XUV Spectroscopy of Strontium Laser Produced Plasmas

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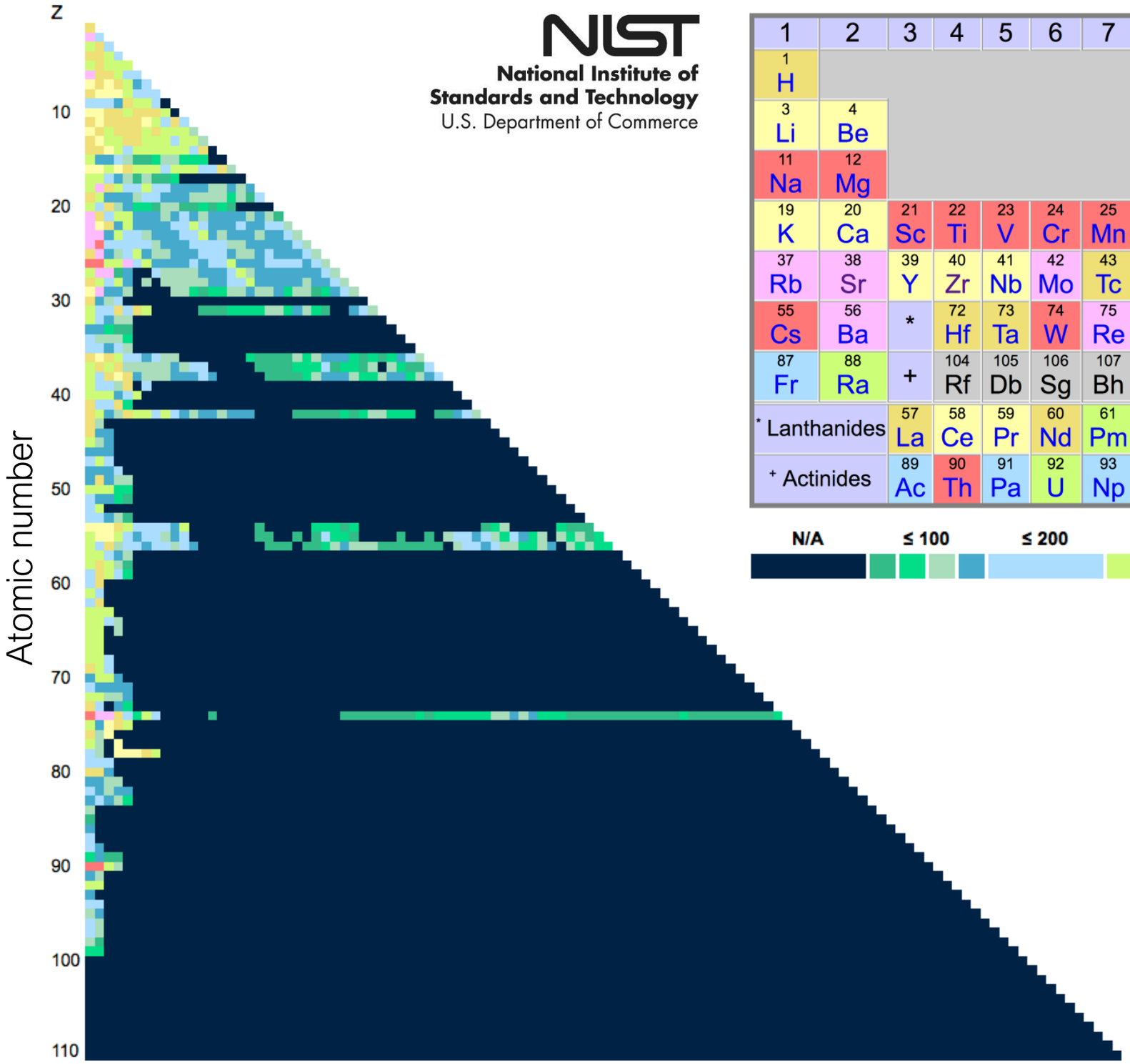
NIST Atomic Spectra Database - Line Holdings



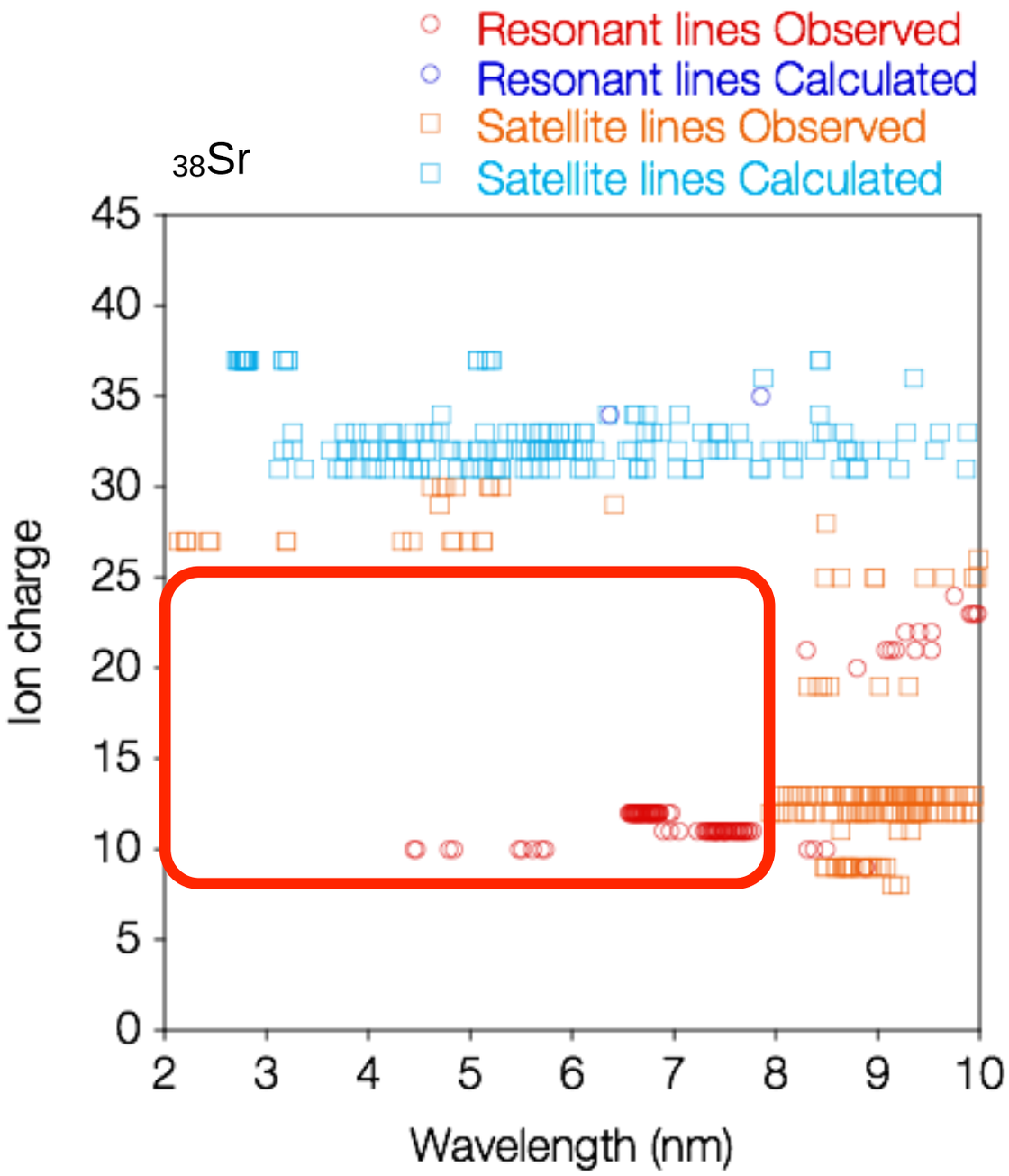
NIST
National Institute of Standards and Technology
U.S. Department of Commerce

