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Plasma Blobs and Turbulence Impacting Magnetic Confinement (A Short Review)

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Abstract: Space-based plasma (i.e., a highly ionized gas or the fourth state of matter) blobs are isolated pockets of this highly ionized gas made up of charged particles. These blobs are believed to have a substantial impact on the structure and dynamics of the cosmos and can be seen in a variety of astronomical objects, including stars, galaxies, and the intergalactic medium. Some plasma blobs are connected to intense phenomena like magnetic reconnection, shock waves, and supernovae, while others may be the result of more passive processes like cooling and gravitational collapse. In both astrophysics and plasma physics, there is ongoing research on the characteristics and behavior of plasma blobs. This phenomenon has a very adverse effect on tokamak-based MCF (magnetic confinement fusion), which is the subject of this short review paper.

Key words: Plasma blobs, plasma edge, interstellar, magnetic reconnection, tokamak, MCF.

1. Introduction

A plasma blob or bubble is an area of space where plasma, an ionized gas with free electrons and ions, is present. The ionospheric heating process or the interaction of energetic particles with the Earth's magnetic field are two ways that plasma might be produced. Radio wave propagation can be altered by plasma bubbles, which can also have an impact on communication and navigational systems.

A plasma bubble, also known as a blob, can have a substantial impact on the confinement and stability of the plasma in MCF (magnetic confinement fusion). In fusion reactors, a technique called magnetic confinement is employed to keep plasma from coming into contact with the reactor walls.

Magnetic reconnection, a process in which the magnetic field lines are rearranged to liberate energy held inside the magnetic field, can be brought on by plasma bubbles. This might cause the plasma to heat up locally, which would raise its pressure and possibly make it unstable by reaching a turbulent regime scenario. Under these conditions, the total confinement effectiveness can be decreased by plasma bubbles because they can generate pathways through which particles can leave the confinement region.

Consequently, it is critical to reduce the development of plasma bubbles. See Fig. 1.

Blobs have the potential to ruin the plasma needed for fusion processes, or basically "wreak havoc" in the plasma state of the matter. The efficiency of fusion reactions in doughnut-shaped fusion facilities known as "tokamaks" is restricted by this bubble-like turbulence that builds up at the edge of fusion plasmas and drains heat from the edge. The DOE's (Department of Energy's) PPPL (Princeton Plasma Physics Laboratory) recently found an unexpected link between the blobs and changes in the magnetic field that keeps the plasma that powers fusion reactions in the device core.

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Fig. 1 Sun surface driven blob phenomena.

Source: Courtesy of Getty Image.

Note that: the meaning of the phrase “wreak havoc” is the act of causing damage, destruction, and/or chaos, in our case within a confined plasma-driven magnetic field. The phrase “wreaking havoc”, which means that someone or something is causing a great deal of trouble or a lot of damage. Before the 19th century, the word “wreak” was already used widely in literature and speech.

The fusion energy that drives the sun and stars is produced on Earth via more research into plasma blob correlation and its function in the heat loss from magnetic fusion reactors. As the physicist Stewart Zweben stated, “These results offer a new facet to our knowledge of the plasma edge heat loss in a tokamak.” This work advances our knowledge of the physics of blobs, which can be used to forecast how well tokamak fusion reactors would operate.

Note that: “Return of the Blob/Bubble” is a surprising link found to edge turbulence in fusion plasma that is discussed in this paper.

Massive amounts of energy are produced by fusion reactions that combine light elements into plasma, the hot, charged state of matter made up of free electrons and atomic nuclei that makes up 99 percent of the observable cosmos. On Earth, scientists are trying to create and control fusion as a safe, clean, and almost infinite source of energy for power plants. They do this by using either MCF [1] or ICF (inertial confinement fusion) [2] as new ways to do things technically over the past few decades.

When reexamining studies performed in 2010 on PPPL’s NSTX (National Spherical Torus Experiment), as illustrated in Fig. 2, the predecessor to today’s NSTX-U (National Spherical Torus Experiment-Upgrade), researchers made the startling connection last year (Fig. 3). The blobs and changes in the magnetic field called “MHD (Magneto-Hydro-Dynamic) activity” happen in all tokamaks, even though they were once thought to happen separately.

