Recent Improvements in the High-Brightness Electrodeless Z-Pinch™ EUV Source for Mask Inspection Tools

ENERGETIQ

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EQ-10

High-Reliability, High-Stability 10Watt EUV Source for EUV R&D

EQ-10SXR

Soft X-Ray Source for Water-Window Microscopy and 6.7nm R&D

EQ-10HP

High-Brightness, 20Watt EUV Source for Metrology & Testing

EQ-10HR

High Repetition-Rate EUV Source for Accelerated Optics Testing

BACKGROUND

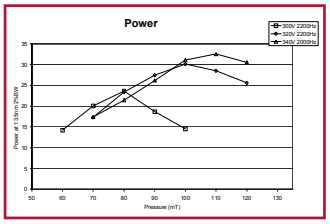
- Energetiq's EQ-10 Series of Electrodeless Z-Pinch EUV sources are widely used around the world as reliable sources of Extreme Ultraviolet (and Soft X-Ray) light. They have evolved in three directions since the introduction of the original 10 Watt, 1.9kHz, 13.5nm source in 2005.
  - Higher Repetition Rate (10kHz) for accelerated testing of EUV optical components (EQ10-HR)
  - Shorter Wavelength (2.88nm) for Water-Window Biological Imaging
  - Higher Brightness/Higher Power (20W) for Actinic Mask Inspection
- The stable nature of the platform makes it a candidate for lower-risk onward development for emerging applications.

EQ-10HP Source for Actinic Mask Inspection

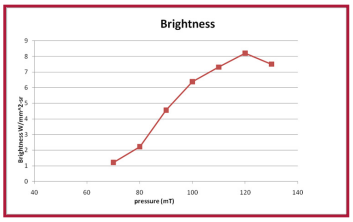
- Based on the standard high-reliability EQ-10 EUV Source
  - Utilizes new bore design with better cooling
  - Improved modulator
- Design allows for up to 7kW input power
  - Improved cooling of source and modulator
- Specifications
  - >20 W of 13.5nm ±1% Power in 2π
  - ~8 W/mm^2-sr brightness

Multiple EQ-10HP Sources Installed for Actinic Mask Inspection Applications
- Operating 24/7
- MTBF > 95%

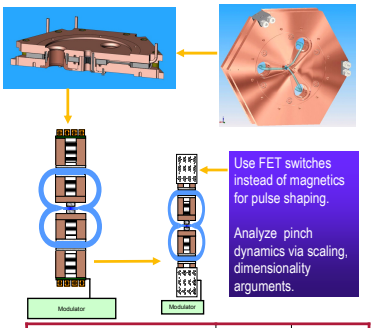
EQ-10HP EUV Power vs. Pressure



EQ-10HP Brightness vs. Pressure



Small, High Frequency Electrodeless Z-Pinch



Use FET switches instead of magnetics for pulse shaping.

Analyze pinch dynamics via scaling, dimensionality arguments.

Modified Z-pinch:
Scale frequency up, size, power down. .

- Scale to a measured EQ-10 plasma
  - Bore geometry: scaling: 1 mm bore diameter plus compression ratio meets plasma size goal. Modest length decrease.
  - Brightness legislated; scaling to EQ-10 performance gives pulse rate.
  - Plasma density: choose to double to ensure optical thickness. (Scaling implies 1.5x sufficient)
- Plasma Conditions for Xenon: Charge state must be ~10 times ionized to radiate in EUV. Electron temperature – from charge state; weak density dependence. Assume unchanged. (25 eV)
  - Density, state, radial size give Bennet current.
  - In base plasma, current peaks above Bennet current. Use same scaling in proposed device.
  - Dynamics scaled via argument due to Ryatov.
  - Inductance assumed reduced by reducing device size.
  - Current, dynamical timescales, inductance determines voltage, power requirements.

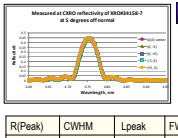
	Existing	Proposed
Bore Diameter: mm	6	1
Length: mm	3	2
Pulse Rate: Hz	2.50E+03	5.56E+04
Brightness: W/mm^2.sr	4.5	100
Compressed Diameter: mm	0.4	0.07
Compression Ratio:	15	15
Uncompressed Ion Density	1.77E+21	3.53E+21
Bennet current: A	6.64E+03	1.56E+03
Peak/Bennet	1.05	1.05
Peak current: A	6.99E+03	1.65E+03
Time to Reach Peak Current: s	2.51E-07	4.18E-08
Total Inductance: H	1.90E-08	9.49E-09
Resistance: Ω	9.87E-02	9.87E-02
Capacitance: F	2.38E-06	8.96E-08
Voltage: V	-1200	-666
Power to Plasma: W	4.21E+03	1.66E+03

