EUV source metrology using transmissive and diffractive optics

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EUV Source Workshop
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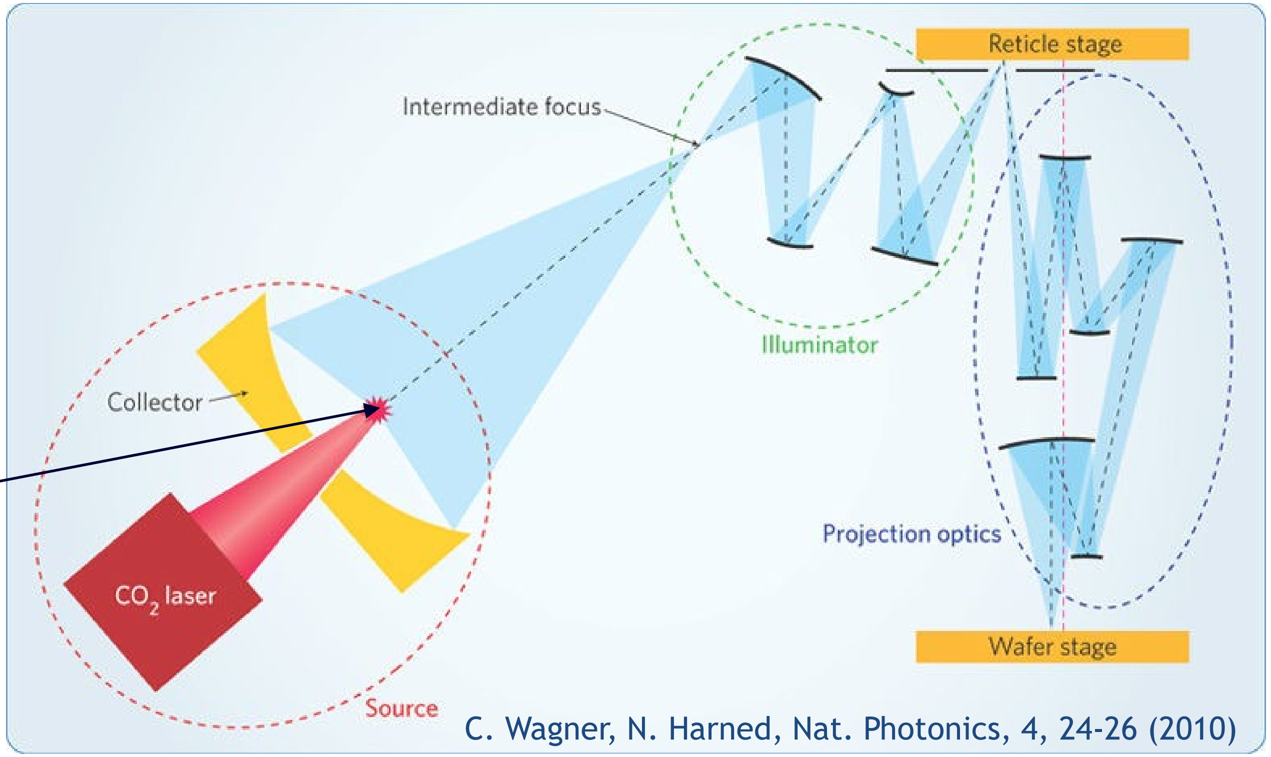
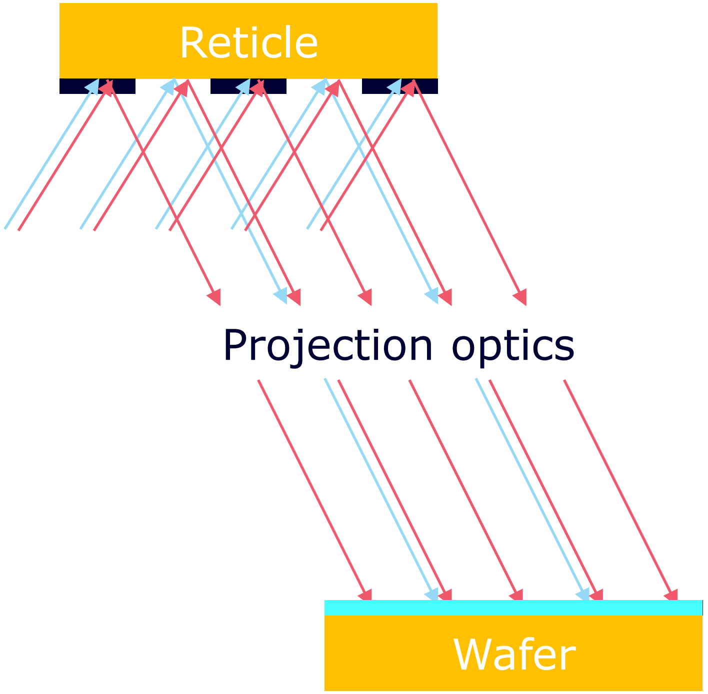
Motivation

EUV emitting plasma

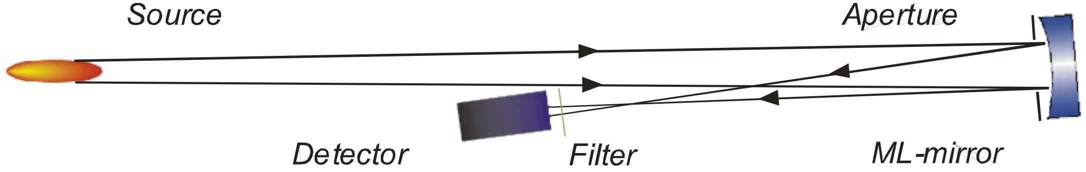


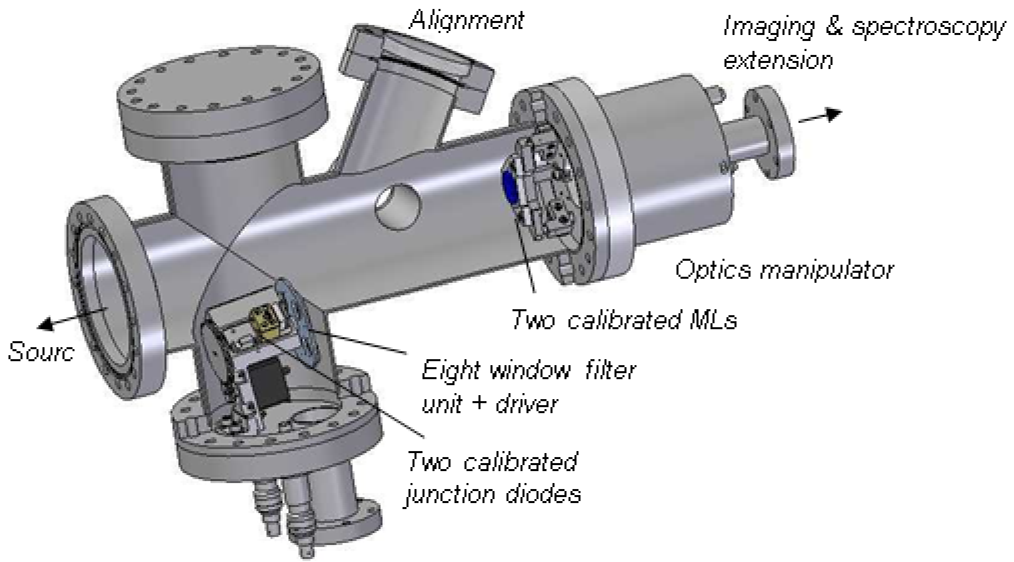
C. Wagner, N. Harned, Nat. Photonics, 4, 24-26 (2010)

