CERN

High Resolution Optical Emission Spectroscopic Study of the ECR Plasma in the GTS-LHC Ion Source

Bichu Bhaskar, Detlef Küchler (CERN)

Introduction

Implementation of Optical Emission Spectrometer

Results from spectroscopic studies.

High resolution spectrum of lead and oxygen.

Conclusion

Motivation

- **No non-invasive diagnostics yet** on the GTS-LHC 14.5 GHz ECRIS $\Rightarrow$ need for line-of-sight spectroscopy.
- Use optical spectroscopy as an **input for automatisation** of the ion source.
- **Practical use:** establish optical diagnostics as a routine *monitoring and control tool* for source performance and stability.

ECRIS: Introduction

- Resonance between external RF frequency and the cyclotron frequency of electrons along magnetic field.

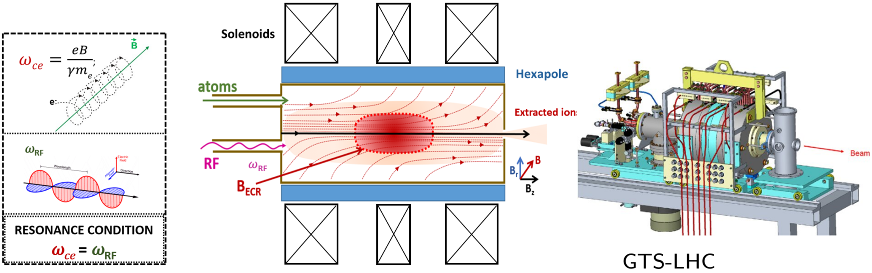
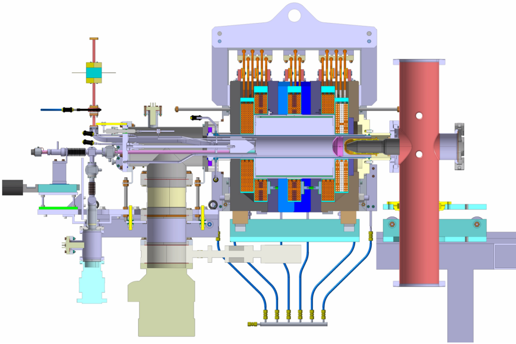


Figure: Schematics of ECR ion source

- Step wise ionisation of atoms and molecules to produce Highly Charged Ions (HCIs).
- Highly charged ions are selected and accelerated downstream.

GTS-LHC ECRIS:Introduction

- Confinement: axial solenoids (3) + radial hexapole $\Rightarrow$ topology
- 14.5GHz, pulsed 10Hz, 50% duty Afterglow mode
- Consists of two micro oven ports
- Beam delivery 24/7 from the source, mostly extracting Pb ions (oxygen buffergas)
- Three electrode extraction system.



GTS-LHC in CERN Injector Chain

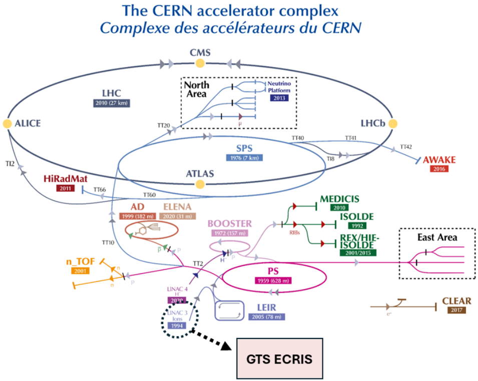


Figure: GTS-LHC in CERN injector complex

Optical Diagnostics in ECRIS: Feasible but Challenging

- **Feasibility:**
  - In ECRIS plasmas, electrons not only ionise but also **excite** atoms/ions.
  - Excited states decay via **spontaneous emission**, giving photons:

$$\lambda = \frac{hc}{E_p - E_k}$$

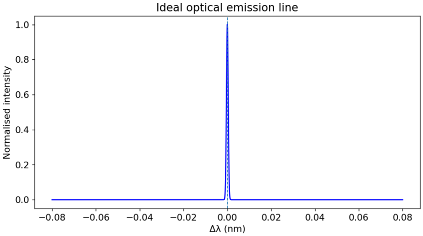
  - These photons exit the plasma and can be measured non-invasively with OES.

- **Challenges:**
  - Overlapping lines from many charge states and species.
  - Strong magnetic field and geometry
  - Intensity depends on multiple processes (EEDF, excitation, ionisation, charge exchange, transport) $\rightarrow$ interpretation is non-trivial.

What Information Can Optical Emission Spectroscopy Provide?