For better fusion reactors, we need to stop the blobs before we can move forward with commercializing MCF and fusion reactors like the Tokomak machine. This means that the following things need to be taken into account:

- An analysis shows a link between magnetic turbulence and blobs in tokamak fusion reactors.
- Fusion projects like ITER (International Thermonuclear Experimental Reactor) require a lot of

lead time, and turbulence can take them offline for weeks (Fig. 4).

- In some portions of research, blobs formed predictably at specific magnetic locations.

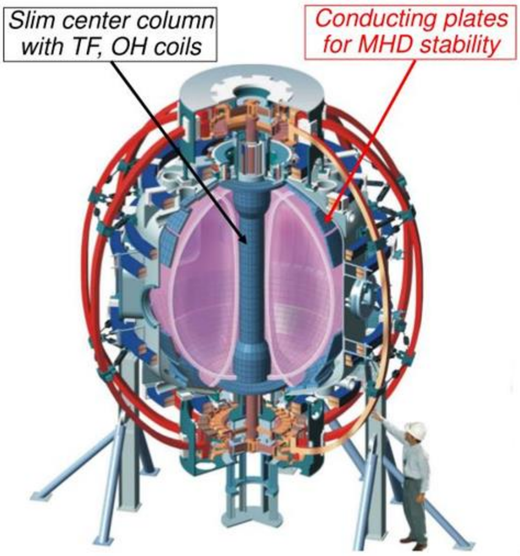

Fig. 2 NSTX (National Spherical Torus Experiment).
Source: Courtesy of PPPL.

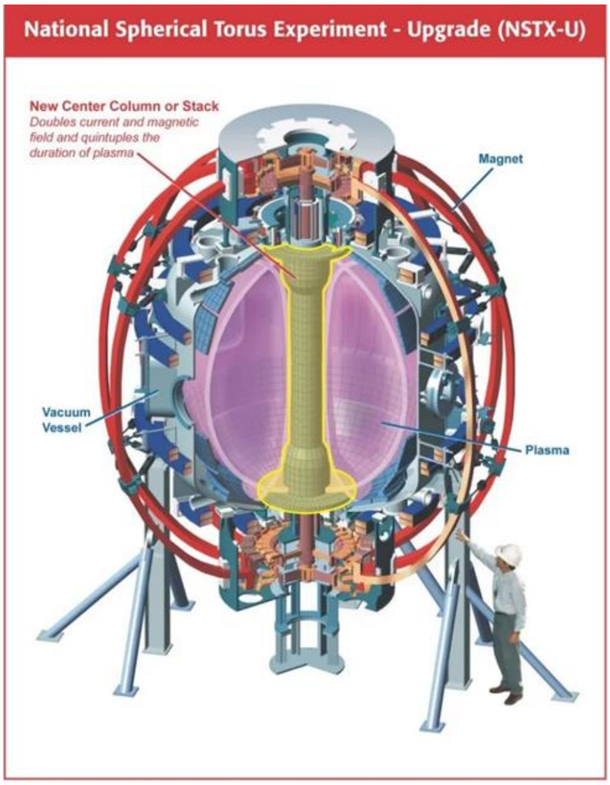

Fig. 3 NSTX-U (National Spherical Torus Experiment-Upgrade).
Source: Courtesy of PPPL.

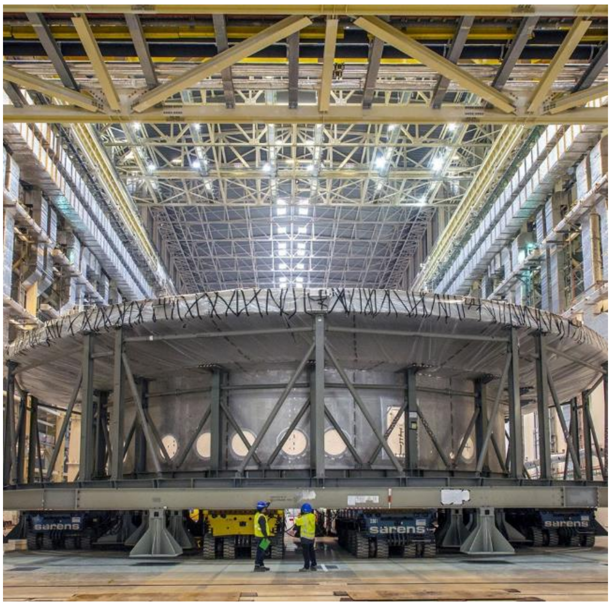

Fig. 4 ITER infrastructure picture.
Source: Courtesy of ITER entity.

