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X-ray spectroscopy diagnostics to study complex supersonic plasma flows with astrophysical relevance in laser plasma

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Motivation - Laboratory astrophysics

Laboratory astrophysics – a tool to study astrophysical phenomena in a controllable conditions and at fast term evolution – using high power lasers

Scalability conditions

Viscosity, heat transfer, radiation flow are negligible $P_e >> 1$ $Re >> 1$ $\tau_{BB} >> \tau_{hydro}$

HD validity $\zeta << 1$

Euler similarity $Eu_1 = Eu_2$

A set of invariants to be preserved

$I_1 = vt / r = St$ Strouhal number

$I_2 = \gamma$ polytropy coefficient

$I_3 = P_{th} t / \rho v r = Eu \times St = St / [\gamma M]^2$

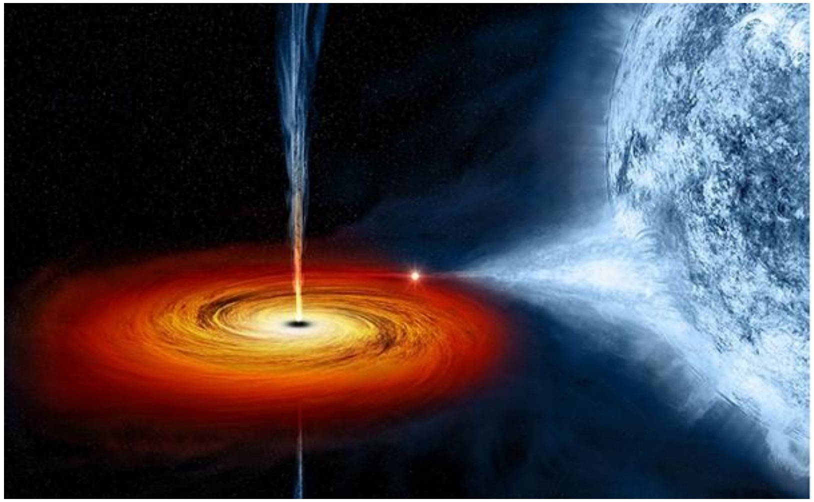
$I_4 = \tilde{L} t / P_{th} \propto t / t_{\tilde{L}}$,

$I_5 = M / [\rho r^{1+d}]$ mass conservation law

$I_9 = tF_R / (P_{th} r) = 1 / Bo$

$I_7 = P_R / (\rho v r) = Eu_R \times St$

$I_8 = E_R / P_{th} \propto 1 / R$

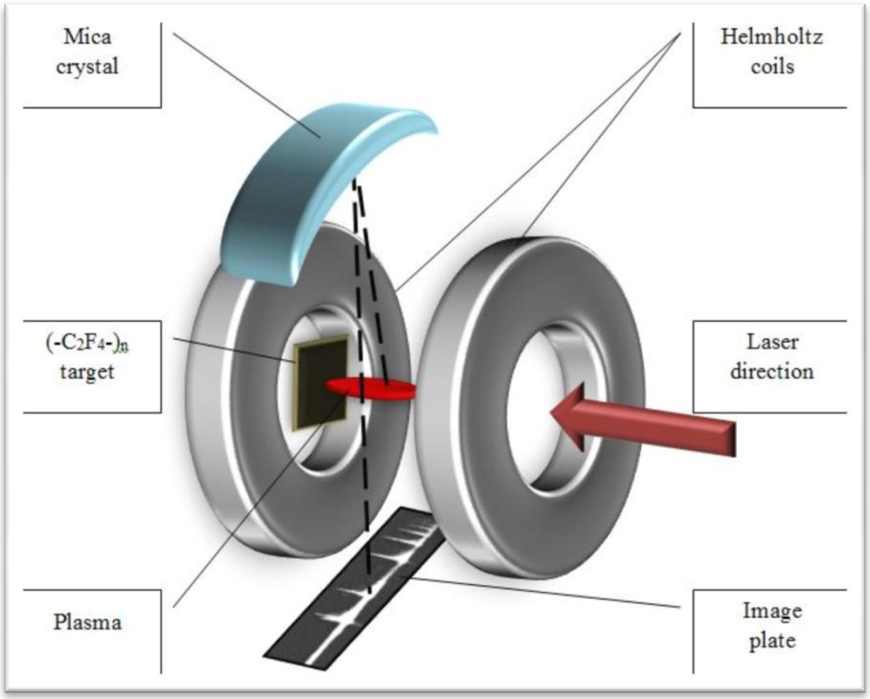


Correspondence to Strouhal number invariant

Parameter	Astrophysical plasma	Laboratory plasma
V, km/s	~ 100 - 1000	up to 1000
r, mm	3E18	1
t , s	3E10	3E-8

