A COMPACT FLEXIBLE PELLET INJECTOR FOR THE TJ-II STELLARATOR

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Abstract— **A compact multi-barrel pellet injector system is being developed for the TJ-II stellarator. Its design is based on the system currently installed at the MST facility (Univ. Winconsin) and will provide maximum flexibility at minimal cost, while also allowing for future upgrades. It is a four-barrel system destined for use both as an active plasma diagnostic and as a plasma fueling source. In order to achieve both objectives it will be sufficiently flexible to allow frozen hydrogen pellets with diameters from 0.4 to 1 mm to be formed and accelerated to velocities between 100 and 1000 m s^{-1}. However, floor space restrictions and nearest-neighbor considerations limits the overall length to <1.7 m (mechanical punch end to final guide tube interfaces). This will be done by redesigns of the MST gun barrel, vacuum coupling, gas dump and guide tube sectors. Finally, the system is completed by stand-alone instrumentation and controls, as well as LabView controlled gas manifolds.**

Keywords-component; stellarator; diagnostics; pellets; fuelling; hydrogen.

I. INTRODUCTION

The TJ-II is a 4-period, low magnetic shear, stellarator device with average minor radius ≤ 0.22 m and major radius of 1.5 m whose magnetic configurations are created by a series of external toroidal, poloidal and vertical field coils [1]. It has been designed to explore a wide range of rotational transforms ($0.9 \leq \iota(0)/2\pi \leq 2.2$) in low shear configurations ($\Delta q/q < -6\%$ in vacuum). To date, central electron densities and temperatures up to 1.7×10^{19} m^{-3} and 2 keV respectively have been achieved in plasmas created and maintained by electron cyclotron resonance heating (ECRH) (f=53.2 GHz tuned to 2nd harmonic, $P_{ECRH} \leq 600$ kW, X-mode polarization). Operation has now commenced of one of two neutral beam injectors (NBI) each of which can produce ≤300 ms pulses of neutral hydrogen accelerated to 40 keV to provide up to 1.2 MW of absorbed additional heating for central electron densities up to 1.6×10^{20} m^{-3} [2]. Furthermore, the possibility of achieving high-density plasmas using Electron Bernstein Wave Heating (EBWH), which has been used successfully in the W7-AS and H-J stellarators, is being explored [3]. It offers a way of overcoming the cut-off density limit associated with ECRH methods (1.7×10^{19} m^{-3} in TJ-II). Preliminary studies highlighted several promising EBWH first harmonic schemes, *i.e.* at 28 GHz [4]. However subsequent studies showed O-X-B1 mode (O mode is converted into X mode which is then converted in EBW absorbed at first harmonic) to be most effective for $n_e(0) \geq 1.1 \times 10^{19}$ m^{-3} [5]. Nonetheless, it comes with the drawback that when $n_e(0)$ drops below 1.1×10^{19} m^{-3}, O-X conversion fails with a subsequent total loss of efficiency. Hence, ECRH together with extra gas puffing, or pellet fuelling, must be used in order to overcome this and achieve the high density required.

For several decades high-speed frozen-pellet injection (PI) systems have been exploited both as diagnostics and for core fueling in magnetically confined plasma devices [6]. Dedicated PI systems are now operated on numerous middle and large-scale fusion devices [7], [8]. It is now intended to install a PI on the TJ-II stellarator. After detailed assessments from scientific, engineering, and economic points-of-view, the model selected is an upgraded version of the Madison Symmetric Torus (MST) system, at Univ. Wisconsin, Madison [9]. This system, generally referred to as a “pellet injector in a suitcase”, consists of a pipe gun device with a four barrel, a cryogenic refrigerator for *in-situ* hydrogen pellet formation, associated diagnostics and a pellet injection line.