Note that: President Ronald Reagan and Soviet leader Mikhail Gorbachev started the ITER 30 years ago. This experimental tokamak fusion reactor, a nuclear fusion plasma reactor where extremely hot, charged plasma spins and generates potentially limitless energy, is one of a few incredibly expensive "miniature suns" across the world, with tens of billions of dollars on the line.

The International Thermonuclear Experimental Reactor (ITER) tokamak has begun construction and plans to start turning on in 2025. Bringing in parts for the 25,000-ton reactor required building a special heavy-duty road, and finally, ITER is the biggest tokamak fusion reactor project, but far from the only one.

Bear in mind that the fluctuating turbulence blobs inside tokamak fusion reactors have been linked, according to researchers from a Department of Energy facility, with general changes to the magnetic fields in these devices. Plasma is heated to temperatures hotter than the sun in tokamaks, which have a donut-like shape. Errors can take weeks to repair.

2. Surprise Clue

The "cross-correlation coefficient", which is utilized to assess a set of the 2010 NSTX trials, was measured by tracking the diagnostic signals of the blobs and the MHD (magneto-hydro-Dynamic) activity in connection to one another. Approximately 10% of those tests revealed a strong link between the two variables.

The researchers then looked at a number of potential causes of the correlation but came up empty-handed. Zweben [3] stated that additional data analysis and modeling will be required in order to comprehend and manage this phenomenon—possibly by readers of the Physics of Plasmas publication.

The study of edge turbulence, which has been observed on tokamaks and other magnetic confinement devices for decades [4-6], is crucial today in the realm of fusion energy development. It is commonly acknowledged that the plasma edge is important for a number of reasons. To prevent damage to plasma-facing components, contaminants in wall content (such as tritium inventory), and recycling in current and future high-performance devices, proper treatment of the energy and particles wasted by the core plasma is necessary. To create the ideal environment for RF (radio frequency) antennae, it will probably be important to comprehend the turbulent SOL (scrape-off layer).

In addition, the physics of edge instabilities, turbulence, strong nonlinearity, convective transport, and the development of coherent structures is useful for tokamak confinement simulations and first principles models, in addition to being intriguing in and of itself [7].

Semi-analytic “blob” models [8-12] (describing the convective propagation of filamentary objects) have been proposed to provide physical insight and to aid in the interpretation of both experiments and simulations, even though numerical simulations are necessary to obtain detailed predictions of the strongly nonlinear edge and SOL turbulent dynamics. According to a theoretical study [13, 14], multiple regimes of blob propagation are known to exist. The radial convection velocity of blobs in these regimes differs depending on the plasma and machine characteristics [15].

3. Understanding of Bubbles/Blobs at Edge of Plasma

The surprising regularity of the trajectory of huge blobs, which move at around the speed of a rifle bullet in studies analyzed in 2015 and 2016, provided the first indication of the correlation. The “scrape-off layer” at the border of a tokamak plasma is where these blobs often move randomly, although in rare instances, all of the huge blobs went at virtually the same angle and speed. Also, the time between each huge blob that showed up at the boundary of the plasma was almost always the same. This was almost exactly the same as the frequency of MHD activity there.

New simulations that have been done by scientists may shed light on the behavior of blobs and bubbles at the plasma edge. At the same time, the simulations did kinetic simulations of two different parts of the plasma edge. This helped physicists start to understand how bubbles and blobs at the edge of plasmas are destroying tokamak confinement efforts by consuming plasma heat.

