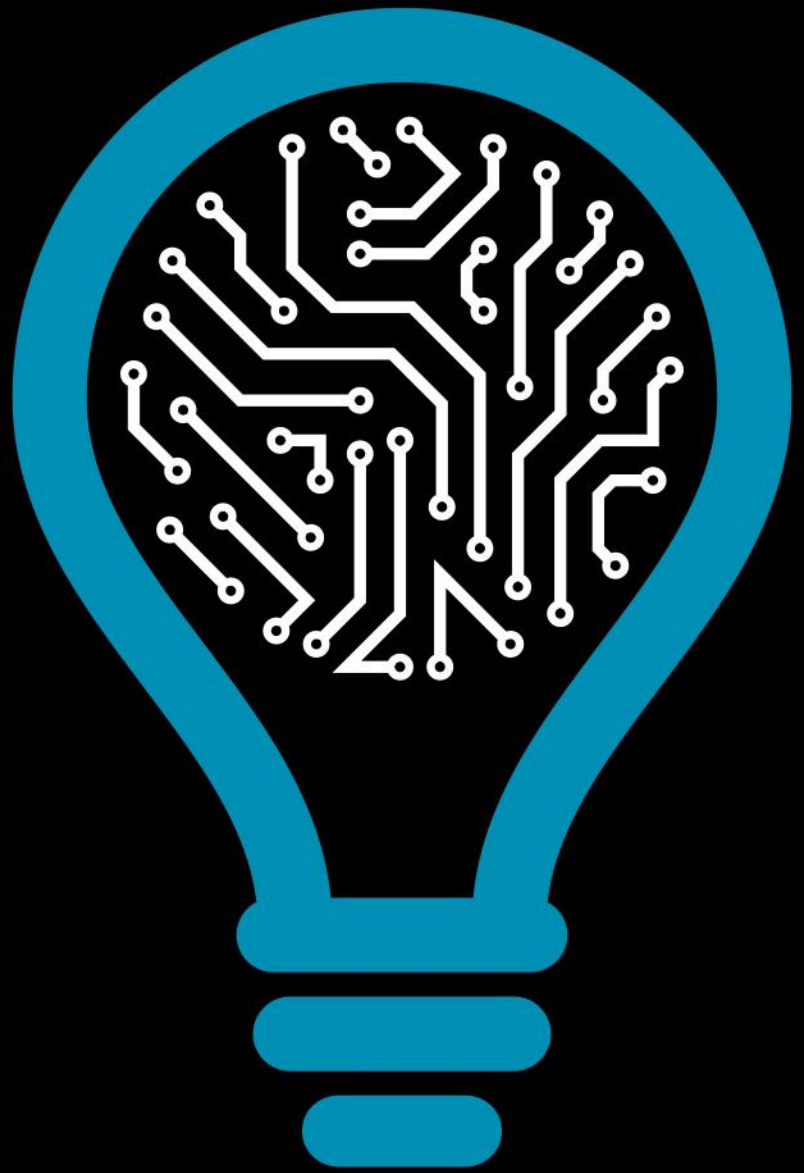
from knowledge production to science-based innovation



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GeoLIBS: Towards real-time identification, classification and quantification of complex minerals in underwater mining applications.

Pedro Jorge

Rui Martins
Miguel Ferreira

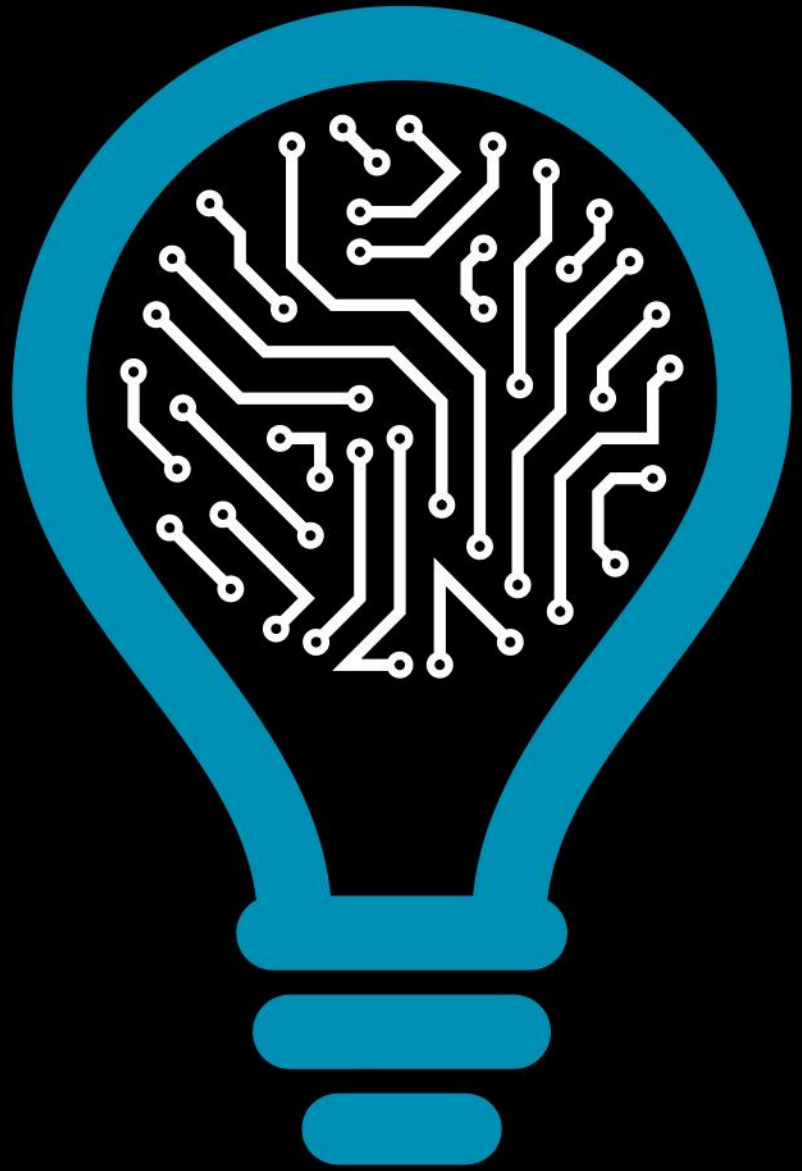
Porto, Portugal

16 November 2017

STRONG MAR

INESCTEC

INSTITUTE FOR SYSTEMS AND COMPUTER ENGINEERING, TECHNOLOGY AND SCIENCE




THE CHALENGE
Autonomous underwater mining!
Where to excavate?
REAL TIME ORE GRADE ASSESSMENT

LIBS for real time grade control

What is LIBs?

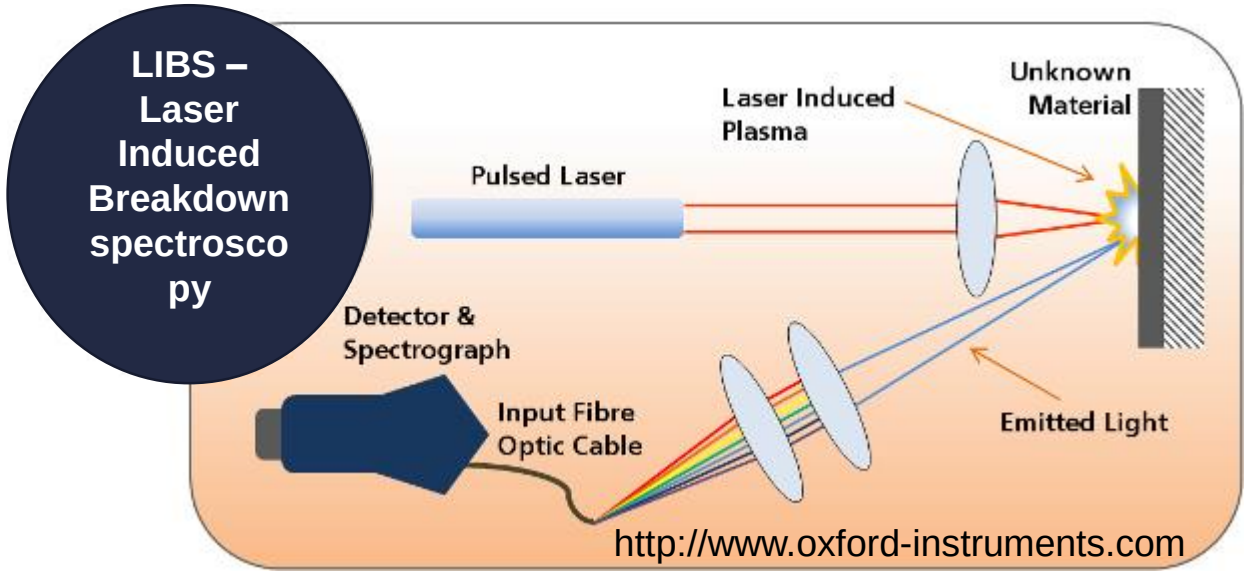
Challenges and opportunities!

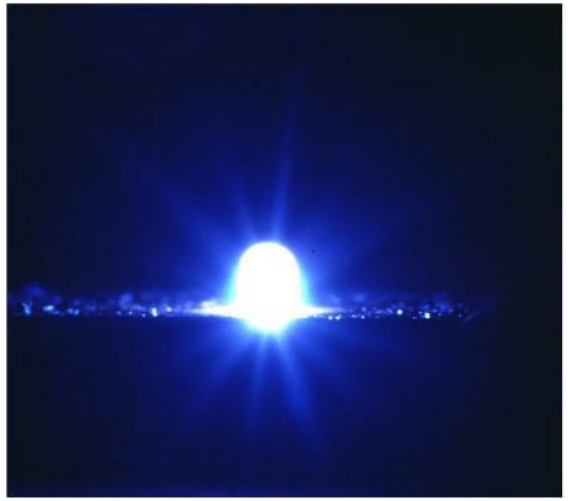
VAMOS real time grade control system

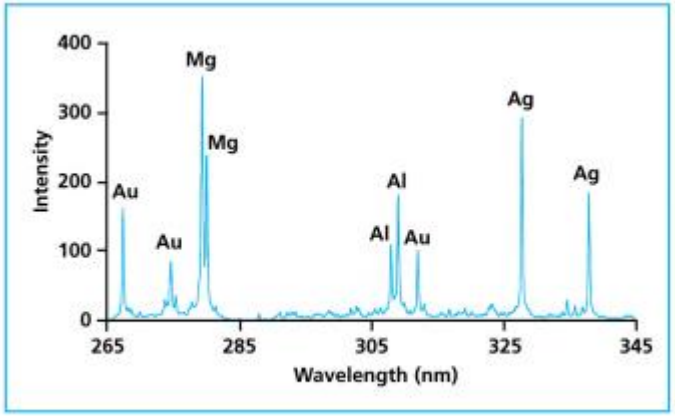
- Development
- Field trials

Future developments and outlook

LIBS – Laser Induced breakdown spectroscopy



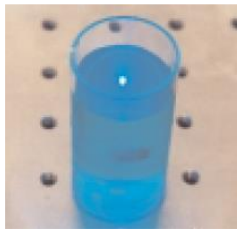


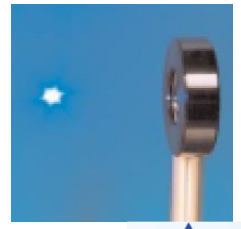


- High energy (>MW/cm2) laser pulse (ns)
- Breakdown of material generates a **plasma**
- Accelerated electrons have broadband emission ~T of plasma
- Cooling down :**Atomic emission lines** from constituent elements observable.

