HIGH RESOLUTION SPECTROMETER DEVELOPMENT FOR ECRIS PLASMA SPECTROSCOPY

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- Plasma physics background
- Photons path from ECRIS plasma to monochromator
- Monochromator POSSU
- Detector and Data acquisition
- Results

MIDAS: **MI**nimization of **D**estructive pl**AS**ma processes in ECR ion source

- Balance equation

Positive, creation terms

$$\frac{dn^q}{dt} = \boxed{+n_e \left\langle \sigma_{q-1\to q}^{\text{ion}} v_e \right\rangle n^{q-1} + n_0 \langle \sigma_{q+1\to q}^{\text{cx}} v_i \rangle n^{q+1}}$$
$$\boxed{-n_e \left\langle \sigma_{q\to q+1}^{\text{ion}} v_e \right\rangle n^q - n_0 \langle \sigma_{q\to q-1}^{\text{cx}} v_i \rangle n^q - \frac{n^q}{\tau^q}}$$

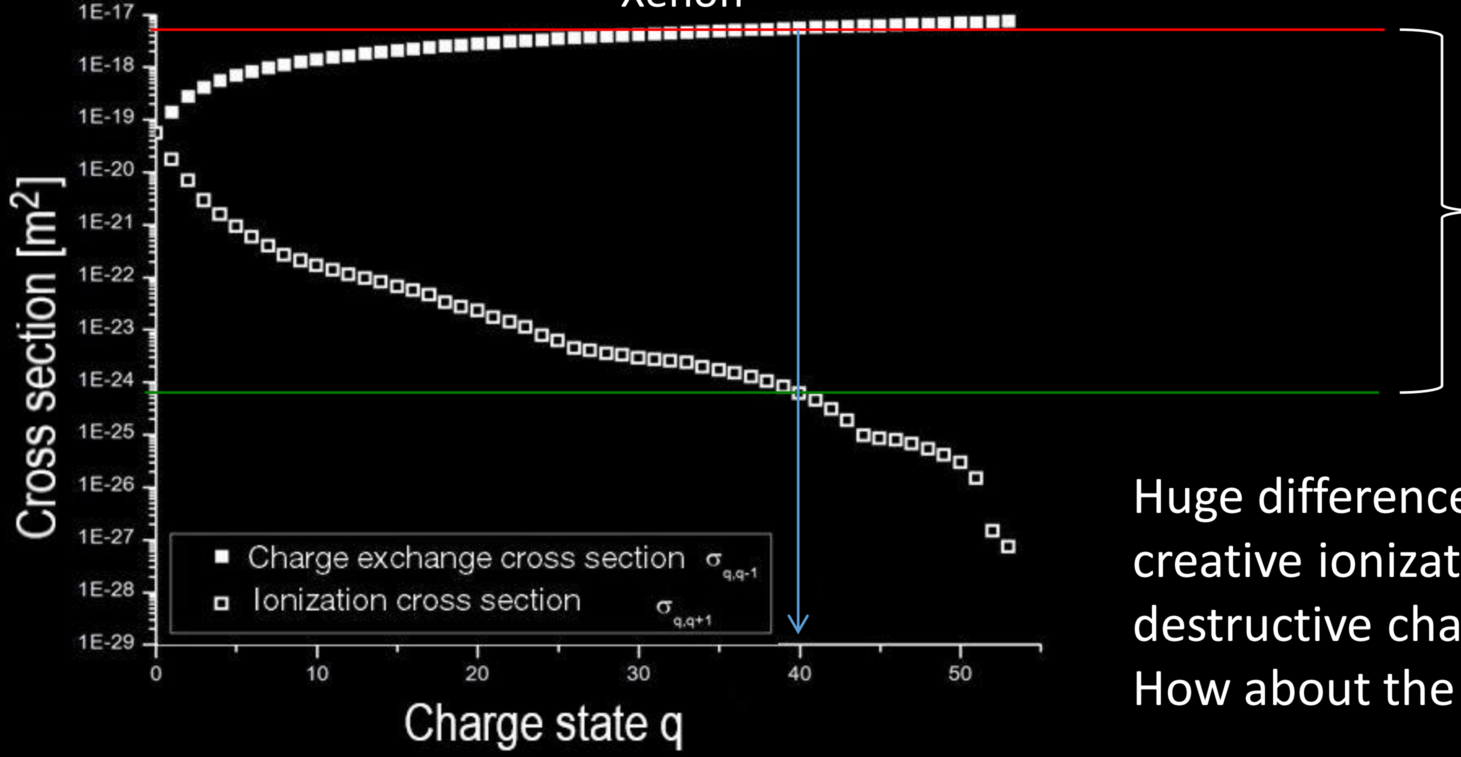
Negative, destruction terms

n_e = electron density, n_0 = neutral density, n_q = ion density, τ = confinement time, σ = rection cross section, v_e = electron velocity, v_i = ion velocity

Cross sections

for ionization and charge exchange reactions

Xenon



7 orders of magnitudes

Huge difference between creative ionization and destructive charge exchange. How about the reaction rates?

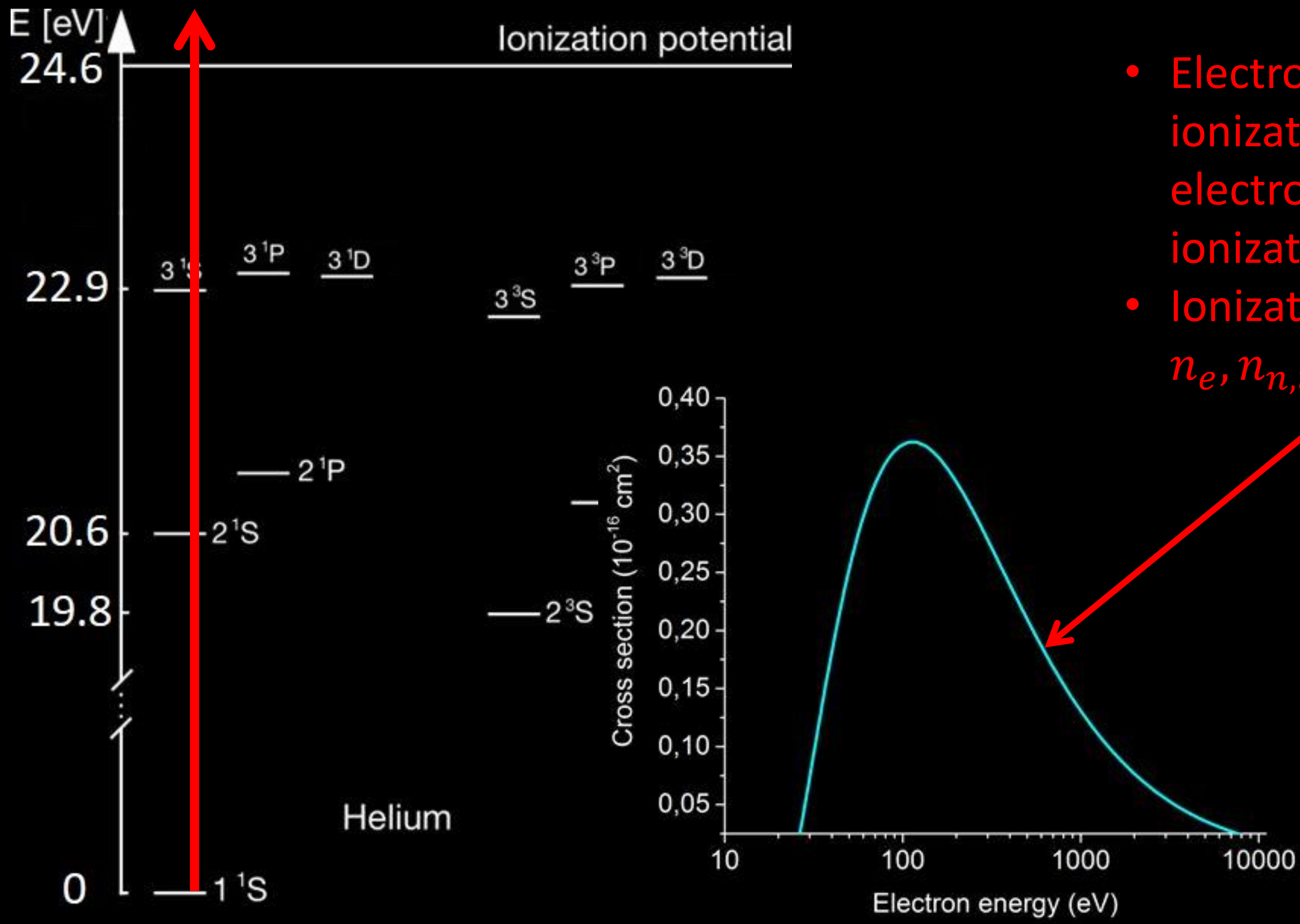
Reaction rates

$$\frac{dn^q}{dt} = +n_e \left\langle \sigma^{\text{ion}}_{q-1\to q} v_e \right\rangle n^{q-1} + n_0 \langle \sigma^{\text{cx}}_{q+1\to q} v_i \rangle n^{q+1}$$
$$-n_e \left\langle \sigma^{\text{ion}}_{q\to q+1} v_e \right\rangle n^q \boxed{- n_0 \langle \sigma^{\text{cx}}_{q\to q-1} v_i \rangle n^q} - \frac{n^q}{\tau^q}$$

Charge exchange reaction rate

- Not that easy to compare anymore
- More information needed from n_e, n_i, v_e and v_i
- New diagnostics is needed

Electron impact ionization

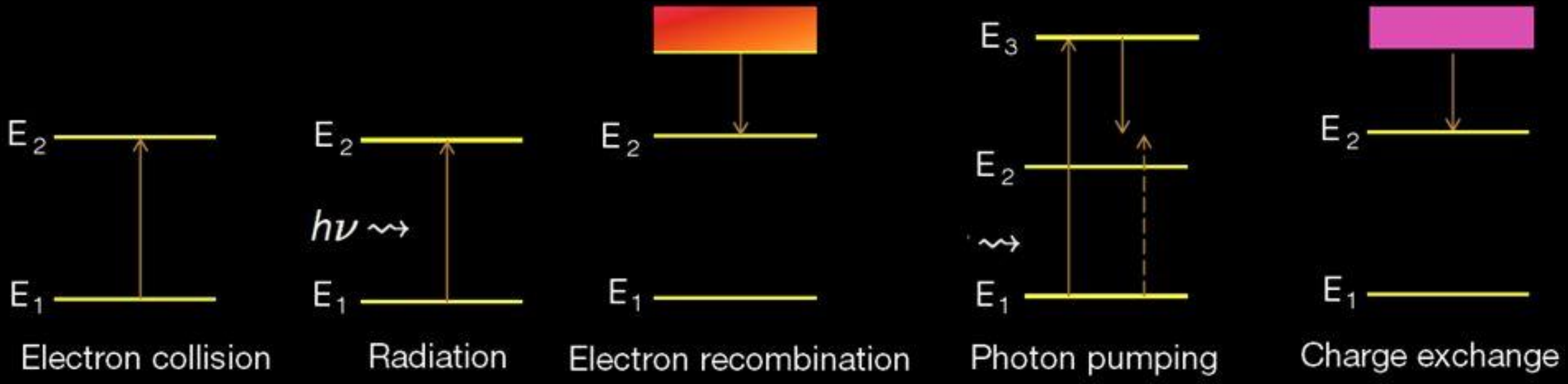


- Electron impact ionization if energy of electron is higher than ionization potential
- Ionization rate $R_i \propto n_e, n_{n,i}, \langle \sigma v_e \rangle$

