**Effect of Toroidal Field Ripple on Edge Confinement**

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## Physics Issues

While the tokamak was conceived as an axisymmetric device, in the "real world" the toroidal magnetic field lines will have undulations, referred to as ripple. There will be two main sources of the toroidal field ripple in ITER. First, the toroidal magnetic field is created by a finite number of toroidal field coils with spaces between them large enough to accommodate ports. The toroidal field ripple from this source will have a high toroidal mode number, equal to the number of toroidal field coils. Use of ferrite inserts underneath the toroidal field coils can mitigate the amplitude of this ripple for a predetermined magnetic field strength. Second, when the test blanket modules (TBM) are installed, their ferromagnetic materials will significantly perturb the local toroidal field. Since the TBM will be grouped together in one section of ITER, the toroidal field ripple from this source will have low toroidal mode numbers, peaked at $n$=1.

Regardless of the source of the toroidal field ripple, it will have two main effects on the transport and confinement of thermal particles. (Note that the effect of ripple on energetic particles will be considered in a separate white paper.) First is the effect on the toroidal rotation. The loss of fast and thermal ions can induce counter-current rotation. Additionally, non-axisymmetric magnetic fields in tokamaks induce a drag force on the plasma toroidal rotation. It is well known that the effect of slowing the toroidal rotation is to increase the transport and reduce the confinement because the E×B shearing rate is decreased. In the worse case, a non-axisymmetric field can cause the plasma rotation to lock to the static field, which usually results in a significant loss of confinement and may lead to a disruption.

The second main effect of toroidal field ripple is to decrease the pedestal height of H-mode plasmas, as seen on JT-60U and JET. If transport is very stiff, this will lead to a reduction in the global confinement time of the plasma. The reduction in the H-mode pedestal height may be related to the reduction in toroidal rotation discussed in the previous paragraph, but it may also be due to the ripple making the edge plasma more stochastic. There appears to be a similarity in this regard between toroidal field ripple and external coils that apply a resonant magnetic perturbation to the plasma edge.

The physics issues are to determine the maximum levels of toroidal field ripple due to either (1) the finite number of toroidal field coils, and (2) the TBM that can be tolerated by ITER and still allow it to accomplish its fusion power and steady-state missions.

## Research Requirements

- Develop a model of ripple induced losses of energetic and thermal particles, and ripple induced toroidal rotation and/or drag. Validate this model by scanning the toroidal field ripple and measuring the change in:
  - Toroidal rotation and drag force.
  - Local transport and global confinement time.

- H-mode pedestal height and width.

  These experimental results also can be used to make empirical predictions for ITER.

- All of the previous experiments should be done for (1) strong torque injection with directional NBI, and (2) weak torque injection, preferably with rf heating. The experimental conditions, expressed as normalized parameters, and plasma shape should be as close as possible to the expected ITER values, and the expected ripple range in ITER should be covered.
- Determine whether the toroidal field ripple effects measured above have any dependence on the relative gyroradius or collisionality, as these dimensionless parameters will vary the most between present-day tokamaks and ITER.

Research Thrusts

The main facility requirement is the ability to vary the toroidal field ripple. For high-*n* periodic ripple, the ideal method is to separately power alternating toroidal field coils. This capability is availably only on JET; it is probably not feasible to add this capability to other tokamaks. Therefore, involvement of JET in this research thrust is important. Other tokamaks can vary the high-*n* toroidal field ripple by changing the outer gap, but the maximum ripple is limited by the value at the outer limiter. Previous experiments on JT-60U can contribute information on the use of ferritic steel inserts.

For low-*n* periodic ripple, new facilities are more feasible. The most promising way to mock up the $n$=1 ripple from the TBM is to add localized external coils in one section of the tokamak. The coil design should reproduce the expected TBM error field as closely as possible. Since this is a powered coil, varying the strength of the ripple will be straightforward. An alternative is to use ferritic materials in one section of the tokamak in the same manner as the TBM itself. However, this is not as desirable as active coils because the level of toroidal field ripple cannot be easily changed.

The research requirements do not need any special diagnostics. As for heating sources, it is desirable for an experimental facility to have both strong directional NBI for high torque injection and strong rf heating for low torque injection. (Balanced NBI also has low global torque injection, but the local torque density may be significant.) Using the tools described in this section, both national and international campaigns should be undertaken to do the experiments listed in the research requirements section. These campaigns should be coordinated with the USBPO and ITPA pedestal groups.