LIBS – Laser Induced breakdown spectroscopy

- Real time composition analysis
- Non destructive (very small ablation area)
- Remote analysis possible (up to 50 m)
- Composition surface profiles, in depth composition profile (with high spatial resolution)
- Little or no Sample preparation
- Suitable to detect any element (including light ones like Li, B)
- Gas, liquid and solid samples





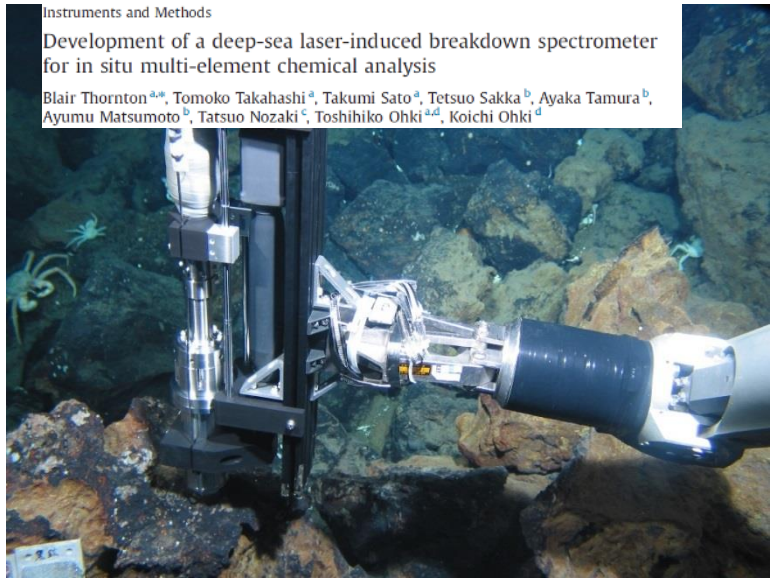
LIBS – Laser Induced breakdown spectroscopy

Contents lists available at ScienceDirect
Deep-Sea Research I
journal homepage: www.elsevier.com/locate/dsri

Instruments and Methods

Development of a deep-sea laser-induced breakdown spectrometer for in situ multi-element chemical analysis

Blair Thornton [a,*], Tomoko Takahashi [a], Takumi Sato [a], Tetsuo Sakka [b], Ayaka Tamura [b], Ayumu Matsumoto [b], Tatsuo Nozaki [c], Toshihiko Ohki [a,d], Koichi Ohki [d]

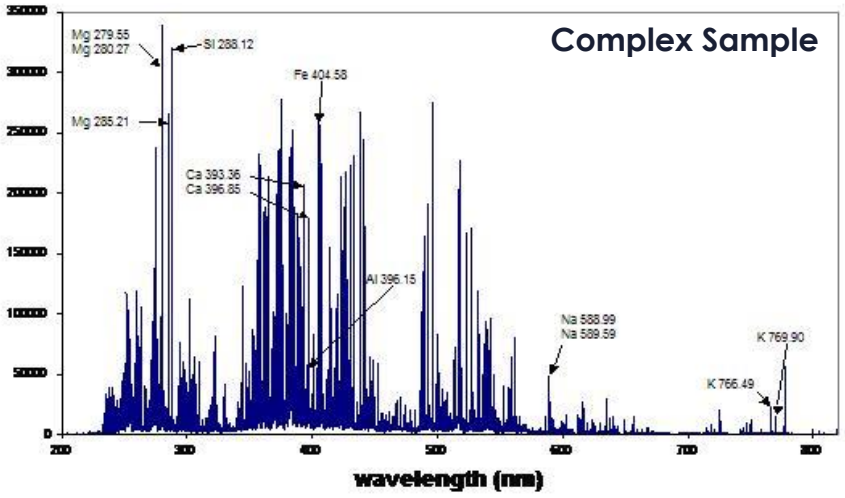


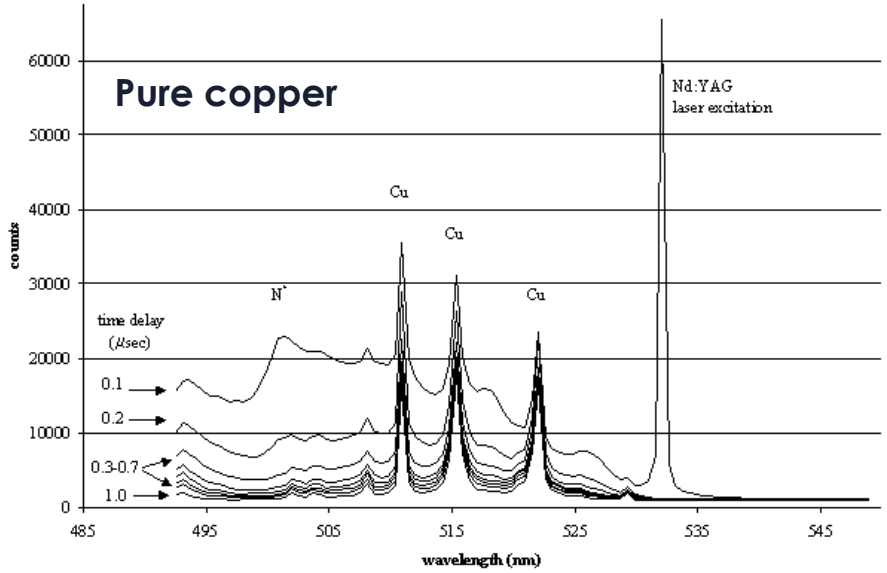
LIBS Challenges

Signal Analysis

Spectra depends on a variety of factors

- Laser parameters (power, wavelength, …)
- Sample state and composition
- Environmental (Pressure, plasma Temperature…)





Spectra acquired with different delays

LIBS Challenges

Identification not always straightforward

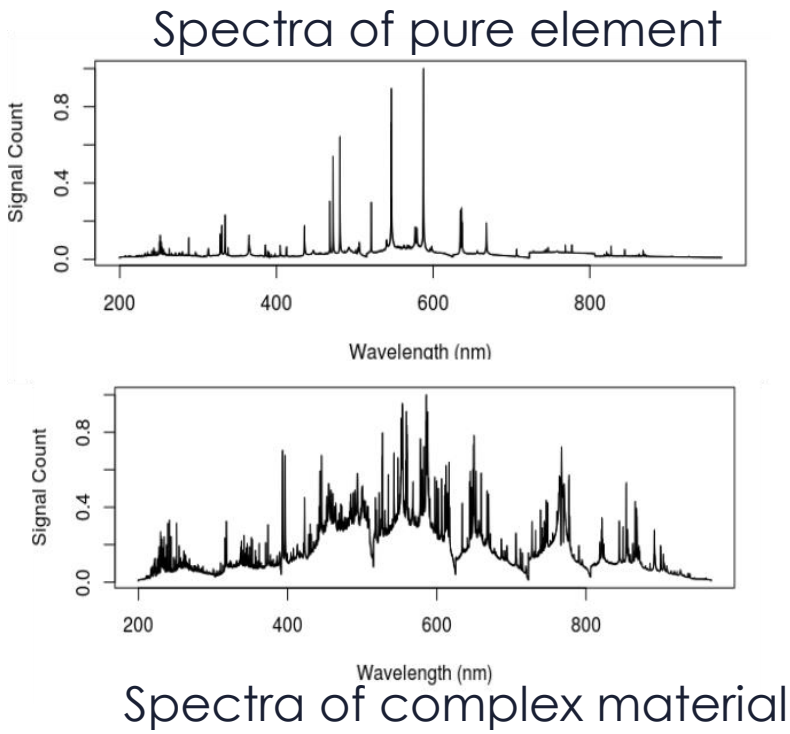
Emission lines not always exclusive

Spectral overlap in complex materials

Matrix effects

Dependence on laser parameters (E, λ, t_p, Δt,…)

Dependence on sampling conditions (air, gas, solid, pressure, surface reflectivity…)



Quantification often faulty and unreliable

(Including in existing products)

GEO LIBS VAMOS Real time grade control system

¡VAMOS! ¡Viable Alternative Mine Operating System!

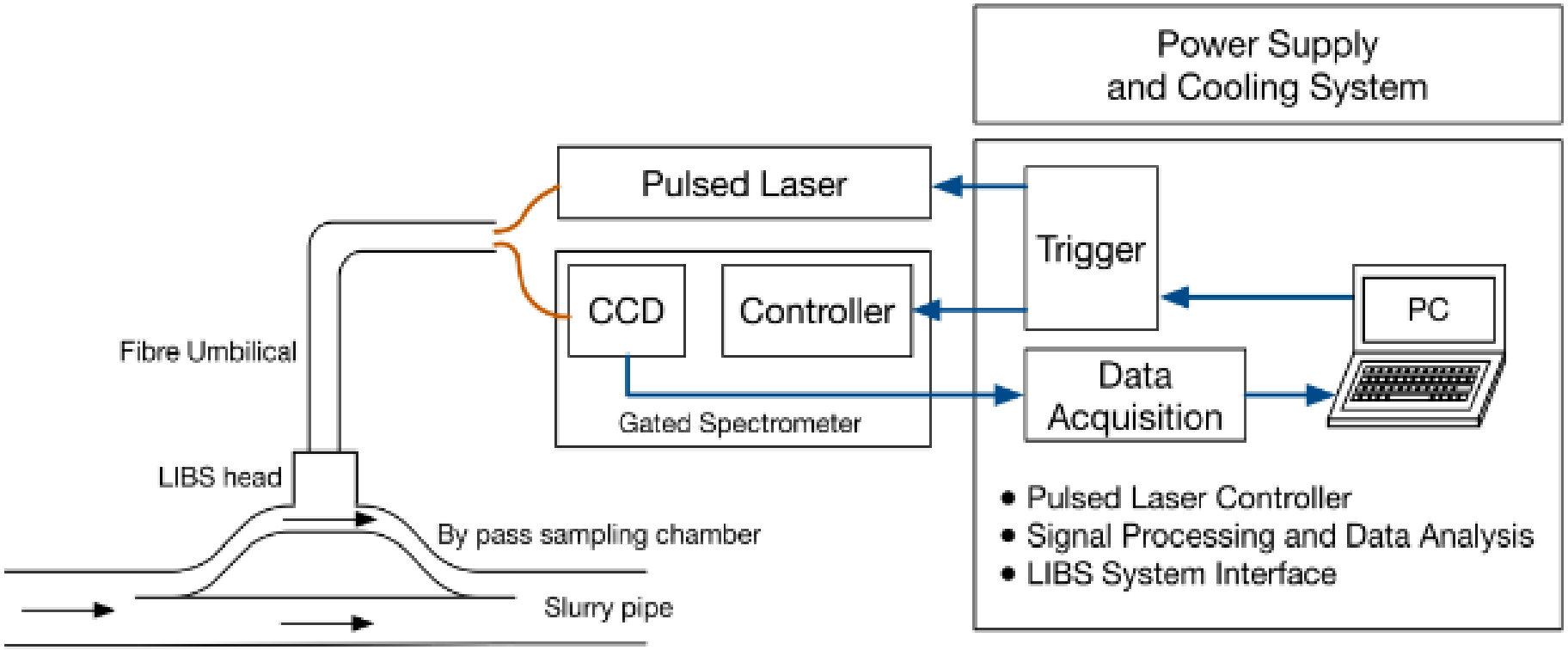
T4.3 Real Time Grade Control (INESC) M5-M30

