White Paper for *Frontiers of Plasma Science Panel*

Date of Submission:	***6/18/2015***

Indicate the primary area this white paper addresses by placing "P" in right column.
Indicate secondary area or areas by placing "S" in right column

	"P", "S"
• Plasma Atomic physics and the interface with chemistry and biology	
• Turbulence and transport	P
• Interactions of plasmas and waves	
• Plasma self-organization	S
• Statistical mechanics of plasmas	

Indicate type of presentation desired at Town Hall Meeting.

	"X"
Oral	X
Poster	
Either Oral or Poster	
Will not attend	

Title:	The physics of unity beta plasmas
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**(Limit text to 3-pages including this form. Font Times Roman size 11.
1 page of references and 1 page of figures may also be included. *Submit in PDF format*.)**

- ***Describe the research frontier* and importance of the scientific challenge.**

The neutron fusion power in tokamaks goes as[1]

$$P_n(MW) = 100B(T)^4R(m)a(m)^2\kappa\beta^2$$

where B is the strength of the toroidal magnetic field, a is the plasma minor radius, R is the plasma major radius, κ is the elongation factor and β is the ratio of kinetic pressure to magnetic pressure. One can clearly see from this formula that fusion power can be split into two factors. The first factor $B^4Ra^2\kappa$ encapsulates all engineering parameters. Improving fusion performances by increasing this factor is costly. For a fixed-size machine, increasing B would require superconductors with larger critical current densities and critical magnetic fields. Increasing Ra^2 would make the tokamak so large that construction and maintenance are impractical. Increasing κ beyond 2 would trigger vertical plasma instabilities difficult to control. As of today, ARIES-AT[2] embodies already a well optimized *engineering* factor. The plasma physics associated with these machines is a well-established, yet still open, area of fusion research. However, the other factor, β^2, represents the challenge in attaining a stable, high performance plasma. This white paper addresses a relatively unexplored regime where beta approaches unity.

In tokamaks, unity beta regimes can only be reached if the current density profile is not symmetric[3]. The immediate result is the existence of a magnetic well. Such equilibriums are stable to major ideal MHD modes[4], including internal *and* external kink modes, according to DCON[5]. An example of stable unity-beta equilibrium for ITER is presented in Figure 1 and Figure 2, together with a standard ITER equilibrium. The unity beta equilibrium has an average beta of 0.13 and a peak beta of 1. The standard equilibrium has an average beta of 0.03 and a peak beta of 0.1. While many different current profiles[6] reach unity-beta, this equilibrium was chosen because it can be evolved from a current-hole equilibrium[7]. Note that the unity-beta equilibrium presented here is not a current-hole equilibrium since there is a pressure gradient inside the region where the toroidal current density is zero.

The physics of strongly magnetized plasmas in the unity-beta regime is actually quite different from the low-beta regime. Beyond tokamaks, reversed-field pinches (RFP) and stellarators are also possible candidates where unity beta equilibriums can exist. Regardless of the device, the physics of unity-beta plasmas is largely unexplored. Changes in the magnetic field topology and dynamical effects now play a major role:

- Geometrical effects:
  - Large Shafranov shifts
  - Very good average curvature
  - Short connection length
  - Magnetic well
- Dynamical effects:
  - Modified drift velocity
  - Magnetic fluctuations become important
  - Modified parallel electrostatic field from non-negligible inductive electric field
  - Modification of electrostatic instabilities such as ion and electron temperature gradient instabilities and trapped electron modes
  - New instabilities such as kinetic ballooning modes and micro tearing modes

This new physics clearly show the wealth of exciting discoveries awaiting scientists working in unity beta research, a field truly at the frontier of plasma science. In our opinion, our understanding of the physics of strongly magnetized plasmas faces two distinct grand challenges:

1. *Can unity-beta equilibriums be produced and studied experimentally in existing devices (tokamak, RFP, stellarator…) and are these equilibriums stable to ideal and resistive MHD instabilities?*
2. *What is the impact of unity-beta effects on turbulence and particle/energy transport?*

