High Brightness Next Generation EUV Lithography Light Source

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EPPRA sas
NANO-UV sas

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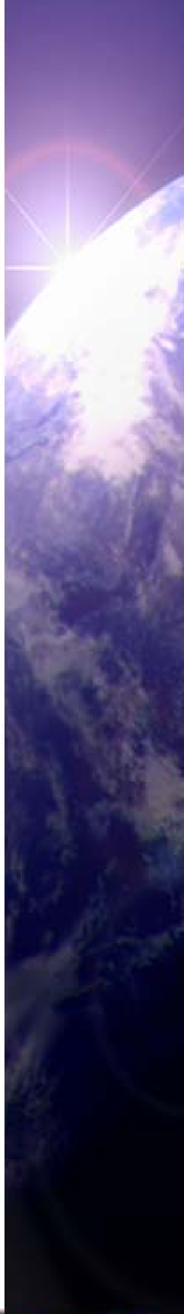

OUTLINE

- Remaining challenges to EUVL deployment
- Plasma radiation sources
- Z*-code EUV source plasma parameter scan
- Extra EUV Emission from Xenon Plasma
- Multiplexed source for high power & brightness
- NANO-UV's source solution:

  - the i-SoCoMo™

  - multiplexer HYDRA™-BE18 for mask metrology

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EUVL

- EUVL lithography considered as the NGL tool holding the most promise for industrial application at 22 nm hp is at a cross road today.
- For HVM EUV lithography applications, EUV powers in the range of 200-500 W in IF are required.
- Actinic mask blank defect inspection and aerial imaging tools are key to enable yielding masks for 22 nm node and beyond that requires EUV sources with extremely high radiant brightness.
- The top challenge to EUVL deployment is the availability of a powerful and reliable light source and the associated optics to collect the EUV photons, the SoCoMo (source collector module)

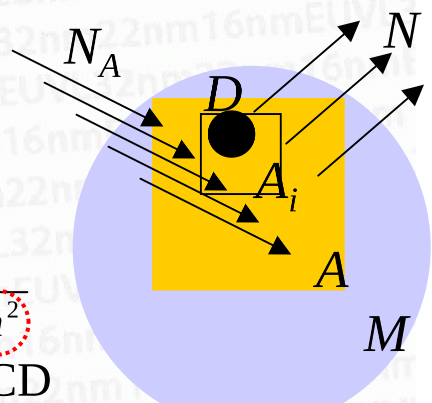
EUV Brightfield Metrology - Requirements

- Mask defect inspection - the source required

- relative defect response > N photon statistics $\frac{D}{A} > \frac{2\sqrt{N}}{N}$ **(K. Goldberg, Hawaii, 2008)**

Consider a CCD array (n×n) detector, pixel size A_p, being used to image the area of the mask under inspection

- magnification of imaging optics, m, hence area to detect a defect is now $A_i = A_p/m^2$, and the total illuminated patch area on mask observed is $A = A_i \cdot n^2$
- total illumination time: $t = t_A \cdot M \cdot m^2/n^2 \cdot A_p$
- illuminating irradiance required: $\frac{N_A}{A \cdot t_A} > \frac{4}{R}\frac{M}{D^2 t \cdot n^2}$
- then for defect size 10 nm, a $(9\mu m)^2$ pixel size, 2048^2 CCD array and full size $(4^2 \times (26\times33)\ mm^2)$ mask inspection:



(reflectivity $R \approx 60\%$)

Magnification, m	40	80	160
Patch area, A (um2)	5.06E-02	1.27E-02	3.16E-03
Illuminating flux density (ph/cm2)	5.47E+15	1.37E+15	3.42E+14
Na illuminating A	1.16E+13	7.26E+11	4.54E+10
Irradiance at mask needed, 10 shots exposure (ph/s cm2)	2.74E+18	6.84E+17	1.71E+17
Mask exposure time (min)	2.16E+00	8.62E+00	3.45E+01

*additional time for positioning and alignment needed in each exposure

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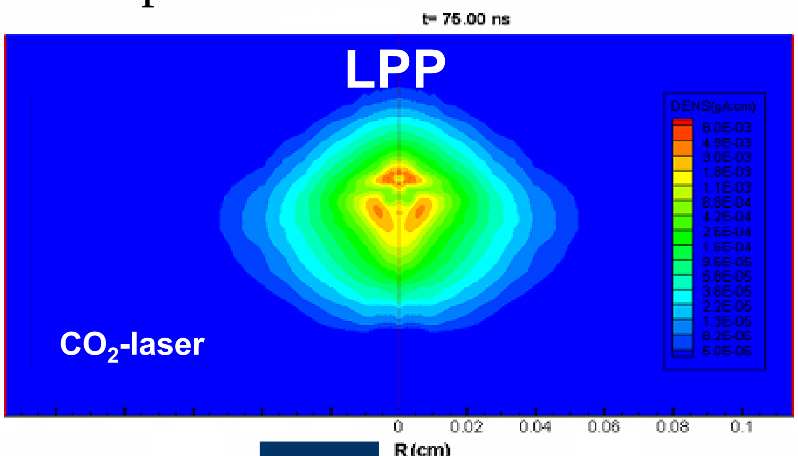
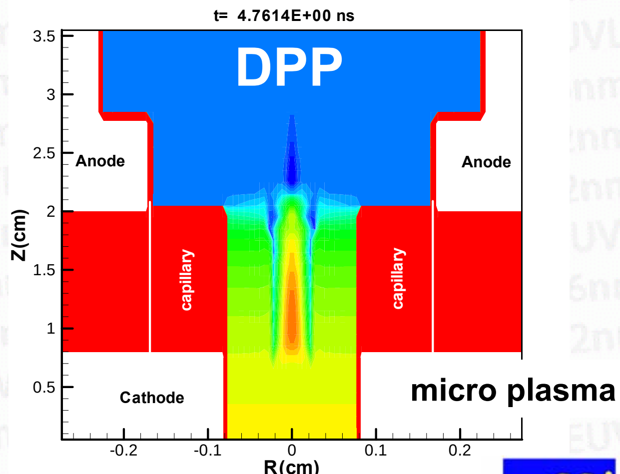
EUV Light Source

- Sn, Xe, Li … High Energy Density plasma is the EUV light source in narrow 2% band @ 13.5nm
- High pulsed power LPP & DPP to produce the the right conditions HED plasma





Z * MHD code modeling

- For HVM - X00 W of in-band power @ IF with etendue < 3mm^{2}sr
- For AIM and ABI – Y0 W/mm^2·sr at wavelength radiance

- kW (source) ⇒ W (IF) is the source of the problem -

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ZETA → Z* RMHD Code → Z* BME tool

model required: nonLTE, multicharged ion plasma

Tables (T_e,ρ) for solid matter & for LTE, non-LTE plasmas of ion compositions: EOS; ionization distribution; rates; non-maxwell electrons; spectral group radiation & transport coefficients

RMHD with energy supply:
(r,z+φ) plasma dynamics in $(E,B)_{r,\varphi,z}$;
nonstationary, nonLTE ionization;
spectral multigroup radiation transport in nonLTE with special spectral groups (for EUV,laser); solid elements sublimation, condensation, expansion into plasma

EEMHD in real cylindrical geometry:
dynamics of electrons → change to 3D PIC;
ionization of weekly ionized plasma
(hollow cathode ionization wave)

DPP
simulation
in real geometry
LPP

Spectral postprocessing:
3D ray tracing;
detailed spectra

Data: ($r,z,v,T_{e,I},\rho,E,$ B, Z,U_ω, etc);
Time evolution (I,P_ω, W, F_ω, etc);
Visualization

Heat flux postprocessing:
element lifetime estimation;
fast particle flux, 3D PIC

