EUV spectra from tin ions – an overview of published data

J. Sheil, R. Schupp, J. Scheers, F. Torretti, L. Behnke, Z. Bouza, Y. Mostafa, R. A. Meijer, W. Ubachs, R. Hoekstra, O. O. Versolato

ARCNL
ADVANCED RESEARCH CENTER FOR NANOLITHOGRAPHY

Outlook

- Provide an overview of published experimental EUV spectra for code benchmarking.

  *Disclaimer: I have not covered **all** publications reporting EUV spectra.*

- Compare ARCNL 1 μm laser-produced plasma experimental spectra to radiation-transported spectra generated for **Problem 2**.

1. Charge-state resolved EUV spectra for benchmarking atomic codes

EUV spectra: Vacuum spark discharge

Charge-state resolved spectra are **essential** for benchmarking spectral calculations from complex atomic & plasma physics codes.

Atomic Spectroscopy group (ISAN, Moscow).

SPECTROSCOPY OF ATOMS AND MOLECULES

Analysis of the Spectra of In XII–XIV and Sn XIII–XV in the Far-VUV Region

S. S. Churilov and A. N. Ryabtsev

https://link.springer.com/article/10.1134/S0030400X06080017

SPECTROSCOPY OF ATOMS AND MOLECULES

Analysis of the $4p^64d^7$–($4p^64d^64f$ + $4p^54d^8$) Transitions in the Sn VIII Spectrum

S. S. Churilov and A. N. Ryabtsev

https://link.springer.com/article/10.1134/S0030400X06050043

SPECTROSCOPY OF ATOMS AND MOLECULES

Spectra of Rubidium-like Pd X–Sn XIV Ions

A. N. Ryabtsev, É. Ya. Kononov, and S. S. Churilov

https://link.springer.com/article/10.1134/S0030400X08120060

INSTITUTE OF PHYSICS PUBLISHING PHYSICA SCRIPTA

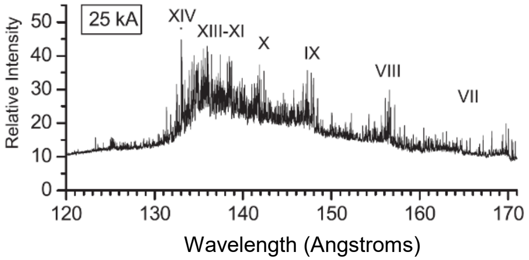
Phys. Scr. 73 (2006) 614–619 doi:10.1088/0031-8949/73/6/014

Analyses of the Sn IX–Sn XII spectra in the EUV region

S S Churilov and A N Ryabtsev

https://iopscience.iop.org/article/10.1088/0031-8949/73/6/014/pdf

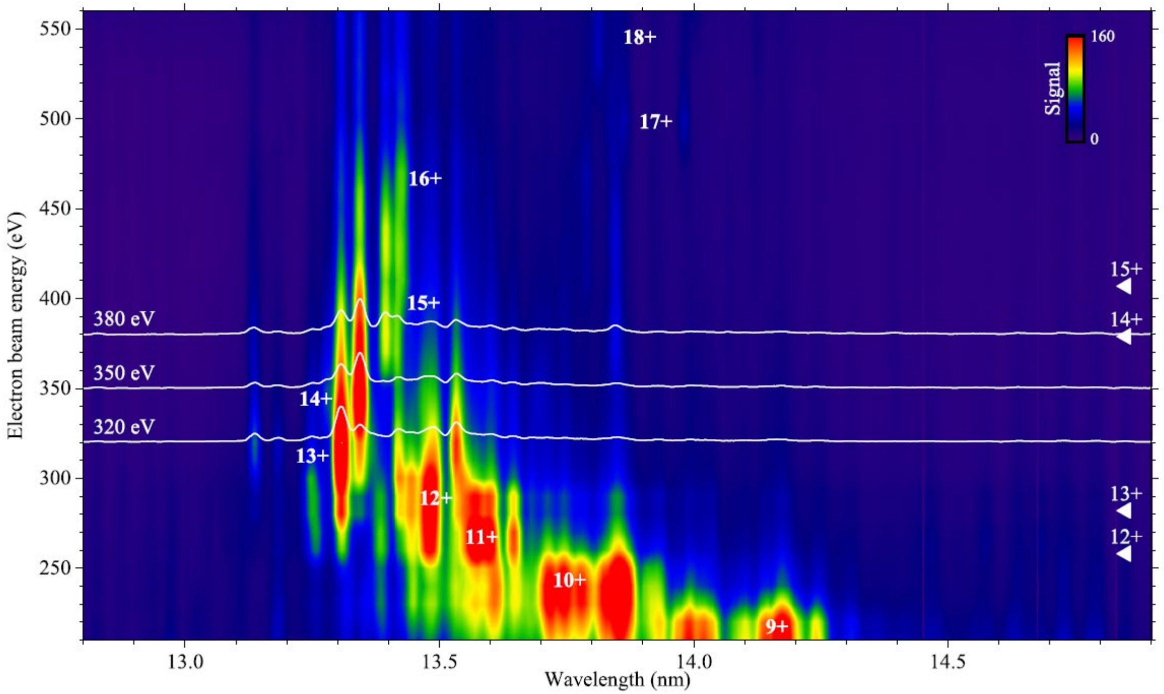
- Experimental spectra recorded in a **vacuum spark discharge**.
- Papers report wavelengths of **$4p^64d^n$ – ($4p^64d^{n-1}4f$ + $4p^54d^{n+1}$)** transitions.



EUV spectra: Electron beam ion trap

Charge-state resolved spectra are **essential** for benchmarking spectral calculations from complex atomic & plasma physics codes.

EUV Plasma Processes group (ARCNL, Amsterdam) **& Highly Charged Ion Dynamics** (MPIK, Heidelberg).



- Experimental spectra recorded in an **electron beam ion trap**.
- Papers report wavelengths of **4p – 4d** transitions in **Sn^{13+} – Sn^{15+}**.