Sub-Tasks

ST4.3.1: Develop a **compact LIBS system** (Laser Induced Breakdown spectroscopy) (INESC)

ST4.3.2: Develop a **methodology for robust calibration** of the LIBS System (INESC)

System Architecture



System parts I: Laser system

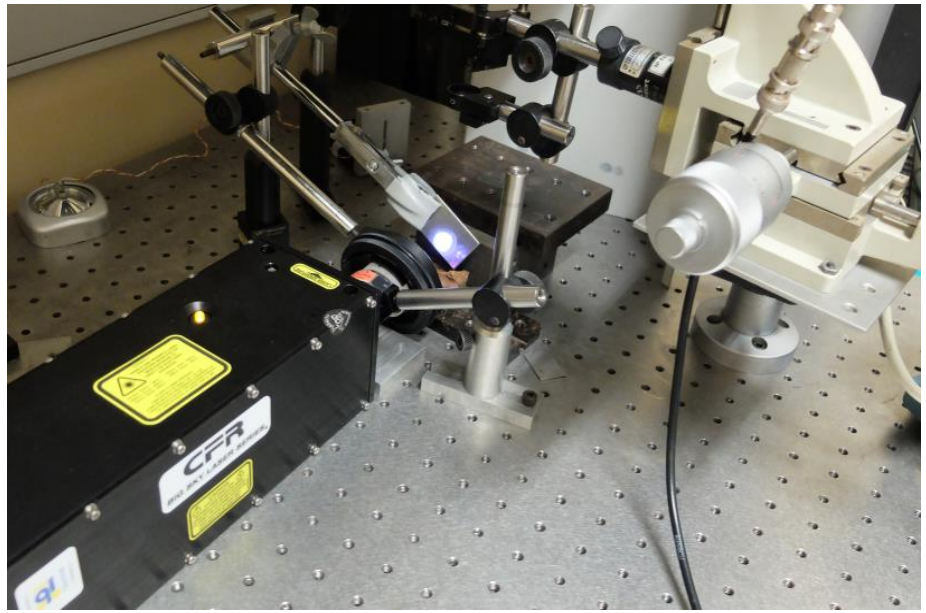
- Solid state Q switch **Laser system** (Nd : YAG)
- Operation wavelength:1064 nm
- Pulse Energy: 200 mJ
- Pulse duration: 8 ns;
- Repetition rate: 20 Hz;
- Average power: 4W.
- Energy Adjustable by setting Flash Lamp/Q Switch Delay time.
- Integrated **Power supply** and water cooling system.

100-240VAC, 50/60Hz, single phase, 850W

Laser head (H x L x W) mm: 84 x 32 3 x 94

System Lab Tests

- Test and optimization of laser parameters (Energy, delay repetition rate, focusing)
- Test of optics for laser delivery and plasma emission collection (fiber optics)
- Test and selection of spectrometers system



System parts II: spectrometer

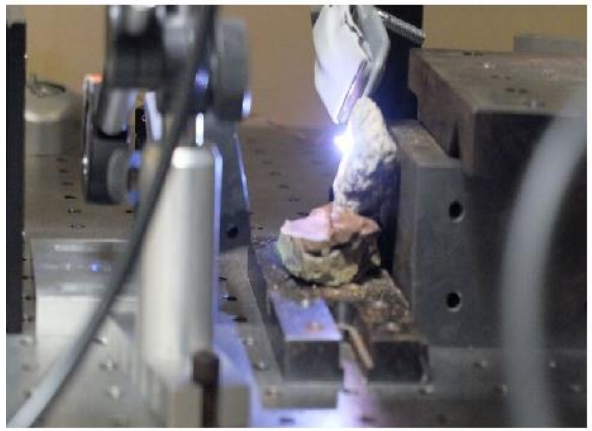
Manufacturer	Model	Optical resolution (nm)	Bandwidth (nm)	No. Pixels	Signal to Noise	Sync
Ocean Optics	HR4000	0.65	200-1100	3648	300:1	Not suitable
Ocean Optics	QE60000	0.65	200-1100	1024	1000:1	Not suitable
Ocean Optics	STS-vis	1.5	350-800	1024	1500:1	Not suitable
Sarspec	RES+	0.75	200-1100	3648	300:1	Not suitable
Sarspec	SPEED+	1.7	200-1100	3648	300:1	OK
Avantes	AvaLIBS 4	0.25	200-1100	4x2048	200:1	OK
Avantes	AvaLIBS 8	0,06-0,18	180-926	8x2048	200:1	OK

- CCD spectrometers tested (for portability and robustness)
- Most of available systems lack resolution or sync ability
- 8 Channel system selected for higher resolution <0.1nm

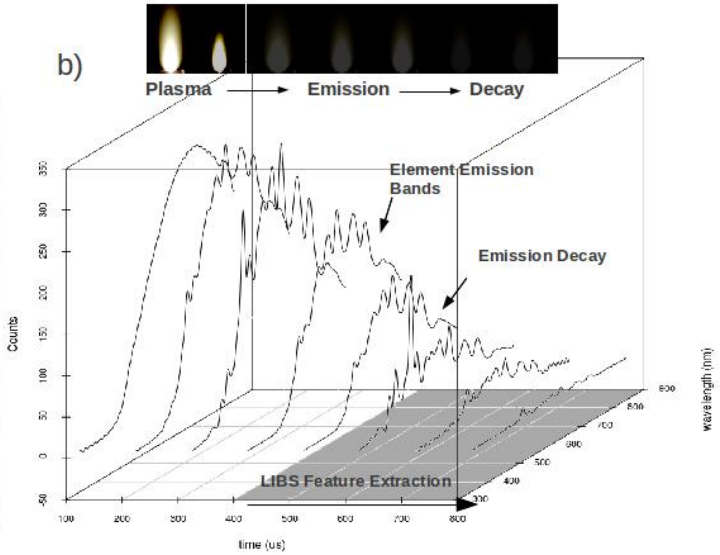
System Lab Tests

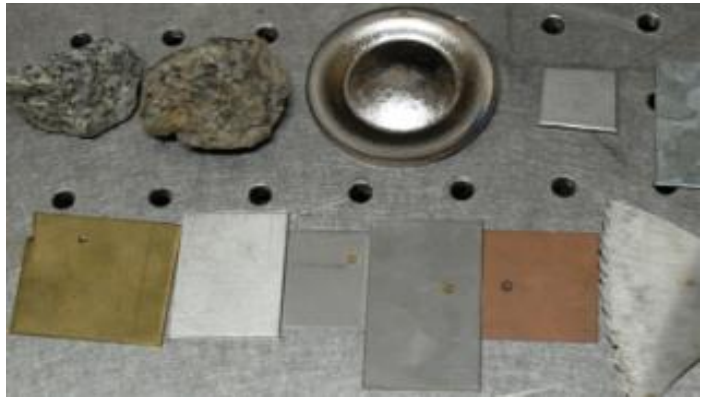
- Test and optimization of system parameters for optimal plasma generation and signal collection.
- System tested with diversity of metal and mineral samples
- Optimization of optical system

a)



b)