6.7nm Electrodeless Z-Pinch Using Neon

EQ-10SXR Soft X-Ray Source Delivers Photons Reliably at 2.88nm:
Modify for use at 6.7nm

- Gas Selection
  - NIST spectral database used
- Search lines with high relative intensity
  - Only gas which appears is Neon
- Operating Parameters
  - 430 V, 1100 Hz,
  - 5.5 kW
  - 400 mtorr
- Output Power
  - ~70mWatts

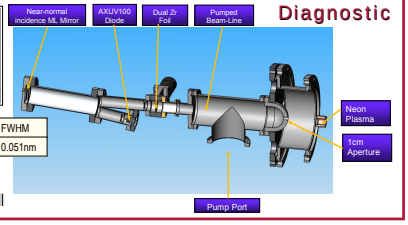
Ion	Observed λ (nm)	Rel. Int.	A_{ki} (s^{-1})	Acc.	E_i (eV)	E_k (eV)	Configurations
Ne VIII	6.5822	1000	3.50e+10	B	15.88881	[204.2389]	$1s^22p$ - $1s^25d$
Ne VIII	6.5895	1300*	4.19e+10	B	16.09330	[204.2429]	$1s^22p$ - $1s^25d$
Ne VIII	6.5895	1300*	6.97e+09	B	16.09330	[204.2389]	$1s^22p$ - $1s^25d$
Ne VIII	6.7382	1500*	3.97e+10	B	0.0000	[184.0070]	$1s^22s$ - $1s^24p$
Ne VIII	6.7382	1500*	3.97e+10	B	0.0000	[183.9816]	$1s^22s$ - $1s^24p$



R(Peak)	CWHM	Lpeak	FWHM
44.31%	6.754nm	6.755nm	0.051nm

- Out-Of-Band Filter
  - Zr Foil & Ar Gas Cell

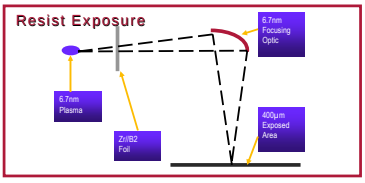
Diagnostic



Practical Integration into Resist Sensitivity Measurement Tool:

- Using ZrB2 foil eliminates need for Argon out-of-band Filter gas
- Focusing optic at 6.7nm increases power density on wafer by more than 100X
- <30sec/mJ exposure time at wafer

Resist Exposure



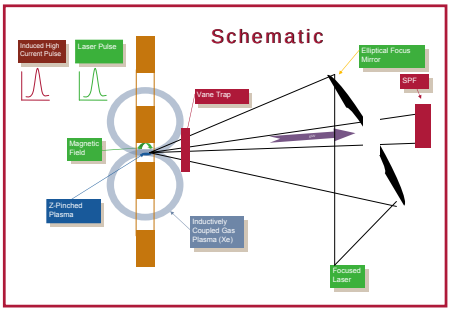
Laser-Enhanced Electrodeless Z-Pinch

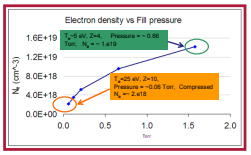
Use Stable Electrodeless Z-Pinch to Make Cold, Dense Xe Plasma: Heat with Pulsed Laser .

The target plasma conditions (density, temperature, charge state) can be tuned to optimize overall system performance. Laser focus determines plasma size.

- Estimate the operating point for the target plasma
  - Consider laser absorption as plasma heats.
  - Use FLYCHK code to estimate parameters.

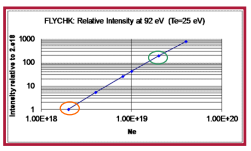
Schematic





T_e	Z	N_e	Optical depth	1/e, mm
5	3.7	1.00E+19	1.67E+01	6.00E-01
10	6.5	2.00E+19	1.85E+01	5.41E-01
25	10.3	4.00E+19	3.24E+01	3.09E-01

As laser pulse starts, cold plasma (5 eV, 1.e19/cm^3) has short e-folding distance – good coupling. As plasma heats, absorption remains good.



- Laser Required for 1W/2π EUV
  - 200W laser @ 0.5% efficiency
  - Expect >0.5% due to optimal target vs. gas jet
- Laser-Heated Pinch requires little real physics extrapolation but does require a high power laser

Estimate Output Brightness:

Bound-Bound radiation ~ (N_e*N_i) * (other stuff that should be roughly constant)

→ (ratio of fill pressures)^2, after reheating

Usual fill pressure 60-90 mtorr; increase by factor of ~ 10

Expect ~ factor of 100 more intensity; FLYCHK says ~ 200

100W/mm^2.sr seems readily achievable