Exploring Light Elements in Steel via LIBS in the Vacuum-UV (VUV)

John T. Costello
School of Physical Sciences & NCPST, DCU

IFATI4, Tokushima University, Japan, Nov 8, 2021.

Talk Outline

DCU
Ollscoil Chathair
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- DCU Laser Plasma & AMO group
- LIBS – Some History
- Why LIBS?
- Why LIBS in the VUV?
- VUV LIBS Experimental setup at DCU
- Single Pulse VUV LIBS Experiments on Steel (2000s)
- Double Pulse VUV LIBS Experiments on Steel (2010s)
- Some Recent VUV LIBS Results on Steel
- Current LIBS Focus and Future Further Developments

LP & AMO Physics Group at DCU (PIs)

Ollscoil Chathair Bhaile Átha Cliath
Dublin City University

John Costello (LP Spectroscopy & Free Electron Lasers)

Emr. Eugene Kennedy (LP Spectroscopy & Synchrotrons)

Jean-Paul Mosnier (Synchrotrons)

Lampros Nikolopoulos (AMO Theory)

Paul van Kampen (Physics Education/Synchrotrons)

Current Postdoctoral and PhD students:
Lazaros Varvarezos, James Campbell, Séamus Cummins, Stephen Durkan, Andrew Foremski, Ross McGarry, Adam Prior and Sadaf Syedah Zehra.

Recent PhD Graduates:
2021: Muhammad Bilal Alli, Hu Lu & Tejaswi Katravulapally
2020: Ben Delaney, Stephen Davitt & Lazaros Varvarezos,

Why Light Elements? e.g., Carbon in Steel…

Carbon steel is an iron- carbon alloy contains 0.005 to 2.1 wt.% carbon

Low Carbon steel (0.005-0.25 wt.%) - **Low strength, high ductility -** Applications automobile body components, structural shapes (I-beams, channel and angle iron), pipes, construction and bridge components, and **food cans**.

Medium carbon steel (0.25 – 0.60 wt.%) - **Medium strength and ductility** - Applications **railway tracks**, train wheels, crankshafts, and gears and machinery parts requiring this combination of properties.

High carbon steel (0.60– 1.25 wt.%) - **High strength , low ductility**, Applications Due to their high wear-resistance and hardness, high-carbon steels are used in **cutting tools**, springs high strength wire and dies.

LP & AMO Physics Group at DCU (PIs)

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Current (Ex-LIBS) Projects:

1. Photoionization of Atoms and Molecules in EUV FEL Fields
2. Ultrafast Optical Pump – EUV Probes of Atoms and Molecules
3. VUV & EUV Photoabsorption via the Dual Laser Plasma Technique
4. Photoionization of Small Molecular Ions at Synchrotrons
5. Development of an Ultrafast Laser Spectroscopy Laboratory

References

1. ***Near-Threshold Two-Photon Double Ionization of Kr in the Vacuum Ultraviolet***, L Varvarezos et al , *Physical Review A* **103** Art. No. 022832 (2021)
2. ***Clocking Auger electrons***, D C Haynes et al, Nature Physics **17** pp.512–518 (2021)
3. ***The 5d → 6p EUV photoabsorption spectra of Pb II and Bi III: evidence of excited states***, H Lu, L Varvarezos, M Bilal Alli, P Nicolosi, J T Costello and P Hayden, *J. Phys. B: At. Mol. Opt. Phys.* **53** 115001 (2020)
4. ***Evolution of L-shell photoabsorption of the molecular-ion series SiH^{n+} (n=1,2,3): Experimental and theoretical studies***, E T Kennedy *et al* P*hys, Rev. A* 2018 **97** 043410
5. https://www.dcu.ie/research/ultrafast-spectroscopy / http://uf-dynamics.org

LIBS – Some History

The first years of laser-induced breakdown spectroscopy, M Baudelet and B W Smith, J. Anal. At. Spectrom. 28, pp624-629 (2013)

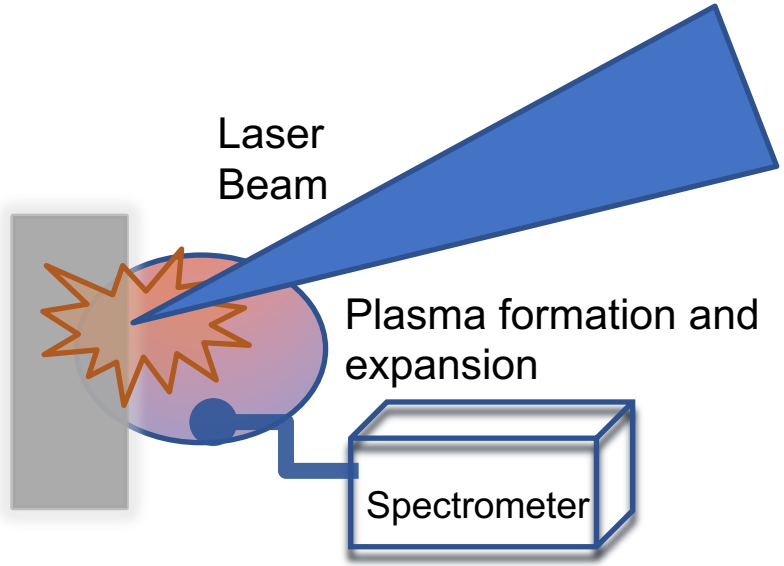

Fig 1. Basic LIBS configuration.

First (Early) LIBS elemental analysis reference:
J Debras-Guédon et al. 1963 C. R. Acad. Sci. **257** p3336.

Le laser: Source d'excitation des spectres pour l'analyse qualitative et quantitative par spectrographie

Par J. Debras-Guedon, N. Liodec et J. Vilnat, Société Française de Céramique, Paris, France

En concentrant au moyen d'une lentille le faisceau monochromatique (6943 Å) de forte énergie, issu d'un «laser» à rubis, sur des cibles de diverses natures et compositions, avec une durée de contact de l'ordre de 100 μsec, on obtient non seulement une volatilisation locale de l'échantillon mais également une émission de photons. En recevant ces photons sur la fente d'un spectrographe, on a pu enregistrer des spectres de raies très complets dans lesquels on a même pu observer des raies d'atome ionisé (potentiel d'excitation 18 ev).

Dans certains cas, on a également obtenu des spectres de bandes moléculaires (CN, CO, Al.0)[1]).

Ce type d'excitation convient particulièrement pour l'analyse ponctuelle, étant donné les très faibles dimensions de l'impact.

Avec une quantité minime de matière, on obtient grâce à la lecture des spectres enregistrés, un nombre considérable de renseignements sur la composition de celle-ci. La zone spectrale habituellement masquée par les bandes de cyanogène (dues à la combinaison de l'azote de l'air avec le carbone des électrodes, utilisées généralement pour l'excitation des spectres) se trouve dégagée. De plus, du fait de la non utilisation d'électrodes, aucune contamination n'est à craindre. On a pu ainsi identifier des taches de très petites dimensions sur des plaquettes émaillées. Des pointés effectués à différents endroits d'un échantillon permettent de tester son homogénéité.

On a montré également tout récemment qu'il était possible d'obtenir des résultats analytiques quantitatifs. On a ainsi dosé dans des aciers, du chrome à des teneurs comprises entre 0,02 et 1%, la précision obtenue permet de donner, par exemple: 0,91% ± 0,04.

Ces essais ont été effectués avec un «laser» du Laboratoire Central des Télécommunications, et l'aide technique de MM. Pauthier et Frichot, de ce laboratoire.

LIBS – Some History

The first years of laser-induced breakdown spectroscopy, M Baudelet and B W Smith, J. Anal. At. Spectrom. 28, pp624-629 (2013)

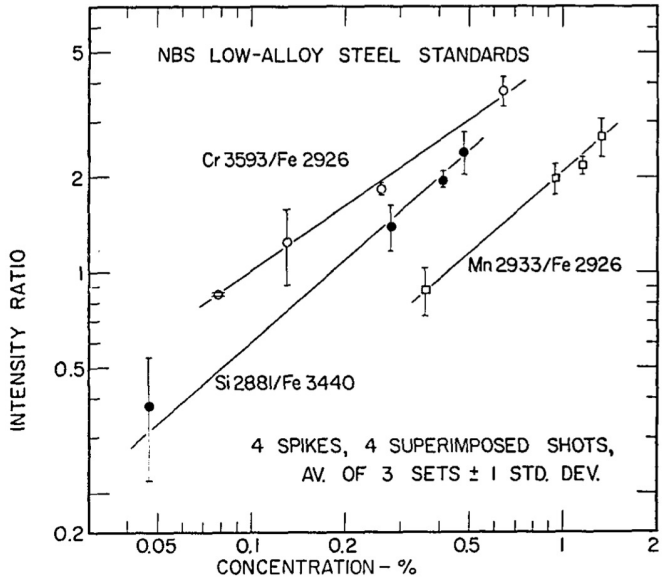

Fig. 8. Typical analytical curves with four-spike laser vaporization and spark excitation.

Laser Probe Excitation in Spectrochemical Analysis 11: Investigation of Quantitative Aspects, S D Rasberry, B F Scribner and M Margoshes, APPLIED OPTICS **6**, pp87-93 (January 1967)

First (Early) LIBS elemental analysis reference:
J Debras-Guédon et al. 1963 C. R. Acad. Sci. **257** p3336.

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Ces essais ont été effectués avec un «laser» du Laboratoire Central des Télécommunications, et l'aide technique de MM. Pauthier et Frichot, de ce laboratoire.

LIBS – Some History: Growth in papers since 1980s

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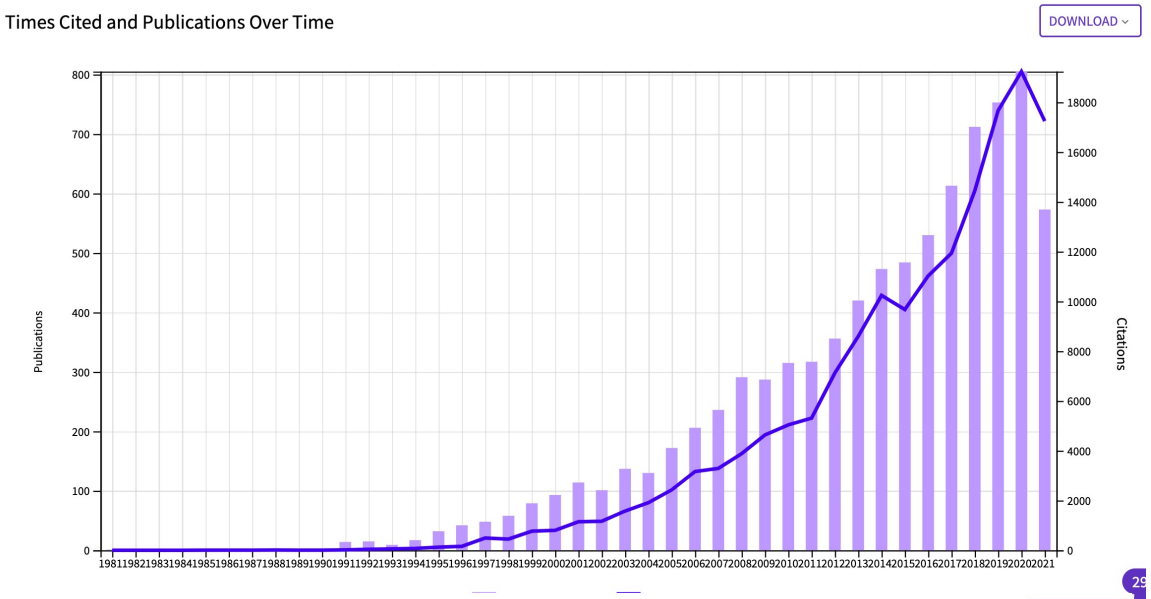
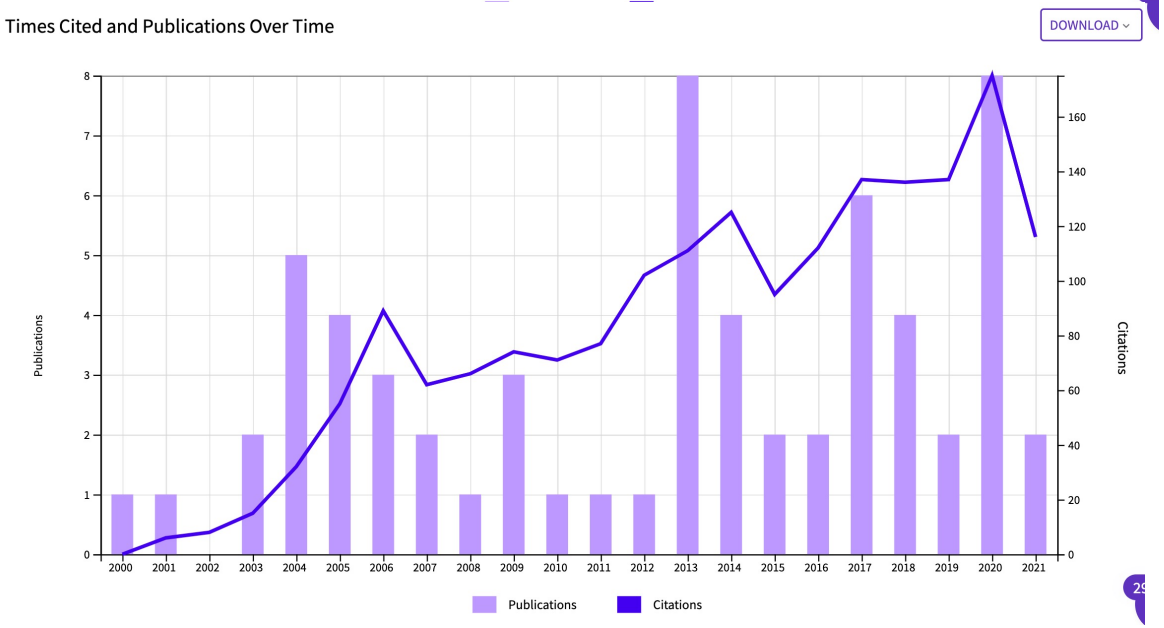
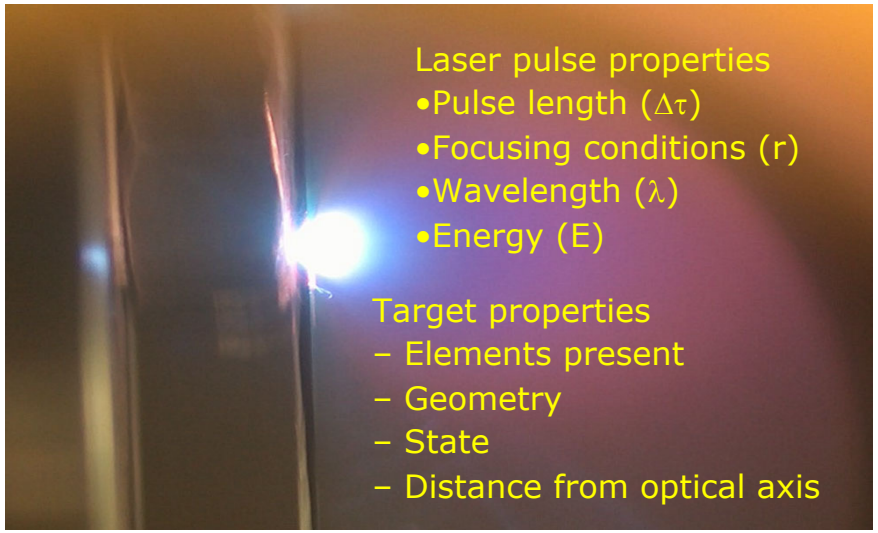




