PLEX SOURCE UPDATE

San Jose Feb 27th 2005

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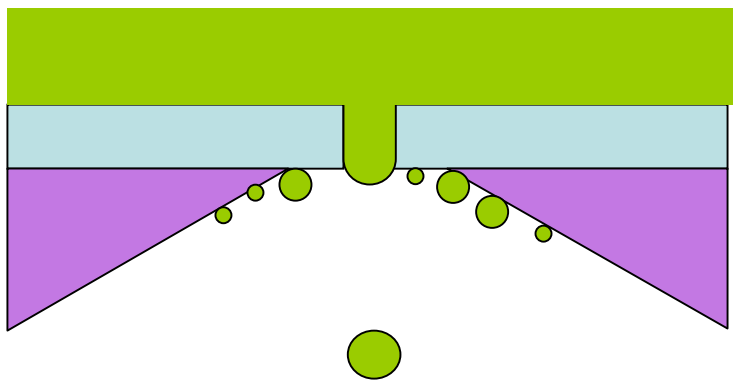
The Injection Pinch?

Paper 5751-63, EUV Source II, Thurs 3.30pm

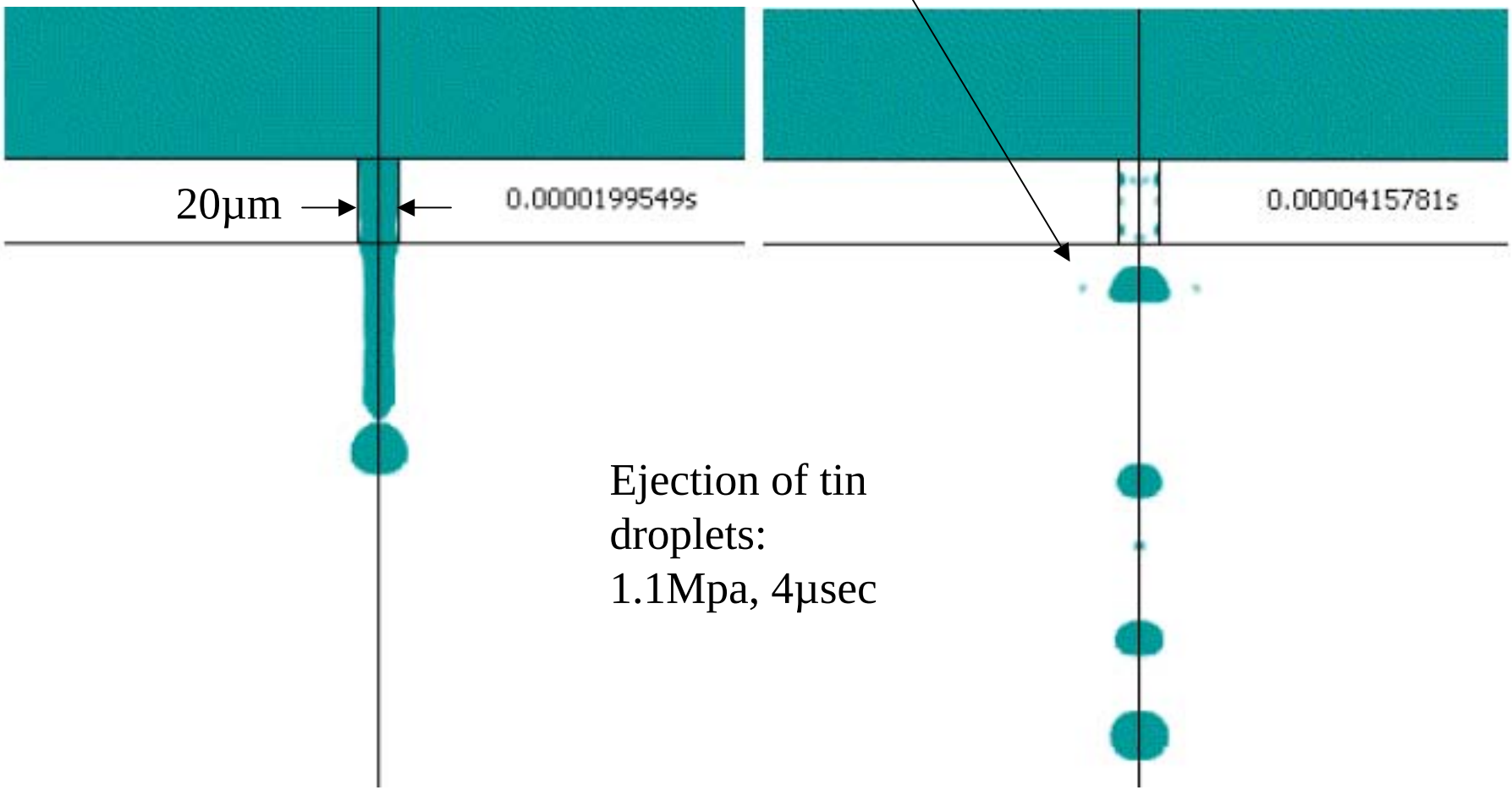
Represents a possible new method to introduce tin into the star pinch discharge, that is expected to yield a small plasma