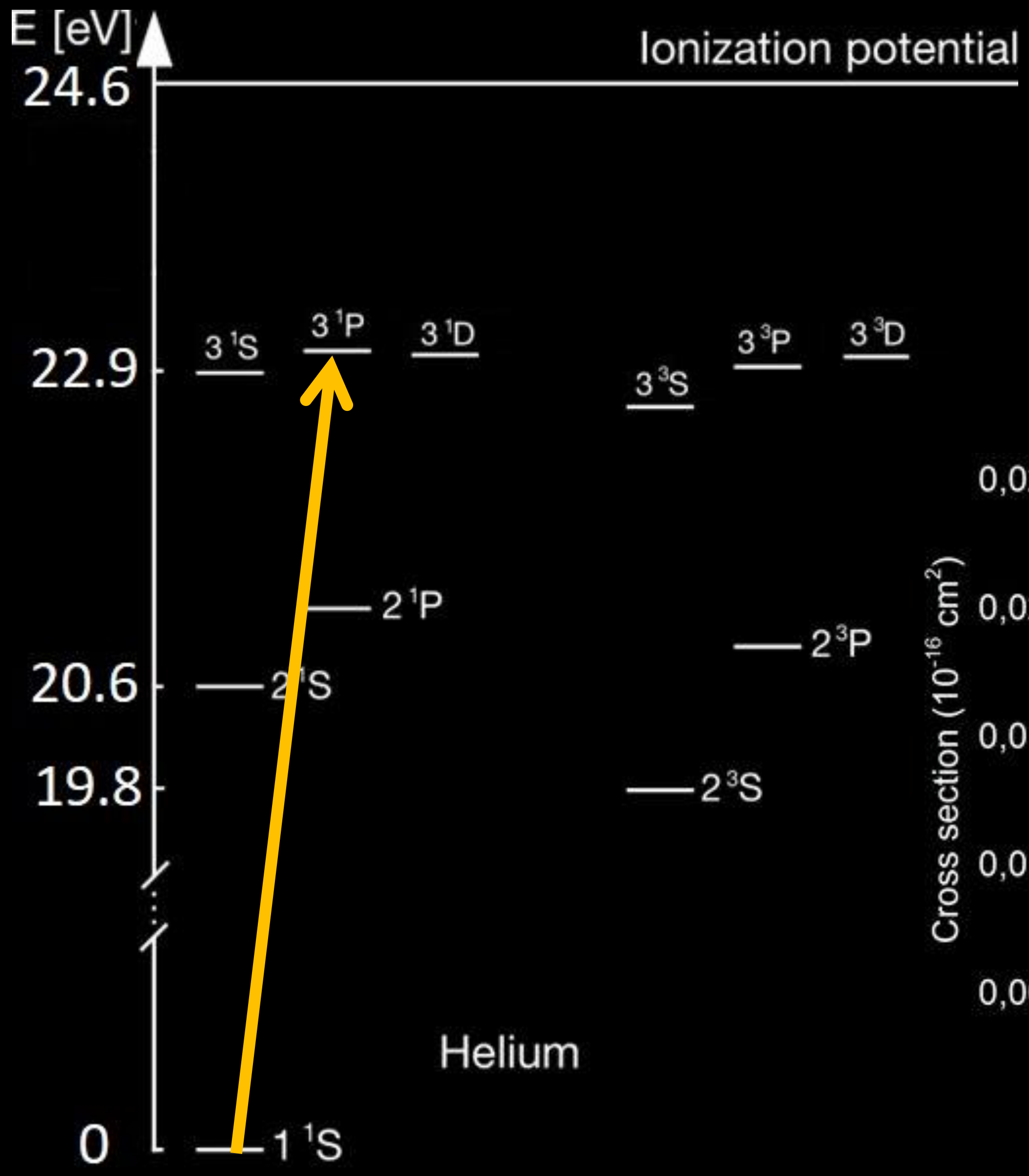
From ECRIS electron energy distribution function

Excitation

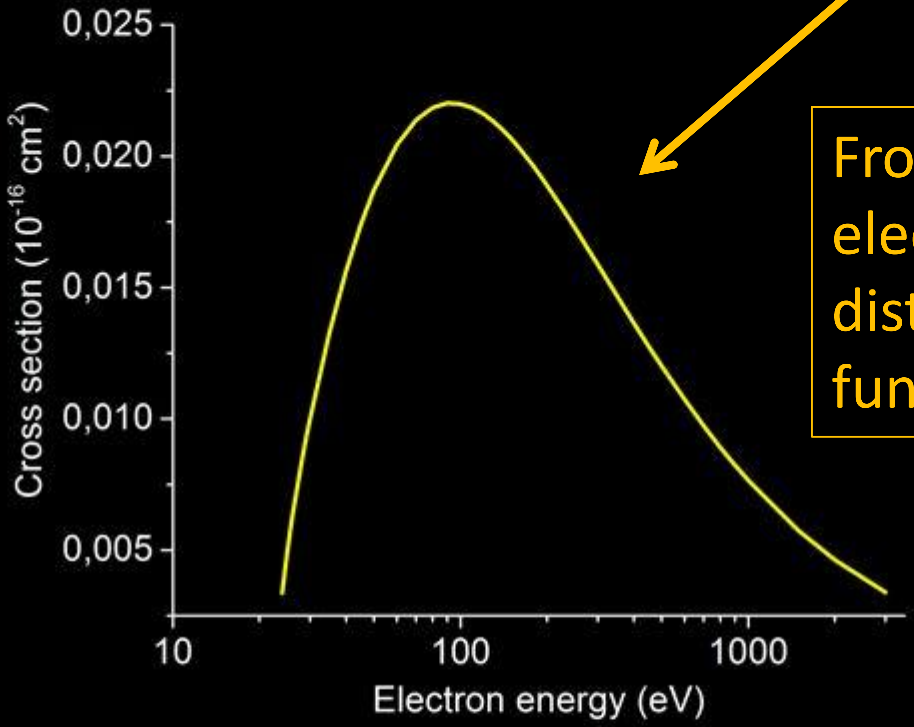
- In addition to ionization, electron can also jump to higher energy stationary state
- These reactions are called excitations



Electron impact excitation

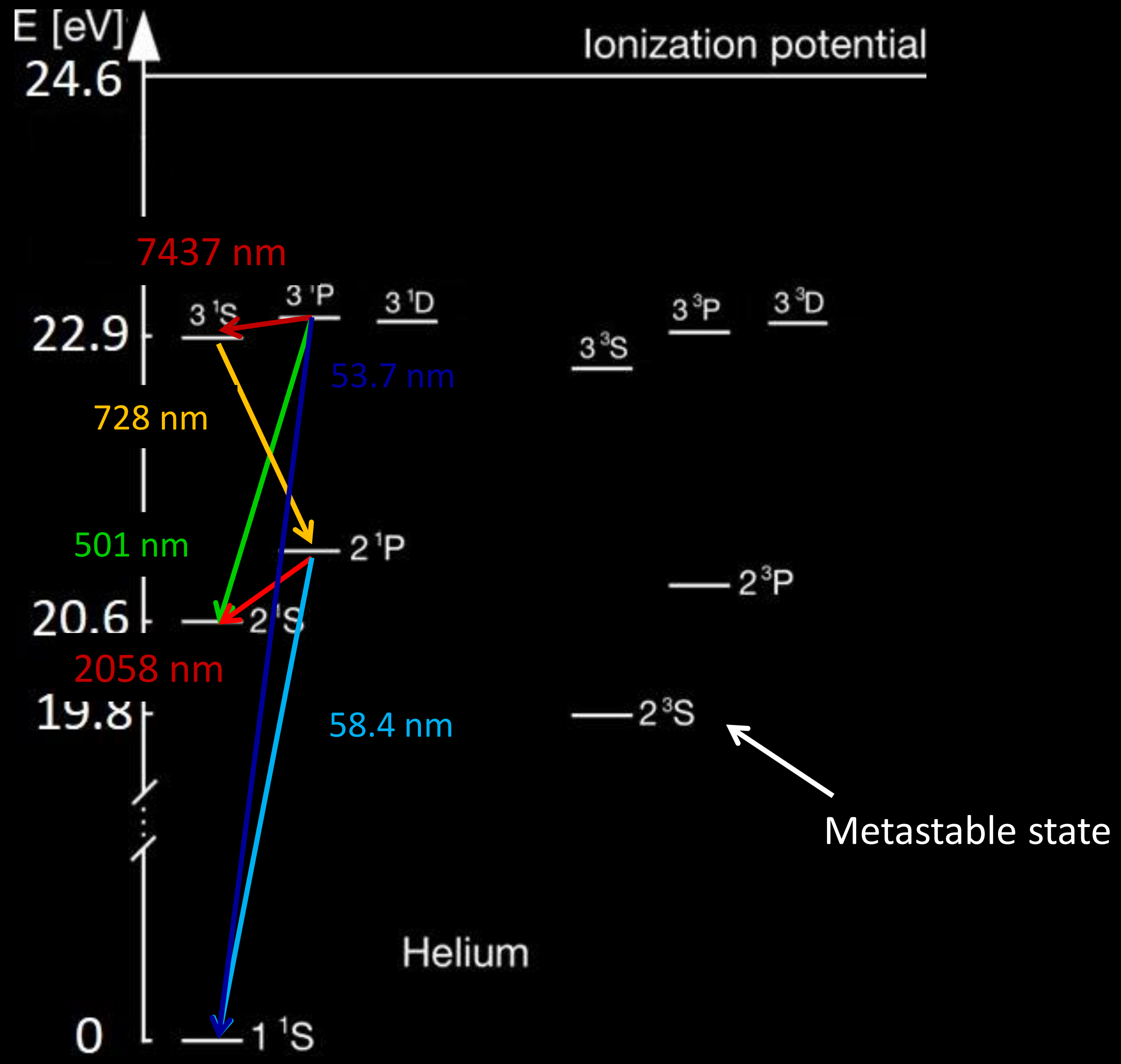


- Electron impact excitation
- Excitation rate $R_e \propto n_e, n_{n,i}, \langle \sigma v_e \rangle$



