# High brightness EUV light source system development for actinic mask metrology

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**NANO-UV sas**
**EPPRA sas**

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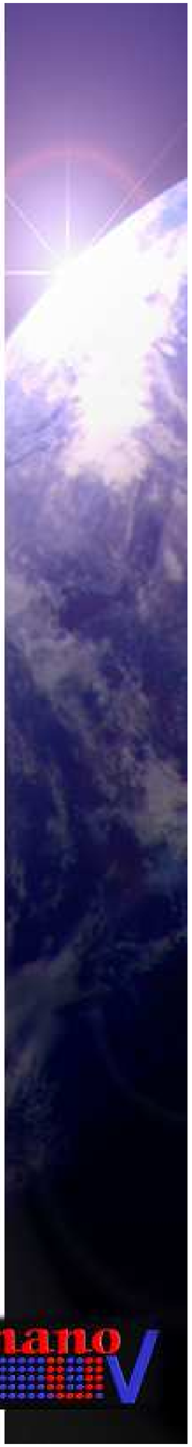
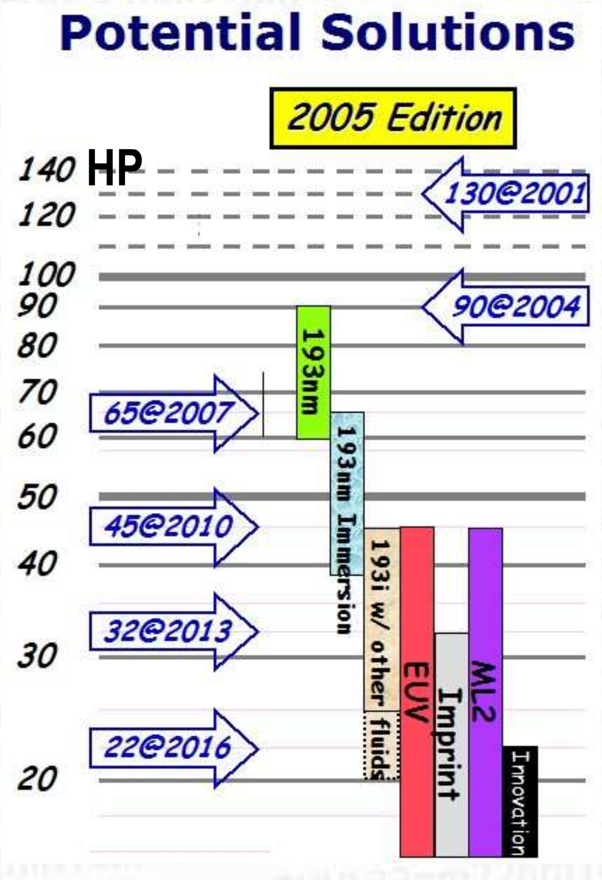


# Outline

- Challenges to EUVL deployment
- Special light source for mask inspection
- ZETA-Z* RMHD codes
- Non-equilibrium plasma kinetic model
  - plasma radiance limit
  - highly charged Xe ion EUV emission
- Combined Nd:YAG-$CO_2$ laser pulse
- Nano-UV: EUV and soft X-ray source
- Multiplexed high brightness EUV sources
- Summary

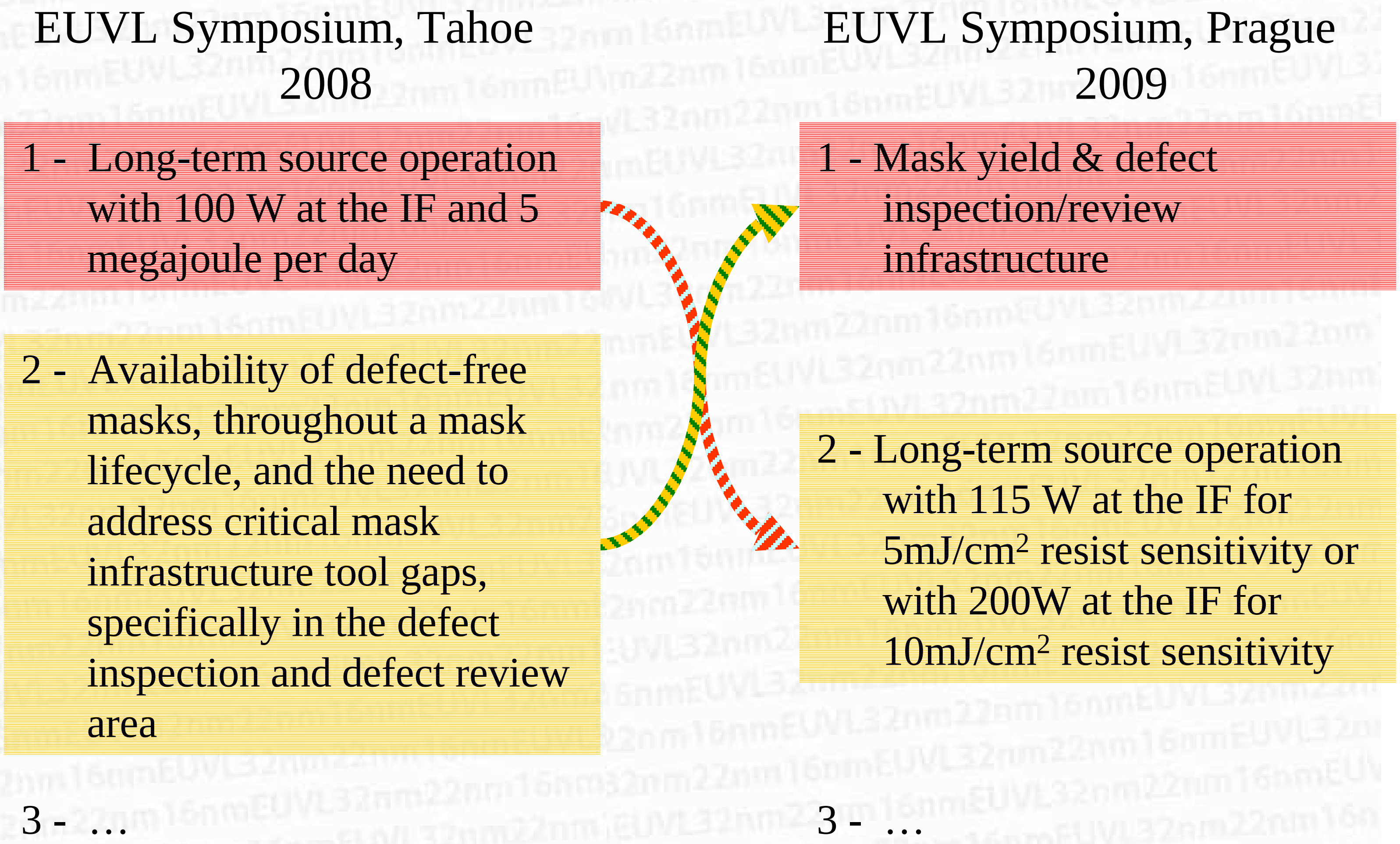
# EUV (13.5nm wavelength) lithography

## chosen for nano features microchip production



EUV source for HVM & actinic mask inspection
- a key challenge facing the industry

# Remaining Focus Areas



EUVL Symposium, Tahoe
2008

1 - Long-term source operation with 100 W at the IF and 5 megajoule per day

2 - Availability of defect-free masks, throughout a mask lifecycle, and the need to address critical mask infrastructure tool gaps, specifically in the defect inspection and defect review area

3 - …

EUVL Symposium, Prague
2009

1 - Mask yield & defect inspection/review infrastructure

2 - Long-term source operation with 115 W at the IF for 5mJ/cm$^2$ resist sensitivity or with 200W at the IF for 10mJ/cm$^2$ resist sensitivity

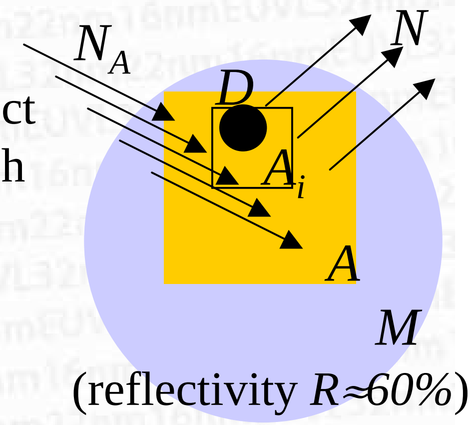
3 - …

**- light source for Litho and mask inspection critical -**

# EUV Brightfield Metrology

## - requirements

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



(reflectivity $R \approx 60\%$)

- 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 $A = A_i \cdot n^2$
- relative defect response > *N* photon statistics
- total illumination time: $t = t_A \cdot M \cdot m^2 / n^2 \cdot A_p$
- illuminating irradiance required: $\dfrac{N_A}{A \cdot t_A} > \dfrac{4}{R} \dfrac{M}{D^2 t \cdot \boxed{n^2}}$
- then for defect size 10 nm, a $(9\mu m)^2$ pixel size, $2048^2$ CCD array and full size $(4^2 \times (26 \times 33)\ mm^2)$ mask inspection:

| 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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# Actinic Mask Inspection
## - key source requirements based on current studies

**Source Workshop 2009 Baltimore**

ZEISS

| | Power in used Field | Field Size | Source Radiance Requirement |
|---|---|---|---|
| AIMS | 0.5 mW | 10x10 um | 50 W/mm2/sr |
| Actinic blank inspection | 10 W | 1x1 mm | 100 W/mm2/sr |

Selete

| Item | Requirements |
|---|---|
| **Wavelength (nm)** | 13.5 |
| **EUV power (in-band) into $2\pi$, at plasma (W)** | >10 |
| **EUV power (in-band), after collector (W)** | >0.1 |
| **Source area (mm$^2$)** | <0.12 |
| **Etendue of source output (mm$^2$ sr)** | <0.01 |
| **Max. solid angle to system (sr)** | <0.1 |
| **Brightness (Wmm$^{-2}$sr$^{-1}$)** | >14 |
| **Repetition rate (kHz)** | >2<br>(higher rep. rate preferable) |
| **Integrated energy stability (%)** | <1<br>(0.1s integration) |
| **Source cleanliness** | <10% throughput loss/30 billion pulses for collector mirror |
| **Spectral purity** | (No large impact) |

| Scan Time (hrs) | # EUV Mirrors | Power @ IF (W) Hi-Res | Power @ IF (W) Aerial | Radiance @ IF (W/mm2-sr) Hi-Res | Radiance @ IF (W/mm2-sr) Aerial |
|---|---|---|---|---|---|
| 1 | 2 | 2.4 | 1 | 1030 | 345 |
| 1 | 4 | 5.8 | 2.5 | 2510 | 840 |
| 3 | 2 | 0.8 | 0.3 | 340 | 115 |
| 3 | 4 | 1.9 | 0.8 | 840 | 280 |

*Probable Long-term requirement*

Etendue at IF: 2 x $10^{-3}$ mm$^2$-sr

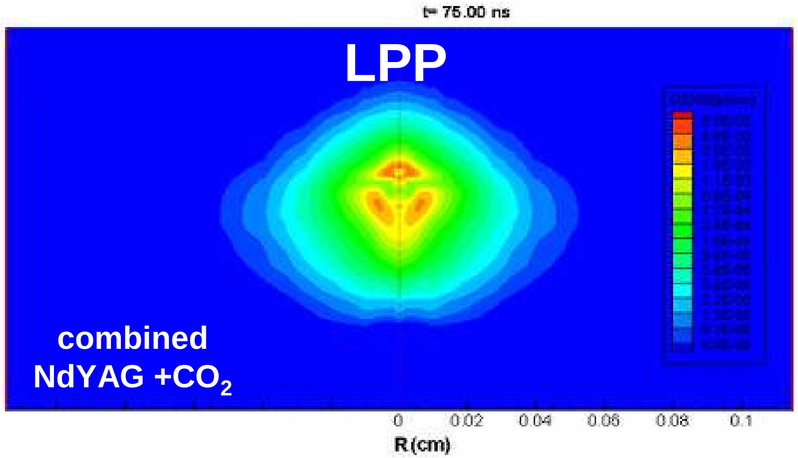
KLA-Tencor Accelerating Yield

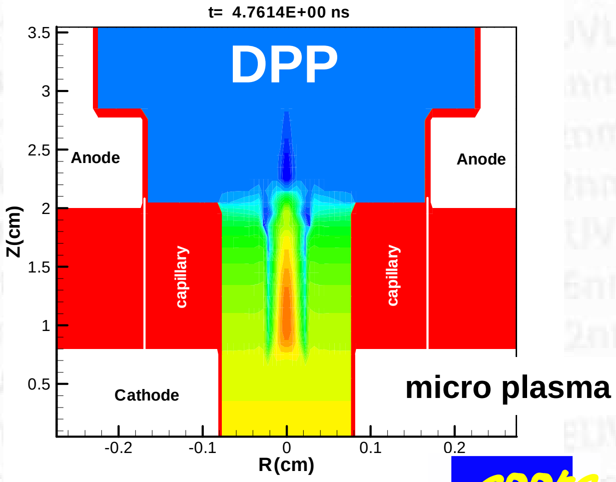
- **High-brightness, small-etendue, high-repetition-rate, and clean light source is preferable**