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	+	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
* Lanthanides		57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
+ Actinides		89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

N/A | ≤ 100 | ≤ 200 | ≤ 500 | ≤ 1000 | ≤ 2000 | ≤ 5000 | > 5000

Reference : https://physics.nist.gov/cgi-bin/ASD/lines_pt.pl

For instance, Sr ions 8+ to 25+, 2 to 8 nm spectra are largely missing



Published line spectra of Sr ions from NIST at 30/04/2019

Sp. Name.	Ion Charge	El. name	Isoel. Seq.	Ground Shells [a]
Sr XI	+10	Strontium	Ni	[Ar]3d^{10}
Sr XII	+11	Strontium	Co	[Ar]3d^{9}
Sr XIII	+12	Strontium	Fe	[Ar]3d^{8}
Sr XIV	+13	Strontium	Mn	[Ar]3d^{7}
Sr XV	+14	Strontium	Cr	[Ar]3d^{6}
Sr XVI	+15	Strontium	V	
Sr XVII	+16	Strontium		
Sr XVIII	+17			[Ar]3d^{3}
Sr XIX				[Ar]3d^{2}
Sr XX			K	[Ar]3d
	+20	Strontium	Ar	[Ne]3$s^2$3p^6
	+21	Strontium	Cl	[Ne]3$s^2$3p^5
Sr XXIII	+22	Strontium	S	[Ne]3$s^2$3p^4
Sr XXIV	+23	Strontium	P	[Ne]3$s^2$3p^3
Sr XXV	+24	Strontium	Si	[Ne]3$s^2$3p^2
Sr XXVI	+25	Strontium	Al	[Ne]3$s^2$3p

Open 3d & 3p sub-shells

Reference : https://physics.nist.gov/cgi-bin/ASD/ie.pl

Some previous studies 4th row: Z = 39(Y) – 42(Mo)

IOP PUBLISHING JOURNAL OF PHYSICS B: ATOMIC, MOLECULAR AND OPTICAL PHYSICS

J. Phys. B: At. Mol. Opt. Phys. **45** (2012) 245004 (6pp) doi:10.1088/0953-4075/45/24/245004

XUV spectra of laser-produced zirconium plasmas

Bowen Li[1], Takeshi Higashiguchi[2], Takamitsu Otsuka[2], Weihua Jiang[3], Akira Endo[4], Padraig Dunne[1] and Gerry O'Sullivan[1]

APPLIED PHYSICS LETTERS **109**, 194103 (2016)

Soft X-ray emission from molybdenum plasmas generated by dual laser pulses

Ragava Lokasani,[1,2,a)] Goki Arai,[3] Yoshiki Kondo,[3] Hiroyuki Hara,[3] Thanh-Hung Dinh,[3,4] Takeo Ejima,[5] Tadashi Hatano,[5] Weihua Jiang,[6] Tetsuya Makimura,[7] Bowen Li,[8] Padraig Dunne,[2] Gerry O'Sullivan,[2] Takeshi Higashiguchi,[3,9,b)] and Jiri Limpouch[1]

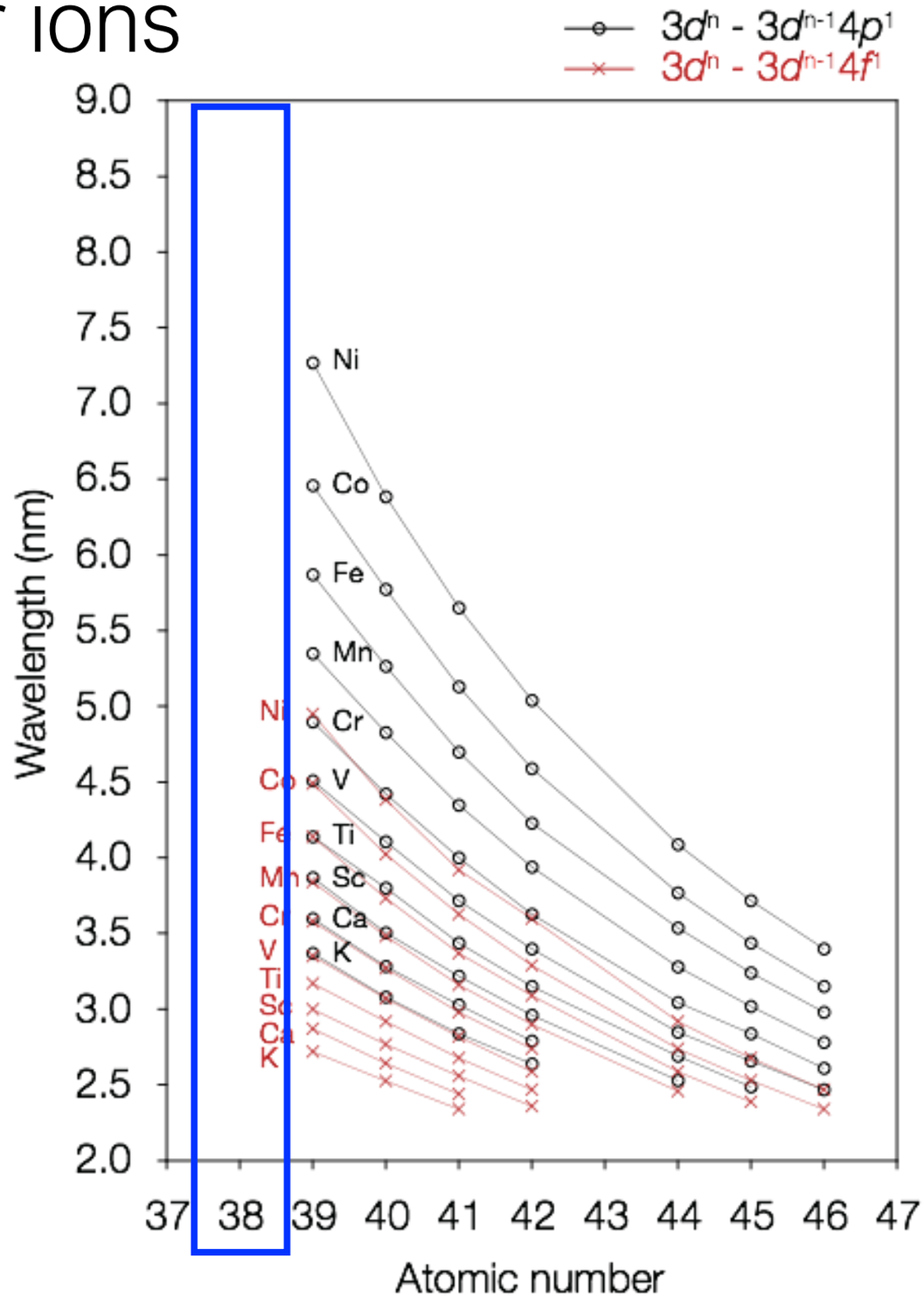
IOP Publishing Journal of Physics B: Atomic, Molecular and Optical Physics

