High Power Laser-Sustained Plasma Light Sources for KLA-Tencor Broadband Wafer Inspection Tools

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Overview

- Motivation: high-brightness light sources for wafer inspection
- Failure of traditional plasma sources to meet K-T power and brightness requirements
- Near-IR Laser-Sustained Plasma (LSP) principles of operation
- Why broadband? Why not pulsed? Why not CO_2 pumped?
- Challenges of the high-power LSP regime

KLA-Tencor Overview

>40 years

Global Leader in Process Control since 1976

~22,000
tools installed worldwide

~6,000
global employees

17
countries

$3.5B
FY17 revenue

$2.1B
R&D investment over last 4 fiscal years

KLA-Tencor's Inspection Portfolio

3900 Series
Broadband Plasma Wafer

2930 Series
Broadband Plasma Wafer

Puma™ 9980
Laser Scanning Wafer

8920
High Sampling Wafer

CIRCL™
All-Surface Wafer

Surfscan® SP5XP
DUV Unpatterned Wafer

eDR7280™
Wafer SEM Review

Teron™ 640
Reticle (Mask Shop)

Teron™ SL655
Reticle (IC Fab)

RDC
Reticle Data Analysis

eS805™
e-beam Wafer

CIRCL-AP™
Wafer-Level Packaging

ICOS® T3 &T7
Component

Klarity® Defect & ACE
Defect Data Management

Comprehensive wafer, reticle and component inspection with advanced data analysis supports defect discovery, process optimization and production monitoring

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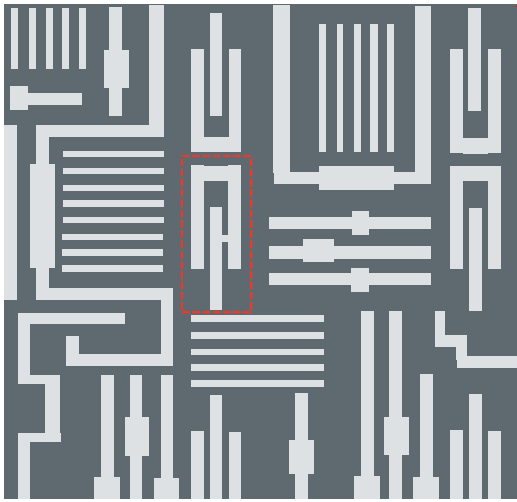
2920 Series
Broadband Plasma Patterned Wafer Defect Inspection



We wish we could resolve it just like that…

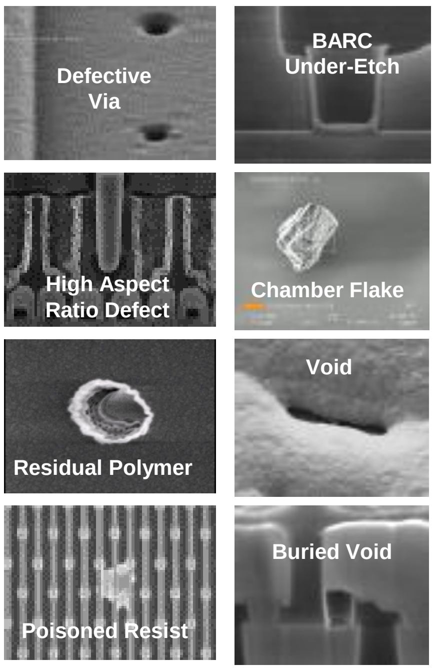
2920 Series

Ultimate optical sensitivity and speed for rapid defect discovery and monitoring

Customer: "We're blind without you guys…"

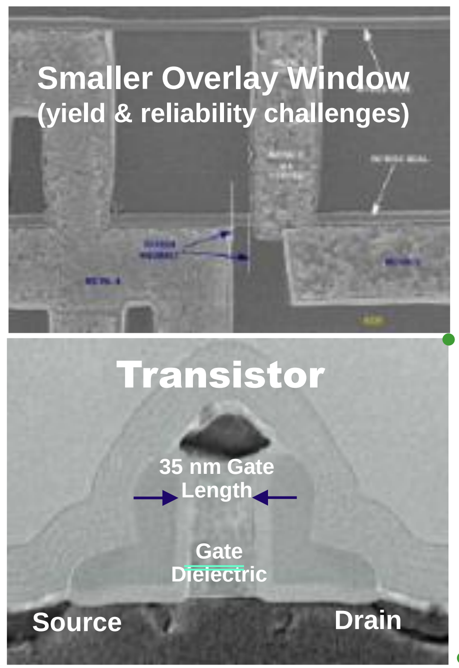
DEFECTS

You can't fix what you can't find



METROLOGY

You can't control what you can't measure

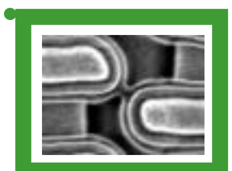


1 cm (10,000,000nm)
Head of a Pin: ~2,000,000nm

1 mm (1,000,000nm)
Human Hair: ~100,000nm

0.1 mm (100,000nm)
Red Blood Cell: ~5,000nm

1 micron (1,000nm)
Bacteria: ~800nm



0.1 micron (100nm)
Semiconductor Bridging Defect: ~30nm

0.01 micron (10nm)
DNA Strand Diameter: ~6nm

KLA-Tencor Provides Systems that Enable Finding Defects and Measuring Critical Dimensions

Some of the defects we can find are this small (<10 nm)

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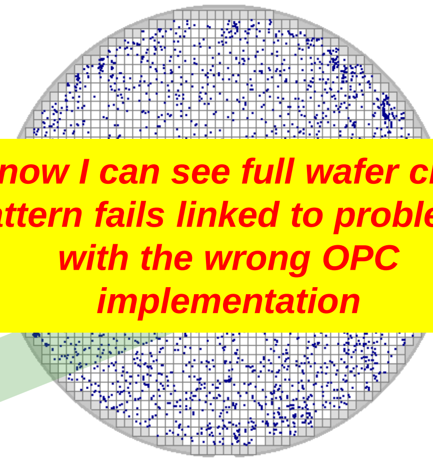
Importance of Full Optical Wafer Inspection to Yield

Find Design Systematics (Occur at PPM)

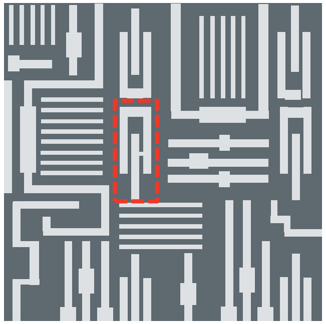
This blue map is worthless

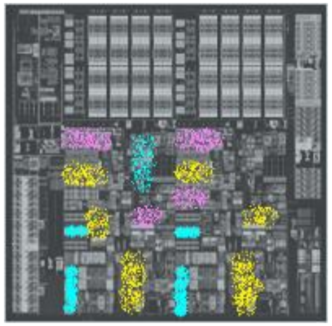
Find all the hard OPC fails in order to fix the mask – the DRC ranking engines are not that good

Design Based Inspection Full Wafer – finds OPC fails



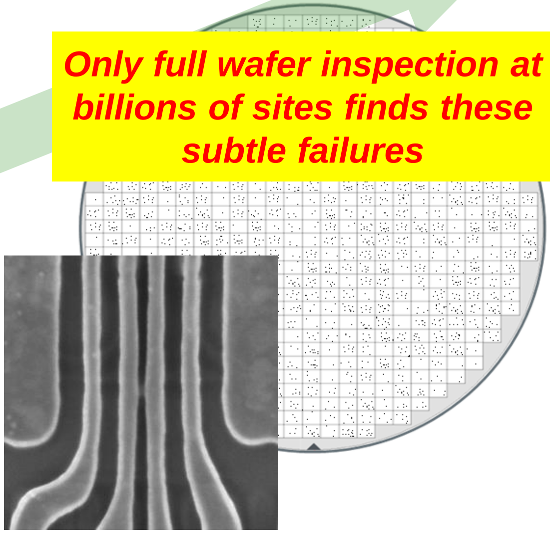
OK now I can see full wafer critical pattern fails linked to problems with the wrong OPC implementation





