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THE JET MULTI-PELLET INJECTOR AND ITS FUTURE UPGRADES

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1. INTRODUCTION

The present multi-pellet injector operating on JET is equipped with three repetitive pneumatic guns for three different pellet sizes capable of pellet speeds to 1.5 kms^{-1}. It has now been operated for more than one year according to its specification, satisfactorily and successfully, and only minor improvements have been made during that time. The best plasma performance in its application has so far been achieved with pellet deposition near the magnetic axis now possible only with relatively cold plasmas [1]. For a given plasma the pellet speed is the only free parameter with regard to the penetration depth, since the pellet size determines the number of particles delivered to the plasma. In order to enable the central deposition also at higher plasma temperatures JET plans to employ an advanced gun system following the principles of hot pneumatics by adiabatic compression in two-stage guns capable of launching initially single, and in a later version multiple, pellets with velocities towards the 5 to 10 kms^{-1} range. We will describe here the present injector - concentrating on the launcher-machine interface and its upgrading - the development programme directed to make a single-pellet high-speed launcher possible and the planning of the implementation of this prototype launcher, as well as briefly outline the preparations for a future multi-pellet launcher system following from the prototype.

2. THE JET MULTI-PELLET INJECTOR

The presently installed injector has been jointly built by JET and the Oak Ridge National Laboratory (ORNL) under a collaborative agreement between the Joint European Torus and the United States Department of Energy which also covers the joint experimental programme for two operational periods from 1987 until 1990. A three-barrel repetitive (up to 5 s^{-1}) pneumatic pellet launcher for nominal pellet sizes of 2.7,4 and 6mm (length and diameter) - built by ORNL - is attached to a JET launcher-machine interface (Pellet Interface) which provides all services to the launcher and its immediate control system and, in particular, provides the differential pumping to match the pneumatic gun to the vacuum pressure and flow requirements of the plasma boundary. The launcher, forming its pellets by punching them with the barrel breech out of an extruded ice ribbon, is capable of accelerating pellets of hydrogen or deuterium, in numbers more than sufficient for JET (up to 32 per tokamak pulse and barrel), with speeds up to 1.5 kms^{-1}; more details can be found in [2]. With its internal gas feed system the three guns can simultaneously operate only with pellets of one sort of fuel and with a common driver gas pressure; no provision could be made to make the launcher compatible with the requirements of tritium operation and remote handling for the active phase of JET.

The Pellet Interface was from the start conceived to match the ORNL Launcher to the JET machine as well as to allow - with a minimum of upgrading - any future launcher and, in particular, two-stage guns to be installed. The current project plan foresees that a simple single-pellet high-speed gun of this type will be employed to assess its merits already in 1989, overlapping with the scheduled operation of the ORNL Launcher. The main components of the Pellet Interface are: vacuum interface comprising also the structural elements for mechanical support; liquid helium (LHe) supply and LHe intermediate storage for launchers; primary fuel and propellant gas supply; specific in-flight pellet diagnostics and signal acquisition; injector control and data acquisition interfacing to the launcher controls but expandable in their own rights for future launchers; interactive unit (PLPS) to protect the machine from undesirable pellet shots during a plasma pulse. The Pellet Interface is described in some detail in [3] and in the following only those details are highlighted which are of particular interest for the future upgrading.