To fuse hydrogen atoms into helium, doughnut-shaped devices called tokamaks must maintain the heat of the ultra-hot plasma they control. But like boiling water, plasma has blobs or bubbles that move around inside the edge of the plasma. This makes the plasma less effective because the bubbles take away the heat that keeps the fusion reactions going.

Recently, researchers at the PPPL of the U.S. DOE have finished new simulations that may shed light on the behavior of blobs at the plasma edge. Two distinct sections of the plasma edge were simultaneously subjected to kinetic simulations using the code XGC1, which was created by a national team located at PPPL. This power shows in a more basic and complete way how heat from the plasma can be transferred to the walls and cause damage.

According to PPPL physicist Michael Churchill, lead author of a paper detailing the findings in the journal

Plasma Physics and Controlled Fusion, “In simulations, we commonly divide two sections at the plasma edge, known as the pedestal and the scrape-off layer, and focus on one or the other.” “Because it uses kinetic ion and electron equations to model both regions simultaneously, XGC1 is special.” In fact, it is important to include both regions in simulations because they affect each other.

Without performing real tests that could be expensive, scientists use simulations to investigate plasma, the fourth and hottest state of matter in which electrons are separated from atomic nuclei. They occasionally offer insights that are not possible through physical experiments. Particularly crucial are simulations of the turbulence at the plasma’s edge, close to where it meets the internal wall of a tokamak. The better scientists can understand this turbulence, the less likely it is that moving plasma blobs will form at the plasma edge. These blobs could remove a significant amount of heat from the confined plasma if they are not managed, which could harm plasma-facing components or impede fusion events. Currently, researchers at Princeton Plasma work for the DOE.

The high-confinement mode, or H-mode, of the XGC1 computer code was used to simulate plasma under circumstances that aid in the retention of plasma’s heat. The results showed that in H-mode, many blobs form between the pedestal and the scrape-off layer, which are near the edge, and move toward the edge while crossing the magnetic field lines.

In plasma, blobs are crucial to the particle’s outward motion. Blobs account for around 50% of the particle loss at the plasma edge, and they have been seen in a variety of plasma devices, including tokamaks, stellarators (Fig. 5), which are figure-eight-shaped fusion reactors, and linear machines. Blobs can draw energy and particles out of the plasma, and you do not want that, according to Churchill. “You want to contain things.”

At the Oak Ridge Leadership Computing Facility, a DOE Office of Science User Facility in Oak Ridge, Tennessee, scientists ran the simulation on Titan, the nation’s fastest supercomputer. The NERSC (National Energy Research Scientific Computing Center), a DOE Office of Science User Facility at Lawrence Berkeley National Laboratory in Berkeley, California, was the site of the majority of the post-simulation analysis. *Plasma Physics and Controlled Fusion* was written by C. S. Chang, Seung-Hoe Ku, and Julien Dominski, all of whom work at PPPL.

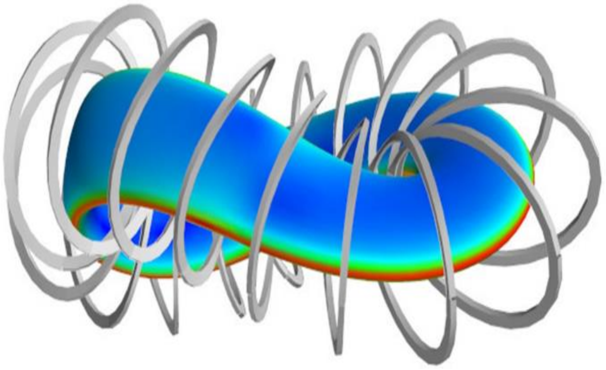

Fig. 5 Artistic View of Stellarator.
(Source: Department of Energy)

Future studies will concentrate on the formation of the blobs and how the tokamak’s shape affects their behavior. It is also important to understand how density, temperature, and electromagnetic force affect how the blobs act.

4. Plasma Turbulence

We can describe this phenomenon in two steps as follows:

4.1 Turbulence in Nature

Fluid characteristics, including pressure, flow rate, and density, rapidly fluctuate in turbulent fluids. The atmosphere, which can cause choppy airline flights, and the water behind the stern of a moving boat are two obvious examples of turbulence in fluids. See Fig. 6a and 6b.