Laser generated jets. X-ray diagnostics concept

Hot/warm plasma (T$_e$ in 10-300 eV range) from the front target surface



X-ray imaging spectroscopy measurements on electron density and temperature with spatial resolution along the jet propagation

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SOP

e laser

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sity

ELFIE facility

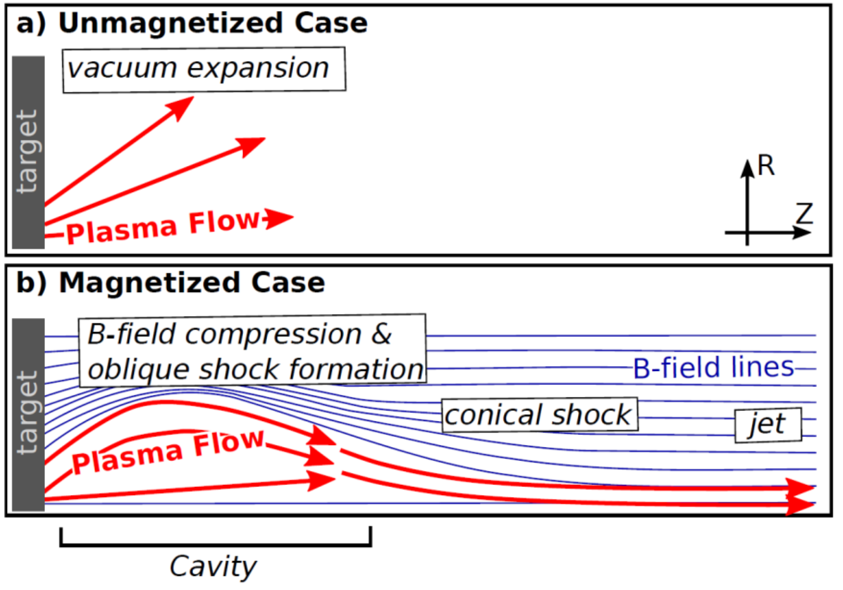
Laser:
Wavelength **λ = 1.053 nm**
Duration **τ = 0.5 – 1 ns**
Energy **E = 5 – 60 J**
Focal spot diameter **D = 750 μm**

FSSR:
Spherically bent mica
Lattice spacing **2d = 19.9376 Å**
Radius of curvature **R= 150 mm**

Magnetic field:
Helmholtz pulsed coils
poloidal component
B = 20 T

For both cases, the studies on a jet evolution can be done in presence of external magnetic field, ambient gas or plasma, solid obstacle, counter-propagating flows etc.

