

Design and Modeling of Vacuum Pumping for Steady-State Pellet Fueling Systems

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Design and Modeling of Vacuum Pumping for Steady-State Pellet Fueling Systems

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Abstract — Future long-pulse magnetic confinement fusion reactors will require density and isotopic mixture control using steady-state repeating pellet injectors. For high energy density burning plasmas, pellet velocities of 1 km/s and above will be required for sufficient plasma penetration to achieve high fueling efficiency. Currently, steady-state repeating injection systems utilize cryogenic extruder systems to produce an extrusion of solid deuterium or deuterium-tritium. In repeating light gas gun injectors, the solid extrusion is cut and simultaneously loaded into a barrel. Once loaded, a fast operating gas valve delivers a high pressure burst of gas to accelerate the pellet down the barrel and into the machine. This process takes ~10 ms to achieve. Adequate gas pumping of the extruder exhaust and injection line propellant gas collection chambers is necessary for optimal operation of the pellet fueling system. Excess solid from the extruder sublimates in an exhaust chamber. The gas pressure in the extruder exhaust chamber must remain low to maintain low heating loads on the cooling mechanism (cryo-refrigerators or liquid helium flow) and to reduce thermal conduction to the extrusion. Pumping the injection line chambers is necessary to limit propellant gas flow into the machine. A numerical simulation code was created to predict temporal pumping performance for these repeating pellet injection systems. This paper will outline the methods and assumptions used to create this model and compare results to the pellet injection system currently employed on DIII-D, the steady-state pellet injection system planned for Wendelstein 7-X, and a brief analysis of the ITER conceptual pellet fueling system.

Keywords— *Vacuum Pumping, Fusion Fueling, Pellet Injection*

I. INTRODUCTION

Future long-pulse magnetic confinement fusion reactors, such as ITER or DEMO, will require the injection of deuterium (D_2) or deuterium-tritium (DT) pellets at a rate of 10 Hz or more [1,2]. These pellet injection systems will be used as part of an active feedback control system to regulate core densities [3]. Pellets with speeds greater than 1,000 m/s will likely be required for high energy density fusion reactor plasmas to ensure adequate penetration into the core. Similar pellet injection systems may be used for edge localized mode (ELM) mitigation, where high frequency (30 - 60 Hz) pellets can be injected from the low field side (LFS) into the plasma edge [4]. Various types of pellet injection systems are currently used throughout the world. The most common are repeating light gas guns and centrifuges. The centrifuge rotates an acceleration arm at a high frequency that can accelerate pellets cut from an extrusion to high speeds, >1000 m/s [5], without the use of propellant gas, which is an advantage compared to the light gas gun approach. The light gas gun steady-state pellet injection system consists of an extruder that produces a steady stream of solid D_2 or DT, a gun mechanism that cuts, chambers, and fires the pellet, and a downstream series of ballast volumes. Pellets are accelerated using a solenoid-driven fast opening gas valve [6] that provides a pulse of high pressure light gas (He, D_2 , or H_2) to the rear of the pellet. Systems of this type are currently used on the Joint European Torus (JET), Large Helical Device (LHD), and DIII-D for high frequency pellet fueling and ELM mitigation experiments [7, 8, 9]. A basic schematic of a repetitive steady-state gas gun pellet injection system is shown in Figure 1.

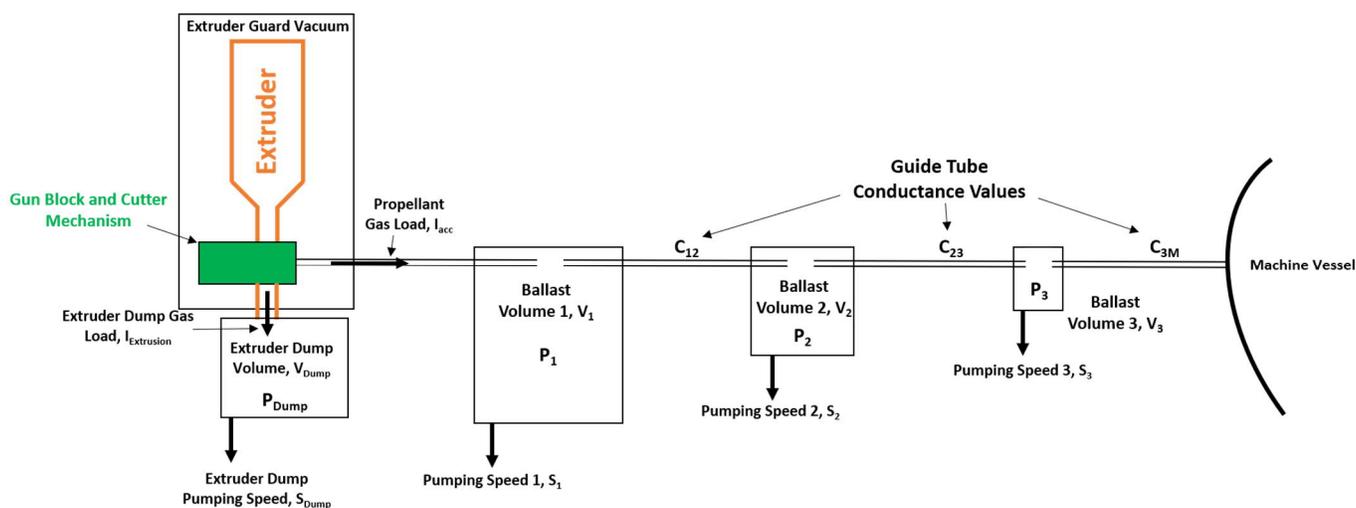


Fig. 1. A general schematic of a steady-state high frequency gas gun pellet injector and downstream ballast volumes.