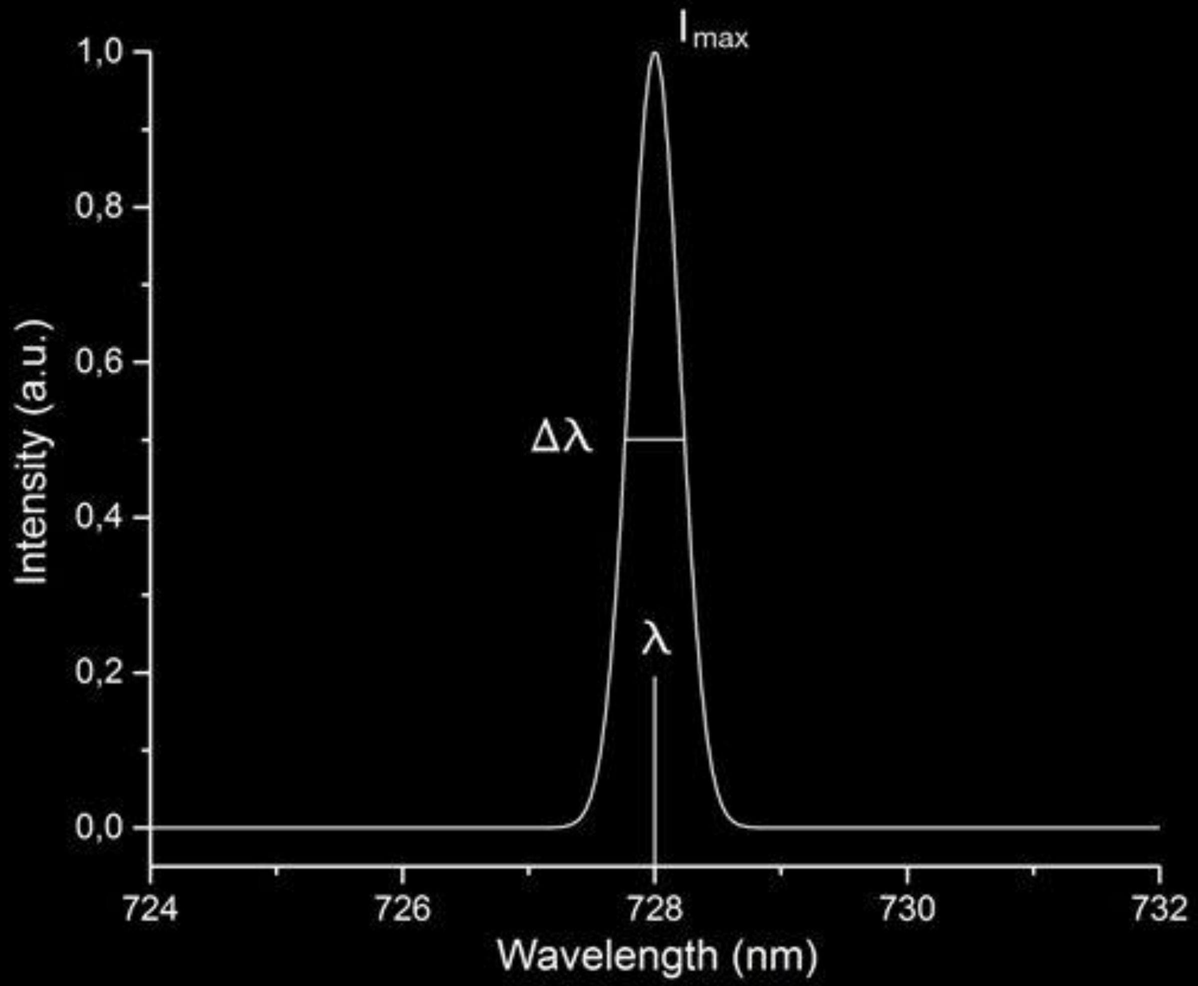
From ECRIS electron energy distribution function

Spontaneous emission



- Due to spontaneous emission electron in excited state undergoes a transition to a lower energy state
- Photon with wavelength of $\lambda = hc/(E_p - E_k)$ will be emitted
- Intensity of emission is $I_\lambda = n(p)A_{pk}$

Spontaneous emission



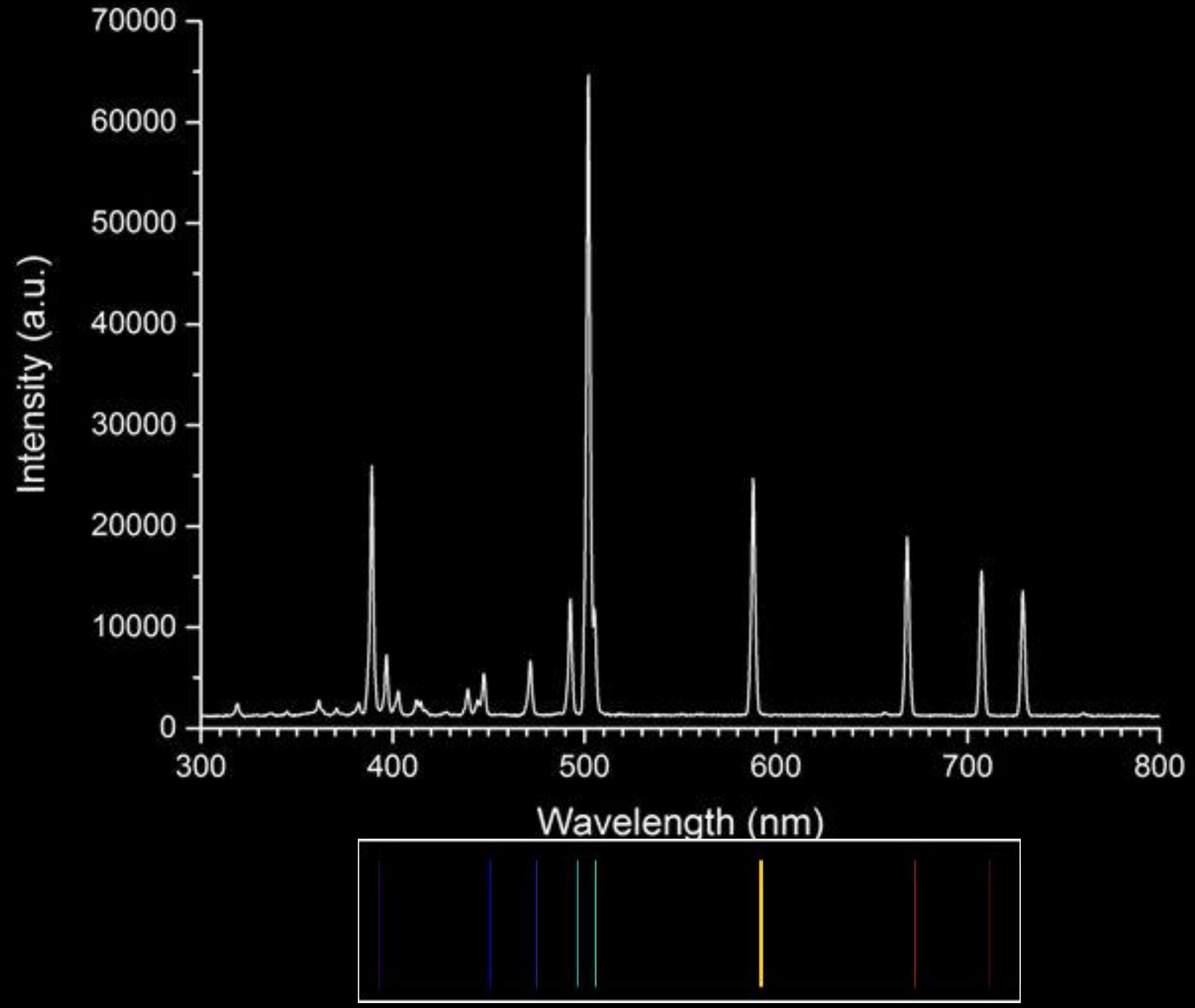
Emission lines do not ever have sharp delta function profile ($\Delta\lambda > 0$)

Profile depends on the broadening mechanism:

- Natural broadening
- Doppler broadening
- Stark/Zeeman broadening
- Collisional broadening
- Instrumental broadening

In our plasma first four are usually small compared to instrumental broadening

Spontaneous emission



Emitted photons can be measured and plotted to wavelength spectrum

Optical emission plasma spectroscopy

The wavelength spectrum of light is like a fingerprint of an element

Plasma spectroscopy can be used to identify particle species in the plasma

&

Light intensity depends on ion density and electron energy distribution function

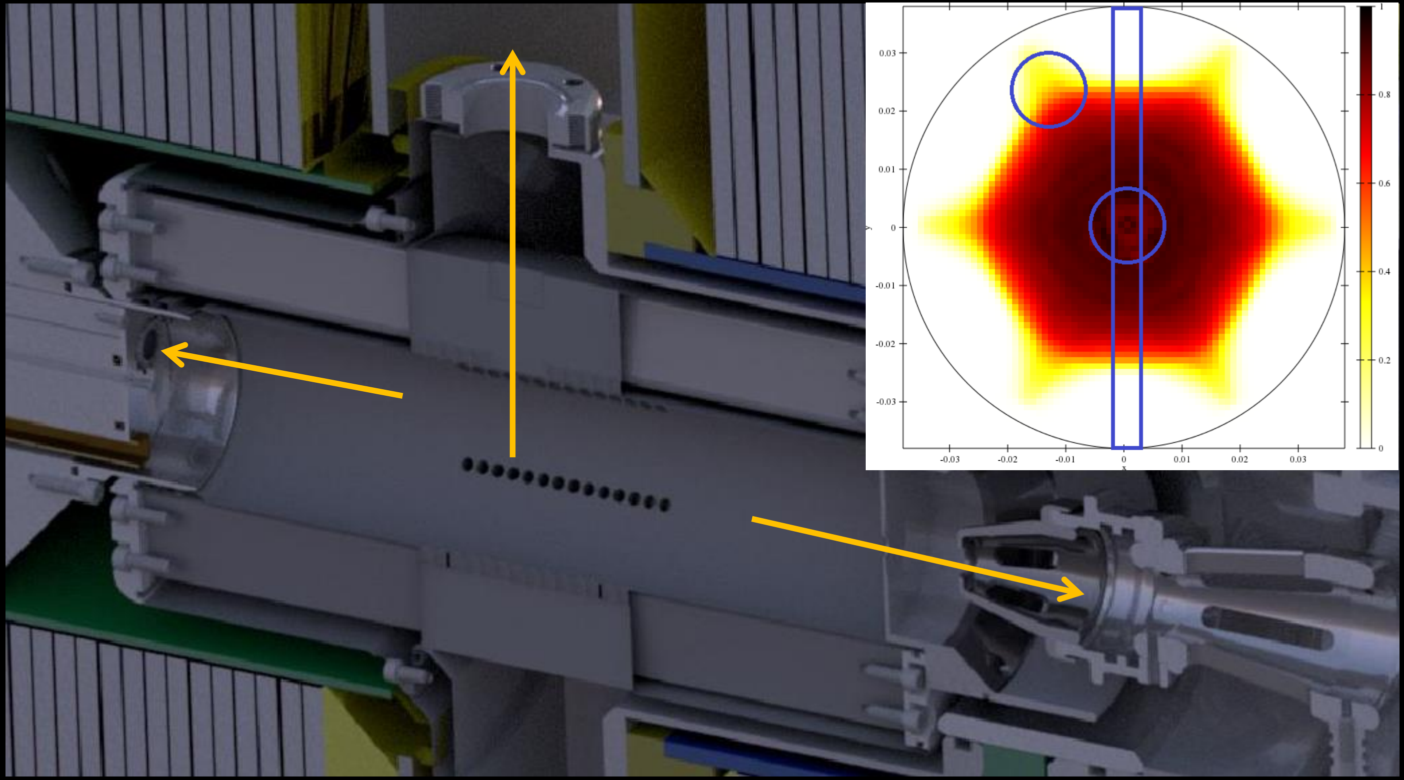
Plasma spectroscopy can give insight on how different methods and different ECR parameters affects on electrons and ions.

