Public

An Introduction to EUV Sources for Lithography

Michael Purvis
ASML

STROBE – Friday, September 25 at 10:00am

Outline

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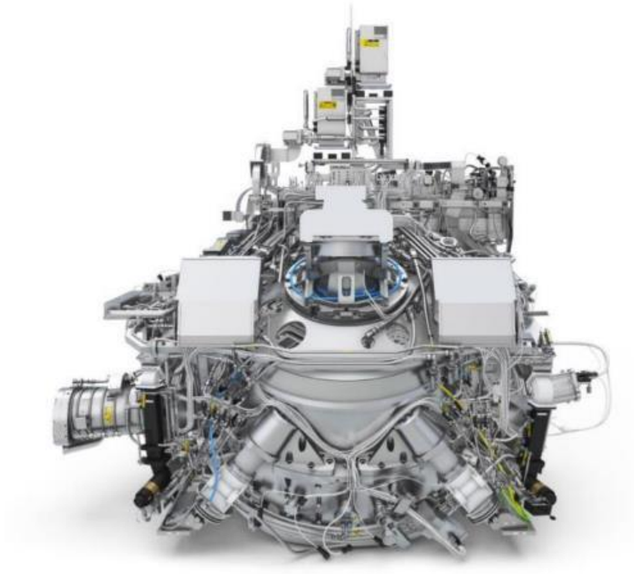


- Background and History
- EUV Lithography in HVM
- EUV Lithography with NXE:3400B
- EUV Source: Architecture
- Principles of EUV Generation
- Challenges and Practicalities

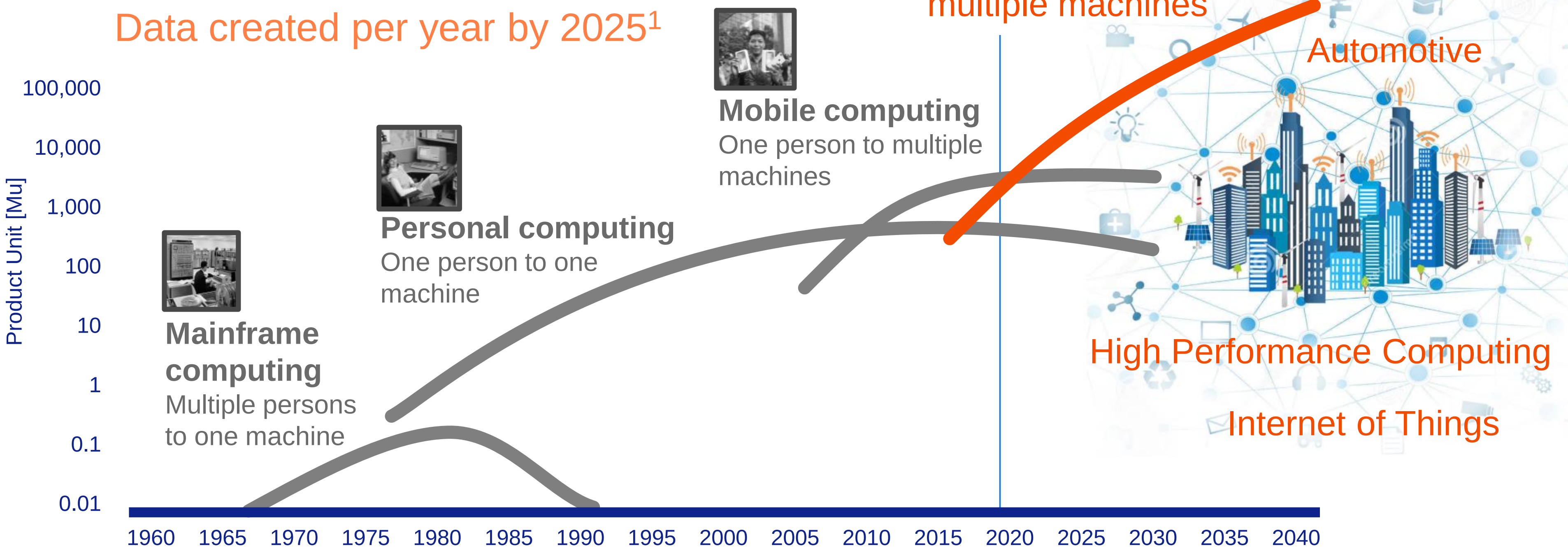
Society’s hunger for chips remains unstilled

175 ZB

Data created per year by 2025[1]

Ubiquitous computing

Multiple machines to multiple machines

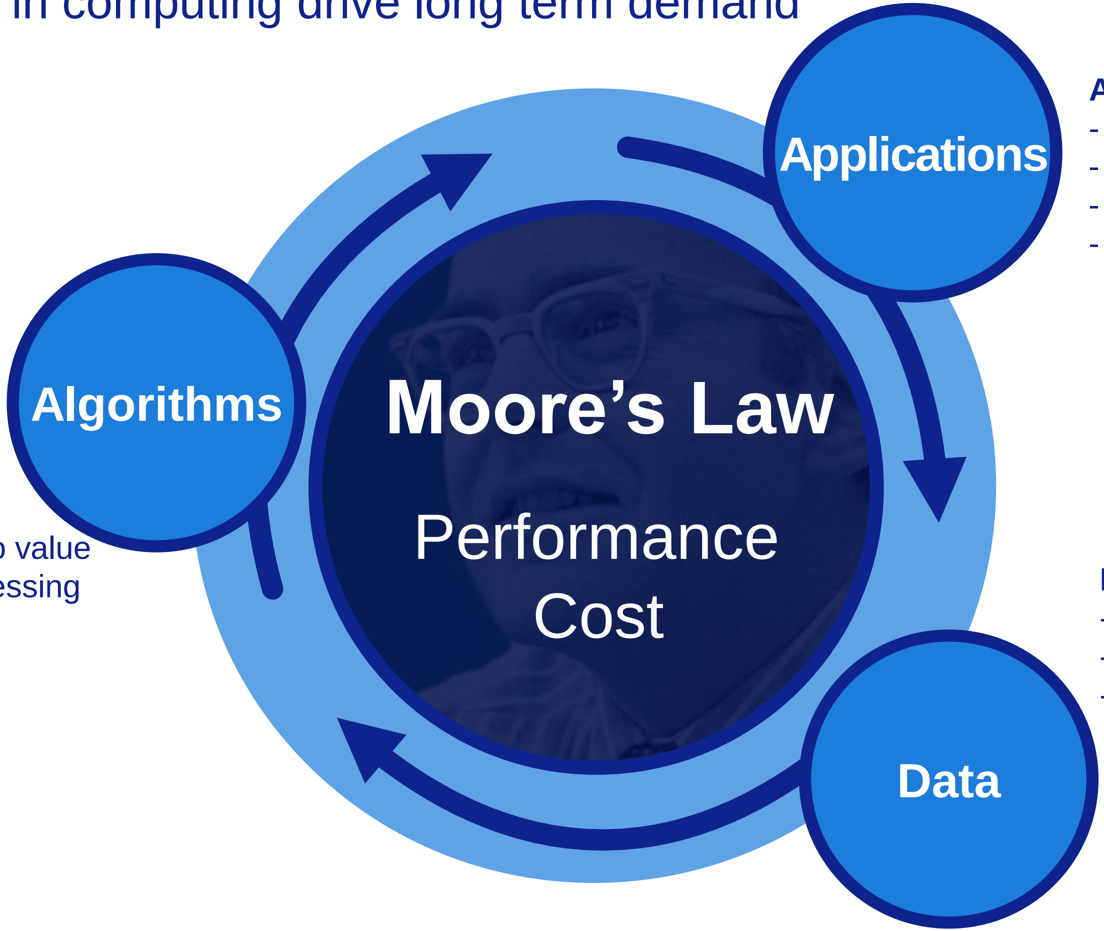


Source: Min Cao, TSMC, “Semiconductor Innovation and Scaling, a foundry perspective”, China Semiconductor Technology Conference, Shanghai, March 2019

[1]David Reijnsel, John Gantz, John Rydning, IDC, Data age 2025, The digitization of the world from edge to core, Nov 2018

Continued demand propels Moore’s Law

Major trends in computing drive long term demand



Applications
- Autonomous decisions
- Immersive resolution
- On-device artificial intelligence
- Virtual / augmented reality

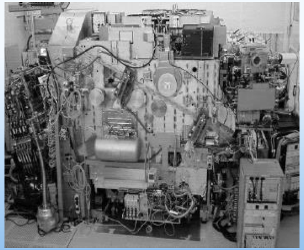
Algorithms
- From big data to value
- Enhanced processing
- Deep learning

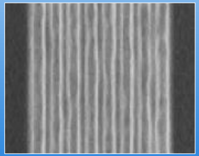
Data
- 5G connectivity
- Real-time latency
- Growing data volumes

EUV industrialization:
from technology demonstration to HVM insertion

2006

ASML ships
world's first full field
EUV tool

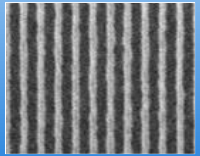




28 nm
Lines and spaces

2010

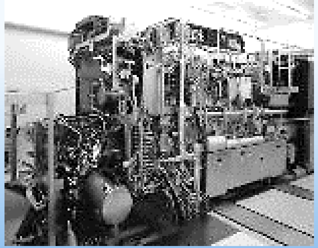
ASML ships 1st NA 0.25
pre-production system
NXE:3100

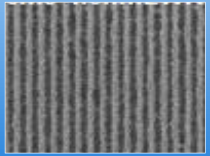


19 nm
Lines and spaces

2013

ASML ships 1st NA 0.33
TD system
NXE:3300B

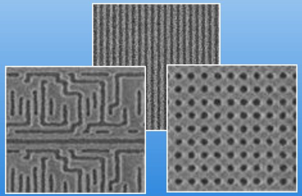




13 nm
Lines and spaces

2017

**ASML ships 1st NA 0.33
HVM system
NXE:3400B**



7 nm and 5 nm
node patterns

And it's here: we see EUV - enabled chips in 2019

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EUV up and running in High Volume Manufacturing


TSMC's 5nm EUV Making Progress: PDK, DRM, EDA Tools, 3rd Party IP Ready

TSMC this week has said that it has completed development of tools required for design of SoCs that are made using its 5 nm (CLN5FF, N5) fabrication technology. The company indicated that some of its alpha customers (which use pre-production tools and custom designs) had already started risk production...


TSMC: First 7nm EUV Chips Taped Out, 5nm Risk Production in Q2 2019

Last week, TSMC made two important announcements concerning its progress with extreme ultraviolet lithography (EUVL). First up, the company has successfully taped out its first customer chip using its second generation 7 nm process technology, which incorporates limited EUVL usage. Secondly, TSMC disclosed plans to start risk production of 5...


Samsung Completes Development of 5nm EUV Process Technology

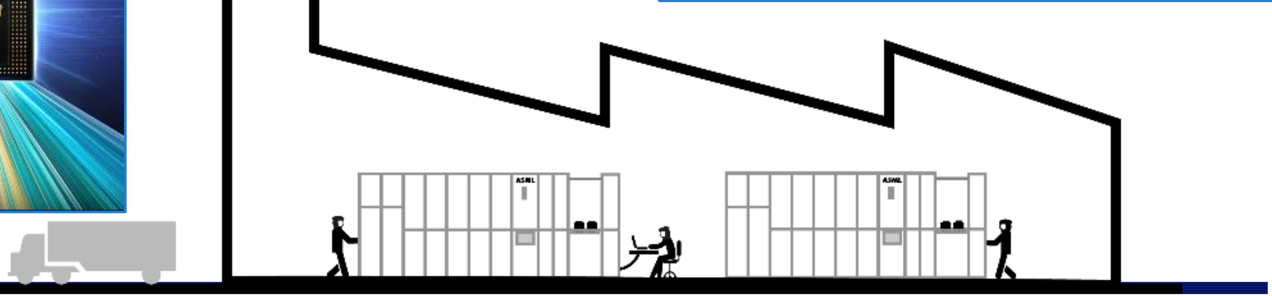
Samsung Foundry this week announced that it has completed development of its first-generation 5 nm fabrication process (previously dubbed 5LPE). The manufacturing technology uses extreme ultraviolet lithography (EUVL) and is set to provide significant performance, power, and area advantages when compared to Samsung's 7 nm process (known as 7LPP)...


TSMC Reveals 6 nm Process Technology: 7 nm with Higher Transistor Density

TSMC this week unveiled its new 6 nm (CLN6FF, N6) manufacturing technology, which is set to deliver a considerably higher transistor density when compared to the company's 7 nm (CLN7FF, N7) fabrication process. An evolution of TSMC's 7nm node, N6 will continue to use the same design rules, making...


Samsung Starts Mass Production of Chips Using Its 7nm EUV Process Tech

Samsung Foundry on Wednesday said that it had started production of chips using its 7LPP manufacturing technology that uses extreme ultraviolet lithography (EUVL) for select layers. The new fabrication process will enable Samsung to significantly increase transistor density of chips while optimizing their power consumption. Furthermore, usage of EUVL...



