Low Velocity Boron Micro-Pellet Injector
For Edge And Core Impurity Transport Measurements

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Abstract

A simple Low Velocity Boron Micro-Pellet Injector has been under development for CDX-U Spherical Torus edge and core impurity transport measurements, and wall conditioning. The injector consists of 16 barrels on a rotatable turret. Each barrel can be loaded with boron powder particles of diameters ranging from 1 to 40 micron diameter in amounts ranging from less than 0.25 mg to more than 2 mg. A selected barrel is manually rotated into firing position using a vacuum precision rotary / linear motion feedthrough. A piezoelectric valve gas feed system triggered by CDX-U discharge timing is used to control H_2 or D_2 propellant gas at a cylinder pressure of 5.8 x10^{-3} Pa (40 psi) or less. The injector barrel-to-CDX-U plasma edge distance is 0.47 m. Initial low mass injections of neutral boron beams were performed into CDX-U plasmas at a velocity of 23 m/s. Measurements were obtained with a filtered gated CCD TV camera, bolometry, visible spectroscopy, and ultra soft x-ray diagnostics. This work is in support of the present CDX-U research program and possible applications on NSTX.

I. INTRODUCTION

High velocity, pneumatic, pellet injection systems are applied routinely for injecting frozen pellets of hydrogen, deuterium, and tritium into the cores of magnetically confined plasmas for fueling, transport, and pellet ablation studies.[1] In addition, similar pellet injection systems have been used to inject low-Z impurity pellets for diagnostic [2] and wall conditioning [3,4] applications. The pellet injection systems used in these applications are typically based on designs requiring sufficiently high pellet injection velocities to insure penetration into the cores of high density, high temperature reactor grade plasmas. Typical pneumatic pellet injection velocities range from about 300 m/s to 1600 m/s. The upper velocity limit is determined by the propellant gas dynamics and the particular injector design; the lower velocity limit is determined by the need for sufficient propellant pressure to dislodge the frozen pellet from the apparatus and initiate its acceleration.

The fueling requirements of large, reactor grade, plasmas continue to motivate the search for higher velocity pellet injection methods including pneumatic, electromagnetic, and centrifuge designs. However, other pellet injector applications could benefit from designs allowing very low injection velocities. Applications involving small, low density, or low temperature plasmas, for example, can make use of lower pellet injection velocities. In addition, plasma edge studies and wall conditioning applications can make use of injection velocities low enough to place pellets at controlled penetration depths in the edge plasma. Applications involving short penetration distances and/or low plasma temperatures require pellet masses small enough to ablate within the desired range. The typical frozen deuterium pellet sizes of about 2 mm diameter, for example, are too large for low velocity applications. Pellets composed of clusters of micron-size particles can be used to facilitate the required ablation rate. This paper describes a simple Low Velocity Boron Micro-Pellet Injector that has been developed for the Current Drive Experiment Upgrade (CDX-U) research program [5], and used to obtain preliminary results for edge and core impurity transport measurements and wall conditioning applications.

II. EXPERIMENTAL APPARATUS

Fig. 1 shows a partial schematic elevation view of the CDX-U Low Velocity Boron Micro-Pellet Injector. The injector consists of 16 barrels on a rotatable turret. Each barrel can be loaded with micron-size boron powder in amounts ranging from less than 0.25 mg to more than 2 mg. A selected barrel is manually rotated into firing position using a precision vacuum rotary feedthrough. A piezoelectric valve gas feed system triggered by CDX-U discharge timing is used to control H_2 or D_2 propellant gas.

The injector is housed in standard commercial vacuum hardware, a "6-Inch Tee" with 11.4 cm I.D. copper conflat flanges. The Tee is oriented with its long-axis horizontal along a CDX-U major radius and its short axis vertical to provide a top view-port. A precision rotary motion feedthrough device with a linear motion feature is mounted off the chamber centerline and connected to the turret, so that as the turret is rotated, successive barrels are brought into alignment with the fixed propellant tube and the CDX-U major radius. The injector could be isolated from the torus by a Torus Interface Valve (TIV). In the initial experiments the distance from the barrel output to the CDX-U edge plasma was 0.47 m.