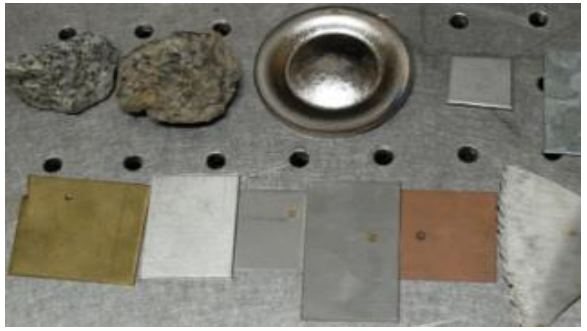


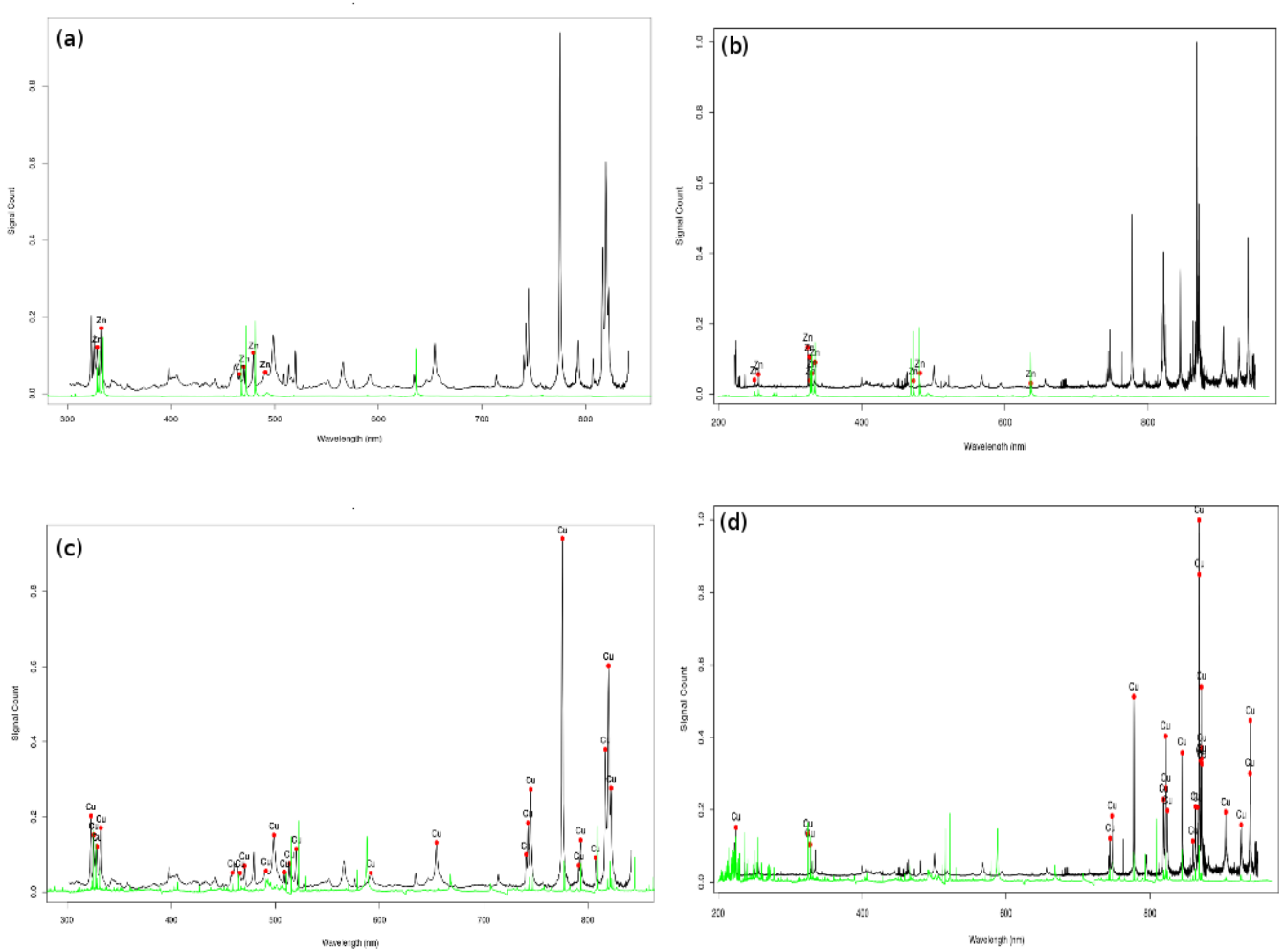


System Lab Tests

- Elements identified by comparison against NIST database. Increased difficulty for complex alloys! Major Challenge in complex mineral!!

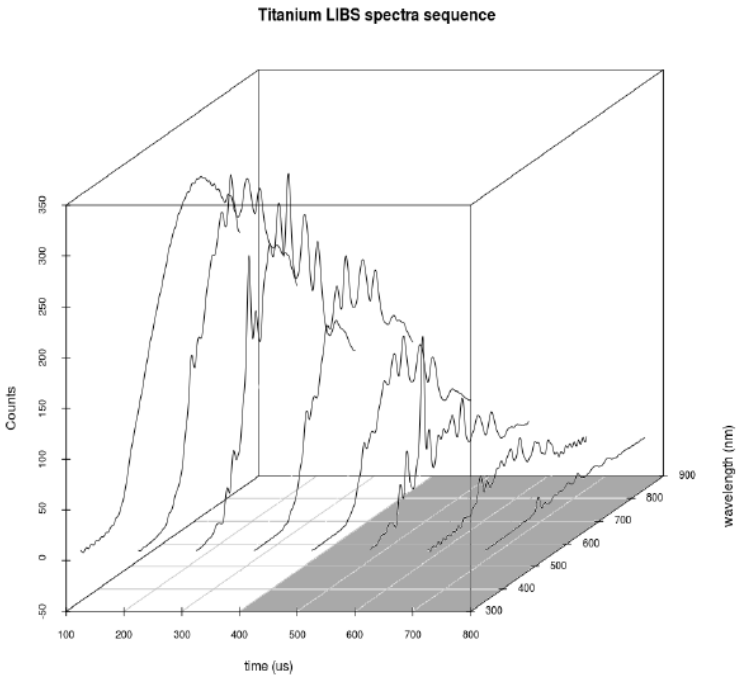
Material	Type	Main Elements
Aluminum	Metal Alloy	Al, Mg, Fe, Zn, Cr
Copper	Metal Alloy	Cu, Zn, Ni
Iron	Metal Alloy	Fe, Mg, Zn
Stainless Steel	Metal Alloy	Fe, Cr, Ni, C, P
Brass	Metal Alloy	Cu, Zn, Sn, Fe
Titanium	Metal Alloy	Ti, Al, V
Calcite	Mineral	Ca, C, O
Granite	Mineral	Si, Al, K, Ca, Fe
Magnetite	Mineral	Fe, O
Wolframite	Mineral	Fe, Mn, W
Lithium	Mineral	Li, Ca





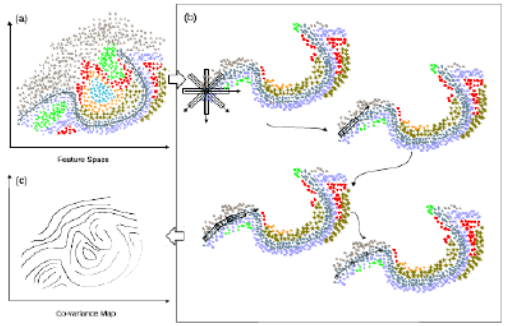
Advances Computer Methods (AI –artificial Intelligence) required

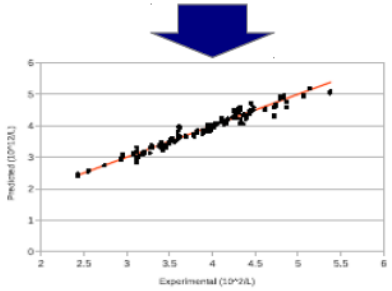
LIBS Spectral Processing For Element Quantification



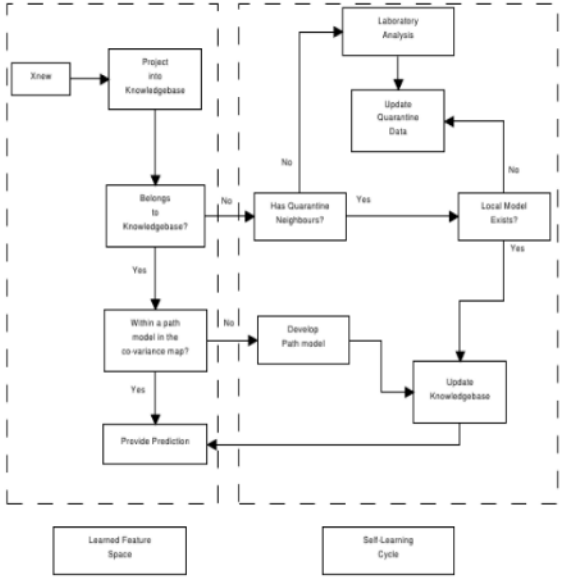
Mineral Dynamic LIBS Fingerprinting
(Tensor Data)

All minerals will have a particular Dynamic LIBS Fingerprint

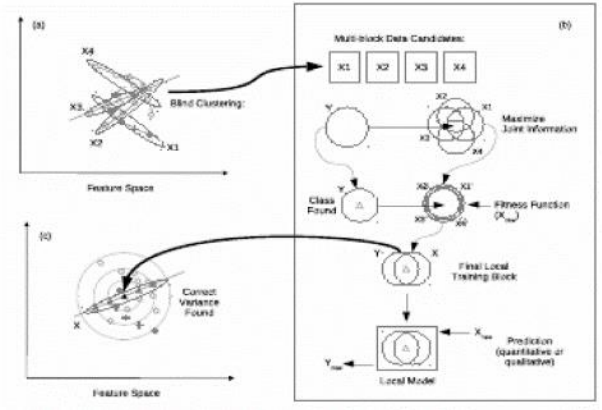




Element Quantification (validation curve)

