XUV Spectra from Plasmas of Second Transition Row Elements Generated by fs Laser Pulses

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Presentation Layout

- Motivation
- Introduction
- Results and Discussion:

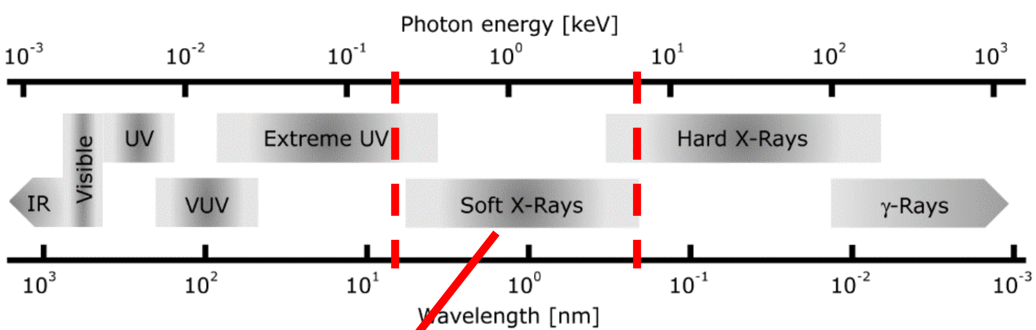
  Section 1: XUV spectra of 2nd transition row elements: identification of 3d-4p and 3d-4f transition arrays

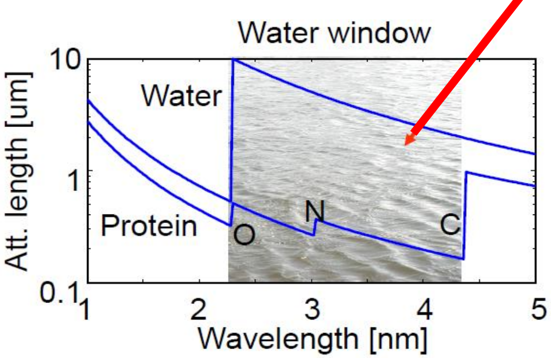
  Section 2: Femtosecond LPPs from 2nd transition row elements
- Conclusion
- Acknowledgments

Motivation

Feasibility of using 2nd transitions row elements as possible candidates for

- **Water window** sources
- **Next generation lithography** (6.X nm).
- **Lower laser intensities** (and electron temperatures of 150 to 300 eV)
- Optimum matching of spectral output - **multilayer mirrors**.



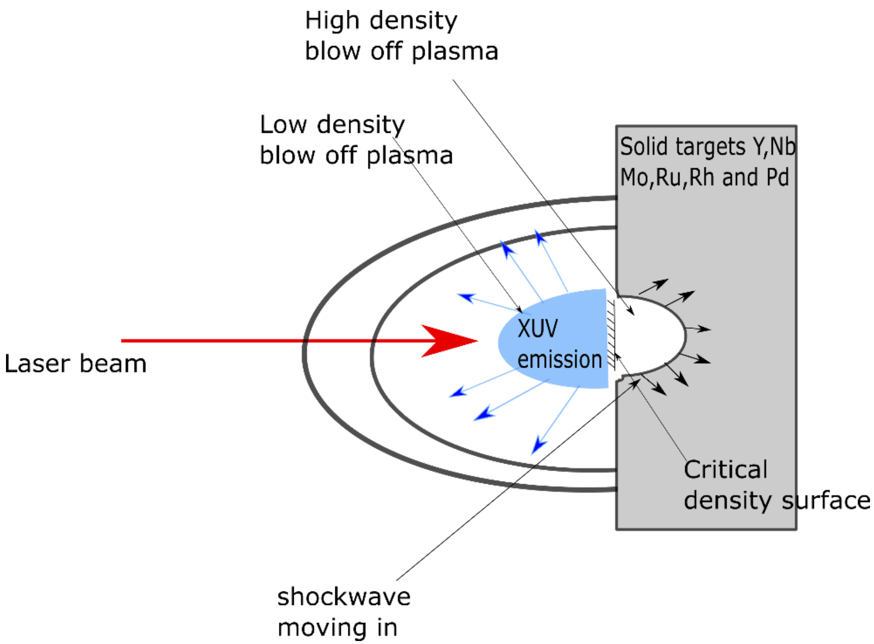


- Water window absorption contrast 2.3-4.4 nm (284-543 eV)
- Relative transparency of water allows investigation of biomolecules, cells and proteins
- Possibility to study thick (~10 μm) objects

Introduction

High power laser intensity focused onto a solid targets in vacuum forms a

- Short lived high temperature,
- High density plasma



Plasma temperature depends on laser intensity (Φ) and wavelength(λ), $T_e(eV) \propto (\lambda^2\ \Phi)^{3/5}$

Laser produced plasma (LPPs) expansion velocity $\approx 10^6$-10^7 cms^{-1}

Critical electron density, depends on laser wavelength n_{ec} $(cm^{-3}) = 10^{21}/\ \lambda^2$[micron]

Spectroscopy of LPPs provide detail information on

- The transitions and electronic structure of highly ionized atoms,
- Allow source optimization.