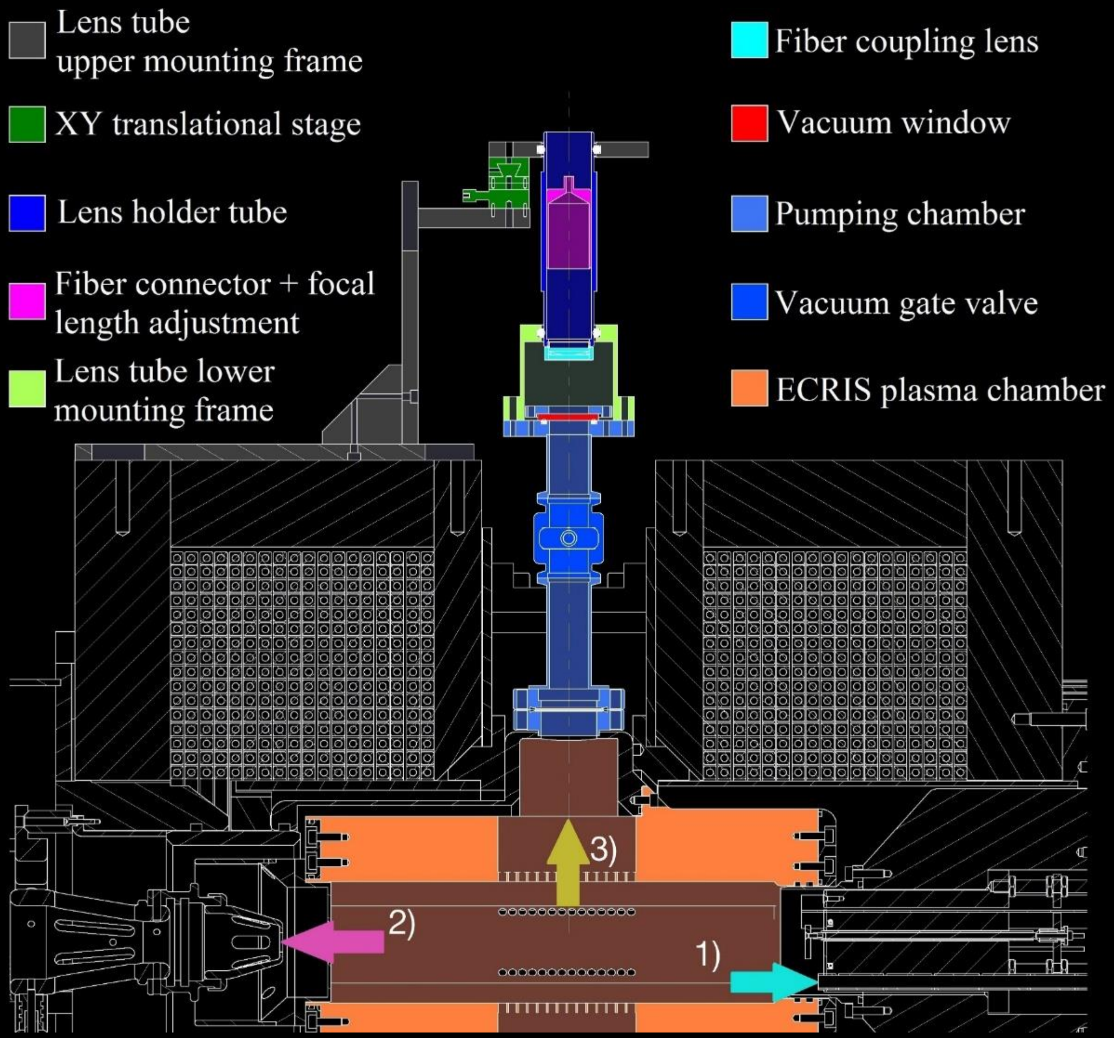
&

The functional shape and the FWHM of emission line depends on multiple broadening mechanisms

Plasma spectroscopy can give insight on ECRIS plasma physics like ion temperature, pressure, electric and magnetic field inside plasma.

ECRIS and light output





Three ports to optically view the plasma:
-Oven port
-Extraction
-Radial pumping holes
→different line of sights

Plasma chamber in 10^{-7} mbar order of magnitude vacuum
→Optically transparent vacuum window needed
Plasma chamber biased in HV
→HV insulation needed

Geometrical extent

- Emitted photon flux from plasma is relatively small
  - Optical path from plasma to detector have to be optimized
- Optical system throughput is $\phi_{\text{out}} = G \cdot t \cdot \phi_{\text{in}}$
- ϕ is radiance, G is geometric extent *and* t is transmittance
- Geometric extent, G, characterizes the ability of an optical system to emit and accept light.
- It is a constant of the system and is determined by the LEAST optimized segment of the entire optical system.

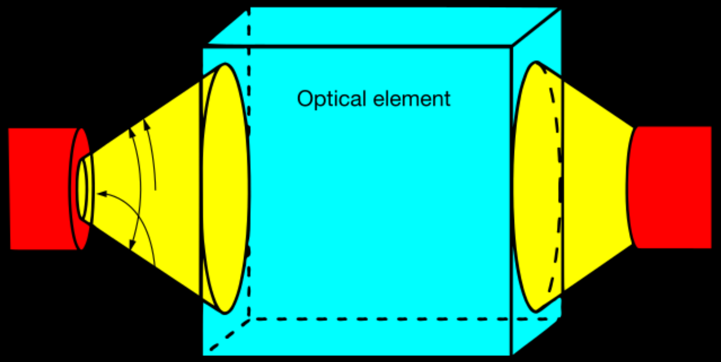
Spectrometer

$$G = \frac{h \cdot n \cdot k \cdot A_G \cdot BP}{L_A \cdot 10^6}$$

- h = height of entrance slit (mm)
- n = groove density of grating (g/mm)
- k = diffraction order
- A_G =illuminated area of grating (mm^2)
- BP =bandpass (nm)
- L_A =input arm length (mm)

Optical elements like lenses and fibers

$$G = \iint dS d\Omega = \pi S (\sin\theta)^2$$



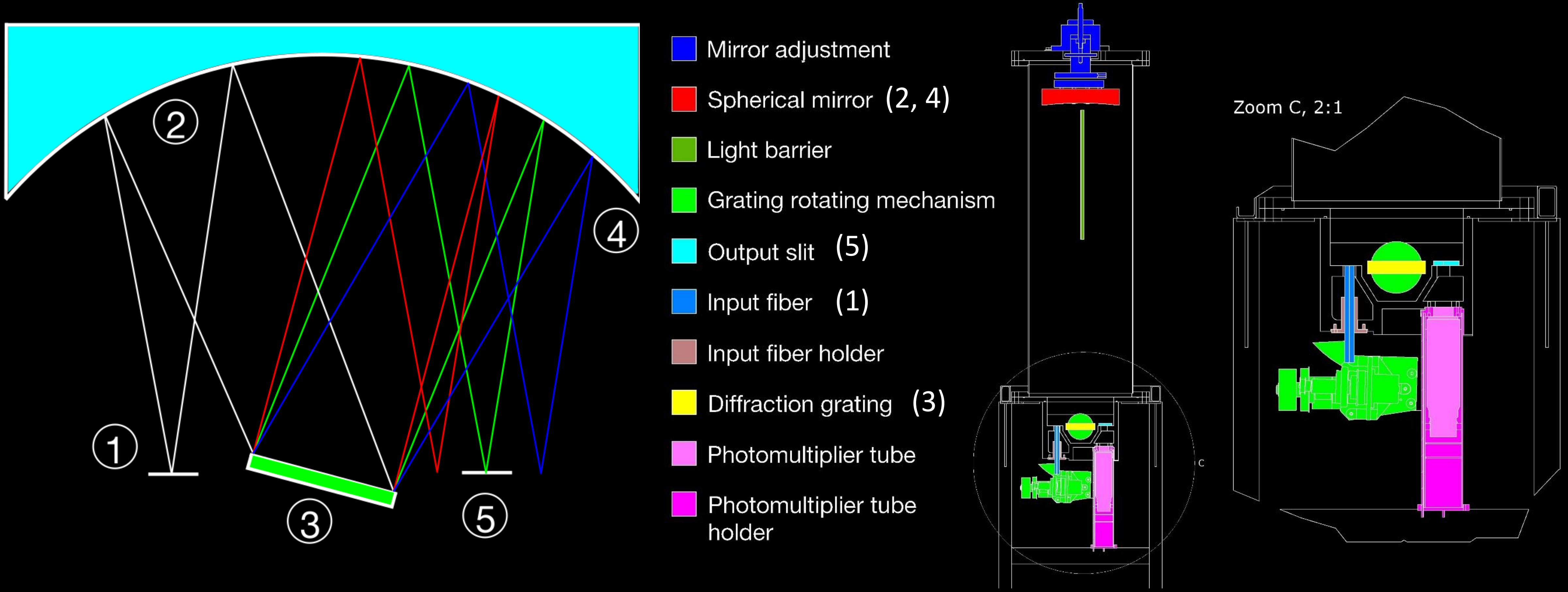
Spectrometer

- Number of emission lines emitted by ECRIS plasma can be high
- Emission line density increases when atomic number increases

  → distance between lines decreases
- High resolution monochromator will be needed

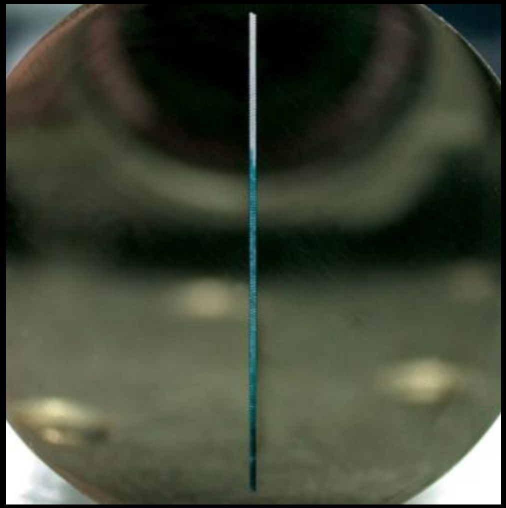
Monochromator POSSU

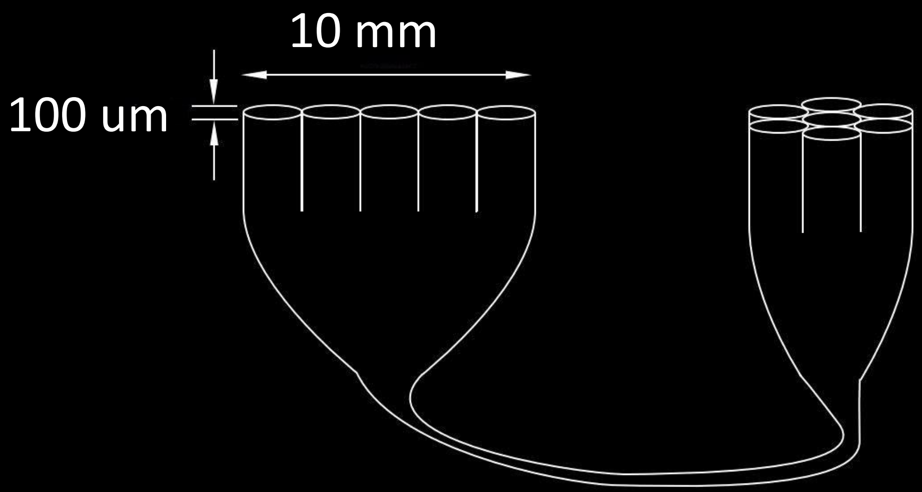
is high resolution Fastie-Ebert type monochromator developed in the JYFL.
Numerical aperture $NA = 0.22$
Geometric extent $G \approx 0.01$

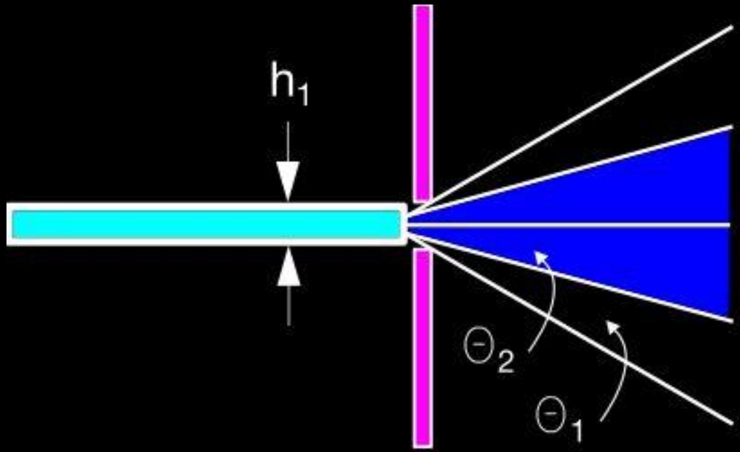


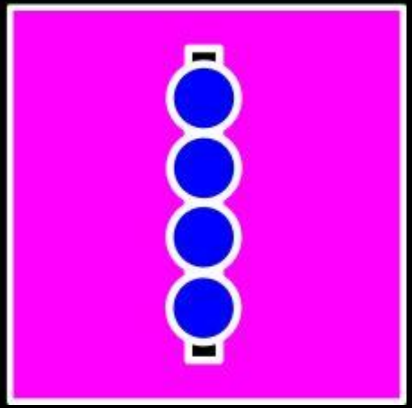
Input to monochromator

Round to linear fiber bundle
Numerical aperture $NA = 0.22$
Geometric extent $G \approx 0.01$
Numerical apertures matched and geometric extent of fiber sets the extent to whole optical system