# EUV Light Source

## - in practice

- Sn, Xe, Li … high energy density plasma - narrow 2% band @ 13.5nm source of EUV light
- LPP & DPP - methods to produce the the right conditions HED plasma



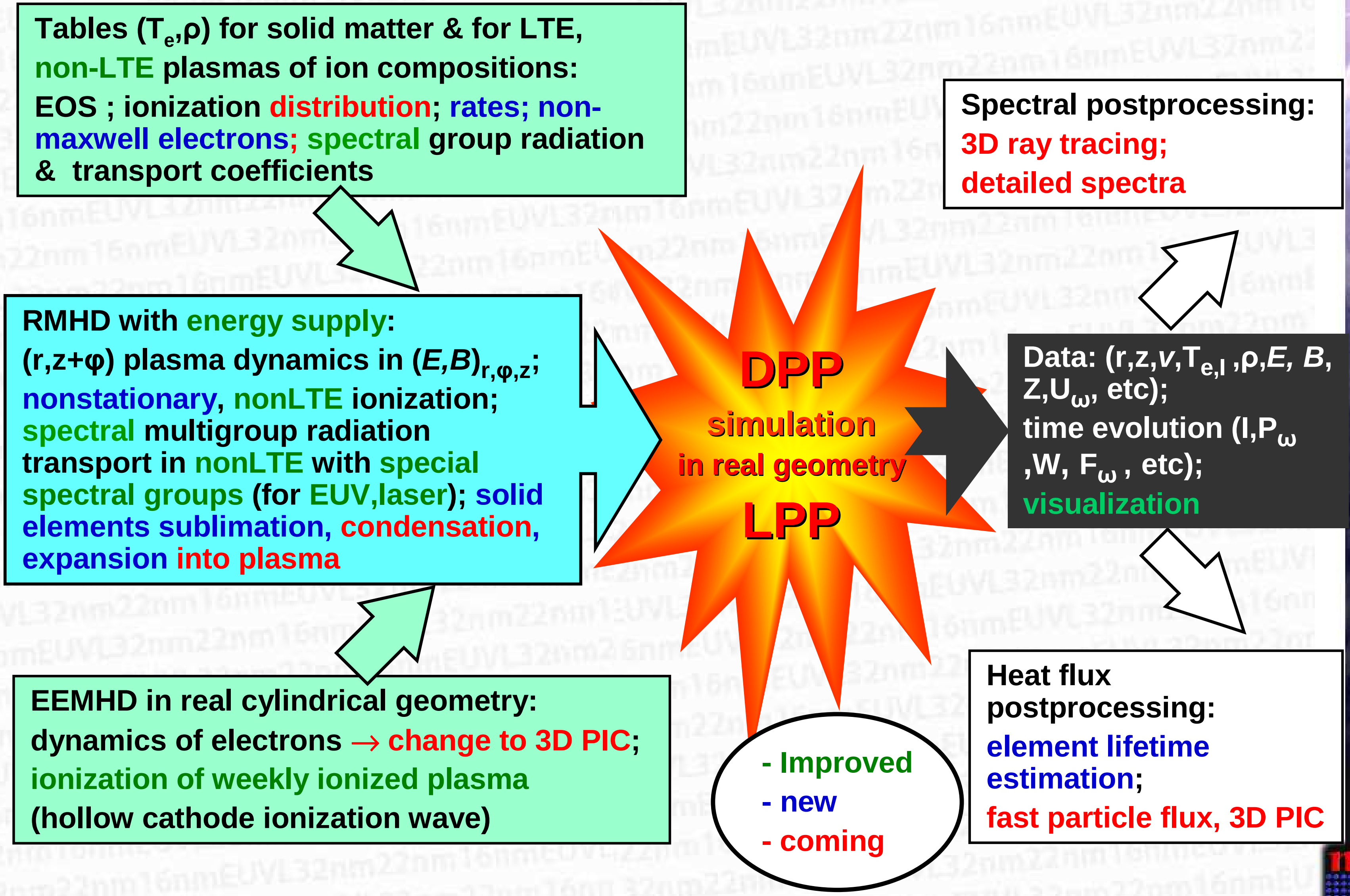


**Z * MHD code modeling**

- For HVM - at least 200-500 W of in-band power @ IF with etendue < $3mm^2sr$ is required

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

# ZETA → $Z^*$ RMHD Code → $Z^*$ BME physical model



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

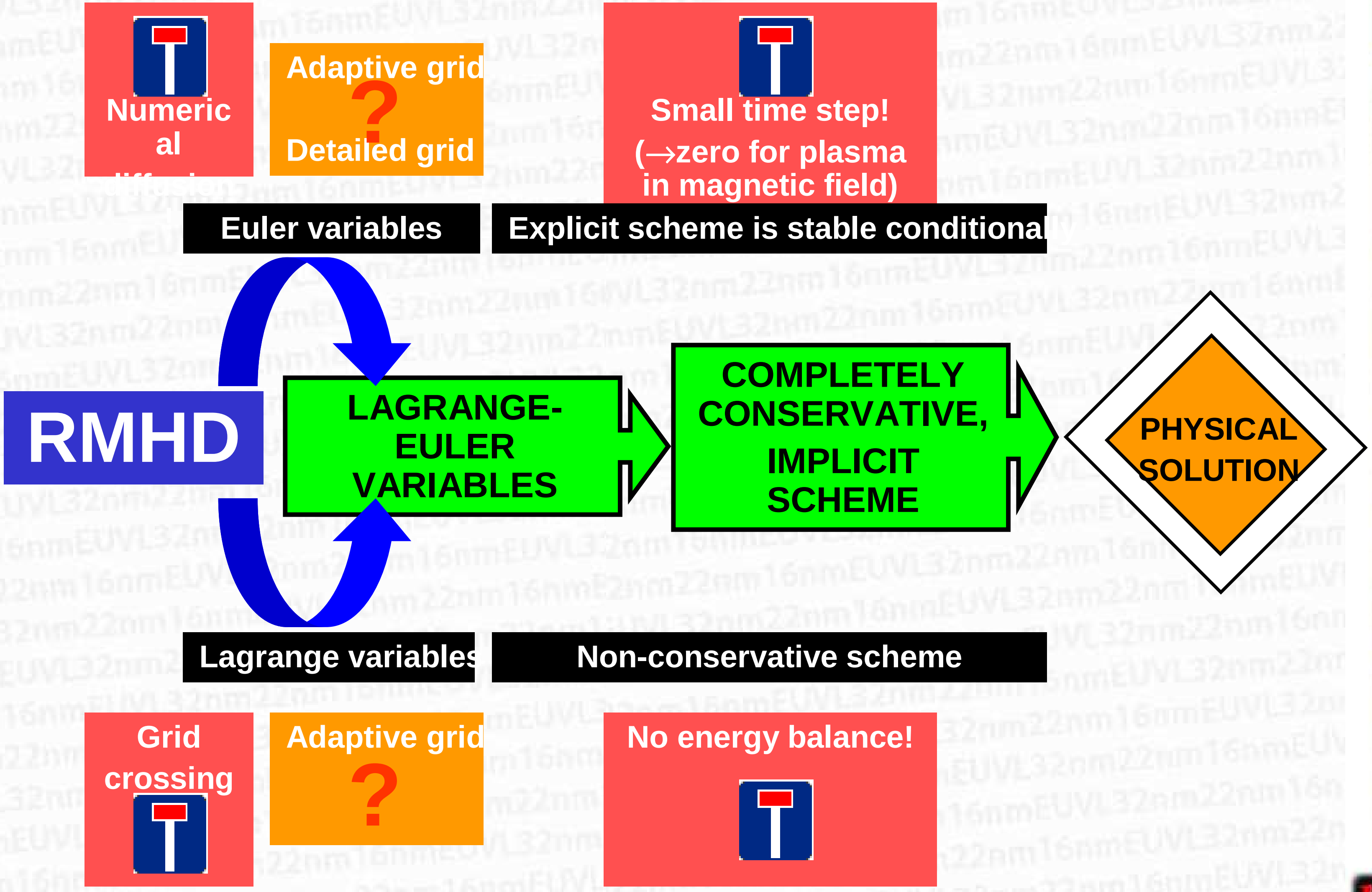
Data: (r,z,v,$T_{e,I}$ ,ρ,E, B, Z,$U_\omega$, etc);
time evolution (I,$P_\omega$ ,W, $F_\omega$ , etc);
visualization

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

- Improved
- new
- coming

# ZETA → Z* RMHD Code → Z* BME

## mathematical model: algorithms & schemes



Numerical

Adaptive grid ? Detailed grid

Small time step! (→zero for plasma in magnetic field)

Euler variables

Explicit scheme is stable conditional

RMHD

LAGRANGE-EULER VARIABLES

COMPLETELY CONSERVATIVE, IMPLICIT SCHEME

PHYSICAL SOLUTION

Lagrange variables

Non-conservative scheme

Grid crossing

Adaptive grid ?

No energy balance!

# EUV Brightness Limit of a Source

- The intensity upper Planckian limit of a single spherical optically thick plasma source in $\Delta\lambda/\lambda$=2% band around $\lambda$=13.5nm

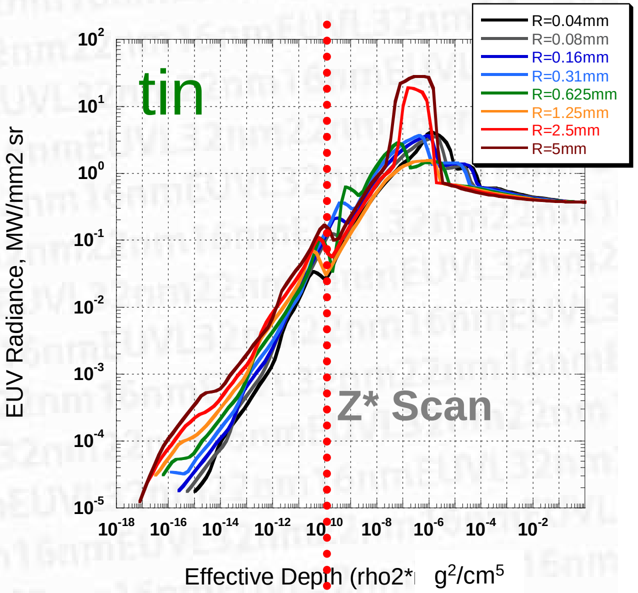
$$I = \frac{2hc^2}{\lambda^4}\frac{\Delta\lambda/\lambda}{e^{\frac{hc}{\lambda T}}-1} \approx \frac{72}{e^{\frac{92}{T(eV)}}-1}(MW/mm^2 sr)$$

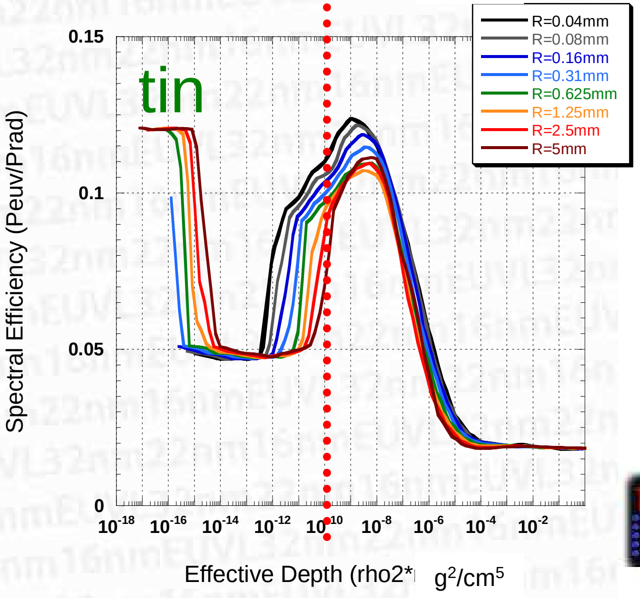
- Source with pulse duration $\tau$ and repetition rate $f$ yields the time-average radiance $L = I\cdot(\tau f)$

- At $T \approx 22eV$ $L \approx 1.1(W/mm^2\ sr)\cdot\tau(ns)\cdot f(kHz)$
- For $\tau = 20 \div 50ns$ $L = 20 \div 50\ (W/mm^2\ sr)/kHz.$

- Plasma self-absorption defines the limiting brightness of a single EUV source and required radiance
- The plasma parameters where EUV radiance is a maximum are not the same as that when the spectral efficiency is a maximum.