Process Design Systematics – Litho/Dep/Etch interaction

Only full wafer inspection at billions of sites finds these subtle failures



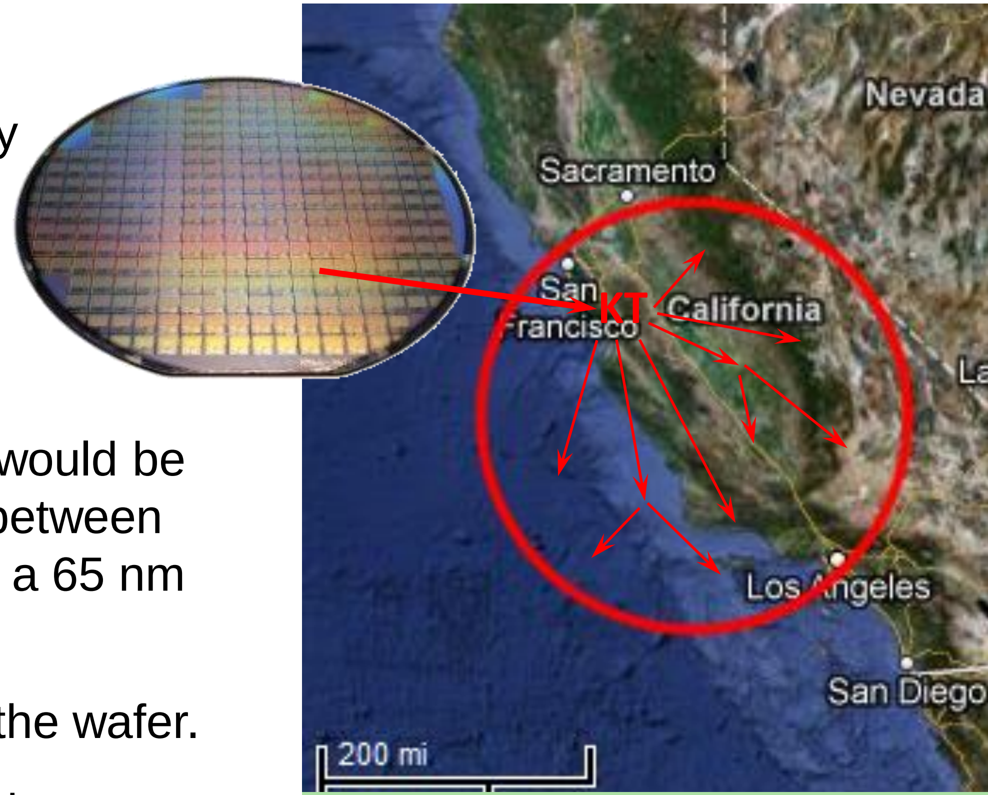
Marginal design, process induced failures – need full wafer to look at 1 Billion pattern sites. Even with 10% optical capture at 1 Billion sites, with 1% fail = 100% probability of capture

The Power of Optical Inspection

Scaling Example

- Suppose we scale a 10-nm defect by 2 million, to the size of a small coin.

10 nm ⟶



- At the same scale, a 300 mm wafer would be 600 km across, roughly the distance between San Francisco and Los Angeles! And a 65 nm pixel would be about 12 cm × 12 cm.

- There are about 17 trillion pixels on the wafer.

- Suppose there are 10-100 coins hidden somewhere in this huge area, and you are given 1 hour in which to find them all. At night.

<u>How can this be accomplished?</u>

Answer: Optical inspection can sample every single pixel in this area and find the defects in about an hour.

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Broadband Plasma Patterned Wafer Defect Inspection

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resolve it just like that…

2920 Series

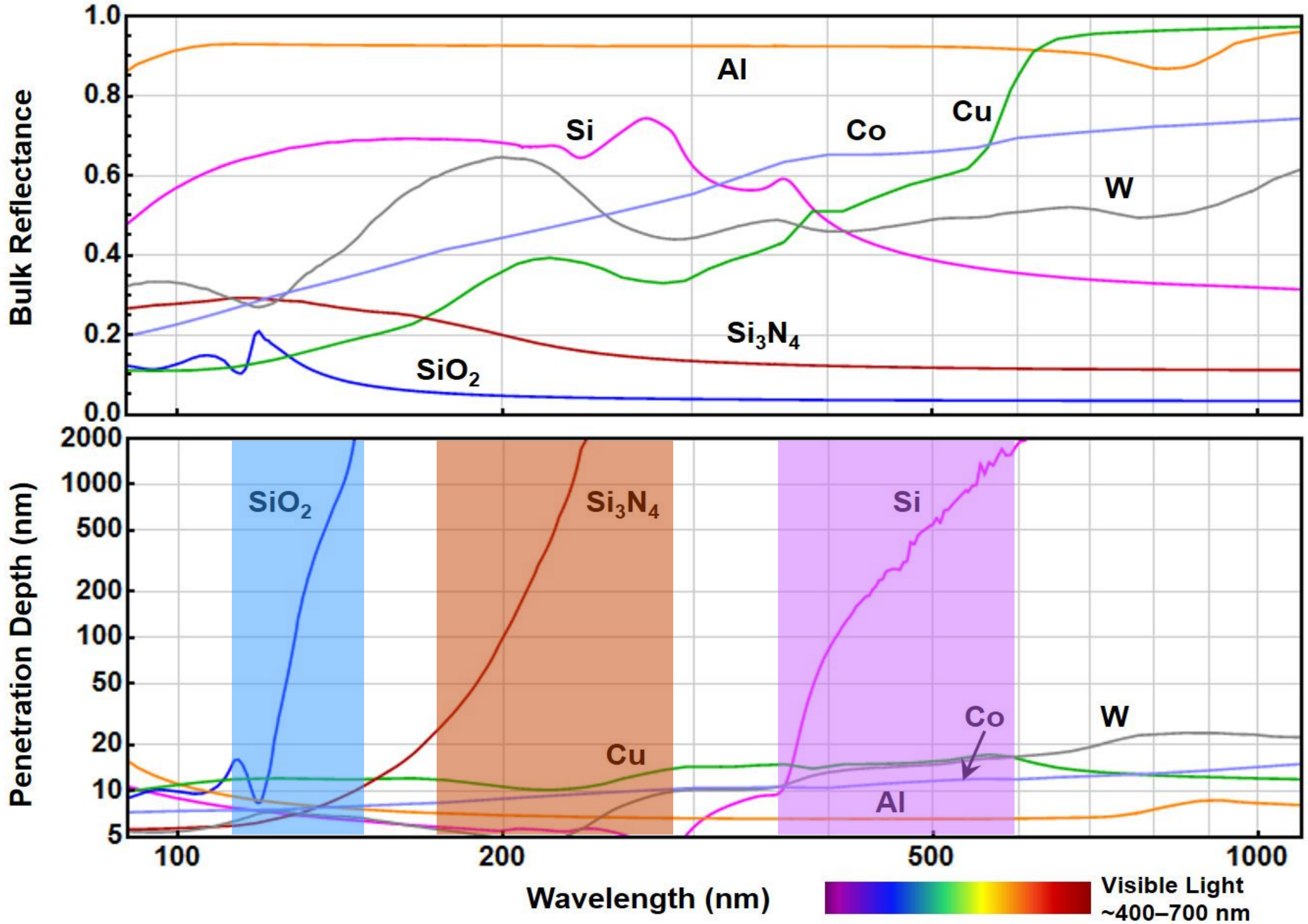
Ultimate optical sensitivity and speed for rapid defect discovery and monitoring

Reflectance and Penetration Depth for Common Semiconductor Materials

- X-Ray – TBD
- EUV – no good.
  No material contrast

- VUV 120-190 nm
  - SiO_2 divide
- DUV 190-250 nm
  - Si_3N_4 divide
- UV 250-450 nm
  - Si divide
- VIS-IR >450 nm
  - alternative sources ok

Powered by LSP



Optical constants from E. Palik, *Handbook of Optical Constants of Solids*, Academic Press, 1998

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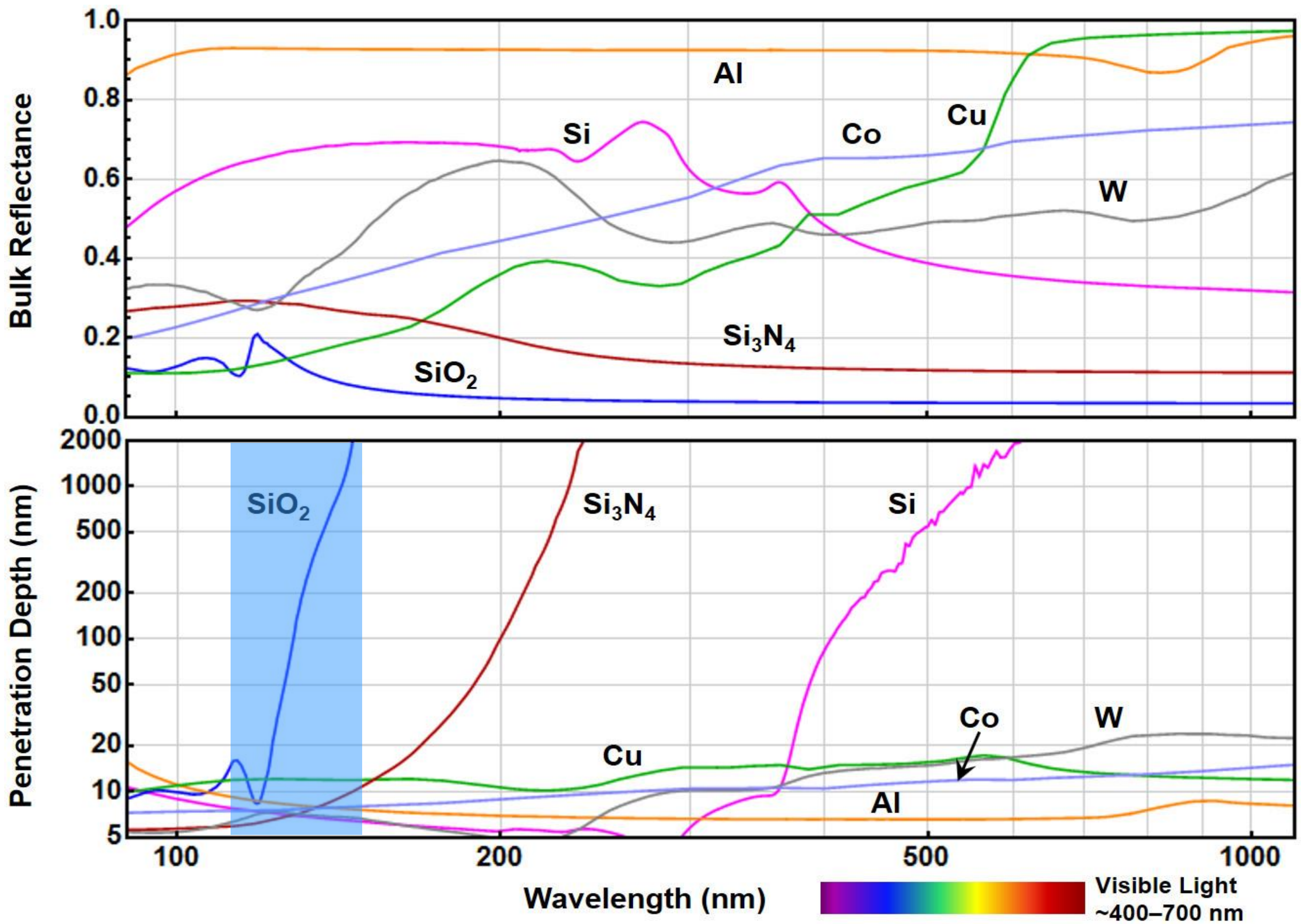
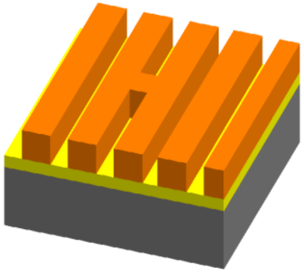
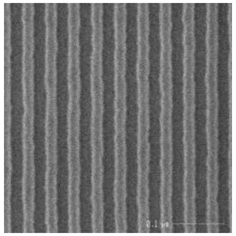