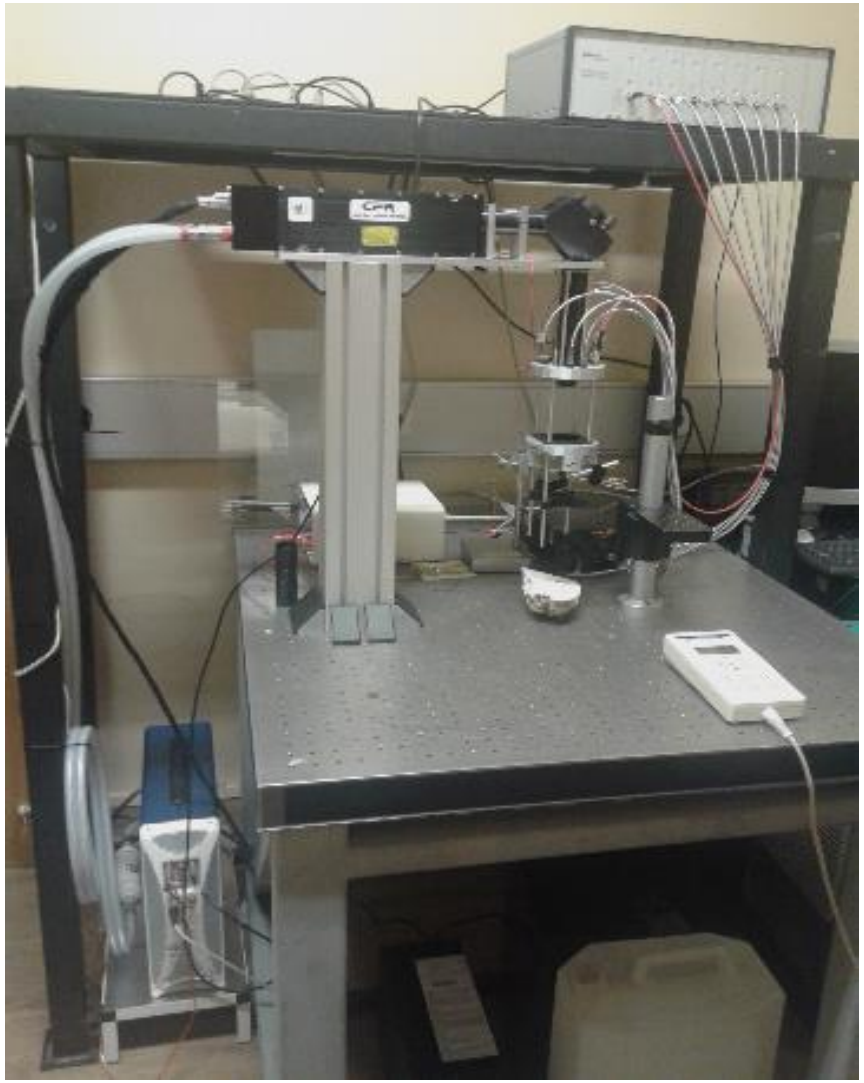


Self-Learning Technology

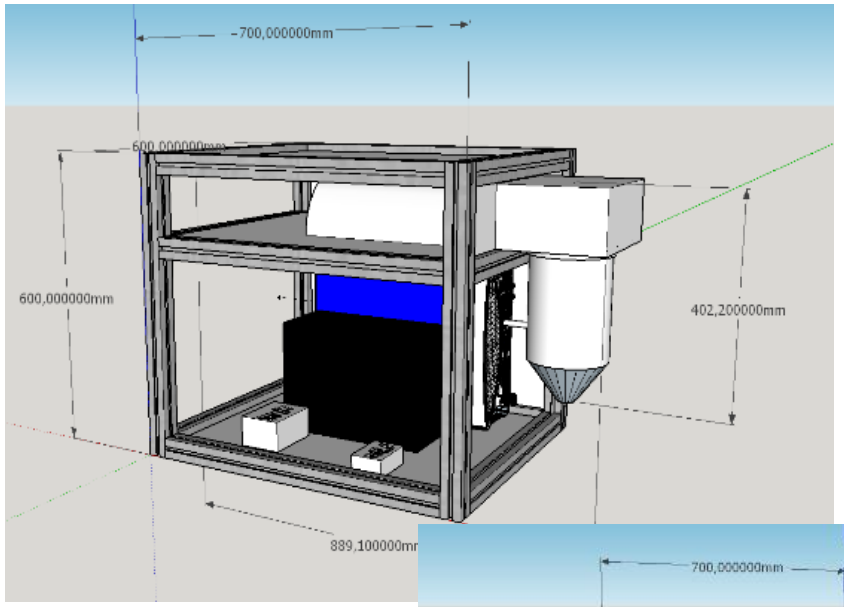


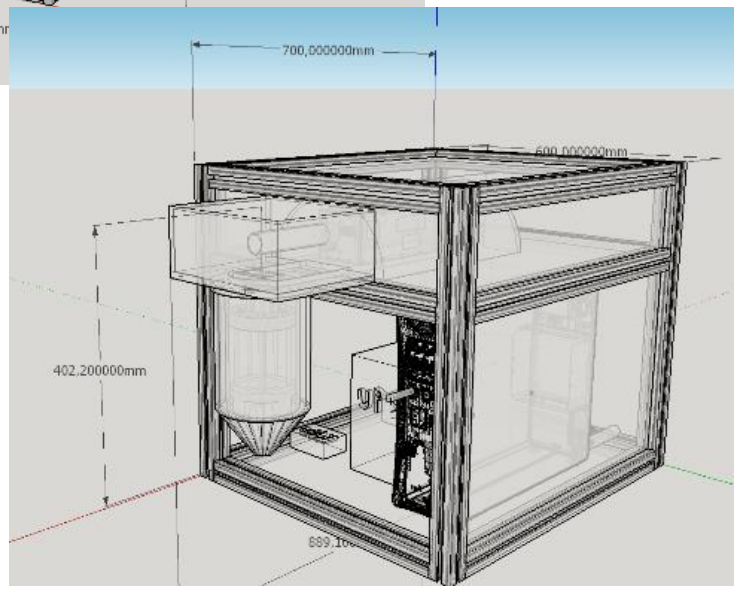
Prototype Assembly

Modular system in LAB

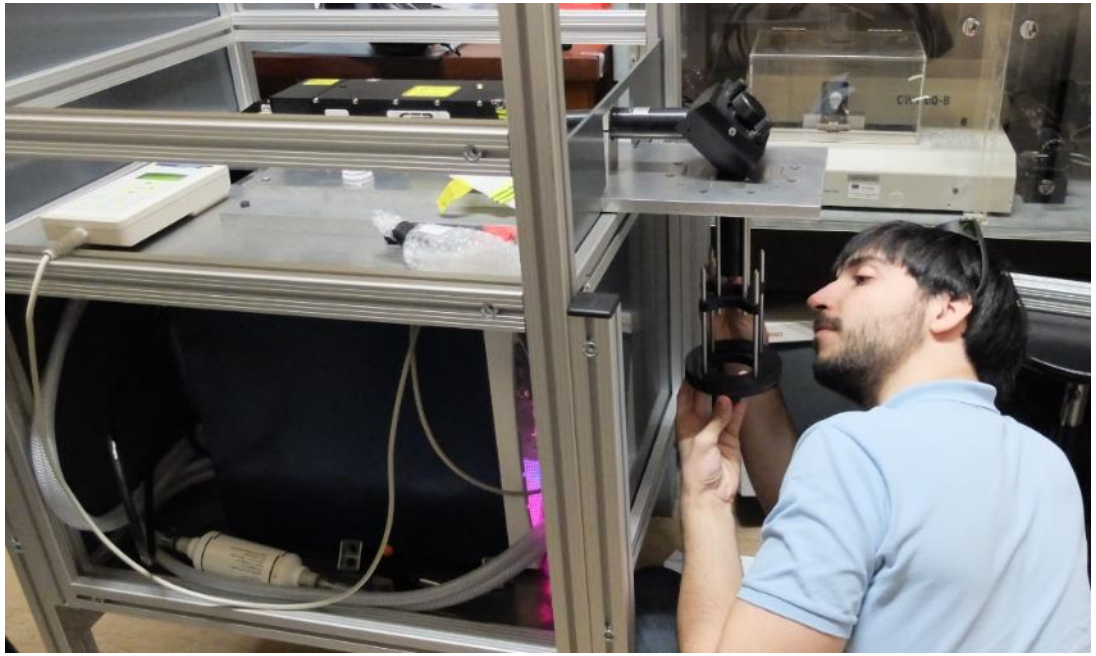


Different arrangements possible for field operation





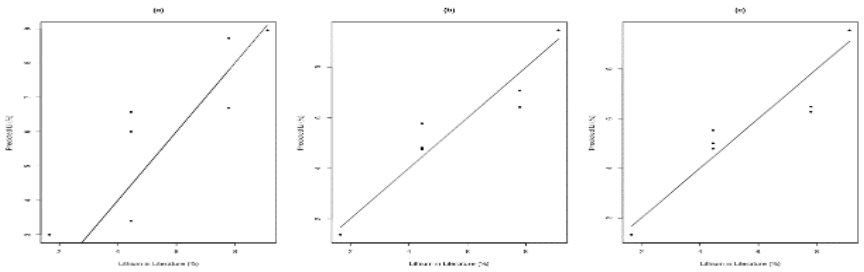
Prototype Assembly



- System modules incorporated prototype for operation at the mine site.
- Initial system validation to be carried out on land.

Preliminary System Validation

- Advanced AI system validated with Lithium case study.
- Successful analysis of complex minerals
- Quantification validated with blind tests.
- **CONFIDENTIAL**



Gelfa Ore
(Lithium veins inside quartz)

Sample 4
(Spodumene)

Sample 7
(Petalite)

Sample 10
(Petalite)

Sample 11
(Petalite)

Sample 13
(Elveite)

Sample 16
(Spodumene))

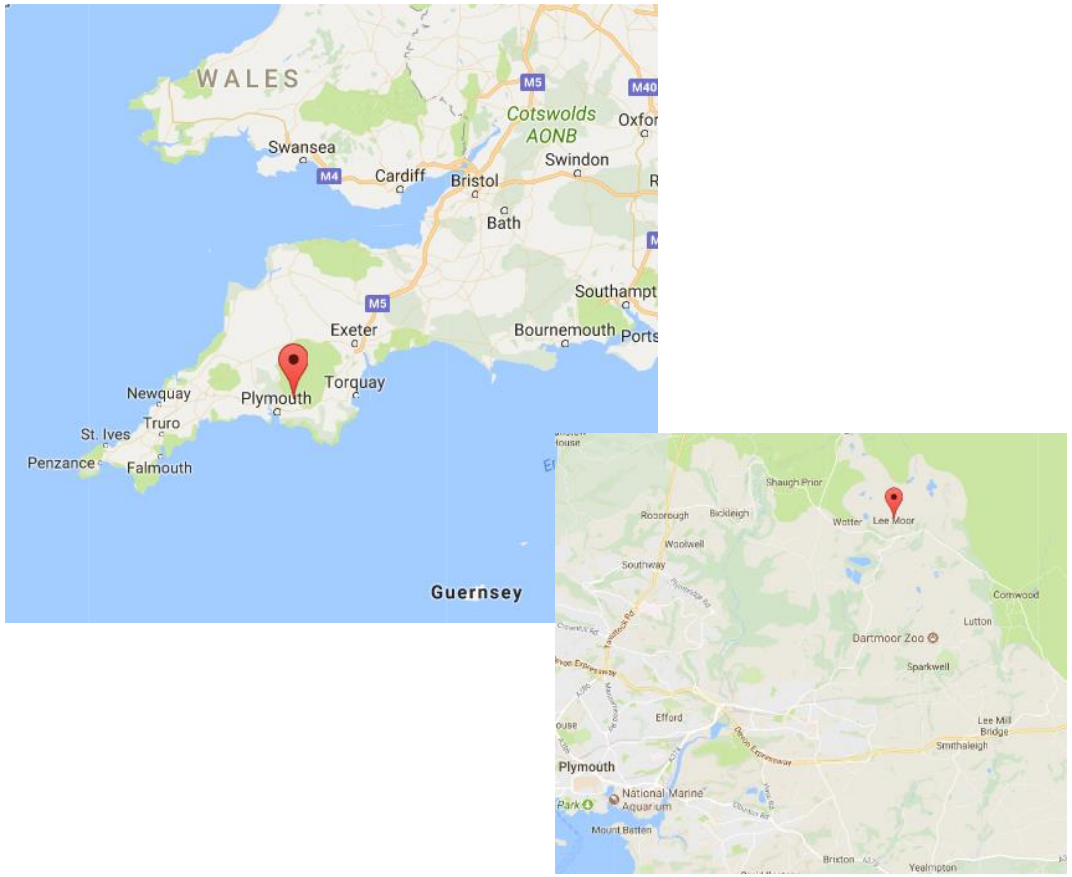
Sample 31
(Litiophilite)