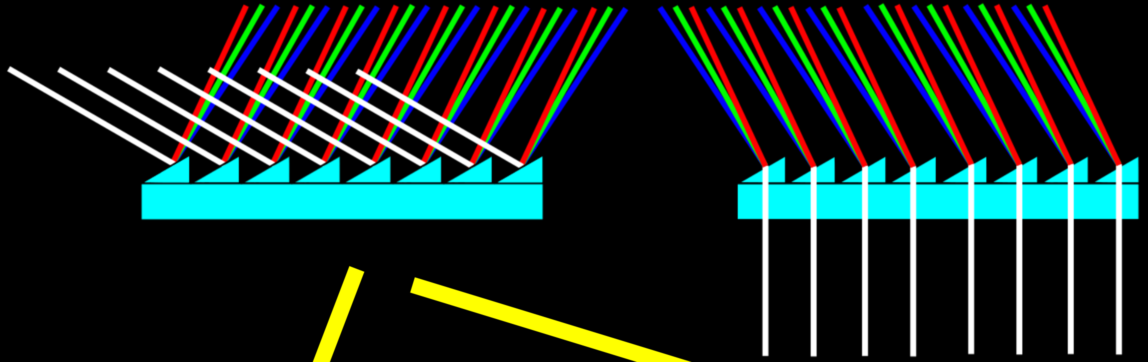






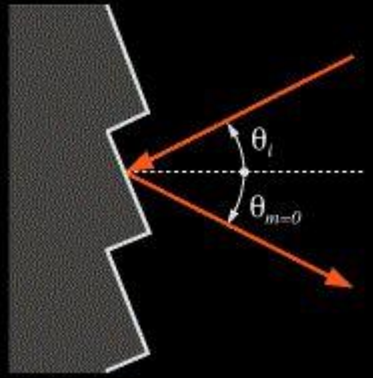
Wavelenght separation

Reflective and transmission diffraction gratings



Dispersion prism

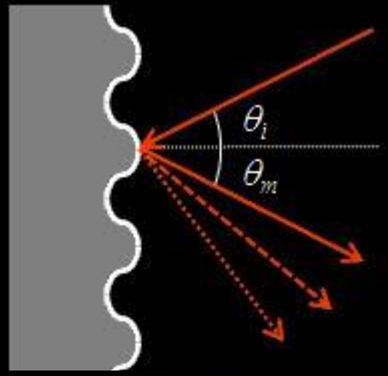
Ruled grating



Better when:

- Working in IR
- Working with low groove density

Holographic grating



Better when:

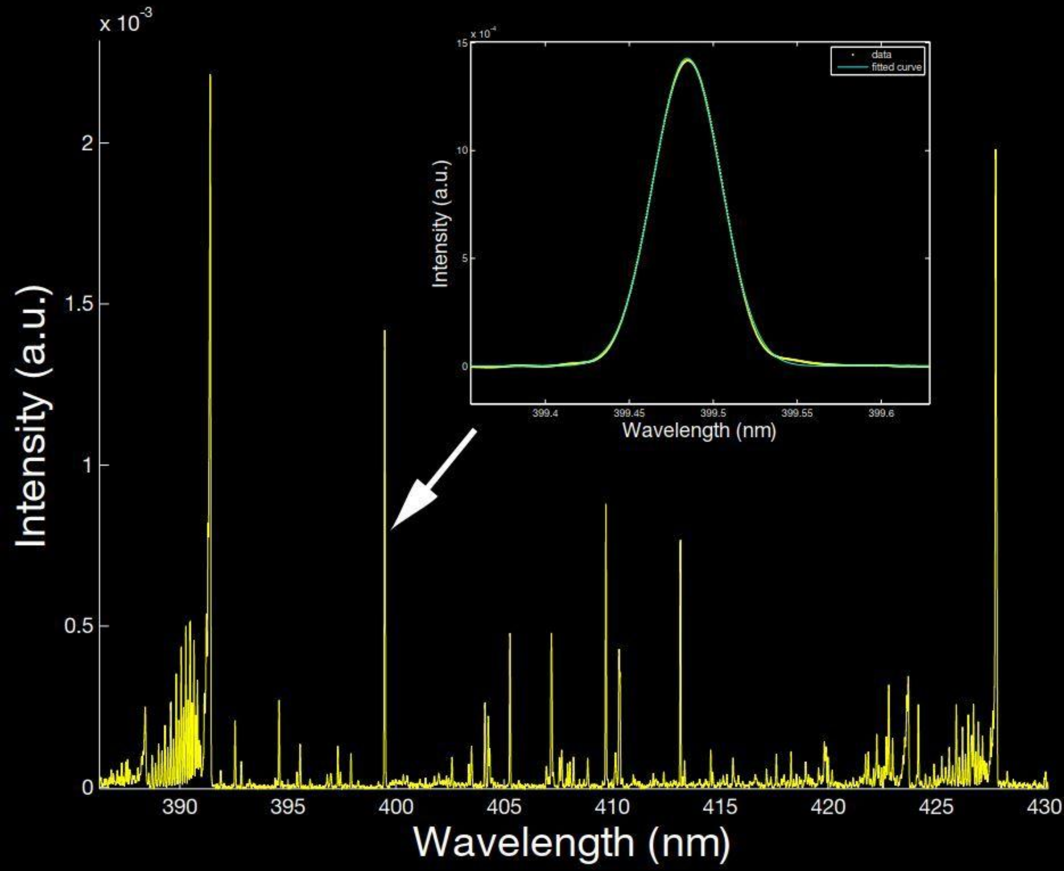
- Working in UV, VIS, NIR
- Working with high groove density
- Working with k > 1 order diffraction

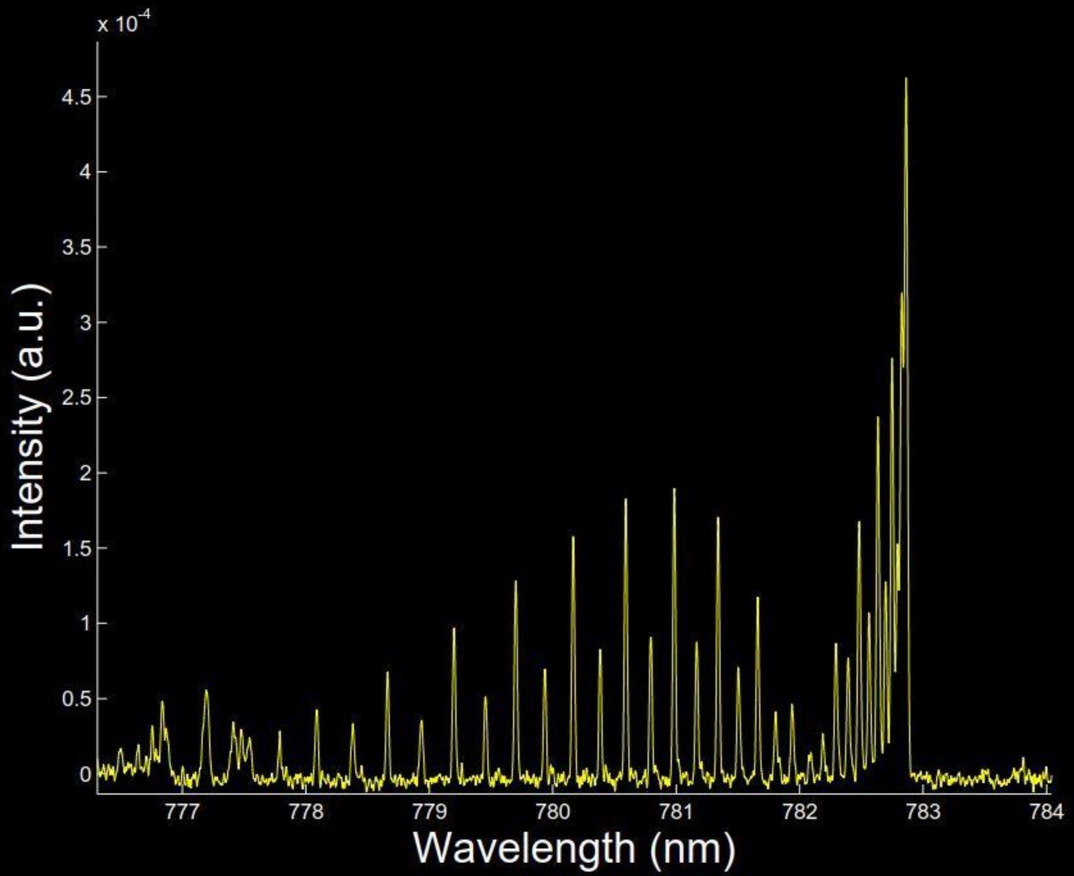
Monocromator resolution

The Wavelength resolution depends on:

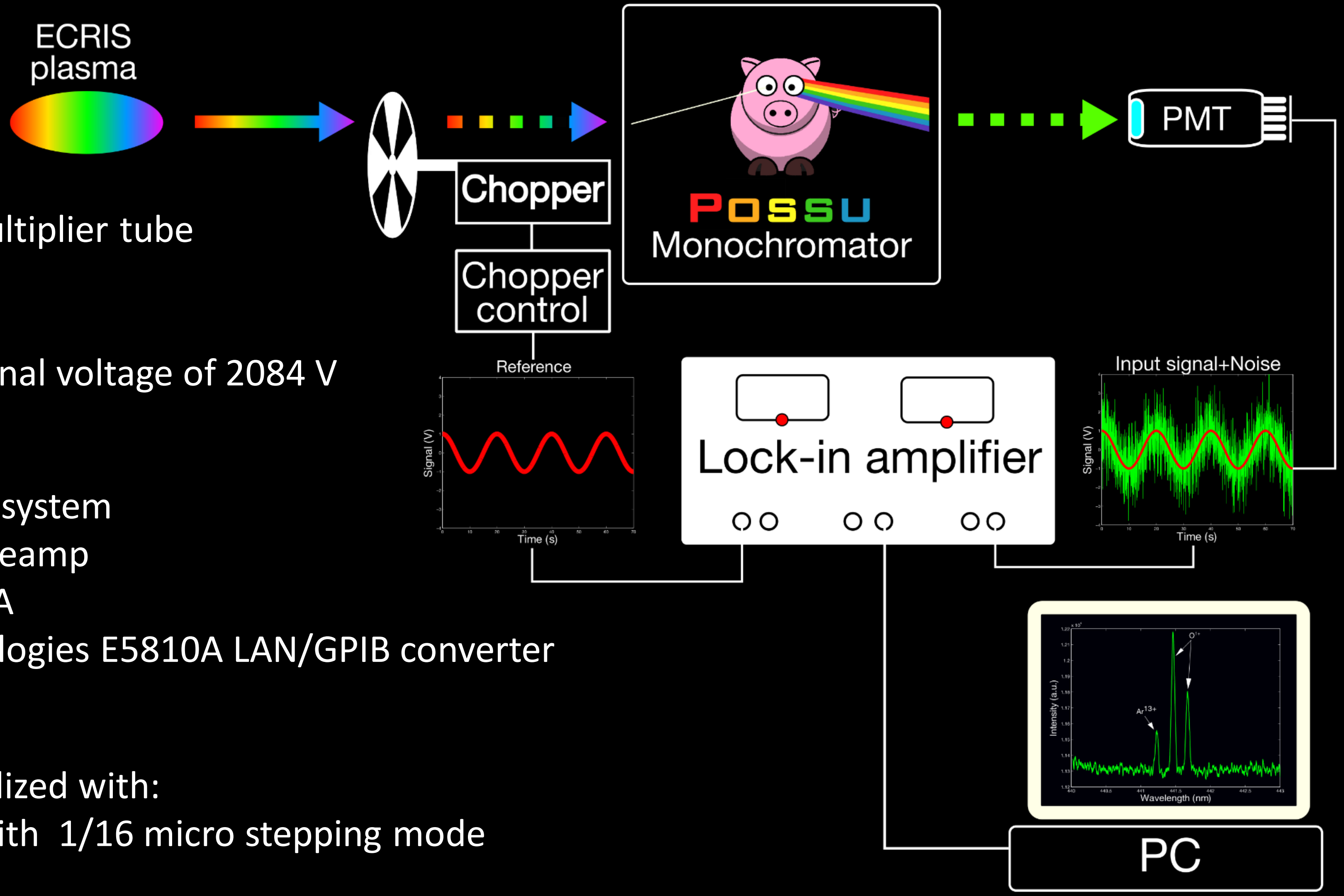
- Width of the slits (Input and Output) → 2 options in POSSU (10 um and 100 um)
- Diffraction grating groove density → 2 options in POSSU (1800 1/mm ruled and 2200 1/mm holographic)
- Focal length → constant (~1 m)