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





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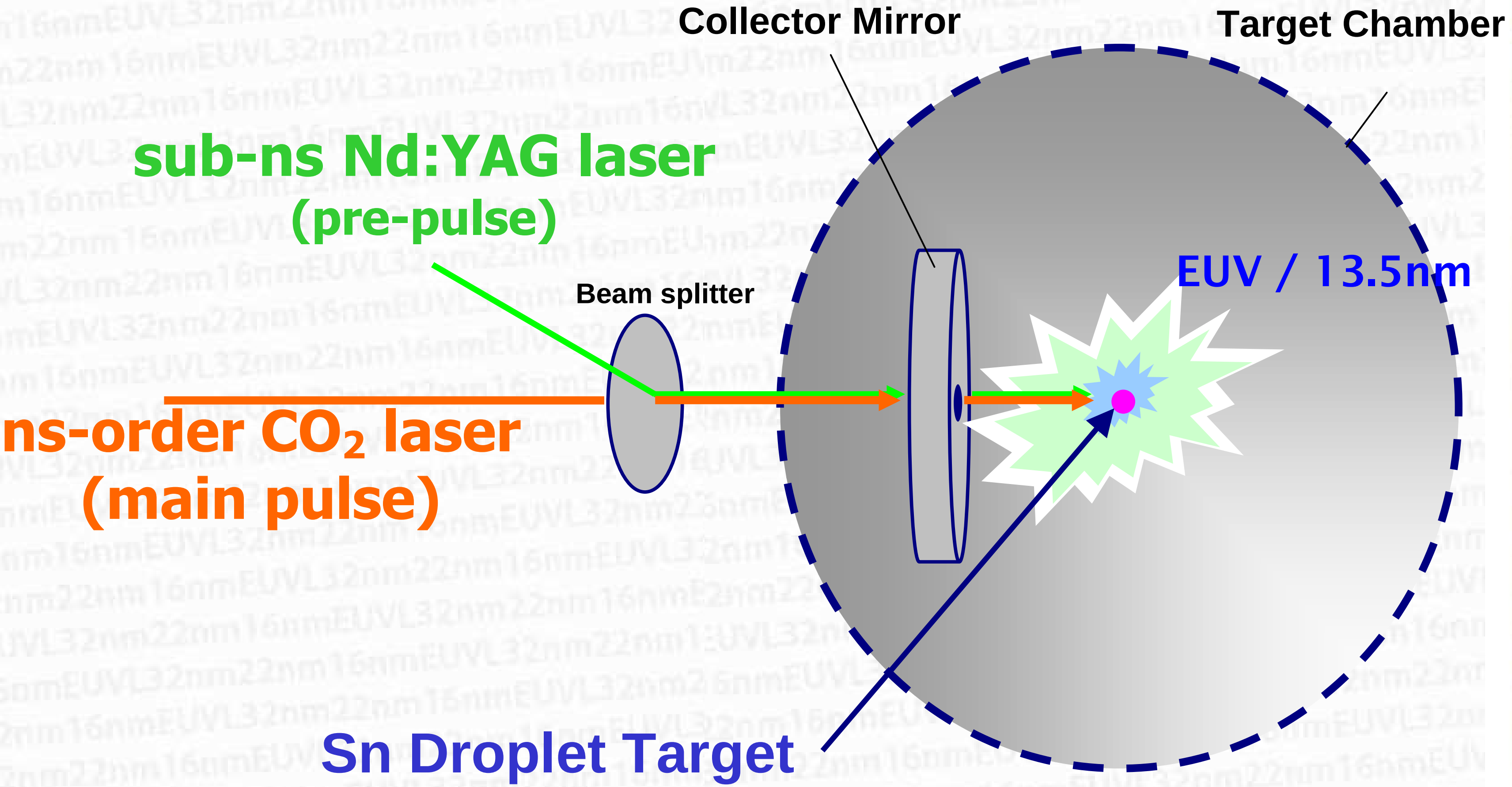
# Combined Nd:YAG - CO$_2$ Laser System



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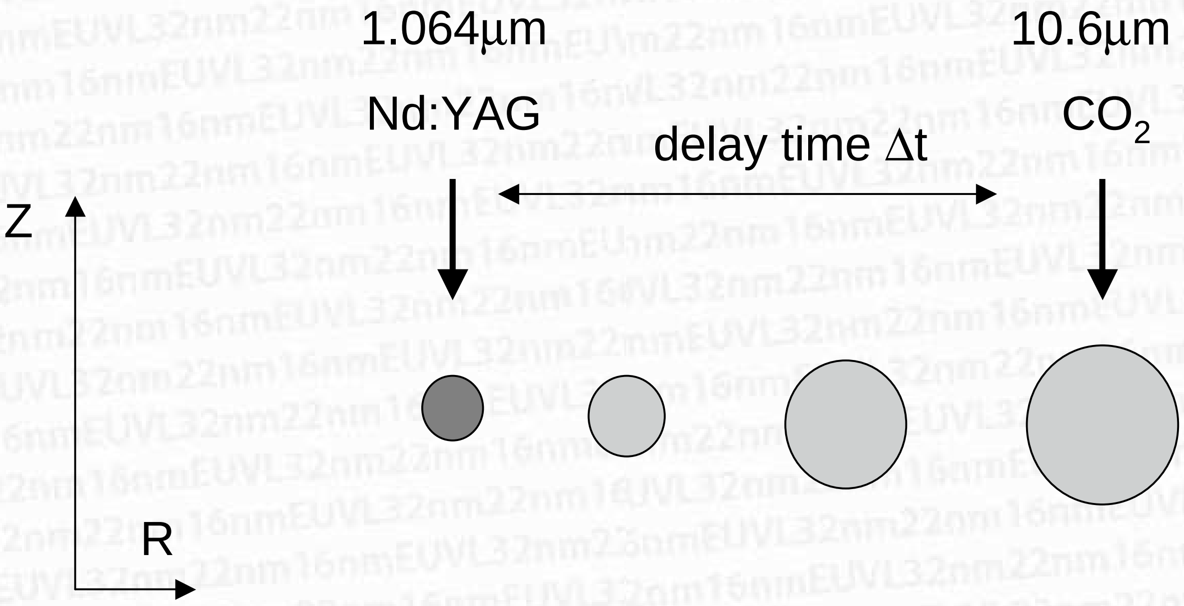
# Combined Nd:YAG - $CO_2$ Laser System - layout



100 times lower density in case of a $CO_2$ laser with respect to a Nd:YAG laser as the main pulse gives a chance

- to increase the EUV emission efficiency by lower reabsorption of EUV radiation
- to reduce debris using a small-size, i.e. low-mass, target

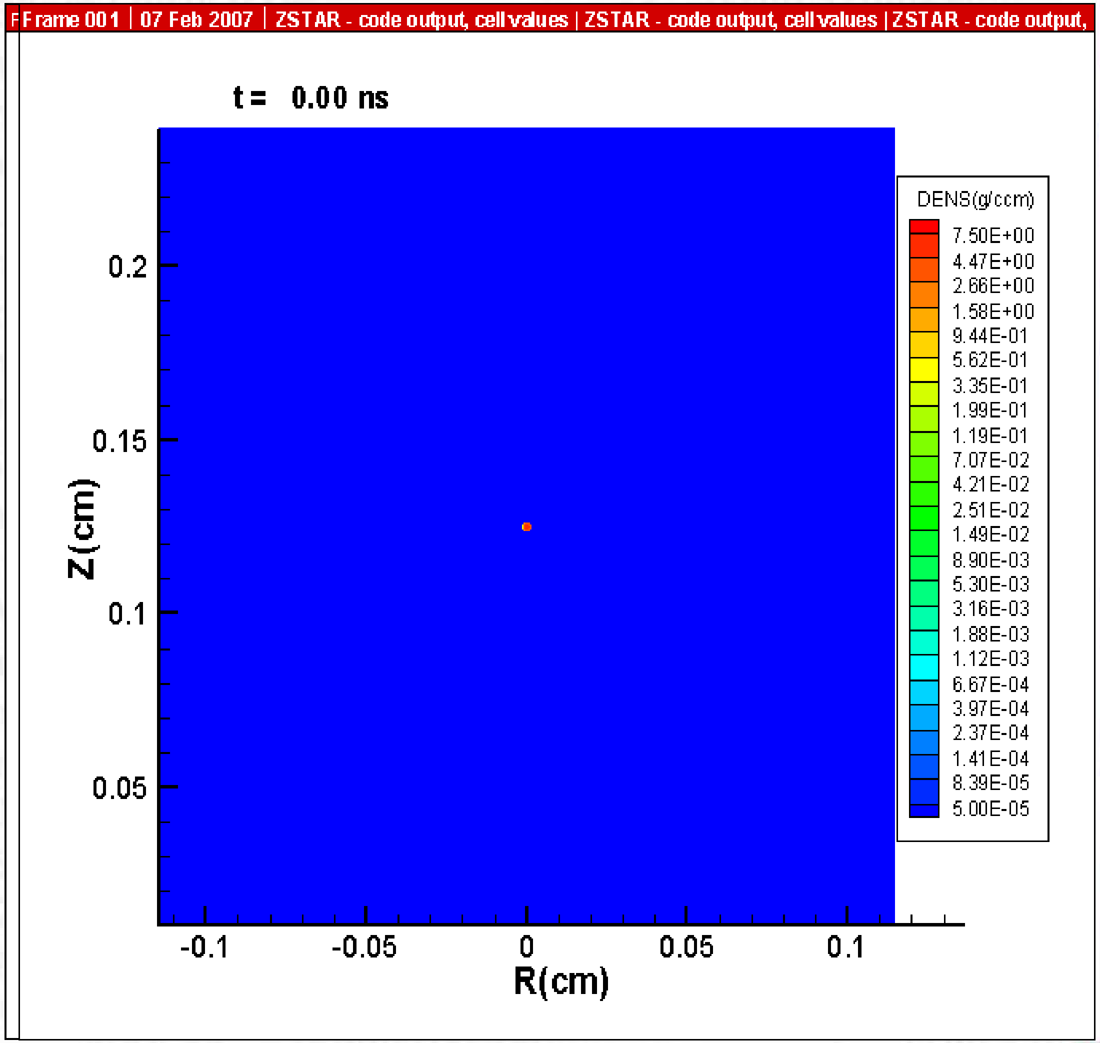
# LPP Dynamics & EUV Emission

## during pre- and main laser pulse

2.5mJ YAG laser pre-pulse energy.

Main laser pulse: $CO_2$, 50mJ, 15ns, 100 µm FWHM spot size.

The delay time between laser pulses is 75ns.



