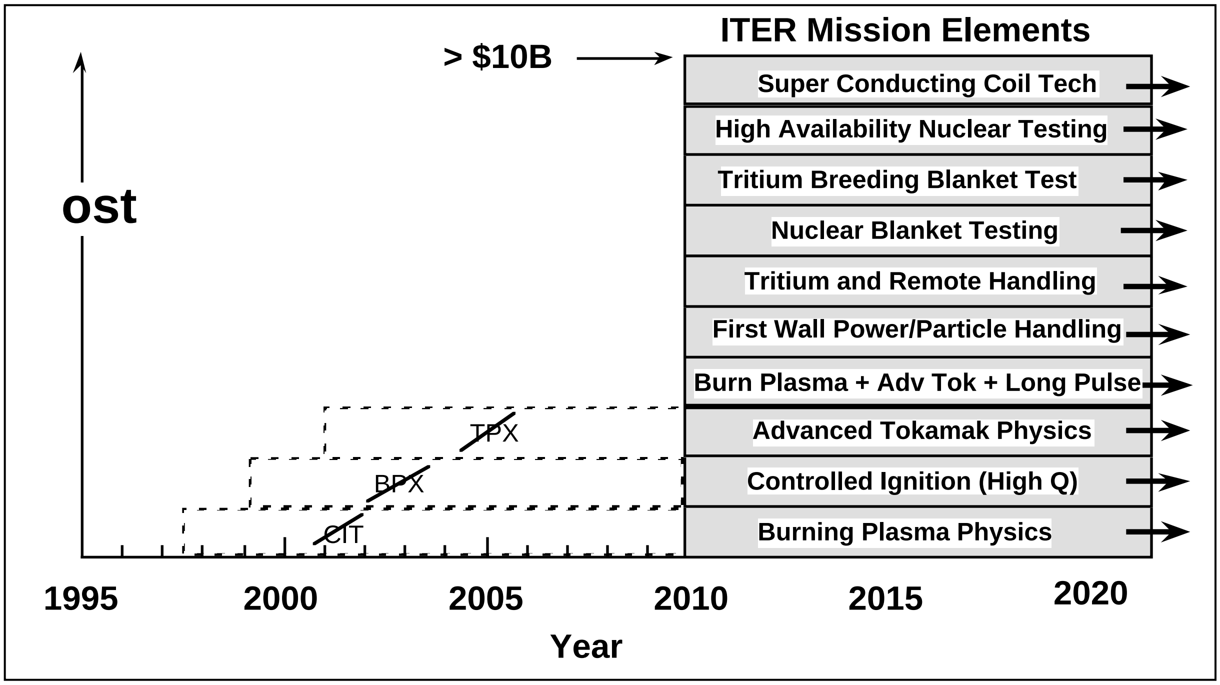
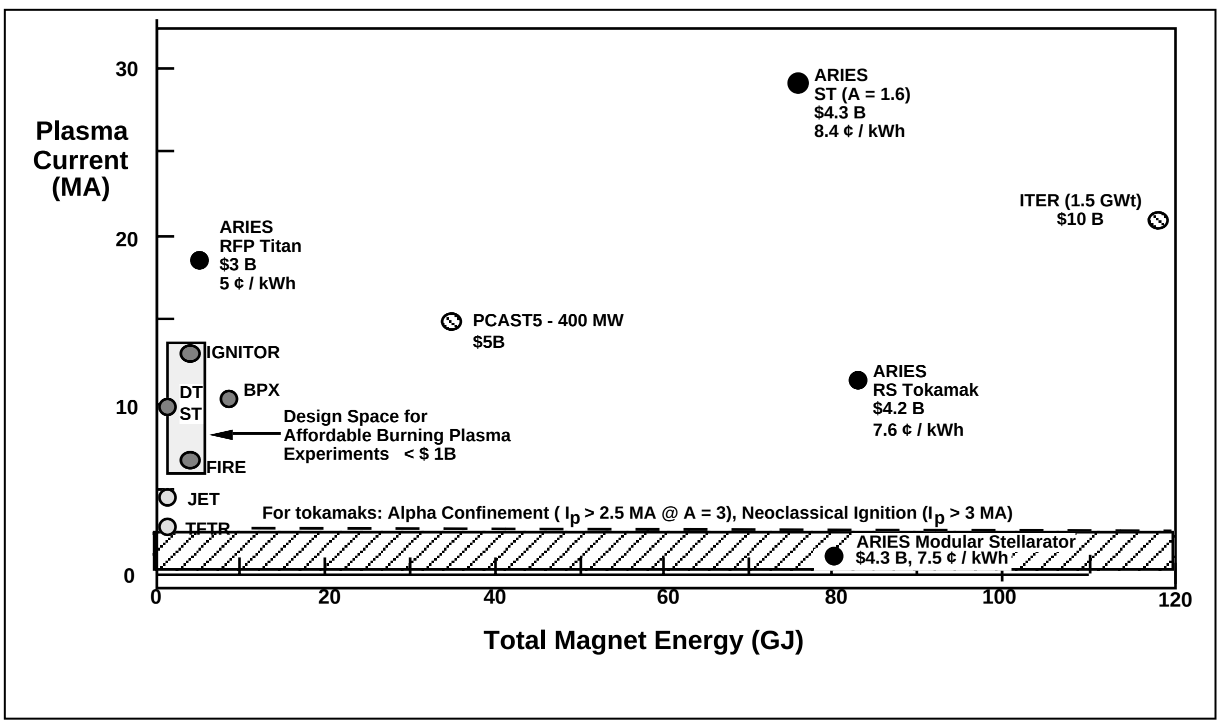


