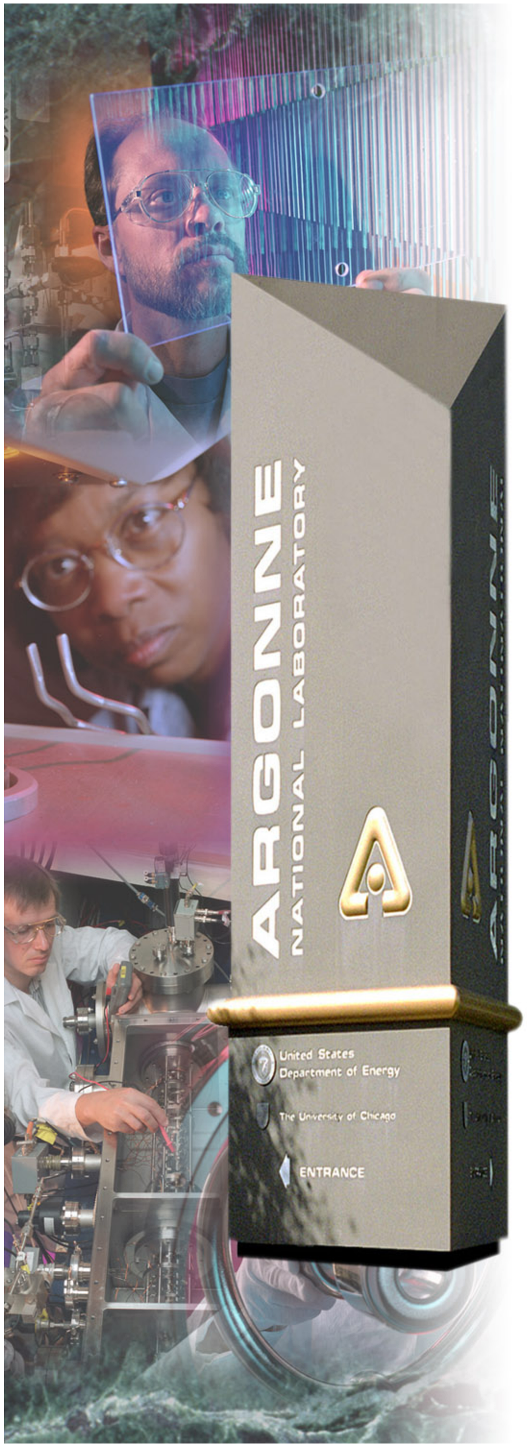
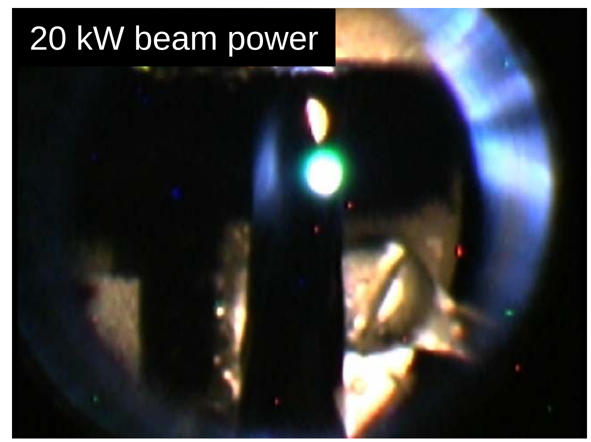


A 20 kW Beam-on-Target Test of the Windowless Liquid Lithium Target for RIA

+

Demonstration of a Liquid Lithium Thin Film Stripper for RIA

J. A. Nolen, C. B. Reed, V. J. Novick, J. R. Specht, Y. Momozaki, and I. C. Gomes



2nd High Power Targetry Workshop
SNS, ORNL
October 13,2005

Argonne National Laboratory

Office of Science
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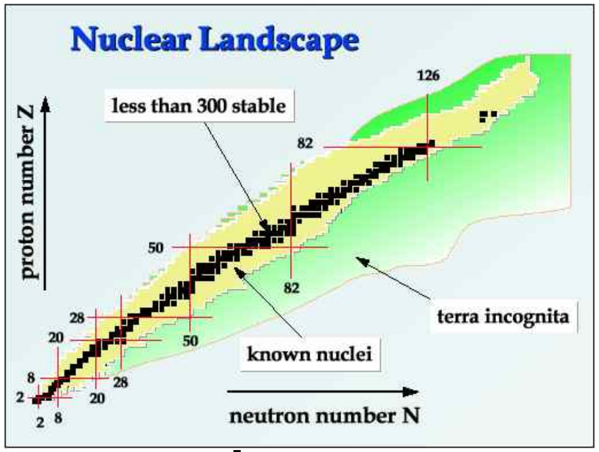
Presentation Outline (Beam-on-target Demonstration)

- **Introduction**
  - What is RIA?
  - What is a "Windowless" Target?
  - Why Liquid Lithium?

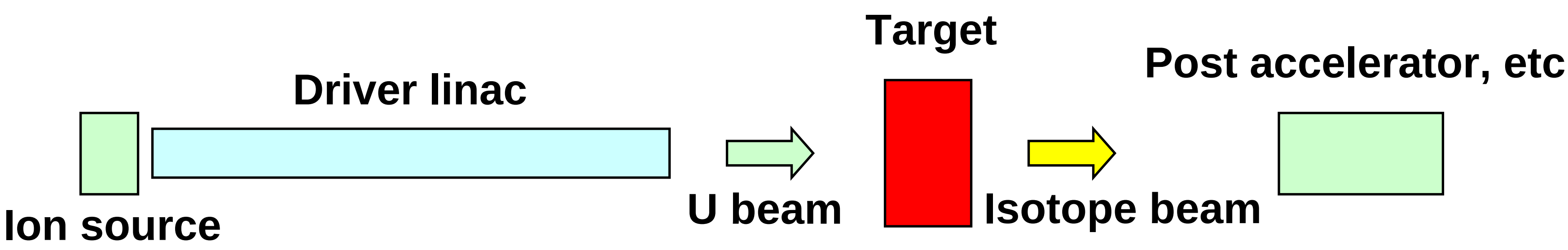


- **20kW Electron Beam-on-target Demonstration**
  - Experimental Layout, Setup, and Instrumentation
  - Results
    - *Video of liquid lithium target under 20 kW beam power*
    - *History of temperatures and pressure*

- **Summary and Conclusions**

What is RIA (Rare Isotope Accelerator)?

- RIA will be the world's most powerful isotope beam accelerator.



- Stable ion beams from protons to uranium are accelerated and bombarded on targets to produce isotope beams by:

1. Spallation, fission (low Z ion beam on high Z target)

or

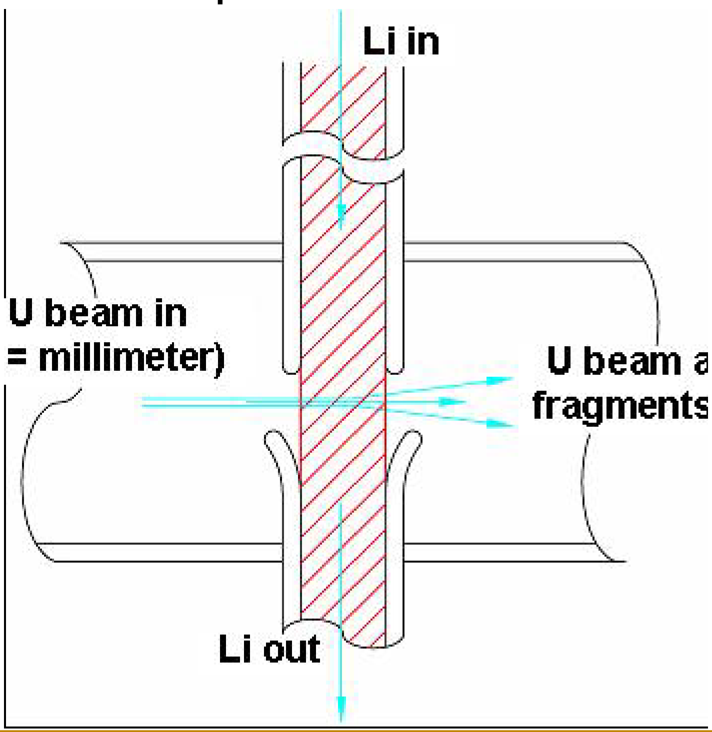
2. Fragmentation (high Z ion beam on low Z target).

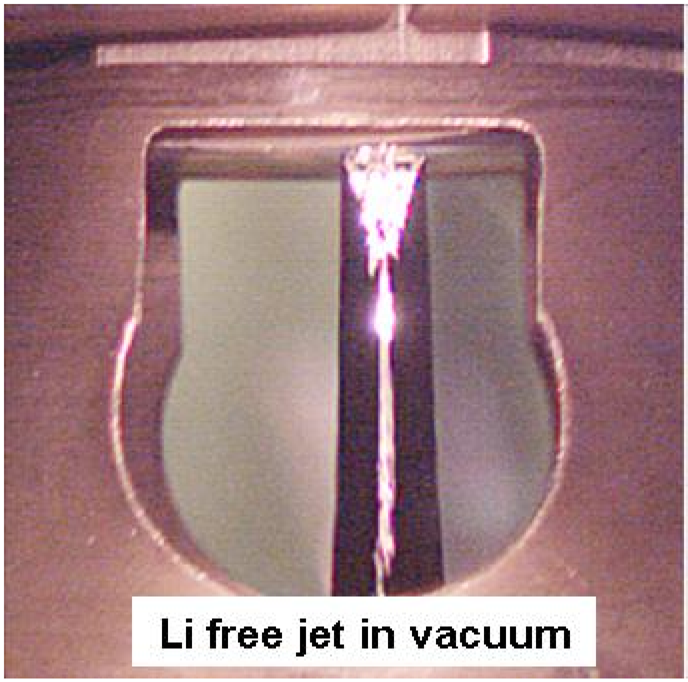
- U beam power density is up to 400 kW per ~1 mm^2
- No *solid* target can handle such loads.

⇒ *Windowless Liquid Lithium Target Concept*

What is a "Windowless" Target?

- **Liquid lithium free-jet forms a "*windowless*" target**
  - Inside the accelerator beam line
    - *No solid confinement structure*
    - *In vacuum*
  - It's possible due to Li's low vapor pressure

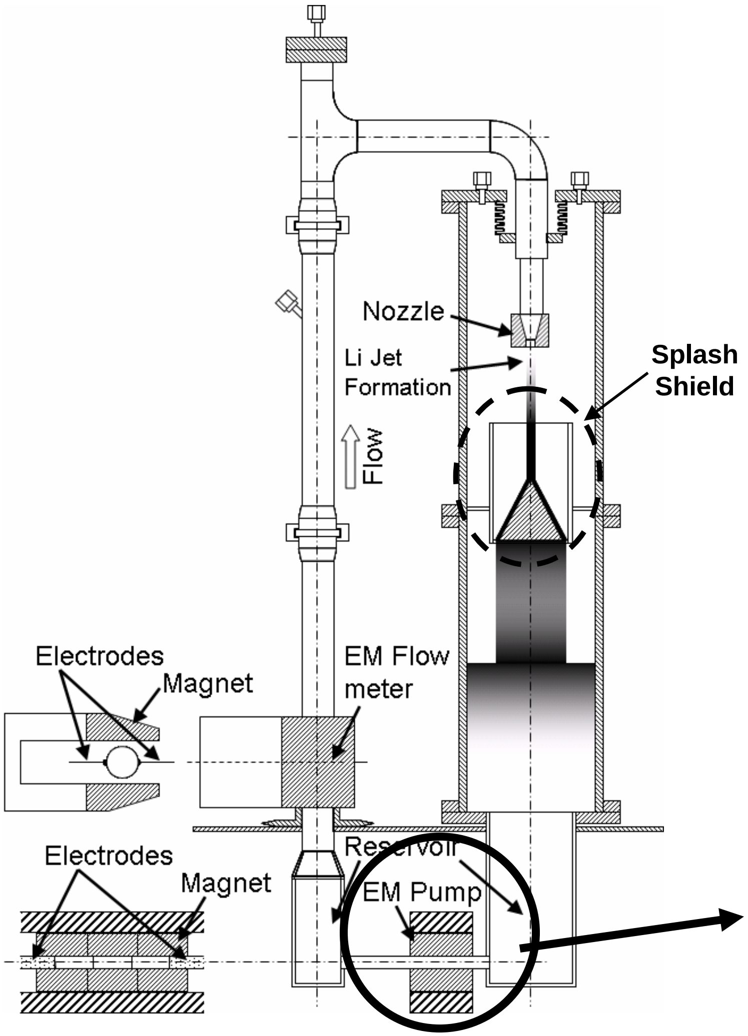




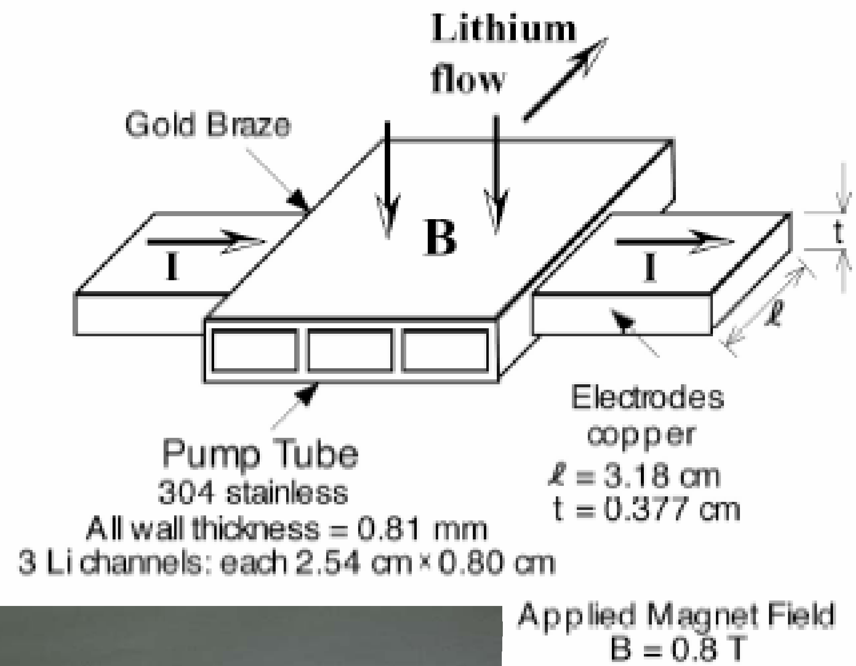
Why Liquid Lithium?

- **Low Z (= 3)---good from nuclear considerations**
- **Large working temp range ΔT ~ 1160 °C**
  - High boiling point (1342^{o}C)
  - Low melting point (181^{o}C)
- **Low vapor pressure (10^{-7} Pa at 200^{o}C)---only Ga and Sn lower**
- **Lowest pumping power required because:**
  - Lowest density (511 kg/m^3)
  - Highest heat capacity (4.4x 10^3 J/kg-K)--- of all liquid metals
  - Low viscosity
- **Low Prandtl No. ~0.05 $\Rightarrow$ excellent heat transfer**
- **Applications**
  - <u>Heat transfer fluid</u> to cool solid targets with <u>light</u>-ion beams
  - <u>Combined coolant and target</u> for high-power <u>heavy</u>-ion beams

Windowless Lithium Target Loop



Windowless Liquid Li Target Loop



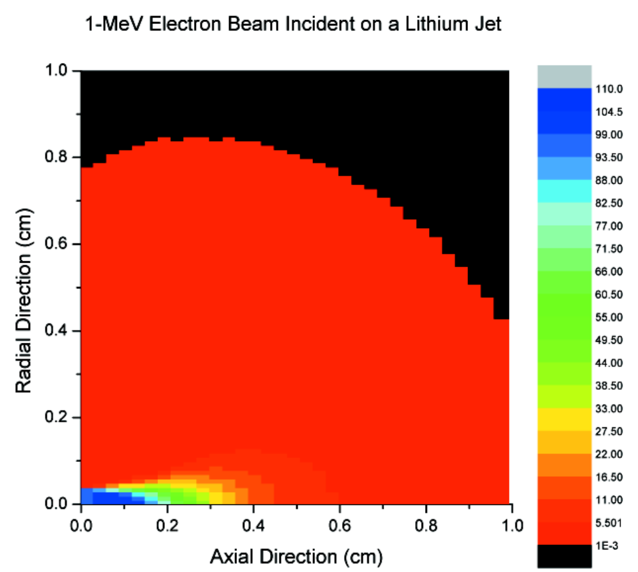
Why do a 20 kW Beam-on-Target Test?

