

CHAMBER CLEARING : THE HYDRODYNAMIC SOURCE TERM

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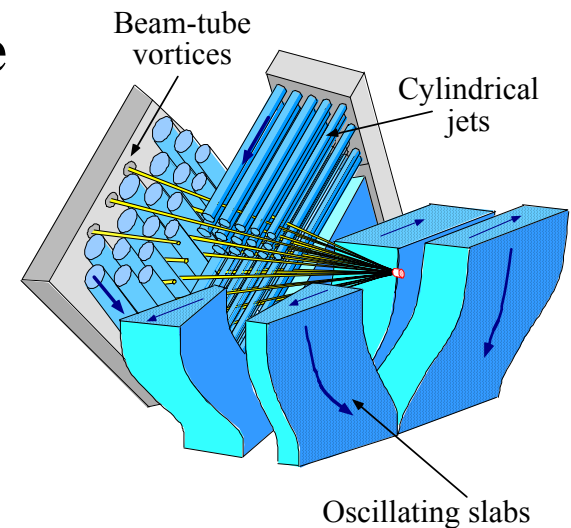
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Problem Definition

- **RPD-2002: Use cylindrical jets and liquid sheets to shield IFE chamber first walls from neutrons, X-rays and charged particles**
 - **Oscillating slabs create protective pocket to shield chamber side walls**
 - **Lattice of stationary jets shield front/back walls while allowing beam propagation and target injection**



Picture courtesy P.F. Peterson, UCB

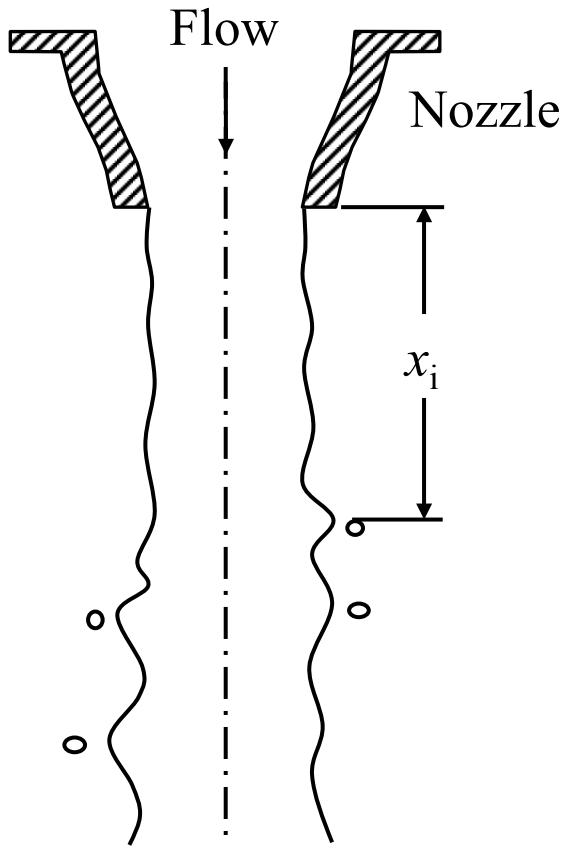


Objectives

- **Estimate rate of droplet formation due to hydrodynamics (turbulent breakup) for the thick liquid protection concept**
- **Provide estimates of droplet size distribution**
 - **How does the hydrodynamic source term compare to vapor generation from target energy deposition?**
 - **Is it compatible with beam propagation requirements?**



Turbulent Breakup



- **Turbulent primary breakup**
 - Formation of droplets along free surface
 - Due to vorticity imparted at nozzle exit
- **Onset of breakup, x_i**
 - Location of first observable droplets
 - $x_i \downarrow$ as $We \uparrow$



Approach

- **Use published models / correlations to estimate upper limits of mass flux and droplet diameters for RPD-2002**
- **Perform experiments for slab jets to obtain mass fluxes for comparison with empirical predictions**
- **Focus on “stationary” (non-oscillating) jets, i.e. beam propagation lattice**



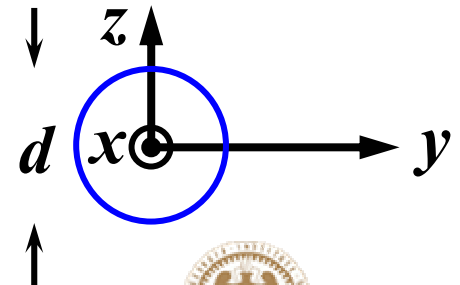
Empirical Work

- **Considerable database from combustion and spray research group at UM (Faeth et al.)**
 - **Most recently: Sallam, Dai, & Faeth, Int. J. of Multiphase Flow, 28, 427 – 449 (2002)**
- **Application constraints :**
 - **Data for round and annular jets**
 - **Fully developed turbulent flow at exit**
 - **No flow conditioning, contraction/nozzle or boundary layer (BL) cutting**
 - **Jets issue into air at atmospheric pressure**
 - **Working fluids: water and ethanol**



Correlation Parameters

- $d = 1.9 - 8 \text{ mm}$
- Reynolds number $Re = U_0 d / \nu = 5,000 - 200,000$ [U_0 average speed; ν liquid kinematic viscosity]
- Weber number $We = \rho_L U_0^2 d / \sigma = 240 - 270,000$ [ρ_L liquid density; σ surface tension]
- Froude number $Fr = U_0^2 / (gd) = 120 - 86,000$



Correlations

- **Radial length scale**

$$\Lambda = d/8$$

- **Onset of droplet formation**

$$\frac{x_i}{\Lambda} = 7560 We_{\Lambda}^{-0.74} \quad \text{where } We_{\Lambda} = \frac{\rho U_o^2 \Lambda}{\sigma}$$

- **Mean droplet size as a function of x ($x \geq x_i$)**

$$\frac{SMD}{\Lambda} = 0.45 \left(\frac{x}{\Lambda We_{\Lambda}^{1/2}} \right)^{0.5} \quad \text{for } We_{\Lambda} = 30 - 34,000$$



Surface Breakup Efficiency Factor

- **Radial droplet velocity relative to jet surface**

$$\tilde{v}_r \cong 0.045 U_o$$

- **Surface breakup efficiency factor**
 - Gives a measure of the flux of droplets from free surface
 - $\varepsilon = 1$ indicates droplets are forming over entire surface area of liquid surface

$$\varepsilon = \frac{G}{\rho_L \tilde{v}_r} \quad \text{where } G \equiv \text{mass flux of droplets}$$

- **Efficiency factor correlation**

$$\varepsilon = 0.012 \left[\frac{x}{(\Lambda We_\Lambda)^{1/2}} \right]$$



RPD-2002 Description

- **Focus on lattice of stationary jets (Beam propagation concerns)**
- **Four quadrants of cylindrical jets**
 - **Each quadrant contains 12 rows of jets with 3 – 6 jets per row**
 - **Jet diameters range from 4.61 – 15.6 cm**
 - **$U_0 = 12$ m/s for all jets**
 - **Streamwise flow dimension taken as 2m for all jets**