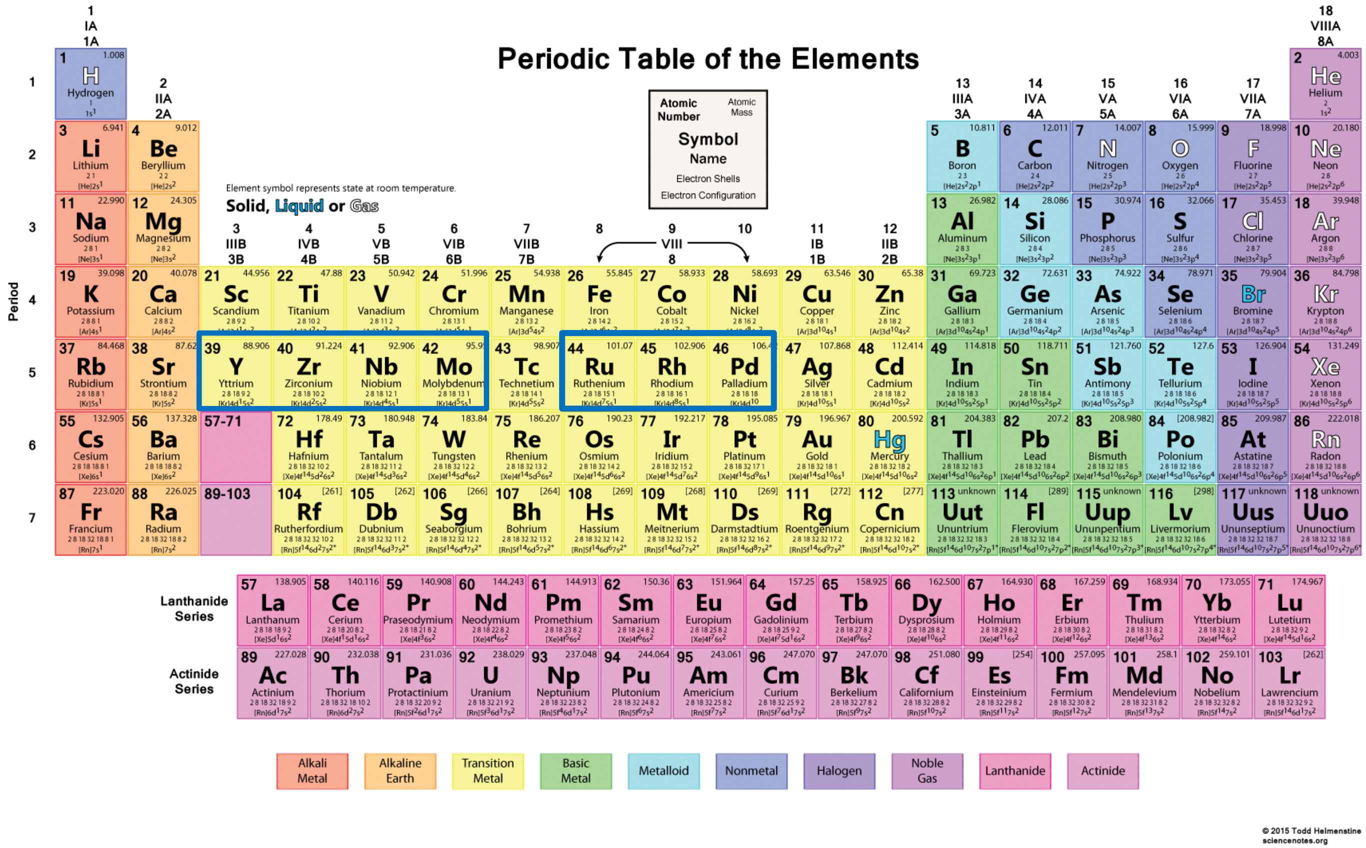
Presentation Layout

- Results and Discussion:

  Section 1: XUV spectra of 2nd transition row elements: identification of 3d-4p and 3d-4f transition arrays.

  The positions of the reflectance peaks of currently available MLMs are compared with the present experimental data.