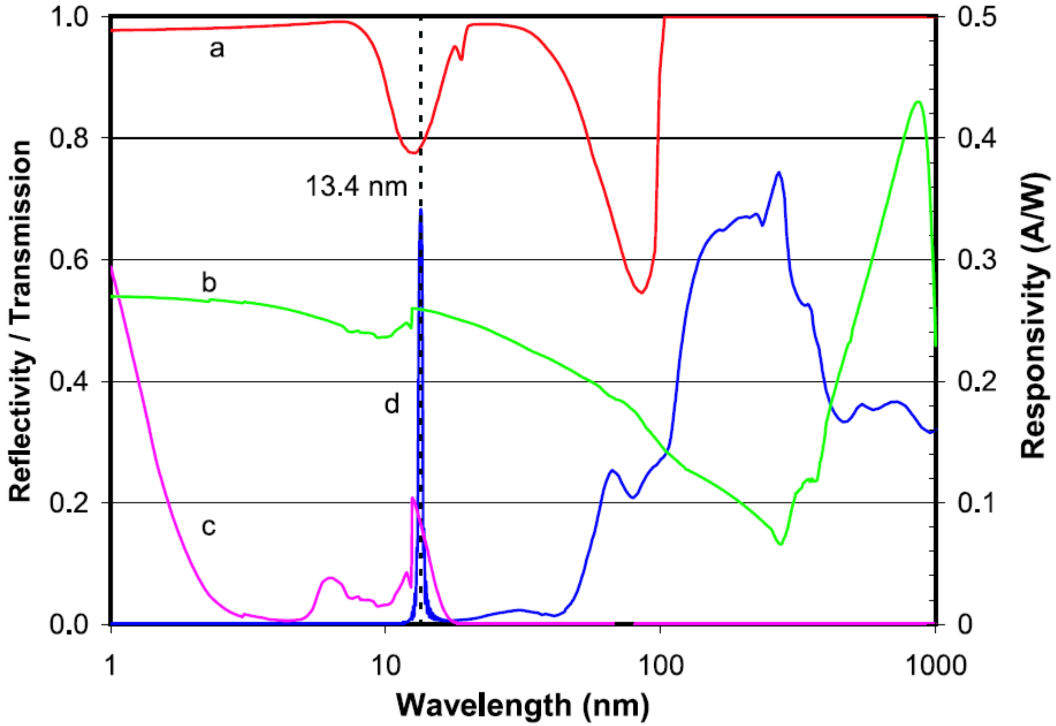


- Light outside the 13.5 nm (±1%) band, spans a broad spectrum (DUV, VIS, NIR)
- Can be reflected from the optics and cause contrast loss, and can be absorbed by H_2
- Need for broadband (both in-band and out-of-band) spectral and spatial monitoring

In-band metrology: Flying Circus approach





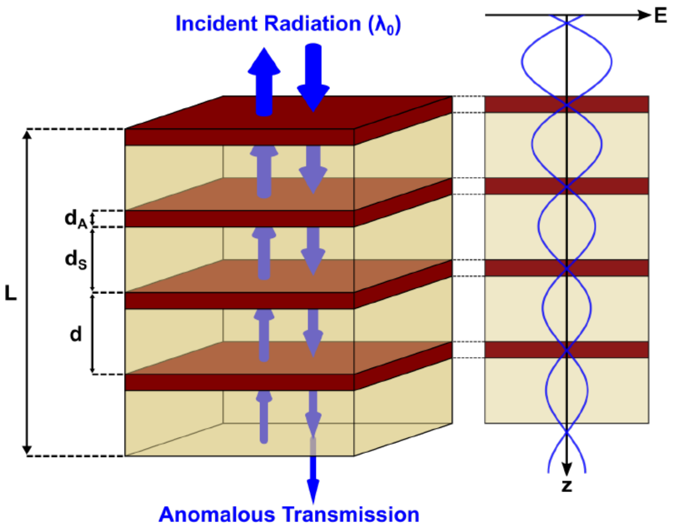


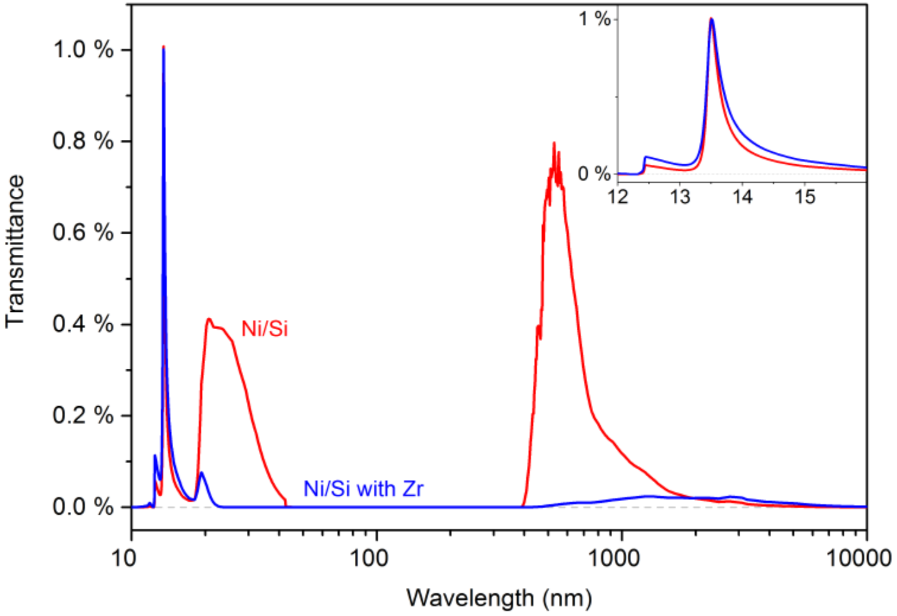
- Absolutely calibrated measurement in the pass-band of the mirror, <%5 calibration uncertainty

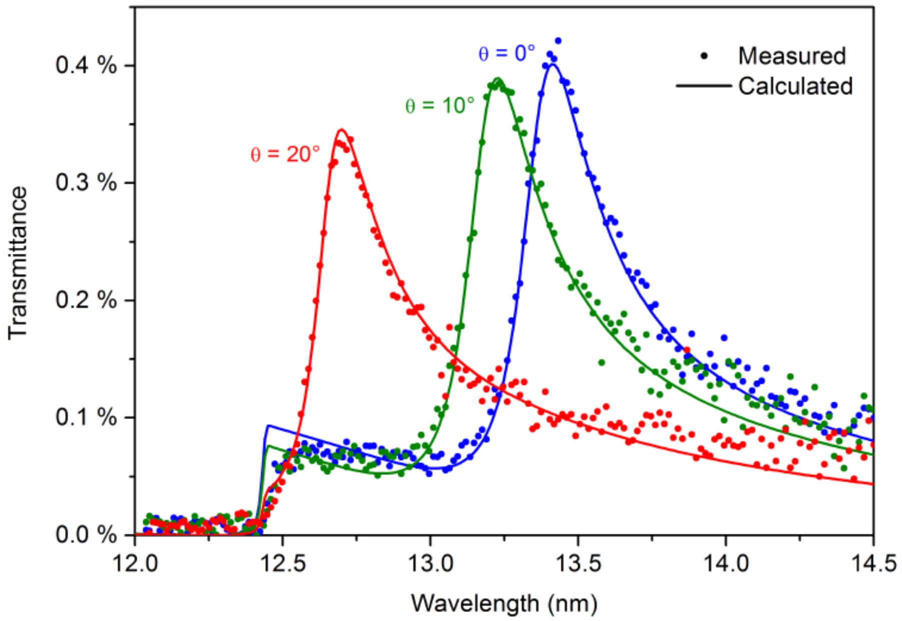
- Enabled a through comparison of early EUV sources in mid-2000s,
- Varieties are in common use nowadays