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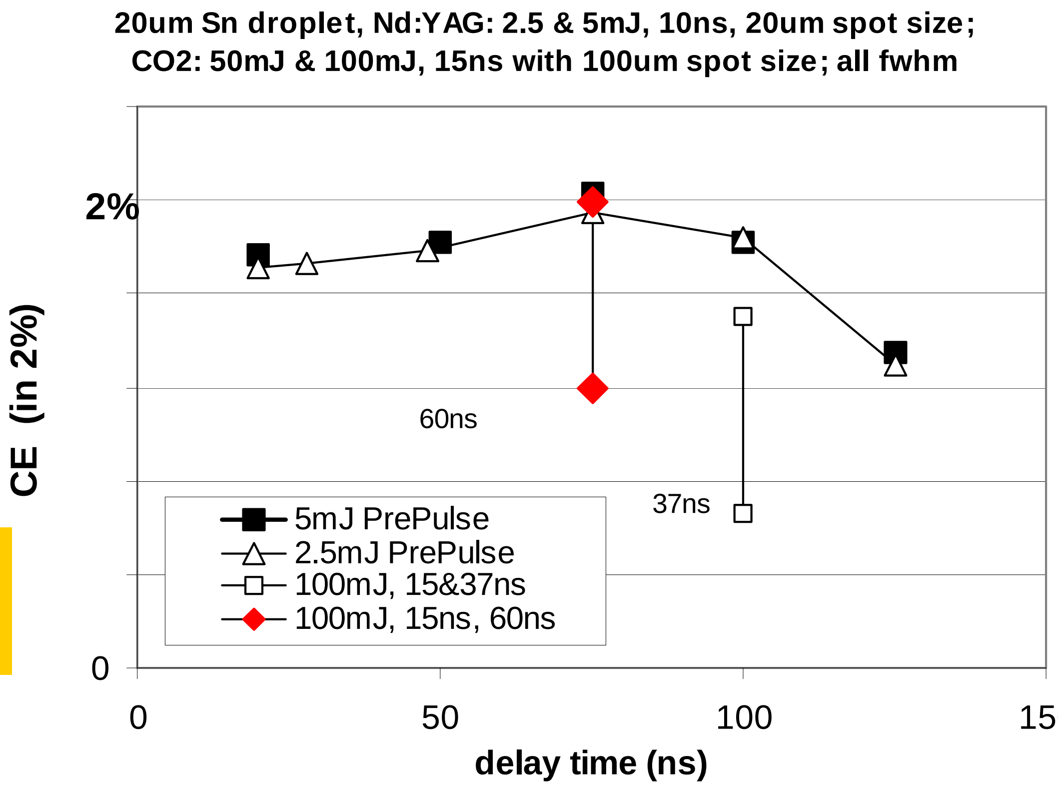
# Conversion Efficiency

## vs. pre-pulse to pulse delay time

Target: 20µm diameter Sn droplet
Pre-pulse laser: Nd:YAG, 10ns fwhm, 20µm spot size, pulse energy 2.5 & 5mJ
Main pulse: $CO_2$-laser, 15, 37 and 60ns fwhm, 100µm spot size



EUV brightness up to
5 W/mm² sr kHz

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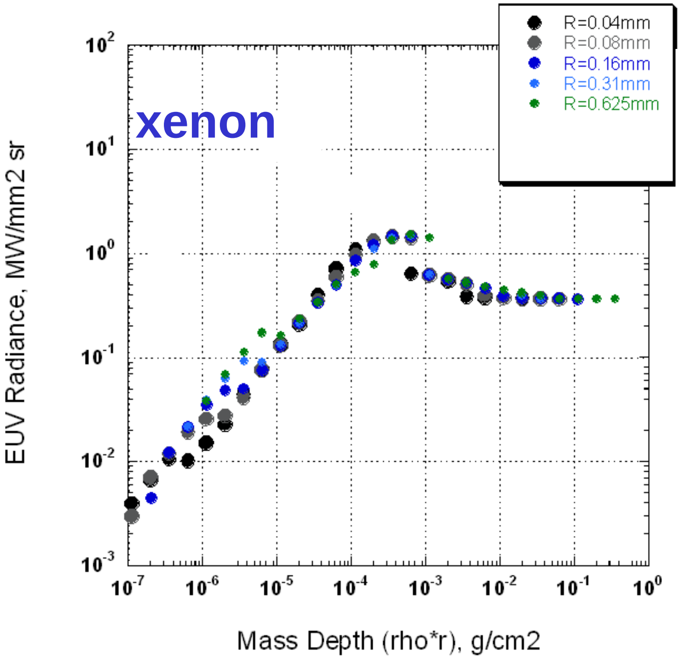
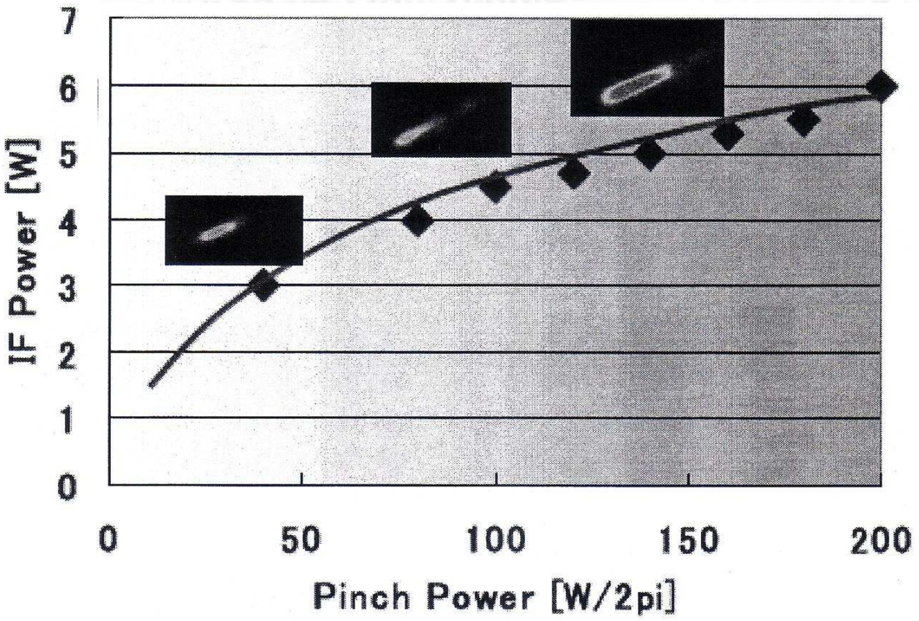
# EUV IF Power Limitation:

## prediction vs. observation

- Xenon plasma EUV emission



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



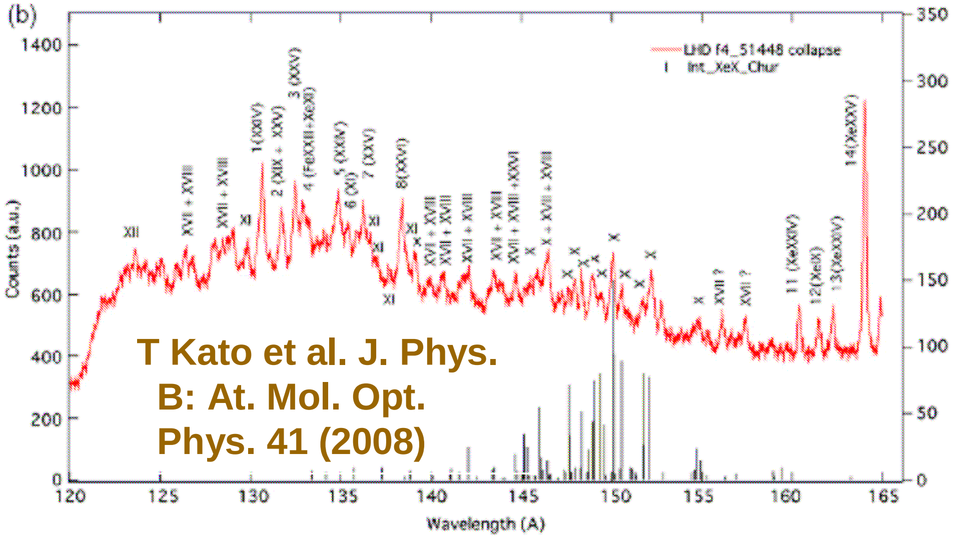
Experimental observation of limitation of the EUV power at IF from xenon DPP source

**[M. Yoshioka et al. Alternative Litho. Tech. Proc. of SPIE, vol. 7271 727109-1 (2009)]**

# Bright EUV Emission

## from highly charged xenon ions

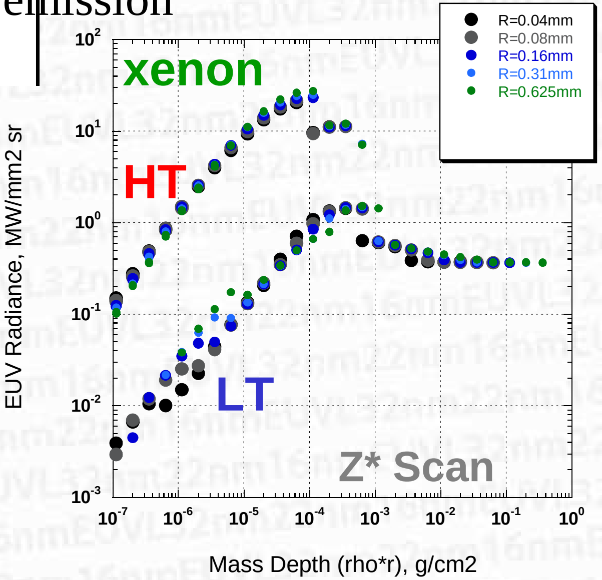
### Tokamak experimental data



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

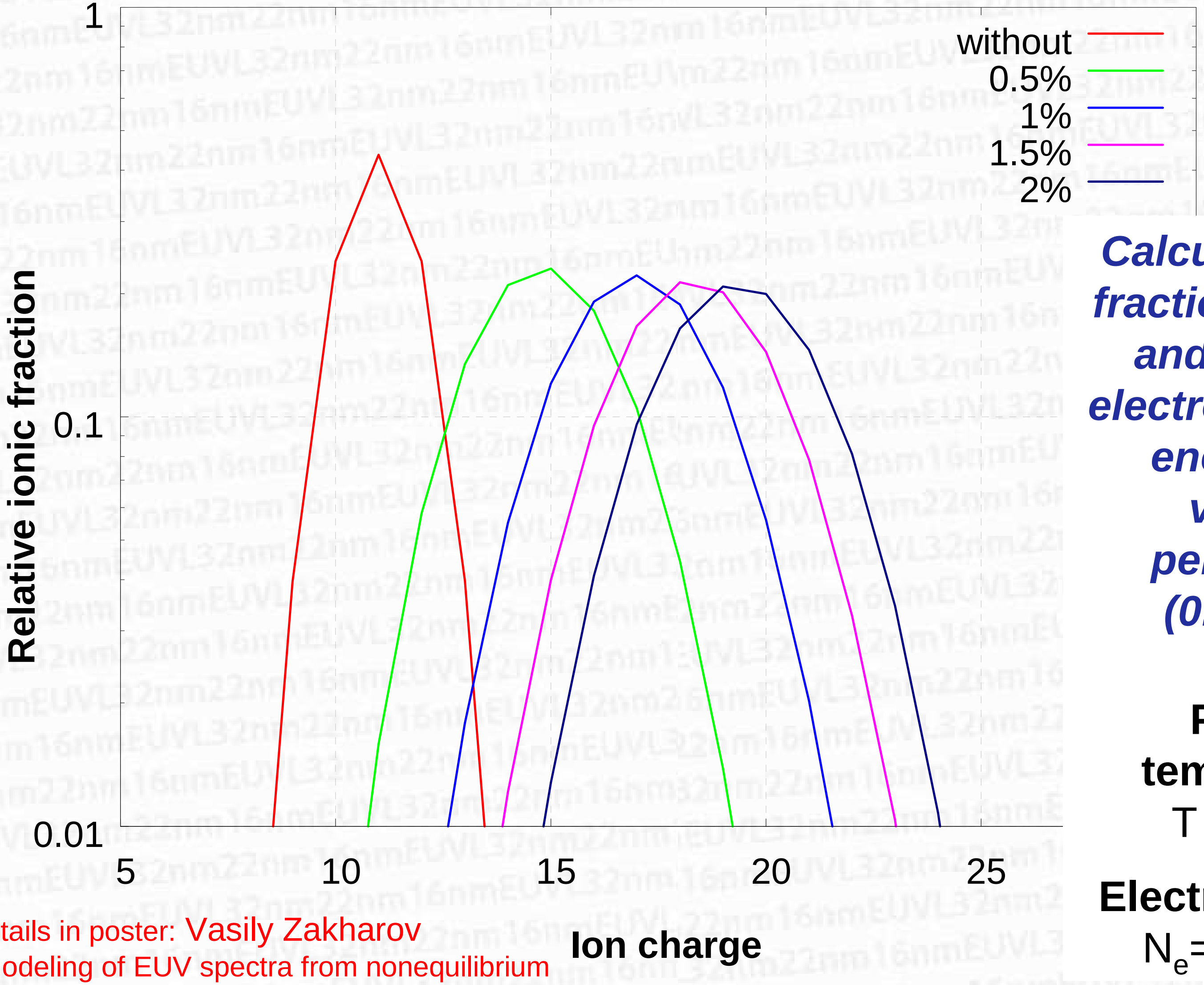
- **XeXXII - XeXXX** produce bright 4f-4d*, 4d-4p*, 5p-4d* [White, O'Sulivan] ($3d^n4f^1 + 3d^n4p^1 \rightarrow 3d^n4d^1$) satellites in EUV range near 13.5nm
- **XeXXII** has ionization potential 619eV