SXR Studied


Periodic Table of the Elements
Atomic Number
Atomic Mass
Symbol
Name
Electron Shells
Electron Configuration
Element symbol represents state at room temperature.
Solid, Liquid or Gas
Period
Lanthanide Series
Actinide Series
Alkali Metal
Alkaline Earth
Transition Metal
Basic Metal
Metalloid
Nonmetal
Halogen
Noble Gas
Lanthanide
Actinide
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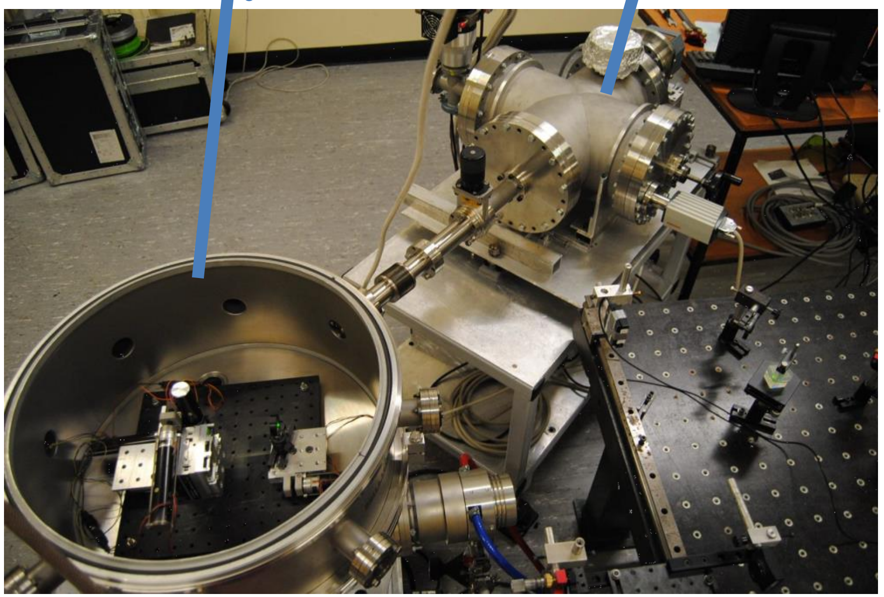
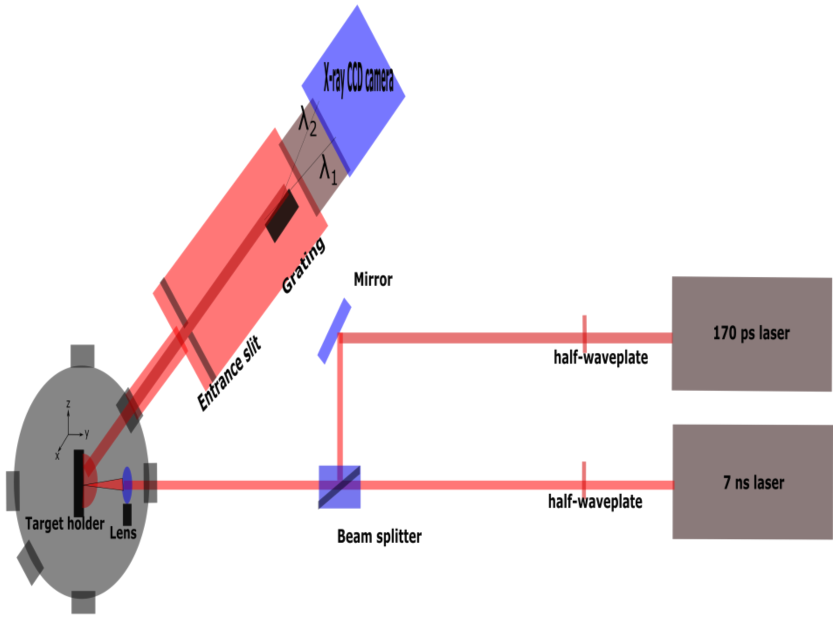
XUV spectra of 2nd transition row elements: identification of 3d-4p and 3d-4f transition arrays