- Improved
- new
- coming

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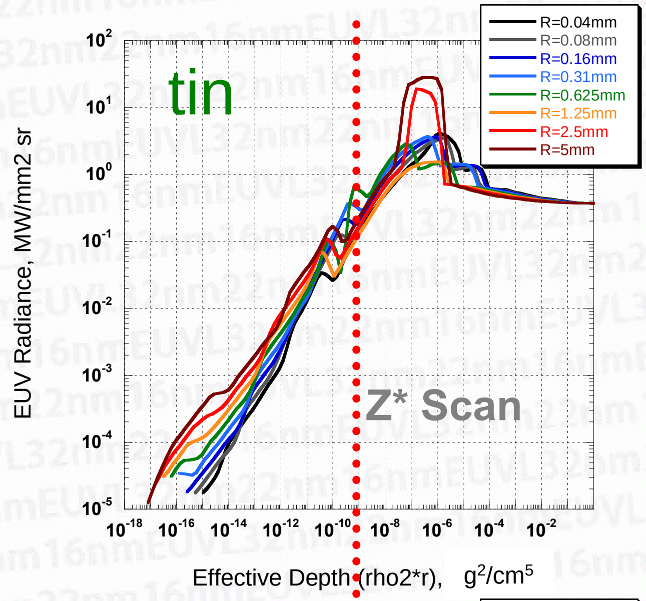
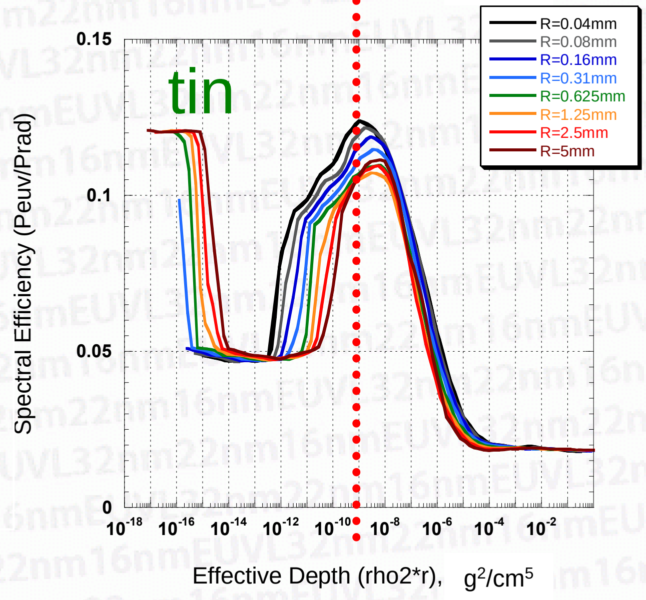
Optimized EUV Efficiency of a Source

- Plasma self-absorption defines the limiting brightness of a single EUV source and required power at given limiting etendue of the optics
- The plasma parameters where EUV radiance is a maximum are not the same as that when the spectral efficiency is a maximum.
- The spectral efficiency is high SE=11-12% at plasma density $\rho = 10^{-4} \div 10^{-3} g/cm^3$.
- The optimum Conversion Efficiency@IF (CE_{IF}) of in-band radiation is maximal at target radius value smaller than $R < 0.38mm$ and decreases like R^{-2} at larger one.

- the Conversion Efficiency of a single source decreases if the in-band EUV output increases (at the same operation frequency)





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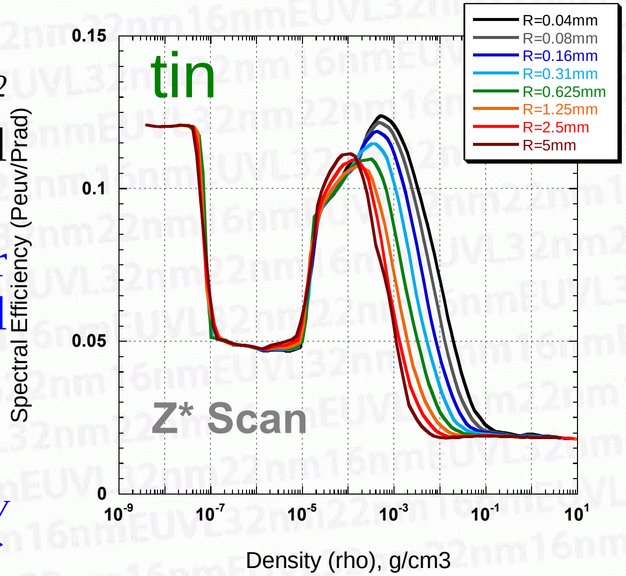
What is achievable with a single source? - LPP

- Critical density for Nd:YAG laser ($\rho_{cr} \approx 2\cdot10^{-2}$ g/cm^3) is in the region of low spectral efficiency (SE).

  Example: to obtain *150W* the in-band power $P_{EUV} = L_{EUV}\cdot E\cdot\tau\cdot f\ (\tau \approx R/C_s)$ in conventional source with 2π-collector the laser power

  $P_l \approx P_{EUV}\cdot 16\,\pi A_s/(\eta_{rad}\cdot E\cdot SE)$

  in optimum $P_l > 50kW$ ($\eta_{rad} \approx 0.5$; $CE_{IF} = P_{EUV}/P_l \approx 0.3\%$) operating with frequency $f > 140kHz$ at $L_{EUV} = 2.5MW/mm^2sr$ and $R = 63\mu m$.



- Increasing the target size the operating frequency may be reduced, but the Nd:YAG laser power should be increased.

- For LPP source based on CO_2-laser the critical density is 100 times less.

  Example: the spectral efficiency may be higher, up to SE ≈ 11%, but lower L_{EUV} resulting in $CE_{IF} \approx 0.7\%$ and laser power $P_l > 22kW$ operating with many kHz $f \propto R^{-4}$. CO_2-laser EUV source requires an additional spectral purity filter and anti-fast-ion protection that reduces the effective CE_{IF}.

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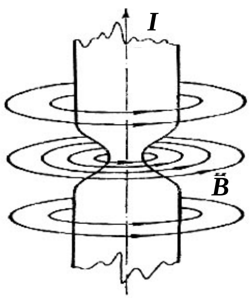
What is achievable with a single source? - DPP

- In conventional single DPP source of Z-pinch type the plasma is heated up and compressed by magnetic field energy and pressure ($B^2/8\pi$). From Bennet ratio $\rho R \leq M_i \cdot R \cdot B^2/(8\pi\, T(Z+1)) \approx 0.5 \cdot 10^{-15} \cdot I^2{}_{[A]} / R_{[cm]}$
- The collectable in-band EUV power for given etendue $E_{[mm^2 sr]}$ is $P_{EUV}(W) \leq 0.16 \cdot 10^{-10} \cdot I^2{}_{[A]} \cdot E \cdot f_{[Hz]}$



- The joule heating should provide enough power: $3 \cdot 10^4 \cdot I^2 / (\pi\, \sigma) \cdot f > P_{EUV}\, 16\, \pi^2 R^2 / (E \cdot SE) \Rightarrow R_{[cm]} < 0.13 \cdot SE^{0.5}$
- For high P_{EUV} from a single source in the optimal regime of high EUV radiance, the current is very high $I_{[A]} \sim 4.5 \cdot 10^5 \cdot R^{0.5}$ supplied during short time $\tau(s) \approx 1.7 \cdot 10^{-6} \cdot R_{[cm]}$, i.e. $dI/dt \sim 2.6 \cdot 10^{11} / R^{0.5}$ (A/s).
- Reducing the current, plasma size or pulse duration increases rapidly the necessary operation frequency and decreases the Conversion Efficiency.

Example: to obtain *150W* of collectable in-band EUV power with π-collector for *R=0.3mm*, the current is *I =8 kA* operating with *f = 160 kHz*. This current should be supplied to the small size plasma during 50ns time.

- By the way, spatial multiplexing *N=40*, *f = 4 kHz* each and *I =8 kA* provides that 150W

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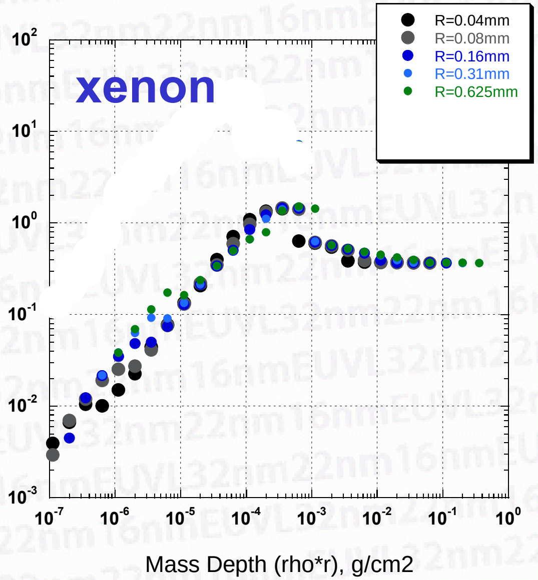
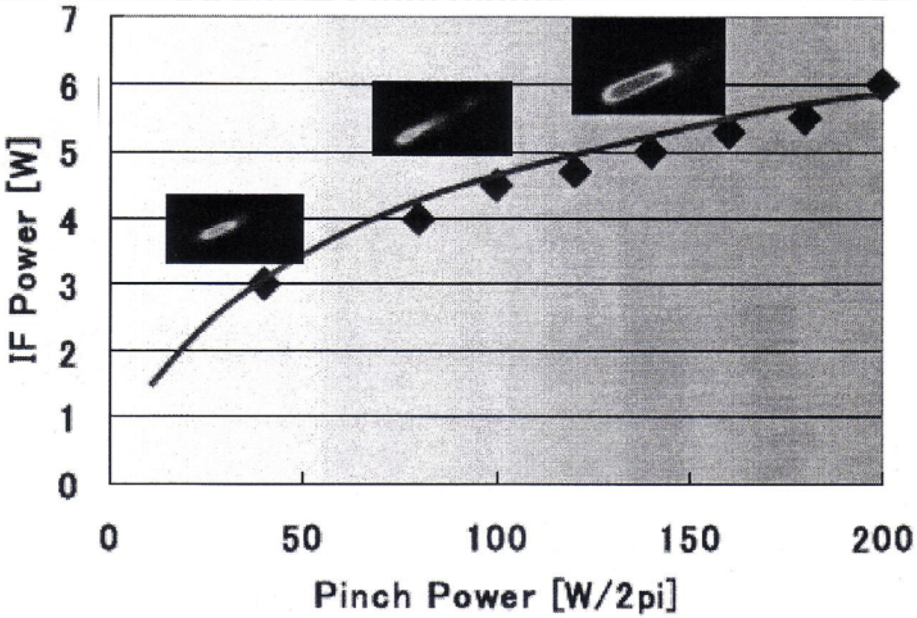
EUV IF Power Limitation:

prediction vs. observation

- Xenon plasma EUV emission



Xenon plasma parameter scan with Z*-code showing the EUV radiance limitation



Experimental observation of limitation of the EUV power at IF from xenon DPP source

