Consensus technical summary of the members of the review panel for Proof-of-Principle Proposals in Fusion Energy Science, June 8-11, 1998

The Reversed Field Pinch (RFP): A Proposal for RFP Research in the U.S.

1. Summary

The committee believes that the RFP is ready for Proof-of-Principle status. The concept has seen some excellent scientific progress in recent years and there is an enthusiastic community with many new ideas for achieving further progress. Solutions are proposed to several highly challenging problems that require solution before the RFP is viable for a Proof of Performance program and ultimately a reactor. The primary focus of the program should remain upon confinement issues. Progress in this area will determine the best means of designing the experiments needed for establishing such future steps as current drive and higher beta.

2. Introduction

The RFP is a relatively mature concept with many years of experimental and theoretical experience. The USA has been a major player in RFP research for many years. Recently, interest in RFPs has been revived largely motivated by the outstanding work of the MST group at the University of Wisconsin. During this time the international program has grown substantially with the construction of large experiments in Japan and Italy. These experiments provide a multiple-machine database and serve as an experimental basis for evaluating the RFP. Given the long history, international interest, and recent technical progress in the RFP concept, it is natural that the USA program should be elevated to Proof of Principle status.

3. The Advantages

The RFP has a number of potential advantages as a reactor as compared to tokamaks and these serve as motivation for pursuing RFP research as an alternate magnetic fusion concept. These advantages include (1) the use of normal magnets, (2) high beta, (3) weak fields at the coils, (4) the possibility of ohmic heating to ignition, and (5) the potential absence of disruptions. There is a similar list of disadvantages, described below, which limit progress towards a reactor.

The RFP concept also has substantial advantages with regard to basic plasma science. It offers an excellent test bed for examining the generation and influence of magnetic MHD turbulence on plasma confinement. This is an issue of interest to the entire fusion program and hence is much broader than only the RFP.

Another issue worth noting is beta. The RFP is inherently a high beta device and typically operates in the range of 5 – 10% and has achieved 15% beta. This is essentially the regime of reactor relevance, though the typical values are somewhat on the low side. Thus, substantial beta has been achieved in an RFP, and though improved beta is advantageous, the viability of an RFP for energy applications relies on achieving substantial reduction of transport and in demonstrating that steady state operation can be obtained.

The committee, as well as essentially the whole USA fusion community, believes the quality of research carried out on the MST experiment is exceptional. We have a great deal of confidence and respect for the MST team. They have introduced several highly innovative ideas including the idea of reducing MHD turbulence, and the resulting degradation in transport, by means of current profile control. Although USA support for RFP research is relatively modest, the MST group is arguably considered to be the world leaders in the program.

This combination of advantages -- reactor benefits, broad contributions to fusion plasma science, and an outstanding team — motivate our recommendation for Proof of Principle status.

4. The Challenges

Engineering issues aside, there are three fundamental scientific problems that must be solved in order for the RFP to proceed to the Proof-of-Performance stage as defined in the USA alternate concept program. These can be summarized as follows.

(1) Confinement: Energy confinement in RFPs has been traditionally poorer than in a tokamak because of the presence of substantial MHD turbulence. Typical thermal diffusivities in an RFP are between 20 – 100 m^2/sec. In a comparably size tokamak, the corresponding value is approximately 5 m^2/sec. A related observation is that the relative magnetic field fluctuation level is on the order of 0.01 as compared to 0.0001 in a tokamak. Interestingly, there is an empirical scaling law satisfied by many different RFP experiments. This scaling is unfavorable at low current but becomes favorable at high current. It actually represents the "best" performance observed in each given device. To their credit the RFP community is not relying on this scaling law to predict improved transport in future devices but is planning to investigate, at a basic level, the source of fluctuations and the resulting anomalous transport. In this connection the use of current profile control to reduce turbulence has already resulted in an increase in confinement time by a factor approaching 5. Further increases are necessary. This will require new

tools, such as the proposed lower-hybrid current drive. Understanding and improving transport is the most critical problem facing the RFP concept and should receive primary emphasis in the PoP program.

(2) Current Drive: An RFP by its very nature requires a large toroidal current. In a steady state reactor, which requires at least 20 MA, this current must be driven externally by non-inductive means. Standard, tokamak RF methods are too inefficient to be of interest. The RFP community is advocating oscillating field current drive (OFCD) which is theoretically predicted to be much more efficient but which has not as yet been demonstrated experimentally. Furthermore, as much as 20% of the total current must be driven by tokamak RF methods for current profile control. The success of OFCD, or some other equivalently high efficiency method is a critical step on the pathway to a steady state reactor.

(3) Resistive Wall Instabilities: The RFP, by virtue of its low safety factor, is theoretically predicted to be unstable to external resistive wall MHD modes. Standard tokamaks and stellarators are typically designed to be stable even with the wall at infinity. Advanced tokamaks are often unstable to a single resistive wall mode, and stabilization of this mode is an important component of AT design. In fact the problem of resistive wall modes is of importance to the entire fusion community, affecting tokamaks, stellarators, RFPs, spheromaks and FRCs. The problem is more difficult in an RFP where several modes are unstable simultaneously. Various forms of stabilization have been proposed (e.g. feedback, smart walls, rotation) but there has been only limited experimental verification. Stabilization of resistive wall modes is another critical problem that must be solved on the path to an RFP reactor.

5. The PoP Proposal: Suggestions

The committee believes that the RFP PoP proposal has correctly identified the major issues to be addressed and has suggested a strategy for solving each of the related problems. The plan is logical and well thought out and the budget requested is appropriate for the tasks. Furthermore, the total funds requested are relatively modest because of the clever use of MST as the base facility.

Nevertheless, the committee feels that the proposed plan is too ambitious. A more appropriate strategy is to make progress on the three critical problems in a sequential manner focusing initially on the problem of transport. Ultimately, the proposed solutions must be shown to work in an integrated manner. At present though, it is premature to worry about integration and the need for a very aggressive program is unwarranted. The following guidelines represent a more serial approach to the RFP PoP. The time scale and funding are spread out and there are ample opportunities to alter the strategy mid-stream before too many funds have been committed.

(1) Confinement is the first priority. The relevant equipment (primarily the lower hybrid power system and related diagnostics) should be purchased and installed on MST. A detailed physics investigation should be carried out as proposed with the goals of understanding transport and improving confinement by means of current profile control.

(2) The next priority is current drive. The principles of OFCD must be tested and compared to theory. The goal here, as stated in the proposal, is to develop an efficient method for driving the large amounts of current required in an RFP.

(3) The resistive wall problem is also important, but it must be recognized that this is a community wide problem. The most appropriate experimental plan must be developed within the context of the entire fusion program. The MST team does not feel that their facility is the appropriate place to study feedback stabilization of this problem, but they are properly encouraging their associated community to investigate this problem.

(4) The measurement of beta limits as suggested in the proposal should be the lowest priority. The reason is that beta achievement is not the key issue for RFP viability, while the other problems are make or break for RFP viability.

The proposal suggests carrying out steps 1,2 and 4 more or less in parallel. The committee suggests prioritizing the experimental effort in accordance to the programmatic importance of the issues.