Fig. 2 shows an expanded view of the 16 barrel rotatable turret and propellant tube in (a) the rotatable position, and (b) in the engaged position. The barrels were fabricated from standard hypodermic needle stock. In the present embodiment, all 16 barrels are 1.91 cm long, 304-SS tubing with an inside diameter of 0.113 cm. The barrels are pressed 0.32 cm deep into equally spaced holes in the 0.95 cm thick, 8.89 cm diameter, aluminum turret and then swaged at the counterbore end. The turret perimeter opposite each barrel is stamped with an identification number to allow barrel identification through the view-port. The input to each barrel has a counterbore of 0.64 cm I.D. and 0.32 cm deep to receive the propellant tube. The propellant tube can be inserted or removed from the turret counterbore using the linear motion feedthrough. An O-ring is mounted near the end of the propellant tube to reduce gas leakage between the propellant tube and the turret counterbore. Other barrel diameters or combinations of various barrel sizes can be easily installed on similar turrets for various experiments.

The barrel positioning was accomplished by first using the linear motion feedthrough to establish a small gap between the turret and the propellant tube (Fig. 2a). The selected barrel was rotated into alignment with the propellant tube axis. The linear motion feedthrough was used to pull the turret gently toward the propellant tube until it was inserted into the counterbore of the barrel input, and the O-ring was pressed against the turret (Fig. 2b).

The propellant tube receives gas from a standard commercial piezoelectric pulsed valve [6] adapted from the gas feed system of the PBX-M Neutral Beam Injection System. The valve is mounted on one end of a 5.1 cm diameter by 15.2 cm long, 304-SS cylinder. The cylinder provides a reservoir of gas beyond the piezoelectric valve for smooth flow into the propellant tube. During the initial experiments, the input to the piezoelectric valve was connected to a standard deuterium gas bottle throttled to a pressure of 5.8 $\times 10^{-3}$ Pa (40 psi). The normal piezoelectric valve opening voltage is about 30 V. However, to insure the prompt, reproducible opening of the valve, a special circuit [7] was used to apply a 10 μsec wide, 200 V voltage spike on the leading edge of the voltage waveform applied to the piezoelectric valve, followed immediately by a reduction of the applied voltage to the operating level. This method overcomes any too strong opening inertia or sticking of the valve seal, and has been found to give reliable and reproducible operation for many years on the gas inputs of the PBX-M Neutral Beam ion sources. The piezoelectric valve circuit was triggered by the CDX-U discharge timing system.

III. EXPERIMENTAL METHOD

In the initial CDX-U boron injection experiments, the micro pellets consisted of 40 micron diameter boron particles assembled into a macro-pellet with various total masses in the range from 0.5 mg to 2 mg. Since such small masses are difficult to measure and prepare, a special preparation technique was developed for the initial experiments. The barrel loading procedure made use of a hypodermic needle-loader device. The needle-loader had an internal diameter of 0.81 mm. A tight-fitting internal plunger was placed in the needle and adjusted so that it was retracted from the end of the needle by an amount equal to the desired pellet length. The needle-loader assembly was inserted into loose boron powder with the plunger set so as to make compacted boron macro-pellets of length 1.5 mm long and 0.81 mm diameter. The needle-loader assembly with its boron load was then inserted into a selected injector barrel. The plunger within the needle was then used to move the compacted cylinder of boron particles from the needle-loader into the barrel. Fifteen barrels were loaded in this manner and one was kept empty for gas throughput tests. Assuming that the powder-density (packing fraction) of the compacted boron was about 0.5 of that of solid boron, this technique produced an estimated total mass of about 0.92 mg. In later work, this packing fraction will be calibrated with an electronic scale.

The appropriate injection trigger time for the initial experiments was determined by varying the gas valve trigger time prior to CDX-U start of discharge and observing the initial effects on the plasma as discussed below. Using this procedure, it was found that the optimum delay was about 21 ms earlier than the desired time for boron appearance in the discharge. Assuming negligible time delay due to the injector gas valve opening with the trigger circuit discussed above, and the micro-particle acceleration time, an approximate transit time of 21 ms for the 0.474 m from the barrel to the plasma edge yields an injection velocity of 22.6 m/s.

Fig. 3 is a partial schematic plan view showing the relative locations of the Low Velocity Boron Micro-Pellet Injector and the diagnostics on CDX-U used for the initial experiments. In future experiments, the injection velocity will be measured directly within the injector using an optical technique, as well as, a fast CCD camera viewing the injection trajectory in the CDX-U plasma. This will allow for monitoring of possible shot-to-shot variations of injection velocity and plasma conditions.