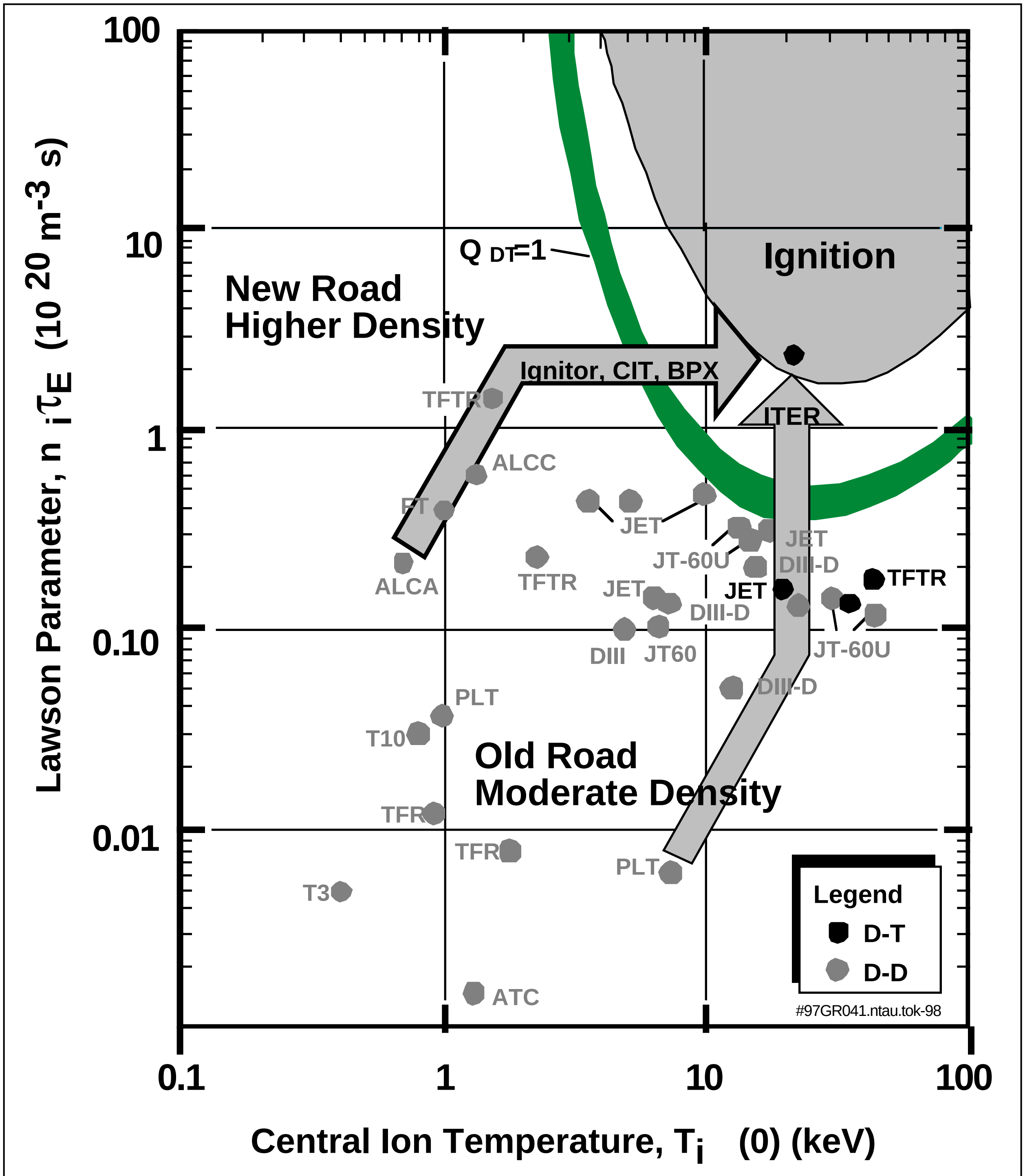
1. Lawson Diagram- A topographical map for fusion that defines the conditions required for deuterium-tritium plasmas to achieve a specific fusion gain.