(M. Yoshioka et al. Alternative Lytho. Tech. Proc. of SPIE, vol. 7271 727109-1 (2009)

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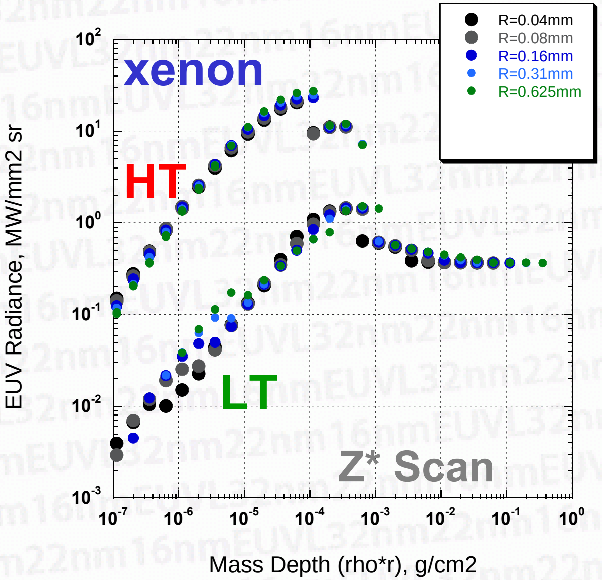
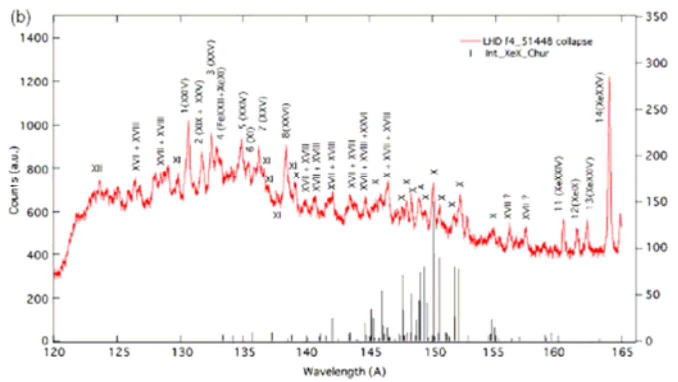
Xenon Revisited-

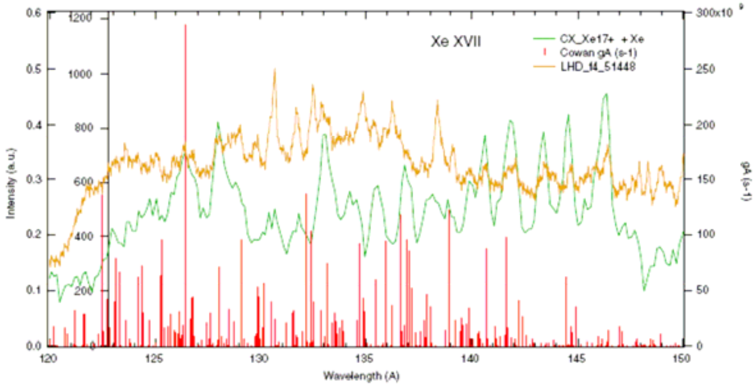
extra EUV emission from xenon plasma

- There are two regimes in transparent plasma of xenon: Low - Temperature (LT) with XeXI and High - Temperature (HT) with XeXVII-XeXXX ions contributing into 2% bandwidth in the spectral region 13-14nm.
- For small size xenon plasma, the maximum EUV radiance in the HT can exceed the tin plasma emission



T Kato et al. J. Phys. B: At. Mol. Opt. Phys. 41 (2008)





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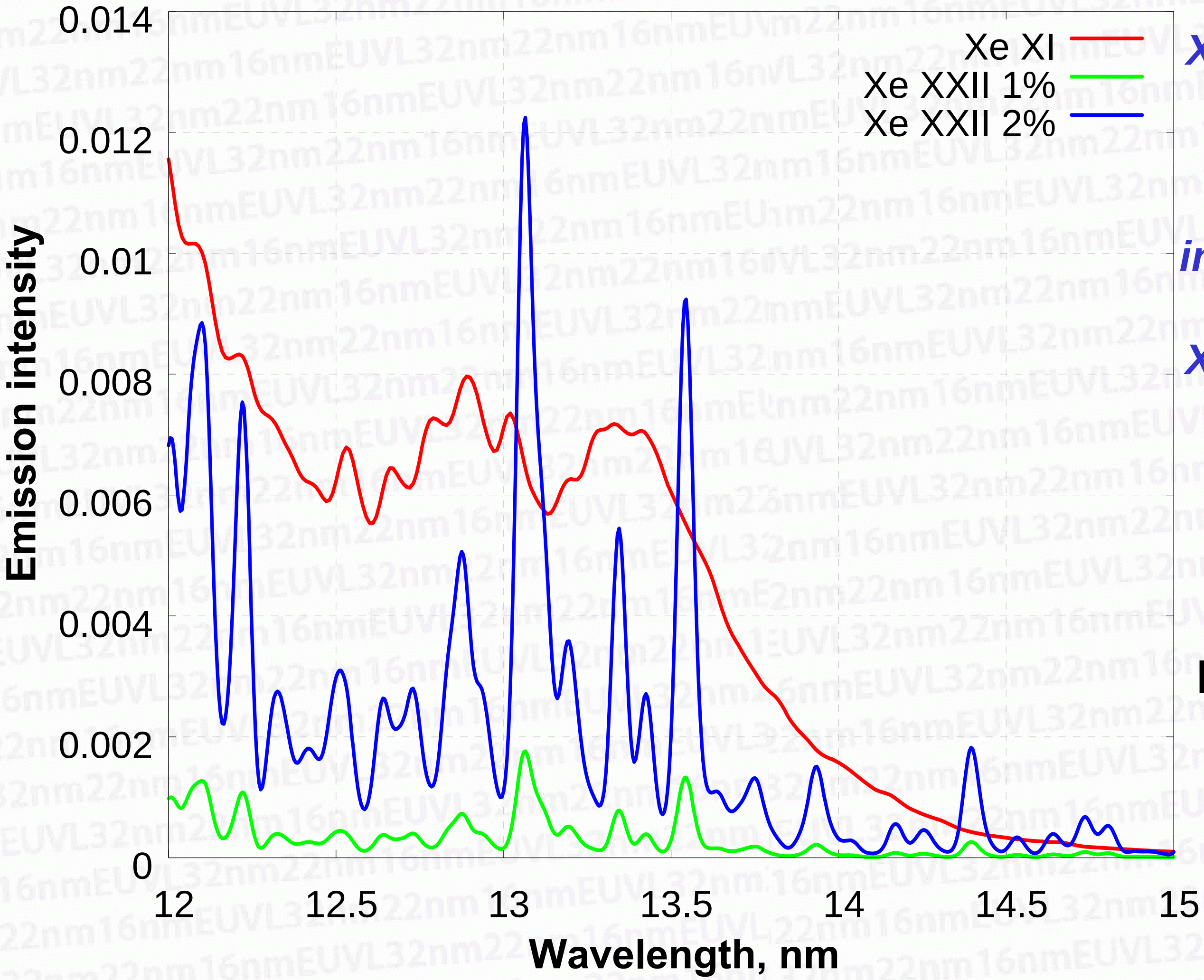
EVU Emission

from xenon plasma with e-beam



Emission of Xe XXII in plasma with fast electrons of various portions (from 1% to 2%) in comparison with the emission of Xe XI from equilibrium plasma