The amount of propellant gas needed to achieve high speed pellets at a high frequency is substantial and its flow into the plasma chamber must be kept to a low rate. The propellant gas is collected by pumping on downstream ballast volumes that are located at gaps in the injection line guide tubes. In the example in Fig. 1, three volumes are used to collect and pump this propellant gas load.

The most common form of pumping is through the use of mechanical vacuum pumps, although, cryopumps have been used in the past [10]. Governing equations originally presented by Sakamoto et. al. [8] for the pressures in these three volumes are:

$$\begin{aligned}
 V_1 \frac{dP(t)_1}{dt} &= I_{acc} + C(t)_{12}(P(t)_2 - P(t)_1) - S(t)_1 P(t)_1 + L_1 \\
 V_2 \frac{dP(t)_2}{dt} &= C(t)_{12}(P(t)_1 - P(t)_2) + C(t)_{23}(P(t)_3 - P(t)_2) - S(t)_2 P(t)_2 + L_2 \\
 V_3 \frac{dP(t)_3}{dt} &= C(t)_{23}(P(t)_2 - P(t)_3) - S(t)_3 P(t)_3 + L_3
 \end{aligned} \tag{1}$$

where P_1 , P_2 , and P_3 are the pressures in associated volumes V_1 , V_2 , and V_3 . I_{acc} is the gas load from the pellet propellant gas. C_{12} and C_{23} represent the conductance values for gas flow between Volumes 1 and 2 and Volumes 2 and 3. S_1 , S_2 , and S_3 are the pressure dependent pumping speeds for the pumps attached to the corresponding stages, and L_1 , L_2 , and L_3 are assumed leak rates for the vacuum components associated with each volume. In this work, the conductances and pumping speeds are functions of pressure and therefore are time dependent unlike the earlier published simulations [8].

This system of equations was coded in Python using a fourth order Runge-Kutta routine [11,12]. The fourth order Runge-Kutta method uses approximations for the slope at four points within the time step and averages these four approximations, weighing the two midpoint increments higher than the beginning or end increments. The stability region of this fourth order trapezoidal solver is calculated within the code. Stability of the Runge-Kutta solver is dependent on the ratio of the step size to the magnitude of change of each function in the system. Keeping the time step small is necessary to ensure stability through large transients in the simulation. The time step for these simulations is kept constant at 1×10^{-6} seconds. A similar routine was written for the single-equation extrusion dump pressure. The pressure in the extruder exhaust chamber (dump) can be expressed as;

$$V_{Dump} \frac{dP(t)_{Dump}}{dt} = I(t)_{Extrusion} - S(t)_{Dump} P(t)_{Dump} \tag{2}$$

where V_{Dump} , P_{Dump} , $I_{Extrusion}$, and S_{Dump} are the volume of the extruder dump, the pressure in the extruder dump volume, the gas load from the extrusion stream, and the pumping speed of the pumping unit connected to the extruder dump. This equation is solved using the same Runge-Kutta method described above. The importance of this model is to determine the steady-state operating pressure of the extruder dump volume and determine if the associated pumps can maintain pressures < 1 bar during a full-volume dump of the extruder material. A low steady-state pressure in the extruder dump volume will limit thermal conduction to cryogenically cooled components, which will limit the heat load on the cooling system. During a loss of cooling scenario, the solid

material generated within the extruder will flash to gas and could possibly result in very high pressures in the extruder dump (depending on the volume of the dump). Maintaining a peak transient pressure of < 1 bar is necessary for two reasons; component longevity and to comply with pressure guidelines for hydrogen at the research laboratories where they are used.

Some injector systems combine pumping of the extruder dump with the first ballast volume, which results in a combined gas load and a convolution of Equations 1 and 2. The new governing equation for the pressure in the first volume is;

$$V_{1+Dump} \frac{dP(t)_{1+Dump}}{dt} = I(t)_{Extrusion+acc} - C(t)_{12}(P(t)_2 - P(t)_{1+Dump}) - S(t)_1 P(t)_{1+Dump} + L_1 \quad (3)$$

where the subscript 1+Dump refers to the combined volume of the extruder dump combined with the first stage ballast volume. $I_{Extrusion+acc}$ is the combined gas flow of the propellant gas and the extrusion exhaust ($I_{acc} + I_{Extrusion}$). The schematics of combined pumping of the first ballast volume and the extruder dump are shown in Figure 2.