RPD-2002 Jet Layout

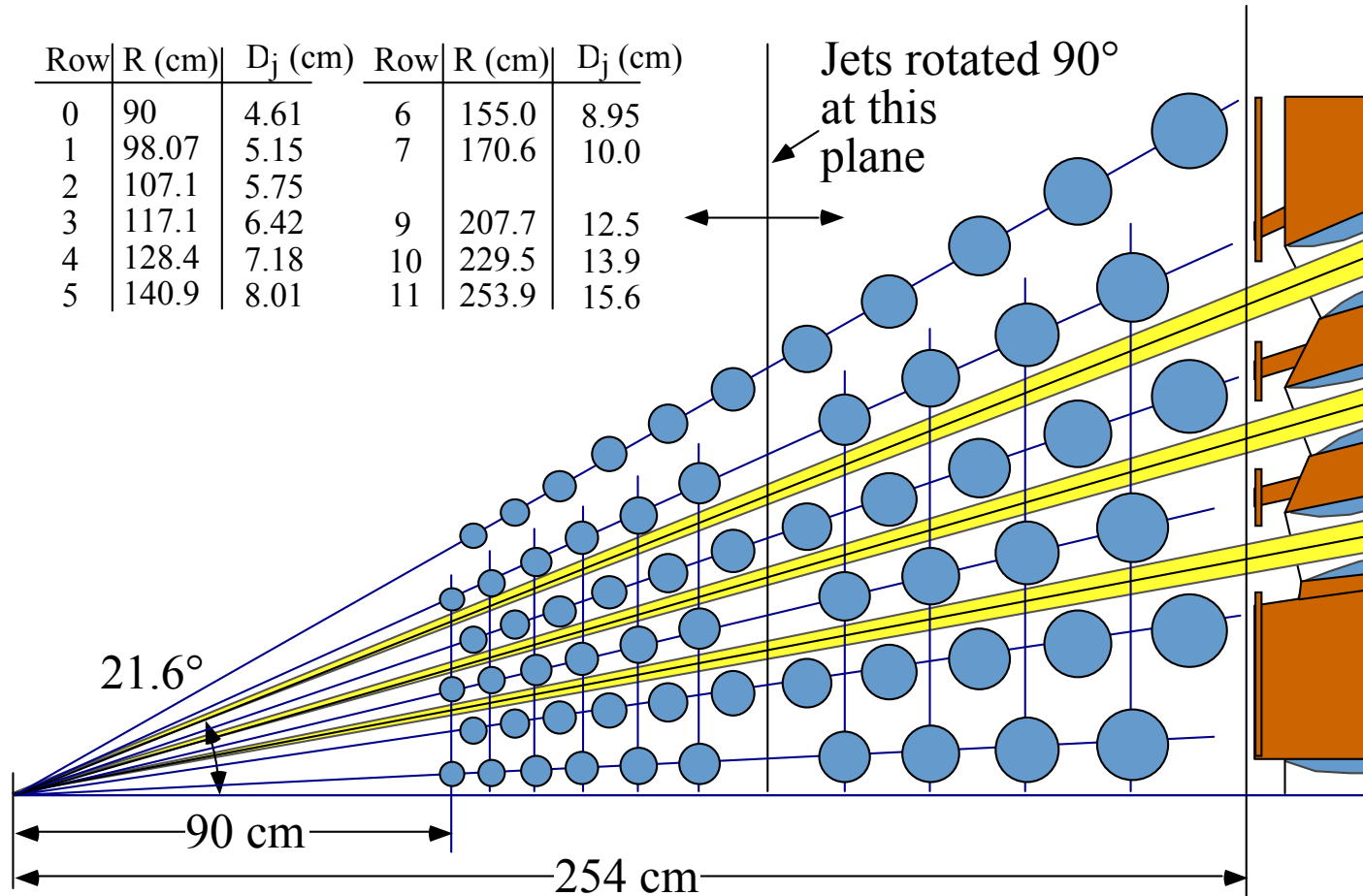


Diagram courtesy P.F. Peterson, UCB



RPD-2002

Correlation Results

- **Total droplet mass ejection rate ≈ 1300 kg/s**
 - Assumes $G(x = 1 \text{ m})$ over entire surface area of each respective jet (Mean value of predictions)
 - $\sim 3\%$ of total jet flow rate
- **SMD ≈ 5.7 mm for all jets at $x = 1$ m**
 - SMD at $x_i \approx 0.82 - 1.0$ mm for $d = 4.61 - 15.6$ cm, respectively



Comments

- **Evaporation rate due to target energy deposition assuming 6 Hz**

	Total (MJ)	X-rays and ions (MJ)	Mass rate (kg/s) *
NRL - DD	154	45	37 - 51
HIF - ID	458	142	116 - 160

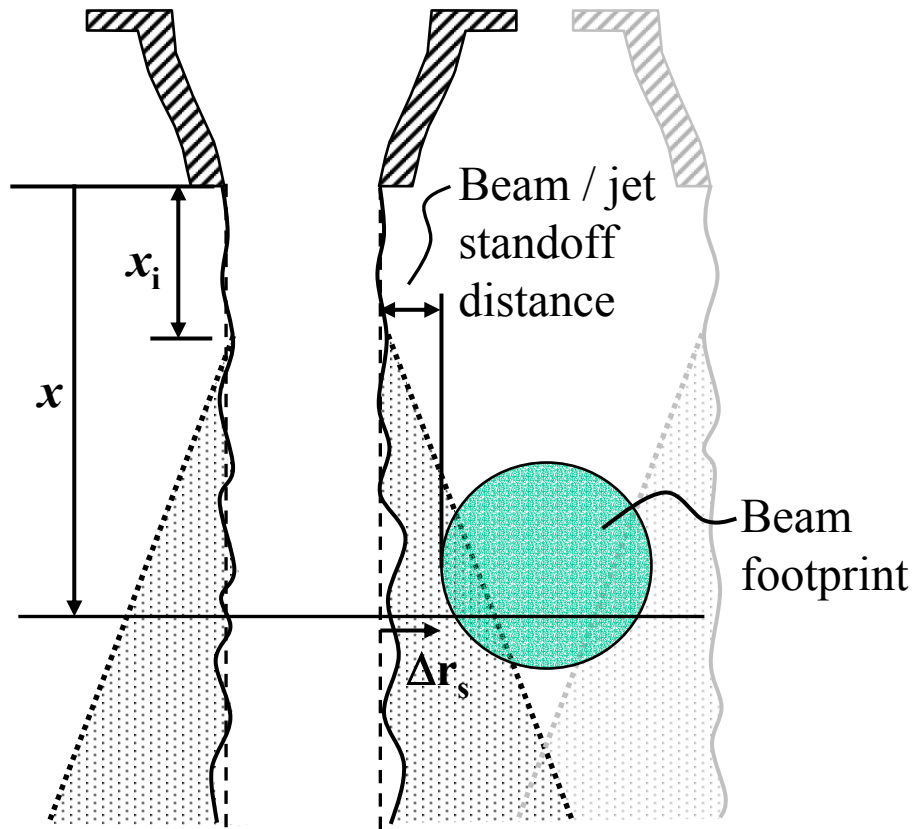
* Saturated Flibe: $\Delta h = h_{fg} = 5.3 \text{ MJ/kg}$

Subcooled Flibe: $\Delta h = 7.3 \text{ MJ/kg}$

- **Hydrodynamic source term ~ 1300 kg/s !**
 - **Must be reduced (Flow conditioning, nozzle, BL cutting, etc.)**



