# A Novel, High-Brightness Electrodeless Z-Pinch™ EUV Source

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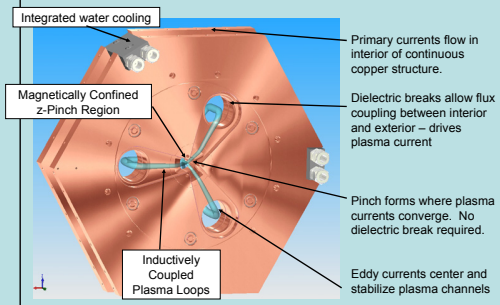
## ABSTRACT

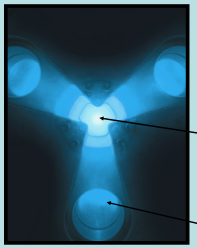
Traditional Z-Pinch discharge plasma sources designed for EUV applications use electrodes to conduct the high current pulse into the plasma. The contact of these electrodes with the high temperature plasma required for EUV production can cause issues of electrode erosion, electrode 'spitting' and even melting. These can be sources of contaminating debris for any optical system connected to the source. Energetiq has a novel approach to the z-pinch discharge plasma where the current pulse is induced into the discharge, rather than conducted. The inductive coupling creates magnetic fields which position the resulting electrodeless z-pinch plasma away from the source walls, thereby allowing relatively straightforward approaches to source cooling.

### Electrodeless Z-Pinch TM EUV Source

$\vec{\nabla} \times \vec{A}$, not $\vec{\nabla} \bullet \phi \rightarrow$ Magnetic, not Electrical, Coupling




### Visible Light of Plasma



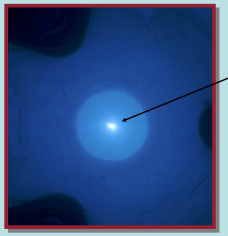
Lower current density and larger initial diameter prevents pinch instability in return loops.

Currents combine in smaller central bore.

Z-Pinch Region

Plasma Return Loops

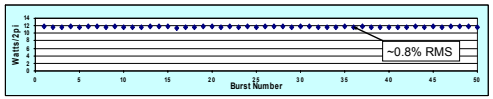
Visible light, long exposure



Pinch Region Magnetically Confined to Center of Source Bore

## PLASMA CHARACTERISTICS

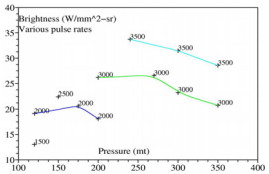
### Power is Stable in CW and Burst Mode




Open–Loop Burst to Burst Stability, 20% Duty Cycle

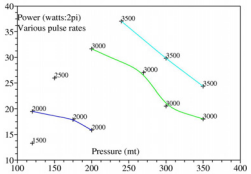
### Power and brightness optimize at different pressures

$$"Brightness" = \frac{Power\ (2\pi)}{2\pi * fwhm\ area}$$



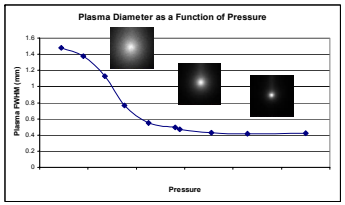

These data are 20% duty cycle; 1 second bursts.

Power in Burst mode



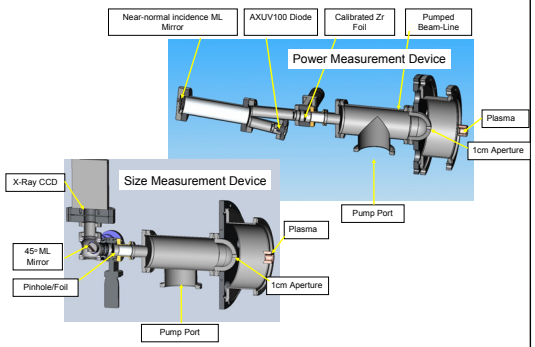

Source size determined by pinhole camera is likely an overestimate – hence "brightness" is probably conservative.

### Controllable Plasma Size

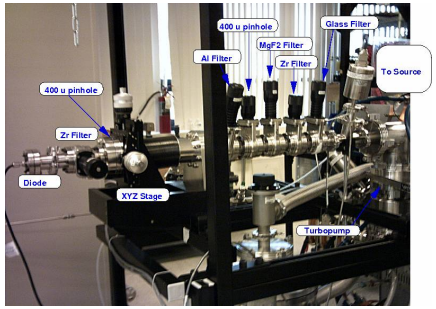



In-band size is controllable via operating pressure.

