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Liquid Lithium Windowless Targets for High Power Accelerators

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Workshop on Applications of High Intensity Proton Accelerators

WG4: SRF LINAC Driven Subcritical Core

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Fermilab

U.S. Department of Energy

UChicago Argonne LLC

Office of Science U.S. DEPARTMENT OF ENERGY

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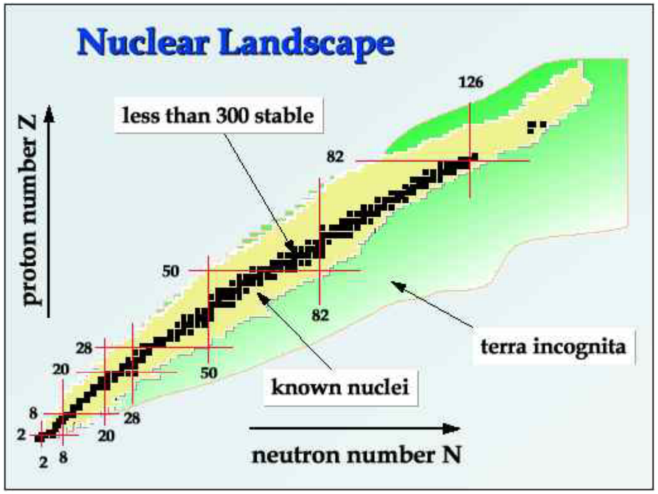
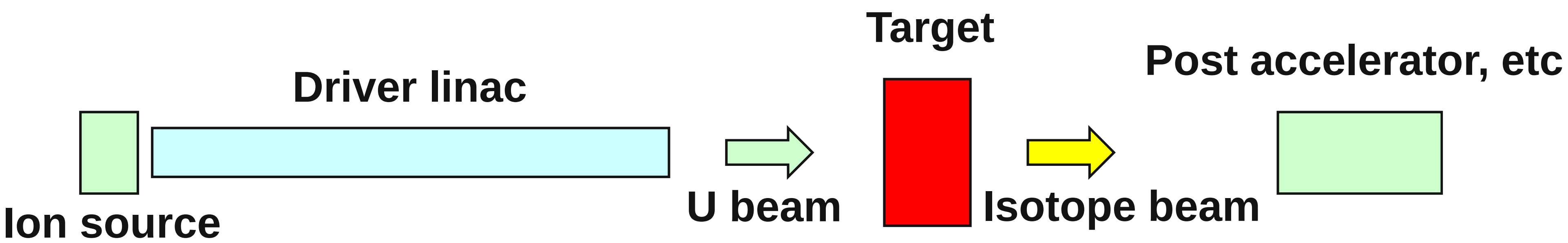
Presentation Outline (Beam-on-target Demonstration)



- Introduction
  - What is FRIB?
  - 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*
- Summary and Conclusions

What is FRIB (Facility for Rare Isotope Beams)?

– FRIB 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)*

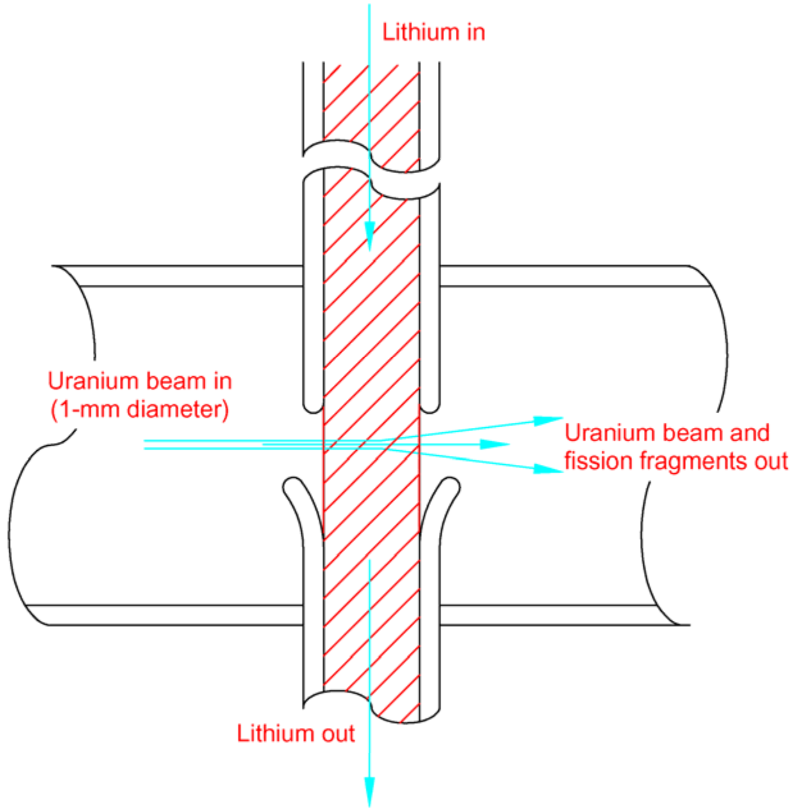
or

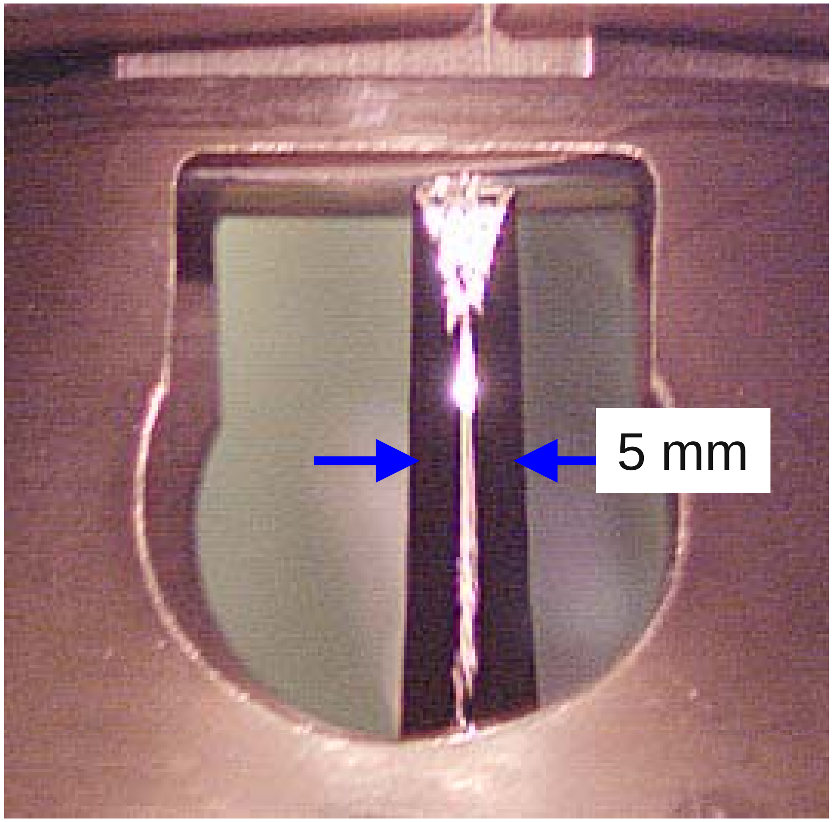
2. *Fragmentation (high Z ion beam on low Z target).*
   – U beam power density is up to 400 kW per ~1 mm^2
   – No *solid* target can handle such loads.

