Optical emission spectroscopy in electric arc furnaces and ladle furnaces – from laboratory to industrial applications

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Process metallurgy research unit

Approximately 35 researchers (picture from 2019)

RESEARCH FOCUS AREAS **(scientific results during last three years)**

I. Reducing agents and reduction metallurgy (2 PhD, 5 M.Sc., approx. 20 pubs)
II. Primary and secondary metallurgy (3 PhD, 5 M.Sc., approx. 25 pubs)
III. Recycling and sustainable metallurgical processes (1 PhD, 4 M.Sc., approx. 25 pubs)
IV. New measurement and treatment methods in metallurgy (2 PhD, 3 M.Sc., approx. 30 pubs)
- Microwaves, laser-based methods, optical emission and Raman spectroscopy

Our OES studies

Characterization of the electric arc

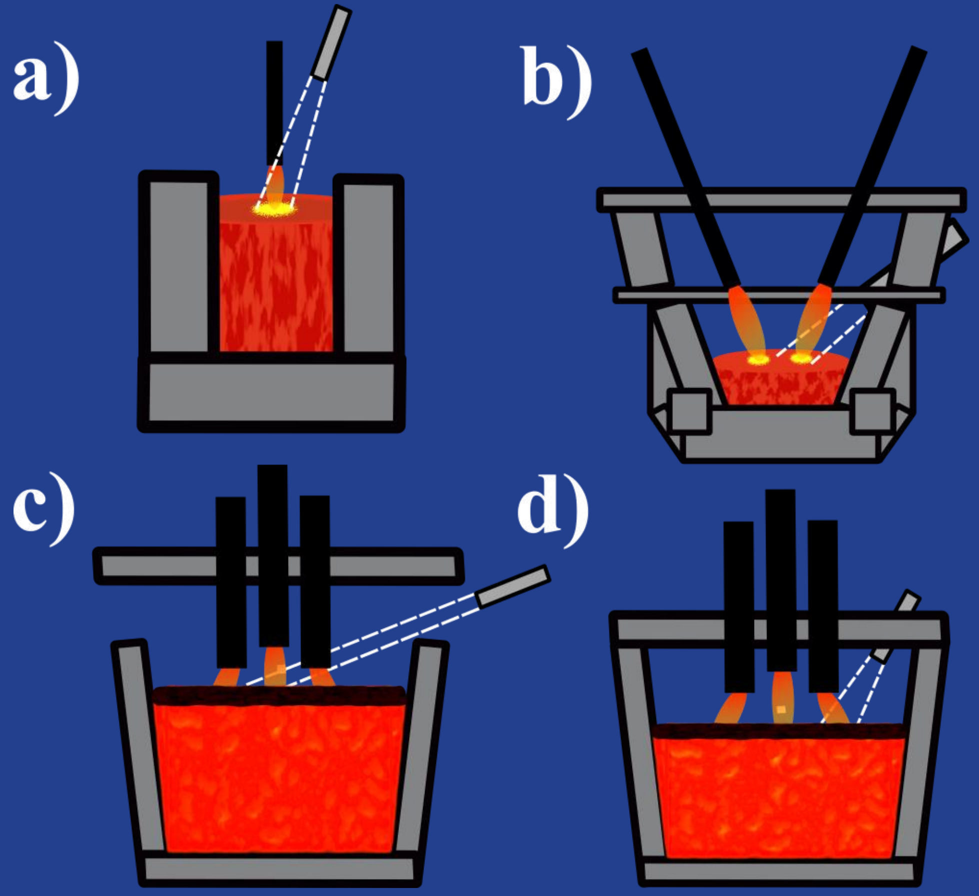
- Temperature of the plasma
- Electron density of the plasma
- Local thermodynamic equilibrium (LTE) assessment
- Electric arc image analysis

Online process control

- Online slag composition analysis
  - Slag components in the spectra: Cr, Fe, Ca, Mg, Mn, Al, Si, Ni, V, Ti
  - Also Na, K, Rb, Cs, Li, N, O, C, H
- Process condition monitoring

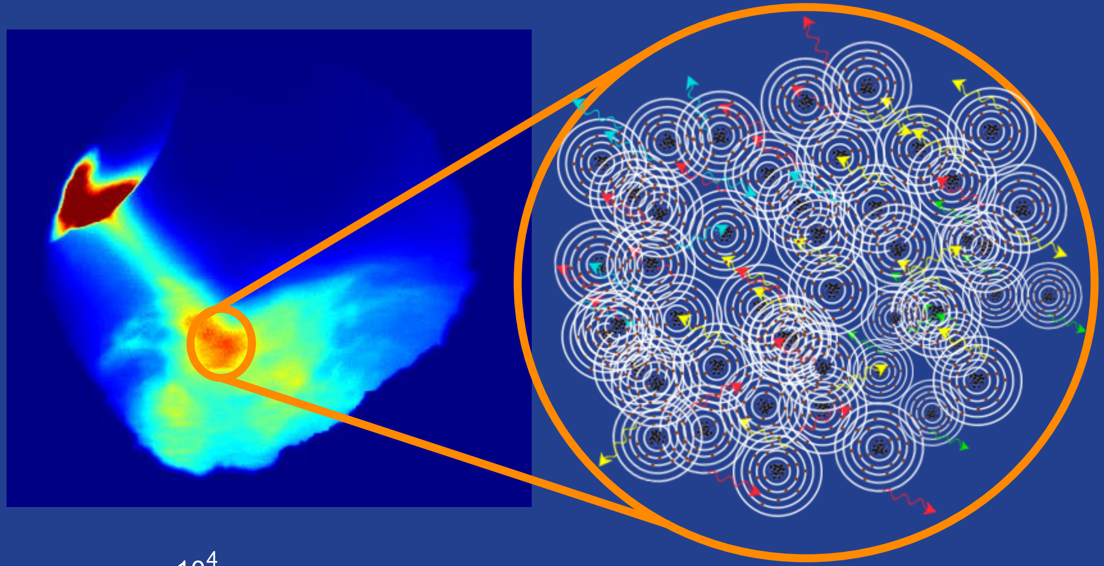
Measurements have been conducted in

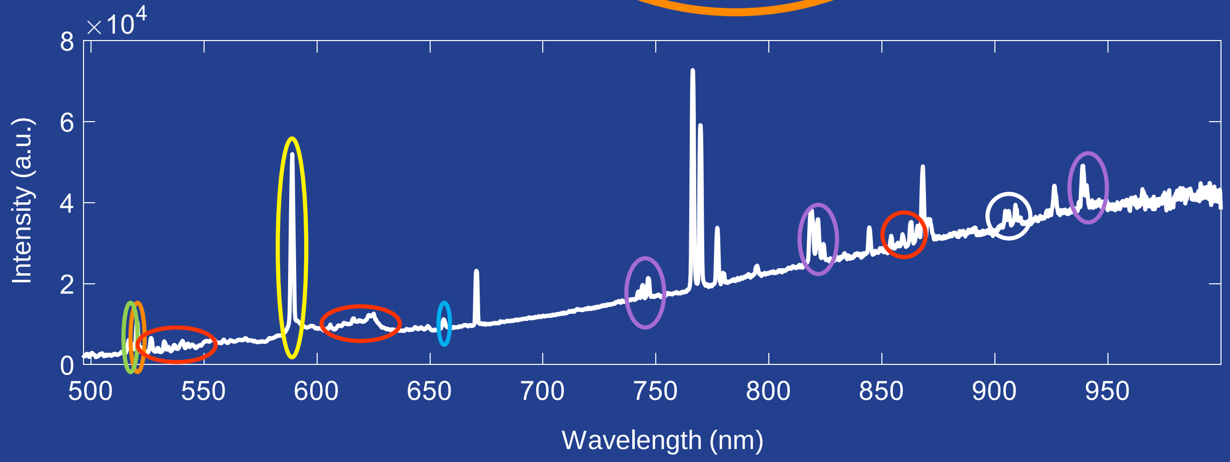
- Laboratory (NANOMO, KTH)
- Pilot-scale (RWTH Aachen)
- Industrial electric arc furnaces and ladle furnaces



Schematic illustrations of the OES setups for
a) laboratory scale (can also be a closed chamber),
b) pilot-scale,
c) industrial ladle furnace, and
d) industrial electric arc furnace

Electric arc OES





The high energy of the electric arc forms plasma

- Plasma consists of both charged and neutral particles (electrons, ions, atoms, molecules, etc.)
- The plasma contains material from the molten bath, atmosphere, and electrodes
  - There's a variety of different particles inside the arc

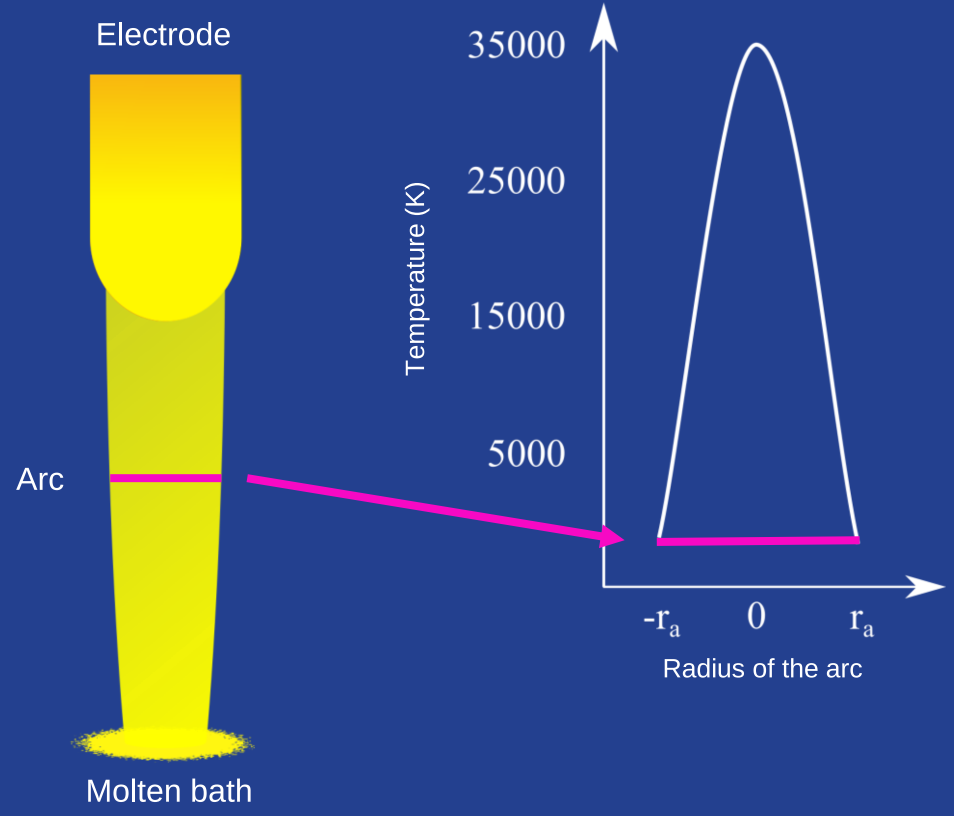
Huge amount of particles radiate inside the arc with their characteristic wavelengths