PHYSICAL REVIEW A **101**, 062511 (2020)

EUV spectroscopy of highly charged Sn^{13+}–Sn^{15+} ions in an electron-beam ion trap

J. Scheers,[1,2] C. Shah,[3] A. Ryabtsev,[4] H. Bekker,[3] F. Torretti,[1,2] J. Sheil,[1] D. A. Czapski,[5] J. C. Berengut,[5] W. Ubachs,[1,2] J. R. Crespo López-Urrutia,[3] R. Hoekstra,[1,6] and O. O. Versolato[1,*]

https://journals.aps.org/pra/abstract/10.1103/PhysRevA.101.062511

PHYSICAL REVIEW A **95**, 042503 (2017)

Optical spectroscopy of complex open-4*d*-shell ions Sn^{7+}–Sn^{10+}

F. Torretti,[1,2,*] A. Windberger,[1,3] A. Ryabtsev,[4,5] S. Dobrodey,[3] H. Bekker,[3] W. Ubachs,[1,2] R. Hoekstra,[1,6] E. V. Kahl,[7] J. C. Berengut,[7] J. R. Crespo López-Urrutia,[3] and O. O. Versolato[1]

https://journals.aps.org/pra/abstract/10.1103/PhysRevA.95.042503

PHYSICAL REVIEW A **94**, 012506 (2016)

Analysis of the fine structure of Sn^{11+}–Sn^{14+} ions by optical spectroscopy in an electron-beam ion trap

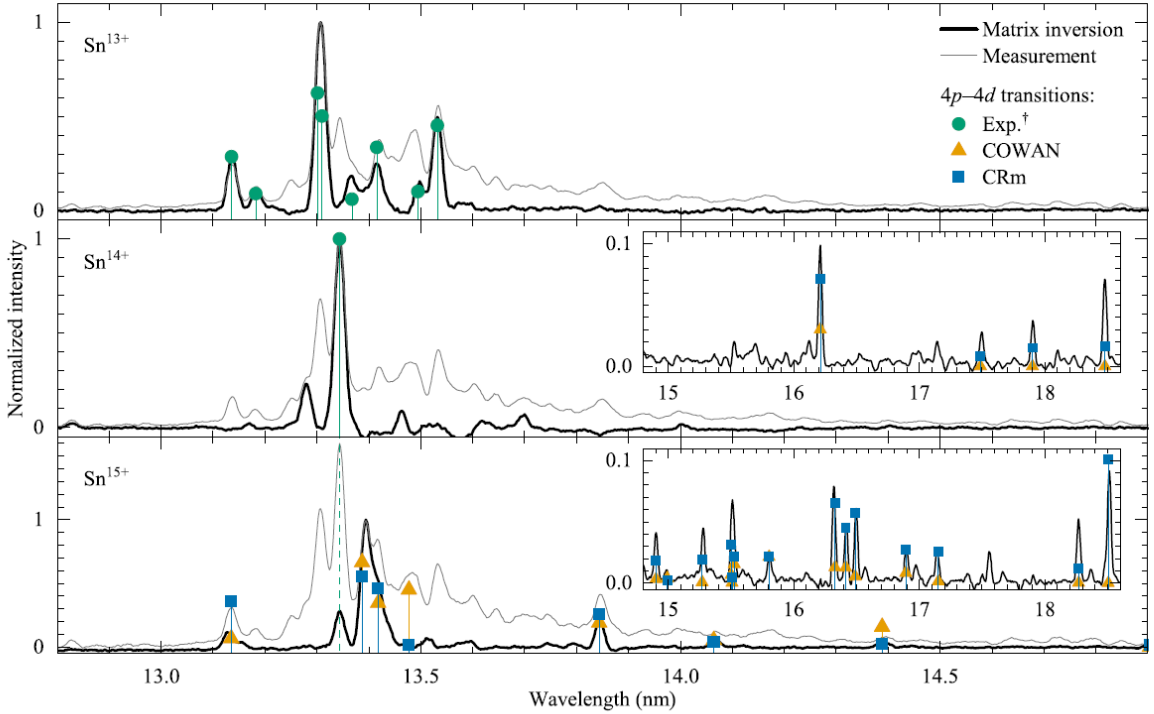
A. Windberger,[1,2] F. Torretti,[1,3] A. Borschevsky,[4] A. Ryabtsev,[5,6] S. Dobrodey,[2] H. Bekker,[2] E. Eliav,[7] U. Kaldor,[7] W. Ubachs,[1,3] R. Hoekstra,[1,8] J. R. Crespo López-Urrutia,[2] and O. O. Versolato[1,*]

https://journals.aps.org/pra/abstract/10.1103/PhysRevA.94.012506

EUV spectra: Electron beam ion trap

Charge-state resolved spectra are **essential** for benchmarking spectral calculations from complex atomic & plasma physics codes.

EUV Plasma Processes group (ARCNL, Amsterdam) **& Highly Charged Ion Dynamics** (MPIK, Heidelberg).



- Experimental spectra recorded in an **electron beam ion trap**.
- Papers report wavelengths of **4p – 4d** transitions in $\mathbf{Sn^{13+} – Sn^{15+}}$.

PHYSICAL REVIEW A **101**, 062511 (2020)

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https://journals.aps.org/pra/abstract/10.1103/PhysRevA.95.042503

PHYSICAL REVIEW A **94**, 012506 (2016)

Analysis of the fine structure of Sn^{11+}–Sn^{14+} ions by optical spectroscopy in an electron-beam ion trap

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https://journals.aps.org/pra/abstract/10.1103/PhysRevA.94.012506

EUV spectra: Charge-exchange spectroscopy

Charge-state resolved spectra are **essential** for benchmarking spectral calculations from complex atomic & plasma physics codes.

Atomic Physics group (TMU, Tokyo) **& Spectroscopy group** (UCD, Dublin).

IOP PUBLISHING JOURNAL OF PHYSICS B: ATOMIC, MOLECULAR AND OPTICAL PHYSICS
J. Phys. B: At. Mol. Opt. Phys. 43 (2010) 065204 (7pp) doi:10.1088/0953-4075/43/6/065204

EUV emission spectra in collisions of multiply charged Sn ions with He and Xe

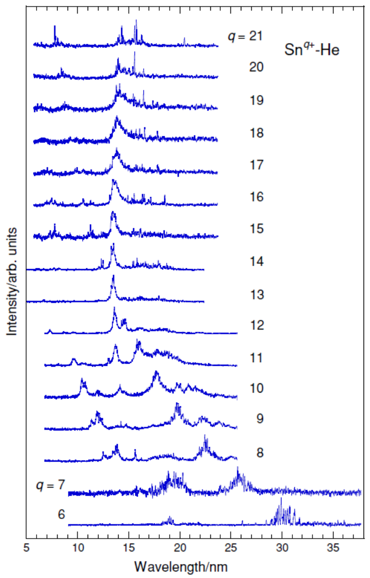
H Ohashi[1], S Suda[1], H Tanuma[1], S Fujioka[2], H Nishimura[2], A Sasaki[3] and K Nishihara[2]

https://iopscience.iop.org/article/10.1088/0953-4075/43/6/065204

Complementary spectroscopy of tin ions using ion and electron beams

H Ohashi[1], S Suda[1], H Tanuma[1], S Fujioka[2], H Nishimura[2], K Nishihara[2], T Kai[3], A Sasaki[3], H A Sakaue[4], N Nakamura[5] and S Ohtani[5]

https://iopscience.iop.org/article/10.1088/1742-6596/163/1/012071



PHYSICAL REVIEW A 79, 042509 (2009)

Transitions and the effects of configuration interaction in the spectra of Sn XV–Sn XVIII