F. Bijkerk, et.al. EUV Sources for Lithography, 721-734, (2006)

In-band metrology: Anomalous transmission filters



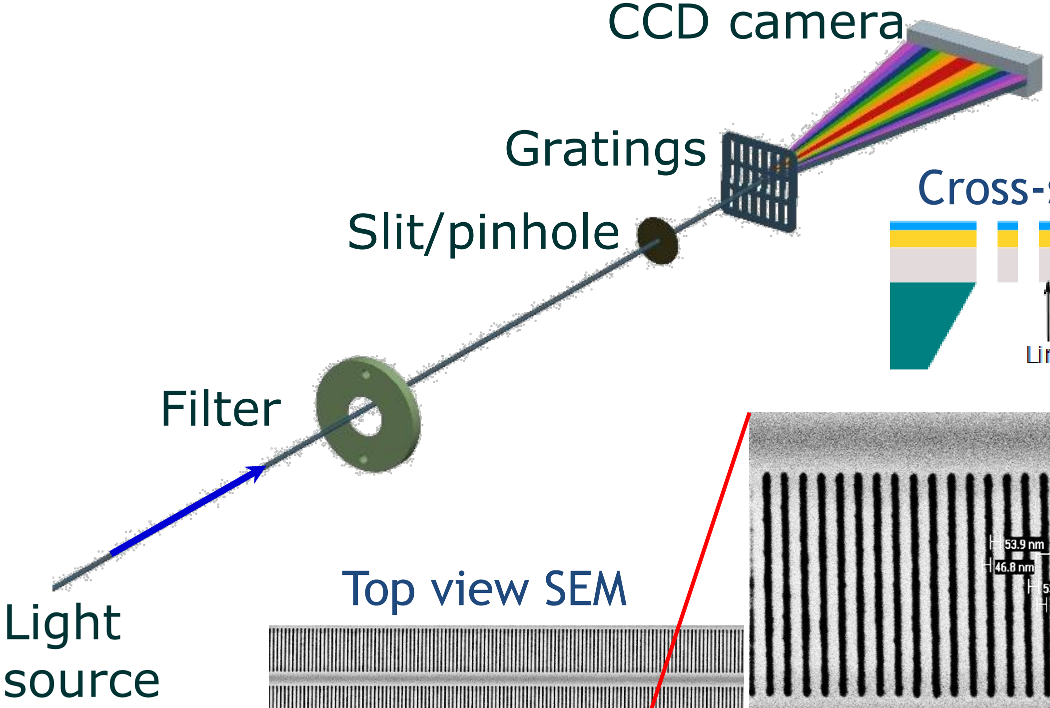




- Based on anomalous transmission (Borrmann) effect
- Can be coated on photodiodes
- 74 bilayers of Ni/Si – transmission 1%, bandwidth FWHM 0.23nm (1.7%) at 13.5nm wavelength
- Passband can be tuned by changing the incidence angle
- Intermixing plays a significant role in the final response, can be improved

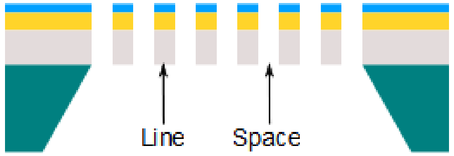
J. L. P. Barreaux, et.al. Opt. Exp. 25(3), 1993 (2017)

Broadband spectroscopy: Transmission grating spectrometer

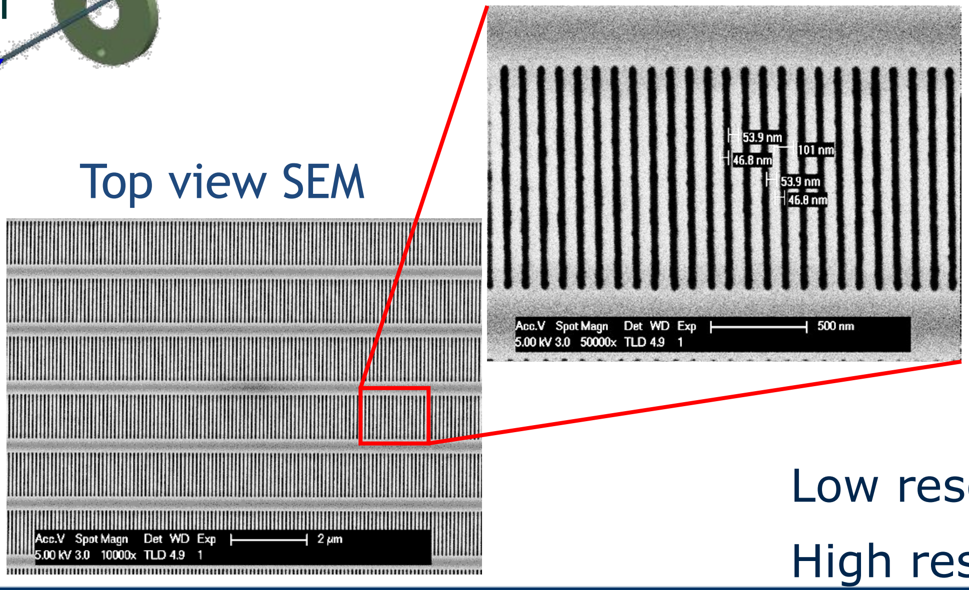


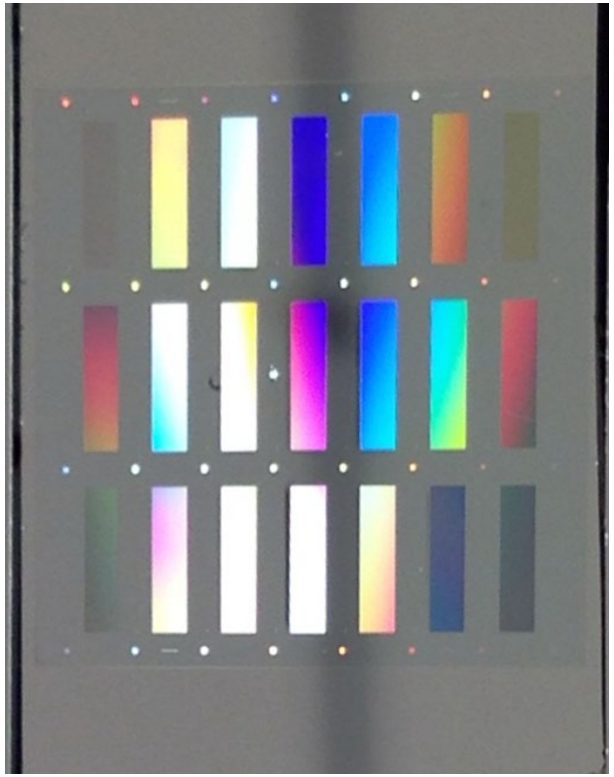
- ✓ Grating chip developed in MESA+ Nanolab
- ✓ 3x7 grating matrix

Cross-section



Top view SEM





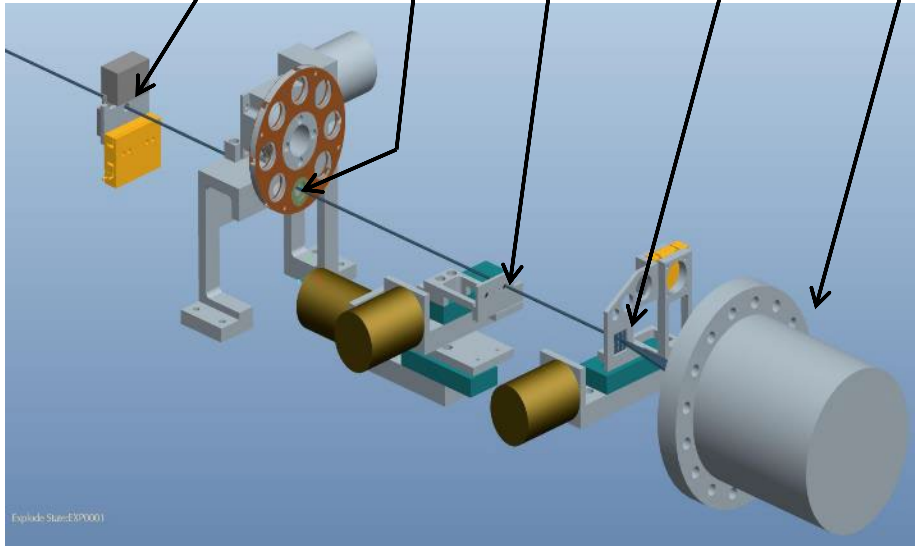
Low resolution gratings (500 lines/mm) for VIS range

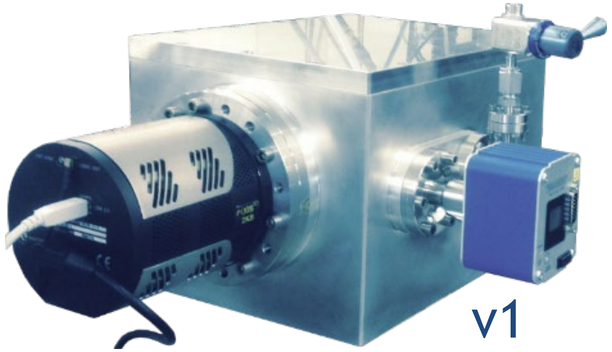
High res. gratings (up to 10.000 lines/mm) for EUV range

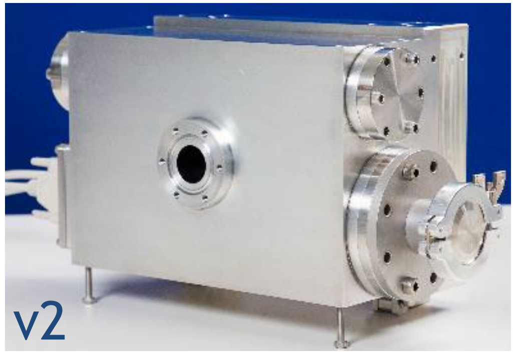
XUV transmission grating spectrometer

- ✓ Broadband coverage
- ✓ Compact design (~20x25x30 cm^3)
- ✓ Computer controlled positioning
- ✓ Straightforward alignment

