# Interim FESAC Priorities Panel Report for

FESAC
Priorities
Macroscopic
Behaviour WG

**Gerald Navratil, Chair**
**Michael Zarnstorff, Vice-chair**

http://www.pppl.gov/priorities/macro/

Fusion Energy Sciences Advisory Committee
Gaithersburg, MD
26-27 July 2004

# Macroscopic Plasma Behavior WG Plan

- Use web-based format to iterate drafts with the community – GAN & MZ acting as Snowmass-like “facilitators” to consolidate comments and input primarily thru submitted web input from the community.
- Working Group mission and plans announced at Priorities Panel community discussion at TTF meeting in late April 2004.
- At ICC 2004 meeting May 25-28 in Madison, WI, a scheduled 3 hour session was held with the community (about 80 participants) to gather input on the structure and approach to the goals and research thrusts of the Macro Working Group.
- Web based working group has 39 registered members.

http://www.pppl.gov/priorities/macro/

# FESAC Priorities Macroscopic Behaviour WG

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Welcome to FESAC Priorities: Macro WG, navratil

Sunday, July 25 2004 @ 06:08 PM EDT

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**Monday** 26-Jul -
**Tuesday** 27-Jul
- Interim Report to FESAC

**Tuesday** 27-Jul -
**Wednesday** 28-Jul
- Priorities panel meeting

**Sunday** 01-Aug
- Final draft deadline

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Welcome to the Macroscopic Behaviour Working Group webpage!
This Working Group was formed by the FESAC Priorities Panel to develop, justify, and prioritize (relatively) research approaches to the following topical questions:

**T1: How does magnetic field structure affect plasma confinement?**
**T2: What limits the maximum pressure that can be achieved in the laboratory?**
**T3: How can external control and plasma self-organization be used to improve plasma confinement?**

Please login and contribute.

Lets use the forums for discussions and announcements (see 'Forum' above)

Note that you can specify that you want email notification of postings to the various Forums. Click 'Track this forum' in the upper right when looking at the various discussion Forums

Please email Mike or Jerry if additional Forums or Topics are needed.

## Drafts of T1, T2, and T3 posted for comment & revision

Wednesday, June 16 2004 @ 12:12 PM EDT
Contributed by: **navratil**

Drafts of topical questions T1, T2, and T3 have been posted for comment & revision. These incorporate input we received at the general discussion at the 2004 ICC Meeting and comments posted to date on this web site. Thanks to all of you for helping to structure this initial draft.

Please review these drafts and submit comments & suggested revisions.

1 comments

**Most Recent Post: 06/24 04:20PM by jarboe [ Views: 26 ]** Edit

## Guidelines uploaded as files

Tuesday, May 18 2004 @ 04:58 PM EDT
Contributed by: **zarnstorff**

the Research Approach Example and Guidelines have been uploaded as files.

Post a comment **[ Views: 6 ]** Edit

## Revised Interim Report Guidelines

Monday, May 17 2004 @ 02:30 PM EDT
Contributed by: **navratil**

Revised Guidlines for preparation of our groups Interim Report due June 11 have been issued by the FESAC Priorities Panel.

read more (257 words)

Post a comment **[ Views: 31 ]** Edit

## Example Research Approach

Friday, May 14 2004 @ 06:33 PM EDT
Contributed by: **zarnstorff**

This Example is from the FESAC Priorities Panel.

NOTE: This document is for illustrative purposes ONLY! Read it for

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  **On:** 06/24/04 12:56 PM
  **Views** 16 **Replies** 0
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  **By:** jarboe
  **On:** 06/24/04 13:06 PM
  **Views** 14 **Replies** 0
- **Draft v1.3 posted**
  **By:** zarnstorff
  **On:** 06/29/04 11:10 AM
  **Views** 40 **Replies** 3
- **Ch. 3 v5.0 posted**
  **By:** zarnstorff
  **On:** 06/24/04 04:19 AM
  **Views** 4 **Replies** 0
- **relaxation is more..**
  **By:** zarnstorff
  **On:** 06/17/04 23:48 PM
  **Views** 27 **Replies** 1

