Initial Results from the MAST Pellet Injector

C.Ribeiro, E.R.Arends[1], R.Akers, K.Axon, L.Baylor[2], J.Dowling, M.Dunstan, S.J.Fielding, L.Garzotti[3], P.Innocente[3], J.de Kloe[1], B.Sass[4], S.Shibaev, A.Sykes, P.Twynam, D.Terranova[3], M.J.Walsh[5], S.You[6], MAST and NBI Teams

EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK
[1]FOM Instituut voor Plasmafysica "Rijnhuizen", Nieuwegein, Netherlands
[2]Oak Ridge National Laboratory, Fusion Energy Division, Tennessee
[3]Consorzio RFX, Corso Stati Uniti, 4-35127 Padova, Italy
[4]EURATOM/Risø National Laboratory, DK-4000 Roskield, Denmark
[5]Walsh Scientific Ltd, Abingdon, Oxon, OX14 3EB, England, UK
[6]Imperial College of Science, Technology & Medicine, London, UK

Introduction

Injection of cryogenic pellets of isotopes of hydrogen is the most promising if not the only technique envisaged so far for refuelling the core of magnetic confinement plasmas. Pellet injection has been extensively used in conventional tokamaks [1] and recently also in the Low Aspect-Ratio Tokamak START [2,3,4]. Deuterium pellet injection into START NBI heated target plasmas resulted in the simultaneous achievement of confinement improvement ($\tau_E/\tau_{E\,(ITER97\text{-}elmf)}$ ~ 1.3-1.4) at high normalised density (Greenwald number [5] ~ 1.1) with ~100% fuelling efficiency at high toroidal beta (β_T ~27%) [3].

A pellet injection programme is currently underway in the Mega Ampère Spherical Tokamak MAST [$I_p \leq 2$MA, $B_T(R_o{=}0.7\text{m}) \leq 0.63$T, $R_o \leq 0.85$m, $a \leq 0.65$m, $R_o/a = 1.3\text{-}2.4$, $k \leq 2$, $\delta \approx 0.5$, NBI (<5MW, >70keV), ECRH (~1MW, 60Hz)]. We describe below the pellet injector hardware and bench tests, the pellet dedicated diagnostics, and preliminary modelling of ablation, magnetic field and fast-ion calculations.

Pellet injector hardware and bench tests

The 8-pellet gas gun injector (PI) built in Risø and recently modified by them to provide MAST-size pellets is now operational at Culham. The nominal cylindrical pellets (length ~ 1.3 x diameter) contain ~ 0.5,1, 2×10^{20} atoms of deuterium from small (1.08mm), medium (1.36mm), and large (1.71mm) breeches, respectively. The pellet velocity V_p ranges between 300-1200m/s. Bench tests have been carried out to characterise and optimise the performance of the pellet catcher (~1.4m length, 40mm diameter cone, $V_p < 1000$m/s) [4] coupled to either of two different guide tubes (PTFE, circular cross section, $Ø^{inner} = 4.0$mm): a test guide tube of ~ 20m length, with a single loop non-uniform radius (minimum ~2.5m), which begins and terminates at the pellet injector, and a ~25m length non-coplanar S-shaped guide tube (minimum ~3m radius) terminating at the MAST device. Low magnetic field side (LFS) mid plane, near-radial injection into MAST has initially been adopted.

Pellets are produced at temperatures between 8.5-9.5K at launch. Relatively low pellet velocity is required since fragmentation is observed in the test guide tube at velocities higher than 600m/s. Experiments using an optimised level of additional electrical heating applied to the barrels have produced U_P= 460-530m/s at low driving gas (H_2) pressure ~5bar, with no significant jitter in release time between the three different sized pellets. From these tests, we assume that pellets with velocities ~500m/s will be delivered without substantial breakage, erosion, or unpredictable time delay through the MAST guide tube (R_{min} ~3m) with little further optimisation. The MAST guide tube has now been fully connected to MAST and initial tests into plasma are commencing.

Dedicated Diagnostics

A broad range of diagnostics associated with the pellet refuelling experiments is currently being commissioned for MAST. They are shown in fig.1. and the main characteristics are summarised below.