Advantages of EUVL : Samsung Infographic

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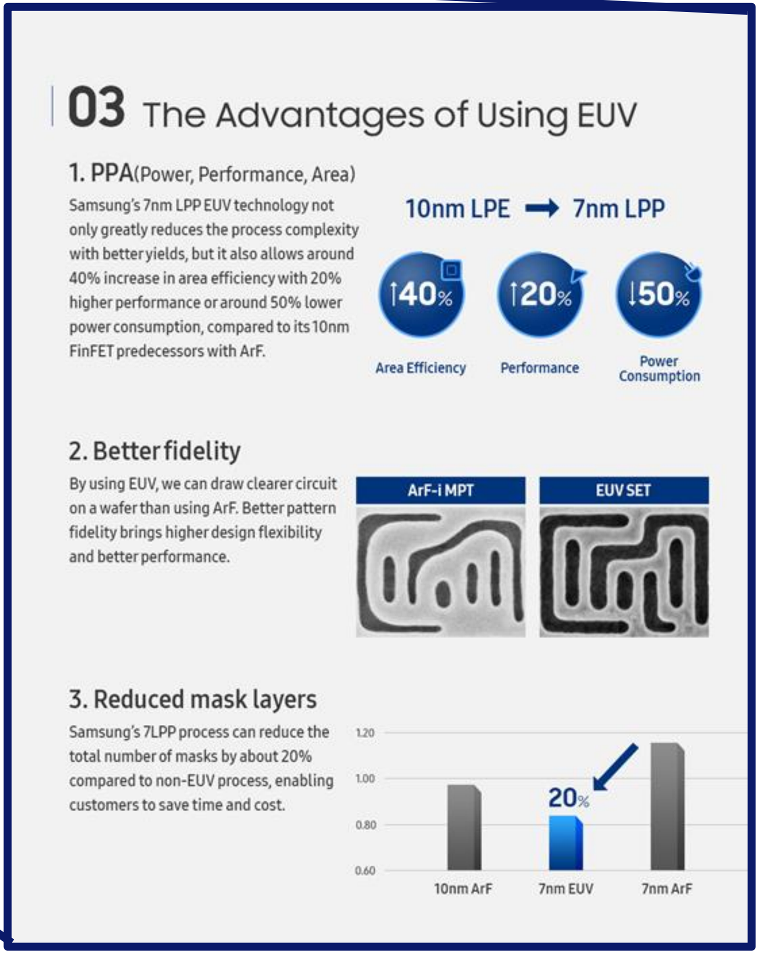
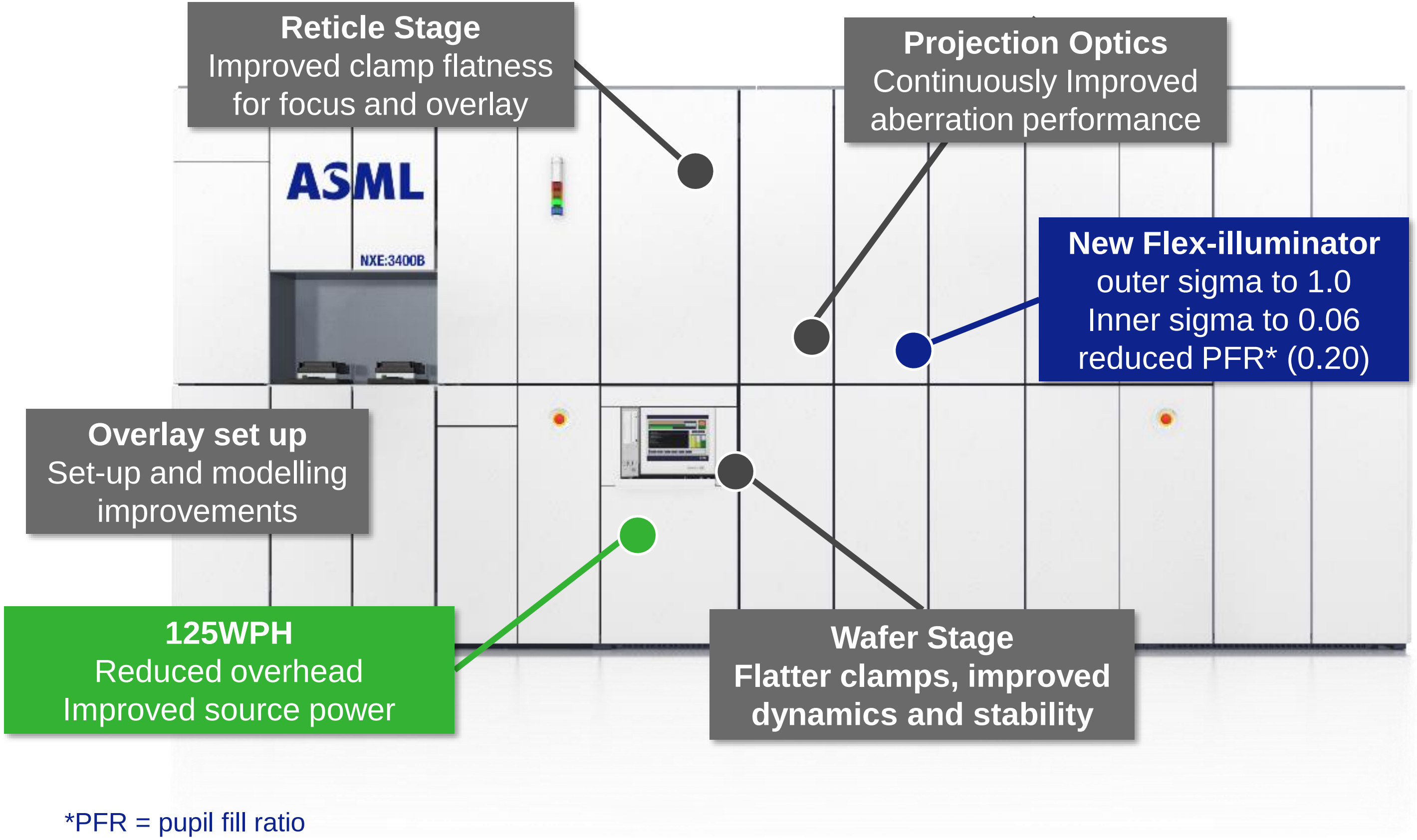


https://news.samsung.com/global/infographic-euv-samsungs-latest-investment-on-developing-next-generation-semiconductor-products

NXE:3400B: 13 nm resolution at full productivity

Supporting 5 nm logic, <15nm DRAM requirements

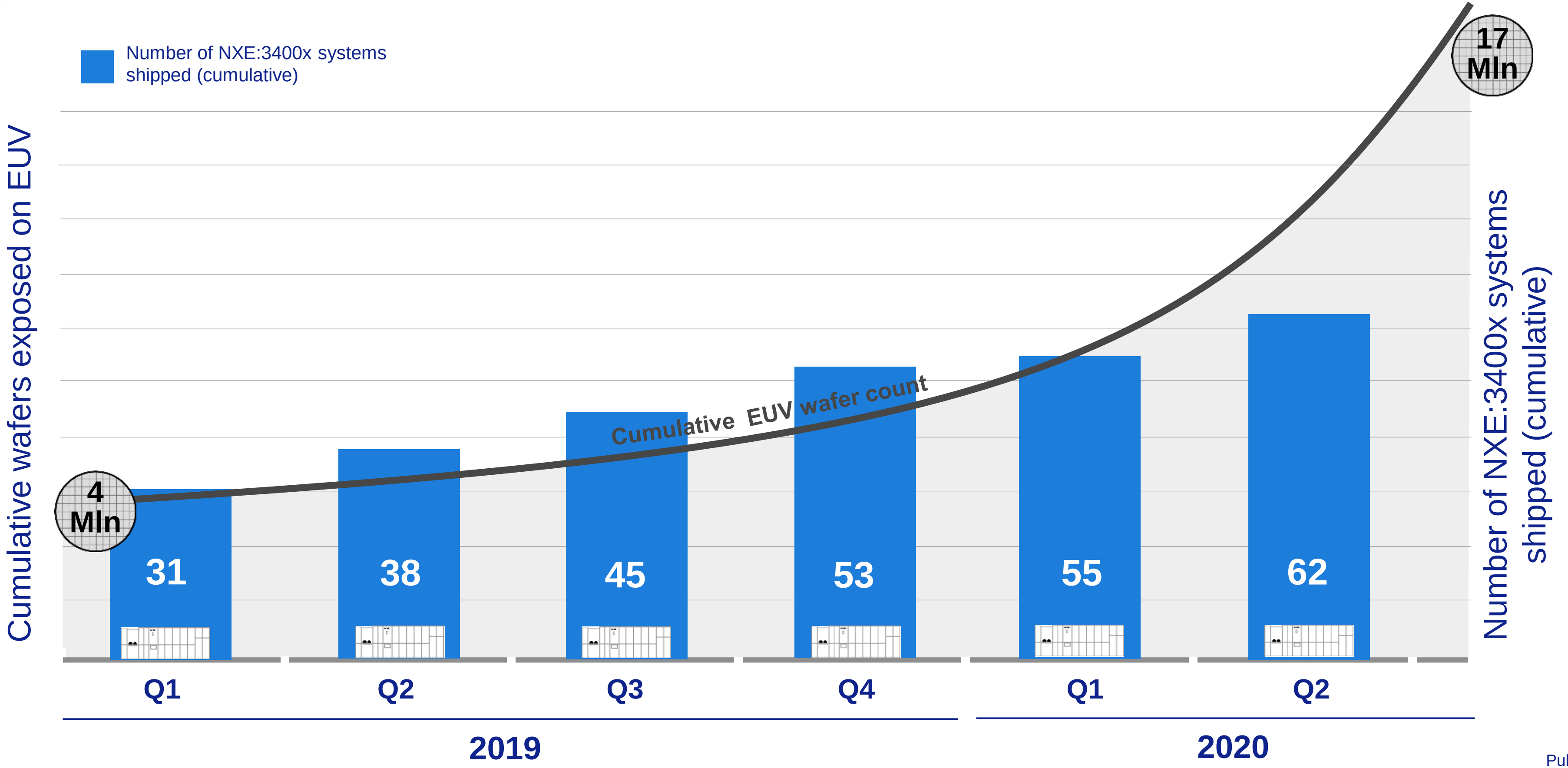


Resolution	13 nm
Full wafer CDU	≤ 1.1 nm
DCO	≤ 1.4 nm
MMO	≤ 2.0 nm
Focus control	≤ 60 nm
Productivity	≥ 125 WPH

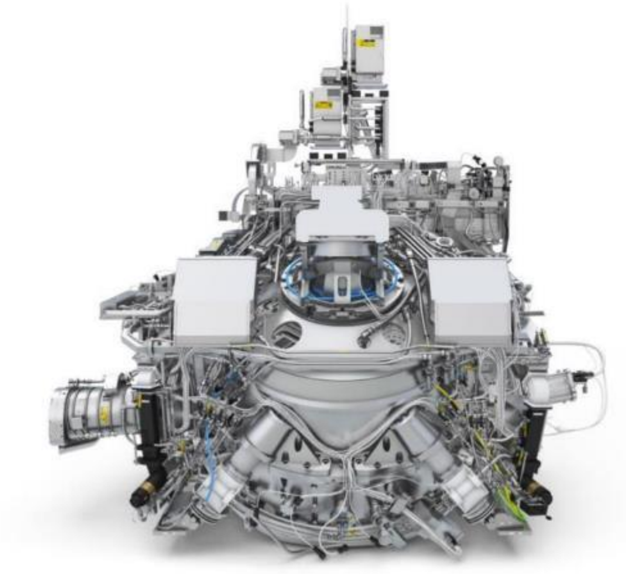
Overlay
Imaging/Focus
Productivity

*PFR = pupil fill ratio

Wafers exposed on EUV systems grows exponentially



Outline



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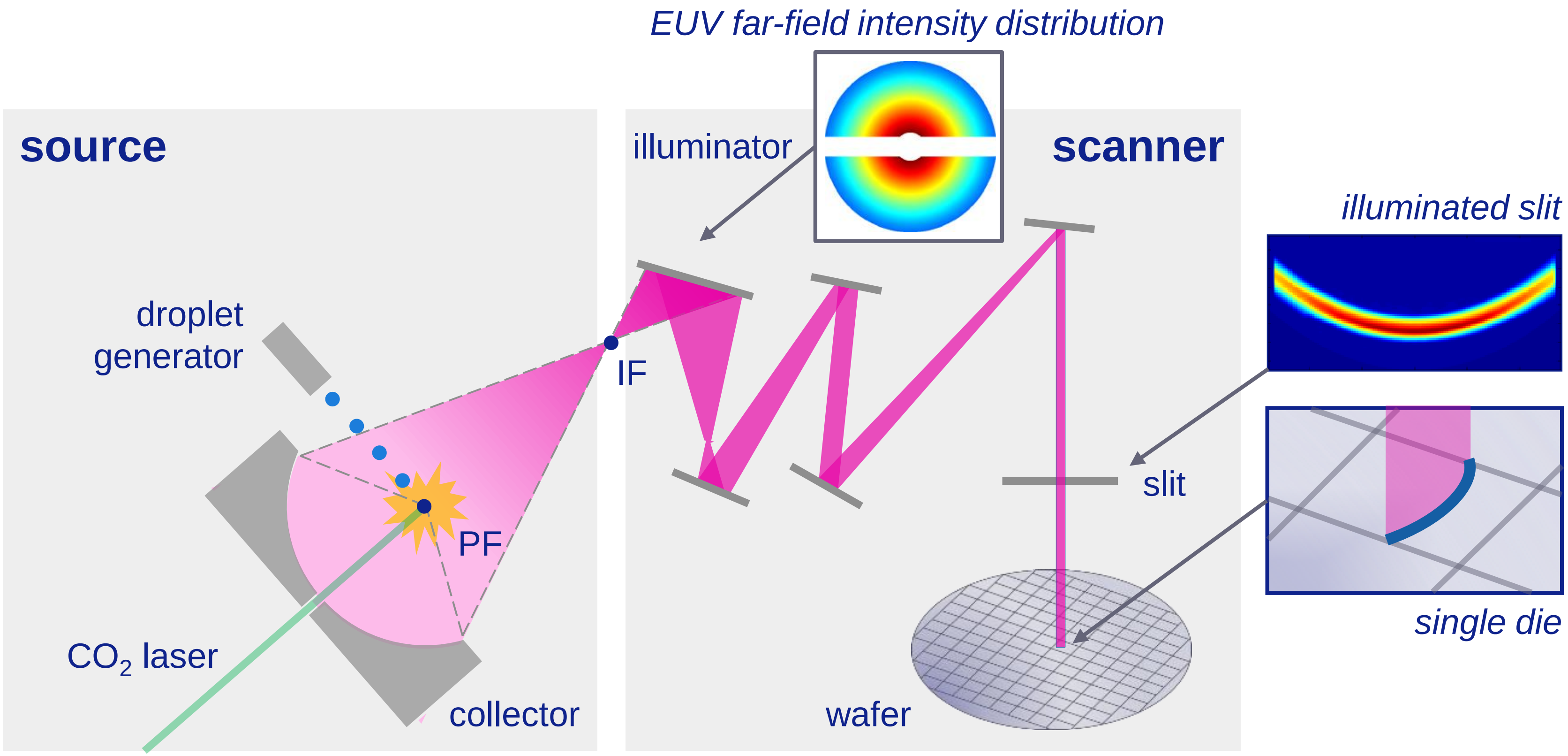
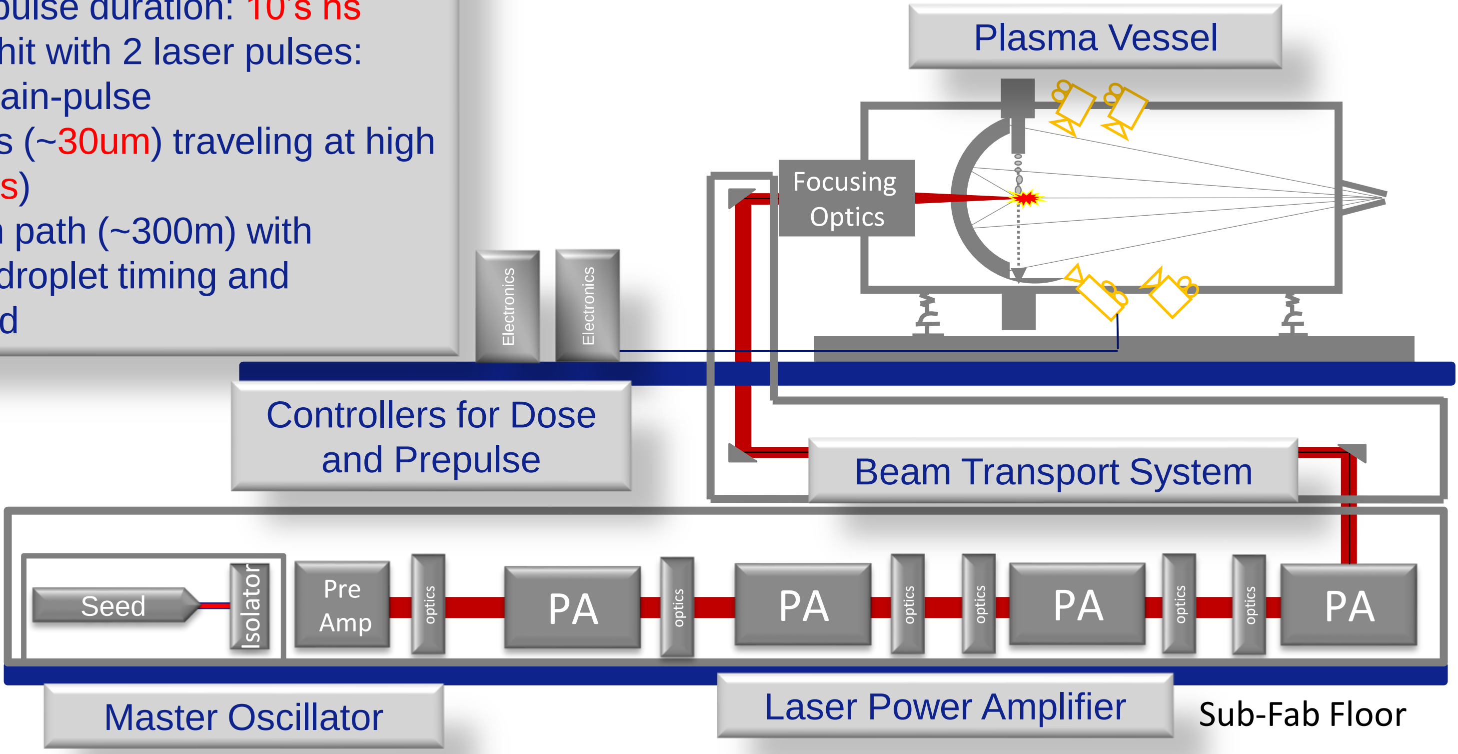
EUV light is generated in the source and guided through the scanner onto the wafer



How does the EUV laser-produced-plasma source work?