Experimental setup at University College Dublin

Vacuum chamber

Spectrometer





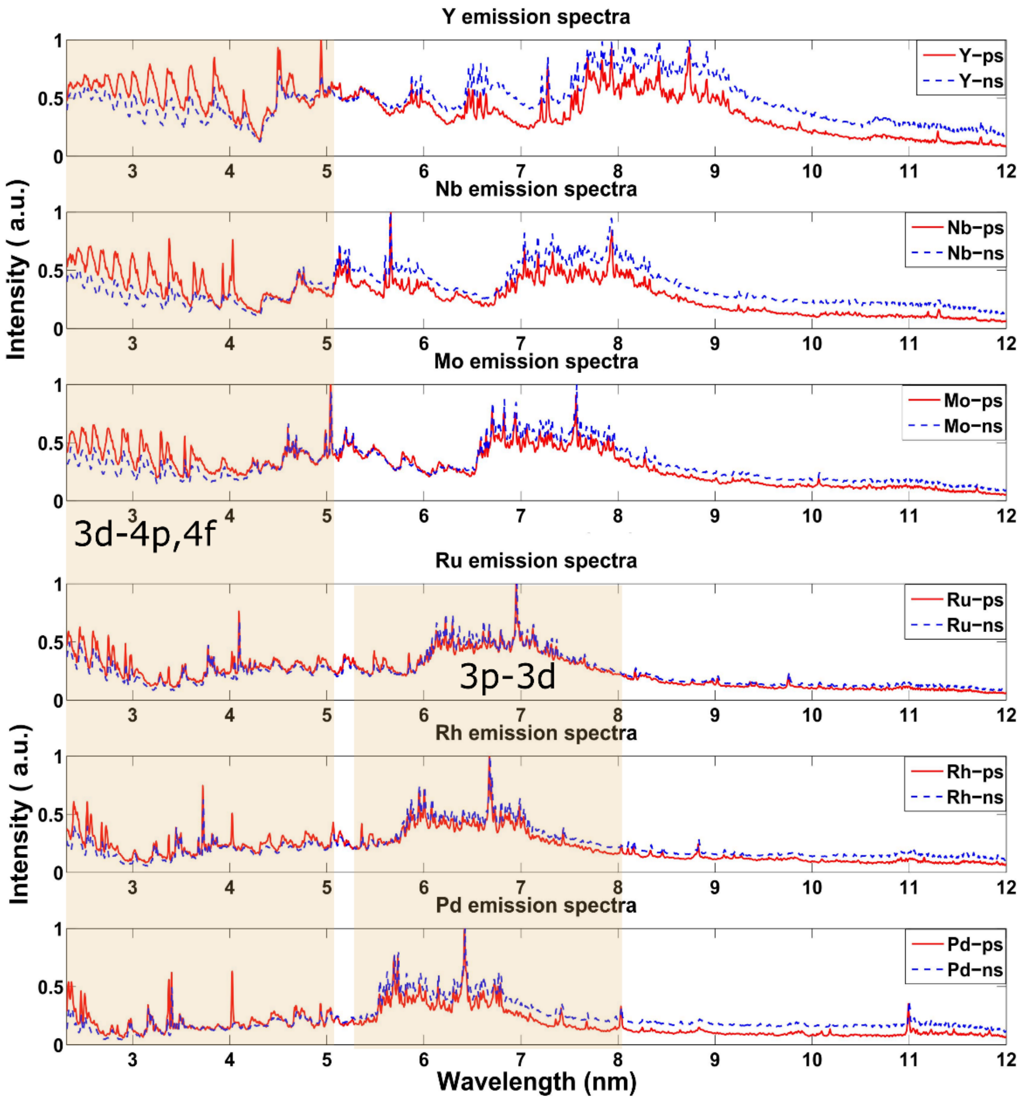
Laser Parameters

Parameter	ns laser	ps laser
Model	Contiuum surelite	EKSPLA
Maximum pulse energy (mJ)	≈ 600	≈ 227
Pulse length (ns)	≈ 7	≈ 0.17
Maximum power density (W/cm^2)	≈ 2.2×10^{12}	≈ 3.4×10^{13}

Spectrometer

Parameter	
Spectrometer	flat-field grazing-incidence
Grooves	1200 per mm/variable line space grating
Spectral resolution	≈ 0.02 nm
Wavelength uncertainty	≈ 0.005 nm

XUV spectra of 2nd transition row elements: identification of 3d-4p and 3d-4f transition arrays

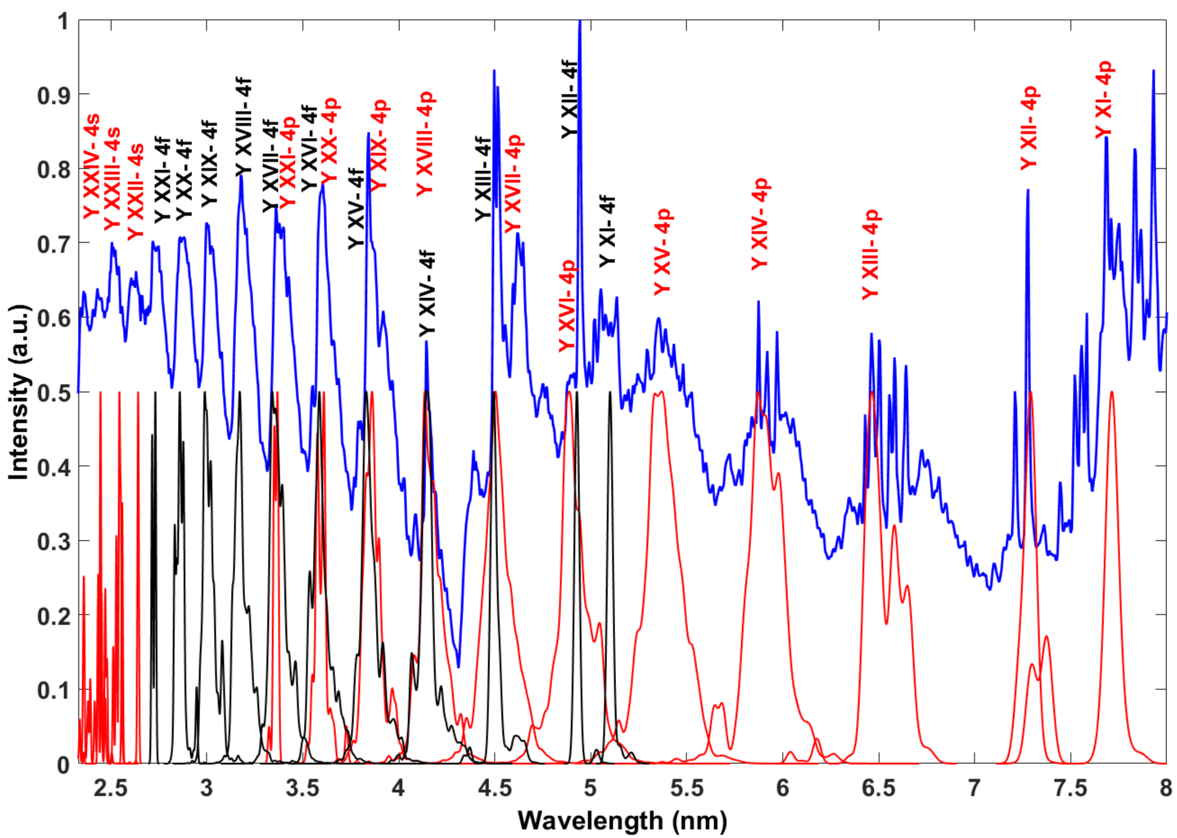


- Emission spectra of 6 elements from 170 ps and 7 ns Nd:YAG laser pulses.
- Spectra are normalized to the highest intensity.

Theoretical Calculations

- The Cowan code models atomic spectra based on the superposition of configurations method, developed by Robert D. Cowan.
- The code numerically calculates radial wave functions in order to determine the transitions set by the user.
- The Schrodinger equation is then solved using the calculated wave functions, which outputs a set of oscillator strengths as a function of wavelength.
- The term energies, electrostatic, spin-orbit and exchange parameters can be scaled as an aid to interpreting the experimental spectrum.
- Calculated spectra using the Cowan code - Y, Nb, Mo, Ru, Rh and Pd : Water window source & BEUV source.