2.1 THE PELLET INTERFACE - DISCUSSION OF COMPONENTS

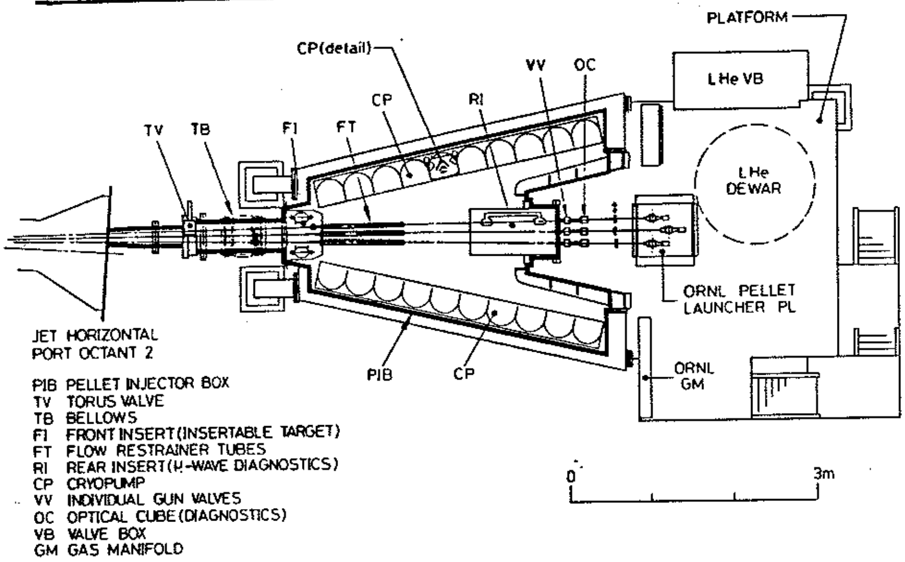

Fig 1: JET Multi-Pellet Injector Schematic - At Present

Fig. 1 shows a schematic of the pellet injector in plan view featuring the ORNL Launcher with its three barrels arranged in a plane 1.9° above the midplane of JET aiming onto a common focal point in the machine horizontal port within a horizontal cone of 4° full angle; underneath the ORNL lines mirrored by the midplane there is room for another three lines, the outer two suitable for the prototype. Pellets are launched (from right to left) and travel in free flight (i.e. without guide tubes) with a ± 0.5° divergence allowance through differential vacuum and specific pellet diagnostics (microwave interferometer to measure pellet mass and speed, pellet photography and off-line target for aiming) into the plasma.

The differential pumping is facilitated by a cryo-condensation pump of ca $8*10^6 \ell s^{-1}$ pumping speed for hydrogen in the 3.5 m long, 7 m high and 1.5 to 2.5 m wide pellet injector box (PIB) of 50 m^3 volume separated from the torus vacuum (reaching into the duct) by flow restrainer tubes of nominally 60 ℓs^{-1} conductance. Under worst conditions the 3 bar*ℓ per pellet of the ORNL 6 mm gun driver gas surge is pumped away with a time constant of ca 7 milliseconds, delivering a theoretical maximum of less than $2*10^{-2}$ mbar*ℓ of hydrogen to the plasma (corresponding to $1.5*10^{-7}$ mbar torus filling pressure); since this surge is not being delivered in an instant the actual fraction into the torus is estimated to be considerably less and has indeed never been detected by any plasma diagnostic, even when more than one restrainer tube was open to the torus. For a two-stage gun estimates of the corresponding driver gas surges (2nd stage only) go as high as 30 bar*ℓ. However, it is believed that the pellet divergence of such guns can be held to about ± 0.1°, decreasing the diameter of the flow restrainer tubes accordingly; optionally a fast muzzle valve can be installed (anyway of possible advantage to solve the piston survival problem in the two-stage gun) and/or a diaphragm, partitioning a small fraction of the cryopump, can be inserted to introduce an additional differential pump stage. The low ultimate base vacuum of the cryopump and its high pumping speed ensure that successive pellets (say more than 50 milliseconds apart) will always see less than the 10^{-2} mbar of foreland pressure believed to be not harmful to pellets in supersonic flight.