But…

This horse fell at the first fence due to unreliability of droplet generation. After 10^4 - 10^5 pulses in the regime of interest there was a tin build-up outside the nozzle that blocked subsequent pulses



Tiny satellite droplets appear in simulation



Ejection of tin droplets:
1.1Mpa, 4µsec

Fluid simulation by Greg Nellis, U. Wisconsin

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We are returning to an equilibrium vapor pressure of metal in the star pinch, namely Lithium

Only 600C needed, vs 1450C for tin

Lithium system advantages:

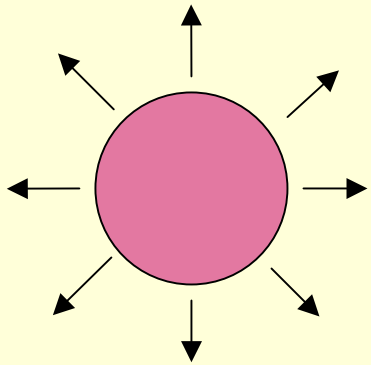
Most pure spectrum (in band)

Possible easy clean-up of collector optic (grazing incidence type)

Less destructive plasma gives much longer life

Li ion momentum 10x less than tin or xenon => barrier easier

Lithium plasma only produces low energy particles



IP (LiI) = 5.392 eV

IP (LiII) = 75.641 eV

LiIII = radiating species

Electron temp = 15eV = ion temp

Asymptotic ion energy = 126eV

Contrast with tin or xenon which have 1keV asymptotic energy

Consequently, Discharge Life is Extended with Lithium

Prior star pinch data with xenon showed sputtering life limit of 6×10^8 pulses (1mm erosion) by plasma exhaust particles

But, sputtering by lithium is very slight, removing main life issue for discharges

