Application of Optical Emission Spectroscopy to Electron Cyclotron Resonance Ion Sources

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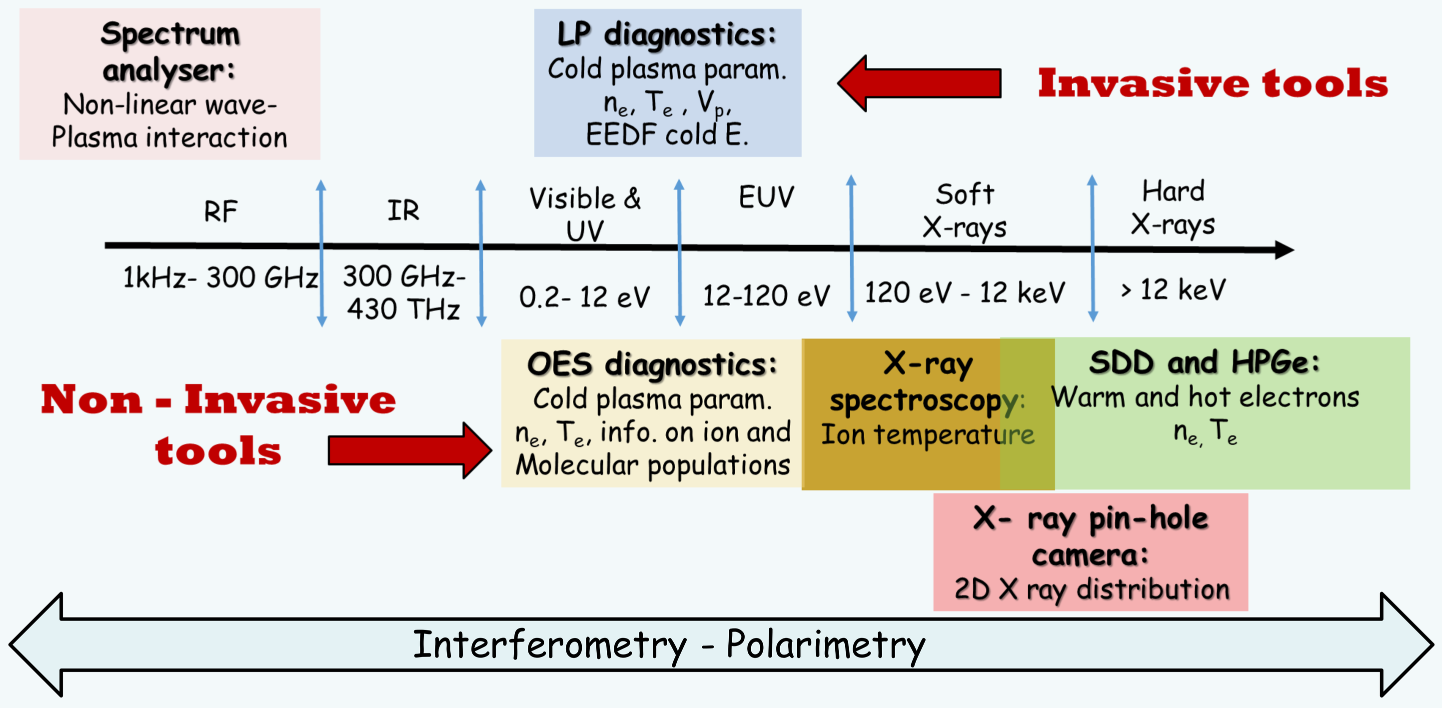
Abstract

Electron Cyclotron Resonance Ion Sources (ECRIS) are widely used to produce highly charged high intensity ion beams for research, medical and industrial applications.
ECRIS performances, namely the charge state distribution and beam intensity, depend critically on the electron energy distribution function.
Further improvements of ECRIS performances can be achieved only by a deeper and deeper understanding of the plasma heating mechanisms and ion generation by means of opportune plasma diagnostics. Amongst others, Optical Emission Spectroscopy (OES) is the most remarkable for application in ECRIS: it is a non-invasive diagnostic able to operate also in high-voltage conditions and it requires only small room for operation. OES has been already tested for plasma diagnostics in proton sources.
This work presents the experimental set-up developed for the plasma diagnostic of the Advanced Ion Source for Hadrontherapy (AISHa), an ECRIS for medical applications, together with the strategy used to relate plasma emission lines in the visible and near-infrared domain to plasma parameters for some ions of interest. Preliminary experimental results on a plasma reactor and perspectives will be also discussed.