The capacity of the cryopump, which is to be regenerated before the safety limit against an hydrogen explosion in the presence of an arbitrary amount of air in the PIB is reached, is currently set at 1000 bar*ℓ. This was sufficient in the past experiments for two experimenting days on average, despite the fact that the PIB was also pumping the complete fuel extrudate of the ORNL Launcher (usually 70% of the accumulated gas). The PIB, initially designed as a pure vacuum vessel for the JET neutral beam injectors, is now being converted into a pressure vessel for 3.5 bar abs. permitting then safely a capacity of 2500 bar*ℓ (the cryopump itself is estimated to pump up to 5000 bar*ℓ and is proven to have a capacity of more than 3000 bar*ℓ). On the basis of 100 bar*ℓ per tokamak pulse on average, i.e. three large pellet shots at highest speed, and negligible amounts of gas from the pellet formation (thought to be facilitated by cryo-condensation) this will then allow operation for at least a full day, and regeneration of the cryopump can easily be performed overnight (ca 6 hours for a

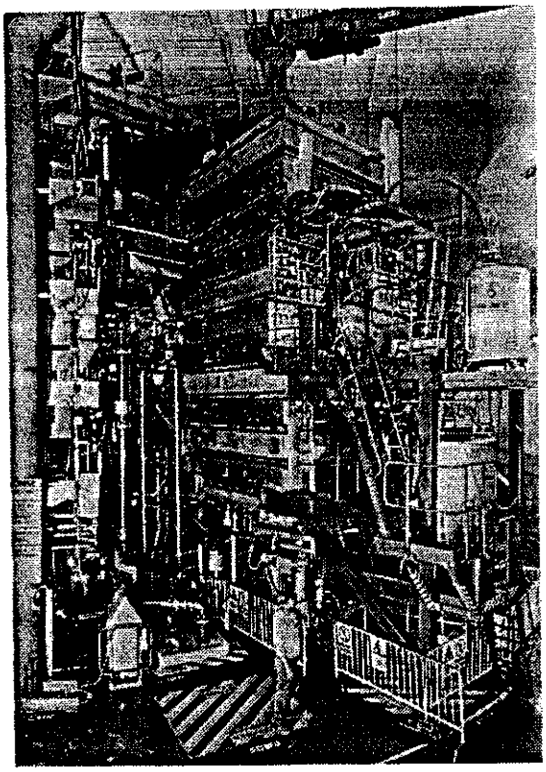

Fig 2: JET Pellet Injector

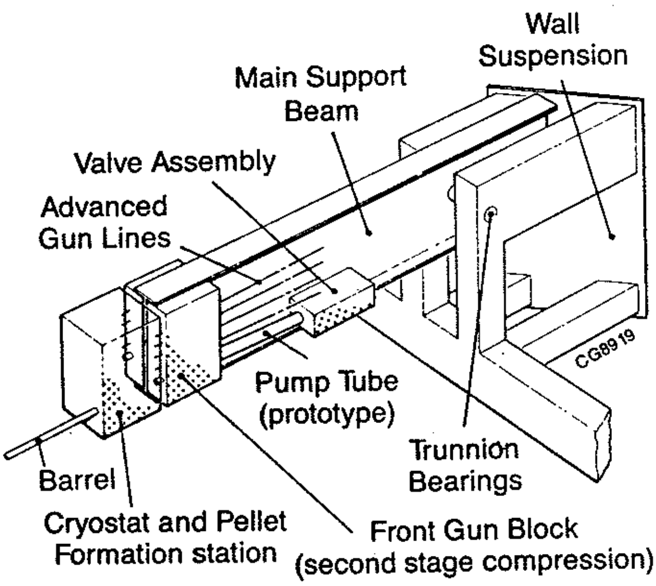

Fig 3: Artist's View of Prototype Extension

complete cycle). Under the above assumptions the differential pumping system will be adequate for the prototype launcher already now, and for an advanced repetitive launcher system in the near future.

Concerning the in-flight diagnostics, the microwave interferometer and the pellet photography are compatible with high pellet speeds as well as with the active phase requirements (in the latter case electronic components like microwave diodes and CCDs have still to be transferred to the JET basement in a known manner). The target for ultrasonic detection of pellet impact in off-line aiming, however, will not function for pellet speeds exceeding the sound velocities of any solid material (and this may be the case already for the prototype). We are pursuing the idea of an in-flight, on-line target where the pellet traverses orthogonal light curtains of spectrally dispersed light: the missing colour is the measure for the pellet trajectory cross point; for off-line testing a dump target with limited life-time will have to be provided. The description of the latter idea as well as that of the present diagnostics can be found in [4].

