Status of the Lithium EUV Source and HVM Prospects

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Abstract

The 13.5nm emission line of hydrogen-like lithium (Li^{2+}) has been excited with more than 10% efficiency in an electric discharge and promises ultimately about 30% efficiency. Lithium has low absorption at 13.5nm and is a light atom that has good thermal transport to carry heat away from the discharge. It is no surprise therefore that lithium has been the subject of several research programs aimed at producing an HVM class source. In this talk we analyze the difficulties encountered in prior lithium work and discuss the solutions we have adopted in order to make a high power source. Primarily, lithium containment and recirculation have been achieved within a heat pipe that doubles as a pulsed discharge. A movie of an operating lithium source will illustrate the process. We have demonstrated a compact lithium EUV "lamp" that emits energetic 13.5nm pulses at 1kHz from a pinch of diameter 800microns and length 2mm. With a 3sterad collector using 50% of the pinch length as its source, we project that with the current demonstration 20W will be available from a single lamp at an intermediate focus in narrow line light at 13.5nm. Development is at an early stage so further power increase is strongly anticipated. Multiplexing of lithium lamps with a grazing incidence mirror at 1kHz rotation frequency provides a direct, low risk development path to powers of several hundred watts delivered at a repetition frequency of the order of 10kHz. Because each lamp is relatively very simple and multiples of a stripped-down nested collector design may be used, the economics of multiplexing should be favorable. We conclude with an estimate of the effort and time needed to bring this new EUV source to industrial readiness for HVM.

Contents of Presentation

The Lithium EUV lamp is now a viable choice for HVM

Highly efficient

Spectrally pure

Re-circulation and no “debris”

Small equipment

Multiplexing projected to >> 200W

Engineering path well-defined

Lithium has fundamental "physics" advantages over tin

	Lithium	Tin
EUV (13.5nm) absorption cross section	2.1×10^{-18} cm^2	1.8×10^{-17} cm^2
EUV discharge production efficiency into 2π sr	>30% (>10% achieved)	3%
Spectral purity	single line	substantial out-of-band
"Debris" management	solved via heat pipe	complex and inefficient
Exhaust ion energy	100 eV	2 keV
Power scaling	multiplexed simple lamps @ N x 1kHz	single high power source plasma @ MkHz
Thermal transport	excellent	poor

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Engineering Path to >200W Li Source for HVM

Scientific proof of principle ← 2010

2,000sec continuous 400Hz ← We are here (5 -10W IF)
(single source - can be multiplexed to much higher)

10,000sec continuous 1kHz ← 1-2 years away

Days continuous 1kHz multiplexed to >200W IF ← 3 years away

Note, "debris" problem already solved

Lithium Fundamentals (1)

Hydrogen-like lithium (Li^{2+}) has a “resonance” transition at **13.5 nm** which is the analog of the hydrogen Lyman alpha transition at 121.6 nm

Just like other resonance transitions (Na, Hg, H) the Lithium 13.5 nm transition can be pumped with >80% efficiency in a plasma discharge.

Lithium is therefore perfectly suited for a 13.5 nm lamp

Lithium Fundamentals (2)

Hydrogen-like lithium (Li^{2+}) is created easily from neutral lithium in a fairly low-temperature plasma (15eV)

In the temperature range 8 - 20eV, Li^{2+} is dominant

The energy needed to create one Li^{2+} ion is only 81eV, which is less than the 13.5 nm photon energy of 91.8eV

Li^{2+} is dominant species for electron temperature range 8 - 20eV

LOCH *et al.* PHYSICAL REVIEW E **69**, 066405 (2004)

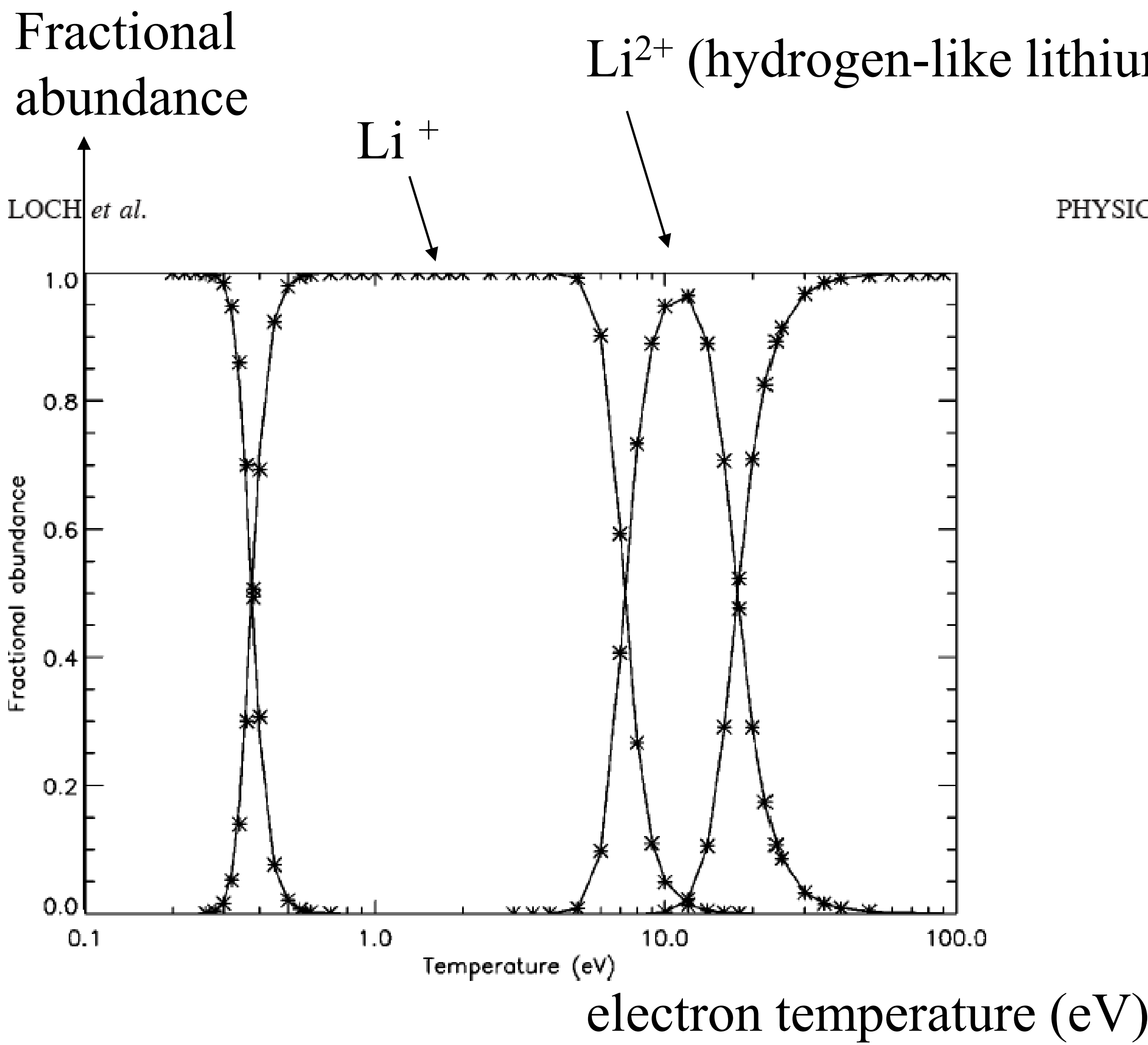

FIG. 1. Ionization balance at $N_e = 10^{14}$ cm^{-3} for the ADAS-1 and LANL-1 calculations. The solid curve shows the ADAS-1 results and the stars show the LANL-1 results. Note that the peak at lowest temperature corresponds to neutral lithium, the one centered at 2 eV is the He-like stage, the one at about 10 eV is the H-like stage, and the last peak is the bare nucleus.