R. D'Arcy,[1] H. Ohashi,[2] S. Suda,[2] H. Tanuma,[2] S. Fujioka,[3] H. Nishimura,[3] K. Nishihara,[3] C. Suzuki,[4] T. Kato,[4] F. Koike,[5] J. White,[1] and G. O'Sullivan[1]

https://journals.aps.org/pra/abstract/10.1103/PhysRevA.79.042509

IOP PUBLISHING JOURNAL OF PHYSICS B: ATOMIC, MOLECULAR AND OPTICAL PHYSICS
J. Phys. B: At. Mol. Opt. Phys. 42 (2009) 165207 (6pp) doi:10.1088/0953-4075/42/16/165207

Identification of 4d–5p transitions in the spectra of Sn XV–Sn XIX recorded from collisions between Sn ions and He

R D'Arcy[1], H Ohashi[2], S Suda[2], H Tanuma[2], S Fujioka[3], H Nishimura[3], K Nishihara[3], C Suzuki[4], T Kato[4], F Koike[5], A O'Connor[1] and G O'Sullivan[1]

https://iopscience.iop.org/article/10.1088/0953-4075/42/16/165207

- Experimental spectra recorded from **collisions** of **Sn^{q+} ions** with **He/Xe** gas.
- Papers report wavelengths of **$4p^6 4d^n$ – ($4p^6 4d^{n-1}$ (4f,5p,5f) + $4p^5 4d^{n+1}$)** transitions.

EUV spectra: Large Helical Device

Charge-state resolved spectra are **essential** for benchmarking spectral calculations from complex atomic & plasma physics codes.

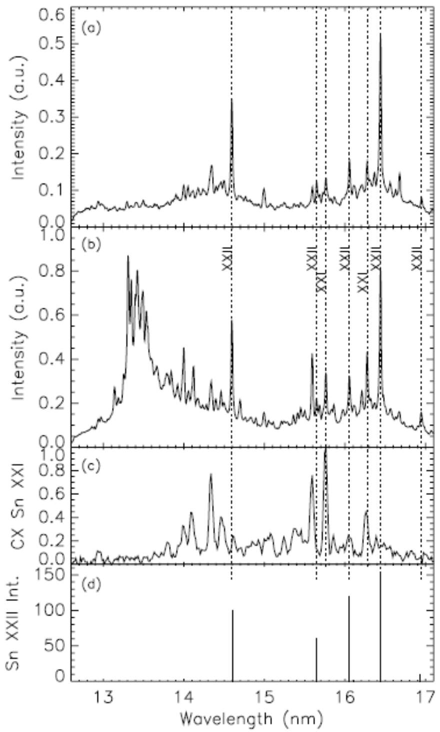
High temperature Plasma Physics division (NIFS, Toki) **& Spectroscopy group** (UCD, Dublin).

IOP Publishing — Journal of Physics B: Atomic, Molecular and Optical Physics
J. Phys. B: At. Mol. Opt. Phys. 43 (2010) 074027 (6pp) — doi:10.1088/0953-4075/43/7/074027

Analysis of EUV spectra of Sn XIX–XXII observed in low-density plasmas in the Large Helical Device

C Suzuki[1], T Kato[1], H A Sakaue[1], D Kato[1], K Sato[1], N Tamura[1], S Sudo[1], N Yamamoto[2], H Tanuma[3], H Ohashi[3], R D'Arcy[4] and G O'Sullivan[4]

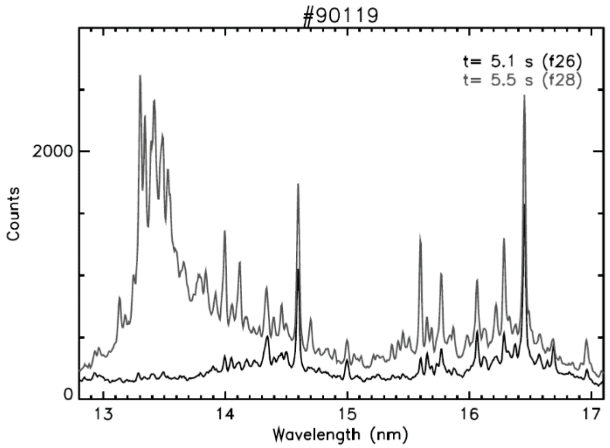
https://iopscience.iop.org/article/10.1088/0953-4075/43/7/074027



Measurement of EUV Spectra from High Z Elements in the Large Helical Device

C. Suzuki*, T. Kato*, H. A. Sakaue*, D. Kato*, I. Murakami*, K. Sato*, N. Tamura*, S. Sudo*, N. Yamamoto†, H. Tanuma**, H. Ohashi**, R. D'Arcy‡, C. S. Harte‡ and G. O'Sullivan‡