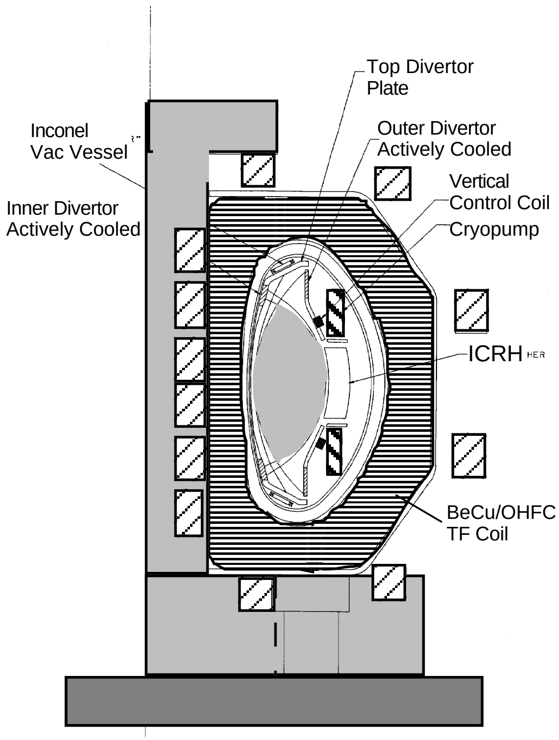
2. The consolidation of multiple missions on a single device for the entire world fusion program has created a barrier to progress, and has increased technical risk due the possibility of single point failure.



3. Comparison of the plasma current and magnet energy for various magnetic fusion burning plasma devices and several 1 GWe power plant designs illustrating cost increasing with plasma current and magnet energy.