GEO LIBS VAMOS

Field Trials at Lee Moor, UK

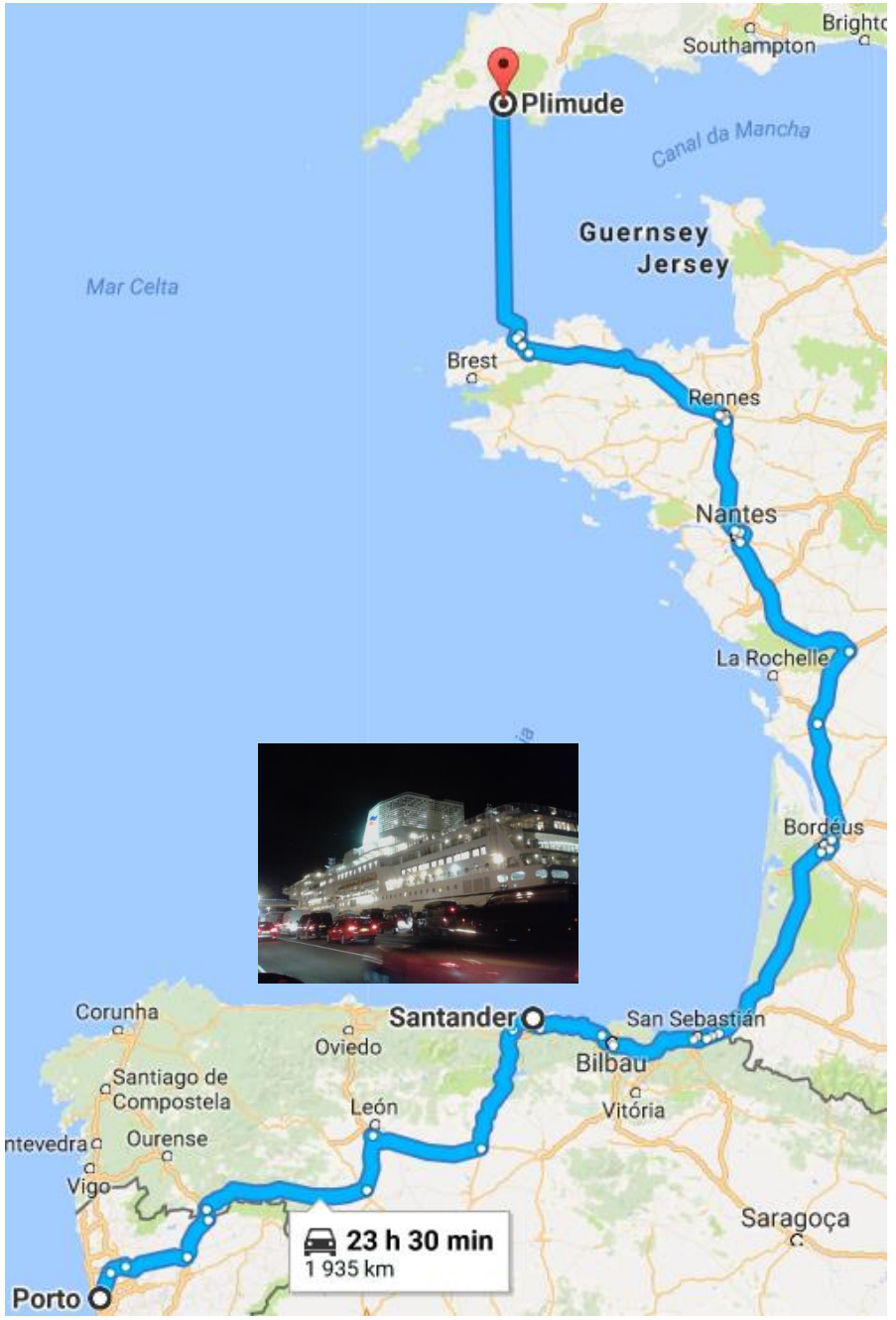
Field Trials at Lee Moor, UK

- **Flooded kaolin mine** pit.
- Owned by Imerys Mineral Ltd.



Field Trials at Lee Moor, UK

- "Portable LIBS System"



Field Trials at Lee Moor, UK

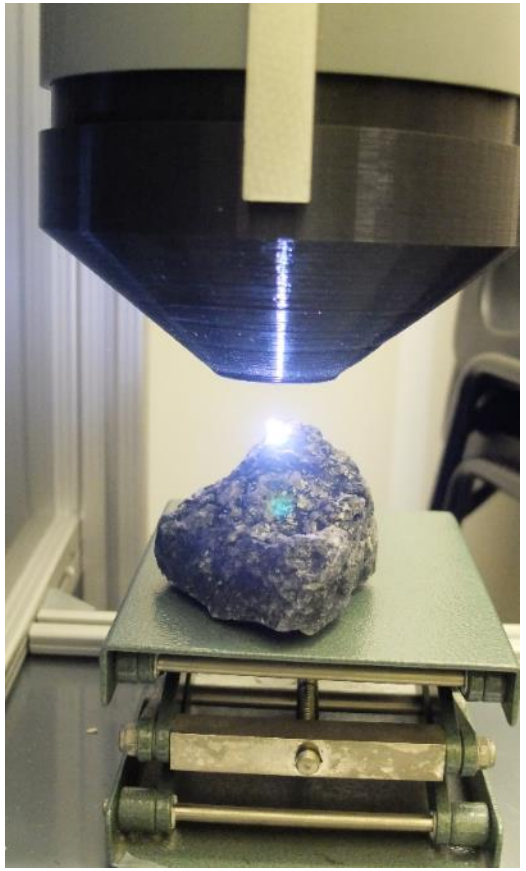
- System Instaled at the mine site.
- A separate “laser” room in technical container.

Field Trials at Lee Moor, UK

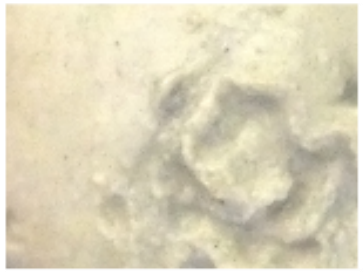
- Samples collected from Slurry pipe output
- Dewatering station output
- From the mining vehicle

Field Trials at Lee Moor, UK

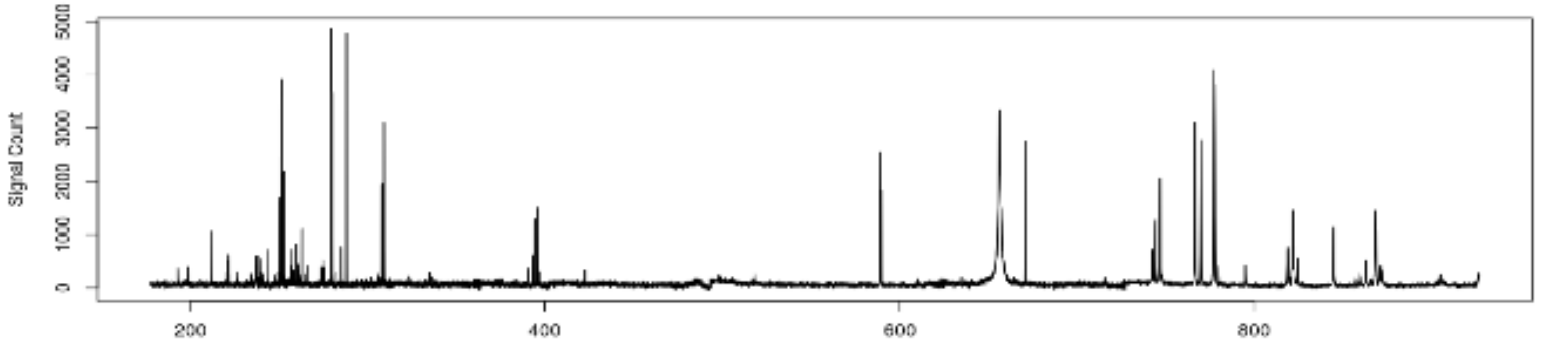
- Sample types
- Different grades of Kaolin
- Different solid samples (granite, others)