- Hundreds of emission lines are observed in the arc

The origins of the emission lines can be identified

- Few examples: Cr, Mg, Na, H, N, Ca, C

Arc plasma analytics



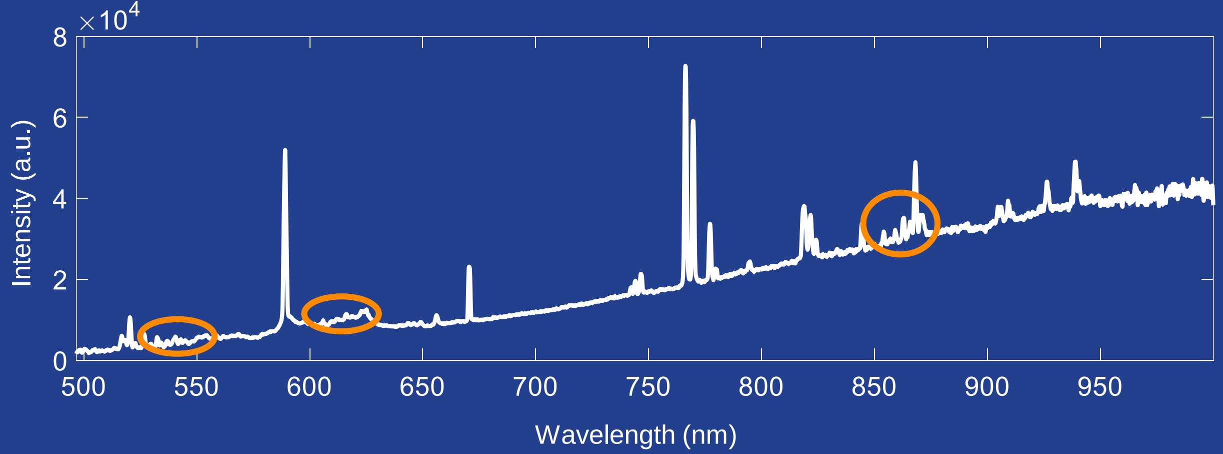
$$7.0 \times 10^{15} \leq \; N_e \; \leq 4.0 \times 10^{17} \; [cm^{-3}]$$

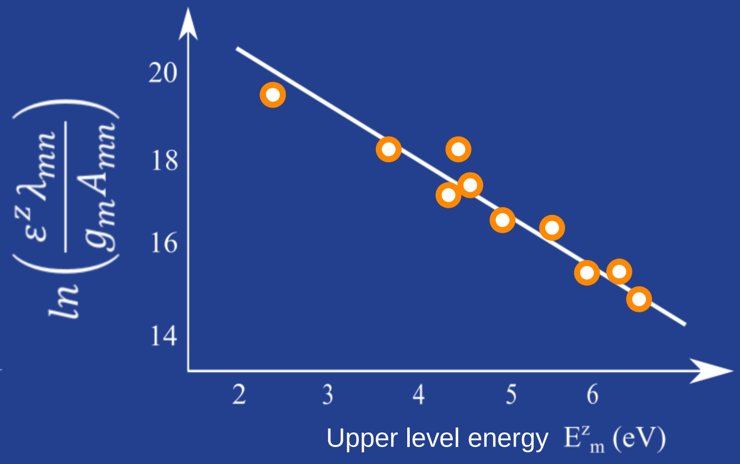
Plasma temperature [1]

$$ln\left(\frac{\varepsilon^z \lambda_{mn}}{g_m A_{mn}}\right) = -\frac{1}{kT} E_m^z + \left(\frac{hcN^z}{4\pi U^z(T)}\right)$$

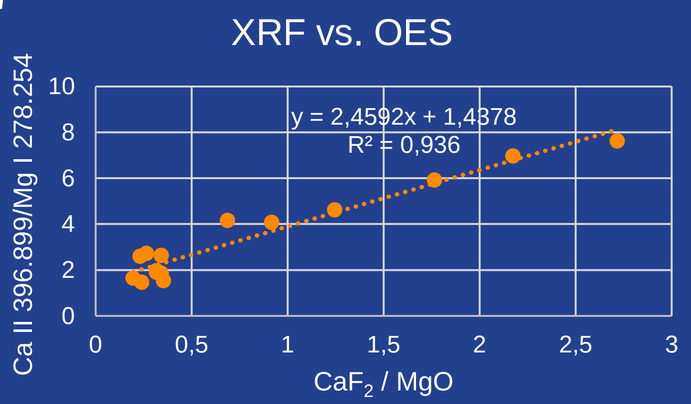
Electron density [1]

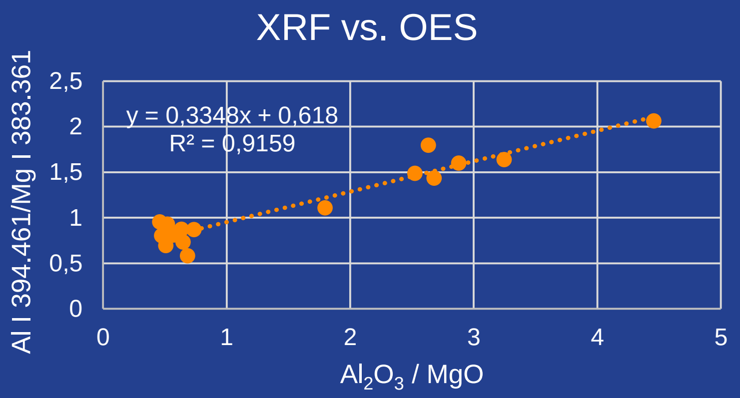
$$N_e = C\sqrt{T^3}\,\frac{I_{mn}^z \lambda_{ij}^{z+1} A_{ij}^{z+1} g_i^{z+1}}{I_{ij}^{z+1} \lambda_{ij}^{z+1} A_{mn}^z g_m^z}\, exp\left(\frac{E_m^z - E_{ion} - E_i^{z+1}}{kT}\right)$$