Shutter Filters Pinhole Grating chip Camera

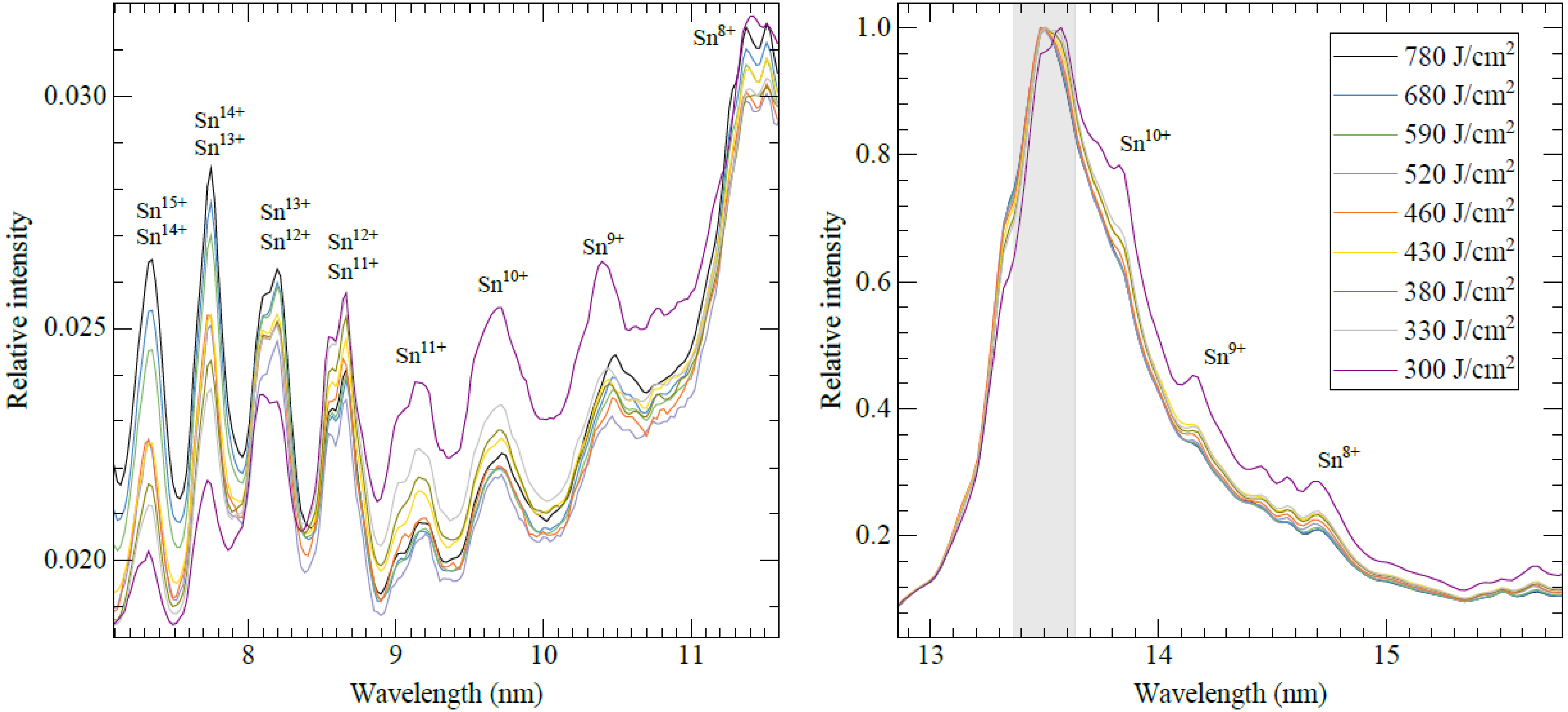






M. Bayraktar, et.al. NEVAC Blad, 54, 14-19 (2016).

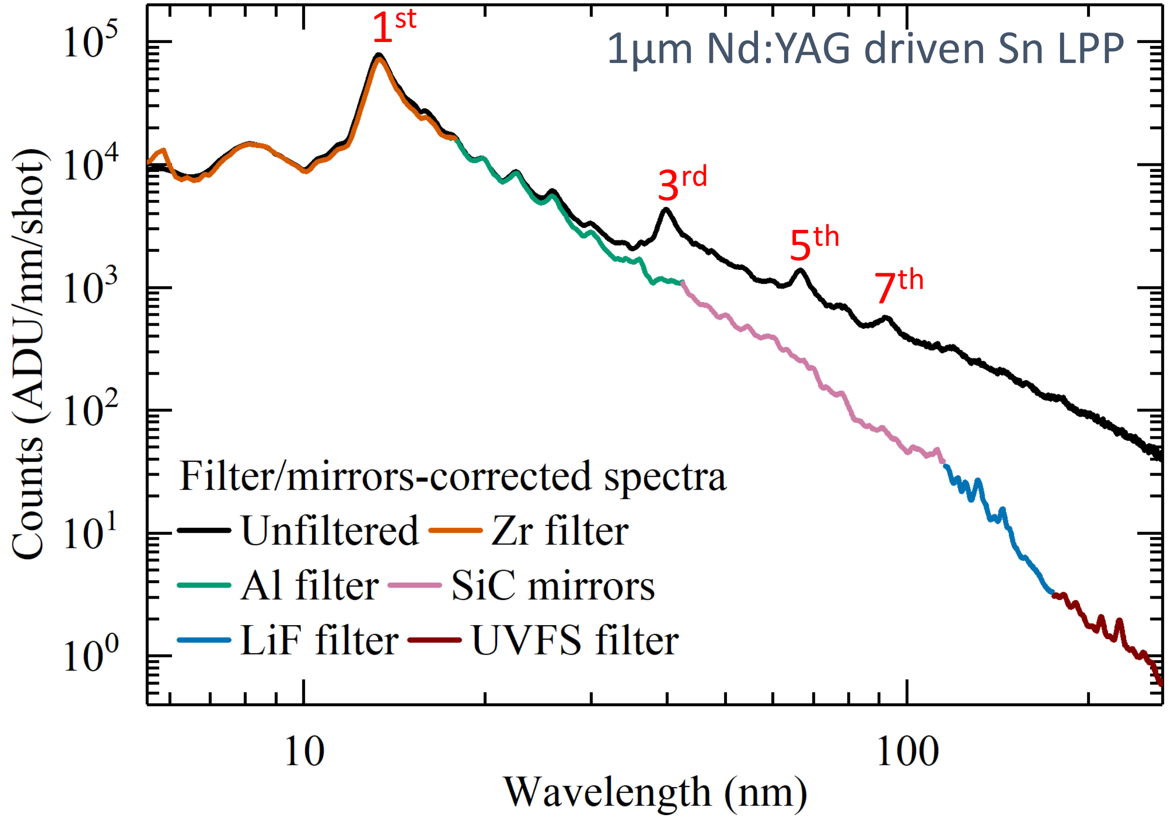
Scaling of emission in an industrial EUV source

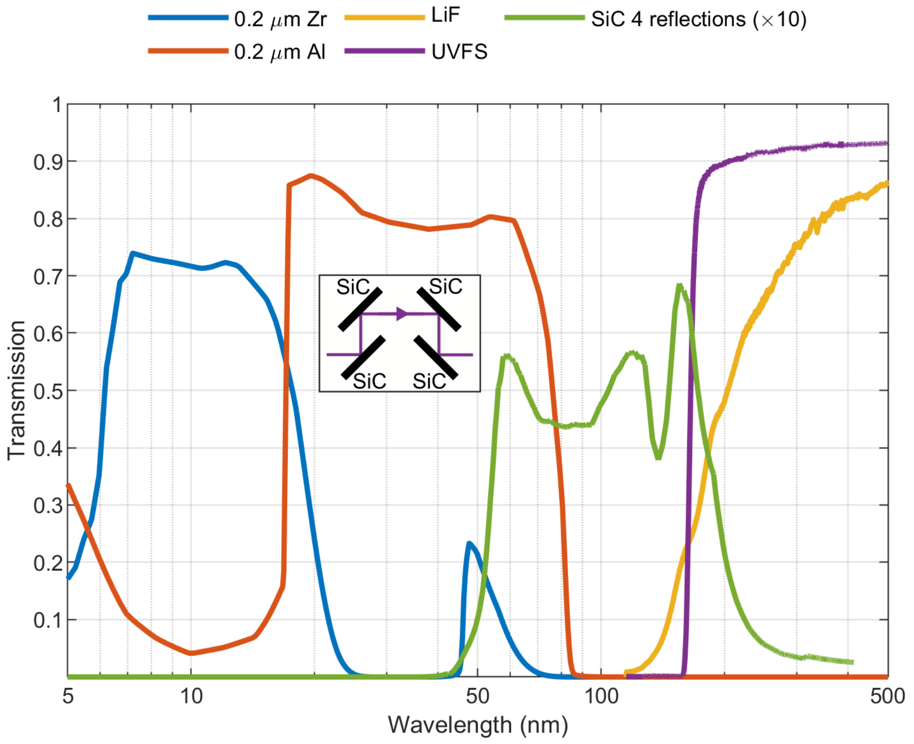


Specific charge states can be resolved clearly in the short wavelength-side of the 13.5nm peak