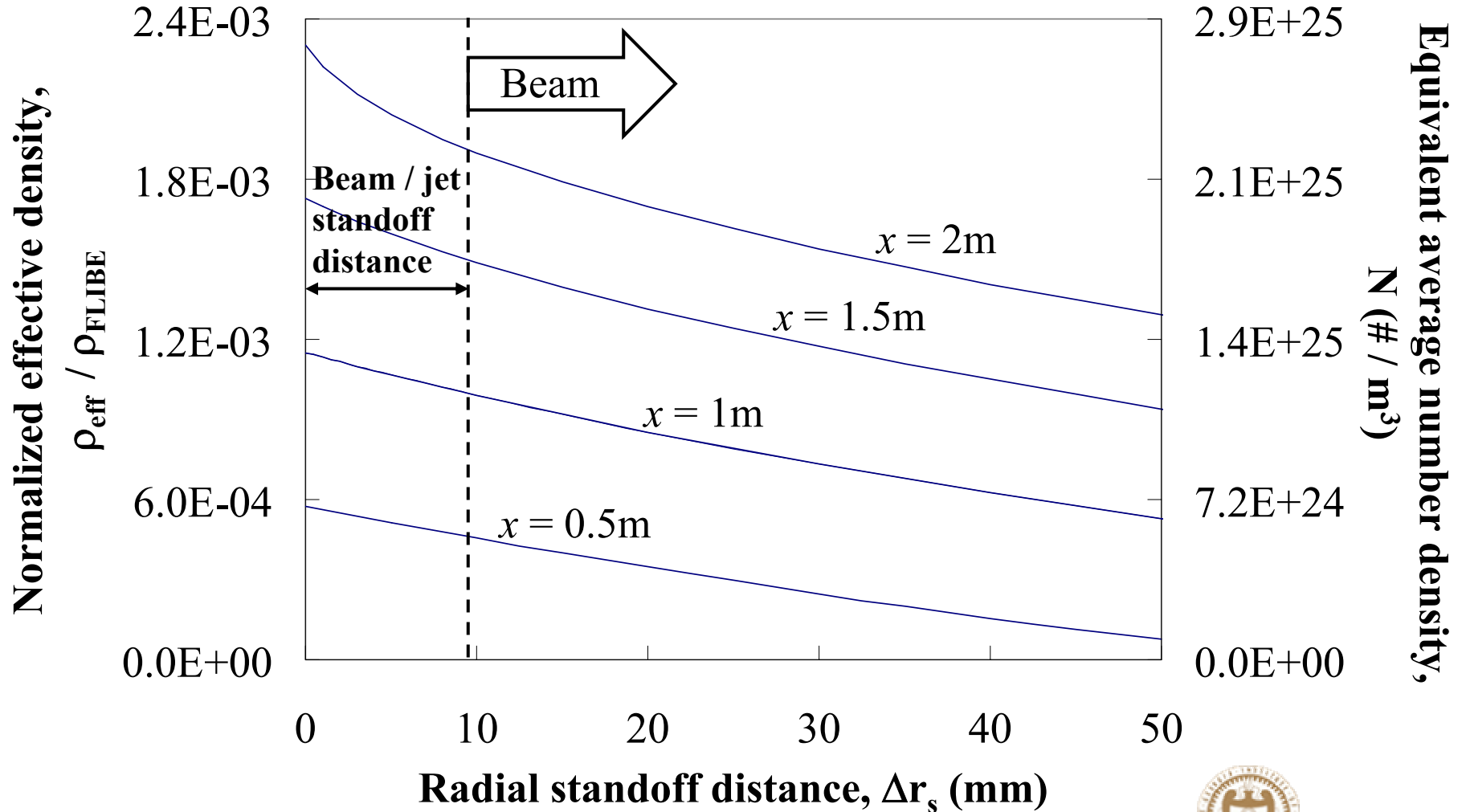
Implications for Beam Propagation



- **Droplets enter into beam footprint**
- **Radial standoff, Δr_s**
 - **Measured from nominal jet surface**
- **Equivalent number density dependent on x and Δr_s**
 - **Ignores jet-jet interactions**



Implications for Typical RPD-2002 Jet: $d = 4.61$ cm (Row 0)

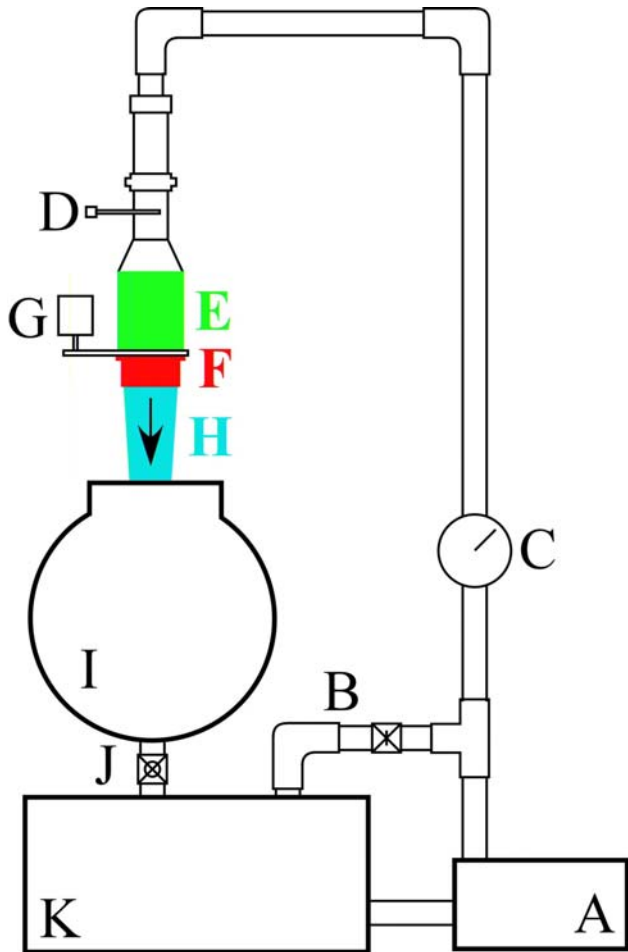


Beam Propagation Compatibility

- **Model predictions imply protection concept is incompatible with beam propagation requirements**
- **However, model is based on :**
 - **Fully developed pipe flow at exit**
 - **No flow conditioning, nozzle or BL cutting**
- **Can nozzles / jets be designed to reduce these number densities to a level compatible with beam propagation requirements?**