Optical constants from E. Palik, *Handbook of Optical Constants of Solids*, Academic Press, 1998

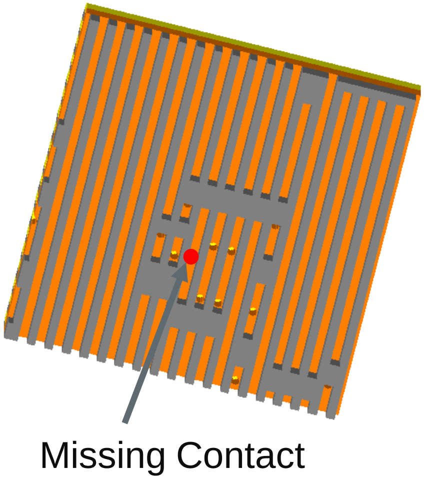
K-T has developed a complete simulation capability to predict S/N. Many defects need VUV.

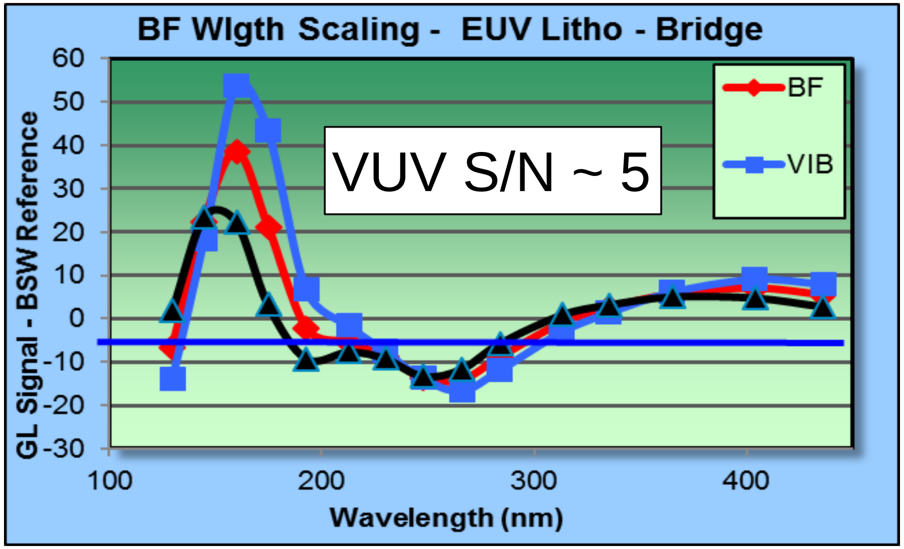


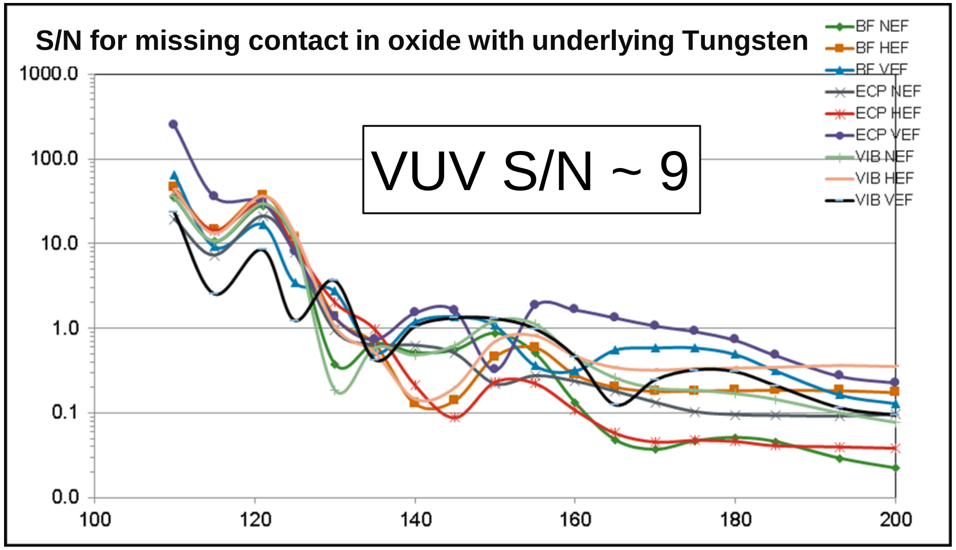
Noise sources like LER must be included to get an accurate answer – here is an example 22 nm EUV Print Check – Modeling of a Bridge



Random logic area containing a missing contact in an oxide layer with underlying tungsten another example showing pronounced S/N improvement in VUV







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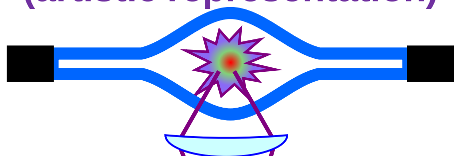
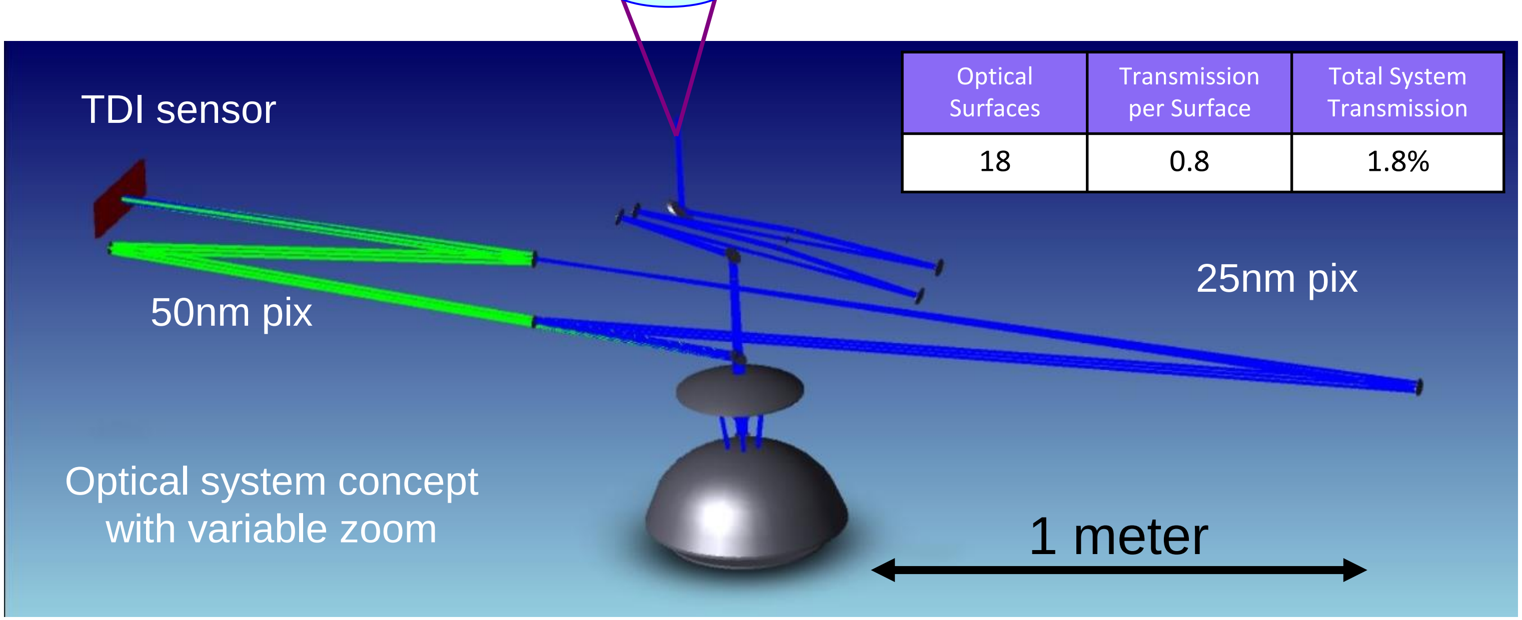
Conceptual Design for a VUV System

WHAT SHALL WE PUT HERE??