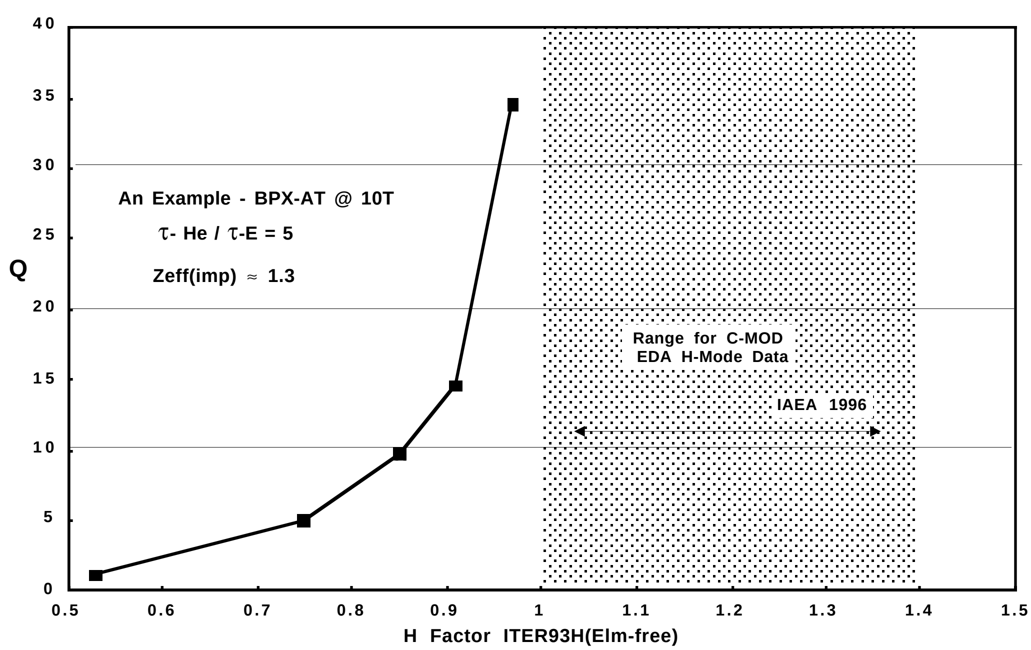


4. Requirements to achieve high gain D-T plasmas illustrating the high-density path.

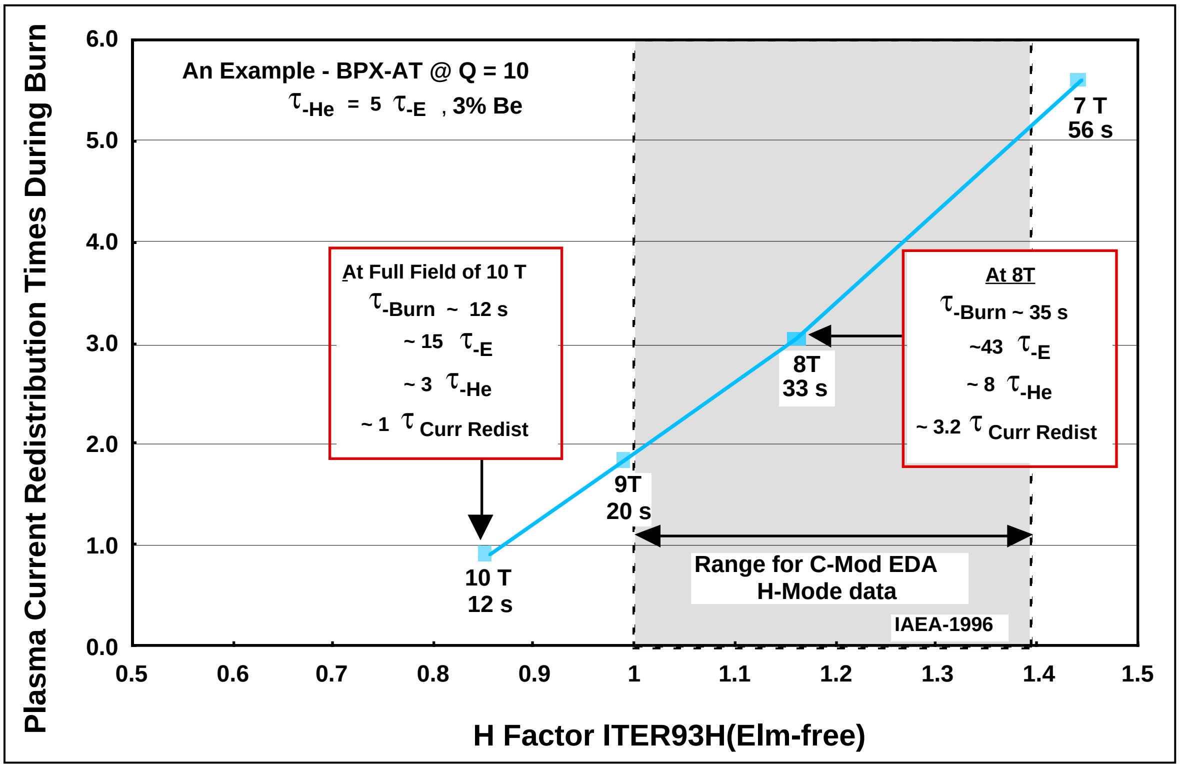


	BPX-AT	ARIES-RS
R(m)	2	5.5
A	4	4
κ	2	1.7
δ	0.3⇑	0.5
B(T)	10	8.0
Ip(MA)	6.25	11.3
Flat top(s)	10	steady
P_{fusion}(MW)	150	2,170

