SYSTEMS AND METHODS FOR PRECISION GENERATION AND DELIVERY OF MICRO-SCALE FUEL DROPLETS FOR HIGH-REPETITION RATE FUSION

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Abstract

A system and method for generating and delivering micro-scale fuel targets into a high-vacuum fusion reaction chamber with high positional stability and high repetition rate. The invention addresses failure modes that arise when micron-scale droplets are injected into vacuum at kilohertz-to-megahertz rates, including evaporative cooling and tip-freezing, nozzle icing and clogging, non-spherical breakup, droplet charge accumulation, and trajectory wander that exceeds a laser focal tolerance of a few microns. In one embodiment, a differentially pumped injection assembly comprises a heated nozzle operated in a controlled Rayleigh breakup regime using piezoelectric excitation that is phase-locked to an external timing reference. One or more intermediate pressure stages suppress flash evaporation during droplet formation while maintaining a low gas load to the main chamber. In some embodiments, droplets are accelerated and steered using electrostatic fields (e.g., charged droplets and deflection plates) and/or aerodynamic focusing (e.g., a coaxial gas sheath). In some embodiments, an in-vacuum droplet metrology subsystem measures droplet position and velocity on a pulse-to-pulse basis and closes the loop on injector parameters to maintain alignment with a fusion driver at repetition rates exceeding 10 kHz.

1 Technical Field

The present disclosure relates to nuclear fusion fuel delivery systems, specifically to high-frequency liquid droplet generators for inertial confinement fusion (ICF) and micro-scale fusion reactors.

2 Background

Traditional ICF utilizes solid, cryogenic fuel pellets that are mechanically placed or injected at low repetition rates (e.g., one per day or one per second). Coherence-controlled fusion architectures, such as the RS Fusion Engine, require a continuous stream of micro-targets (e.g., 10 μm radius) delivered at kilohertz frequencies (1 kHz - 1 MHz) into a high-vacuum chamber.

Injecting micron-scale liquid droplets into a vacuum presents significant challenges:

1. **Evaporative Freezing**: The rapid evaporation of the liquid surface in a vacuum causes the droplet to freeze almost instantly, potentially deforming its shape and altering its trajectory.

2. **Trajectory Instability**: Small droplets are easily perturbed by gas currents or nozzle irregularities, causing them to miss the laser focal point (which may be only a few microns wide).

3. **Nozzle Clogging**: Freezing at the nozzle tip can block the flow.

Existing droplet generators (e.g., for EUV lithography or inkjet printing) do not operate in the high-vacuum, high-velocity regime required for fusion.

3 Definitions (Non-Limiting)

As used herein:

- **Micro-target**: a liquid or partially solidified droplet having a characteristic diameter between 1 μm and 500 μm.

- **Differential pumping**: maintaining multiple pressure regions separated by one or more apertures so that the droplet formation region may be at a higher pressure than the reaction chamber.

- **Rayleigh breakup control**: imposing a perturbation on a liquid jet to produce uniform droplet size and spacing.

- **Fore-chamber**: an upstream region where droplet formation occurs at intermediate pressure to reduce flash evaporation and freezing at the nozzle.

4 Summary

The invention provides a "Differentially Pumped Droplet Injector" that isolates the liquid generation process from the hard vacuum of the reaction chamber.

Core Concept

The fuel is pressurized and forced through a micro-nozzle vibrated by a piezoelectric transducer at a controlled Rayleigh breakup frequency, forcing the jet to break up into uniform droplets. Droplet generation occurs in a fore-chamber at intermediate pressure (e.g., 0.1–100 Torr) to suppress flash evaporation while permitting efficient pumping. The droplets pass through one or more skimmers (small apertures) into a high-vacuum reaction chamber (e.g., 10^{-6}–10^{-3} Torr). The nozzle is actively heated (and optionally the skimmer is heated) to prevent freezing at the tip and aperture. In some embodiments, droplets are intentionally charged at the nozzle and are subsequently guided and/or corrected using electrostatic optics.