Optical Emission Spectroscopy (OES) diagnostics



OES is probably the most remarkable diagnostics for application in ECRIS under routine operations: it requires little room for operation (just a quartz window to access the plasma light), it does not affect nor is affected by plasma, and it works also in high-voltage conditions, typical in ECRIS. According to the instrumentation sensitivity, OES allows the detection of the emission spectrum produced by neutral and charged plasma particles.
If a proper model is available, emission lines provide information about electron density n_e, electron temperature T_e, ion temperature T_i, neutral abundances, densities of highly charged ions and rotovibrational molecular spectrum.

$$\frac{2}{V_{ex}}\sum_{q=1}^{N}\frac{I^q}{eq} \approx n_e n_0 <\sigma v>_{0\to1}^{inz} + n_0 n_i^{N+1} <\sigma v>_{N+1\to N}^{cx} - n_e n_i^{N} <\sigma v>_{N\to N+1}^{inz}$$

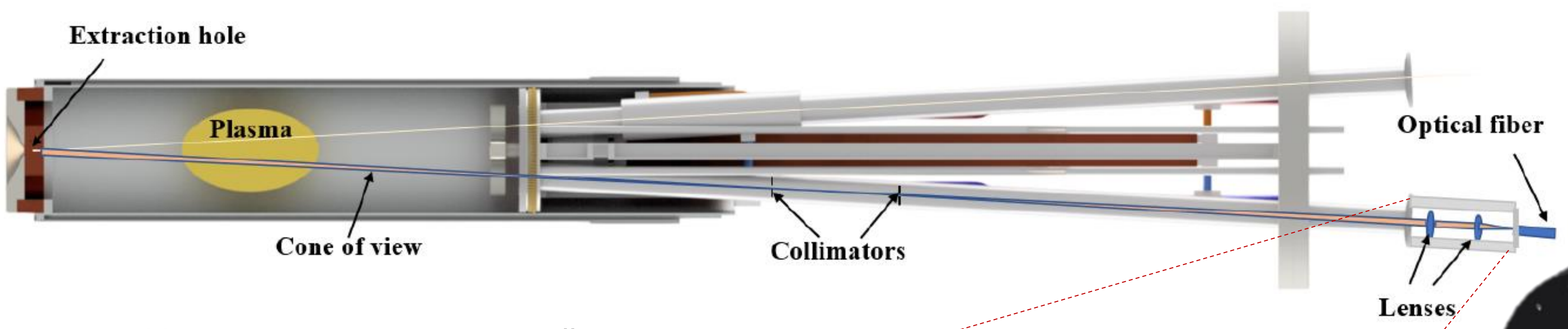
$$\sum_{q=1}^{q_{max}}\frac{I^q}{eq} \approx \frac{V_{ex}}{2} n_e n_0 <\sigma v>_{0\to1}^{inz}$$

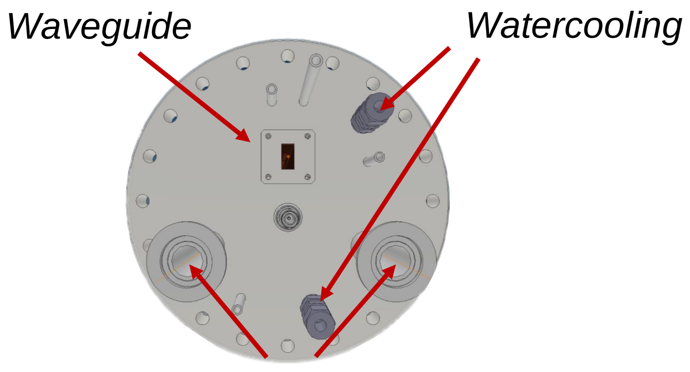
Beam parameters are directly related to plasma parameters. Therefore, the estimation of plasma parameters by non-invasive diagnostics (like OES) will make easier the control and tune of the beam parameters.

