Scientific Issues and Gaps for High-Performance Steady-State Burning-Plasmas

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Introduction

Fusion energy is a potential energy source for the future with many attractive features. For sixty years, the central theme of the international magnetic fusion effort has been to develop magnetically confined plasmas as a possible heat source for an electricity producing power plant.
Recently, the FESAC Priorities, Gaps and Opportunities Panel identified three themes for the long term research agenda for the development of Magnetic Fusion Energy. These themes are described in terms of the "functional" requirements for a fusion power based power plant.

Theme A – Creating a High-Performance Steady-State Burning Plasma
(a heat source from magnetic fusion)
Theme B – Taming the Plasma Materials Interface
(interface between heat source and furnace wall, and extracting plasma exhaust power)
Theme C – Harnessing the Power of Fusion
(extracting neutron power, breeding tritium, remote handling, safety/environment)

These themes describe the natural progression in the research and development of a new heat source for an electrical power plant. This progression is the same as that followed in fission power R&D. First the physical principles of the heat source are understood and demonstrated including control mechanisms suitable for a power plant. Then the technology development is undertaken to provide for the efficient extraction of heat from the source and closure of the fuel cycle along with other technologies required for economic attractiveness. Plasma technologies and materials development occurs at each step as required to enable progress. The present international fusion road map follows this general strategy. In the following discussion DEMO is a prototype power plant, differing only in availability.

Theme A involves the coupling of the key issues for a fusion powered heat source – high fusion power gain ($Q > 30$), sustainment with full non-inductive current drive, plasma exhaust at high power densities with neutron wall loads of ~ 4 MWm^{-2}, power plant relevant plasma and particle exhaust, and plasma control including off-normal events with minimal power, at pulse lengths sufficiently long to address these issues. The strategic challenge is to determine the scale and order at which these coupled issues can be most effectively integrated and resolved.

High-Performance Steady-State Burning Plasma Issues

High Fusion Gain – requires good confinement (reduced transport) at fusion temperatures with profiles determined by self (alpha) heating. Present understanding suggests that plasma transport and pressure limits are sensitive to the details of the pressure and current profiles. High gain benefits from core plasma operation near the highest densities and pressures allowable with core plasma temperatures of ~15 keV. Resolution of this issue requires time scales much longer than the energy confinement time and the plasma profile evolution time.

Sustainment with full non-inductive current drive – a high-gain steady-state plasma will allow very little power for plasma current drive (P_{cd}) and plasma control (P_{cont}) with $P_{cd} + P_{cont} = 5P_{\alpha}/Q$. Typical power plant regimes require a large bootstrap current (70 to 90%) and efficient current drive system for the remaining 30 to 10%. The current drive efficiency benefits from core plasma operation at the highest temperatures allowable. Resolution of this issue needs core plasma durations of several plasma current redistribution times.

Plasma exhaust at high power densities – a neutron wall loading of ~4 MWm^{-2} requires a core plasma energy exhaust (particle energy plus radiation across the core plasma boundary) of ~ 1MWm^{-2}. The exhaust energy needs to be optimally distributed among the first wall plasma facing components (PFC), the divertor chamber surface and the divertor target. It will likely be necessary to inject radiating impurities into the edge of the core plasma and into the divertor chamber to optimize and control the distribution of the exhaust power. The exhaust particle flux (fuel + alpha ash + impurities) needs to be transported effectively to the divertor chamber for D–T fuel recovery and removal of the alpha ash and impurities. Maintaining an optimum fuel mixture of D–T using external fueling is part of this issue. Particle wall interactions require that particles are at very low temperatures (≤ few eV) and effective radiation benefits from higher density. Resolution of this issue requires time scales of several particle confinement times of the core plasma to address particle transport, several thermal time constants of the plasma facing components to bring the PFCs surface to operating temperature, several particle diffusion times in the PFCs to achieve self conditioning and particle flux equilibrium and several surface erosion time constants to address erosion/mass migration and lifetime issues of the PFC surfaces. Neutron irradiation effects of PFCs are also important and would be addressed by Theme B Thrusts.

Plasma control including off-normal events – Very effective plasma control will be needed to ensure that the plasma does not exceed operational limits when the core plasma parameters and profiles are determined primarily by self-heating. The control must be sufficiently robust that only a few full disruptions occur per annum. Plasma control using auxiliary heating, shear flow drive or current drive are limited to $P_{cd} + P_{cont} = 5P_{\alpha}/Q$, or 10 to 20% of the alpha power in typical power plant study. Modification of the fuel isotopic mix is another potential control mechanism. This issue could be addressed with plasma durations of several plasma profile redistribution times.

High-Gain/Sustaiment/Plasma Exhaust Coupling –The most challenging issue is the coupling (integration) of these individual issues. High fusion gain depends on plasma profiles that are determined by self-heating and coupled to the plasma edge. Plasma sustainment must be accomplished with very little external power and therefore relies heavily on a high bootstrap fraction and high temperature plasma core. However, the plasma edge is transporting high power density exhaust and would like high density and low temperature. It is not clear that the highly self organized state (self-heating, self-stabilized plasma profiles, self-driven plasma current and self-conditioned PFCs) actually exists and is stable. This non-linear coupling is the critical issue that must be resolved to establish the scientific basis for a tokamak based fusion heat source.

High-Performance Steady-State Burning Plasma Gaps

Individual metrics relevant to High-Performance Steady-State Burning Plasma Issues are shown in Table I. The key metrics for a range of tokamak based fusion plants is given in the right hand columns. There are huge gaps between the capabilities of today's experiments and those required for a tokamak fusion power plant.