- **Windowless Liquid Target Concept Looks Promising**
- **But No Operational Experience under Simultaneous:**
  - High vacuum environment (< 10^{-4} Pa)

    and
  - Extreme thermal loads

- **Experimental demonstration is absolutely necessary using a prototype windowless liquid lithium target before implementing in RIA.**

- **MCNPX calculations show that a 20 kW, 1 MeV electron-beam applied on a lithium target produces a similar thermal load to that of a 200 kW, 400 MeV/nucleon U beam on the lithium target.**



20 kW Beam-on-Target Test

- **MCNPX** :

  for RIA, 200-kW uranium beam on Li

  1MeV, 20 mA, 1mm ϕ e-beam on Li

  } peak energy deposition = 2 MW/cm^3 deposited in the first 4 mm

- **Test Objectives:**

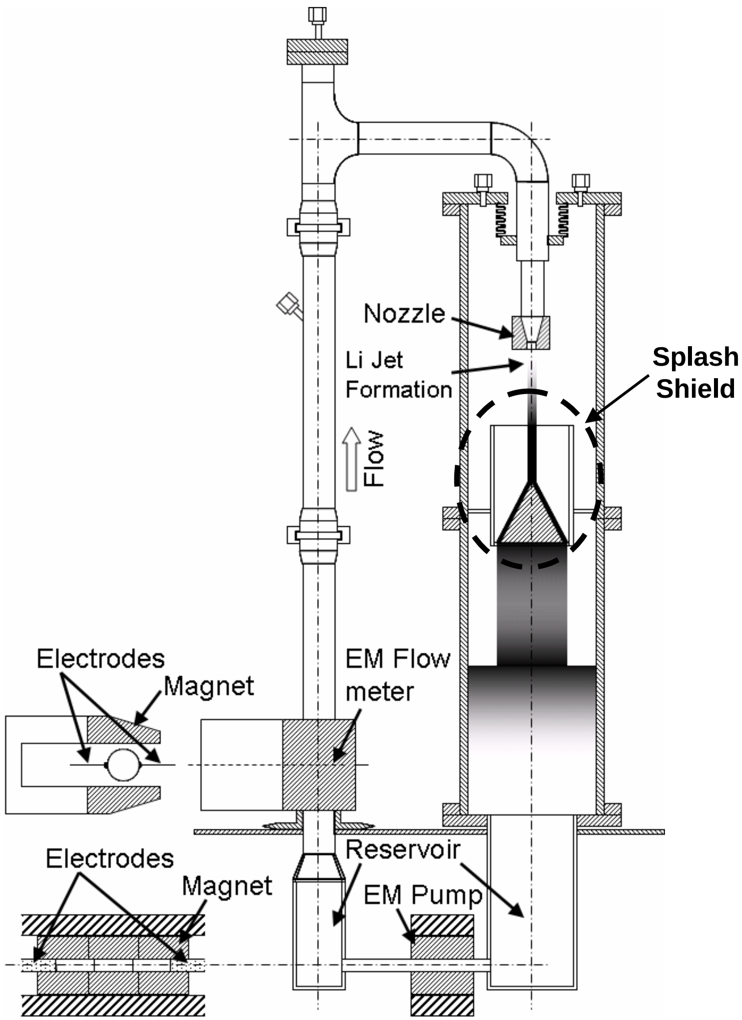
  Using this equivalence, demonstrate that power densities equivalent to a 200-kW RIA uranium beam:

  - Do not disrupt the Li jet flow
  - Li ΔT (across beam spot) is modest (~ 180º C)
  - Li vapor pressure remains low

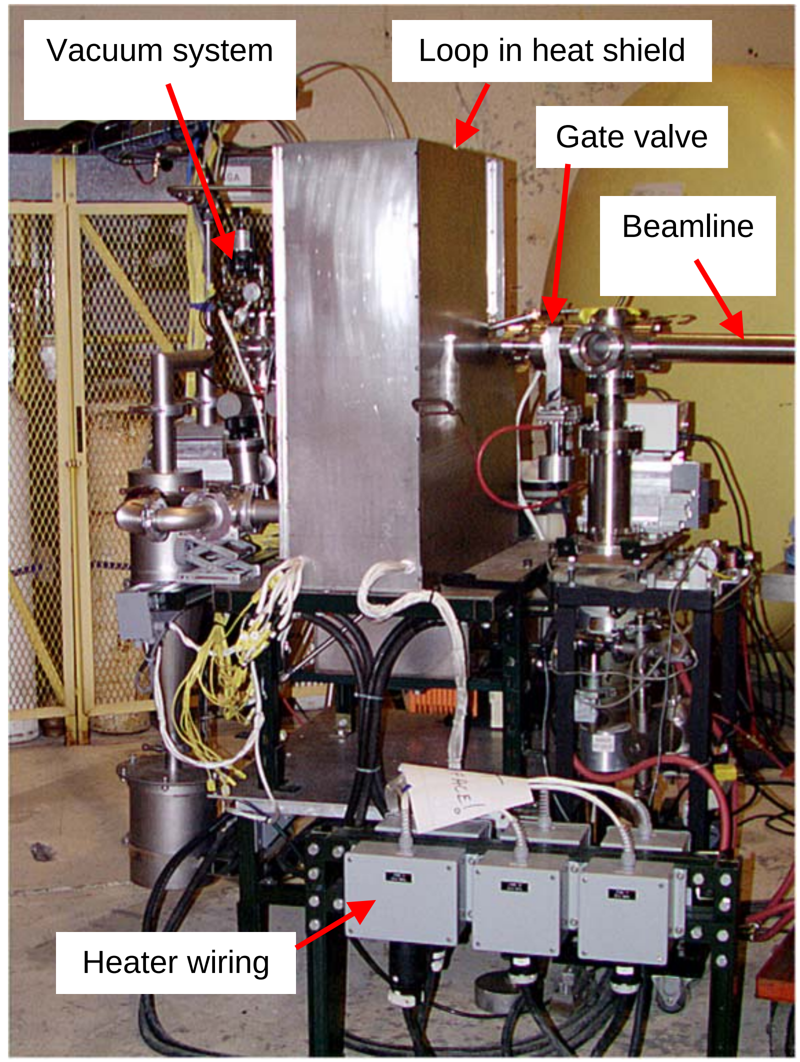
- **Overall Objective:**

  To show that 2 MW/cm^3, deposited in the first 4 mm of the flowing lithium jet, can be handled by the windowless target

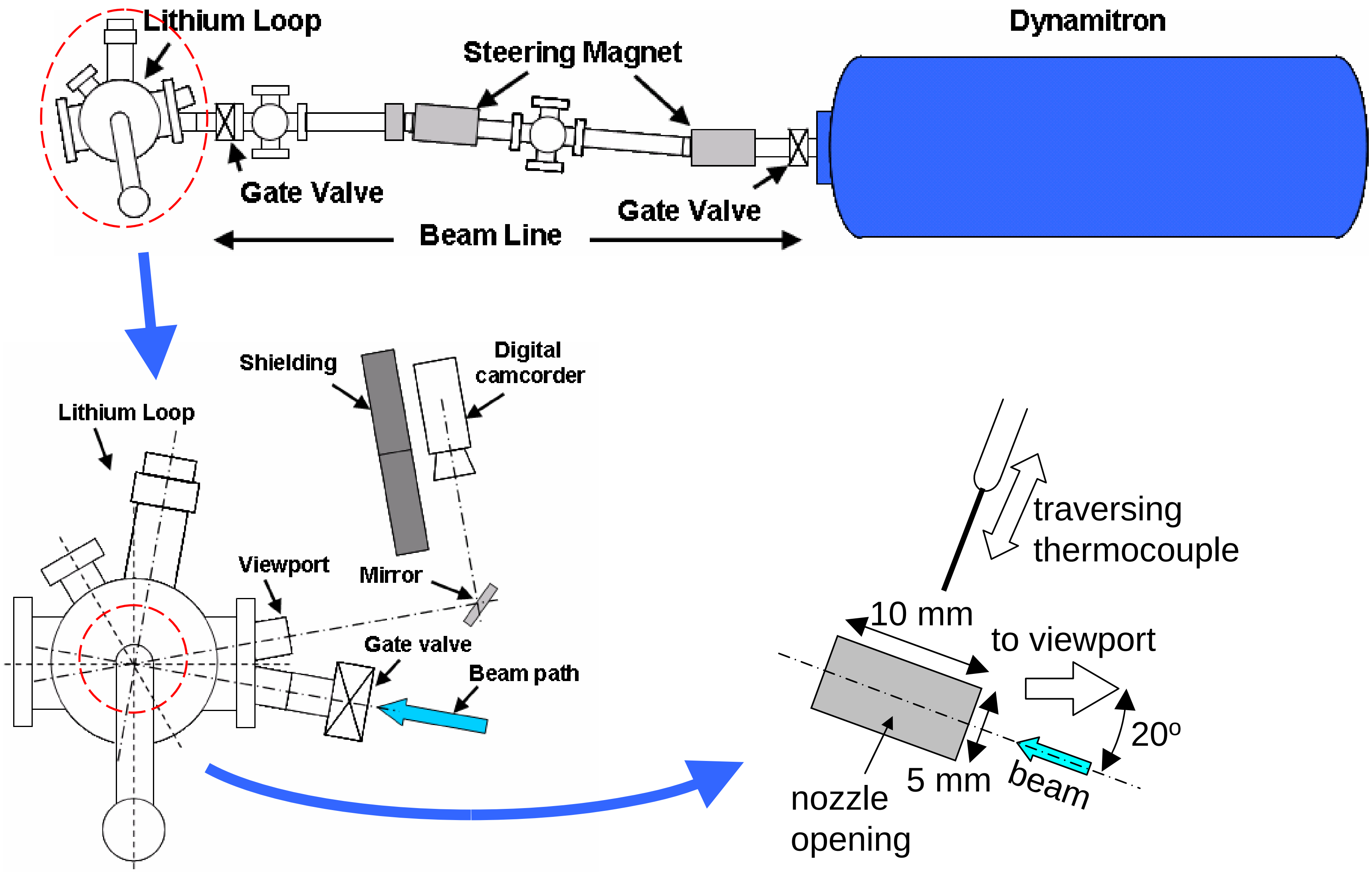
Experimental Layout, Setup, and Instrumentation



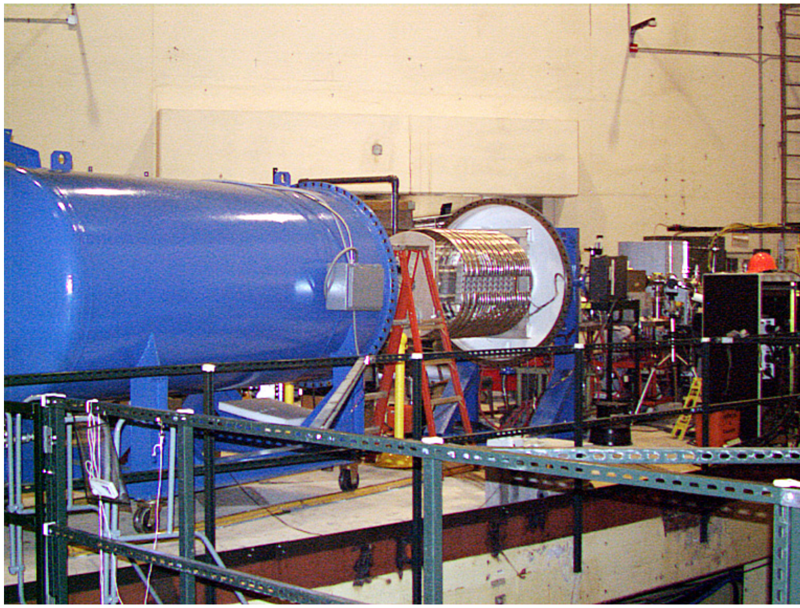
Windowless Liquid Li Target Loop



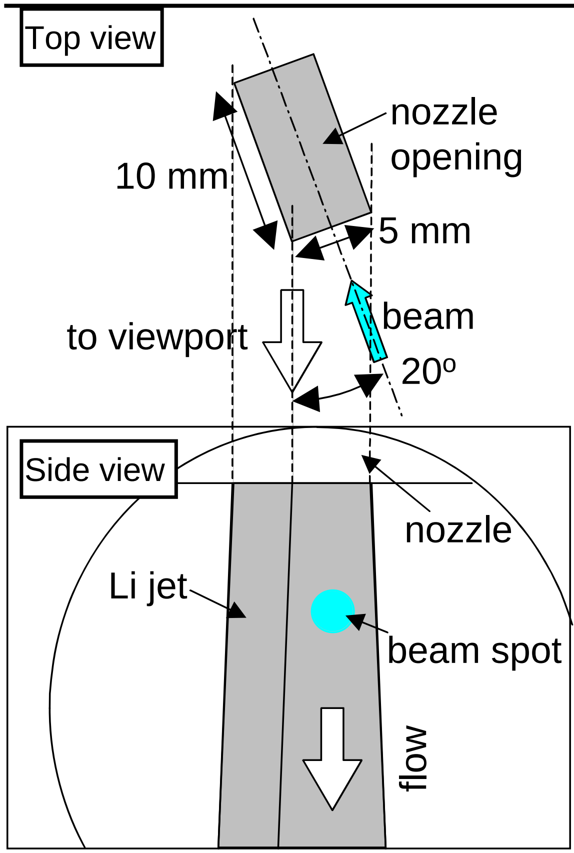
Experimental Layout, Setup, and Instrumentation