F. Torretti, et.al. J. Phys. D: Appl. Phys. 53, 055204 (2020)

Absolutely calibrated spectra in the 5.5-265 nm range





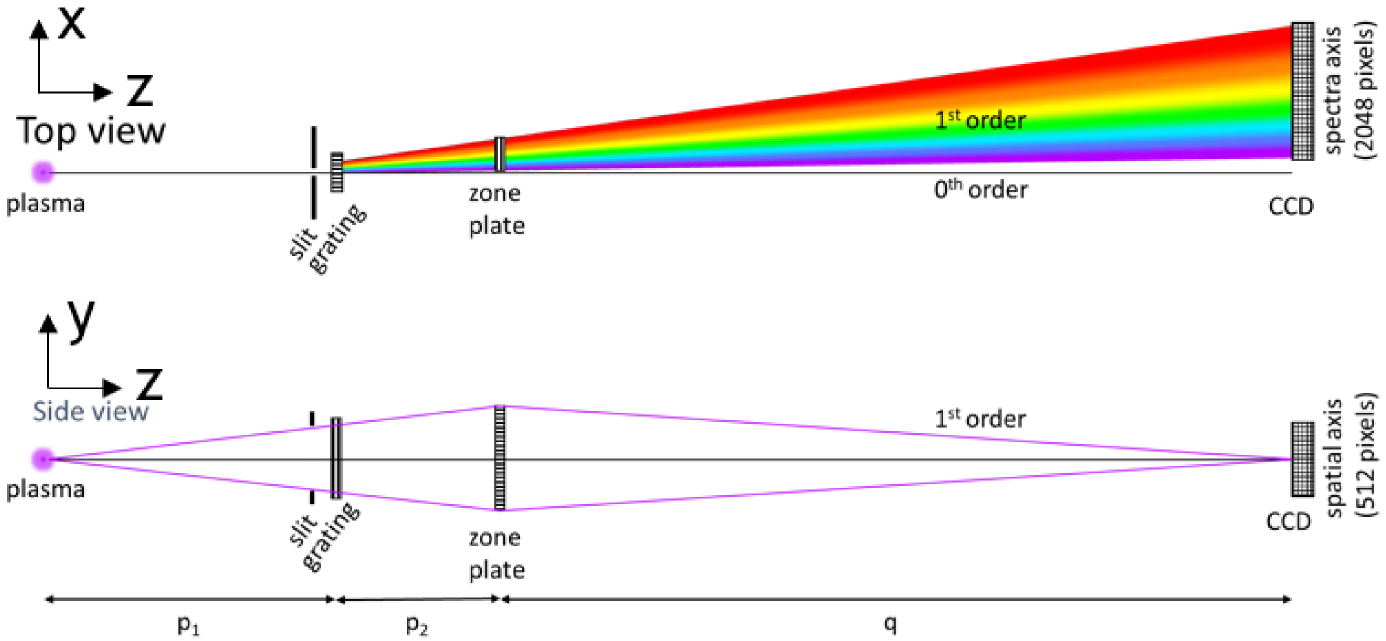
- ✓ Strong higher diffractions orders of the 13.5nm peak are suppressed by the set of filters
- ✓ SiC 4-bounce filter enables to measure the otherwise inaccessible 40-115nm range

Z. Bouza, et.al. AIP Adv. 11, 125003 (2021)

Broadband spectroscopy and imaging using zone-plates

Y. Mostafa, Z. Bouza, et. al. Opt. Lett. 48, 4316-4319 (2023)

- Pinhole imaging with foil filters – broad spectral coverage but limited spatial resolution
- Imaging using multilayer mirrors – decent spatial resolution but limited spectral coverage
- **Combination of transmission gratings with dispersion matched zone-plates – broadband spectral coverage + decent spatial resolution**

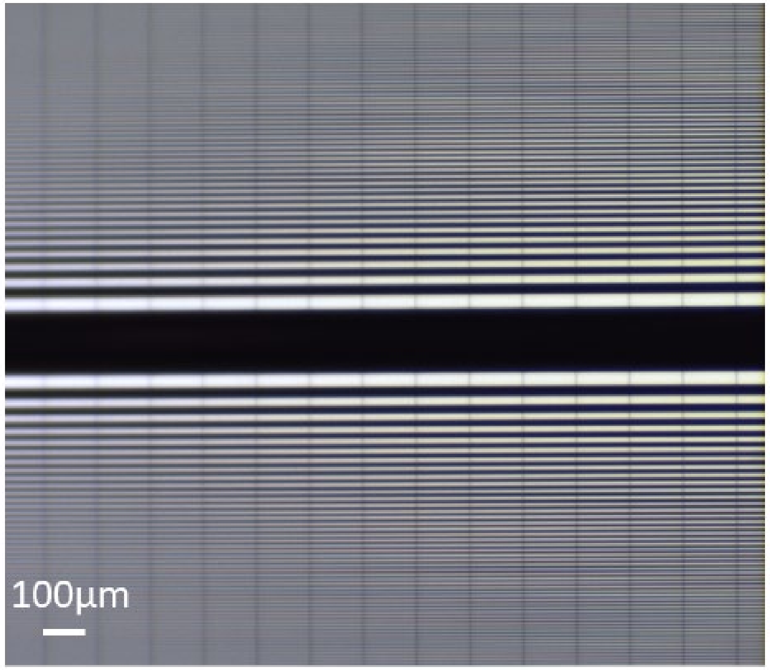


- Spectroscopy on x-axis
- Imaging on y-axis

- Light focusing using zone-plates is strongly wavelength dependent
- How to have good focusing for a broad wavelength range (e.g. 5-80 nm)?

Dispersion-matched zone-plates enable broadband spectroscopy and imaging

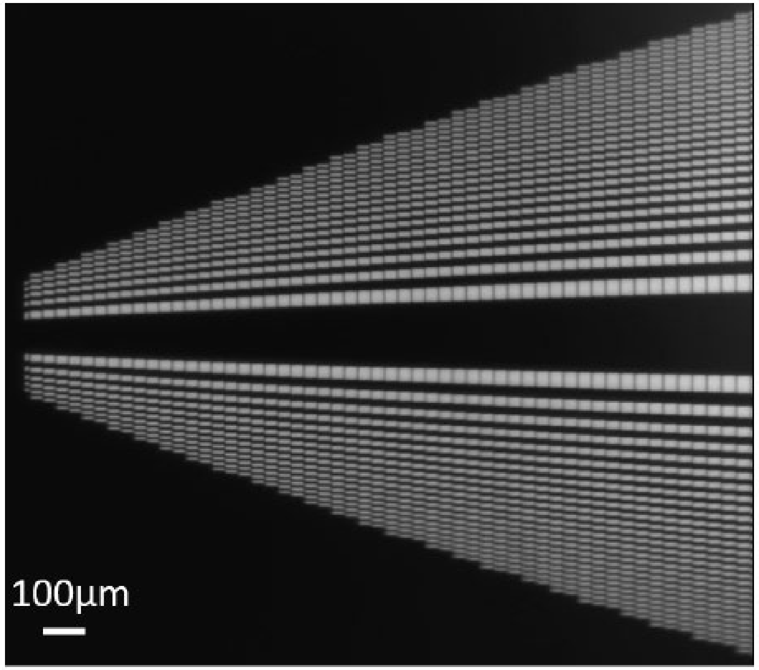
1D zone-plate designed to focus a single wavelength



$$r_{i,n} = \sqrt{n\lambda_i \left(f + \frac{n\lambda_i}{4}\right)}$$

- Radius $r_{i,n}$ of each zone n is dependent on the wavelength λ_i
- As the wavelength increases, the zone radius increases
- Resulting in tapered zone plates