**Who's Online**

navratil

# Macroscopic Plasma Behavior WG Plan

## Registered members of the Macro Working Group:

Michael Zarnstorff
Gerald A Navratil
James F Lyon
Allan Reiman
Dale Meade
Martin Peng
Mickey Wade
Robert Granetz
Earl Marmar
Adil Hassam
Amanda Hubbard
Ted Strait
J. Manickham
David Gates
Ming Chu
Michael E Mauel
Darren Garnier
Joe Snipes
Jon Menard
Glen Wurden
Richard Milroy
Steve Wolfe
Ron Stambaugh
Cary Forest
Ray Fonck
Chuck Greenfield
Paul Bellan
Ron Miller
Jim Bialek
Darren Craig
John Sarff
Thomas Intrator
Tim Luce
Rob Goldston
Stewart Prager
Jim Van Dam
Ned Sauthoff
Rich Hawryluk
Tom Jarboe

**39 Total**

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FESAC Priorities Macroscopic Behaviour WG

# Macroscopic Plasma Behavior Theme

- Deals with the overall behavior of magnetically confined plasmas, including the effects of the magnetic equilibrium structure on plasma confinement (T1), the processes which limit the total pressure of a confined plasma (T2), and methods to improve the fusion performance by externally plasma control and use of the plasma nonlinear self-organization(T3).
- Macroscopic plasma behavior is due to the nonlinear interaction of the plasma with the confining magnetic field, electric fields, and plasma flows: these determine and are determined by, self-consistently, the cross-field transport and confinement time of the plasma, the presence of instabilities, and the generation of plasma currents.
- Interaction of the plasma and the fields determines the maximum pressure that can be reliably confined in a given magnetic field configuration, and thereby the fusion power that can be produced.
- Thus, understanding and controlling these phenomena in high pressure plasmas is crucial to developing our fundamental understanding of magnetically confined plasmas (O1), producing configurations that can confine a burning plasma (O2), and for developing practical fusion energy (O3).

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# Macroscopic Plasma Behavior Topical Questions

- T1. How does magnetic structure affect fusion plasma confinement?
- T2. What limits the maximum plasma pressure that can be achieved in the laboratory?
- T3. How can external control and plasma self-organization be used to improve fusion performance?

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FESAC Priorities Macroscopic Behaviour WG

# T1. How does magnetic structure affect fusion plasma confinement?

- The distribution of the magnetic field determines many critical properties of the plasma.
- Magnetic field topology, spatial shape, symmetry, helical pitch and shear are key factors in determining the confinement of the plasma energy, the limits on plasma pressure, the presence of instabilities, the local suppression of plasma turbulence, and the methods required to sustain the configuration.
- Varying the external distribution of the magnetic field is one of the most accessible and potent mechanisms for controlling the plasma behavior.
- Due to modification of the magnetic field by plasma current, there are several arrangements of the magnetic field that confine plasma and offer possible advantages for achieving practical fusion power.

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# T1. How does magnetic structure affect fusion plasma confinement?

- Understanding the effect of different field distributions is of fundamental importance (O1) and provides the basis for designing useful fusion systems. In particular, these characteristics are key to determining whether a plasma will burn (O2) and whether it will be economically attractive for producing power (O3).
- Many astrophysical phenomena (*e.g.* plasma confined in solar magnetic arcades, in jets emanating from plasma surrounding black holes, and in extra-galactic plasma confined in radio lobes) are critically influenced by magnetic field structures. These share common physics principles that can be productively studied in magnetically confined fusion plasmas (O1).

# Research Approach

## T1. How does magnetic structure affect fusion plasma confinement?

- Many variations of magnetic structure are compatible with plasma confinement and a large number has been studied theoretically and in past experiments. A number of configurations are being actively studied, with differing key magnetic structure characteristics, providing a suite for developing and validating our understanding of the underlying physics. The different magnetic configurations offer various natural advantages for fusion energy and to explore open issues that are not fully understood.
- To understand the roles played by the magnetic field in these configurations and to understand how to manipulate the field to accomplish the fusion energy objectives, research in a flexible set of experiments with promising magnetic geometries must be carried out and diagnosed at an adequate level so as to determine the role of the magnetic structure in confinement, stability, and sustainability.
- Theory and computation must be employed to guide and interpret experimental research and to put results from a specific configuration in a broader context.

# Research Thrusts

## T1. How does magnetic structure affect fusion plasma confinement?

### **T1-A.** Understand the role of plasma shaping on plasma confinement

Variations in plasma boundary shape (*e.g*. triangular cross-section, 3D shaping, and aspect ratio) strongly affects plasma stability and cross-field transport. Extensively studied in tokamaks and the spherical torus configurations, but a full theoretical understanding continues to be developed. The mechanisms by which the plasma confinement is modified by plasma shape are expected to be configuration dependent. While some theoretical predictions are available (e.g. theoretical predictions that 3D shaping can improve the plasma stability in stellarators), and have motivated particular experiments, understanding these effects in non-tokamak configurations remains to be investigated.

