Compatibility of Physics and Engineering in Magnetic Fusion
White Paper on Magnetic Fusion Priorities

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The compatibility of the requirements of physics and engineering is the fundamental issue in the achievement of useful magnetic fusion energy. Issues that must be addressed include:

- Control of the location of the steadystate power loading on structures.
- Avoidance of sudden, large, and localized power and force loads.
- Maintenance of the magnetic configuration for an adequate time period.
- Limitations on the diagnostics and actuators in the fusion environment for use in feedback control.

Freedom in the physics design can be used to circumvent these issues, which could otherwise provide insurmountable difficulties of engineering.

The equilibrium of a fusion plasma is determined by (1) the externally produced magnetic fields, (2) the plasma pressure profile, and (3) the profile of the net current flowing along the magnetic field lines within the plasma. In a fusion plasma, the last two of these are largely self-determined, so the freedom of physics design is primarily in the externally produced magnetic field.

The primary freedom in the physics design of fusion plasmas, the external magnetic field, is limited by engineering constraints on the coils that produce that field:

- Coils must be separated from the plasma by approximately 1.5m to allow room for blankets and shields.
- The magnetic field at the coils is a measure of engineering difficulty while the field at the plasma provides benefits, so this ratio must be kept small.
- Adequate maintenance access to the core of the fusion device can be prevented by the coils.

Engineering constraints on the coils coupled with the divergence and curl free nature of the magnetic field between the coils and the plasma, $\vec{B} = \vec{\nabla}\phi$ with $\nabla^2\phi = 0$, determine the design freedom with remarkable clarity. Laplace's equation, $\nabla^2\phi = 0$, determines the matrix that relates the Fourier components of $\vec{B}\cdot\hat{n}$ on a toroidal surface on the plasma side of the coils to the Fourier components of $\vec{B}\cdot\hat{n}$ on a toroidal surface just outside the plasma. A decomposition of this matrix allows an efficiency ordering of the various spatial distributions of $\vec{B}\cdot\hat{n}$ on the plasma surface by the strength of the required magnetic field at the coils with each distribution in the ordering requiring exponentially more field at the coils than its predecessor. The low order distributions require not only a relatively weak field be produced by the coils but are also consistent with smooth coils since the required fields at the coils vary slowly through space.

Approximately ten times as many non-axisymmetric external magnetic field distributions, ~ 50, are consistent with distant coils than axisymmetric distributions. Non-axisymmetric fields are also required for an externally produced rotational transform and robust, passive vertical stability of the plasma.

Methods of easing the limitations of coils on maintenance access are defined by Laplace's equation, $\nabla^2\phi = 0$. In a torus, solutions have the general form $\phi = \mu_0 G_0 \varphi/2\pi + \phi_s$, where G_0 is the current in coils that encircle the plasma poloidally, φ is a toroidal angle, and ϕ_s is a single-valued function of position, which is determined by $\vec{B}\cdot\hat{n}$ on a toroidal surface on the plasma side of the coils. In principle, only one coil has to encircle the plasma poloidally to produce G_0. Otherwise, the magnetic field can be produced by easily demountable windowpane coils or even magnetic materials such as superconducting tiles. High-order external magnetic field distributions in the efficiency ordering are too weak at the plasma to have a significant effect and can have any amplitude at the coils that improves the design. Enormous unexplored design freedom exists in the coils that produce the external magnetic field.

An understanding of the constraints on the engineering of magnetic fusion systems requires an understanding of the plasma effects of all of the external magnetic distributions. Even within the constraint of nominally axisymmetric configurations, the required accuracy of construction, which is thought to be $\delta B/B \lesssim 10^{-4}$, is determined by the plasma response to non-axisymmetric fields.

The United States has traditionally had a leadership role in plasma design using external magnetic fields—particularly non-axisymmetric fields. Most Americans with expertise in this area are over 60, and a number have recently retired. Funds required for even a robust theoretical/computational program, ~ 5 M\$/yr., have not been available. Experiments with a construction cost of a few hundred million dollars apiece, $\sim$10% of the U.S. contribution to ITER construction, will be required to clarify the sensitivity and effectiveness of various magnetic field distributions for plasma control.