II. DESIGN CONSIDERATIONS

Although the technology is mature several challenges exist for the TJ-II PI. In the first instance miniature pellets (≤0.5 mm diam.) are required to avoid raising the density above the gyrotron cut-off, *i.e.* 1.7×10^{19} m^{-3}. These sizes will push current technology and know how, in particular the mechanical punch/propellant valve propulsion system. Furthermore modifications are needed to the light-gate and microwave-cavity pellet diagnostics in order to maintain sensitivity over the pellet size range (0.4 to 1 mm). In addition, floor space restrictions and nearest-neighbor considerations require that the PI´s overall length be minimized (mechanical punch end to final guide tube interfaces). This will be achieved by a redesign of the MST gun-barrel, vacuum-coupling and gas-dump sectors. In the following sections, a brief description of the pellet injector will be provided.

A. TJ-II geometry

The TJ-II possesses a complicated vacuum-vessel geometry, a bean-shaped plasma cross-section and a fully 3-dimensional plasma structure [1]. See Fig. 1. Nonetheless, it has excellent diagnostic access (96 portholes distributed among 32 sectors). After reviewing considerations such as occupancy [10], NBI shadow [2], plasma orientation with respect to the central coil,

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and porthole availability, sector B2, which possesses direct line-of-sight access from top, outside, and bottom portholes, as well as from a tangential porthole located in the nearby sector A8, was selected. See Fig. 2.

B. Pellet size and velocity

Modeling performed with a Neutral Gas Shielding (NGS) pellet ablation code predicts that the largest frozen hydrogen pellets that may be injected into TJ-II ECRH plasmas are 0.4×0.4 mm^2 (cylinders) [11]. This is equivalent to 3×10^{18} particles. Larger pellets can trigger plasma collapse by increasing the electron density above the gyrotron cut-off value, *i.e.* 1.7×10^{19} m^{-3}. The modeling also predicts that miniature pellets must be accelerated to several 100´s m s^{-1} in order to penetrate into such plasmas Delivery of intact miniature pellets at such velocities will be a challenge.

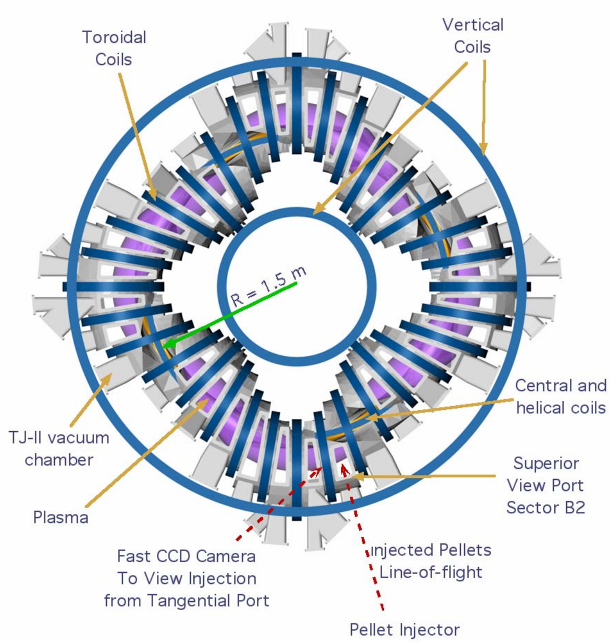

Figure 1: Top view of the TJ-II stellarator showing the coils, vacuum chamber, plasma plus locations of heating systems and diagnostics.

An EBWH system, operating in O-X-B1 mode, is being commissioned for TJ-II in order to achieve efficient microwave heating for central densities, $n_e(0)$, near and above 1.3×10^{19} m^{-3}. Moreover the O-X-B1 scheme is effective only for $n_e(0)$ $\geq1.1\times10^{19}$ m^{-3}. Pellet injection at high velocities ($\leq$1000 m s^{-1}) offers an efficient means of achieving such central densities when heating with ECRH, whilst a multiple-barrel PI system provides additional flexibility as more pellets, in particular large ones (up to 1 mm), can be injected sequentially to maintain or further increase density.