VUV lamp concept (artistic representation)



A lamp with radiance in the range of Watts/nm/mm²/srad and power in the range of hundreds of Watts in VUV



Optical Surfaces	Transmission per Surface	Total System Transmission
18	0.8	1.8%

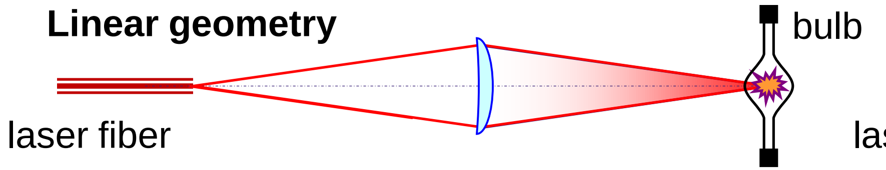
Conceptually, optics is doable

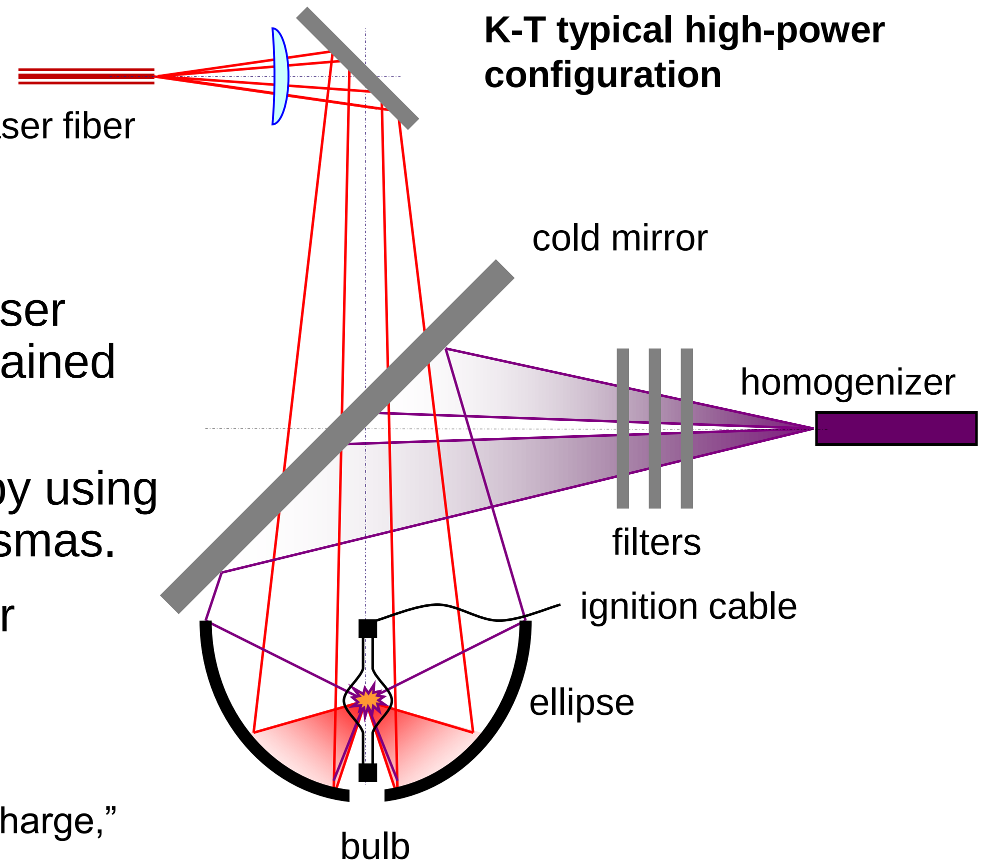
Key Challenges for VUV Optics – All Reflective System
- **Optical mirror design and manufacturing has been pioneered by EUV – difficult but achievable**
- **Multiple surfaces to implement optical signal enhancement techniques are a light budget challenge**
- **Aluminum provides excellent reflectivity in VUV, but protective coatings are “invention”**

Introduction: Laser Sustained Plasma

Concept: ~ 1kW CW IR laser focused to sustain plasma. The fluence in the focus is lower than needed for gas breakdown but enough to sustain the plasma once ignited.

There are different pump schemes utilized for different applications:





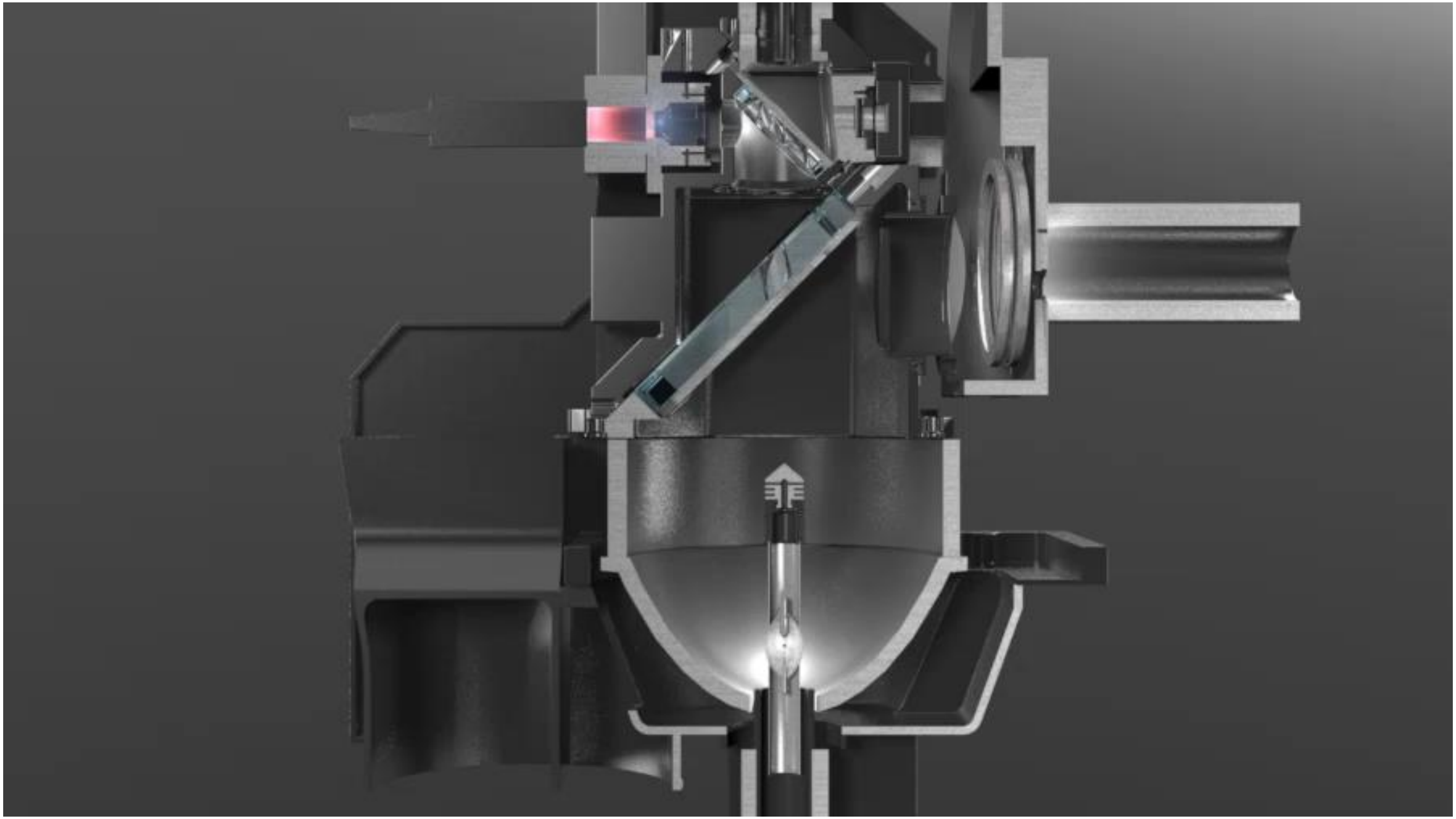
Unlike plasmas originated by a pulse air breakdown and attainable with modest laser pulse energies, CW plasmas can be sustained only when pumped by >~100 W lasers.

First attempted in Siberia in Dark Ages* by using 10 μ CO_2 laser. They got ~1 cm size plasmas.

Use of ~1 μ solid state fiber-coupled laser results in sub-mm size plasmas.

* N. A. Generalov, V. P. Zimakov, G. I. Kozlov, V. A. Masyukov, and Y. P. Raizer, "Continuous Optical Discharge," ZhETF Pis. **11,** No. 9 (1970).