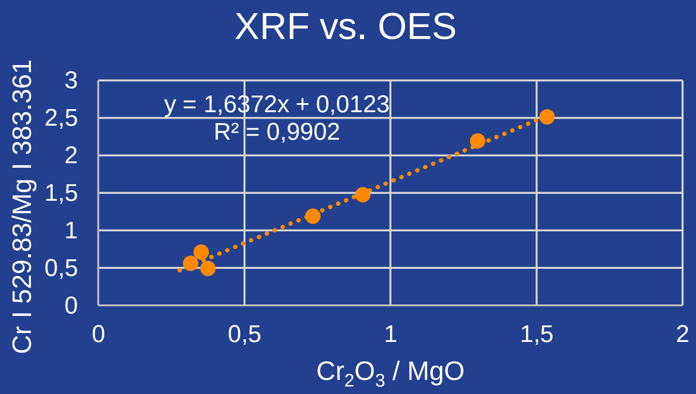


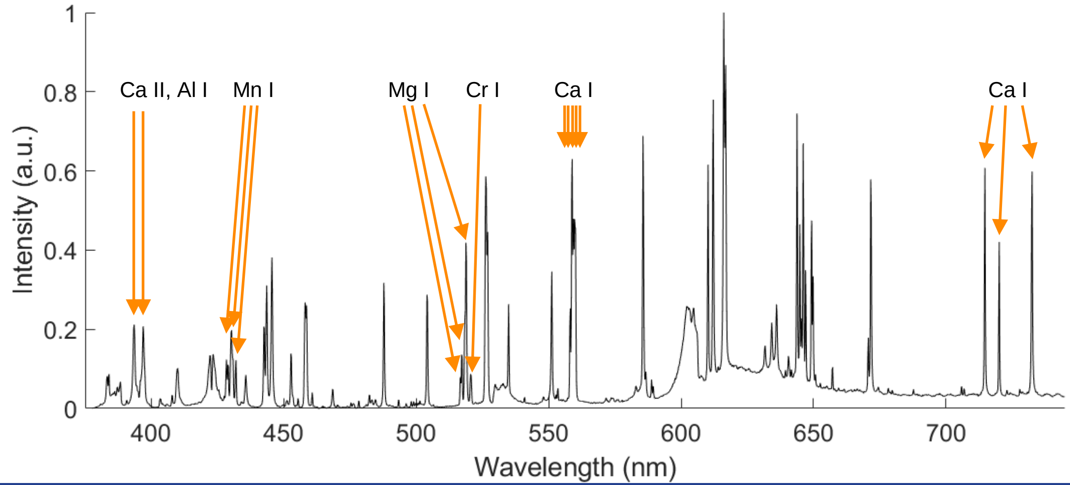


Case study: laboratory arc spectra

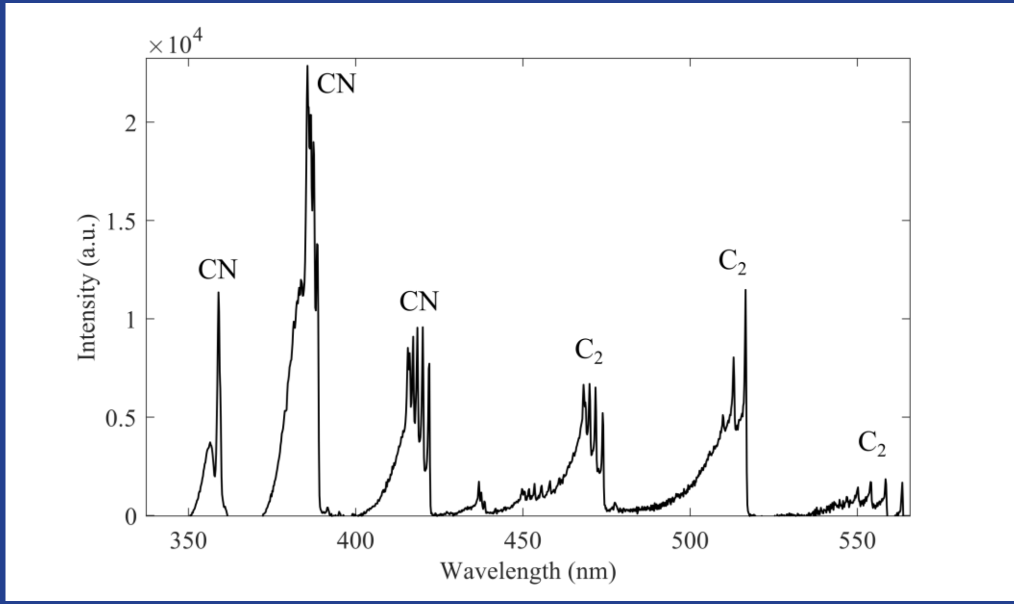






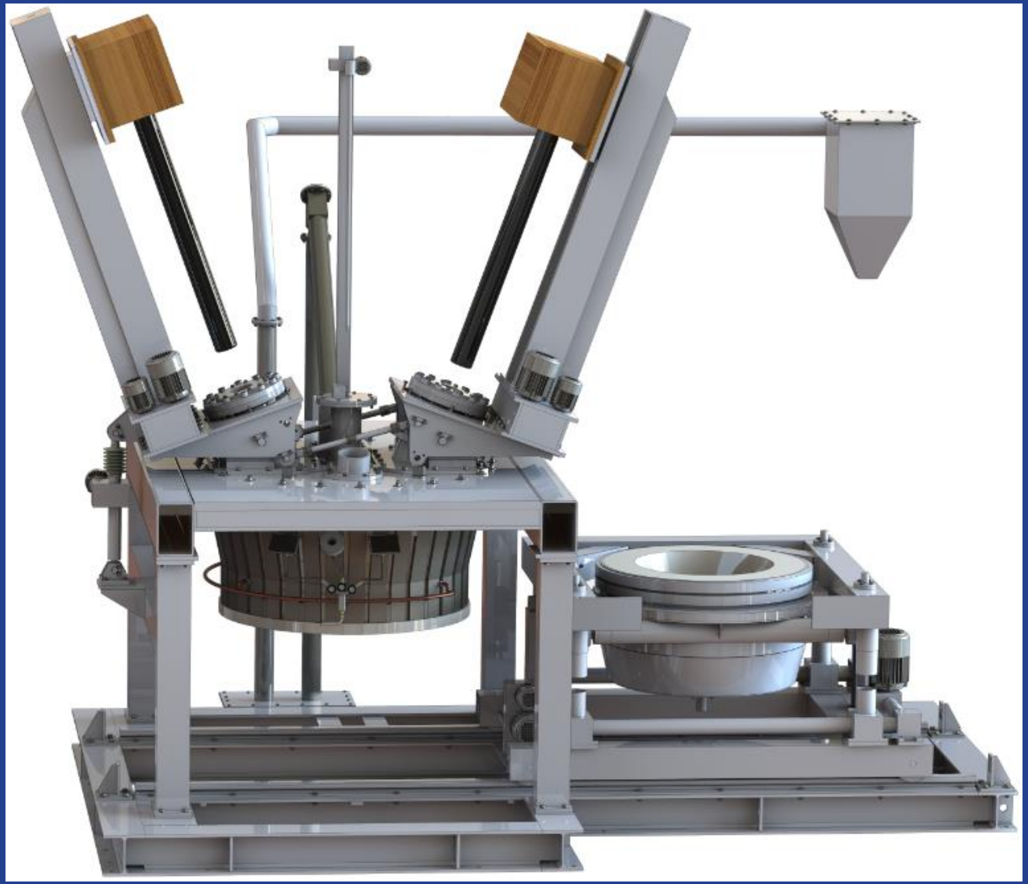


Optical emissions from the slag components



Molecular optical emissions

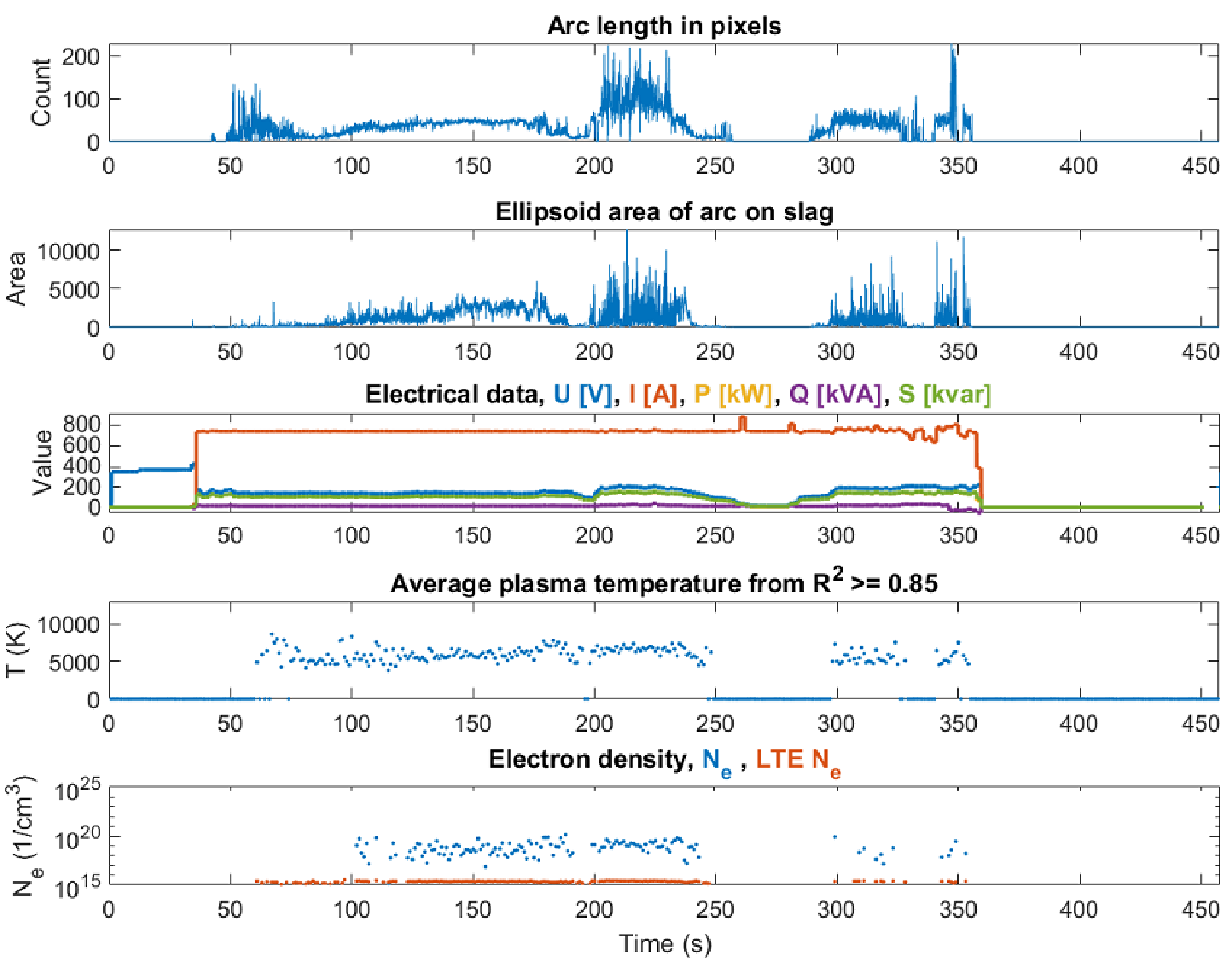
Case study: pilot-scale AC EAF

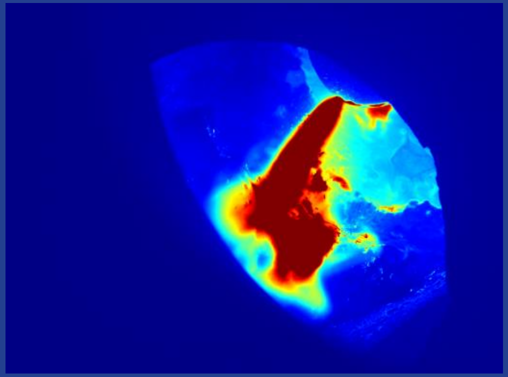


Pilot-scale EAF at Aachen (Germany) [2]

– **Pilot-scale AC EAF**
  - Capacity 200 kg, 2 graphite electrodes
  - Three spectrometers (AVASPEC) and single-lens reflex camera (Baumer)
    - Located on top of the furnace
    - Spectrometers from Luxmet (Oulu)