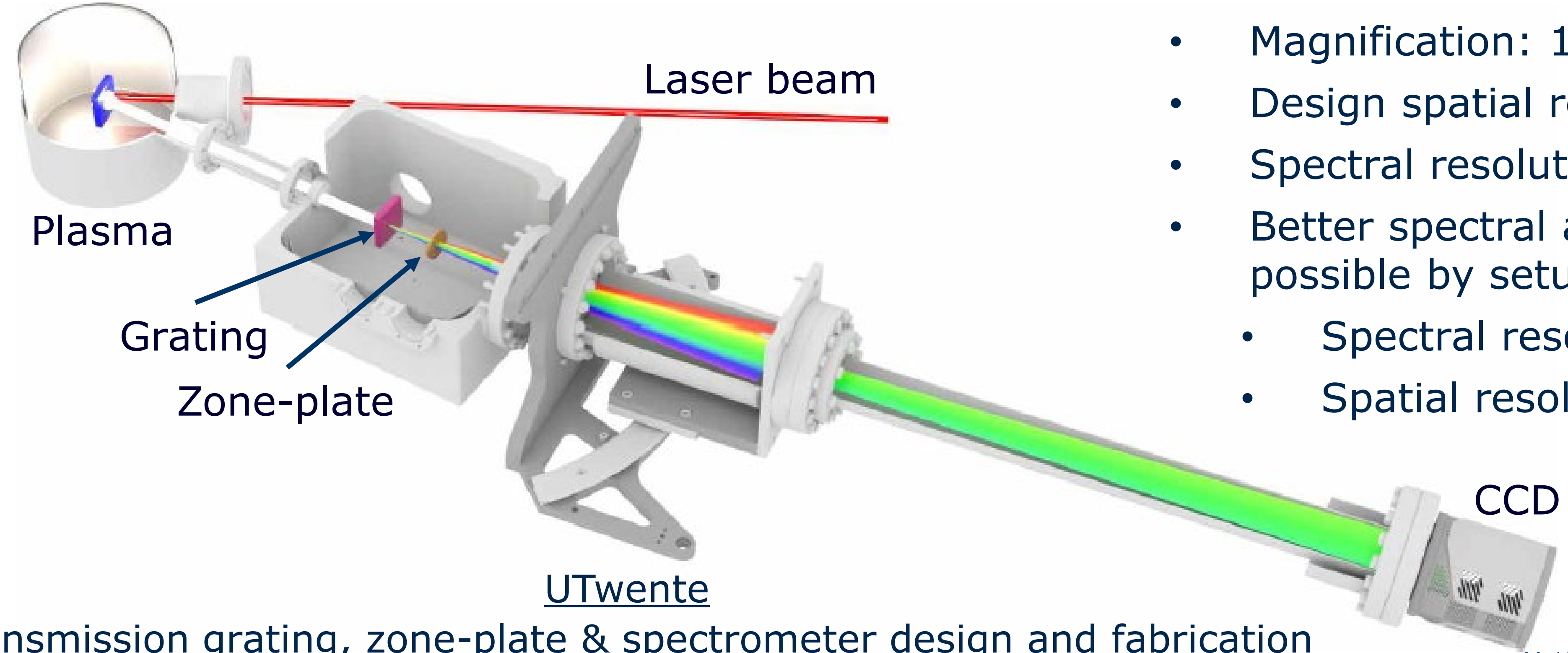
1D tapered zone-plate designed to focus 5-80 nm wavelength range



Y. Mostafa, et. al. Opt. Lett. 48, 4316 (2023)

Experimental implementation

ARCNL
EUV source and experiments

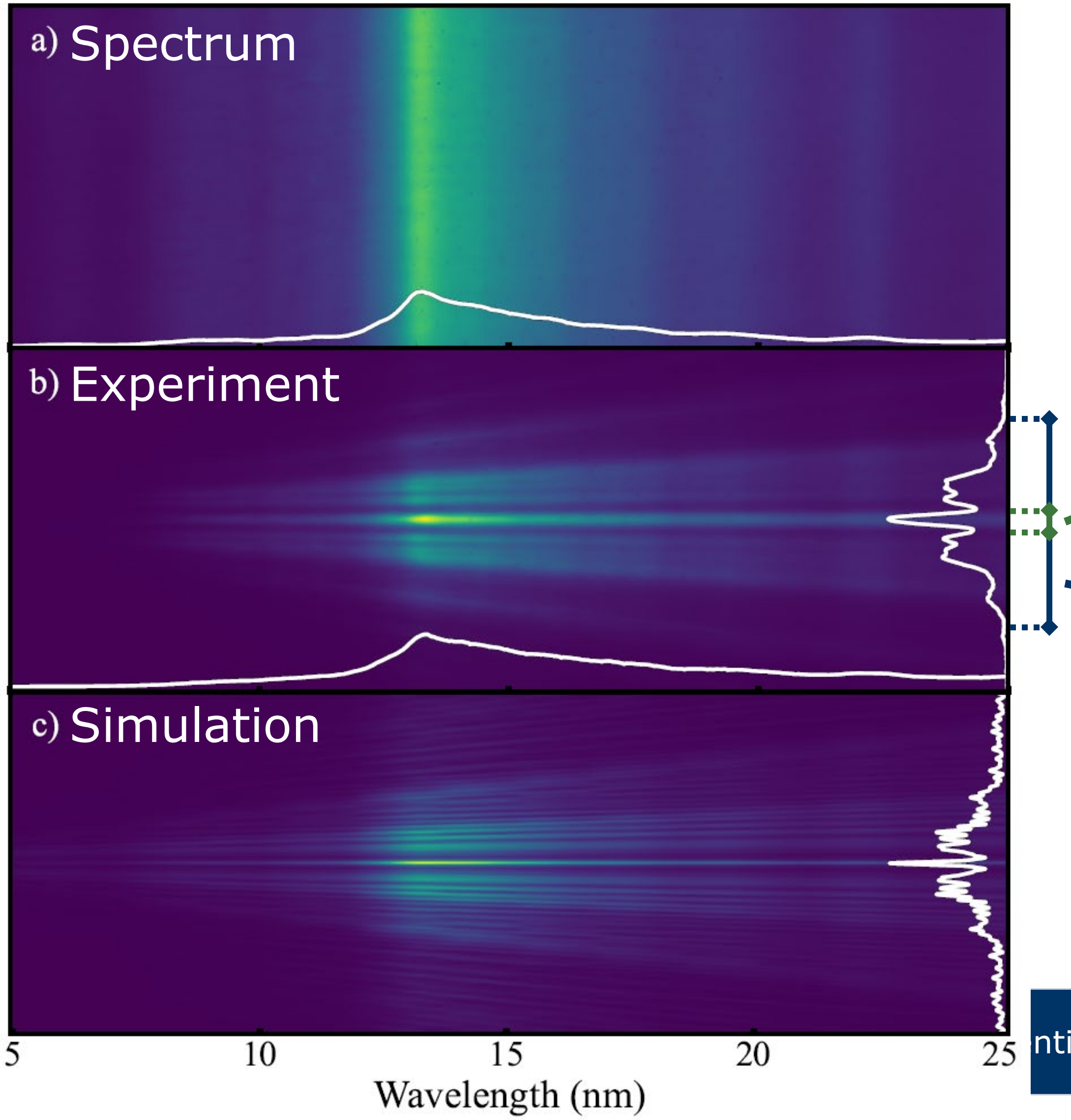


UTwente
Transmission grating, zone-plate & spectrometer design and fabrication

- Nd-YAG laser at 1 um
- Sn solid target
- Beam size: 60 um FWHM
- Magnification: 1.9
- Design spatial resolution: 10 um
- Spectral resolution: 0.8 nm @13.5nm
- Better spectral and spatial resolutions possible by setup configuration
  - Spectral resolution: < 0.1 nm
  - Spatial resolution: < 1 um