Dynamitron -- Beam Line -- Li Target



20 kW Electron Beam on Lithium Jet in Vacuum



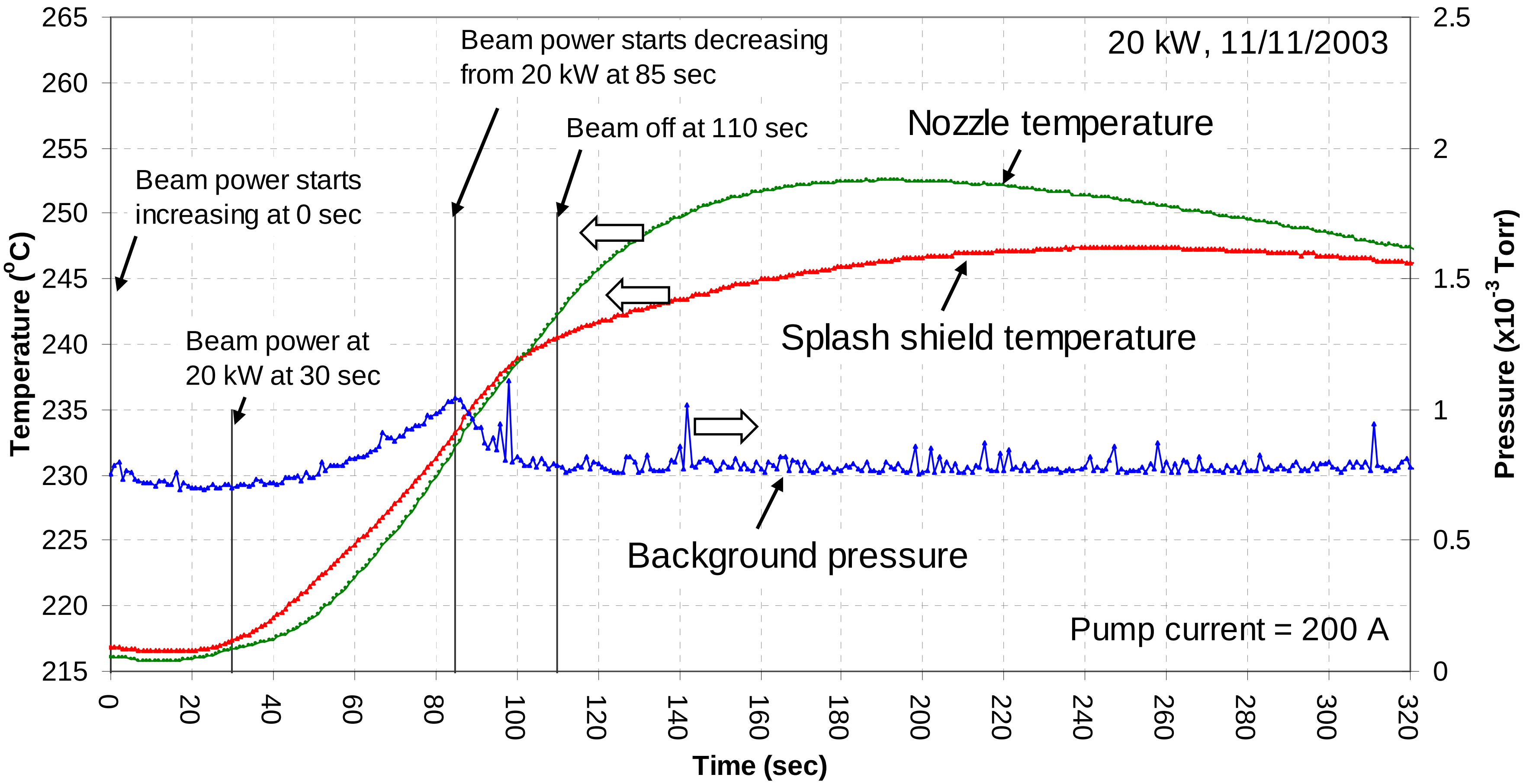
Schematic Beam-Jet Arrangement

Jet velocity ~ 1.8 m/s Re ~ 11,000

QuickTime™ and a
DVD/DVCPRO - NTSC decompressor
are needed to see this picture.

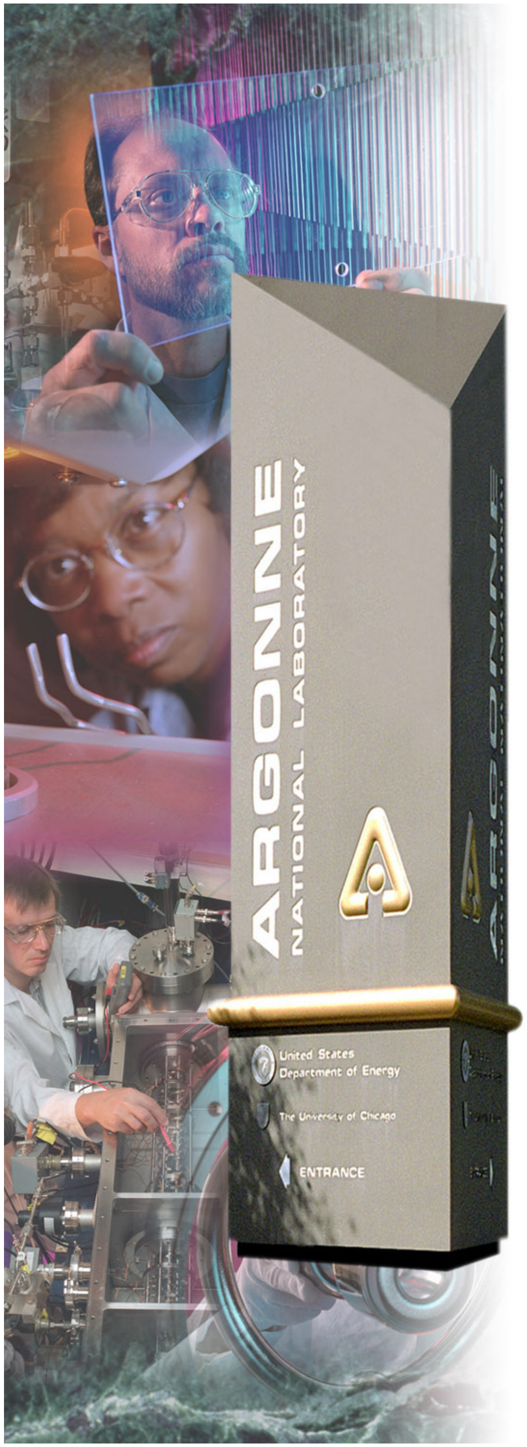
Results

- History of Temperatures and Pressure at Li Flow of 1.8 m/s and Beam Power of 20 kW.
  - No significant pressure increase.



Summary and Conclusions

- **Experimental demonstration of windowless liquid lithium target concept for RIA was performed.**
- **Stable jet formation under beam powers up to 20 kW within 1 mm beam spot, (thermally equivalent of a 200 kW, 400 MeV/u uranium beam), was confirmed at a jet velocity as low as 1.8 m/s.**
- **A 55 second beam irradiation at 20 kW resulted in a temperature rise of only ~30 K in bulk lithium temperature and a temporary background pressure rise of only ~ 0.3 mTorr.**
- **Steady-state background pressure remained constant.**



Demonstration of a Liquid Lithium Thin Film Stripper for RIA

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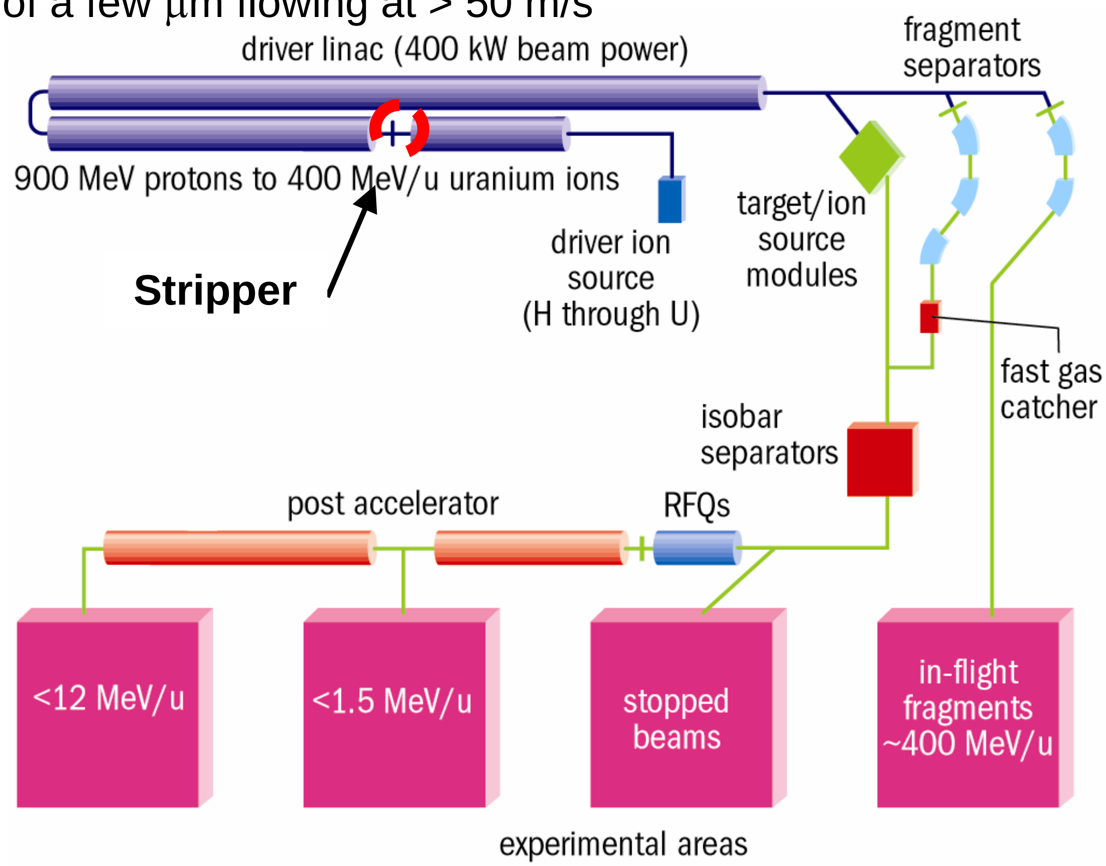
Outline (Lithium Thin Film Stripper)

- **Introduction**
- **Liquid thin film formation scheme**
- **Development of stability diagram**
  - Selecting simulants
- **Experimental layout, setup, and instrumentation**
  - Critical design parameters
- **Experimental procedure**
- **Results**
  - Image of liquid lithium thin film
  - History of parameters
- **Summary and future plan**

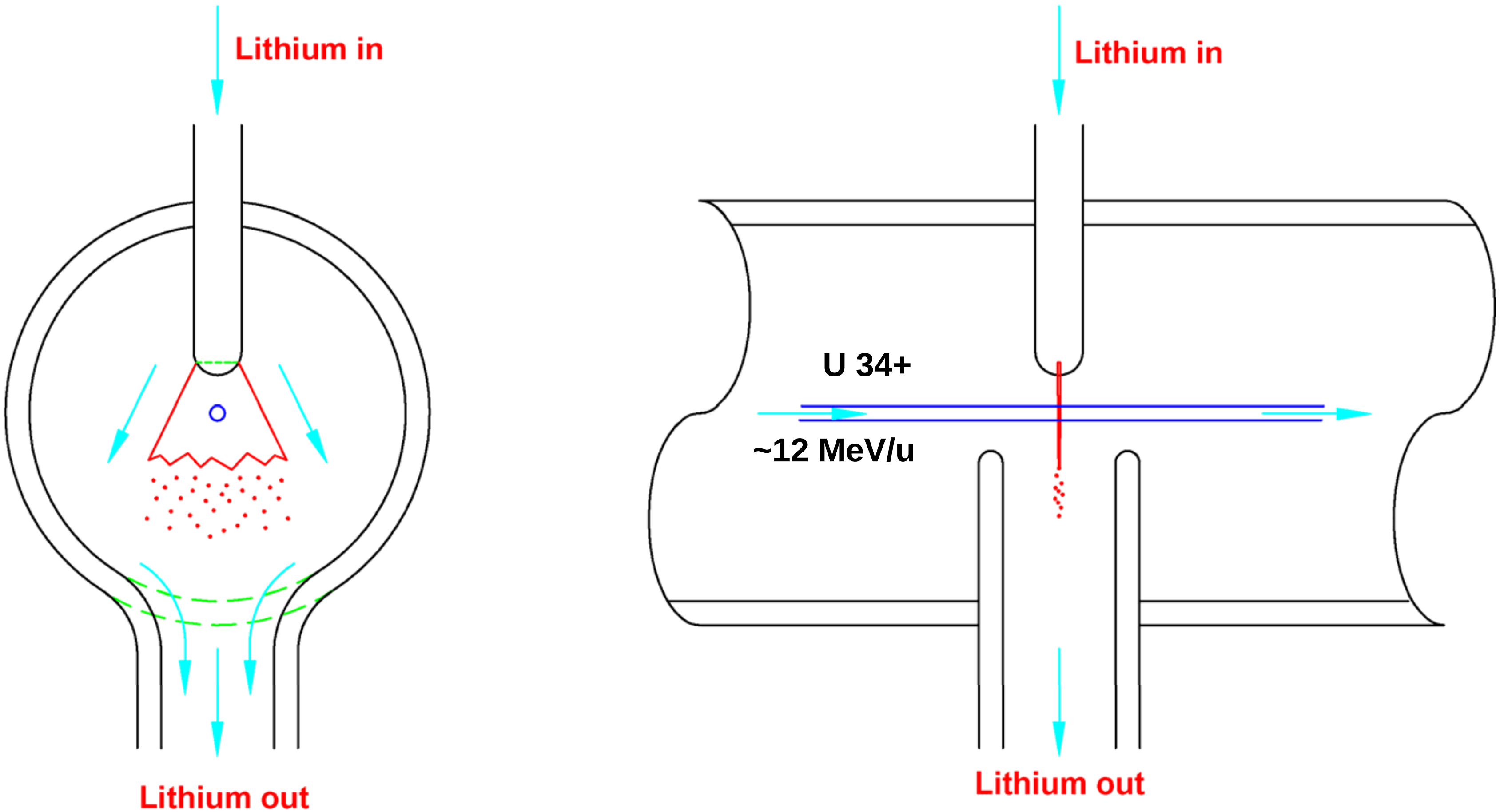
Introduction

- **Proposed Stripper**
  - Incident U beam of 34+ at ~12 MeV/u and 6 particle-μA within ϕ of 1mm spot, resulting power deposit of ~ 300 W.
  - Li film of a few μm flowing at > 50 m/s



Introduction (cont'd)

- **Conceptual diagram of liquid lithium thin film stripper**



Introduction (cont'd)

- **A thin liquid film is <u>inherently unstable</u>!**
  - Li film formation may occur only within a certain range of parameter domain.
- **Liquid lithium is <u>extremely difficult</u> to work with.**
  - Changing some parameters may require weeks of work.

However…

- **Hydrodynamics of a thin film in vacuum involves only:**
  - <u>inertial force</u>,
  - <u>viscous force</u>,
  - <u>surface tension force</u>.

- **Thus hydrodynamic behavior (including stability) can be described by only two dimensionless parameters, *Re* (= inertial force / viscous force) and *We* (= inertial force / surface tension force).**

  → Use of simulants to check feasibility and to determine requirements for liquid Li stripper as preliminary experiments is possible.