Case study: pilot-scale data





Arc length

Area on slag surface

Electrical data of the furnace

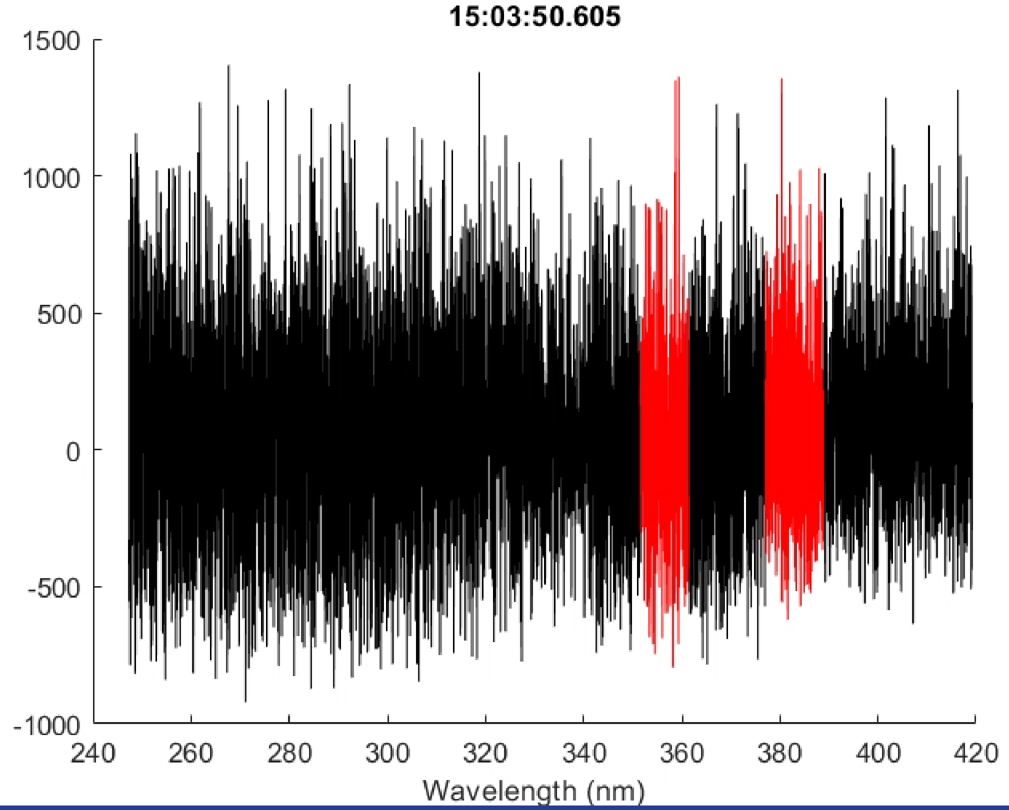
Plasma temperature with Cr I lines

Electron density with Ca I and Ca II lines

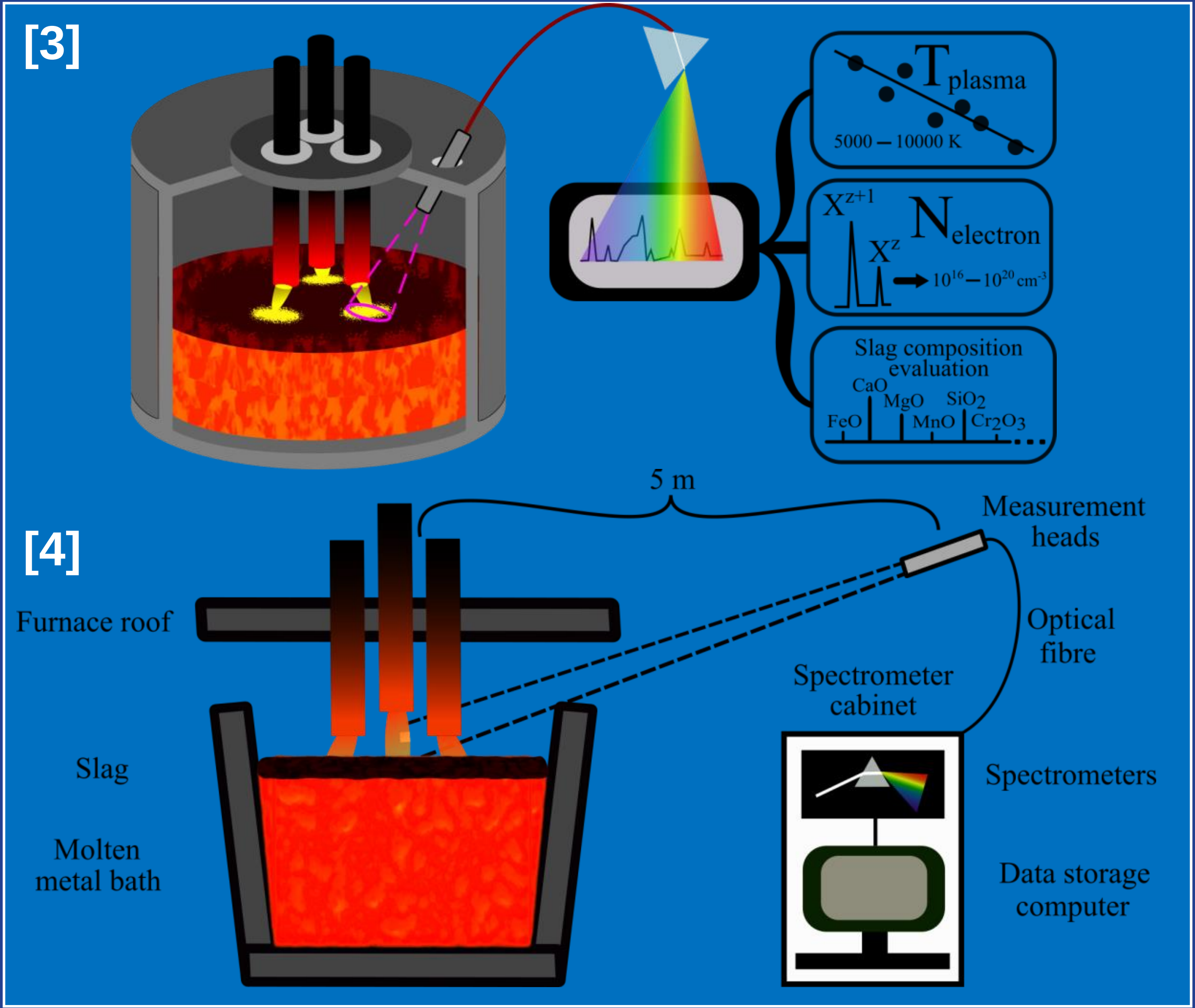
Case study: CN recombination in plasma

Molecular optical emissions from CN have been highlighted with red color

View into the pilot-scale AC furnace (camera and spectrometers at the furnace roof)



OES studies in industrial furnaces



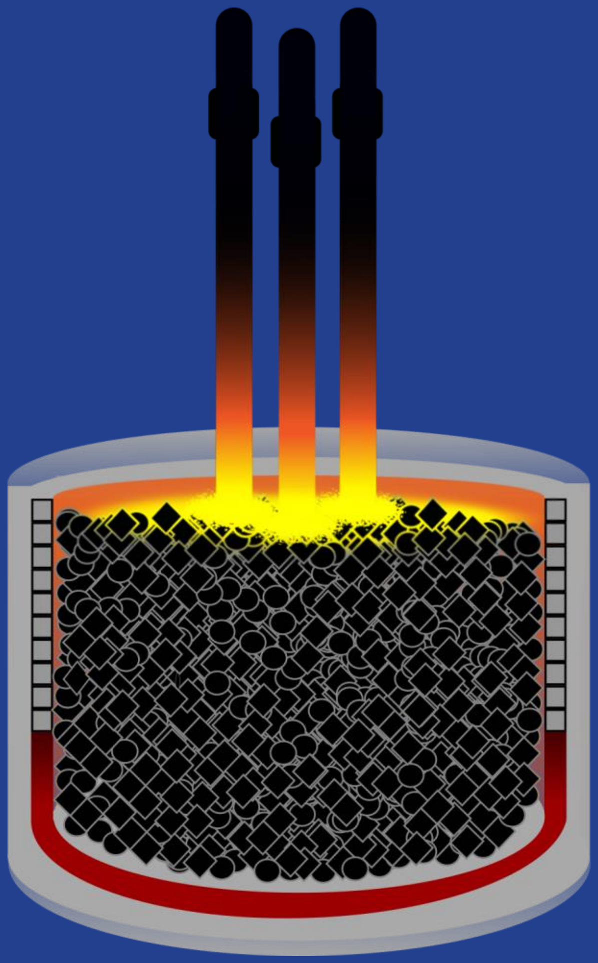
Electric arc furnace

- Process condition monitoring
- Radiative heat transfer in different steel grades
- Plasma analytics
- Slag component evaluation

Ladle furnace

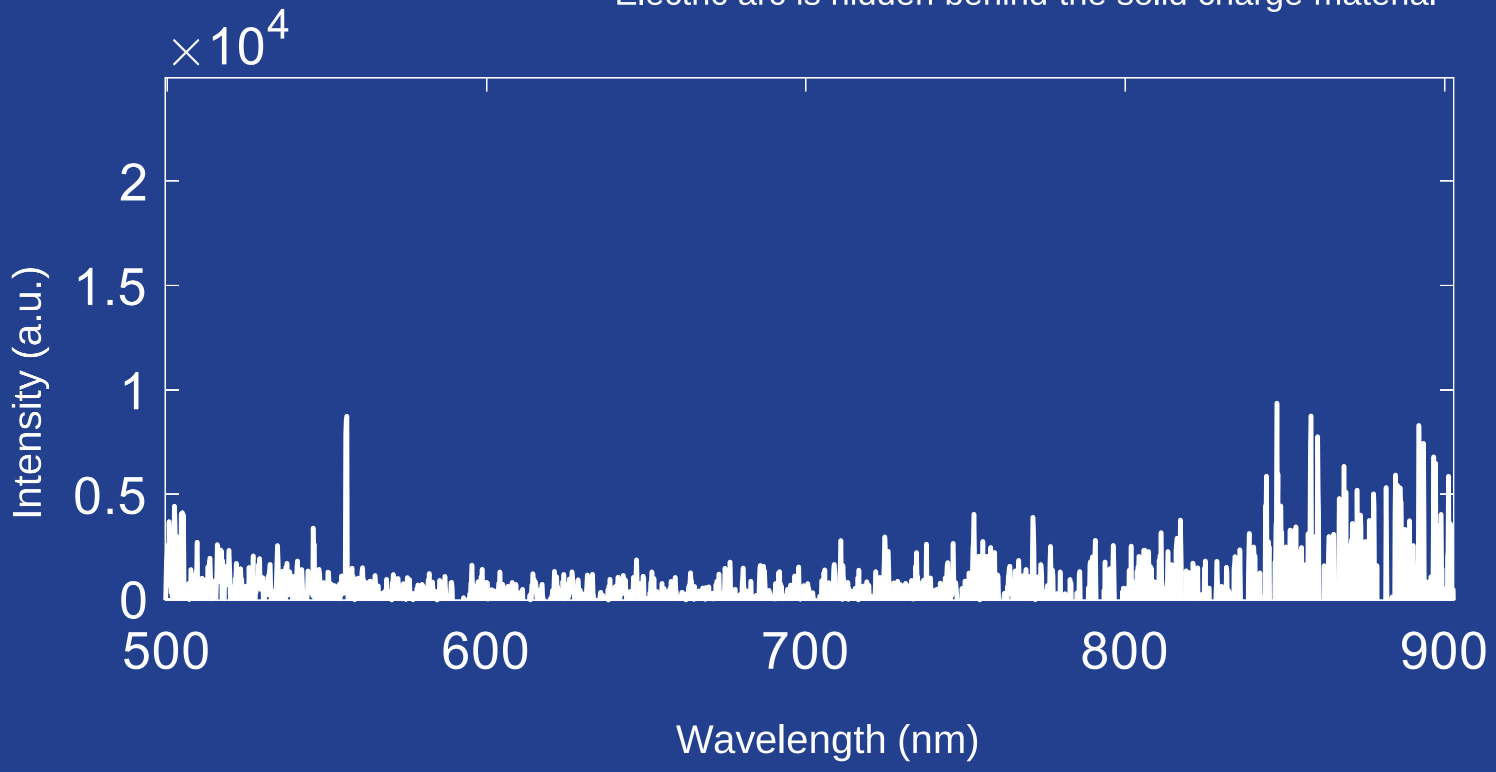
- Slag composition analysis (focus has been on MgO, MnO, CaF_2, CaO)
- Manuscript: molecular optical emissions from CaO and CaF

