CHAMBER CLEARING : THE HYDRODYNAMIC SOURCE TERM

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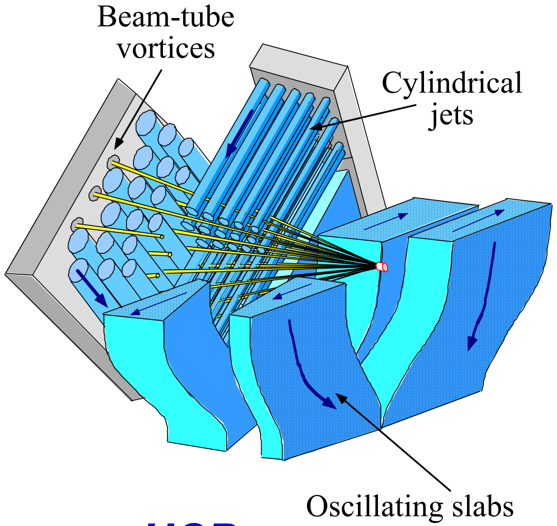
Problem Definition

- **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**

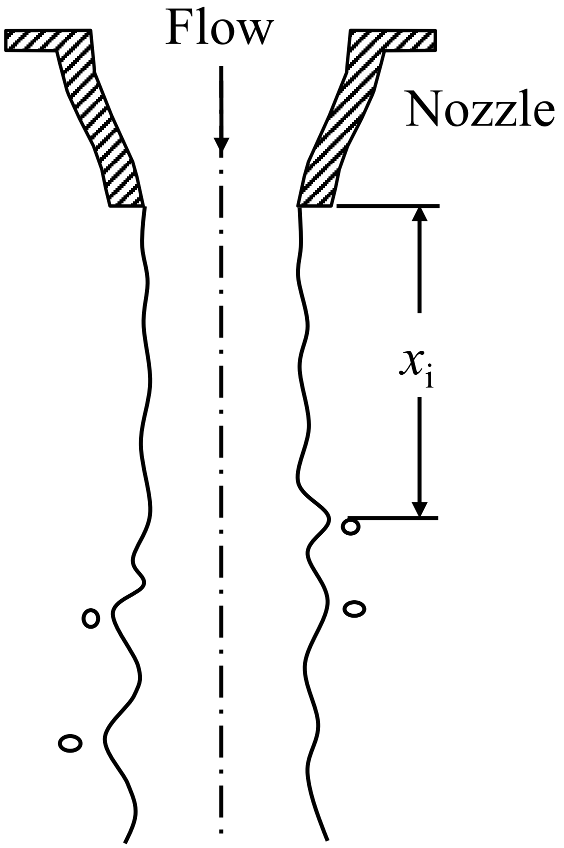


Picture courtesy P.F. Peterson, UCB

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 ↓ as *We* ↑**

Approach

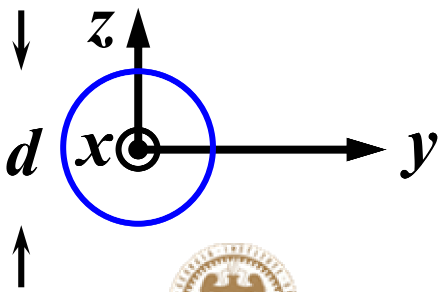
- Use published models / correlations to estimate upper limits of mass flux and droplet diameters for RPD-2002
- Perform experiments for slab jets to obtain mass fluxes for comparison with empirical predictions
- Focus on “stationary” (non-oscillating) jets, i.e. beam propagation lattice

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

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



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
  - ε = 1 indicates droplets are forming over entire surface area of liquid surface

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

- Efficiency factor correlation

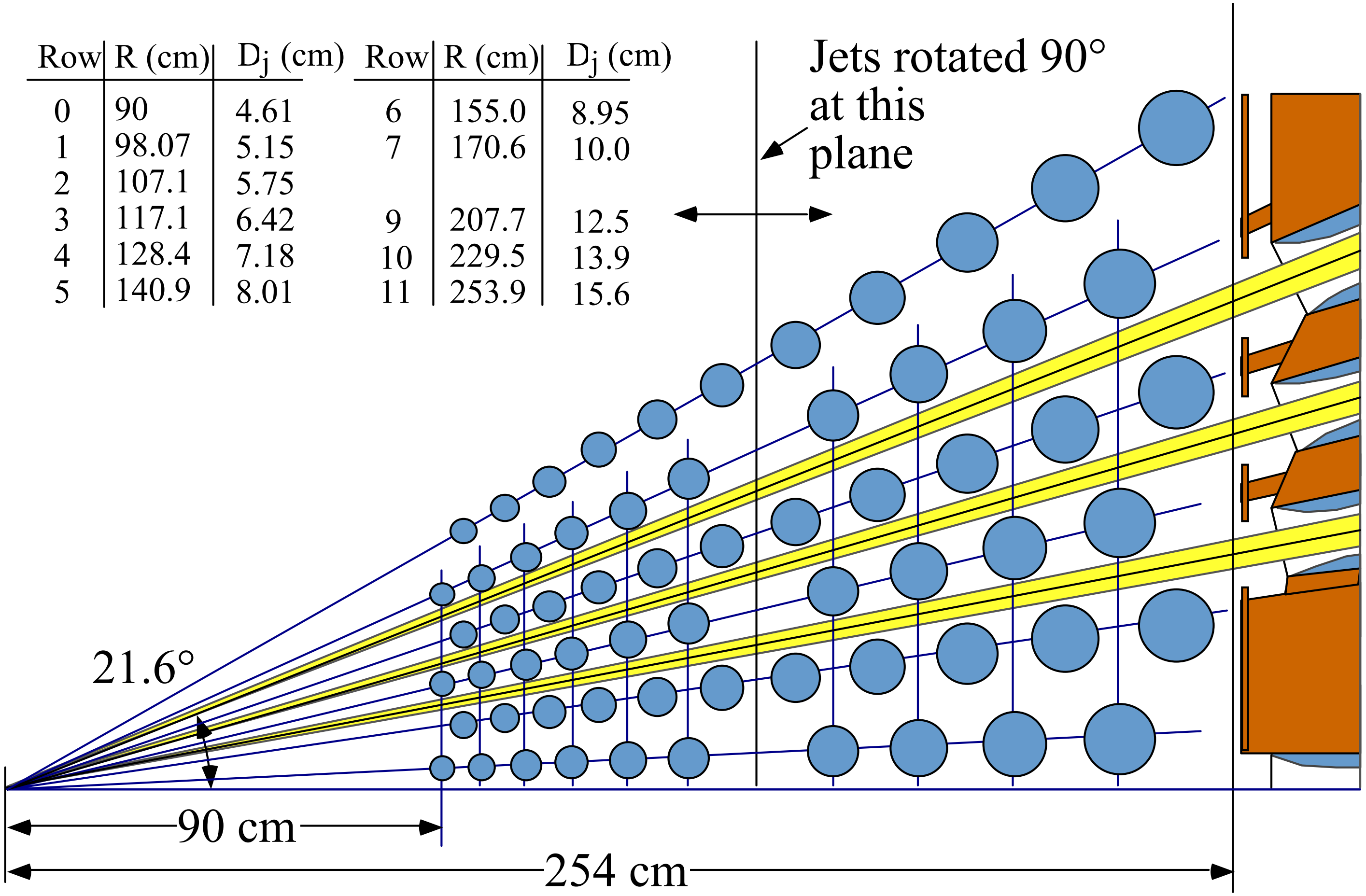
$$\varepsilon = 0.012 \left[x \big/ \left(\Lambda\, We_\Lambda^{\;1/2} \right) \right]$$