Energy of fast electrons

E = 5 keV

Plasma temperature

T = 40 eV

Plasma electron density

$N_e = 10^{17}$ 1/cm^3

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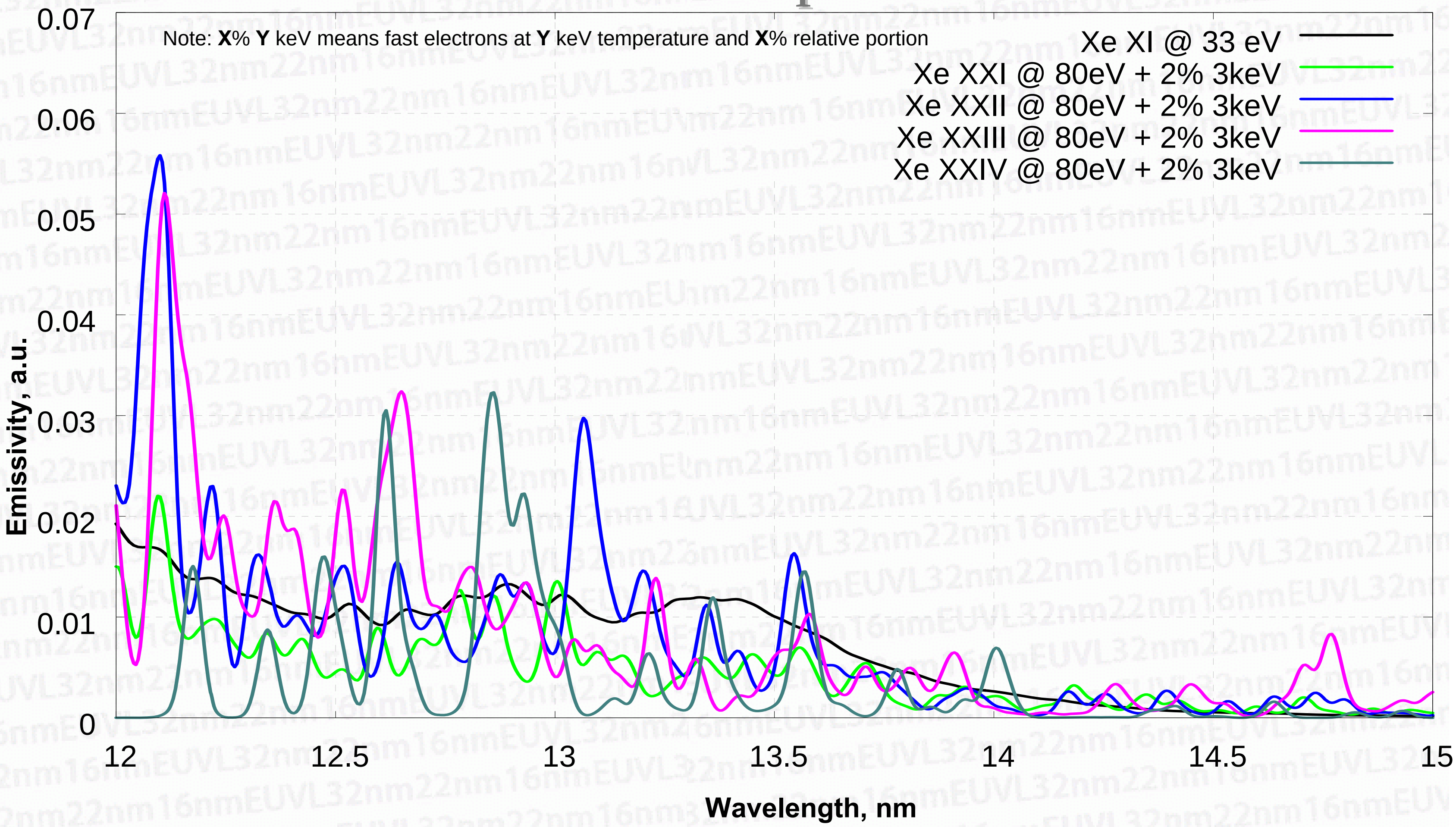
Non-equilibrium Kinetic Modeling
of xenon plasma with e-beam



EUV emission spectra of various Xenon ions from non-equlibrium plasma at 80 eV with 2% of fast electrons at 3 keV in comparison with emission spectrum of Xe XI ions from plasma at 33 eV (black). Electron density = 10^{17} cm^{-3}

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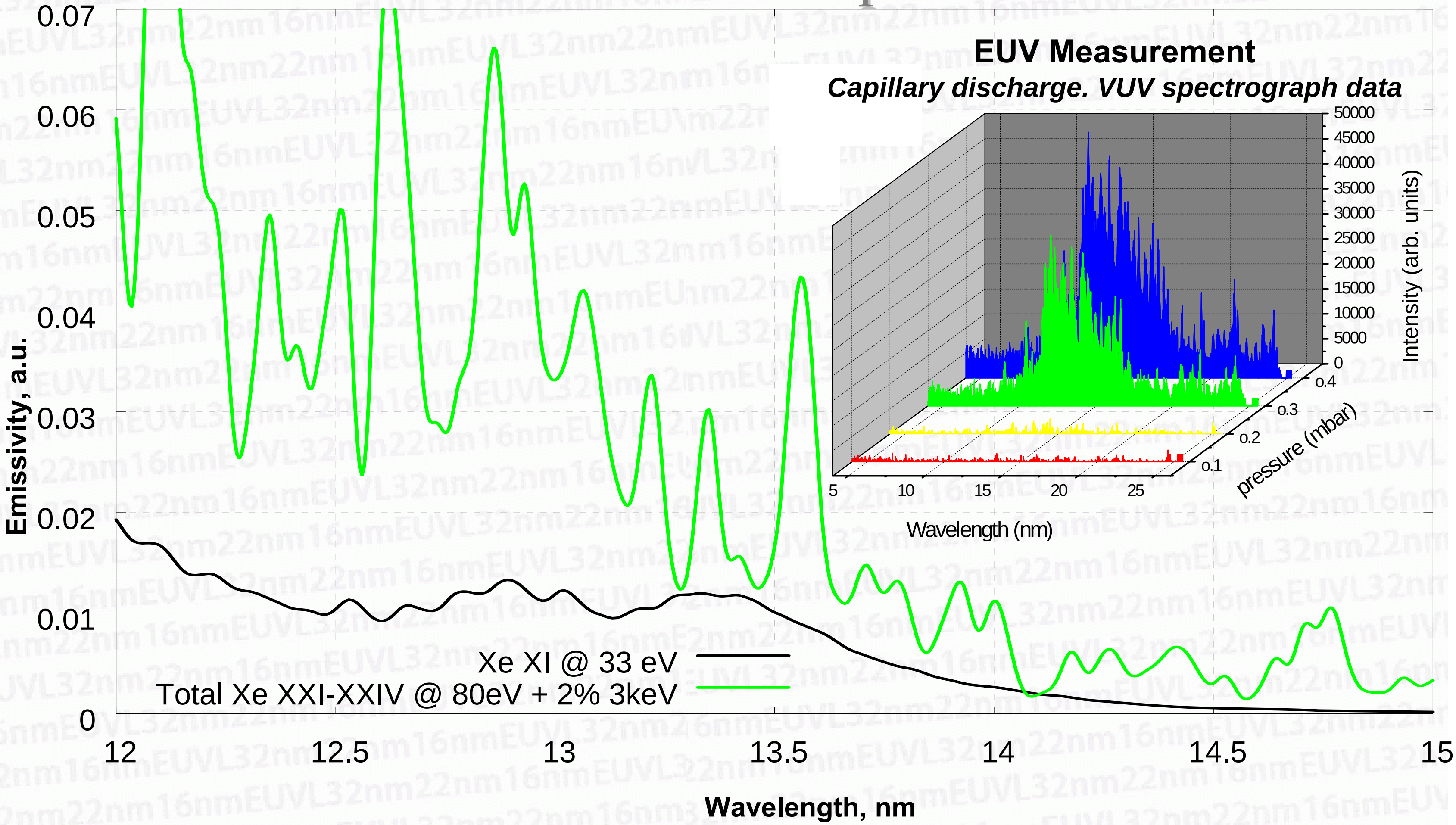
Total Emission of Xe XXI-Xe XXIV ions from plasma with e-beam



Total EUV emission spectra of Xe XXI - XXIV ions from non-equilibrium plasma at 80 eV with 2% of fast electrons at 3 keV in comparison with emission spectrum of Xe XI ions from plasma at 33 eV (black). Electron density $N_e = 10^{17}$ 1/cm^3

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Multiplexing

- a solution for high power & brightness

- For small size source, the intensity of the in-band emission is maximal in almost transparent plasma at

$$\rho R = (\rho R)^{\wedge},\ near\ \kappa_{\omega} R \sim 1$$

- The etendue from a single small size source is low enough $E_1 = A_s \Omega << 3\ mm^2\ sr$ to be multiplexed.
- The EUV power of multiplexed N sources is

