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First Measurements of Hiro Currents in Vertical Displacement Event in Tokamaks

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Specially designed tiles were setup in the 2012 campaign of the EAST tokamak, to directly measure the toroidal surface currents during the disruptions. Hiro currents with direction opposite to the plasma currents have been observed, confirming the sign prediction by the Wall Touching Vertical Mode (WTVM) theory and numerical simulations. During the initial phase of the disruption, when the plasma begins to touch the wall, the surface currents can be excited by WTVM along the plasma facing tile surface, varying with the mode magnitude. The currents are not observed in the cases when the plasma moves away from the tile surface. This discovery addresses the importance of the plasma motion into the wall in vertical disruptions. WTVM, acting as a current generator, forces the Hiro currents to flow through the gaps between tiles. This effect, being overlooked so far in disruption analysis, may damage the edges of the tiles and is important for the ITER device.

Disruptions [1] are an undesirable aspect of tokamak operation, which causes large mechanical and thermal loads on the vessel and in-vessel structures. Understanding disruption events, particularly how currents flow to the plasma facing surfaces, is the key basis for disruption modeling and vessel design. In the past, the currents to the tile surface were measured far away from the center of the contact zone of the plasma with the tiles (wet zone) [2, 3] and interpreted as so-called "halo" currents from the open field lines outside the plasma core. In 2007 in the analysis of JET data, these halo currents are found to be in a clear contradiction with the sign of measurements. The sign of the currents in the wall, opposite to the plasma current, was explained by the theory of wall touching kink mode (WTKM) in Refs.[4, 5], which introduced the Hiro currents excited by the kink instability.

The Hiro currents are responsible for the forces acting by the plasma on the wall. At the same time they slow down the instability and provide a temporary equilibrium for the plasma. The Hiro currents are necessary to slowdown the instability, which acts for them as a current generator.

In the case of WTKM, the electric circuit for Hiro currents consists of the wet zone of the wall (or plasma facing in-vessel components) connected to a force-free strip at the surface of the plasma [4, 5]. This current sharing effect was used to justify the confusion of Hiro currents as a subset of halo currents [6]. In fact, the physics of Hiro currents gives no basis for their mixing with what could be the halo currents.

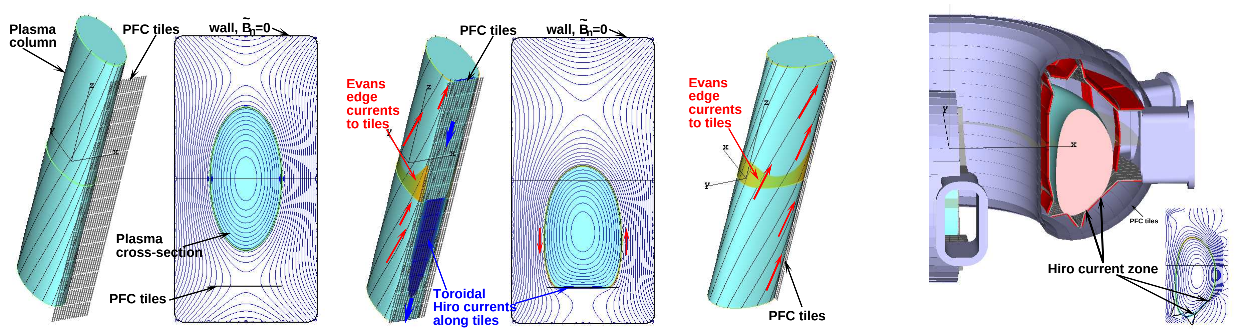
Being the consequence of magnetic flux conservation due to the disruption time being much shorter than the magnetic field penetration time to the plasma, Hiro currents have to be excited also in a pure axisymmetric Wall Touching Vertical Mode (WTVM) $m = 1, n = 0$, corresponding to a Vertical Displacement Event (VDE). The physics mechanism of their excitation is described in Ref. [5]. Here, we give an illustration of the current generation during WTVM using a simplest case of vertical instability of a straight plasma column with a uniform current and elliptical cross-section.

Fig. 1a shows a plasma column (at left) and the cross-section of a magnetic configuration inside the conducting wall of a rectangular cross-section (a right). The external quadrupole field is frozen into the wall, which is ideal with respect to perturbations. The vertical instability is excited in the downward direction. A surface with conducting tiles is inside the wall in the path of the downward motion of the plasma. It simulates the plasma facing tiles between the wall and the plasma in tokamaks. In the simulation model it is assumed that when plasma touches the tiles it shorts the gaps between tiles, thus creating macroscopic electric circuits for the currents along the tile surface. These Hiro currents stop the development of a fast instability and provide a temporary equilibrium.