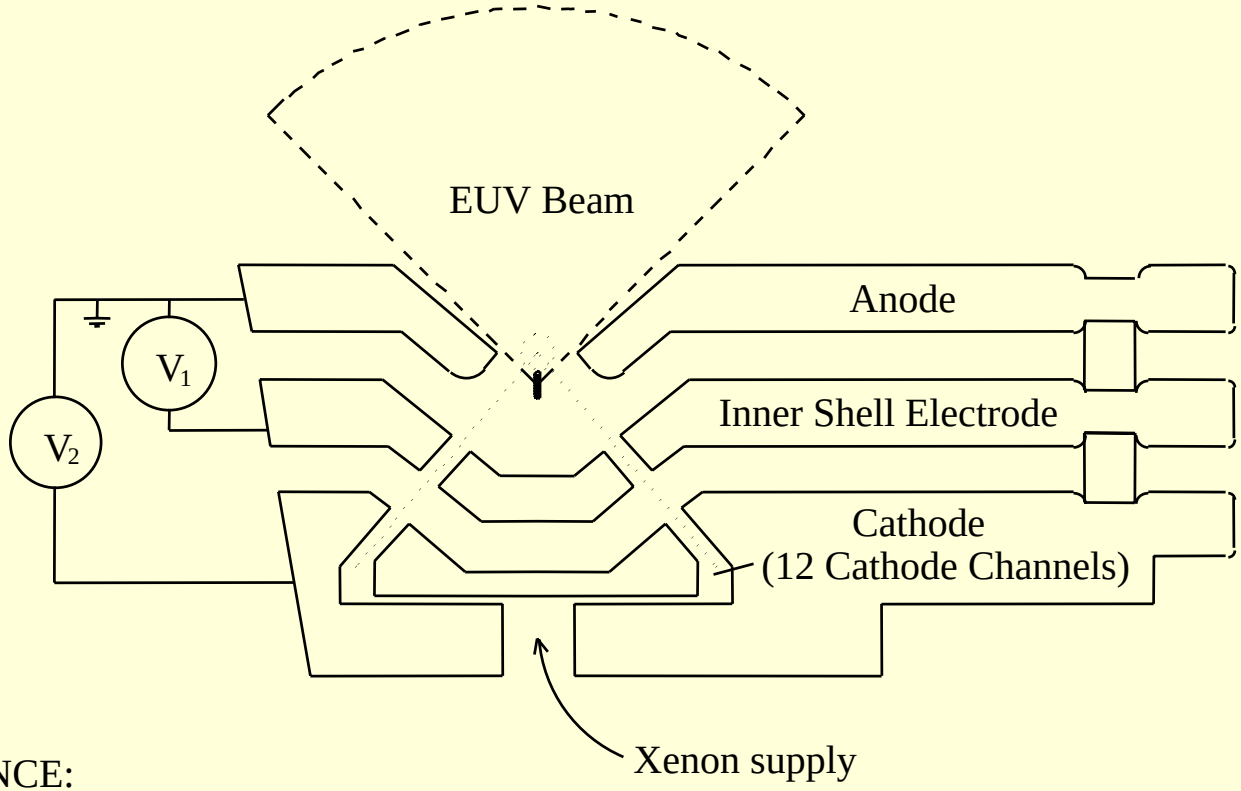
Physical sputtering threshold Li on Tungsten is approx. 150eV

J. P. Allain* estimates $S < 1 \times 10^{-4}$ at 100eV and 0.0112 at 200eV

At plasma exhaust 126eV, if $S = 1 \times 10^{-3}$ and considering a surface 5mm from the plasma, there are 2×10^{10} pulses to 1mm erosion

These estimates are being confirmed by experiments of Li on W in IMPACT by J. P. Allain et al.

Compact Lithium Star Pinch / Geometry Test with Xenon



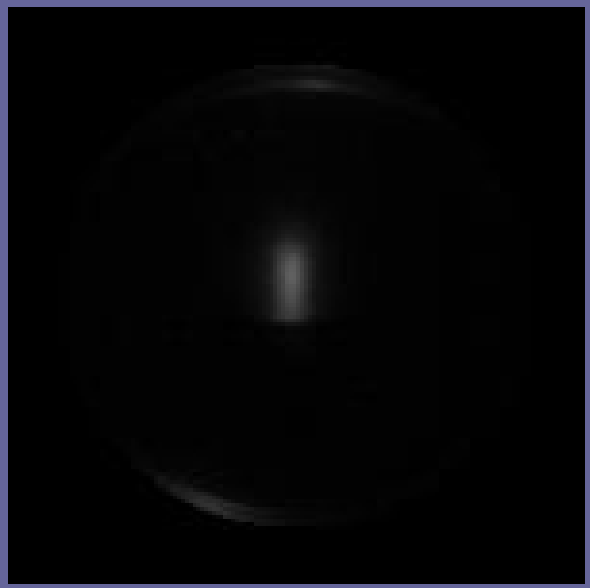
SEQUENCE:

Inner shell held negative 1kV (approx) running DC discharge

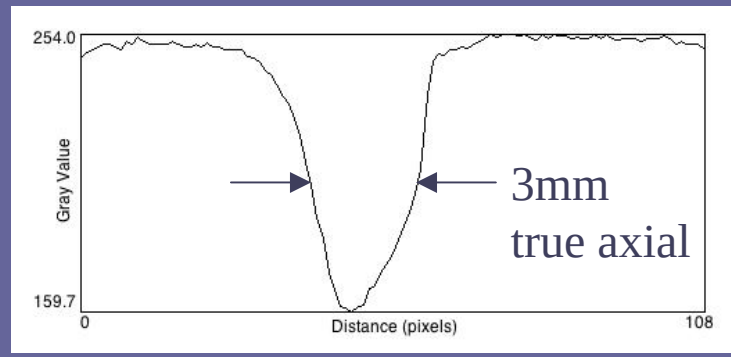
Inner shell pulsed -5kV for 500nsec

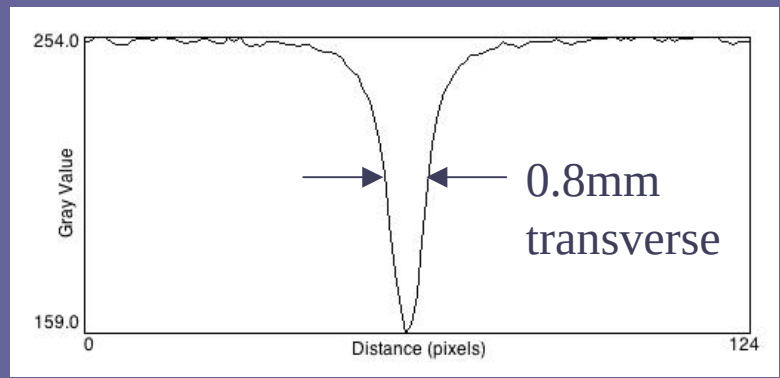
Cathode-anode circuit energized via solid state mag-switched pulser - drives pinch discharge

Compact Star Pinch 3.3kHz test, Xe



13.5nm image, 20 deg.





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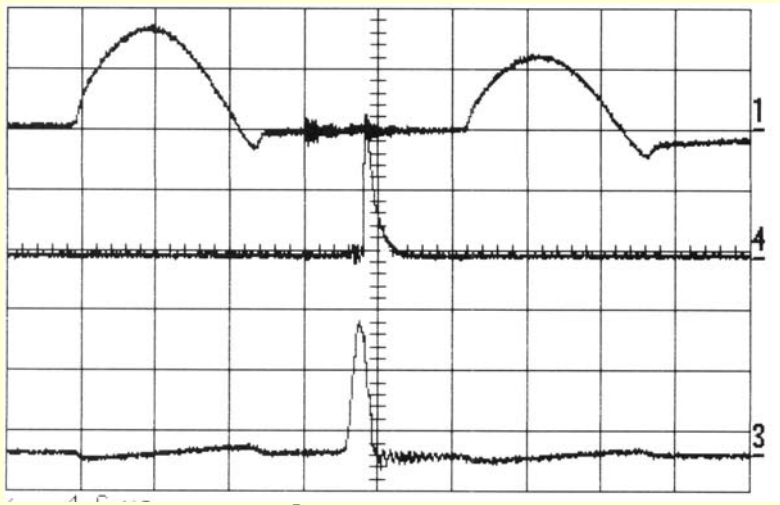
Compact Star Pinch at 3.3kHz with Xe



2 µsec/div

64% energy recovery,
7J dissipated in
plasma + electrodes

4.8mJ/sr/pulse, in band

50% in etendue (out of 3mm) --> 10W at IF

Xe performance in compact star pinch is 1.4x better than in prior large volume star pinch, because smaller plasma size