⇒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





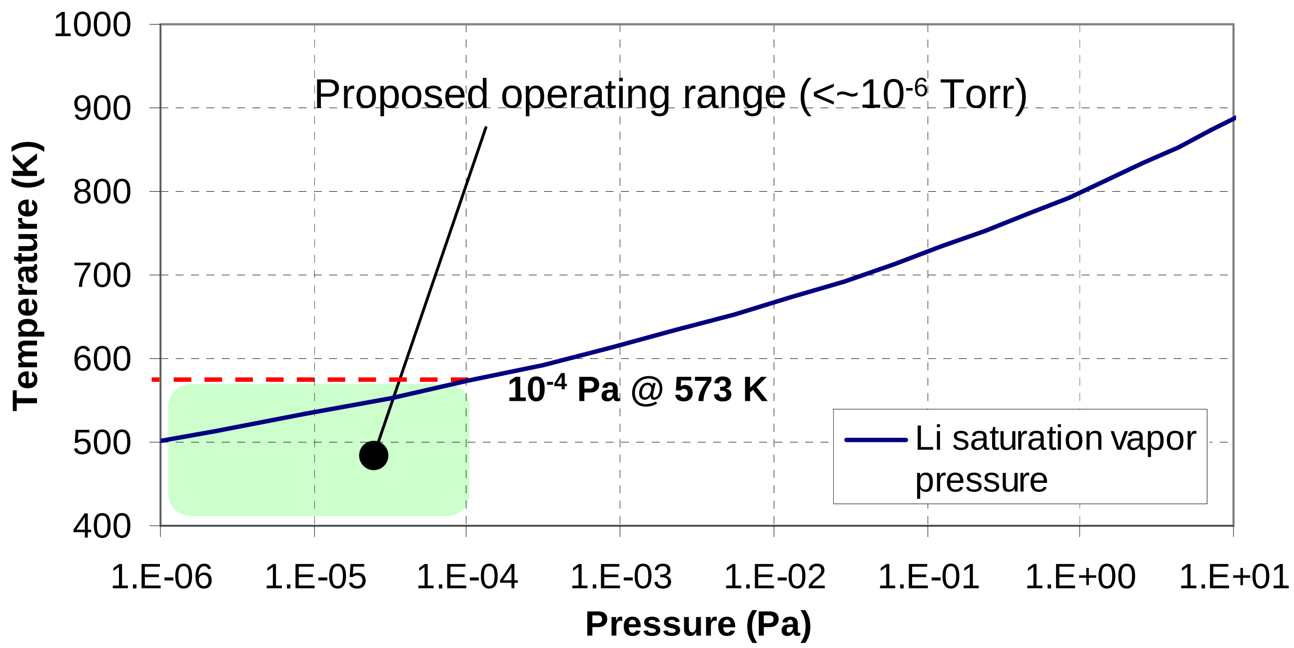
5 x 10 mm liquid Li jet flowing at 10 m/s in vacuum.

Why Liquid Lithium?

- Low Z (= 3)---good from nuclear considerations
- Large working temp range $\Delta T \sim 1160$ °C
  - High boiling point (1342°C)
  - Low melting point (181°C)
- Low vapor pressure (10^{-7} Pa at 200°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 $\Longrightarrow$ excellent heat transfer
- Applications
  - Heat transfer fluid to cool solid targets with light-ion beams
  - Combined coolant and target for high-power heavy-ion beams

About lithium

- Low vapor pressure (10^{-7} Pa at 200 ° C).
- Bulk Li temperature can be as high as 573 K while being compatible with accelerator vacuum (10^{-4} Pa or 10^{-6} Torr).
- Local peak temperature can be much higher (900 K or above?).

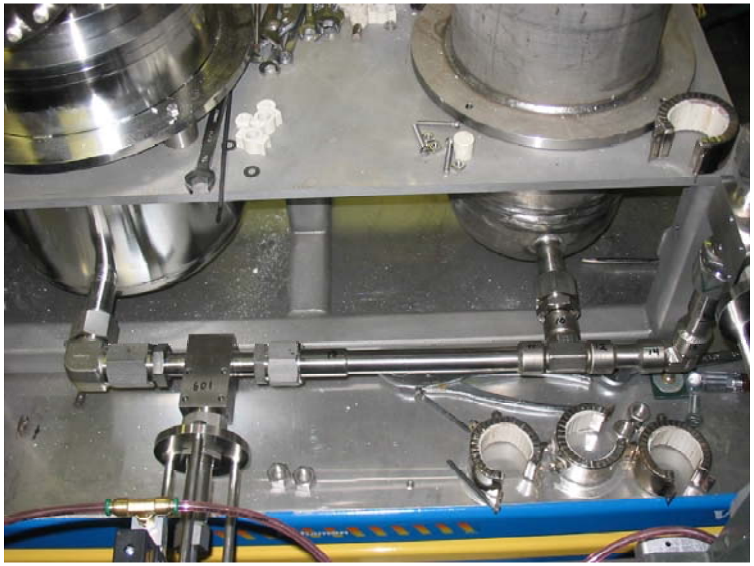


About lithium

- Alkali metal.
- Reactive, but least reactive among alkali metals.
- Silver in color, very soft, can be easily cut by knife.