J. Phys. B: At. Mol. Opt. Phys. **48** (2015) 245009 (12pp) doi:10.1088/0953-4075/48/24/245009

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

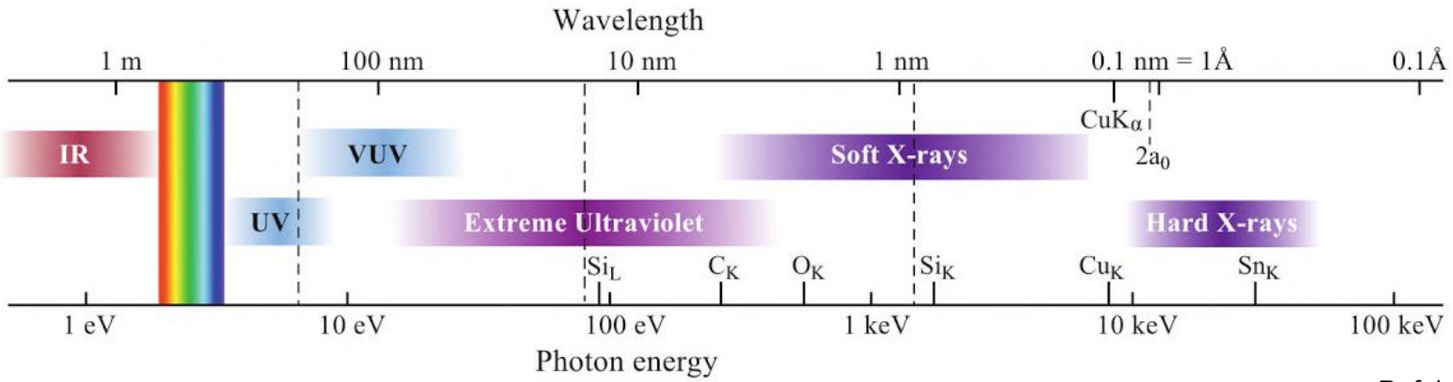
Ragava Lokasani[1,2], Elaine Long[2], Oisin Maguire[2], Paul Sheridan[2], Patrick Hayden[2], Fergal O'Reilly[2], Padraig Dunne[2], Emma Sokell[2], Akira Endo[3], Jiri Limpouch[1] and Gerry O'Sullivan[2]

High possibility of resonant transitions from open 3*d* sub-shells of Sr ions



Reference :
E. Alexander, *et. al.* 1971 *J. Opt.Soc. Am.* **61** 4 508-514
R. Lokasani, *et. al.* 2015 *J. Phys. B: At. Mol. Opt. Phys.* **48** 245009
B. Li *et. al.* 2012 *J. Phys. B: At. Mol. Opt. Phys.* **43** 245004