Source: Clarivate Web of Science

Search Phrase:
Laser Induced Breakdown Spectroscopy



Search Phrase:
LIBS and VUV

Why LIBS?

- Simple principle underlying a potentially powerful analytical technique: Spectral line wavelength acts as the identifying fingerprint of an element (classification) and the same spectral line intensity acts as a proxy for concentration determination

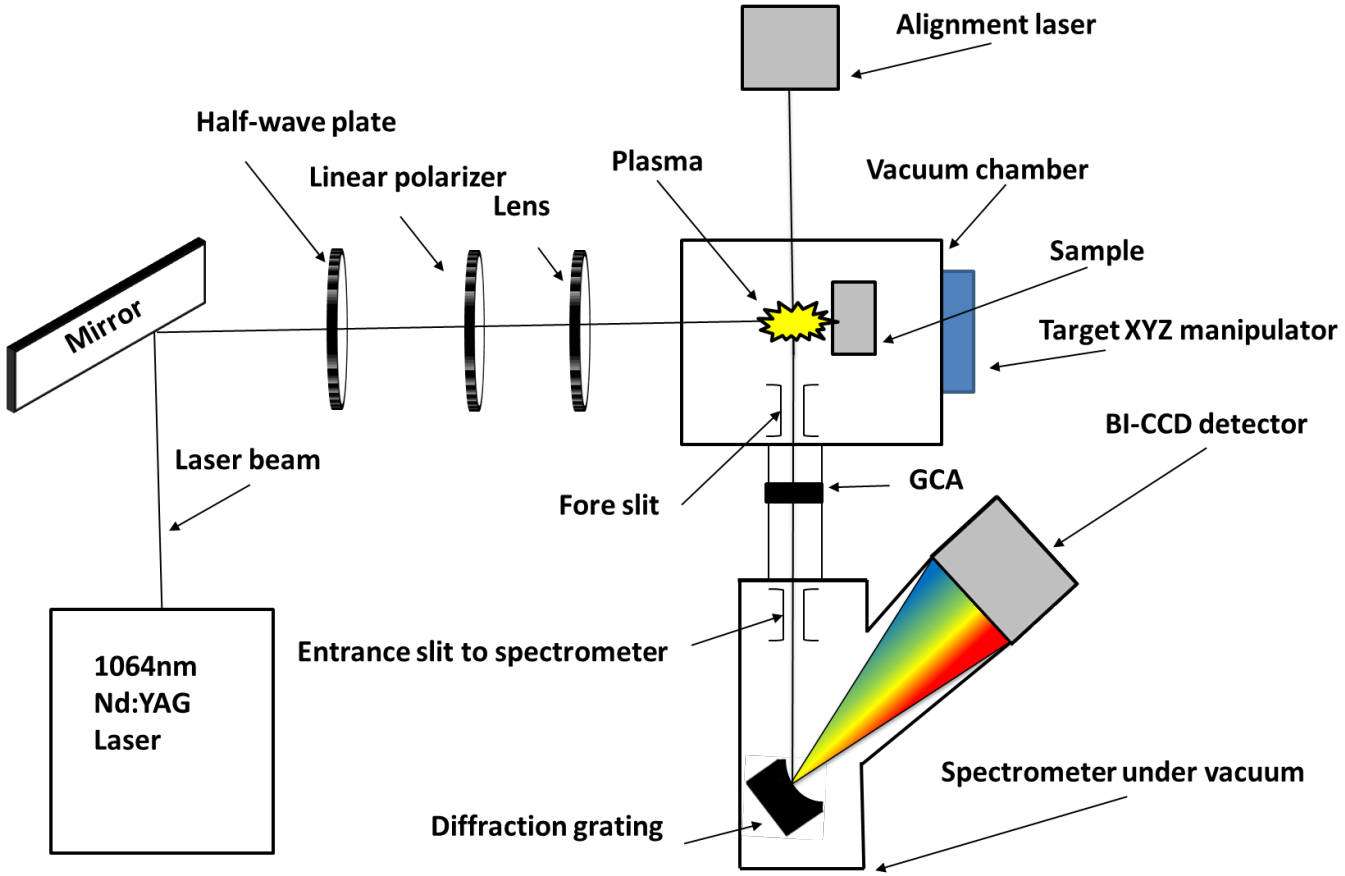
- Samples need little or no preparation, thereby removing the risk of contamination or loss of analyte associated with a preparation process

- LIBS can be made minimally ablative, so a negligible amount of the sample is destroyed

- Samples can be in any phase: Solid, liquid or gas, they can be conductors, semiconductors, or insulators

D A Cremers and L J Radziemski. ***Handbook of laser-induced breakdown spectroscopy***. John Wiley & Sons (2013)

Why LIBS?



- Simple and economical experimental setup
- Highly flexible – laser can be directed toward/focused on remote targets or targets in extreme or hazardous environments
- Easy plasma light collection (mirrors, lenses & fibers)

D A Cremers and L J Radziemski. ***Handbook of laser-induced breakdown spectroscopy***. John Wiley & Sons (2013)

Why LIBS in the VUV?

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REMINDER.

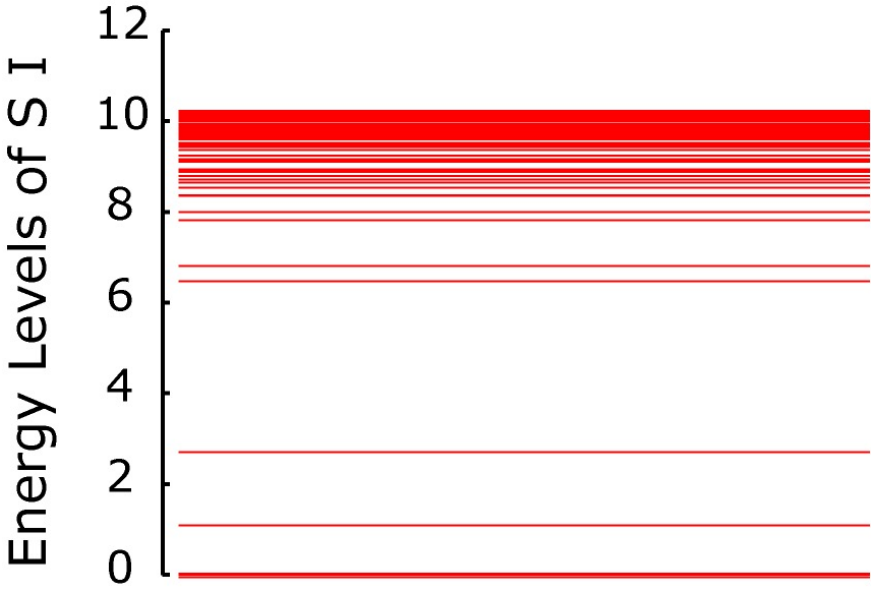
- ***Qualitative analysis***: *Each element (and ion-stage)* in a sample *produces a unique spectral signature*, hence elements present in the target material can be identified
- ***Quantitative analysis:*** Elemental concentrations can (with effort) be determined from the intensity of spectral lines

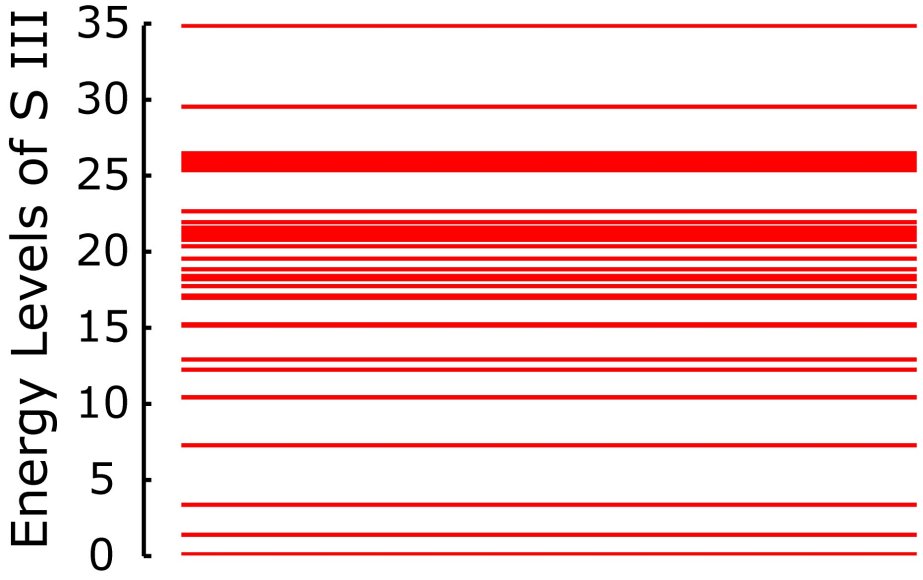
But why work in the (awkward) VUV spectral range?

1. The spacing between spectral lines in the VUV region is significantly larger compared to the visible and infrared regions. As result the spectra are less cluttered with more distinct, and easier to select, spectral lines

2. Working in the VUV allows access to an abundance of resonance (connected to the ground state) transitions in atoms and ions at which are, in general, stronger than transitions between excited states. Hence one obtains spectra with better signal-to-noise ratio (SNR), and signal-to-background, ratio (SBR)

Why LIBS in the VUV?