Electric arc furnace process

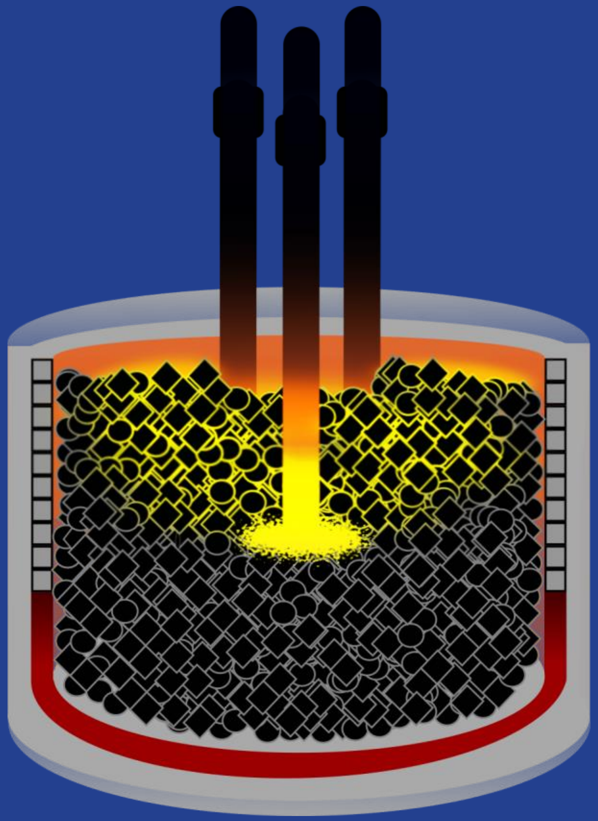


Ignition

- Beginning of the melting process
- Practically nothing is observed in the spectra
    - The arc can be observed momentarily depending on its visibility
    - Electric arc is hidden behind the solid charge material

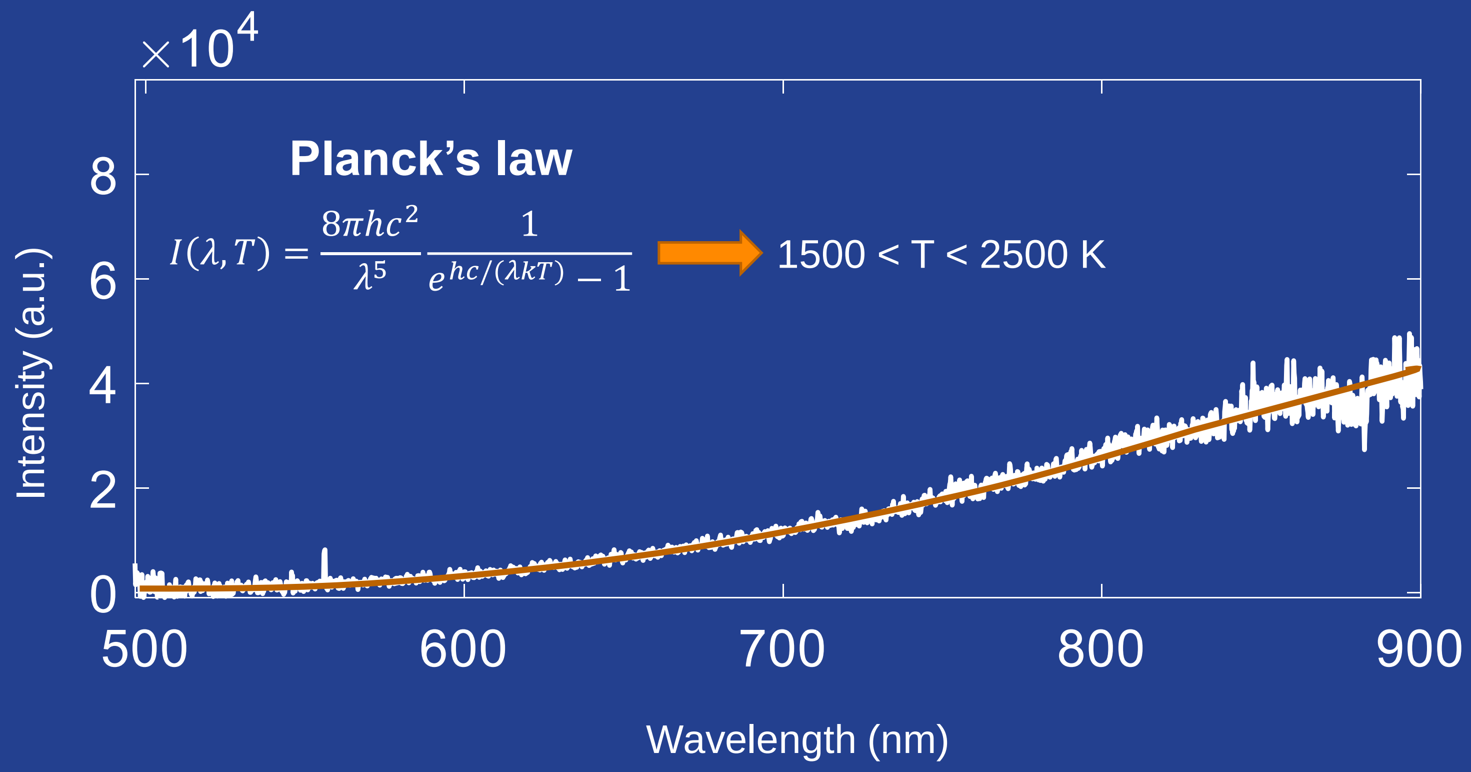


Electric arc furnace process



Drilling/boring

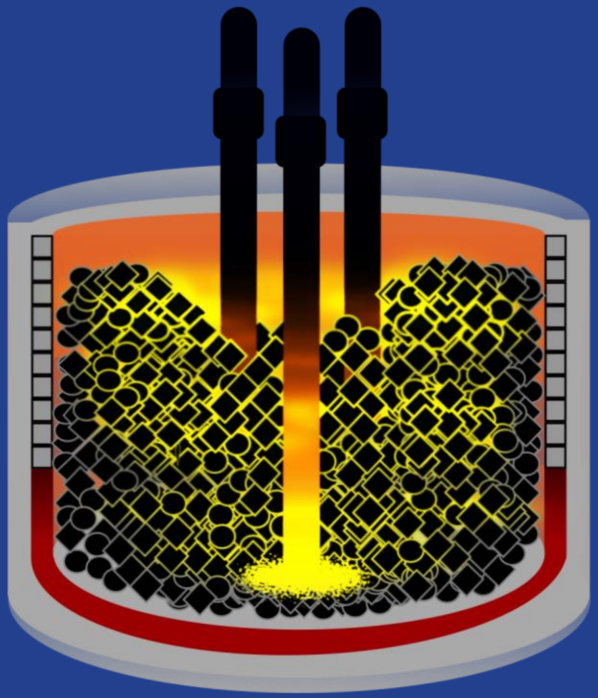
- Electrodes are lowered
- Heat radiation from the melting material is observed

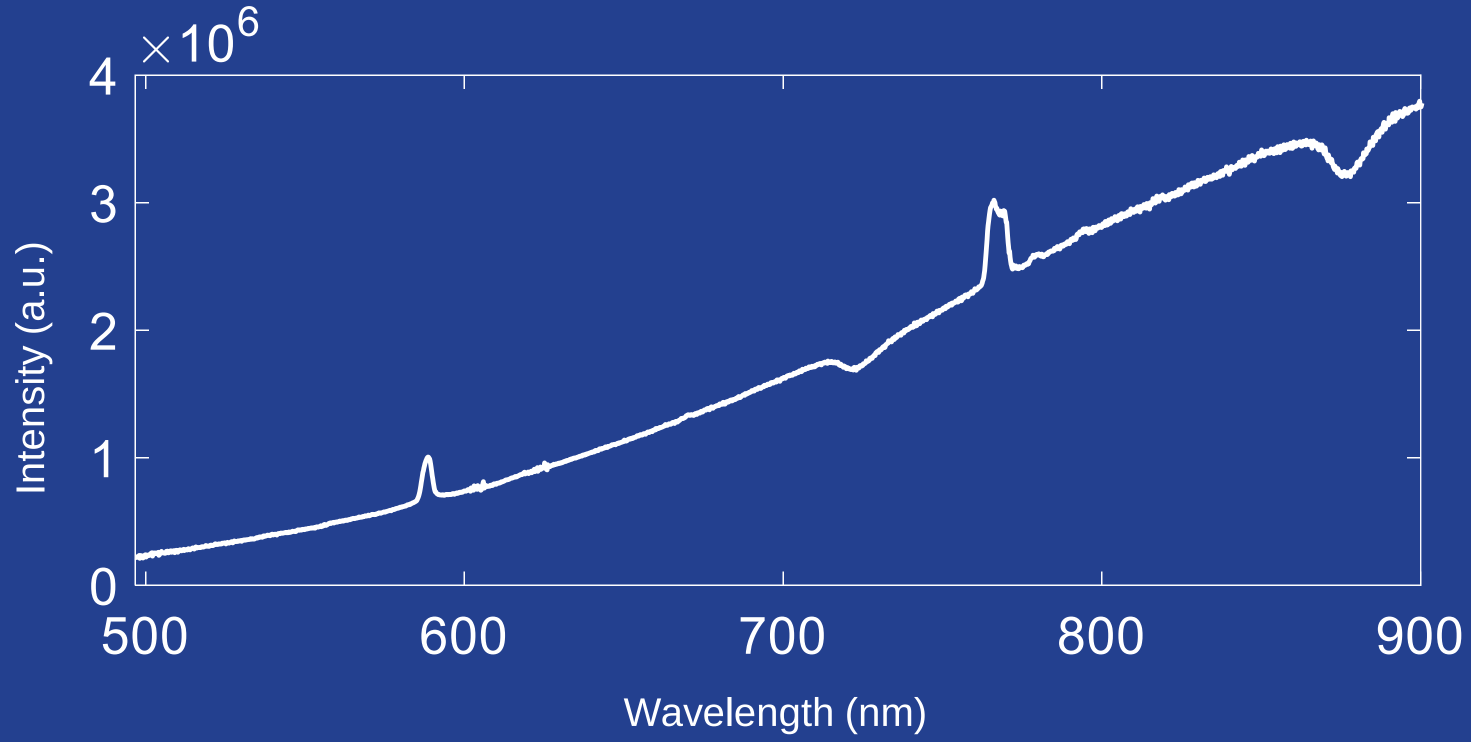


Electric arc furnace process

Beginning of the formation of the molten bath

- Electrodes are at their lowest position
- Solid charge material blocks the view to the arc
- Alkali emission lines are observed in the spectrum (Na, K)