Finally, plasmas with line-averaged electron densities $\geq6\times10^{19}$ m^{-3}, central electron temperatures, $T_e(0)$, between 200 and 300 eV, and ion temperatures, T_i, above 120 eV have been attained with NBI additional heating [12]. NGS modeling predicts that pellets can reach the center of NBI plasmas when accelerated to low velocities, e.*g*., ~200 m s^{-1}. Accelerating to high velocities is undesirable as little ablation will occur. In addition, these pellets injected can be large, $>10^{19}$ particles, in order to have a notable contribution to fueling.

C. Nearest neighbor and space considerations

Firstly, the requirement to deliver unbroken miniature pellets accelerated to $\leq$1000 m s^{-1} rules out locating the PI far from the TJ-II since they would not survive being fired along curved guide pipes due to stresses from centrifugal and impact forces [13]. Rather, they would only survive such velocities along straight or very loosely bent guide pipes. Secondly, the high occupancy of floor space around sector B2 limits the overall PI length to $\leq$1.7 m (from rear of the propulsion system to the final PI/TJ-II coupling interface).

D. Additional design considerations

Additional design features include the capability to vary the pellet line-of-flight as the TJ-II magnetic axis location is dependent on magnetic configuration. For example, the plasma center can vary by ±5 cm in the vertical. In addition, a 60 mm guide pipe separation, as well as the small plasma minor radius ($\leq$22 cm) and the 4 times periodicity, necessitates slight bending (*i.e.* large curvature radii) of some of the final guide tubes so that all lines-of-flight pass through the plasma center.

III. TJ-II PELLET INJECTOR

A. Pellet Injector System

The TJ-II PI is a modified version of the "pellet injector in a suitcase" type developed at Oak Ridge National Laboratory (ORNL) and installed on the Madison Symmetric Torus (MST), *i.e.*, a 4 barrel pipe-gun device [8], [9]. It will have the same capacity but only two barrels will be incorporated when delivered (additional barrels will be installed later). The TJ-II PI will be as flexible as possible with minimum cost. Hence tried and tested technology will be employed whenever possible (*e.g.* propellant valves, *etc.*). For instance, slightly modified designs will be used for the vacuum chamber (gun box), the cryogenic cold-finger and refrigerator interface, and the combined mechanical punch/propellant valve firing system. See Section III.C.

B. Pellet Propulsion

Each injection line can be equipped with a mechanical punch/hydrogen propellant valve combination or a close-coupled hydrogen propellant valve; these acceleration options provide pellet velocities from ~100 to ~1000 m s^{-1}. The mechanical punch is of standard design although the requirement for reduced pellet sizes, $\leq$0.5 mm, necessitates additional testing, and possibly some modification, to ensure reliable pellet breakaway; small bursts of propellant gas can be supplied to boost acceleration. For higher velocities, the close-coupled propellant valve design employed in the compact flexible PI system on MST will be used [9]. The valves are set to predetermined pressures using a gas manifold consisting of valves, pressure transducers, volumetric tanks and tubing to supply gas both for pellet formation and propulsion.