IV. Initial Results

Fig. 4a shows the CDX-U discharge wave-forms without boron injection for the plasma current (I_p), density (N_e), bolometry signal, the central cord of the Ultra-Soft X-Ray vertical array (USXR) detecting the C V and B IV emissions, and the O VI and B III intensities. Fig. 4b shows the same wave-forms for boron injection. Thomson scattering profiles were not available for the experiments reported in this paper. Without boron injection, the B III signal was below the noise level. With boron injection, at about 3000 μs into the discharge, the B III signal began to increase, and as the B III intensity grew, the I_p and the other wave-forms exhibited the occurrence of an MHD event at 5000μs (possibly triggered by the boron impurity influx) followed by a cooling of the plasma and subsequent reheating. Without boron injection, the O VI signal began increasing as I_p started increasing after 3200μs. Similarly, with boron injection, the O VI signal started increasing after 3200μs and at about the same intensity but after the MHD event at 5000μs, the O VI intensity dropped by about a factor of 2 relative to the emission the discharge without boron, remained lower as the plasma reheated, and then became comparable again at the end of the discharge. This may be indicative of boron wall conditioning due to movement of ionized boron and oxygen from the plasma to the walls during the MHD event and a brief oxygen gettering action by the deposited boron. However, as a result of the MHD event at 5000μs, the plasma may not have generated oxygen at the same rate, and this needs to be investigated. There was little evidence during subsequent discharges of a gettering effect from accumulated boron. This may be due to the small quantity of boron injected per discharge and the small total number of discharges (five) with suitable conditions in this initial experiment.

Fig. 5 shows the USXR array vertical emission profile without and with boron injection. The emission profile during boron injection is vertically asymmetric above the mid-plane. This plasma vertical displacement effect is attributed tentatively to a brief vertical displacement of the CDX-U plasma equilibrium which has been previously noted to occur during high recycling and high impurity influx conditions. This topic is beyond the scope of this paper and will be discussed elsewhere.

Fig. 6 shows CCD TV camera tangential views of the CDX-U plasma through a B III filter (a) without and (b) with boron injection integrated over the duration of the discharge (20 ms camera scan time). In Fig. 6b, the injection proceeds from left to right. A large deposition is seen at the outer major radius with a decreasing penetration to the inner major radius. In addition, the vertical asymmetry evident in Fig. 5 during boron injection is also seen in Fig. 6b. The use of a fast frame rate TV camera in future experiments will allow resolution of the injection trajectory and the evolution of micro-pellet ablation.

V. Discussion

Low velocity, micro-pellet injection into spherical tori suggests interesting and novel experiments. Conventional pellet injection involves relatively large fueling pellets injected into large high temperature, high density, reactor grade plasmas with high toroidal fields at high velocities for core penetration. The relevant pellet physics involves flux incident on the pellet from relatively small Larmor radius orbits along incident field lines, magnetized plasma effects, and self-shielding by the ablating cloud of neutrals surrounding the pellet. [1] Low velocity, micro-pellet injection into spherical tori with relatively low toroidal fields (0.1-0.6T) may involve different pellet ablation physics. The helical Larmor orbits of incident plasma flux may be sufficiently large, for example, that pellet ablation may occur under unmagnetized plasma conditions. In addition, in spherical tori, given the large orbits at the outer major radius compared with the much smaller more compact orbits near the center column, suggests the possibility of observing interesting effects as the micro-pellet penetration depth is varied.

In order to study the effect of injected particle size, a simple dependence of particle diameter at a given plasma location was simulated using typical CDX-U plasma profiles (T_i (0) = 84 eV, N_i (0) = 7.2 x10^{18} m^{-3}) and known boron evaporation rates as a function of temperature [8]. Under these conditions, the characteristic times for complete ablation of boron particles of 1 and 40 micron diameters were found to vary almost linearly with particle diameter from 2 ms to 84 ms, respectively, being almost a factor of 40 smaller for the 1 micron diameter particles. In the initial experiments, a maximum boron particle size of 40 micron diameter was used. In future experiments, boron particle diameters down to 1 micron will be used to study micro-pellet ablation rates, plasma transport conditions, and wall conditioning effects.

In the initial experiments, injected micro-pellet masses of 0.92 mg were used. The amount of injected mass can be increased by a factor of 10 relatively easily, or decreased to very low values. Below a certain mass, (e.g., about 0.25 mg), rather than weighing, it may be more practical to measure the injected mass using calibrated plasma emission intensities.

The results shown in Fig. 4b and discussed above, suggest a possible wall-conditioning effect during boron injection. The internal wall area of CDX-U is about 6 m^2. The deposition of 1 monolayer of boron over this surface would require about 2 mg of material. The 0.92 mg boron micro-pellet injections discussed above corresponded to the deposition of less than half of a monolayer per discharge. This material was probably transported to limiter surfaces and recycled into the plasma until charge exchange interactions caused its loss to the far walls, where gettering proceeded until saturation.[8] Future investigation of this process will be performed to optimize the preconditions and requirements for CDX-U boronization via micro-pellet injection.