Iso electronic sequence of published mean unresolved transition array (UTA) peak



Ref.1

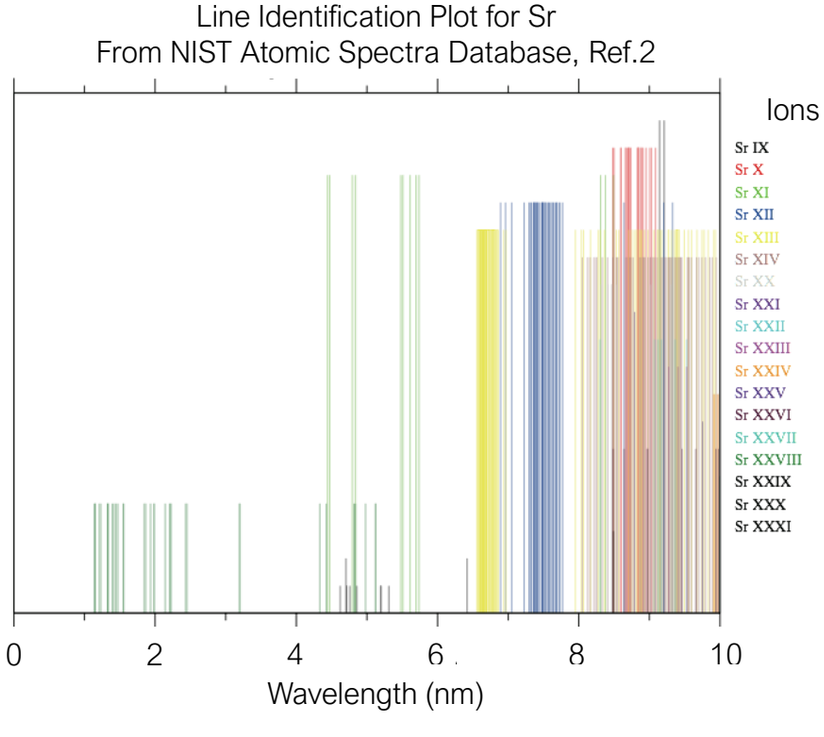
Application

EUV lithography 13.5 nm
Beyond EUV 6.x nm
Water Window 2.3 to 4.4 nm

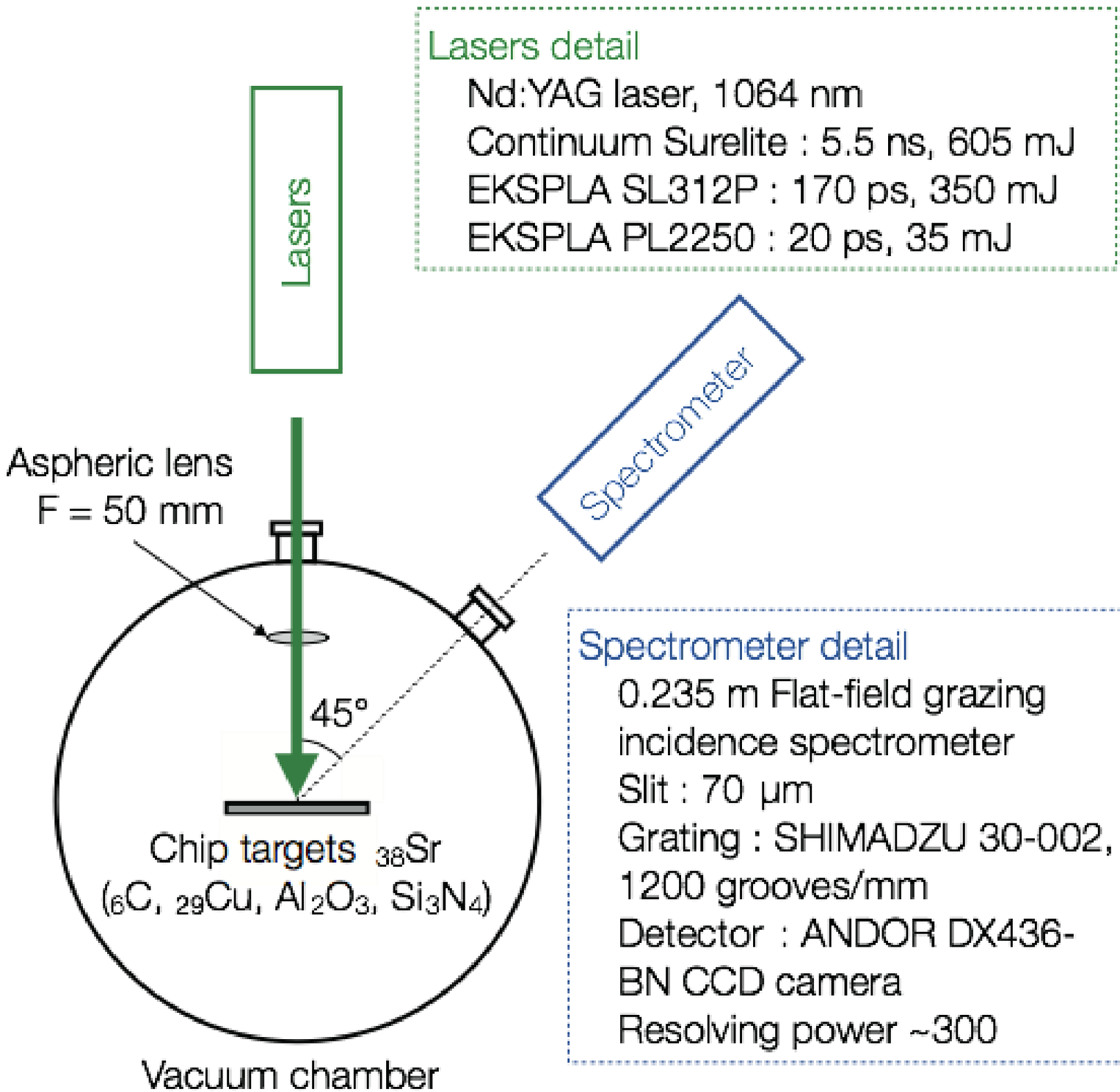
Extreme Ultraviolet and Soft X-ray Spectroscopy of Strontium Laser-Produced Plasmas

Observed Data are Largely missing or Incomplete

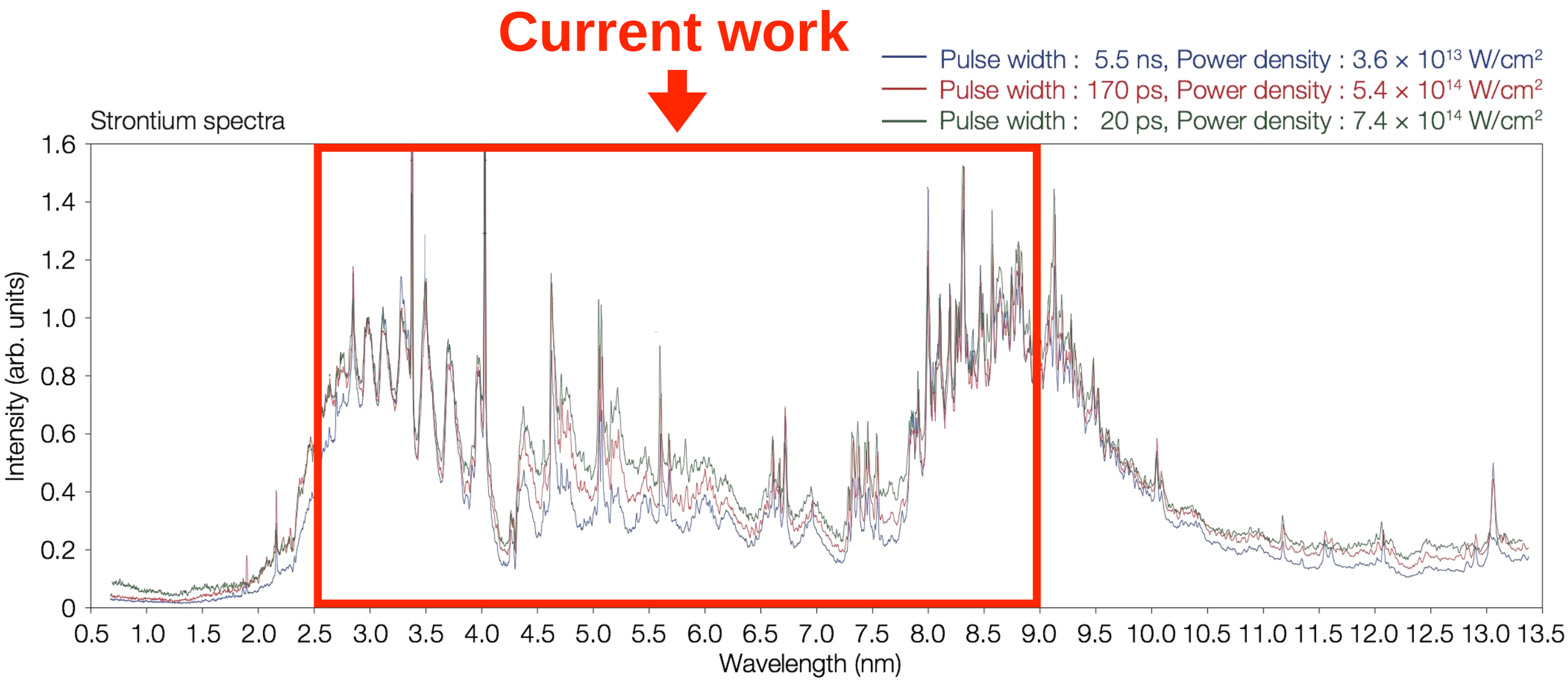
Ion charge : 8+ to 25+
(Covering open 3*p*, 3*d* sub-shells)
Ionization Energy : 158 to 1211 eV



