Control of a High-Gain Fusion Plasma - A Crucial Step to Magnetic Fusion Energy

Dale Meade
Fusion Innovation Research and Energy
dmeade@pppl.gov

A tokamak fusion power plant will require a fusion plasma gain (Q_p) > 30. Achieving Q_p>30 is a necessary step in a Tokamak Roadmap to fusion energy. This should be done as early as feasible, since it would be a clear signal that fusion energy was ready for the significant investments needed to make fusion power a reality.

Historically, the US Plan A for magnetic fusion included an early Ignition Physics demonstration based on a modest technology extrapolation (Cu coils), and additional facilities in parallel– long-pulse high-performance non-burning plasma with superconducting coil technology, volume neutron source (VNS) for blanket development and a neutron irradiation facility for materials (FMIT). This was the US plan in 1976, 1987 and 1990. By 1989, the US had completed a national conceptual design for the Compact Ignition Tokamak (CIT) that was in the FY 1989 budget with Plant and Capital Equipment (PACE) funding. Unfortunately, the DOE Director of Energy Research was able to cancel the project due to lack of confidence that it would ignite. However, based today's confinement projections, **CIT would have achieved a Fusion Gain of 35!** The US fusion community made a huge strategic mistake by abandoning CIT in 1989.

In the early 1990s, a Plan B emerged namely that it would be cheaper in the near term for the US to join the EU, RF and JA in an engineering design activity (EDA) to design a power plant scale International Thermonuclear Experimental Reactor (ITER). This project ran into a road block in 1997 when the estimated total construction cost exceeded $10B and the US left the ITER project. During the next five years, the ITER Design activity reduced the mission and the plasma volume by a factor ≈2, thereby reducing the estimated total cost of ITER to $5B. In parallel, the US National Next Step Option (NSO) activity focused on a Pre-conceptual design of a US based burning plasma experiment, Fusion Ignition Research Experiment (FIRE), that was an advanced and updated version of CIT.

In the early 2000s, a technical assessment was made by the US fusion community at Snowmass that the next step for the US should be a Burning Plasma Program and that "both ITER and FIRE were suitable for satisfying the burning plasma mission" and that FIRE "is a lower risk option, as it requires "smaller" extrapolation in physics and technology basis." In 2002, the estimated US cost to participate in ITER was $500M while the cost to the US to build FIRE at a "Green Field" site was estimated to be $1.2B. Since the US cost for ITER was less than FIRE, the NAS review recommended and the US Administration decided to join the ITER partnership.

Fifteen years later, we find that the US share of ITER construction cost is now estimated by DOE to be between $4.7B and $6.5B. There is an agreed baseline schedule with no contingency for a reduced scope 1st plasma no earlier than Dec 2025. However, there is not an agreed baseline cost and schedule for 1st DT experiments, but there is a estimated date for DT operation of no earlier than 2036 that is used for planning purposes. The DOE has indicated that it will make a decision in the Nov 2017 - Jan 2018 on whether or not to stay in ITER as part of their preparation of the FY 2019 President's Budget Proposal .

Recommendation: Given this uncertainty, it is prudent for the US Fusion Community to begin the development of a burning plasma option for the future.

This paper describes a possibility for the US to return to plan A – a nearer-term lower-cost burning plasma experiment that would be part of an overall Multi-Machine Strategic Plan for achieving practical fusion energy.

After the Snowmass meeting the FIRE design activity continued for another two years and significantly improved the high performance advanced tokamak scenarios. That design activity was completed with a successful Physics Validation Review in April 2004. This would be the starting point to assess various options for a nearer-term lower-cost burning plasma experiment.

Option 1- Mission: Same Burning Plasma capability as ITER: $Q_p = 10$ and similar t_{dur}/t_{CR}
Restart FIRE 2004 design activity with minor updates.
FIRE Physics Validation Review -
FIRE, A Test Bed for Advanced DEMO (ARIES) Physics and Plasma Technology.
This would be a robust, low risk and the fastest approach.

Option 2 - Mission: significantly beyond ITER burning plasma capability, explores the challenging DEMO plasma regime in which plasma self-heating dominates over external heating sources ($Q_p > 30$, $f_a > 85\%$), the plasma's self-generated current dominates over external current drive ($f_{bs} \sim 80\%$, the plasma pressure is high, and the plasma radiates a significant fraction of its power over a sufficient time scale ($>10\ \tau_E$, $> 5\text{-}10\ \tau_P$, $> 4\ \tau_{CR}$). The creation and control of a high-gain, high-bootstrap burning plasma in the laboratory is a milestone that the tokamak was ready to take the next step, the development and exploitation of Demo level fusion technology. **This would be a high visibility achievement easily understood outside the fusion community**

Start with FIRE 2004 design point and look at all aspects for incremental changes in physics and engineering needed to achieve $Q_p > 30$, $> 4\ \tau_{CR}$. The near term would activities include:

Physics
- assess impact of small changes to optimize plasma size and shape
- review tokamak confinement results since 2002 for possible areas of improvement
- review advances in plasma exhaust esp. detached radiating divertors at high density
- update the enabling technologies- heating, current drive and plasma fueling

Engineering
- assess improvements in configuration, design concepts for coils, support structure and vacuum vessel,
  - e.g., bucking and wedging of the TF/CS assembly to increase B for 10T to 12 T
- assess recent advances such as additive manufacturing
- improvements in materials – structural strength, conductivity, neutron tolerance

Review industrial manufacturing capabilities, assembly and cost estimates

Investigate site options (Tritium inventory < 30 gm, Low Hazard Nuclear facility)

These assessments would then be used to define a baseline design point for a pre-conceptual design study.

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