Development of a novel optical diagnostic for Shattered Pellet Injectors of the ITER Disruption Mitigation System

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Shattered Pellet Injection (SPI) is the baseline technology of the current ITER Disruption Mitigation System (DMS)[1]. The basic principle of the system is that cryogenically cooled large pellets are launched with velocities of up to 800 m/s, shattered on a structure and a collimated spray of pellet shards penetrates deep into the ITER plasma. As the DMS is a key for ensuring the lifetime of in-vessel components, the reliability of the successful pellet injection must be guaranteed. Altogether 27 injectors are planned to be brought into operation from the beginning of the pre-fusion power operation phase of ITER.

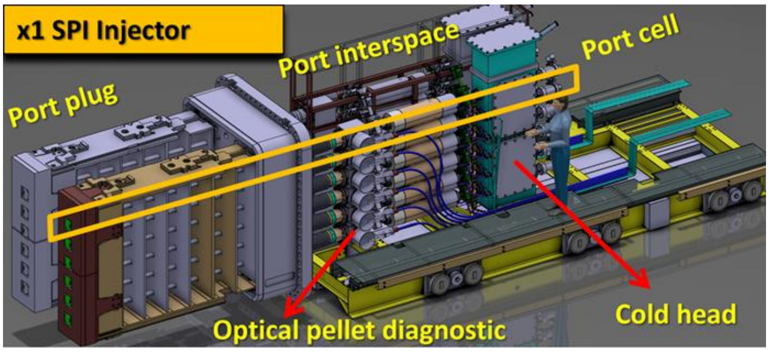

Fig. 1. Shattered Pellet Injectors of the ITER Disruption Mitigation System.

A novel optical diagnostic system is being developed for the DMS which will not only detect the successful pellet launch, but also will measure the basic parameters of the pellet (size, integrity, velocity, trajectory). The main aim of the diagnostic is to detect whether the pellet is broken, spins or the flight path is tilted, thus likely will not reach the shattering plate. Additionally, to the challenging primary objectives the diagnostic, two additional functions were proposed.

1. Half of the pellet flight path is in the port plug, while the other half in the port interspace area. The two parts are joint with flexible bellows and can be misaligned as much as ~30mm due to thermal expansion of the vacuum-vessel. The diagnostic should be capable of measuring the alignment with ~1mm precision.
2. The pellet plasma interaction as well as the disruption evolution should be monitored by measuring the light intensity in three spectral regions (H, Ne lines) with sufficiently good temporal resolution. The plasma light is expected to be reflected on the shatter plate and transmitted to the observation chamber by reflections.

Design Constraints

The ITER Optical Pellet Diagnostic (OPD) will face the same harsh environment as DMS preliminary design review the applicability of the proposed system should be assessed. The main drivers of the design were: environmental factors (radiation, magnetic field), accessibility, modularity resulting from installation in a remote handling port.

An observation chamber was designed ~2 meters from the pellet gun in the port interspace area as it shown in Figure 1. The shut-down dose rate (SDDR) after ~12 days cooling time is estimated to be ~100μSv/h at the location of the observation chamber of the OPD. The maintenance of OPD parts in the interspace area is practically not possible during the nuclear phase, and access to the port cell will also be very limited. Additional to the high SDDR, the overall dose during expected lifetime of the diagnostic (10^{18} n/cm^2 neutron fluence and 1 MGy gamma) sets a strong limitation on the applicable techniques and materials. In the original concept imaging fibre bundles were proposed to transmit the collected light from the observation chamber to the detectors. The above-mentioned dose excludes imaging fibre bundles in this application, as transmission would be lost quite fast.