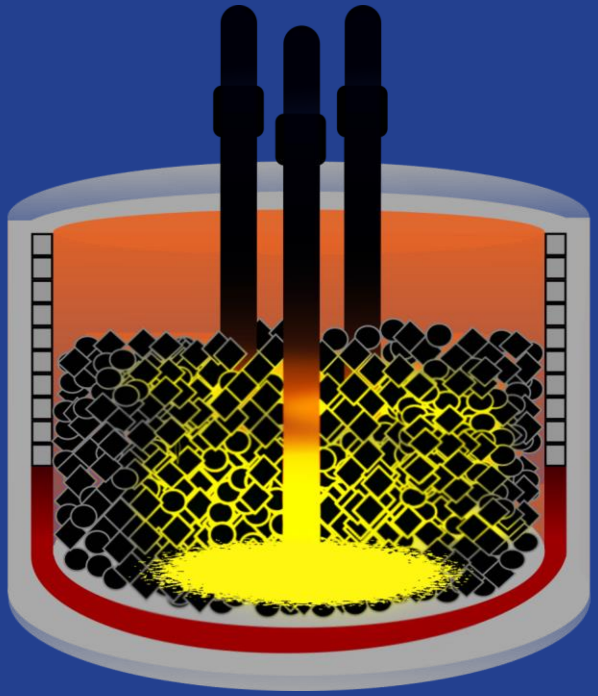


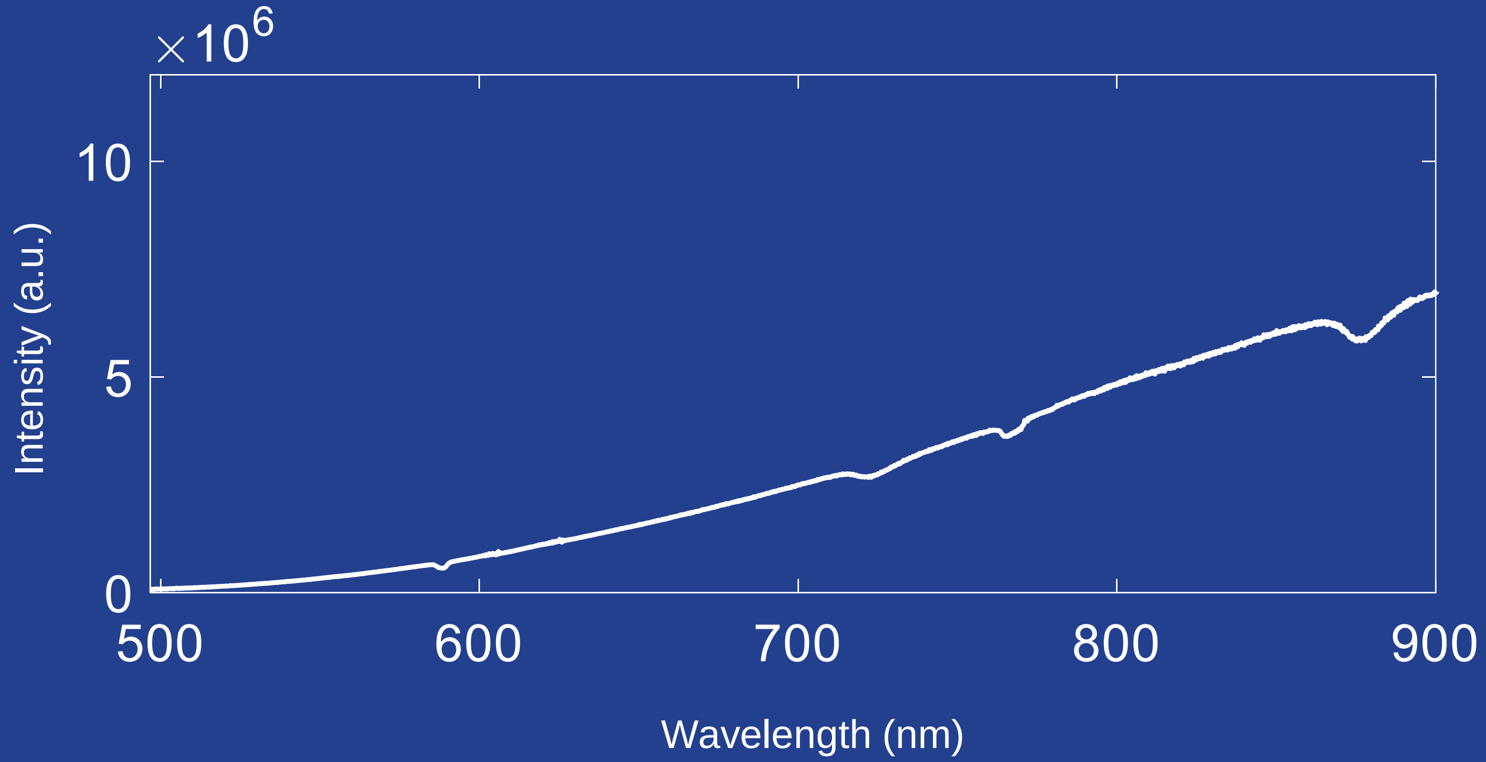


Electric arc furnace process

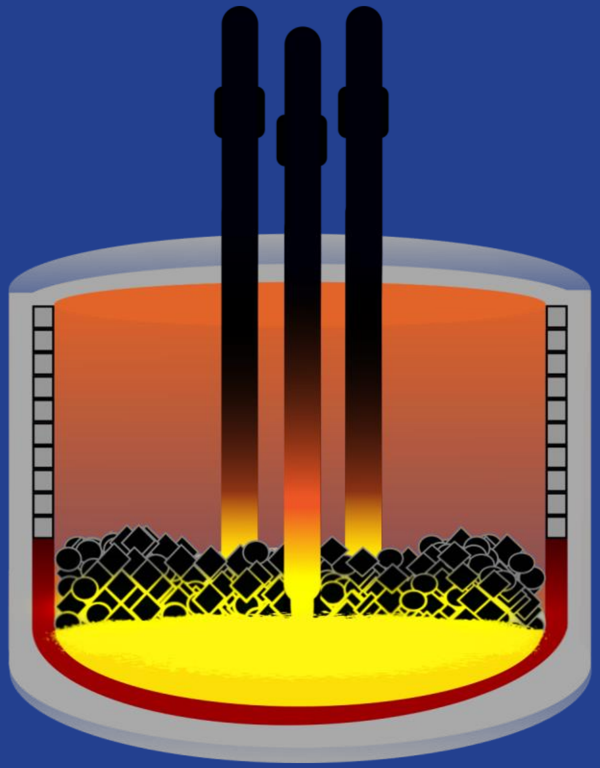
Main heating period

- Intensity of the observed light increases
  - Especially for heat radiation
- The solid charge material still blocks the view to the arc