### **T1-B.** Understand the effect of magnetic structure within the plasma

The characteristics of the magnetic field inside the plasma also strongly affect plasma confinement. These include the topology of the magnetic field, the magnetic rotational transform (or safety factor), the local and global shear of the rotational transform, and the local curvature of the magnetic field. These internal characteristics depend on the distribution of pressure and current within the plasma, as well as the externally imposed magnetic fields, and have a direct effect on the local stability and cross-field transport properties of the plasma. The significance of these effects has been demonstrated in all configurations, but predictive understanding in all but the major configurations under study remains limited

### **T1-C.** Understand the effect of self-generated currents.

In some configurations, such as the RFP or AT, a significant portion of the magnetic field is self-generated by the plasma. This includes the effects of plasma dynamos, the pressure driven currents, and reconnection of externally injected magnetic helicity. In addition, in all plasma configurations with large normalized plasma pressure (beta) the pressure-driven diamagnetic current can modify the magnetic field. In these cases, the non-linear effect of the plasma-generated currents can modify the magnetic equilibrium geometry and topology, and provide an additional source of energy for instabilities. This can result in either positive or negative effects on plasma confinement. Understanding these effects and developing methods to avoid or control them is crucial for a successful burning plasma experiment. Understanding and control of these effects is crucial for achieving practical fusion energy using the Advanced tokamak, RFP, and ST configurations. These effects may not be so important for stellarators and other configurations dominated by external control, but they have not yet been explored.

# T2: What limits the maximum plasma pressure that can be achieved in the laboratory?

- The energy in a confined plasma can be released through one or more of the many degrees of freedom in a magnetized plasma and sets limits on the maximum pressure than can be confined.
- Fusion reactivity and power production depend roughly as the square of plasma pressure: understanding what plasma phenomena set these limits and how to optimize the magnetic configuration and/or to extend these limits through active control of these limiting phenomena, is critical to the study of burning plasma (O2) and making practical fusion energy (O3) since
- The theoretical framework to characterize and predict these pressure-limiting phenomena has been a principal driver for fundamental understanding of plasma physics (O1) with application both to confined plasmas in the laboratory as well as natural plasma systems in astrophysics.

# Research Approach

## T2: What limits the maximum plasma pressure that can be achieved in the laboratory?

- The basic sources of free energy that can be tapped by pressure limiting phenomena in a confined plasma are: (i) the thermodynamic energy stored in the plasma pressure itself which can be released by expansion of the plasma volume, and (ii) the energy stored in the magnetic fields generated by electric current flowing in the plasma.

- A substantial base understanding of the pressure limiting phenomena driven by these two free energy sources has been developed over the past 50 years of plasma physics research. However, further advance in our fundamental understanding is required to achieve the overarching goals.

- Advances are required both in quantitative predictive understanding of the basic phenomena as well as in the means by which these phenomena can be passively or actively controlled or their consequences mitigated: an integrated effort in experiment, modeling, and theory is necessary.

- Control of these phenomena is integral to developing understanding.

# Research Thrusts

## T2: What limits the maximum plasma pressure that can be achieved in the laboratory?

### **T2-A.** Long scale-length electromagnetic phenomena characterized by the system size.

This thrust is directed at understanding and control of long scale length in two basic manifestations: (i) the release of free energy through long scale length displacements of the equilibrium fields (internal and external) resulting in the loss of the system through contact with the surrounding material structure; and (ii) the release of free energy through the reconnection of magnetic flux surfaces inside the confined plasma resulting in loss of plasma pressure and in some cases the loss of plasma equilibrium.

### **T2-B.** Short scale-length electromagnetic phenomena characterized by the Larmor radius.

This thrust is directed at understanding and control of shorter scale length pressure limiting phenomena down to the Larmor radius scale size. These local phenomena do not destroy the global plasma equilibrium, but rather set local maximum values of the allowed local pressure gradient thru enhanced transport or through cyclic relaxation processes, and hence limit the maximum value of plasma pressure.