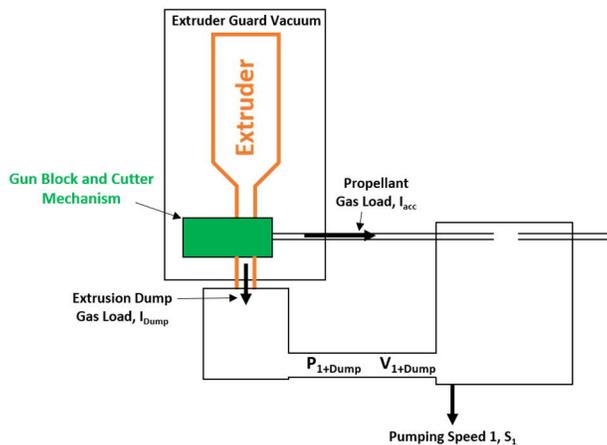


Fig. 2. Schematics of a pumping system which combines the extruder dump and first stage ballast volume pumping.

The remainder of this paper will discuss the specific methods and assumptions made when solving the above system of equations, a realistic validation using parameters from the DIII-D repetitive pellet injector, preliminary conceptual design of the vacuum system for the Wendelstein 7-X (W7-X) steady state pellet injection system, and a brief analysis of the conceptual ITER pellet fueling system.

II. MODELING BALLAST VOLUME PRESSURE

The pressure in the three ballast volumes is essentially a balance between incoming propellant gas and the ability of the chosen vacuum pumps to exhaust the incoming gas. To model the ballast volume pressures, geometrical parameters of the system must be accurately known. The size of each volume and the lengths and diameters of each guide tube section are the most important. The size of each volume affects the dynamics of the system by changing how rapidly a steady state pressure is reached. For example, if

a volume is large, it would take longer to reach its steady state pressure. Conductance values influence the rate at which gas can flow between volumes, and more importantly, into the plasma chamber. These values are pressure dependent. The pressure dependency of the conductance is driven by the type of flow regime experienced for the range of pressures within the system. Laminar flow, Knudsen flow, and molecular flow are the types of flow regimes that occur at the pressure ranges experienced in these systems. Conductance values are calculated using the Knudsen equation. The Knudsen equation is normally valid for air but can be modified for flow of the helium or other gasses by applying a correction factor [13]. Although this is a two-gas system (He and D₂), the assumption is made that helium is the only gaseous material flowing through the guide tubes. It is assumed that the fuel material remains primarily in solid form and that the extruder exhaust is adequately pumped. The Knudsen equation is given by;

$$C = 135 \frac{d^4}{l} \bar{P} + 12.1 \frac{d^3}{l} \cdot \frac{1 + 192 \cdot d \cdot \bar{P}}{1 + 237 \cdot d \cdot \bar{P}} (L/s) \quad (4)$$

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$$I(t)_{acc} = A \sin(\omega t) + A \quad (5)$$

that, when integrated, provides a gas flow of approximately 10% of A at a frequency of 10 Hz ($\omega = 2\pi \cdot 10$). In Equation 5, A is an amplitude (A/10 is the desired gas load per shot at $\omega = 2\pi \cdot 10$), ω is a frequency, and t is time.

The Python code is structured so that initial conditions for pressure are the only input besides constant system geometry. For pellet injector systems in general, the initial pressure in all three stages is assumed to be 1×10^{-7} mbar. The initial pressure is used to define the initial pumping speed for each stage and initial conductance values between stages. Once the initial values are set, the equations are solved within a for-loop, each iteration of the for-loop being a time step. As the code steps through the for-loop, it calculates pressure for the next time step, which is then used to calculate pumping speeds and conductance values for the next time step as well. As these values are calculated, they are stored in an array. The arrays are used to plot the pressures, pumping speeds, and

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conductance values for the specified time duration. Along with plots, the code calculates the gas flow out of the final stage into the plasma chamber based on the pressure in the third stage.

III. MODELING EXTRUDER DUMP PRESSURE

To model the extruder dump pressure separately from the downstream volumes, the same Runge-Kutta for-loop structure is used. To determine whether pumping is sufficient to handle a full-volume dump of the extruder, the gas load, $I_{\text{Extrusion}}$, is changed based on trends seen in previous extruder laboratory tests. Figure 3 shows the pressure spike measured during a full-volume dump of a twin-screw extruder. Approximately 77.5 bar-L of D_2 was dumped during this warm up event. The warm up is not instantaneous and therefore the dump takes over ~50 seconds and the pressure reaches a maximum of ~475 mbar in the ~10 L dump volume. The outflow from the extruder is not constant during the dump but is approximated in the code as a constant flow. The code approximates the transient phenomenon by increasing the gas load to an average value for a specific duration, normally denoted by the amount of gas in the extruder (in mbar-L) divided by the approximate time in which a full-volume dump occurs. To simulate steady state extruder operation, the code uses a gas load based on the maximum extruder throughput, minus the gas inventory of the pellets that are accelerated out of the barrel.

