PPPL digest
PRINCETON PLASMA PHYSICS LABORATORY
A United States Department of Energy Facility
JULY 2006

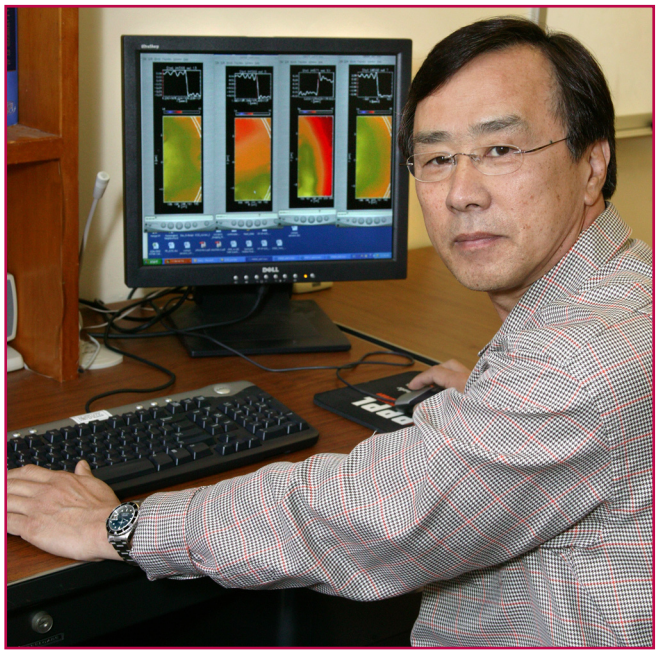
PPPL Collaboration Yields Important Fusion Science Advance

In two back-to-back *Physical Review Letters*, and a full article in *Physics of Plasmas*, all published in May 2006, Princeton Plasma Physics Laboratory (PPPL) physicists, along with colleagues from the Netherlands and California, report the first two-dimensional images of local electron temperature fluctuations during the crash time of the so called 'sawtooth' instability — one of the most important and familiar plasma phenomenon. The sawtooth instability has never been adequately described, even with the most advanced computer simulations. The experimental work was performed on the TEXTOR device, a tokamak located at the Forschungszentrum Jülich, Germany.

"The history of the sawtooth instability is as long as that of tokamak plasma research," according to PPPL physicist Hyeon Park, who is the lead author of the *Physical Review Letters*, one reporting experimental results and the other reporting the impact of these results on the theoretical modeling of the m/n = 1/1 mode (resistive kink instability). "The sawtooth oscillation in high temperature toroidal plasmas is the repetitive growth and decay of the core plasma pressure and/or core current through a driven magnetic reconnection process," he noted. (See Figure 1 on page 2) The work of Park and his colleagues revealed definitively the detailed dynamics of this process in the core of tokamak plasmas. Such insight has not been available until now and may lead to the ability to control and manipulate the instability, substantially benefiting the performance of future fusion reactors such as ITER.

Magnetic Reconnection

The sawtooth instability in the core of the tokamak plasmas involves magnetic reconnection — the topological change of the magnetic configuration in a plasma through the breaking and rejoining of magnetic field lines. The magnetic reconnection process has been observed in laboratory plasmas, as well as in those comprising solar flares and those in interstellar space. In particular, recent observations