	Observable		Obtainable
High resolution	Emission line shift		Ion drift velocity
	Broadening	Doppler	T_i
		Stark	n_e
Low resolution	Splitting Zeeman		Magnetic field
	Intensity ratios		T_e, n_e, $N(H)/N(H_2)$
	Intensity		N_i

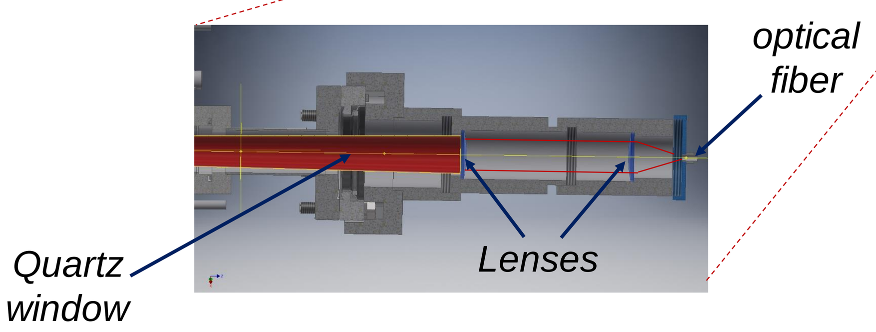
Experimental set-up on the AISHa test-bench

A proper diagnostics flange and optical coupling system have been designed to focus the light coming from a well-defined cone of view into an optical fiber connected to an iHR550 Horiba spectrometer. The lens focal length and the collimator dimensions have been chosen to create a cone of view focused on the extraction hole of the plasma chamber. This precaution avoids plasma light reflected by the chamber walls from being acquired by the spectrometer.

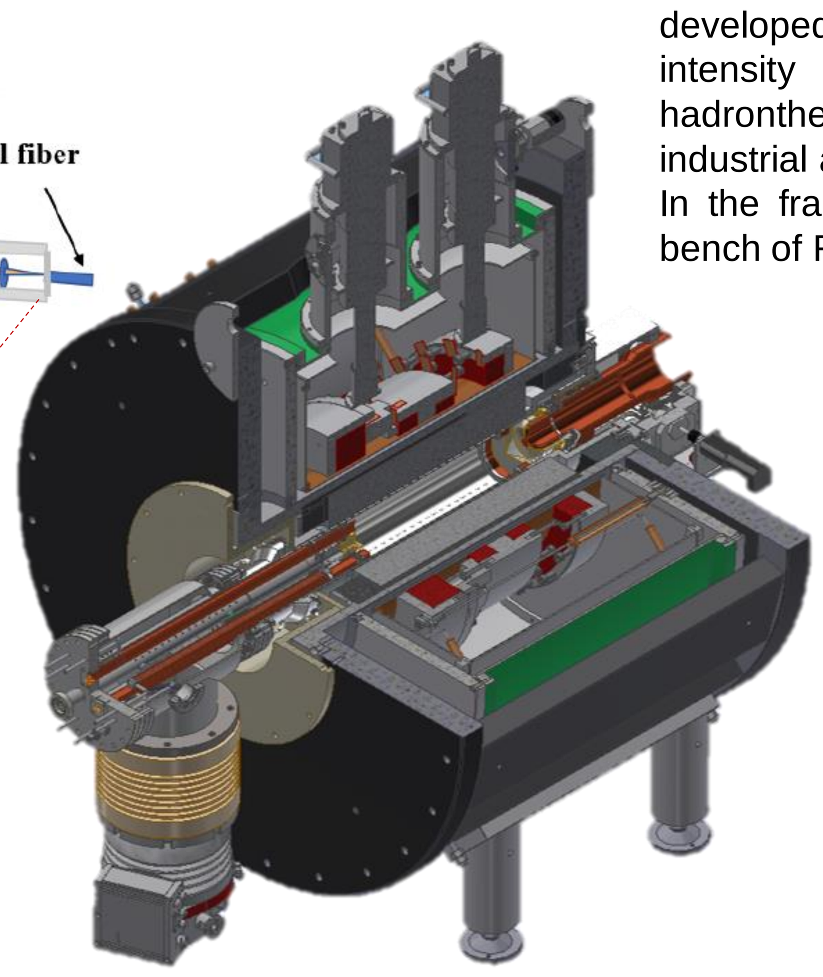




Front-view of the AISHa diagnostics flange



Render view of the optical coupling system



The Advanced Ion Source for Hadrontherapy (AISHA)

The Advanced Ion Source for Hadrontherapy (AISHa) is an electron cyclotron resonance ion source operating at 18 GHz, developed at the INFN-LNS, with the aim of producing high intensity and low emittance highly charged ion beams for hadrontherapy purposes, but also to be a suitable choice for industrial and scientific applications.
In the framework of the IONS project, AISHa will be the test-bench of R&D activities on OES diagnostics in ECRIS plasmas.