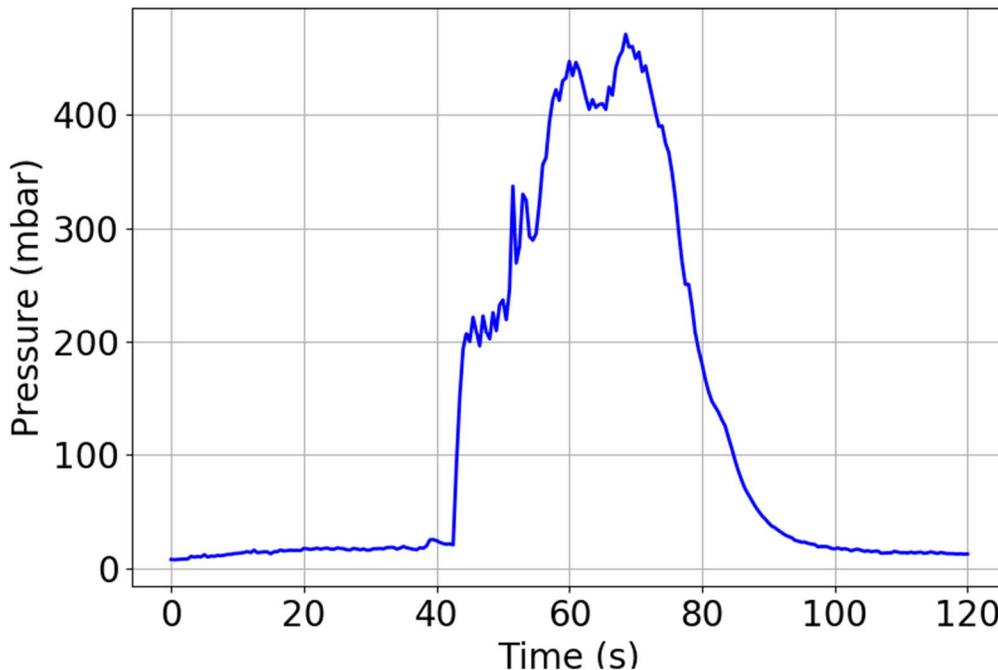


Fig. 3. A plot showing the pressure in a ~10 L extruder dump volume during a full-volume extruder dump caused by a loss of cooling thermal runaway.

IV. RESULTS AND DISCUSSION

The code was benchmarked against the results in the work by Sakamoto [8] by keeping the pumping speeds and conductance values constant as was reported in this work. The current repetitive DIII-D pellet injector was also used to validate the code. The DIII-D system parameters are listed in Table 1. This test was conducted with a gun that is only connected to the 1st and 2nd ballast volumes and bypasses the third ballast volume to the torus isolation valve. Pellet strings were fired for 5 second durations at 5 Hz. The propellant valve is held open for 1.3 ms, which translates to an approximate gas load of 12.3 mbar-L per shot (as measured experimentally). The maximum pressure seen in the 2nd stage after five seconds was 8.3×10^{-5} mbar (6.2×10^{-5} Torr). This test was conducted with no gas load from the extruder into the 1st stage ballast volume. The pump used for the 1st stage is a Varian TV301 NAV turbo pump backed by a large rotary vane pump (~ 50 m³/h). The 2nd stage uses a Pfeiffer TPU 180H turbo pump and the 3rd stage 3 uses a Pfeiffer TPU 062H turbo pump, although the 3rd stage pump was not used in this validation test. The 2nd and 3rd stage turbos are backed by a common rotary vane pump with a pumping speed of ~ 50 m³/h. The schematics for this system are shown in Figure 4. Fits for these pumping speed curves were put into the code and used to ensure the accuracy of the results. Figure 5 shows a temporal plot of the calculated pressures in the 1st and 2nd stages, and a comparison with the experimental results. Since there is no extruder dump load, the equations in Equation 1 are sufficient for this scenario. To get an input gas load, I_{acc} , of ~ 12 mbar-L/shot at 5 Hz, A and ω are set as 60 and 31.4, respectively. The code predicts the pressure in the 2nd stage to be 9.4×10^{-5} mbar after five seconds of operation. The DIII-D injector is designed to operate for < 10 seconds so steady state pressures are never reached. Only the 2nd stage pressure is available experimentally.