Y. Mostafa, et. al. Opt. Lett. 48, 4316 (2023)

Results – experiment vs simulation



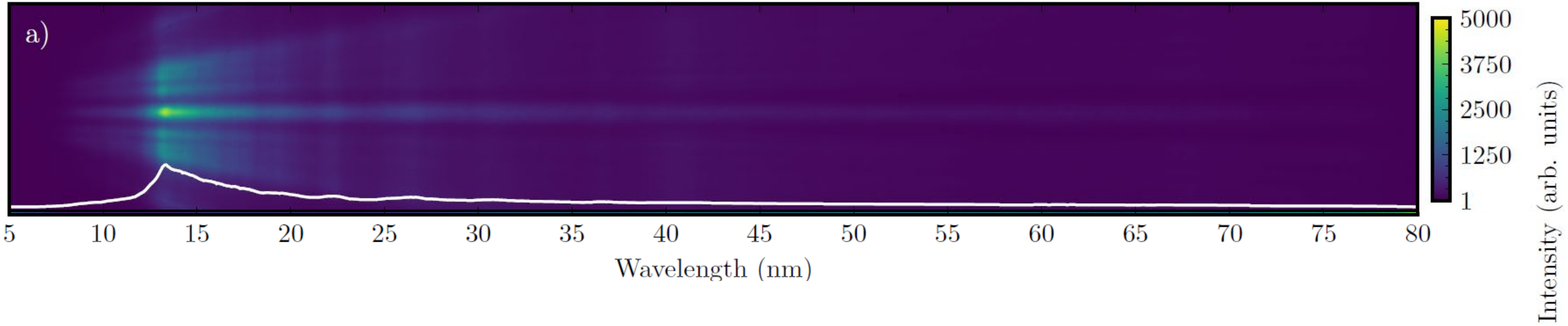
- Spectrum without zone-plate, as a reference
- Spectral resolution 0.8 nm
- Prominent 13.5 nm peak is visible

- Experimental recording with zone-plate inserted
- Horizontal band at the center corresponds to the focused plasma light
- Zero- and other zone-plate orders are visible at both sides of the plasma light

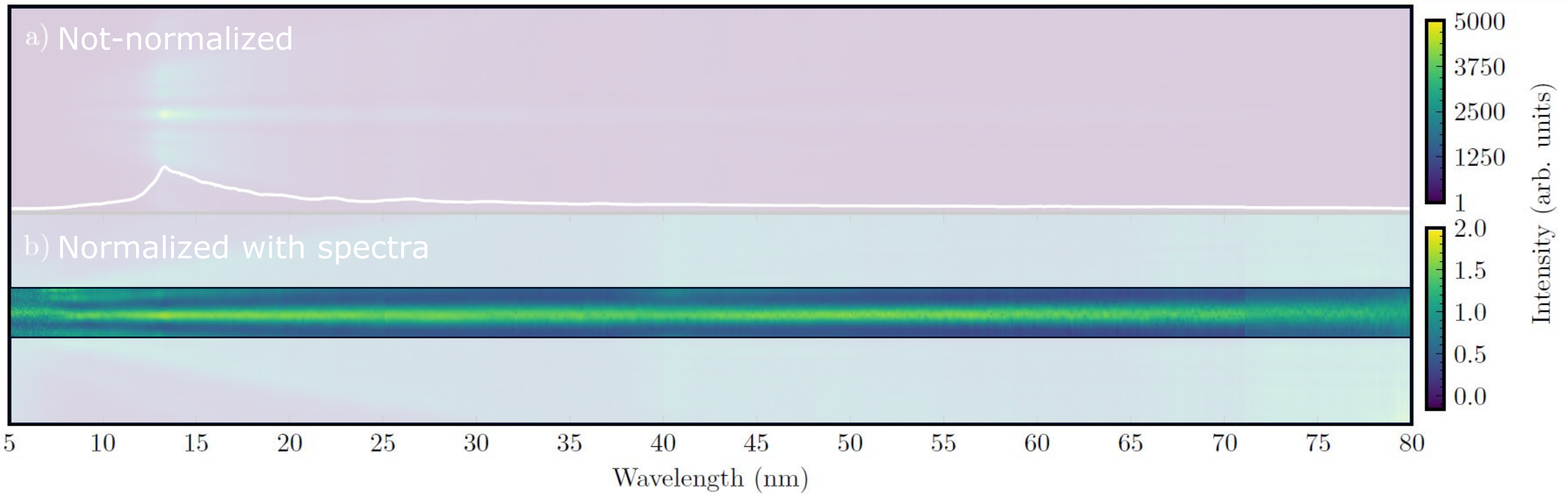
- Wave propagation simulation, assuming zone-plate is illuminated with a plane-wave, yielding the theoretical design resolution (10 um) of the zone-plate

Y. Mostafa, et. al. Opt. Lett. 48, 4316 (2023)

Broadband imaging and spectroscopy in the 5-80 nm range using zone-plates



Broadband imaging and spectroscopy in the 5-80 nm range using zone-plates



- Broadband imaging and spectroscopy in the 5-80 nm range is possible
- Normalized image shows a widening central band, indicating increasing plasma size with increasing wavelength as anticipated

Conclusions

- In-band metrology using Flying Circus and Anomalous transmission filters approaches
- Broadband metrology using transmission gratings
  - Broadband spectroscopy in the EUV-NIR range, compact setup with good spectral resolution
  - Measurements using HHG, prototype EUV light source (ASML) and research type LPP sources (ARCNL)
  - Enables to observe distinct emission lines of the tin plasma
- Dispersion-matched zone-plates enable broadband spectroscopy and imaging
  - 0.8 nm spectral resolution and 10 um design spatial resolution
  - Broad spectral coverage 5-80 nm
  - Better spectral (<0.1 nm) and spatial (<1 um) resolutions possible
  - Wave propagation simulations verify the spatial resolution and the proof-of-principle of the tool
  - Laser-produced-plasma investigated with the tool show increasing plasma size with increase wavelength, as expected

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ASML Veldhoven Source Performance Team
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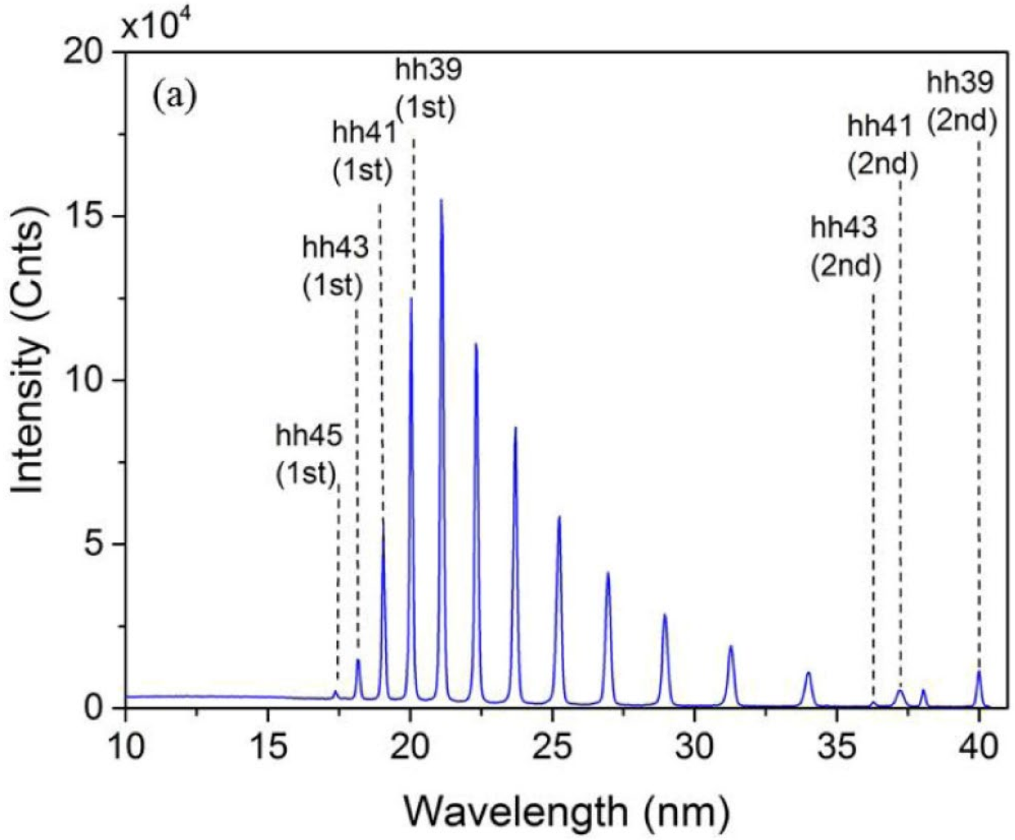
Dr. Francesco Torretti
Dr. Ruben Schupp
Dr. Lars Behnke
Prof. Dr. Wim Ubachs
Prof. Dr. Oscar Versolato