Fig. 1b shows the calculated plasma cross-section in this equilibrium with a wide plasma-tile contact zone. The Hiro currents (in blue) are excited along the tiles in the opposite direction to the plasma current. These currents create the force on the tile surface. The blue color corresponds to the opposite direction of the Hiro currents relative to the plasma current, and the shape of blue zone in Fig. 1b reflects their amplitude and profile.

As a counterpart to Hiro currents, the edge Evans currents (orange color) are excited along the free plasma surface as predicted in Ref. [5]. The Evans currents flow in the same direction as the plasma current. They are force-free and are localized at the plasma edge. They may enter the tile surface poloidally near the edges of the wet zone. Fig. 1c shows the paths of the Evans currents along the free plasma surface.

According to the theory of WTVM, supported by these simulations, the Evans edge plasma currents can explain the earlier measurements of currents to the tiles, thus, leaving no room for insignificant or even fictitious halo



(a) (b) (c) (d)

FIG. 1: Vertical instability of elongated plasmas. (a) Initial unstable equilibrium of a straight plasma column in a quadrupole external field. (b) Plasma equilibrium maintained by Hiro currents flowing along the tile surface. (c) Free surface of the plasma with directions of Evans currents along magnetic field lines. (d) Non-linear phase of vertical instability in the EAST geometry with the Hiro current zone calculated by the VDE numerical code.

currents.

Fig. 1d shows an example of VDE simulation the of WTVM in EAST tokamak when the plasma created the wet zone in the lower divertor region during a vertical disruption event. Accordingly, the Hiro currents are expected in toroidal direction in this zone.

The remarkable property of Hiro currents in an axisymmetric VDE is that they are generated by the plasma motion to the wall without current sharing with the plasma. This one reason does not allow mixing the Hiro currents with "halo" currents.

In this letter, we present the experimental results of our recent Hiro currents measurement in the EAST tokamak. The special tiles were designed and installed in the divertor area to directly measure the toroidal surface currents during disruptions. We have observed their direction opposite to the plasma current as in previous analysis of JET data with $m/n = 1/1$ WTKM and confirming the sign prediction for the WTVM, explained above.

The schematic configuration of the measurement is shown in Fig. 2. In order to measure the surface currents in the wet zone, special Mo tiles have been designed, with a shunt resistor of known resistance placed between any two adjacent tiles. Two leads brought the voltage on the resistor out of the vessel. This system was implemented in the 2012 campaign of EAST, with three tiles located near the top of the lower outer divertor at port A in the toroidal direction as is shown in Fig. 3. These tiles are twice the length of the original graphite tiles to allow the toroidal currents flow through the resistor easily.

Here we have referred to the techniques used by S.P. Gerhardt in the National Spherical Torus Experiment [7]. To avoid direct contact with the plasma, the sensor is vertically placed inside the Mo tiles. The sensor is positioned near the gap between the two neighboring tiles. The key component of the sensor is the resistive shunt element, made from 0.4 mm thick stainless steel. A strip of this material is bent into an 'Z' shape. Each side of the 'Z' is

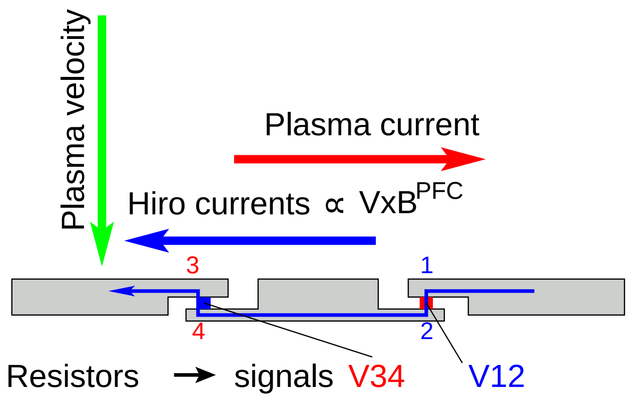


FIG. 2: The principal scheme of measurement of toroidal currents along the plasma facing tile surface. The diagnostics measures the voltage between terminals 1,2 and 3,4 of resistors connecting tiles.