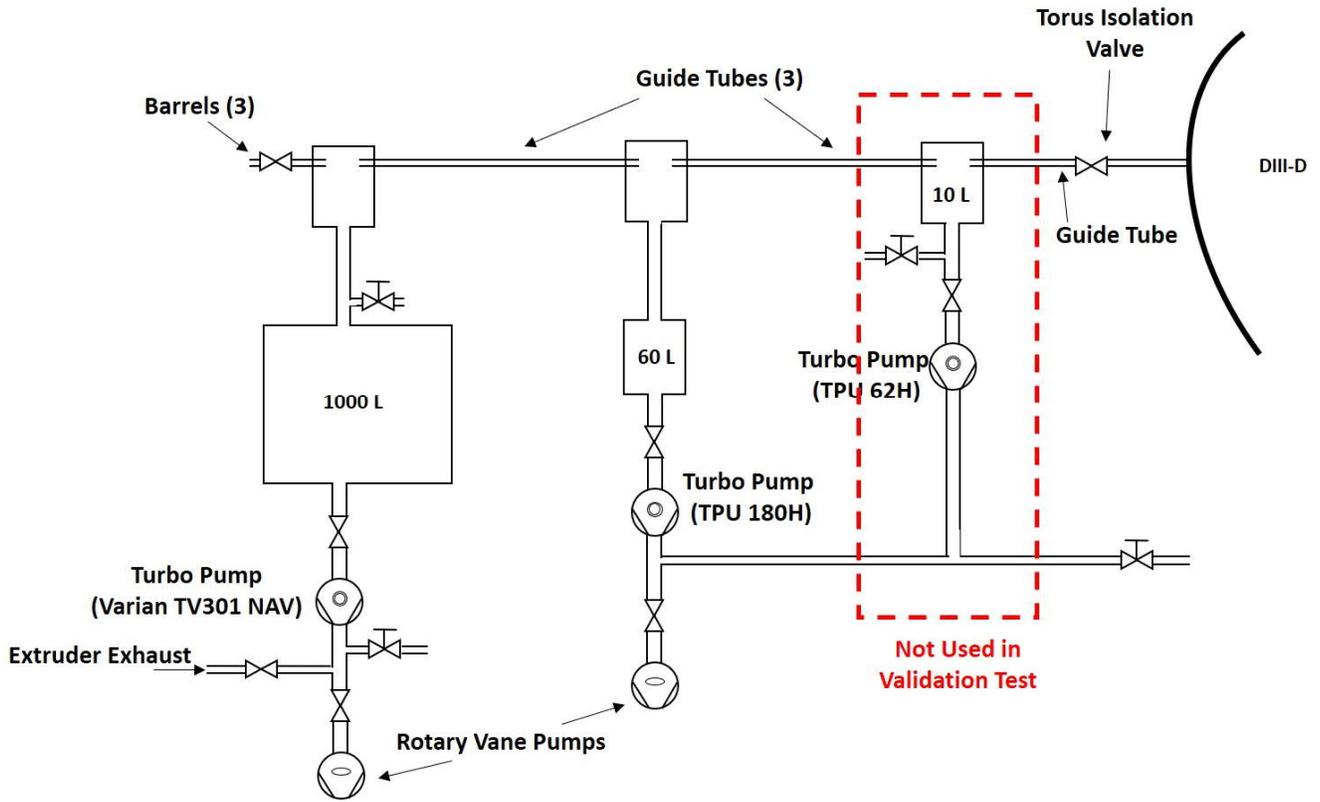


Fig. 4. A schematic of the currently used DIII-D Pellet injection vacuum system.

Table 1. Physical parameters of the DIII-D pellet injection vacuum system.

Volume 1	1000 L
Volume 2	60 L
Volume 3	10 L
Drift Tube Diameter (Stage 1-2)	0.63 cm
Drift Tube Diameter (Stage 2-3)	3 cm
Drift Tube Diameter (Stage 3-machine)	4 cm
Drift Tube Length (Stage 1-2)	33 cm
Drift Tube Length (Stage 2-3)	310 cm
Drift Tube Length (Stage 3-machine)	100 cm
Initial Pressure of Volumes	1E-7 mbar