Key Advantages

- **Phase Stability**: Droplets remain liquid during formation, ensuring perfect sphericity (surface tension dominates).
- **Trajectory Precision**: High-velocity ejection (e.g., > 10 m/s, optionally > 50 m/s) minimizes transit time and transverse drift.
- **Continuous Operation**: Piezo-drive enables tunable frequencies from 10 kHz to 1 MHz.
- **Vacuum Compatibility**: Differential pumping prevents the fuel vapor from degrading the main chamber vacuum.

5 Detailed Description

5.1 System Architecture

The injector assembly comprises:

1. **Fuel Reservoir**: A pressurized supply of liquid fuel (e.g., cryogenic hydrogen isotopes, a boron-containing liquid or slurry, or other fusion-relevant compounds).
2. **Piezo-Actuated Nozzle**: A capillary nozzle (e.g., sapphire, ceramic, metal, or glass) coupled to a piezo-electric transducer.
3. **Heater Block**: A resistive heating element surrounding the nozzle tip to maintain temperature above the freezing point.
4. **Differential Pumping Chamber**: one or more intermediate chambers maintained at partial vacuum (e.g., 0.1–100 Torr) by one or more pumps.
5. **Skimmer**: one or more apertures separating the fore-chamber(s) from the main reaction chamber (e.g., 10^{-6}–10^{-3} Torr), aligned to the droplet trajectory.
6. **Optional Charge Control**: electrodes configured to impart a controlled charge to droplets, and/or to neutralize droplets using an ionizer.

7. **Optional Steering/Focusing**: electrostatic deflection plates, einzel lenses, or aerodynamic focusing elements configured to correct droplet trajectory.

8. **Optional Metrology**: one or more optical sensors configured to measure droplet position/velocity and generate an error signal for closed-loop control.

5.2 Rayleigh Breakup Control

The piezo transducer is driven at a frequency f derived from the jet velocity v and jet diameter d:

$$f \approx \frac{v}{4.5d}$$

This forces the liquid jet to break up into droplets of uniform size and spacing (the Rayleigh instability regime). By locking the piezo drive to the Master Clock, the droplet generation is synchronized with the laser pulse train.

5.3 Multi-Stage Vacuum Interface (Non-Limiting)

In one embodiment, the fore-chamber is followed by a first skimmer into a second chamber and then a second skimmer into the main chamber. The first stage limits gas flow into downstream regions while allowing the droplet stream to propagate. The second stage provides additional isolation to maintain the main chamber vacuum while still operating the nozzle in a regime that avoids immediate freezing at the tip. Skimmer apertures may be conical and heated to reduce fuel deposition.

5.4 Trajectory Stabilization and Correction

In some embodiments, the injector charges droplets to a known polarity and magnitude (e.g., by applying a bias voltage to the nozzle or to a charging electrode). Downstream electrostatic elements provide:

- **Coarse Alignment**: slow adjustment to align the mean trajectory to the reactor centerline.

- **Fine Correction**: high-bandwidth deflection based on measured droplet error relative to a desired interception point.

In some embodiments, a coaxial low-mass gas sheath (e.g., helium) provides aerodynamic focusing in the fore-chamber while differential pumping prevents excessive gas load in the main chamber.

5.5 In-Vacuum Metrology and Closed-Loop Control

Droplet position and velocity may be measured using stroboscopic illumination synchronized to the pulse train, forward-scatter detection from a probe laser, or time-of-flight between two measurement planes. A controller (e.g., FPGA or microcontroller) may adjust one or more of: nozzle drive amplitude, nozzle temperature, reservoir pressure, charging voltage, and electrostatic deflection signals to maintain a target alignment budget (e.g., $< 5\ \mu$m RMS at the focal plane).

5.6 Downstream Catcher and Fuel Recirculation (Non-Limiting)

In some embodiments, a downstream catcher is positioned beyond the interaction region to intercept droplets that are not consumed by the fusion process. The catcher may include a cooled surface, a liquid bath, or a porous capture medium compatible with the fuel, and may be coupled to a return line to recycle fuel back to the reservoir. In some embodiments, the catcher is differentially pumped or shielded to reduce vapor backstreaming into the reaction chamber.