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_o = 12 m/s for all jets
  - Streamwise flow dimension taken as 2m for all jets

RPD-2002 Jet Layout

Row	R (cm)	D_j (cm)	Row	R (cm)	D_j (cm)
0	90	4.61	6	155.0	8.95
1	98.07	5.15	7	170.6	10.0
2	107.1	5.75			
3	117.1	6.42	9	207.7	12.5
4	128.4	7.18	10	229.5	13.9
5	140.9	8.01	11	253.9	15.6



Jets rotated 90° at this plane

Diagram courtesy P.F. Peterson, UCB

RPD-2002
Correlation Results

- **Total droplet mass ejection rate ≈ 1300 kg/s**
  - **Assumes $G(x = 1\ \mathrm{m})$ over entire surface area of each respective jet (Mean value of predictions)**
  - **~ 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**

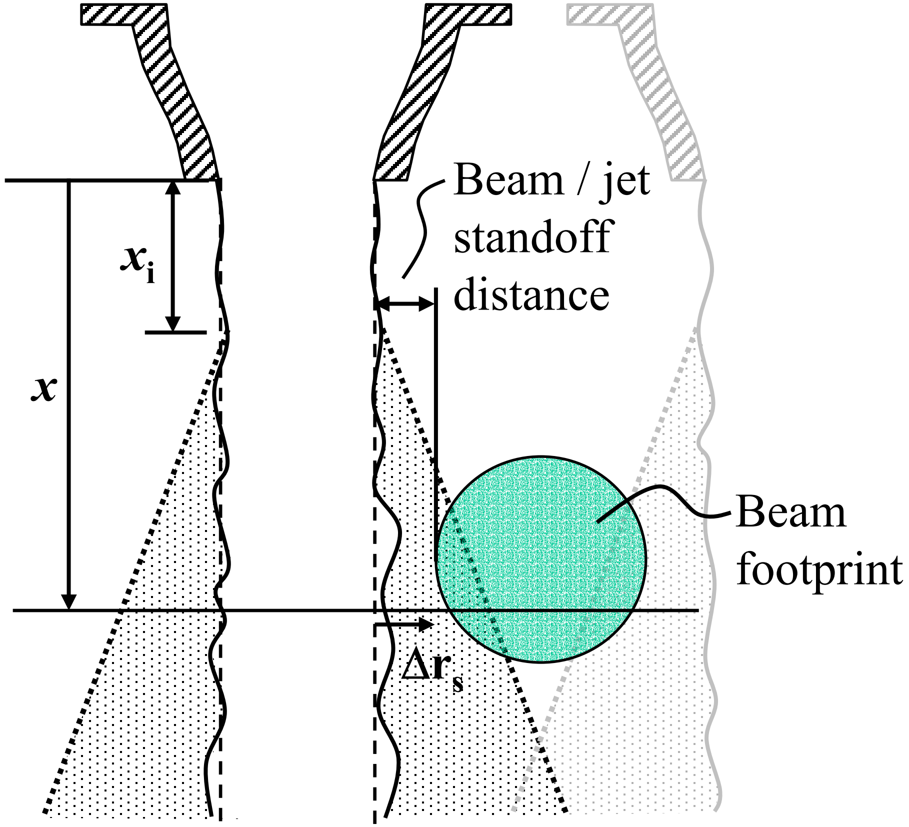
	Total (MJ)	X-rays and ions (MJ)	Mass rate (kg/s)
NRL - DD	**154**	**45**	**37 - 51**
HIF - ID	**458**	**142**	**116 - 160**

*

* Saturated Flibe: $\Delta h = h_{fg} = 5.3$ MJ/kg
Subcooled Flibe: $\Delta h = 7.3$ MJ/kg