Studies of plasma jets phenomena – Recombining plasma



B ~ (tens of)T

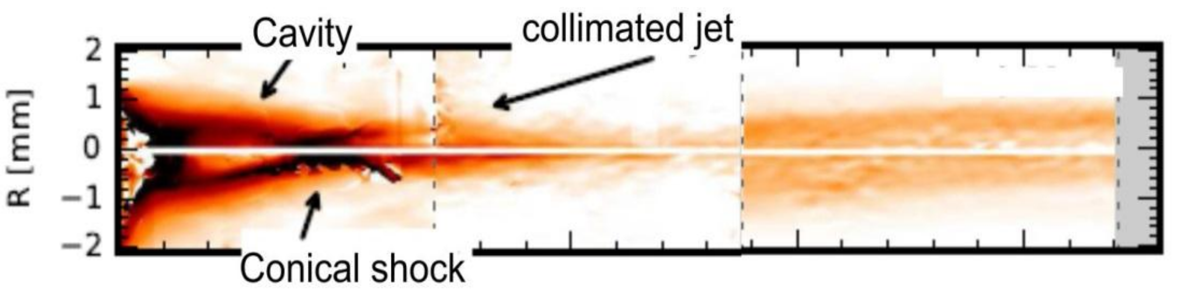
NS Long pulse of

$I = 10^{13}$-10^{14} W/cm^2

Cm long propagating plasma flow far away from the laser interaction area

Few eV/tens of eV electron temperatures – below inner-shell ionization

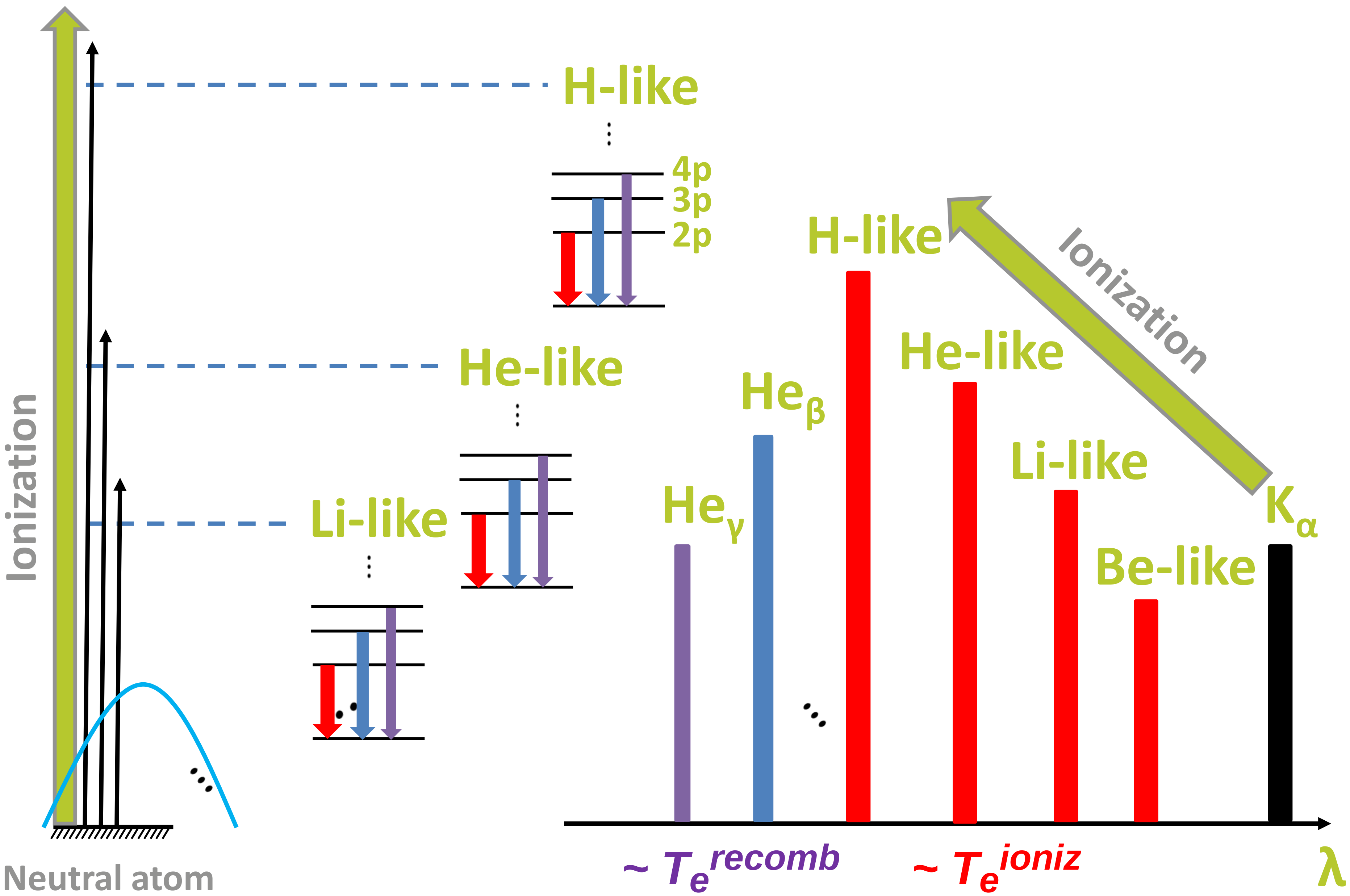
Electron densities much lower than critical – 10^{18}-10^{19} cm^{-3} range