https://aip.scitation.org/doi/10.1063/1.3585803

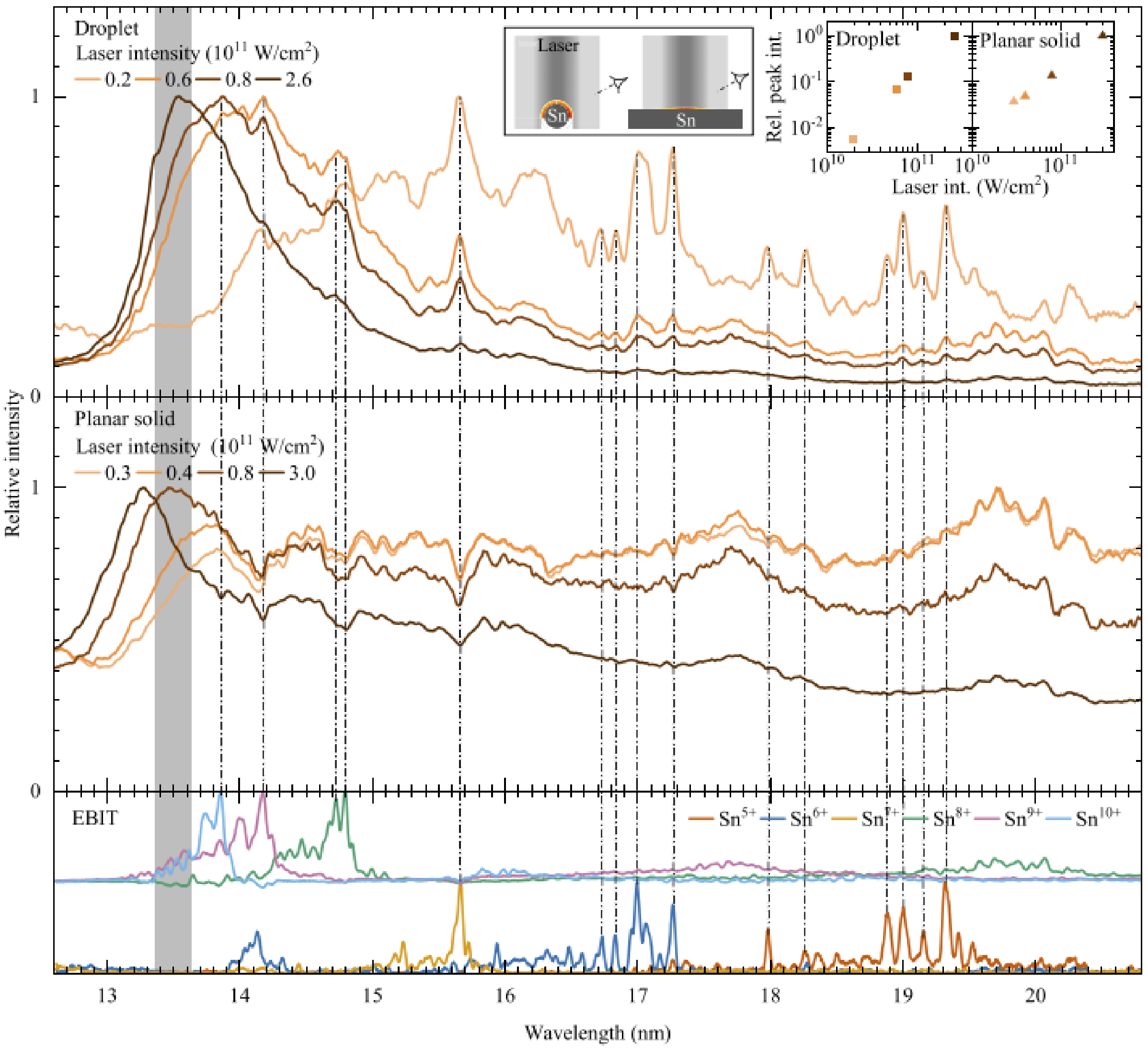


- Experimental spectra recorded from low-density magnetic confinement fusion plasma.
- Papers report wavelengths of **4p – 4d** transition in Sn XIX, XX, XXI (also **4d – 4f**) XXII.

2. EUV spectra from laser-produced plasmas (**ARCNL data**)

EUV spectra: 1 µm laser-driven plasmas

1. "**Long**-wavelength" out-of-band emission



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IOP Publishing

Journal of Physics B: Atomic, Molecular and Optical Physics

J. Phys. B: At. Mol. Opt. Phys. **53** (2020) 195001 (10pp)

https://doi.org/10.1088/1361-6455/aba3a8

EUV spectroscopy of Sn^{5+}–Sn^{10+} ions in an electron beam ion trap and laser-produced plasmas

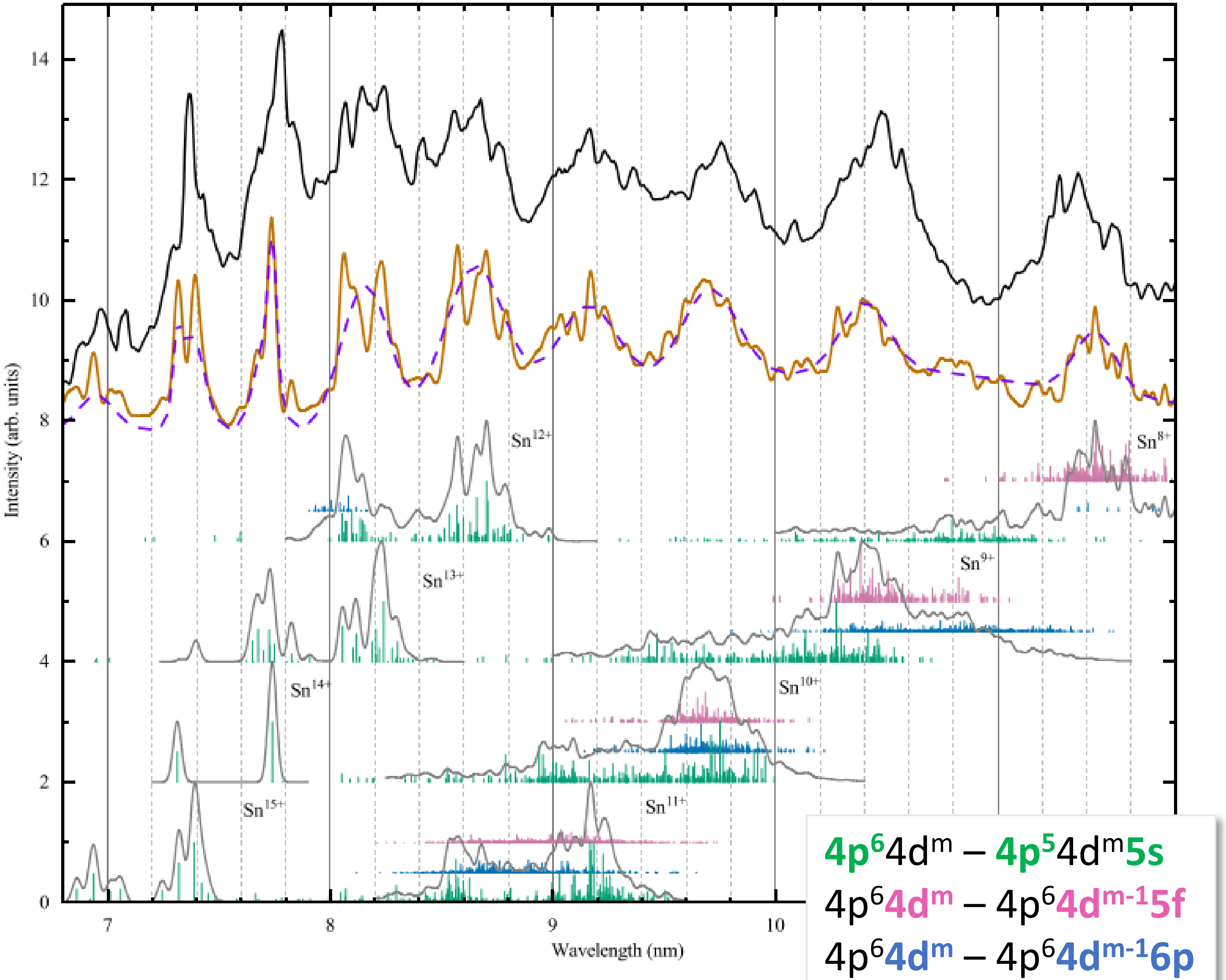
Z Bouza[1,7], J Scheers[1,2,7], A Ryabtsev[3], R Schupp[1], L Behnke[1], C Shah[4,8], J Sheil[1], M Bayraktar[5], J R Crespo López-Urrutia[4], W Ubachs[1,2], R Hoekstra[1,6] and O O Versolato[1,2]

https://iopscience.iop.org/article/10.1088/1361-6455/aba3a8/meta

- Experimental spectra recorded in an **electron beam ion trap** and **laser-produced plasmas** (1 µm Nd:YAG).
- Papers reports wavelengths of **4p – 4d** & **4d – (4f, 5p, 5f, 6p, 6f)** transitions in tin ions.