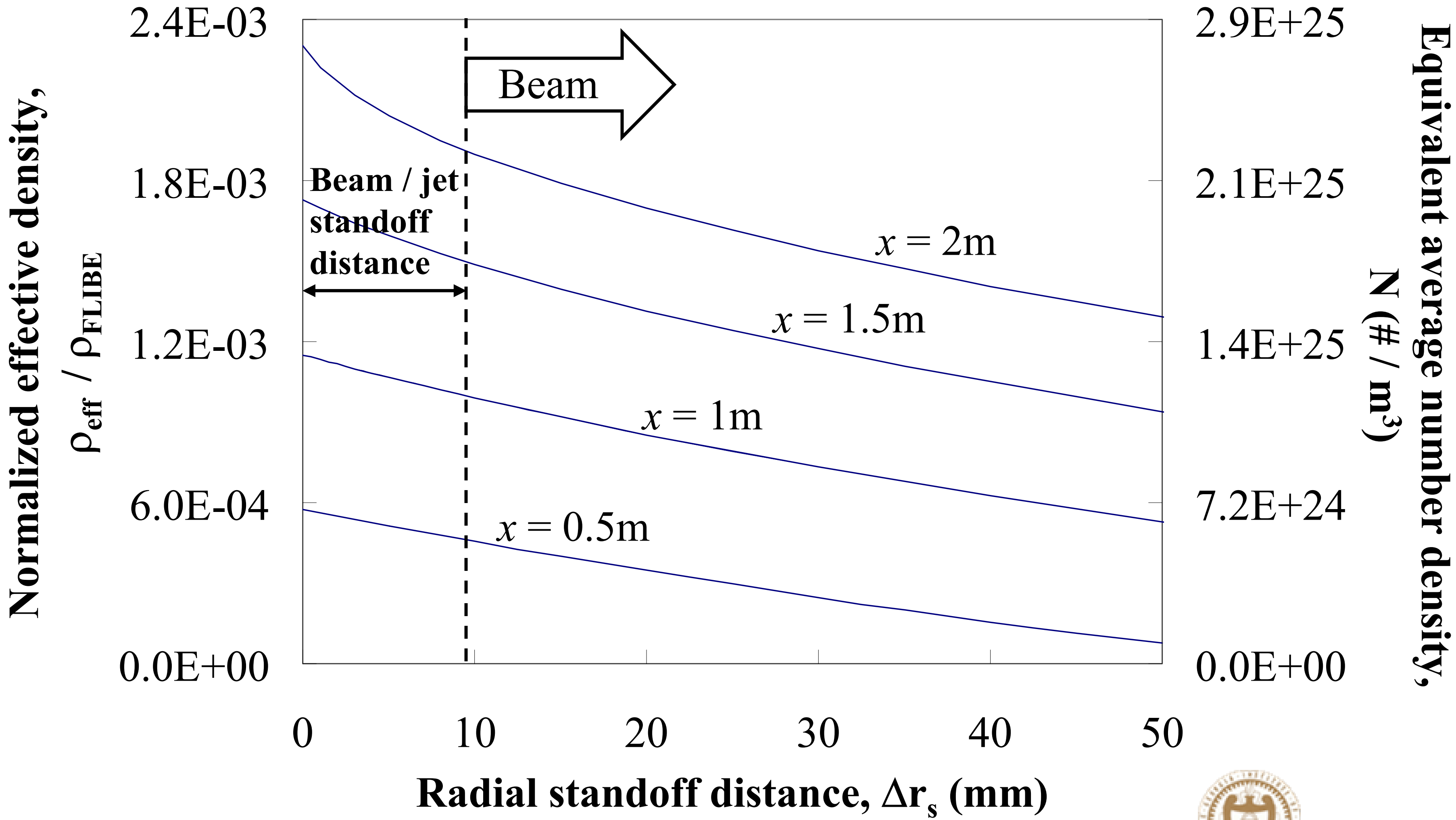
- **Hydrodynamic source term ~ 1300 kg/s !**
  - **Must be reduced (Flow conditioning, nozzle, BL cutting, etc.)**

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**

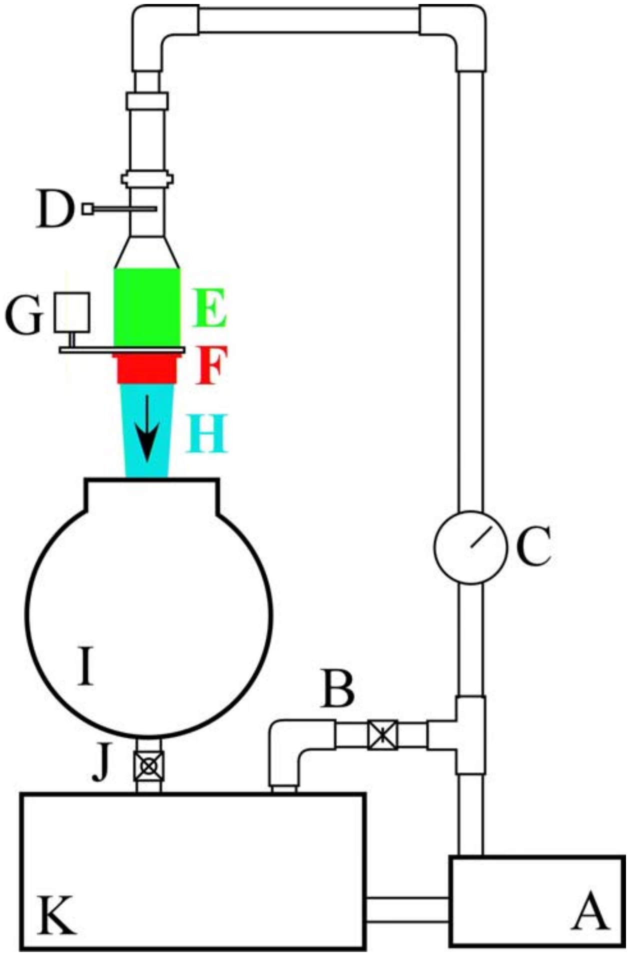
Implications for Typical RPD-2002 Jet: *d* = 4.61 cm (Row 0)



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?