### **T2-C.** Equilibrium limits and the onset of magnetic stochasticity.

The plasma pressure is limited by ability of the external coils to maintain a suitable magnetic equilibrium with the magnetic field lines confining the plasma do not intersect the surrounding structure. In magnetic fields with a continuous symmetry (e.g. axisymmetric toroidal configurations), these limits are well established and are set by the geometry and strength of the external magnetic fields. In fully three-dimensional magnetic fields or in magnetic fields produced by turbulent self-organization, the equilibrium pressure limits are not established or understood. In these cases, the magnetic field could develop island structures or become stochastic, due to the plasma pressure-driven current, leading to a significant loss of plasma energy. The maximum pressure is thus determined by the non-linear response of the plasma to local changes in the magnetic field topology. This is very challenging to diagnose experimentally or model theoretically.

# T3: How can external control and plasma self-organization be used to improve fusion performance?

- All confined plasmas exhibit a combination of externally applied magnetic and electric fields (external control) together with plasma generated magnetic and electric fields generated by the plasma current, pressure gradient, and mass flow (self-organization).
- The plasma current, pressure gradient, and mass flow are determined by the sources (of current, heat, or momentum) and the local transport processes, which depend on the magnetic structure.
- Heating in a burning plasma is dominated by fusion produced alpha particles, which adds an important new nonlinear element to the complex interaction between external control and self-organized behavior of the plasma.
- The degree to which self-organized phenomena dominate the plasma behavior varies with magnetic configuration. Optimizing desirable aspects of self-organized behavior (*e.g.* efficient steady-state current drive, simplified external coil geometry, or high plasma pressure limits relative to magnetic field strength) in combination with desirable aspects of external control (*e.g.* steady-state external fields or improved equilibrium stability or greatly improved particle-orbit confinement or RF driven flows) offers several options for improved fusion power systems that are critical to achieving the goal of practical fusion energy.

# Research Approach

## T3: How can external control and plasma self-organization be used to improve fusion performance?

- Three primary drivers of confined plasma self-organization on a macroscopic plasma scale are the plasma pressure gradient, the magnetic turbulence driven (dynamo) plasma current, and large-scale plasma flows (or radial electric fields).
- On a fundamental level the plasma pressure gradient and mass flow are determined by sources of heat, particles, and momentum, and the local transport processes being explored in response to topical questions T4 and T5, and magnetic dynamo driven by magnetic reconnection and turbulent fields being explored in response to topical questions T5 and T6.
- The research approach for topical question T3 focuses on the interplay between external control and global self-organizing effects of these basic phenomena on the macroscopic plasma equilibrium and their impact on improved fusion energy performance.
- The goal of T3 is to understand these mechanisms and their potential to improve fusion performance.

# Research Thrusts

## T3: How can external control and plasma self-organization be used to improve fusion performance?

### **T3-A.** Understand and control pressure gradient driven plasma currents and flow self organization.

In all magnetically confined plasmas the pressure gradient driven electric currents and mass flows will modify or sustain the equilibrium confining magnetic fields as the plasma pressure is increased. This thrust seeks to understand and use these self-driven currents and mass flows to improve fusion energy performance of the confined plasma with emphasis on achieving ‘steady-state’ high pressure confined plasmas or confined plasmas with relatively high pressure and simplified external equilibrium field coil structure.

### **T3-B.** Understand the use of dominant external control.

In conjunction with plasma self-organization, the imposition of external control through (i) shaped external magnetic fields imposing symmetry or local stochastic symmetry breaking or (ii) through driven mass flows and electric fields, can lead to ‘steady-state’ equilibria, plasma flow through symmetry effects, improved single particle confinement, or enhanced stability at high pressure. This research thrust is directed at advancing our understanding across a broad class of external control approaches ranging from application of 3D quasi-symmetric equilibrium magnetic fields, application of a strong external dipole equilibrium magnetic fields, and application of strong externally applied electric fields or torques to produce equilibria with dominant ExB mass flow.

### **T3-C.** Understand and control magnetic dynamo driven plasma current self organization.

Confined plasmas seek to expend their stored energy so as to approach a ‘minimum energy’ state, and can excite long scale length MHD turbulence which can maintain the equilibrium magnetic field by the conversion of momentum or magnetic flux into sustaining plasma current. The existance of these ‘dynamo’ processes that sustain planetary and astrophysical magnetic fields are well established. Similar phenomena have been found to sustain laboratory confined plasmas of the reversed field pinch and spheromak configuration, which operate near to a magnetic ‘minimum energy’ state. This research thrust seeks to understand and use this self-organized sustaining current to maintain high-pressure plasmas with relatively weak externally supplied confining magnetic field.

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