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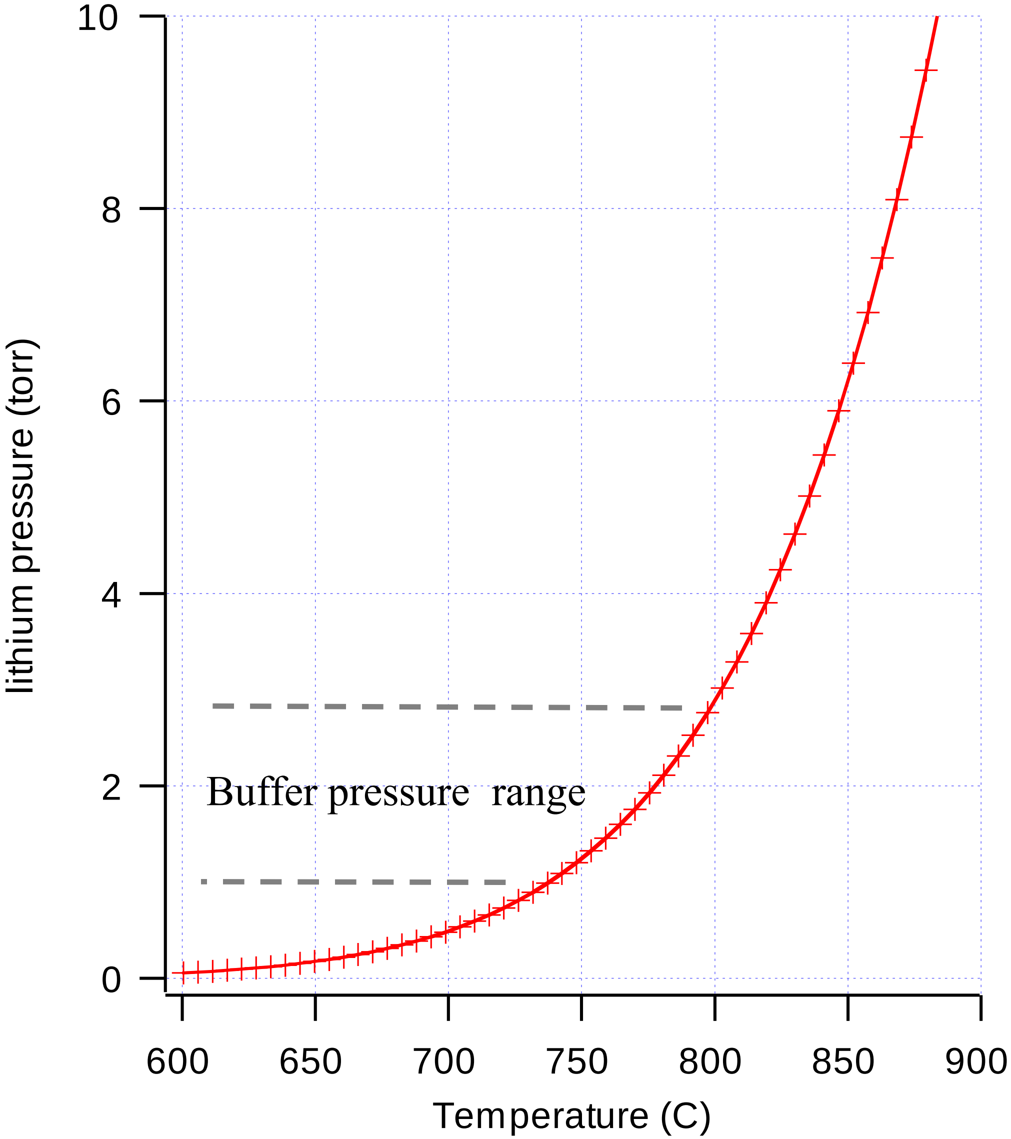
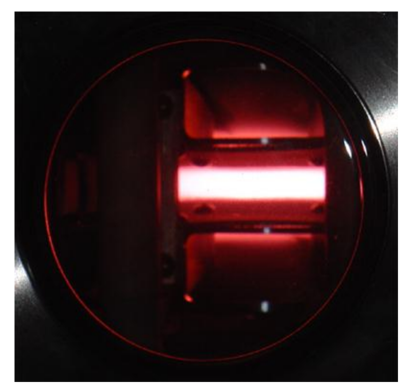
Lithium Fundamentals (3)



Lithium has a high vapor pressure at modest temperature

A lithium discharge apparatus runs at 750C, 'orange' heat



Lithium Fundamentals (4)

Lithium at 700C, and above, can be contained almost indefinitely in vessels comprising molybdenum, 304 stainless steel and several other metals
e.g. > 25,000 hrs at 1400C in Mo heat pipe tests

(M. A. Merrigan "Heat Pipe Technology Issues"Los Alamos Natl Lab Rept LA-UR-84-1238)

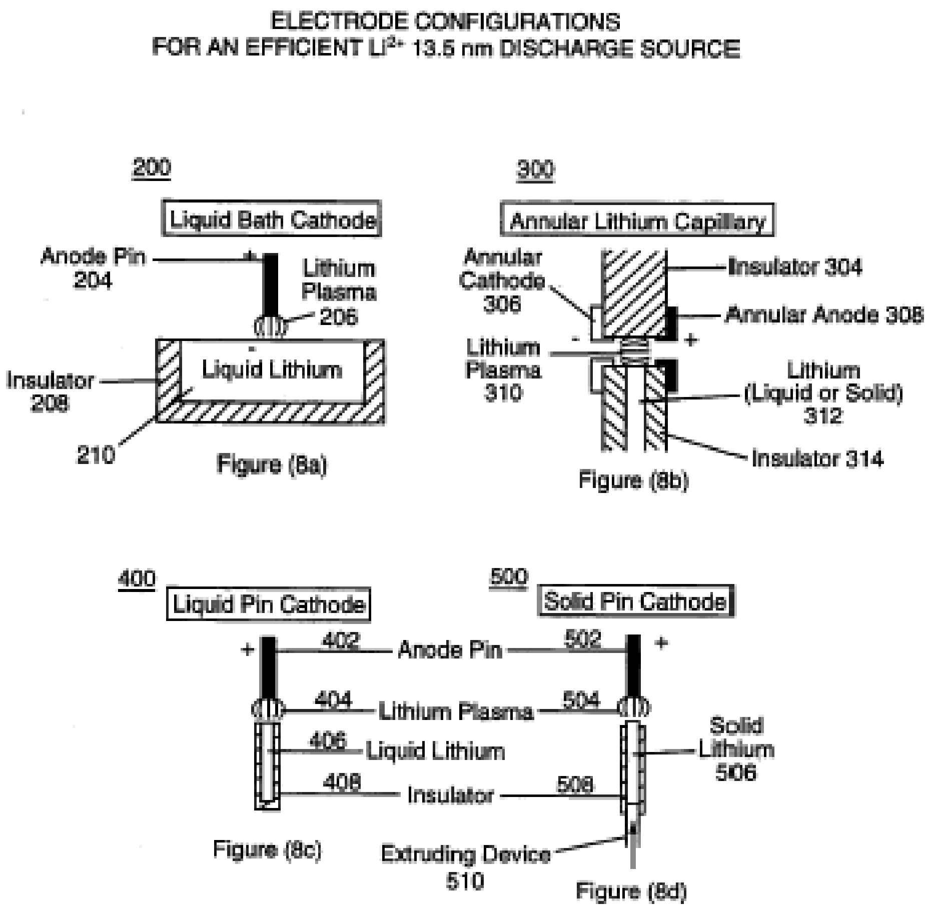
BUT…

Hot lithium reacts with all insulators

This has been a killer problem in the conventional discharge configurations employed by several groups in the last 20 years

Conventional discharge technology could not be transferred to lithium (1)

For example, arc-like discharge proposed by Silfvast needed an insulator in contact with hot lithium, and did not provide for lithium control



Silfvast 5,499,282 (1996)

