UTILIZING A VISIBLE CAMERA IN THE FIRST OPERATION PHASE(S) OF A FUSION DEVICE

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An overview visible camera is an indispensable diagnostic system for every magnetic fusion device. Its importance is key, especially during the first operation phase, as well as throughout the early stage of life of the reactor. The operational and scientific significance of such a system is shown through examples later; however, the other aspect of a camera-based diagnostic, which is hardly stressed enough, is the human factor. We tend to forget in the rapidly evolving world of AI-based applications that science is actually practiced by people – and vision is the sense providing the vast majority of the information reaching us. Because of this, scientists will always have the wish, no matter how detailed data they get from other sources, to “see” what is happening inside an experiment; this helps them to understand the observed phenomena. The importance of video diagnostics is further increased by the fact that newly built fusion experiments are not abundant in diagnostics, and future fusion power plants are also very likely to be equipped with only the most necessary diagnostics systems. Out of those, only a few are able to provide 2D/3D information about the plasma, which, on the other hand, has an increasing importance with machine size, especially during the start-up phase. JT-60SA, the world’s largest superconducting tokamak, entered integrated commissioning and first plasma operation (IC & OP1), achieving first plasma in October 2023. IC & OP1 was started with a limited set of diagnostics, including EDICAM, a wide-angle visible overview camera system [1]. Similarly, Wendelstein 7-X (W7-X), the world’s largest superconducting stellarator, entering first operation and achieving first plasma in 2015, was also started with only a few installed diagnostics, one of which was an EDICAM camera system [2].

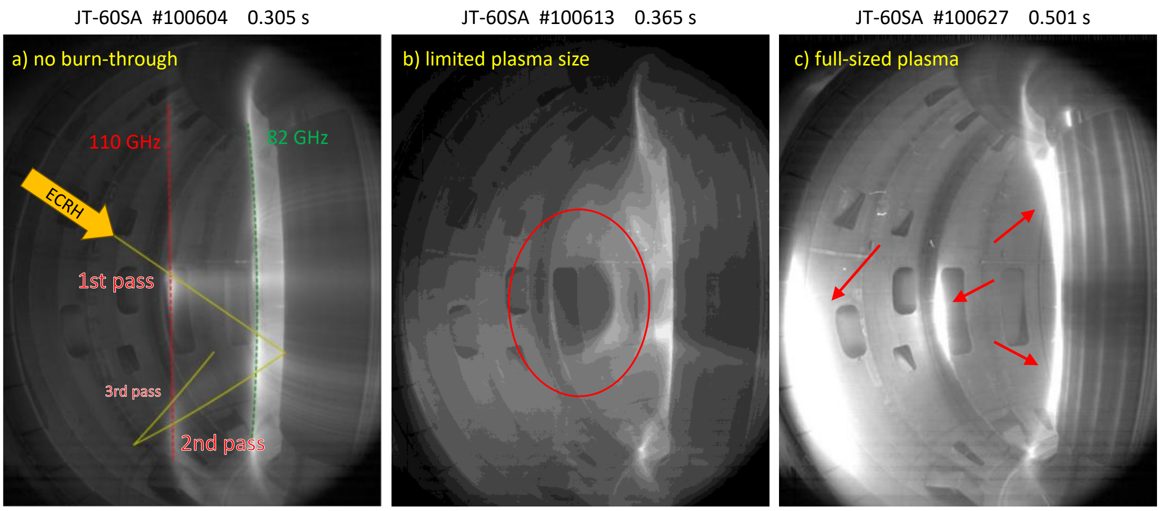

Fig. 1. EDICAM snapshots from JT-60SA OP1. (a) Early plasma attempt, without successful burn-through. The traced trajectory of the 110 GHz heating wave is shown in yellow. (b) First tokamak plasma. A (semi-)circular light emission pattern surrounds the plasma (indicated by the red ellipse). (c) Full-sized tokamak plasma, touching first wall elements, accompanied by strong light emission (indicated by red arrows).