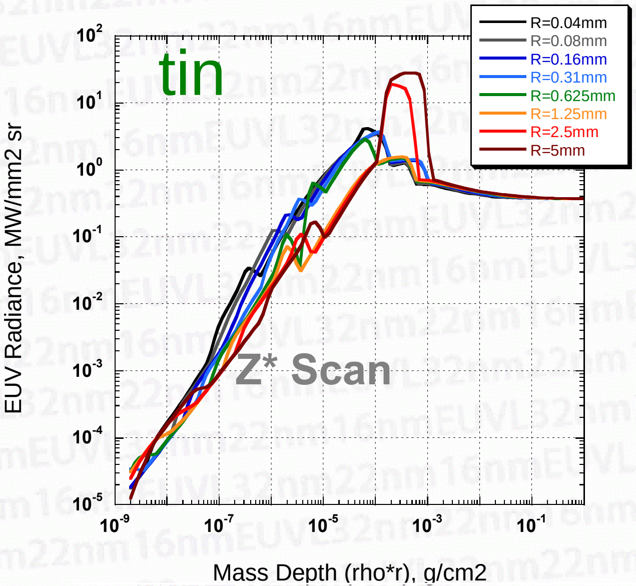
$$P_{EUV} = Np_{EUV} \propto \tfrac{4}{3}\pi R \cdot N \cdot (\rho^2 R^2)^{\wedge} \cdot \Omega \cdot t \cdot f;$$

$$as\ n_i' \propto n_i n_e$$

$$Finally: P_{EUV} \propto \sqrt{E \cdot N \cdot \Omega} \cdot t \cdot f, \quad as\ R \sim \sqrt{E/(N \cdot \Omega)}$$

- To increase the power significantly we have to increase the plasma dimension *R*, or operation frequency *f*, or number of sources *N.*

$\Rightarrow$ The EUV source power meeting the etendue requirements increases as $N^{1/2}$



- Decreasing the plasma size doesn't reduce the EUV radiance (if the plasma optical depth is kept constant)
- This allows efficient re-packing of radiators from 1 into *N* separate smaller volumes without losses in EUV power

- **problem is the physical size of SoCoMo**

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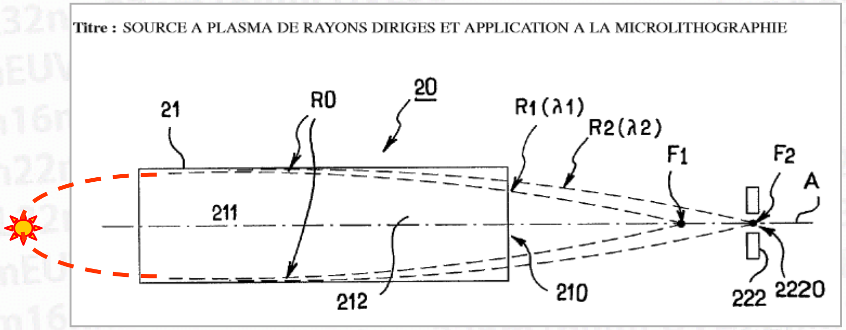
High Brightness EUV Source

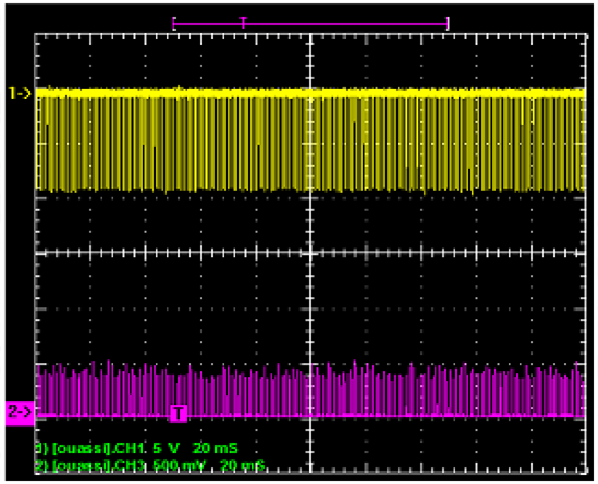
i-SoCoMo™

- Pilot production unit spec
  - compact form factor
  - mm spot size at up to 1 m distance
  - 10^{16} photons/cm^2/s/ @ 4% BW in-band EUV irradiance
  - 3 kHz continuous
  - 3.3 kW average power consumption
  - 1 Gshot lifetime to service
  - in-build photon collection & projection plasma structure - **PlasmaLens™**

CYCLOPS™BE-16



WO 2005/038822 A2



Discharge voltage

EUV

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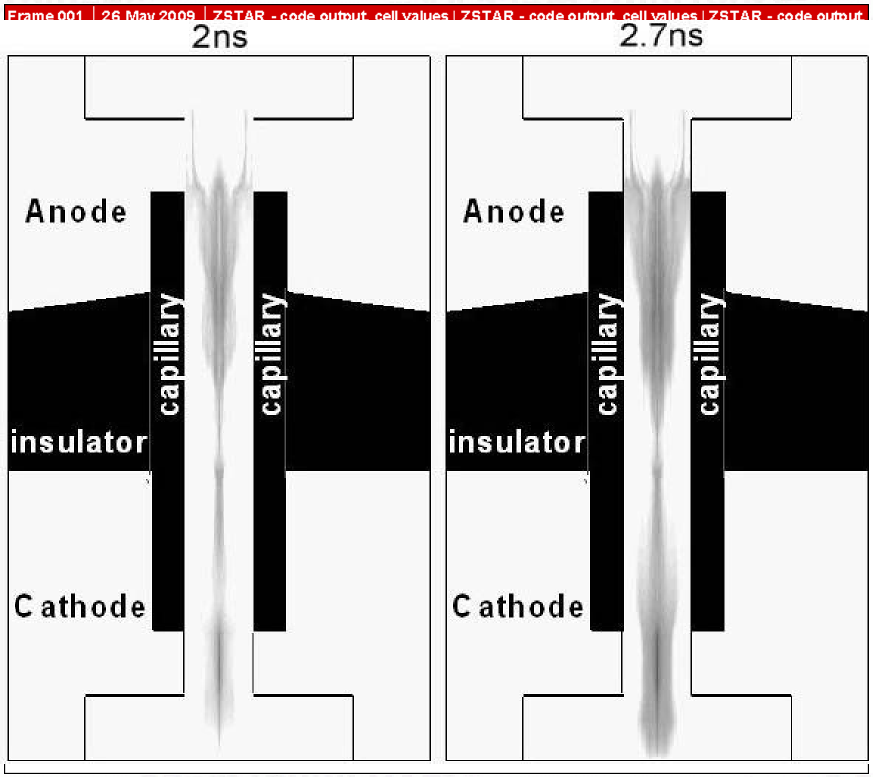
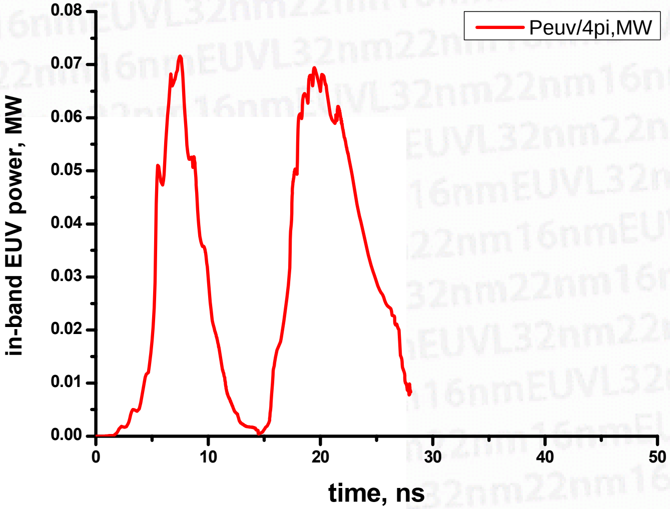
CYCLOPS™BE-16 EUV Source Unit

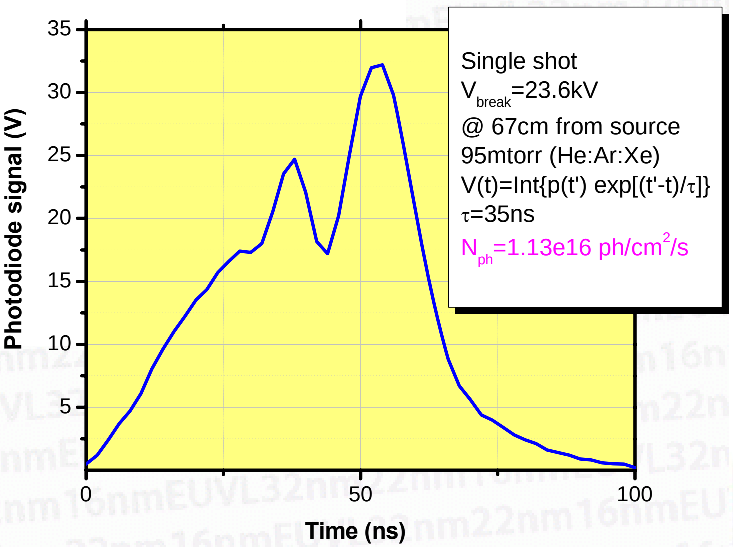
modeling & measurements

Hollow cathode triggered capillary discharge

a beam of run-away electrons ⇒ e-beam gas ionization ⇒ ionization wave ⇒ radiation-MHD