There is no insulator that can withstand hot lithium

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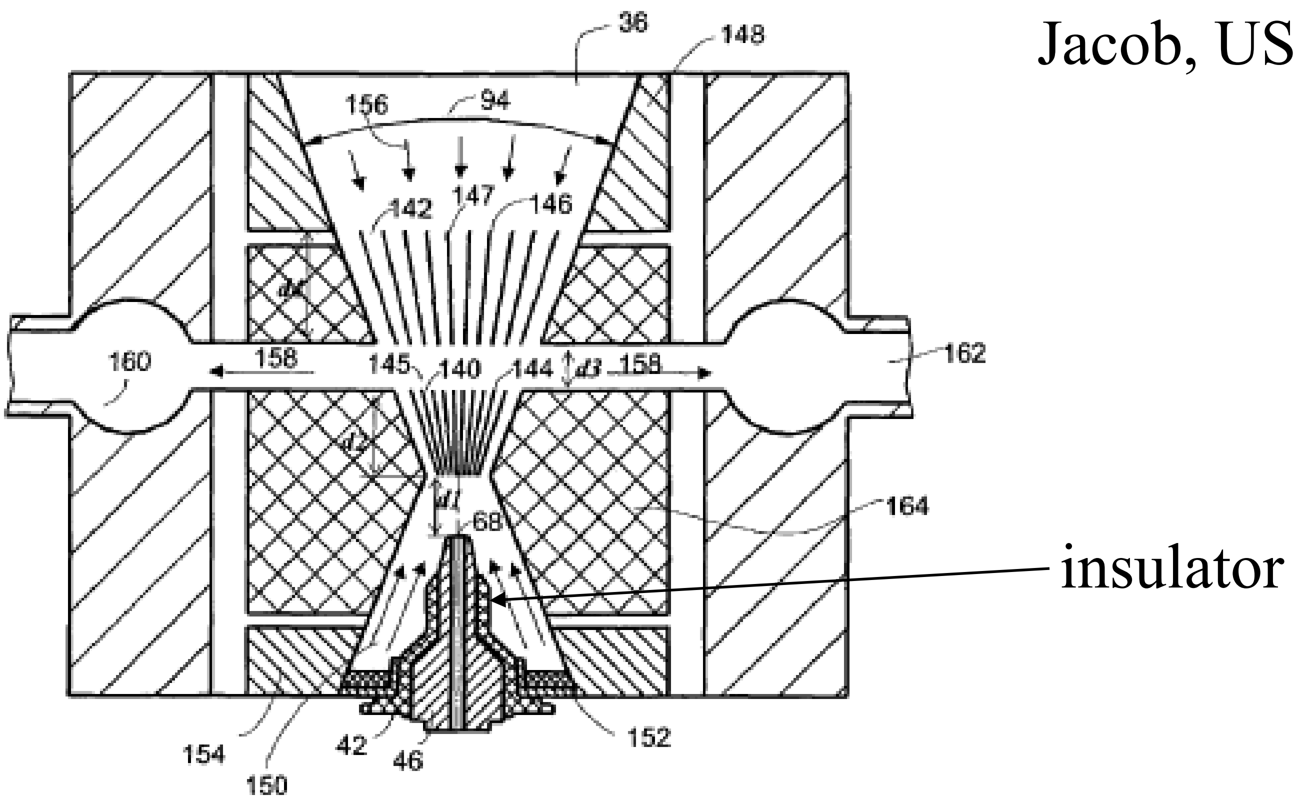
Conventional discharge technology could not be transferred to lithium (2)

The dense plasma focus proposed by Jacob et al. also required a hot insulator in contact with lithium, although here lithium was trapped in a debris collector, to be re-circulated via a gas stream

Jacob, US 7,002,168 (2006)



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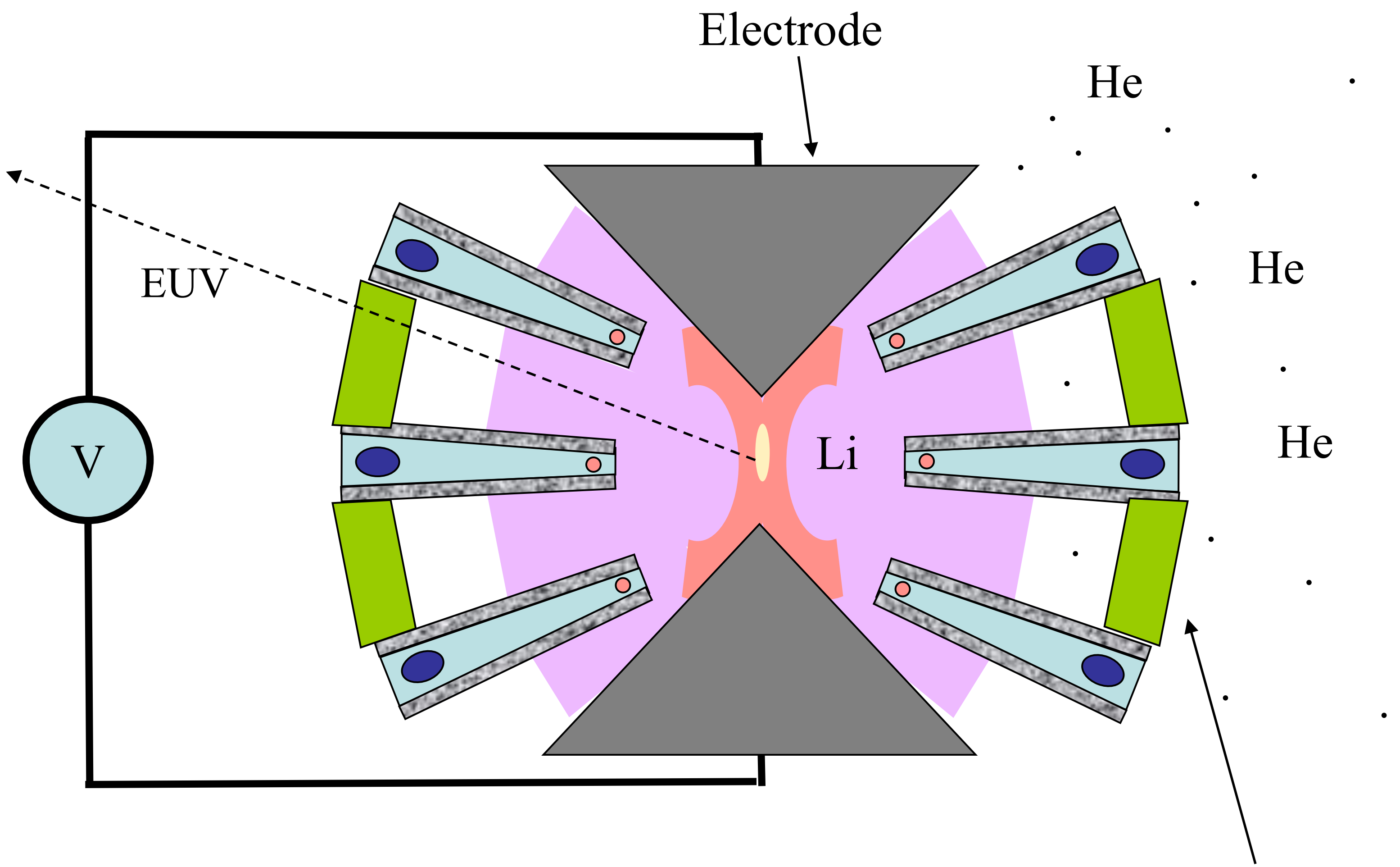
PLEX wide angle heat pipe avoids lithium contact with insulators