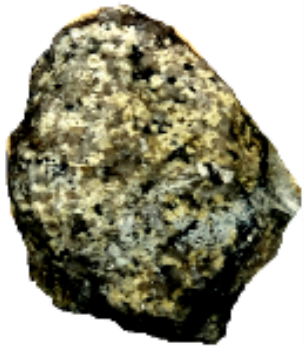


Field Trials Results

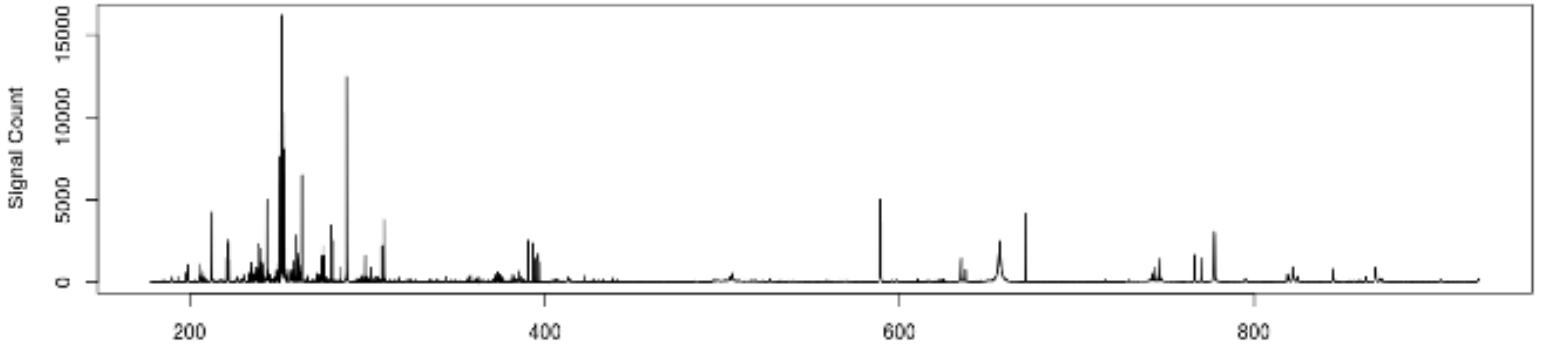


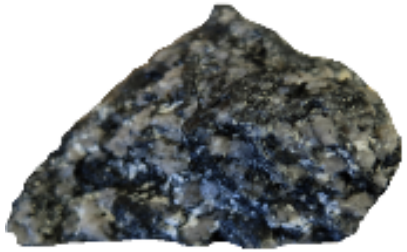
Kaolin



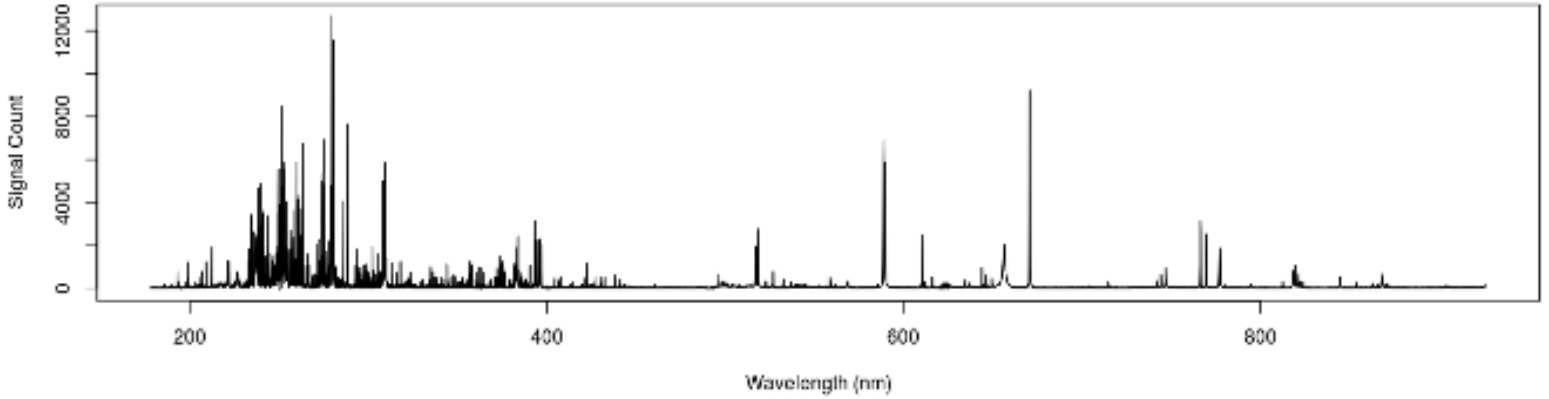


Granite



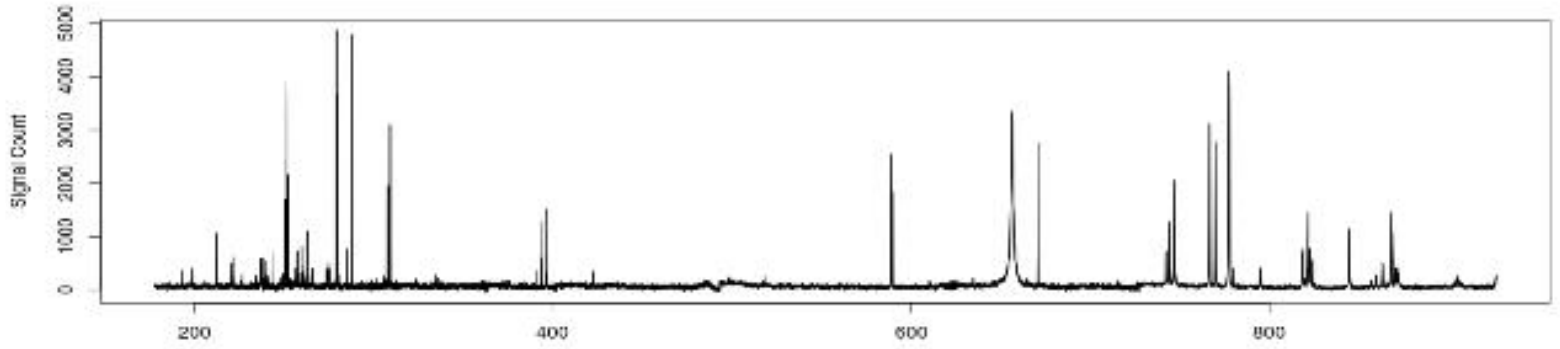


Black Rock

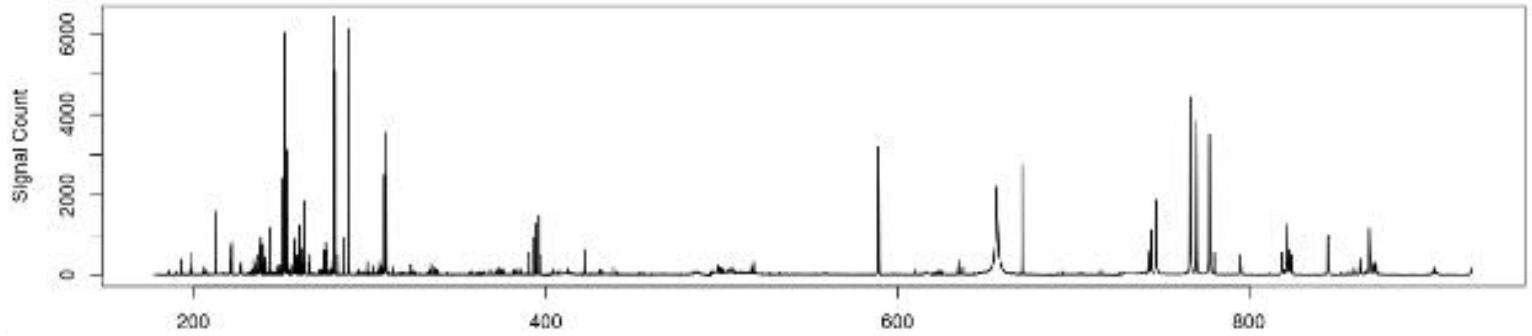


Field Trials Results

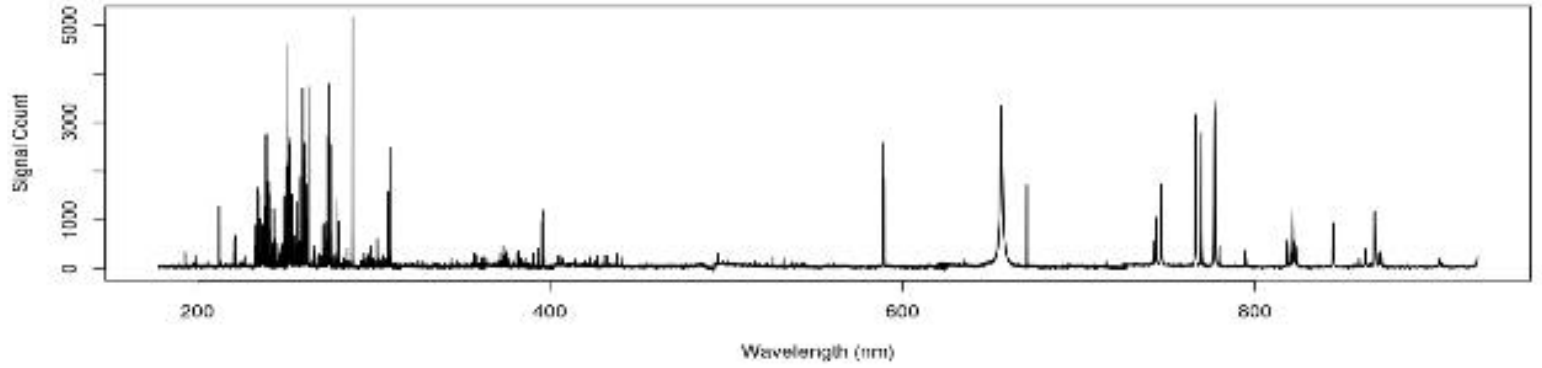
Kaolin



Kaoline in Granite

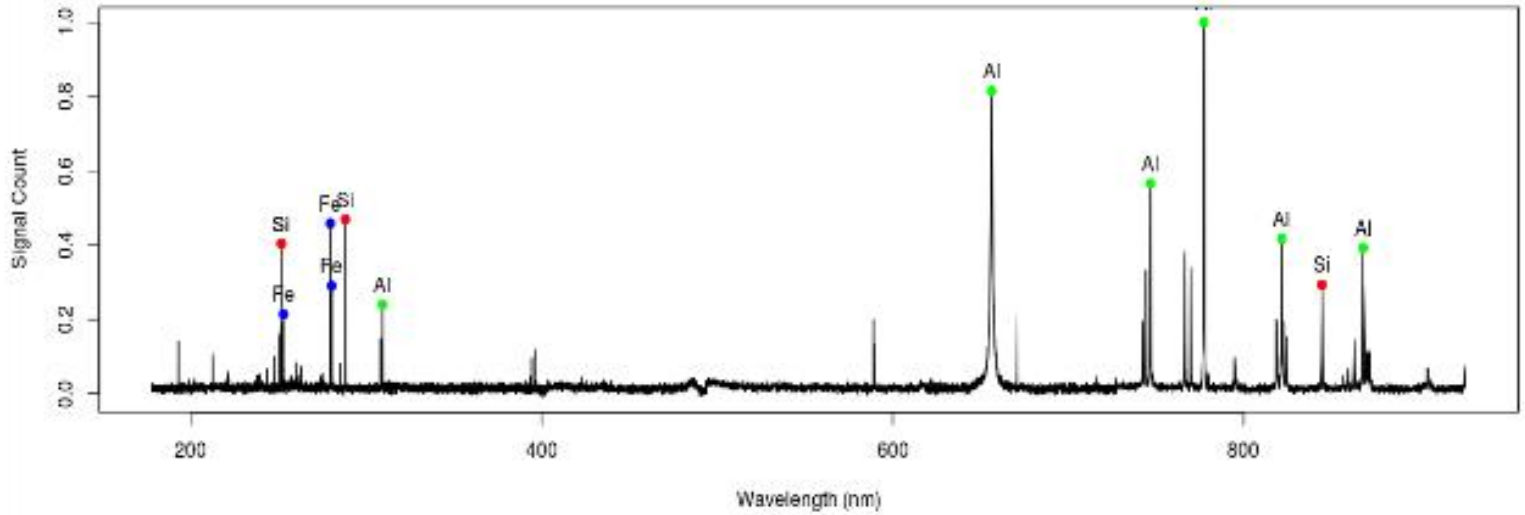


Kaoline in Sand Deposit



Field Trials Results

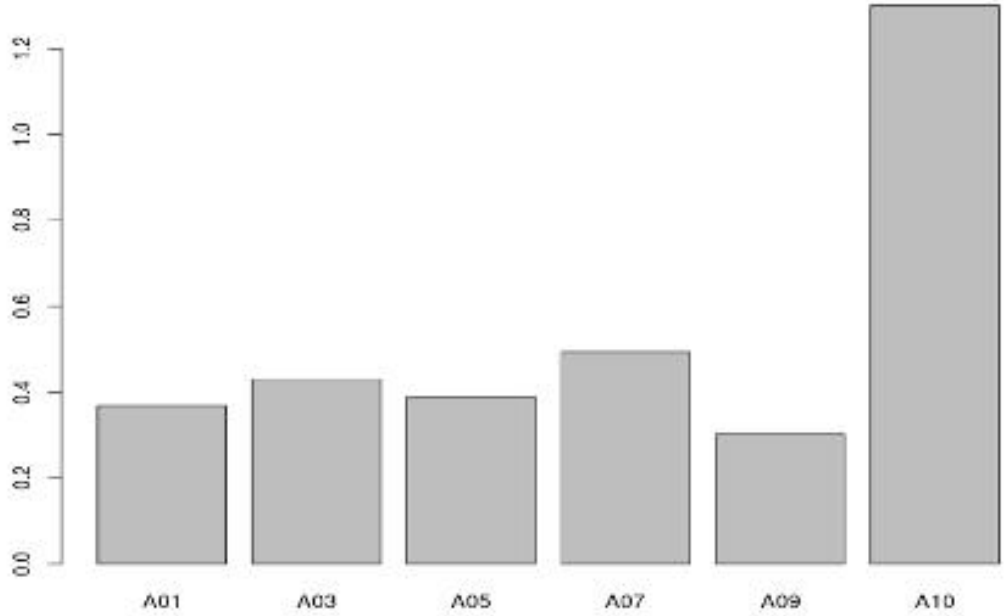
Kaoline



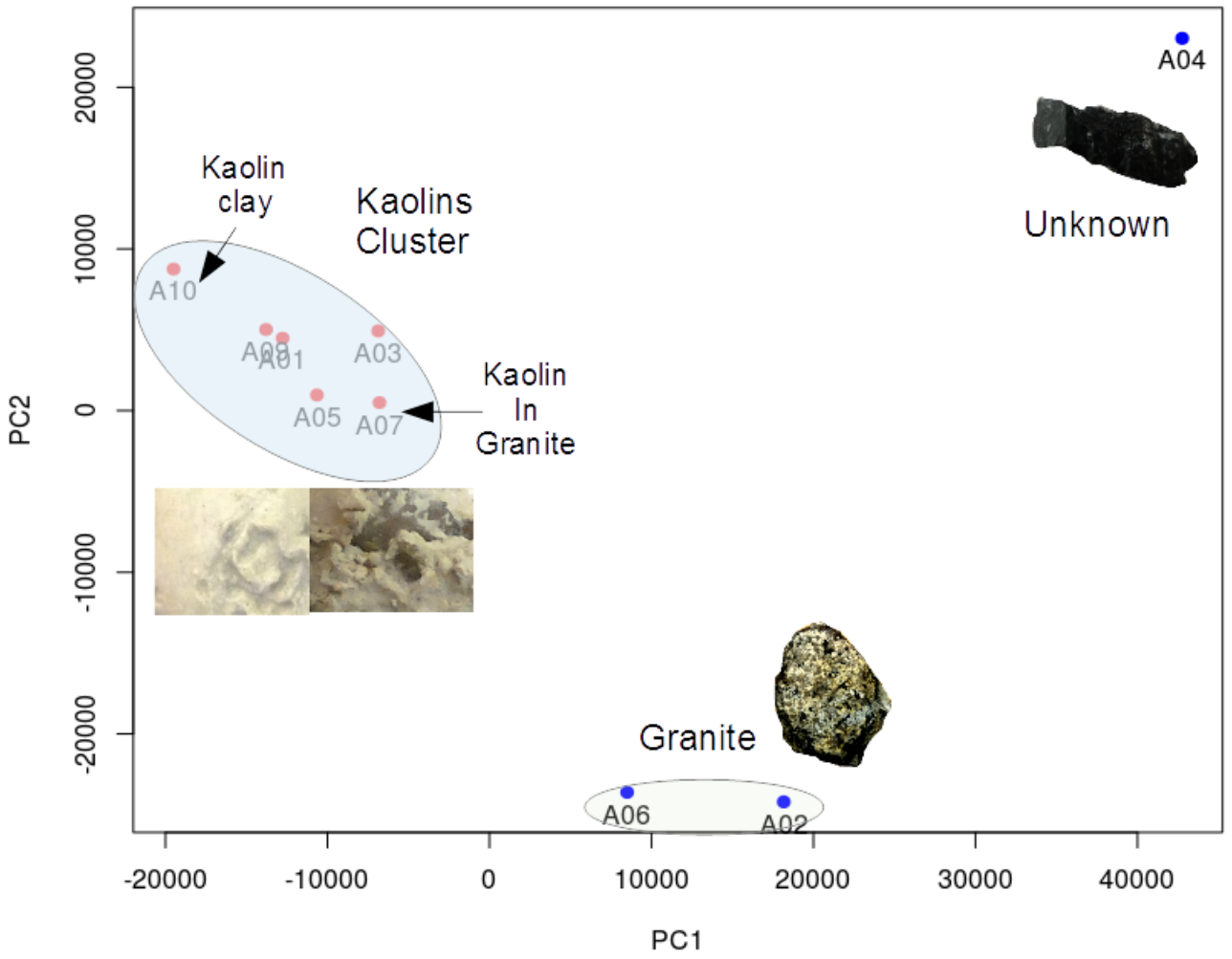
Kaoline Quality Index based on Ratio Si/Al bands

A09

A10



Field Trials Results



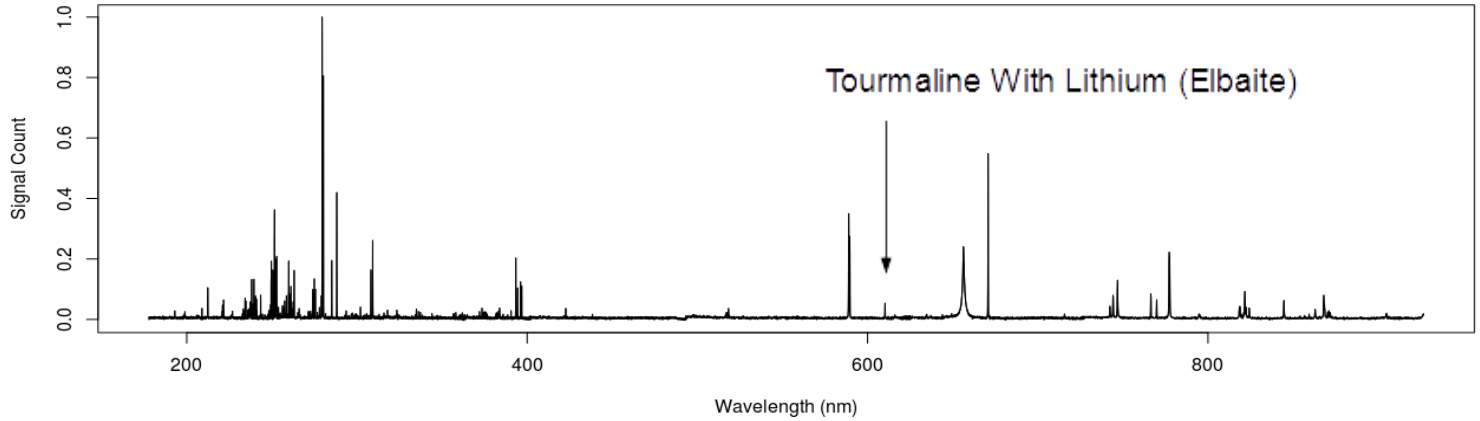
LIBS Feature Space

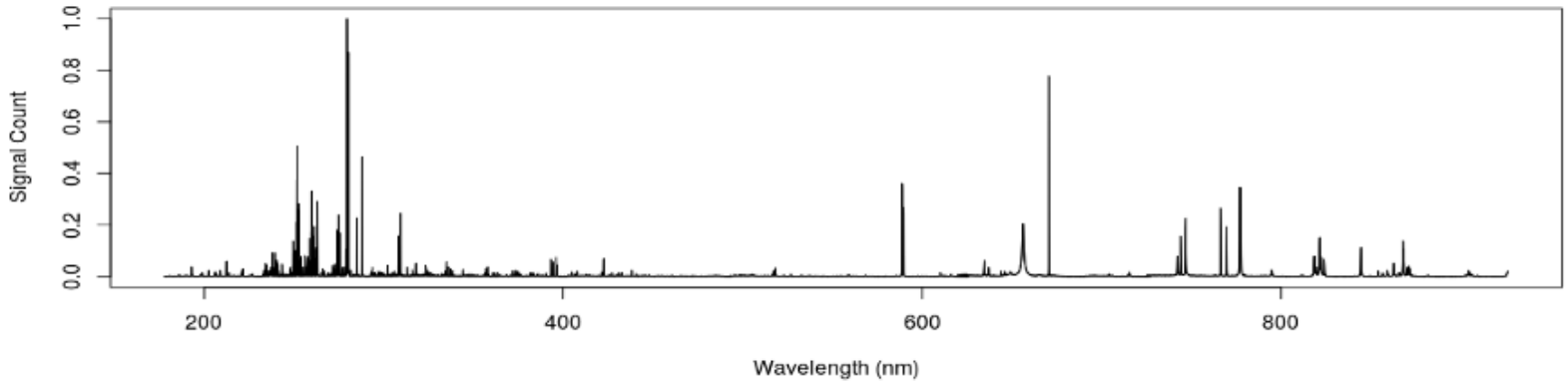