→ Optical resolution 10 pm FWHM @ 632 nm





Data Acquisition



Detector:

High sensitivity, Peltier cooled photomultiplier tube

- ET-Enterprises 9816B PMT
- Spectral range 290 – 870 nm
- 5000 A/lm anode sensitivity at nominal voltage of 2084 V

Data acquisition:

Phase sensitive lock-in data acquisition system

- Stanford Research Systems SR570 preamp
- Stanford Research Systems SR830 LIA
- IEEE-488 GPIB bus to Agilent Technologies E5810A LAN/GPIB converter

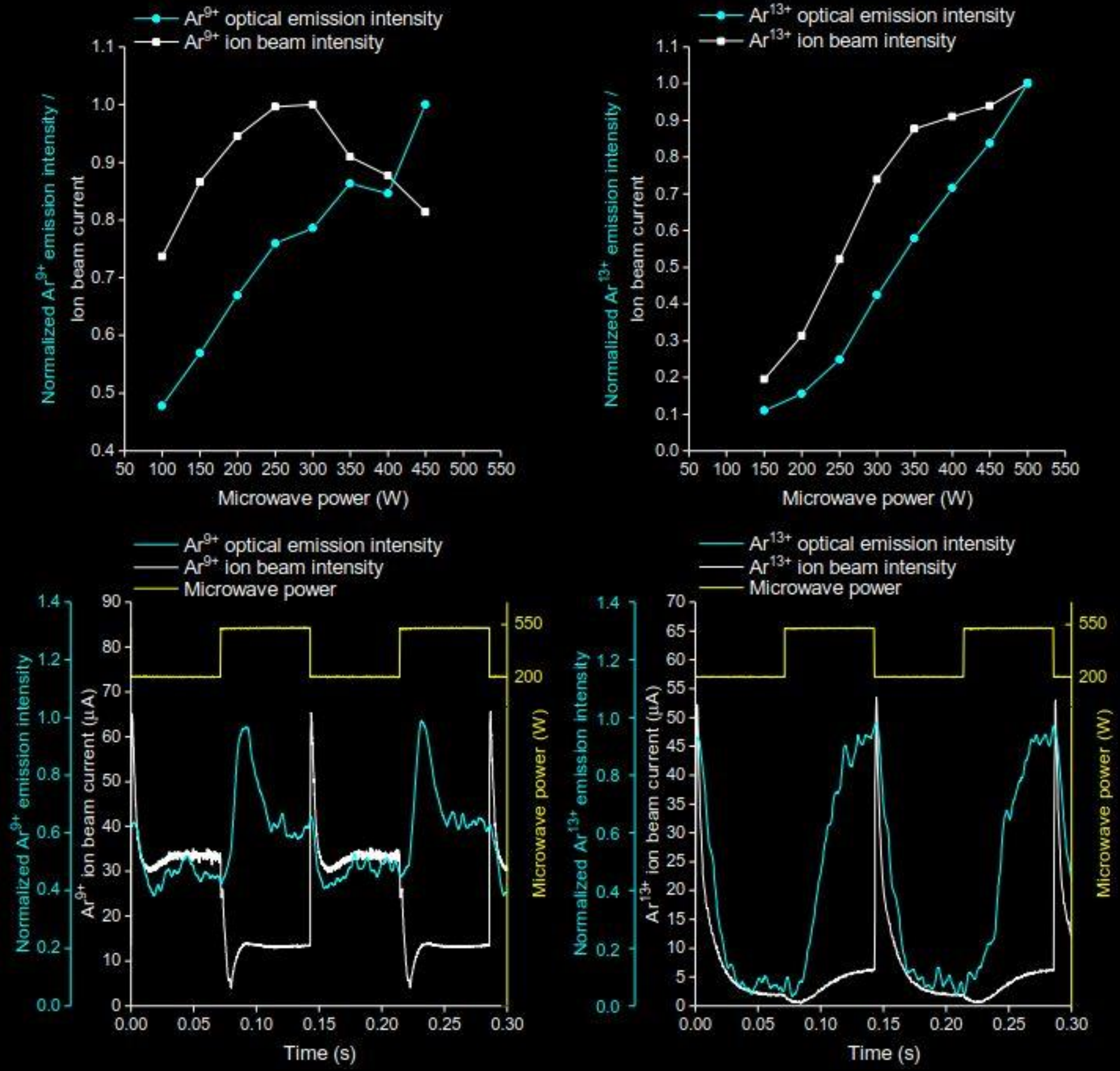
Control:

Rotation of the diffraction grating is realized with:

- 0.9◦/step NEMA 17 stepper motor with 1/16 micro stepping mode
- 1:1600 gearbox
- Arduino UNO micro controller

The intensity of the Ar^{9+} and Ar^{13+} optical emission and ion beam current

- The relative changes in both the optical emission and the ion beam current have been measured in CW and amplitude modulation (AM) operation mode.
- The observation implies that in CW mode the ion currents could be limited by diffusion transport and electrostatic confinement of the ions rather than beam formation in the extraction region and subsequent transport.

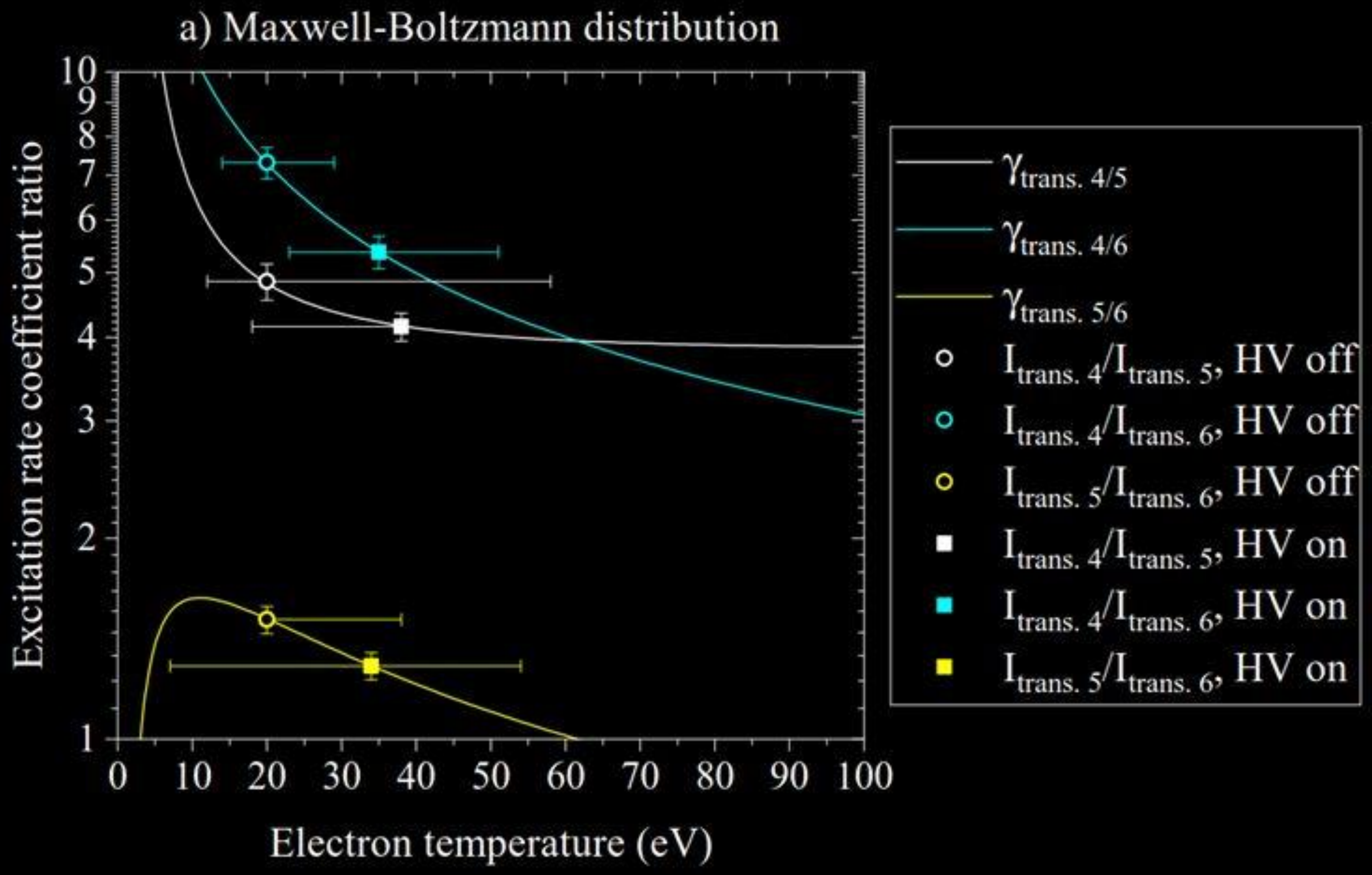


R. Kronholm, *et. al., Accepted for publication in AIP Conference Proceedings (2018)*

Spectroscopic study on cold electron population

The temperature of the cold electron population Te have been determined for Maxwell-Boltzmann and Druyvesteyn energy distributions

- The temperature was found to change from 40 ± 10 eV to 20 ± 10 eV when the extraction voltage of the ion source is turned from on to off.
- The rate coefficient of neutral to 1+ ionization was found to decrease to 42% and 1+ to 2+ ionization to 24% of the original.