- 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 at 13.5nm.
- For small size xenon plasma, the maximum EUV radiance in the HT can exceed the tin plasma emission



# Non-Equilibrium Kinetics

## Xe ions population vs. e- fraction



***Calculated ionic fractions without and with fast electrons of 5keV energy and various percentage (0.5%-2%)***

**Plasma temperature**

T = 40 eV

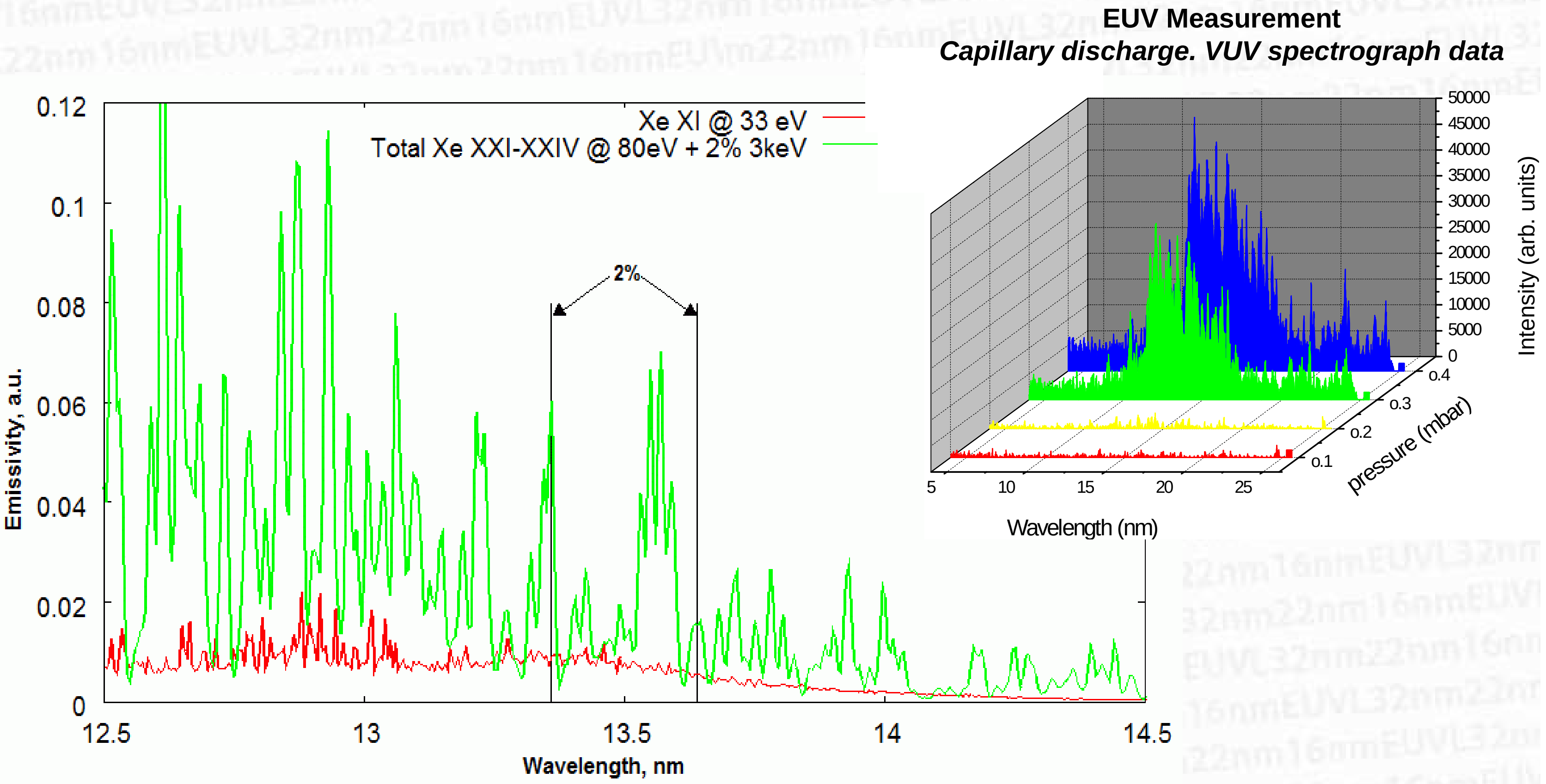
**Electron density**

$N_e = 10^{17}$ cm$^{-3}$

details in poster: Vasily Zakharov
“Modeling of EUV spectra from nonequilibrium xenon plasma with high energy electrons”

# Emission of Highly Charged Xe Ions

## - from e-beam triggered discharge plasma



**EUV Measurement**

***Capillary discharge. VUV spectrograph data***

**Bright EUV emission in 2% band at 13.5 nm can be achieved from highly charged xenon ions in plasma with small percentage of fast electrons**

details in the poster: Vasily Zakharov "Modeling of EUV spectra from nonequilibrium xenon plasma with high energy electrons"

# Multiplexing

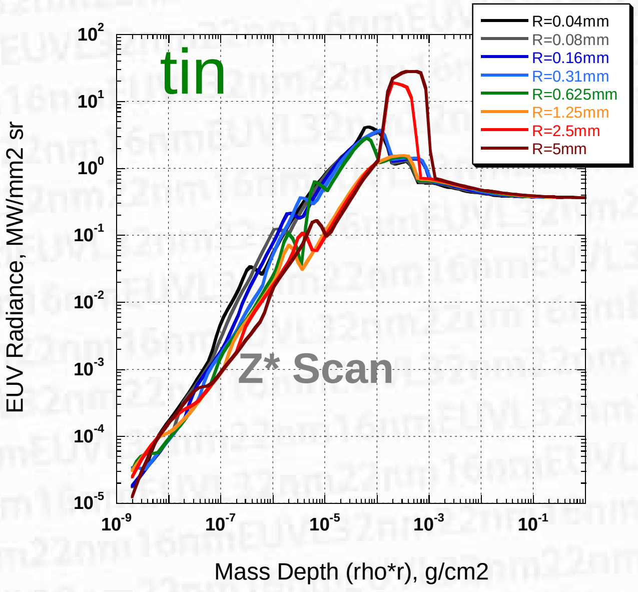
## - a solution for high power & brightness

- Small size sources, with low enough etendue $E_1=A_s\Omega << 1\ mm^2\ sr$ can be multiplexed.
- The EUV power of multiplexed N sources is

$$P_{EUV} \propto \sqrt{E \cdot N \cdot \Omega} \cdot \tau \cdot f$$

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

- This allows efficient re-packing of radiators from 1 into *N* separate smaller volumes without losses in EUV power



- Spatial-temporal multiplexing: The average brightness of a source and output power can be increased by means of spatial-temporal multiplexing with active optics system, totallizing sequentially the EUV outputs from multiple sources in the same beam direction without extension of the etendue or collection solid angle

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

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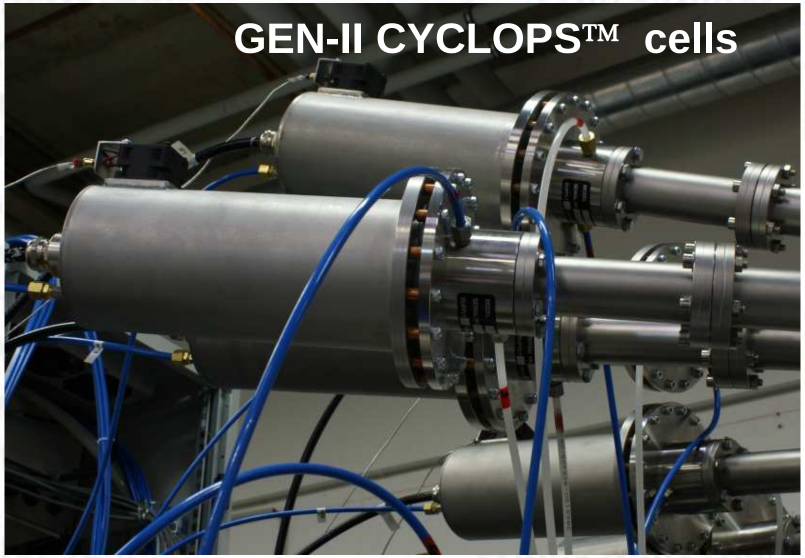
# Nano-UV: High Brightness EUV Source

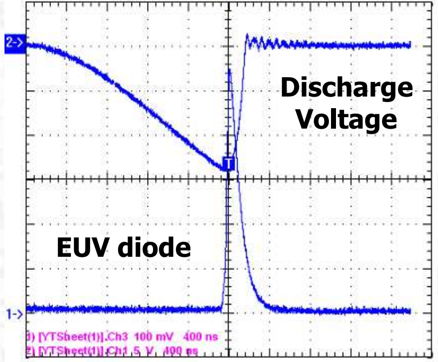
## capillary discharge pulsed micro-plasma

### Measured Performance

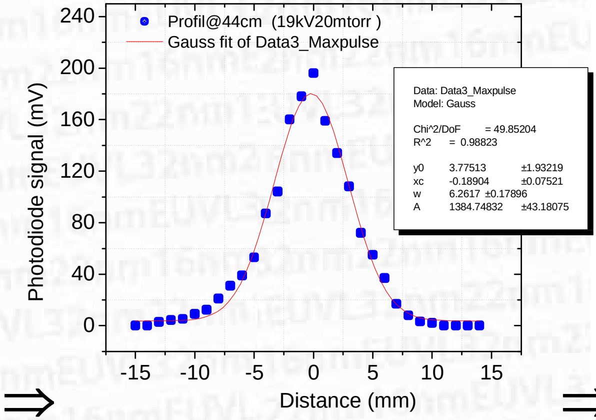
- use SXUV20 Mo/Si filtered diode (IRD) coated (110 nm Al) on $Si_3N_4$ (50 nm) to reject OoB
- 3 nm EUV band (12.4 nm -15.4 nm)
- coated (110 nm Al) on $Si_3N_4$ (50 nm) to reject OoB
- irradiance measured at 44 cm -
- 0.8 $W/cm^2/s$ at 1 kHz, 19 kV
- beam FWHM - 7.4 mm, (1/e2) spot = 12.5 mm
- EUV power at beam spot - **0.44W at 1 kHz**
- typical etendue $5.10^{-3}$ to $1.10^{-2}$ $mm^2.sr$
- discharge in He/Ar/Xe admixture