Table I. Individual Issue (Metric)	Today* ($>10\tau_E$)	ITER	ARIES-I	ARIES-AT	Gap IT to AR
Fusion Gain (Q)	< 0.2	5	20	50	4 to 10
Sustainment** (P_{cd}/P_α)	>25	1	0.25	0.1	4 to 10
Current Drive fraction ($1-f_{bs}$) (%)	~30	~50	32	9	1.5 to 5
Plasma Pressure (atm)	1.6	2.5	10	10	~4
Fusion Power density (MWm^{-3})	0.3	0.5	4	4.7	~9
Neutron Wall Loading (MWm^{-2})	0.1	0.5	2.5	3.3	5 to 7
Plasma Control* (P_{cont}/P_α)	>25	1	0.25	0.1	4 to 10
Exhaust Power Density (P_{heat}/A_{ps} (MWm^{-2})	0.85	0.2	1	1	5

* Not all simultaneous

** Current Drive Power + Plasma Control Power = 5 P_α/Q

ITER contributions to closing the High-Performance Steady-State Burning Plasma Gaps

ITER will make major contributions to closing these gaps. The pulse length of ITER (~2,500 s) in the non-inductively sustained mode of operation is sufficiently long to address the issues described above. However, there will still be significant gaps for individual issues related to the High Fusion Gain operating mode of a power plant:

Fusion Gain Gap	**a factor of 5 to 9**
Sustainment Gap	**a factor of 5 to 10**
Power Density Gap	**a factor of 5**

The largest Gap by far is in the coupling (integration) of these individual issues. Since these issues are coupled and must be attained simultaneously, it is appropriate to quantify the Coupling Gap as the product of the individual gaps. By this measure, **the Coupling Gap is ~ 100**.

D-D Tokamak Contributions to closing the High-Performance Steady-State Burning Plasma Gaps

The new long pulse superconducting tokamaks in Asia (EAST, KSTAR, and JT60-SA) are expected to make valuable contributions to the basic understanding of plasma transport and stability of sustained advanced tokamak modes in non-burning plasmas with profiles defined entirely by external actuators. These devices are capable of pulse lengths sufficient to address plasma related issues. In addition, they will extend understanding of high bootstrap fraction plasmas with externally defined plasma profiles, and coupling to a plasma edge characterized by modest exhaust power densities. However, since these are non-burning plasmas, they are not able to address the critical issues of high performance plasmas, steady-state sustainment, plasma edge and plasma control when the plasma profiles and power balance are defined by alpha heating.

Can the effects of alpha heating be simulated on D-D tokamaks, to close the Gaps remaining after ITER?

In order to address the plasma physics issues of DEMO, the core plasma of the simulator must have dimensionless parameters similar to DEMO, this is possible only if both plasmas have the same similarity parameter, $S = BR^{5/4}$ and the same geometry. (Kadomtsev-1974) Therefore the size of the simulation plasma (and cost) will be in the same ball park as the real burning plasma. In addition, there fuel isotopic effects on plasma behavior. A non-neutron producing hydrogenic H-H plasma simulation does not simulate the behavior of a D-D plasma, and it is known from TFTR and JET D-T experiments that there are isotopic effects going from D-D to D-T.

Probably the biggest deficiency of using a non-burning plasma to simulate the behavior of a burning plasma is the lack of self (alpha) heating. Alpha heating of a DEMO relevant plasma will require power levels of 30 to 100 MW of power. The self-heating is due to an isotropic distribution of initially 3.5 MeV alpha particles that deposit their energy ≈ 80% to electrons and ≈20% to fuel ions. The strength of the alpha heating source must vary in space and time as $n_D n_T \langle\sigma v\rangle$. In principle, beams of 3.5 MeV neutral alpha particles could be injected from multiple injectors to create ~ isotropic distributions with the correct spatial profile, but the cost and complexity will certainly exceed the cost and complexity of using D-T. One could use electron cyclotron heating to heat only the electrons but the effects of fast alpha instabilities and fuel ion heating would be absent. Again the cost of 50 to 100 MW of ECRH would be large.
It should also be noted that a high-performance steady-state plasma running with reasonable experimental availability will produce significant D-D reactions that will produce both tritium and neutrons that will activate the internal components. In KSTAR and JT60-SA there will be no internal remote handling, so this imposes a limit on the number and pulse length of high performance pulses. This limit can be increased by internal remote handling tritium recovery systems and significant shielding of external components as planned for TPX. In the end, significant costs will be expended to deal with nuclear effects without getting any of the benefits. This would argue that alpha heating is the cheapest way to heat a DEMO relevant plasma.

Some Guiding Principles for Thrusts to Close the High-Performance Steady-State Burning Plasma Gaps

1. Since the critical Coupling Gap is so large, there should be a high priority Thrust to address this issue at the earliest time and at the smallest size/cost. It is the “Proof of Fusion” as a suitable heat source, and would not be wise to delay resolution of this issue and then be forced to resolve it late in the development cycle on DEMO at the largest cost and/or highest risk.

2. Adopt a time sequence for Thrusts similar to that followed in fission power R&D and other high technologies where one addresses Theme A first, namely establish the basis for a High-Performance Steady-State Burning-plasma as a fusion heat source, then employ that understanding and capability to address Theme B, and with that in hand move on to Theme C. Many Thrusts like that proposed above will address both items in Theme A and Theme B.

3. Look for facilities to accomplish the Thrusts that follow a sequence allowing for upgrades to spread the costs over time while making progress that bootstraps the funding to make the next upgrade/step. The high energy (Tevatron) and basic energy science (APS, SNS, etc) groups have been extremely successful with this strategy.