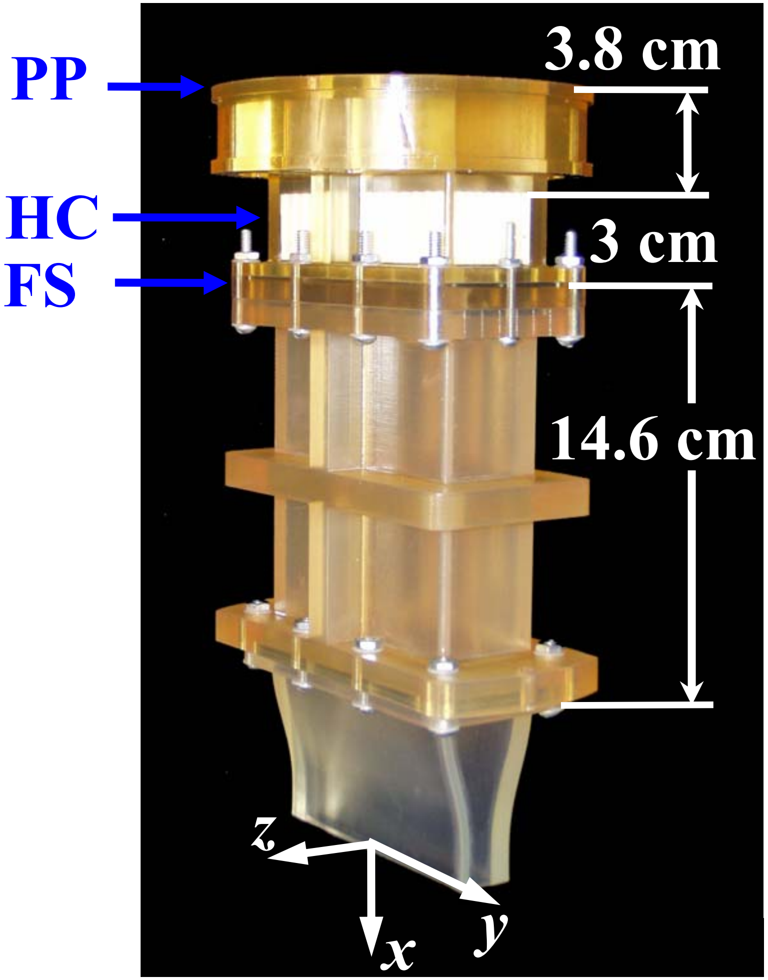
Flow Loop



- 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		
F	Nozzle	G	Oscillator (Not used)
H	Sheet	I	400 gal tank
J	Butterfly valve	K	700 gal tank

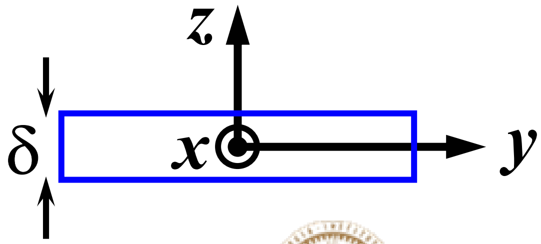
Flow Conditioning



- **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**

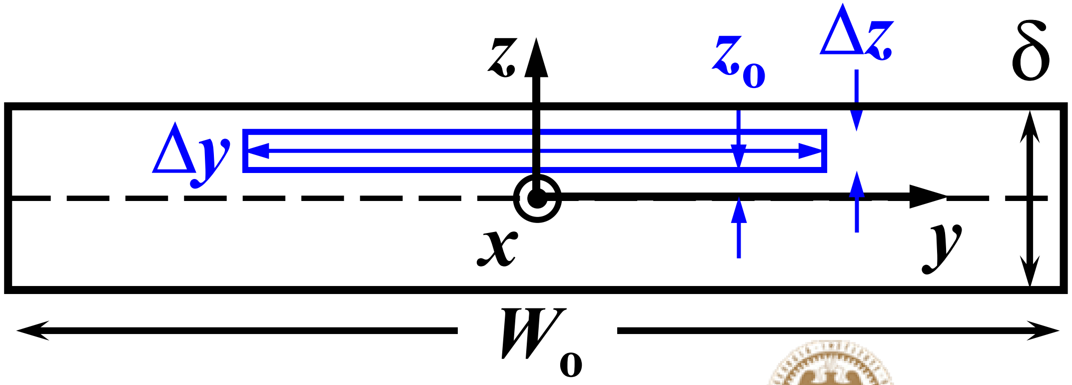
Experimental Parameters

- **δ = 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 ρ_L / ρ_G = 850** [ρ_G gas density]
- **Near-field: $x / \delta \leq 25$**