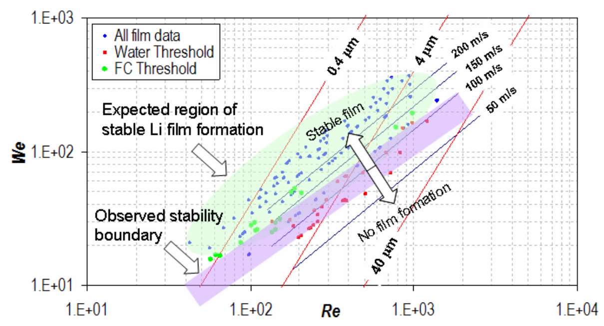
Introduction (cont'd)

- **Development of a thin liquid lithium film is divided into three steps:**

1. Experimentally develop a liquid thin film formation scheme,

2. Experimental development of a "film stability diagram" for the film production scheme using simulants,

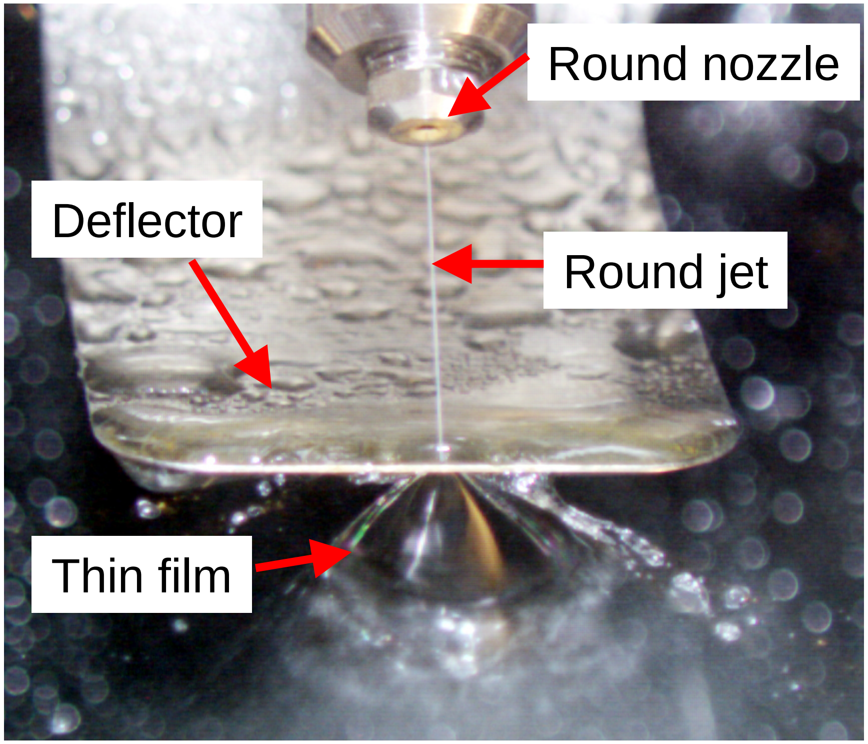
   This diagram will provide the range of design parameters, such as film thickness and velocity, that are potentially capable of producing a stable, smooth liquid lithium film.



3. Experimentally demonstrate formation of a thin film liquid lithium jet and confirm that the film is appropriate to be used as a stripper (thickness, film stability, size, and velocity etc).

Liquid thin film formation scheme

- **Direct method (using a slit to produce a thin film) seems to be extremely difficult.**
  - manufacturing such a slit and plugging during operation are the biggest concern.
- **Indirect method**

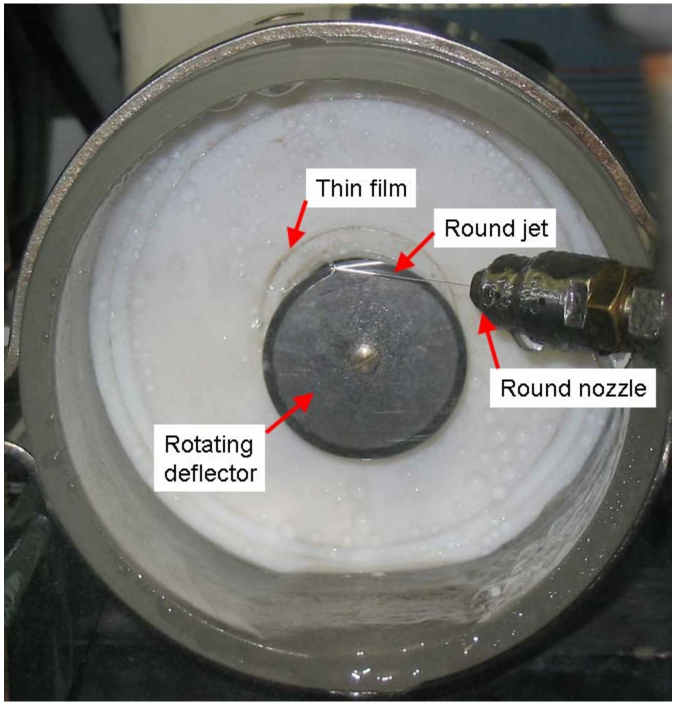


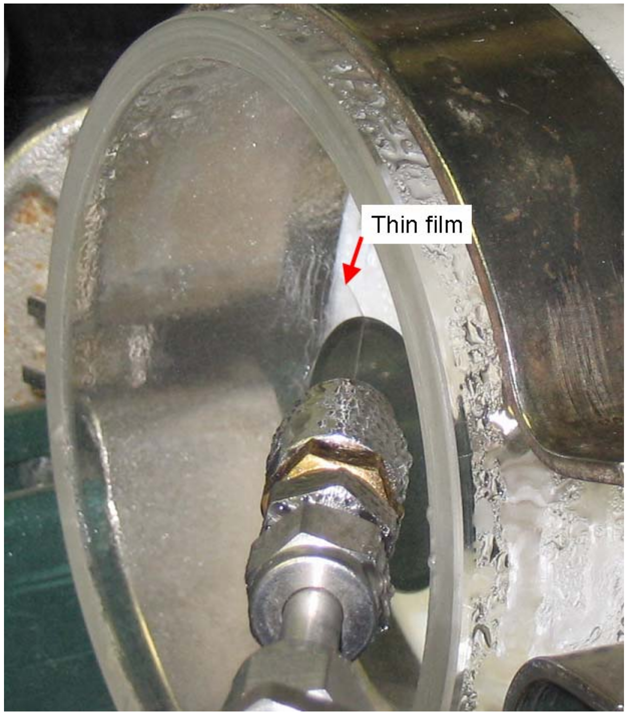
Thin film formation after impact on a stationary deflector

In this method, it is expected that the velocity of a thin film is similar, but slightly less than that of a round jet, requiring relatively large drive pressure.

Liquid thin film formation scheme (cont'd)

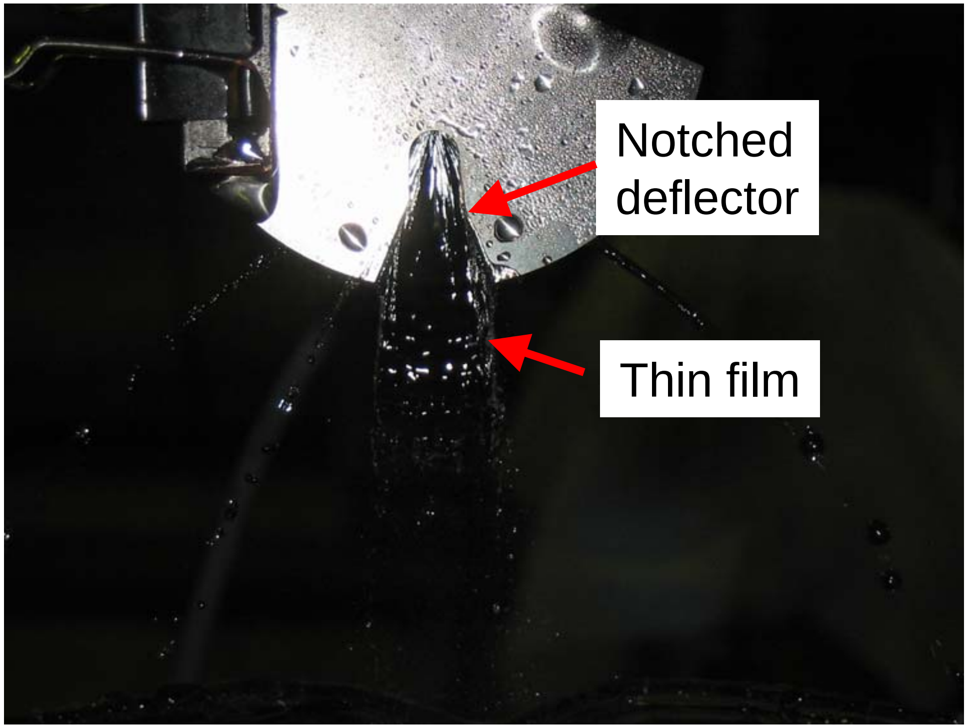
- **Indirect method**
  - To reduce drive pressure, two other methods are suggested:
    1. *use of a rotating deflector that accelerates the film,*
    2. *use of a notched deflector that gives stability to the film at lower jet velocities.*





Thin film formation using rotating disk

Liquid thin film formation scheme (cont'd)

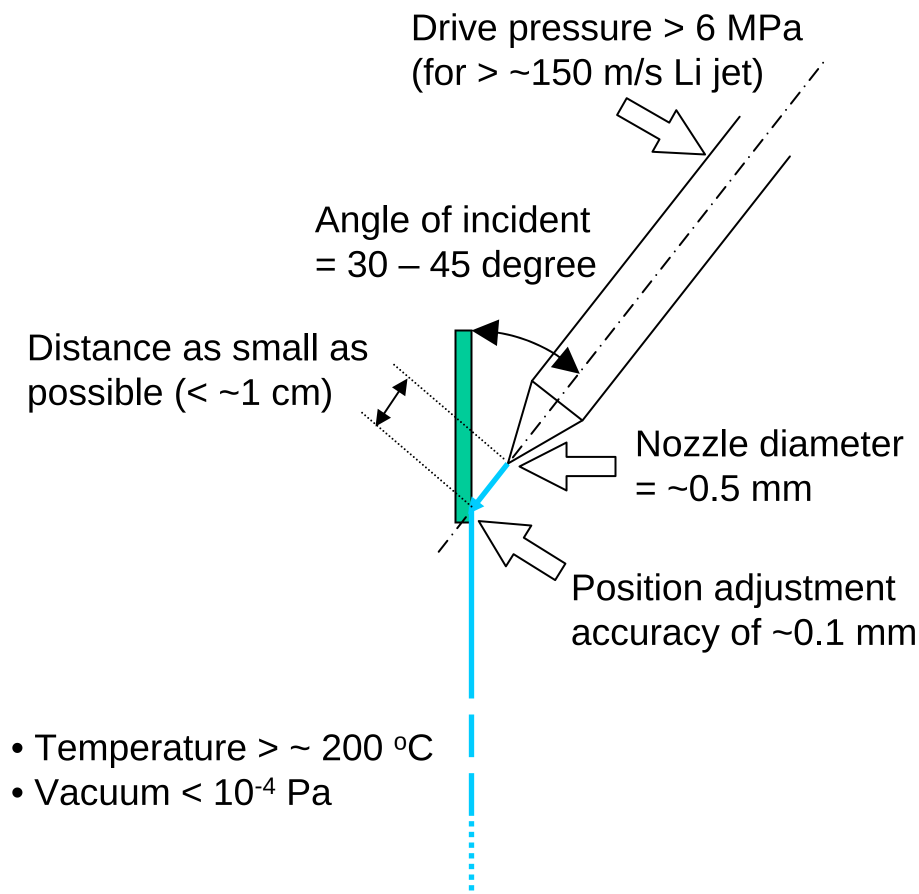


Thin film formation using notched deflector

- **Summary**
  - The rotating disk disturbs liquid significantly and the thin film does not appear smooth.
  - For the notched deflector, since the most of the film edge is attached to the deflector, the quality of the film is significantly more affected by microscopic imperfections on the deflector, resulting in the formation of the poor quality film.
  - As a conclusion, using a stationary deflector appears to be the best scheme.

Experimental layout, setup, and instrumentation

- **Critical design parameters**
  - Determined based on these 1st and 2nd phase experiments.



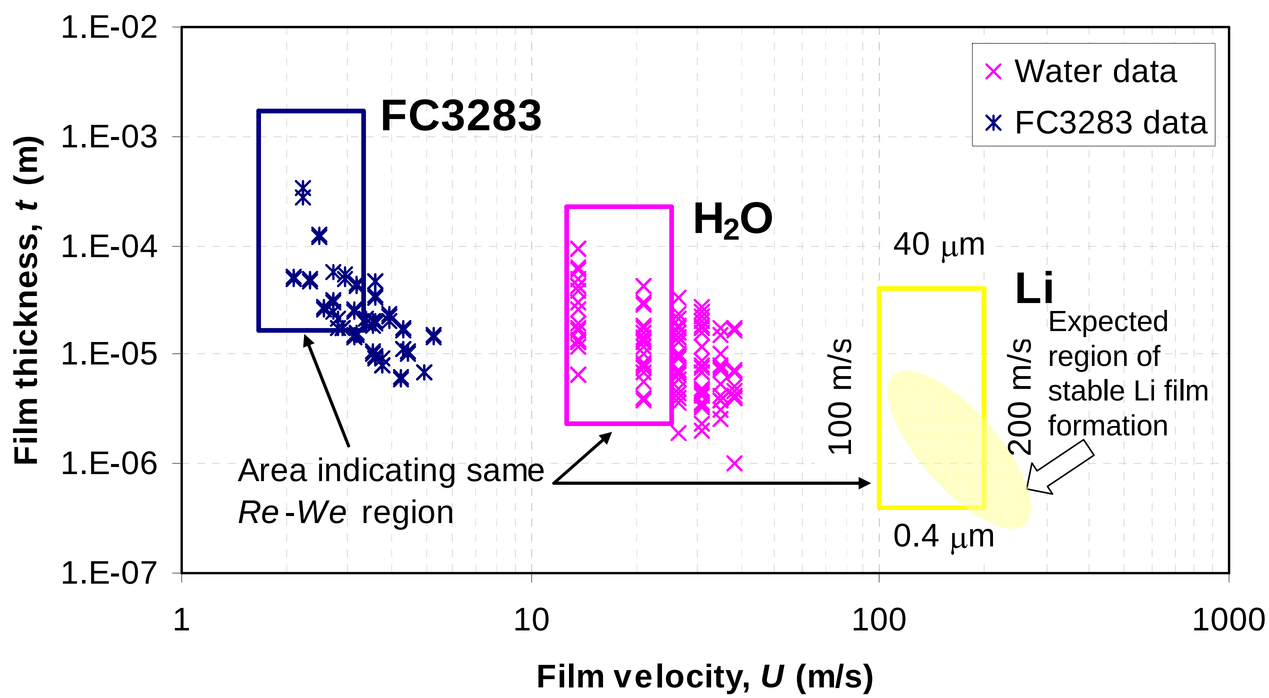
Development of the stability diagram

- **Selecting simulants**
  - No liquid has similar physical properties to lithium!
    - *Direct simulation is **impossible**.*
  - Surprisingly, **water** seems to be one of the closest including various liquid metals except alkali metals, although its physical properties are quite different (see Table on next page).
  - FC-3283 (one of Fluorinerts from 3M) is quite interesting, because **differences between FC and water are similar to those between water and lithium** while keeping *Re* and *We* the same (see Table and Figure on next page).
    - *If insignificant differences between FC and water films at the same Re and We are observed, so would be between water and lithium films!*
  - Both water and FC-3282 are inert and non-hazardous, which significantly reduce complexity, difficulty, and cost of performing experiments.

