State of the art and perspective of high-speed pellet injection technology

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HIGHLIGHTS

- Larger and hotter fusion devices require high speed pellets for fuelling and density profile tailoring.
- Long plasma pulses require repetitive pellet injector.
- A R&D program is outlined to build on existing expertise by ENEA and ORNL to build a fast and repetitive injector suitable for future fusion devices.

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ABSTRACT

The injection of cryogenic pellets from the low field side (LFS) has long been in use for core fuelling of fusion devices, but injection from the high field side (HFS) has proved to provide a more effective core particle deposition, despite the severe limitations imposed to the pellet speed (\(\leq 300\) m/s) by inboard accessibility. In the future, an alternative approach may be that of injecting high-speed pellets from the HFS, through suitable “free-flight” paths, eliminating curved transfer systems. Furthermore, the expected length of the plasma discharges will require steady-state repetitive systems. ORNL and ENEA have been collaborating on high-speed injectors since 1990; they successfully realized a high-speed repeating pellet injector (2.55 km/s at 1 Hz). Since then, good progress has been achieved on both fronts of steady-state extruders, and operation and reliability of two-stage guns. A comprehensive R&D program is therefore proposed to investigate how far speed limits and repetition rates of combined two-stage guns and steady-state extruders technologies can be extended. Simulations results are presented showing pellet penetration for several injection locations on a tokamak under construction such as JT60-SA, on the basis of one set of design plasma parameters.

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1. Introduction

The early experiments with cryogenic pellets carried out in ORMAK [1] around 1977 were motivated mostly by the need of finding methods for plasma fuelling, complementary to gas and Neutral Beam injection, in view of upcoming larger fusion devices. Injection was performed from the low field side (LFS) of the machine. However, with higher plasma temperatures and larger plasma sizes, this technique becomes increasingly inadequate to ensure effective core particle deposition with the pellet speeds that single stage guns can produce. More recent results have shown that the pellet mass deposition is strongly affected by the injection location with respect to the toroidal magnetic field [2]. Injection from the high field side (HFS) gives better results, despite the severe limitations imposed to the pellet speed (\(\leq 0.3\) km/s) by inboard accessibility. As of today, laboratory tests indicate the maximum speed for the delivery of intact pellets with large curvature guiding tubes to be limited to 1 km/s, with great effort and at the cost of a large erosion (only 20% of the original mass is delivered). For reasonable pellet sizes, this speed is barely sufficient to reach inside the pedestal region of future burning plasma reactors [3]. An alternative approach may be that of injecting high-speed pellets from the HFS, through suitable “free-flight” paths, thus eliminating curved transfer systems [3].

Furthermore, since the expected length of the plasma discharges will require repetitive systems, capable of firing pellets at frequencies no less than 10 Hz (according to present DEMO requirements), the development of such systems is also going to be discussed here.

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On the contrary, the use of pellets for ELM mitigation, important as it is, will not be addressed in the present work.

The purpose of this paper is indeed that of reviewing the results obtained with two-stage guns (TSG), including those that have never been operated on actual machines, and of repetitive systems, to highlight their achievements and to point out the improvements needed for possible applications to the fusion devices of next generation.

Building on the expertise deriving from the long-time collaboration of ORNL and ENEA on high speed injectors [4], a comprehensive R&D program is proposed that includes several innovative techniques, to investigate how far speed limits and repetition rates of combined two-stage guns and steady-state extruders technologies can be extended. Simple simulation results are presented to determine the best pellet injection options based on the expected plasma parameters for future devices, for example JT60-SA.

2. State of the art for high speed pellet injectors

Conventional injectors, based on single-stage pneumatic guns or centrifuges, can reliably provide cryogenic pellets (with diameters of 1–10 mm) at speeds up to 1.3 km/s and suitable repetition rates (1–10 Hz or greater). Alternatively, a limited number of pellets can be produced in separate barrels before the plasma pulse and fired sequentially [5] during the pulse.

“Pipe gun” injectors, based on in situ condensation of hydrogen/deuterium pellets, have proven to reliably achieve velocities over 3 km/s in the laboratory, when combined with two-stage pneumatic guns [6,7], as well as up to 2.5 km/s on the FTU machine in the single barrel configuration [8], thus the speed being limited in this case by the small size of the plasma. A multi-shot (8 barrels), two-stage injector for FTU was also tested in the laboratory [9]. The most advanced version of the two-stage “pipe gun” injector is the four-barrel injector (of different diameters) IPI, built in collaboration between ENEA and ORNL for the IGNITOR experiment, and designed to reach 4 km/s with pellet diameters between 1.9 and 4.4 mm [10]. To extend its functionality, each barrel is permanently equipped with both single and double stage valves that can be alternatively operated without requiring manual intervention (Fig. 1).

The quest for intact, high speed pellets has highlighted a number of critical issues associated with pellet formation and propulsion. Regarding the former, good temperature control during the ice formation is a key factor to determine the final strength of the pellet: temperatures need to be smoothly lowered to ~7 K and kept stable to ensure good resistance. For the latter, an innovative magnetically actuated valve has been adopted for proper shaping of the propellant pressure pulse to improve pellet acceleration. The use of fast closing valves (<10 ms, patent pending) allows to drastically reduce the expansion volumes of the propellant gas removal system (Fig. 2). The set of sophisticated diagnostics that have been installed on the IPI injector has allowed to detect some second order effects preventing the pellets from reaching intact the target at higher speed, such as the thickness of the barrel bore, or the changes in flight asset causing the pellet to hit the side of the narrow channel guiding the pellet through the light gates and microwave mass probe [11]. While these technical problems have been addressed, lack of funding has prevented new experimental campaigns to take place to verify if all problems have been solved. At present only the single stage part of the injector is routinely in use, thanks also to the possibility of remote access control implemented on the system [10], for studies aimed at minimizing the amount of propellant gas following the pellet [12], and to characterize a selectable guiding tube system [13].

3. Progress with repetitive injectors

Pipe-gun injectors, in their present configuration, are not ideal for repetitive, semi-continuous operations, as required by envisaged long-pulse devices, since the proper formation of a pellet takes times of the order of minutes. In the area of repetitive systems, other than those characterized by very low pellet speeds, in the 1990s a test facility was assembled at ORNL, combining a Frascati repeating two-stage light-gas gun and an existing ORNL piston extruder, equipped with a pellet chambering mechanism/gun barrel assembly. The main issues to be investigated were the strength of extruded deuterium ice as opposed to that produced by in situ condensation in pipe guns (hence the highest acceleration which can be given to the pellet without fracturing it), and the maximum repetition rate at which the system could operate without degradation in performance. The original goal of this Frascati/ORNL collaboration was thoroughly met in the course of three joint experimental campaigns carried out in 1993–95, with sequences of up to 30 pellets launched at a repetition rate of 1 Hz and speeds up to 2.5 km/s [4]. The extremely compact design of the TSG, featuring small reservoir and pump tube volumes, as well as a very light piston with a short stroke time inside the pump tube, was a deci-

Fig. 1. The single and double stage valves installed on the IPI 4-barrel, TSG injector at ORNL (from [12]).

Fig. 2. The gas removal system associated to the fast closing valves for the IPI injector.
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