- VUV gA values 1 to 2 orders of magnitude greater than vis-IR (e.g. S III and S I)

SIII

λ (nm)	*gA (s^{-1})*	*lower*	*upper*
68.07	1.4×10^{10}	$3s^2 3p^2$	$3s^2 3p3d$
286.35	5.5×10^{8}	$3s^2 3p4p$	$3s^2 3p4d$

SI

λ (nm)	*gA (s^{-1})*	*lower*	*upper*
130.31	4.8×10^{8}	$3s^2 3p^4$	$3s^2 3p^3 4s$
861.72	1.6×10^{7}	$3s^2 3p^3 4s$	$3s^2 3p^3 4p$

Single Pulse VUV LIBS Experiments on Steel (2000s)

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Dublin City University

Spectroscopy of Steels At Atmospheric-Pressure and in Air, J Belliveau, L Cadwell, K Coleman, L Huwel, H Griffin, Applied Spectroscopy **39** pp. 727-728 (1985)

Work *on steel* continues to today :

1. Aguilera J.A, Aragon C, Campos J., *1992 Appl. Spectrosc.**46** pp. 1382-1387.*

2. Aragon C, Aguilera J.A, Campos J., *1993. Appl. Spectrosc.**47** pp. 606-608.*

3. **J M Vadillo**, C C Garcia, S Palanco, J J Laserna, 2009. *Spectrochimica Acta Part B-Atomic Spectroscopy **13**, pp.793-797*

4. **P Porizka,** J Klus, D Prochazka, E Kepes, A Hrdlicka, J Novotny, K Novotny and J Kaiser, 2016. *Spectrochimica Acta Part B-Atomic Spectroscopy **123**, pp.114-120.*

5. Sturm V, Erben B, Fleige R, Wirz W., *2019 Opt. Express **27** pp. 36855-36863.*

6. Zhang, Y., Sun, C., Yue, Z., Shabbir, S., Xu, W., Wu, M., Zou, L., Tan, Y., Chen, F. and Yu, J., *2020 Optics Express **28** pp. 32019-32032.*

7. S Grunberger, S Eschlbock-Fuchs, J Hofstadler, A Pissenberger, H Duchaczek, S Trautner, **J D Pedarnig**, *2020, Spectrochimica Acta Part B-Atomic Spectroscopy **169**, Article No. 105884*

8. MC Cui, Y Deguchi, G X Li, **Z Z Wang**, H R Guo, Z X Qin, C F Yao, D H Zhang, *2021, Spectrochimica Acta Part B-Atomic Spectroscopy **180**, Article No. 106210*

Single Pulse VUV LIBS Experiments on Steel (2000s)

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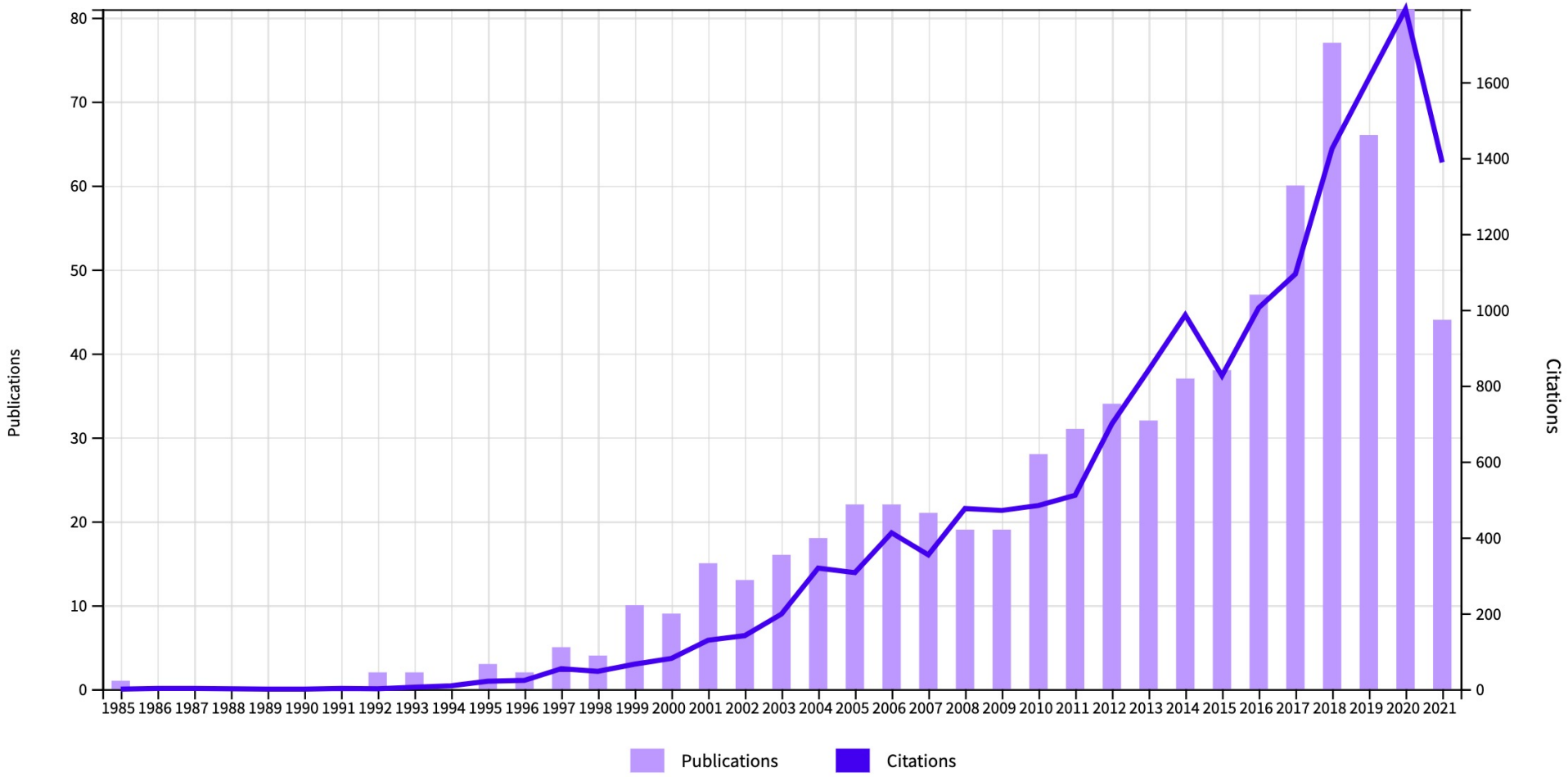
Spectroscopy of Steels At Atmospheric-Pressure and in Air, J Belliveau, L Cadwell, K Coleman, L Huwel, H Griffin, Applied Spectroscopy **39** pp. 727-728 (1985)

Work on LIBS applied to *steel* continues to today:



Single Pulse VUV LIBS Experiments on Steel (2000s)

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Dublin City University

Steel analysis with laser-induced breakdown spectrometry in the vacuum ultraviolet, V Sturm, L Peter and R Noll, Applied Spectroscopy **54**, pp. 1275-1278 (2000) – Single channel (PMT) detection

Time integrated laser-induced plasma spectroscopy (LIPS) in the vacuum ultraviolet for quantitative elemental characterisation of steel alloys, M A Khater, P van Kampen, J T Costello, J P Mosnier and E T Kennedy, *J Phys. D: Appl. Phys.* **33,** pp2252-2262 (2000) - IPDA

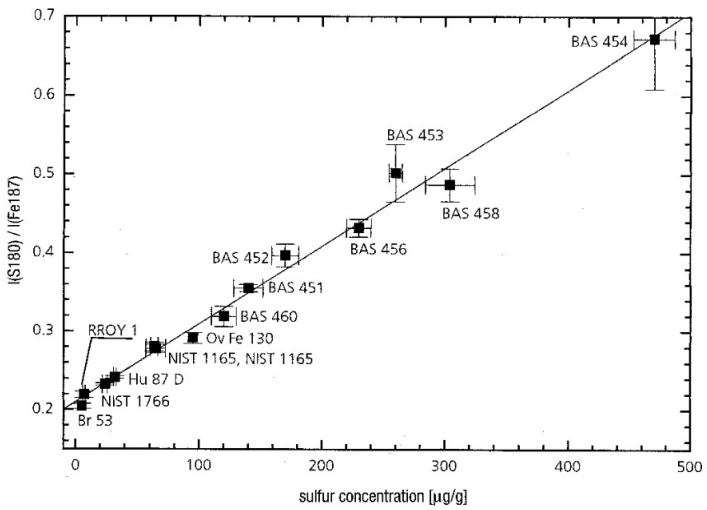

FIG. 6. Calibration curve for sulfur for the emission line 180.73 nm. For abbreviations, see Fig. 4.

TABLE II. Results of the calibration measurements with LIBS: limit of detection (LOD_{3s}), background equivalent concentration (BEC), concentration range of the calibration, and square of the correlation coefficient (r^2).

Element	LOD_{3s} (µg/g)	BEC (µg/g)	Concentration range (µg/g)	r^2
C	7	530	0–1800	0.999
P	9	640	0–600	0.998
S	8	210	0–500	0.987
Mn	9	320	0–14 000	0.999
Ni	6	500	0–700	0.991
Cr	7	330	0–1000	0.991
Si	11	680	0–6000	0.990

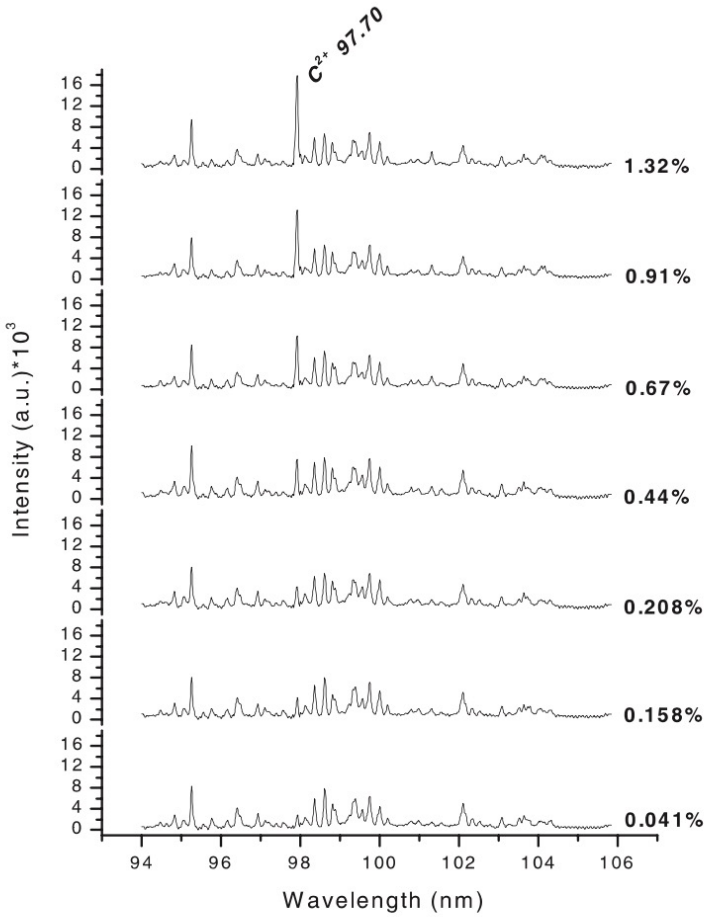

Figure 5. Relative emission intensity of the C^{2+} 97.70 nm line as a function of the carbon content. The axial distance from the target surface is 1.5 mm.

Table 4. Limits of detection for the five carbon lines used.

Line (nm)	Limit of detection (ppm) Present work	Balloffet *et al* [58][a]
45.96 III	148 ± 19	—
68.73 II	208 ± 28	—
90.41 II	130 ± 12	—
97.70 III	87 ± 10	100
117.57 III	154 ± 31	—

[a] Using the sliding vacuum spark.

Single Pulse VUV LIBS Experiments on Steel (2000s)

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Dublin City University

Optimisation of the Emission Characteristics of Laser Produced Steel Plasmas in the Vacuum Ultraviolet: Significant Improvements in Carbon Detection Limits, M A Khater, J T Costello and E T Kennedy, *Applied Spectroscopy*, **56,** pp970-983 (2002) - CCD

TABLE II. Detection limits for carbon in steels measured using various direct analytical techniques. Also shown is the *carbon* spectral line used in each case.

Author	Reference [year]	Method/detection limit, μg/g
Balloffet and Romand	28 [1955]	Vacuum Spark/100 (C(III) 97.7 nm)
Aguilera et al.	17 [1992]	LIPS/65 (C(I) 193 nm)
Khater et al.	1 [2000]	LIPS/87 ± 10 (C(II) 97.7 nm)
Sturm et al.	18 [2000]	LIPS/7 C(I) 193 nm)
Hemmerlin et al.	19 [2001]	LIPS/5; Spark/1 (C(II) 133.6 nm)
Khater et al.	Present [2001]	LIPS/1.2 ± 0.18 (C(III) 97.7 nm)