- ***Describe the approach to advancing the frontier and indicate if new research tools or capabilities are required.***

On the experimental side, the study of unity-beta plasmas could be first undertaken in machines with conductive shells (e.g. Madison Symmetric Torus at the University of Wisconsin Madison, the High Beta Tokamak at Columbia University). The shell reduces the constraints on MHD stability (e.g. external kink modes). This approach allows flexibility in tailoring equilibriums to study a particular physics direction rather than being limited by stability considerations. Building on the experience of present facilities, the next step would be a dedicated machine where unity-beta research would be integrated with other exploratory magnetic confinement research. A specific effort should focus on developing new techniques to generate and sustain unity-beta equilibriums:

- Since these equilibriums rely on poloidal currents to equilibrate the pressure gradient, poloidal current drive schemes are required.
- Rapid fueling and heating systems are also needed. To avoid large plasma disturbances many low energy fueling and heating drivers homogenously distributed throughout the machine are preferred to a single localized high power driver. The Shafranov shift in unity-beta equilibriums does bring the magnetic axis closer to the outboard side, alleviating some energy constraints on these drivers.

Diagnostics development is also required and will benefit our understanding of both low-beta as well as unity-beta plasma research:

- Stability:
  - Current profile measurements are key to MHD stability and at the heart of finding a path to stable unity-beta equilibriums. Motional stark effect (MSE) may not be able to reach the center of unity beta discharges. New techniques to increase MSE precision and penetration depth are required.
  - Resistive wall mode measurements are also required to reduce the risks of MHD instabilities. Instability mitigation techniques using external coils may be necessary to sustain unity-beta equilibriums
- Confinement and transport:
  - Large shear will generate large zonal flows. Techniques to measure such flows are not fully mature. Yet, they are an important part of turbulence suppression and they will be surely important in reducing transport at unity beta.
  - While turbulent ion transport is different in unity and low betas, existing techniques can be used to study it in both type of discharges. However, electron transport is not yet resolved by present techniques. High k fluctuation diagnostics need to be developed.
  - Ion temperature fluctuation measurements are crucial to our understanding of ion turbulence and should be developed
  - We expect magnetic fluctuations to also have an important role on transport. Measurements at low and high wavenumbers are necessary.
  - High resolution turbulence imaging is also required. Improvements of existing techniques such as beam emission spectroscopy or correlation radiometry of electron cyclotron emission are paramount.

On the theory side, fast equilibrium, stability and transport codes are required not only to formulate new unity-beta equilibriums but also to interface with real-time feedback systems controlling the stability of unity-beta plasmas. Fast and robust two fluid magnetohydrodynamic codes should also be developed to look more carefully at the macroscopic implications on the electron channel in mass, energy and momentum transports. Finally gyro-kinetic theory should be developed to capture better the turbulent regimes present in low-beta and unity-beta discharges.

- ***Describe the impact of this research on plasma science and related disciplines and any potential for societal benefit.***

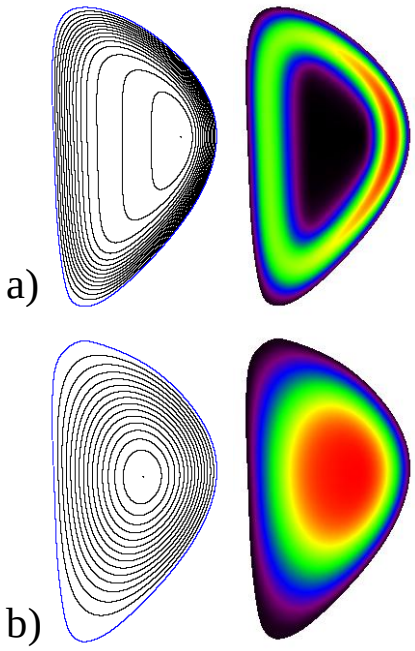
Tokamak, RFP and stellarators are ideally suited to study plasma turbulence and transport due to their large size. This is a tremendous advantage over smaller, higher density plasma devices where turbulence and fluctuations are too small to resolve. For instance, the knowledge of transport and turbulence at large beta (>1) is important to other fusion scheme such as MagLIF[8]. Astrophysical plasmas have large beta (>1) and are turbulence dominated. Here again insight in unity-beta regimes will prove crucial in understanding celestial dynamics. Unity-beta devices can definitely improve our understanding of turbulent regimes at unity-beta.