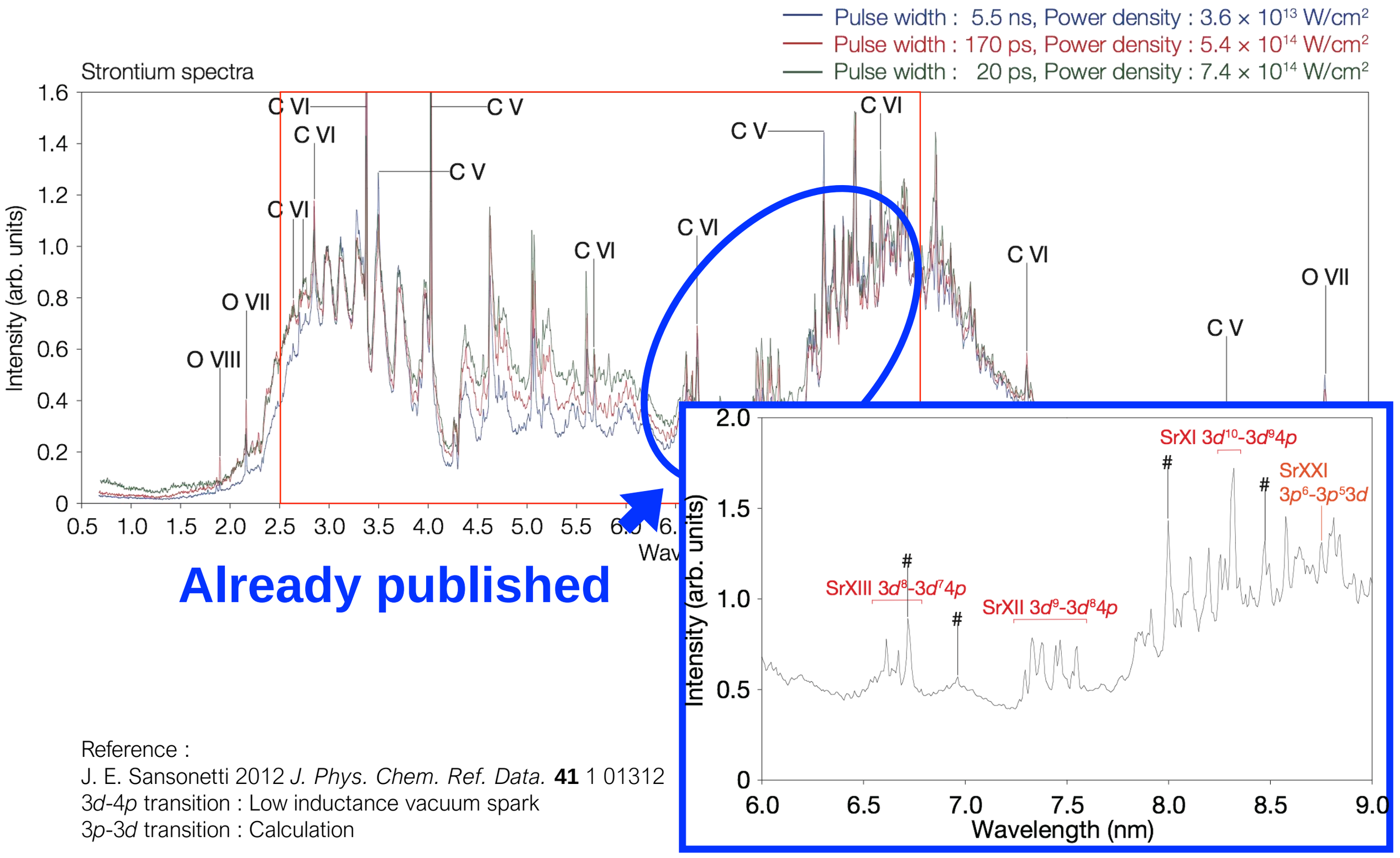
Experimental apparatus of LPP



Typical LPP strontium spectra



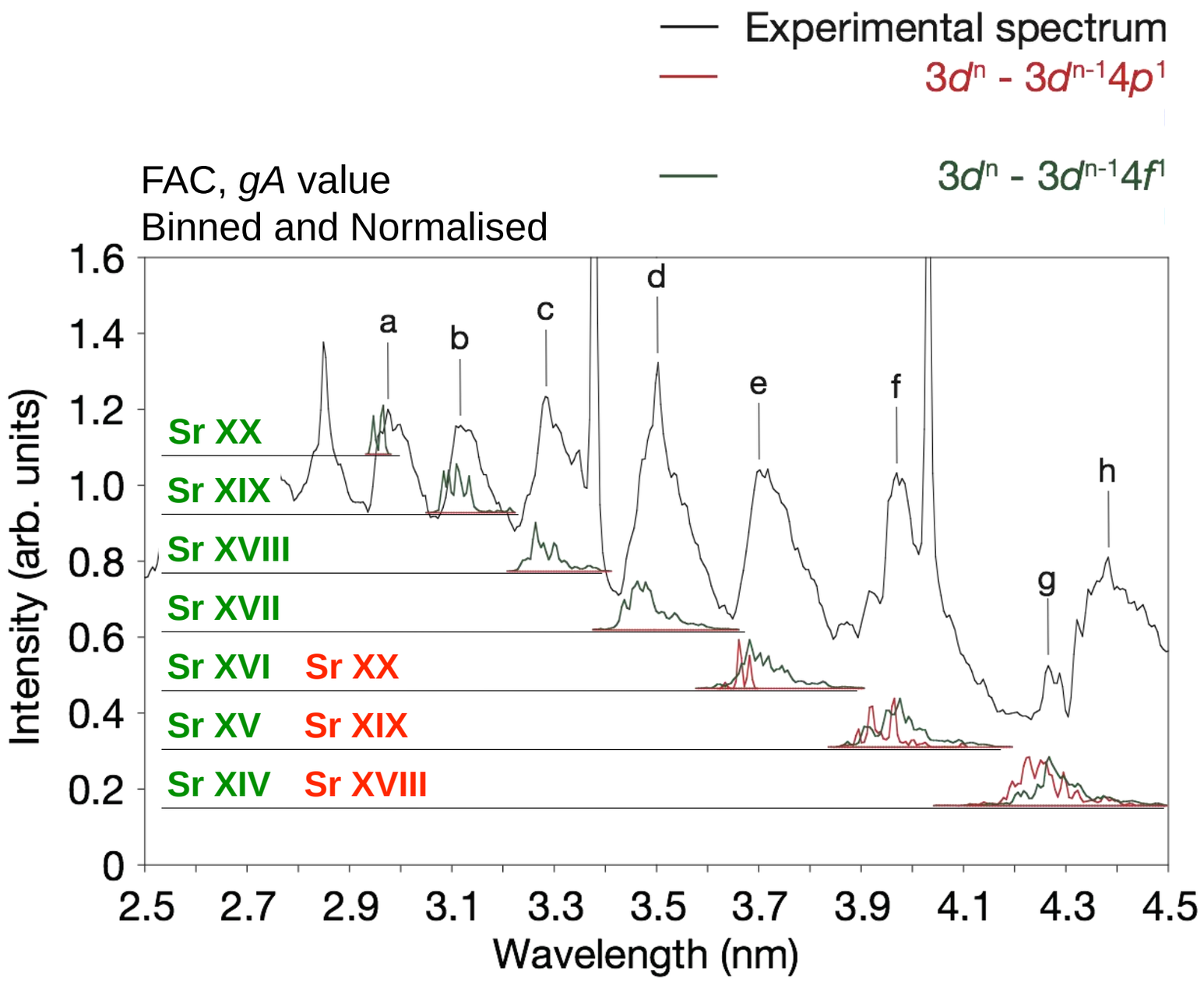
Typical LPP strontium spectra



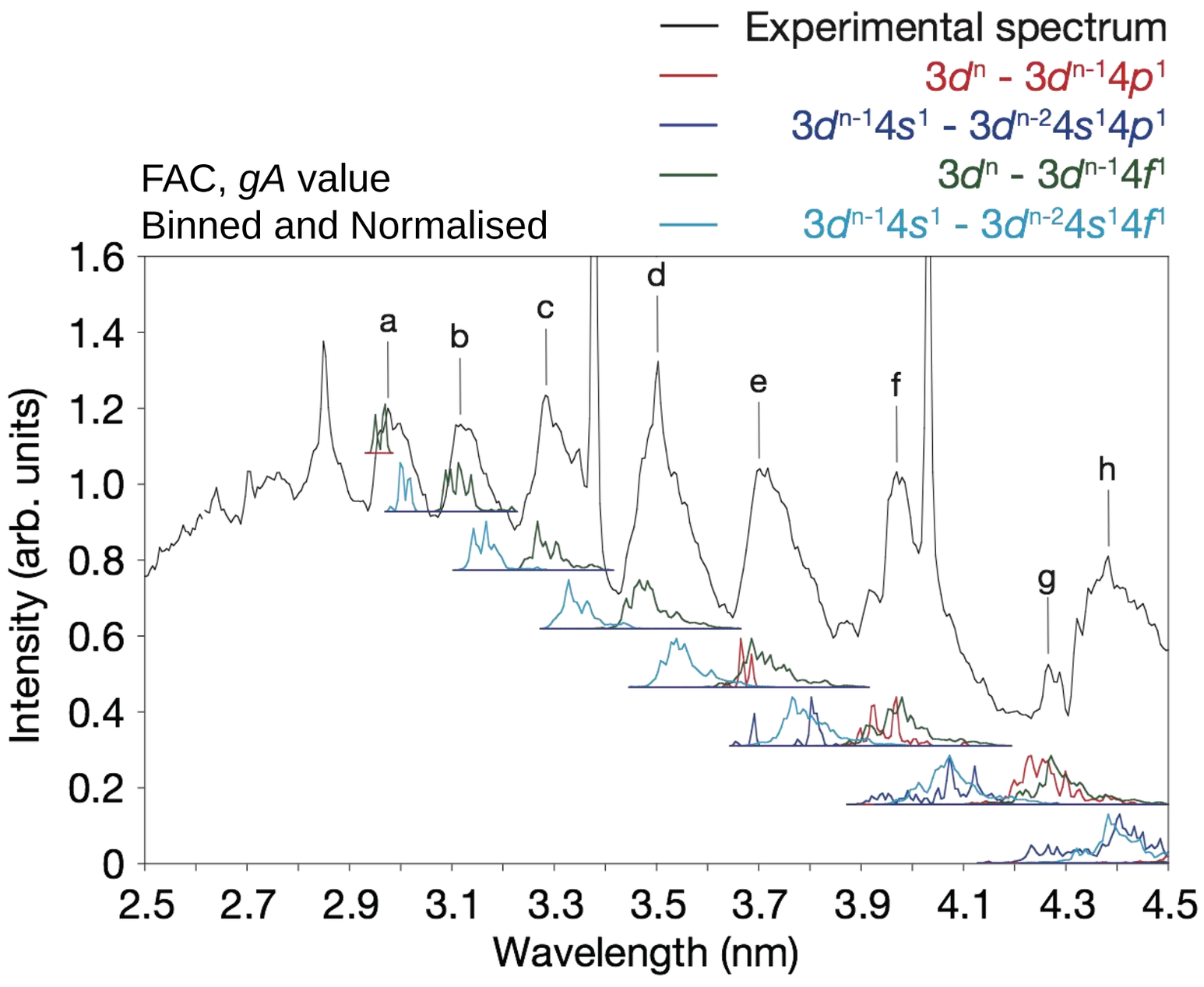
Already published

Reference :
