Investigation of pellet cloud dynamics in the magnetic geometry of Wendelstein 7-X stellarator

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Cryogenic pellet injection is one of the prime candidates to fuel large-scale fusion devices such as tokamaks and stellarators. Pellets are usually injected from the magnetic high field side (HFS) of a tokamak therefore the grad(**B**) drift polarizes the pellet cloud and the formed electric field (**E**) pushes the pellet cloud towards the plasma centre via **ExB** drift which is favourable for deep particle deposition and higher fuelling efficiency [1]. For stellarators the magnetic geometry is not axial symmetric therefore the situation is more complex and no clear advantage of the HSF pellet injection is reported yet. So far dedicated experiments to investigate the pellet cloud dynamics were conducted on tokamaks only [2][3]. These experiments are based on the observation of the visible light (both line radiation and bremsstrahlung) emitted by the pellet cloud particles. These observations can be summarised briefly as follows. As the cryogenic pellet enters the confined hot plasma it starts to ablate forming a dense cloud elongated along the field line. The cloud around the pellet is a dense spherical neutral cloud with a few centimetres diameter, shielding the pellet completely from the incoming energy flux. The spherical flow of the neutrals turns into a channel flow after their ionisation forming a magnetic field aligned cloud, extending for several tens of meters until its pressure equals the plasma pressure. The cloud closely around the pellet (the first few tens of centimetre) - observable by visible diagnostics - travels together with pellet. From time to time (typically every few tens of microseconds) part of this cloud is erupted and detached from the main cloud, and flies away with a speed of a few km/s. On ASDEX Upgrade this erupted cloud was associated with the drifting cloud showing the classical grad(**B**) drift for both HFS and magnetic low field side (LFS) injection towards the LFS of the tokamak. Additionally, an upward movement of the detached cloud was seen both for normal and reversed magnetic field, but its drive is not yet understood [2][3]. On Wendelstein 7-X stellarator similar experiments were conducted and the aim of this contribution is to summarize the results obtained so far.

For the second experimental campaign (OP1.2a) of the Wendelstein 7-X (W7-X) stellarator, started in 2017, a cryogenic pellet injector capable of both inboard and outboard injection was installed. The blower gun from ASDEX Upgrade was adapted to produce Hydrogen pellets [4]. The cylindrical pellets of 2mm diameter and length can be accelerated by Helium propellant gas to speed of maximum 250m/s with a repetition frequency up to 50Hz. The original nominal pellet size (particle content of 3.3 10^{20} protons) is reduced in the HFS (29m) and LFS (15m) flight tubes by a factor of about 0.6 and 0.25, respectively [5].

A tangentially viewing fast-framing video observation system, designed for ultra fast pellet observation (up to 600 kHz, Photron SA-5 camera), was also developed and commissioned. Presently, by selecting appropriate regions of interest on the CMOS sensor, the system can observe both inboard and outboard injected pellets with about 150kHz frame rate (6.7μs temporal resolution). The camera is triggered for each individual pellet by the light emission of the ablating Hydrogen pellet, observed by a photodiode. No wavelength selection was applied. Therefore, we assume that the majority of the detected radiation is line radiation (H_α). This way short movies about the pellets are recorded. The position of the clouds was determined by calculating the centre of mass of a certain contour (e.g. 90% of the maximum) or by manual selection. The ‘pixel’ coordinate system was calibrated to the stellarator coordinate system by assuming that the pellet (and cloud) does not leave the poloidal plane of the designated pellet injection.

For OP1.2a island divertors were installed to ensure good pumping and controlled plasma-wall interaction. The island divertor is implemented by creating large 5/5 magnetic islands at the plasma boundary intersected by the divertor plates. Significant pellet ablation (visible cloud radiation) was observed only when pellets penetrated into the confined plasma region, independently of the pellet injection direction. No significant pellet ablation was observed in the island region, independently of whether the pellet trajectory crossed the O (HFS injection) or X point regions (LFS injection).