Fast electrons shift the xenon plasma ionization equilibrium increasing the in-band EUV emission from capillary discharge

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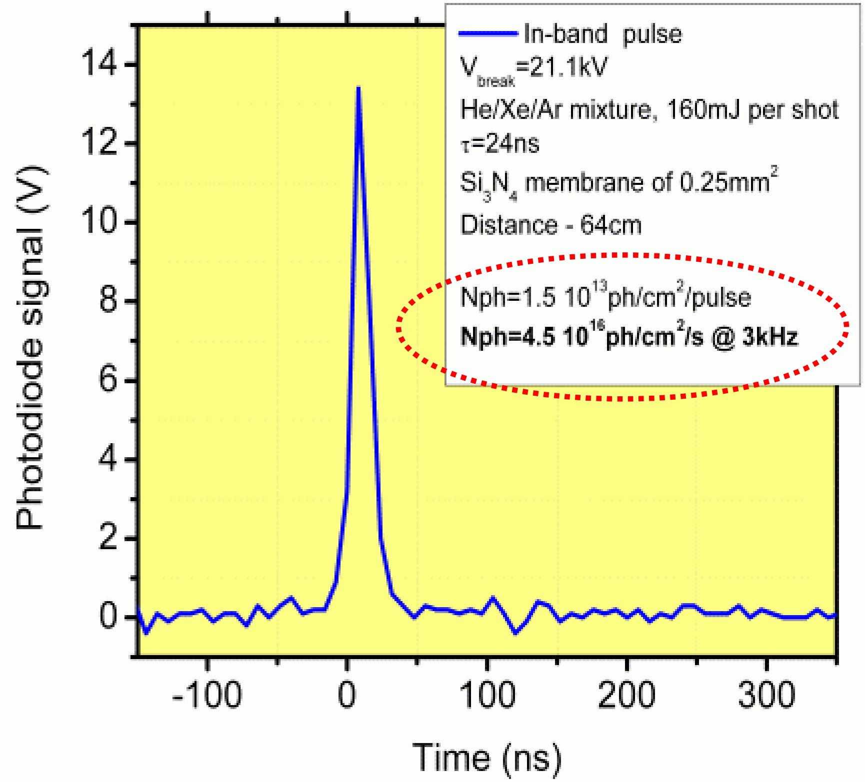
CYCLOPS™ BE-16 for Metrology

- Exceptional source brightness* and power** at 3 kHz

* irradiance - greater than $4 \cdot 10^{16}$ EUV photons/cm^2/s measured at 64 cm from the source over a 5 mm^2 area, 13.5nm, 4%BW

** equivalent source power - more than 30 kW (2π sr, 13.5 nm, 4% BW)



XIL beamline at the Swiss Light Source

Energy range:	10 - 135 eV
Flux (91 eV):	2.4 x 10^{15} ph / s / cm^2 / 2.8%BW / 0.3A
Spot size:	4 mm x 4 mm

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Source Characteristics

- Emission properties measured
  - time averaged source diameter

    0.6 mm FWHM

    1.02 mm^2 spot size ($1/e^2$)
  - emission angle

    0.32° half angle

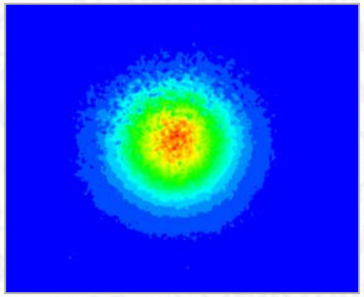
    9.5 e-5 steradian
  - source etendue

    9.7 e-5 mm^2.sr
  - EUV radiant brightness*

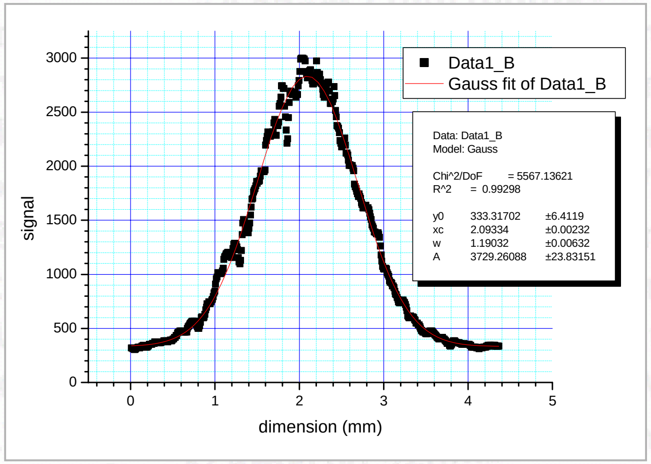
    4.5 e18 photons/(mm^2.sr.s)/4% BW [1s average]

    8.3 e22 photons/(mm^2.sr.s)/4% BW [1 pulse peak]

    * using average signal on SXUV5 diode of 10^{11} photons (91 eV) after 2 ML reflection



Source image through 400 μm pinhole
- 1 min exposure, 6 E4 shots integrated
image sensor at 108 cm from source



Guassian fit of emission profile recorded

\- **a very bright source for metrology** -

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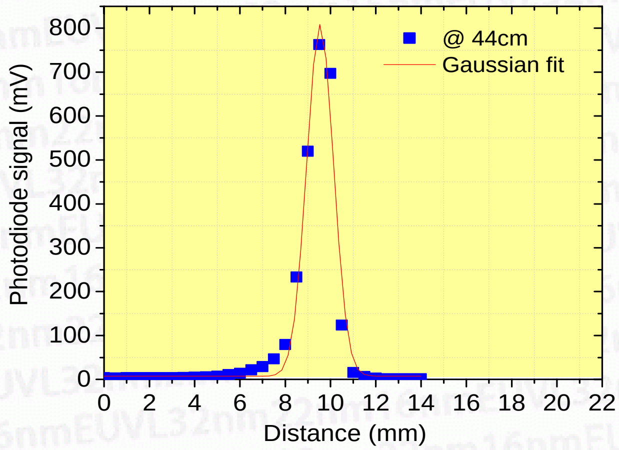
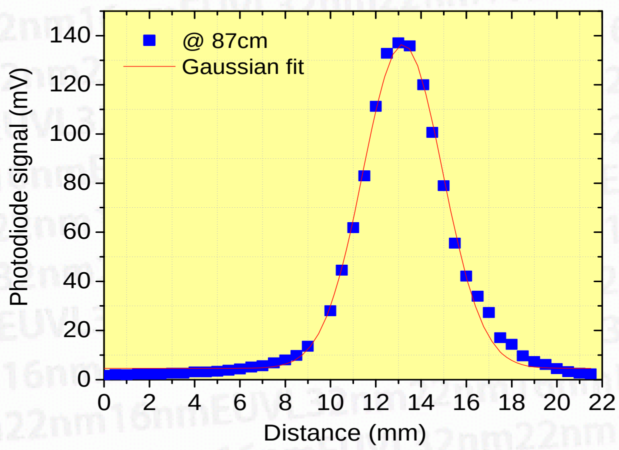
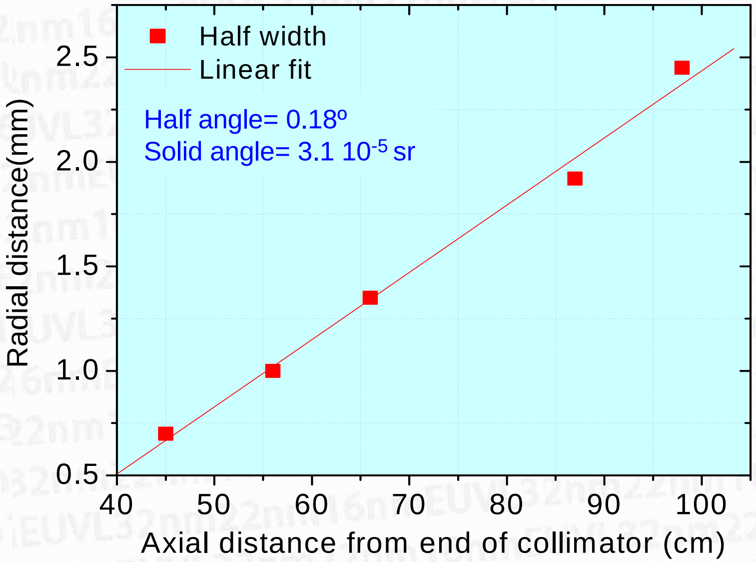
PlasmaLens™