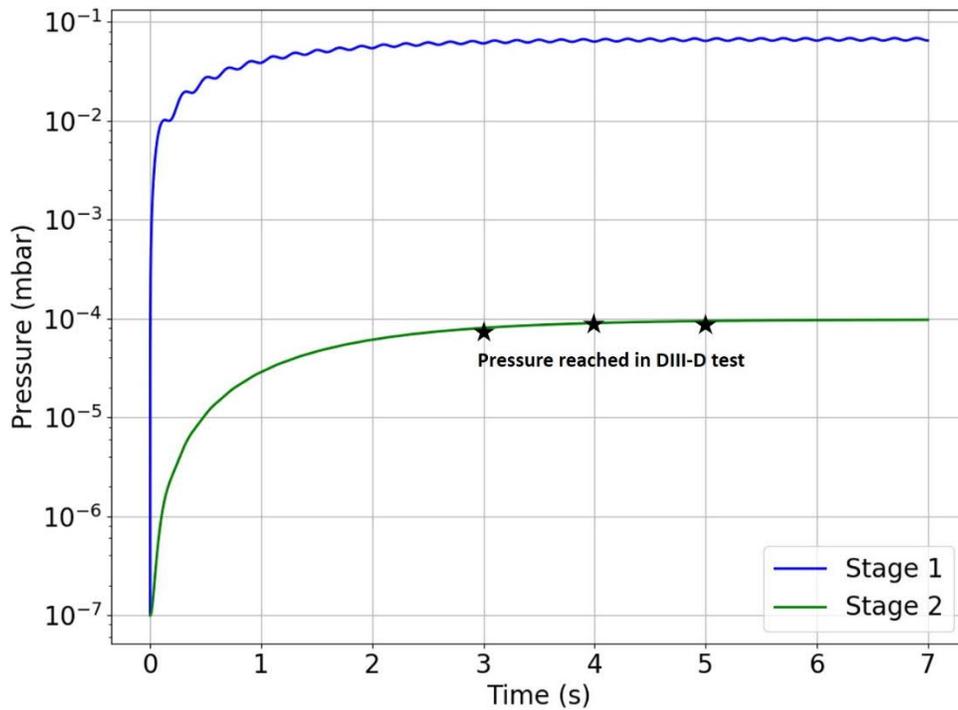


Fig. 5. A plot showing the simulated pressure in each stage of the DIII-D repeating pellet injector. The simulation was conducted with an incoming gas load of ~ 12 mbar-L/pulse at 5 Hz.

A continuous pellet fueling system is being designed for H_2 and D_2 operation on W7-X. This analysis only addresses D_2 operation. The W7-X injection system will be designed to operate at steady state for up to 30-minute duration plasmas. This paper assumes that the W7-X design will be similar to the DIII-D system and will combine pumping of the extruder dump and the first ballast volume. The pumping system is being designed for the worst-case gas loads, which will consist of a steady solid D_2 flow of 0.5 bar-L/s from the extruder, a propellant gas flow of 0.1 bar-L/pellet at a rate of 10 Hz, and a transient gas flow of 3.2 bar-L/s for a 30 second extruder dump at the end of the 30-minute run. The transient load simulates a dump of the solid held within the extruder and is the worst-case gas load scenario that the W7-X pumping system will encounter. Table 2 shows a list of the parameters of the planned injection line ballast volumes and drift tubes. A Pfeiffer WS 5500 WWH pumping system will pump the first stage and extruder dump. This pumping system consists of three pumps in series; an Okta 6000 M roots pump, an Okta 1000 M roots pump, and a Cobra NS 0600 C dry screw pump. The second and third stages will be pumped by a Pfeiffer HiPace 400 and a Pfeiffer HiPace 80 turbo pump with a molecular drag stage, both backed by a dry roughing pump. Table 3 lists these pumps and their corresponding attributes. These pumping curves were fit and put into the code to accurately predict the steady state operating pressures. Figure 6 shows the results of the simulation run using the W7-X parameters. The steady-state pressures predicted for Stage 1, 2, and 3 are 2.47 mbar, 1.3×10^{-3} mbar, and 3.9×10^{-6} mbar, respectively. The pressure in the 3rd stage results in a steady state flow rate of 1.6×10^{-7} mbar-L/s of helium into the plasma chamber.

Table 2. Physical parameters of the proposed W7-X pellet injection vacuum system.

Volume 1	100 L
Volume 2	100 L
Volume 3	2 L
Extruder Dump Volume	100 L
Drift Tube Diameter (Stage 1-2)	0.5 cm
Drift Tube Diameter (Stage 2-3)	0.65 cm
Drift Tube Diameter (Stage 3-machine)	0.8 cm
Drift Tube Length (Stage 1-2)	50 cm
Drift Tube Length (Stage 2-3)	50 cm
Drift Tube Length (Stage 3-machine)	400 cm
Initial Pressure of Volumes	1E-7 mbar

Table 3. Parameters of pumps listed for the W7-X steady-state pellet injector.

Pumping System	Pumps	Type of Pump	Injector Stage	Nominal Helium Pumping Speed at 50 Hz Power (m ³ /h)
Pfeiffer WS 5500 WWH	Pfeiffer Okta 6000 M	Roots Pump	First Stage and Extruder Dump	5410 at 1 mBar
	Pfeiffer Okta 1000 M	Roots Pump		
	Cobra NS 0600 C	Dry Screw Pump		
Single Turbo Backed by Dry Roughing Pump	Pfeiffer HiPace 400	Turbo Pump	Second Stage	1728 at 10 ⁻³ mBar
Single Turbo Backed by Dry Roughing Pump	Pfeiffer HiPace 80	Turbo Pump	Third Stage	205 at 10 ⁻³ mBar