Radial field (max)	1.3
Axial field (max)	2.6/0.4/1.7
Operating frequency (GHz)/power (kW)	17.3–18.3/1.5
Cryostat length/diameter (mm)	620/5650
Extraction voltage (kV)	20–40
Plasma chamber ø (mm)	92 mm
Extraction hole ø (mm)	7.2
Distance between maxima of the axial field (mm)	370
Distance between microwave port and B_{min} (mm)	203
Length of the resonance zone (mm)	<10
Distance between the plasma electrode and B_{min} (mm)	167

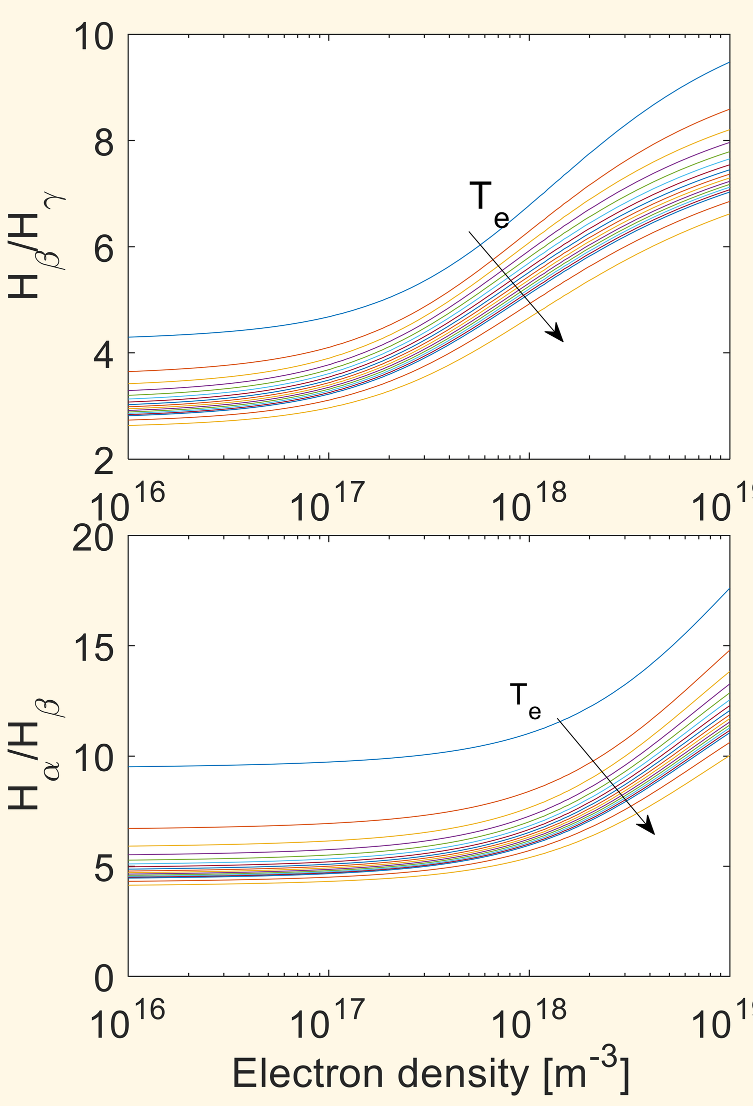
Theoretical approach

Collisional Radiative (CR) model

$$\frac{I_{pk}^1}{I_{lm}^2} = \frac{X_{pk}^{eff}(T_e, n_e, ...)}{X_{lm}^{eff}(T_e, n_e, ...)}$$