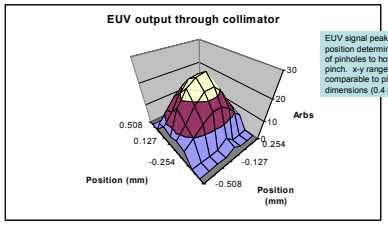
Bore diameter can be varied easily also, controlling plasma diameter




## OUT-OF-BAND LIGHT




Two-pinhole Collimator + filters, diode reduce collection area ambiguity

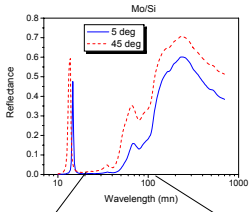


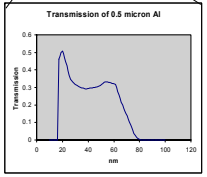

EUV signal peak in x-y position determines alignment of pinholes to hot core of pinch. x-y range of data comparable to pinhole dimensions (0.4 mm diam)

| Filter | Band (nm) | Transmission | Diode Sensitivity | Fraction |
|---|---|---|---|---|
| Zr & MLM | 13.5(+/- 1%) | | | 1.000 |
| MgF2 | >120 | .85 (measured) | 0.25 | 0.002706 |
| Borofloat | >350 | .85(same as MgF2) | 0.25 | 0.000666 |
| MgF2 - Borofloat | 120-350 | | | 0.00204 |
| Zr | 10-20 | .283 (measured) | 0.2 | 2.68879 |
| Al | 17-70 | 0.4 CXRO | 0.2 | 0.076294 |

### Discussion on Out-of-Band Light Measurements

- Measurements of out-of-band light are very sensitive to the measured plasma region.
- Hot EUV-emitting core is surrounded by cooler halo In typical application, only light from hot core is collected.
- DUV emission quite low ---0.2%.
- Wide-band EUV emission roughly 3X in-band EUV (Likely 11 nm, stopped by first mirror)
- Al passband (17-70 nm) 8% -- but not passed by mirror
- In the 20 nm-60 nm range, source emission is about 7% of nominal EUV power.
- Mo/Si MLM reflectivity small in this range. (Plot courtesy Eric Gullikson, LBL)
- Guestimate 5%-15% transmission –
  - OOB light in this band < 1% after 1st mirror




## THEORY

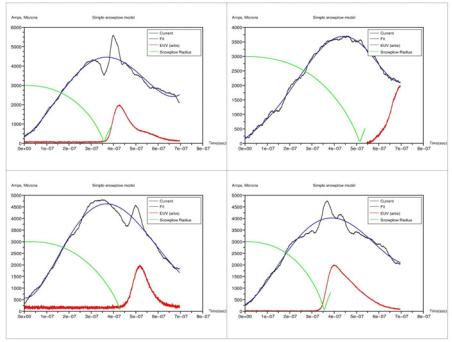
### Simple Snowplow Model Predicts Pinch Time

Based on Krall & Trivelpiece, *Principals of Plasma Physics*
Sheshadri, *Fundamentals of Plasma Physics*

1D model;
- Use measured voltage to estimate plasma current;
- Measured chamber pressure
- Known bore diameter.
- Fit current vs. time by polynomial
- Use fitted current on RHS of snowplow equation

**Integrate ...**

$$d/dt\left[\pi\rho(r_0^2 - r^2)dr/dt\right] = -\mu_0 I^2(t)/(4\pi r)$$



- EUV output on relatively slow diode – assume pinch occurs where EUV starts to increase.
- Remarkably accurate prediction given simplicity of model
- Experimentally, pinch can occur before or after current peak
- "Glitch" in current at pinch time may be plasma inductance increase due to pinch -- V=d/dt(LI) = 0 on pinch timescale; L goes up, I goes down...
- Simple model may be useful for scaling to higher power

### Conclusion

**Electrodeless Z-Pinch can be used to produce high brightness EUV for a variety of applications.**

**Plasma size may be controlled simply by gas pressure, allowing separate optimization of power and brightness.**

**Out-of-band light is low.**

**Design is scalable to higher power levels.**