Insulator rods run cool and are protected by helium buffer from lithium

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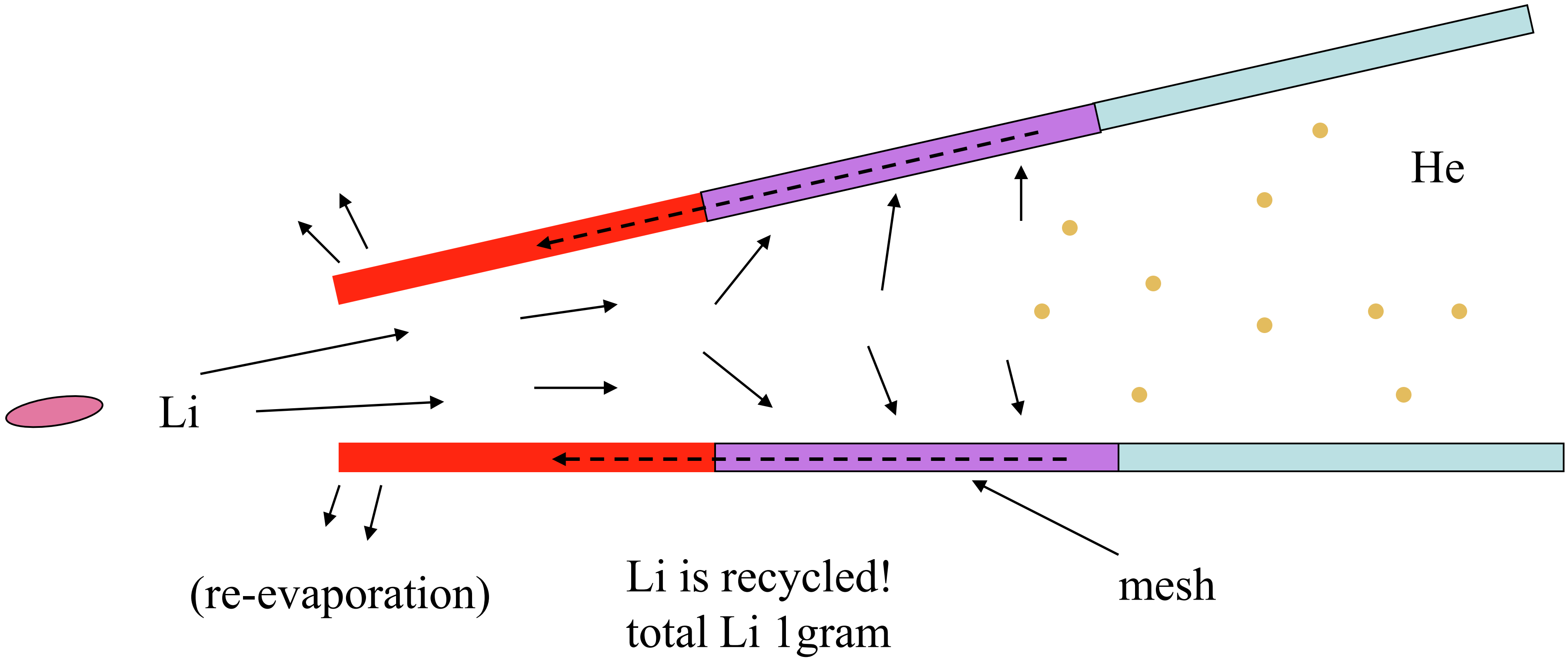
The heat pipe <u>is</u> a "debris" barrier!

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

Li momentum per ion = 0.086 x Sn momentum per ion.



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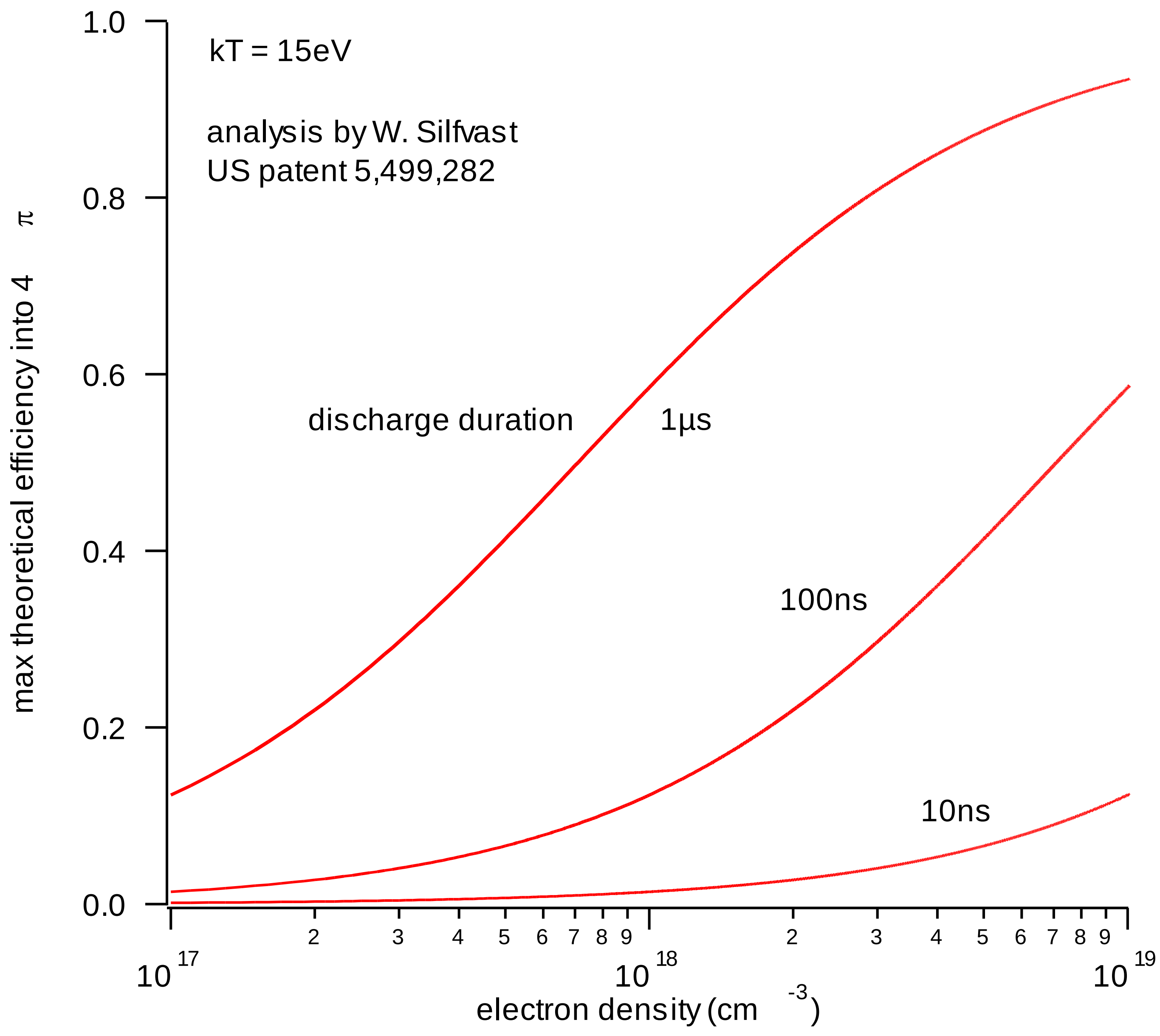
"Debris" problem solved:

1. Li disposition after operation is all within 6cm of plasma
2. Li^{+} ions are stopped within 3cm of plasma (B field present)
3. EUV-sensitive diode positioned at 25cm from plasma shows negligible degradation in cumulative 10 hours operation
4. Li re-circulation is established via condensation/reflux
5. Pure helium buffer provides interface with collector optic

Our chamber window has remained crystal clear for 2 years with no cleaning.

Efficiency of 13.5nm production approaches 100%



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Silfvast simple discussion of efficiency/output energy

Process $Li^{2+} ground + e^{-}(fast) \rightarrow Li^{2+} resonance + e^{-}(slow)$

$$Li^{2+} resonance \rightarrow Li^{2+} ground + h\nu(13.5nm)$$

Resonance level population in typical 15eV plasma $n(2) = 3x10^{-23}\, n_e^{\,2}$

13.5nm energy radiated per pulse $E_r = n(2)VA_{21}\, h\nu_{21}\Delta\tau_P$

Plasma energy investment $$E_{IN} = n_e V \frac{3}{2}kT + N^{2+}V\frac{3}{2}kT + N^{2+}VE_I$$

Efficiency $$\varepsilon_{MAX} = \frac{E_r}{E_r + E_{IN}}$$

V = volume of plasma, Δt_P = pulse duration, $E_I = 81eV$

What are the necessary discharge conditions?