Flow Loop

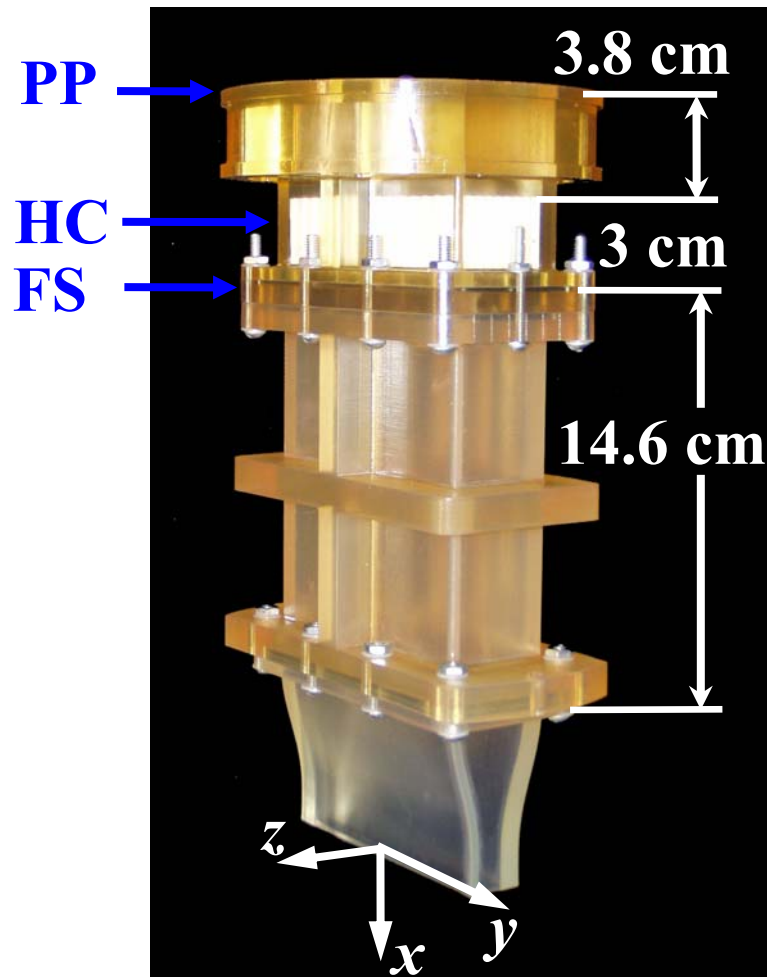


- Pump-driven recirculating flow loop
- Test section height ~ 1 m
- Overall height ~ 5.5 m

A	Pump	B	Bypass line
C	Flow meter	D	Pressure gage
E	Flow straightener	G	Oscillator (Not used)
F	Nozzle	I	400 gal tank
H	Sheet	K	700 gal tank
J	Butterfly valve		



Flow Conditioning

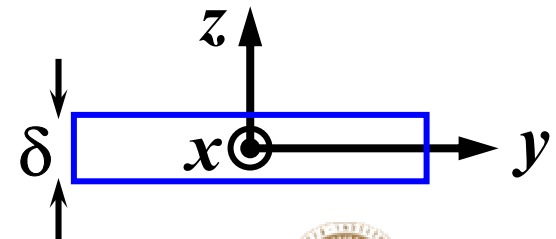


- **Round inlet (12.7 cm ID) to rectangular cross-section 10 cm × 3 cm ($y \times z$)**
- **Perforated plate (PP)**
 - Open area ratio 50% with staggered 4.8 mm dia. holes
- **Honeycomb (HC)**
 - 3.2 mm dia. × 25.4 mm staggered circular cells
- **Fine mesh screen (FS)**
 - Open area ratio 37.1%
 - 0.33 mm dia. wires woven w/ open cell width of 0.51 mm (mesh size 30 × 30)
- **5th order contracting nozzle**
 - Contraction ratio = 3
- **Note: No BL trimming**



Experimental Parameters

- $\delta = 1$ cm; aspect ratio $AR = 10$
- Reynolds number $Re = 130,000$ [U_o average speed; ν liquid kinematic viscosity]
- Weber number $We = 19,000$ [ρ_L liquid density; σ surface tension]
- Froude number $Fr = 1,400$
- Fluid density ratio $\rho_L / \rho_G = 850$ [ρ_G gas density]
- Near-field: $x / \delta \leq 25$

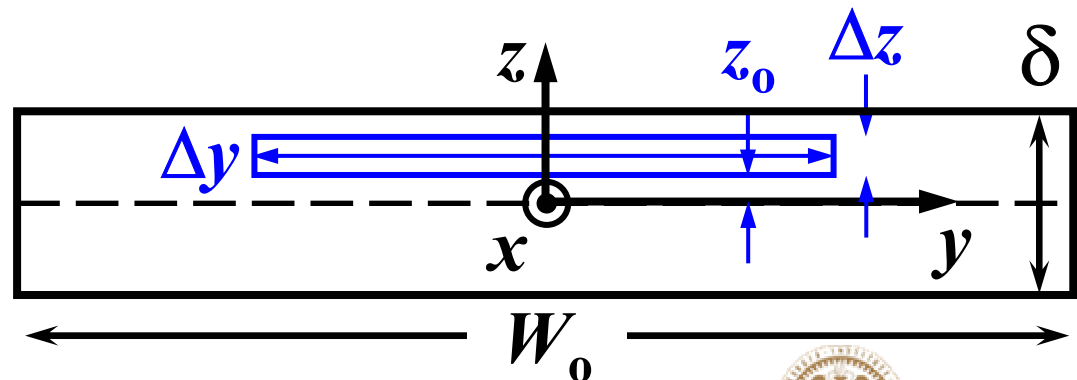


Liquid Cumulative Distribution Function

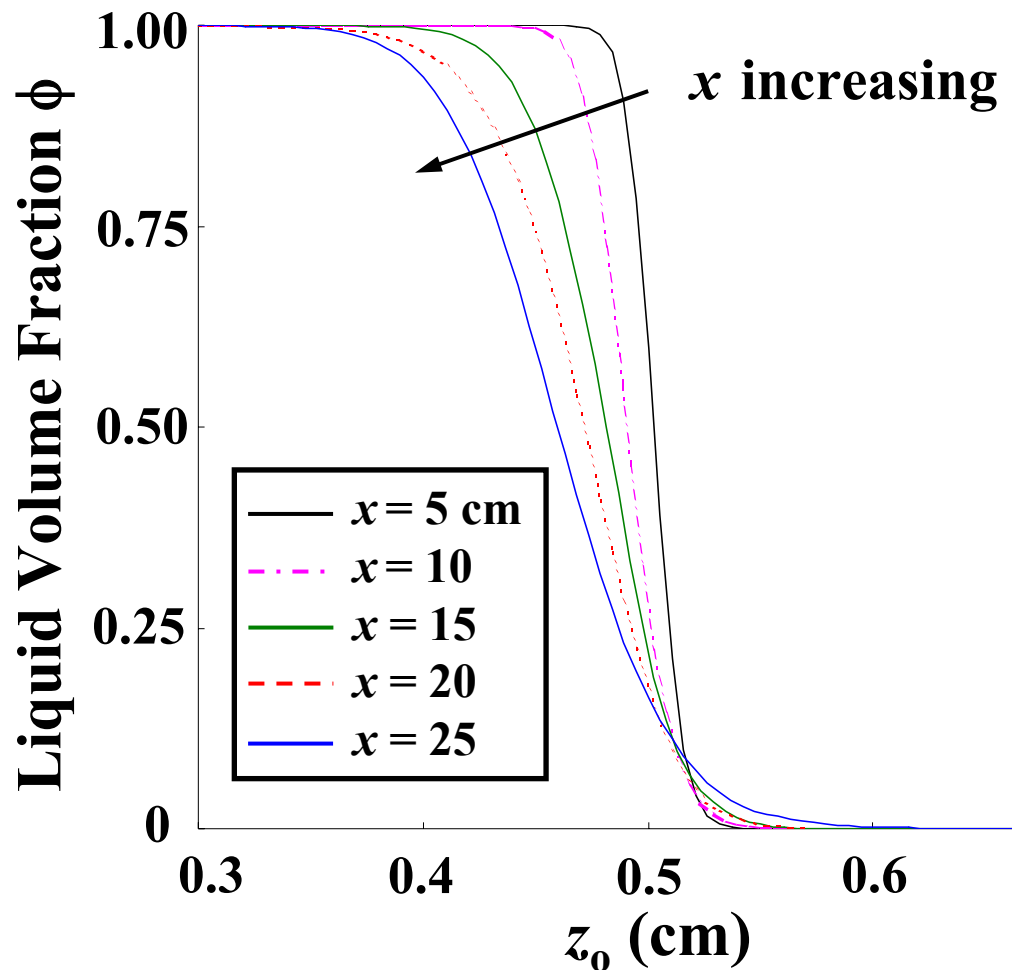
- **Liquid cumulative distribution function (LCDF) = liquid volume fraction ϕ within a $\Delta y \times \Delta z$ “box” located at z at given x**
 - Results for box at nozzle edge useful in neutronics calculations
- **Calculate liquid volume fraction in rectangular box at given x location: box spans $-0.5\Delta y \leq y \leq +0.5\Delta y$;**