EUV spectra: 1 μm laser-driven plasmas

2. "**Short**-wavelength" out-of-band emission



OPEN ACCESS
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Journal of Physics B: Atomic, Molecular and Optical Physics
J. Phys. B: At. Mol. Opt. Phys. **51** (2018) 045005 (9pp)
https://doi.org/10.1088/1361-6455/aaa593

Short-wavelength out-of-band EUV emission from Sn laser-produced plasma

F Torretti[1,2], R Schupp[1], D Kurilovich[1,2], A Bayerle[1], J Scheers[1,2], W Ubachs[1,2], R Hoekstra[1,3] and O O Versolato[1]

https://iopscience.iop.org/article/10.1088/1361-6455/aaa593

- Experimental spectra recorded from a **laser-produced plasma** (1 μm Nd:YAG).
- Papers reports wavelengths of **4p – 5s, 4d – 5f/6p** transitions in tin ions.

PHYSICAL REVIEW A VOLUME 50, NUMBER 5 NOVEMBER 1994

Statistics and characteristics of xuv transition arrays from laser-produced plasmas of the elements tin through iodine

Winnie Svendsen* and Gerard O'Sullivan

EUV spectra: Laser-produced plasmas

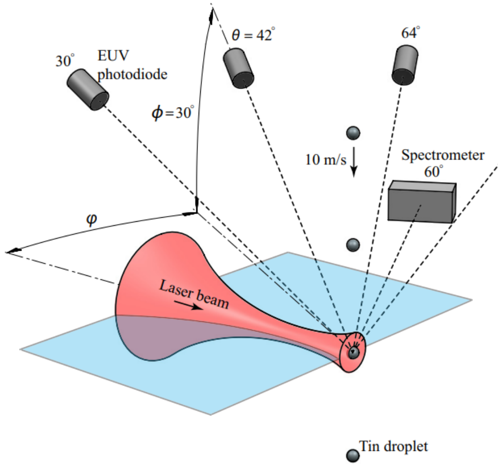
1 µm (Nd:YAG) laser-produced tin plasma spectra

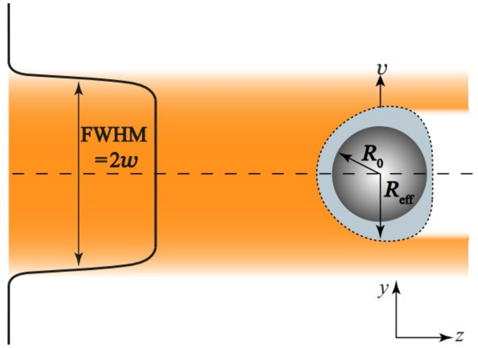
PHYSICAL REVIEW APPLIED **12,** 014010 (2019)

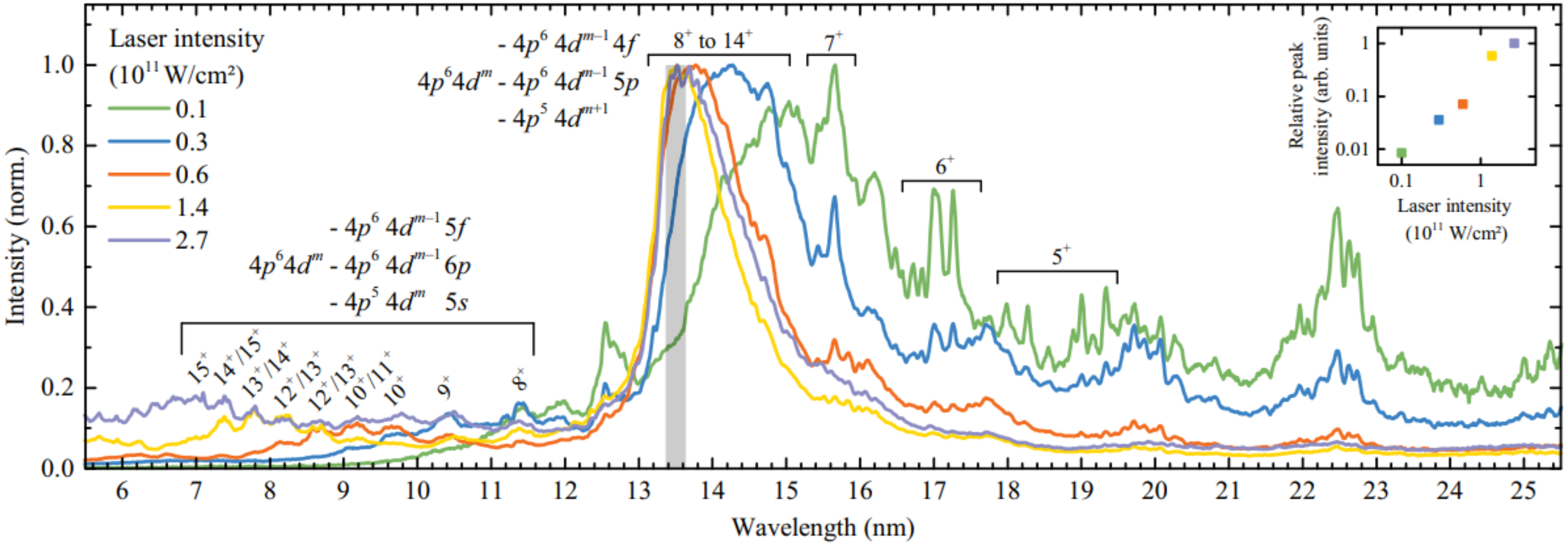
Efficient Generation of Extreme Ultraviolet Light From Nd:YAG-Driven Microdroplet-Tin Plasma

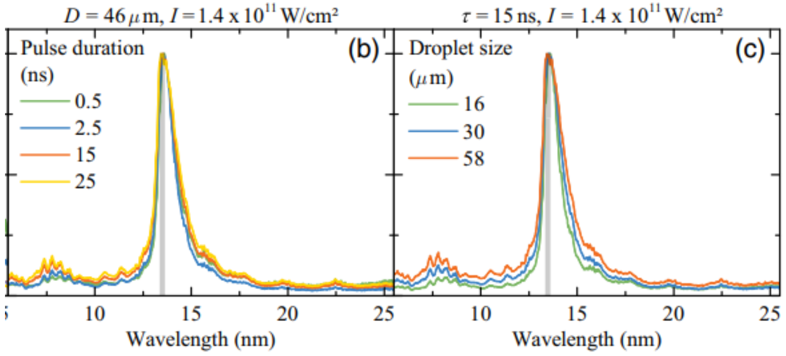
R. Schupp,[1] F. Torretti,[1,2] R.A. Meijer,[1,2] M. Bayraktar,[3] J. Scheers,[1,2] D. Kurilovich,[1,2] A. Bayerle,[1] K.S.E. Eikema,[1,2] S. Witte,[1,2] W. Ubachs,[1,2] R. Hoekstra,[1,4] and O.O. Versolato[1,*]

https://journals.aps.org/prapplied/abstract/10.1103/PhysRevApplied.12.014010









EUV spectra: Laser-produced plasmas

1 µm (Nd:YAG) laser-produced tin plasma spectra

Applied Physics Letters ARTICLE scitation.org/journal/apl

Radiation transport and scaling of optical depth in Nd:YAG laser-produced microdroplet-tin plasma