Material compatibility

- Compatible materials
  - Structural materials
    - *Stainless steel.*
    - *Many refractory metals (Ta, Mo, Nb, W, V, Be).*
  - Non-metals
    - *SiC and AlN have been reported compatible.*
  - Gasket materials
    - *Stainless steel gasket, O-ring and annealed soft iron gaskets.*
  - Cover gas
    - *Inert gases (He, Ar, etc).*



Material compatibility

- Incompatible materials
  - Structural materials
    - *Copper, Aluminum.*
    - *Glass, Plexiglas.*

  - Other materials
    - *Most oxides and ceramics (Al_2O_3 etc are not compatible).*
  - Gasket materials
    - *Conventional gasket materials are not compatible (Cu, Ni, Al, Viton®, PTFE) and may be even reactive.*
  - Cover gas
    - *Most gases containing nitrogen (Li reacts with nitrogen and Li_3N violently decomposes on contact with moisture).*
  - Oils (organic materials) are incompatible.

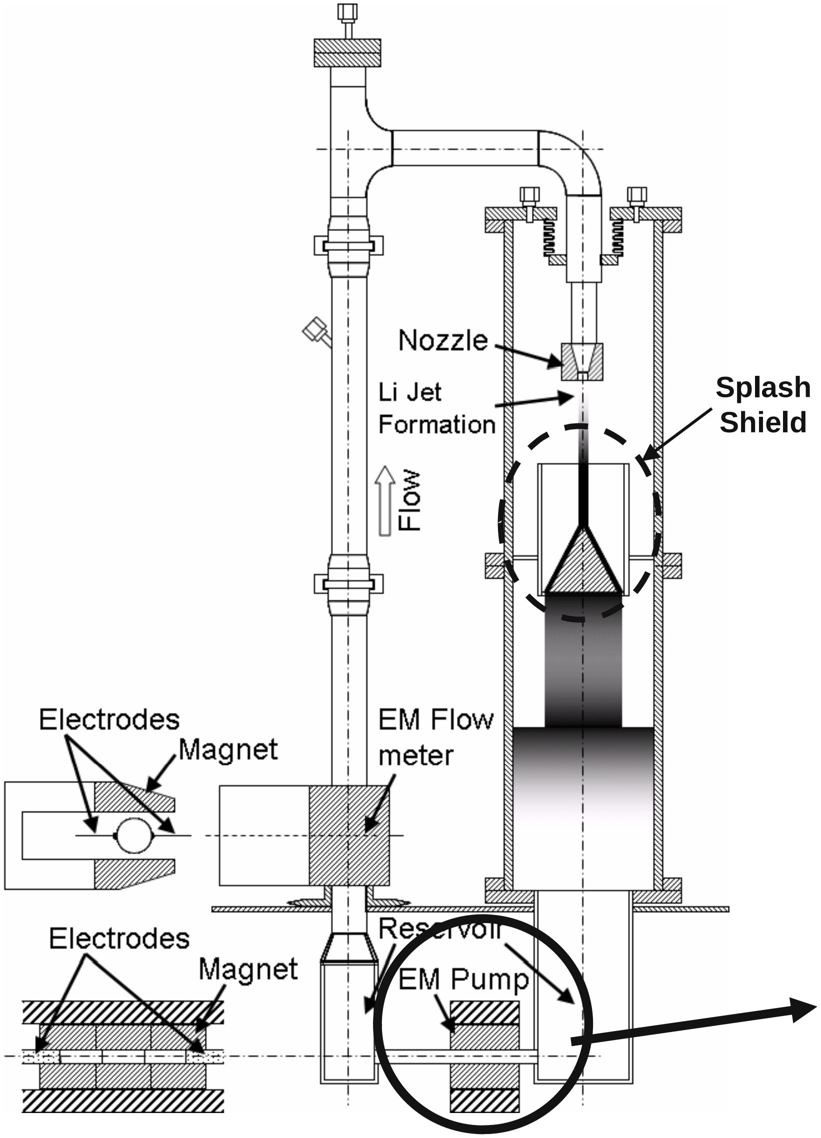
Lithium handling

- Normally least reactive among all alkali metals
  - Completely dry air reacts with Li very slowly even at elevated temperatures.
  - Impurities in lithium tend to accelerate reaction with air.
  - Controlling moisture is very important.
  - Li reacts with concrete.
    - *Liquid Li explosively reacts with concrete.*
    - *Full metal containment (floor, wall, ceiling).*