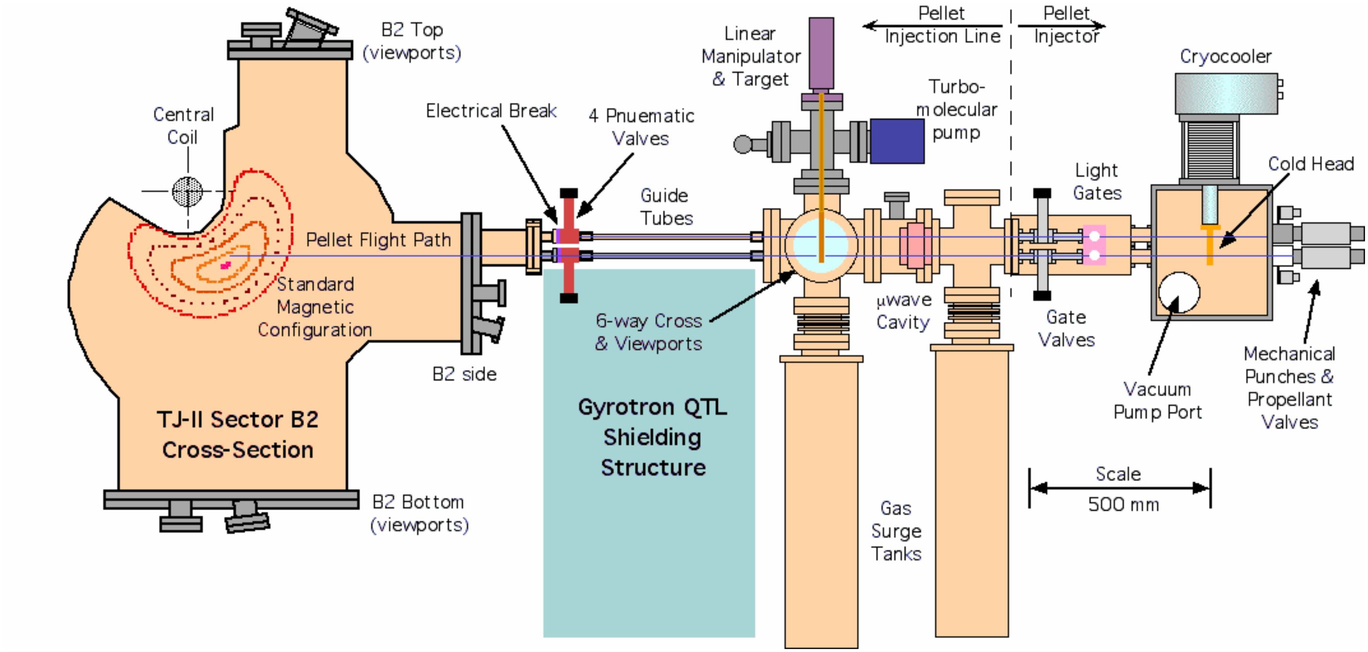

Fig. 2. Schematic cross-section of the TJ-II vacuum chamber and pellet injection systems.

C. Pellet Injection Line

The TJ-II PI length limit necessitates combining, eliminating or redesigning several of the components in the MST PI line, in particular a shortened gun barrel, redesigned vacuum coupling and gas dump sections [14]. In the first instance only minor changes to the designs of the gun box, the light gate/photography station and gate valve assembly, and the microwave cavity vacuum chamber are required. However, a redesign of the PI line, while maintaining all essential features, was made. See Fig. 2. First, a four-way vacuum cross provides vacuum flange ports for mounting a turbomolecular-based vacuum system (the pressure must be $\leq 10^{-7}$ mbar to open to the TJ-II vacuum chamber) and a gas surge tank. Second, a 6-way cross provides mounts for a second surge tank, a target plate mounted on a vacuum linear manipulator, and two viewports for visual access. This plate provides a target for test firing pellets when the mini pneumatic gate valves at the TJ-II vacuum port are closed. The target is a 1 mm thick plate that can be lowered into and raised out of the line. One of the important aspects of this redesign was to ensure that the propulsion gas removal, the pellet diagnostics and system testing were not compromised. Estimates for gas removal.

D. Diagnostics

The TJ-II PI is furnished with a similar set of diagnostics to that of MST, *i.e.*, fast pressure transducers on the propellant gas exhausts, shock accelerometers on the pellet punches, light gates (timing information) and photography stations on the gun barrel muzzles close to the gun box, and a toroidal microwave cavity (pellet mass measurement plus additional timing information) located downstream to intercept and simultaneously monitor all four guide tubes [9]. A toroidal microwave cavity similar to but narrower and shorter than the MST version is being prepared. A frequency of 13 to 14 GHz will be required in order to detect pellets in the 0.3 to 0.8 mm range. This corresponds to between 3×10^{18} and 3×10^{19} hydrogen atoms. Finally, the 0.5 m light-gate to microwave cavity separation, fixed by the length limitation, will not compromise pellet velocity measurements (at 1000 m s^{-1} the time interval between signals is 0.5 ms).