The low velocity micro-pellet injector used for initial CDX-U injection experiments allows for convenient variation of three injection control variables, *i.e.*, particle size, total mass, and velocity, over a wide range for edge and core impurity transport measurements. Wall conditioning effects can also be studied with this technique.

ACKNOWLEDGMENTS

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FIGURE CAPTIONS

1. Partial schematic elevation view of Low Velocity Boron Micro-Pellet Injector.

2. Expanded schematic view of the barrel, turret, and propellant tube in (a) the rotatable position, and (b) in the engaged position.

3. Partial schematic plan view showing the relative location of the Low Velocity Boron Micro-Pellet Injector and diagnostics on CDX-U Spherical Torus.

4. CDX-U discharge wave-forms in relative units (a) without B injection; plasma current (I_p), density N_e, bolometry signal, central cord of USXR vertical array showing C V and B IV emission, and the B III and O VI intensities, and (b) with boron injection. On the x-axis, each time division corresponds to 4 µsec.

5. USXR array vertical emission profile without boron injection and with boron injection.

6. CCD TV camera tangential views of CDX-U plasmas through a B III filter and integrated over the duration of the pulse (a) without boron injection, (b) with boron injection.

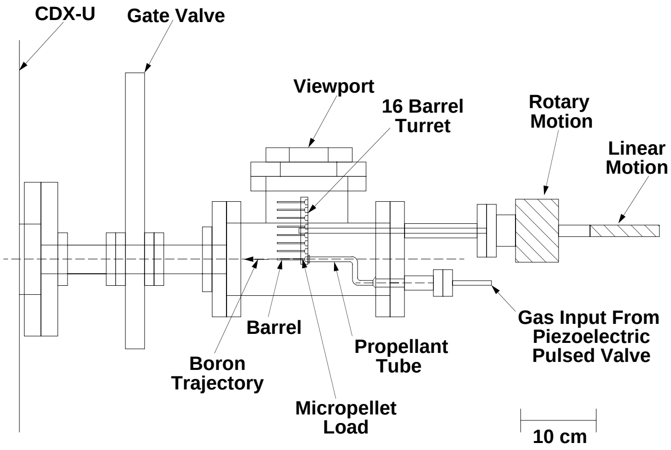

CDX-U
Gate Valve
Viewport
16 Barrel Turret
Rotary Motion
Linear Motion
Gas Input From Piezoelectric Pulsed Valve
Barrel
Propellant Tube
Boron Trajectory
Micropellet Load
10 cm

Fig. 1

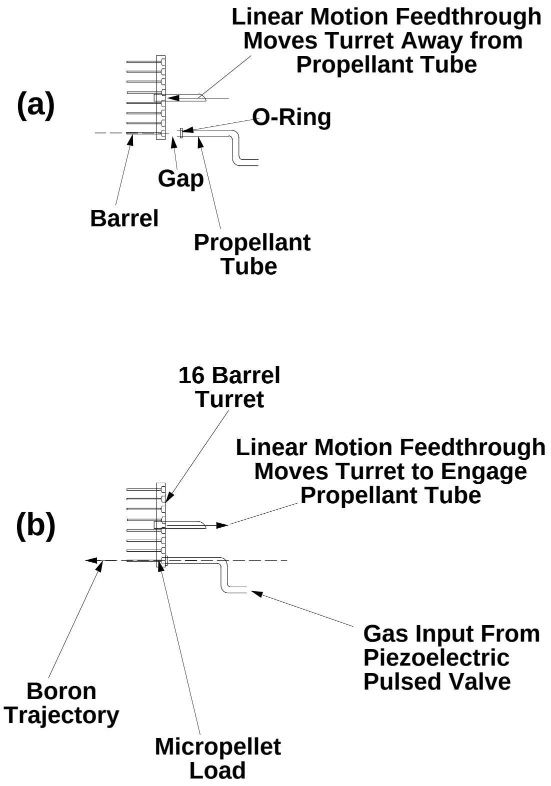

Linear Motion Feedthrough
Moves Turret Away from
Propellant Tube
(a)
O-Ring
Gap
Barrel
Propellant
Tube
16 Barrel
Turret
Linear Motion Feedthrough
Moves Turret to Engage
Propellant Tube
(b)
Gas Input From
Piezoelectric
Pulsed Valve
Boron
Trajectory
Micropellet
Load