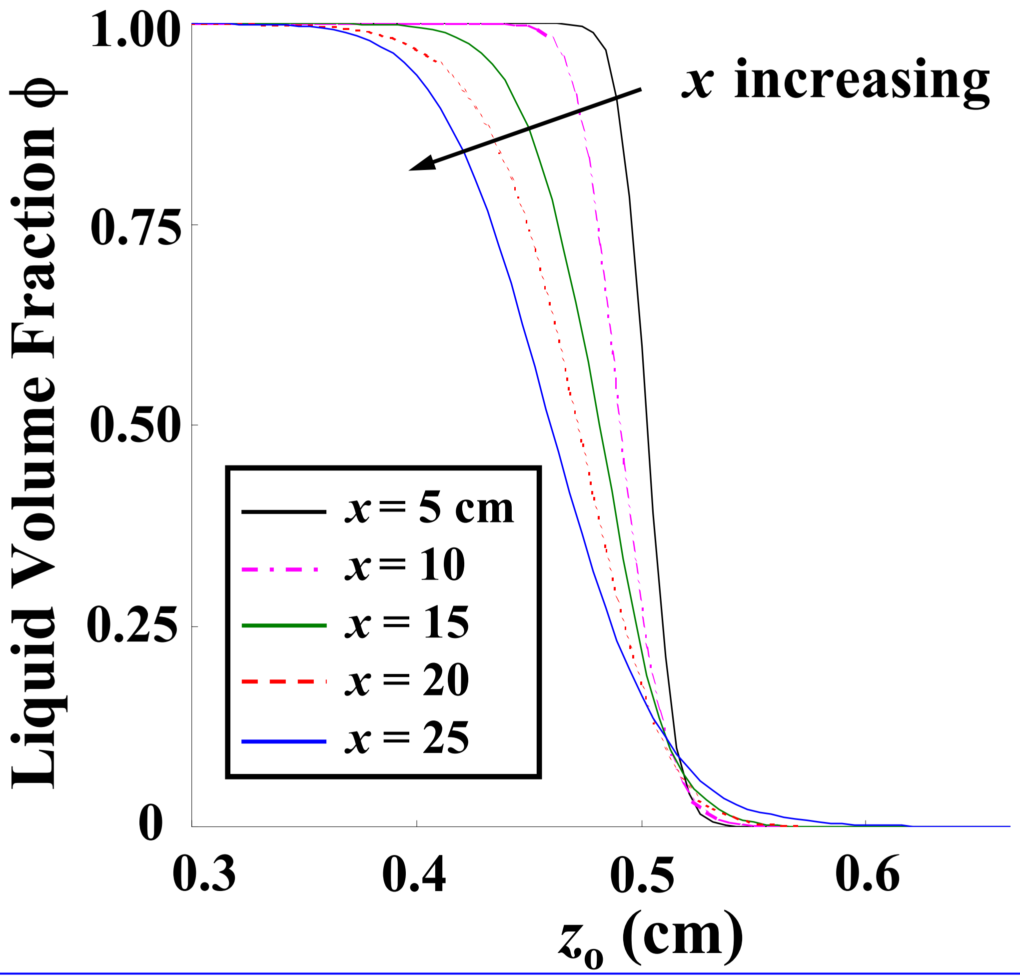


Liquid Cumulative Distribution Function

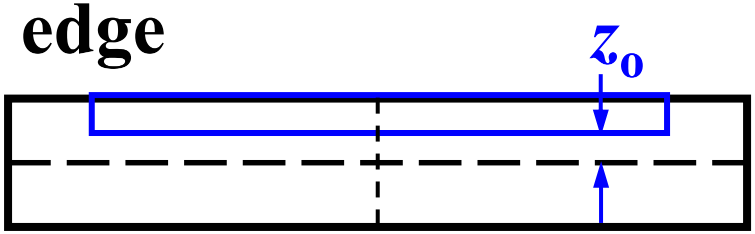
- **Liquid cumulative distribution function (LCDF) = liquid volume fraction ϕ within a $\Delta y \times \Delta z$ "box" located at z at given x**
  - Results for box at nozzle edge useful in neutronics calculations
- **Calculate liquid volume fraction in rectangular box at given x location: box spans $-0.5\Delta y \le y \le +0.5\Delta y$; $z_o \le z \le z_o + \Delta z$**
  - $\Delta z / \delta = 0.01$
  - $\Delta y / W_o = 0.1 - 0.8$



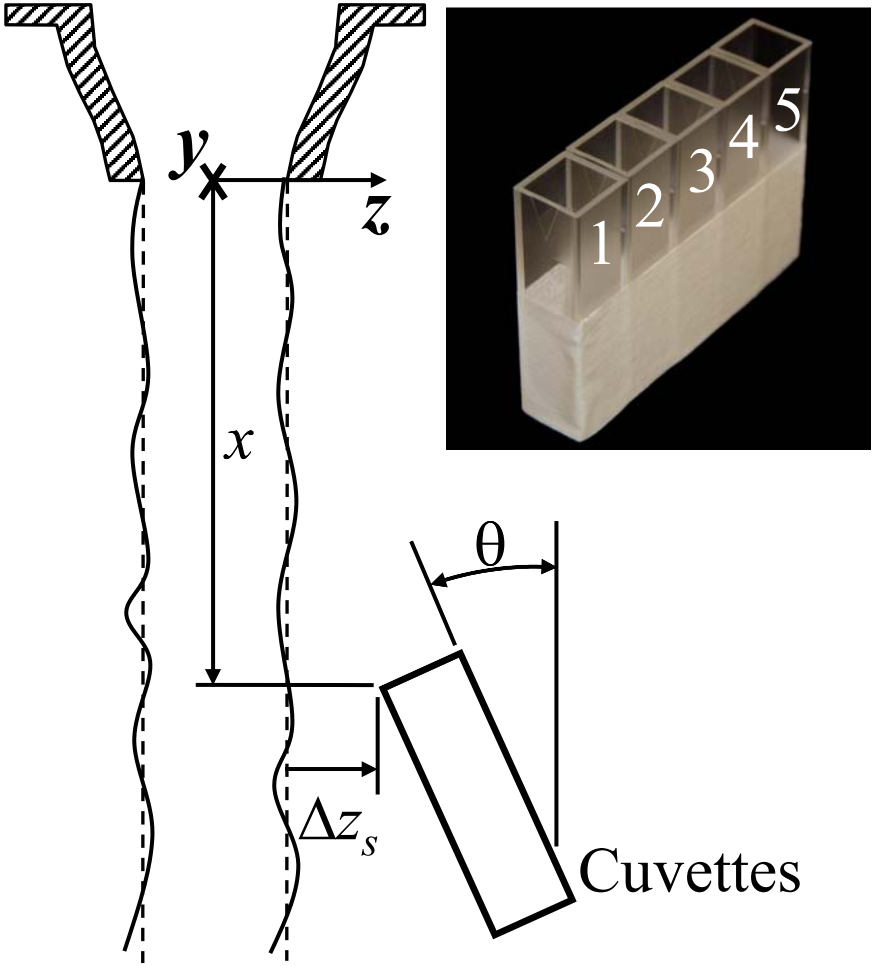
LCDF: *Re* = 130,000



- **Fluctuations↑ as *x*↑**
- **Thickness of "fully flooded" (ϕ = 1) region↓ as *x*↑**
- **Box dimensions 0.01 cm × 6 cm**
- **z_o = 0.5 cm ⇒ nozzle edge**

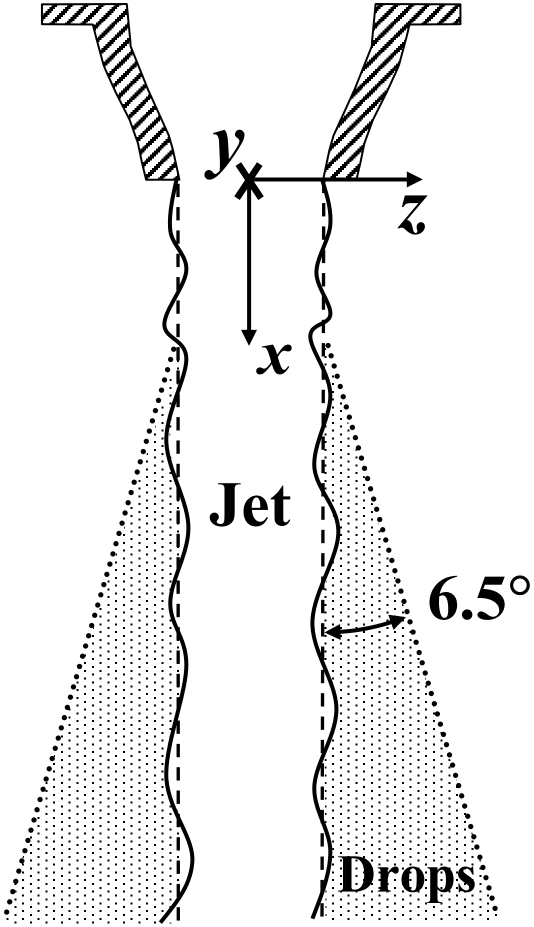


Preliminary Mass Collection Experiments



- Cuvette opening = 1 cm × 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 ~ 6 – 25 std. deviations of surface ripple, $\sigma_z(x)$
  - Experiments repeated to determine uncertainty in data
- Shallow angle of inclination, $\theta = 6.5°$
- Samples acquired over 0.5 – 1 hr