Interferometry data on N_e map

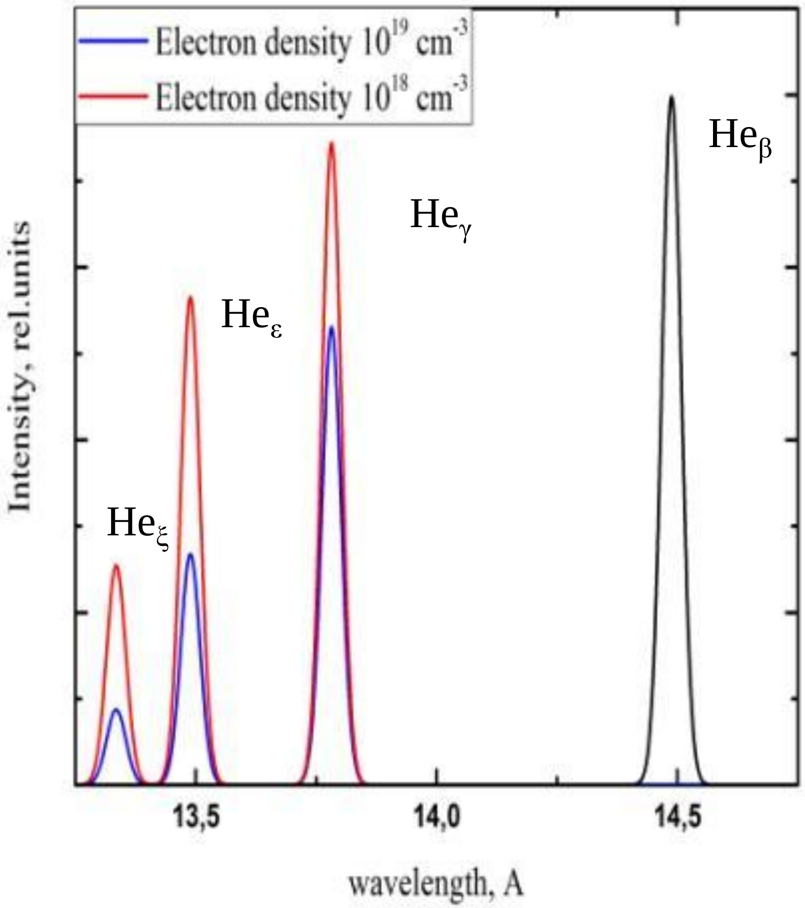
Recombining (i.e. ionization is negligible) plasma approach is valid – appropriate diagnostics is needed to be (re)emerged.