Furthermore, with the help of innovative technologies such as AI (artificial intelligence) and ML (machine learning) in conjunction with DL (deep learning) [16], one can model turbulence for better understanding and encountering it in nature [17].

(a)

(b)

Fig. 6 (a) Choppy airline trip image; (b) whirlpools of water image.
Source: Leonard da Vinci. RL 12660. Windsor Royal Library.

4.2 Turbulence in Interstellar Space

In an ionized gas called plasma, ions and electrons coexist side by side but have not yet united to create atoms. The most prevalent form of ordinary stuff in the universe, plasma, is frequently turbulent. The interstellar space and star atmospheres are two instances of turbulent astrophysical plasmas. More specifically, turbulence is common in many areas of our geospace, including the magnetosheath, cusps, magnetotail, and ionosphere, as well as the solar wind and ion foreshock zone (Fig. 7).

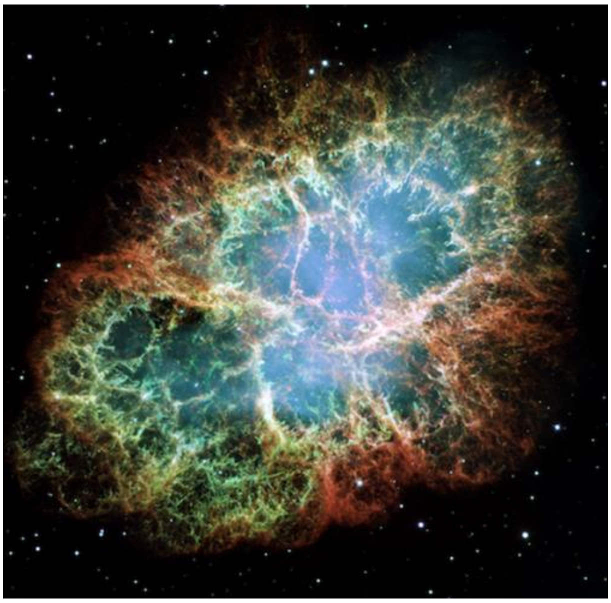

Fig. 7 Turbulence in an astrophysical object image.
Source: NASA, ESA, J. Hester, A. Loll (ASU); Acknowledgement: Davide De Martin (Sky Factory).

Fig. 7 shows a classic example of turbulence in an astrophysical object: the Crab nebula, which is a very turbulent supernova remnant.

Large-scale motion is converted into small-scale motion and heat through turbulence. The reason for this energy loss in typical fluids is fluid viscosity. However, in collisionless plasmas, energy is lost as a result of plasma waves and particles interacting. Understanding turbulence is crucial because it affects the heating and acceleration of particles like cosmic rays and solar energetic particles. Additionally, it is significant because it has a significant impact on the magnetosphere’s structure, dynamics, and input of mass and energy.

Why practical, self-sustaining fusion reactions have been challenging to achieve can be explained by one straightforward phenomenon: The plasma, a superheated, electrically charged gas that circulates inside fusion reactors, can lose a lot of heat due to turbulence. This keeps the plasma from heating up to the levels required to dissipate the electrical attraction between atomic nuclei, which, in turn, keeps those nuclei from fusing. But first, scientists must comprehend that turbulence in order to control it. See Fig. 8.

Understanding plasma turbulence, new tokamak fusion reactor experiments reveal details of a cooling process, potentially bringing practical fusion closer. This part of the study at the MIT (Massachusetts Institute of Technology) under their PSFC (Plasma Science and Fusion Center) has now taken a significant