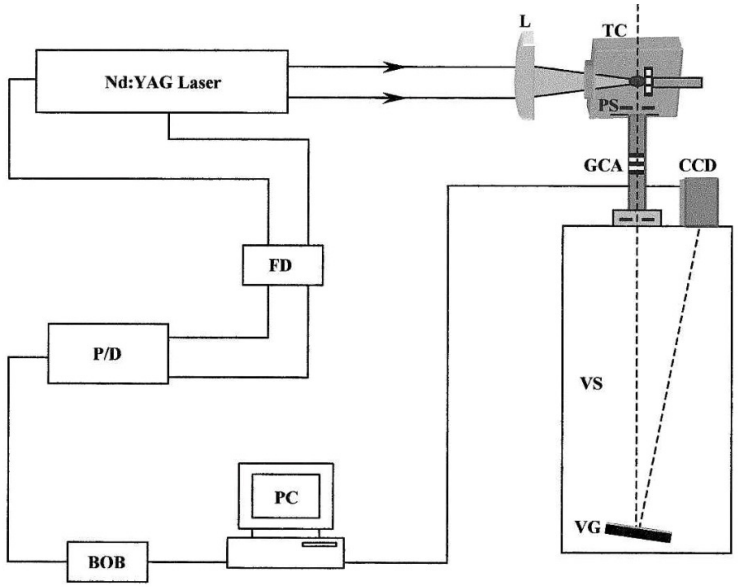
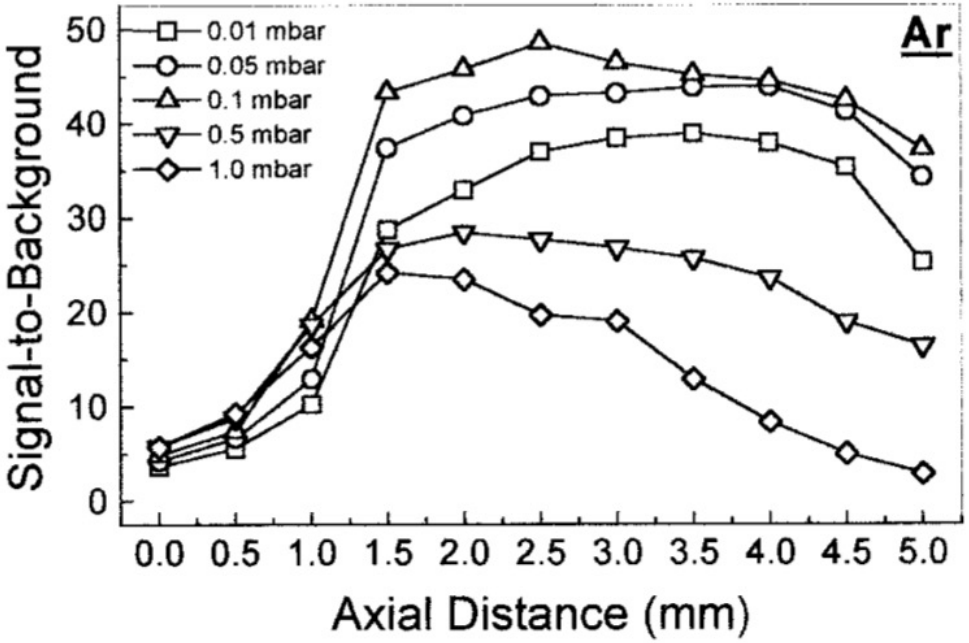


FIG. 1. Schematic diagram of the experimental set-up. ***L*** is a plano-convex cylindrical or spherical lens; ***TC*** is the target chamber; ***PS*** is the pre-slit; ***GCA*** is a glass capillary array; ***CCD*** is a VUV-sensitive charge-coupled device; ***VS*** is a 1 m VUV spectrometer; ***VG*** is a VUV grating; ***BOB*** is a breakout box; ***P/D*** is a pulse/delay generator; ***FD*** is a frequency divider unit; and ***PC*** is a personal computer.

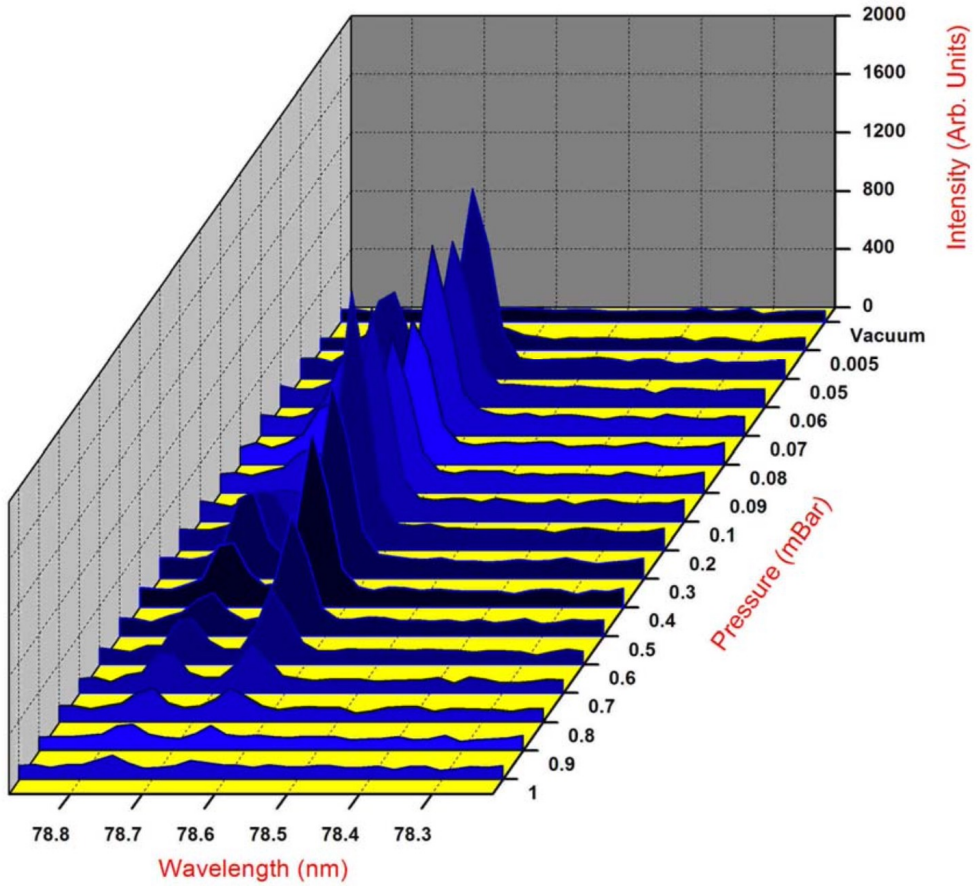


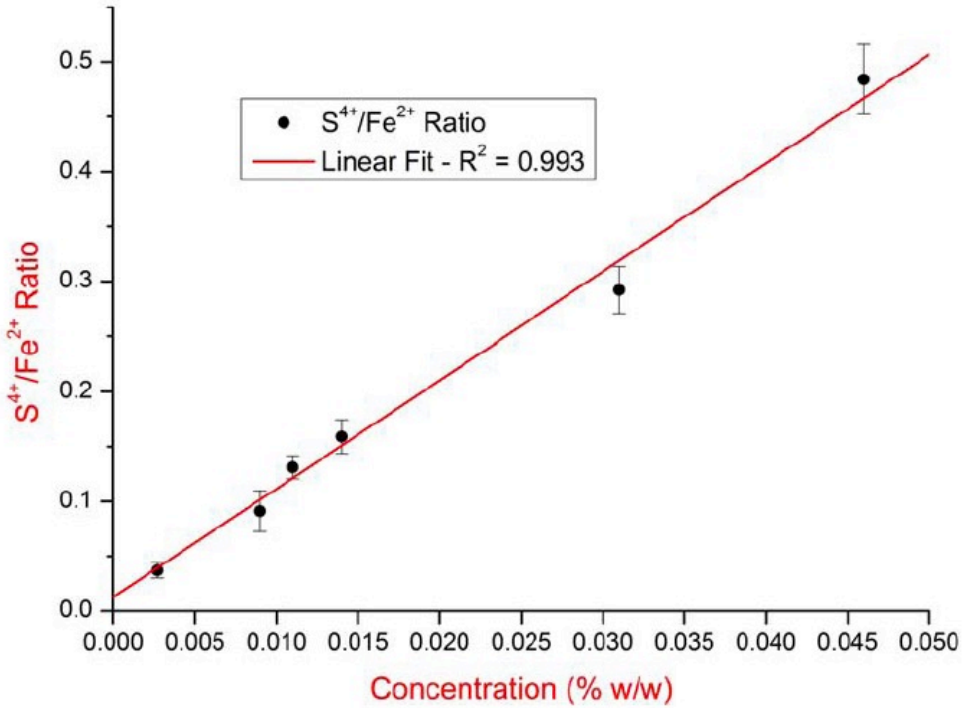
Single Pulse VUV LIBS Experiments on Steel (2000s)

Eoin O'Leary, PhD Thesis, Dublin City University, (2007) ***VUV Laser-Induced Plasma Spectroscopy For Low Level Sulphur Detection In Steel*** (CCD)

Line: S^{4+} (78.65 nm)

Sulphur/Steel in N_2 Background Gas





Limit of Detection of 1.7 ppm achieved using the S V emission line at 78.65 nm

Double Pulse VUV LIBS Experiments on Steel (2010s)

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Dublin City University

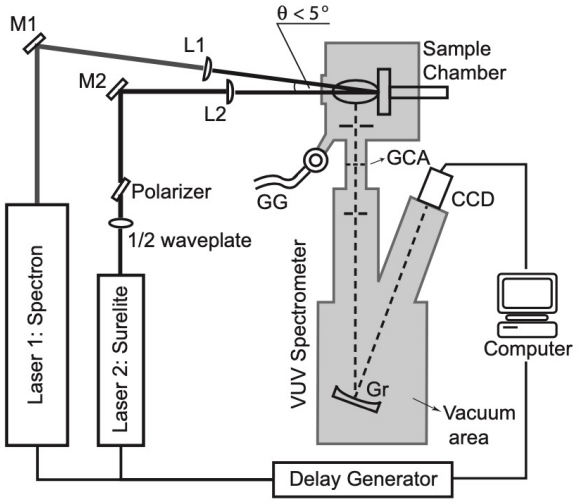


Fig. 1. Schematic of experimental apparatus. M1 and M2: Mirror 1 and mirror 2, L1 and L2: Lens 1 and lens 2, GG: gas gauge, Gr: grating, GCA: Glass Capillary Array, CCD: charge-coupled device.

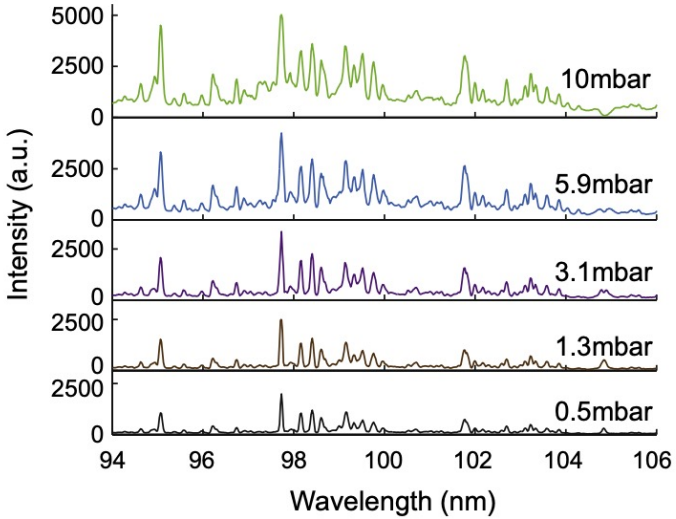


Fig. 4. Recorded emission spectra under different pressures of argon. Double-pulse excitation in the collinear reheating mode with an inter-pulse delay of 100 ns. C% = 0.041%.

Dual-Pulse Laser Induced Breakdown Spectroscopy with Ambient Gas in the Vacuum Ultraviolet: Optimization of Parameters for Detection of C and S in Steel, X Jiang, P Hayden, J T Costello and E T Kennedy, *Spectrochimica Acta Part B: Atomic Spectroscopy* **901** pp106-113 (2014)

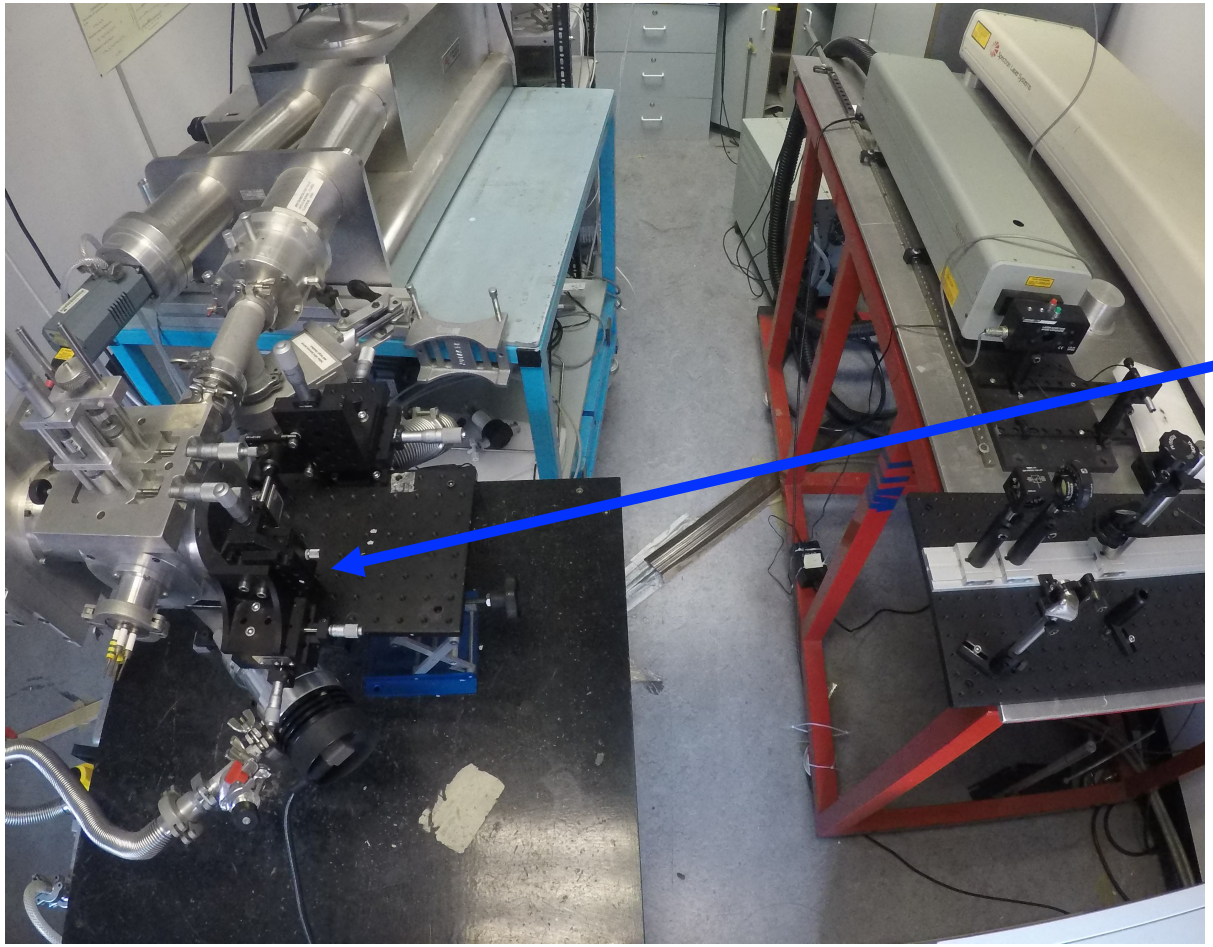
Table 3
Measured data for the LOD calibration for C and S in steel under various conditions with the improvement factor denoted by α. DP: double-pulse, SP: single-pulse.

