

Z-Pinch and Astron: Inertial Plasma EUV Sources

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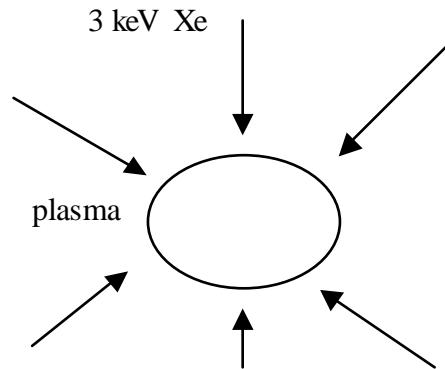
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Inertial Plasma Sources of EUV



1. Plasma energy is delivered via kinetic energy of xenon
2. $>20\text{eV}$ plasma temp. required to produce Xe^{10+} for radiation at 13.45nm
3. EUV radiation is emitted in recombination during plasma expansion
4. 15% of all input energy is radiated in $10 - 15\text{nm}$ xenon bands (into 4π)
5. 5 – 10% of $10 - 15\text{nm}$ xenon band is in 2% BW at 13.4nm

FUNDAMENTAL EFFICIENCY IS 0.75 – 1.5%

6. Inertial formation allows distant walls to handle power

BUT

7. Not all of 4π can be collected (optics limit)
8. Plasma size, coupled with etendue may further restrict collection angle
9. Acceleration of xenon is not 100% efficient

Inertial Plasma Sources of EUV

HYPOTHETICAL EXAMPLE (demonstration of physics of 50W source):

Collection of 30% of $2\pi = 1.9\text{sr}$ (such as LPP condenser)

Acceleration efficiency 40% (Z-pinch)

⇒ OVERALL EFFICIENCY 0.045 – 0.09%

**50W USABLE EUV => 110kW – 55kW PRIME POWER
depending on spectrum**

Assume first wall heat loading of 500W cm^{-2} and 40% accel. efficiency

⇒ required to have plasma 2.6 – 1.9 cm from first wall

PLEX is working with two inertial plasma approaches:

CYLINDRICAL PLASMA, MAGNETIC ACCELERATION (Z – Pinch)

SPHERICAL PLASMA, ELECTROSTATIC ACCELERATION (Astron)

10^7 pulse mirror test (Z-Pinch)

Mo-Si mirror from Osmic, on crystal Si substrate, peak 13.5nm

Mirror positioned 58cm from plasma, at 7.5deg. reflecting onto diode

55% transmitting “honeycomb” at 7cm from plasma to control Xe flow and pass EUV (0.1sr transmitted)

Axial signal measured in 13.5nm band on spectrometer CCD

Run of 35hrs at 80Hz, 70J stored, performed over 5 x 7hr days.

Mirror/diode signal decreased by $16\pm 5\%$ relative to CCD signal

Mirror analysis at Zeiss showed surface oxidation to be main cause of loss

Alumina pinch liner replaced twice at 4×10^6 pulse intervals

Likely source of active oxygen is liner ceramic

95% up time, balance taken for liner changes

Liner erosion was near anode, implying that reverse current arcs were main cause. New modulator will have no reverse current

Alumina liner material will be replaced by sapphire

Near Term Z-Pinch Development Path

Parameter	Feb. 2,000	Dec. 2,000
Repetition Rate	100Hz (max150)	>= 500Hz
Input Power	10kW	20kW
Stored Energy	50-100 J	20-40 J
Beam Intensity W/2%BW/sr	4	16 (driver efficiency doubled)
Driver	6 parallel thyratrons (limited to 500Hz,) 10 ⁹ pulses)	single solid state/ magnetically modulated (>2,000 Hz, 10 ¹⁰ pulses)
Pinch Chamber	30mm dia. X 30mm	25mm dia. X 20mm
Source Size	3.2mm FWHM	2.7mm FWHM
Solid Angle (etendue 0.8mm²sr)	0.1sr	0.14sr
Usable Beam (2%BW into etendue)	0.4W	2.2W
Liner Heat Load	37Wcm ⁻² (measured)	180Wcm ⁻² (estimated)

Near Term Z-Pinch Development Path (contd)

Parameter	Feb. 2,000	Dec. 2,000
Liner Life	4×10^6 (limited by erosion of reverse current)	$>10^8$ (no reverse current, improved material)
Liner Material	alumina	sapphire
Liner Change Time	30min.	10min.
Electrode Life	2×10^7 (limited by deposition of liner material)	$\gg 2 \times 10^8$
Cleanliness	Reflect. down 16% At 1×10^7 pulses, 60cm (top layer oxidation)	$>10^8$ pulses for 10% loss (control of oxygen via lower erosion, etc)
Condenser	distance 50-100cm (simple optic, easily replaced)	same
Xenon use	low	Xe recovery

Ultimate Limits for Z-Pinch ?