Ionization / recombination modes as appeared in spectra

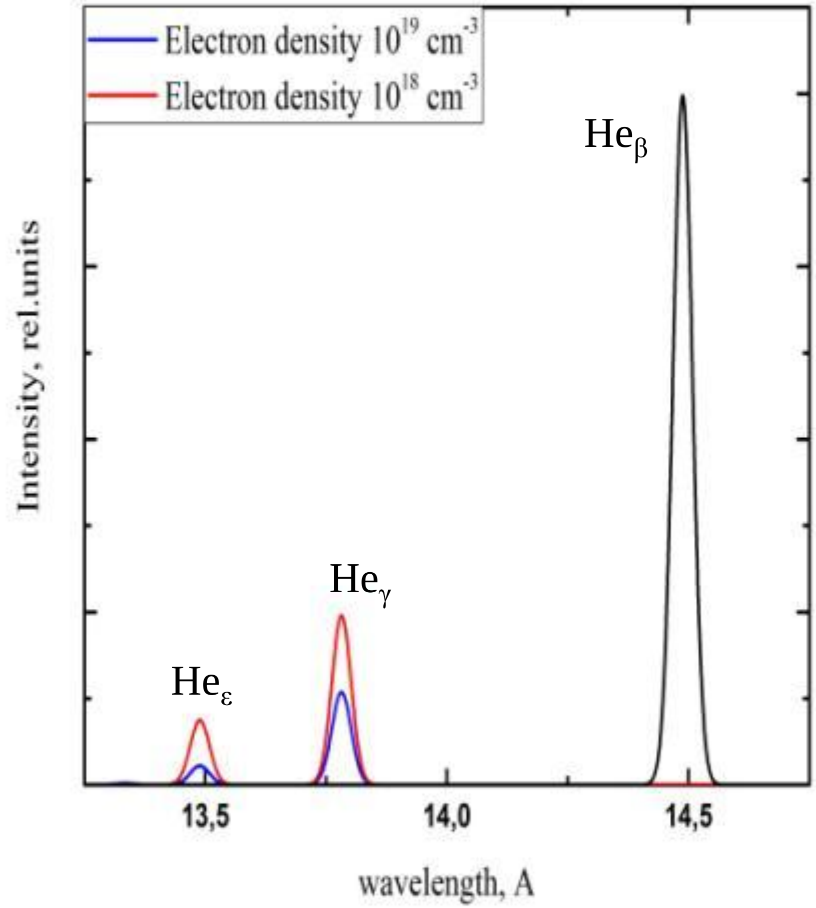


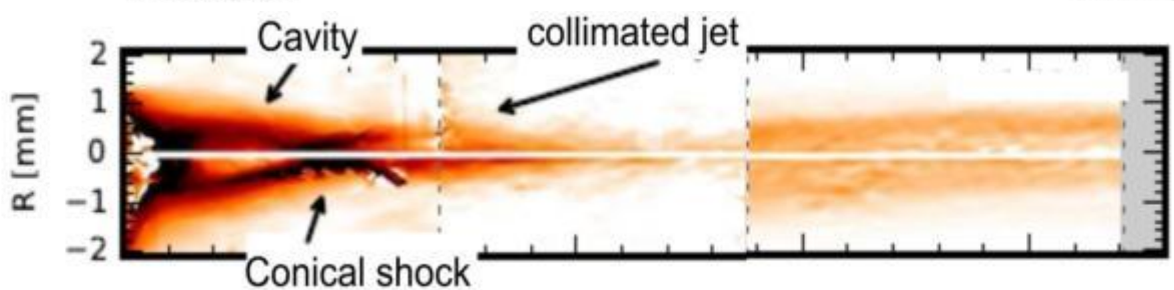
Recombining vs Ionizing plasma spectra