2.2 HIGH-SPEED GUN - MECHANICAL LAY-OUT

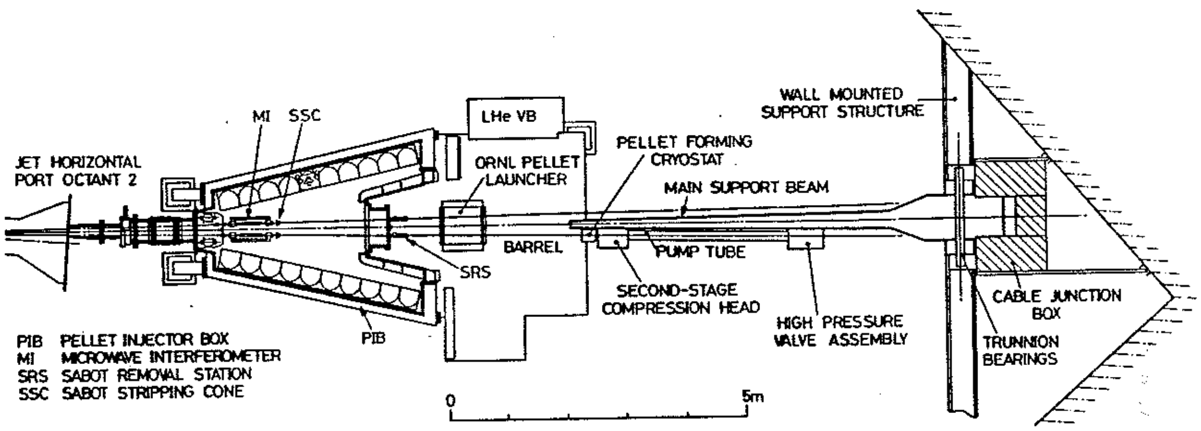

Fig 4: JET Injector Schematic - Future Upgrade

Fig. 3 shows an artist's view and Fig. 4 a schematic of the injector lay-out modified for the acceptance of two-stage guns whereby the mechanical requirements for the prototype and the advanced gun system turn out to be very similar: the main features being their lengths (for reasons of limited torus hall space the maximum length which can be made available for barrel and pump tube combined is in the order of 10 m and that may well be needed) and the impact of the piston with energies of >100 kJ which is reflected in a millisecond or so, leading to impact forces in the order of several hundred tons. The prototype as well as later guns will be mounted on a large steel beam the rear end of which is suspended from the torus hall wall by a massive structure deeply anchored into the concrete. The beam inclusive of its launchers can be tilted into a vertical position in the manner of a drawbridge to make way for the movements of large equipment around the machine; the trunnion bearings are also to take a large fraction of the piston reversal momentum. Currently the beam is under detailed design and the wall suspension is out for manufacture and will be mounted in about 2 months time.

3. DEVELOPMENT PROGRAMME

JET established closely monitored development contracts with major European laboratories to investigate the principles for building a high-speed gun, adopting the principle of "hot" pneumatics in the belief that none of the more exotic principles of pellet acceleration (like electromagnetic or rocket propulsion) can be made to work within the limited lifetime of the project. The basic philosophy of JET's approach has been outlined in [5].

Ernst-Mach-Institut (EMI), Freiburg FRG, developed in conjunction with JET the first small version of the two-stage gun with encouraging results (1985 to 1987): Using a 1.5 m long barrel of 6 mm I.D., a 1 m long cylinder (often referred to as pump tube) of 3.5 cm I.D. and a light piston of ca 0.1 kg driven by ca 200 bar into ca 5 bar of hydrogen, plastic pellets of 50 mg could be accelerated up to 4.6 kms^{-1}; using a pellet formation cryostat developed by CENG this experimental set-up produced a maximum pellet speed of unsupported 6 mm pellets of 2.7 kms^{-1}, limited by erosion effects, and of sabot supported 5 mm pellets of 3.8 kms^{-1} [6].