EUV light source parameters of note:

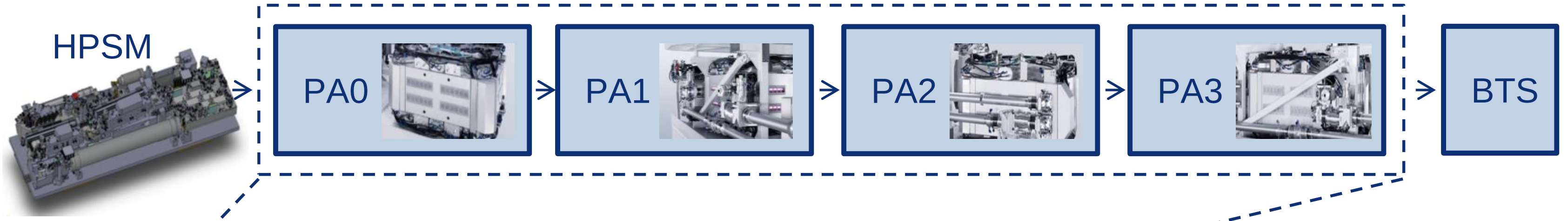
- High power CO2 laser: >20kW pulsed
- Laser and EUV pulse duration: 10's ns
- Each tin droplet hit with 2 laser pulses: Pre-pulse and main-pulse
- Small tin droplets (~30um) traveling at high velocity (~100m/s)
- Long laser beam path (~300m) with precise laser-to-droplet timing and targeting required

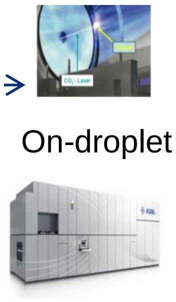


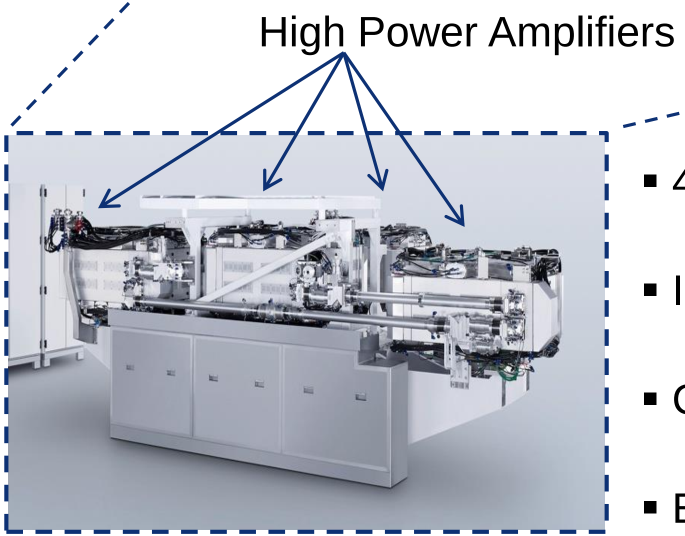
MOPA - Master Oscillator Power Amplifier

Industrial high power CO_2 laser

High beam quality for gain extraction and EUV generation

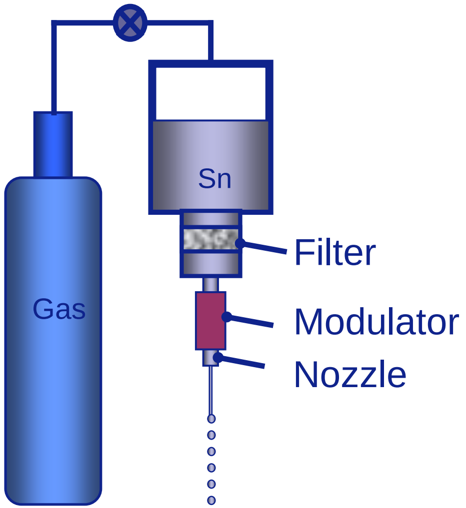




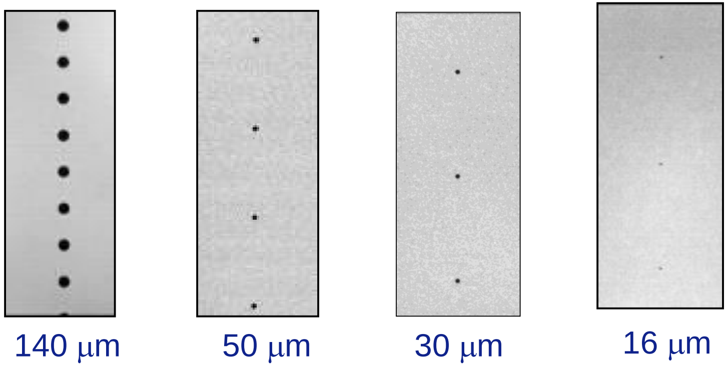


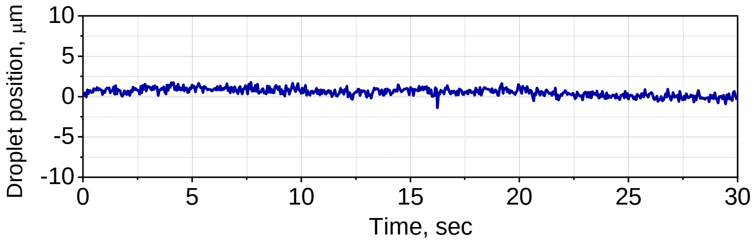
- 4 cascaded power amplifiers (PAs) in HPAC
- Individually optimized geometry and settings
- Connected by relay optics
- Extensive metrology between amplifiers & at DL exit

Droplet Generator: Principle of Operation



- Tin is loaded in a vessel & heated above melting point
- Pressure applied by an inert gas
- Tin flows through a filter prior to the nozzle
- Tin jet is modulated by mechanical vibrations

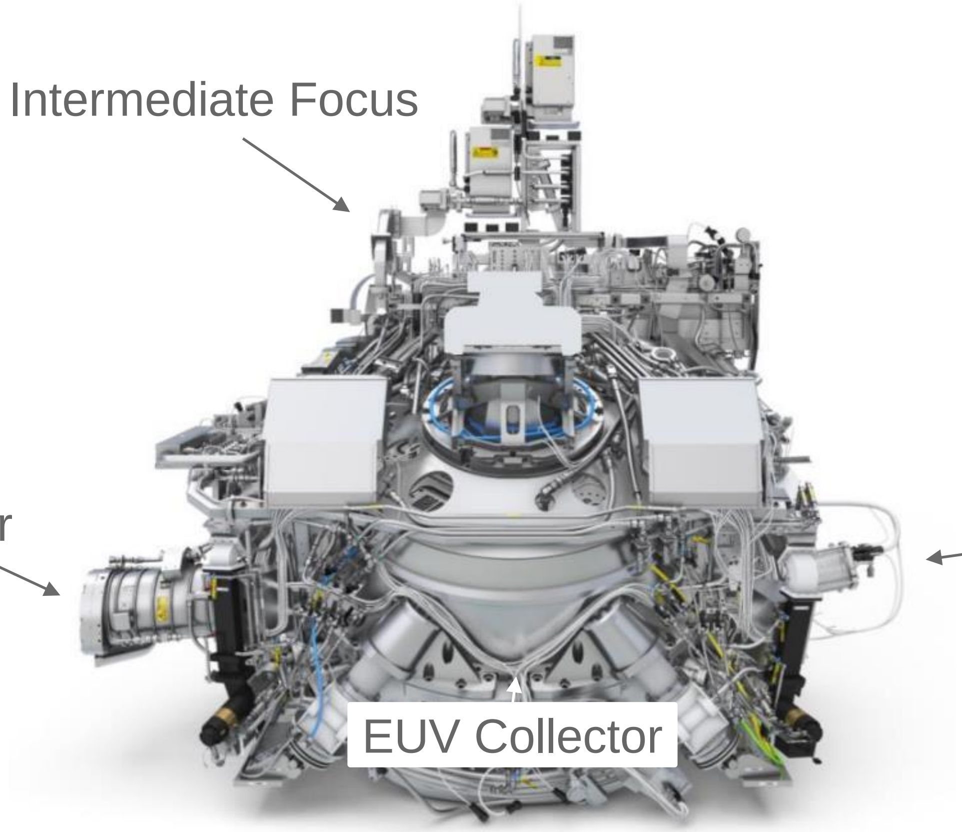




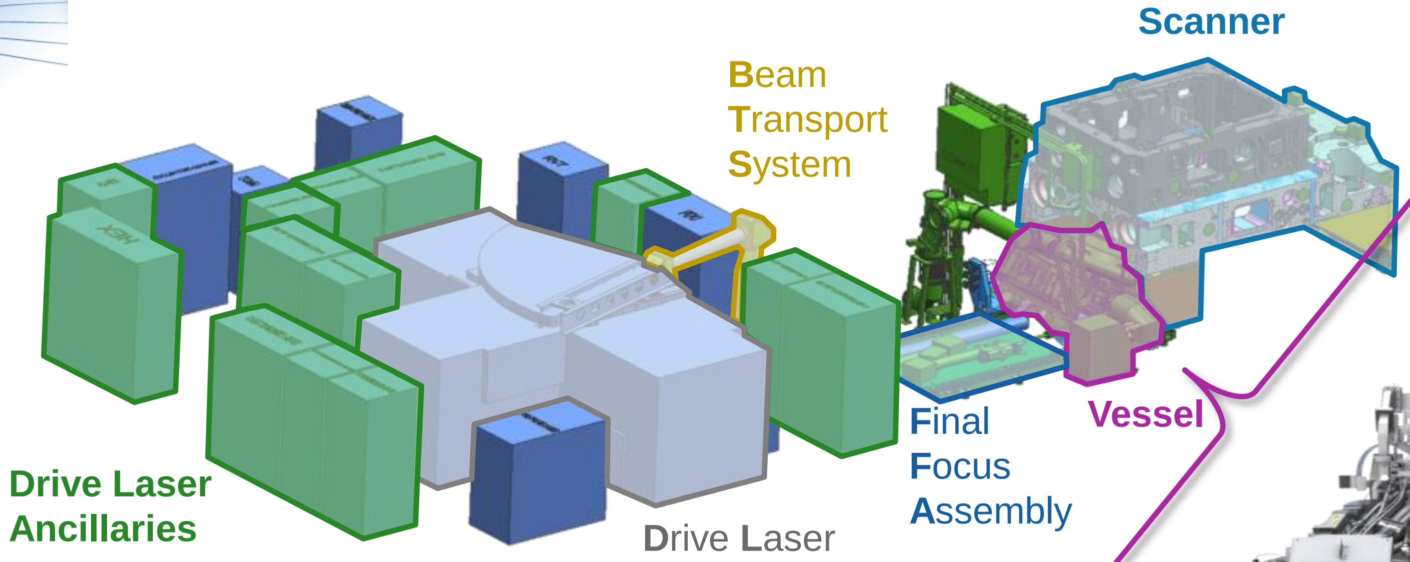
Short term droplet position stability σ~1μm