Cite as: Appl. Phys. Lett. **115**, 124101 (2019); doi: 10.1063/1.5117504
Submitted: 2 July 2019 · Accepted: 5 September 2019 ·
Published Online: 19 September 2019

View Online Export Citation CrossMark

R. Schupp,[1] F. Torretti,[1,2] R. A. Meijer,[1,2] M. Bayraktar,[3] J. Sheil,[1] J. Scheers,[1,2] D. Kurilovich,[1,2] A. Bayerle,[1] A. A. Schafgans,[4] M. Purvis,[4] K. S. E. Eikema,[1,2] S. Witte,[1,2] W. Ubachs,[1,2] R. Hoekstra,[1,5] and O. O. Versolato[1,a)]

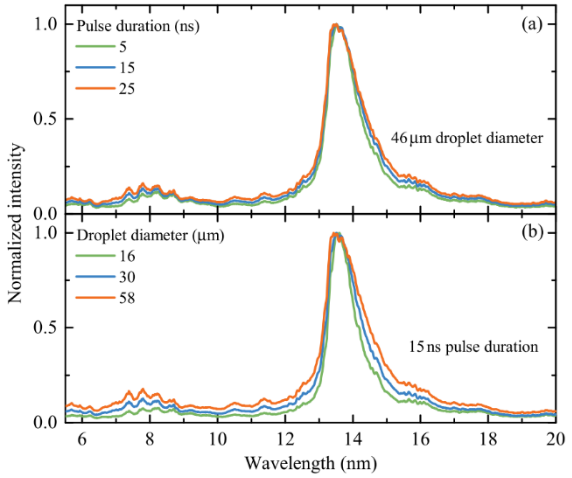
https://aip.scitation.org/doi/full/10.1063/1.5117504

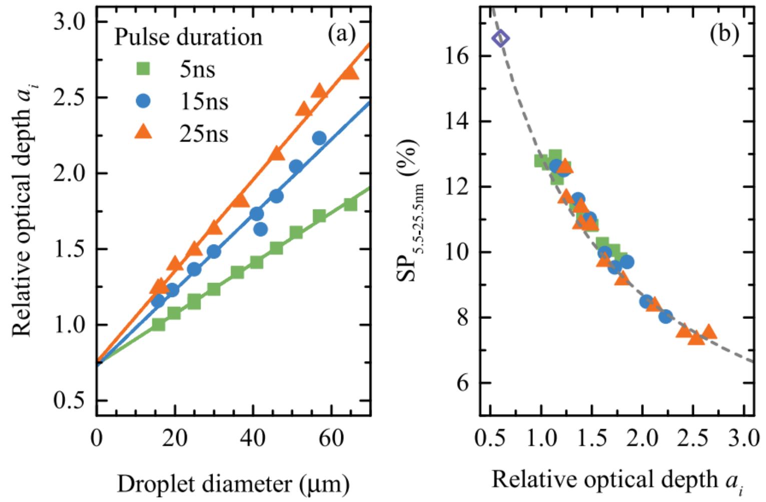
Radiation transport through a **1D single temperature**, **single density** plasma in LTE with a wavelength-specific **optical depth** $\boldsymbol{\tau_\lambda}$

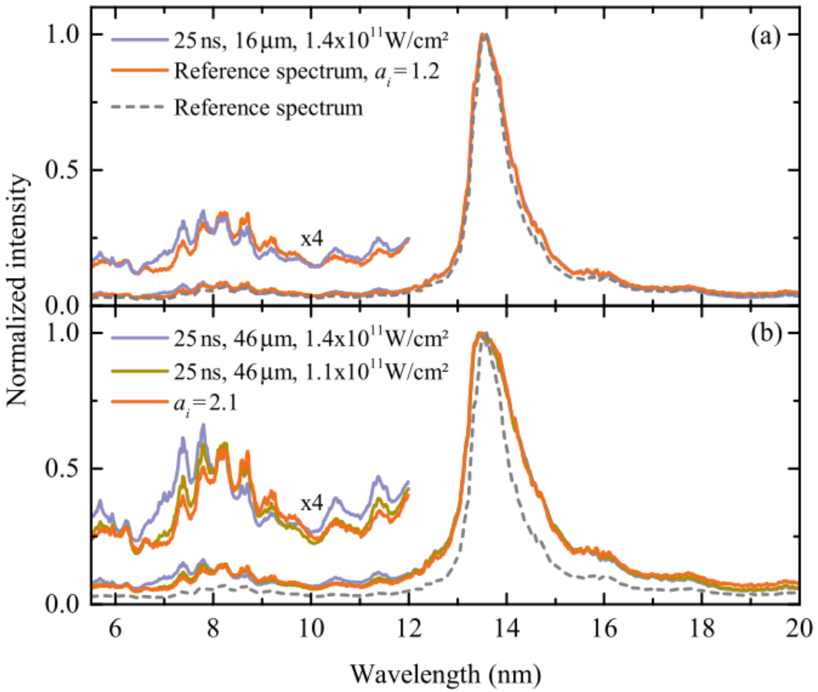
$$L_\lambda = S_\lambda\left(1 - e^{-\tau_\lambda}\right)$$

Spectral radiance Planckian

Can reproduce an experimental spectrum "i" using a reference spectrum and the so-called "relative optical depth" $\boldsymbol{a_{\lambda,i} = \tau_{\lambda,i}/\tau_{\lambda,reference}}$