- Optical properties
  - single Gaussian profile fitting to obtain radiation half width
  - source diameter ($1/e^2$ spot size) 2.5 mm at 44 cm from exit of PCS; 69 cm from plasma source





Slit-scan spatial profile



- **very small etendue: < 10^{-4} mm^2.sr** -

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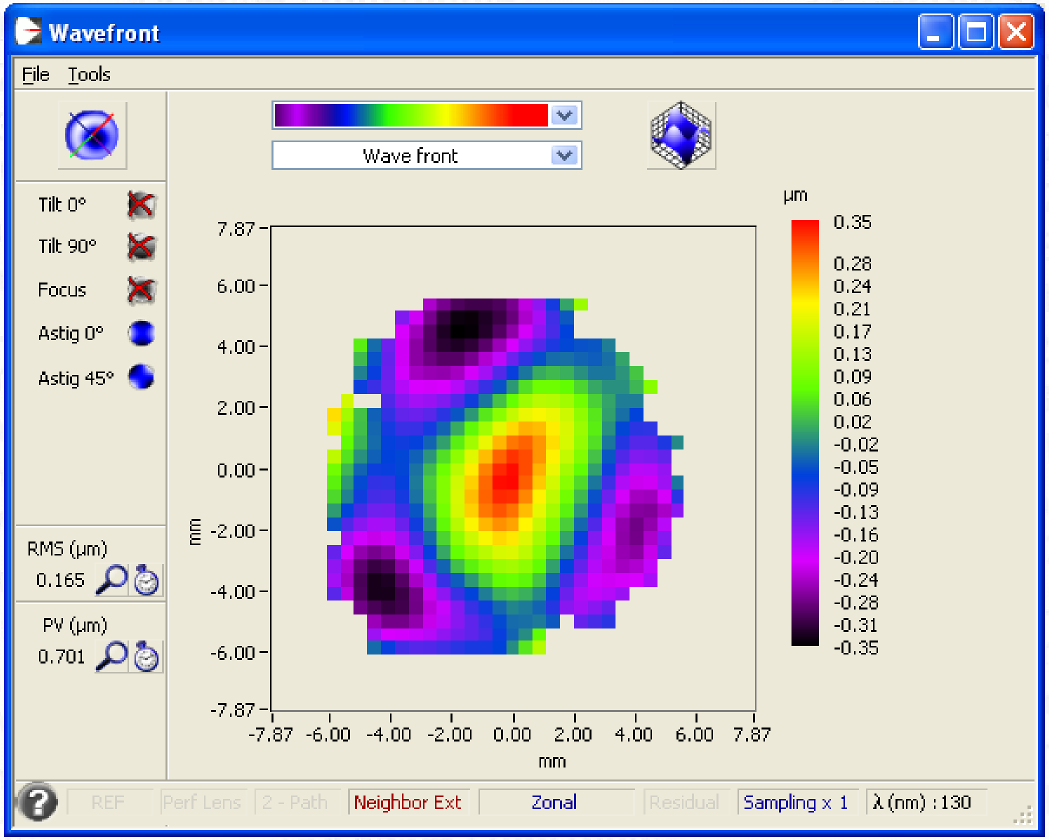
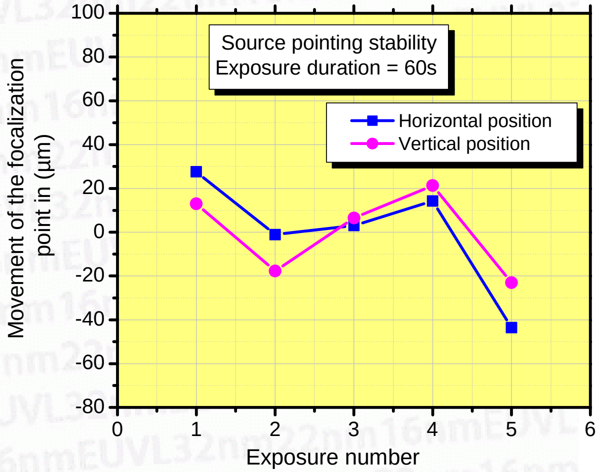
Wavefront Characteristics

HASO™ X-EUV Shack-Hartmann wavefront sensor measurements *





Exposure time = 60s at 1kHz repition rate

Beam divergence half angle =0.18°

EUV beam diameter = 9.1mm at distance between CCD and focal spot =1430mm

Etendue =4.4e-5 mm² sr

* with support of G. Dovillaire, E. Lavergne from Imagine Optic and P. Mercere, M. Idir from SOLEIL Synchrotron

Imagine Optic www.imagine-optic.com

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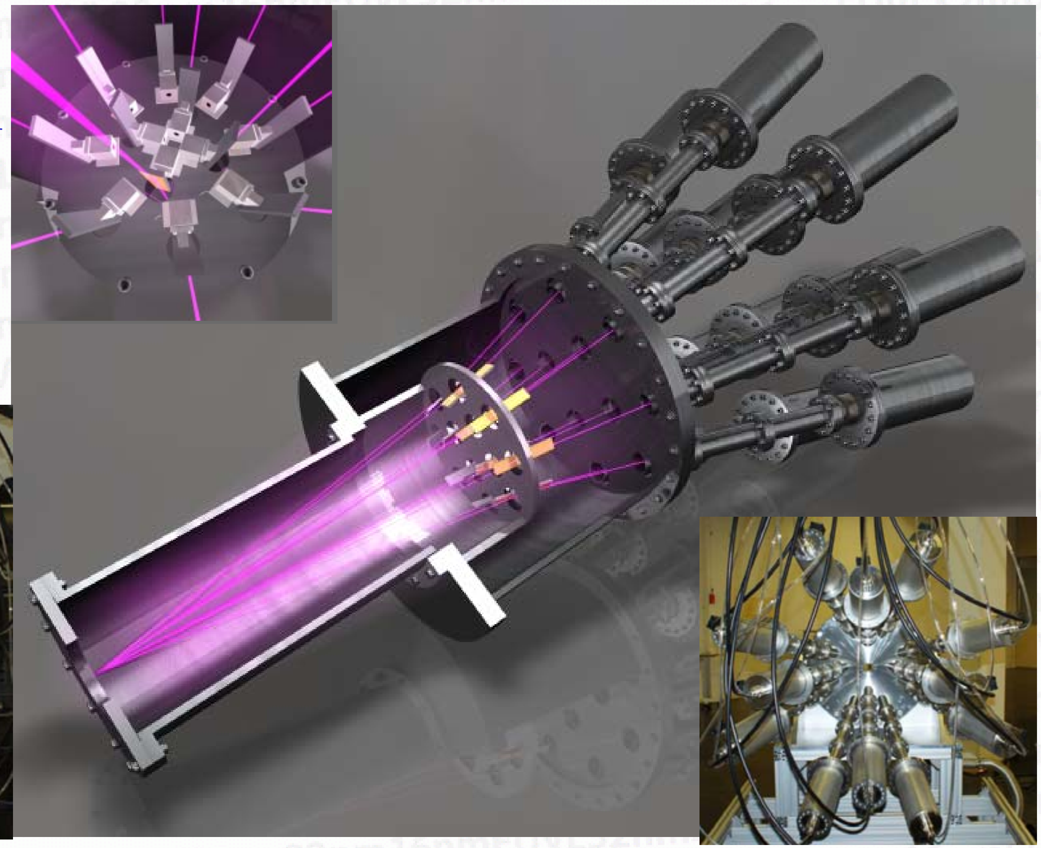
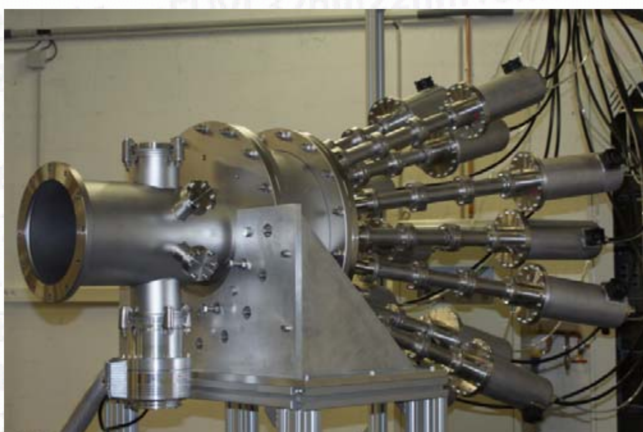
nano UV

HYDRA™-12BE18

- a EUV source for mask metrology

- Design Specification
  - 10^{18} photons/cm^2/s/2% BW in-band EUV irradiance
  - 12x i-SoCoMo™ units working at 5 kHz each
  - configurable pupil fill
  - etendue ~ 10^{-2} mm^2.sr