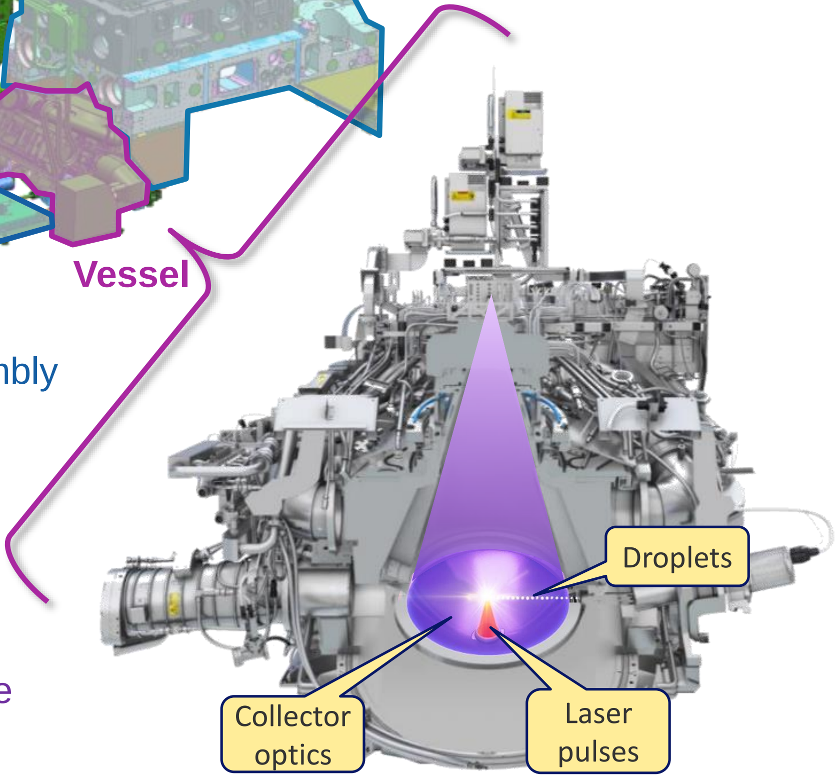
NXE:3XY0 EUV Source: Main modules

Populated vacuum vessel with tin droplet generator and collector



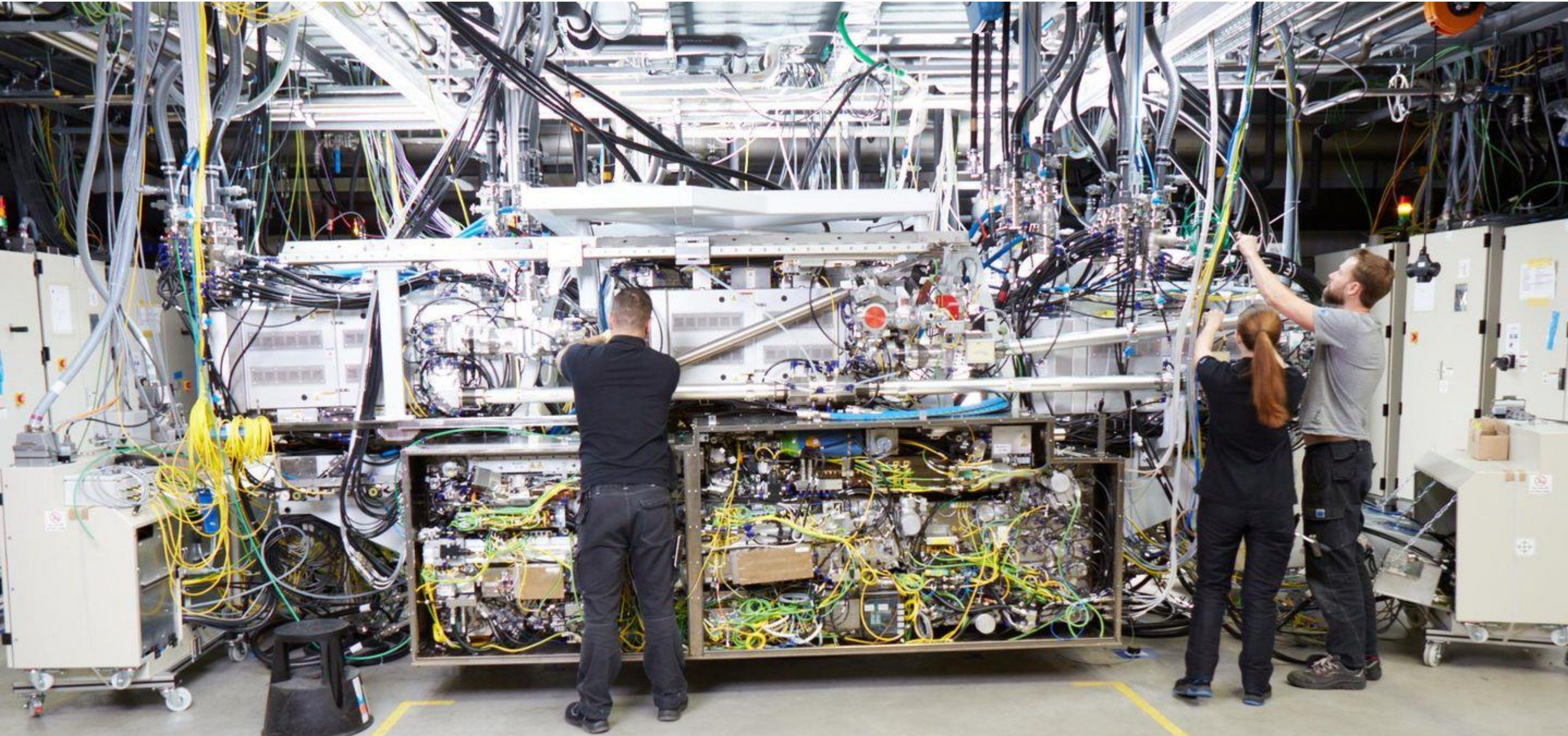
Introduction to the NXE EUV source



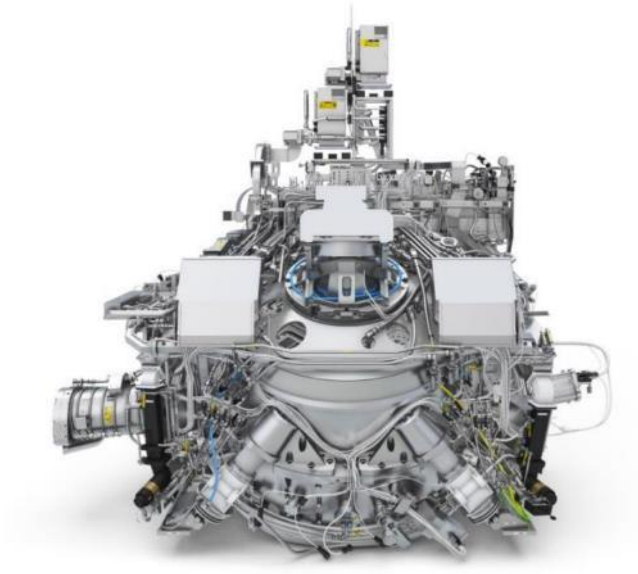


Laser Produced Plasma EUV source

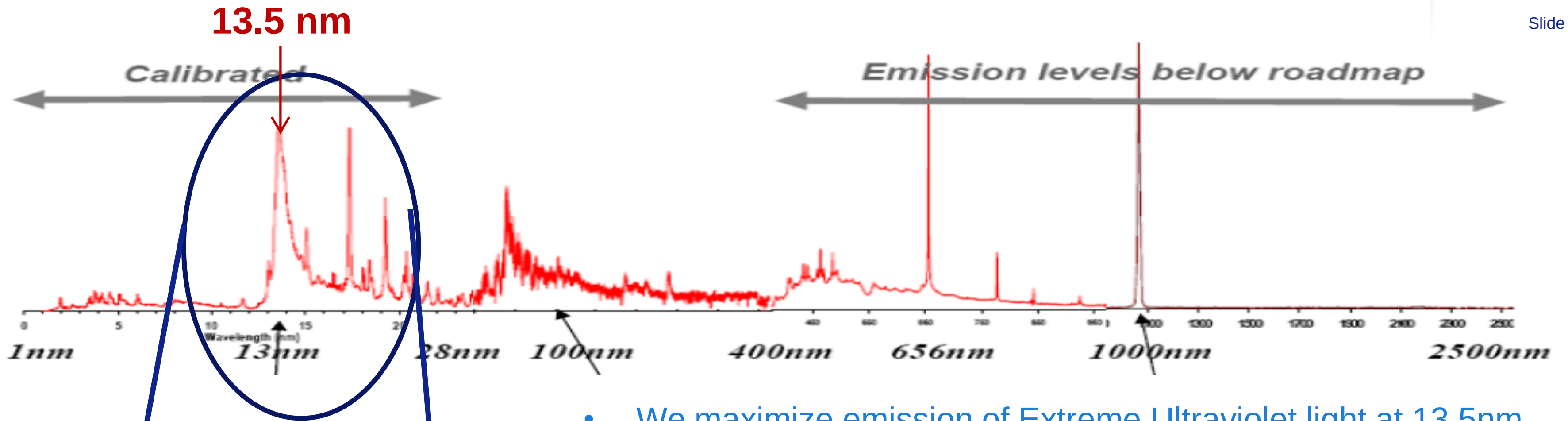
- Droplets (fuel) at 50kHz
- Laser pulses (energy source), Main pulse and Pre pulse
- Collector optics (direct light to scanner)

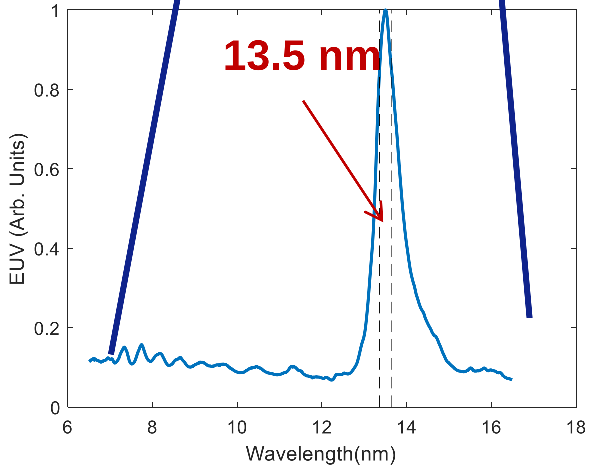


Outline



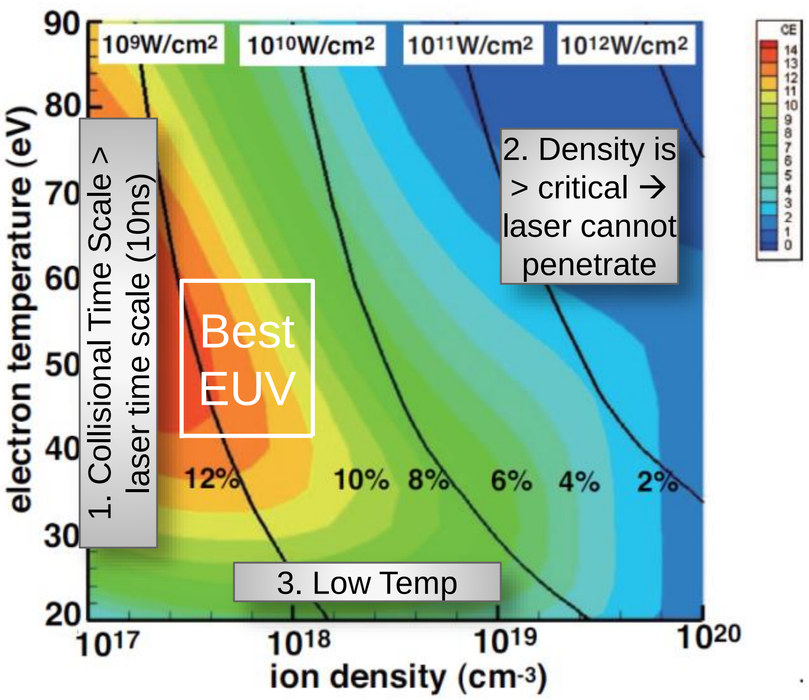
Understanding light emitted by Sn plasma





- We maximize emission of Extreme Ultraviolet light at 13.5nm
  - "Line radiation" from a "U.T.A.", light produced by many bound-bound transitions or light emitted by the transition of an electron within a Sn ionabout 15% will make it to the scanner.
- Other wavelengths are removed by the multi-layer mirror EUV optics
- Roughly 40% of the power dumped into the plasma is emitted by radiation, of that radiation about 15% will make it to the scanner.

Laser Produced Plasma Density and Temperature



Nishihara et al. (2008)

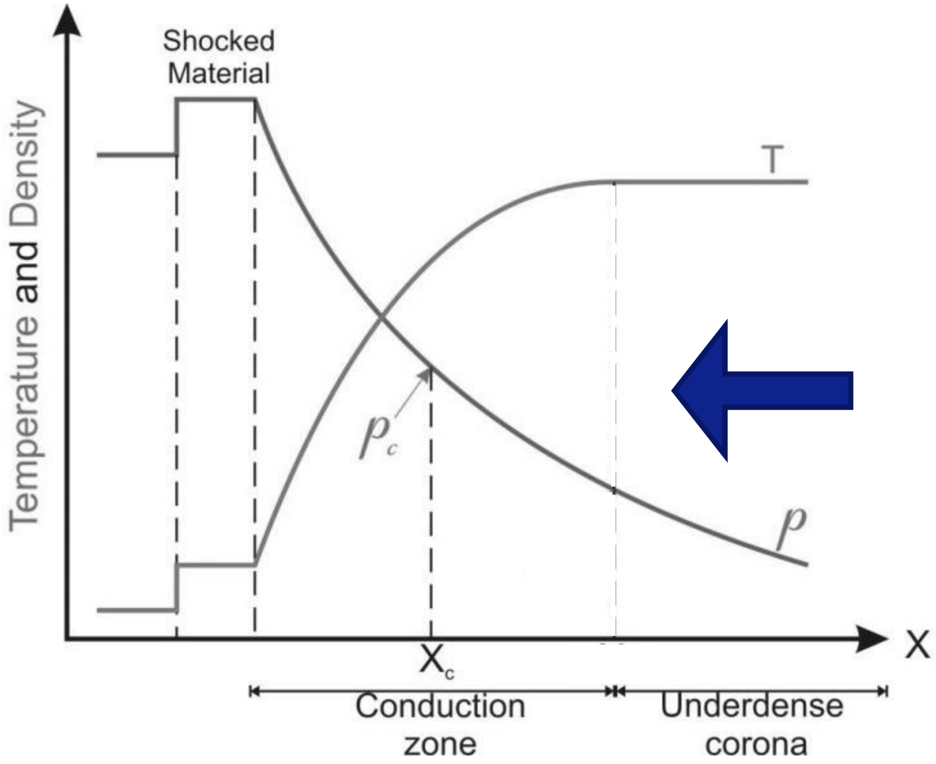
Conditions for optimal plasma

1. Temperatures between 50-100eV
2. Ion densities 10^{17}- 10^{18} #/cm3
3. Large volume with density and temperature
4. Long time scale to maintain density and temperature

Three distinct regions exist where Sn is not much use for making EUV:

1. Low density
   - Collisional excitation process is not efficient
2. High density
   - Laser cannot reach material directly, it’s reflected out of this region.
3. Low temperature
   - Plasma is not hot enough to really support ionizations for max. EUV

A basic picture of laser interaction with a plasma



A 1D cartoon of laser interaction

- Laser energy is absorbed primarily through inverse bremsstrahlung absorption.

$$K_{IB} = \left(\frac{\upsilon_{ei}}{c}\frac{\omega_P^2}{\omega^2}\right)\left(1-\frac{\omega_P^2}{\omega^2}\right)^{-1/2} = K_o n_c T(x)^{-3/2}\frac{n(x)^2}{n_c^2}\left(1-\frac{n(x)}{n_c}\right)^{-1/2}$$

- Laser energy is deposited up to the critical density surface

$$n_C = \frac{m\varepsilon_o}{e^2}\frac{\left(2\pi c^2\right)}{\lambda^2} = \frac{1.1x10^{21}}{\lambda_{\mu m}^2}$$

For λ=10.6um light ~10^{19} #cm^{-3}

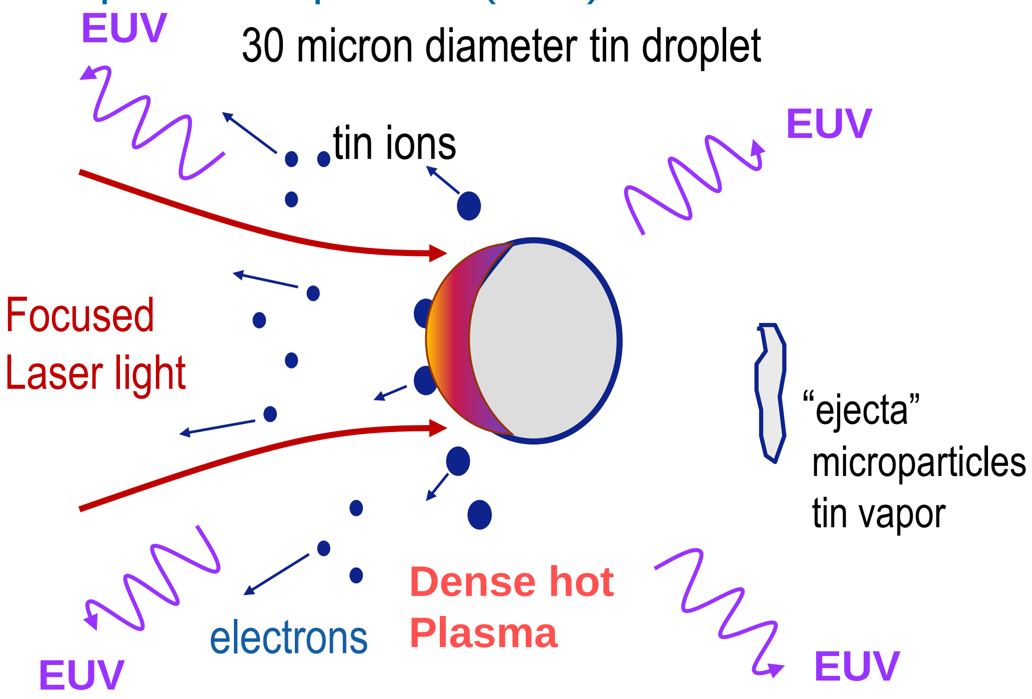
- Heat is then transferred beyond the critical density through heat conduction

$$q = -K_o T^{5/2}\frac{\partial T}{\partial x}$$

- EUV is generated within the plasma where temperature is sufficient to produce Sn ions of interest and the density is as high as possible.