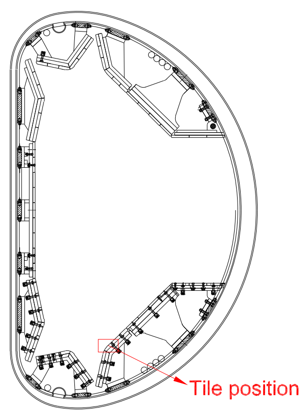


FIG. 3: Cross-section of the EAST vacuum vessel and the plasma facing tile covered surfaces. The red rectangle shows the position of 3 special tiles for measuring toroidal currents along the surface of the tiles.

fit inside a 0.5 mm deep pocket machined on the surface of the tile. When the tile is then install in EAST, each side of the 'Z' presses against one tile, while the two adjacent tiles hold the resistor tightly. A stainless steel wire is spot-welded to each bend of the 'Z'. The resistivity of the wire is not important because the wires only transmit the shunt voltage and carry essentially no current. When currents flow on the tile surface, they will pass from one tile to another through the resistor. Thus, we can extract the information on how currents flow in the tiles by comparing the measured voltages of the two resistors. The currents flowing through the resistor mainly consist of two sources, the toroidal and vertical ones. By comparing the difference of the voltages, we can also obtain information on the vertical currents.

Figs. 4a,b show the examples of two typical vertical disruption events, downwards and upwards respectively.

In Fig. 4, the black line represent the waveform of the plasma current I_{pl} prior and during the disruption. The green line is the waveform of the first vertical moment M_{IZ}

$$M_{IZ} \equiv \int z j_\phi dr dz, \quad (1)$$

representing the vertical position of the center of the toroidal plasma current j_ϕ multiplied by the total plasma current I_{pl}. It is measured directly as a combination of the signals from poloidal magnetic probes (Mirnov coils). Three sets of Mirnov coils with full poloidal coverage are installed in the EAST tokamak. In Fig. 4 the M_{IZ} waveforms from the nearest to Mo Hiro tiles set is overlayed with two M_{IZ} waveforms from two other cross-sections (black lines). Essentially all the M_{IZ} signals are identical indicating good azimuthal symmetry of the VDE. The plasma current and the first vertical moment have been normalized for convenience.

The blue and red curves, marked by 'V12', 'V34', represent the voltage from the resistors in Fig. B.

The vertical moment identifies the motion of the plasma during the disruption. It is very clear that the plasma begins to move vertically during the initial phase of the VDE disruption prior to the plasma current spike. During the plasma current quench there is an interesting and unexpected phenomenon of a reverse plasma motion downward. The real reason for the bouncing back remain unknown. Plasma inertia, slower decay of Hiro currents relative to plasma current, or just an overreaction of the vertical feedback stabilization system are not excluded and are left for future experiments and simulations.

As the measurement system is installed on the lower side, the signals of the Hiro currents from resistors are anticipated in the downward disruptions, while not in the upward case. The observations indeed confirm this prediction. Unfortunately, the measurement system in the upper divertor area was absent to better compare the results. The expected currents should be detected by this extra system in the upward disruptions, while not in the downward case, just opposite to the one located on the lower side.

Both resistor sensors have detected obvious signals when the downward disruption began. The wires brought out the electric potential, and the voltage is obtained by subtracting the electric potential of the lower part from the upper part of the resistor. Thus, the positive sign of the voltage suggests downward currents. The two resistors are in the clockwise direction (viewing from the top). Currents flowed downwards in one resistor, while upwards in the other one, indicating the surface currents flowed in the clockwise direction. The plasma current direction in EAST was counterclockwise, which means direction of the surface currents (Hiro currents) in the wet zone was opposite to the plasma current.