Optics Concept

To meet the DMS physics requirements a relatively large pellet (max. 28.5mm x 57mm) with the velocity of 100-800 m/s needs to be fired into the plasma. This hydrogen, neon or mixed pellet has to be observed in a quite small volume (<100mm flight path). The pellet will be imaged from two directions; with horizontal view and, through a mirror, with a roughly vertical one as shown in *Fig. 2* to provide 3D trajectory and better integrity information. Three high resolution images are required to be taken during the flight in the observation chamber. **The measurement aims are planned to be fulfilled by a combination of cameras and detector array.** Based on detailed optical modelling of the pellet shadowgraphy scheme was selected for the observation. Two diffusors are lit up with single fibre coupled lasers using custom designed free form mirrors. The shadow of the pellet

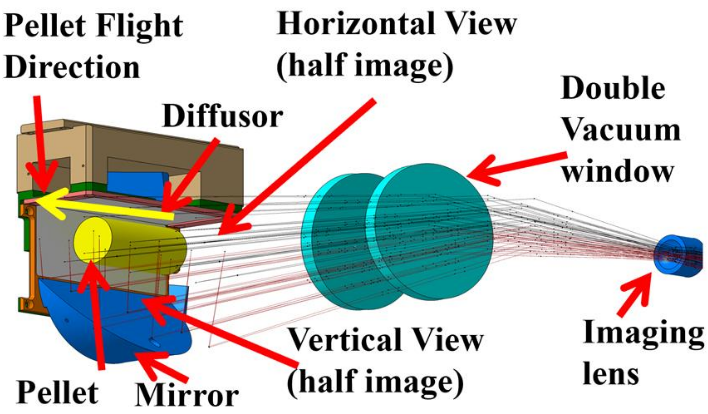

Fig. 2. Optical design of the front-end optics.

is imaged to the detectors, which gives much better contrast than the direct reflections from the pellet. The number of in-vessel optics is kept minimal, the imaging lens is placed outside of the ITER double vacuum window. The two pellet views plus the view of the end of the flight tube are combined into one image plane. This image is transmitted behind the bio-shield with a relay optics system, which is made of a combination of radiation hardened lenses and free-form and flat metal mirrors. The setup of the diagnostic is shown in *Fig. 3*. This ensures that the system should resist the harsh ITER environment.

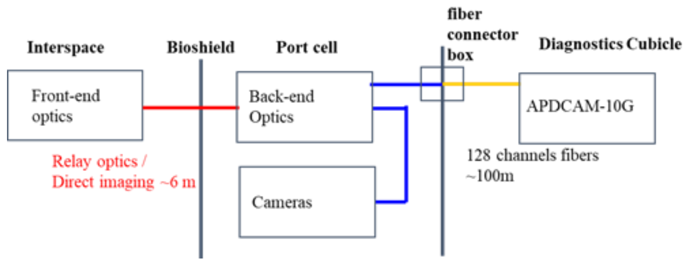

Fig. 3. Scheme of Optical Pellet Diagnostic.

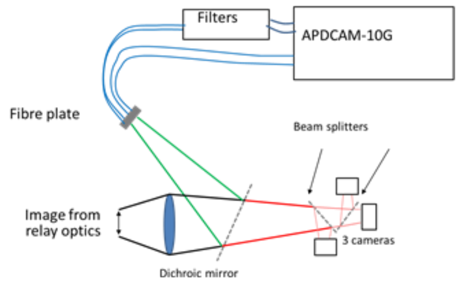

Fig. 4. Schematic of the back-end optics.

After a dog-leg in the bioshield the light is split between a camera system of three CMOS cameras and a 128 channels APDCAM-10G ultrafast high sensitivity detector camera, as shown in *Fig. 4*. The custom designed APDCAM camera is placed in the diagnostics area, where they are protected from the radiation and other environmental effects, while providing better access for maintenance. The fibres start on the fibre plate where the pellet is imaged and view along narrow lines of sight perpendicular to the pellet velocity as shown in *Fig 5*.

The APDCAM-10G camera continuously samples with 2 MHz frequency in 120 predefined spatial positions and the ***pellet properties, including the integrity and trajectory information can be reconstructed from the detector time traces***.