However, small plasma-wall distance only suitable for Li

Increase in output from Xe --> Li depends on

Li efficiency

Li plasma size

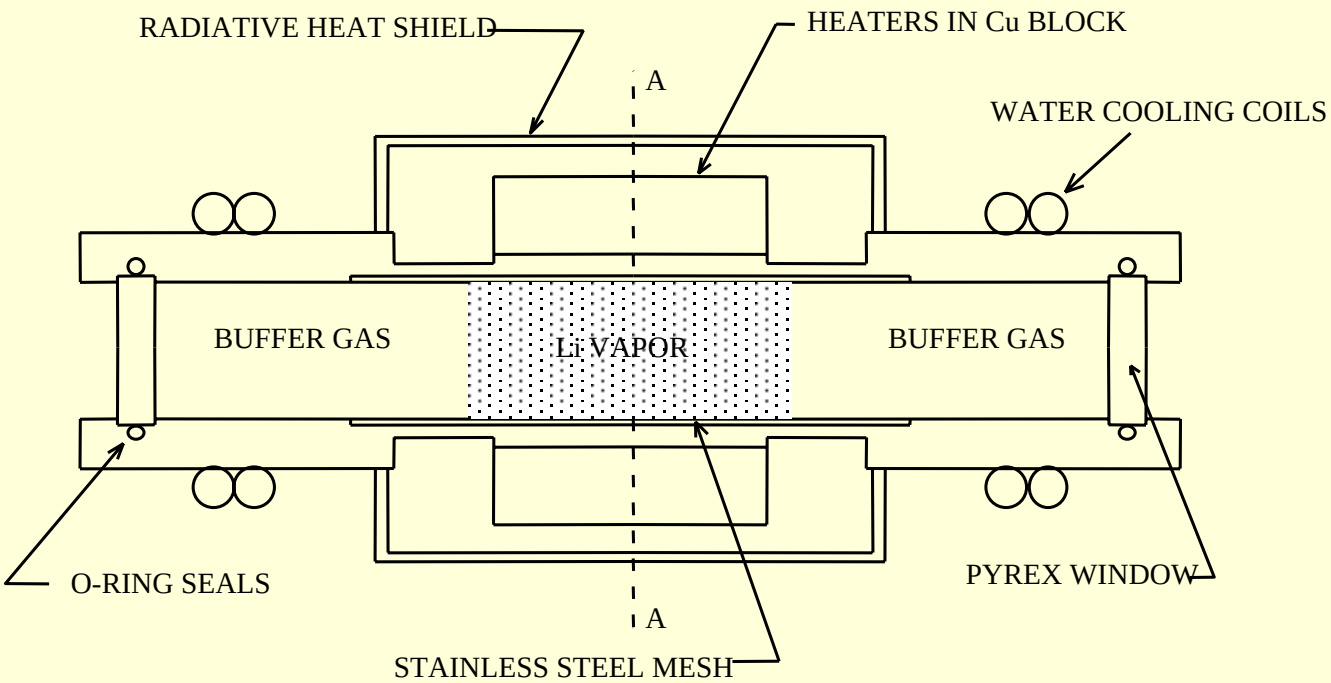
Dynamic match between plasma and circuit

For 1.5% Li efficiency we could achieve 30W at IF

For 2.5% Li efficiency, 50W, in this experiment.

Lithium Vapor Pressure - Use of Heat Pipe

$$VP_{Li}(Pa) = 3\times10^{-5}\exp(1.5\times10^{-2}T) \qquad \text{For } T < 1300\text{K}$$



Need 620C for Star Pinch typical operating point of 20 Pa

No problem in a heat pipe
(see Boyd et al, Optics Lett. 5, 117-119(1980))

