Thrust #8:
Understand the highly integrated dynamics of self-sustained and dominantly self-heated burning plasmas

C. Kessel, with

D. Anderson, P. Bonoli, A. Garofalo, B. Lipschultz, D. Meade,
M. Murakami, F. Najmabadi, E. Synakowski

MFES Research Needs Workshop, Bethesda, MD

June 8-12, 2009

The exploration of the high performance fusion core plasma regime is a fundamental step to verify the existence of viable plasmas for fusion power production

- Plasma self-heating dominates external heating sources
- Plasma self-driven current dominates external current drive sources
- Plasma pressure is high
- Plasma density is high
- Plasma transport of energy, particles, momentum, and current are strongly interdependent
- MHD stability properties are coupled in the presence of fast alphas, high pressure, high pedestal pressure, and error fields
- Significant core/pedestal radiation
- Plasma purity determined from a balance of fusion, radiation, and current drive efficiency
- Pulse lengths of several current profile re-distribution times

DEMO CORE TARGET PARAMETERS TO BE REACHED SIMULTANEOUSLY (based on power plant and other studies)

$\beta_N^{\text{no wall}} < \beta_N < \beta_N^{\text{with wall}}$	normalized plasma pressure
$\beta_N^{\text{ped}} \approx 0.5\text{-}1.0$	normalized plasma pressure near the plasma edge
$3 < q_{95} < 5$	degree of magnetic field twist near the plasma edge
$I_{\text{non-inductvie}}/I_{\text{plasma}} = 1$	fraction of plasma current not provided by a external solenoid
$0.65 < (I_{\text{bootstrap}}/I_{\text{plasma}}) < 0.90$	fraction of plasma self-generated current
$n/n_{\text{Gr}} \approx 1$	ratio of plasma particle density relative to an empirical limit
$P_{\text{alpha}}/P_{\text{input}} \approx 4\text{-}9$	ratio of plasma self-generated power to externally injected power
$P_{\text{rad,core}}/(P_{\text{alpha}}+P_{\text{input}}) \approx 0.35\text{-}0.5$	ratio of power radiated from the plasma core relative to the total power heating the plasma
$Z_{\text{eff}} < 2.5$	weighted sum of ion charge in the plasma
$\tau_{\text{pulse}} >> \tau_J$	plasma operation time compared to the current profile redistribution
Supporting elements	
Efficient fueling and pumping, with particle control of the DT fuel, He ash, and impurities.	
Efficient coupling of heating and current drive power into the plasma.	
Consistent pedestal density and temperature to provide high core performance with fueling and divertor compatibility.	
Multi-level feedback control on parameters ranging from plasma shape to current profile to MHD modes.	
Plasma sustainment over many current diffusion (considered the longest time constants for the core plasma) without disruptions and with acceptable transients.	

The strongly coupled burning plasma regime poses some basic questions

- **Under these conditions, what is the plasma configuration that emerges from these self-consistent internal physics processes?**

- **In the strongly coupled burning plasma what maximum stability properties will the plasma access?**

- **How can such strongly coupled burning plasmas be established and sustained with much less external power and current drive than in present experiments? What is the most attractive core burning plasma regime that can be achieved? (Thrust 3 & 5)**

- **How will self-heated plasmas interact with their material interfaces, and what is the self-consistent core / scrape-off layer / divertor plasma state?**

ITER will break new ground for the world fusion program

ITER-AT(SS) plans to demonstrate a DT plasma with a P_{alpha}/P_{input} of approximately 1, for a baseline pulse of 3000 s (≈ 7-8t_J).

The plasma is expected to be just below the no wall beta limit.

Here the current would be 100% non-inductive with a bootstrap fraction of about 50-65%.

The flexibility of the mixture of heating and current drive sources on ITER is in question.