J. E. Sansonetti 2012 *J. Phys. Chem. Ref. Data.* **41** 1 01312
3*d*-4*p* transition : Low inductance vacuum spark
3*p*-3*d* transition : Calculation

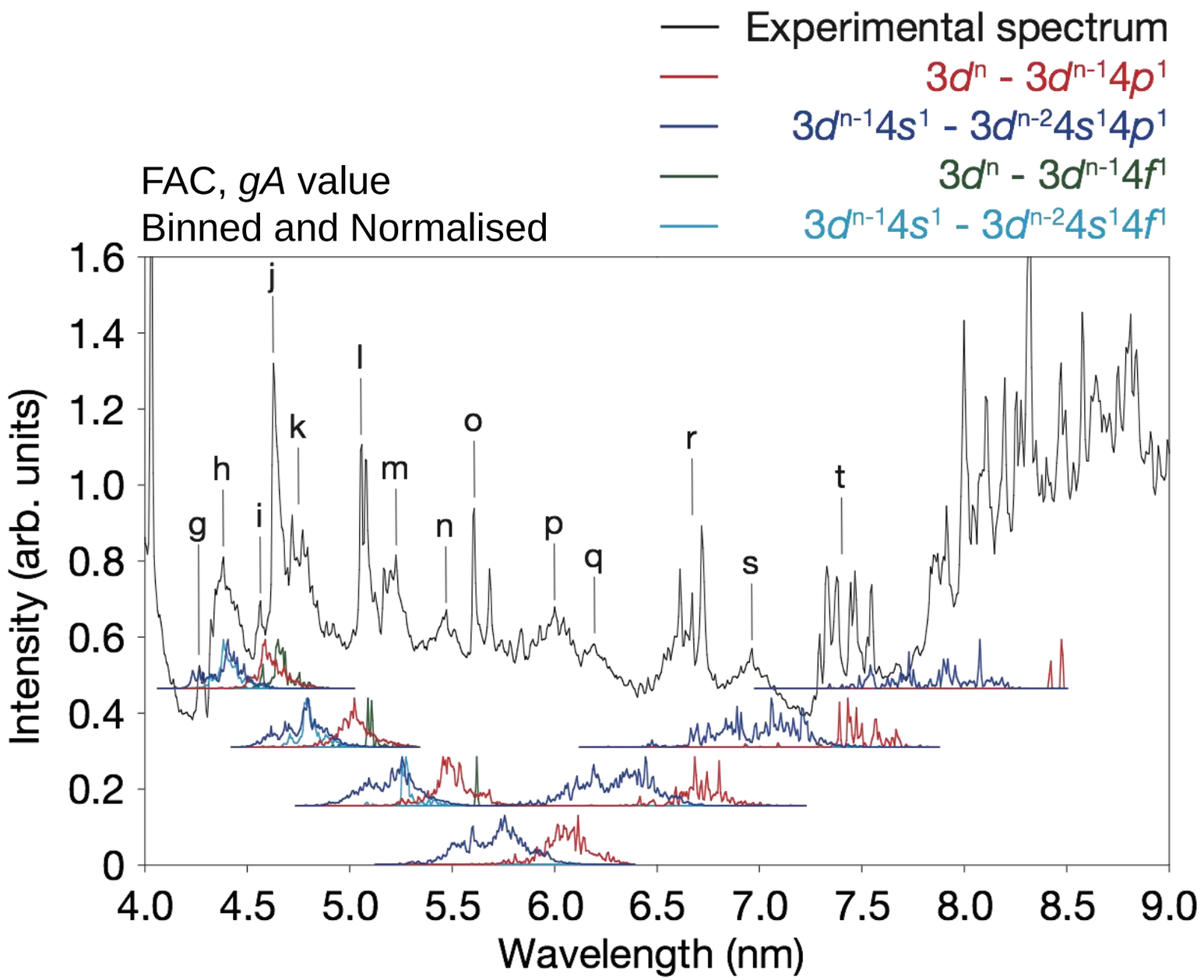
$3d^n$ - $3d^{n-1}4p$, - $3d^{n-1}4f$ resonant transitions (2.5 to 4.5 nm region)