Centre d'Etudes Nuclaires de Grenoble (CENG) of the CEA, F, complemented the endeavour by developing suitable cryogenics for the pellet formation by cryo-condensation and established a data base for the formation of pellets as well as their mechanical behaviour during the acceleration (since 1985). A new 300 bar fast-valve was developed and 6 mm deuterium pellets were accelerated to 2.1 kms^{-1} with conventional pneumatics [7,8]. Recently a repetitive (within minutes) cryostat was developed and successfully tested which allows to cryo-condense pellets into sabots in a position outside the barrel, to compact them if needed and to finally load them into the gun breech; a second cryostat of this type was delivered to JET.

An alternative approach was followed by Riso National Laboratory, DK, who undertook to investigate an electrical arc gun (1984 to 1988): The initially promising results were finally not competitive, the major difficulties being low electrical arc efficiency, ineffective arc fuelling and impurities.

3.1 PROTOTYPE DEVELOPMENT STATUS

In 1987 JET took the decision to prepare a prototype high-speed gun for a proof-of-principle experiment; this gun should be capable, in its lifetime, of delivering a few pellets to the plasma but preferably should be ready for one shot into each tokamak pulse with a minimum of maintenance (say once a week). JET has built a testbed to integrate the above mentioned resulting elements with the aim - after some intermediate steps - to build and test a gun ready to be transferred into the torus hall where implementation preparation would proceed in parallel.

The principle difficulties lie mainly in three areas:

1) The mechanical weakness of the ice (0.5 MPa) of unsupported pellets limits the possible acceleration to ca $5*10^{6}$ ms^{-2} (and makes them vulnerable to shocks from bursting discs or similar fast valves) and the maximum attainable speed to less than 3 km^{-1} due to a velocity dependent erosion effect [6]. The technique of supporting the pellets by sabots (cartridges) has so far proven the remedy to both limitations.

2) The penalty for this measure are larger masses (factors of 6 to 30) to be accelerated requiring proportionally higher driver energies and the requirement to safely remove the sabot so that only the ice enters the

plasma. Employing pump tubes of 6 and 8 cm I.D. and by 3 m long, the previous speeds have been attained with the greater mass. First attempts of sabot removal have been successful, separating the pellet from the sabot by gas pressure, either by now deliberately using erosion effect (slotted sabot), or by using the driving pressure to pressurize the rear part of a split sabot [9]; another option is the application of eddy current heating on a thin metal film inside the sabot. The resulting pressure exerts a transverse momentum to the sabot sections causing them to part. Sabot stripping is achieved in the PIB using a cone a few meters downstream from the muzzle.

3) Even for a modest repetition requirement the pump tube piston has to survive the impact at the barrel nozzle and the tailoring of the cushion of gas not immediately leaving through the barrel is of high importance. In our guns teflon and metal pistons with teflon piston rings were already reusable for some 20 times. Cleaner solutions employing metal to metal and to ceramic low-friction partners are currently under investigation.

At present preparations are in hand for probably the final round of intermediate experiments before finalizing the design of the version to be installed on the torus after extensive testing on the testbed. The main issues are the areas listed above, as well as the soundness of conception and proof of reliability of the CENG cryostat for two-stage gun operation. We are optimistic that the prototype can operate on JET in 1989.

3.2 ADVANCED LAUNCHER PREPARATIONS

Meanwhile CENG in conjunction with CEN Saclay are concentrating their efforts to design and test a truly "repetitive" gun for several pellets per tokomak pulse approaching 1 Hz. The present phase is devoted to working out the principles and establishing the design elements. The main issues here are high-speed movements within the cryostat for re-arming the breech and the fast handling of the pump tube first and second stage gas loads. The final design, however, has to take into account the tritium and remote handling requirements, even if tritium pellets were not being employed. The latter option is still being considered. At the end of this contractual phase in the middle of 1989 the CEA hopes, in close collaboration with JET, to present a conceptual design for the advanced launcher and shows some interest in taking responsibility for its procurement provided the prototype can prove its value.

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APPENDIX 1.

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