Recombination plasma

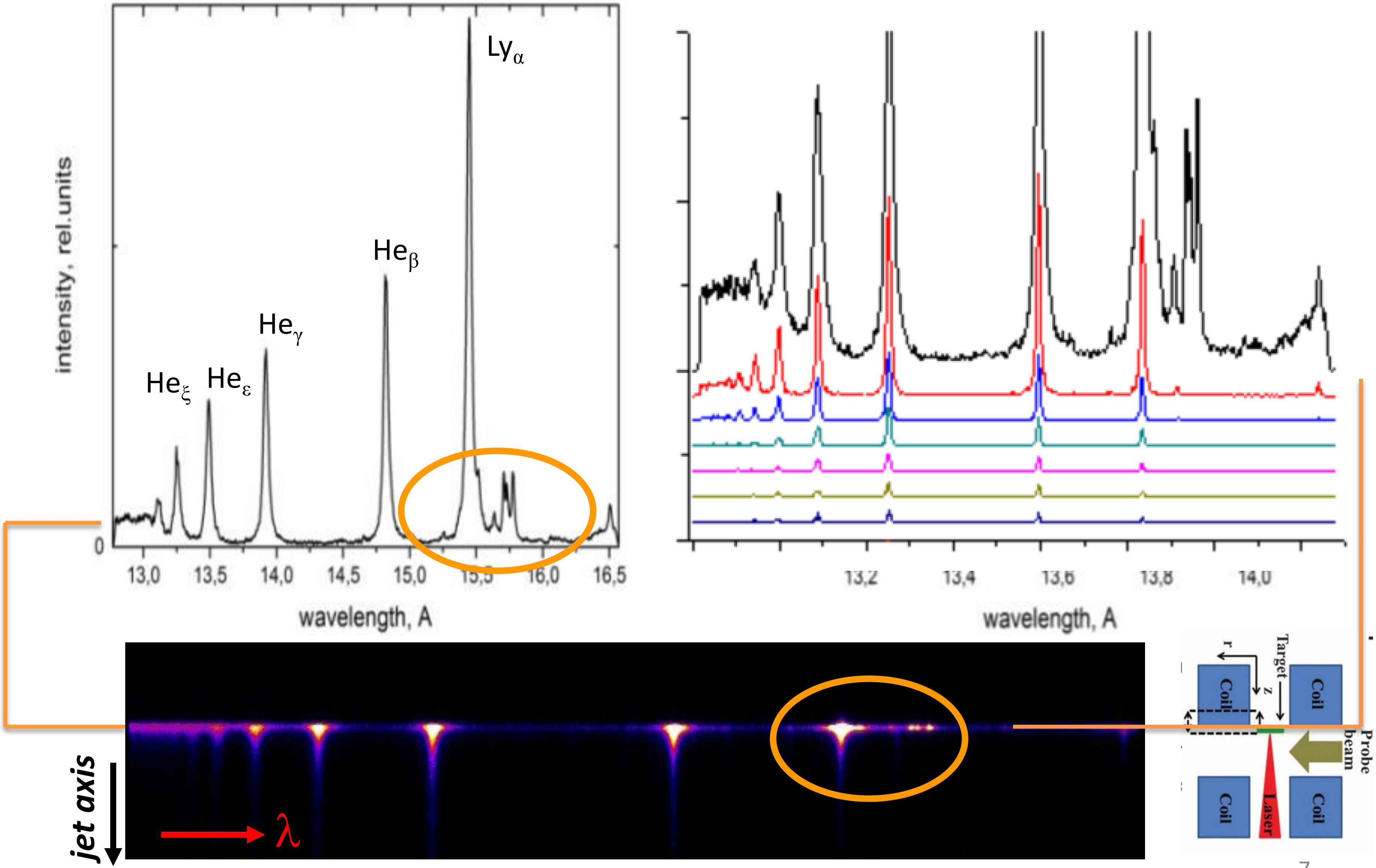


Ionizing plasma

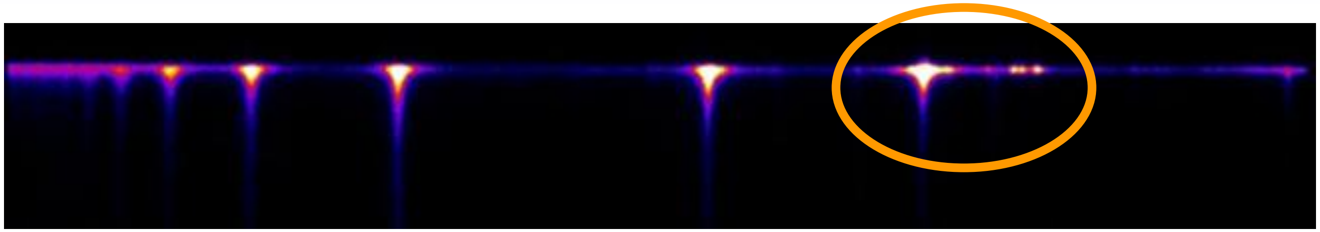


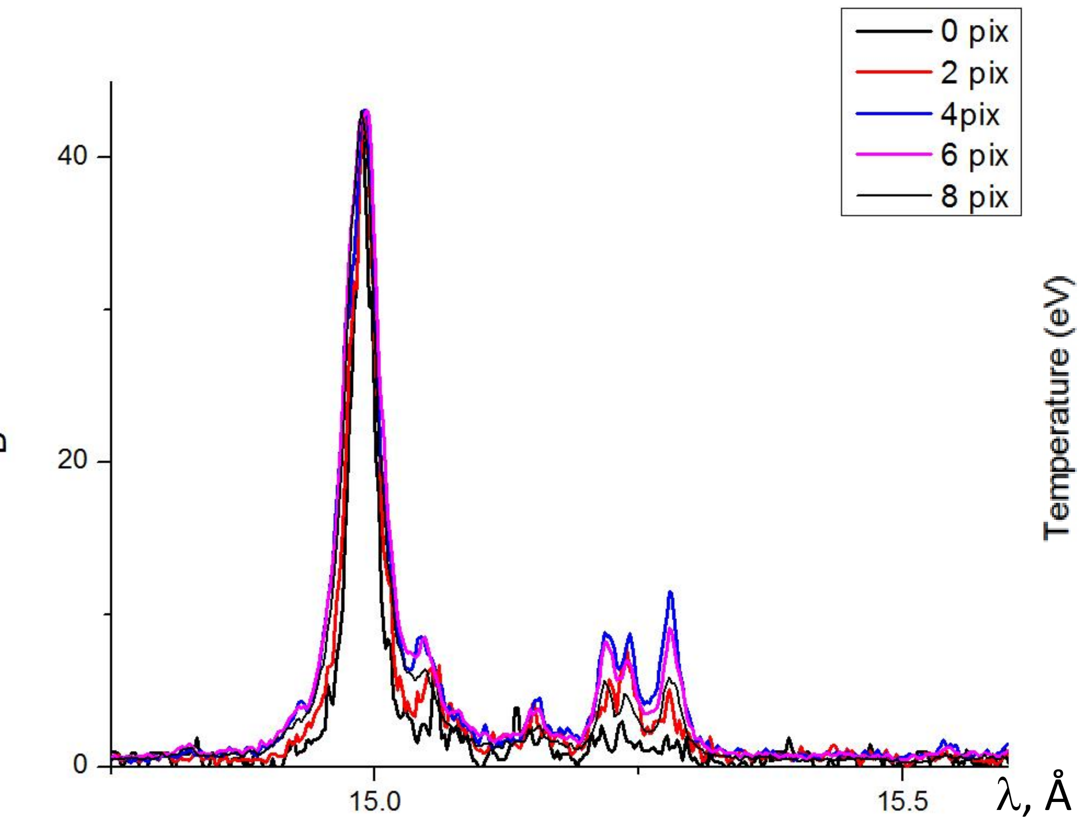