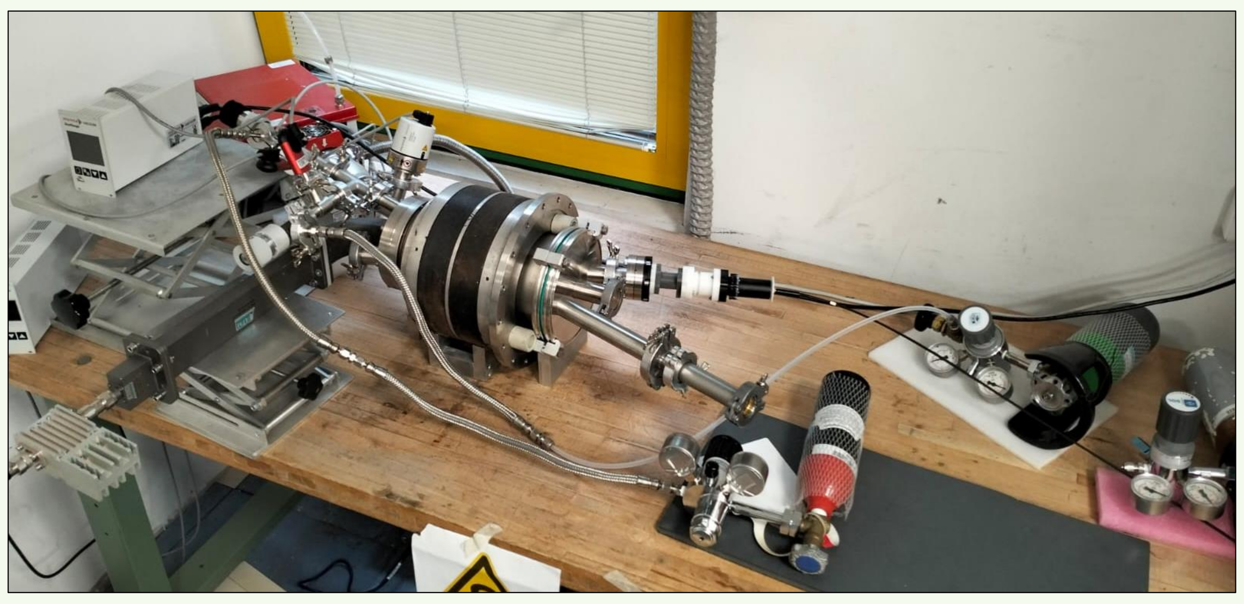
Line ratios are functions of plasma parameters.

The comparison between theoretical and experimental line ratio permits the evaluation of plasma parameters.



Example of line ratio for Hydrogen Balmer lines evaluated by means of CR models.

OES set-up commissioning on Plasma Reactor

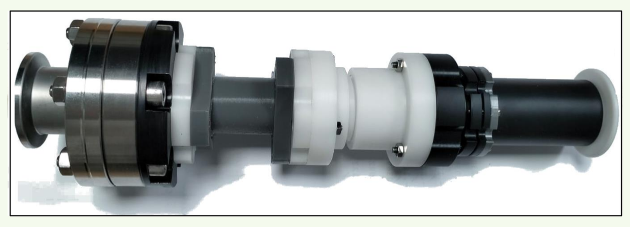


The plasma Reactor is a flat-magnetic field plasma trap used for OES set-up commissioning. Hydrogen, helium and neon plasmas in overdense conditions have been generated by Electron Bernstein Wave heating. Typical working conditions are 3.8 GHz microwave frequency, $1.5\cdot10^{-4}$ mbar neutral pressure and 0-150 W microwave power).

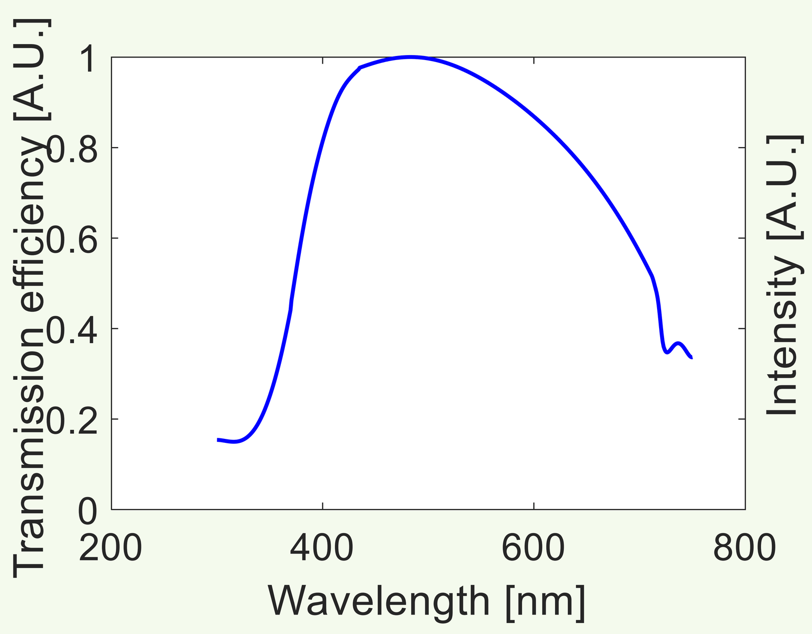
Horiba iHR550

iHR550 is currently sensitive in the 300-750 nm wavelength domain with a spectral resolution of ~20 pm. Upgrade to the 150-1500 nm range is foreseen.