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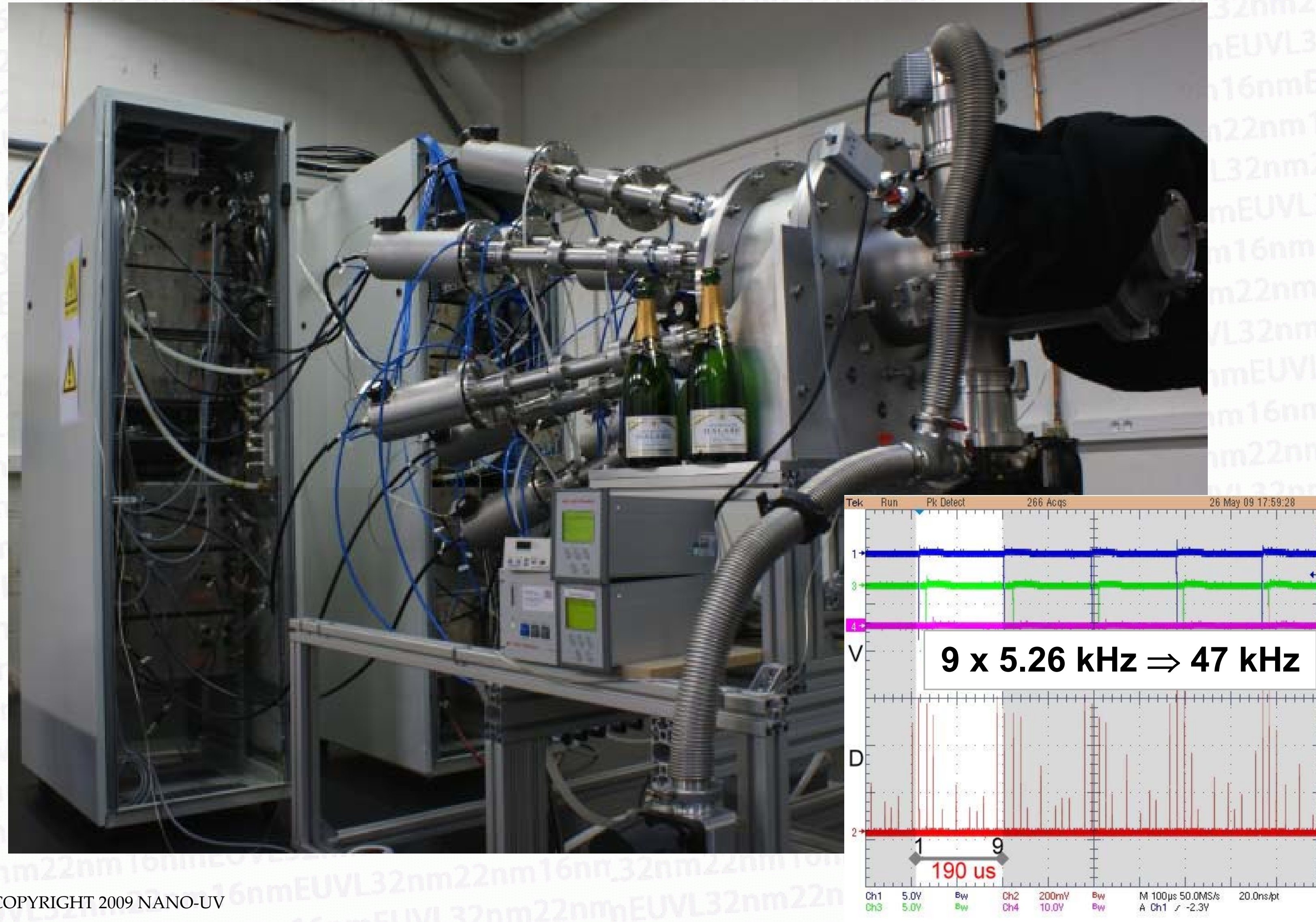
HYDRA™-12BE18

- demonstrating spatial multiplexing



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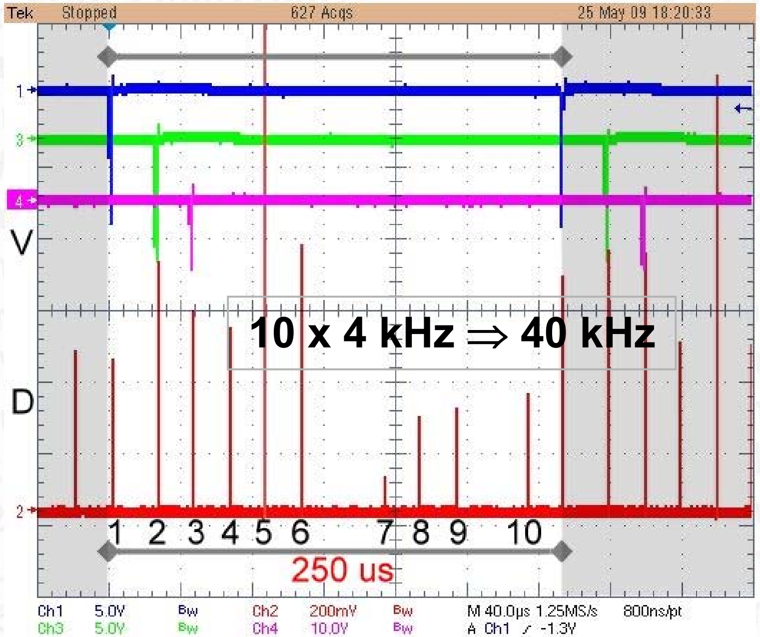
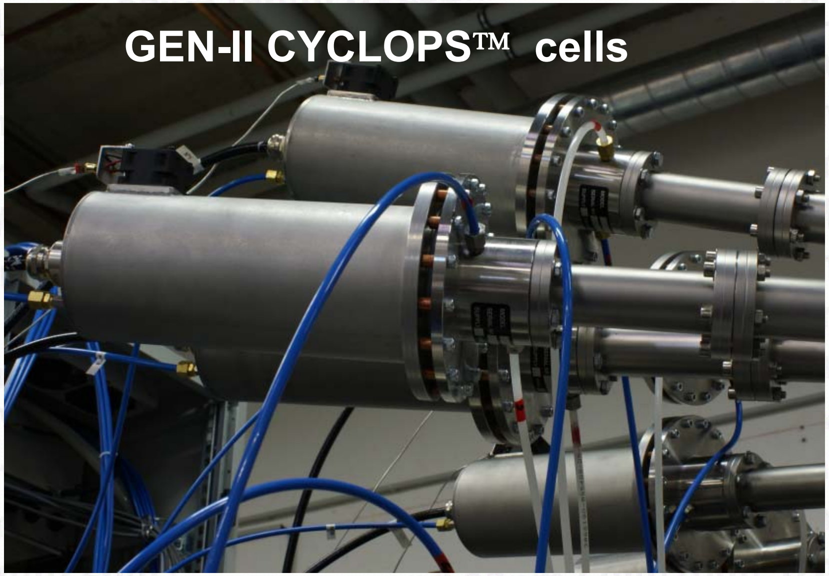
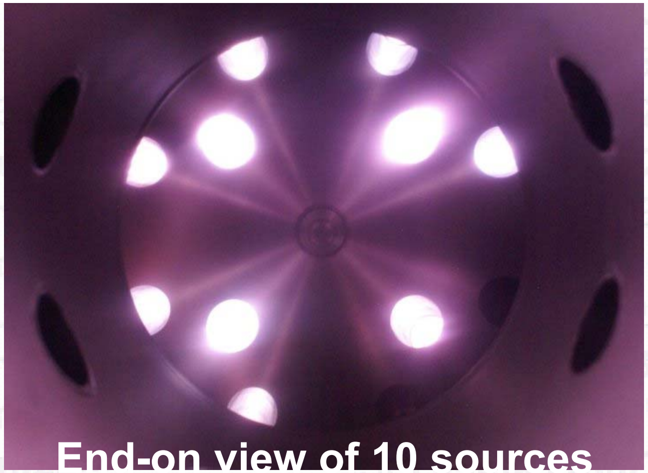
HYDRA™-12BE18

- a 40 kHz continuous source

- System Performance
  - spatial multiplexing well behaved
  - small cross talk in sequential operation
  - plug and play
  - needs to tune individual cell
  - 10x i-SoCoMo™ units commissioned so far




GEN-II CYCLOPS™ cells


End-on view of 10 sources

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Summary

- Knowledge of the behaviour of multicharged ion non-equilibrium plasma with ionization phenomena, radiation and fast particles transfer is critical for EUV source development
- Self-absorption defines the limiting brightness of a single EUV source, required for the HVM and AIM tools with high efficiency at given the limiting etendue of the optics
- The required irradiance can be achieved by spatial multiplexing, using multiple small sources
- Extra EUV in-band emission may be achieved from highly charged Xe ions in plasma with fast electrons
- NANO-UV presents a new generation EUV light source unit, incorporating the i-SoCoMo™ technology, together with early experiences of operating sources in a multiplexed configuration, which can satisfy the source power and brightness requirements for an at-line mask inspection tool, and in future for HVM .

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