**GEN-II CYCLOPS™ cells**



**Spot-scan spatial profile** ⇒

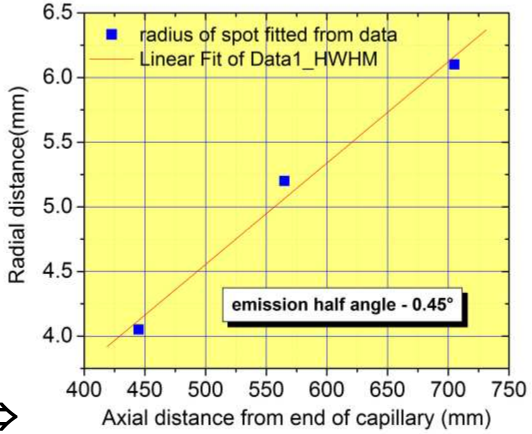


Data: Data3_Maxpulse
Model: Gauss

Chi^2/DoF = 49.85204
R^2 = 0.98823

| | | |
|---|---|---|
| y0 | 3.77513 | ±1.93219 |
| xc | -0.18904 | ±0.07521 |
| w | 6.2617 ±0.17896 | |
| A | 1384.74832 | ±43.18075 |

⇒



emission half angle - 0.45°

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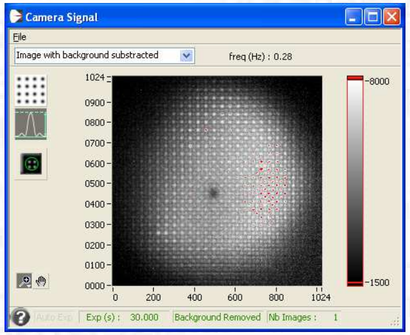
# Source Characteristics

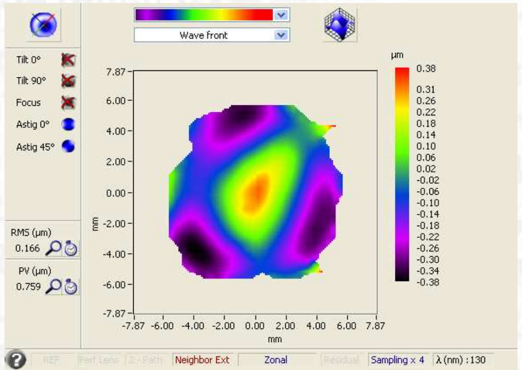
## - wavefront measurement

**HASO™ X-EUV Shack Hartmann wavefront sensor - (manufactured by Imagine Optic)**

**1890 mm**



**Acquired image**
**60s exposure,**
**source at 1 kHz**



**Derived wavefront**
**166 nm RMS (12 λ)**

**& 760nm PV (58 λ)**

- EUV beam diameter d= 9.75 mm at 1890 mm from source
- Beam divergence half angle =0.19°
- Solid angle **Ω** = 0.0345 msr
- Etendue $E = 2\pi R \cdot \Omega \cdot RMS$ $= 5 \cdot 10^{-5}$ mm$^2$sr

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

# Capillary Discharge EUV Source

## typical parameters

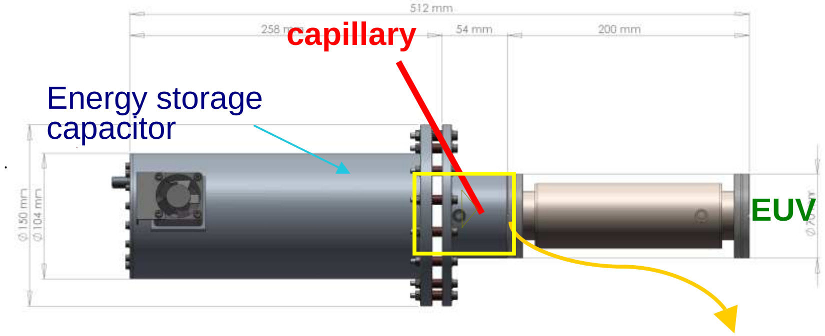
**Power source**

| | |
|---|---|
| Charge energy | 0.1 – 0.5 J |
| Current | 5 - 10 kA |
| Pulse | ~10-20 ns |
| **Capillary dimension:** | ∅ 0.8-1.6 mm<br>L = 12-18 mm |

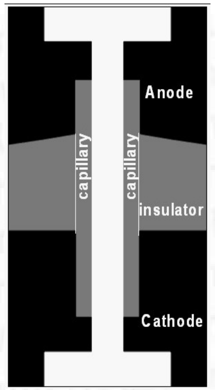
**Various electrode geometries**

**Gas:**

0.1-1mbar Ar+He;
Xe, Sn, Li, Kr, N, … admixtures
(for narrow-band radiation source)



Experimental set up



Example of simulated geometry

**Capillary discharge dynamics & emission features:**

E-beam, plasma channelling ($\varepsilon$>>1)

Volumetric MHD compression (skin depth >>plasma diameter)

Highly ionized ions (fast electrons)

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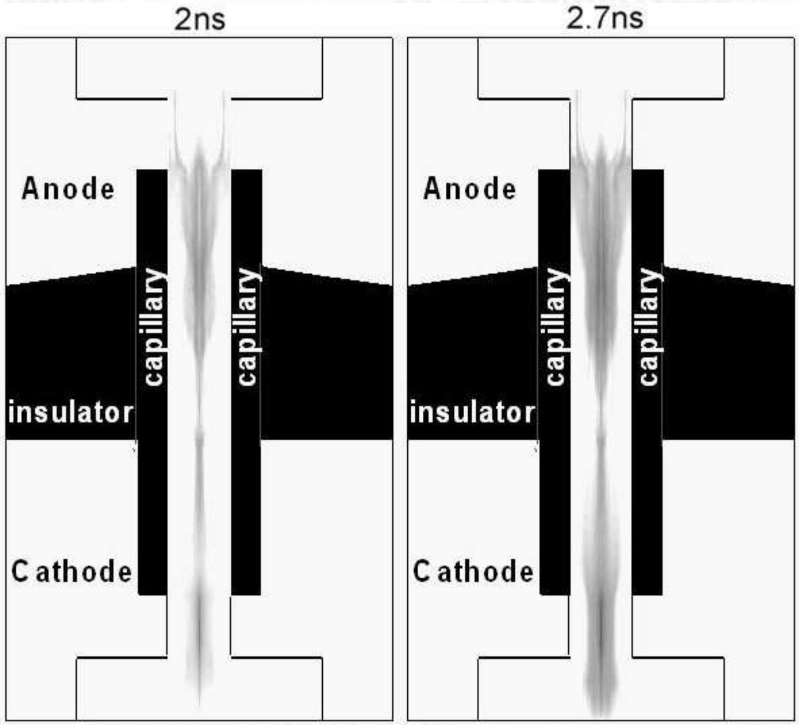
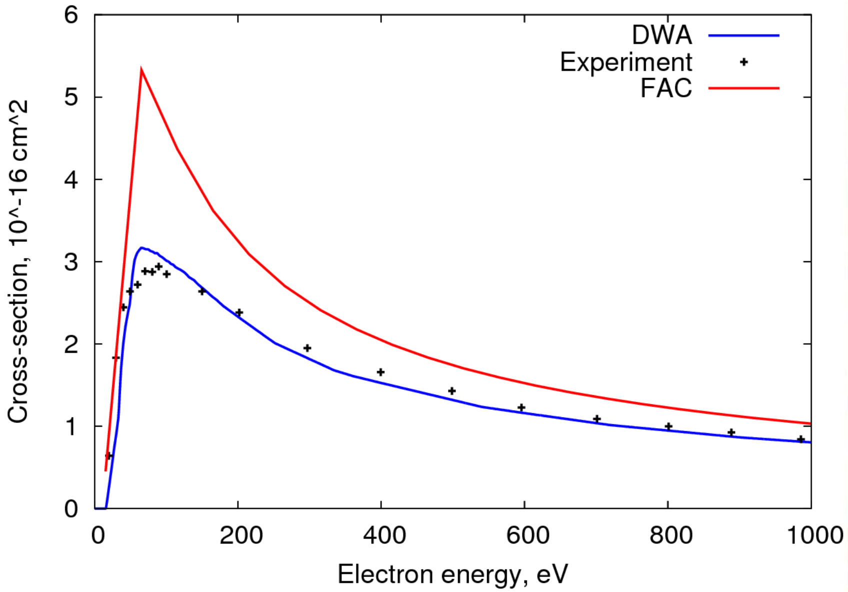
# Capillary Discharge EUV Source

## electron beam and ionization wave



**Ionization cross-section of argon atoms**



**Pre-ionization in capillary discharge (ion density $n_i$ ):**

- **axial beam of run-away electrons,**
- **ionization of the gas by beam and secondary electrons,**
- **the ionization wave forces out the electric field**

# MHD of Radiating Plasma

## capillary discharge dynamics

**Low thermal pressure** $p < \frac{B^2}{8\pi}$ , **high magnetic field diffusion** $\sqrt{c^2 t / 2\pi\sigma} > R_0$

**Volumetric compression**

$$\rho = \rho_0 \frac{R_0^2}{R^2}; \quad v_r = r\frac{\dot{R}}{R}; \quad \ddot{R} = -\frac{2}{mc^2}\frac{I^2}{R}; \qquad t(\xi) = t_0 \tfrac{\sqrt{\pi}}{2} Erf(\sqrt{ln\xi})$$

$$I(t) = I_0$$

$$B = \frac{2I}{c}\frac{r}{R^2}; \quad j_z = \frac{I}{\pi R^2}; \quad m = \pi R_0{}^2 \rho_0 \qquad t_0 = \sqrt{m}\frac{cR_0}{I_0}; \quad \xi = \frac{R_0}{R}$$

**Initial axial pressure gradient** : $m(z) = \pi R_0{}^2\ \rho_0(z);\ \ R(t,z) \sim \rho_0(z)^{-1/2}$

**Long capillary:** $L >> R_0$ **Radial current:** $j_r = \frac{Ir}{\pi R^3}\frac{\partial R}{\partial z};$

**3-D volumetric compression:**

$$\ddot{R} = -\frac{2}{mc^2}\frac{I^2}{R}; \qquad \Longrightarrow \qquad v_r = r\frac{\dot{R}}{R}$$

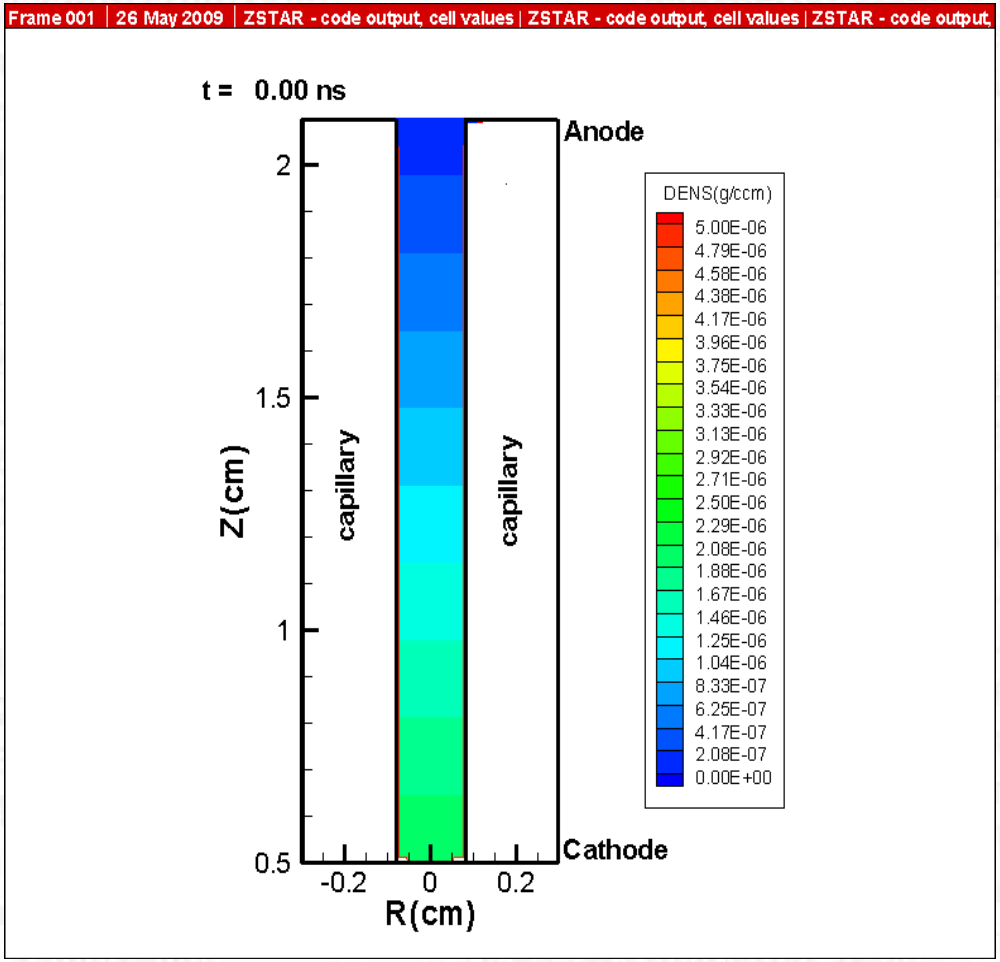
$$u(z,t) \equiv v_z / r^2 \qquad \dot{u} = \frac{2I^2}{mc^2}\frac{\partial R/\partial z}{R} \qquad v_z(r,z,t) = \frac{2r^2}{R^2}\int_0^t \frac{I^2}{mc^2}\frac{\partial R/\partial z}{R}dt'$$