$$z_0 \leq z \leq z_0 + \Delta z$$

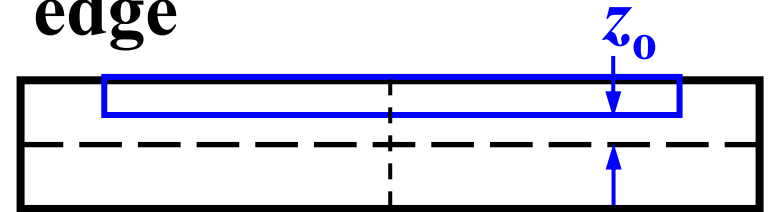
- $\Delta z / \delta = 0.01$
- $\Delta y / W_0 = 0.1 - 0.8$



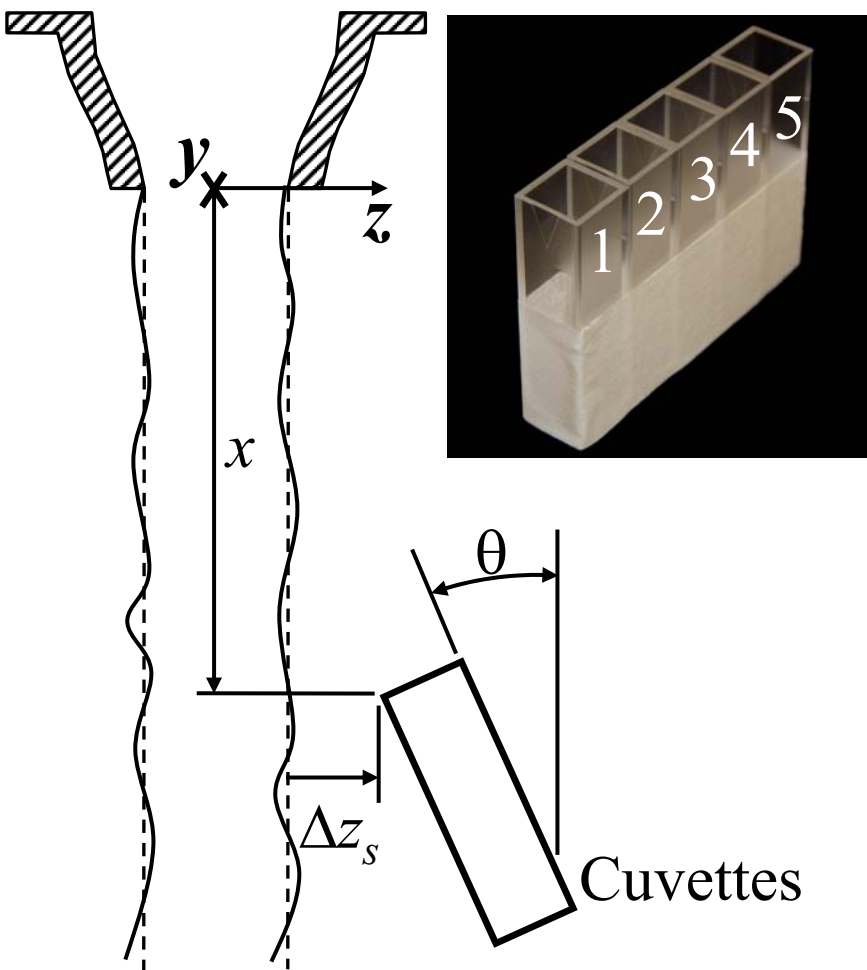
LCDF: $Re = 130,000$



- Fluctuations \uparrow as $x \uparrow$
- Thickness of “fully flooded” ($\phi = 1$) region \downarrow as $x \uparrow$
- Box dimensions $0.01 \text{ cm} \times 6 \text{ cm}$
- $z_0 = 0.5 \text{ cm} \Rightarrow$ nozzle edge



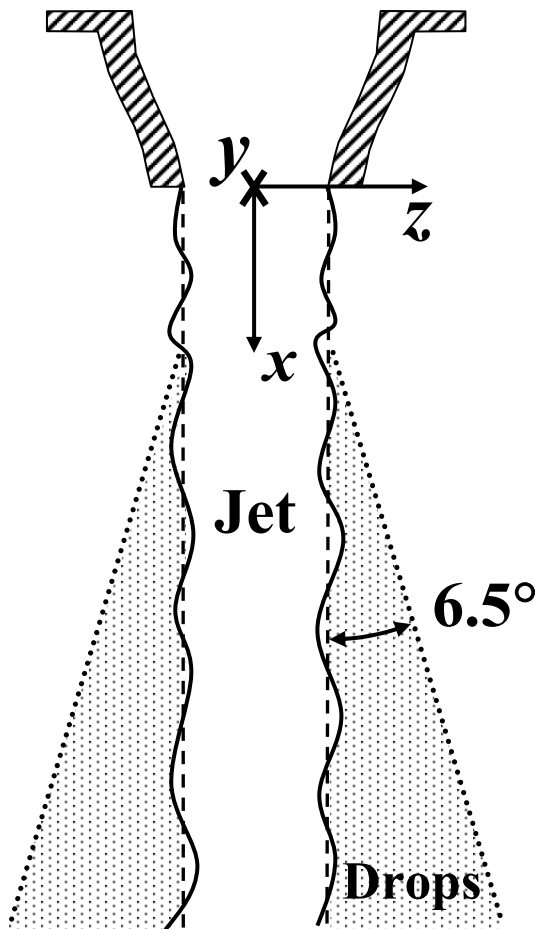
Preliminary Mass Collection Experiments



- **Cuvette opening = 1 cm \times 1 cm w/ 0.9 mm walls**
- **5 cuvettes placed side by side**
 - **Cuvette #3 centered at $y=0$**
- **Located at x , Δz_s away from nominal jet position**
 - **Δz_s varied from $\sim 6 - 25$ std. deviations of surface ripple, $\sigma_z(x)$**
 - **Experiments repeated to determine uncertainty in data**
- **Shallow angle of inclination, $\theta = 6.5^\circ$**
- **Samples acquired over 0.5 – 1 hr**