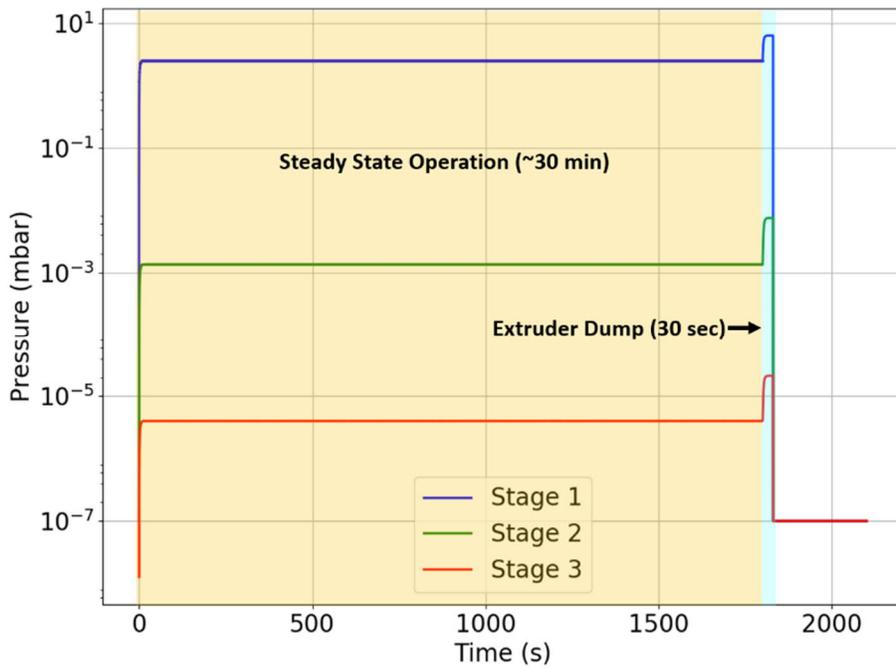


Fig. 6. A plot showing the pressures in each stage of the proposed W7-X vacuum system. This plot shows the steady state operation pressures with a full-volume extruder dump at the end of the 30 minute steady state operation.

Failure analysis of the pumping system was conducted to determine the maximum gas load per pellet that the pumping systems will be able to handle at an injection frequency of 10 Hz. A helium propellant load of >600 mbar-L/pulse and a steady-state hydrogen/deuterium extrusion load of 500 mbar-L/s causes a runaway pressure increase in the pumping system as the turbo pumps on Stages 2 and 3 lose pumping capability. Helium propellant gas flows higher than 120 mbar-L/pulse will result in a reduction of pumping efficiency of the first stage, Pfeiffer WS 5500 WWH, pump because the pressure in the 1st stage will be greater than 2 mbar. At this pressure the pumping speed of the Pfeiffer WS 5500 WWH starts decreasing rapidly. Although pumping efficiency of the first stage is reduced at propellant loads above 120 mbar-L/pulse, runaway pressure rise will not occur until propellant gas flows of 600 mbar-L/pellet are used. Figure 7 shows a plot of the pressures for each stage versus time for sustained propellant loads of 600 mbar-L/pulse combined with a steady extrusion (hydrogen/deuterium) load of 500 mbar-L/s. These gas loads result in a shutdown of the vacuum system after about 170 seconds of operation. Figure 8 shows a plot of the pumping speeds for the pumps on each stage. The collapse in pumping of the 2nd stage results in the collapse of pumping of the 3rd stage. At 1 bar, the Pfeiffer WS 5500 WWH has a nominal helium pumping speed of 650 m³/h, which is not capable of preventing the pumping collapse of the second and third stages. The for-loop within the code breaks when the pressure in Stage 3 reaches atmospheric pressure (~ 1 bar) to prevent the solver from going unstable.

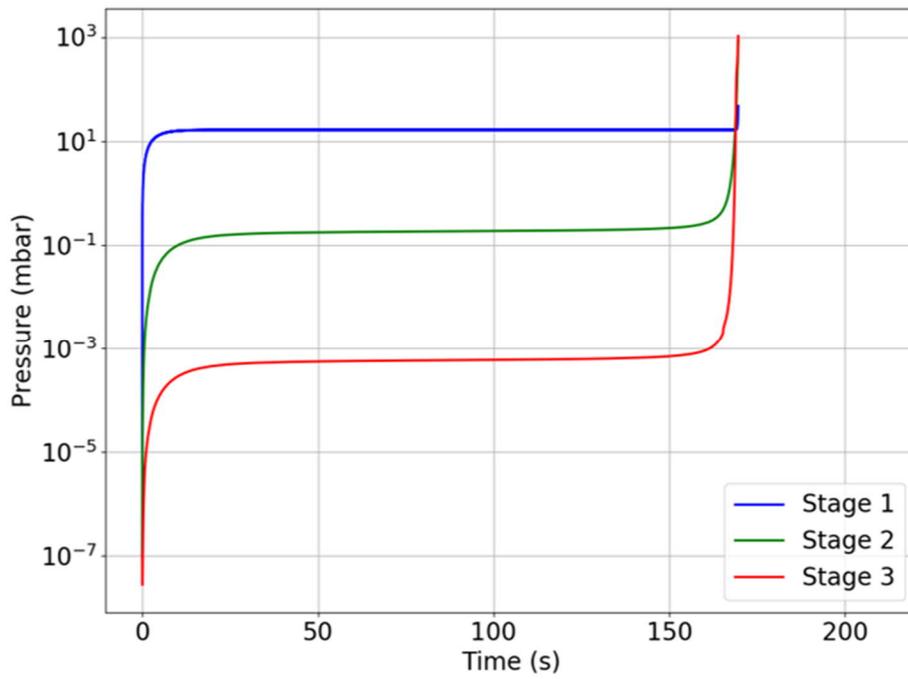


Fig. 7. A plot showing the pressures in each stage for a propellant load of 600 mbar-L/pulse and an extrusion load of 500 mbar-L/s, for the proposed W7-X vacuum system. The drastic increase in pressure is caused by a collapse of pumping in Stages 2 and 3.