Ideal peak

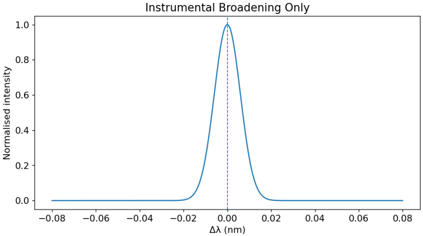
- A delta-like line (conceptual reference)
- Impurity detection
- Light intensity depends on ion density and the electron energy distribution function



What Information Can Optical Emission Spectroscopy Provide?

Instrumental (Gaussian)

Finite instrument response produces a Gaussian profile.



What Information Can Optical Emission Spectroscopy Provide?

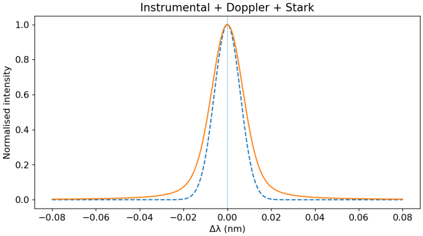
Doppler broadening & Stark

Thermal motion broadens the line (Doppler); electric microfields add Lorentzian wings (Stark).

Ion temperature from Doppler width at λ_0:

$$T_i = \frac{m_i c^2}{8 \ln 2 \, k_B} \left(\frac{\Delta \lambda_D}{\lambda_0} \right)^2$$

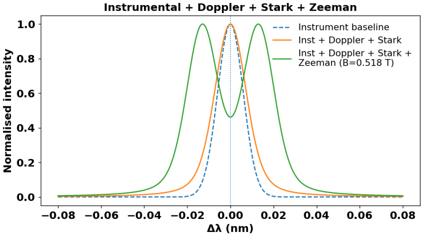
where m_i: ion mass, k_B: Boltzmann constant, c: speed of light, $\Delta\lambda_D$: Doppler FWHM, λ_0: line rest wavelength.



What Information Can Optical Emission Spectroscopy Provide?

Combined including Zeeman splitting

Final line shape includes instrumental, Doppler, Stark, and Zeeman.

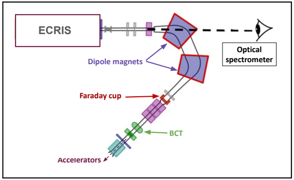


Zeeman axial splitting (for $\sigma^{\pm}$ components):

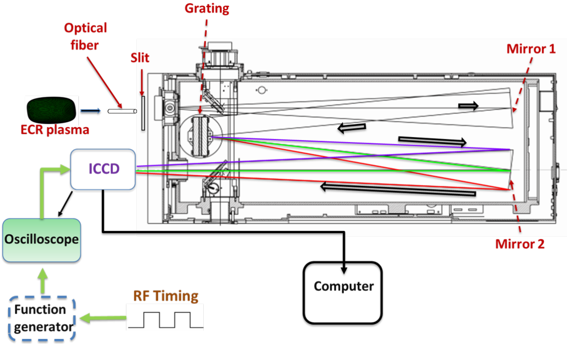
$$\Delta\lambda_\sigma = \frac{\lambda_0^2}{c}\,\frac{\mu_B}{h}\,g_{\text{eff}}\,B \qquad \Rightarrow \qquad \text{separation} = 2\,\Delta\lambda_\sigma$$

where μ_B: Bohr magneton, h: Planck's constant, g_{eff}: effective Landé factor of the transition, B: magnetic field strength.

Optical spectroscopy: Diagnostic setup



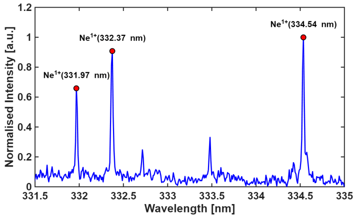
Schematics of diagnostics



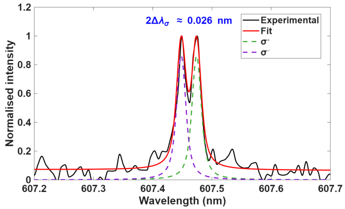
Experimental setup

Measurement results from Neon OES

- Why Ne? Single day run at LHC for Ne nuclear imaging.
- Measurement performed with ICCD gated at the centre of RF timing signal
- Calibration using low-pressure gas discharge Ne pen-ray lamps
- Ion temperature of Ne^{1+}: $\mathbf{7 \pm 4}$ **eV**
- All measured neutral Ne lines (585–650 nm) exhibited Zeeman splitting
- B field: $\mathbf{0.5182 \pm 0.005}$ **T**