Fig.2

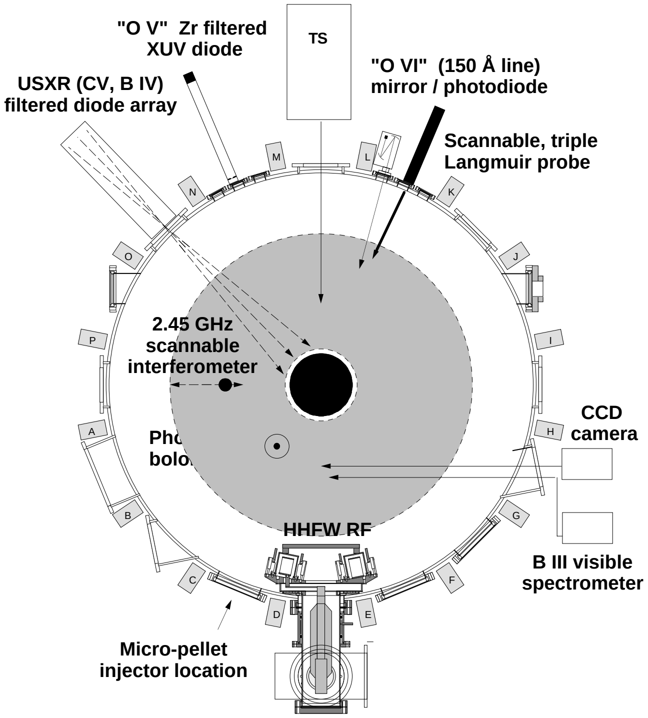
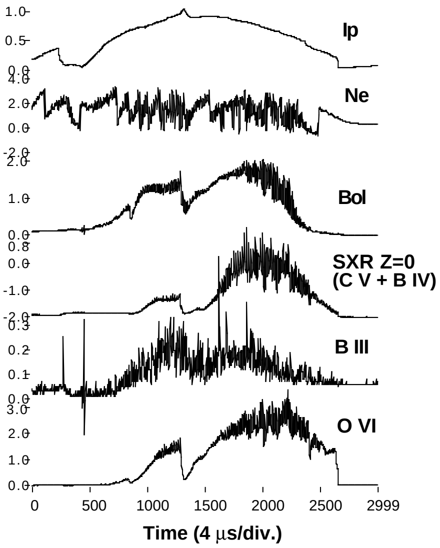
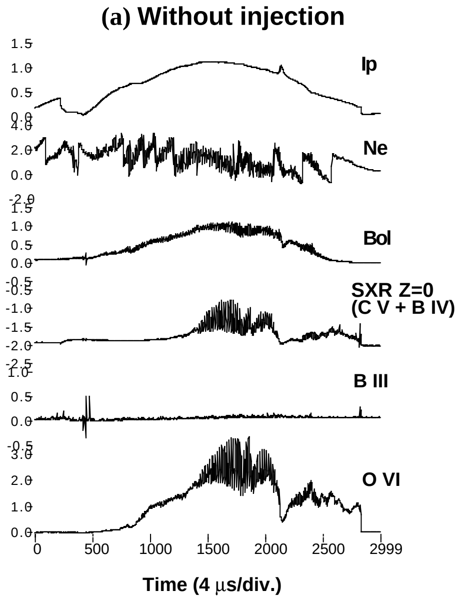

"O V" Zr filtered
XUV diode
TS
"O VI" (150 Å line)
mirror / photodiode
USXR (CV, B IV)
filtered diode array
Scannable, triple
Langmuir probe
M
L
N
K
O
J
P
I
2.45 GHz
scannable
interferometer
A
H
CCD
camera
Pho
bolo
B
G
HHFW RF
C
F
B III visible
spectrometer
D
E
Micro-pellet
injector location

Fig. 3

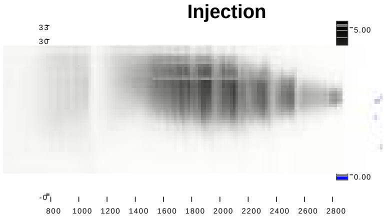


(b) With B injection


(a) Without injection
Ip
1.5
1.0
0.5
0.0
Ne
4.0
2.0
0.0
-2.0
Bol
1.5
1.0
0.5
0.0
-0.5
SXR Z=0
(C V + B IV)
-0.5
-1.0
-1.5
-2.0
-2.5
B III
1.0
0.5
0.0
-0.5
O VI
3.0
2.0
1.0
0.0
0
500
1000
1500
2000
2500
2999
Time (4 µs/div.)

Shot Before Injection

Injection



Time (4 µs/div.)