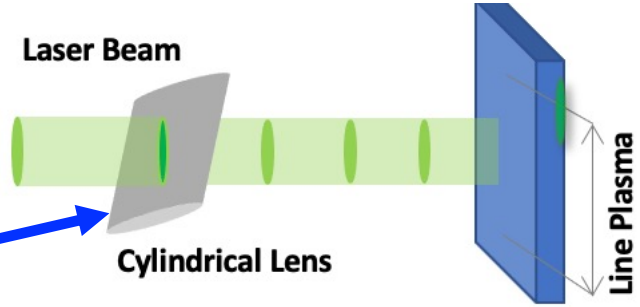
Line	Mode	Ambient Gas type	Linear fit R^2	LOD (ppm)	α
C III	SP	Vacuum	0.9715	54.0	
		N^2	0.8749	9.7	
		Ar	0.9953	12.6	
		He	0.9607	17.2	
	DP	Vacuum	0.9883	13.6	3.97
		N^2	0.9786	2.9	3.34
		Ar	0.9978	3.6	3.5
		He	0.9880	5.7	3.0
S V	SP	Vacuum	0.9615	51.2	
		N^2	0.9890	7.3	
		Ar	0.9960	9.8	
		He	0.9869	12.4	
	DP	Vacuum	0.9721	8.9	5.75
		N^2	0.9980	1.5	4.87
		Ar	0.9937	2.4	4.08
		He	0.9865	3.4	3.65

Some Recent VUV LIBS Experiments on Steel

Syedah Sadaf Zehra, PhD Thesis, DCU (2021 - in correction), ***Time Resolved and Time Integrated VUV LIBS for the Detection of Carbon in Steel*** (CCD)

Change of focus – from point to linear laser plasma plumes





Spectral range: 10 - 35 eV (120 - 35 nm) / 1m ARC normal incidence, Andor BI-CCD, Nd:YAG: 6 ns, 460 mJ

Some Recent VUV LIBS Experiments on Steel

From point to linear laser plasma plumes - benchmarking the DCU VUV LIBS System

Ollscoil Chathair Bhaile Átha Cliath
Dublin City University

LOD for C in Steel – Point Laser Focus *in Vacuo*

Previous Studies

This work

First the bad news !!

Single pulse LIBS – 4mm C(III) 97.7 nm [1]

In vacuo

LoD = 54 ppm [1]

In air at 0.1 mbar

LoD =1.2 ppm [2]*

Double pulse LIBS *in Vacuo* – 4mm

LoD = 13.6 ppm [1]

Improvement Factor

$$\alpha = \frac{LoD_{sp}}{LoD_{dp}}$$

α = 3.97 [1]

Single pulse LIBS *in Vacuo* – 4mm

C(III) 97.7 nm

LoD = 316 ppm [3]

$$LoD = \frac{3\sigma_B}{S}$$

[1] X Jiang, P Hayden, J T Costello and E T Kennedy, *Spectrochimica Acta Part B: Atomic Spectroscopy* 901 106-113 (2014
[2] M A Khater J T Costello and E T Kennedy *Applied Spectroscopy*, 56 970-983 (2002)
[3] SSZ Thesis, DCU (2021)

Some Recent VUV LIBS Experiments on Steel

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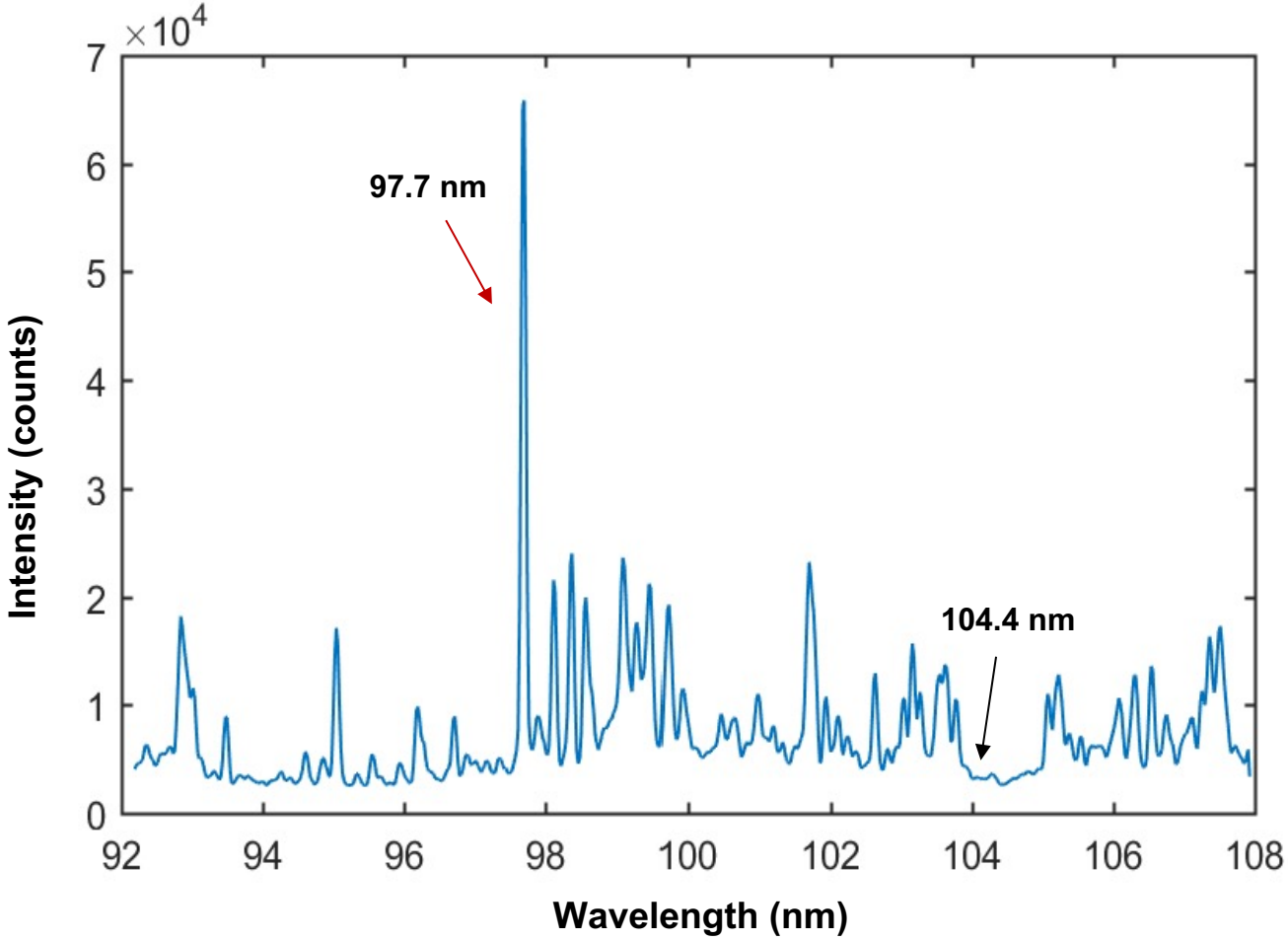
Ollscoil Chathair
Bhaile Átha Cliath
Dublin City University

Change of focus – from point to linear laser plasma plumes

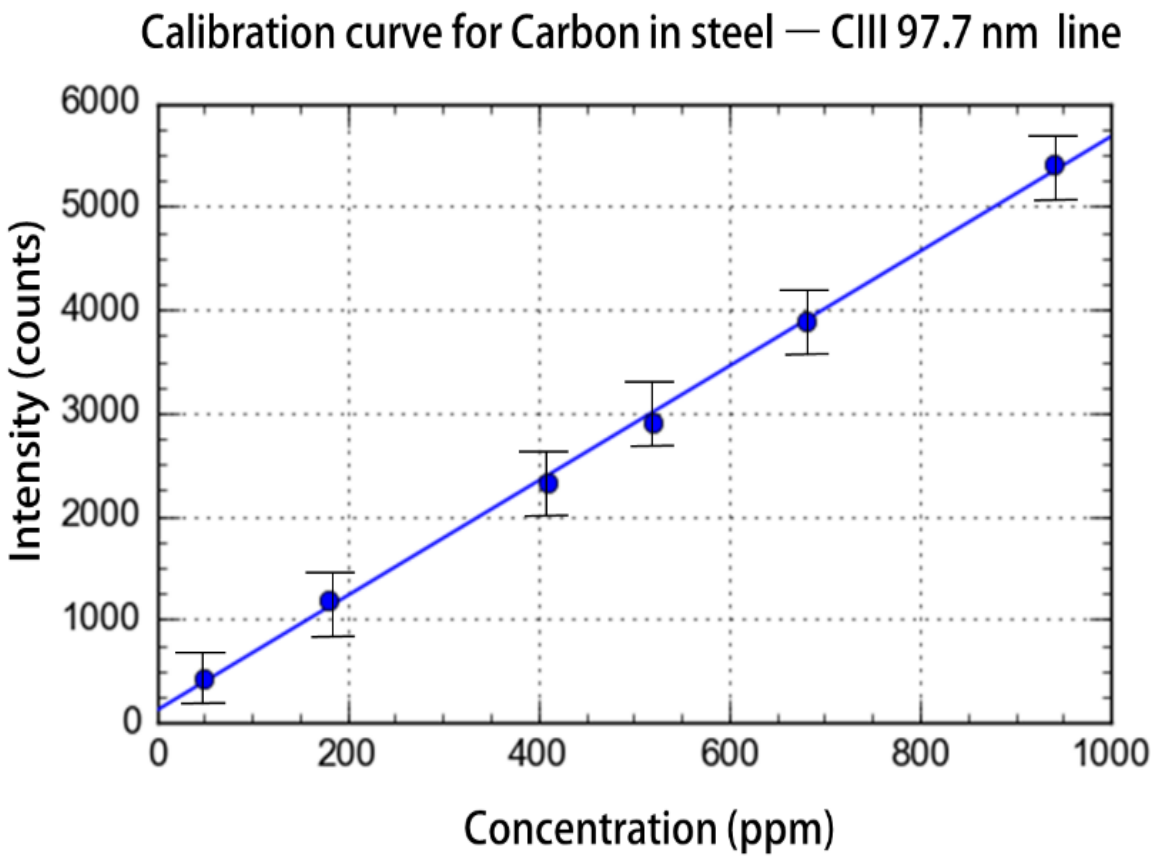


Spectrum obtained with the target CRM 12 X 15252P with a carbon concentration of 940 ppm. Red arrow – the 11 pixels integrated around the C III $1s^22s2p$ ($^1P_1$) to $1s^22s^2$ ($^1S_0$) line at 97.7 nm. Black arrow – the background was obtained by integrating 11-pixel values around 104.4 nm.