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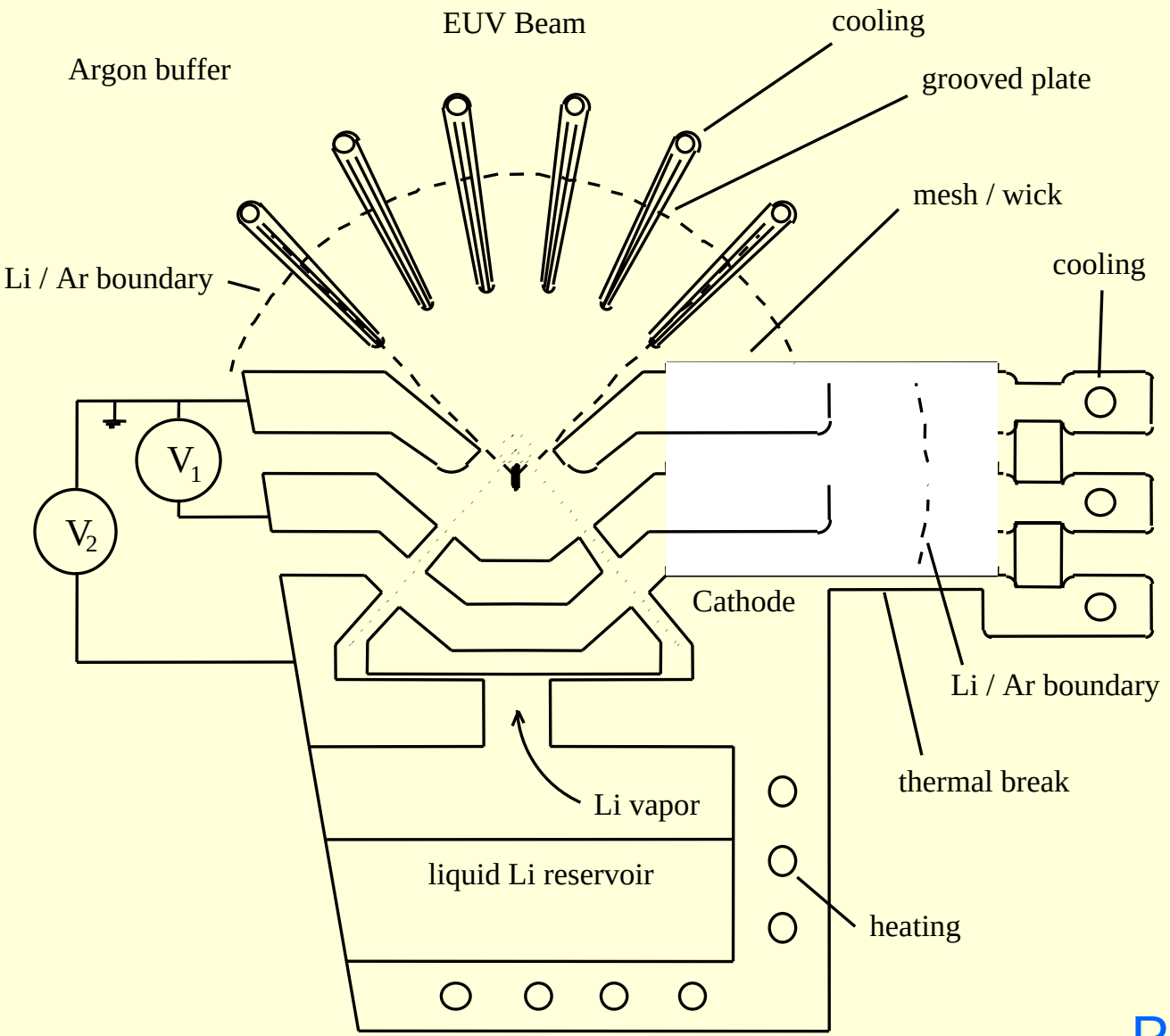
3-D Heat Pipe Li EUV Source



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Thermal Management (30kW)

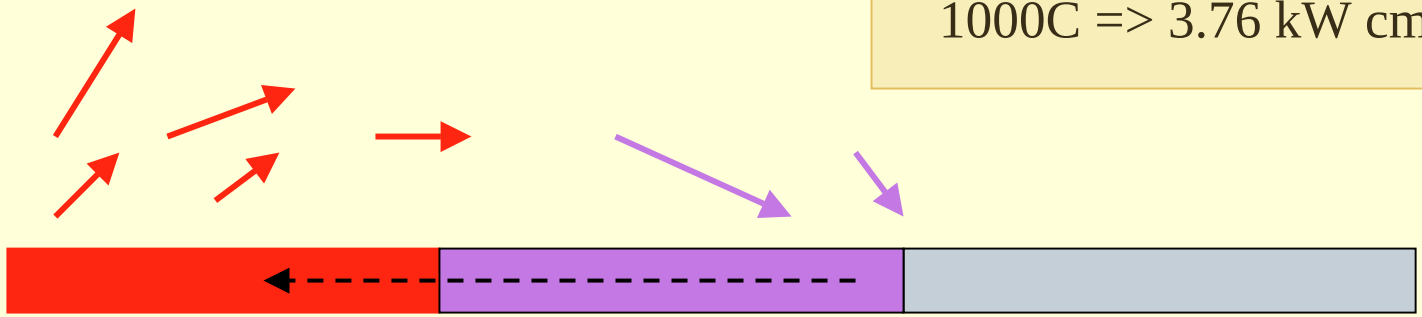
Li evaporation rate $G = 3.5 \times 10^{-8} \dfrac{\exp\left(1.5 \times 10^{-2} T\right)}{\sqrt{T}}$ g cm^{-2} sec^{-2}