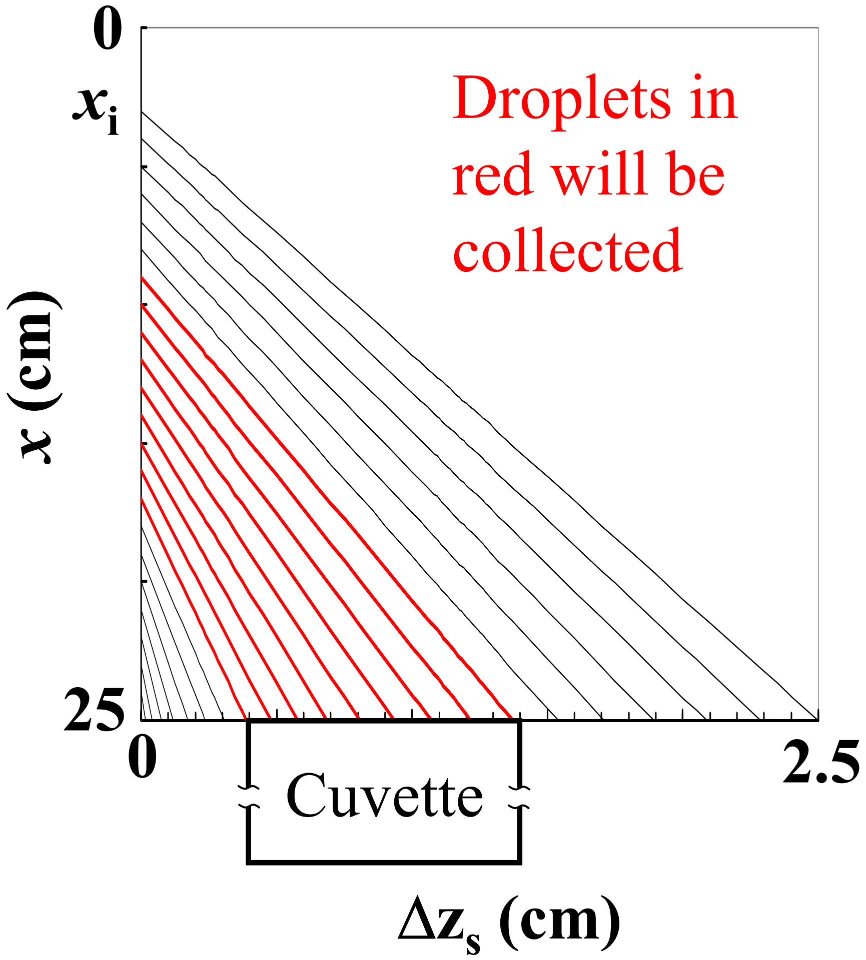
Droplet Trajectories



- Droplets follow ballistic path based on $\tilde{u}$ and $\tilde{v}$
  - Absolute streamwise and radial velocities

    $\tilde{u} = 0.78 \cdot U_o, \quad \tilde{v} \leq 0.088 \cdot U_o$
  - Neglects gravitational and aerodynamic effects
- Droplet "halo" forms starting at x_i
  - Droplets only inside halo