Development of the stability diagram (cont'd)

- **Water and FC-3283**

	Lithium		FC-3283	Water	Lithium
Temperature [K]	473.15	Temperature (K)	R.T.	298.15	473.15
Density [kg/m³]	515.0	Density ratio	3.53	1.94	1
Surface tension [N/m]	0.392	Surface tension ratio	0.0408	0.1835	1
Viscosity [Pa-s]	5.72E-04	Viscosity ratio	2.45	1.59	1



Development of the stability diagram (cont'd)

- **Other considerations**
  1. Effects of surrounding air on film breakup,

  2. Effects of drive pressure, nozzle size, angle of the impinging jet relative to the deflector plate, distance between the nozzle exit and the deflector, and jet to deflector edge distance on film formation,

  3. Velocity measurement of the droplets after film breakup using Phase Doppler Particle Analysis (PDPA) to estimate actual velocity of the water film,

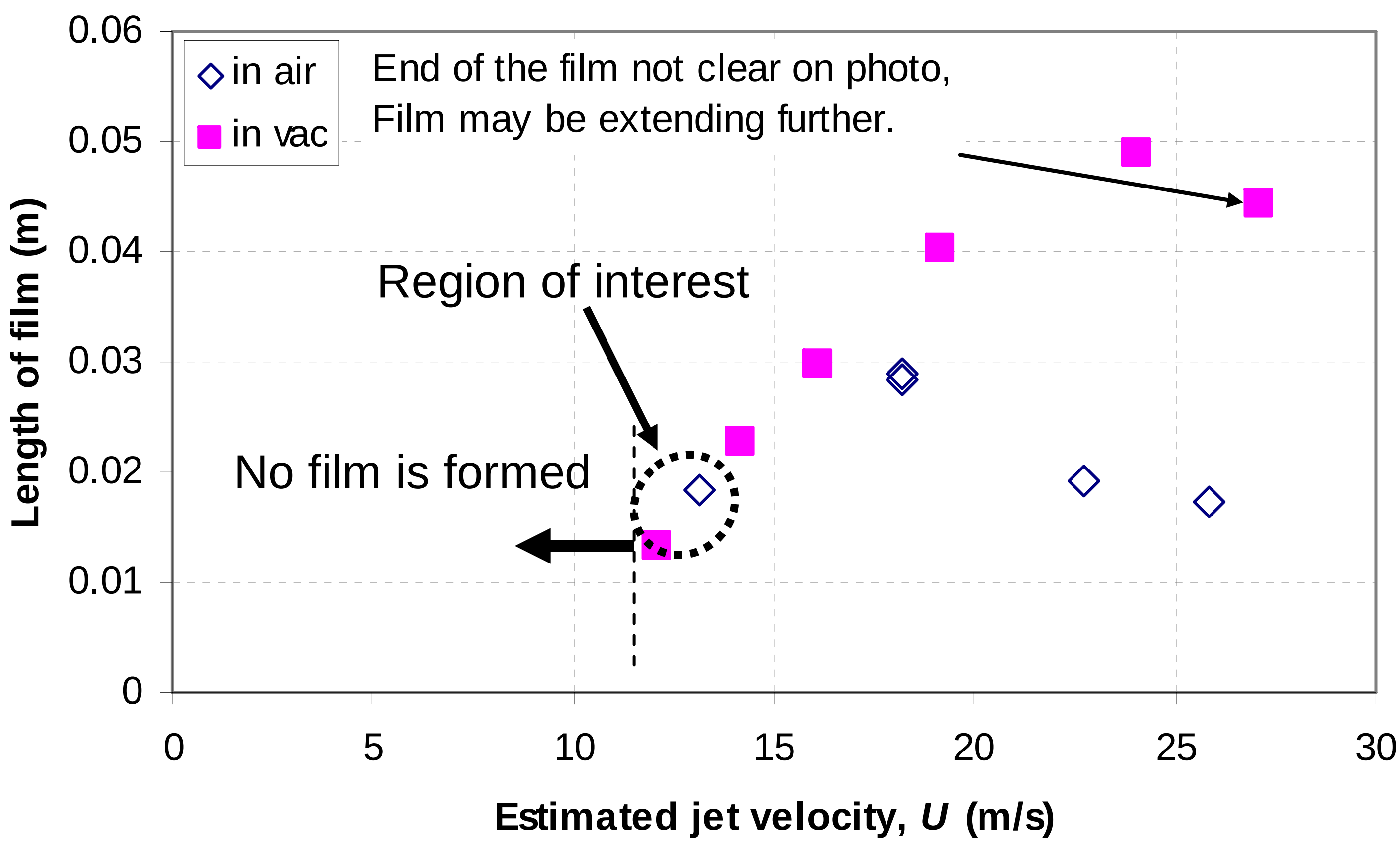
  4. Confirmation that the stability diagram represented by *Re* and *We* numbers is universal for other fluids with different properties as the theory suggests by plotting the stability diagram for water and FC-3283 on the same graph in *Re* and *We* space. They should form the same stability diagram.

Development of the stability diagram (cont'd)

- **Experimental conditions**
  - Nozzle sizes: 0.1 mm (4 mils) – 1 mm (40 mils),
  - Jet velocity: 10 – 30 m/s for water,
    2.1 – 5.3 m/s for FC-3283,
  - Angle between jet and deflector: 15 – 60 degrees
    - *Jet velocities for water and FC-3283 corresponding to a 50 m/s Li film (6.4 m/s for water and 0.83 m/s for FC-3283) were not achievable due to instability!*

Development of the stability diagram (cont'd)

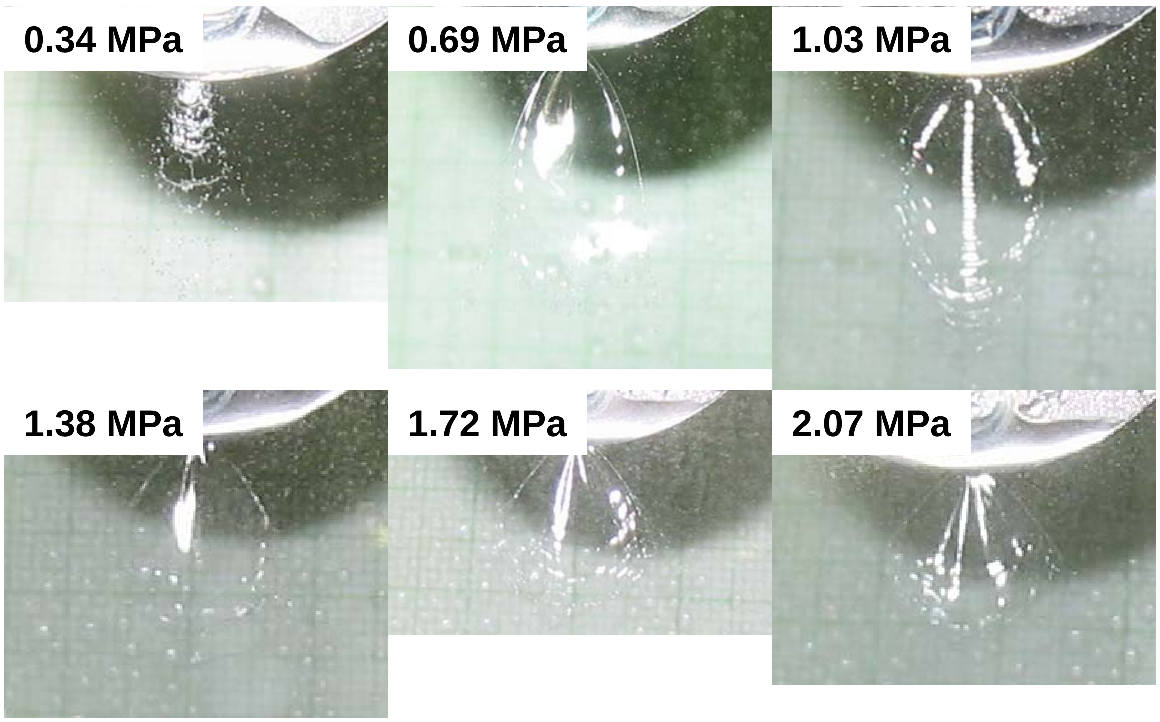
- **Effects of surrounding air**
  - Insignificant at < 15 m/s for water testing.



Development of the stability diagram (cont'd)

- **Effects of drive pressure**
  - Operating window exists.
    - *When pressure is too low, jet did not form a film due to instability (at 0.34 MPa) and when pressure is too high (at > ~1 MPa), the film became wavy*

0.254 mm nozzle, 34.2 deg impact angle

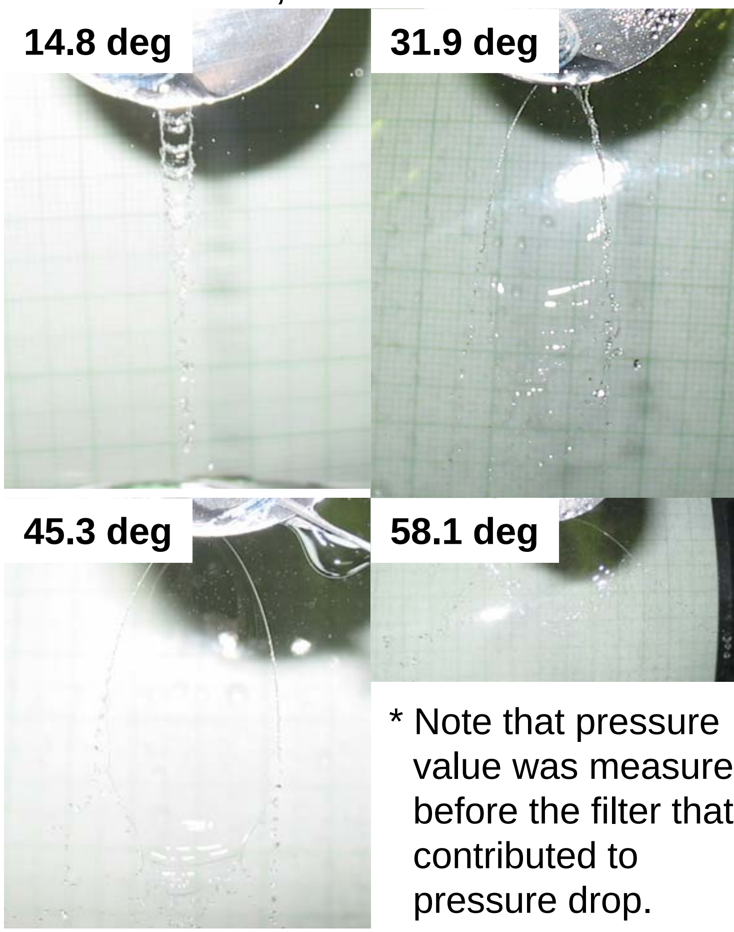


* Note that pressure values were measured before the filter that contributed to pressure drop.

Development of the stability diagram (cont'd)

- **Effects of nozzle size and angle of the impinging jet relative to the deflector plate**
  - Optimum windows exist.

0.508 mm nozzle, 0.34 MPa

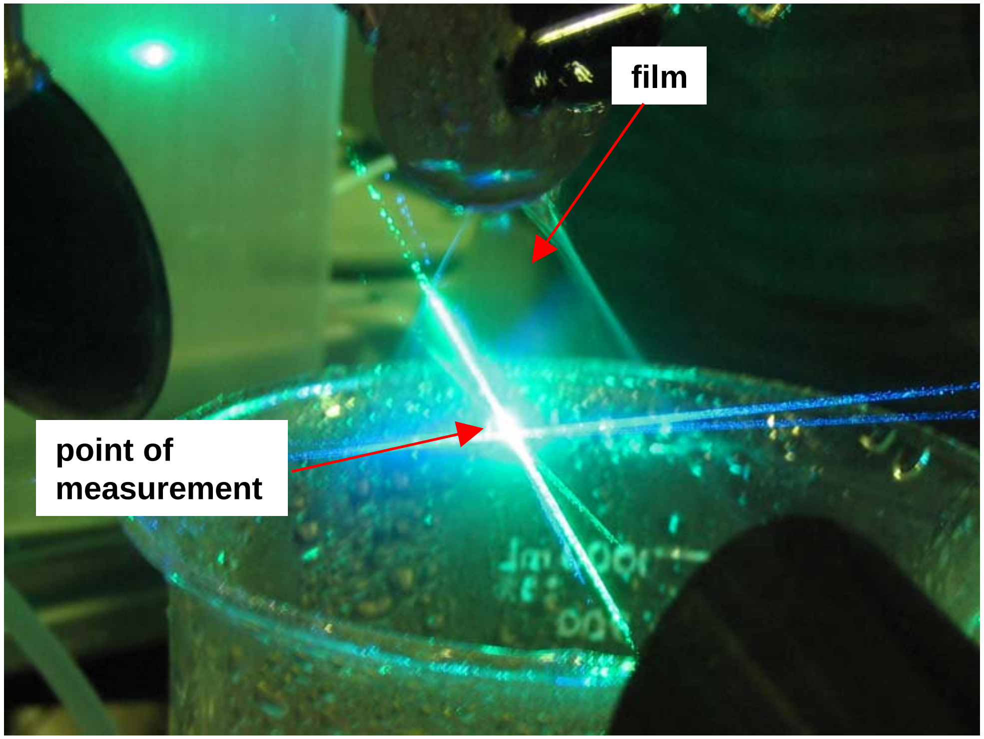


* Note that pressure value was measured before the filter that contributed to pressure drop.

- *Jet angle of between 30-45 degrees and nozzle diameters of 0.25 mm (10 mils) – 0.5 mm (20 mils) (see Figure). A film produced by a jet issued from the large diameter nozzle (1.0 mm = 40 mils) appears wavy at almost all conditions and is not suitable for the stripper.*

Development of the stability diagram (cont'd)

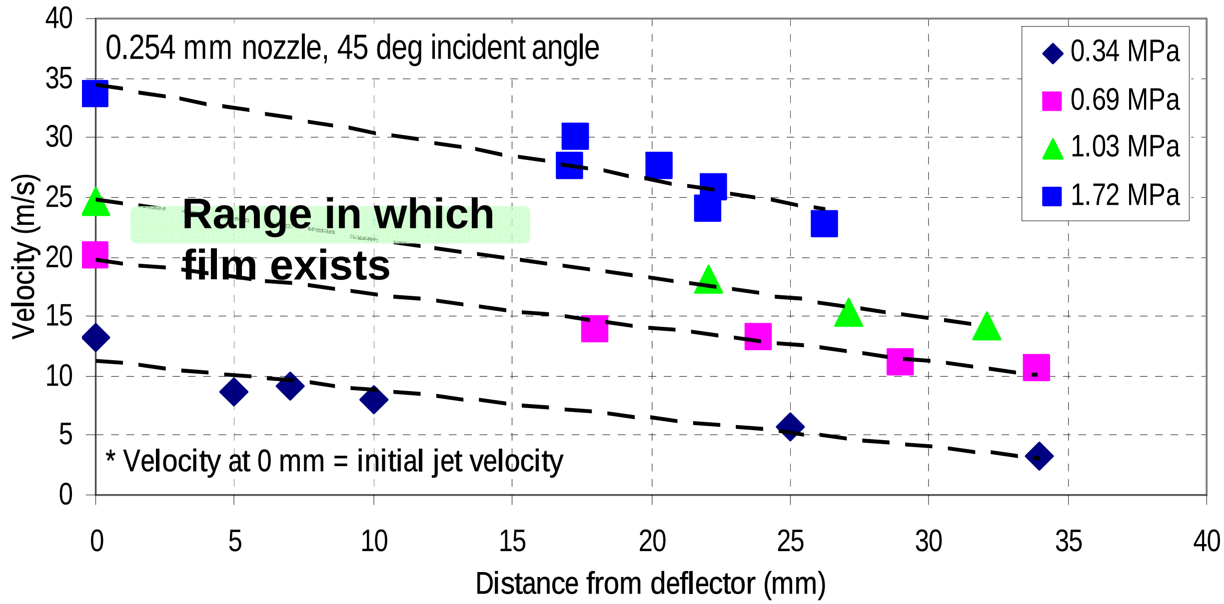
- **Velocity measurement of the droplets after film breakup using Phase Doppler Particle Analysis (PDPA)**



Droplet velocity measurement after film break up using PDPA.