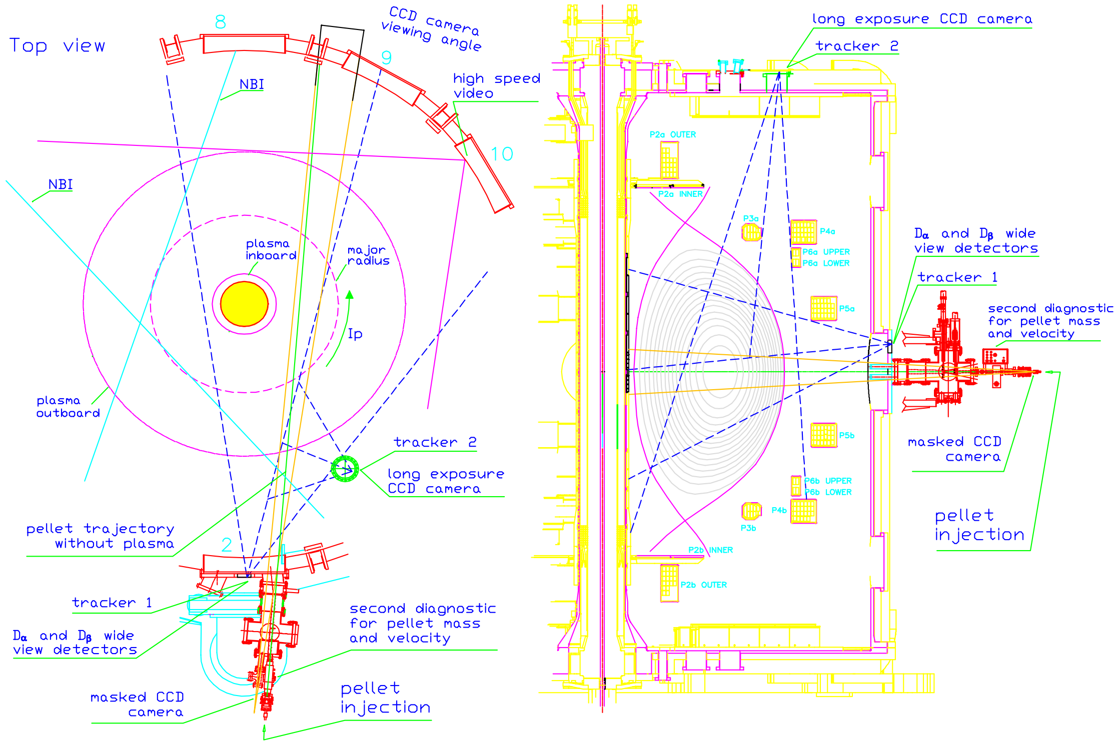

Fig.1 Pellet injection and diagnostic positioning on MAST

1-Pellet mass & velocity diagnostics: Each diagnostic unit comprises a microwave cavity and two photo-detectors barrier, measuring the pellet mass and the velocity respectively. There are diagnostic units at the PI and at the MAST port.

2- D_α and D_β detectors. The D_α signal is used for monitoring the pellet ablation rate [6]. The detectors are photo multipliers (Thorn EMI S20-9658B) with typical rise time of 10ns and quantum efficiency of 9% and 21% for D_α and D_β wavelengths, respectively. From the ratio of the D_α and D_β emission the electron temperature of the pellet cloud can be inferred as a function of time, and is a vital parameter for estimating the local pellet particle displacement due to the expected ExB drift of the pellet cloud [7]

3- Long exposure CCD camera. This is a conventional black & white Hitachi KP-M1 with 756(H)x581(V) pixels with framing and exposure times of 20ms, covering the total ablation process of consecutive pellets.

4- Pellet tracker [8]: Trackers are installed close to the mid-plane and at the top of the vessel. Each consists of a D_α light 2-D Position Sensitive Detector (PSD) which tracks the centre of mass of the emitting cloud, allowing a 3-D time resolved pellet trajectory reconstruction. Optimisation of pellet particle deposition, ablation and trajectories, and fast particle studies are the major objectives. The absolute spatial resolution is a few millimetres determined approximately by half of the pellet cloud size, ~3 cm and ~ 1cm along and perpendicular (radially and slightly high poloidally due to the local pitch angle) to the total magnetic field line direction. The time resolution is 1μs. The trackers are on loan from RFX Padua and the analysis programmes have been adapted to MAST viewing and plasma geometry.

5- Mask CCD camera: This instrument is intended to measure the local magnetic field pitch angle and the pellet cloud emission (calibrated) structure [9]. The camera uses a cooled 2D CCD sensor (1024x1152 pixels with 13x13μm pixel size) and measurements of up to 23 frames per plasma shot with highest temporal resolution of 13.4μs are possible. The sample rate will be 3MHz with 3Mb sample memory. For typical MAST vessel and plasma geometry, the ~2m distance from camera to pellet results in a spatial resolution of the pellet cloud of ~5mm. For a deuterium pellet we estimate a magnetic field pitch angle resolution of ~ 1°, which is to be compared with a target plasma such as #2482 above, in which a pitch angle of ~ 38° is predicted by LOCUST code at the outboard side (R_o+a = 1.27m).

In addition the average density of the pellet cloud can be inferred from its emission, using the electron temperature obtained from D_α / D_β ratio measurements, so avoiding the use of Stark broadening techniques that are complex and use sophisticated equipment.