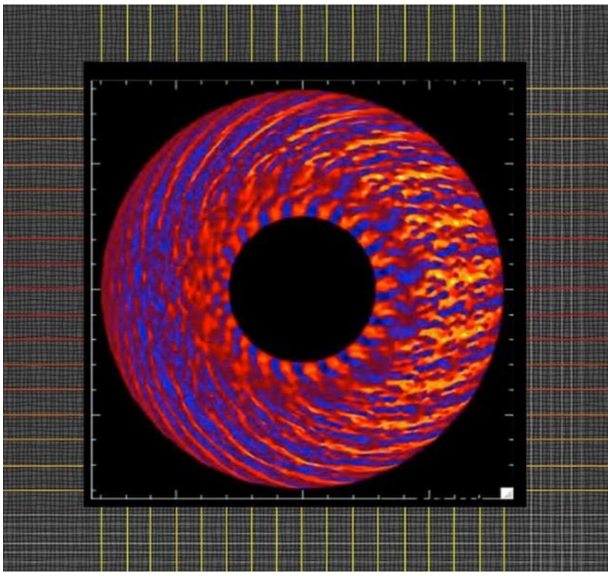

Fig. 8 Plasma turbulence study image at MIT.

step in that direction by quantifying a previously unknown type of small-scale turbulence that can have big effects on cooling the plasma in a reactor.

Other studies in respect to the plasma blob that are done within PSFC in a magnetically confined plasma show that fluctuations in density, temperature, etc. near the plasma edge are prevalent, which are conducted under the MIT program VTF (Versatile Toroidal Facility).

These oscillations frequently have a non-diffusive nature, which means that rather than flowing randomly about the chamber, the particles form coherent structures that convect (i.e., transport heat or fluid by means of convection) outward in the direction of the walls. Since they frequently line themselves with the magnetic field, these spreading structures are sometimes known as filaments or blobs. Blob-based plasma transport is often undesirable because it can weaken the chamber walls and compromise plasma confinement. See Fig. 9, where a movie from Stewart Zweben at the PPPL shows blobs at the edge of NSTX using gas puff imaging [15].

And here is the movie of blobs that was created controllably by MIT in their VTF facility (Fig. 10).

In contrast to tokamaks, where one can only view blobs when they are produced by the main plasma, VTF allows us to control and construct blobs in a reproducible manner. Furthermore, Langmuir probes can be utilized extensively without melting to reveal the precise internal structure of the blobs because the VTF plasma is transient and has a low density. Our setup for the experiment is shown in the diagram in Fig. 11.

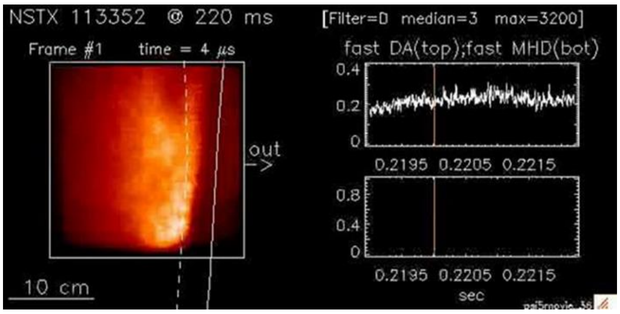

Fig. 9 Zweben (4 MB, mpeg).

Source: http://www.pppl.gov/~szweben/.

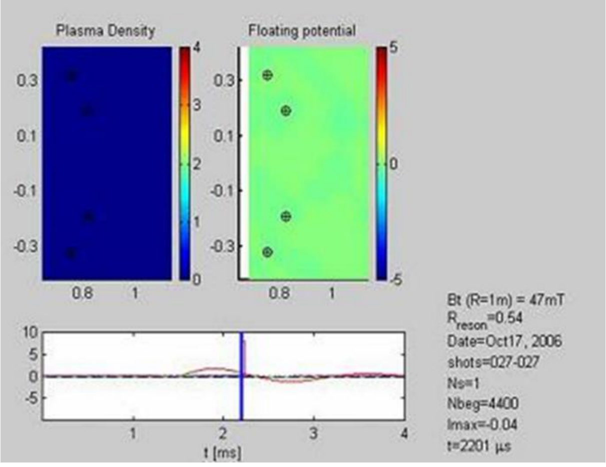

Fig. 10 VTF (200 KB, mpeg).

