Improvements in pulse-to-pulse stability to the EQ-10 Electrodeless Z-Pinch EUV Source

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Abstract:

The Energetiq EQ-10 is a medium-power (10 W/2π, 13.5nm +/- 1%, Xenon) EUV source suitable for a variety of mirror testing, resist exposure, and defect inspection applications. The device operates as an electrodeless z-pinch discharge source. A current pulse shaped by a pulse compression system drives the plasma z-pinch.

Field experience has identified pulse to pulse reproducibility as a critical requirement for many EUV applications. One potential source of irreproducibility is the pulse compression system- the modulator. The modulator is designed as a series of pulse compression stages, each comprising a capacitance and saturable inductance. Because the source is not an ideal, perfectly matched load, the final state of the system after each pulse (which becomes the initial state for the next charging cycle) is not consistent, resulting in pulse-to-pulse variability.

The modulator was recently redesigned to improve power handling and stability. A goal of the redesign is to force the compression stages to a well-defined state prior to each charging cycle, thus reducing or eliminating this source of variability We will show data analyzing the pulse to pulse stability improvements with the new modulator.

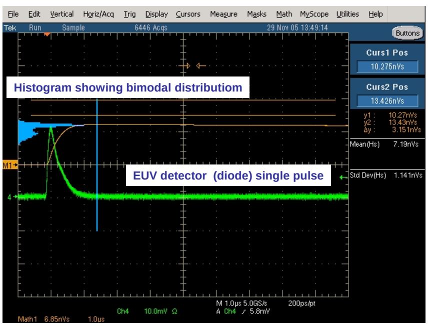
Background:

EQ-10 source is based on an inductive z-pinch. More than 15 units are installed on various EUV platforms around the world.

The source generates pulses of EUV energy at rates of 1-3 kHz.

(References below)

Ideally, each EUV pulse is identical to the last. In practice, variability is observed. Process conditions have a significant effect on pulse-to-pulse variability, but that is not the whole story.



Potential causes of EUV output instability –

- Long term (many hours)
  - Component wear/breakdown (Bore conditioning, component degradation/failure)
- Medium term (minutes)
  - Wall conditioning, plasma effects, ,source pressure control
- Short term (seconds, pulse-to-pulse)
  - Plasma effects
  - Electrical pulse stability
  - Does the electrical system deliver a constant energy per pulse??

Pulse forming system can be modeled as a driven collection of nonlinear resonant circuits.

A clear recipe for Chaos!

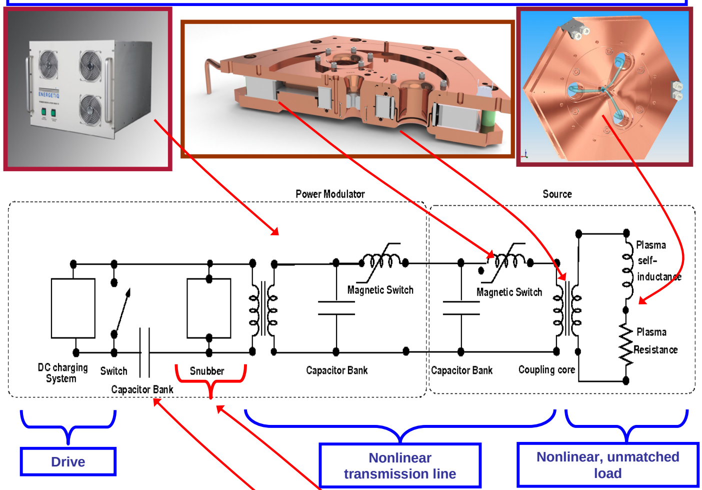
See for instance:

Wood, J. R. Chaos: a real phenomenon in power electronics
In APEC 89. Fourth Annual IEEE Applied Power and Electronics Conference and Exposition. Conference Proceedings 1989 (Cat. No.89CH2719-3) pp. 115-124.
URL http://dx.doi.org/10.1109/APEC.1989.36959

Deane, J. H. B., Sept 1994. Modeling the dynamics of nonlinear inductor circuits. IEEE Transactions on Magnetics 30 (5), 2795-2801.
URL http://dx.doi.org/10.1109/20.312521

Balyakin, A. A., Ryskin, N. M., August 2001. Chaotic oscillations in a nonlinear lumped-parameter transmission line. Radiophysics and Quantum Electronics 44 (8), 637-644.
URL http://dx.doi.org/10.1023/A:1012529706961

Simplified schematic diagram of power system and source.