Calculated and experimental yttrium spectra with ions



The experimental spectrum of yttrium (blue) with synthetic spectra obtained from Cowan code calculations.

(*R. Lokasani et al, J. Phys. B* ***48*** *(2015), 245009*)

Unresolved transition arrays (UTA) Statistics

- UTA has too many lines to identify individual transitions.
- Energy levels and spectral distributions can be parameterized statistically in terms of moments of the array *(Bauche,and Bauche- Arnoult, Phys. Scripta **T40**,(1992), 58)*
- The general nth moment for transitions between configurations *a* and *b* is given by

$$\mu_n(a-b) = \frac{\sum_{m,m'}[|<m'|H|m'>-<m|H|m>]^n \quad |<m|D|m'>|^2\,]}{\sum_{mm'}\ |<m|D|m'|>|^2}$$

where *D* is the electric dipole operator and sum runs over all states *m*, *m*' of configurations *a* and *b* respectively

- First moment μ_1 gives the average value of the weighted mean wavelength of the UTA. Width is $\sigma = \left[\mu_2 - (\mu_1)^2\right]^{1/2}$

niobium UTA Table

Ion Stage	Transition	μ_1 (nm)	Width (nm)	UTA Peak (nm)	Observed UTA range (nm)	Previously identified spectral range (nm)
Nb XIII	$3d^{10}\,4s - 3d^9\,4s\,4p$	5.86	0.119	5.93	5.5-6.4	5.7-6.5 [24,22,25,23]
	$3d^{10}\,4s - 3d^9\,4s\,4f$	4.02	0.019	4.03	4-4.2	
Nb XIV	$3d^{10} - 3d^9\,4p$	5.6	0.02	5.65	5.5-5.72	5.5-5.75[26,24,21,22,25]
	$3d^{10} - 3d^9\,4f$	3.91	0.017	3.92	3.92-4.1	3.9-4.5 [26,24,21]
Nb XV	$3p^6\,3d^9 – 3d^8\,4p$	5.14	0.069	5.13	4.8-5.4	4.8-5.4 [24,28,27,21]
	$3p^6\,3d^9 – 3d^8\,4f$	3.62	0.037	3.63	3.5-3.84	
	$3p^6\,3d^9 - 3p^5\,3d^{10}$	7.58	0.289			7.3-8.1[27,29,30,21,24]
Nb XVI	$3p^6\,3d^8 – 3d^7\,4p$	4.71	0.077	4.7	4.5-5	4.49-4.9[33,24]
	$3p^6\,3d^8 – 3d^7\,4f$	3.21	0.752	3.37	3.25-3.6	3.2-3.5[24]
	$3p^6\,3d^8 - 3p^5\,3d^9$	7.5	0.445			6.8-8.7[31]
Nb XVII	$3p^6\,3d^7 – 3d^6\,4p$	4.33	0.076	4.35	4.1-4.6	4.1-4.5[24]
	$3p^6\,3d^7 – 3d^6\,4f$	3.1	0.042	3.16	3-3.3	
	$3p^6\,3d^7 - 3p^5\,3d^8$	7.5	0.539			6.9-8.75[34]
Nb XVIII	$3p^6\,3d^6 – 3d^5\,4p$	4	0.07	4	3.9-4.2	
	$3p^6\,3d^6 – 3d^5\,4f$	2.98	0.04	2.98	2.9-3.15	
	$3p^6\,3d^6 - 3p^5\,3d^7$	7.5	0.599			
Nb XIX	$3p^6\,3d^5 – 3d^4\,4p$	3.71	0.062	3.72	3.55-3.91	
	$3p^6\,3d^5 – 3d^4\,4f$	2.82	0.037	2.82	2.7-2.91	
	$3p^6\,3d^5 - 3p^5\,3d^6$	7.47	0.636			
Nb XX	$3p^6\,3d^4 – 3d^3\,4p$	3.46	0.052	3.44	3.3-3.6	
	$3p^6\,3d^4 – 3d^3\,4f$	2.68	0.033	2.68	2.6-2.75	
	$3p^6\,3d^4 - 3p^5 3d^5$	7.47	0.651			
Nb XXI	$3p^6\,3d^3 – 3d^2\,4p$	3.23	0.042	3.22	3.12-3.33	
	$3p^6\,3d^3 – 3d^2\,4f$	2.55	0.028	2.56	2.5-2.64	
	$3p^6\,3d^3 - 3p^5\,3d^4$	7.49	0.643			
Nb XXII	$3p^6\,3d^2 – 3d^1\,4p$	3.02	0.029	3.03	2.9-3.13	
	$3p^6\,3d^2 – 3d^1\,4f$	2.44	0.022	2.44	2.4-2.6	
	$3p^6\,3d^2 - 3p^5\,3d^3$	7.52	0.61			
Nb XXIII	$3p^6\,3d – 4p$	2.84	0.01	2.84	2.7-2.9	
	$3p^6\,3d – 4f$	2.33	0.007	2.34	2.2-2.3	
	$3p^6 3d - 3p^5 3d^2$	7.57	0.54			7.2-8.12[35]

Weighted mean wavelengths, widths UTA observed range, observed wavelength peak from experimental spectra

(*R. Lokasani et al. J. Phys. B* ***48*** *(2015), 245009*)