a) High electron density, ideally $>10^{18}$ cm^{-3}

b) Long pulse duration, ideally > 1 μsec

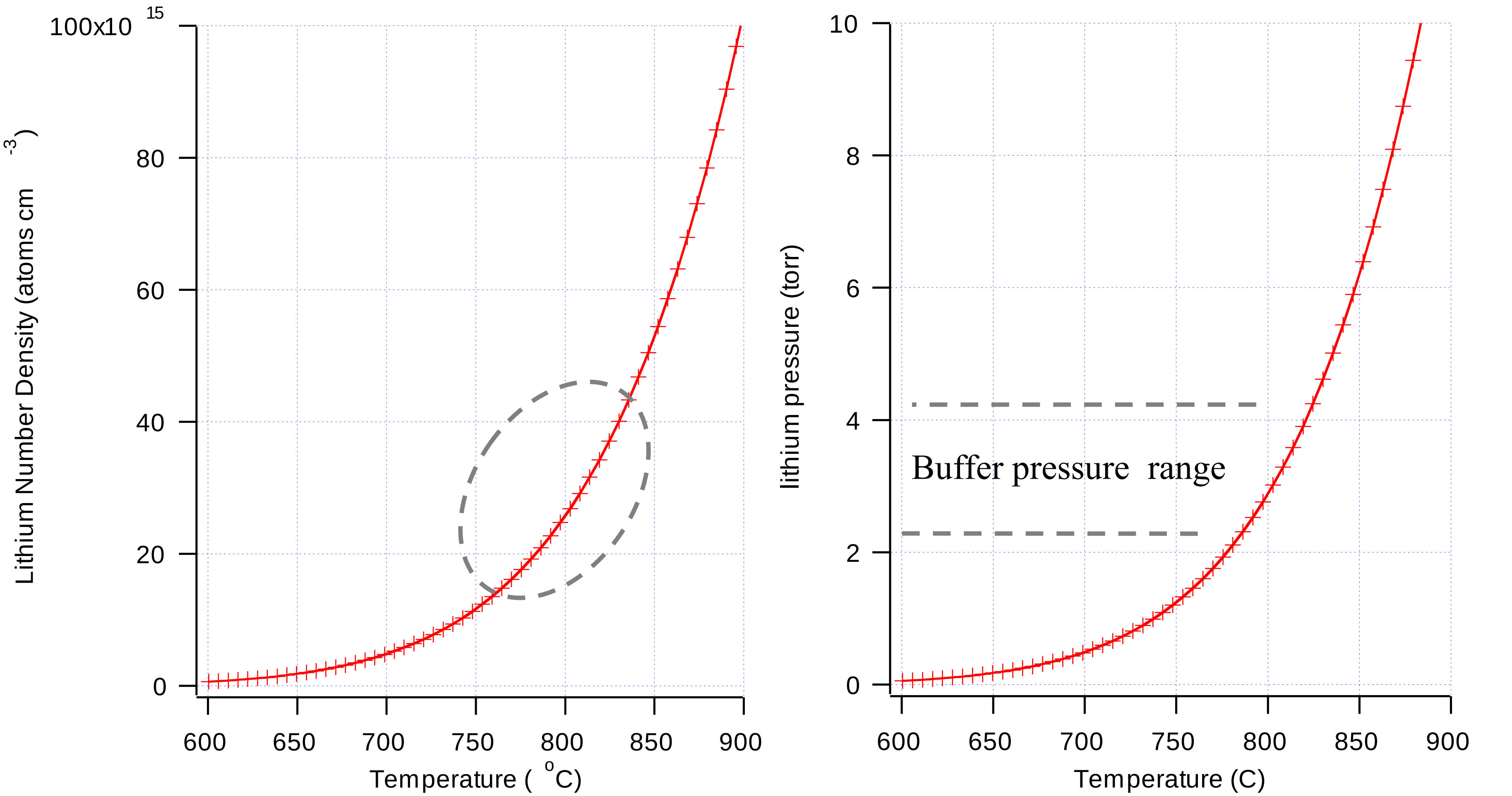
(note that laser-plasma limit of about 10 nsec is inadequate)

For very high efficiency the plasma density should be 10^{19}cm^{-3}

Available lithium density is in the range 10^{16} -> 10^{17} cm^{-3}

Compression in pinch by 100 - 1,000 times is necessary

Temperature sets resting Li density



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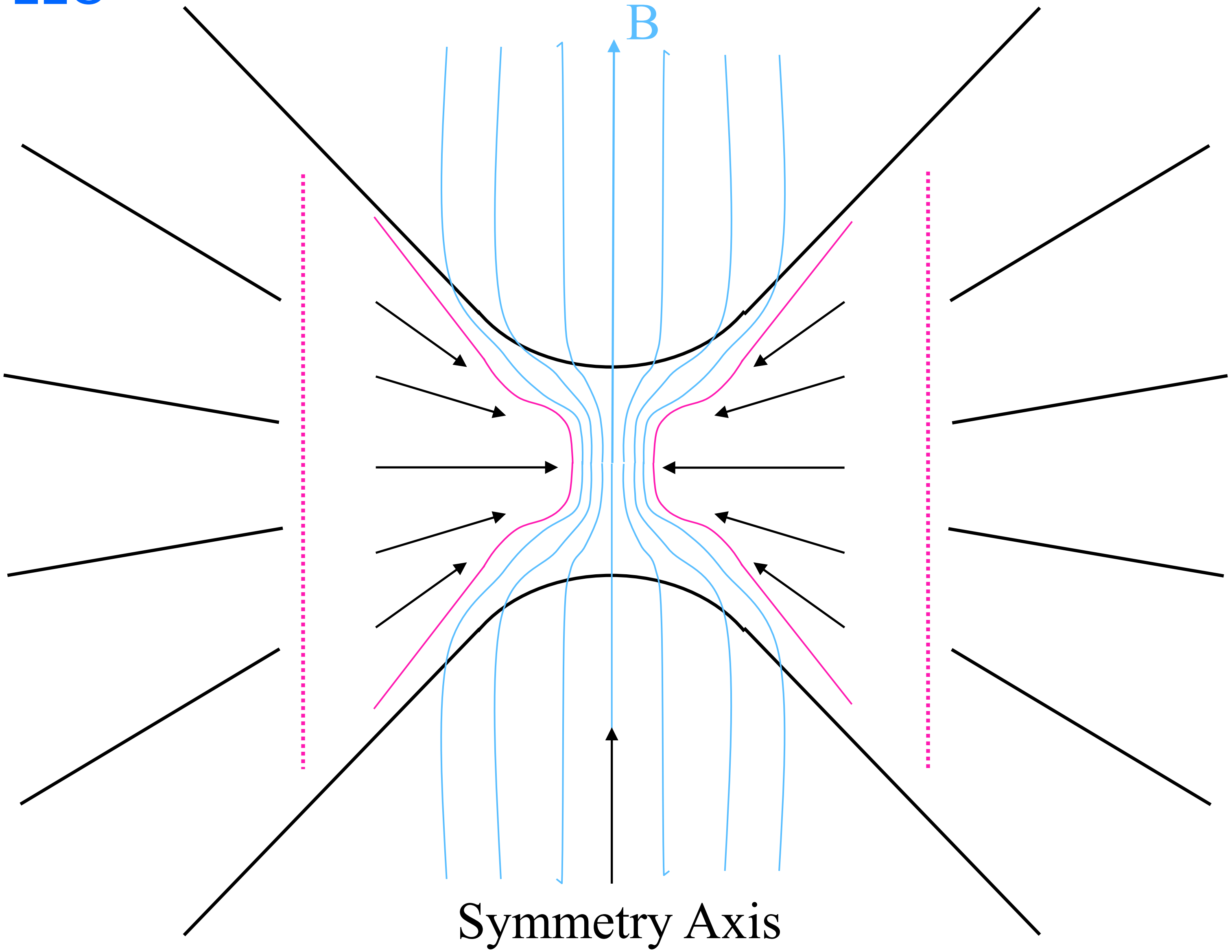