Potential source of chaotic behavior –

A current pulse, reflected from the mismatched, nonlinear load, deposits variable charge in the main capacitor bank.

In addition, reflected pulse may leave saturable magnetics in an undefined state.

Both effects lead to "memory" – initial conditions for next pulse depend on details of the last pulse.

Results in classical chaos

Cure

Snubbing system, originally designed to protect the semiconductor switch in high-power operation.

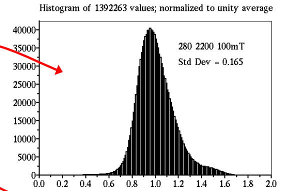
Also forces initial conditions for each pulse to be identical.

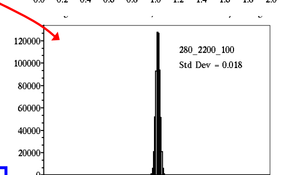
Serendipitous effect!

Result

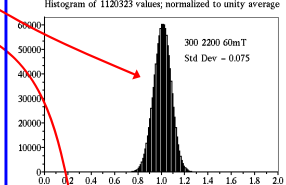
Conditions:	Standard Deviation		Ratio
V_Hz_mT	New	Old	Old/New
280_2200_100	0.0179	0.1651	9.20
280_1900_90	0.0190	0.0756	3.97
280_1900_70_2	0.0215	0.0804	3.74
280_1900_110	0.0223	0.1221	5.47
280_2200_80	0.0268	0.1009	3.76
300_2200_80	0.0359	0.0534	1.49
320_1900_100	0.0371	0.0773	2.08
320_1900_80	0.0402	0.0568	1.41
320_1900_60	0.0667	0.0876	1.31
300_2200_60	0.0705	0.0752	1.07

Histogram of 1392263 values; normalized to unity average

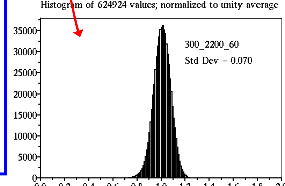




Histogram of 1120323 values; normalized to unity average



Histogram of 624924 values; normalized to unity average



Observations

- An improvement in reproducibility is observed for all operating conditions.
- The degree of improvement seems to vary with plasma conditions – higher operating pressures show (generally) more improvement.
- Old modulator – low pressure is better.
- New modulator – high pressure is better.
- New modulator, higher pressure, is best.

Postulate

The reason that there is not much improvement at lowest pressures, is that the plasma is a matched load there – hence the old result can't be much improved by the snubber circuit. In addition, another source of instability, not correctible by the snubber, dominates at low pressure.

Conclusions

The modified modulator allows both higher power operation, and improves energy stability, allowing stable operation at plasma conditions that were unstable with the original modulator.

[1] Denbeaux, G., Naulleau, P., Horne, R. G. S., Besen, M., First use of the Energetiq 10w Electrodeless EUV Plasma source. In: 2005 International EUVL Symposium, San Diego, CA.

[2] Horne, S. F., Besen, M. M., Smith, D. K., Blackborow, P. A., Dagostino, R., 2006. Application of a high-brightness electrodeless Z-pinch EUV source for metrology, inspection, and resist development. In: Proc. SPIE. Vol. 6151.

[3] Blackborow, P. A., Gustafson, D. S., Smith, D. K., Besen, M. M., Horne, S. F., D'Agostino, R. J., Minami, Y., Denbeaux, G., 2007. Application of the Energetiq EQ-10 electrodeless Z-Pinch EUV light source in outgassing and exposure of EUV photoresist. In: Proceedings of SPIE. Vol. 6517.

[4] Blackborow, P.A., Partlow, M.J., Horne, S.F., Besen, M.M., Smith, D.K., Gustafson, D.S., "EUV Source Development at Energetiq," Emerging Lithographic Technologies XII 6921(1), p. 692121, SPIE, (2008).

[5] S.F. Horne, J. Silterra, and W. Holber, "A compact soft X-ray microscope using an electrode-less Z- pinch source," Journal of Physics: Conference Series, vol. 186, 2009, p. 012028+.

[6]Horne, S. F., Niell, F. M., Partlow, M. J., Besen, M. M., Smith, D. K., Blackborow, P. A., Gustafson, D., 2009. Development of a high-pulse-rate euv source. Vol. 7271. SPIE, pp. 72713A+.