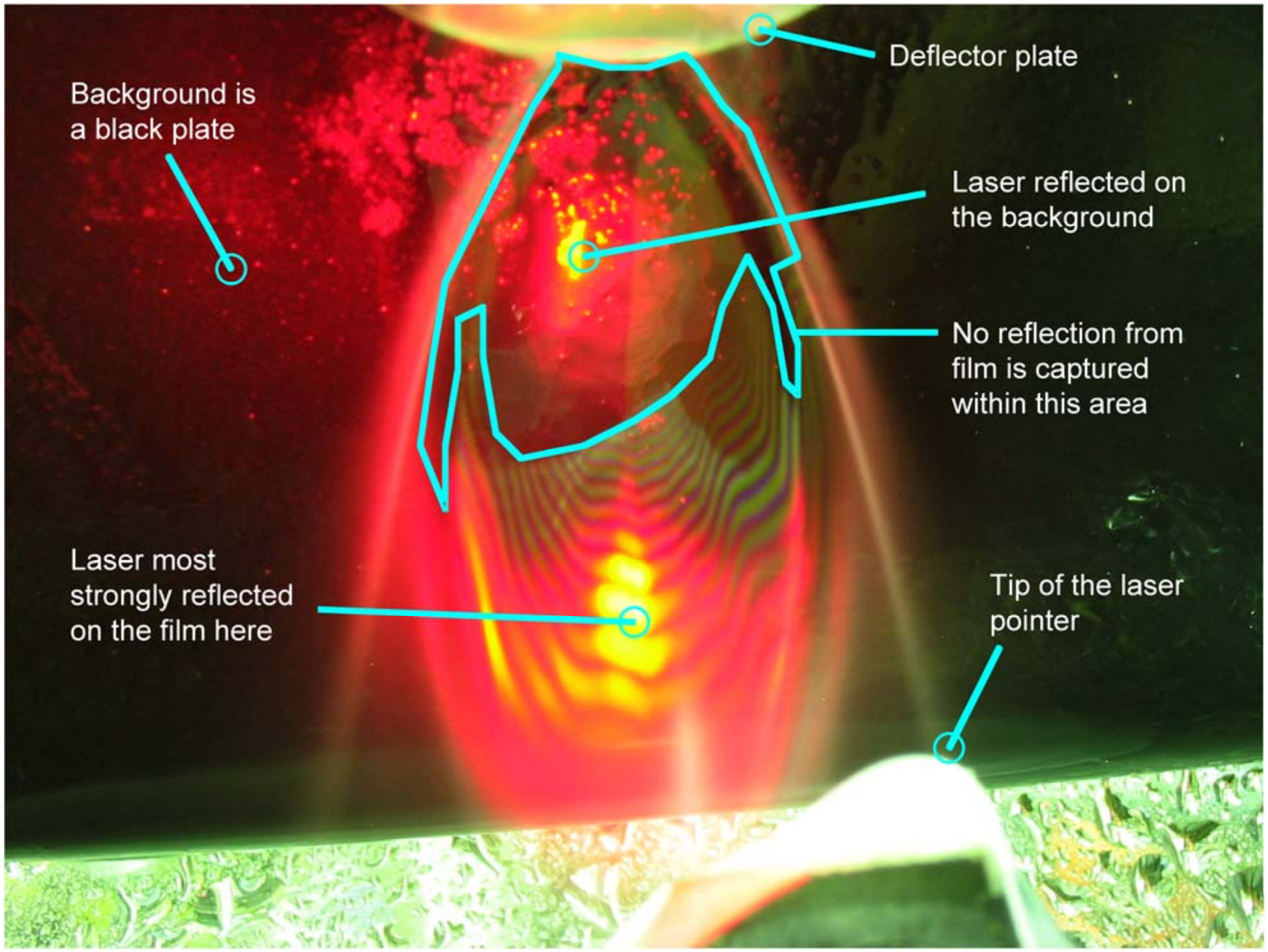
Development of the stability diagram (cont'd)

- **Velocity measurement of the droplets after film breakup using Phase Doppler Particle Analysis (PDPA)**
  - The film velocity seems to be somewhat slower than the initial jet velocity. Although no direct measurement was possible, it appears that jet velocity can be interpolated from the droplet velocity after break-up measured by PDPA and initial jet velocity



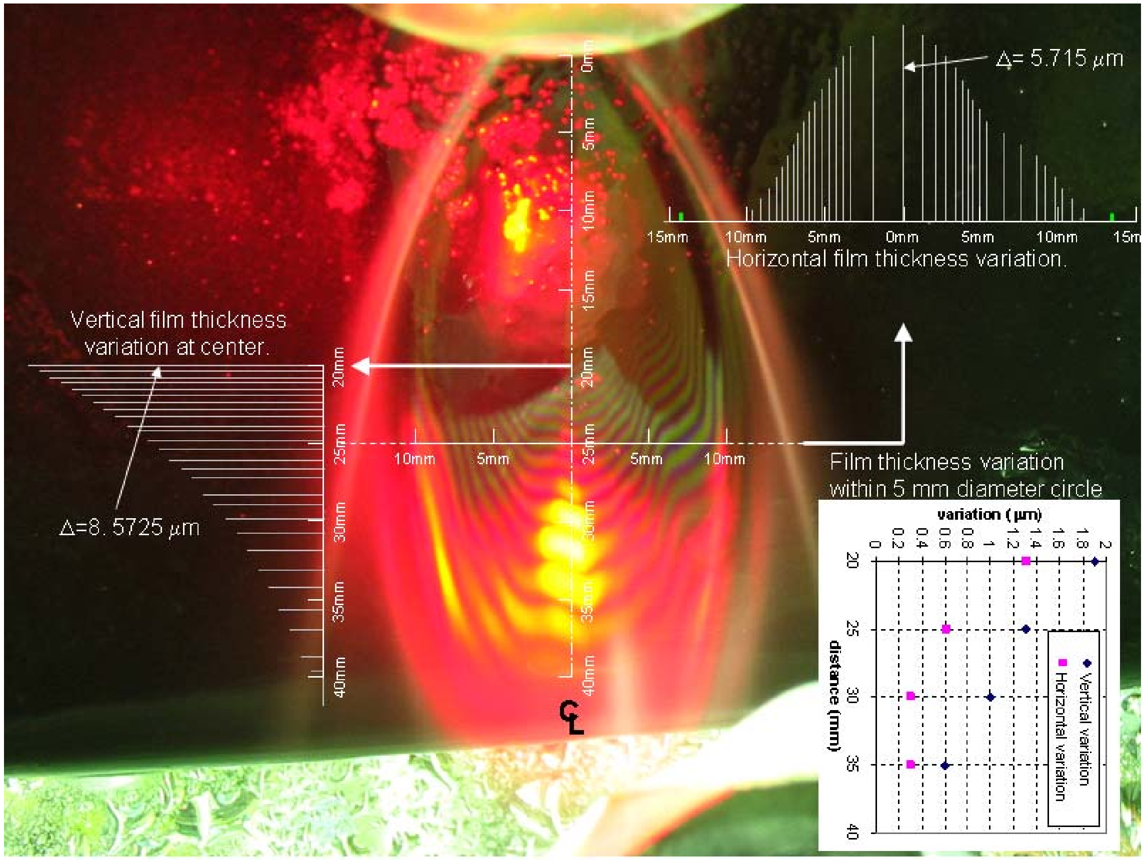
Development of the stability diagram (cont'd)

- **Film uniformity measurements using monochromatic light source**
  - Visually observing interference pattern on the film indicated the uniformity of the film.



Development of the stability diagram (cont'd)

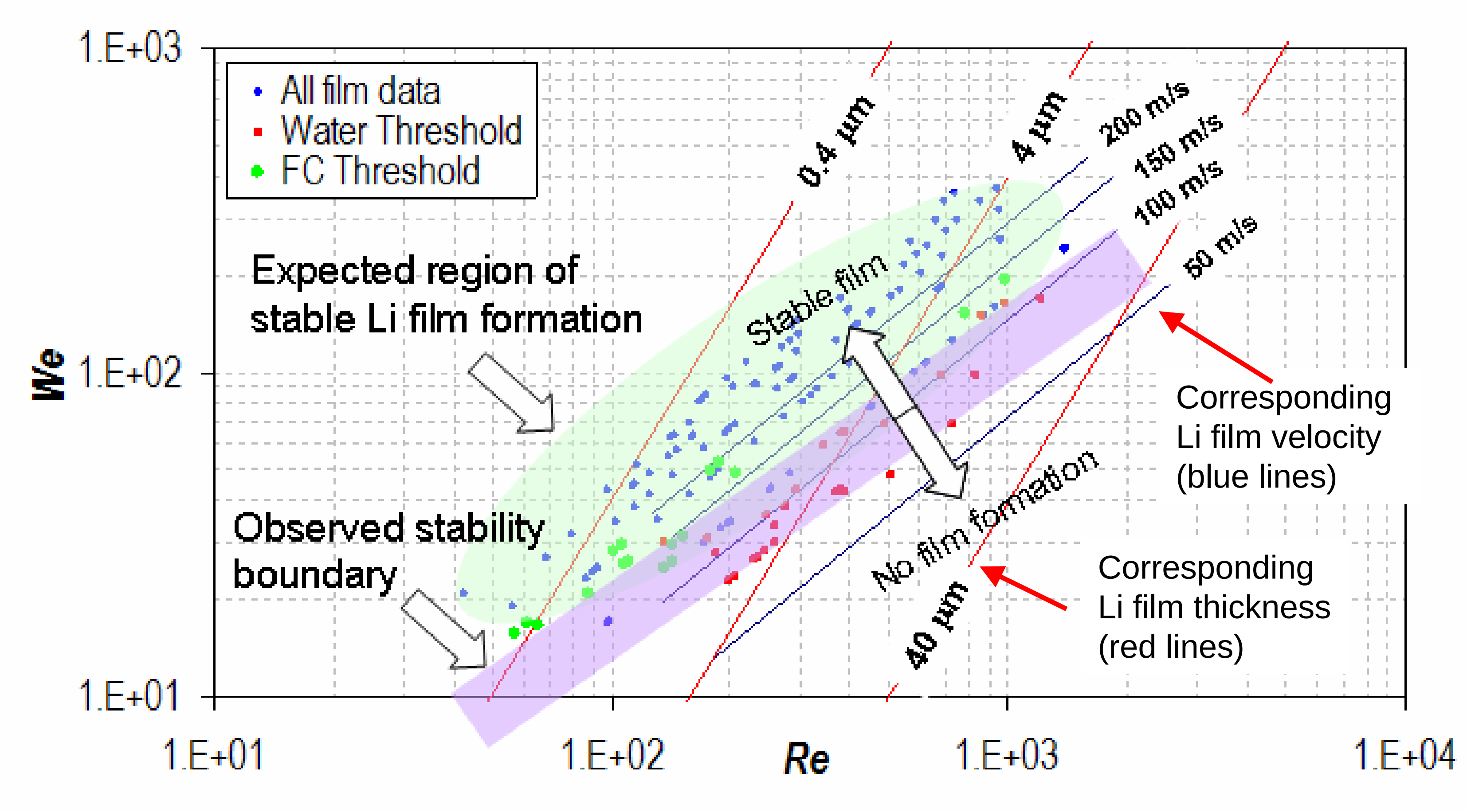
- **Film uniformity measurements using monochromatic light source**



A film produced using the 0.5 mm nozzle showed that the variation in film thickness within the expected beam diameter of 5 mm on the film is < 1 μm (See Figure).

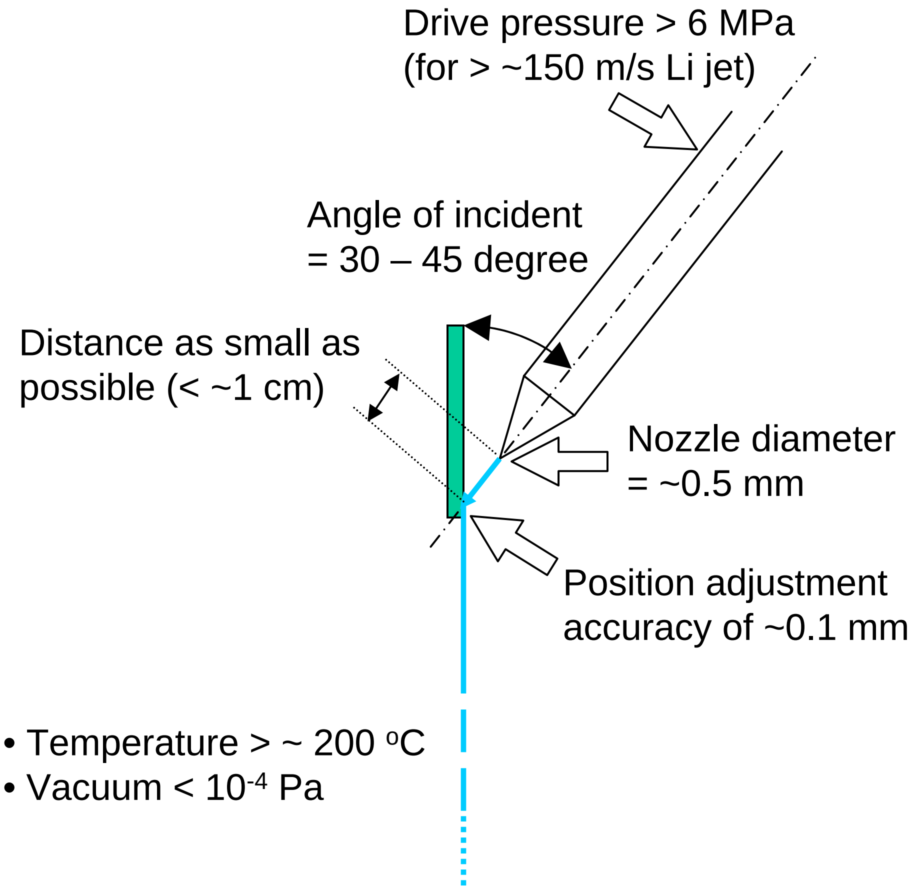
Development of the stability diagram (cont'd)

- **Stability diagram**



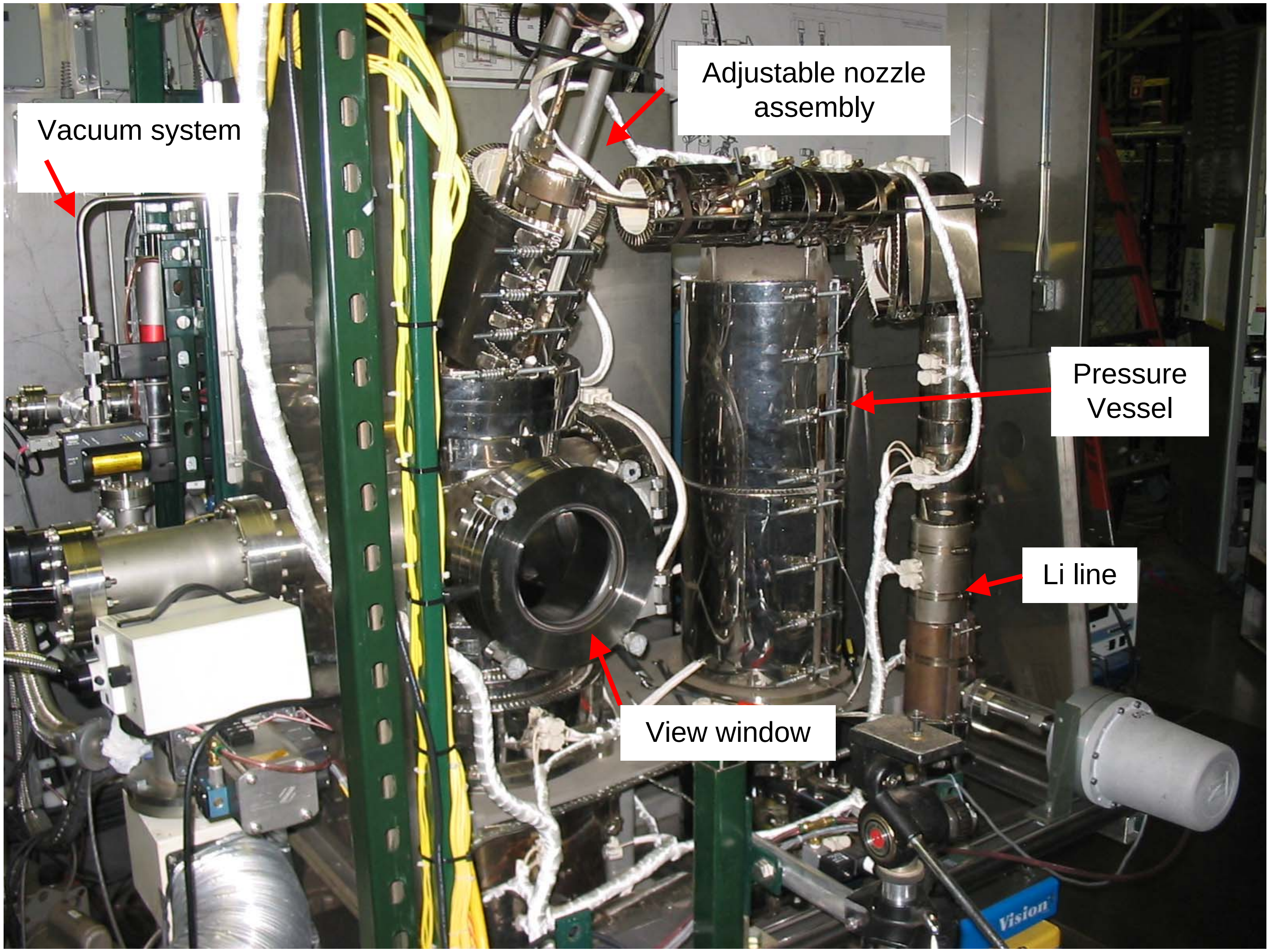
Experimental layout, setup, and instrumentation

- **Critical design parameters**
  - Determined based on these 1st and 2nd phase experiments.