Liner Heat Load

Feb. 2,000 Z-Pinch had liner area of 28cm^2 and measured heat load of 37Wcm^{-2} at 10kW prime power.

To have reduced plasma size, future pinches may have smaller liner, e.g. 16cm^2 which increases heat load by 1.75x

Solid state power supply is 2x more efficient at delivering power to pinch, so 2x increase in heat load for same prime power.

Wall heating in Feb 2,000 pinch seemed uneven, because more erosion near anode due to reverse current. Lack of reverse current will cut total heating by (?) 0.7x

Estimated heat load for Dec 2,000 design at 20kW is therefore $2 \times 37 \times 1.75 \times 2 \times 0.7 = 180\text{Wcm}^{-2}$

Extension seen possible to prime power of 60kW $\Rightarrow 540\text{Wcm}^{-2}$ for same geometry.

Scaled usable EUV power is then 6.6W into 0.14sr at 2% BW.

Other improvements should be possible:

Capture of Reverse Beam

Z-pinch emission in close to axial direction is stimulated (close to Planck distribution). Radiation passes down plasma length without absorption. Reverse direction radiation should be able to be reflected by a multilayer mirror and sent back through the plasma in the forward direction, adding to the collected beam. A 66% mirror is assumed, leading to $6.6\text{W} \times 1.66 = 11\text{W}$ usable.

Reduced Plasma Size

Partly spherical geometry leads to higher electron density so that EUV recombination radiation is emitted at smaller radius, allowing a larger solid angle of radiation to be used

For example 2.0mm FWHM \Rightarrow 1.8x solid angle increase compared to 2.7mm FWHM at same etendue $\Rightarrow 11 \times 1.8 = 20\text{W}$ usable

Multiplexing

The Z-pinch has low incidence angles on the condenser mirror, because small solid angles are used, and the condenser is typically 60 – 100cm distant. Two (or more) Z-pinch heads can be disposed at a few cm separation, appearing to be at only 5deg. different angles to the condenser. The output of two Z-pinches can be multiplexed by a ± 2.5 deg. oscillation of the condenser elements (assumed to be many small elements that collect light and relay it to a field mirror).

Conclusion

Usable Z-Pinch O/P (2%BW in etendue) scales to 10 – 20W at 60kW Prime Power, and with 2-fold multiplexing to 20-40W at 120kW Prime Power.

Astron: Principle and Current Experiment

3 keV xenon ions generated in multiple acceleration gaps and aimed at center of sphere. Ions then neutralized:



3 keV neutral xenon atoms converge to form hot plasma

pulse duration 50nsec

20% acceleration efficiency previously measured for argon

first wall at 25mm

discharge tests in progress 3J at 400Hz achieved

small central plasma seen

Comparison of Astron with Z-Pinch

(Note: Astron is only a concept at this stage. Z-Pinch is well-researched). The parameters relate to a single, non-multiplexed source.

Parameter	Z-Pinch	Astron
Ultimate usable power (2% BW)	20W	>50W
Electrode area (cathode + anode)	8cm^2	48cm^2
Distance of 30eV plasma from walls	12mm	25mm
Area of first wall (for cooling purposes)	20cm^2	54cm^2
Preionization	required	not necessary
Materials	ceramic wall	refractory metal wall
Erosion	principal life issue	estimated negligible
Collection solid angle	0.14sr (large plasma)	>1sr (spherical plasma)
Repetition rate	estimated $5 \times 10^3 \text{Hz}$	estimated $>10^4 \text{Hz}$
Cost of Ownership	like excimer	like excimer
Capital cost	like excimer	like excimer
Cleanliness	OK	estimated excellent