Peaks **a** to **f** are blended resonant and satellite lines

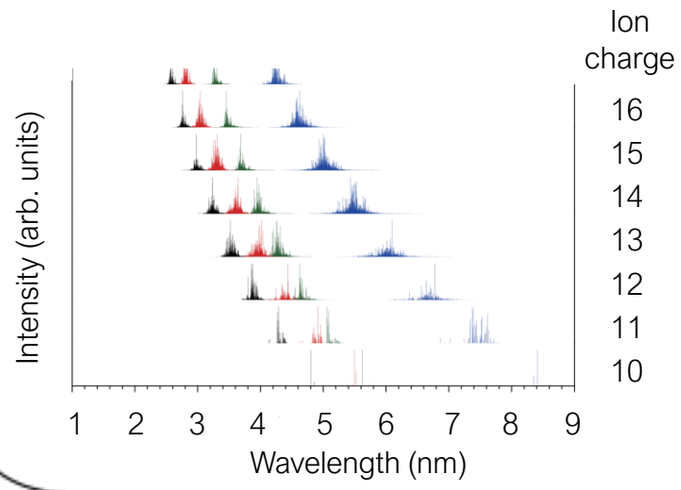


Resonant and satellite lines in the 4.0 to 9.0 nm region form separate peaks



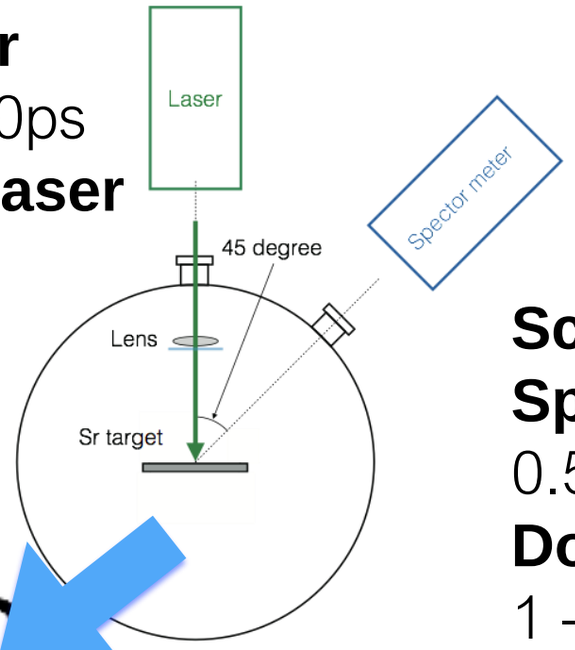
Simulation in UCD

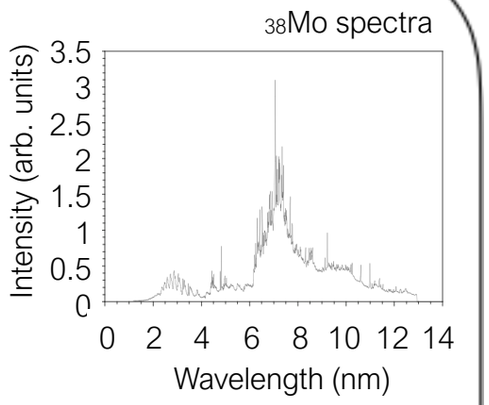
Cowan atomic structure code
FAC (Flexible Atomic Code)
GRASP (General Purpose Relativistic Atomic Structure Package)



LPP experiment in UCD

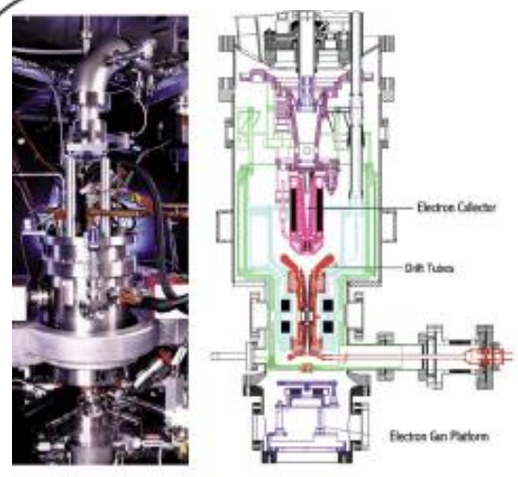
Nd:YAG laser
7ns, 170ps, 20ps
Ti:Sapphire laser
38 fs
CO_2 laser
50 - 200 ns

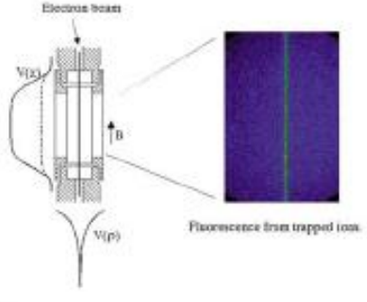




Schwob Fraenkel Spectrometer
0.5 - 36 nm
Double grating
1 - 8 nm
1 - 20 nm

New Sr data

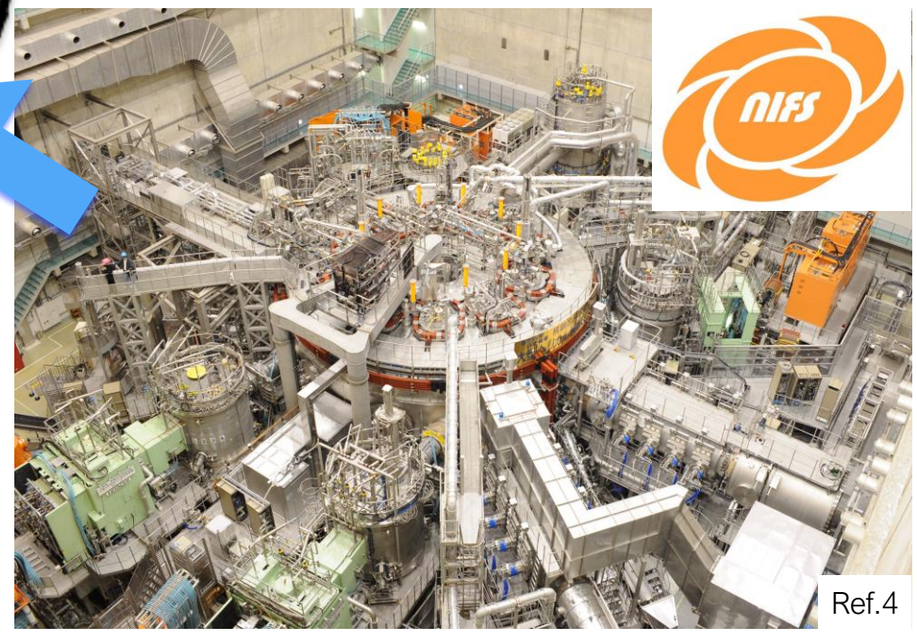




Ref.3

EBIT (Electron Beam Ion Trap)
in NIST, **USA**
with Dr. Yuri Ralchenko

NIST
National Institute of Standards and Technology
U.S. Department of Commerce

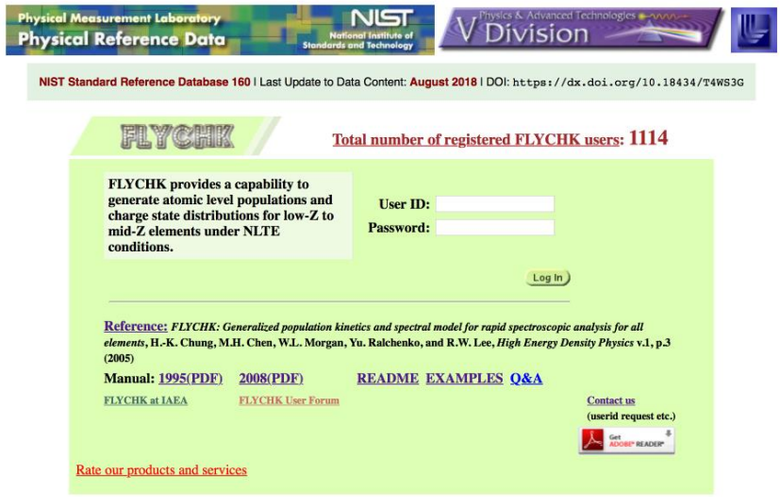


Ref.4

LHD (Large Helical Device)
in NIFS, **Japan**
with Dr. Chihiro Suzuki

Future work: Study the discrepancy between predictions of CR model and experimental populations