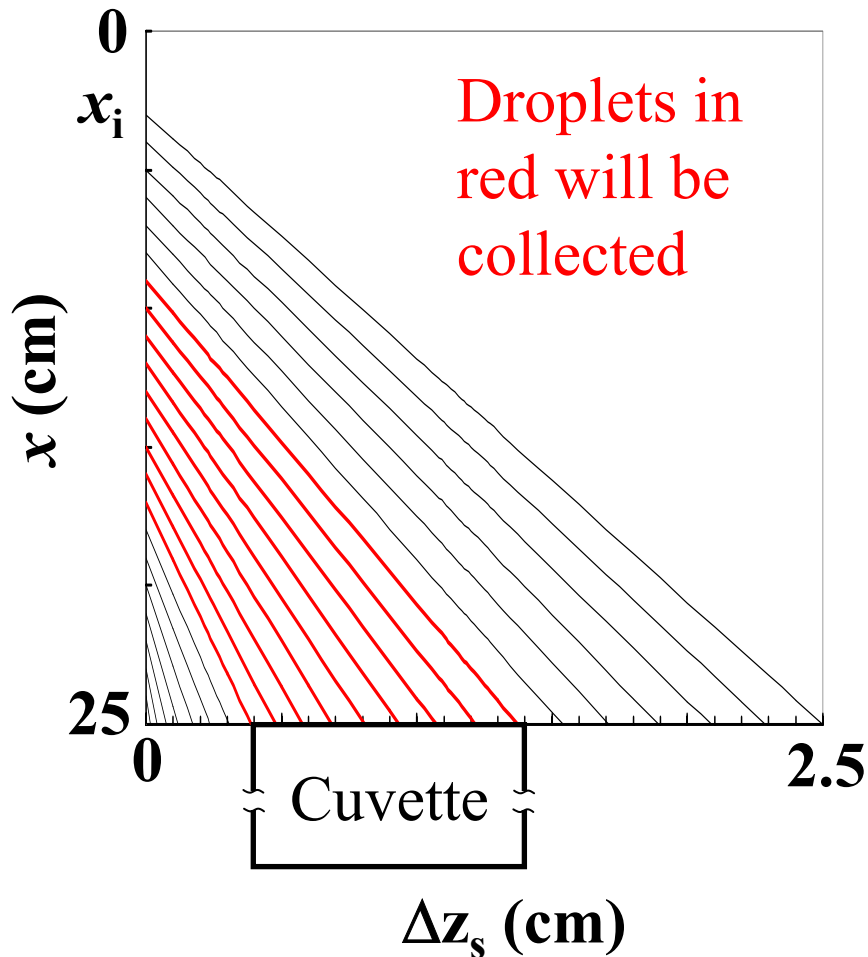
Droplet Trajectories



- **Droplets follow ballistic path based on \tilde{u} and \tilde{v}**
 - Absolute streamwise and radial velocities
$$\tilde{u} = 0.78 \cdot U_0, \quad \tilde{v} \leq 0.088 \cdot U_0$$
 - Neglects gravitational and aerodynamic effects
- **Droplet “halo” forms starting at x_i**
 - Droplets only inside halo