Similar to the fast-framing video observations of ASDEX Upgrade pellet experiments, the radiation from both the cloud attached to pellet and from drifting (already detached) clouds could be observed simultaneously if the temporal resolution was better than 10 μs. Sometimes more than two detached clouds are seen on a single video frame. The W7-X video observation system allowed us to track both the attached and the drifting clouds. A database of about 90 pellets (both LFS and HFS injected) were built which contains the position of the clouds as a function of time. Target plasmas were created with various magnetic configurations: standard (EIM, ι_0~0.85 ι_a~1.), standard with reversed field and high iota (FTM, ι_0~1.02 ι_a~1.2).

To visualise the direction of the detached cloud movement, fig.1. shows their position (red symbols) relative to relative to the fitted trajectory position on the major radius - vertical coordinate (R-z) plane for HFS (a.) and LFS (b.) injection. The trajectory was fitted by using the centre off mass of the 90% contour of the maximum cloud radiation, and the attached cloud positions are also plotted (blue symbols). It can be seen here that the pellet cloud drifts dominantly outward from the plasma for both HFS and LFS injections and for all magnetic configuration. In some cases inboard drift is also observed, but at the moment we cannot determine if this is a real result or it is caused by the processing algorithm. This observation is in contradiction with tokamak results where the HFS injection case is always accompanied by favourable inboard pellet cloud drift. It appears that at the W7-X stellarator, the inboard pellet injections did not show the advantageous behaviour for fuelling.

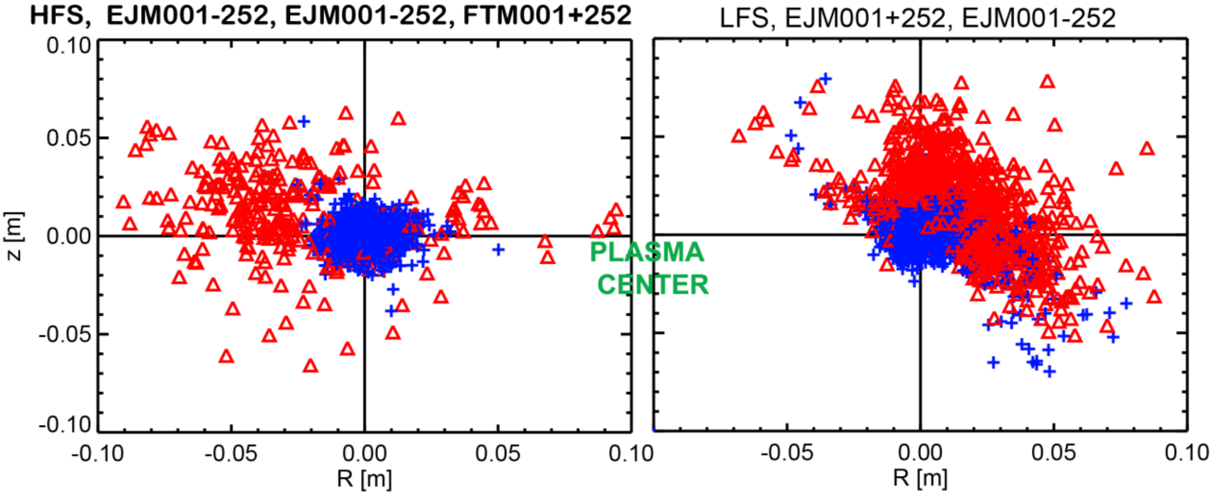

Fig.1. Position of the attached and the detached/drifting cloud relative to the fitted trajectory position for HFS (a.) and LFS (b.) injection. The trajectory was fitted by using the centre off mass of the 90% contour of the maximum cloud radiation.