Hyeon Park

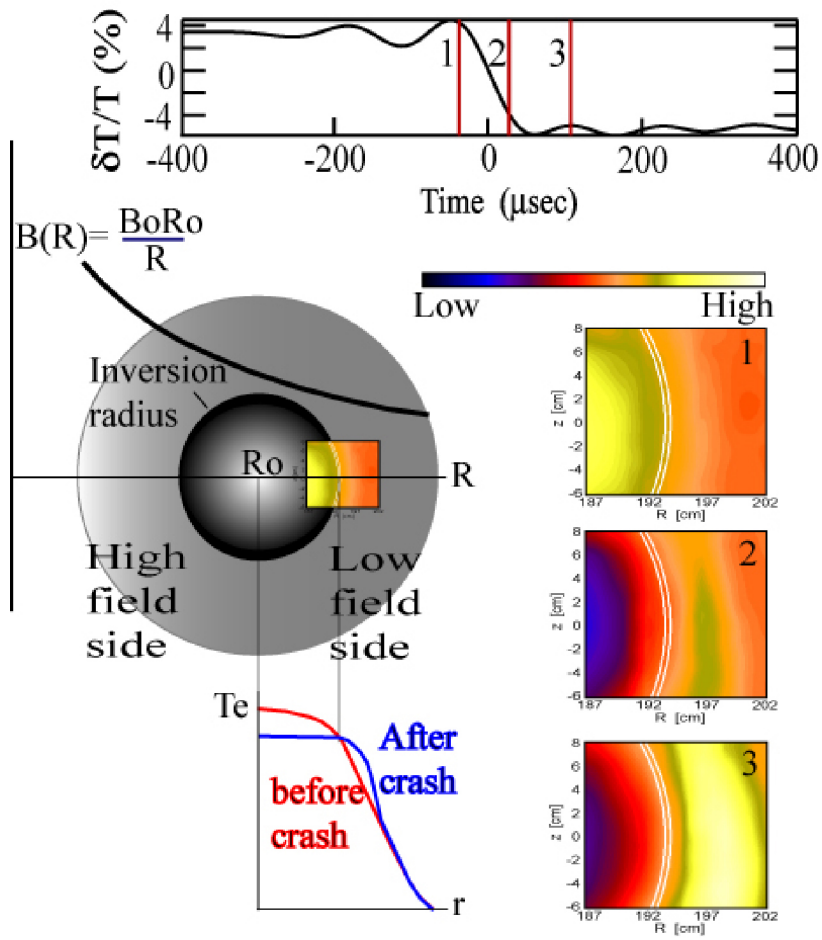


Figure 1. The schematic of core temperature profile changes along with the poloidal cross-section of the toroidal plasma and the time history of the electron temperature at z = 0 and R = 187 cm are provided. Two-dimensional composite images of electron temperature fluctuations during the sawtooth crash phase are shown with the poloidal view of the plasma. (1) Partial image of the hot spot before the reconnection corresponds to a peaked profile of the electron temperature; (2) Transient image taken in the middle of the reconnection process; (3) Image after the reconnection is completed, corresponds to a flattened temperature profile.

of sawtoothing radio frequency emissions from solar flares suggest that the physical mechanism underlying this behavior may be universal in current carrying toroidal plasmas. During the crash, the nested magnetic field ruptures in the core of the plasma, and stored plasma energy abruptly bursts out to the periphery. Amelioration and control of this non-benign disruptive behavior in its early stage is important, because it can grow further and can lead to a catastrophic end of the entire discharge, or can disrupt the flow of particles (fueling and ash in fusion devices). Consequently, understanding of the sawtooth oscillation in these plasmas will be highly beneficial for solar and interstellar physics, as well for optimizing the control of magnetic fusion devices such as ITER.

There are numerous physical models and supporting experimental observations that describe the underlying magnetic reconnection process of the sawtooth crash from first principles to explain the changes in magnetic topology during the crash time. The fundamentals of the magnetic reconnection processes have been studied in the laboratory with sophisticated probes that can be inserted into the plasma. These probes produce remarkable two-dimensional and even three-dimensional images of the reconnection processes. However, in the core of the tokamak plasmas, such tools are not available. Con-