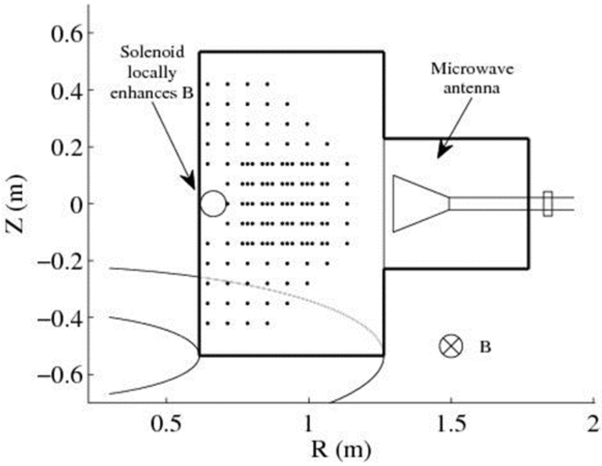

Fig. 11 An experimental set at MIT VTF facility.

Source: MIT VTF.

Fig. 12 The solenoid used to enhance the toroidal magnetic field.
Source: MIT Plasma Facility.

The plasma that is created at MIT VTF facility is by a short (60 μs) burst of microwaves at 2.45 GHz with a power of 15 kW. The resonance condition for electron-cyclotron resonant breakdown at this frequency is that the local magnetic field be 87 mT. The background toroidal magnetic field (into the figure) is only 40 mT, but it is enhanced locally by the solenoid's magnetic field (see the picture in Fig. 12) to give local breakdown. The result: a ring/filament of plasma near the inner wall that extends all the way around the machine. The blob then propagates outward at some fraction of the sound speed as v_s equal to $v_s = T_i/m_i$, based on the solenoid used to enhance the toroidal magnetic field as illustrated in Fig. 12. Note that T_i is presenting the temperature of Electrons, while m_i is the mass of Ions.

Based on the work of the MIT PSFC (Plasma Science and Fusion Center) team, they have observed for the first time the nonlinear mushroom shape of the blobs. Fig. 13 shows the blob at three locations separated by 100. The mushroom shape is consistent with that seen in many simulations, one of which, due to Garcia et al. [18], is shown at the bottom right of Fig. 13. On the upper right is the electrostatic structure, which shows charge buildup at the top and bottom of the blob. This charge build-up, which in the single-particle picture is due to grad-B and curvature drifts, gives a downward electric field that gives an outward velocity.

The same team at PSFC at MIT has investigated the dependencies of the blob velocity, which is important because it determines plasma losses (transport) at the edge of tokamaks and other plasmas.

The average blob velocity is found to scale inversely with the neutral density in the chamber (our ionization fraction is only about 1%), as illustrated in Fig. 14 here and reported by this team.

The electric field in the blob and the resulting $\vec{E}\times\vec{B}$ drift velocity can be quantitatively compared to the blob velocity determined by density measurements. The following diagram shows the agreement. At low pressures, the measured electric field is too low due to systematic errors associated with low-density floating potential measurements. Note that the electric field is measured as the vertical gradient of the floating potential, so we are assuming that the electron temperature is constant along the vertical direction. See Fig. 15.