All diagnostic signals are digitised by VME model units (sample rate < 10MHz, 0.5Mb memory) except the PI mass & velocity diagnostics that use a PC-card.

Modelling

Modelling of the ablation process using the PELLET code [1], without fast-ion corrections, has been performed assuming V_p= 500m/s. The target plasma is taken from shot #2482 at time 0.100s [Ip ≤ 1.03MA, $B_T(R_o)$ =0.51T, R_o = 0.74m, a = 0.53m, R_o/a = 1.4, k = 2.1, δ = 0.4, P_{inj}(NBI) ~0.5MW, q_ψ(95%) = 5.0, β_T = 3.4, β_N = 0.92). Measured electron (T_e) and density (n_e) profiles from the multi-point Thomson Scattering [10] are used and $T_e = T_i$ is assumed. Using the Neutral Gas Shielding model with mono energetic charged particles (NGS-Mono) to characterise of the surrounding plasma, the pellet penetration depth is λ_p = 0.23, 0.28, 0.31m, for the small, medium, and large pellet size, respectively. This leads to relatively deep penetrations, λ_p/a = 0.44, 0.52, 0.58, respectively. The expected ablation times are 0.47, 0.55, 0.62ms, respectively, assuming the pellet suffers no radial velocity change inside the plasma. Note that better agreement is usually observed between NGS-Mono calculations and experiment than if the local plasma is assumed to be Maxwellian (NGS-Maxw model), which tends to overestimate the ablation rate and produce lower λ_p values [1].

The local magnetic field structure at the outboard of discharge #2482 reveals no magnetic well or significant reduction of the total magnetic field decay (~1/R). Therefore no difference in the pellet particle deposition due to the ExB drift of the pellet cloud is expected compared to the counterpart scenario in conventional high aspect ratio tokamaks [3,4]. The magnetic field configuration is given by the Monte-Carlo finite Larmor radius orbits code LOCUST [11] which also predicts a fast-ion pressure profile peaked around the magnetic axis, ~ R=0.75m. Note that the large pellet is modelled to penetrate to R ~ 0.97m, which is approximately the position where the fast-ion pressure profile has decayed to half of its peak value.

Summary and discussion

The MAST multi-pellet injector is operational. Tests have shown that good transmission can be obtained through a 2.5m bend-radius guide tube provided that relatively low pellet velocities (<600m/s) are used. Injection through the 25m-guide tube into MAST is about to be carried out. A broad range of dedicated diagnostics has been installed on MAST and is being commissioned.

Modelling of pellet injection, using experimentally determined plasma profiles and an injection velocity of 500m/s indicates adequate penetration, although no enhanced ablation by fast ions has been included. Analysis of the radial distribution of fast-ion velocity and density will be conducted in order to estimate the toroidal and poloidal deviation expected for the pellet, as observed in START [3], and the effect of these ions on the ablation rate. Any pellet deviation has a direct impact on the optical view and resolution of dedicated pellet diagnostics such as the mask CCD camera as well as on the local fuelling efficiency and plasma profile control.

Acknowledgement. This work is funded jointly by UK Department of Trade and Industry, and EURATOM. We are grateful to FOM for the pellet injector, RISO for technical assistance, Consorzio RFX for pellet diagnostics and personnel, and to ORNL for the NBI system and PELLET code.

[1] Milora et al., Nucl. Fusion, 35 (1995) 657.
[2] C.Ribeiro et al., in proceedings of the 25th EPS Conference, Praha, 1998 (European Physical Society, Geneva, Switzerland, 1998), Vol. **22**C, p.842.
[3] C.Ribeiro et al., to be submitted to Phys. Rev. Lett.
[4] C.Ribeiro et al., in proceedings of the 21st SOFT Madrid 2000 (Symposium on Fusion Technology). To appear in Fusion Engineering and Design.
[5] M. Greenwald et al., Nucl. Fusion **28** (1988) 2199.
[6] M.J. Dunning et al., Nucl. Fusion **30** (1990) 919.
[7] B. Pégourié and L. Garzotti, in proceedings of the 24th EPS Conference, Berchtesgaden, 1997 (European Physical Society, Geneva, Switzerland, 1997), Vol. **21**A, p.157.
[8] Garzotti L. et al., Phys. Rev. Lett. **84** (2000) 5532.
[9] I.V. Miroshnivok, Rev. Sci. Instrum. **66** (1995) 389
[10] E.R.Arends et al., to be submitted to Plasma Phys. Controll. Fusion.
[11] R.J. Akers et al., in proceedings of the 25th EPS Conference, Praha, 1998 (European Physical Society, Geneva, Switzerland, 1998), Vol. **22**C, p.2014.