Fundamentals: EUV Generation in LPP

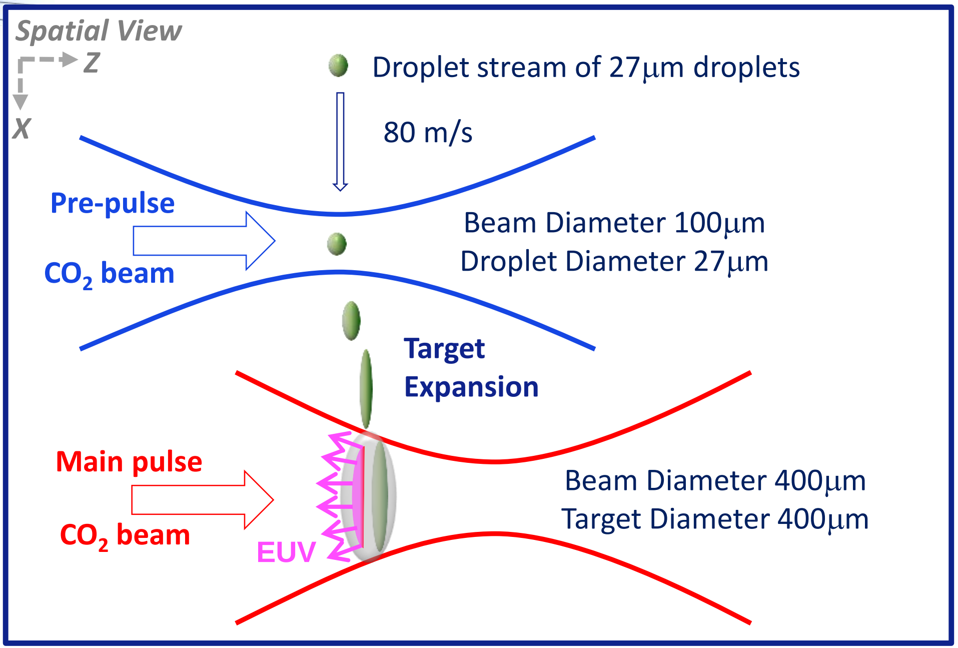
Laser produced plasma (LPP) as an EUV emitter

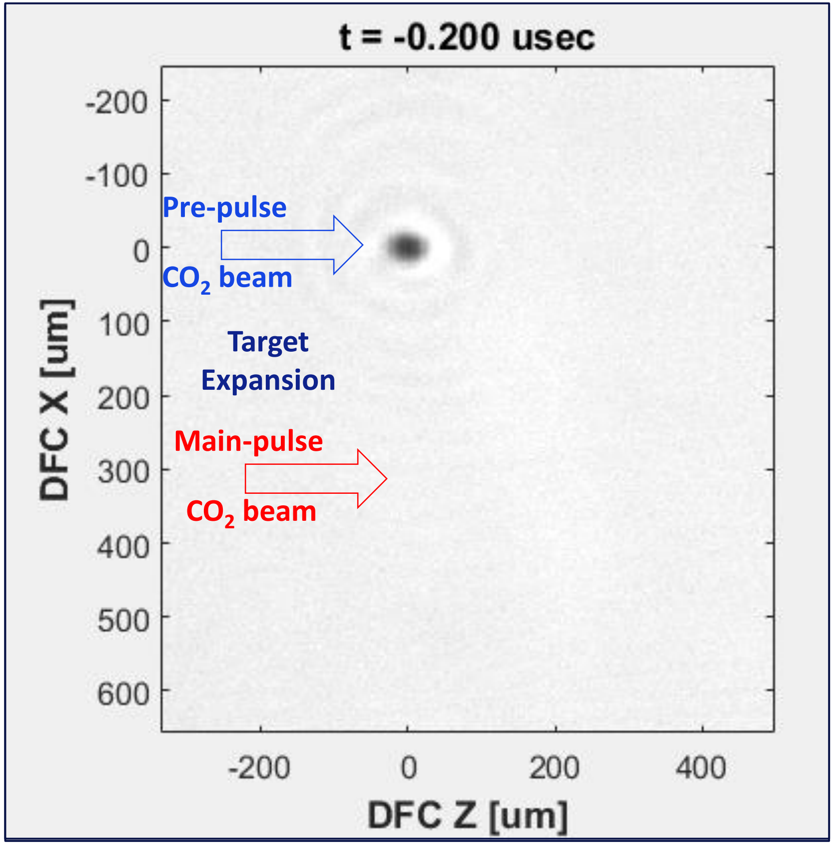


Tin Laser Produced Plasma Image

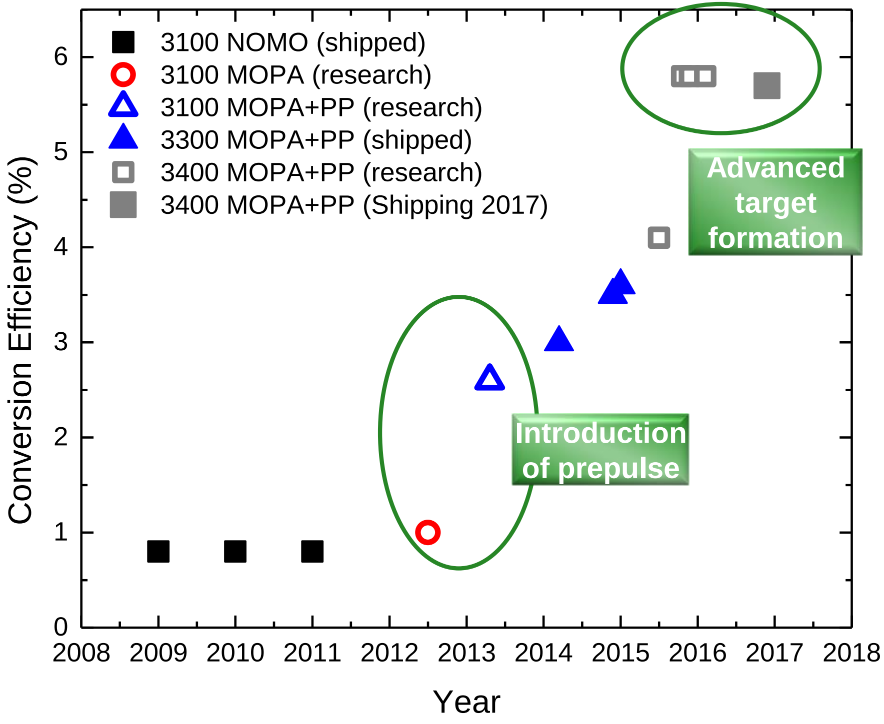
1. High power laser interacts with liquid tin producing a plasma.
2. Plasma is heated to high temperatures creating EUV radiation.
3. Radiation is collected and used to pattern wafers.

EUV Source: MOPA+PP Operation

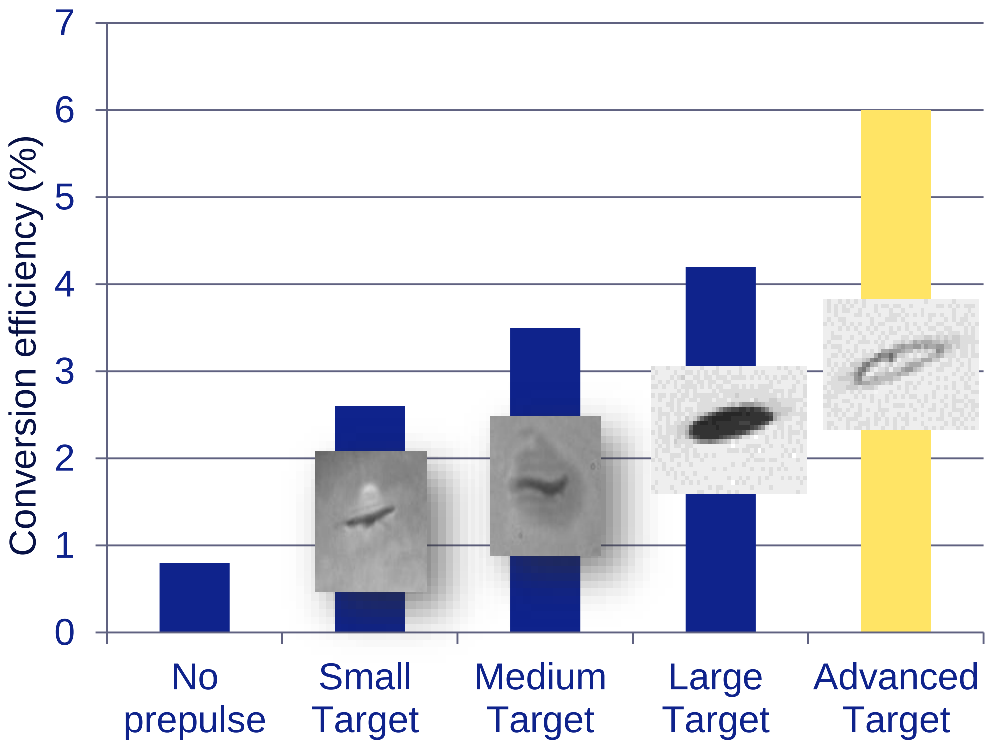




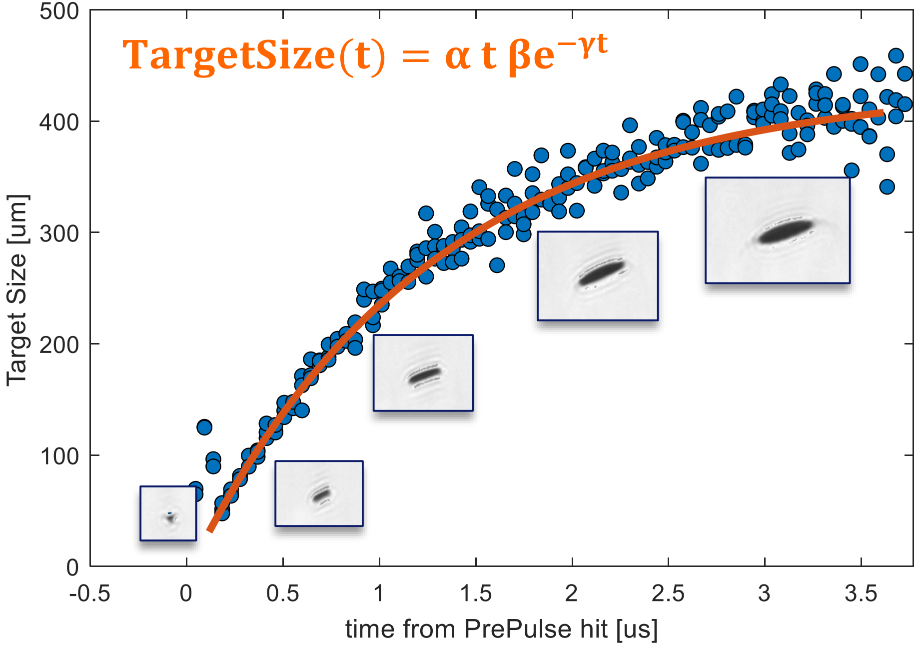
Target formation is critical for high CE plasma



Conversion Efficiency vs target type



Semi-empirical models use physics to connect different experimentally measured sensitivities



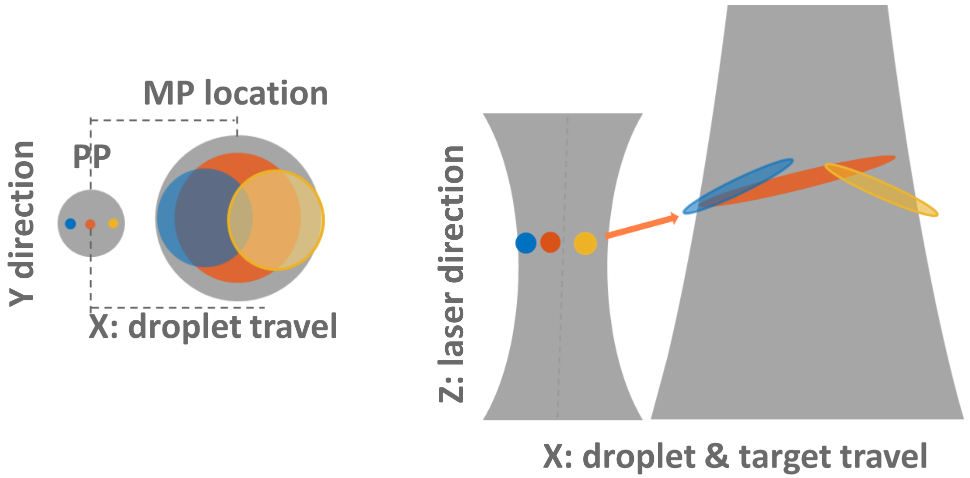
Target formation is very reproducible and follows simple

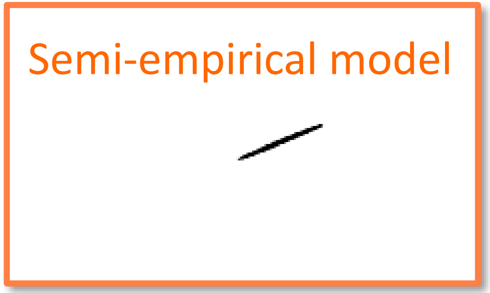
A **semi-empirical model** is a mix of

1. physics
2. fits from data

→ **simple formulas** capture behavior

Example:
The time Pre-Pulse hits affects droplet expansion

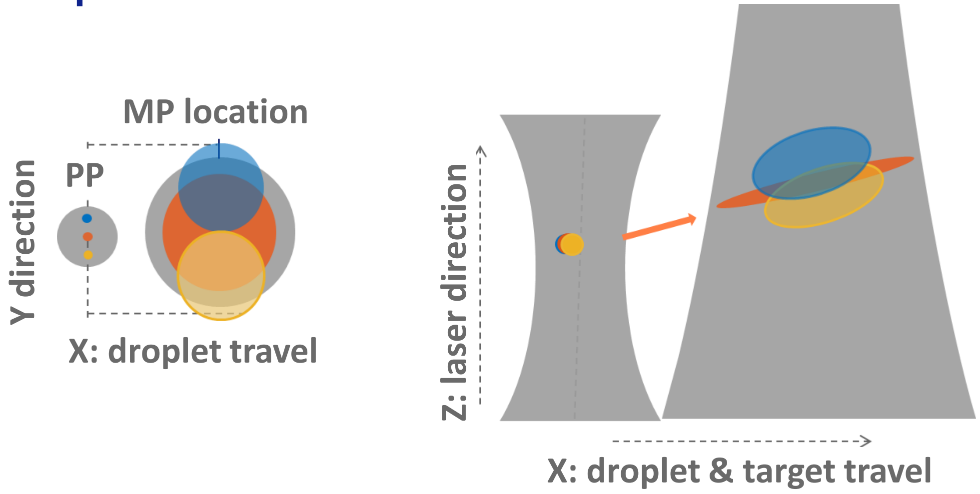




Scan of droplet position in PP beam along direction of droplet travel

How: combination of physics and data fit

Example:
Droplet location in Pre-Pulse affects expansion rates

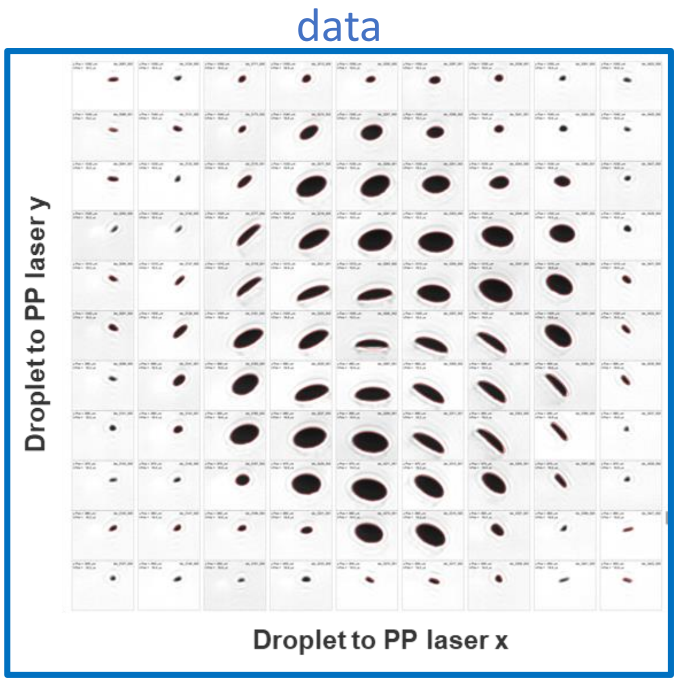


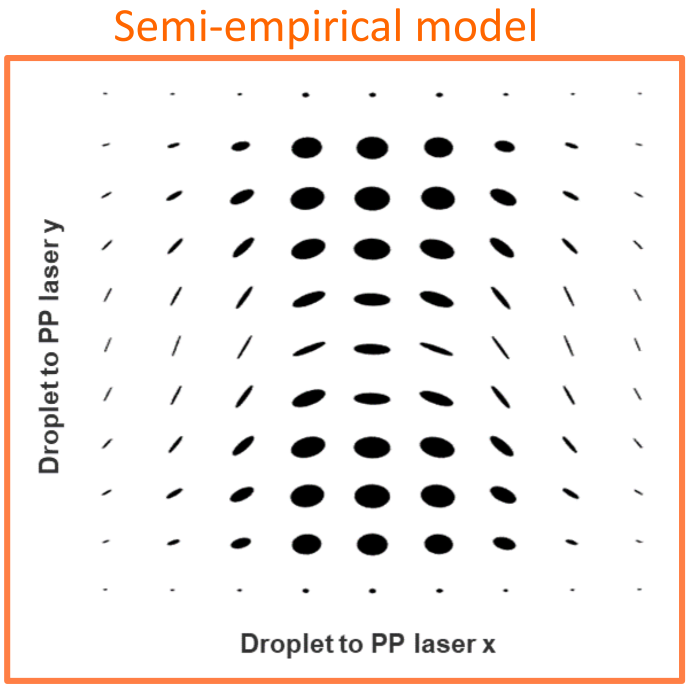
Scan of droplet position in PP beam along direction perpendicular of droplet travel

How: combination of physics and data fit

Full-model can capture a much more complex behavior

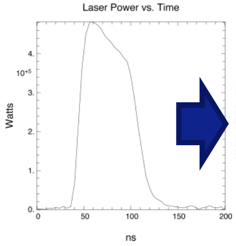
Over 10 independent variables can affect Target formation, giving a vast range of Target sizes and positions.