Some Recent VUV LIBS Experiments on Steel

Change of focus – from point to linear laser plasma plumes

TISR VUV LIBS Emission for C/Steel Calibration



Carbon in steel intensity calibration curve. Six different samples with carbon concentrations of 50 ppm to 940 ppm were used to construct the curve.

$$LoD = \frac{3\sigma_B}{S}$$

where σ_B standard deviation of the background

S slope of the calibration curve (slope sensitivity)

LoD = 50 ppm

Some Recent VUV LIBS Experiments on Steel

Ollscoil Chathair Bhaile Átha Cliath
Dublin City University

TISR VUV LIBS - Line Plasma

Case 1: TISR point plasma VUV LIBS target at 2 mm

TISR point plasma VUV LIBS target at 4 mm

LoD = 316 ppm
SBR= 2.8
R^2 = 0.9998

TISR line plasma VUV LIBS

LoD = 50 ppm

SBR= 4.4

R^2 = 0.9998

$$LoD = \frac{3\sigma}{S}$$

Improvement Factor

$$\alpha = \frac{LoD_{TISR\ pointplasma}}{LoD_{TISR\ line\ plasma}}$$

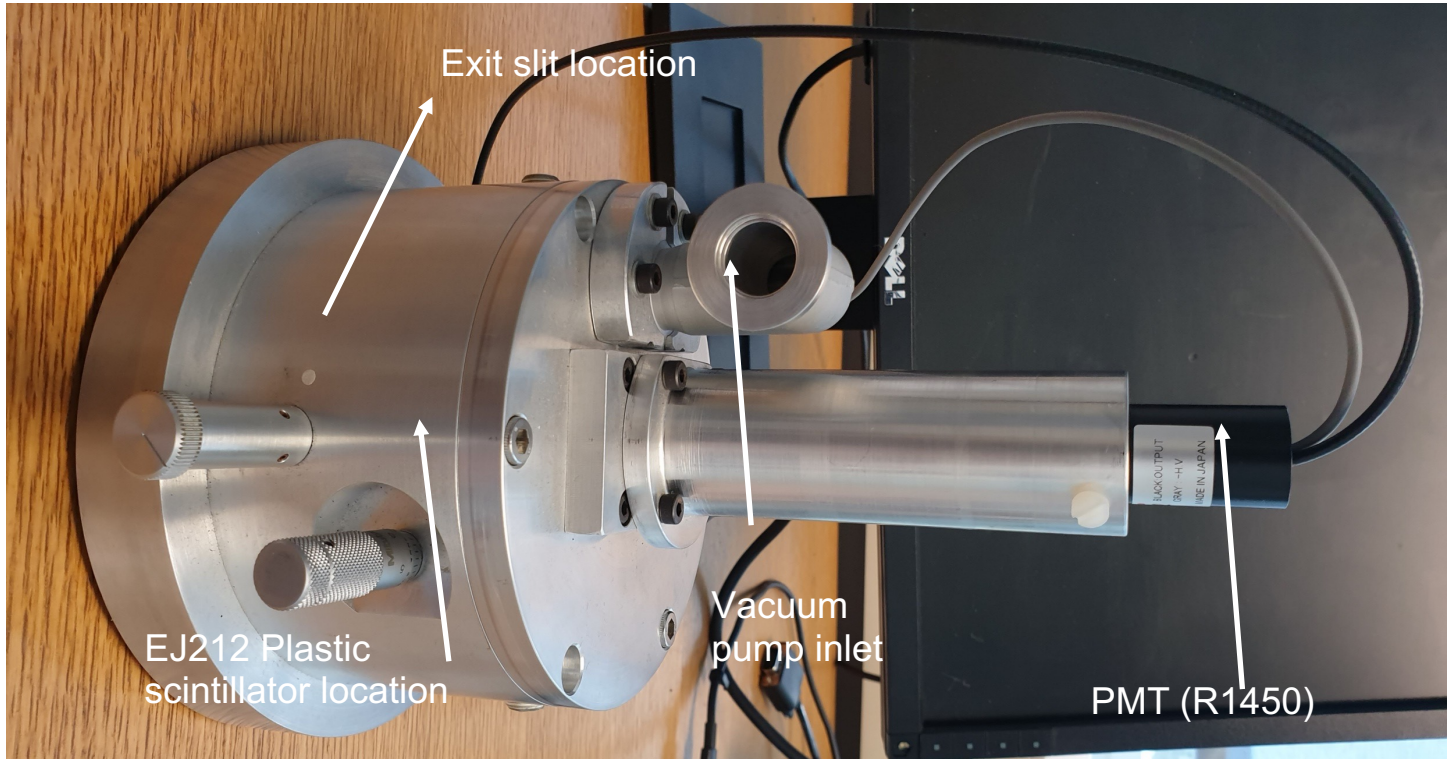
TISR VUV LIBS (Target at 4 mm)

LoD gain, $\alpha = 6.3$

Some Recent VUV LIBS Experiments on Steel

Back to the Future – Single channel TR (SR) VUV LIBS

V Sturm, L Peter and R Noll, Applied Spectroscopy **54**, pp. 1275-1278 (2000) – Single channel (PMT) detection



Time resolving VUV detector, showing the flange NW16 containing the plastic scintillator and photomultiplier tube (Tr < 5ns).

Some Recent VUV LIBS Experiments on Steel

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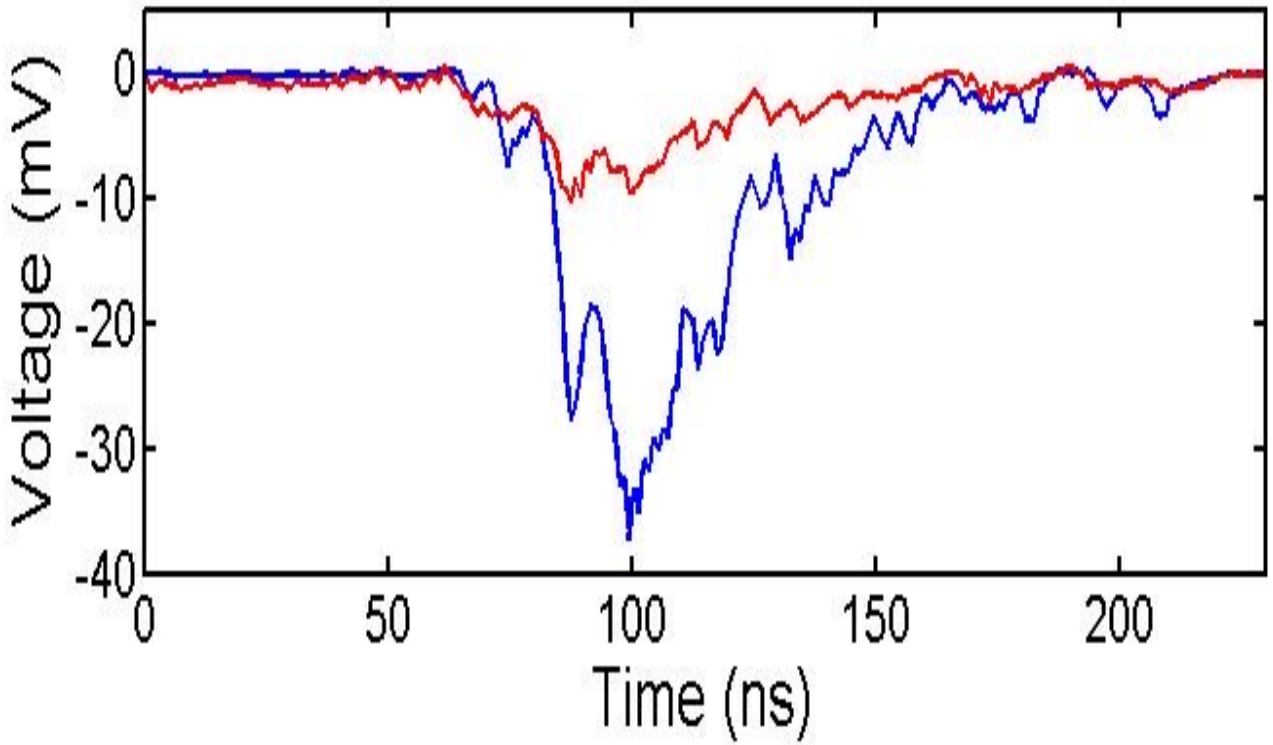
Dublin City University

Back to the Future – Single channel TR (SR) VUV LIBS

Time Resolved LIBS Emission



Time resolved plasma emission at 97.7 nm (carbon line) and 104.4 nm (continuum) for the steel target with a carbon concentration of 2080 ppm.

Some Recent VUV LIBS Experiments on Steel

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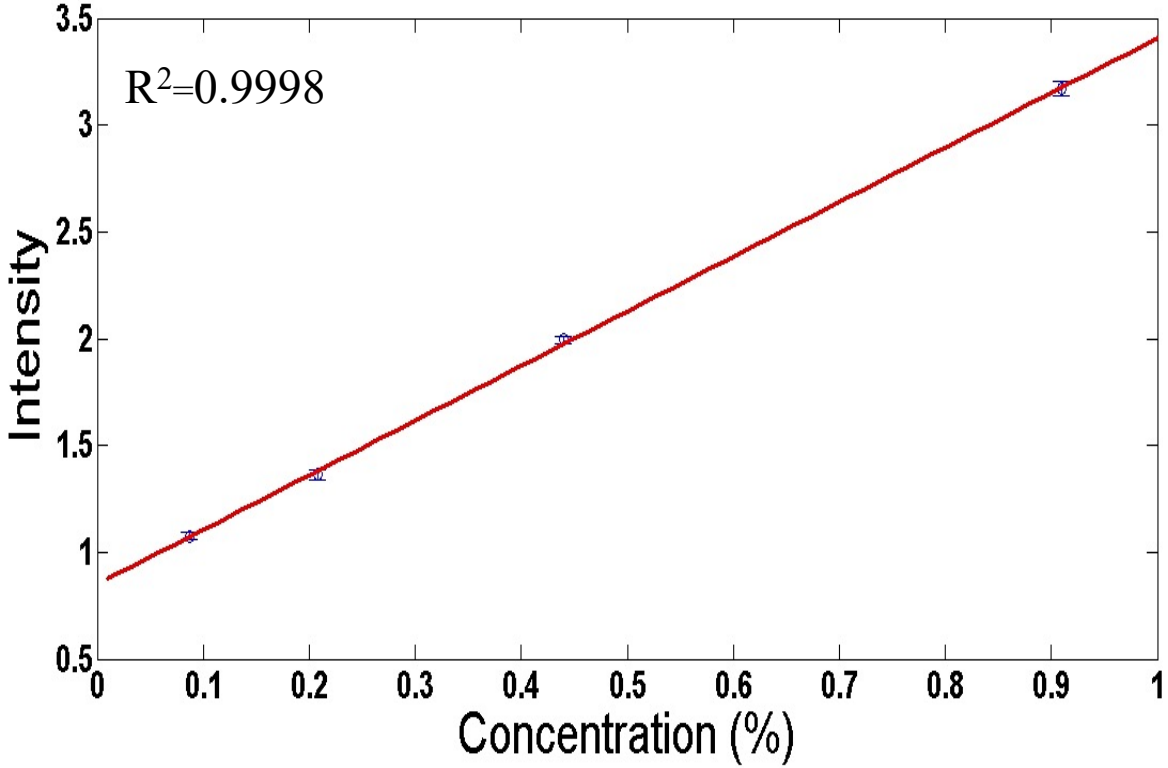
Dublin City University

Back to the Future – Single channel TR (SR) VUV LIBS

TR LIBS Emission – Carbon Calibration



Time resolved VUV LIBS calibration curve for spectra recorded with the ***target located 2 mm from spectrometer optical axis.***

$$LoD = \frac{3\sigma_B}{S}$$

LoD = 56 ppm

Some Recent VUV LIBS Experiments on Steel

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Dublin City University

Time Resolved LIBS

Case 1: TISR point plasma VUV LIBS target at 2 mm	
LoD	224
SBR	2.4
R^2	0.988

Case 2: TISR point plasma VUV LIBS target at 4 mm	
LoD	316
SBR	2.4
R^2	0.9998

Case 3: TR point plasma VUV LIBS target at 2 mm	
LoD	56
SBR	3.3
R^2	0.9998

Some Conclusions on VUV LIBS

Ollscoil Chathair Bhaile Átha Cliath
Dublin City University

1. VUV LIBS has shown low single digit (in ppm) LoDs
2. The LoD is very dependent on laser, focusing conditions and target geometric parameters
3. The absolute LoD is difficult to compare from experiment to experiment as 'S' is very dependent also on detector SNR, spectrometric system throughput and 'σ' on VUV photon and background fluctuations (Poisson), along with considerations in 2 above
4. Line focus gains in (relative) LoD depend on having area detectors and quasi-stigmatic spectrometric optics to take advantage of the change in focus geometry
5. So a (VUV) LIBS std for steel is hard (not impossible)

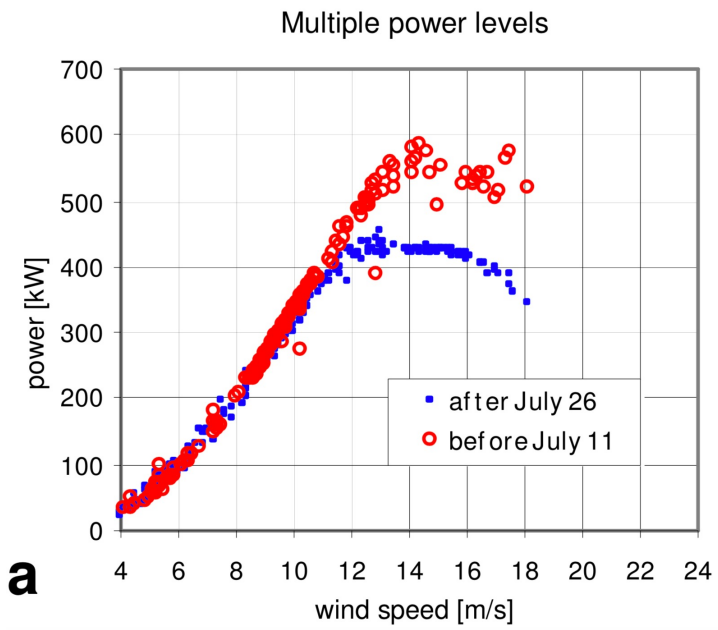
Current LIBS Focus and Future Developments