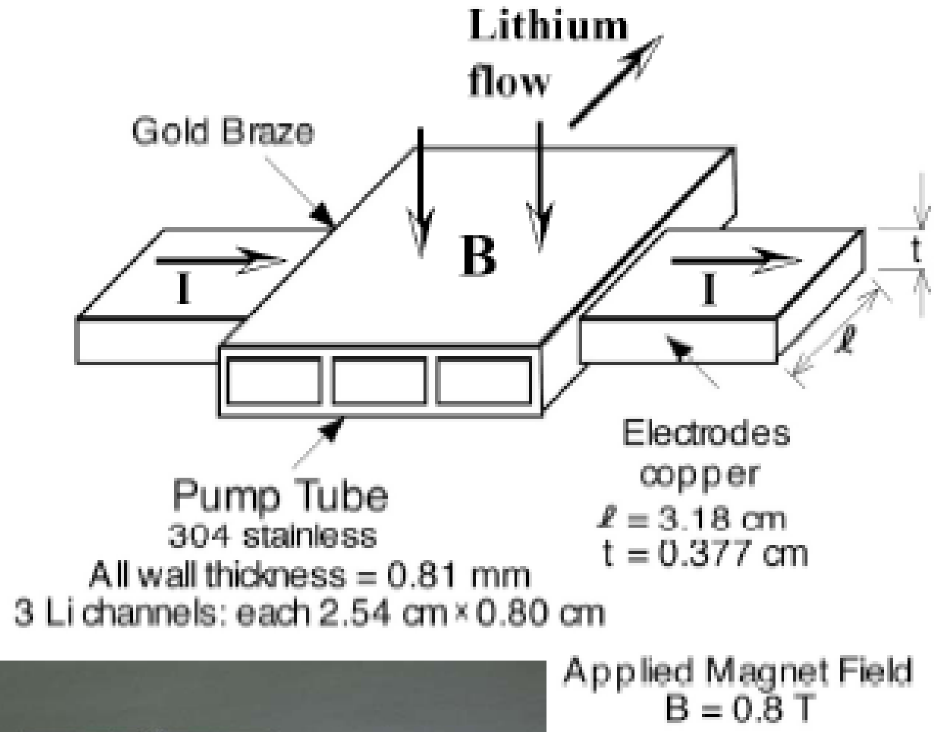
System construction

- Tubing, piping, connection
  - Stainless steel tubing, pipe.
  - Full penetration welding is good.
  - VCR fitting (≤ 1 inch) with stainless steel gasket, CF flange with annealed iron gasket.
  - Grooved flange with metal O-ring may be fine.
  - Avoid compression fittings.
- Valve
  - Full metal weld bellow valves (Swagelok BW or UW).
  - No suitable ball valves are known to ANL.
  - Throttling may be achieved by electromagnetic means.

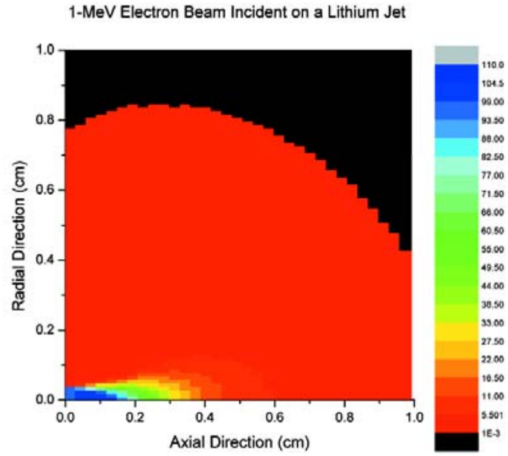
Windowless Lithium Target Loop



Windowless Liquid Li Target Loop



20 kW E-beam-on-Target Test at ANL



- MCNPX **:**

  FRIB , 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:

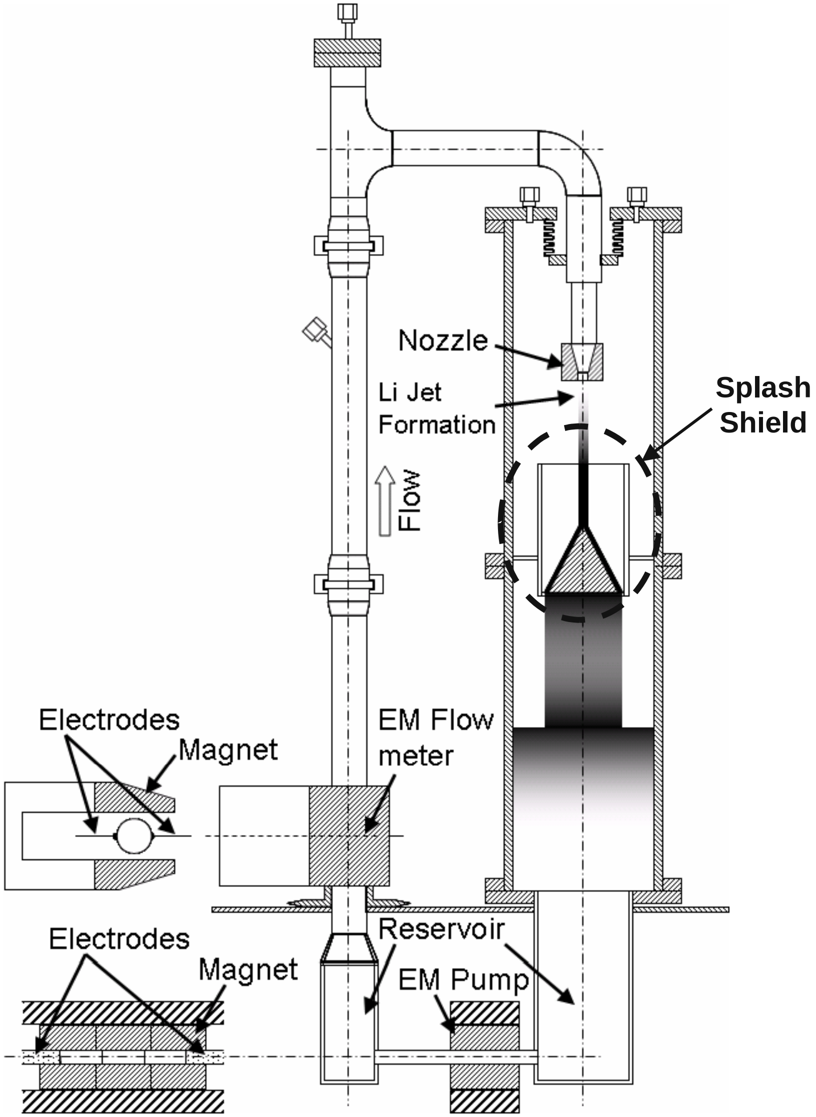
  Using this equivalence, demonstrate that power densities equivalent to a 200 kW RIA uranium beam:

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

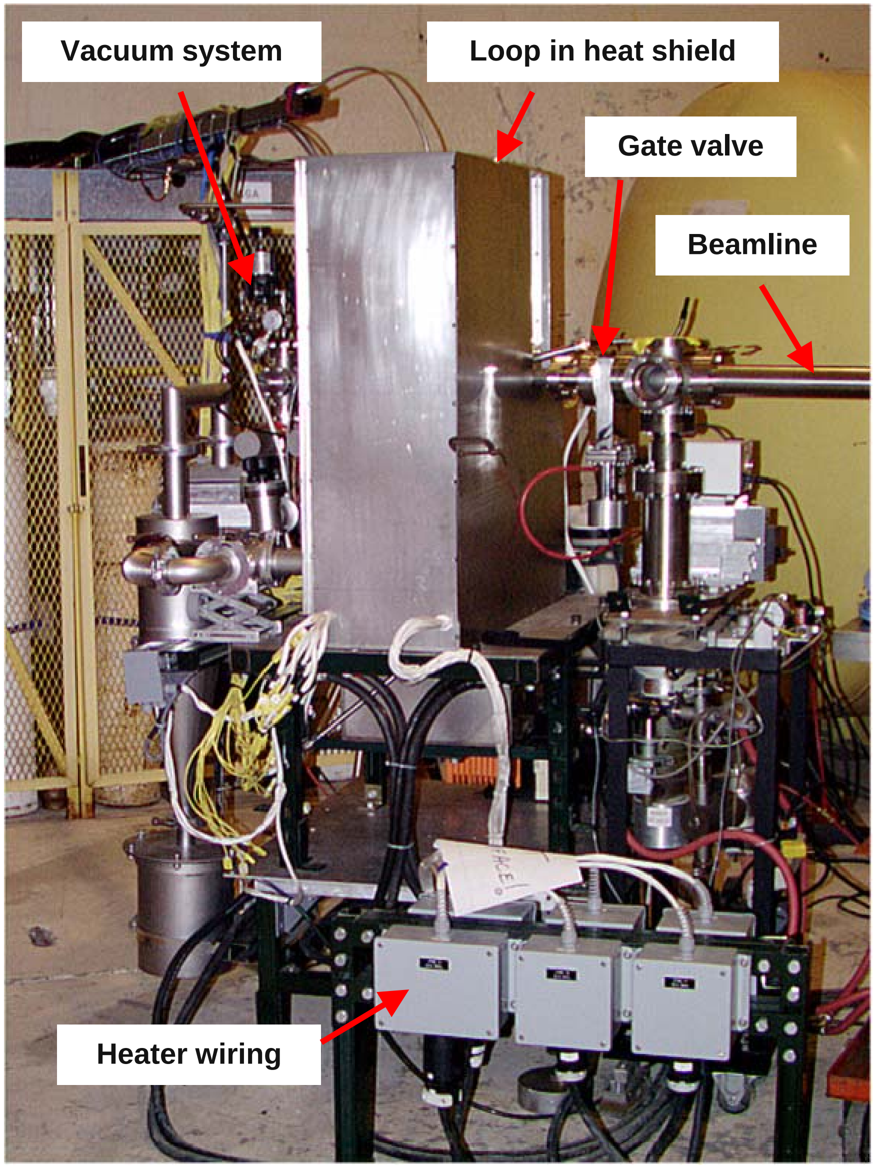
- Overall Objective:

  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

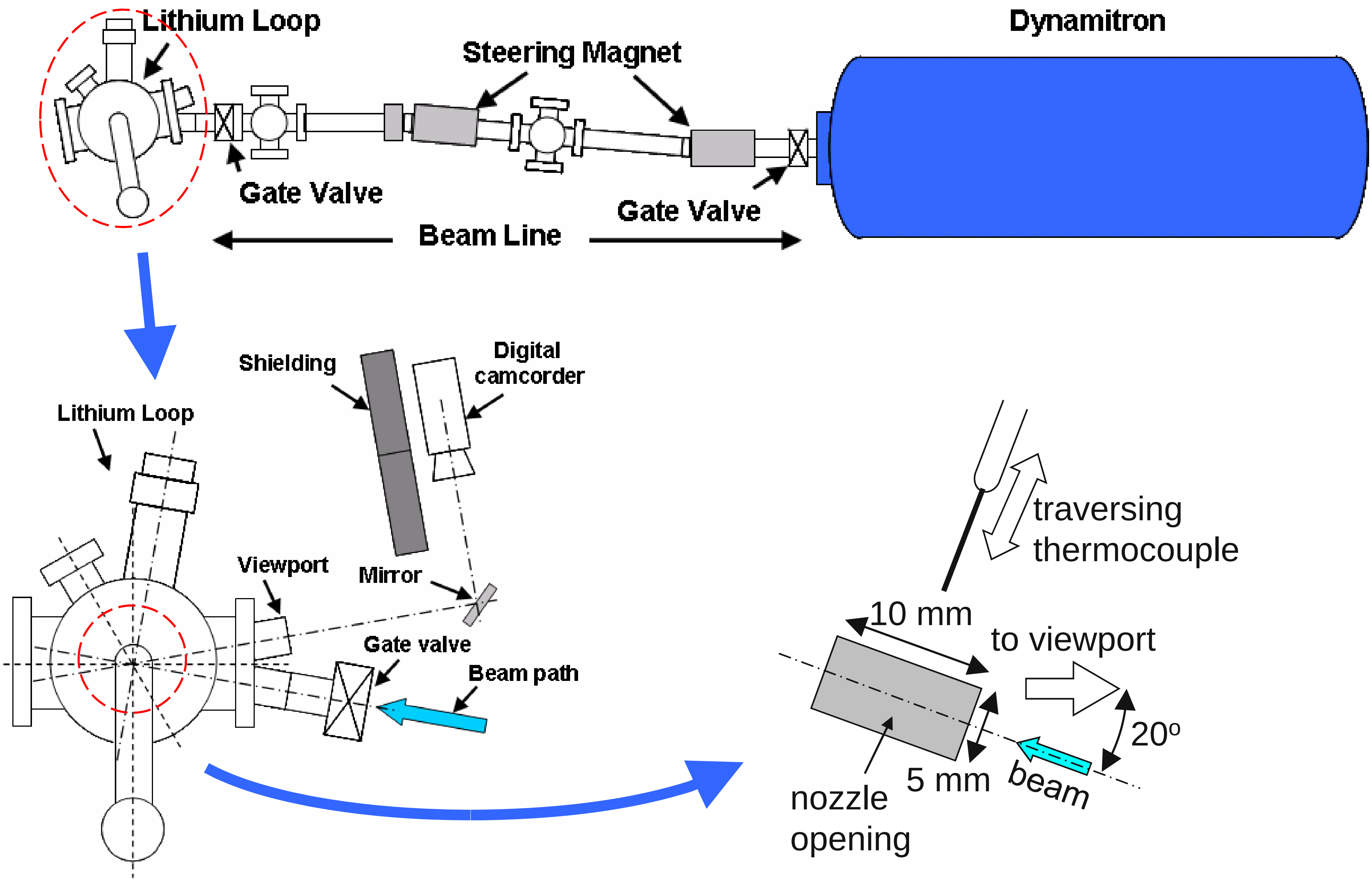
Experimental Layout, Setup, and Instrumentation