Multilayer mirrors matched with present experimental data

Material	Wavelength(nm)	Reflectivity (%)	Observed UTA Peak
Cr/V	2.42	9	
Cr/Ti	2.73	17	
TiO_2/ZnO	2.74	29	Mo XIX (3d-4f) Ru XVIII (3d-4f)
Cr/Sc	3.12	32	
Cr/Sc	3.14	21	
Cr/Sc B_4C	3.15	32.1	Mo XXI (3d-4p) Pd XX (3d-4p)
Cr/Sc	3.35	10	Y XVII (3d-4f)
Cr/Sc	3.37	5.5	Y XXI (3d-4p) Nb XVI (3d-4f)

Peak wavelength and percentage reflectivity of different multilayer mirrors matched to UTA peaks from the present experimental data. (*R. Lokasani et al, J. Phys. B* ***48*** *(2015), 245009*)

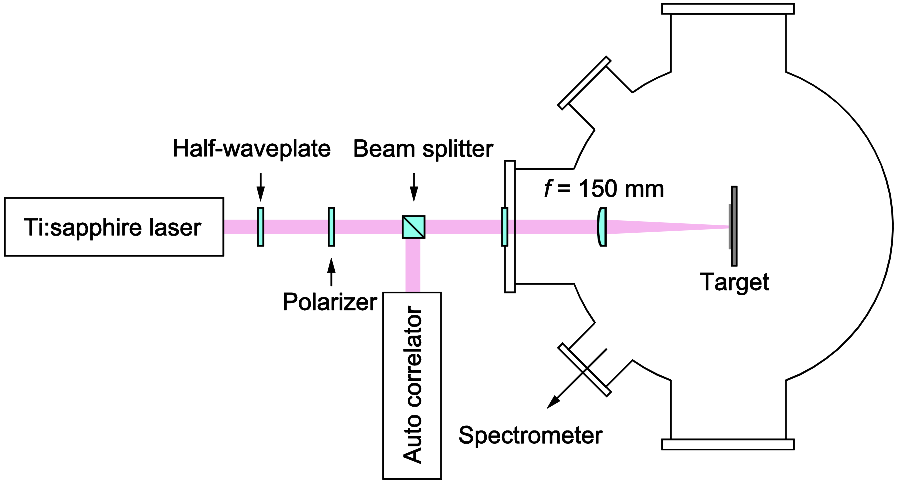
Section 2: femtosecond LPPs from 2nd row transition elements

femtosecond LPPs from 2nd row transition elements

Laser parameters

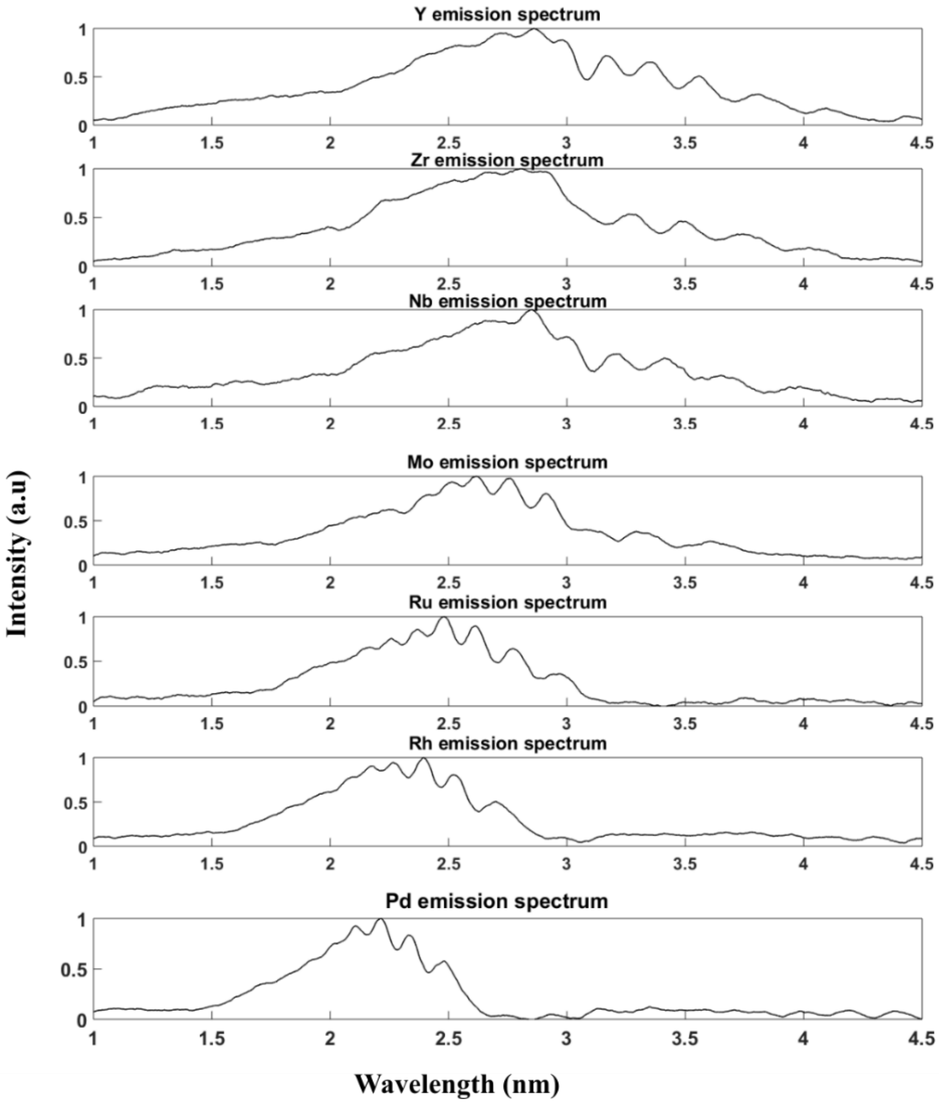
Czech Technical University in Prague

Parameter	fs laser
Maximum pulse energy (mJ)	≈ 10
Pulse length (fs)	≈ 65
Laser	Titanium-Sapphire laser
Wavelength	805 nm
Energy used in the experiment (mJ)	4.5



Schematic diagram of the experimental apparatus.