Further, unity-beta equilibriums are ITER relevant. While ITER does not plan on using unity-beta scenarios to reach the 500 MW fusion target, the possible degradation of the Nb_3Sn cable may force ITER to run at lower fields during the D-T campaign. A reduction in 10 % of magnetic fields would result in a drop of 40 % in fusion power, according to the equation presented in our introduction. The only possibility to reach nominal fusion power in this conditions is to increase the plasma beta by 20 %. This cannot be done with symmetric current profiles, which are Troyon limited[9].

References (Maximum 1 page)

[1] K. Myamoto, Fundementals of plasma physics and controlled fusion, Iwanami Book Service center, p.306, Tokyo (1997)
[2] F. Najmabadi et al., Fusion Engineering and Design **80**, 3 (2006)
[3] P.-A. Gourdain, J.-N. Leboeuf, R. Y. Netches, Phys. Plasmas **14**, 112513 (2007)
[4] P.-A. Gourdain, J.-N. Leboeuf, Phys. Plasmas **16**, 112506 (2009)
[5] A. H. Glasser, The direct criterion of Newcomb (DCON) for the stability of an axisymmetric toroidal plasma, Los Alamos Report LA-UR-95-528, 1997
[6] S. C. Cowley, P. K. Kaw, R. S. Kelly, R. M. Kulsrud, Phys. Fluids B 3, 2066 (1991)
[7] T. Fujita, Nucl. Fusion **50**, 113001 (2010)
[8] S. A. Slutz, M. C. Herrmann, R. A. Vesey, A. B. Sefkow, D. B. Sinars, D. C. Rovang, K. J. Peterson and M. E. Cuneo, Phys. Plasmas **17**, 056303 (2010)
[9] F. Troyon, R. Gruber, H. Saurenmann, S. Semenzato, and S. Succi, Plasma Phys. Contr. Fusion 26, 209 (1984)

Figures (maximum 1 page)



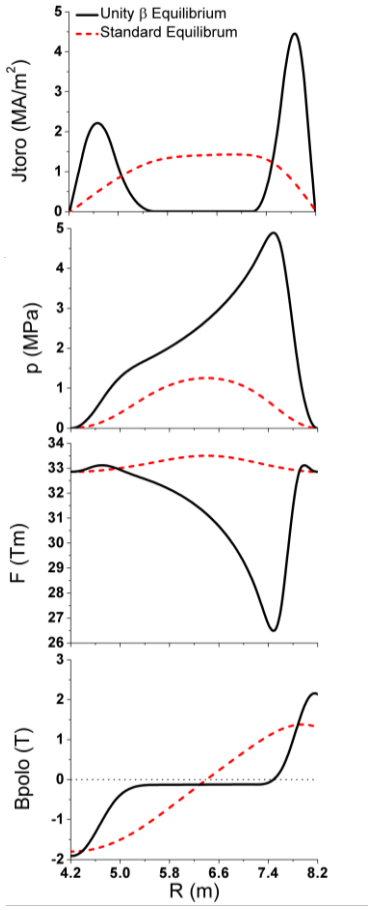


Figure 2. a) Unity beta (dual) equilibrium and b) standard equilibrium flux surfaces (left) and toroidal current distributions (right) for ITER.

Figure 1. Current, pressure, toroidal function and poloidal field profiles for the standard and unity beta equilibriums presented in Figure 2. Both equilibriums have