ITER provides an early glimpse of the self-heated plasma regime

	ITER-AT	ARIES-I	ARIES-AT
β_N (%)	2.5-3.0	3.2	5.4
f_{BS}	0.48-0.68	0.68	0.89
n/n_{Gr}	1.0	1.04	0.95
q_{cyl}, q_{95}	3.8-4.5	4.4	3.0
Z_{eff}	1.4-2.0	1.73	1.83
f_{rad}^{core}, MW (P_{rad}^{core}/P_{in})	0.2-0.3	0.48	0.36
f_{rad}^{div}, MW (P_{rad}^{div}/P_{in})			0.43
P_{SOL}/A_p	0.14	0.45	0.56
P_{SOL}/P_{in}	1.36	2.52	6.25
P_α/P_{in}	1	3.8	8.8
$\langle N_W \rangle$, MW/m^2	0.6	2.5	3.3
τ_J, s	200-400	300	275
Duration, s	3000	~3×10^7	~3×10^7

Activity #1a

Examine the ITER advanced tokamak scenarios in detail (Thrust 4), with focus on

1) expanding the flexibility in heating and current drive sources
2) extending to larger alpha power relative to input power
3) extending above the no wall beta limit with MHD feedback control

Develop proposals for extending the present ITER AT program to higher fusion core plasma performance.

Activity #1b, in parallel with #1a

US to begin scoping and design studies for a flexible DT facility to pursue high performance fusion core plasma exploration at high P_{alpha}/P_{in}. *Significant consideration should be given to phased missions, integrating the core-edge coupling.* Based on these studies, make a decision on construction of a DT device in the US.

Scenario I: Pursue moderate pulse length (> 5 t_J) DT highly coupled (large P_{alpha}/P_{input}) high performance fusion core plasma able to utilize conventional materials for in-vessel components to validate the fusion power plant plasma regime. This mission is followed by pulse extension to long and then ultra long pulses, where the plasma performance can be kept the same or reduced to allow the longer time scale plasma material interface and neutron material effects to be studied.

Scenario II: Pursue long to ultra long pulse at first with a moderately coupled core ($P_{alpha}/P_{input} \approx 1$) to emphasize the study of the long time scale plasma material interface and neutron material effects. This mission is followed by a push to increase the coupling of the high performance core plasma to large P_{alpha}/Pi_{nput}.

Activity #1b, cont'd…..The need to validate the core-edge coupling in a burning plasma reflects our growing recognition of its importance

- Heat loads
  - Divertor and first wall power handling
  - Radiation in divertor
  - Power scrape off width
- Particle transport
  - Controlling DT fuel and He ash
  - Generation and behavior of impurities
  - Particle retention in the solid materials
  - High temperature walls
  - The high density limit
- Material evolution
  - Neutron damage
  - Plasma damage and erosion (redeposition)
  - Melting
  - Fast ion or electron impingement
  - Generation of debris - dust, flakes…

How do these affect the high performance core plasmas?

Activity #1b, cont'd

CORE - EDGE TARGET PARAMETERS, in addition to CORE TARGETS TO BE REACHED SIMULTANEOUSLY
(based power plant and other studies)

$\tau_{pulse} >> \tau_{PFC}$	plasma operation time compared to the plasma facing component equilibration times
$3 < \tau_p^* / \tau_E < 10$	ratio of the global particle confinement time inside the vacuum chamber to the plasma energy confinement time in the plasma
$q_{peak,div} \leq 10$ MW/m^2	peak heat flux on the divertor material surface from particles and radiation
$q_{peak,\ FW} < 0.5\text{-}1.0$ MW/m^2	peak heat flux on the first wall material surface from particles and radiation
$P_{rad,div}/(P_{alpha}+P_{input}) > 0.45$	ratio of power radiated in the divertor region relative to the total plasma heating power
$\tau_{FW,lifetime} > 3$ years	lifetime of first wall material before replacement
$\tau_{div,lifetime} > 3$ years	lifetime of divertor material before replacement
$T_{FW} > 500\text{-}1000^oC$	operating temperature of first wall material surfaces
Supporting elements	
Plasma sustainment over many PFC times (considered the longest time constants for the PFC material evolution) without disruptions and with acceptable transients.	
Controlling the tritium inventory in plasma facing materials, production of debris (dust)	

Activity #1b, cont'd

It is unrealistic to consider that the US will construct several DT facilities to prepare for DEMO. Therefore it's recognized that a DT facility could and should be phased in multiple ways to address multiple missions associated with the core and core-edge challenges for high performance DT fusion plasmas.