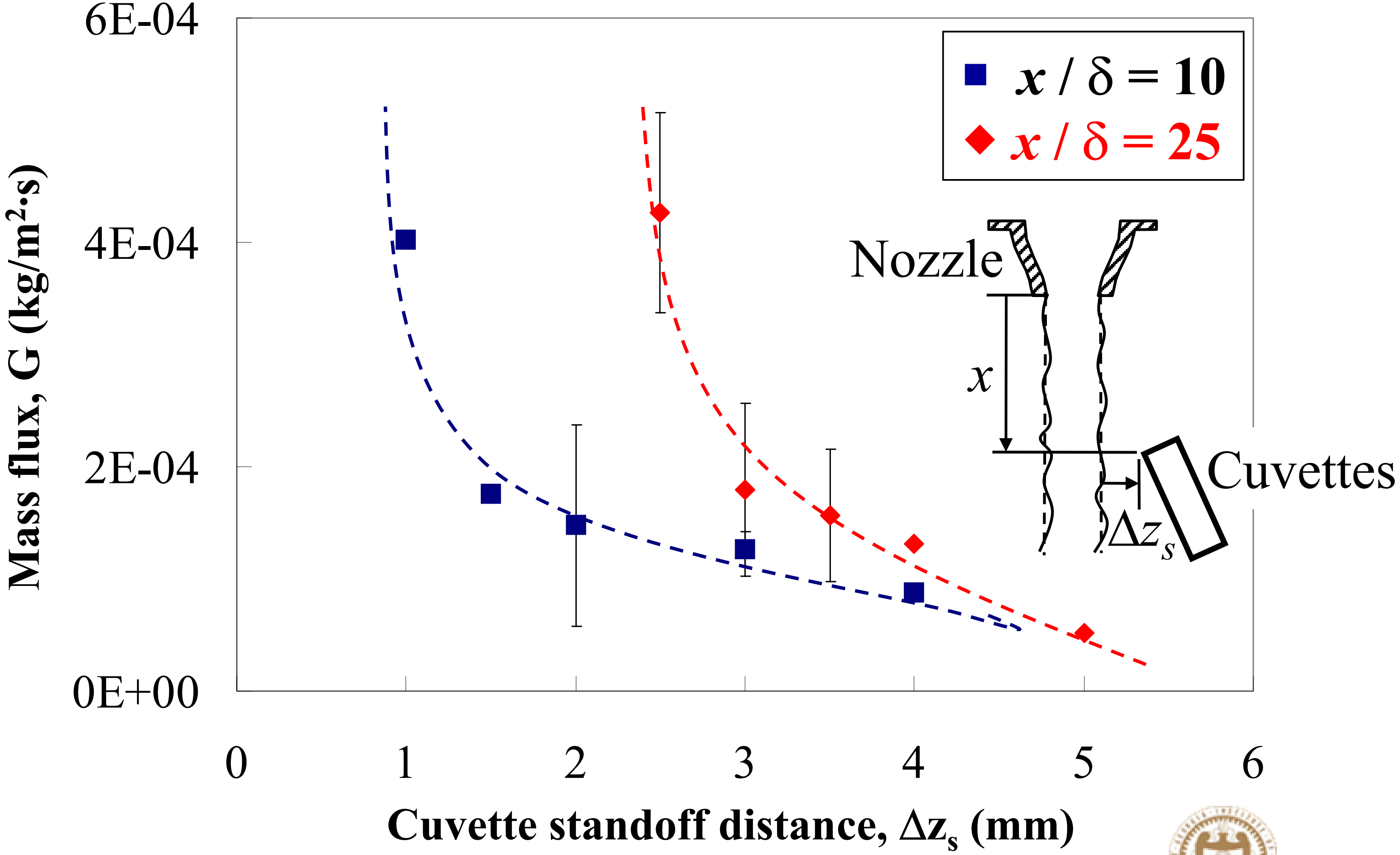
Collected Droplets



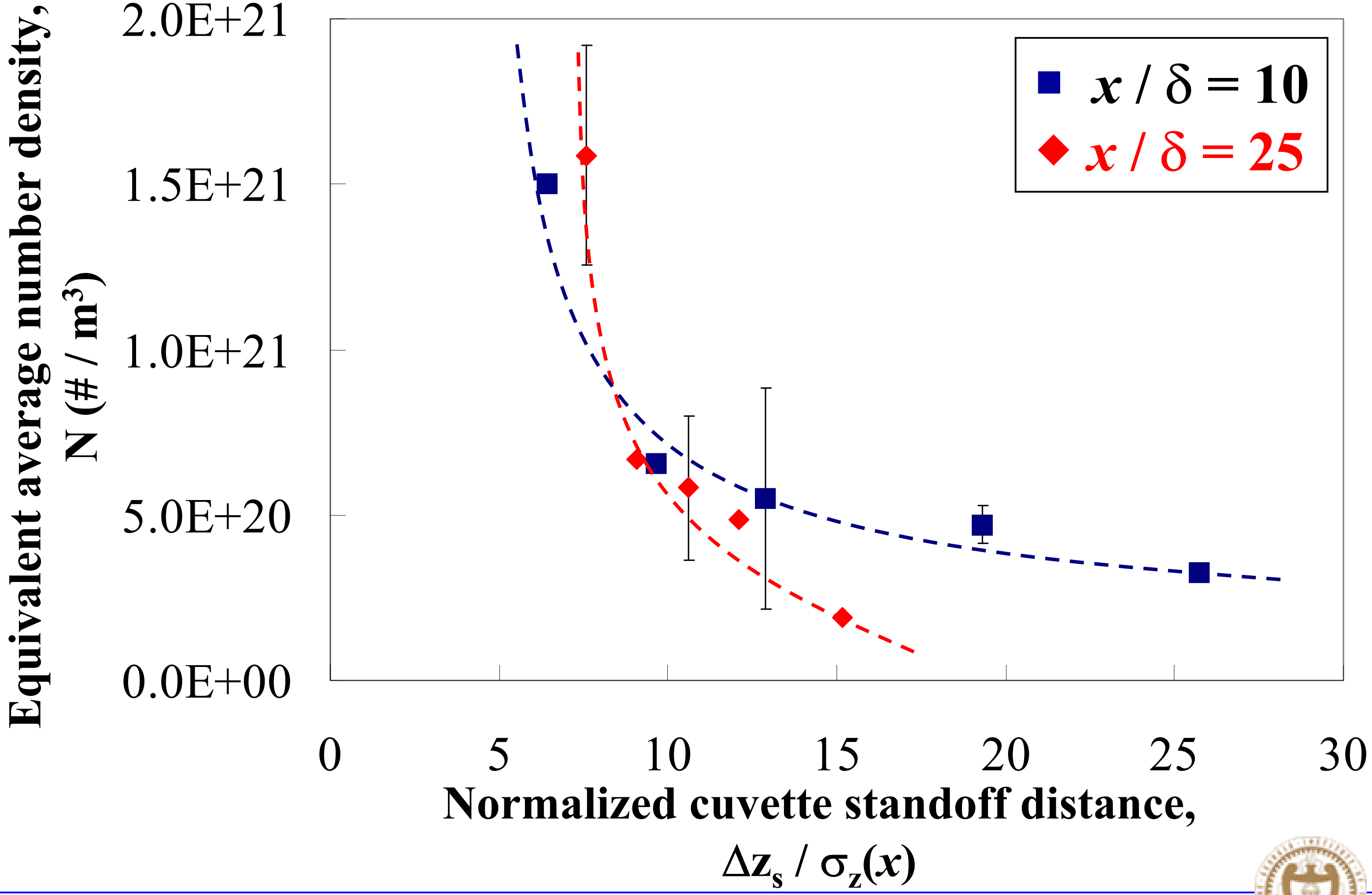
Droplets in red will be collected

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

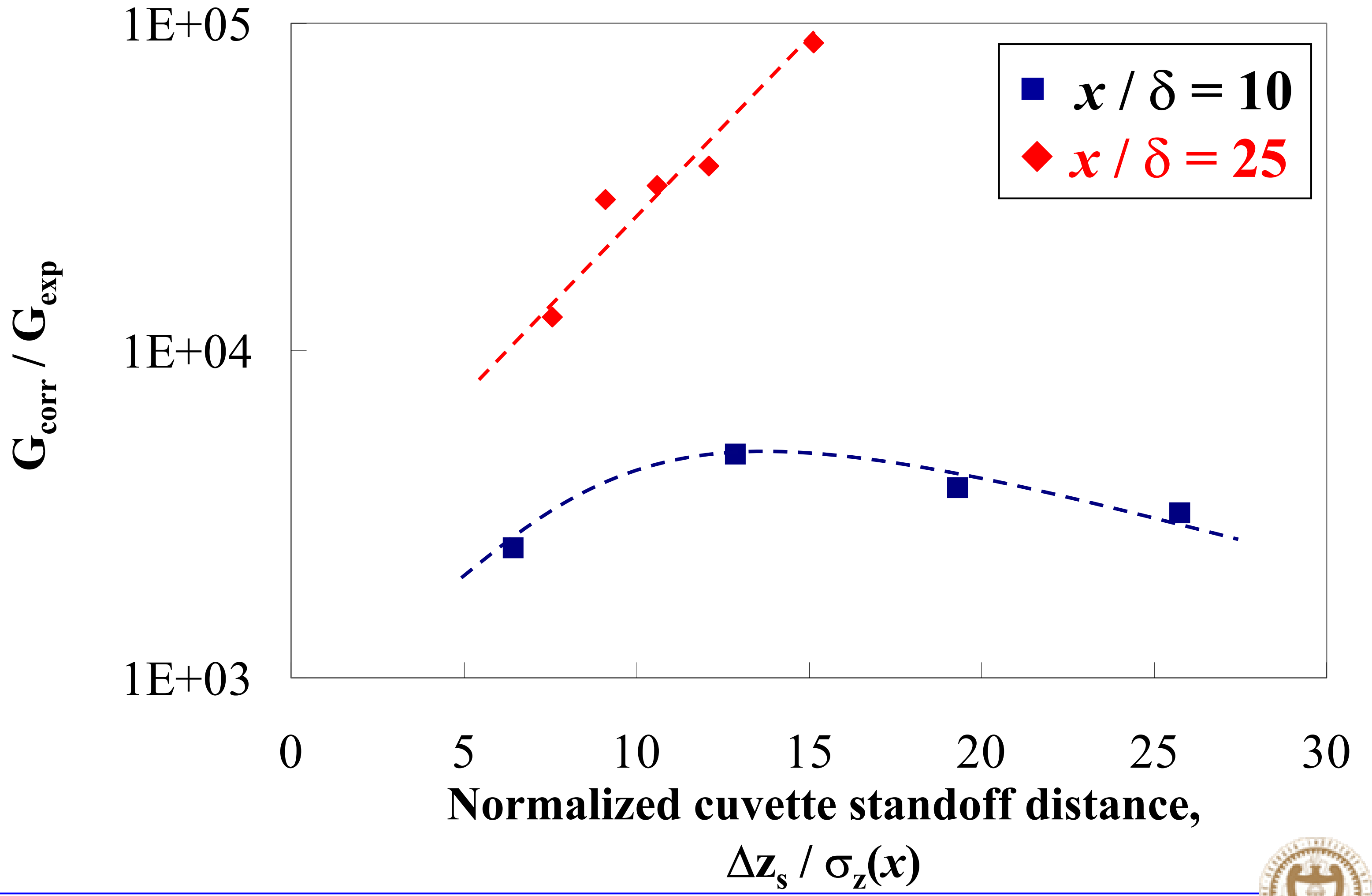
Experimental Mass Flux



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
  - $G(x_i) \approx 0.26 - 1.2 \times 10^{-4}$ kg/m²·s
  - $G(x = 1\text{m}) \approx 3.4 - 21 \times 10^{-4}$ kg/m²·s