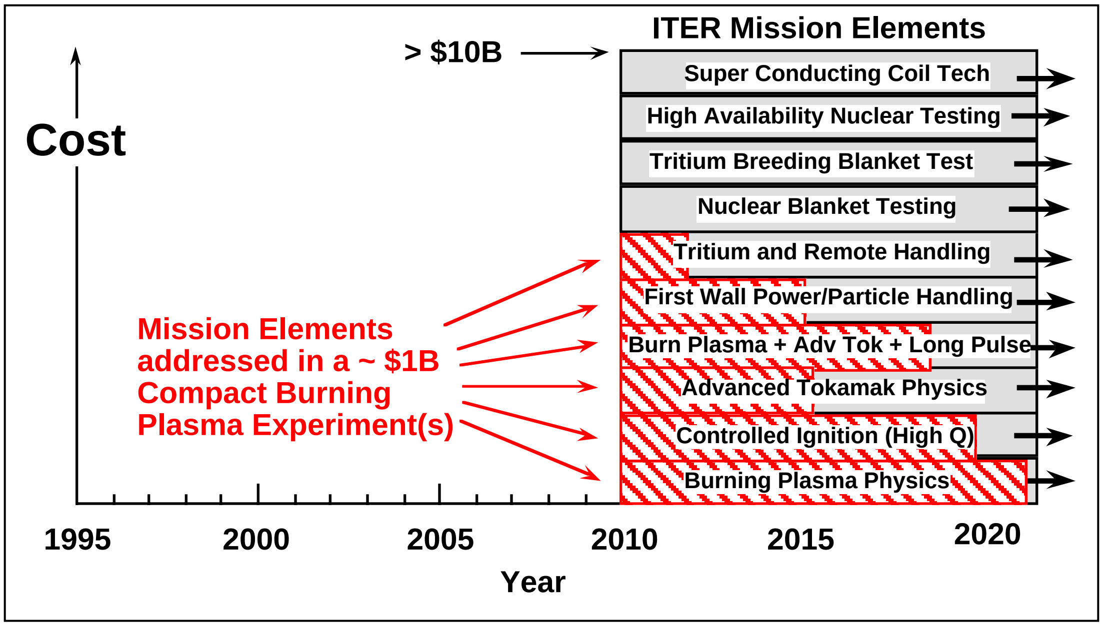
5. A compact high field tokamak (BPX-AT) to explore burning plasmas and begin the investigation of advanced physics regimes in strongly burning plasmas. The parameters of BPX-AT are compared with those of ARIES-RS the tokamak power plant design.