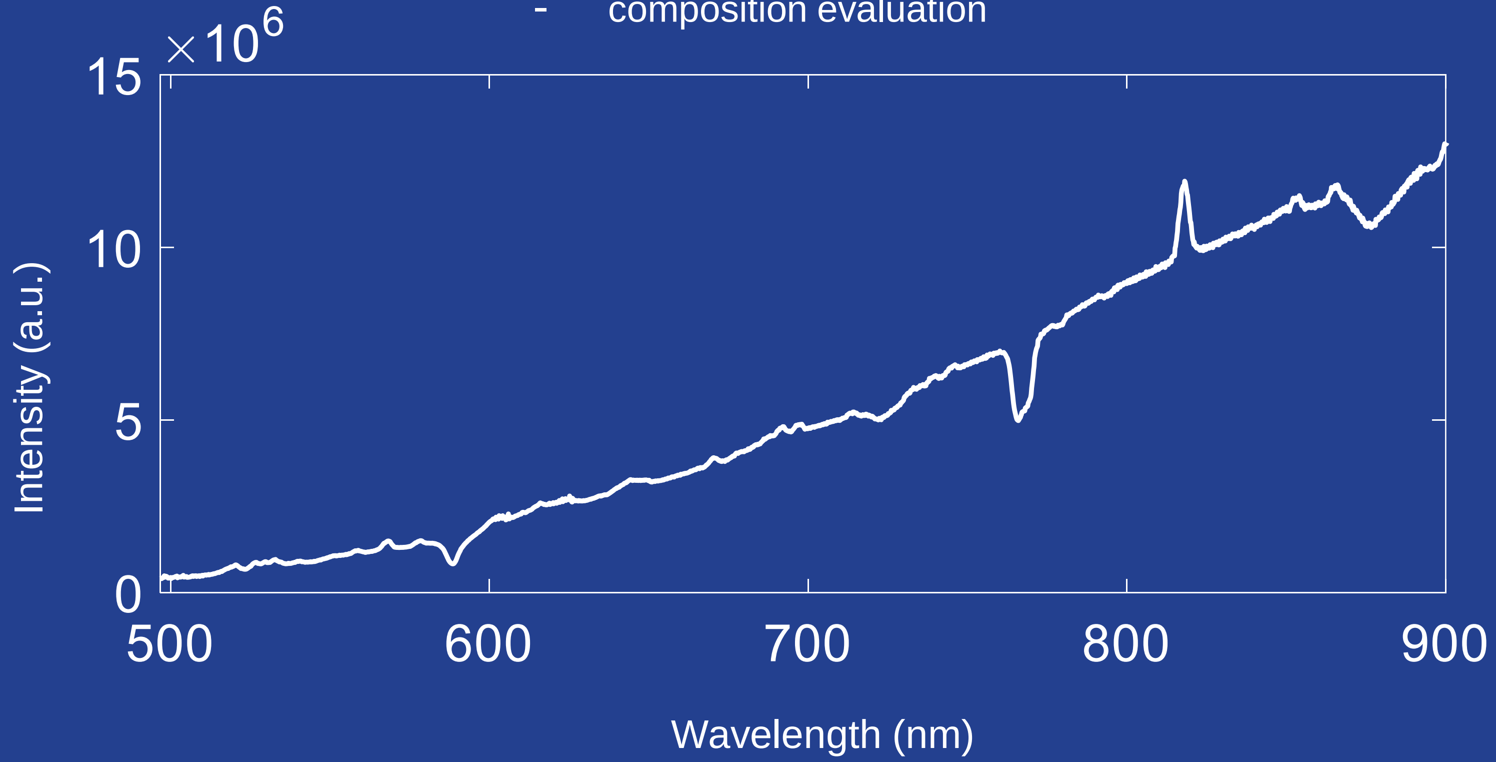


Electric arc furnace process

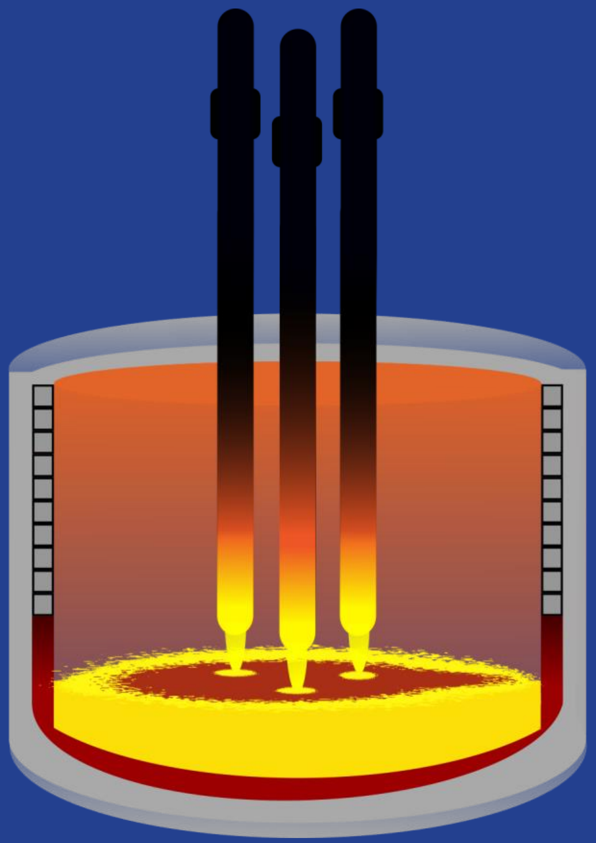


Down-melting period

- Most of the solid charge material is molten
- Electric arc can be observed momentarily or constantly
- Slag components can be identified
  - composition evaluation

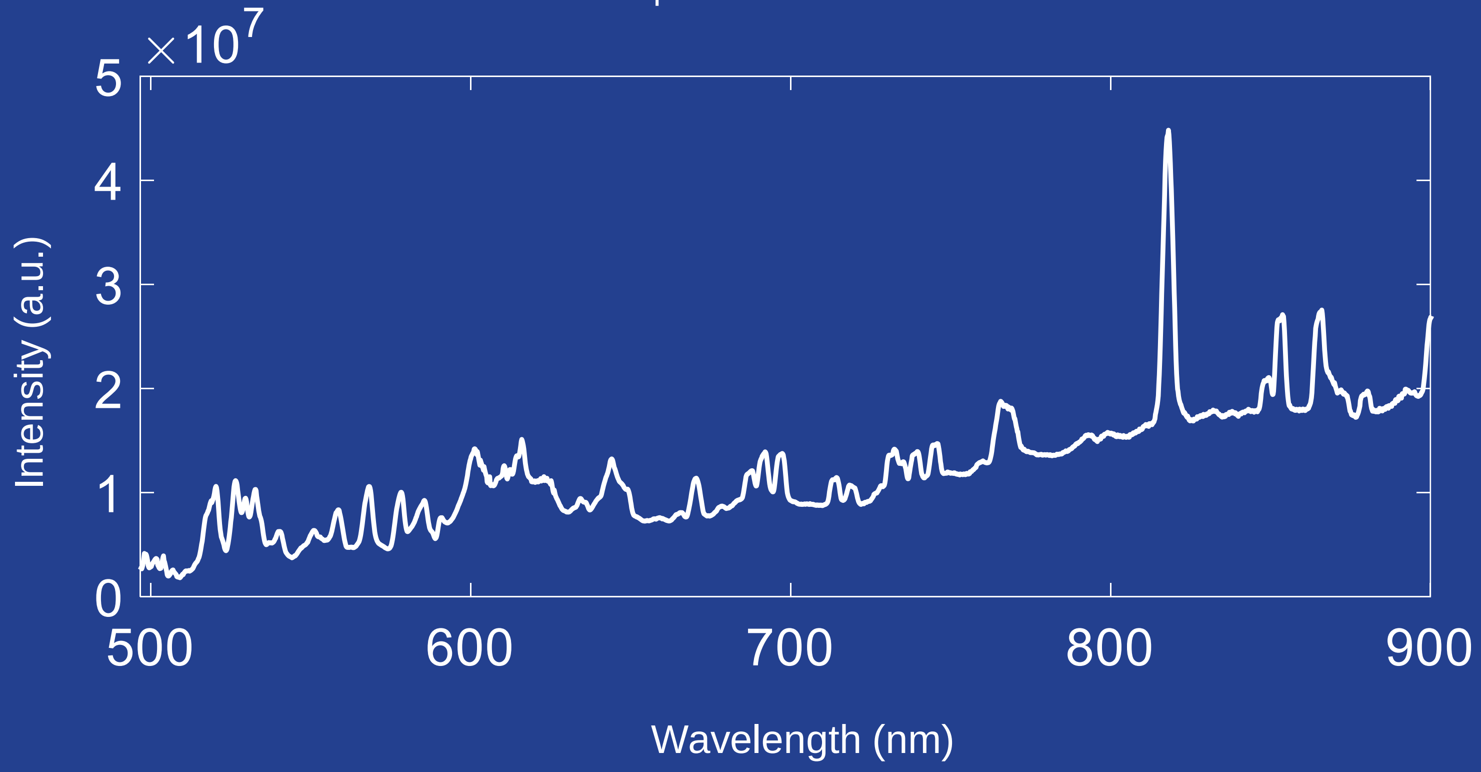


Electric arc furnace process



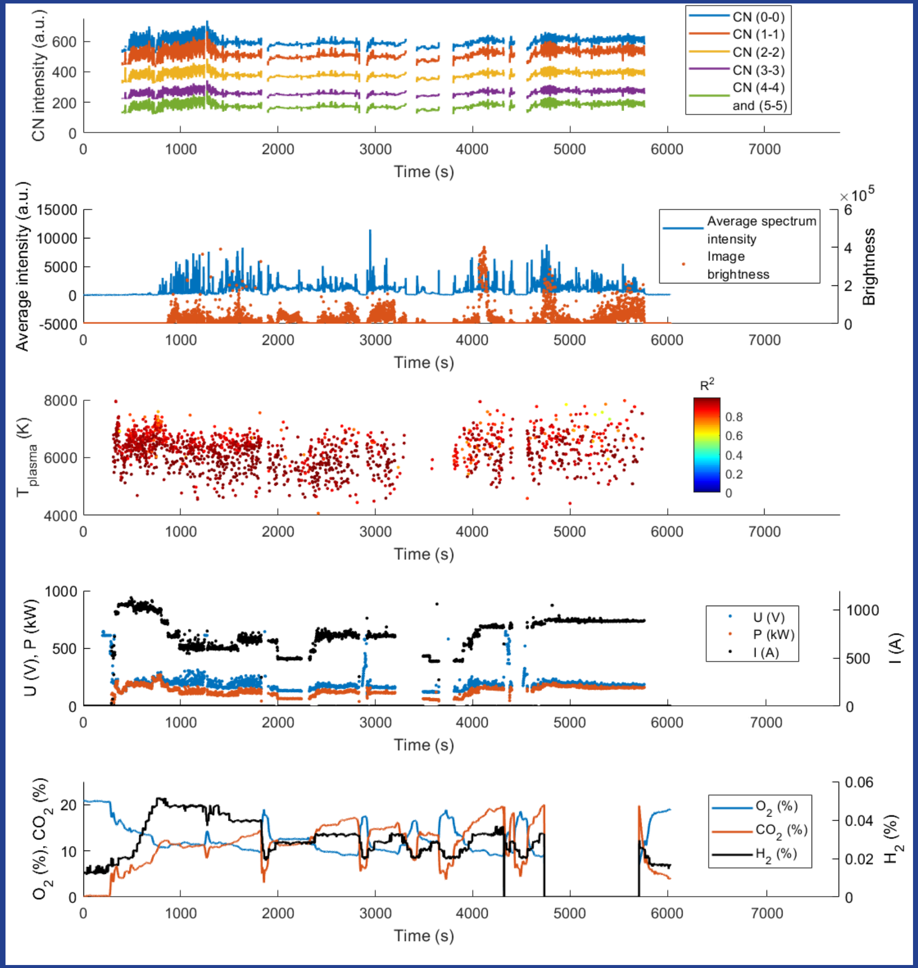
Heating/flat bath period

- End of the melting process
- Solid charge material is completely molten
- The electric arc spectra are observed clearly
    - composition evaluation