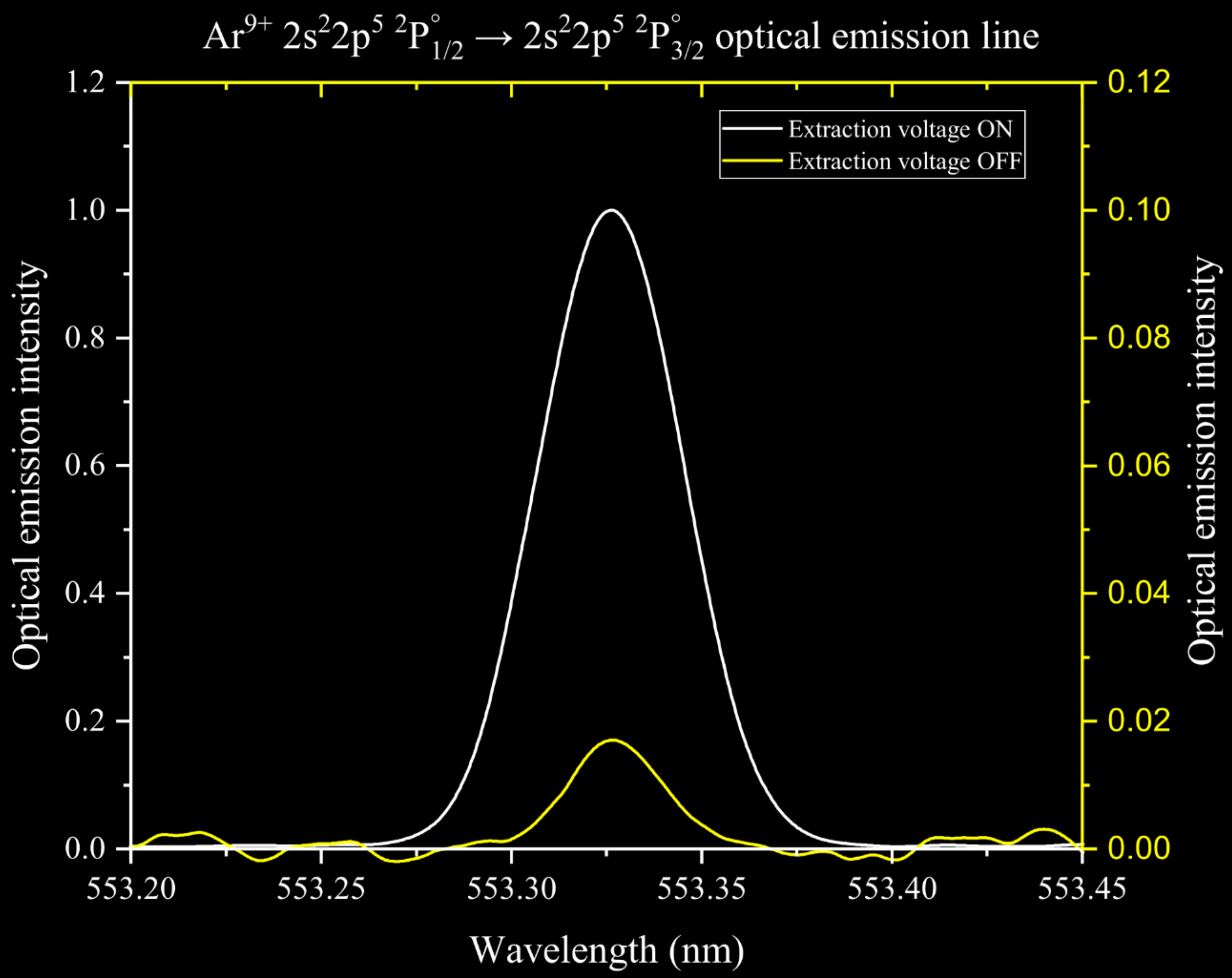


Leading to…

R. Kronholm, *et. al., Review of Scientific Instruments,* vol. 89, no. 4, *(2018)*

The effect of HV on/off to high charge states

Switching off the high voltage reduces the emission intensity of Ar^{9+} ion by almost two orders of magnitude.

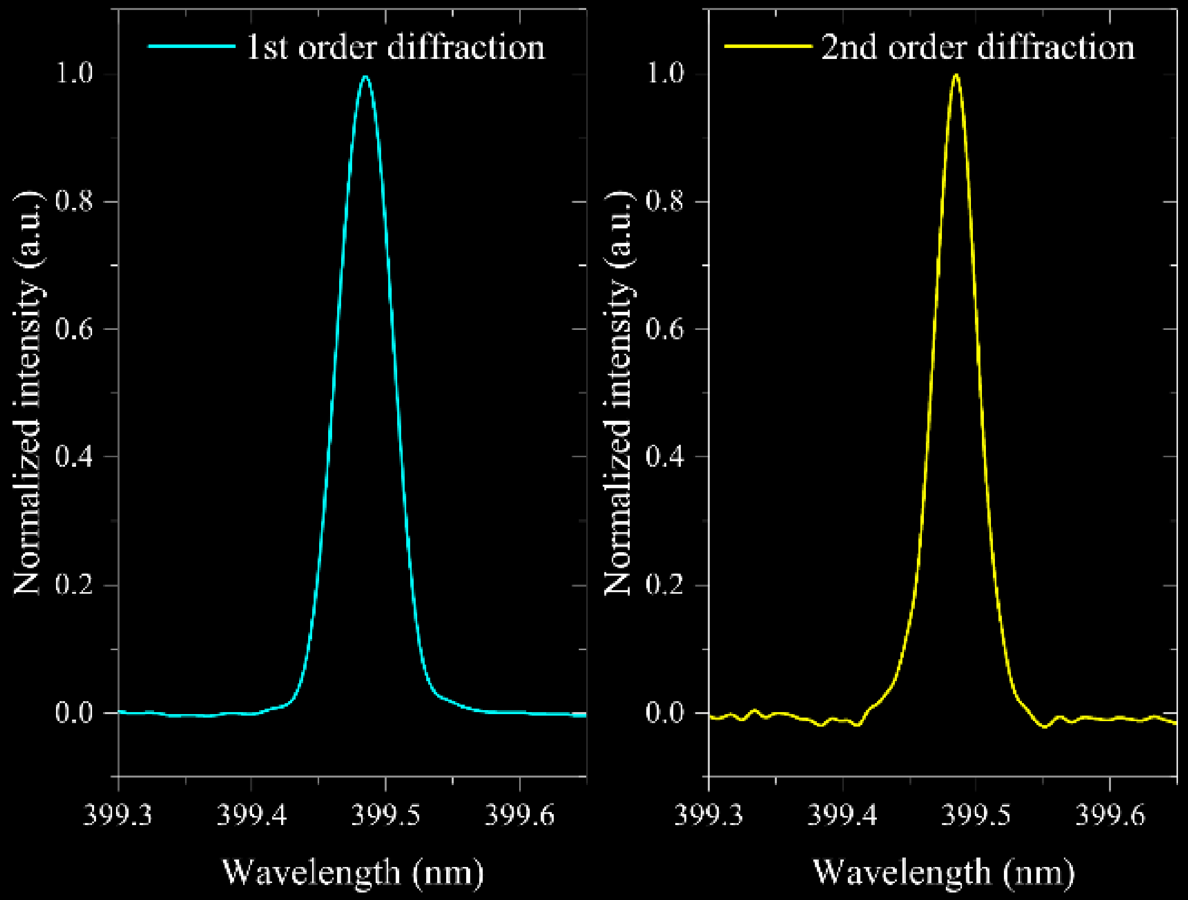


Line broadening

- Measured broadening differs from instrumental broadening
- Must complete test to find out the cause of broadening