To reveal the effect of the magnetic geometry grad(**B**) was calculated along the magnetic field line starting from a selected point along both the HFS and LFS pellet trajectory for all magnetic configurations. Fig.2. shows the R, z and toroidal components of the grad(**B**) as a function of the distance from the trajectory point along the field line for HFS (a.-d.) and for LFS (e.-h.) for the standard configuration. The red curves are values averaged along the pellet cloud (both direction from the pellet). The polar diagram shows the variation of the direction of the grad(**B**) on the R-z plane. As it can be seen the radial component of grad(**B**) is dominantly negative for both HFS and LFS, therefore a HFS → LFS pellet cloud drift is expected for both injection geometries, which is in contradiction with the HFS observations. We do not have an explanation of this phenomenon, even more, detailed simulations taking into account the magnetic geometry of the W7-X plasmas predicts the classical HFS → LFS drift [6]. The averaged value of the vertical component tends to zero as we move away from the pellet along the pellet cloud, which indicate that no vertical pellet cloud drift is expected. This is also in contradiction with the observation, while clear vertical drift (both upward and downward) was observed (fig.1.).

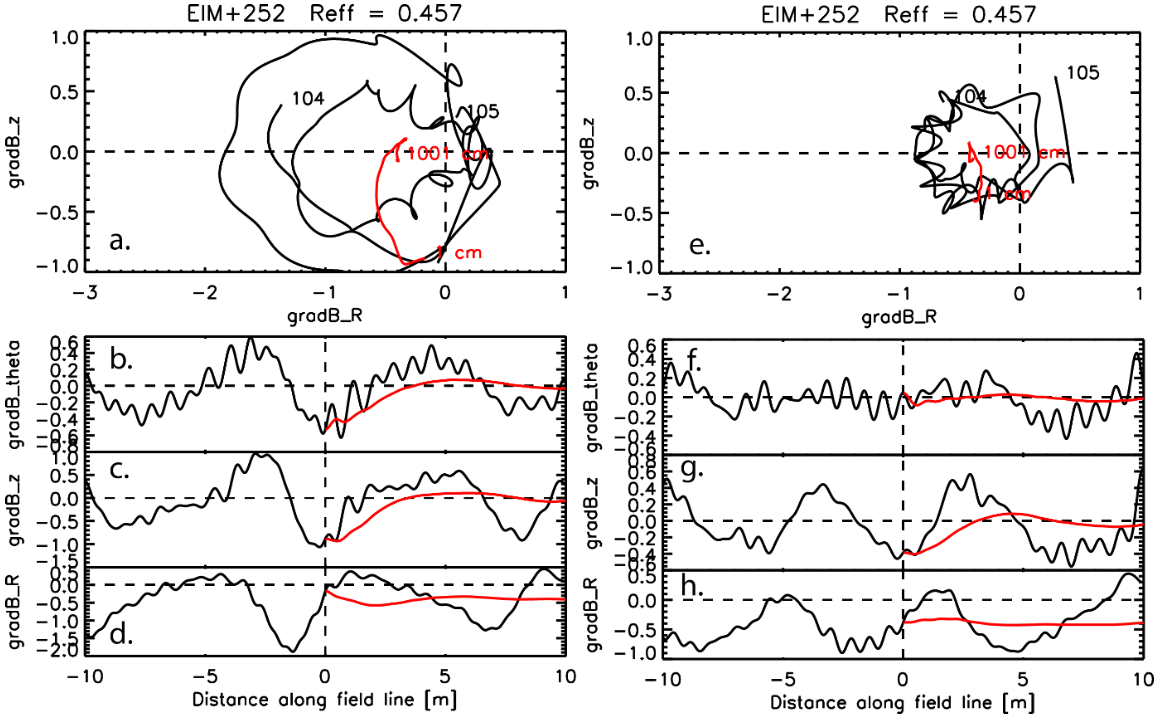

Fig.2. Radial, vertical and toroidal components of the grad(B) as a function of the distance from the trajectory point along the field line for HFS (a.-d.) and for LFS (e.-h.) for the standard configuration. The red curves show the averaged values. The polar diagram show variation of the direction of the grad(B) on the R-z plane.

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