FLYCHK code (NIST)

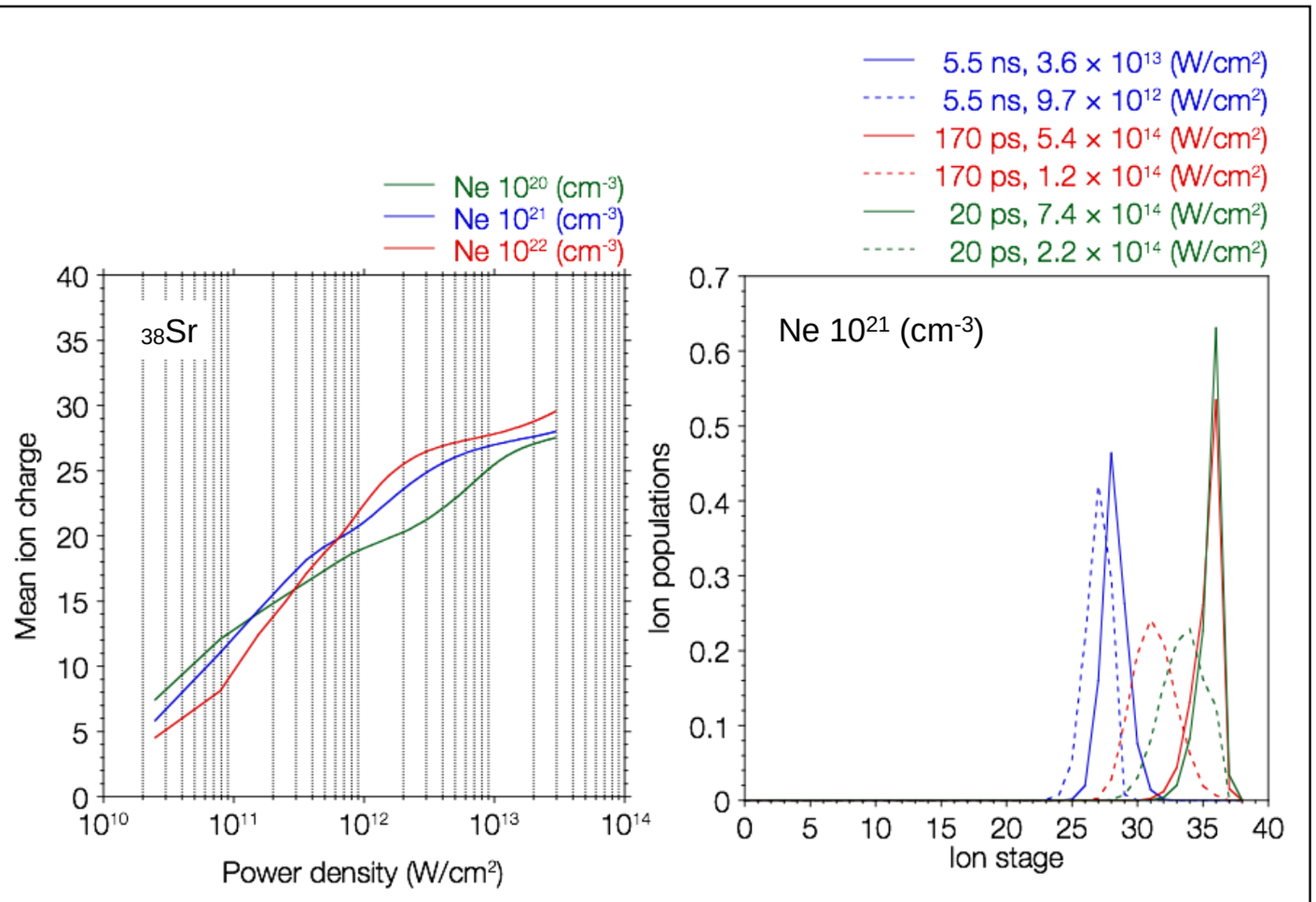


Reference : https://nlte.nist.gov/FLY/

Radiative Deflagration model & Collisional Radiative (CR) model

T (eV) ≈ $5.2 \times 10^{-6}\, A^{1/5}\, (\lambda^2 \Phi^{3/5})$

T : Plasma temperature
A : Atomic number
λ : Laser wavelength
Φ : Laser power density



Influenced by the radius of plasma?

➡ **LPP with fine control laser power density by 5.5 ns, 170 ps & 20 ps Nd:YAG lasers**

Latest:

Soft x-ray emission from laser-produced strontium ions

Takanori Miyazaki, Gerry O'Sullivan and Padraig Dunne
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E-mail: takanori.miyazaki@ucdconnect.ie

May 2019

Abstract. Soft x-ray spectra, in the range from 2 nm to 9 nm, were recorded from strontium plasmas formed by pulses from 20 ps, 170 ps and 5.5 ns Nd:YAG lasers operating at the fundamental wavelength of 1064 nm. Features due to $3d$ - $4p$ and $3d$ - $4f$ transitions were identified by comparison with spectra from adjacent ions and atomic structure calculations with both the Cowan code and the Flexible Atomic Code (FAC). As in the spectra of ions of other elements in the fifth row of the periodic table, resonant lines $3d^n$ - $3d^{n-1}4p^1$, $3d^n$ - $3d^{n-1}4f^1$ and satellite lines $3d^{n-1}4s^1$ - $3d^{n-2}4s^14p^1$, $3d^{n-1}4s^1$ - $3d^{n-2}4s^14f^1$ of $\Delta n = 1$ were observed over the 3.0 nm to 8.5 nm region, emitted by 10+ to 19+ ions. These $\Delta n = 1$ transitions provide a range of narrow band emission features which may match to specific multi layer combinations for reflective

Reference

1. D. Attwood, "*SOFT X-RAYS AND EXTREME ULTRAVIOLET RADIATION Second edition*", Cambridge University Press, P2, Fig.1.1 (2016).
2. NIST Atomic Spectra Database, Line Identification Plot. https://physics.nist.gov/PhysRefData/ASD/lines_form.html.
3. J. D. Gillaspy, "Highly charged ions", J. Phys. B: At. Mol. Opt. Phys. 34, R93-R130 (2001).
4. NIFS Web, LHD photo. http://www.lhd.nifs.ac.jp/lhd/image/LHD_11th_cycle.jpg

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