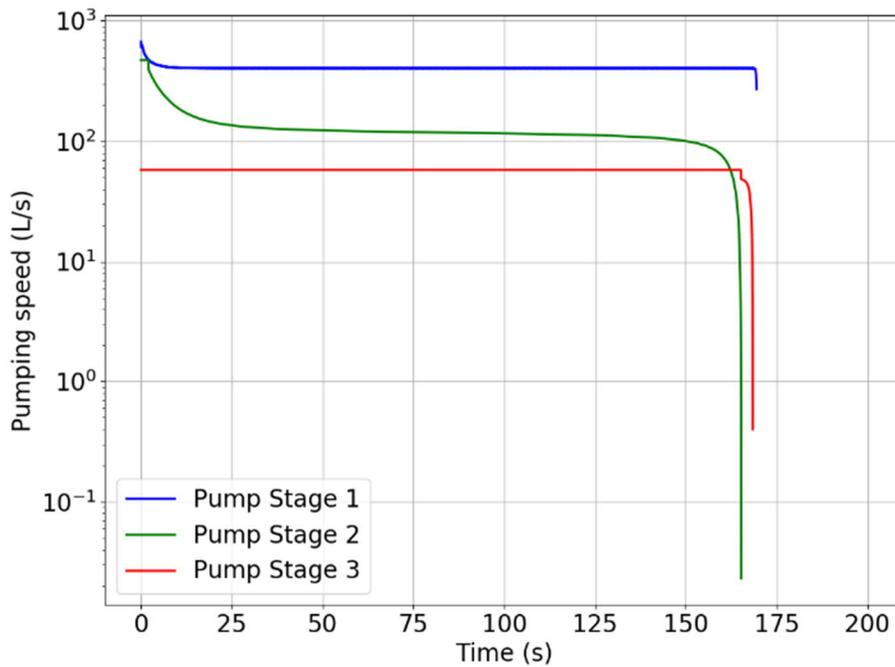


Fig. 8. A plot showing the collapse of pumping speeds of the Stage 2 and 3 pumps of the proposed W7-X vacuum system at 600 mbar-L/Pulse at 10 Hz.

The current conceptual design for the ITER steady state pellet fueling system is very similar to the DIII-D and W7-X systems in that it contains three injection line ballast volumes and a pump for each volume [14]. The 1st stage will be pumped by a custom

tritium compatible piston pump that has a maximum pumping speed of 150 m³/h [15]. The second and third stage pumps have not yet been identified. The ITER fueling system will launch fueling pellets at ~4 Hz at speeds no greater than 300 m/s to ensure survivability through the bent guide tubes, which is a much smaller propellant gas load than the high speed W7-X pellet fueling system. Propellant gas loads for the relatively slow ITER fueling pellets is assumed to be 10 mbar-l/pellet. If the ITER system has the same ballast volume sizes, guide tube geometry, and 2nd and 3rd stage pumps as the W7-X system, the resulting pressure in the 1st stage of the ITER pellet injection system is predicted to be 3.3 mbar, which should be compatible with the gas gun operation.

V. CONCLUSIONS

In conclusion, the code can accurately predict pressures within the injection line ballast volumes by incorporating pressure dependent pumping speed curves and conductance values. The test measurements from the DIII-D pellet injection system were used to verify the accuracy of the code. The test yielded a 2nd stage pressure of 8.3×10^{-5} mbar after five seconds of propellant valve pulses at 5 Hz. The code predicted this pressure to be 9.4×10^{-5} mbar, which is ~13% error. Simulations show that the gas loads predicted for the design of the W7-X steady-state pellet injector can be handled while maintaining adequate pressures when using the pumps previously described. The predicted gas loads for normal steady state operation are 100 mbar-l/pellet at 10 Hz, plus 500 mbar-l/s extruder exhaust. Pumping speed of the Pfeiffer WS 5500 WWH starts to decrease with a propellant gas flow of 120 mbar-l/pellet at 10 Hz, plus 500 mbar-l/s extruder exhaust. Although the pumping speed of the 1st stage drops, low vacuum pressure is still maintained. A failure analysis predicts that catastrophic loss of pumping will not occur until a propellant load of >600 mbar-l/pellet is introduced. The probability of delivering this amount of propellant is highly unlikely. Overall, the proposed design of the W7-X steady-state pellet injection vacuum system is adequate for the proposed steady-state operation scenario. A transient analysis was also carried out using a full-volume extruder dump as the worst-case scenario to determine whether the chosen pumps could handle the large gas load (3200 mbar-l/s for 30 sec). Peak pressures within the ballast volumes during this transient are well within the tolerable limit of 1 bar. A simulation of the ITER conceptual steady state pellet fueling system using the tritium compatible piston pump on the first stage yielded a predicted pressure of 3.3 mbar in the first stage.

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