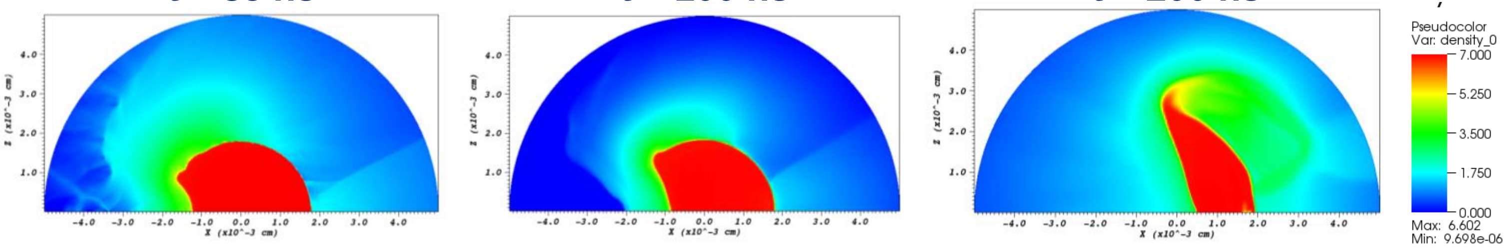
Radiation hydrodynamics provides insight into the plasma

Pre-pulse modeling



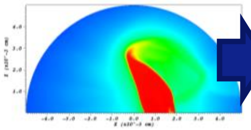
Input

t = 35 ns   t = 100 ns   t = 200 ns

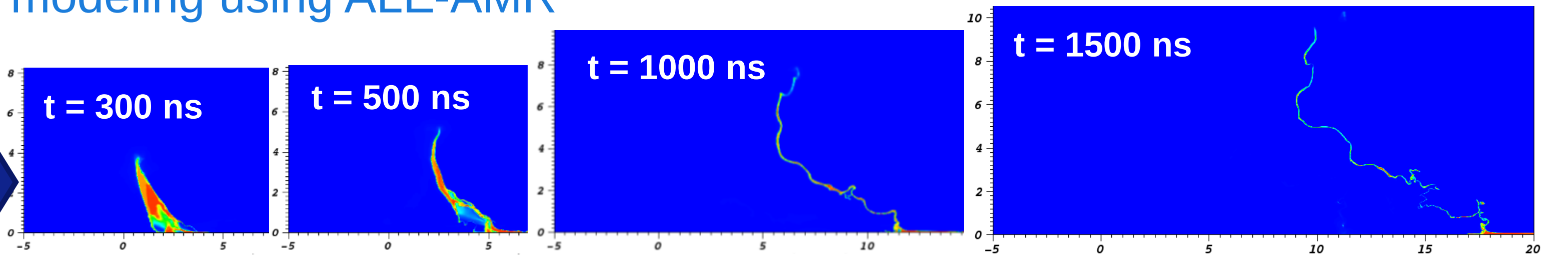


A small plasma forms at the front side of the droplet that initiates the forces and subsequent shock waves that drive the expansion process.

Drift phase modeling using ALE-AMR



Input



An adaptive mesh tracks the expanding droplet material for more than 2us.

What plasma simulation capabilities have we developed?

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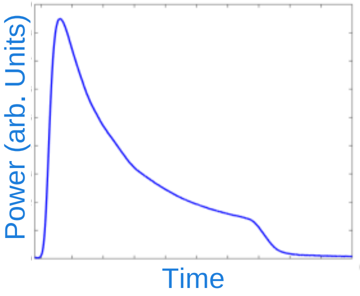
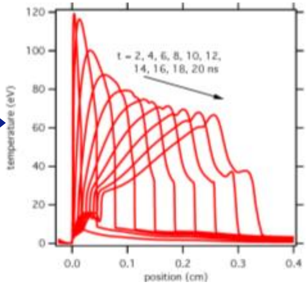
Main-pulse modeling using LLNL code HYDRA

Main-pulse shape

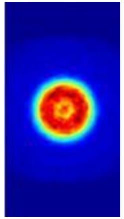


1D:
real pulse shape

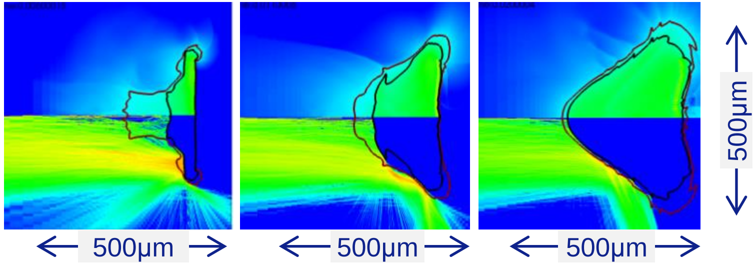


1D simulations are fast and useful for problems that require rapid feedback and less accuracy

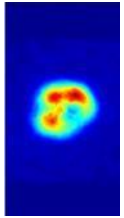
2D:
+ symmeterized beam profile

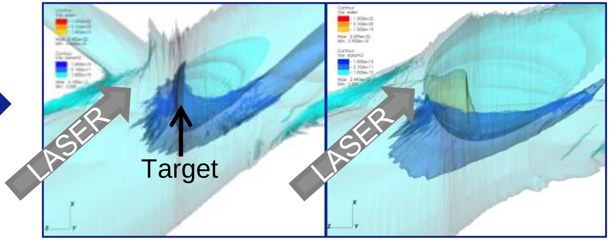


Electron density (top half) with laser light (bottom half)



3D:
+ real asymmetric profile



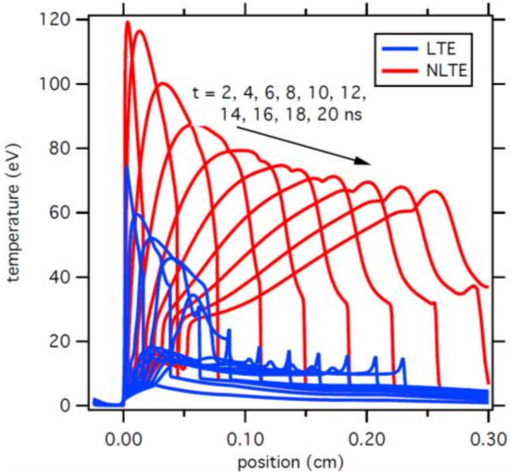


2D and 3D simulations are run for the full duration of the Main pulse. Results include temperature, electron density, spectral emission, etc.

Sn target using a real irradiance distribution

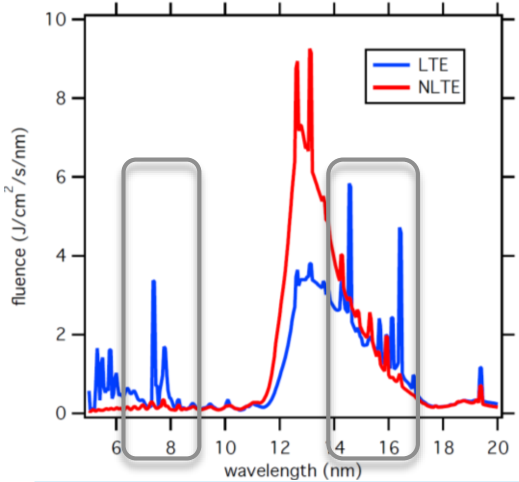
Atomic simulations useful for EUV radiation predictions

Understanding the assumption of a thermal distribution of excited states



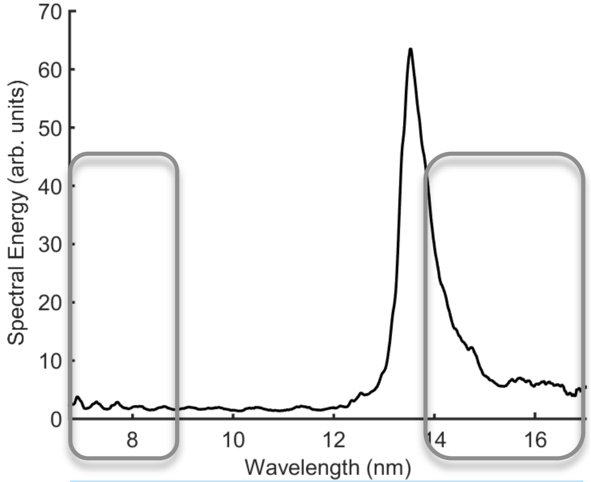
1D calculations confirm that the assumption of a thermal distribution of excited states is not a good approximation.

LTE and NLTE simulations using the same atomic configurations



Calculations that assume LTE lead to emission at higher photon energies.

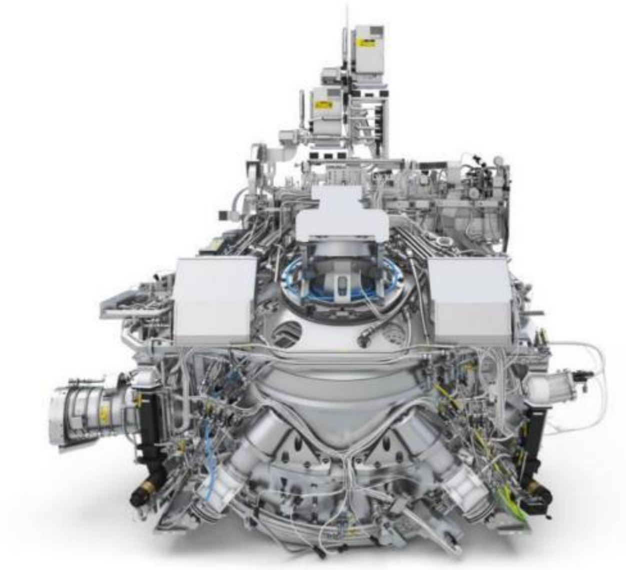
Measured EUV spectra



Simulated Spectra were improved using NLTE.

LTE = **L**ocal **T**hermal **E**quilibrium

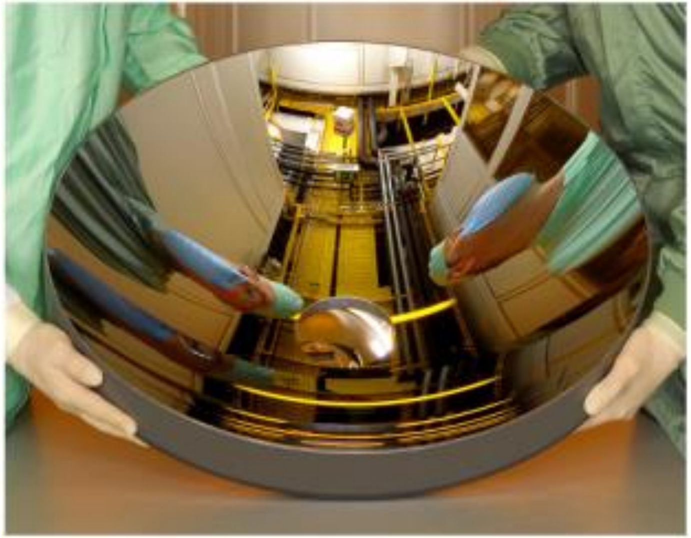
Outline



- Background and History
- EUV Lithography in HVM
- EUV Lithography with NXE:3400B
- EUV Source: Architecture
- Principles of EUV Generation
- Challenges and Practicalities

EUV Collector: Normal Incidence

- Ellipsoidal design
  - Plasma at first focus
  - Power delivered to exposure tool at second focus (intermediate focus)
- Wavelength matching across the entire collection area
- IR spectral filtering

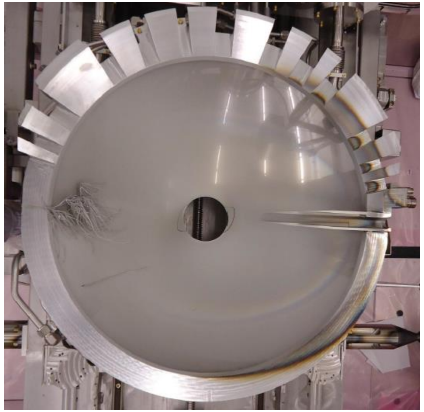


Normal Incidence Graded Multilayer Coated Collector

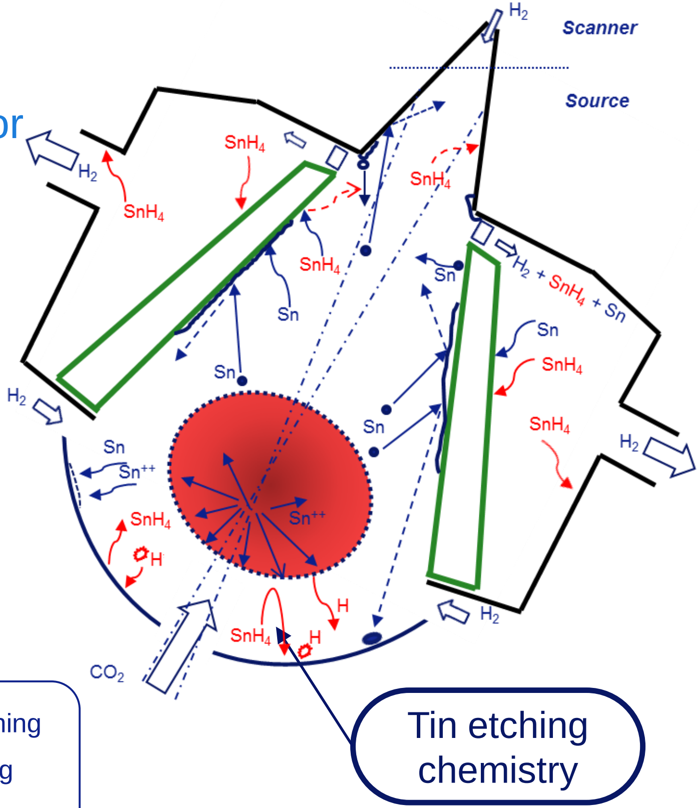
Tin management architecture

Transport, collection and tin removal from critical surfaces

- Keep collector, EUV path and metrology clean
- 1 nm of Sn reduces reflectivity by 20%
  - Mass of 1 s operation uniformly spread over collector
  - 10^7 s lifetime wanted
- Strategies:
  - Gas transport
  - Liquid and solid tin collection modules
  - Tinphobic/tinphilic surfaces
  - Etching chemistry