**In particular, for the constant current $I(t) = I_0$ and cylindrical capillary with radius $R_0$**

$$v_z(r,z,t) = \frac{r^2}{2t_0\sqrt{ln\left(\frac{R_0}{R}\right)}}\frac{R_0}{R}\left[ln\left(\frac{R_0}{R}\right)\left(1 + \frac{t}{t_0}\right) - \frac{t}{2t_0}\right]\frac{\partial\, ln\rho_0}{\partial z}$$

# Capillary Discharge EUV Source

## increasing ionization degree effect



Plasma density dynamics

**3D volumetric compression**

**At EUV emission maximum**

**$\rho=5\cdot10^{-7}$g/cm$^3$, $T_e$=18eV.**

**Without taking into account of fast electrons the plasma ionization degree is <Z>=7.3;**

**EUV yield is 6μJ.**

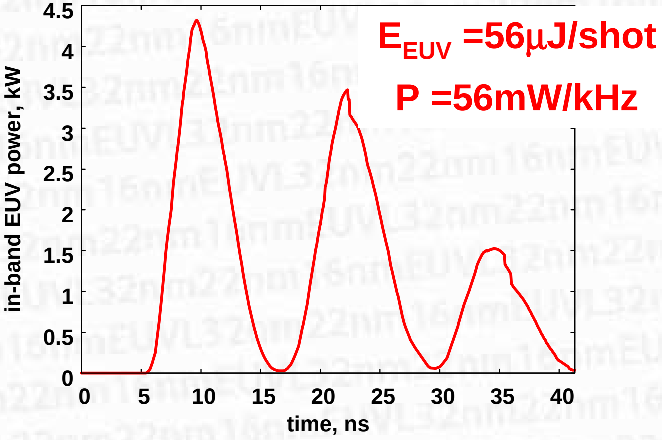
**WITH 0.1% of fast electrons <Z>=8.8;**

**EUV yield is 30μJ (26 μJ in experiment).**

# Gen II EUV Source

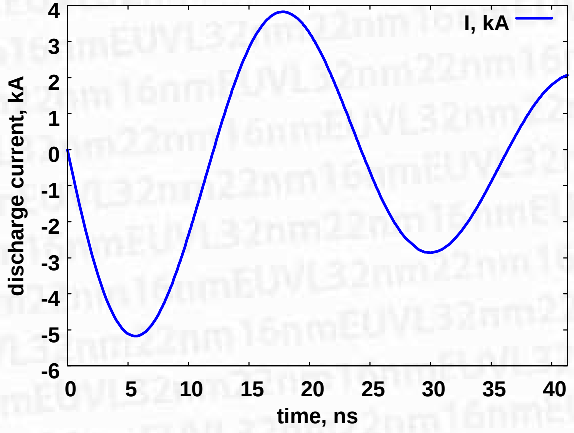
## - characteristics from Z* modelling

### 19kV charge, 1.2 nF capacitor

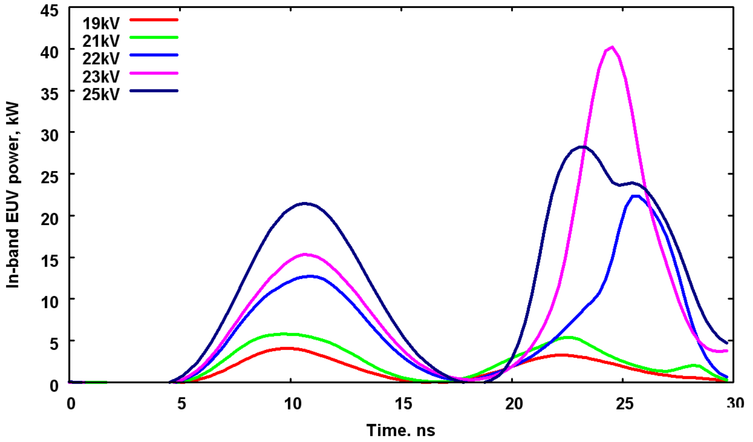


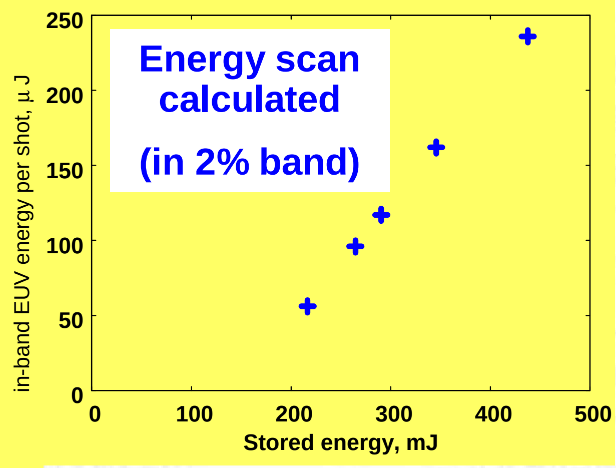
$E_{EUV}$ =56µJ/shot

P =56mW/kHz



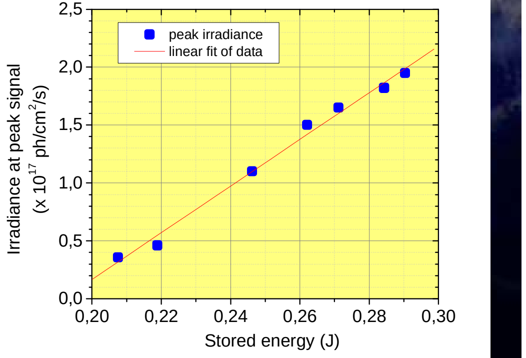
### >19kV charge energy scan





**Energy scan calculated**

**(in 2% band)**



**Experimental energy scan**

**(20% band)**

# Next Generation Modelling Tools

## - FP7 IAPP project FIRE

- Theoretical models and robust modeling tools are developed under international collaboration in the frames of European FP7 IAPP project FIRE
- The FIRE project aims to substantially redevelop the Z* code to include improved atomic physics models and full 3-D plasma simulation of
  - ✓ plasma dynamics
  - ✓ spectral radiation transport
  - ✓ non-equilibrium atomic kinetics with fast electrons
  - ✓ transport of fast ions/electrons
  - ✓ condensation, nucleation and transport nanosize particles.
- Modelling can be the key factor to scientific and technological solutions in EUVL source optimization with fast particles and debris to solve current EUVL source problems as well as extending their application to 22nm and beyond.
- The research and transfer of knowledge is focused on two major modeling applications;
  - ✓ EUV source optimization for lithography and
  - ✓ nanoparticle production for nanotechnology.
- Theoretical modelling will be benchmarked by LPP and DPP experiments

# HYDRA™-ABI
# - spatial multiplexing for blank inspection

- Design Specifications
  - 60 W/mm$^2$.sr in-band 2% EUV radiant brightness at the IF
  - 0.6 W at the IF
  - etendue $10^{-2}$ mm$^2$.sr
  - source area - 31 mm$^2$ / TBD
  - **optimized for mask blank inspection**
  - **4x** i-SoCoMo™ units working at 3 kHz each
  - no debris / membrane filter
  - **close packed pupil fill**
- Current Status
  - 4 units integration & characterization
  - single unit optimization
  - ML mirrors evaluation & modelling

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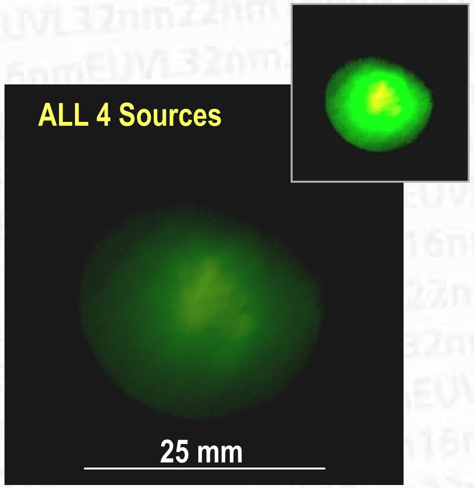
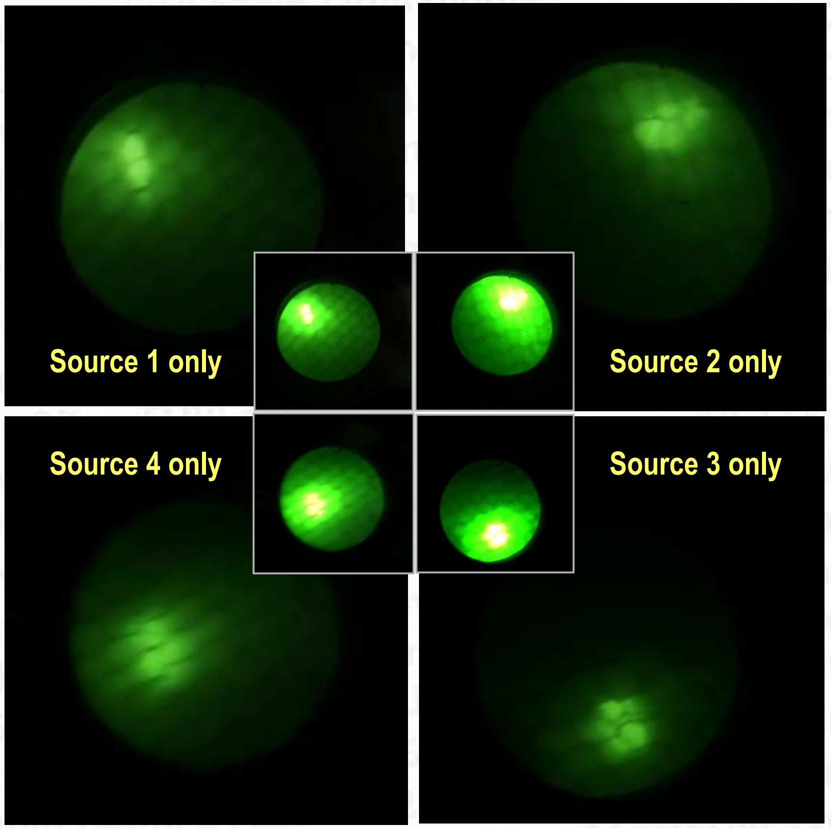
# HYDRA$^{4}$-ABI™