Appendix

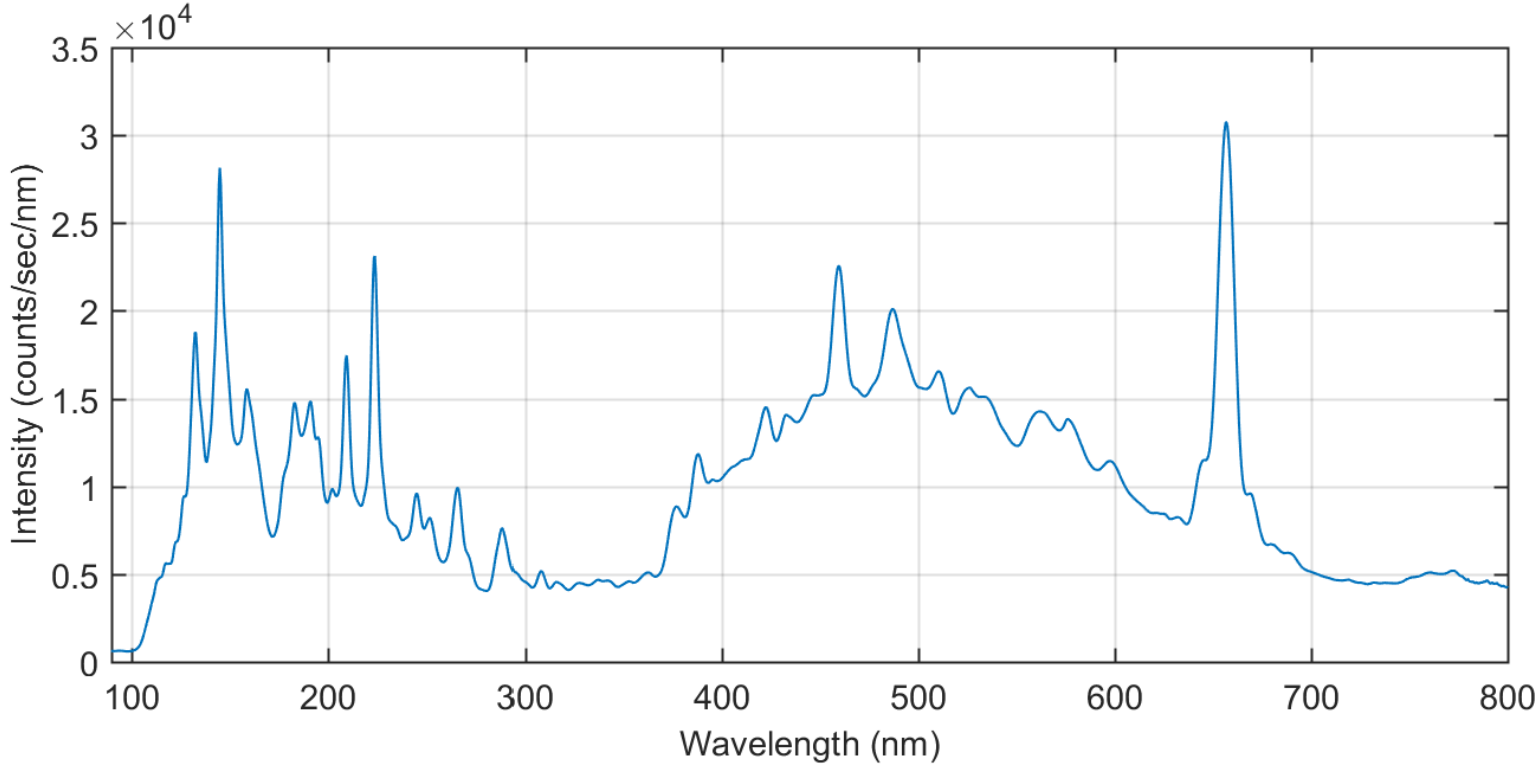
Resolution test in a HHG source



- Design resolution 0.09 nm at 21 nm (37^{th} harmonic)
- Measured resolution < 0.13 nm[5]
- Can be configured for 0.05 nm resolution at 13.5 nm

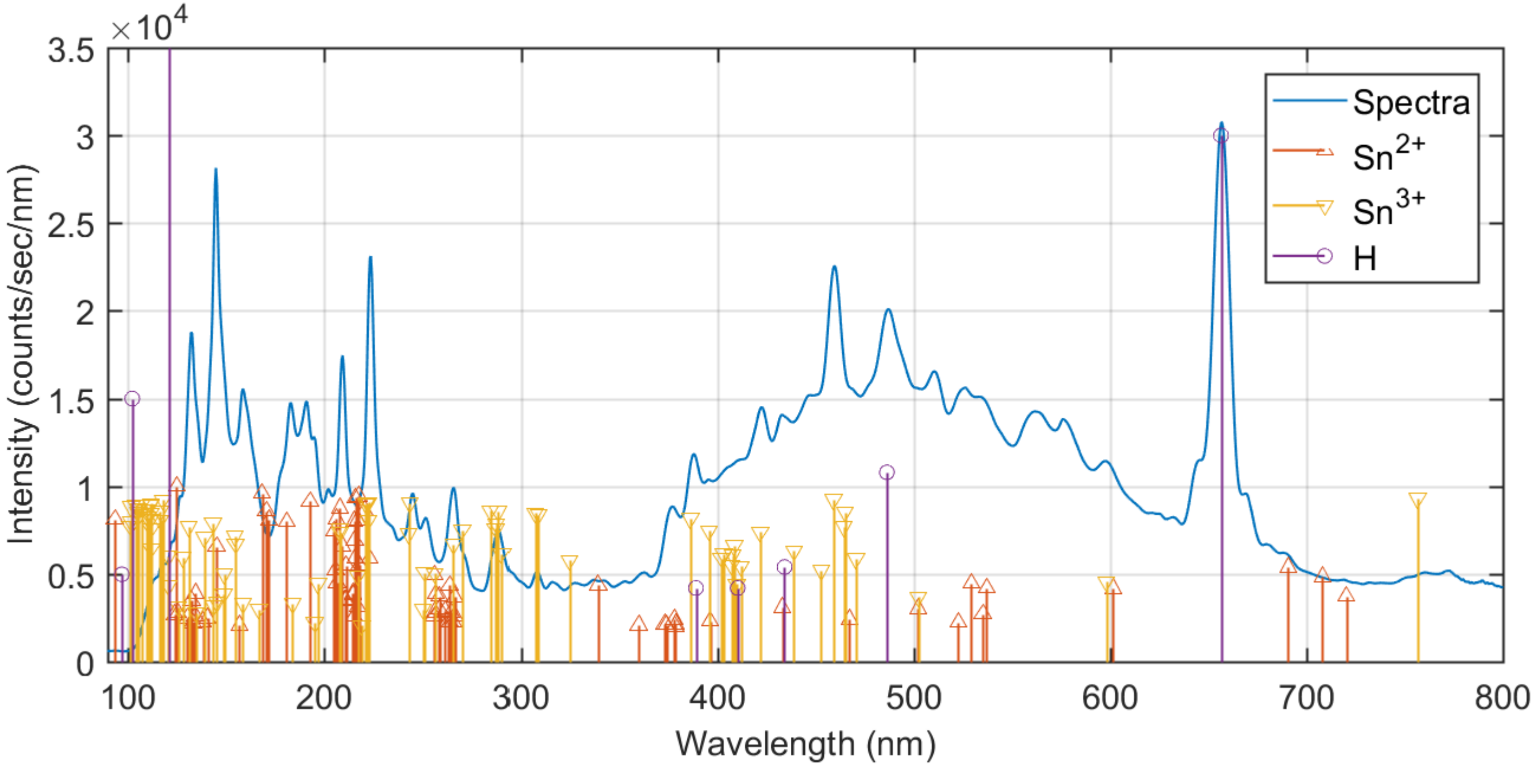
[5] J. Goh et.al. Opt. Exp. 23, 4421 (2015).

Demonstration in the DUV, VIS, NIR range



- Low but detectable DUV-NIR intensity
- Distinct peaks and broad features in the spectra

Assigning emission lines



- Peaks originate from higher diffraction orders, line and continuum emission
- Higher diffraction orders can be filtered out by spectral windows (eg. LiF, MgF_2, UVFS…)
- Sn^{+2}, Sn^{+3} and H lines correlate with observed spectra