K-T Production Lamphouse



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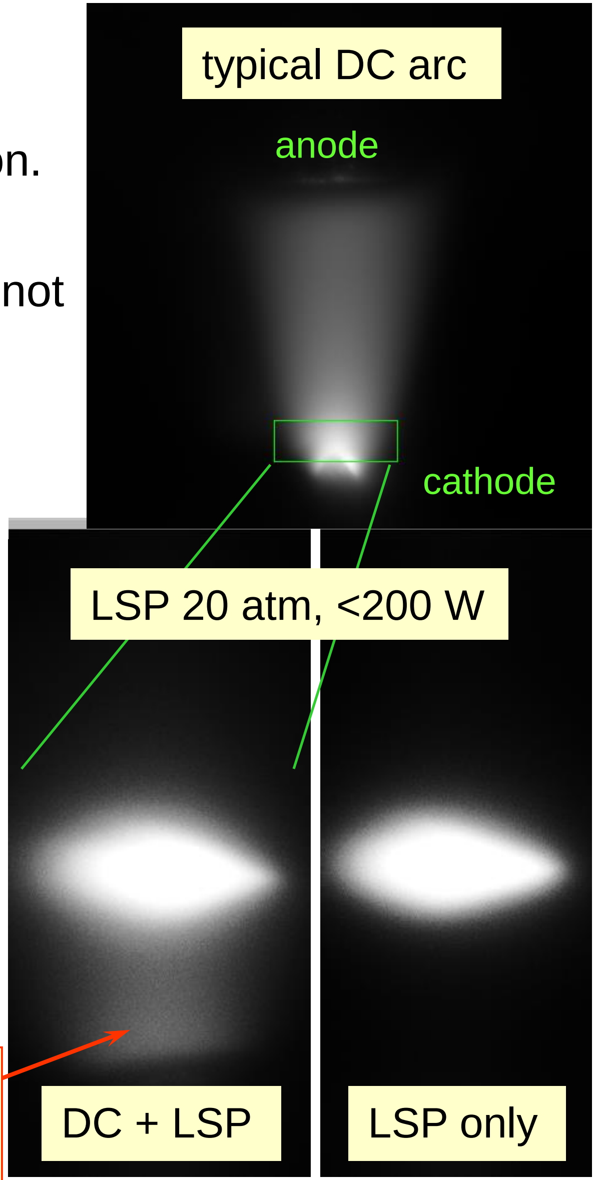
LSP. Enabling Optical Inspection of Wafers

- High-brightness (radiance) lightsources are needed for high speed optical inspection of wafers. A broad range of wavelengths is required for flexibility in optical mode selection.
- DC-driven electrical arc sources have been traditionally employed for microscope illumination. Their brightness has not been significantly improved for many years and is limited by maximum cathode current density.
- LSP can operate at a large distance from any structural components and is limited by different set of conditions governing laser-plasma interaction.
- Plasma brightness (spectral radiance) can be improved by orders of magnitude compared to traditional arc lamps, especially in the UV.
- Brightness improvement is the result of tight plasma confinement, typically, sub-mm size.

Sustainable operation demonstrated in a linear bench configuration.

LSP in 20 atm Xe bulb is much smaller and much brighter than the DC arc.

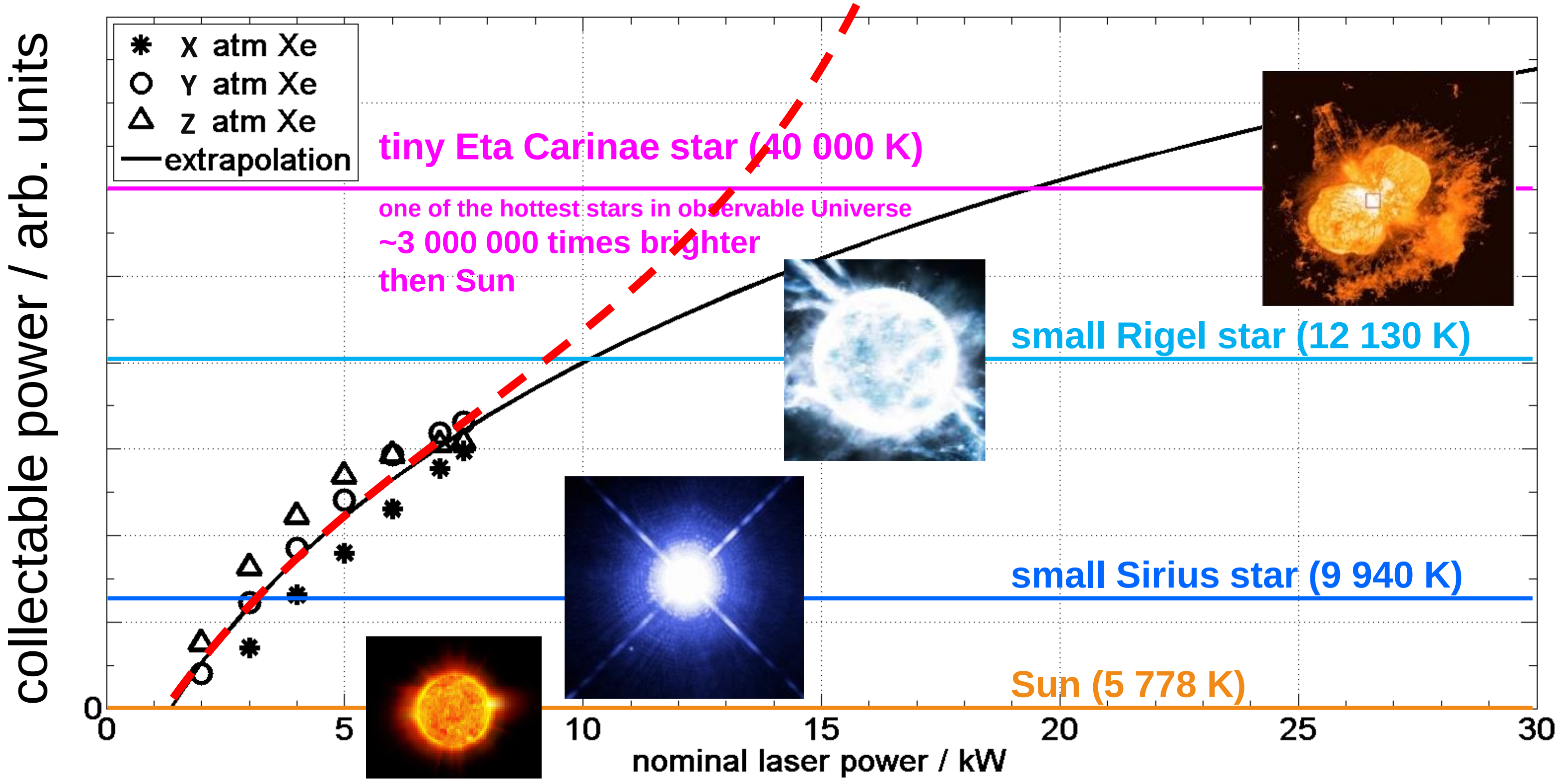


350 W DC arc: not the brightest lamp ever, but can you see it?

How Much Is Too Much?

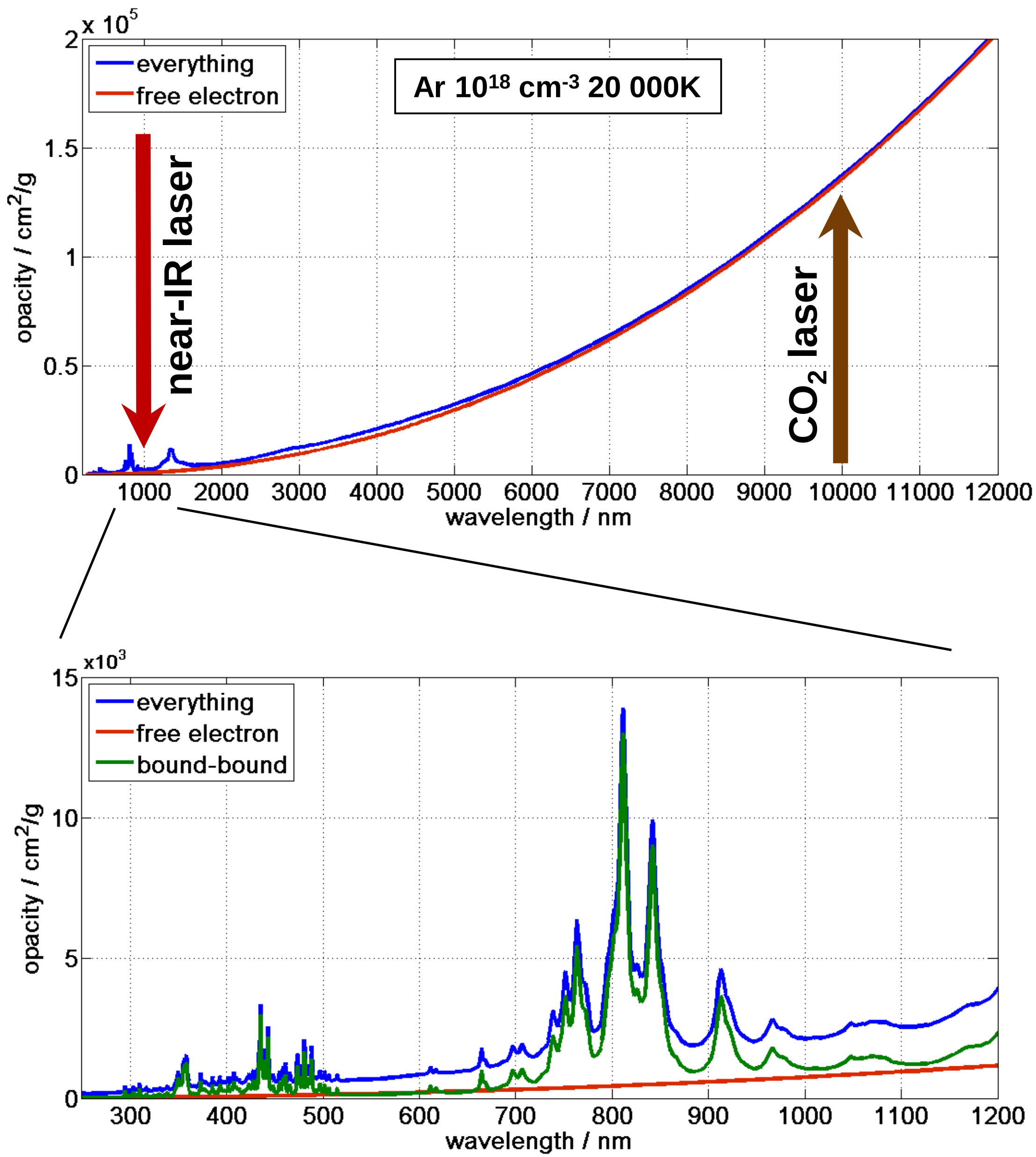
Artistic representation of roadmap requirements