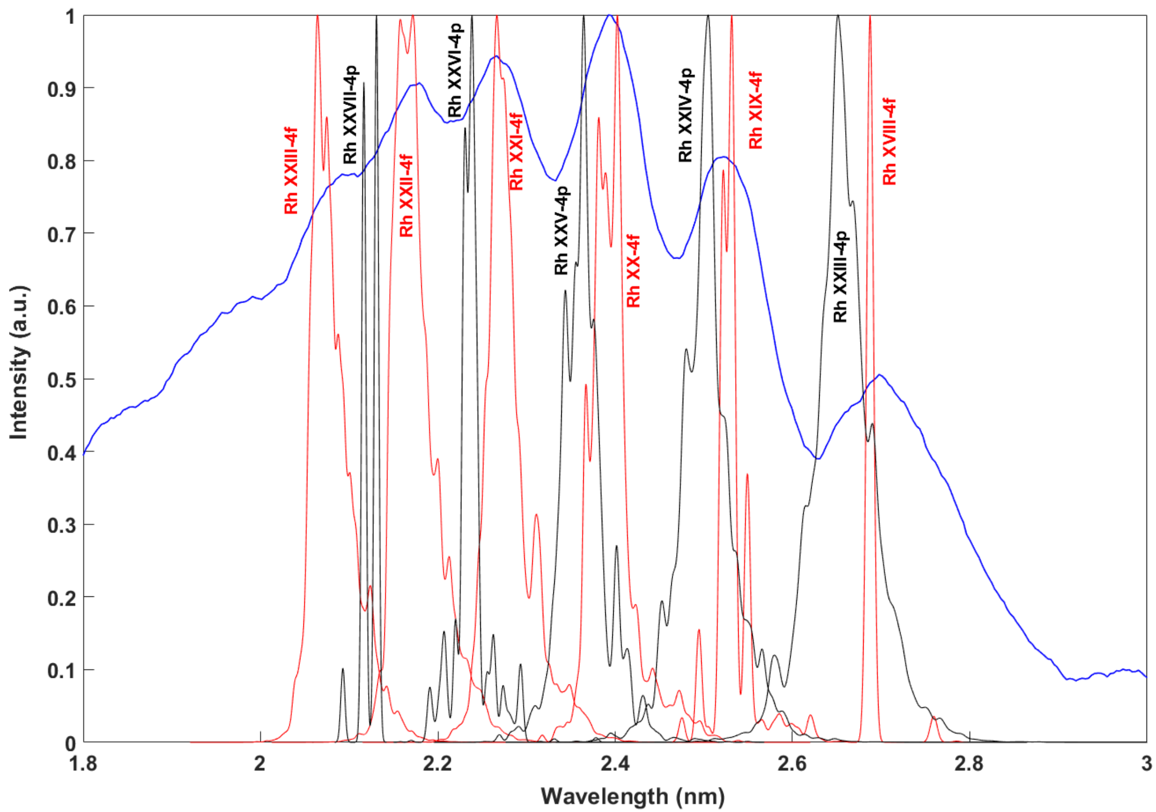
femtosecond LPPs from 2nd row transition elements



- Emission spectra of Y, Zr, Nb, Mo, Ru, Rh and Pd from plasmas produced by a femtosecond Titanium-Sapphire laser with a pulse width 65fs.