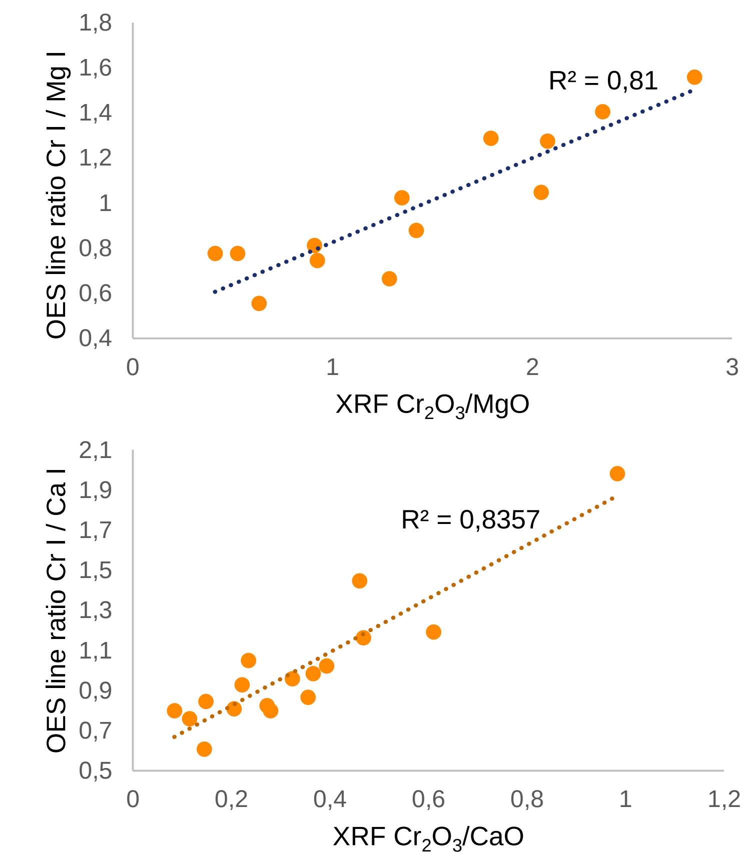


EAF and LF OES

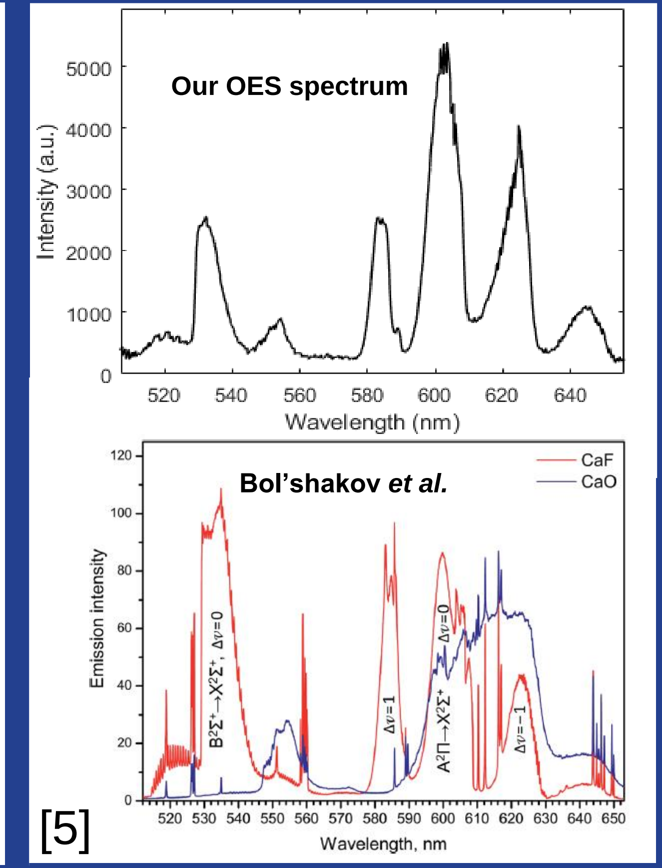
Time evolution



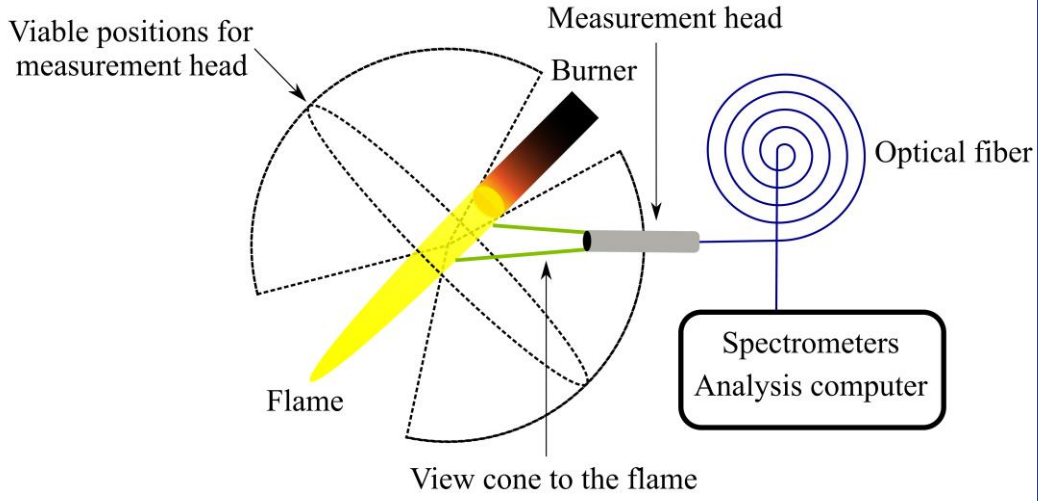
Emission line ratios vs. XRF slag composition



Molecular optical emissions



Potential future topics for OES reserach



Hydrogen applications

- Hydrogen flames, plasmas
- Process condition monitoring
  - Arc characteristics from the spectra
  - Plasma temperature
  - Detection of impurities

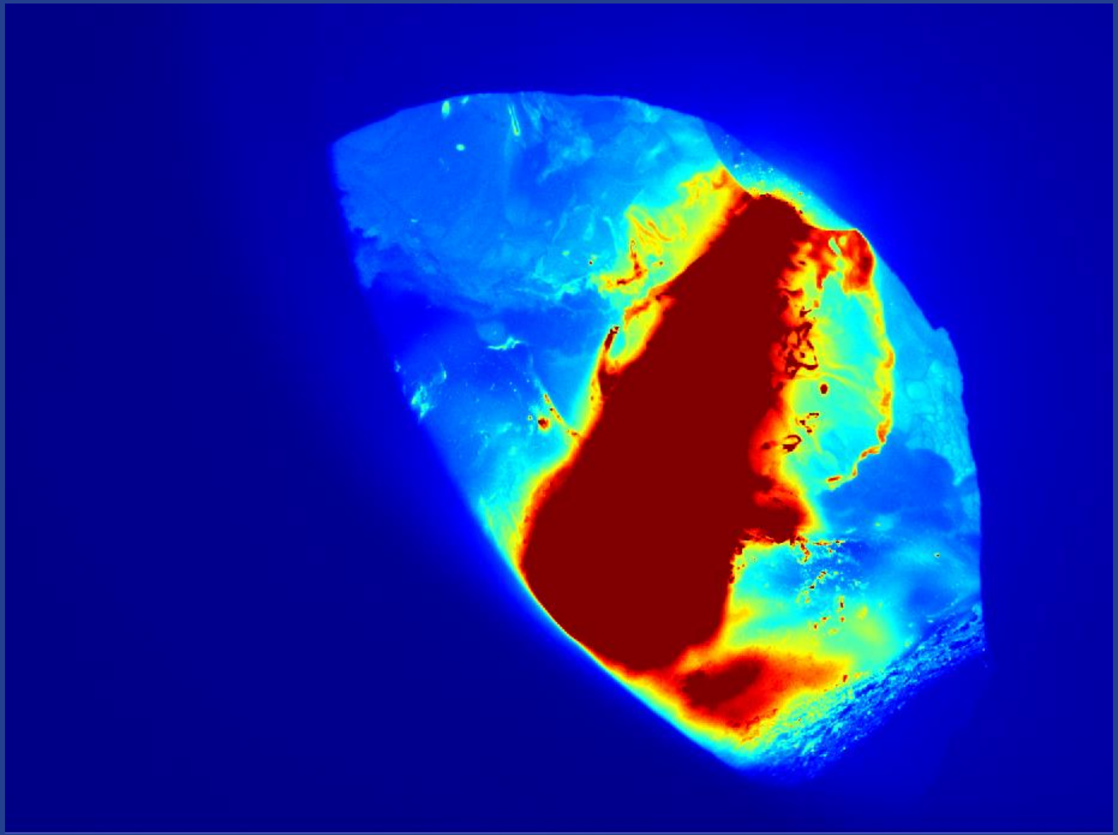
Burners

- Flame spectroscopy
- Process condition monitoring
  - Flame temperature
  - Detection of impurities

Continuation of electric arc furnace and ladle furnace research

- Online slag composition analysis
- Process condition monitoring

Summary



Optical emission spectroscopy in EAF and LF

- Realtime data acquisition
  - Up to several tens of spectra per second (limited only by how fast the data analysis is)

- Fast analysis times
  - Requires that emission line selection has been done efficiently!

- Potentially viable solution for on-line *in situ* slag compotision analysis

- A tool for process control
  - Arc characterization with
    - Plasma temperature
    - Electron density
    - Local thermodynamic equilibrium
  - Radiative heat transfer from the spectra
  - Evaluation of molten bath temperature
  - Evaluation of melting of the solid charge material

Thank you!

References

[1] C. Aragón and J. A. Aguilera, Characterization of laser induced plasmas by optical emission spectroscopy: A review of experiments and methods, Spectrochimica Acta Part B, 63: 893-916 (2008).

[2] H. Pauna et al., Pilot-scale AC electric arc furnace plasma characterization, Plasma Research Express, 1(3): 035007 (2019).

[3] H. Pauna et al., Optical emission spectroscopy as an on-line analysis method in industrial electric arc furnaces, Steel Research International, 91(11): 2000051 (2020).

[4] H. Pauna et al., Industrial Ladle Furnace Slag Composition Analysis with Optical Emissions from the Arc, ISIJ International, 60(9): 1985-1992 (2020).

[5] A. A. Bol'shakov et al., Spectral emission enhancement by an electric pulse for LIBS and LAMIS, Journal of Analytical Atomic Spectrometry, 32: 657-670 (2017).