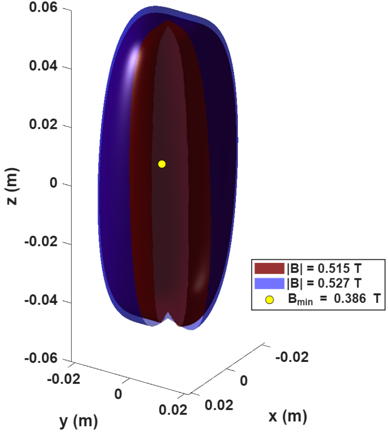
High resolution OES of Ne^{1+}



Zeeman splitting in neutral Ne

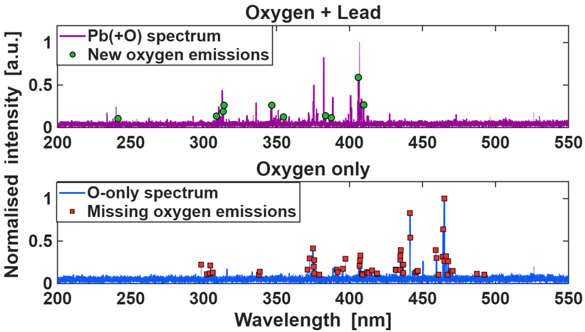
Iso-magnetic field surface corresponding to neutral Ne emissions

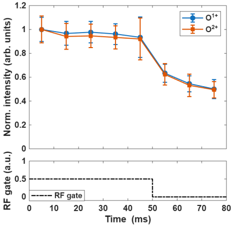
- 3D B-field corresponding to coil currents : 1250/250/1220 A
- $B_{ECR} = 0.518\,T$
- Neutral Ne emission close to resonance zone



Iso-magnetic field surfaces corresponding to neutral Ne emission.

Measurement of lead and oxygen OES





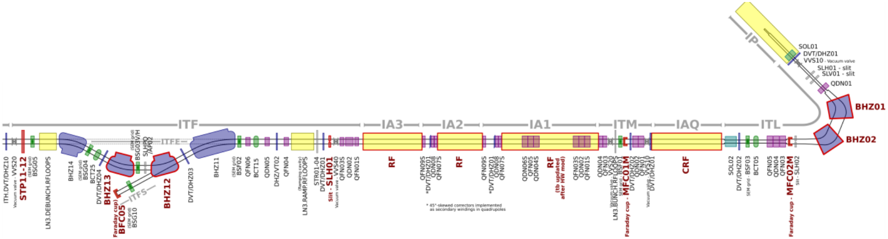
Spectral modification with Pb introduction

- First measurement of Pb OES
- Observed redistribution of oxygen emission lines when Pb is introduced.

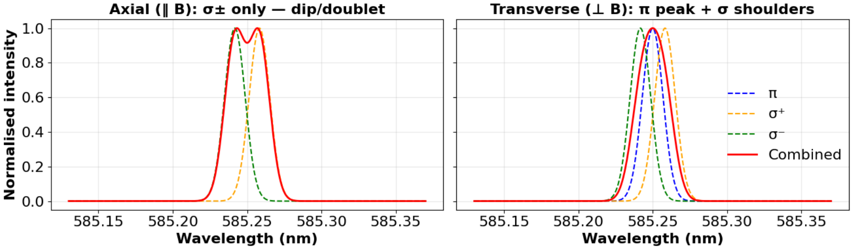
Conclusion

- Implemented a high-resolution optical emission spectrometer, providing first diagnostic results toward routine, non-invasive monitoring of ECRIS performance.
- First measurement of Zeeman splitting in ECRIS which could also help to gain insight into spatial resolution of optical emissions in ECRIS.
- Measured well-resolved Pb optical emission lines in oxygen background.

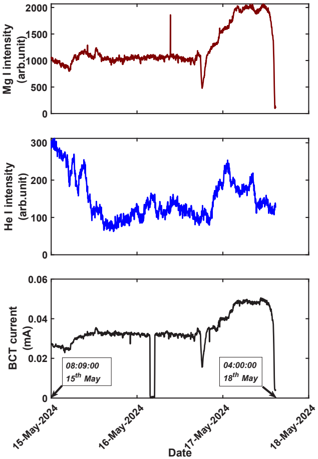
Additional slide



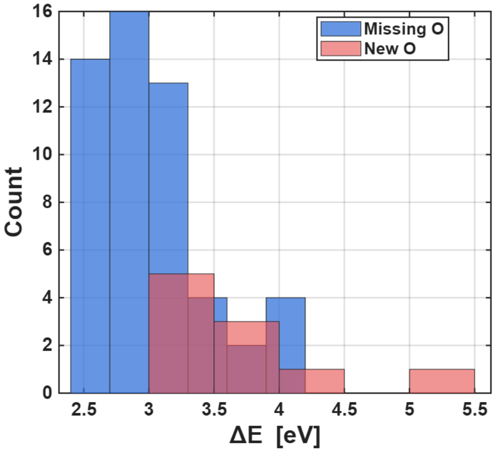
Viewing angle



Intensity vs extracted current



ΔE distribution



CERN

home.cern