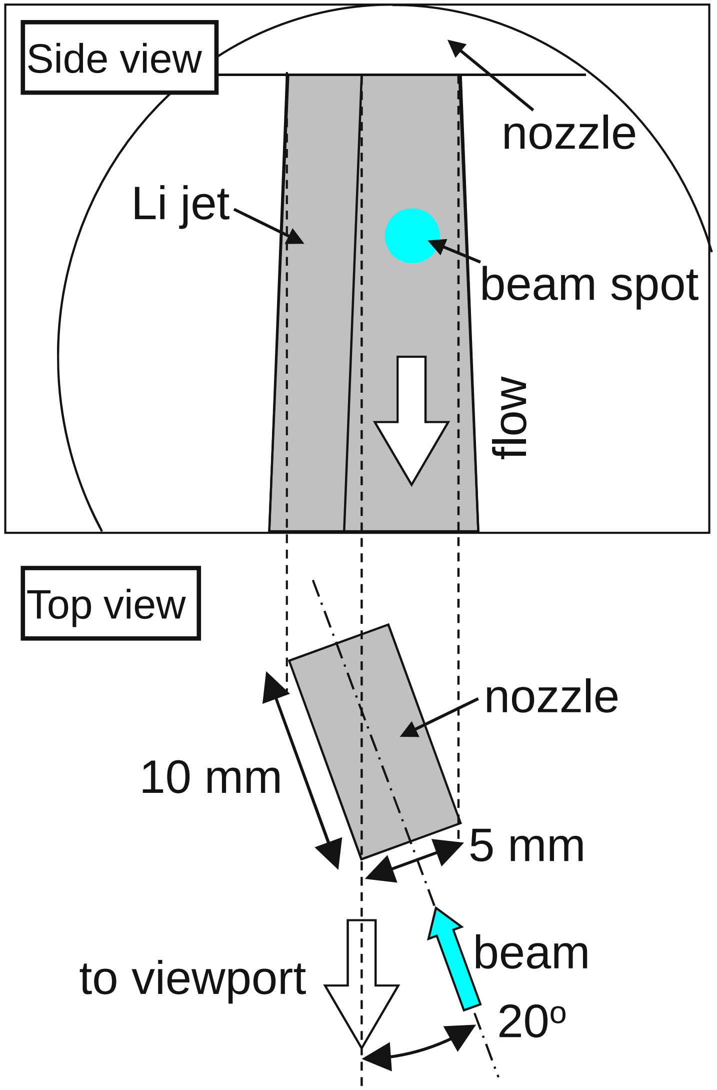
Windowless Liquid Li Target Loop



Experimental Layout, Setup, and Instrumentation

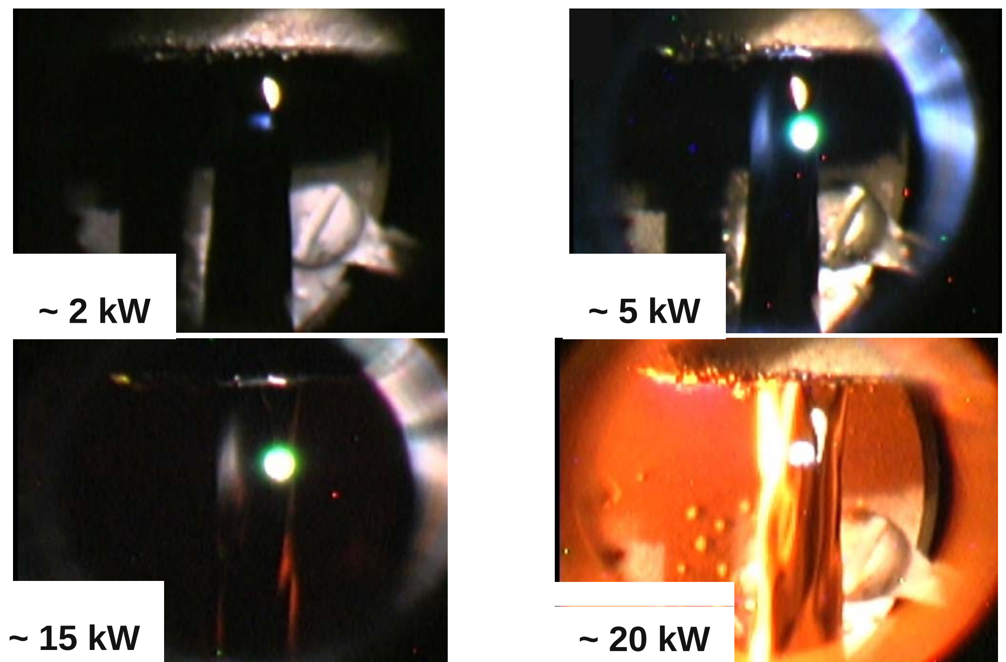


Windowless Liquid Lithium Target During Beam on Experiment

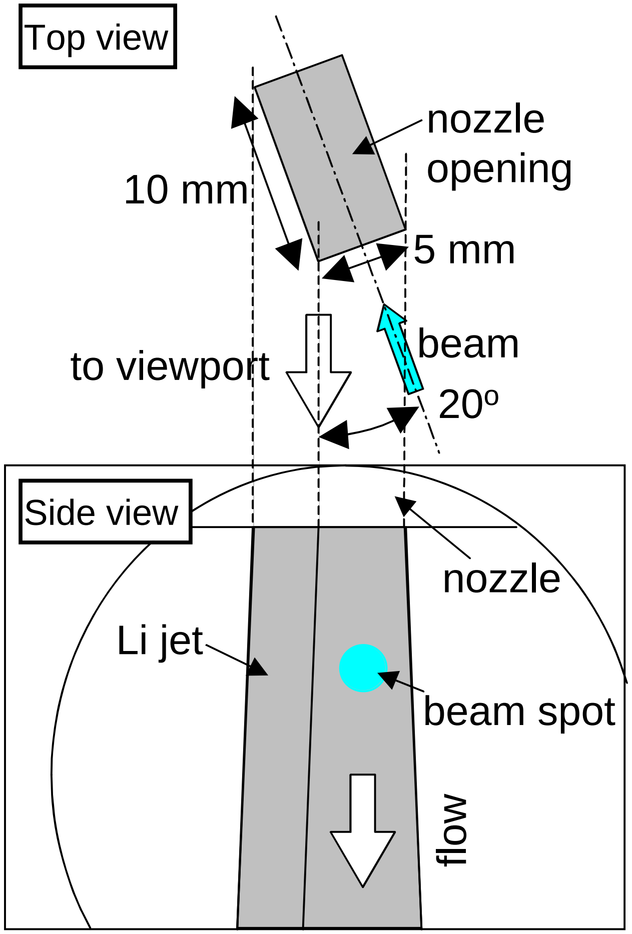


A 20 kW electron beam was applied on the Windowless Liquid Li Target.