3-D compression pulse guided by electrodes --> high density

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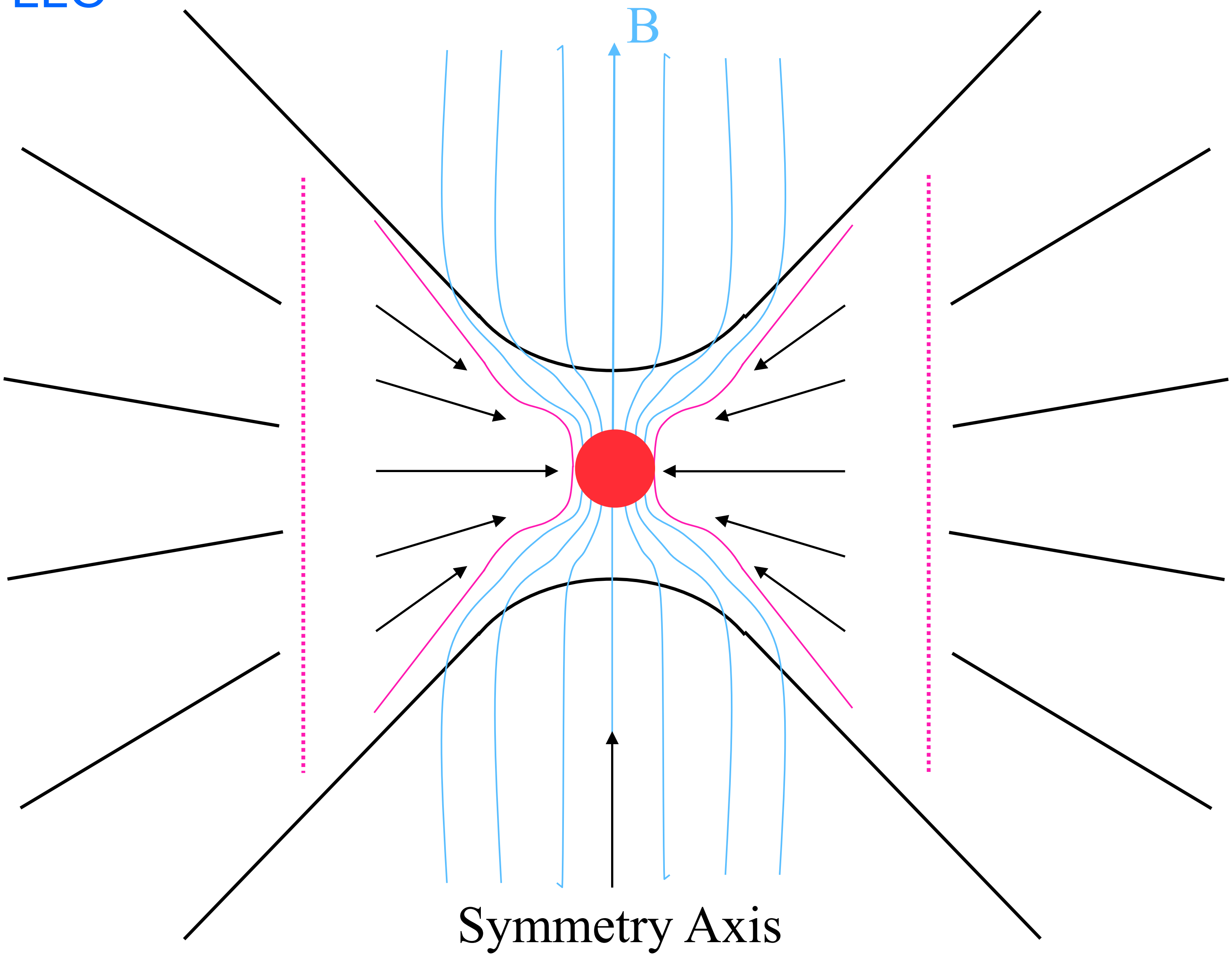
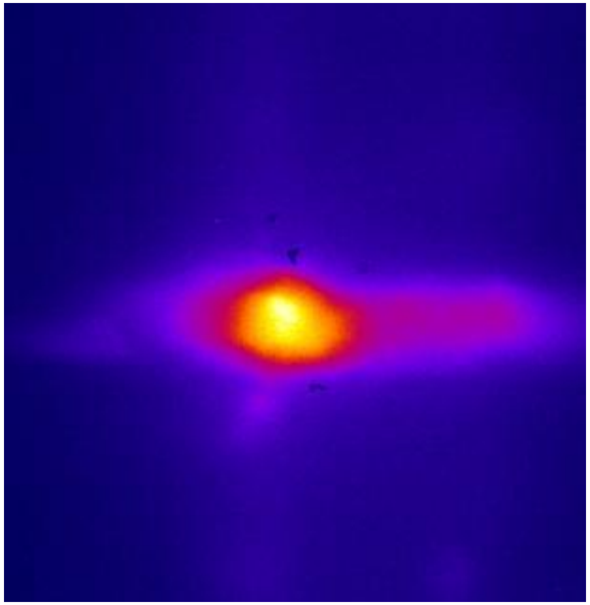


Plasma compresses magnetic field, protecting electrodes

Lithium Source Spot Size is Small



13.5nm image:

Superposition of 80 pulses at 400Hz

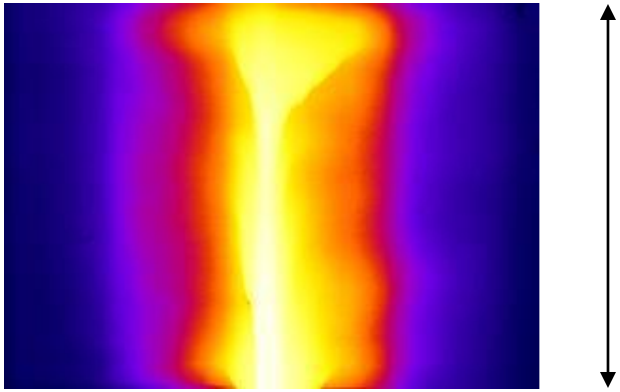
Spot size 800µm FWHM

30mJ/pulse

Higher energy Lithium Pinch Data

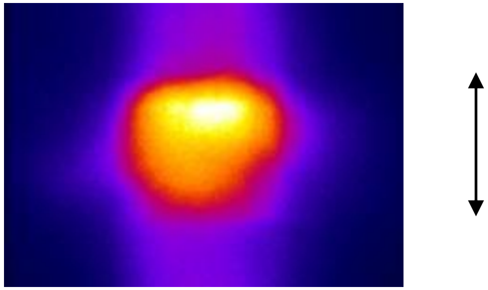
Plasma size may be selected via geometry and Li density

1kHz, 50 pulses
superimposed



Pinch length 4.5mm
160mJ/mm/pulse

200Hz, 20 pulses
superimposed



Pinch length 1.5mm
70mJ/mm/pulse

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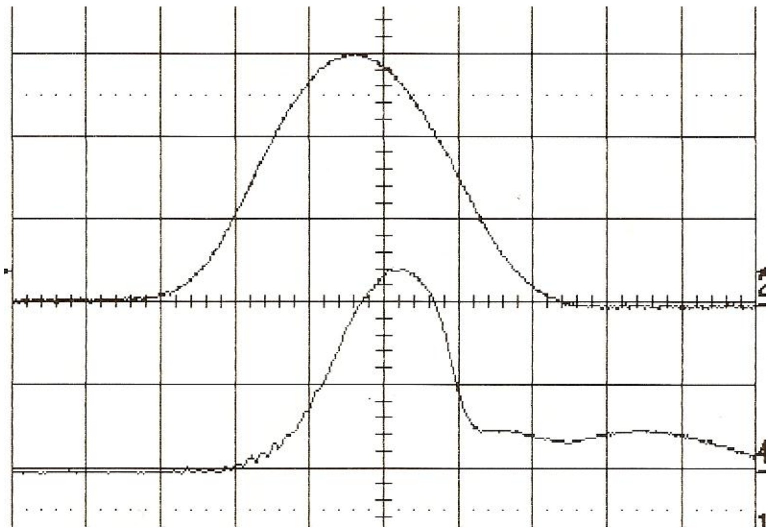
EUV pulse duration >1µsec

Diode: SXUV 100 Si/Zr (IRD) Pinch: 200Hz, 70mJ/mm
Diode "window" approx. 12nm (decreasing) to 20nm

Pinch current
(arb. units)



EUV signal

Time (500 nsec/div)

Diode response < 50nsec, EUV "tail" is a saturation effect

The lithium Z pinch has demonstrated >10% efficiency (2π sr, electrical to 13.5nm).