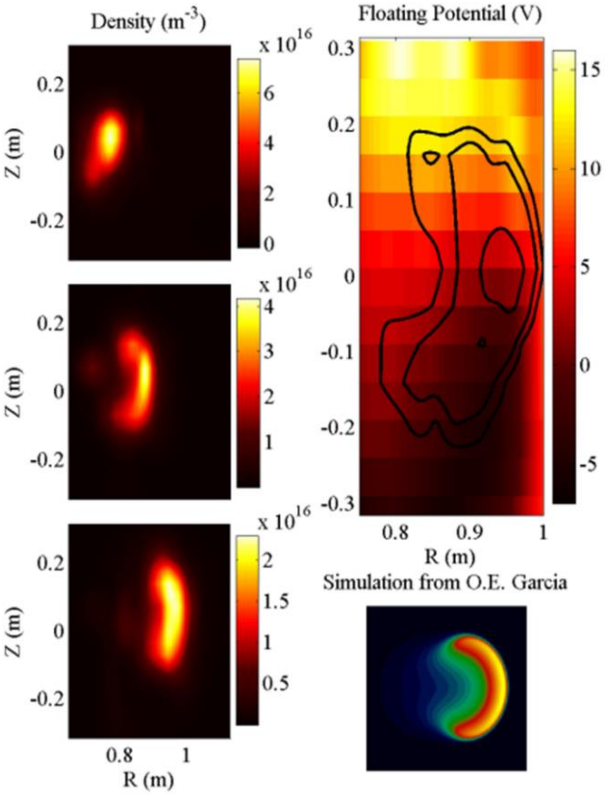

Fig. 13 Nonlinear mushroom shape of the blobs.
Source: MIT VTF.

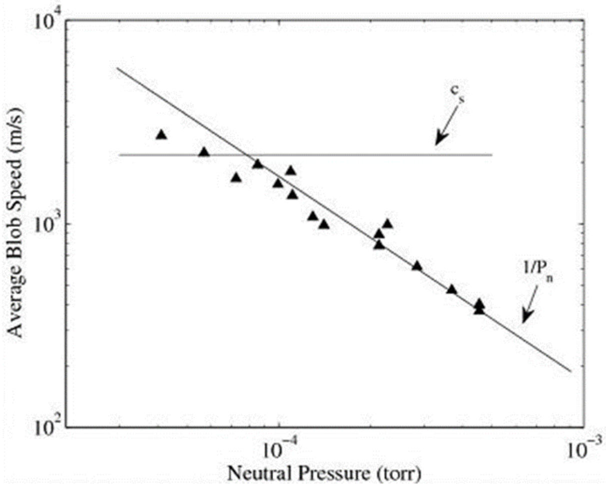

Fig. 14 The blob loses momentum to the neutrals.
Source: MIT VTF.

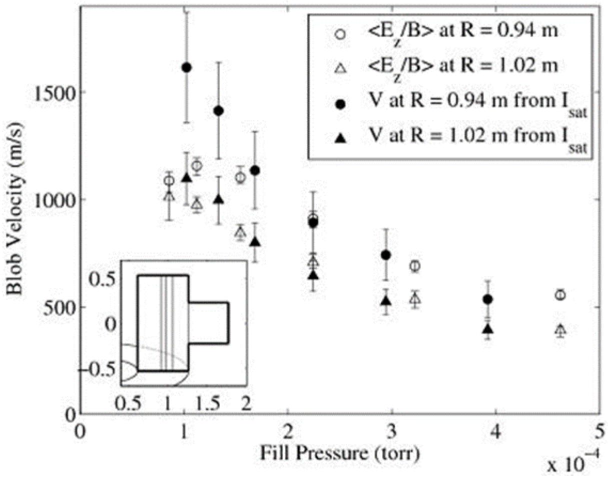

Fig. 15 Blob velocity vs. fill power measurement.
Source MIT VTF.

The $\vec{E} \times \vec{B}$ graph shows three things:

(1) The 1/Pn dependence.

(2) Agreement with velocity measured from ion saturation measurements (filled symbols).

(3) That velocity decreases as blob propagates to larger *R*.

Note that at MIT, the inset illustrates the layout of the Langmuir probe lines used for these measurements.

5. Conclusions

The fastest objects observed in the universe are blobs or bobbles of superheated plasma, ejected from black holes in the cores of extremely active galaxies known as blazars. These blobs, with as much mass as the planet Jupiter, have been observed moving at 99.99% of the speed of light. According to Albert Einstein's Theory of Special Relativity, the only thing capable of traveling at the speed of light, 299,792,458 m/s, is light itself. When matter is accelerated to significant fractions of the speed of light, it takes more and more energy to accelerate it further.

Researchers from a Department of Energy lab say they have linked the fluctuating turbulence blobs inside tokamak fusion reactors with overall changes to the magnetic fields in these devices. Tokamaks are donut-shaped fusion reactors where plasma is brought up to temperatures hotter than the sun, and disruptions can require weeks of work to fix.

Moreover, whatever we do in the world of MCF, keep in mind that: *For Better Fusion Reactors, We Must Stop the Blobs.*

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