Latent heat of evaporation = 19.6 kJ g^{-1}

800 C => 204W cm^{-2}

900 C => 877 W cm^{-2}

1000C => 3.76 kW cm^{-2}



Heat removal by Li itself!

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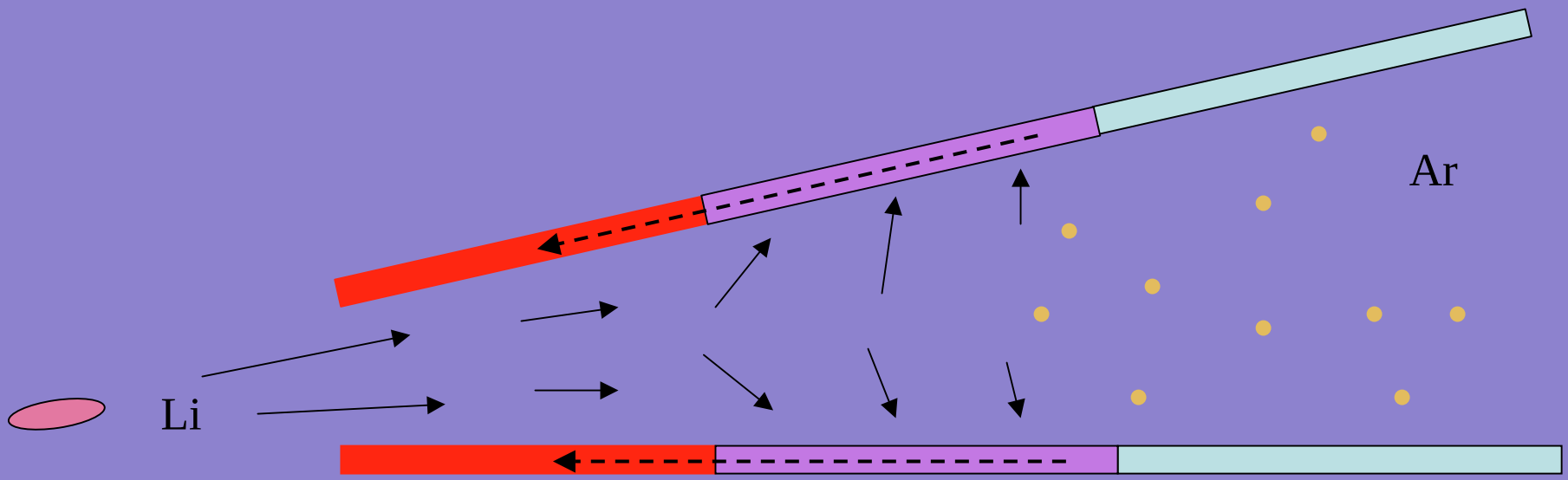
The heat pipe is a “debris” barrier!

Problem is measured by momentum per ion $\sqrt{2E_iM_i}$

Li momentum per ion = 0.086 x Sn momentum per ion



Li is recycled!

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Beyond 115W

Li has high ion acoustic velocity, so 20kHz possible

20kHz x 3J = 60kW requires cathode at 20mm to carry heat but anode can remain at 5mm and plasma stays compact

Anode life >$2x10^{10}$ pulses

Cathode life $7x10^{9}$, but extends when Li feed protects surface

Power at 60kW could exceed 200W at the IF

Summary

Injection pinch abandoned because droplet generation unreliable

Simple design of star pinch prototyped for use with metal vapor

Lithium chosen over tin for many reasons

Lithium star pinch projects to HVM

Work supported in part by DARPA/MTO