For a new fusion machine, especially a tokamak, the first critical challenge during the initial plasma operation is plasma start-up. Plasma is initiated usually by wave heating (ECRH) in stellarators, and ECRH is also often used in tokamaks to assist breakdown, especially in superconducting devices where the inductive electric field cannot reach as high values as in the case of a copper central solenoid. Heating waves are absorbed in a small, spatially localized volume at the crossing of the wave and the corresponding resonance layer; if the wave is not fully absorbed, it propagates further within the plasma vessel and gets reflected by a first wall component (e.g. on the central column), passing the resonance layer again – this process repeats until the wave energy is fully attenuated. Either way, plasma is initiated in a very small volume compared to the plasma vessel itself, and so this small, localized plasma needs to grow, ionizing the surrounding gas (and allowing for plasma current in case of tokamaks) to develop a full-sized plasma discharge ("burn-through"). This difference between the initiated plasma volume and the plasma vessel clearly increases with machine size, and so does the challenge in achieving burn-through. An example of unsuccessful burn-through can be seen on Fig 1. (a) for a tokamak and Fig 2. (a) for a stellarator. Although these images are highly dissimilar (following the vacuum magnetic field in both cases), what they still have in common is that they can clearly be distinguished from images showing a (well-)developed plasma. Fig 1. (b) shows the first ever tokamak plasma achieved in JT-60SA: one can clearly recognize the (semi-)circular emission pattern, called radiation belt, in the center of the image. The presence of the radiation belt is a solid evidence of a tokamak plasma, as it follows the shape of the formed magnetic flux surfaces. Its location denotes the plasma edge, as conditions for visible light emission are not suitable either on the inside (too hot) or outside (too cold, low density) of it. A very similar radiation belt can be seen for successfully formed stellarator plasmas as well, Fig 2. (b).

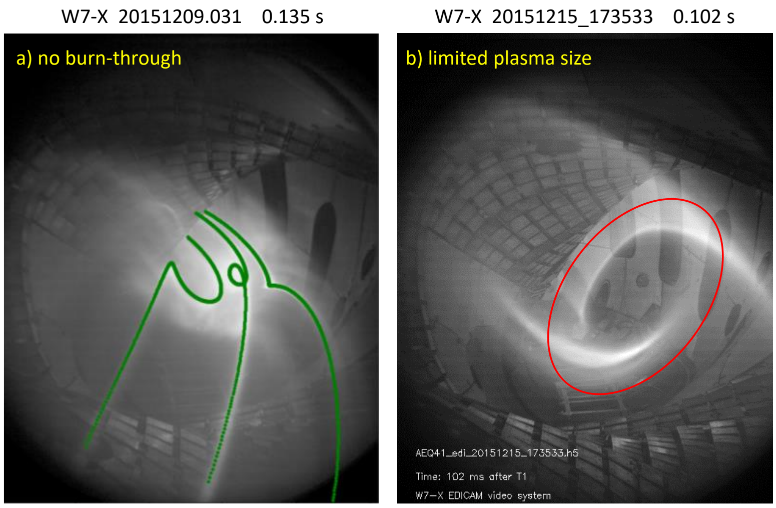

Fig. 2 EDICAM snapshots from W7-X OP1. (a) Early plasma attempt, without successful burn-through. The observed emission pattern follows precisely a magnetic field line, traced for three toroidal turns (green). (b) One of the first successful plasmas.

If we infer qualitatively the plasma size using images (b) from both figures, we can clearly determine that the plasmas are significantly smaller than the available volume in the vacuum vessel. While there can be various reasons behind this (e.g. magnetic configuration, heating scheme, impurity content), we can state without doubt that burn-through was achieved (images are different from (a) images), and there is headroom for improvement. When plasmas reach their possible maximum size, they get in contact with first wall elements, such as the divertor, or the limiters and the central heat shield. The latter case is shown on Fig 1. (c) for JT-60SA. Here, instead of the radiation belt, the image is dominated by the excessive light emission produced by plasma-wall interactions (PWI). This is a clear difference, once again, w.r.t the (b) images, which can be used to confirm qualitatively but unmistakably, that the plasma has reached its full size – a finding which denotes an important milestone during the commissioning of a magnetic fusion device.

Besides bulk plasma radiation, a visible video diagnostic system can also be used to detect and observe a wide range of phenomena, such as intended PWI (e.g. divertor strike-lines, their location and its evolution in time), unwanted PWI (hot-spot formation on the first wall: plasma displacement, fast particles, instabilities, runaway electron impact etc.) or UFOs. Any solid object that enters the plasma undergoes ablation, accompanied by excessive light emission. Thus, UFOs can be detected with ease, and in many cases their source can also be traced back, allowing for the identification of possible failures and easing their repair. These features of a visible video diagnostic make it a necessary operational system for all magnetic fusion devices.

REFERENCES

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