EUV emission is quasi-steady for 1µsec

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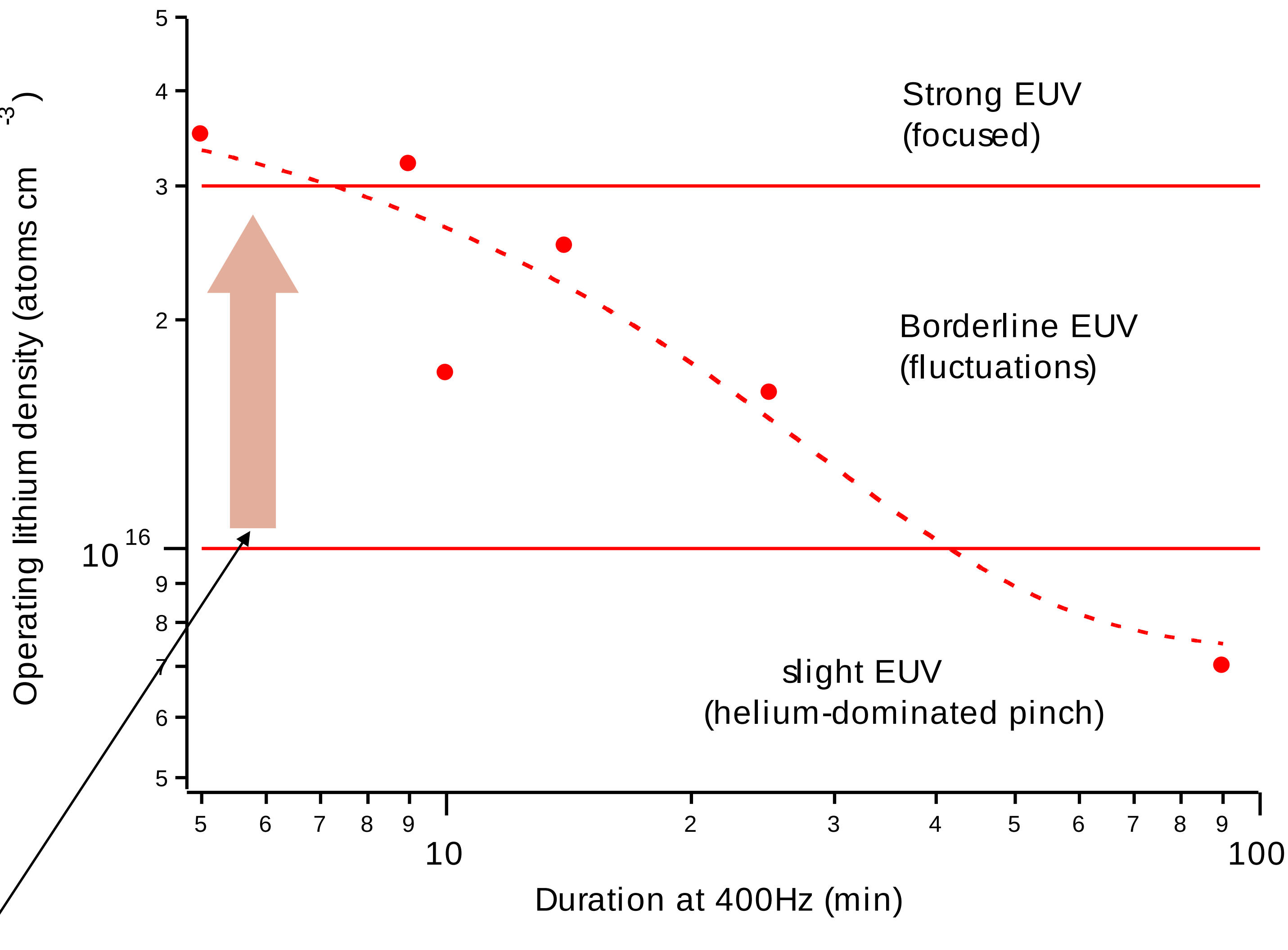
Lithium atom density measurement versus run duration



"bootstrap" effect: EUV radiation heats device to give increased Li

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Technical Summary

1. Present limit on run duration is poor vacuum (10^{-4} torr) causing lithium reactions

⇒ needs stepper-quality vacuum

2. Operating on lower bound of successful lithium density

⇒ improve heater performance

3. Electrode demonstrated to >10^7 pulses at 400Hz

=> target 10^9 (at 1kHz) for manufacturing use

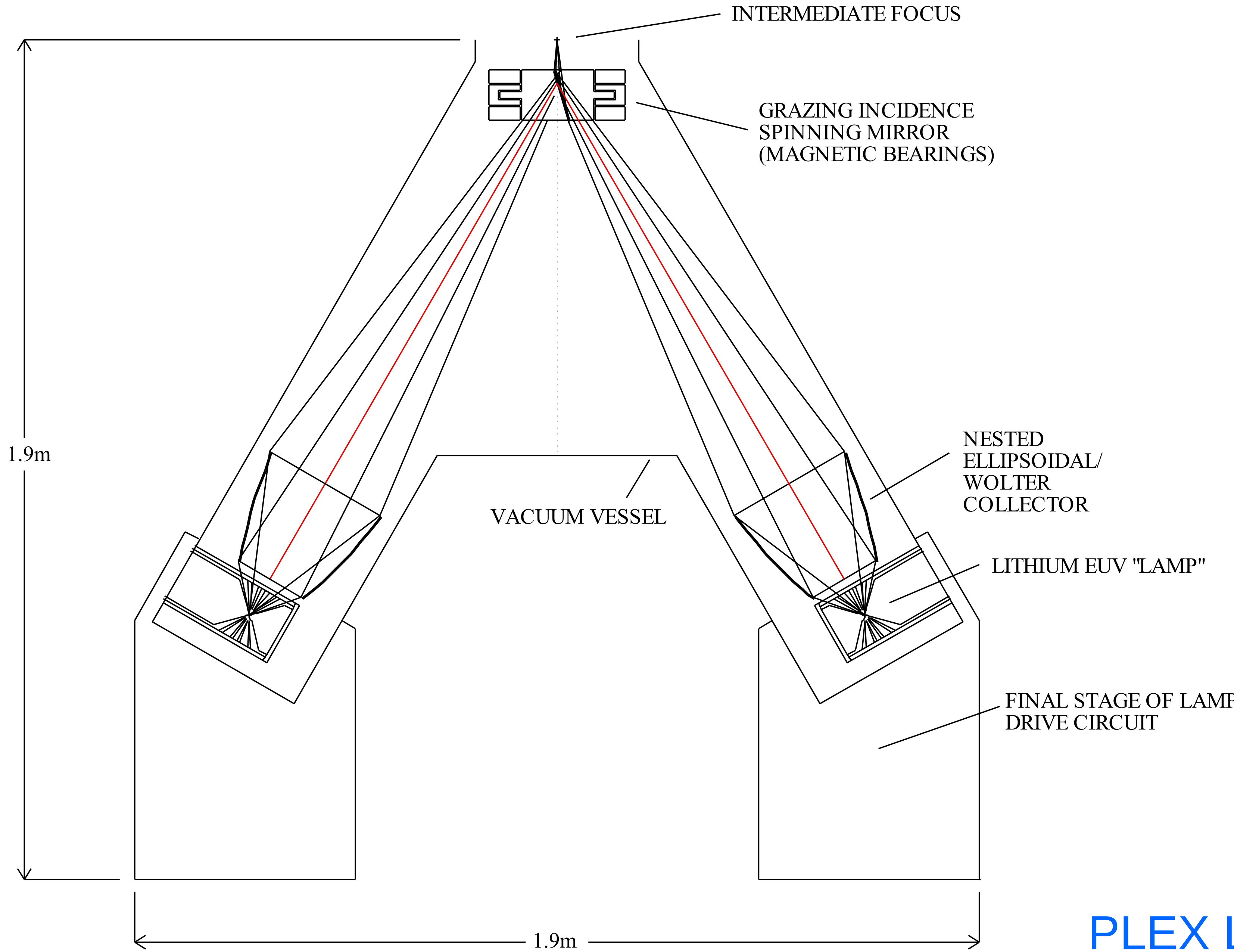
Multiplexing for HVM

Because the lithium lamp is compact and relatively simple it can be economically multiplexed to reach much higher HVM power