Ollscoil Chathair Bhaile Átha Cliath
Dublin City University

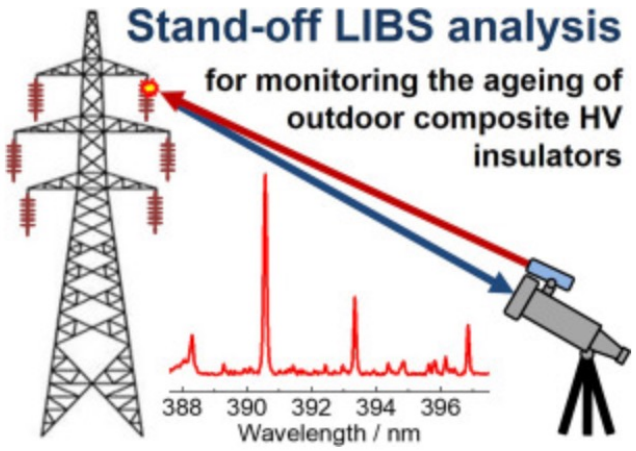
Theme: ***LIBS on 'Materials for the Energy Transition'***

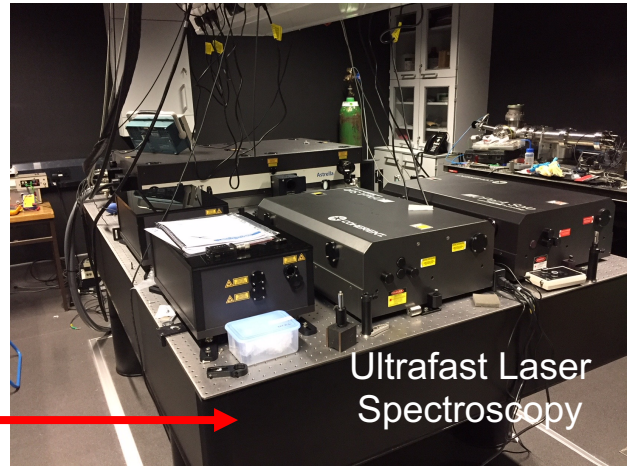
Focus: Wind Energy (*Batteries, Hydrogen, Nuclear, etc.*)

NATURE | VOL 412, 2001, pp42-43



Spectrochimica Acta Part B 165 (2020) 105768

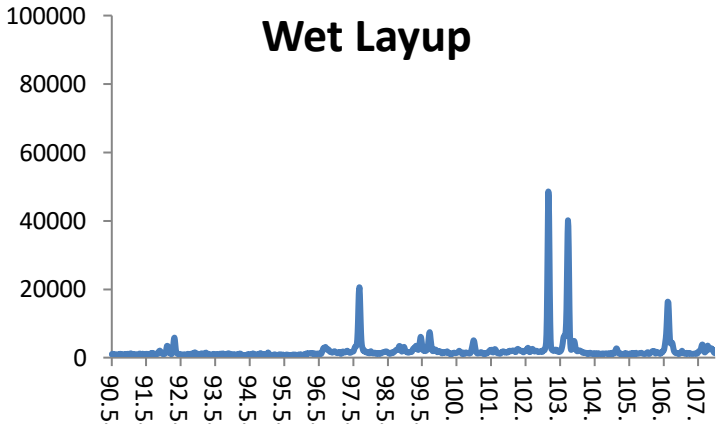


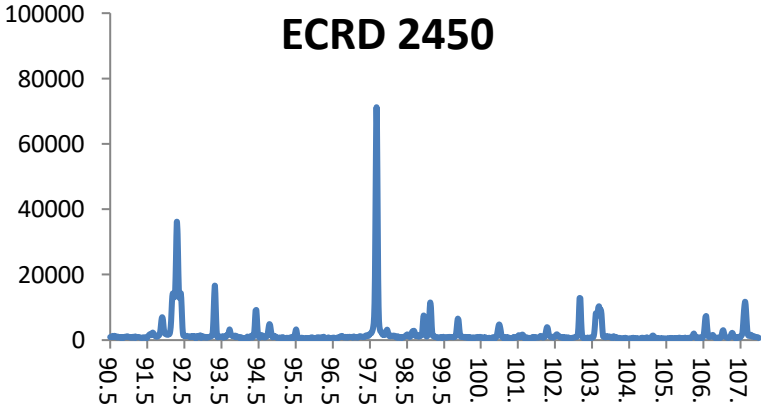


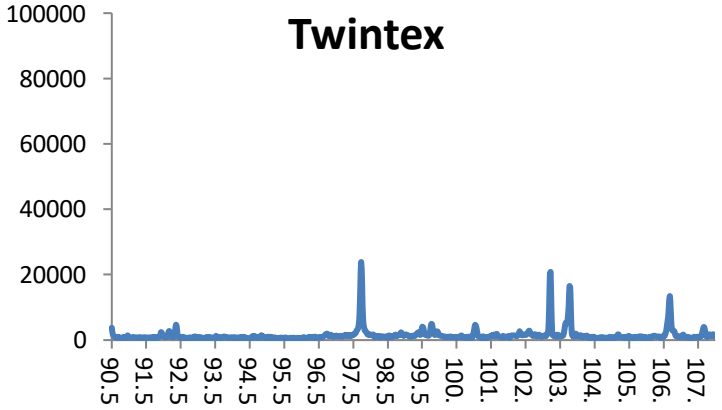
EUVL Resist Materials (Synthesis & Dynamics)

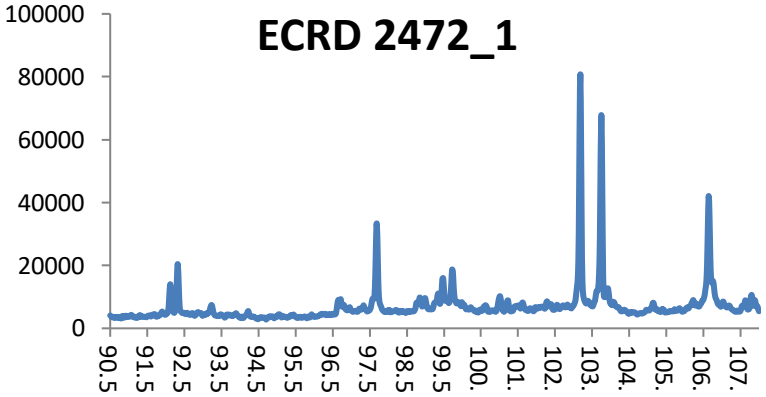
Current LIBS Focus and Future Developments

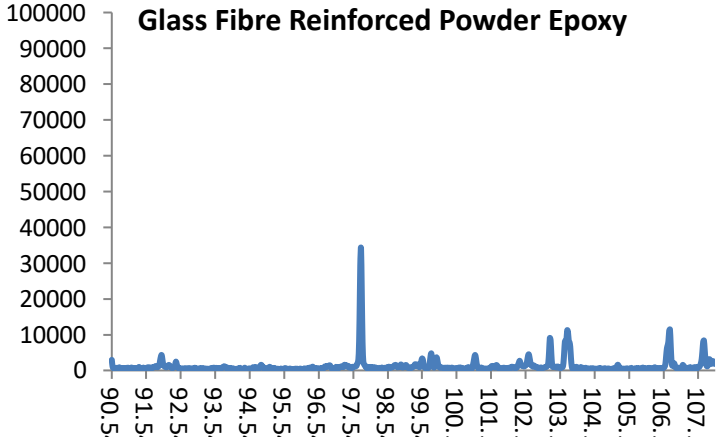
Early view: VUV LIBS
Spectra of Selected Blades









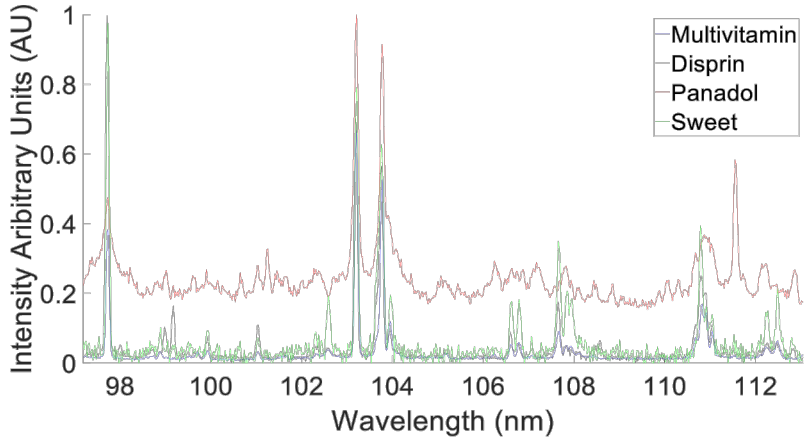


Current LIBS Focus and Future Developments

Theme: ***LIBS for Future Pharmaceutical PATs***

Focus: ML- Assisted Chemometrics (P Hayden (now UCD) + IBM)

A)



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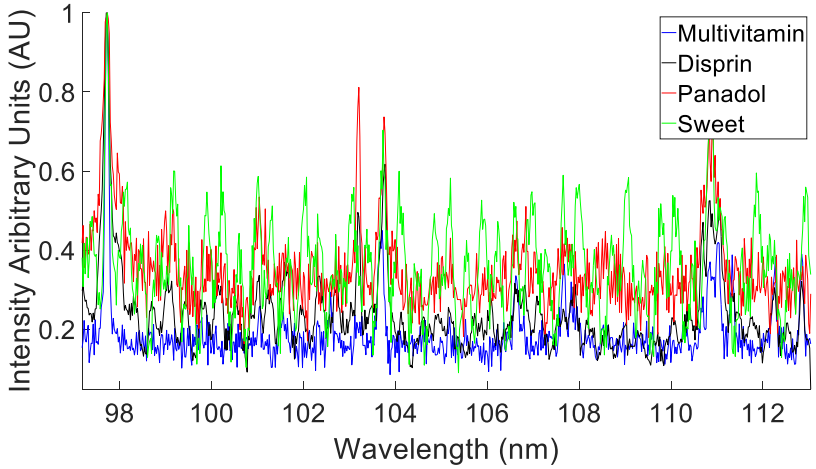


M B Alli, PhD Thesis, DCU (2021)

Table 5.4: % Accuracy ,comprehensive study, 160 spectra tested.

	Wavelength Range		
Technique	**65 nm**	**105 nm**	**Average**
SOM 2x2	52.50	0.00	**26.25**
SOM 3x3	81.25	10.63	**45.94**
SOM 4x4	73.13	32.50	**52.81**
SOM 5x5	81.25	13.75	**62.50**
PCA	66.25	41.88	**54.06**
COMP	69.38	0.63	**35.01**
CNN	95.00	91.88	**93.44**

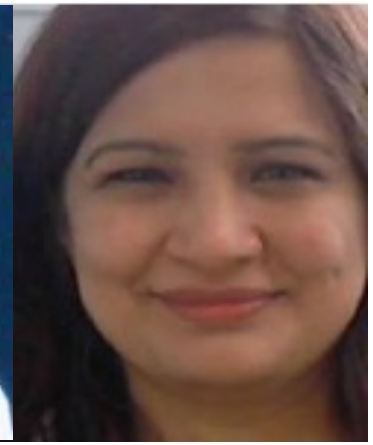
Acknowledgements – VUV LIBS Students/PDs