The phasing of a DT facility,

A series of steps that can be taken toward the goal of core and edge plasma self-consistency ultimately reaching "as close as possible" to DEMO parameters.

The pulse lengths and duty cycles for the device can be progressively extended to provide the needed neutron fluence and plasma fluence to develop the understanding for following steps, identifying the effects on the plasma core.

Material qualification can be developed in conjunction with other facilities (IFMIF, ITER, ..),Theme 3, Thrust 13 & 14. The impact of the material evolution on particle control and debris generation, and tritium retention can be observed in a staged program.

Non-burning DD core and core-edge plasma demonstrations will serve as important guides for DT plasma development

- Simultaneous demonstration of multiple target parameters
- Sustainment for multiple current re-distribution times
- Plasma feedback control methods
- Possibly "simulate" the alpha particle heating source with external electron heating sources
- Techniques for avoiding disruptions and minimizing large transients

- Core-edge, see Thrust 12

- Although DD plasmas can be used to explore operating regimes for DT, they do not confirm their existence due to the complex nature of self-organization with strong alpha heating

Activity #2a

Continue program on US tokamaks (and ST) facilities (C-Mod, NSTX, DIII-D) to establish the simultaneous high performance plasma parameters (β_N, f_{BS}, $P_{rad,core}$, etc.) in non-burning DD.

Present tokamaks in the US should pursue upgrades to heating and current drive systems, as well as pulse extension to few current diffusion times.

These devices should identify attractive plasma configurations for ITER and beyond in DD.

The access to combinations of high beta, high non-inductive plasma current, high bootstrap fraction, long pulse lengths, other dimensionless plasma parameters, and mix of external control tools varies among the US tokamaks.

The results of the US (and international) experiments will need to be interpolated to establish a more universal physics basis. Methods for controlling the plasma current profile and radiated power fractions can be explored.

Activity #2b

Take advantage of the long pulse Asian non-burning DD tokamaks to establish the simultaneous high performance plasma parameters (β_N, f_{BS}, $P_{rad,core}$, etc.)

1) longer pulse lengths

2) all four heating and current drive sources for flexibility in plasma configurations

3) control system development

Examine areas where device program plans for the Asian devices can be enhanced or expanded to provide a greater physics database, and establish a strong collaboration to pursue this.

Although there are conventional solutions to a number of issues for the high performance steady state burning plasma regime, some of these have significant uncertainty

Consideration should be given to the use of three-dimensional magnetic fields to influence MHD and avoid disruptions based on stellarator research (Thrust 17). In addition, these fields may provide rotational transform, reducing the current drive requirements, or may influence the plasma's resilience to the density limit observed in tokamaks.

The exploration of advanced divertors, including liquid metal approaches, should be pursued, to understand their potential for handling the high particle and power loads in a fusion power plant as well as the particle control and material evolution issues.

The possibility of new more powerful control, with flow shear or alpha particle "engineering" (Thrust 3), on internal plasma profiles may be possible because of its strong coupling.

The ultimate goal of DT plasma development

- Establish the experimental validation and predictive simulation capability (Thrust 6) to project behavior and performance to the DEMO device with confidence.

- The basis for this projection is research on high fusion gain core plasmas and self-consistent coupled core-edge plasmas and material interfaces.

- *The US should take full advantage of the burning experiments in ITER, and examine how to expand these opportunities.*

- *The DEMO requirements for a high performance plasma go beyond ITER's goals, and the US should pursue a complementary DT facility with a more focused physics program.*

- *Any realistic DT facility will phase its missions to stage the DT core / edge / material interface plasma development, progressively approaching the final pre-DEMO configuration.*