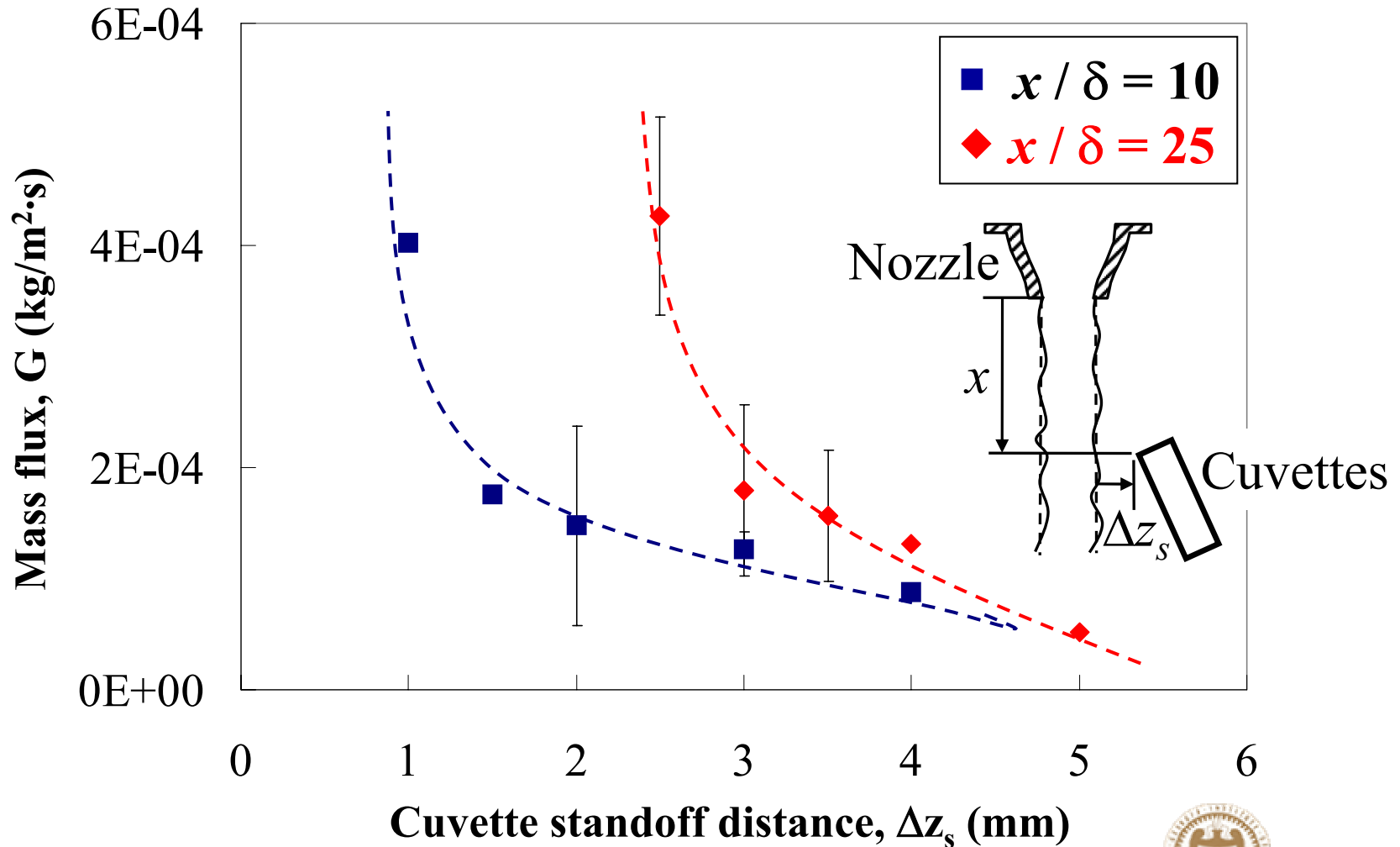
Collected Droplets



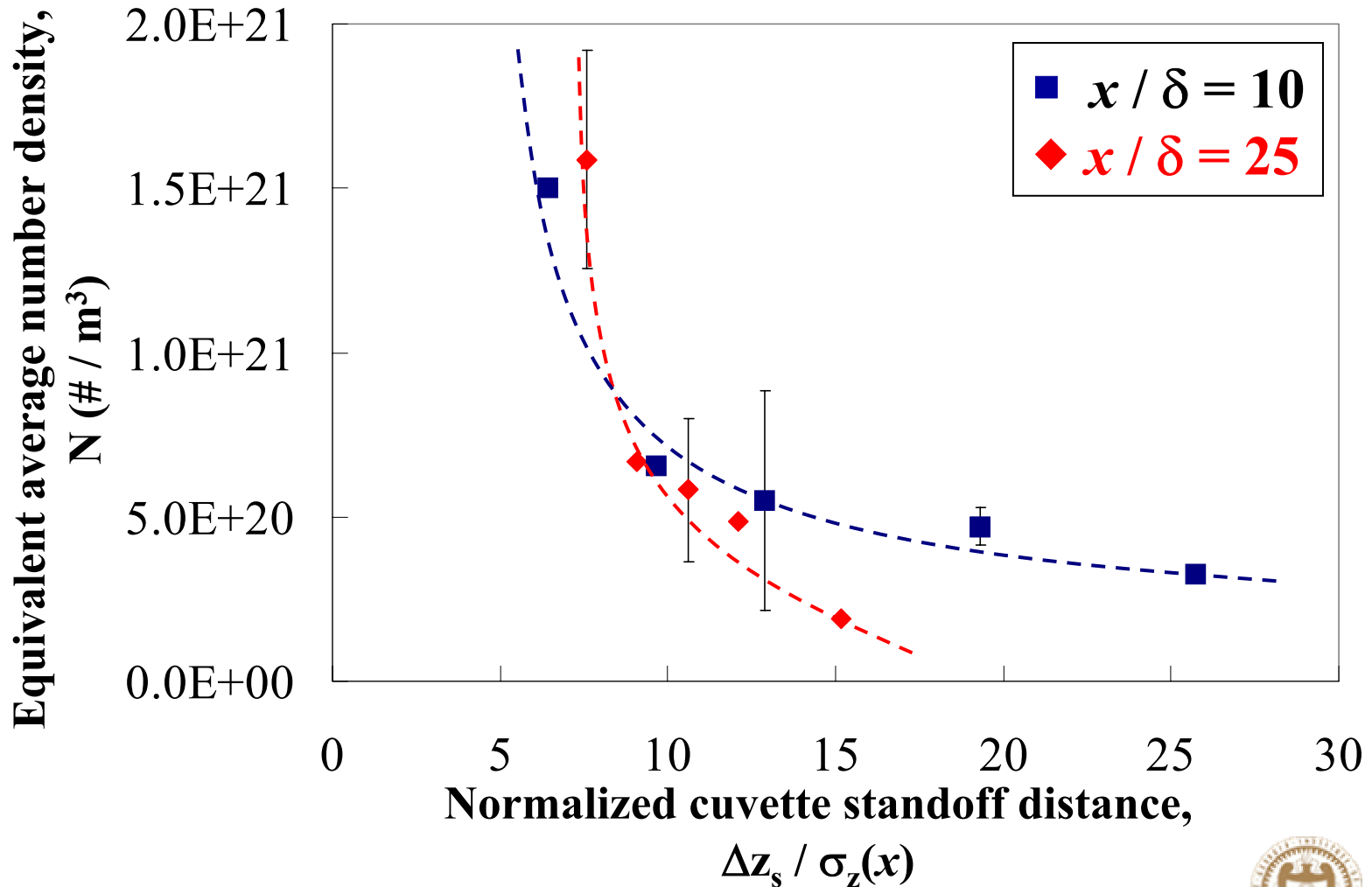
- **Droplets w/ intersecting trajectories into cuvette will be collected**
- **Cuvette shown at $x = 25$ cm, $\Delta z_s = 4$ mm, and $\theta = 0^\circ$**
- **Note: $z = 0$ corresponds to nominal free surface of jet**