Li jet is confirmed stable in vacuum with a U beam equivalent thermal load.



20 kW Electron Beam on Lithium Jet in Vacuum



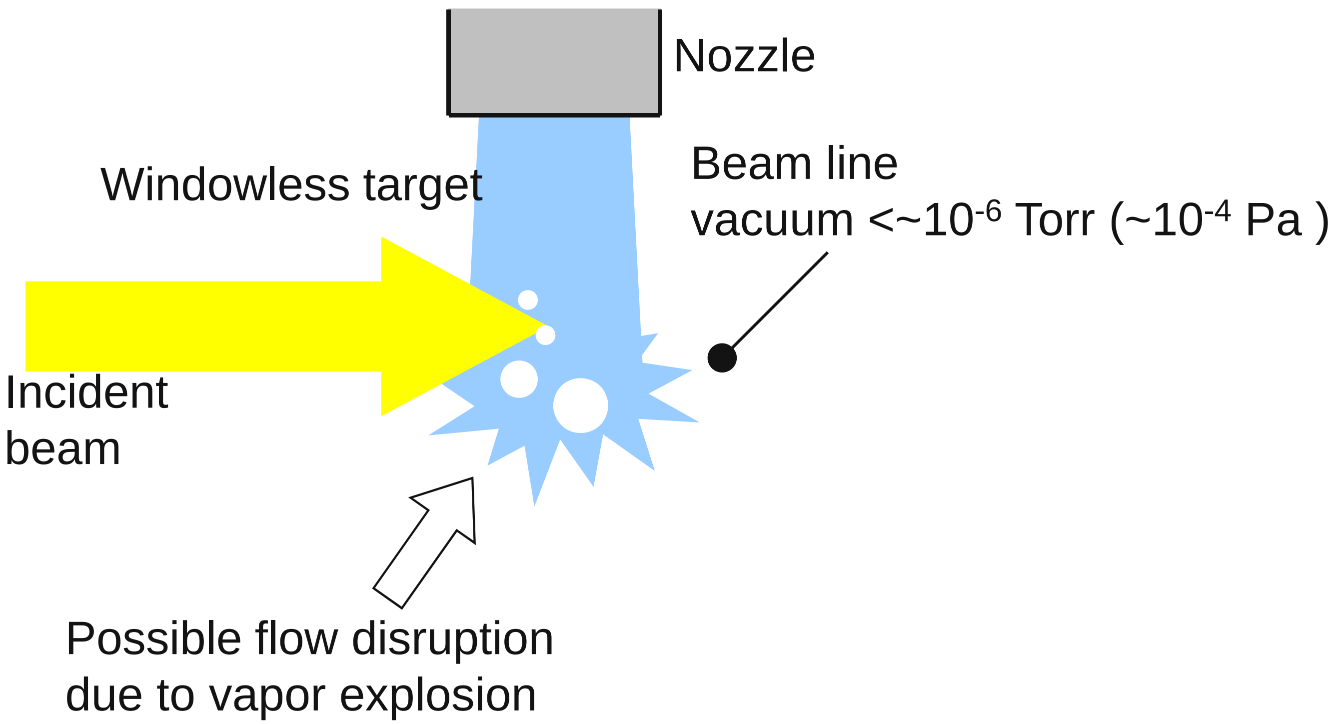
Schematic Beam-Jet Arrangement

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

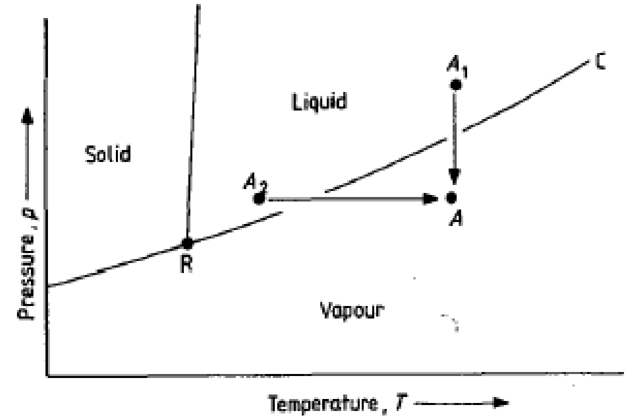
QuickTime™ and a
DV/DVCPRO - NTSC decompressor
are needed to see this picture.

What about boiling?

- If flow velocity is too small to sufficiently suppress temperature rise in liquid
  - Bulk boiling may occur
  - Disrupting the target



Boiling <=> Cavitation



– Liquids exhibit finite tensile strength:

- *ex: experiments found mercury's tensile strength*

  > ~40 MPa at RT!!!

Liquids can exist without breaking (boiling) when $P_{SAT} > P_{LIQ}$

Mercury's tensile strength

- Measuring tensile strength of Hg **(Briggs)**
  - Larger & larger negative values were obtained
    - *By outgassing*
    - *Raising temperature*