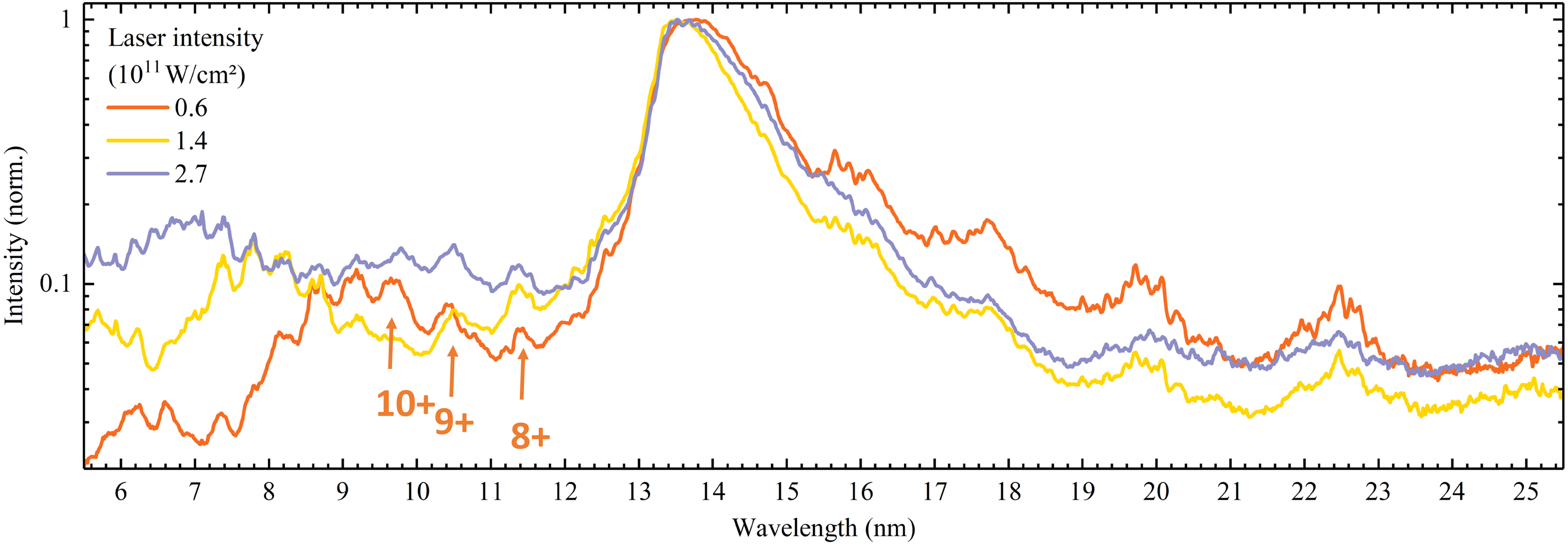




EUV spectra: Laser-produced plasmas

1 µm (Nd:YAG) laser-produced tin plasma spectra

What are the dominant charge states in the plasma? –> **Look at the short wavelength emission!!**



Let us compare the **orange spectrum** to the code comparison problem "radiation transport through a uniform tin sphere"

Recall: Radiation transport problem

Problem 2a

This problem investigates radiation transport through a **uniform sphere** of tin plasma.

The plasma temperature (for both electrons & ions) is set to **25 eV** and the mass density and sphere radius are defined below.

ID	SSR1	SSR2	SSR3	SSR4
ρ	0.0002 g/cm^3	0.0002 g/cm^3	0.02 g/cm^3	0.02 g/cm^3
R	100.0 μm	1000. μm	1. μm	10. μm

Goal: Obtain a self-consistent **radiation field** & **material properties** throughout the sphere under the assumption of steady-state non-LTE conditions.

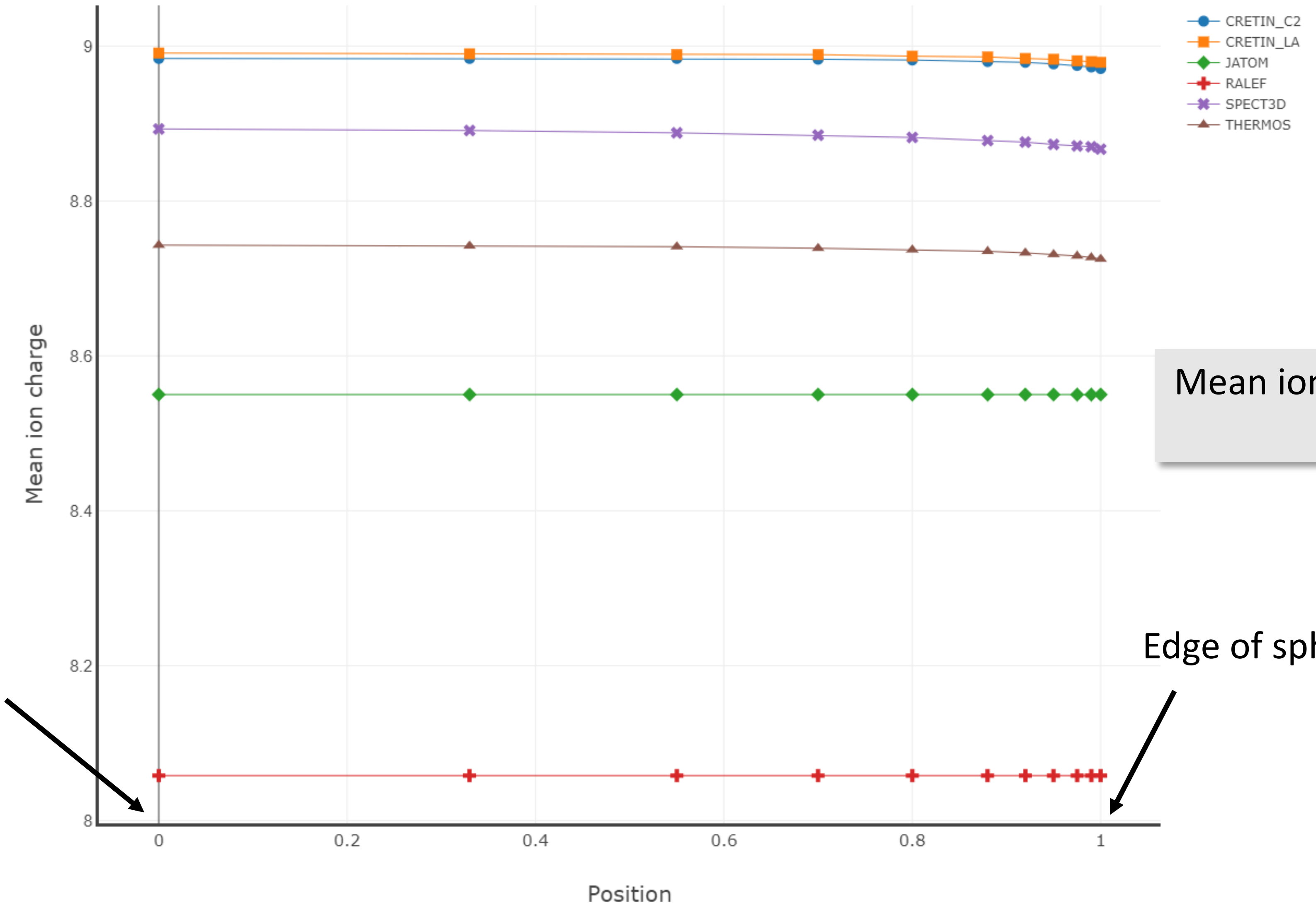
Requested quantities: Gross plasma parameters (mean ion charge, energy density, etc.), emission & absorption coefficients and the spectral power:

$$P_\nu = 4\pi r^2 F_\nu \quad , \quad F_\nu = \oint \hat{\mathbf{n}} \cdot \hat{\Omega} \, I_\nu(\theta,\phi) \, d\Omega$$