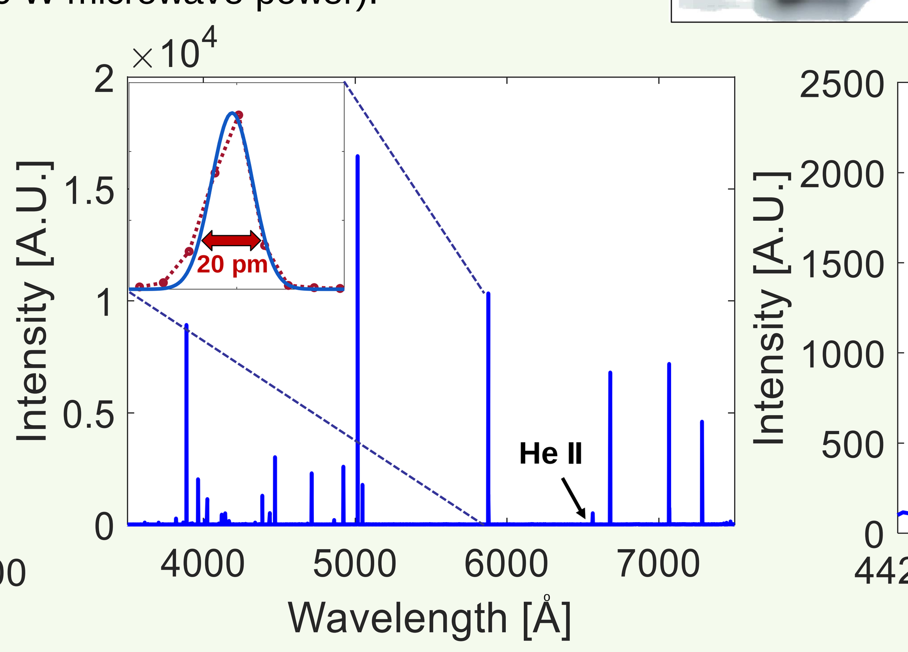
Range	*150 to 1500 nm*
Resolution	*~0.02 nm*
Aperture	*f/6.4*
Focal length	*550 mm*
Scan speed	*160 nm/sec*



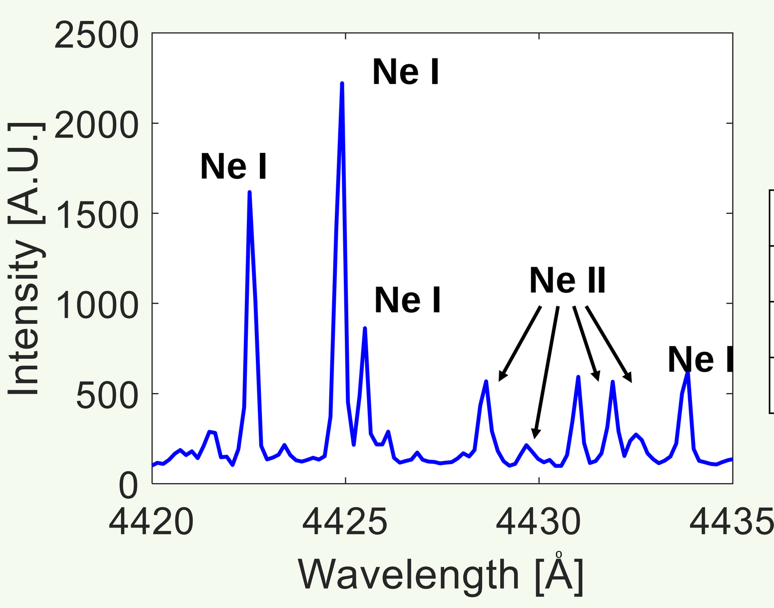
Picture of the optical coupling system



Transmission efficiency in A.U. of the entire optical coupling system.



Neutral He emission lines in the 3500-7500 Å range acquired in PR in typical work conditions. He II emission lines at 6560 Å are also visible.



Ne I and Ne II emission lines in the 4420-4435 Å range.

Emission wavelength and relative intensity of single emission Ne lines.

Line	*Rel. Int.*
Ne I @4424.8	3000
Ne II @4428.5	960
Ne II @ 4429.6	180

OES diagnostics set-up detects also low relative intensity lines. Results are promising for detection of highly charged ion emission lines.