DCU
Ollscoil Chathair
Bhaile Átha Cliath
Dublin City University

M Khater

E O'Leary

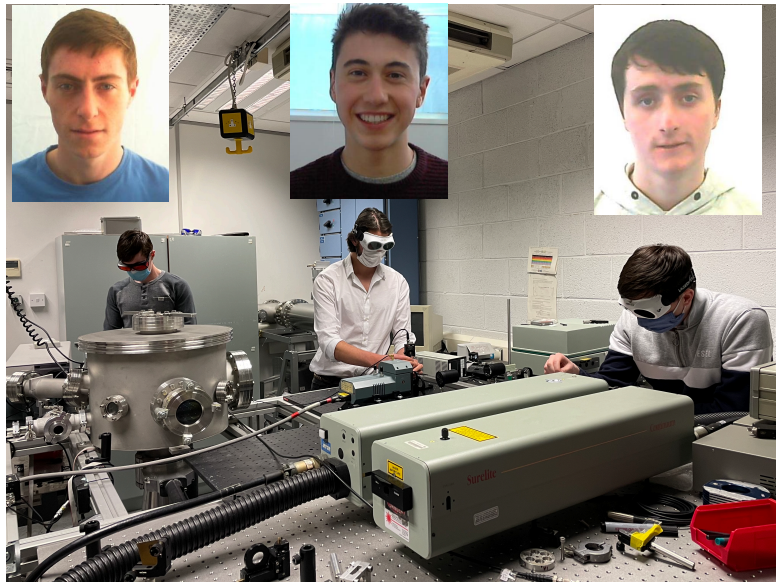
Xi Jiang



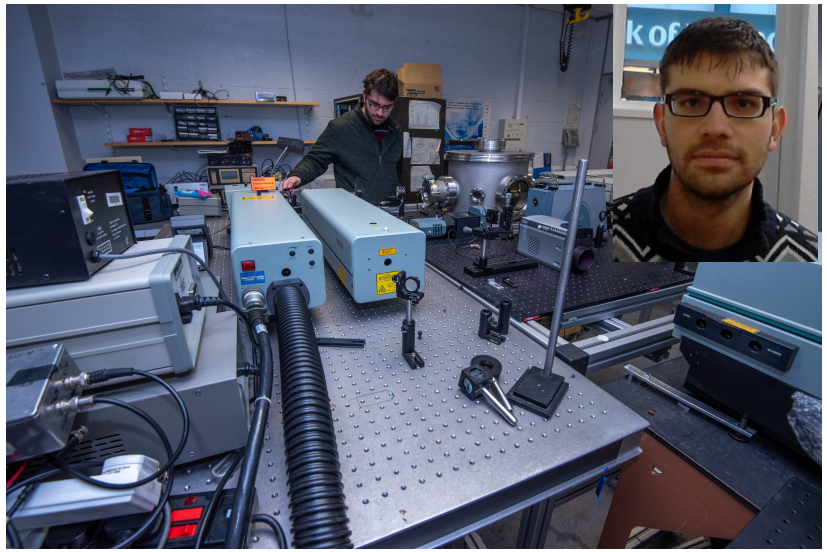
Sadaf Zehra

Muhammad B Alli

Ross



Stephen / Séamus / James



Lazaros

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SEAI - Sustainable Energy Authority Of Ireland - Research, Development & Demonstration (RD&D) programme

Some Conclusions on VUV LIBS

1. VUV LIBS has shown low single digit (in ppm) LoDs
2. The LoD is very depe[illegible] focusing conditions and target geo[illegible]
3. The absol[illegible] are from experiment to exp[illegible] so on detector SN[illegible] and ‘σ’ on VUV photon [illegible] Poisson), along with consid[illegible]
4. Line focu[illegible] LoD depend on having area detectors and [illegible]atic spectrometric optics to take advantage [illegible] change in focus geometry
5. So a (VUV) LIBS std for steel is hard (but not impossible)

Combine line laser focus with dual pulse excitation / gaseous environment along with time resolved & space resolved multichannel detection for VUV LIBS LoD in the ppb range?

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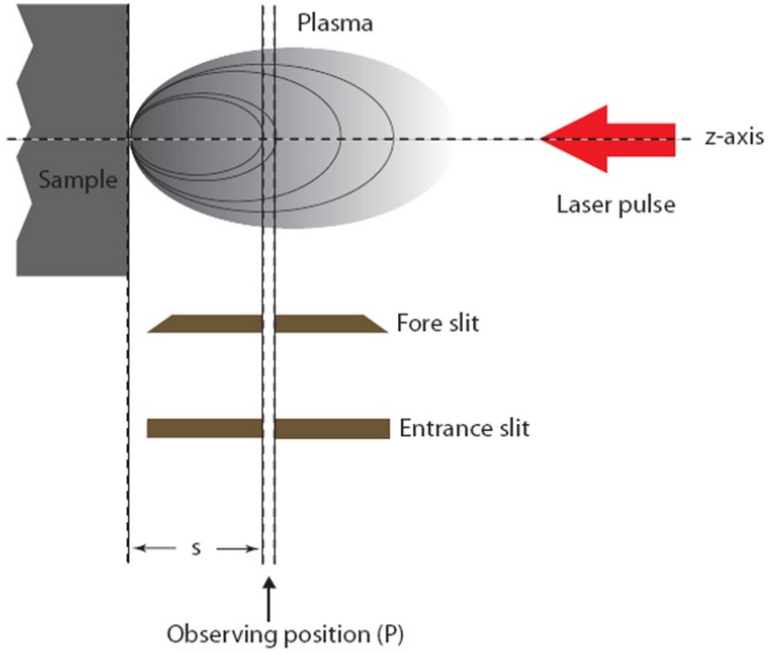
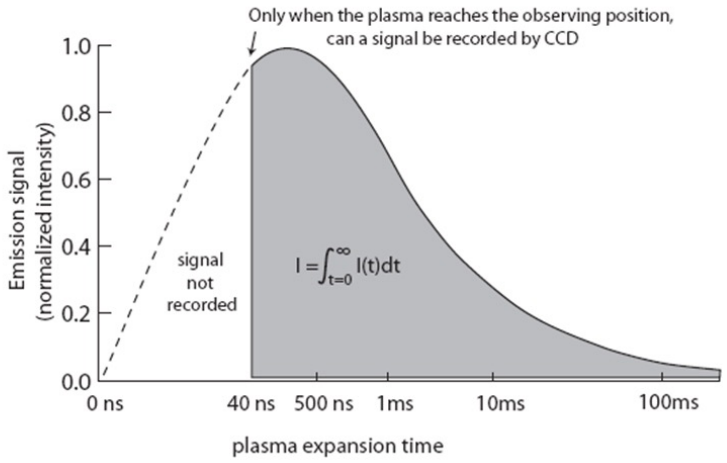
Dublin City University

EXTRA SLIDES

EXTRA SLIDES





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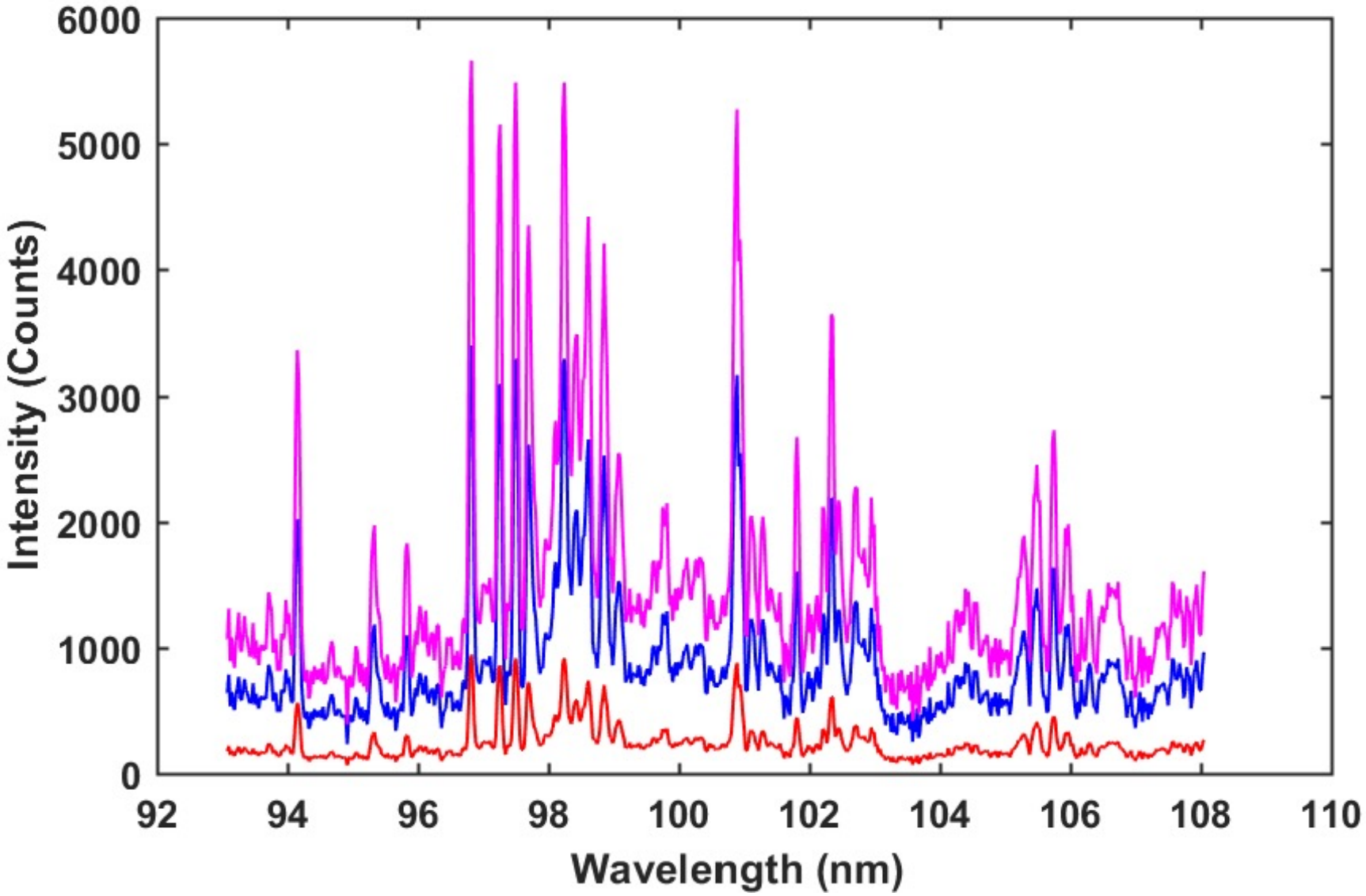
EXTRA SLIDES



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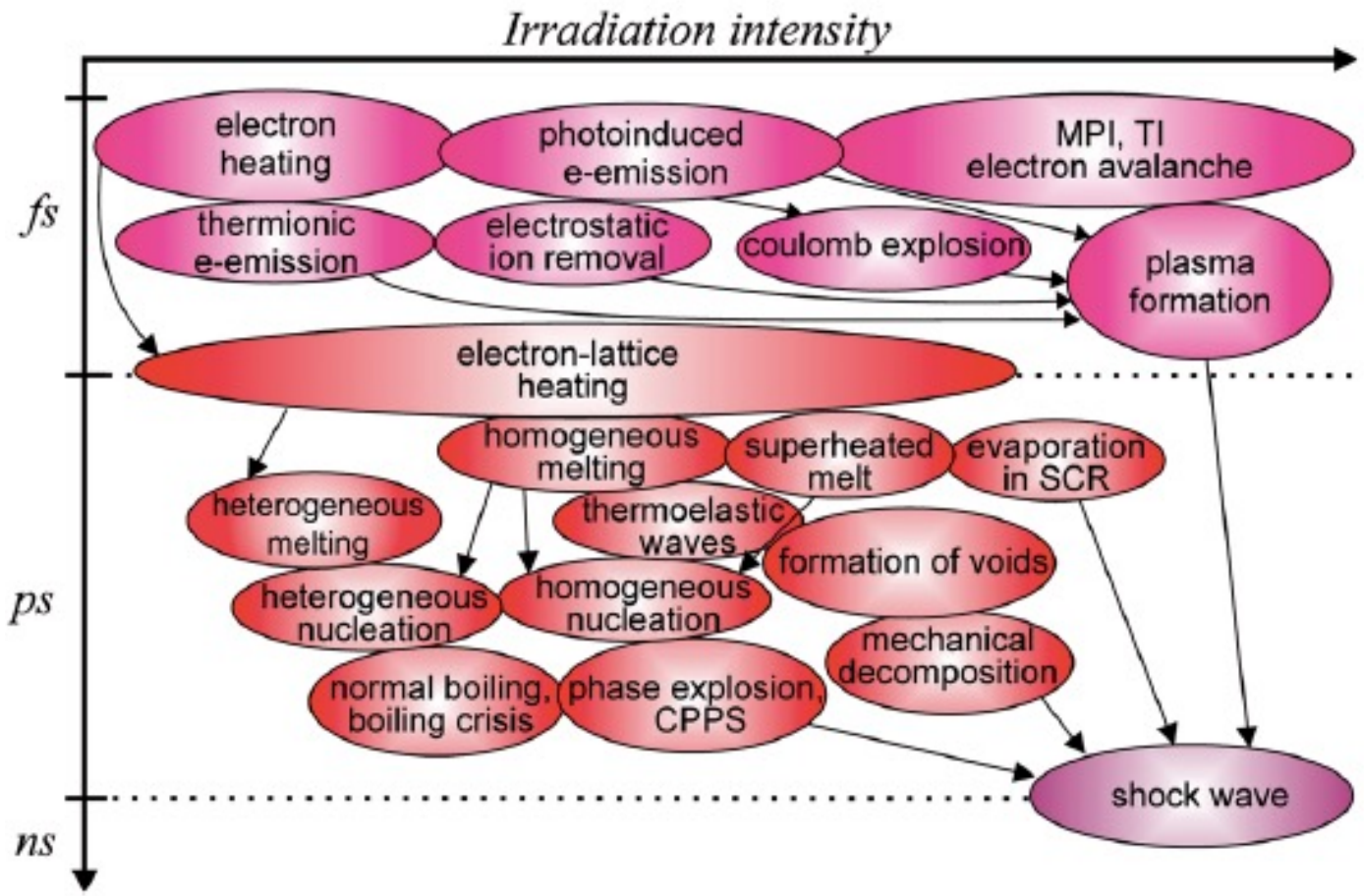

J. Anal. At. Spectrom. **31** 90 (2016)