- More than 10 times brighter source is required for inspection compared to wafer printing
- Once in the high-power regime, brightness starts to saturate
- It is hard to be brighter just by increasing pump power



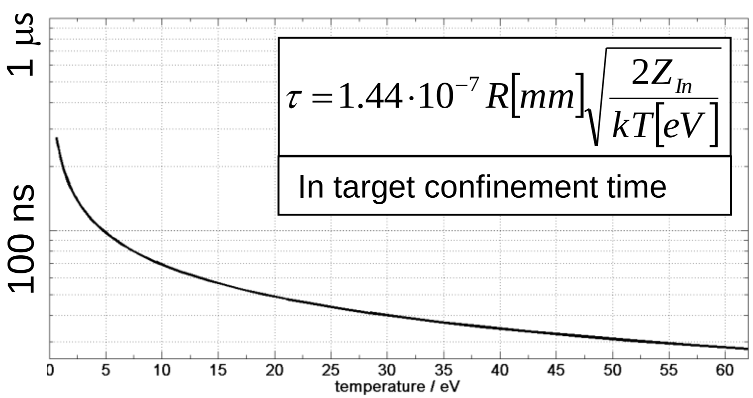
NIR vs. CO_2

- The main laser absorption mechanism for CO_2 lasers formerly used for LSP is inverse Bremsstrahlung. Not so for near-IR lasers! Much of the absorption comes from bound-bound transitions in highly excited neutrals (theoretical spectra on the right).
- Absorption coefficients are much lower in near-IR, enabling much smaller, higher pressure LSP.
- Typical CO_2-sustained plasmas are a few *cm* in size. Typical near-IR-sustained plasmas are few hundred *microns* and proportionately brighter.
- There is a strong dependence of absorption on the pump laser wavelength, allowing optimization of plasma performance.

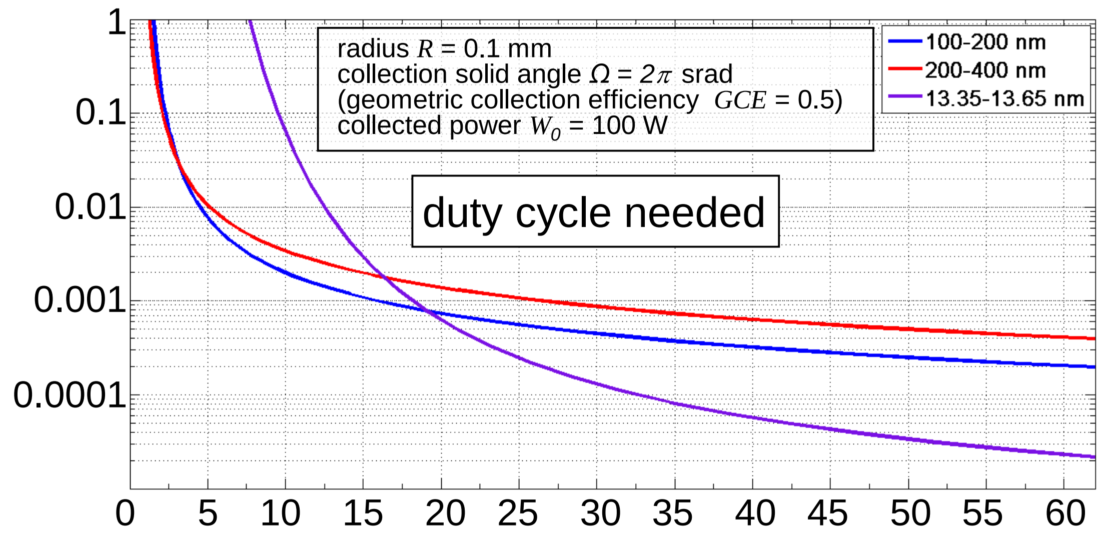


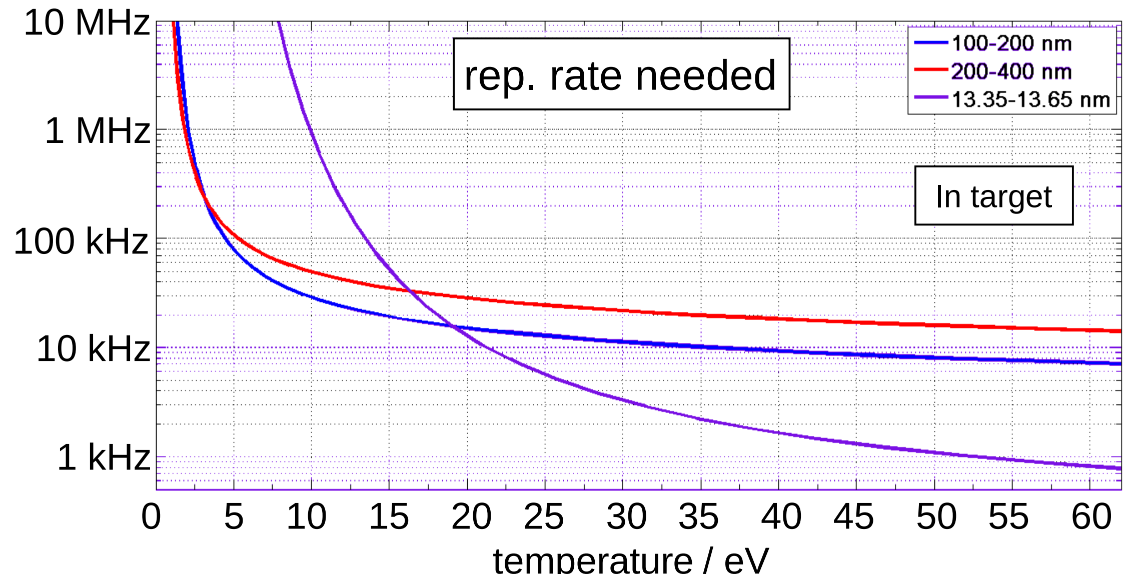
Why Not Pulsed?

- The duty cycle is calculated by comparing the required power output with integrated Black Body emission for each of the bands.
- Repetition rates are calculated by dividing the duty cycle by inertial confinement time assuming indium target (Z_{In}=115).
- In order to meet our requirements, we essentially need a Cymer-style illuminator: >20 kHz rep. rate with plasma temperatures of >30 eV. (Assuming that we can get to near-Black-Body performance when operating in this regime!)



How to collect 100W of light from R = 100µ Black Body?





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Proof of Concept VUV Lamp House

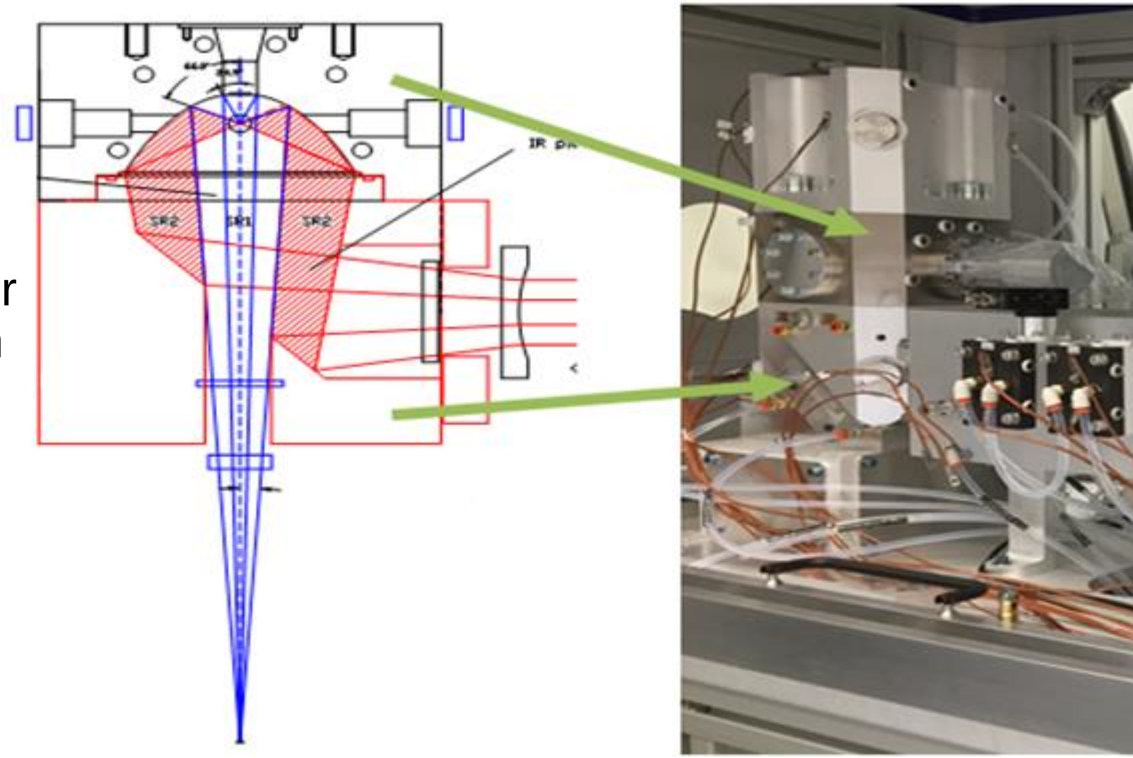
KT has developed LSP prototype VUV lamp houses for proof of concept and for VUV-related experiments