5.7 Anti-Icing and Self-Cleaning Operation (Non-Limiting)

In some embodiments, the injector includes temperature sensing at or near the nozzle tip and executes an anti-icing control loop. The control loop may modulate heater power based on measured temperature, inferred flow impedance, and/or detected droplet irregularities. In some embodiments, the injector performs periodic self-cleaning cycles (e.g., short high-power heating pulses, reversed flow, or an applied electrical bias) to remove deposits and prevent clogging.

5.8 Thermal Management

To prevent ”flash freezing” upon exit:

- The nozzle is heated to compensate for the latent heat of vaporization.
- The fore-chamber creates a local vapor pressure shield around the jet, reducing evaporation rates during the critical breakup phase.
- In some embodiments, droplets are permitted to partially solidify *after* passing a skimmer, after sphericity and spacing have been established.

6 Claims

1. A target delivery system for a nuclear fusion reactor, comprising:
    - A nozzle assembly configured to eject a liquid fuel jet;
    - A piezoelectric transducer coupled to the nozzle assembly, configured to perturb the liquid jet at a frequency sufficient to induce Rayleigh breakup into uniform droplets;
    - A heating element thermally coupled to the nozzle assembly to prevent freezing of the liquid fuel;
    - At least one differential pumping region enclosing the nozzle assembly, maintained at an intermediate pressure; and

- At least one aperture connecting the differential pumping region to a high-vacuum reaction chamber and aligned with a trajectory of the droplets.

2. The system of claim 1, wherein the intermediate pressure is between 0.1 Torr and 100 Torr.
3. The system of claim 1, wherein the high-vacuum reaction chamber is maintained at a pressure below 10^{-3} Torr.
4. The system of claim 1, wherein the piezoelectric transducer is synchronized to an external timing signal.
5. The system of claim 4, wherein the external timing signal is derived from an optical clock or optical frequency comb distributed to a fusion module.
6. The system of claim 1, wherein the fuel droplets have a diameter between 1 micron and 500 microns.
7. The system of claim 1, wherein the jet velocity exceeds 10 meters per second.
8. The system of claim 1, further comprising a heated skimmer configured to reduce deposition of fuel at the aperture.
9. The system of claim 1, further comprising a charging electrode configured to impart an electrical charge to droplets.
10. The system of claim 9, further comprising an electrostatic steering system configured to correct a droplet trajectory based on the electrical charge.
11. The system of claim 1, further comprising an optical metrology subsystem configured to measure droplet position at or near a fusion focal plane.
12. The system of claim 11, further comprising a controller configured to adjust at least one of: reservoir pressure, nozzle temperature, piezo drive amplitude, droplet charge, or electrostatic steering, based on the measured droplet position.
13. The system of claim 1, further comprising a downstream droplet catcher aligned to intercept droplets after an interaction region and configured to collect unburned droplets for recycling.
14. The system of claim 1, further comprising a coaxial gas sheath configured to provide aerodynamic focusing in at least one differential pumping region.
15. The system of claim 1, wherein the droplets are generated at a repetition rate exceeding 10 kHz.
16. The system of claim 1, further comprising a fuel recovery subsystem configured to collect unburned fuel or vapor from at least one differential pumping region.
17. A method for delivering fusion fuel targets, comprising:

- Pressurizing a liquid fuel source;
- Ejecting the fuel through a heated nozzle into an intermediate-pressure region;
- Perturbing the nozzle and/or jet to break the fuel jet into a stream of droplets with controlled size and spacing;
- Differentially pumping the intermediate-pressure region while transmitting the droplet stream through at least one aperture into a high-vacuum region; and
- Intersecting the droplets with a fusion driver in the high-vacuum region.

18. The method of claim 17, further comprising charging the droplets and steering the droplets using an electrostatic field.

19. The method of claim 17, further comprising measuring droplet position using an optical sensor synchronized to a pulse train and adjusting injector parameters based on an error signal.

20. The method of claim 17, further comprising executing an anti-icing cycle by increasing a nozzle temperature above a threshold and/or modulating heater power based on a detected droplet irregularity.