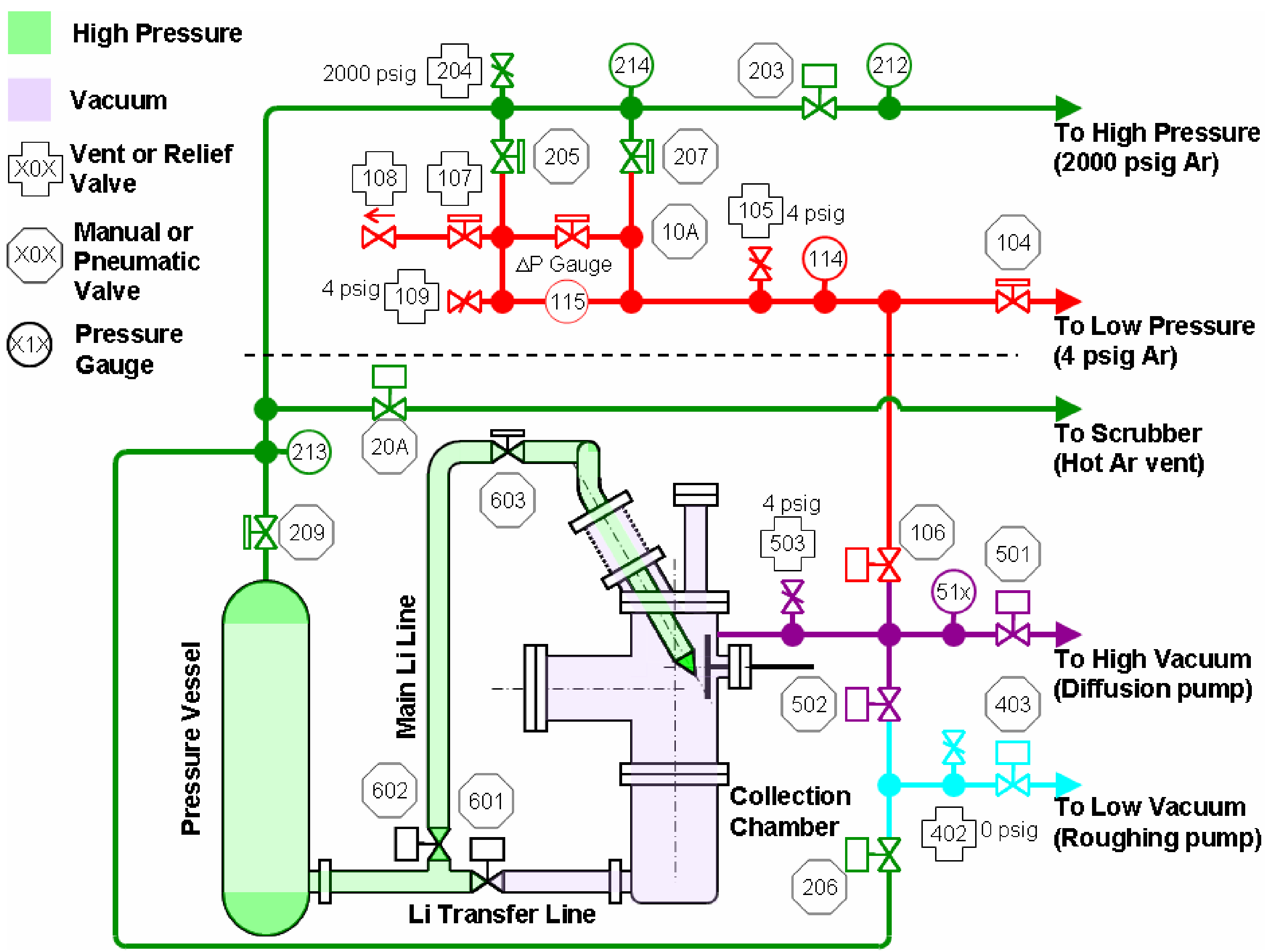


- Temperature > ~ 200 ^oC
- Vacuum < 10^{-4} Pa

Experimental layout, setup, and instrumentation (cont'd)

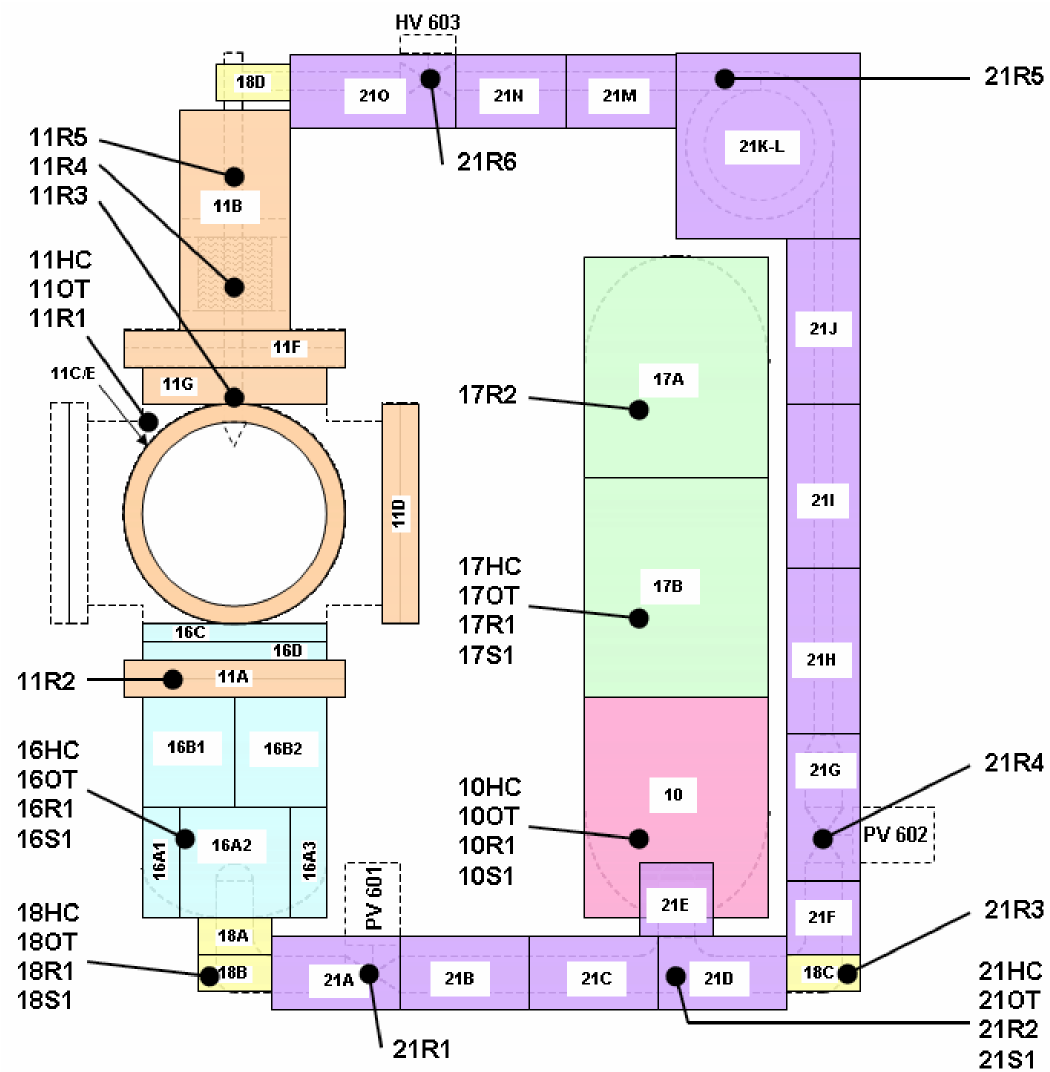


Experimental layout, setup, and instrumentation (cont'd)



- *Once-through system.*
- *Li inventory ~20 liters.*
- *Drive pressure up to 13.6 MPa (2000 psig).*
- *Pumped by air-cooled diffusion pump.*
- *Vacuum in low 10^{-7} Torr at room temperature.*
- *Adjustable deflector.*
- *Adjustable nozzle.*

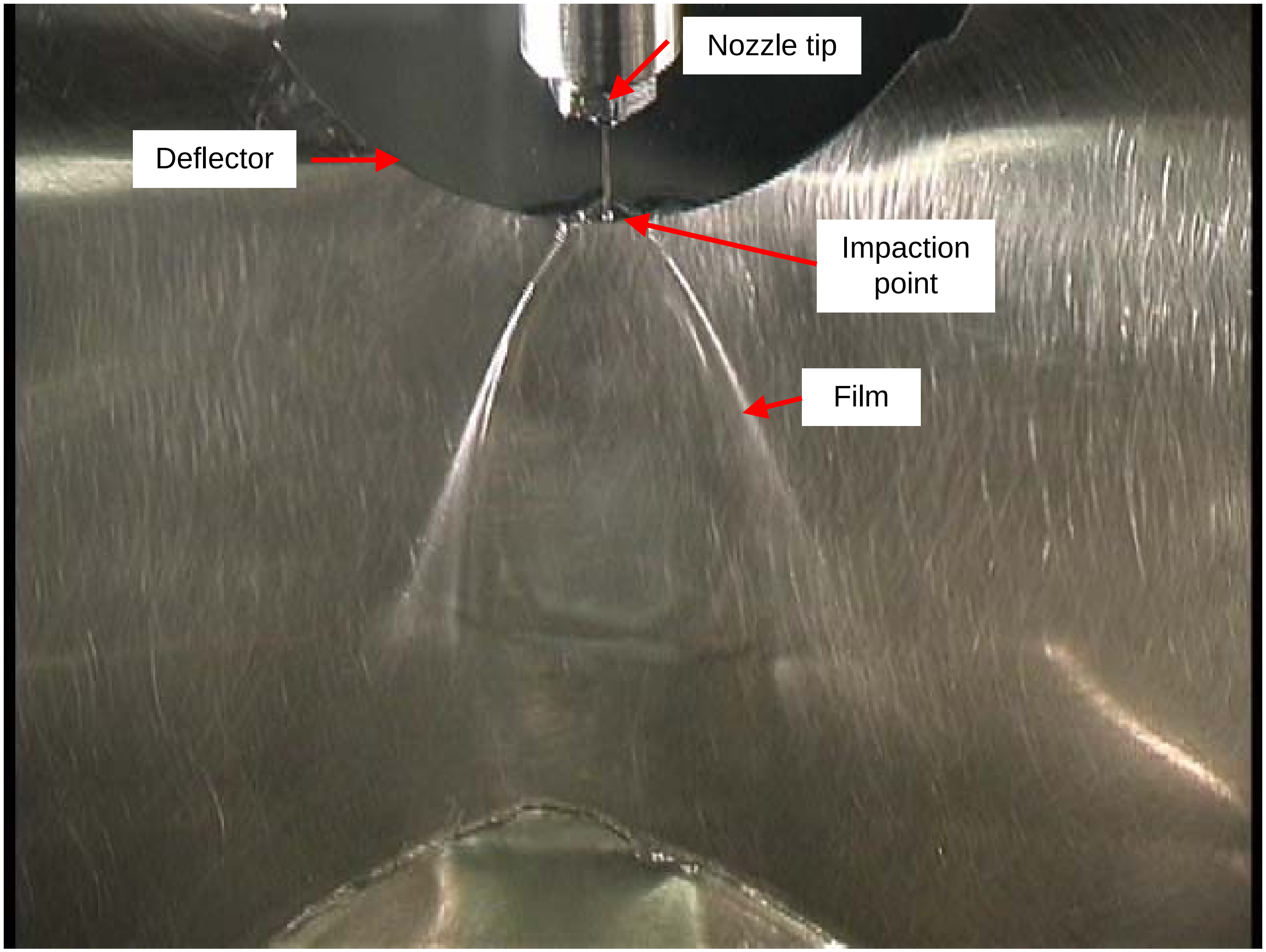
Experimental layout, setup, and instrumentation (cont'd)



- 6 independent heater zones.
- 6 controlling type-K, TCs
- Total of 21.6 kW.
- 20 monitoring type-K, TCs along the loop.
- Laptop PC with LabVIEW continuously records data.

