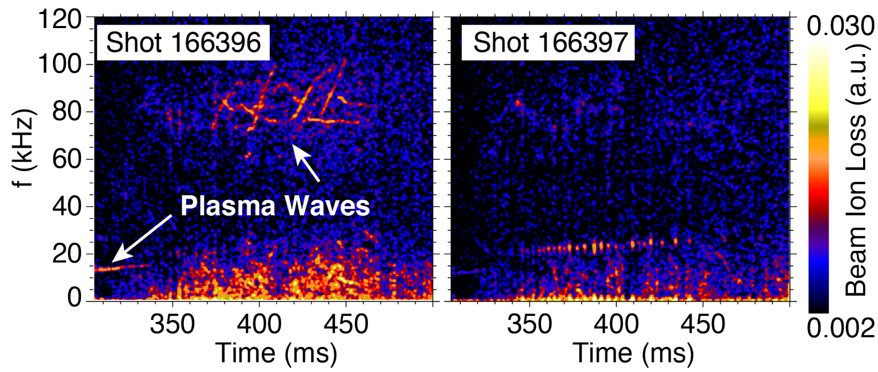
Unique Particle Beams Bring Plasma Control and Fusion Experiments to New Heights

Immensely powerful particle beams are used in magnetically confined fusion devices around the world to provide heating, current drive, and diagnostic capability. Scientists and engineers at the DIII-D tokamak have recently succeeded in developing an entirely new way of operating their beam system by varying its parameters during the approximately 6 second plasma shots and, in the process, demonstrating unprecedented control of plasma behavior. The neutral beam system injects up to 20 MW of power, equivalent to the power use of about 15,000 homes. Changing the ways in which this system operates is a significant effort, especially considering the size and complexity of each beam system, and the scale of one of the neutral beam housings is shown in the photo to the right (there are four housings and a total of eight beams at DIII-D).

Members of the DIII-D Neutral Beam Group stand in front of a beam housing. This section neutralizes ions that then pass onward to the tokamak, while also capturing the ions that fail to neutralize.

Up to now, neutral beams have operated by accelerating ions through a large (and fixed in time) voltage and then passing them through a dense gas such that some of them neutralize and reach the tokamak plasma. These fixed acceleration voltages reach values up to 90,000 Volts in order to maximize the resulting ion velocity (i.e., the injected neutral after it ionizes in the plasma) and, therefore, the beam heating power. Experiments in recent years have shown, however, that the velocity of the beam ions can cause those ions to produce or amplify electromagnetic plasma waves that then kick the ions into the walls of the tokamak. This presents a dilemma because high beam power is necessary to produce relevant plasma temperature for experiments, but the beam ion loss both reduces the plasma temperature and can lead to costly damage along the tokamak walls.

Varying the beam voltage, or energy, in time allows for both a reduction of beam ion losses due to plasma waves and the maximization of input beam power. As the plasma is produced, heated, and evolving in time, the behavior of the plasma waves changes such that ions of different velocities interact with them. The DIII-D neutral beams can be given preprogrammed energy profiles that ensure the wave-ion interactions are minimized. The beam ion energy is then increased to maximum values when interactions are precluded due to other plasma effects. An example of reduced plasma wave activity is shown below. This experiment involves two shots with the same plasma parameters and, importantly, the same total neutral beam power of 6 MW. The shots differ in the time evolution of the energy as the four injected beams vary between 55 and 75 kV. The resulting spectrograms come from measurements of beam ions hitting the wall, so any strong fluctuations indicate that a plasma wave is ejecting the ions. The left plot shows many coherent plasma waves, while the companion shot on the right features a great reduction in wave activity. These promising initial results motivate additional experiments aimed at developing optimum beam energy profiles in other plasma scenarios of interest.



*Spectrograms of measured beam ion loss. Both plasma shots feature the same total beam power of 6 MW, but the shot shown on the right utilizes a beam energy program that greatly reduces the amplitude of coherent plasma waves.**

Another benefit realized through this engineering development is that plasma control is improved. The beams affect plasma rotation by applying a torque, and low torque scenarios are important to understand since future tokamak reactors will have considerably less torque input than existing machines. Previously, DIII-D experiments varied the beam torque by turning the beams on and off rapidly (e.g., in 5 ms segments), with the undesirable result that the beam power (and plasma temperature, etc.) is also modulated. Controlled changes in the beam energy allow for continuous variation and control of the beam injected torque. This technique has been demonstrated* across a range of low torque values, including 0 N-m, that are relevant to reactor-scale tokamaks such as ITER.

Future work will extend the energy range and speed of the neutral beam system. DIII-D experiments will then be capable of applying this new technique to a range of plasmas, taking advantage of the control and diagnostic opportunities it provides. Ultimately, these experiments are intended to unravel some of the physics mysteries behind wave-ion interactions and other plasma behaviors in fusion relevant regimes.

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*D.C. Pace, et al., Nuclear Fusion (2016, *submitted*)

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

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