Problem 2: Radiation transport

- Radiation transport through a uniform sphere
- T_e = **25 eV**, ρ = **0.01 g/cc**, Radius = **10 μm**

Mean ion charge as a function of "normalised distance" in the sphere



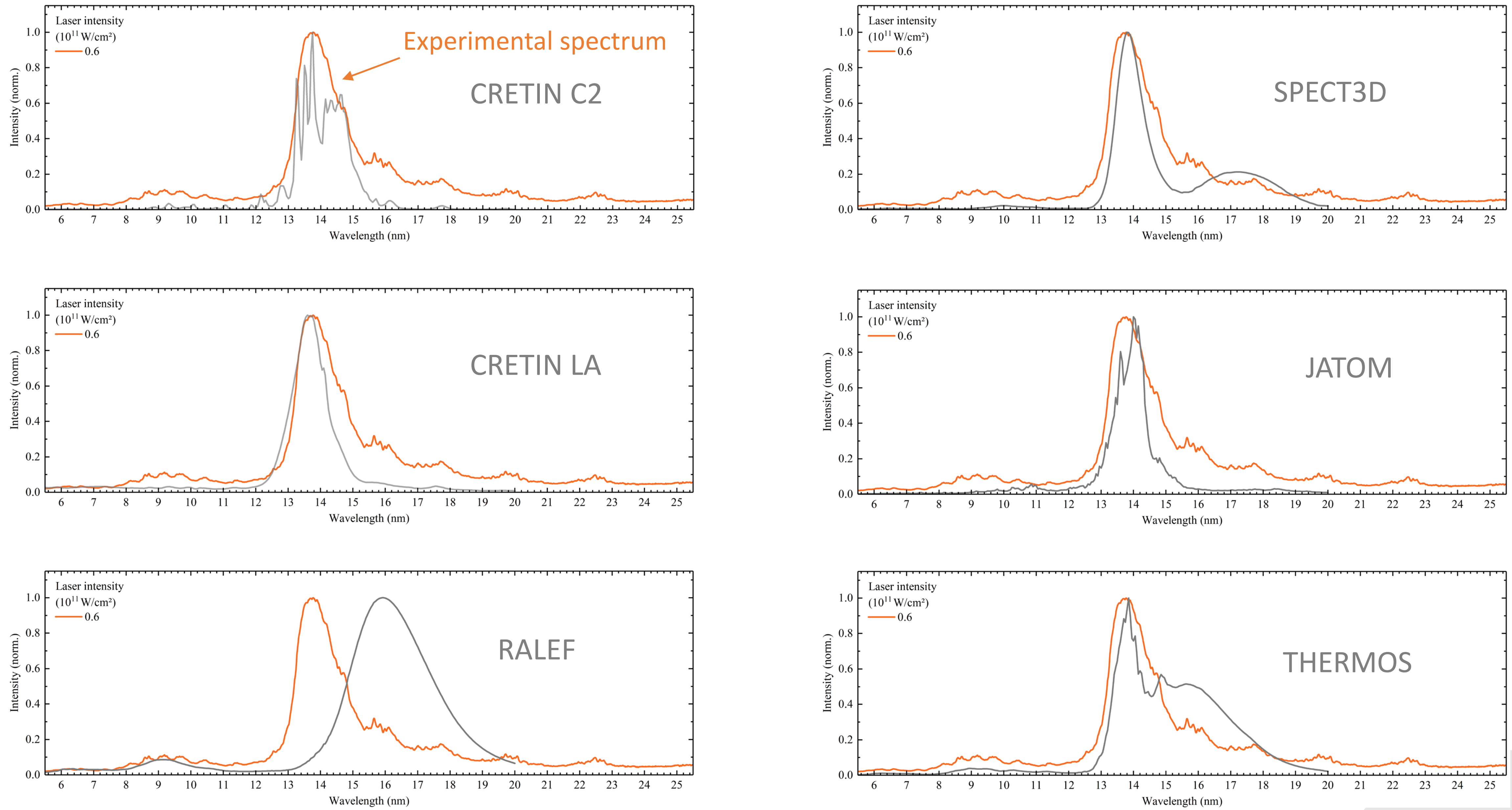
Center of sphere

Edge of sphere

Mean ion charge ranges between **Sn^{8+}** and **Sn^{9+}**

Problem 2: Radiation-transport

- Radiation transport through a uniform sphere
- T_e = **25 eV**, ρ = **0.01 g/cc**, Radius = **10 μm**



EUV spectra: Laser-produced plasmas

2 µm (Nd:YAG) laser-produced tin plasma spectra

PHYSICAL REVIEW RESEARCH **3**, 013294 (2021)

Characterization of 1- and 2-μm-wavelength laser-produced microdroplet-tin plasma for generating extreme-ultraviolet light

R. Schupp,[1] L. Behnke,[1,3] J. Sheil,[1] Z. Bouza,[1,3] M. Bayraktar,[2] W. Ubachs,[1,3] R. Hoekstra,[1,4] and O. O. Versolato[1,3,*]

https://journals.aps.org/prresearch/abstract/10.1103/PhysRevResearch.3.013294

Research Article Vol. 29, No. 3 / 1 February 2021 / *Optics Express* 4475

Optics EXPRESS

Extreme ultraviolet light from a tin plasma driven by a 2-µm-wavelength laser

L. BEHNKE,[1] R. SCHUPP,[1] Z. BOUZA,[1,2] M. BAYRAKTAR,[3] Z. MAZZOTTA,[1,2] R. MEIJER,[1,2] J. SHEIL,[1] S. WITTE,[1,2] W. UBACHS,[1,2] R. HOEKSTRA,[1,4] AND O. O. VERSOLATO[1,2,*]

https://opg.optica.org/oe/fulltext.cfm?uri=oe-29-3-4475&id=446982

OPEN ACCESS
IOP Publishing Journal of Physics D: Applied Physics
J. Phys. D: Appl. Phys. **54** (2021) 365103 (12pp) https://doi.org/10.1088/1361-6463/ac0b70

Characterization of angularly resolved EUV emission from 2-μm-wavelength laser-driven Sn plasmas using preformed liquid disk targets

R Schupp[1], L Behnke[1,2], Z Bouza[1,2], Z Mazzotta[1], Y Mostafa[1,2], A Lassise[1], L Poirier[1,2], J Sheil[1], M Bayraktar[3], W Ubachs[1,2], R Hoekstra[1,4] and O O Versolato[1,2,*]

https://iopscience.iop.org/article/10.1088/1361-6463/ac0b70/meta

Droplet target, Gaussian temporal & spatial profiles