Experimental layout, setup, and instrumentation (cont'd)

- **Testing all functionalities of the loop using FC-3283**



Experimental layout, setup, and instrumentation (cont'd)

- **Testing all functionalities of the loop using FC-3283**

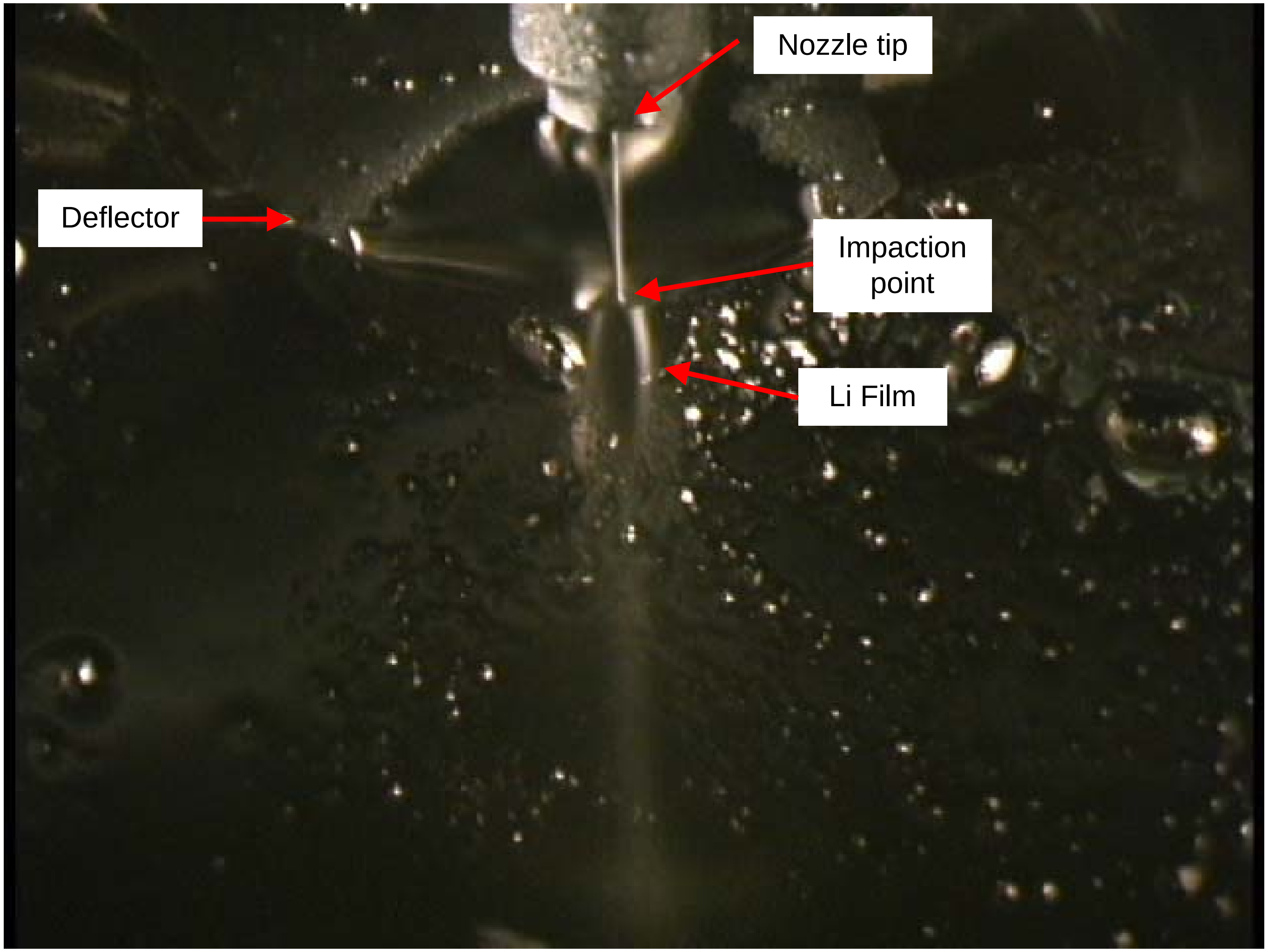
QuickTime™ and a
DV/DVCPRO - NTSC decompressor
are needed to see this picture.

Experimental procedure

1. The setup is normally kept under vacuum (low 10^{-7} Torr),
2. Set system temperature (@ ~225 ^{o}C),
3. Start recording data,
4. Set drive pressure at ~100 psig,
5. Establish a jet at low velocity (~50 m/s),
6. Fine nozzle alignment,
7. Stop Li flow and set drive pressure at desired value (> 100 psig),
8. Establish a jet at high velocity,
9. Adjust drive pressure by venting Ar driving gas,
10. Stop flow before Li runs out.

Results

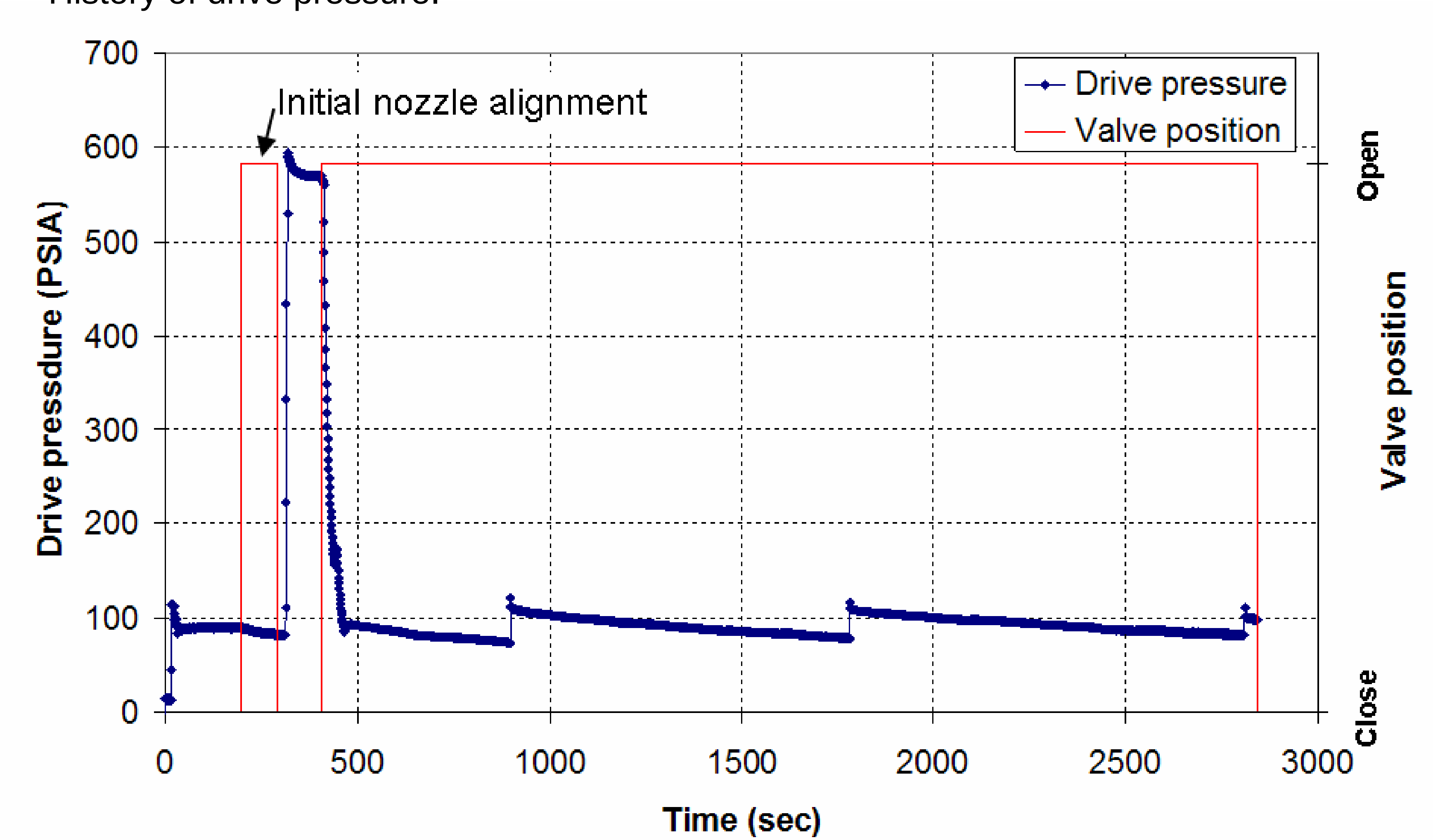
- **Successful Li film formation**



- *Drive pressure at ~0.62 MPa (~90 psia).*
- *Estimated Li velocity at ~50 m/s.*
- *Orifice diameter of 0.5 mm (20 mil).*
- *Film width is ~5 mm.*
- *Estimated film thickness is ~25 μm.*
- *Continued for ~40 min.*

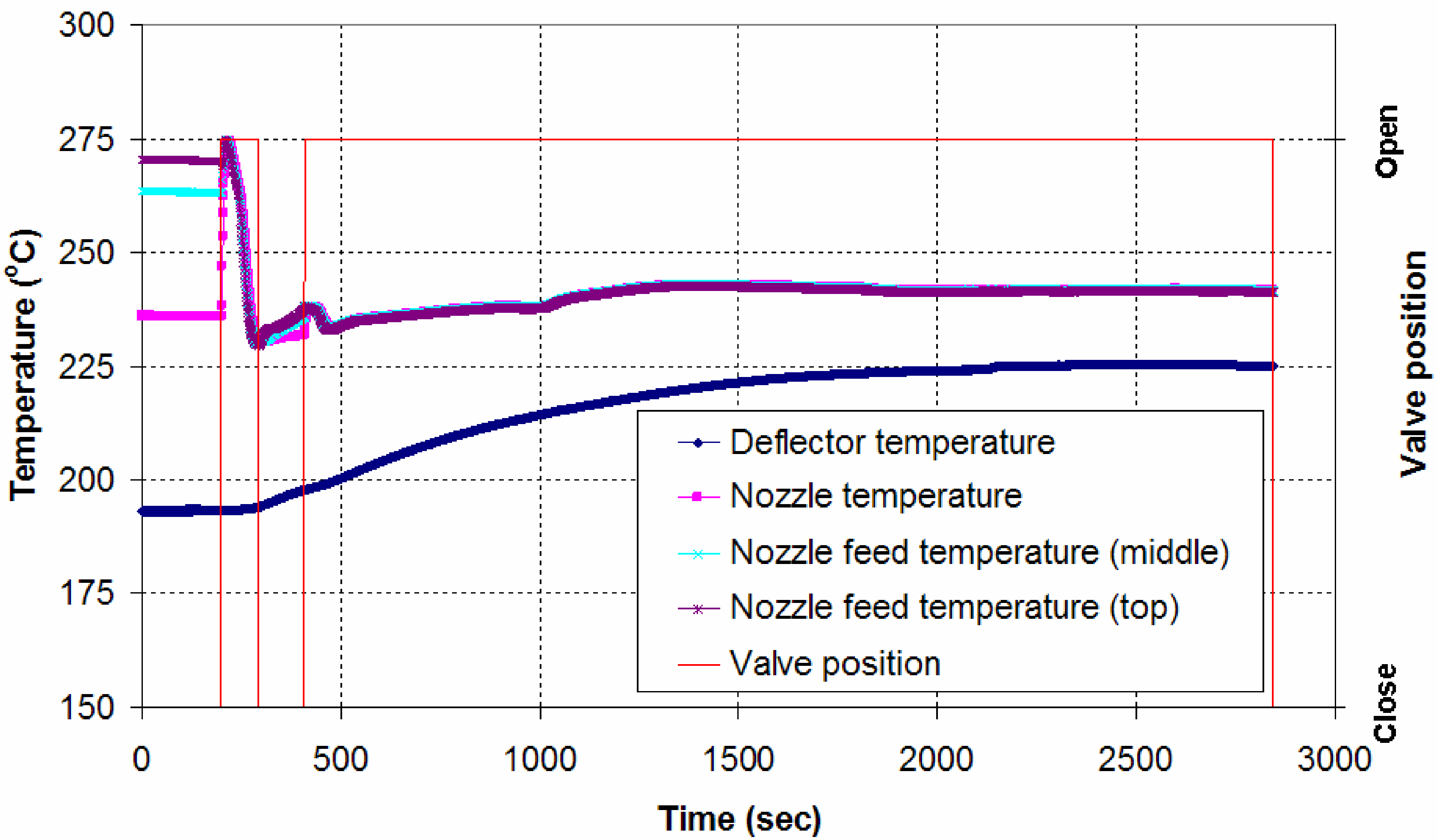
Results (continued)

- History of drive pressure.



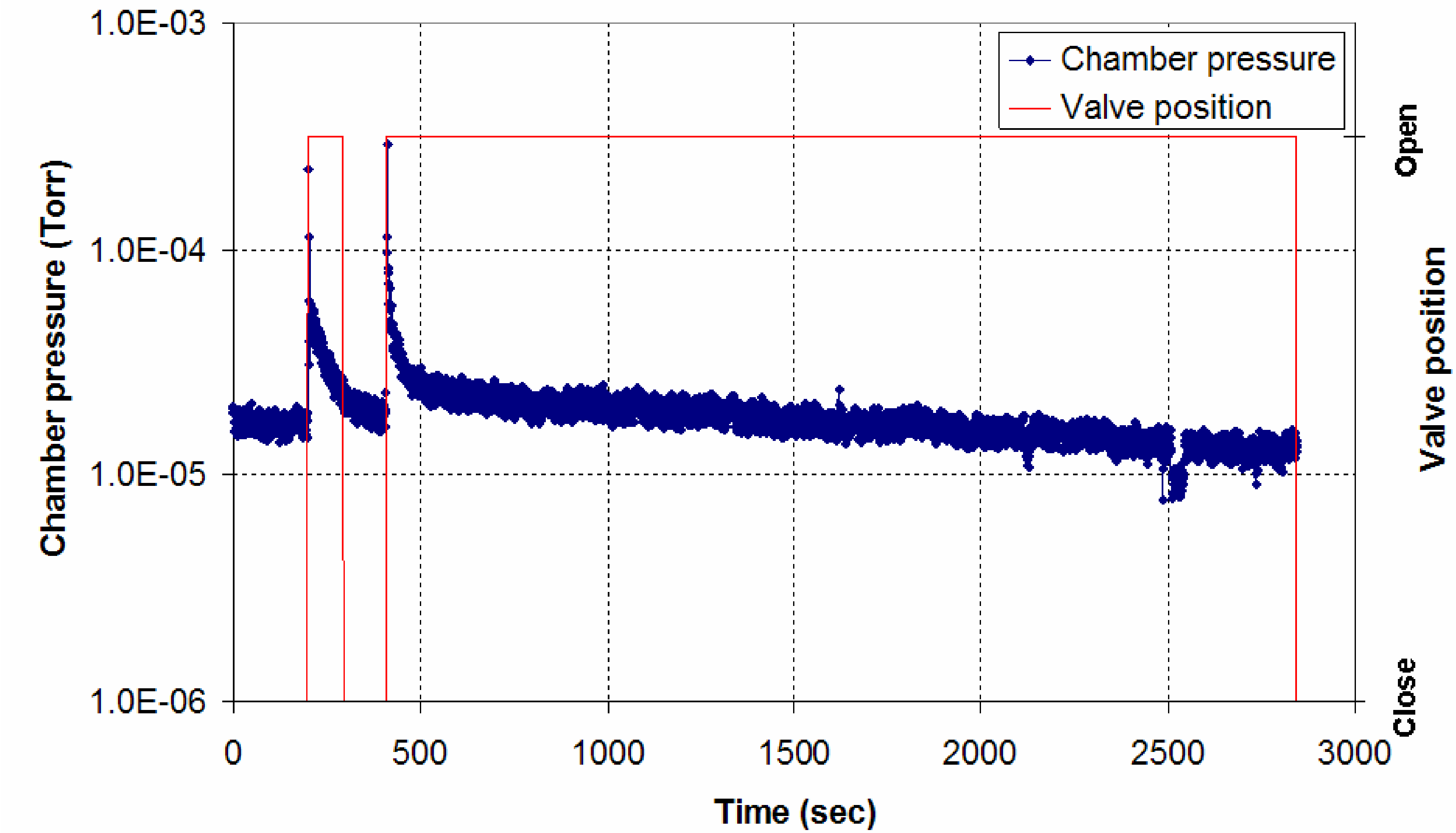
Results (continued)

- History of nozzle and deflector temperatures.



Results (continued)

- History of chamber pressure.



Results (cont'd)

- Movie

Summary and future plan

- **Experimental demonstration of liquid lithium thin film was performed.**

- **Film parameters:**
  - stable
  - ~ 5 mm in width
  - ~ 25 μm in thickness
  - jet velocity of ~ 50 m/s
  - under vacuum ~ 2 x 10^{-5} torr
  - operated for 40 min

- **More parametric studies are planned.**