The APDCAM-10G camera has real-time calculation capacity in the firmware, and the pellet is detected in real-time as it flies in front of the dedicated APDCAM-10G pixels. A high-power laser with 100 ns pulse length and three CMOS cameras are triggered as the pellet arrives to dedicated parts of the observation volume, which is shown in *Fig. 5*. The CMOS camera exposure time is defined by the fast laser pulse. ***In the nuclear phase the optical pellet diagnostic will only rely***

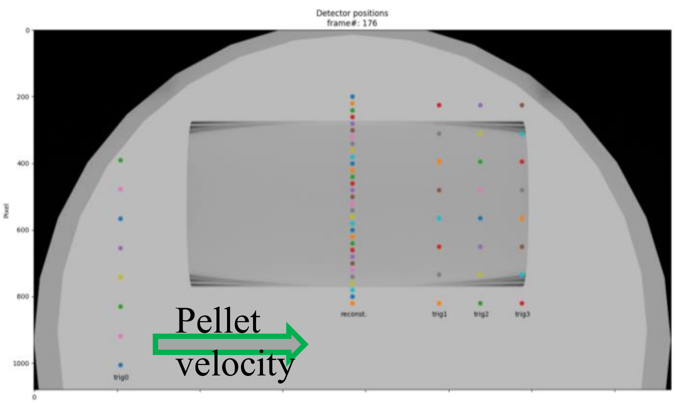

Fig. 5 Modelled pellet with optical fibers of the APDCAM-10G camera.

on the APDCAM-10G detector measurements, as the radiation will likely damage the CMOS cameras in the port cell.

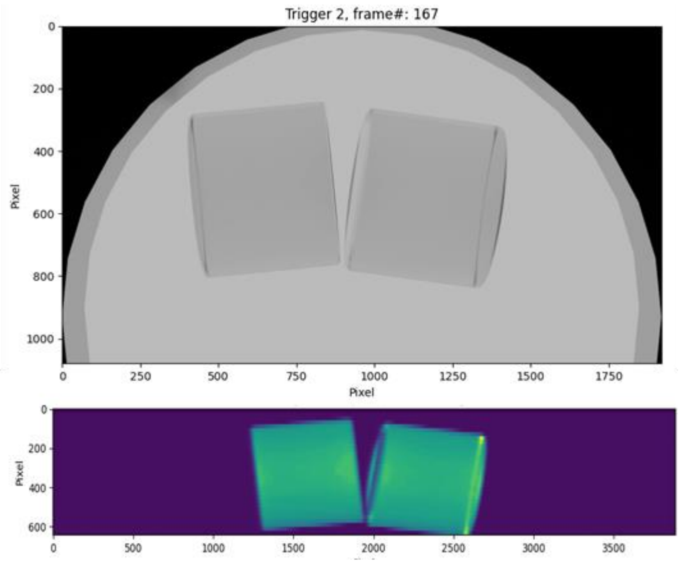

Fig. 6 Modelled broken pellet and the reconstructed image from the APDCAM signals.

Modelling

The pellet images reconstructed from modelled APDCAM signals are compared to the modelled broken images. The pellet velocity is calculated from the detector signals and used in the reconstruction method. The spatial resolution is set by the fibre size and distance in the fibre plate. The reconstruction, which is shown in Fig. 6 represents well the original modelled image.

Summary

An Optical Pellet Diagnostic is being designed for the ITER DMS system. The concept utilizes two detector systems: a CMOS camera system and an ultrafast high sensitivity APDCAM-10G detector camera. The system will provide three high resolution images of the pellet few centimetres apart as well as high temporal resolution APDCAM-10G signals, which can be reconstructed to lower spatial resolution pellet images. A radiation resistant optics, including a ~6m long relay optics system was designed, which transmits the light from the interspace area to the port cell, where the CMOS cameras are located behind the bioshield. The APDCAM-10G cameras are to be placed in the diagnostic building and connected by fibre bundles. This setup combines good spatial resolution imaging during commissioning of the system in the non-nuclear phase of ITER and still reliable operation in the nuclear phase. The optics design is finished, and the opto-mechanics are being designed and manufactured. The OPD test system will be operational in Q3 2021in the DMS test laboratory at the Centre for Energy Research, Budapest, Hungary.

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[1] M.Lehnen et al., Proceedings 27th IAEA-FEC (2018).