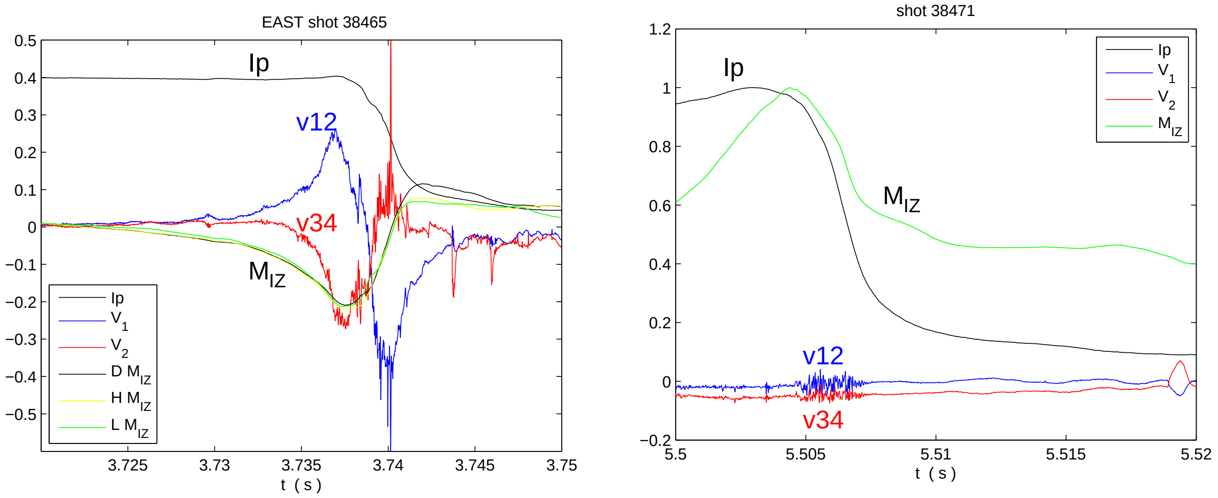
In the upward case in Fig. 4b, there were no substantial voltages detected, especially in the time range of interest, which is in accord with expectation, since Hiro currents are located on the upper side in this case. The absence of the resistor signals in the case of the upward disruption in Fig. 4b represents a proof that the measured signal is not related to the eddy currents in the in-vessel structures. The eddy currents would produce similar signals of opposite polarities for down- and upward VDE.

This discovery of the Hiro tile currents in the toroidal direction, which are opposite to the plasma current corresponds to predictions by the WTVM theory [5], and is different from believed in the early years. This discovery also confirms the findings in JET of Hiro currents due to asymmetric m/n=1/1 kink mode.

Interestingly, the downward motion of plasma and the Hiro currents have started earlier than the plasma current spikes. The so-called spike, an increase in the total plasma current immediately preceding the current quench, is a common phenomenon observed on many devices. The theory of Hiro currents suggests the transfer of negatively directed Hiro currents into the conducing wall as one possible explanation. Statistical results of the disruptions in EAST also show Hiro currents and the spikes appeared during the similar period. It should be noted that plasma currents also are measured externally in EAST, different from that in JET, the fact, which may object such an explanation.

According to the WTVM theory and simulations, the Hiro currents are proportional to the mode magnitude, i.e., the magnitude of the surface displacement of the instabilities. In Fig. 4a, we observed exactly the same variation of the expected signals, corresponding well with predictions.

In summary, the Hiro currents in the toroidal direction opposite to the plasma currents, predicated by the earlier theory, have been directly observed for the first time in the EAST tokamak by specially designed tiles in the recent campaign. The theory of WTKM and Hiro currents, which gave a remarkable explanation of the



(a) (b)

FIG. 4: Waveforms of plasma current I_{pl}, first vertical moment M_{IZ}a and voltages V12,V34 on resistors between the Mo tiles for two similar plasma EAST discharges (a) 38465 with a downward VDE, and (b) 38471 with an upward VDE.

toroidal asymmetry in the plasma current measurements in JET, are further confirmed in EAST for the case of wall touching vertical mode. Disruptions in tokamaks are too complicated to be completely understood. The observation from both downward and upward VDEs unambiguously excluded eddy currents as an explanation of the observations. The necessity of the plasma contact with the wall is confirmed. At the same time, the generation of the Hiro currents during the upward bouncing of the plasma in the late phase of downward VDE was not envisioned by the theory (although does not contradict it).

For large devices, like ITER, the potential upward disruptions can generate the Hiro currents between the beryllium tile between the vessel structure and the plasma. The damaging effect of these currents on tile edges remain to be analyzed.

The axisymmetric vertical disruption represents the simplest case for developing a complete theory and simulations and still contains many physics effects which require more theory and computational development. The present 'VDE' numerical code (Fig. 1d), created for simulations of EAST VDEs, is in an early phase of development with only the magneto-hydrodynamic part implemented. While predicting the right position of the Hiro current generation zone, it cannot reproduce many details of experimental measurements. But together with diagnostics it gives a basis for deeper understanding of disruption physics, including the plasma edge and plasma-wall interactions, determining the plasma time behavior and distribution of electromagnetic and thermal loads.

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