First 3300 collector lasted 60 seconds



Sn — Sn vapor (diffusion debris)

Sn^+ — Fast Sn ion (line of sight debris)

Sn — Sn particle

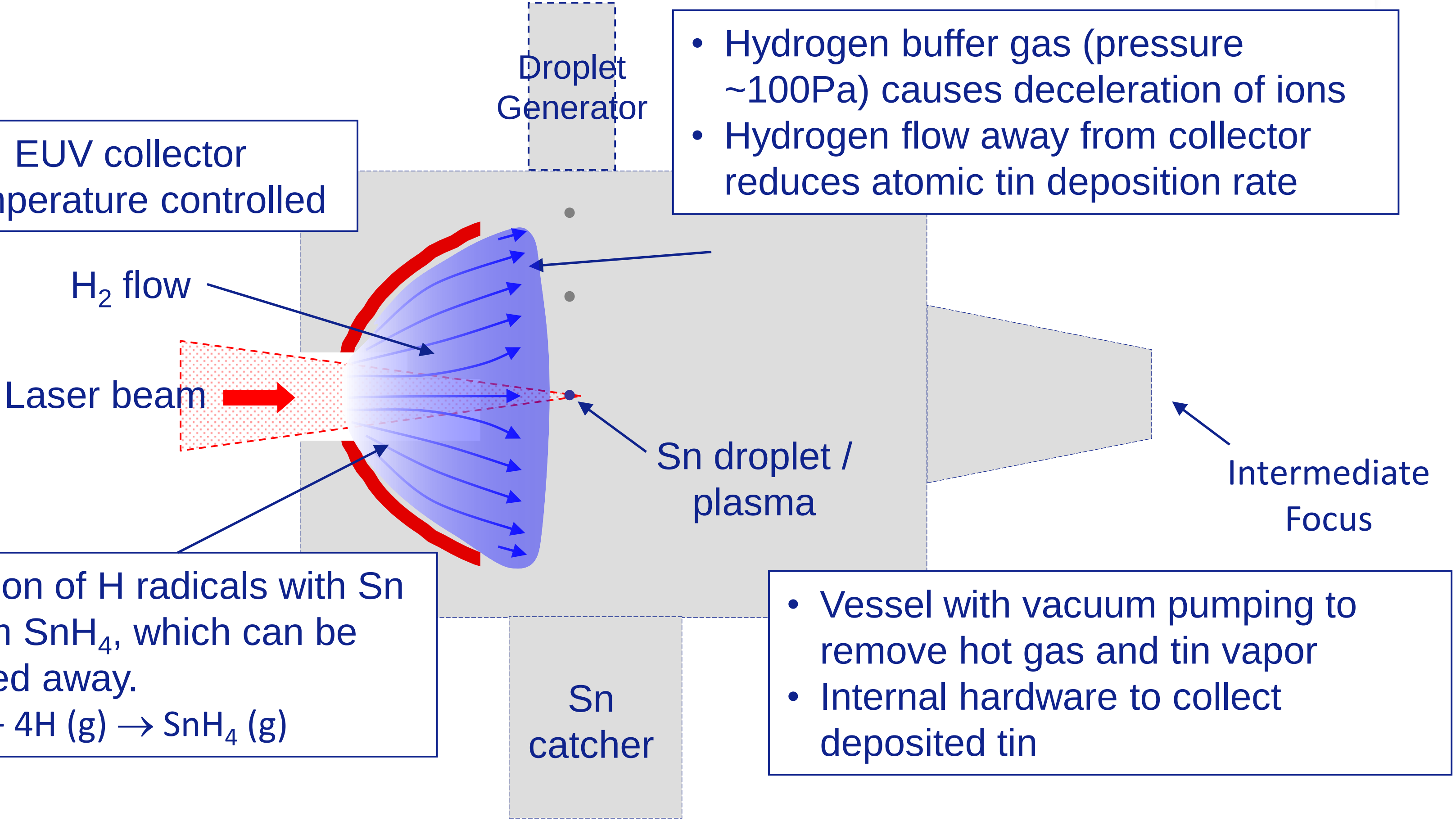
Sn — Sn scattering / splashing

Sn dripping / dropping

Collector Protection by Hydrogen Flow – Transport

EUV collector
Temperature controlled

- Hydrogen buffer gas (pressure ~100Pa) causes deceleration of ions
- Hydrogen flow away from collector reduces atomic tin deposition rate



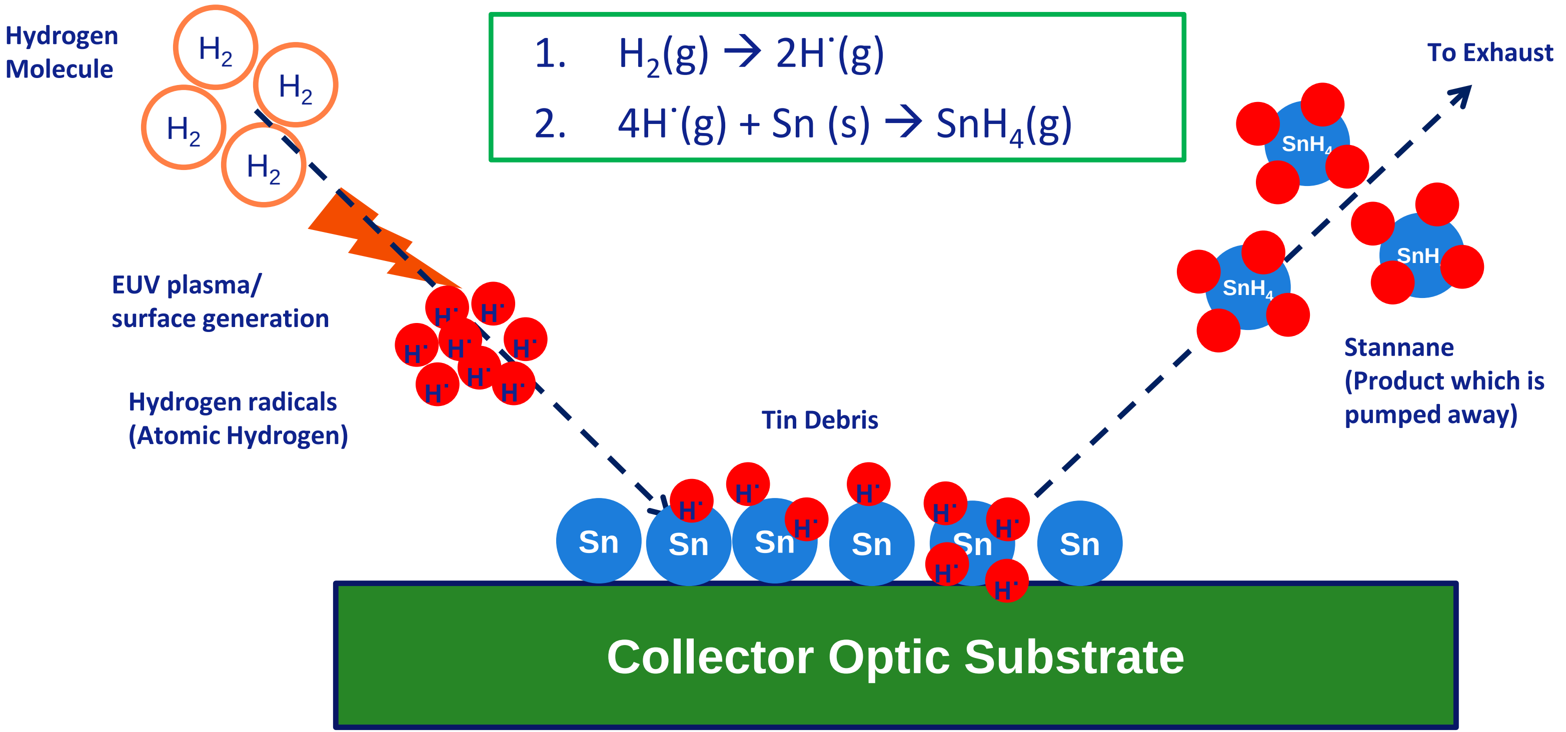
Reaction of H radicals with Sn to form SnH_4, which can be pumped away.

$Sn\ (s) + 4H\ (g) \rightarrow SnH_4\ (g)$

- Vessel with vacuum pumping to remove hot gas and tin vapor
- Internal hardware to collect deposited tin

Collector protection by tin etching – Tin removal

1. $H_2(g) \rightarrow 2H^{\cdot}(g)$
2. $4H^{\cdot}(g) + Sn\ (s) \rightarrow SnH_4(g)$



Main Challenges:

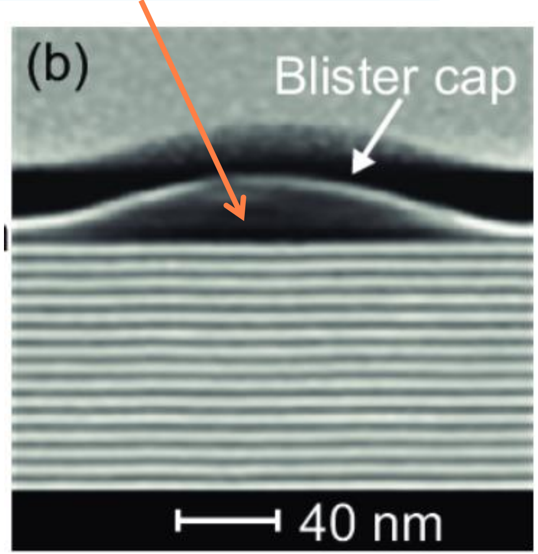
- Low lifetime of hydrogen radicals
- Instability of Stannane

Collector Lifetime - Coatings

Materials selection is key to protect surfaces from contamination

- Need robust coatings as we increase power
- Plasma-surface interaction plays a key role

Example of MLM coating damage



Bos, R. & all, Journal of Applied Physics, 120 (2016)

Coating + cap

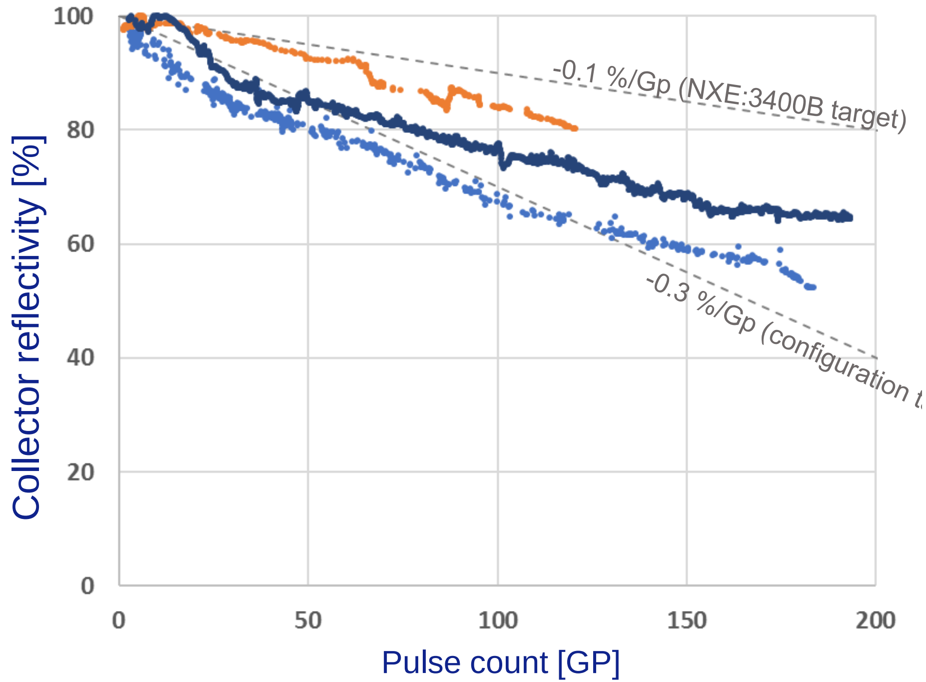
Caps are used to protect the MLM

Current challenges:

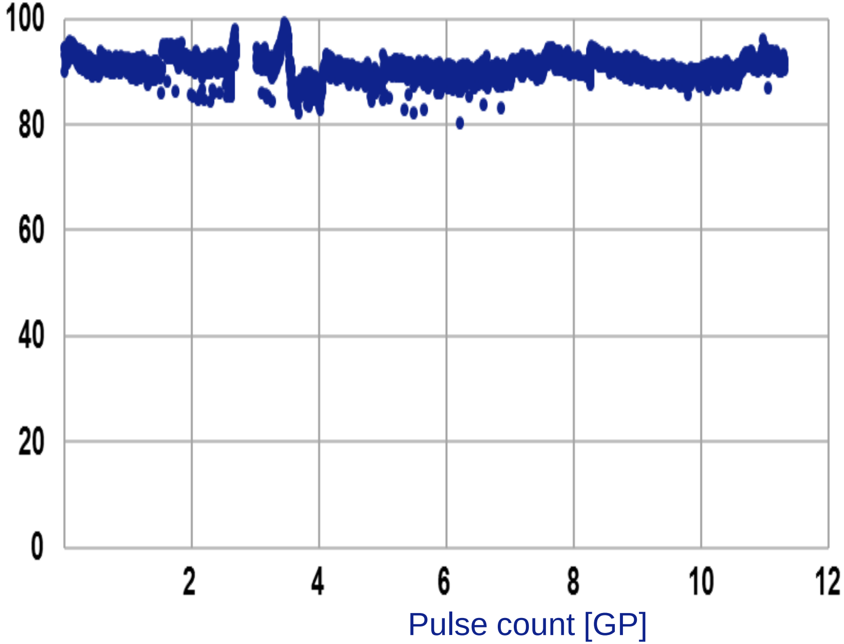
1. Tin contamination
2. Coatings: damage/blistering →new coatings under evaluation

Collector degradation <0.1%/GP for NXE:3400B@125wph

ASML



NXE:3400B base configuration



NXE:3400B test configuration (ASML factory)