Pump laser power 6 kW under sustained operation, operation pressure up to 50 atm

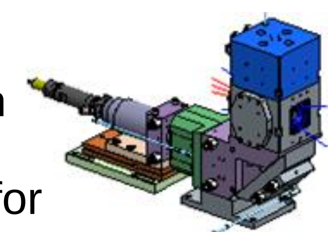
Enables testing of efficiency and lamp house components

End goal is development of a plasma source which exhibits stable operation over 6 weeks with minimum PM down time.

Various higher-power architectures are being considered for the production version.

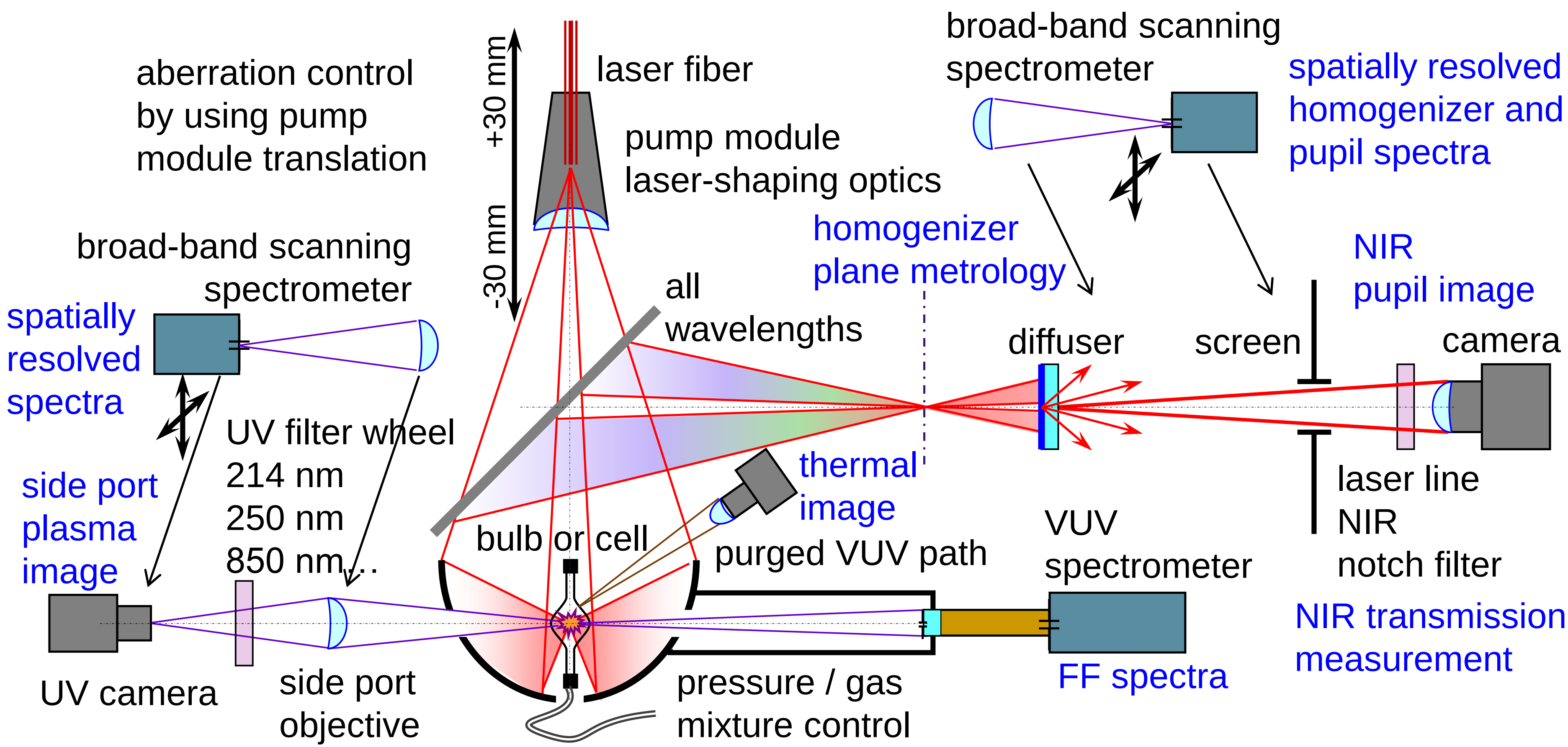


Low-power 1 kW “budget” version of VUV lightsource (of a different architecture) has been designed for internal VUV metrology applications.



LSP Metrology

Automatic control and data collection and large array of metrology options allows accurate and well-controlled experiments to be conducted at KT.



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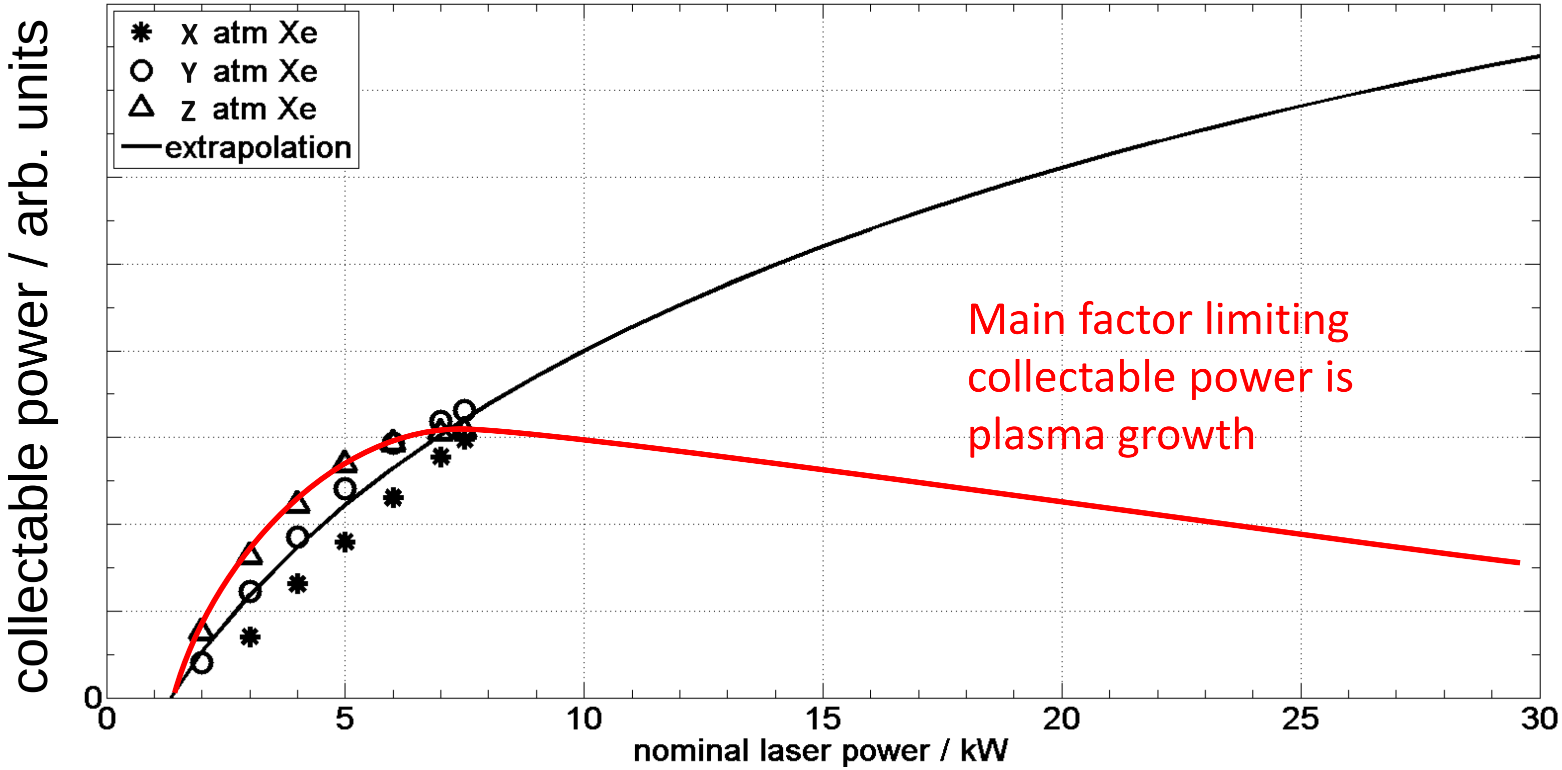
Staying on the Curve

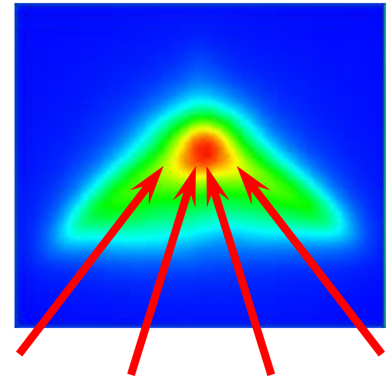
- More than 10 times brighter source is required for inspection compared to wafer printing
- Once in the high-power regime, brightness starts to saturate
- It is hard to be brighter just by increasing pump power



How to Make LSP Brighter?