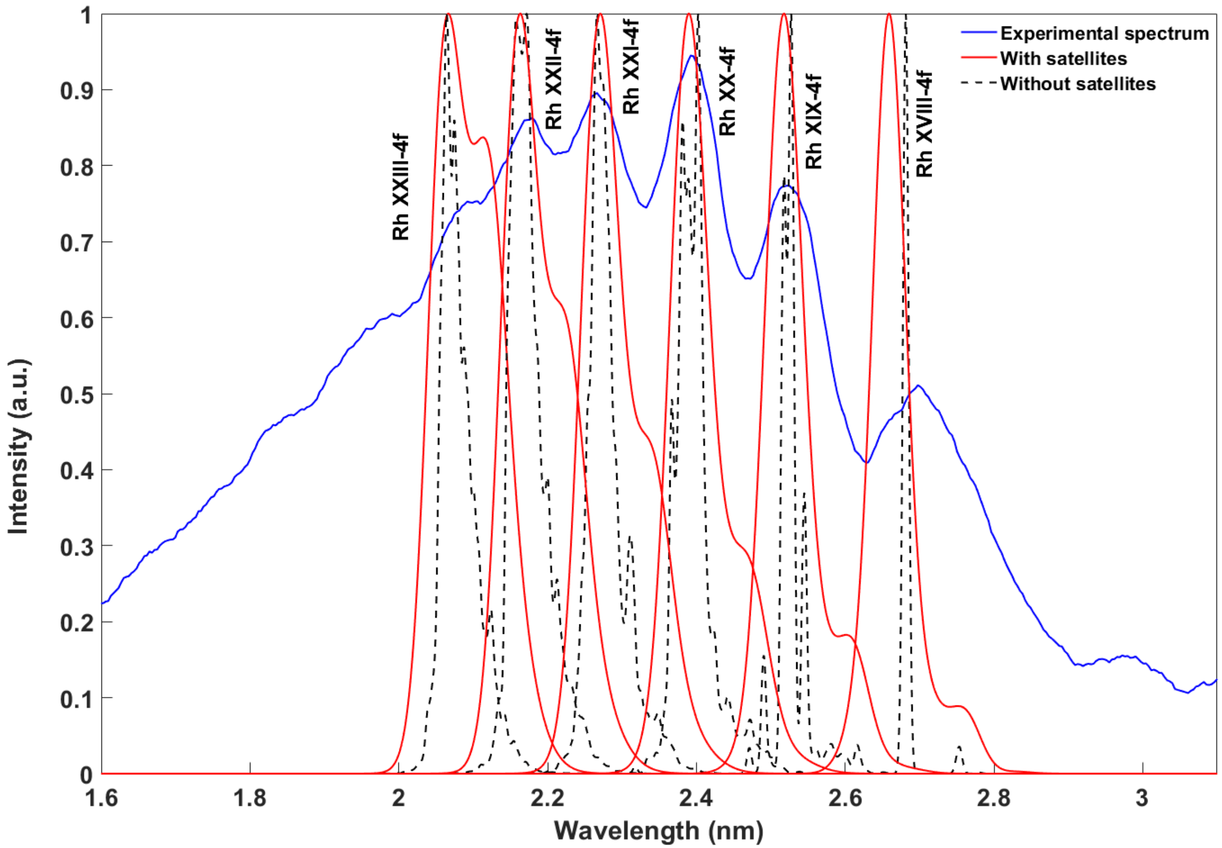
(*R. Lokasani et al, J. Phys. B* ***50*** *(2017)*,)

femtosecond LPPs from 2nd row transition elements



The experimental spectrum of Rh (blue) with synthetic spectra obtained from Cowan code calculations.

Rh spectra with satellites and with out satellites



- The measured emission spectrum (blue) from a Rh target with spectra calculated by the Cowan code with satellites (red solid lines) and without satellites (black dashed lines).
- Included satellites were $3d^{n-1}4s$-$3d^{n-2}4s4f$.

*(R. Lokasani et al. J. Phys. B **50** (2017),)*

Mean wavelengths and UTA widths (in nm) of 3d-4f transitions

Ion stage	Calculated mean wavelength (FAC)	Calculated UTA width (FAC)	Calculated mean wavelength (Cowan)	Calculated UTA width (Cowan)	Measured in present experiment	Measured in experiment [1]
	Ruthenium 3d-4f transitions					
Ru XVII	2.94	0.015	2.91[1]	0.01	2.92	2.92
Ru XVIII	2.76	0.025	2.74[1]	0.028	2.74	2.74
Ru XIX	2.60	0.029	2.59[1]	0.029	2.59	2.59
Ru XX	2.47	0.029	2.46[1]	0.029	2.46	2.46
Ru XXI	2.34	0.028	2.34	0.028	2.35	-
Ru XXII	2.24	0.026	2.23	0.026	2.24	-
Ru XXIII	2.14	0.023	2.13	0.024	2.14	-
	Rhodium 3d-4f transitions					
Rh XVIII	2.69	0.014	2.67[1]	0.013	2.69	2.68
Rh XIX	2.53	0.023	2.52[1]	0.025	2.52	2.53
Rh XX	2.40	0.026	2.39[1]	0.026	2.39	2.39
Rh XXI	2.29	0.026	2.27	0.026	2.26	-
Rh XXII	2.18	0.025	2.17	0.026	2.17	-
Rh XXIII	2.08	0.024	2.07	0.024	2.08	-
	Palladium 3d-4f transitions					
Pd XIX	2.48	0.013	2.46[1]	0.013	2.46	2.47
Pd XX	2.35	0.021	2.33[1]	0.022	2.34	2.34
Pd XXI	2.23	0.023	2.21	0.023	2.21	-
Pd XXII	2.12	0.024	2.11	0.024	2.1	-
Pd XXIII	2.03	0.023	2.02	0.023	2.01	-

- Mean wavelengths and UTA widths (in nm) of 3d-4f transitions in Ru, Rh and Pd ions calculated with the FAC and Cowan codes.

(1) (*R. Lokasani et al. J. Phys. B **48** (2015), 245009*)

Conclusions

- Identified 3d-4p, 3d-4f and 3p-3d transitions in 6 elements from LPP spectra.
- UTA statistical approach was applied for isoelectronic series of all elements.
- The focus was on $\Delta n=1$ 3d–4p and 3d–4f transitions, which are more intense in the LPPs created with ps pulses and appear at shorter wavelengths.
- Transitions in Mo indicate that it might be particularly suitable for use with TiO_2/ZnO and Cr/Sc B_4C MLMs with reflectance peaks at 2.74 and 3.15 nm, respectively.
- Transitions from higher ionization states are clearly demonstrated in the spectra emitted from Ru, Rh and Pd targets heated by the femtosecond laser.
- The use of low to moderate energy fs lasers as potential high brightness sources for XUV metrology, is a topic worthy of further study.

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