E. Controls and Data Acquisition

PI control and data collection will be incorporated into current TJ-II systems. TJ-II protocol stipulates that all diagnostics be controlled remotely during device operation. The TJ-II PI will use stand-alone instrumentation that is personal-computer (PC)-based and housed in a single instrument cabinet. System controls are handled with National Instruments input/output cards operated with LabView software. Integration is done via an Ethernet network and HTML pages [14]. These can be accessed from the TJ-II control-room during device operation. For data collection a set of fast channels, arranged on commercially available four-channel PCI boards mounted on the controlling PC, will collect signals from the shock accelerometer, pressure transducer, light-gate and microwave cavity. These acquisition boards provide up to 10 Msample s^{-1} sampling capability as well as 12-bits of ADC resolution. The resultant data will be incorporated into the TJ-II data acquisition system for subsequent analysis. Several TJ-II diagnostics use this autonomous system, which is controlled by in-house software developed using LabView [15], hence development work will be minimal.

F. PI to TJ-II Coupling and Support Structure

Quasi-transmission line (QTL) shielding in the neighboring Sector B3 partially obstructs access to Sector B2. See Fig. 3. In order to circumvent this problem a PI to TJ-II coupling comprising of four guide tubes fitted with small vacuum bellows, electrical isolators, and miniature pneumatic gate valves, plus an adapter flange mounted on the tube protruding from the B2 access port, is proposed. The guide tubing and vacuum bellows (straight or slightly curved) permit raising and lowering the PI in order to vary the lines-of-flight through the plasma center by ± 5 cm, while the pneumatic vacuum valves protect the TJ-II against sudden vacuum pressure increase. The PI and all its components will rest on a dedicated support structure with up/down movement. The swivel of this structure is limited to ±3º. Finally, Telfon® o-rings and screw inserts provide an electrical break with the TJ-II vacuum chamber.

H. Timetable

PI fabrication and testing will continue through 2005 in parallel with support structure and access port manufacture. It is expected to commission the PI on TJ-II in mid-2006.

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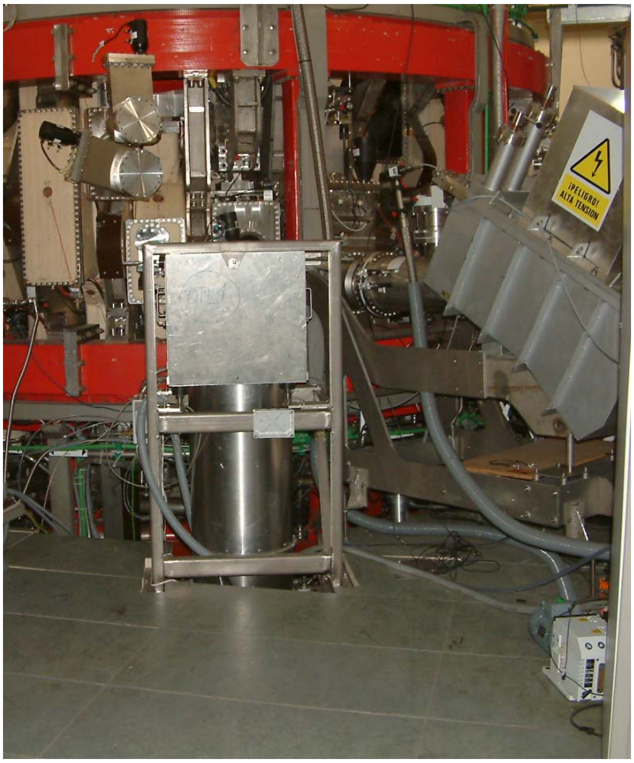

Figure 3: Photo of sector B3 showing the side access port and QTL support structure plus shielding.

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