Increase of IR pump laser power:

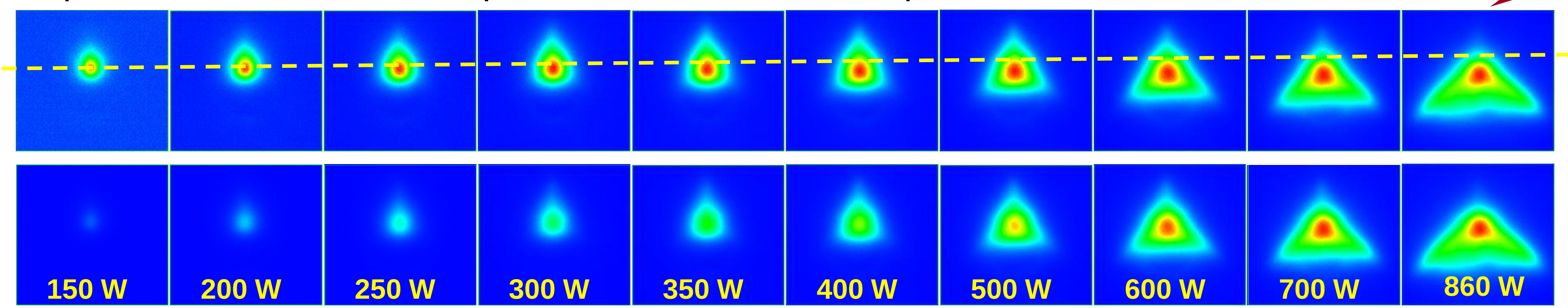
- At first leads to a brighter plasma as long as the size does not change (close to sustainability threshold)
- Higher pump powers result in plasma growth in the direction toward the laser and little change in plasma brightness
- Continuing increase in the pump power leads to the plasma separating from the focus and to the onset of plasma instabilities



pump laser direction

Top: normalized to max. amplitude. Bottom: same exposure

more pump power

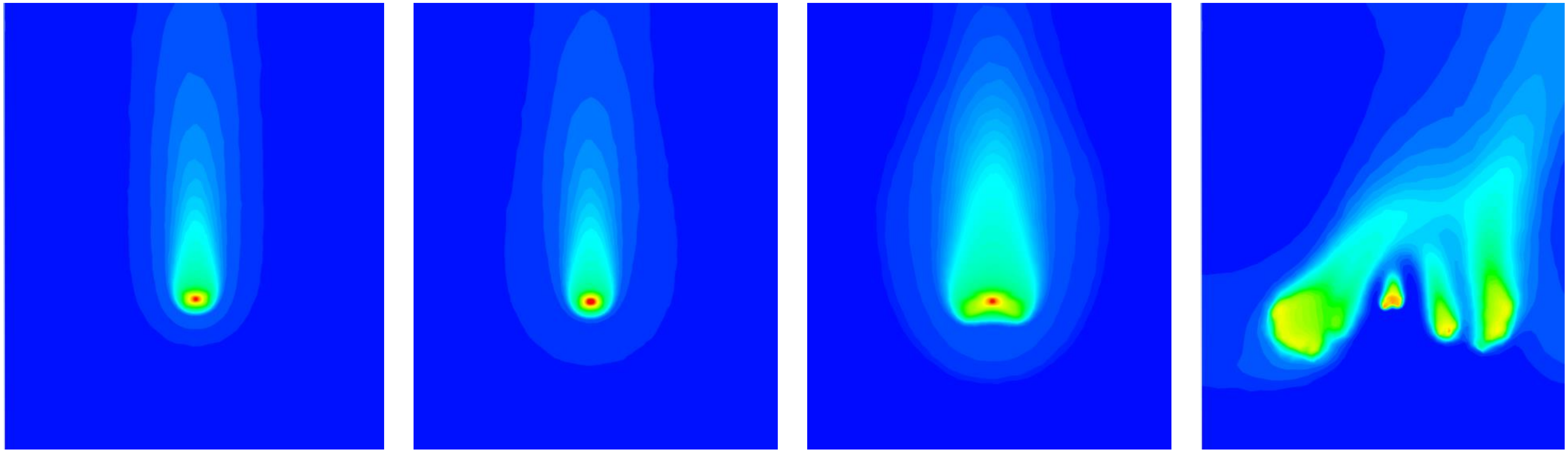


More IR pump power increases plasma temperature and brightness; little growth in size

More pump increases plasma size, little change and even decrease in temperature; plasma shifts toward the laser

Modeling Plasma Growth and Instabilities

- A set of state-of-the-art LSP models have been developed to describe temperature distributions and apparent plasma shapes starting from a pump laser raytrace. The models reveal most interesting details in plasma operation regime and help optimizing the source performance.
- The temperature distributions below show developing of instabilities in high-power plasmas. Instabilities arise at the extreme side of plasma growth.



Examples of modeled temperature distributions

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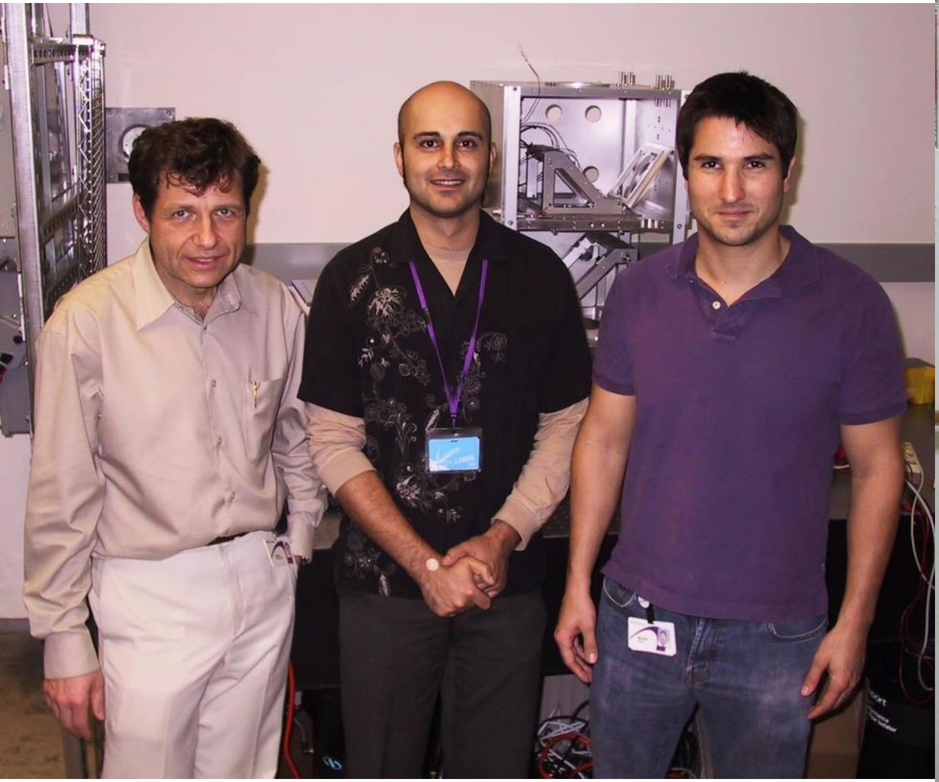
KLA-Tencor: Having Fun with LSPs and Beyond

- At K-T, we are pushing LSP performance to orders of magnitude higher brightness and power than alternative broad-band CW source in UV-DUV-VUV spectral regions.
- In the immediate future, we foresee no fundamental limitations to LSP brightness (spectral radiance) for our applications.
- However, we welcome other solutions that beat LSP in performance or cost.

- LSP plasmas are complicated. Optimal LSP operating conditions depend on the spectral region for collection, etendue requirements, and available pump power. Accurate modeling and understanding plasma behavior are required to succeed in building an optimal source.
- Plasma confinement is one of the most challenging problems for higher power operation. Fascinating physics is happening there!

Making It Possible
Tech. Development Team



Ilya Bezel, Patrick Casey, Gil Delgado, Matthew Derstine, Ken Gross, Greg Kirk, Jamie Nam, Matthew Panzer, Anatoly Shchemelinin, David Shortt, Richard Solarz, John Szilagyi, Amir Torkaman, Wei Zhao, Yanming Zhao