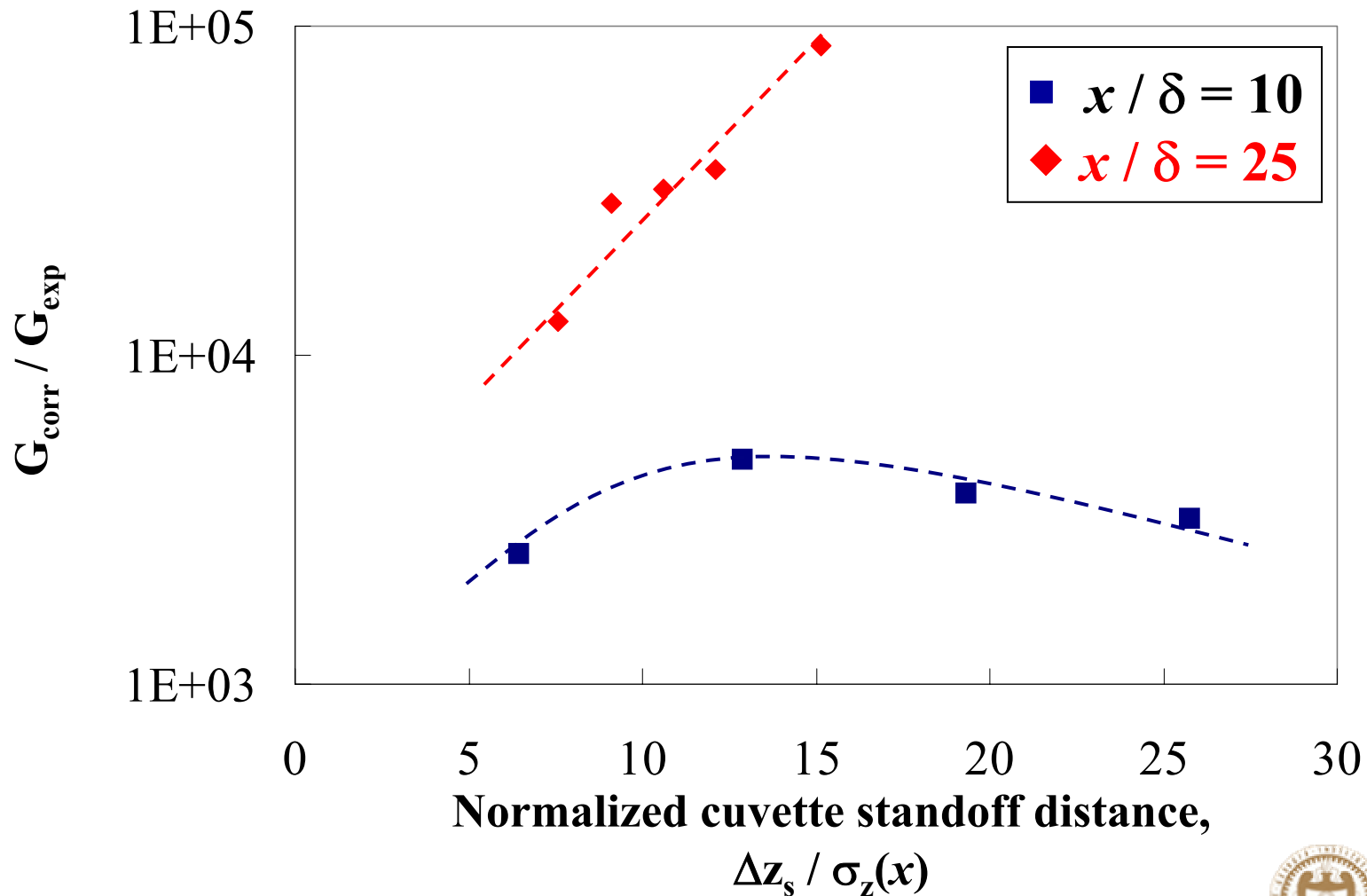
Experimental Mass Flux



Experimental Number Density



Model Comparison



Observations

- **Flow straightening and contracting nozzle significantly reduce droplet ejection (factor of $10^3 - 10^5$)**
- **BL cutting shown to have considerable impact on suppression of breakup**
[Wu et al. 1995; Pemberton et al. 2003]
- **Correlation significantly over predicts mass rate of ejected droplets**



Implications for RPD-2002

- **Assuming droplet emission reduced by 10^4**
 - $G(x_j) \approx 0.26 - 1.2 \times 10^{-4} \text{ kg/m}^2 \cdot \text{s}$
 - $G(x = 1\text{m}) \approx 3.4 - 21 \times 10^{-4} \text{ kg/m}^2 \cdot \text{s}$
- **Summing over all rows of jets**
 - $\sum \dot{m} \approx 0.13 \text{ kg/s}$ ($< 3 \times 10^{-4} \%$ of flow)
- **Hydrodynamic source term may be reduced to \ll evaporation rate due to energy deposition (37 – 160 kg/s)**
- **However, number density in the beam path prior to target implosion may still be unacceptable**



Conclusions

- **Hydrodynamic source term may be very significant**
- **Model predictions indicate concept incompatible with beam propagation requirements**
- **Initial experimental data with flow straightening reduces droplet mass flux (& number density) by 3 – 5 orders of magnitude**
- **Beam propagation still questionable**
- **Must configure jet design to minimize droplets**
- **Need quantitative experiments to confirm quality of prototypical jets**



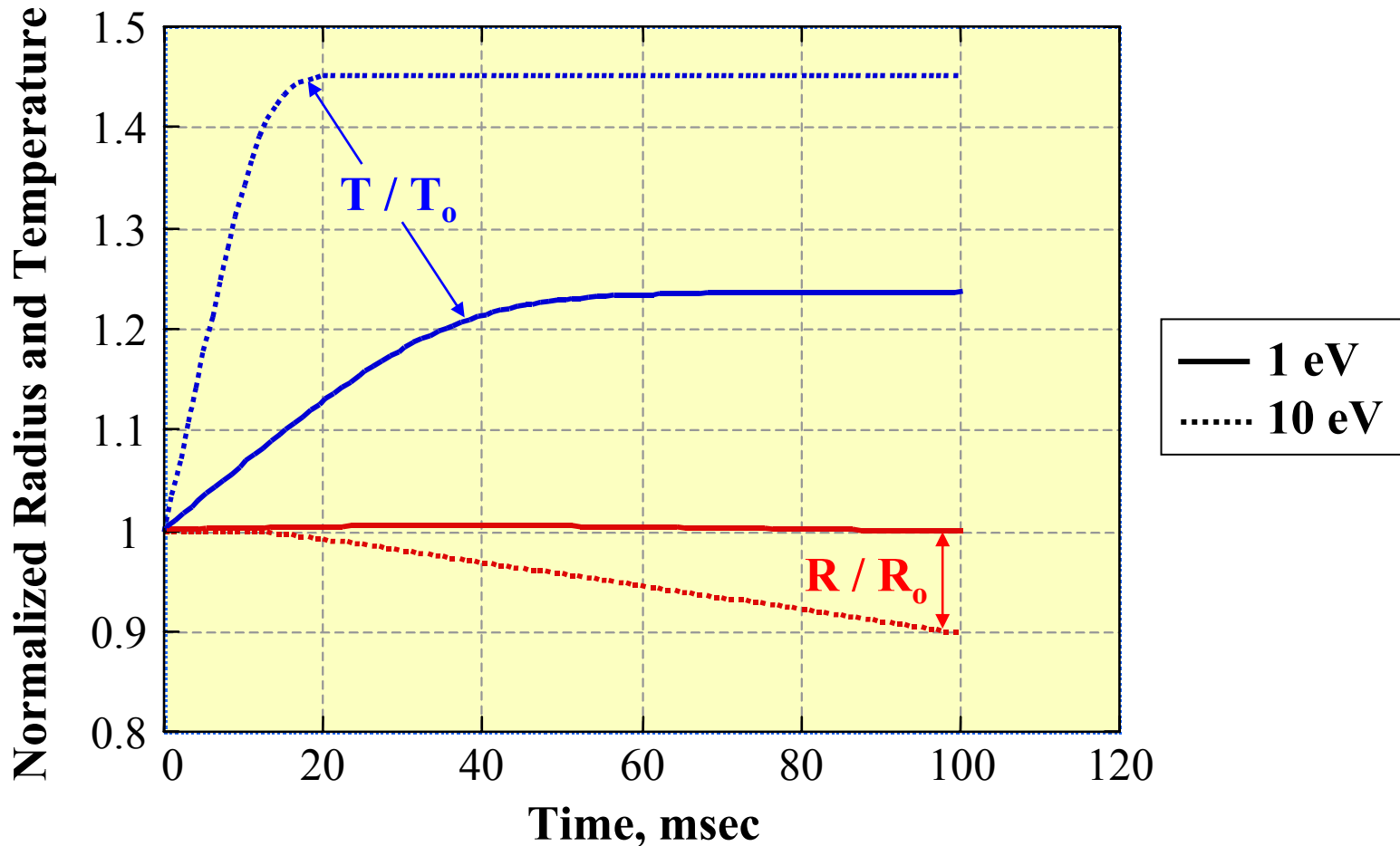
What Happens to the Droplets?

- **How long do liquid droplets survive in the chamber environment?**
- **Use Hassanein's HEIGHTS Package to study the evolution of a single spherical liquid lead droplet in an "infinite sea" of superheated lead vapor**
- **Parameters :**
 - **Ambient (Chamber) Temp:** 1 and 10 eV
 - **Ambient Pressure:** 0.01 and 0.1 torr
 - **Initial Droplet Diameter:** 10 and 100 μm
 - **Initial Droplet Temp:** 800 K



HEIGHTS Results*

(Lead, 10 μm , 0.1 Torr)



* I. Konkashbaev, A. Hassanein, and S.I. Abdel-Khalik (April 2003)



What are the Implications?

- **Liquid droplets will likely survive between shots!!**
- **Vacuum pumping requirements may be excessive**
- **For the path forward:**
 - **Verify calculations using prototypical experiments**