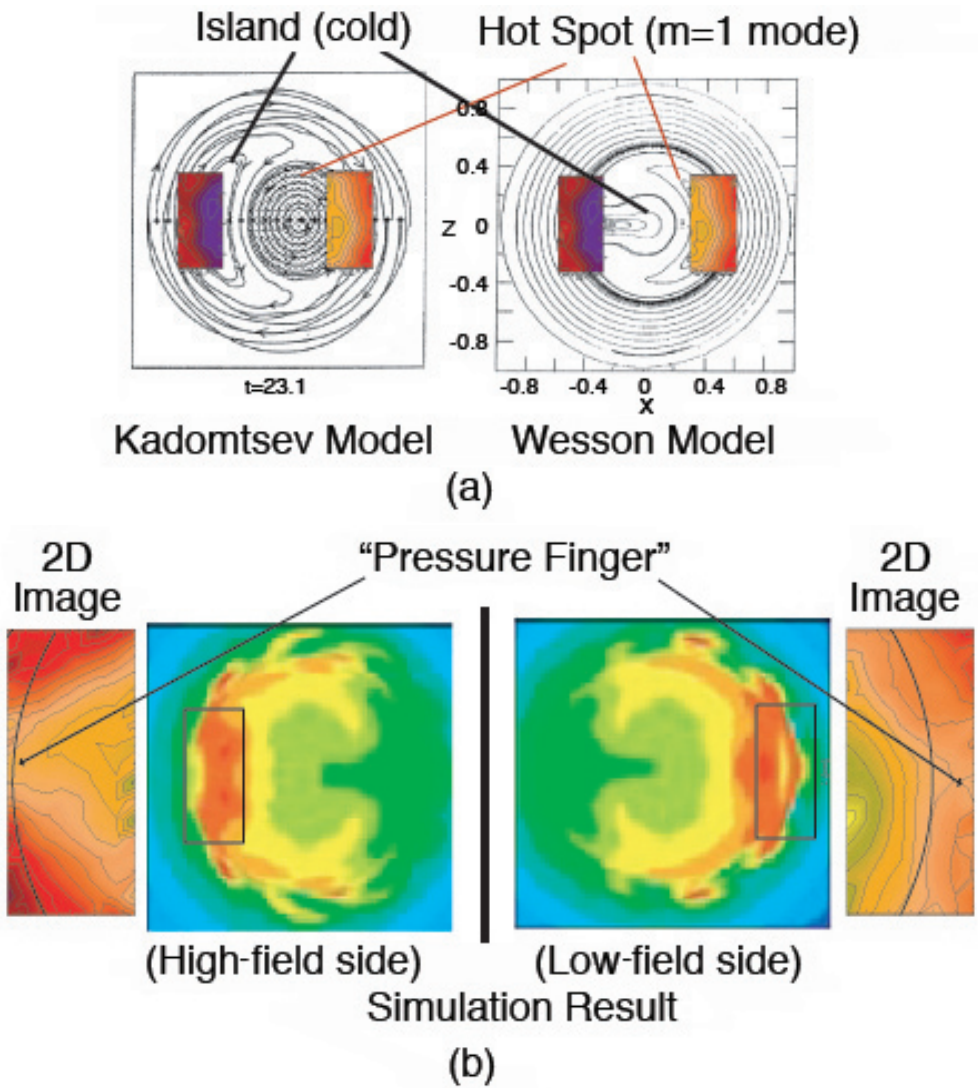


Figure 2. (a) Experimental two-dimensional images of the hot spot and island formations are overlaid for comparison on the two-dimensional line patterns from the full reconnection model developed by Kadomstev and the quasi-interchange model developed by Wesson. (b) The two-dimensional frames of the high- and low-field side of the hot spot with fully grown ballooning modes from the simulation are directly compared with the relevant experimental two-dimensional images of the "pressure finger" from the high- and low-field side. In the ballooning model, the "pressure finger" only grows in the low field side and heat is dispersed through shorted magnetic field (global stochastic magnetic field) whereas the heat flow is highly collective in experimental images.

ventional diagnostic systems routinely employed in tokamaks have a limited capability, only applicable to interpret the symmetric system well before the crash (stage 1 in Figure 1) and well after the crash (stage 3 in Figure 1) due to the fact that the crash (reconnection) phenomenon is highly nonlinear and asymmetric during the critical moment.

Two-dimensional Pictures

In the work reported in *Physical Review Letters*, detailed two-dimensional images of the electron temperature fluctuation during the crash time clearly demonstrate that conventional one-dimensional diagnostic systems and X-ray tomography cannot deliver the knowledge needed to understand the physics of the reconnection phenomena. Furthermore, the two-dimensional pictures of the perturbation of the magnetic field, inferred from the flow of the electron temperature changes, make it possible to compare experimental results directly with predictions from the prominent theoretical models. In fact,

one model (quasi-interchange model - Wesson) has already been discarded on the basis of the results, and the limitations of two other models (full reconnection model - Kadomtsev and Ballooning mode model – Park, Nishimura), which describe only part of the sawtooth evolution, became clear as shown in Figure 2. These results will certainly assist theoreticians to adjust their existing models or develop new ones. Physicists hope that this will lead eventually to a complete understanding of the sawtooth instability and how it can be controlled.

Hyeon Park explained the importance of this understanding for burning plasma devices such as ITER. "The sawtooth instability will cause helium produced in the deuterium-tritium fusion reactions to be exhausted from the center of the plasma to its edge in an uncontrolled manner. The helium ash will hold 20% of the fusion energy produced, and in a burning plasma device, this energy will be the predominant source of plasma heating. Once it has imparted its energy to the bulk plasma, the helium must be swept out to the edge of the plasma and removed. Otherwise it will build up, cool the plasma, and the fusion reaction will stop. However, if the sawtooth instability is not properly controlled, the helium will be swept out prematurely. So it would really be great, if we had a 'knob' on the fusion reactor to turn the instability on and off and to regulate its amplitude and frequency."

Intense Microwave Beam

The sawtooth instability can also trigger a catastrophic disruption of the entire plasma. In high-beta plasmas, the m = 1 mode can couple to the m = 2 and 3 modes, leading to disruption. Interestingly, using an extremely intense microwave beam (1 million watts), the Dutch team was able to heat the TEXTOR plasma very locally. Depending on where the heating took place, they found that the frequency of the sawtooth instability could be varied. This should make it possible not only to regulate the exhaust of the helium ash from the center of the plasma thereby preventing a large reduction of the plasma temperature and pressure at the core, but also to decouple with the instabilities further outside the q ~ 1 surfaces (m = 2, and 3 modes), so that the sawtooth oscillation does not lead to the disruption of the discharge.

New Microwave Camera

The important results reported here followed seven long years of research and development supported by U.S. Department of Energy. Success is largely due to advances in microwave nano-technology. Specifically, array technology and state-of-the-art wide-band millimeter wave and intermediate-frequency electronics fabrication techniques developed by the University of California at Davis enabled the creation of a new microwave camera with high spatial and temporal resolution. The camera provided two-dimensional pictures of electron temperature fluctuations utilizing Electron Cyclotron Emission Imaging, a well-established electron temperature measurement technique. PPPL and UC Davis physicists designed, thoroughly tested, and installed the microwave camera on TEXTOR. Strong technical support from colleagues from the FOM-Institute for Plasma Physics Rijnhuizen in the Netherlands was the key for the success of the collaboration.

With the upgraded Electron Cyclotron Emission Imaging system, which will have expanded radial coverage (from 8 cm to 16 cm), continued exciting experimental results from TEXTOR are anticipated in the near future.

The **PRINCETON PLASMA PHYSICS LABORATORY** is operated by Princeton University under contract to the United States Department of Energy.

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