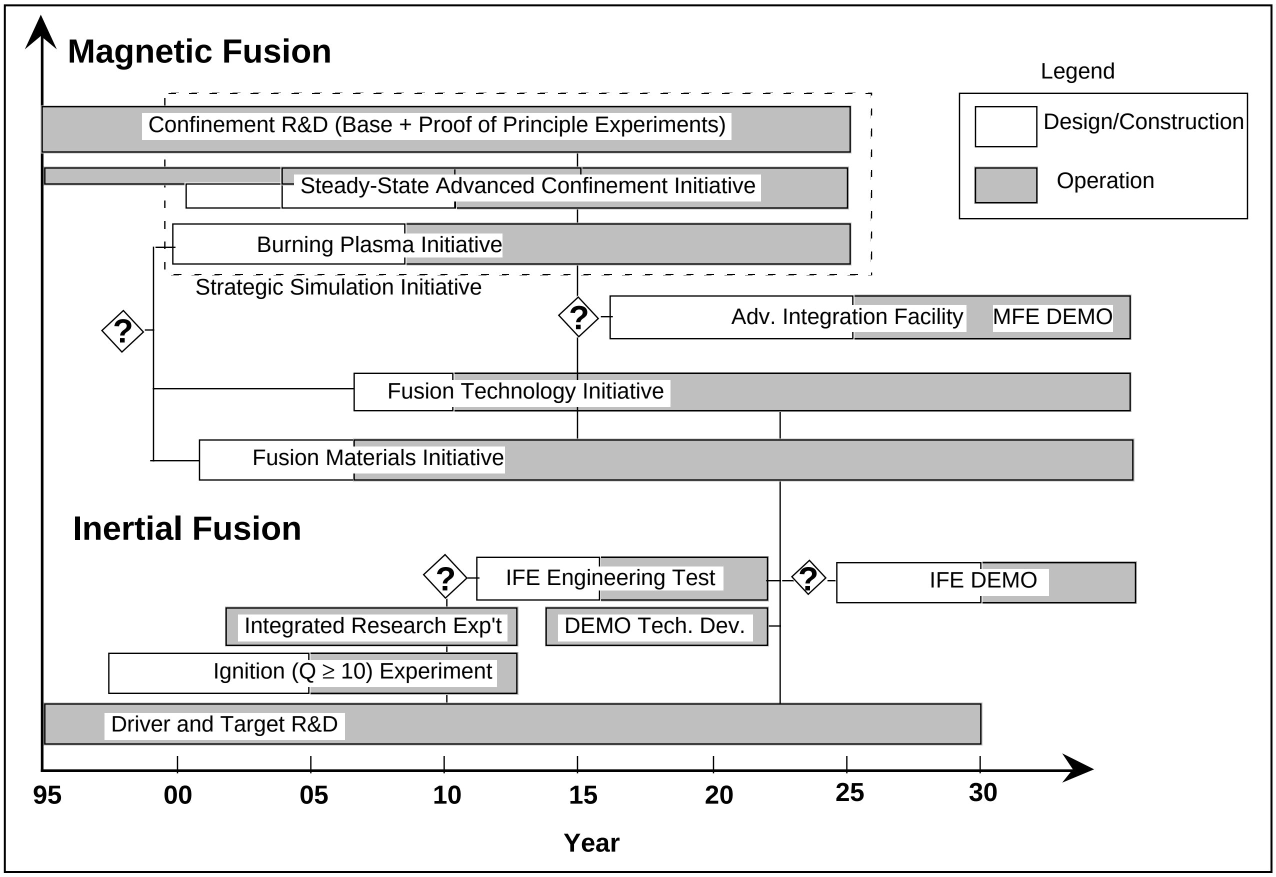
6. Compact high field tokamaks can access the strongly burning plasma regime (Q ~ 10) based on today's tokamak data base.



7. Compact cryogenically-cooled copper-coil tokamaks can access the "long pulse" burning plasma regime with modest improvements in confinement.



8. A significant fraction of the ITER mission can be accomplished using ~$1B compact burning plasma tokamaks. Only those issues that are tightly coupled (e.g., advanced tokamak physics and burning plasma physics) must be integrated on a single facility. Other facilities focused on long-pulse advanced confinement, nuclear technology and materials would address the remaining issues in the Modular Strategy for magnetic fusion.



9. A Modular Approach for the MFE and IFE Fusion Programs. The MFE and IFE programs have similar elements such as high gain (Q ~ 10) ignition experiments, advanced confinement or drivers for improved efficiency and high duty cycle, and technology/materials development.