Field Trials Results

Sample A4

Common Peaks: 34
Exclusive Tourmaline: 31
Exclusive S4: 25

Tourmaline

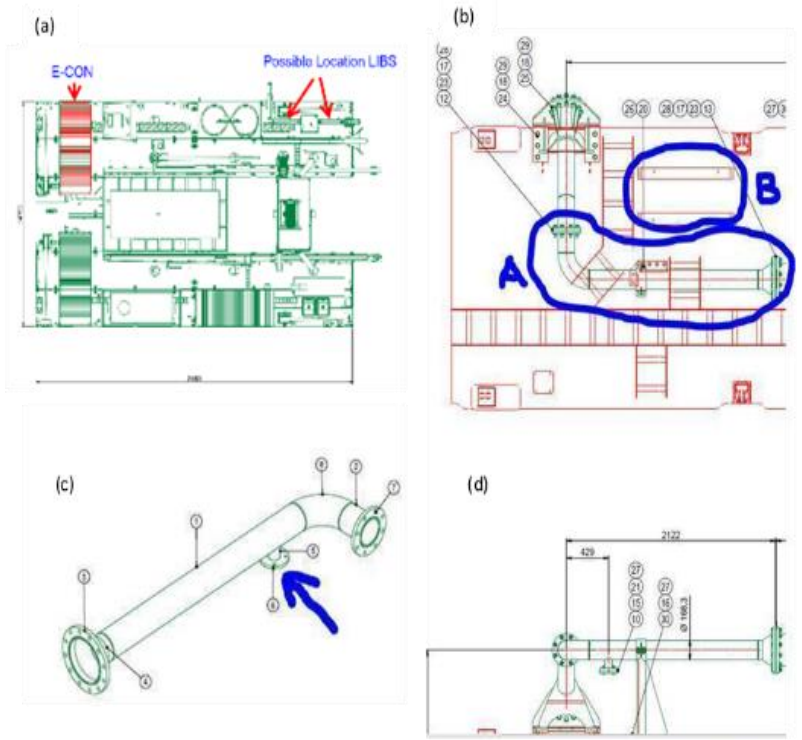




Conclusions and outlook

- **Prototype LIBS system assembled**
- **System AI validated in blind tests (quantification)**
- System validated in field trials in mine site.

- NEXT
- Implement **double pulse solution** for operation in water
- Incorporation of slurry circuit bypass for on-line monitoring



Acknowledgments

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- INESC TEC Centre for Robotics & Autonomous systems

- Pedro Jorge (Optical sensors /LIBs /Spectroscopy)

- Rui Martins (LIBS/spectroscopy/signal processing)

- Miguel Ferreira (Optics/Spectroscopy)

- Carlos Gaspar (Electronics)

Enjoy Portugal!