In contrast, the individual tin sources are very complex and highly stressed in order to generate the full EUV needs at a single plasma location

The 1kHz frequency of a lithium lamp is compatible with combination via a rotating grazing incidence mirror into a single intermediate focus beam

SCHEMATIC OF MULTIPLEXED LITHIUM EUV SOURCE



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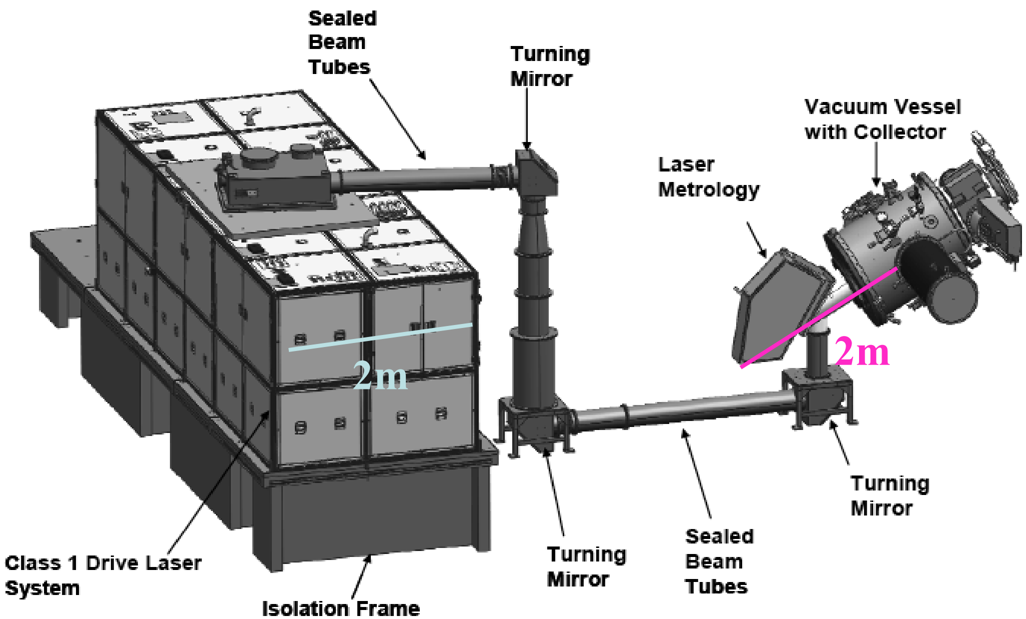
PLEX Lithium Source will be Quite Small Compared to LPP Tin Source

50W Tin EUV Source

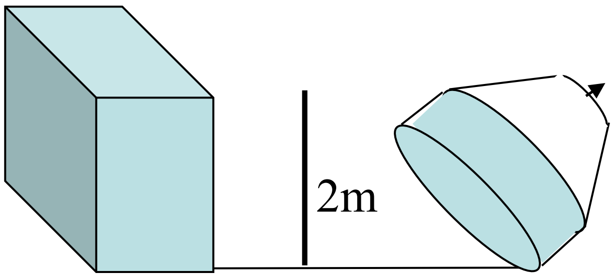
Laser
(6m L x 2m D x 3m H)



200W PLEX multiplexed Lithium EUV Source

Power Supplies
(4m L x 1m D x 2m H)

Source/condenser module
(2m Dia. x 2m L)



Scales approximately same; tin source power = 25% of lithium source power

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LHDP

The laser heated discharge plasma (LHDP) is an ancillary concept that should allow higher power from a single lamp, reducing the number of multiplexed lamps

Direct EUV heating of electrodes is lessened

US patent 8,269,199 Sept 18th 2012

Publication: "Laser-Heated discharge plasma EUV source" J. Phys. D Appl. Phys., 43, 105201 (2010).

Status: concept not yet tested due to success of direct discharge EUV production in lithium

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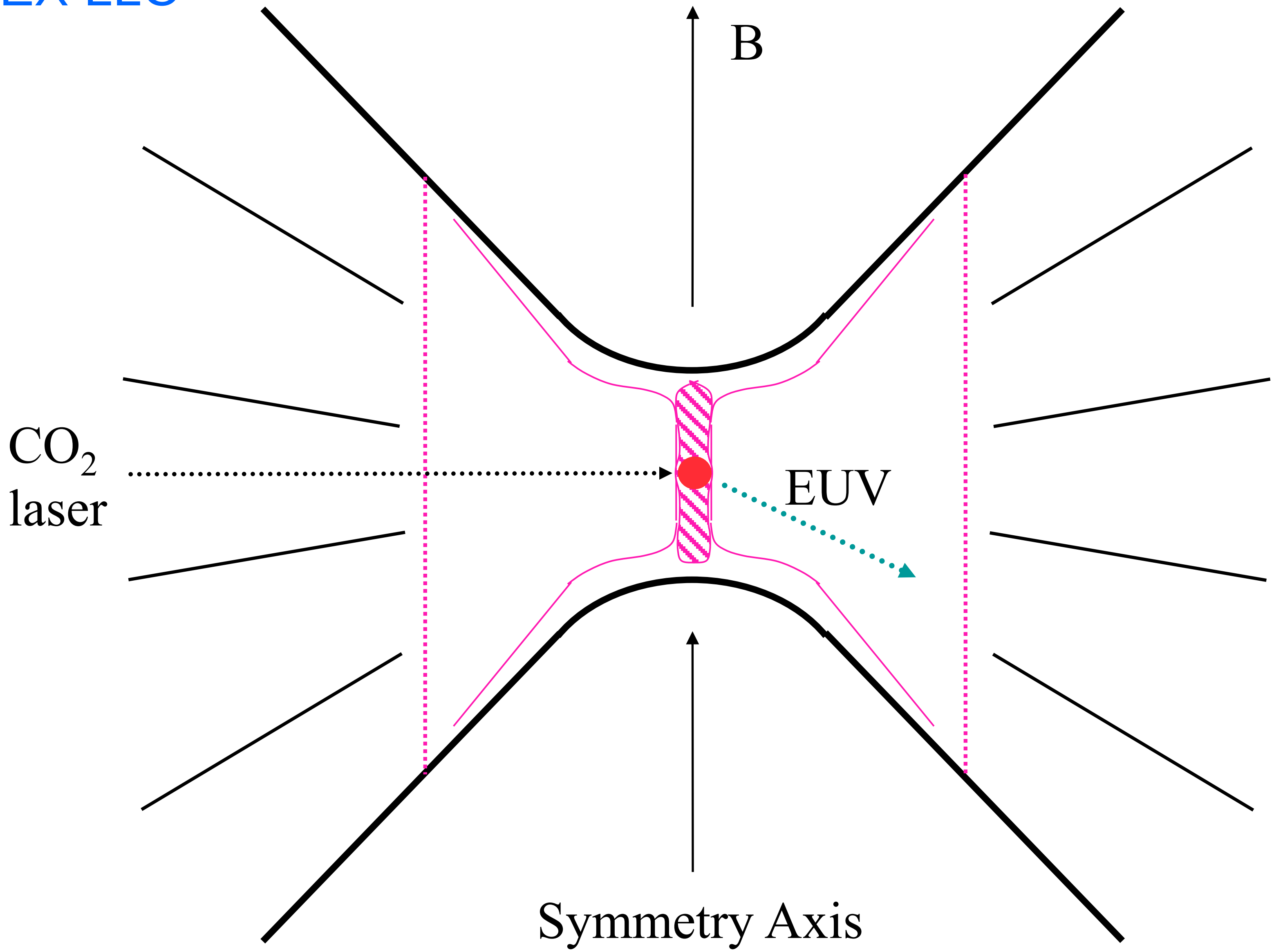

LHDP concept applied to Z-pinch lithium plasma

Summary and Conclusions

Substantial technical progress has been made by PLEX on the discharge lithium EUV source including:
Longer operation
Smaller plasma size
Reliable lamp operation

A path to HVM power has been described, involving:
Higher sustained repetition frequency
Multiplexing of simple lamps

To be available in time, industry financing is needed and/or a technology transition to a designated "Source Supplier"