} ⇒ *Improve wetting*

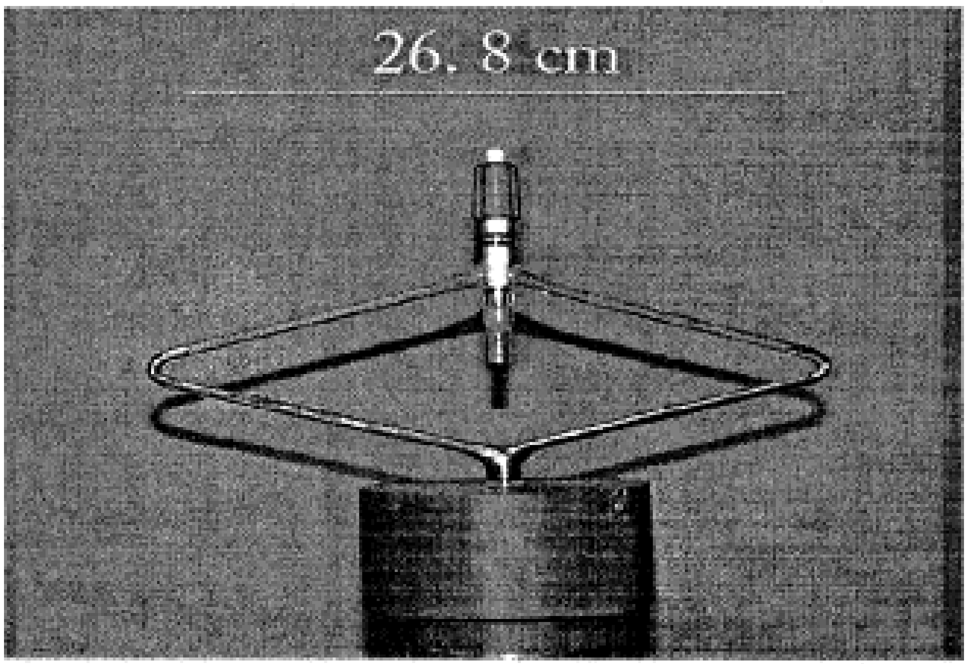


Figure 1. Detail of glass spinner. The distance between the helium-mercury

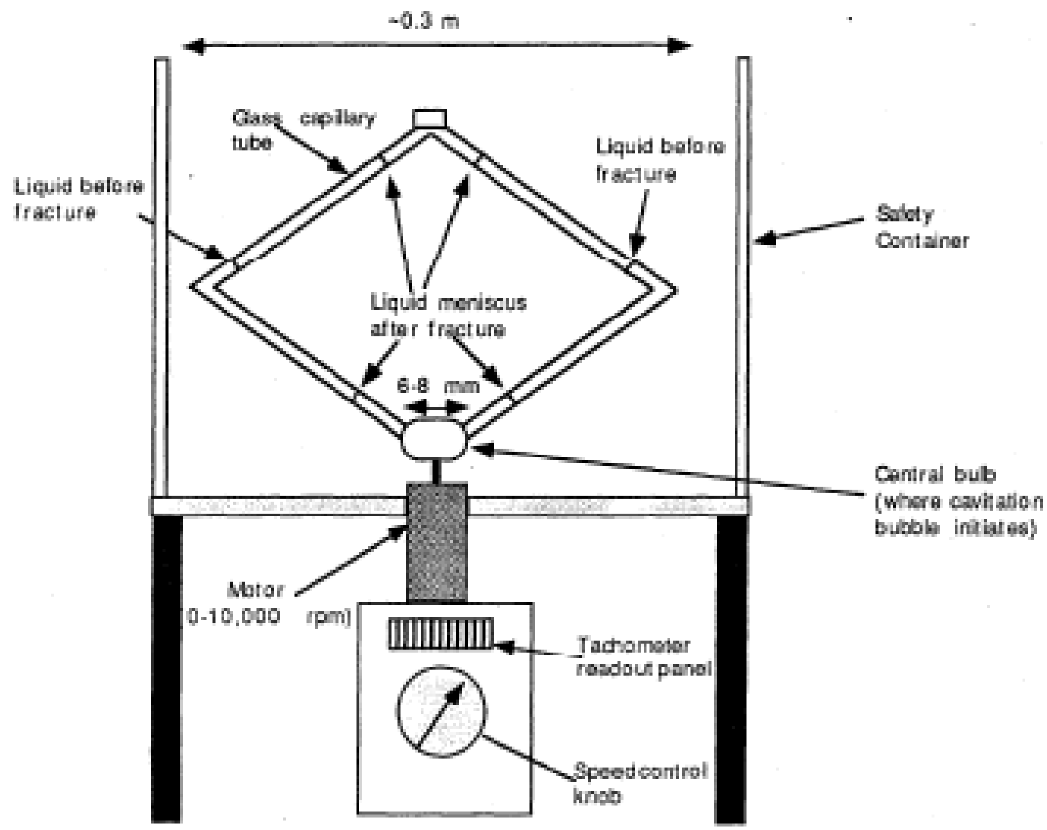
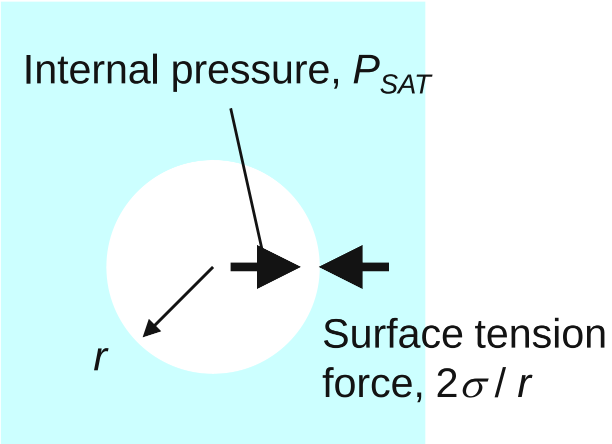


Figure 1: Schematic sketch of fluid cavitation threshold monitoring apparatus

Homogeneous nucleation boiling

- Bubble formation
  - In homogeneous nucleation (lack of nucleation sites), bubbles only exist in a liquid when there is a balance of surface tension forces against vapor pressure inside the bubble.
  - Therefore, initial bubble size must be extremely small.
  - For an extremely small bubble…



$\rightarrow$ Very large surface tension force,
$\rightarrow$ Very large vapor pressure in bubble,
$\rightarrow$ Temperature must be close to critical point ($\sigma \sim 0$ as $T \rightarrow T_c$)

T_c = 3223 K for Li

  - Homogeneous nucleation boiling reported when T>~0.9T_c *(laser ablation).*

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Summary

- A beam-on-target experiment using a 1 MeV, 20 kW e-beam was performed at ANL that showed stable operation of a windowless Li target in high vacuum.
  - Temporary background pressure rise of only ~ 0.3 mTorr.
  - Steady-state background pressure remained constant.
  - No boiling was observed.

- Simulating calculations show that the estimated peak temperature in Li in the experiment was ~900 K or 0.27 T_c.

- Observations and calculations support a model of homogeneous nucleation boiling in windowless targets that enables very high peak subsurface temperatures, without boiling.