- Summing over all rows of jets
  - $\sum \dot{m} \approx 0.13$ kg/s ($< 3 \times 10^{-4}$ % of flow)
- Hydrodynamic source term may be reduced to << 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

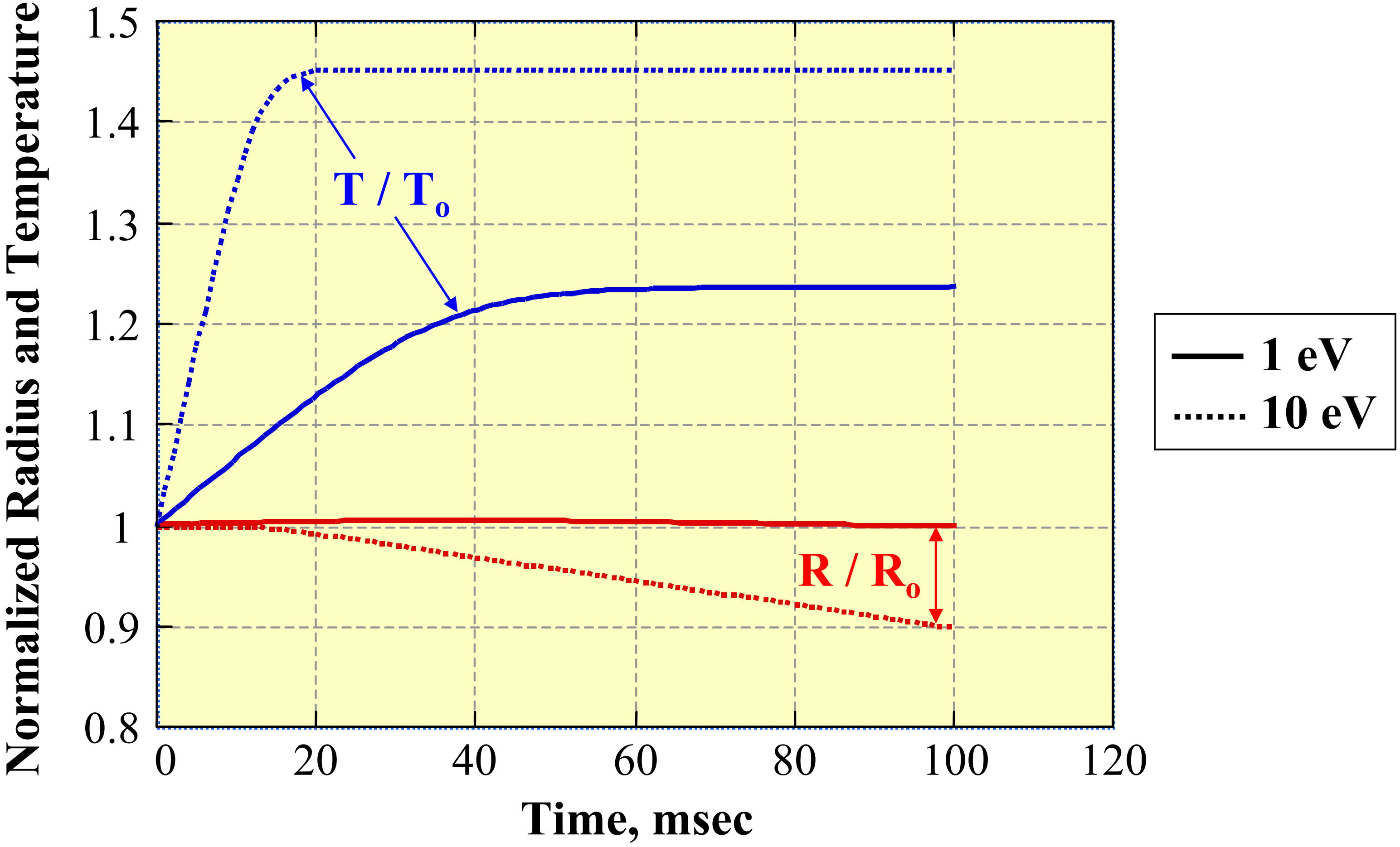
Conclusions

- 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, 10μm, 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**