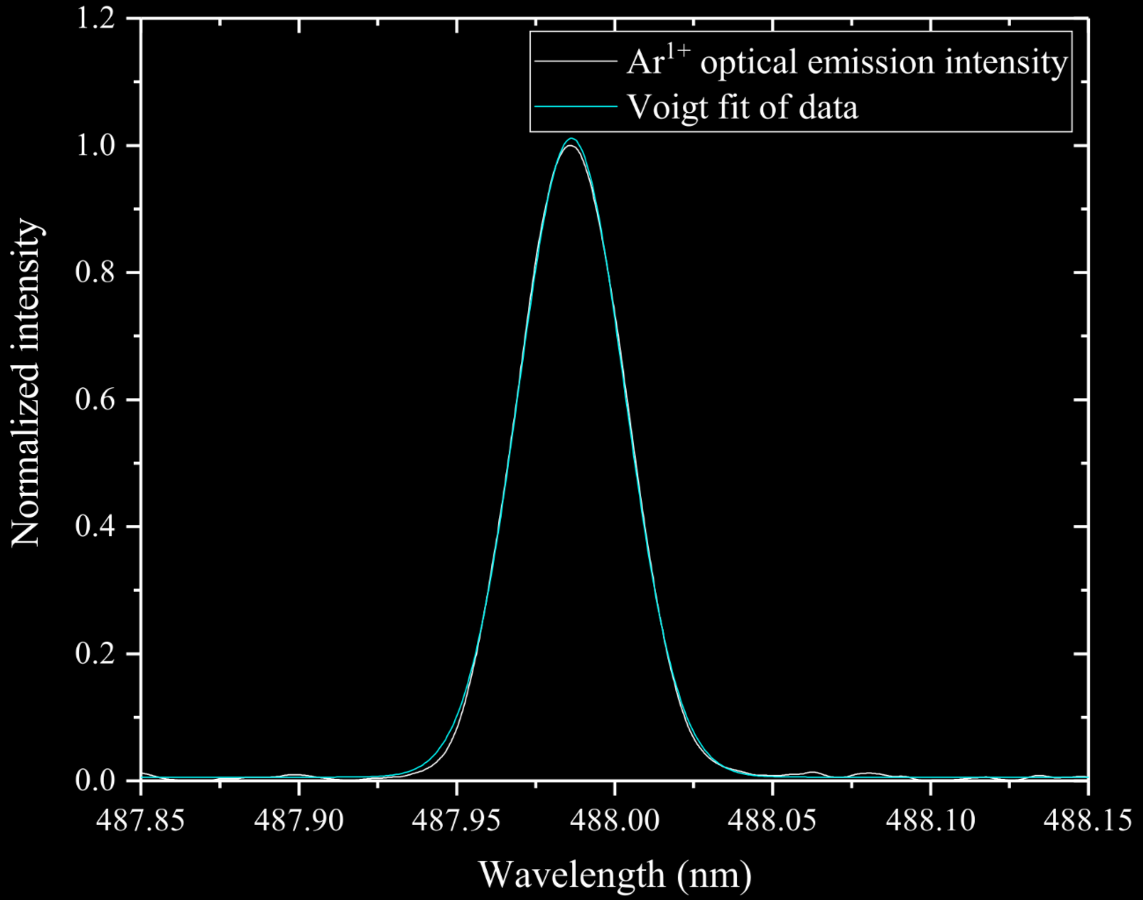
Effect of diffraction order

FWHM = 48.7 pm　　FWHM = 36.6 pm



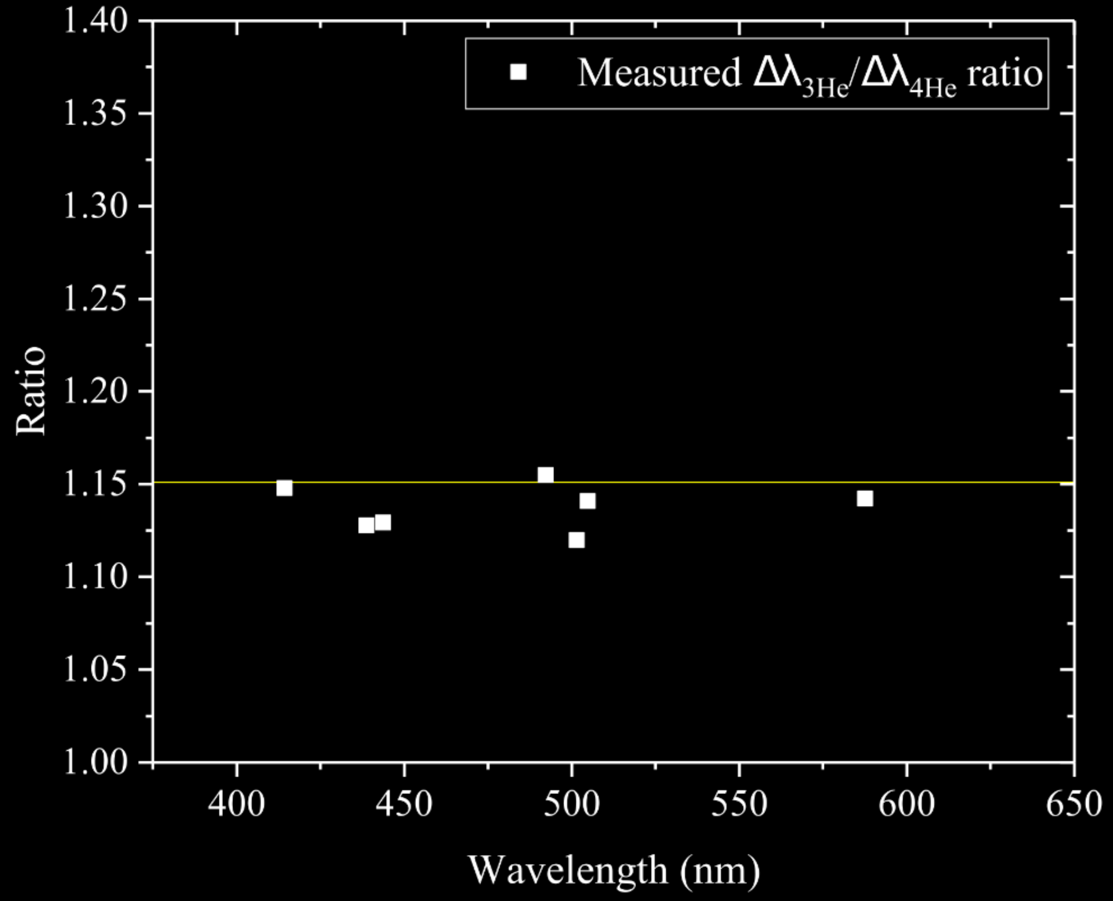
Functional shape of the peak

Gaussian FWHM = 39.5 pm, Lorentzian FWHM = 3E-18

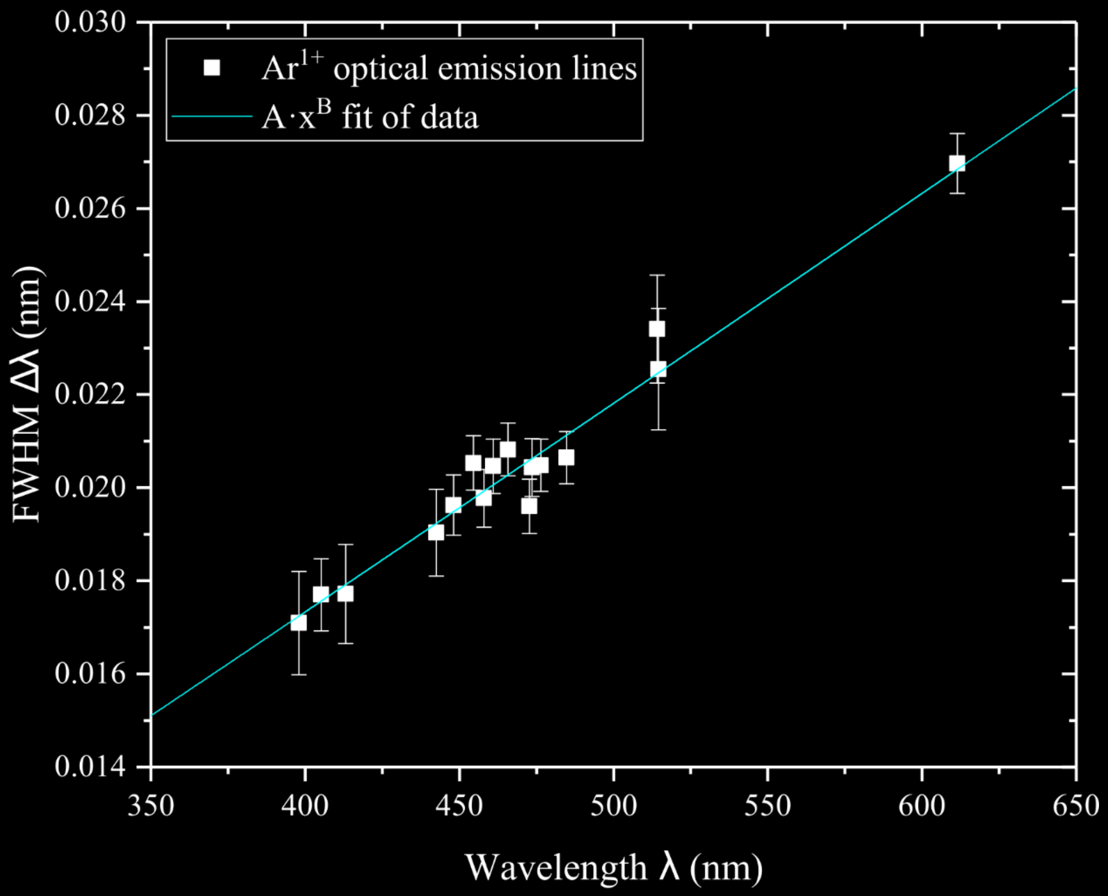


Line broadening

Mass dependency



Wavelength dependency



Line broadening

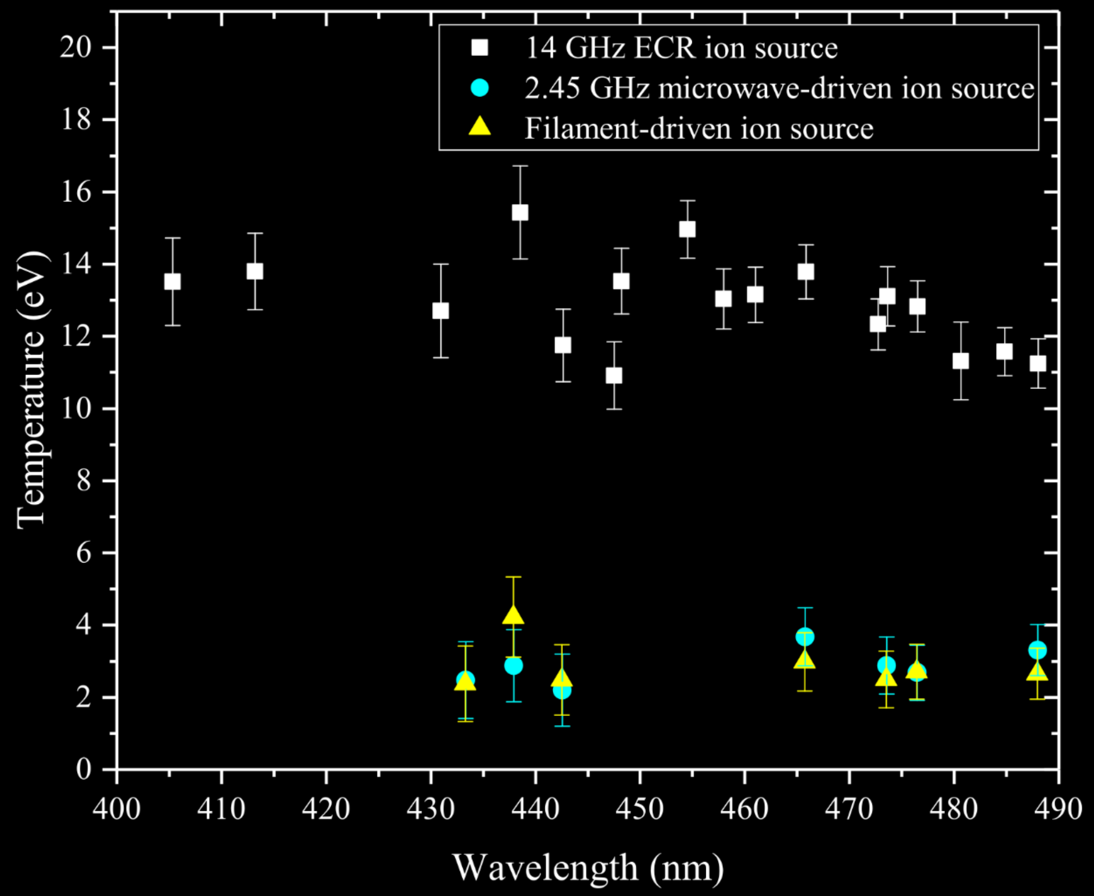
- FWHM in 2nd order diffraction > 0.5 * 1st order diffraction
- Functional shape of the emission line is Gaussian
- FWHM depends on the mass
- $\Delta\lambda / \lambda$ = constant

$\longrightarrow$ Characteristics of Doppler broadening

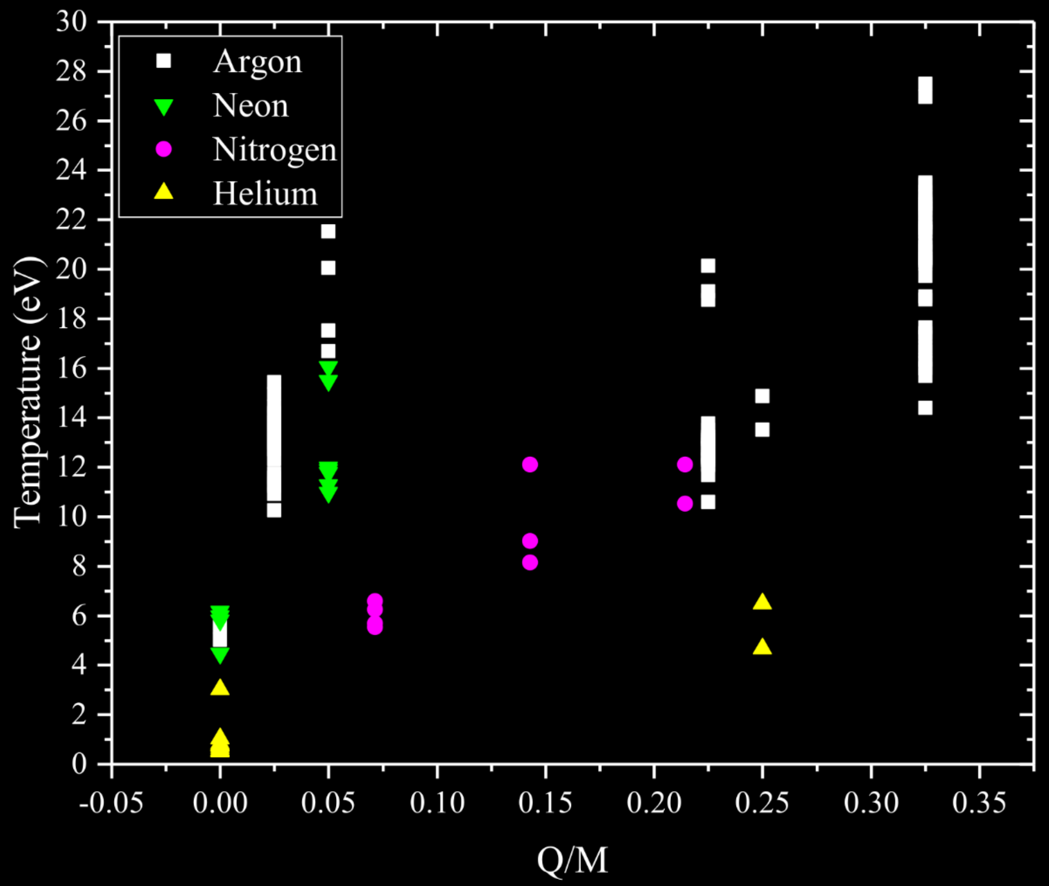
$$\frac{\Delta\lambda}{\lambda} = 2\sqrt{2\ln 2\frac{kT}{mc^2}}$$

Ion temperatures

Comparison between different ion sources, Ar^{1+}



Comparison between elements and charge state



R. Kronholm, *et. al., To be published*

Results

- Back to original question about n_e, n_i, v_e and v_i:
  - Emission line-ratio method $\longrightarrow n_i, v_e$
  - Emission intensity vs. beam intensity $\longrightarrow n_i$
  - Emission line broadening $\longrightarrow v_i$

Thank you

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