## - pupil arrangements

- **Radiation observed on a fluorescent screen 70 cm downstream**



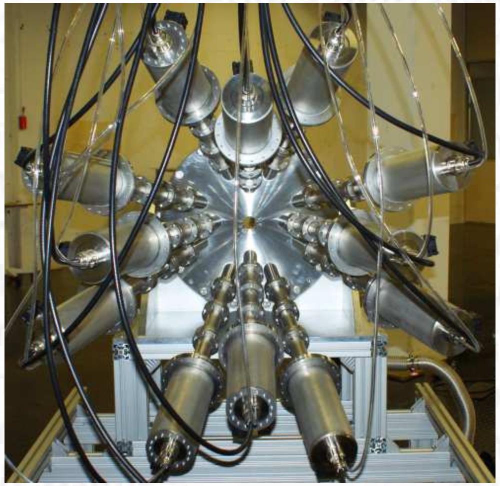
All 4 sources aligned to a point

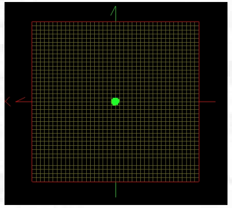


Each source turned on separately and aligned to a different corner

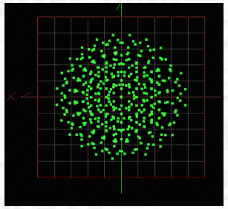
# HYDRA™-AIMS
## - spatial multiplexing with variable sigma

- Design Specifications
  - 100 W/mm$^2$.sr in-band 2% EUV brightness
  - 2.4W at the IF
  - etendue - 2.4 10$^{-2}$ mm$^2$.sr (50% fill pupil)
  - source area - 4 mm$^2$ / variable sigma
  - **optimized for aerial image measurements**
  - **12x** i-SoCoMo™ units, 5 kHz working each
  - no debris / membrane filter
  - **variable pupil fill and sigma**
- Current Status
  - system characterization
  - single unit optimization
  - ML mirrors modelling

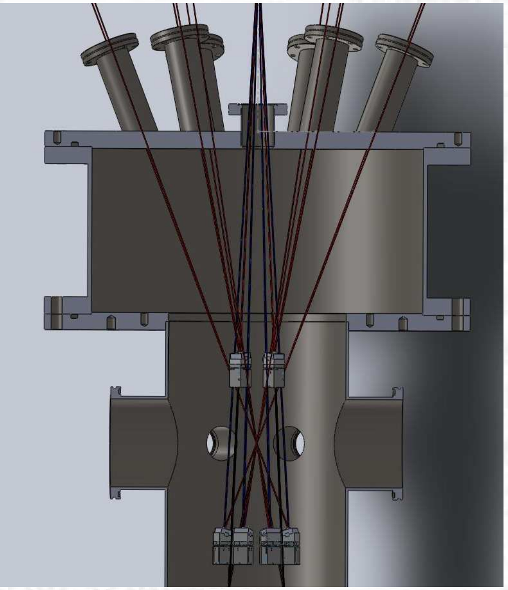




curved ML

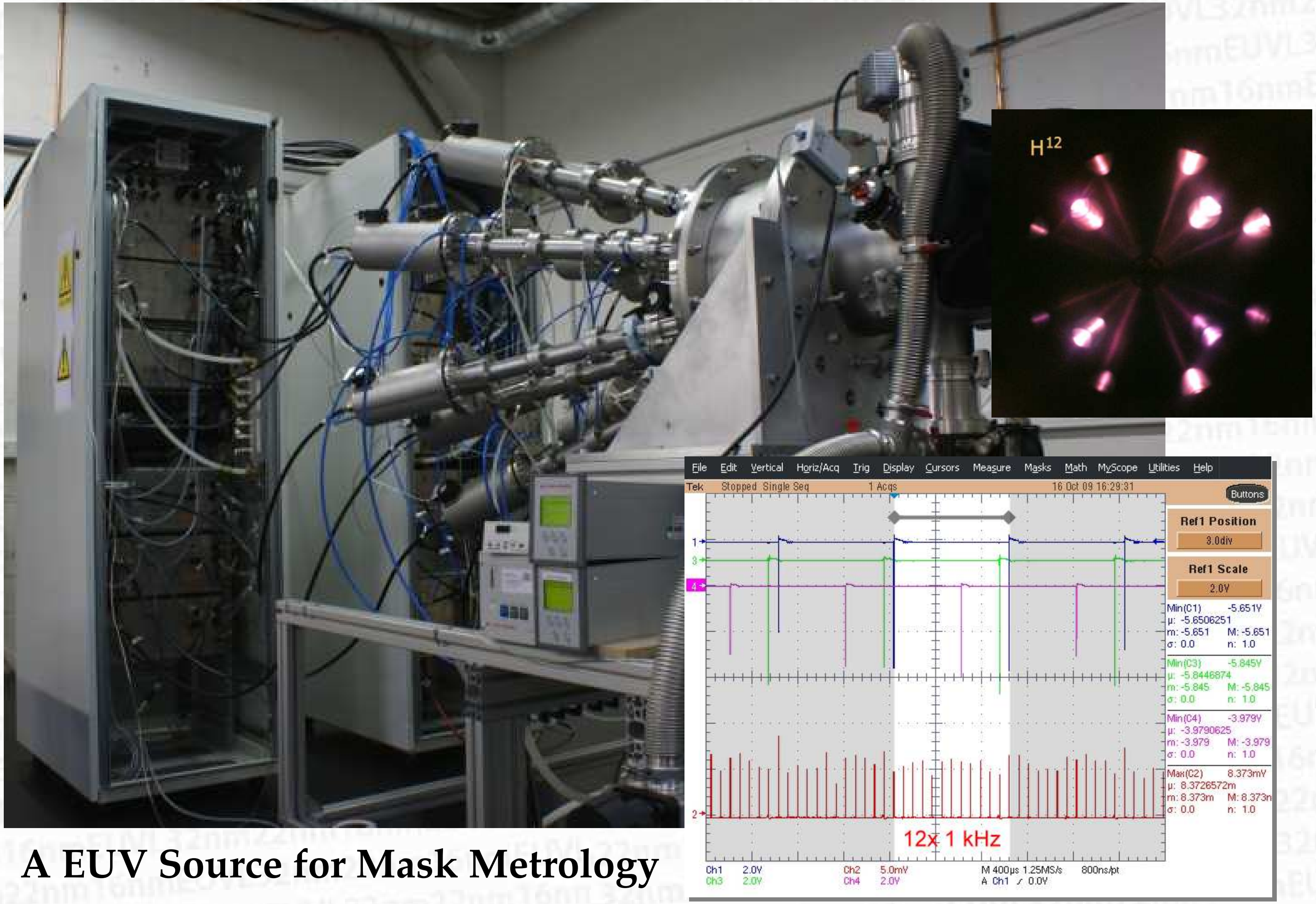


plane ML



# HYDRA$^{12-}$AIMS™

## - prototype system



```
Tek   Stopped  Single Seq          1 Acqs                 16 Oct 09 16:29:31

Min(C1)        -5.651V
μ: -5.6506251
m: -5.651      M: -5.651
σ: 0.0         n: 1.0
Min(C3)        -5.845V
μ: -5.8446874
m: -5.845      M: -5.845
σ: 0.0         n: 1.0
Min(C4)        -3.979V
μ: -3.9790625
m: -3.979      M: -3.979
σ: 0.0         n: 1.0
Max(C2)        8.373mV
μ: 8.3726572m
m: 8.373m      M: 8.373n
σ: 0.0         n: 1.0

Ch1   2.0V            Ch2  5.0mV         M 400μs 1.25MS/s    800ns/pt
Ch3   2.0V            Ch4  2.0V          A  Ch1  ⁄  0.0V
```

**A EUV Source for Mask Metrology**

# HYDRA™-APMI

## - unique temporal & spatial multiplexing

- Design Specifications
  - 1200 W/mm².sr in-band EUV radiant brightness
  - 2.4 W at the IF
  - etendue - 2. $10^{-3}$ mm².sr
  - source area - 20 mm²
  - **optimized for patterned mask inspection**
  - 8x i-SoCoMo™ units working at 3 kHz each
  - 24 kHz temporally multiplexed
  - no debris / membrane filter
  - **Gaussian output spot**
- Current Status
  - optics design & modelling
  - single unit optimization
  - mechanical design

# 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

- Extra EUV in-band emission may be achieved from highly charged Xe ions in plasma with fast electrons

- The required irradiance can be achieved by spatial multiplexing, using multiple small sources

- NANO-UV presents a high brightness 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 tools for actinic mask inspection and in future for HVM .

# Acknowledgement

- R&D team & collaborators
  - R&D team of EPPRA and Nano-UV
  - Pontificia Universidad Catolica de Chile
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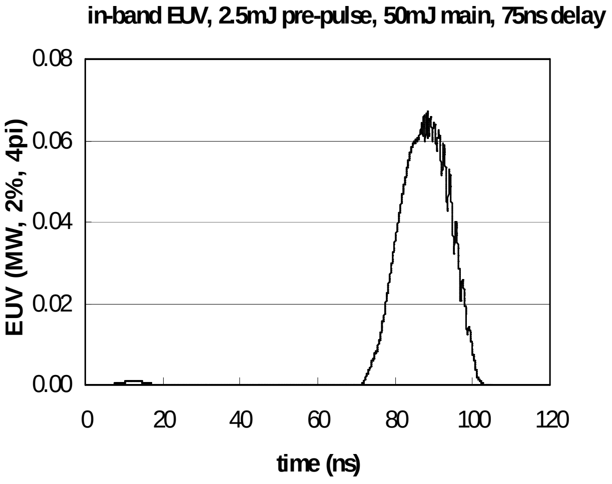
  - Keldysh Institute of Applied Mathematics RAS, Moscow, Russia
  - University College Dublin
  - King’s College London
  - EUVA, Manda Hiratsuka, Japan
- Sponsors - EU & French Government
  - ANR- EUVIL
  - FP7 IAPP
  - OSEO-ANVAR
- RAKIA
- COST

# Combined Nd:YAG-$CO_2$ laser pulses

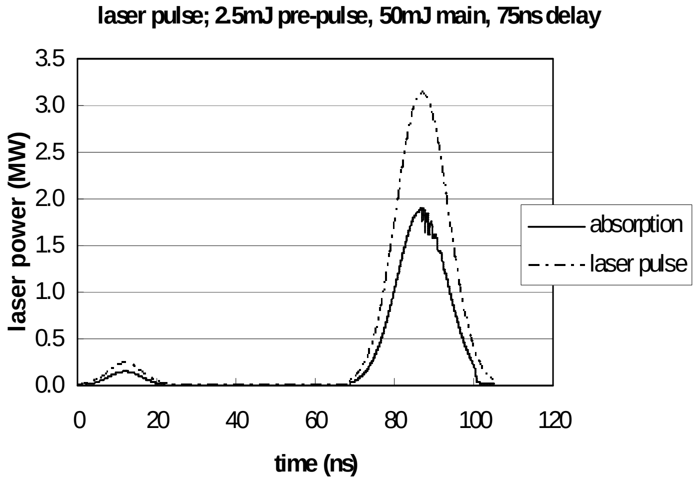
## laser absorption & EUV emission

20 μm Sn-droplet,
2.5mJ Nd:YAG pre-pulse, 10ns fwhm
50mJ $CO_2$ main-pulse, 15ns fwhm
75ns delay time between both laser pulses

EUV emission



Laser pulse shapes



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# Plasma-electrode interaction mechanisms

- **heating of the electrodes by joule dissipation at electrode-plasma transition;**

**thermal instability:** $\sigma(T) \sim \sigma_0 \frac{\theta}{T}$ $\quad c_v \frac{\partial T}{\partial t} = \frac{j^2}{\sigma}$

$$T = T_0 e^{\int \gamma dt} \qquad \gamma = \frac{j^2}{\sigma_0 \theta c_v}$$

- **surface heating & plasma cooling by means of plasma thermal conduction;**

- **surface heating and damage by plasma radiation;**

- **optical elements damage by fast ions & atoms emitted from the plasma (ambipolar and E-field acceleration, shocks, Maxwell tails etc).**

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# Heat loading on electrodes and insulator

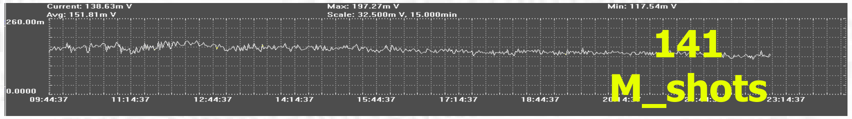
## Z*BME modelling

**Capillary discharge:**

**Charge energy 0.4J/pulse**
**Operation frequency 3kHz**

**Low energy unit provides:**

- **Low heat loading on electrodes and insulators**
- **Long lifetime**



- **Low debris production**