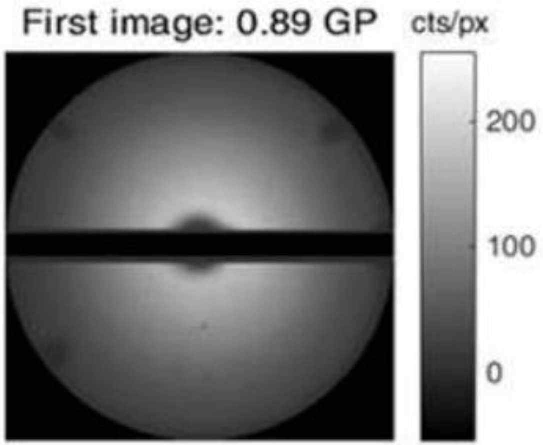
0.1-0.3%/GP

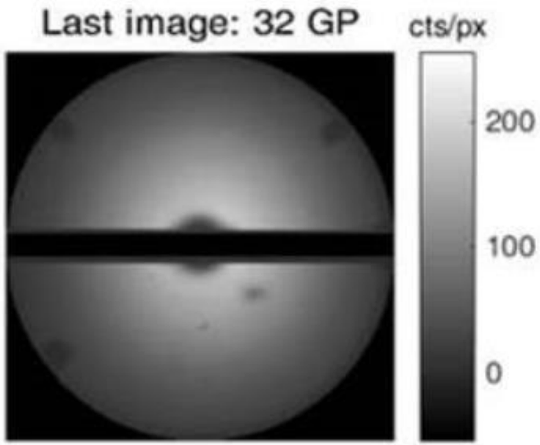
<0.1%/GP

Research progress on collector lifetime

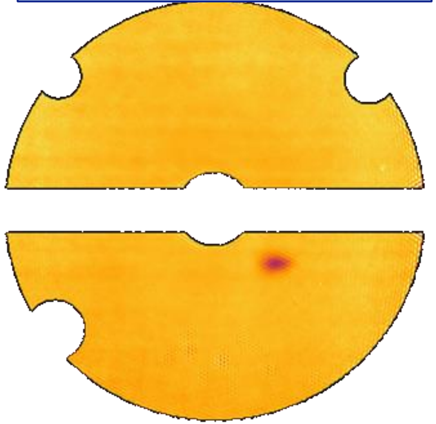
Demonstrated <0.03%/Gp

Feasibility research on proto next gen source has demonstrated < 0.03%/Gp





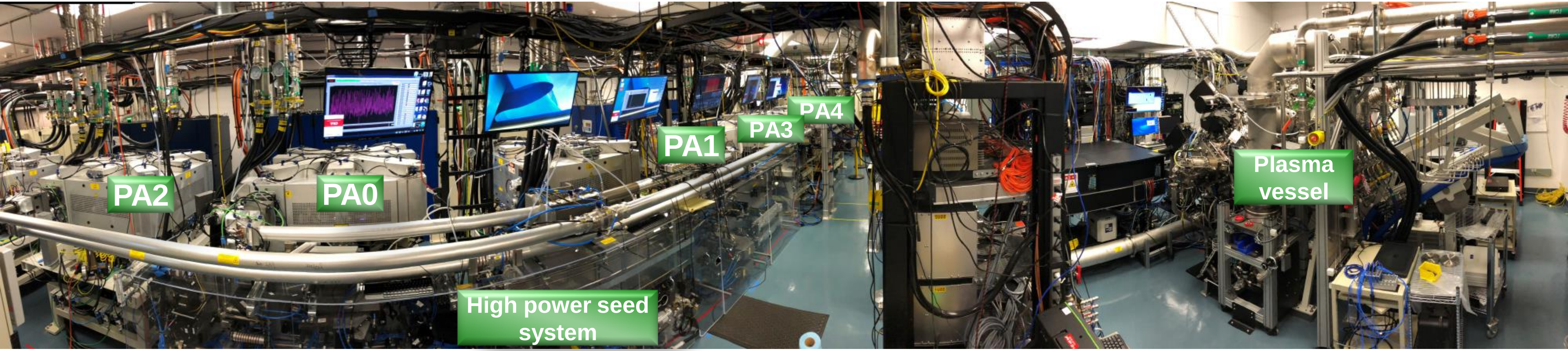
32-GP Collector Life Test: difference image



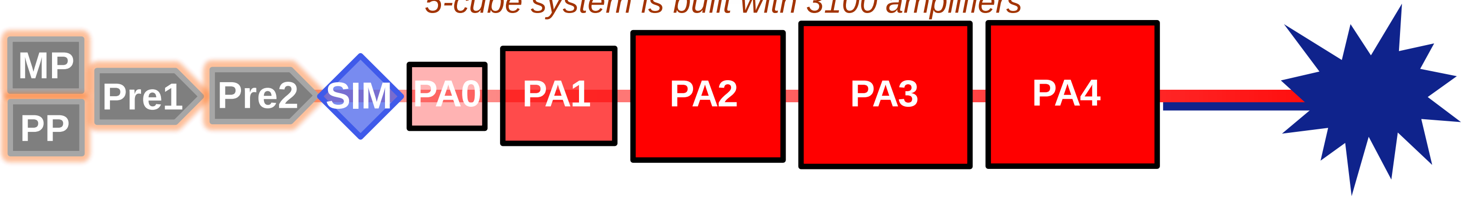
<0.03%/GP

Some learning from research can be rapidly introduced to the product through the gas and flow conditions

EUV Power Scaling:
Research System incorporates High-Power CO_2 chain

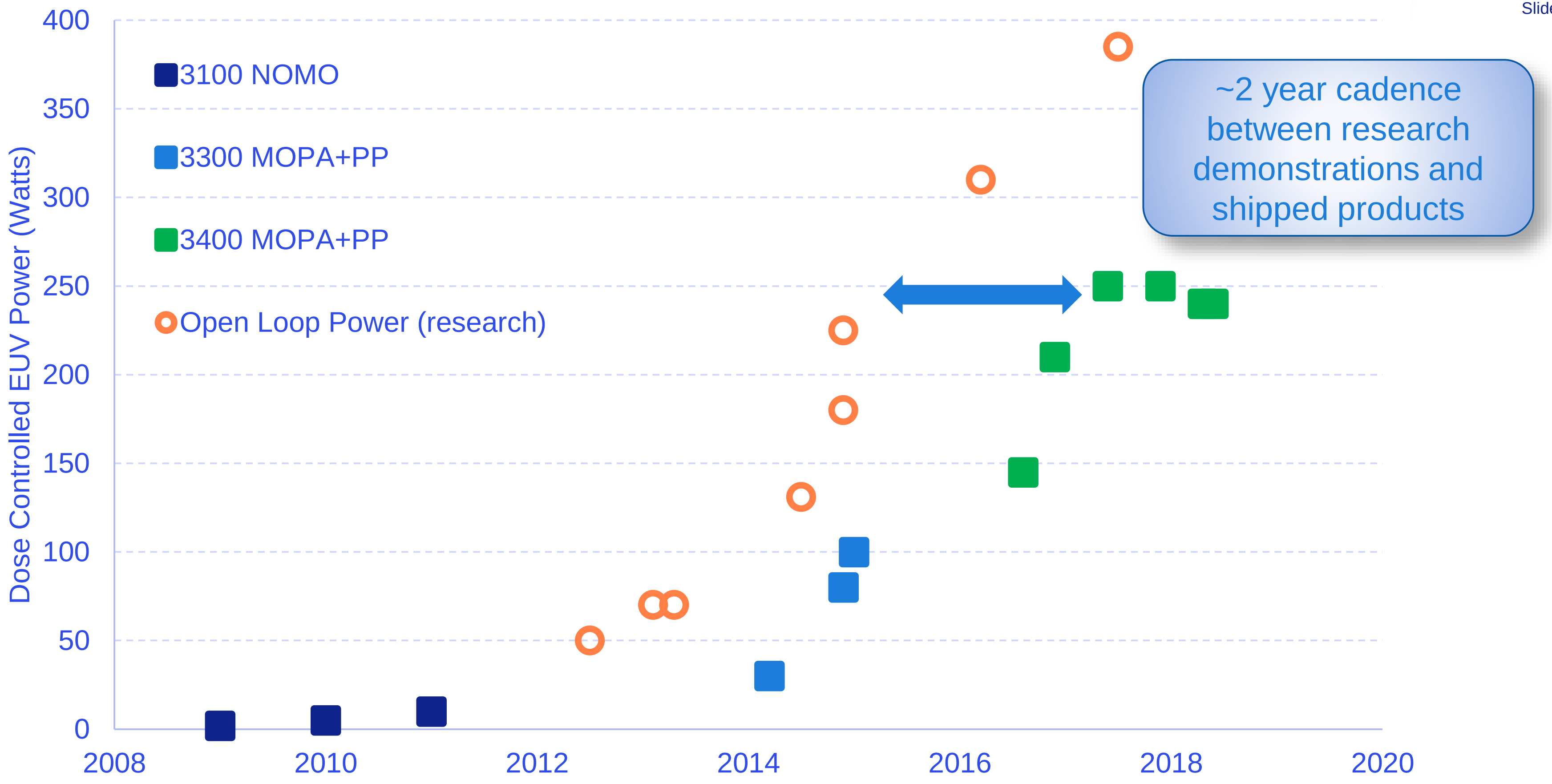


5-cube system is built with 3100 amplifiers



Research system only capable of short burst (15ms) operation due to thermo-optical limitations of final focus

Power scaling on track to meet product roadmap



High-NA system architecture finalized

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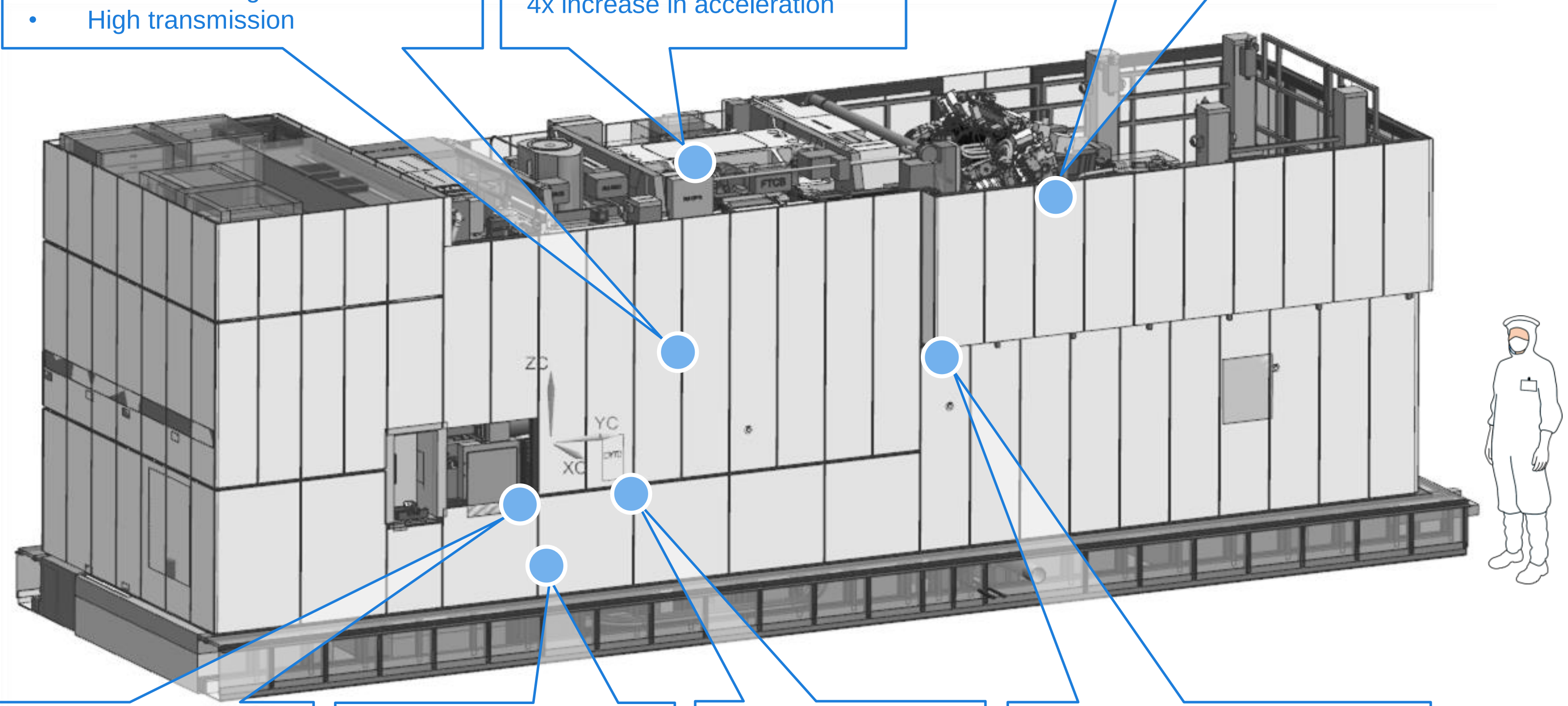
Improved Source position
Allows for larger transmission, compatible with 0.33 NA

Lens & illuminator
- NA 0.55 for high contrast
- High transmission

Mask Stage
4x increase in acceleration



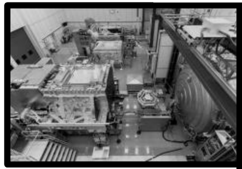
Improved metrology
2~3x improvement in overlay/focus

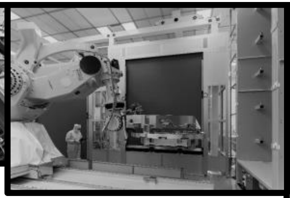
Wafer Stage
2x increase in acceleration

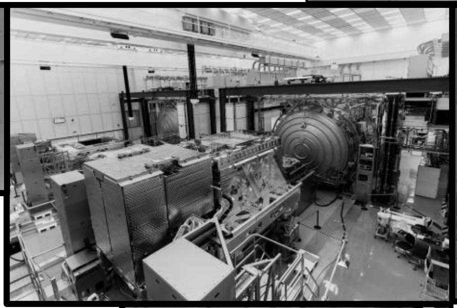
Cooling hood
Mitigate wafer heating

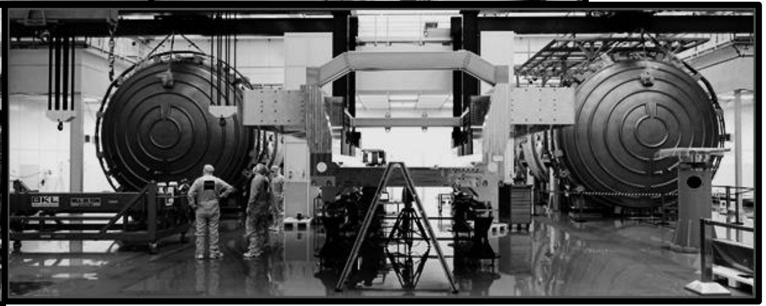
New Frames
Improved thermal and dynamic control with larger optics

Optics fabrication in progress, metrology in place





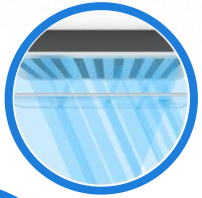


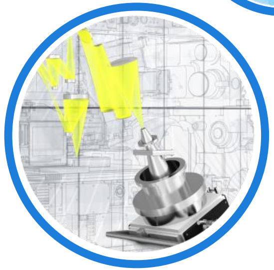


EXE:5000 system global design completed

Solid progress on system design and optics development and – manufacturing

Summary





EUV chips have made it to the end market!

Our customers are ramping up EUV for the 7nm Logic node and preparing for the 16nm DRAM node with systems deliveries and qualification on-going. EUV layers adoption continues to grow to reduce patterning complexity and cost

ASML EUV lithography systems continue to improve on productivity and availability supporting our Logic and DRAM customers roadmap while maintaining, state of the art overlay performance and year on year cost reduction

- Dose-controlled power of 250W on multiple tools at customers
- Droplet Generator with improved lifetime and reliability >700 hour average runtime in the field>3X reduction of maintenance time
- Collector lifetime improved to > 100Gp (4X at 3X higher power)

Availability improvements are well underway to meet our customers requirements, with the NXE:3400C supporting >90% availability

Path towards 500W EUV demonstrated in research

- EUV CE is up to ~ 6 %
- In burst EUV power demonstration up to 500W
- CO_2 Laser development supports EUV power scaling

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ASML US LP, 17075 Thornmint Ct. San Diego, CA 92127-2413, USA

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