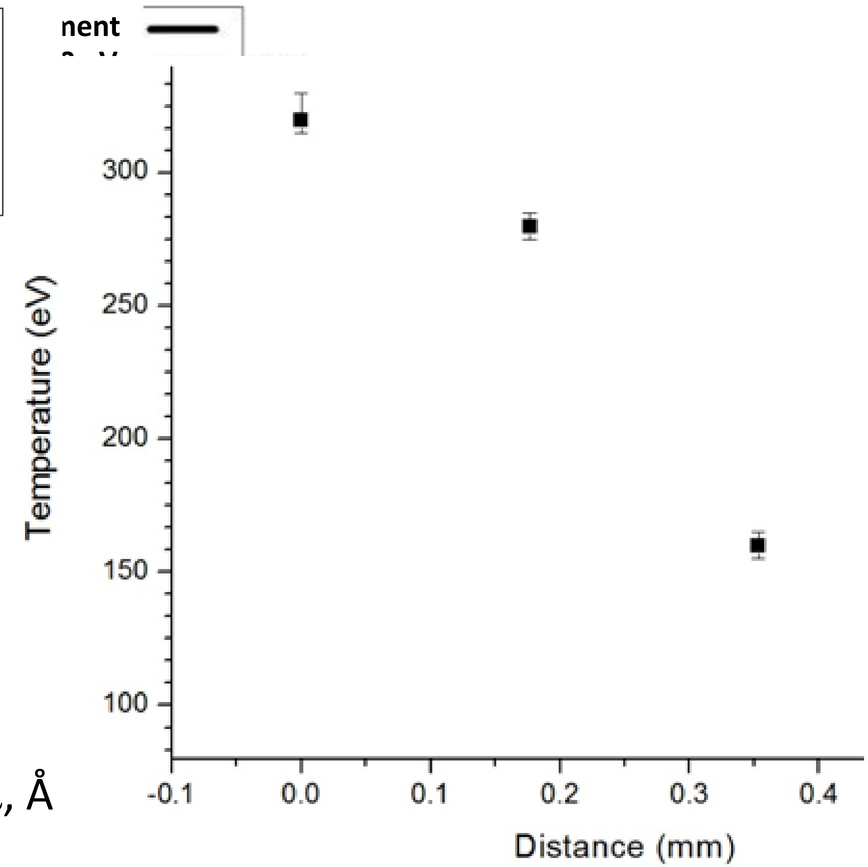
Typical x-ray spectra emitted by a plasma jet



Plasma parameters at laser irradiated target – Lya satellites





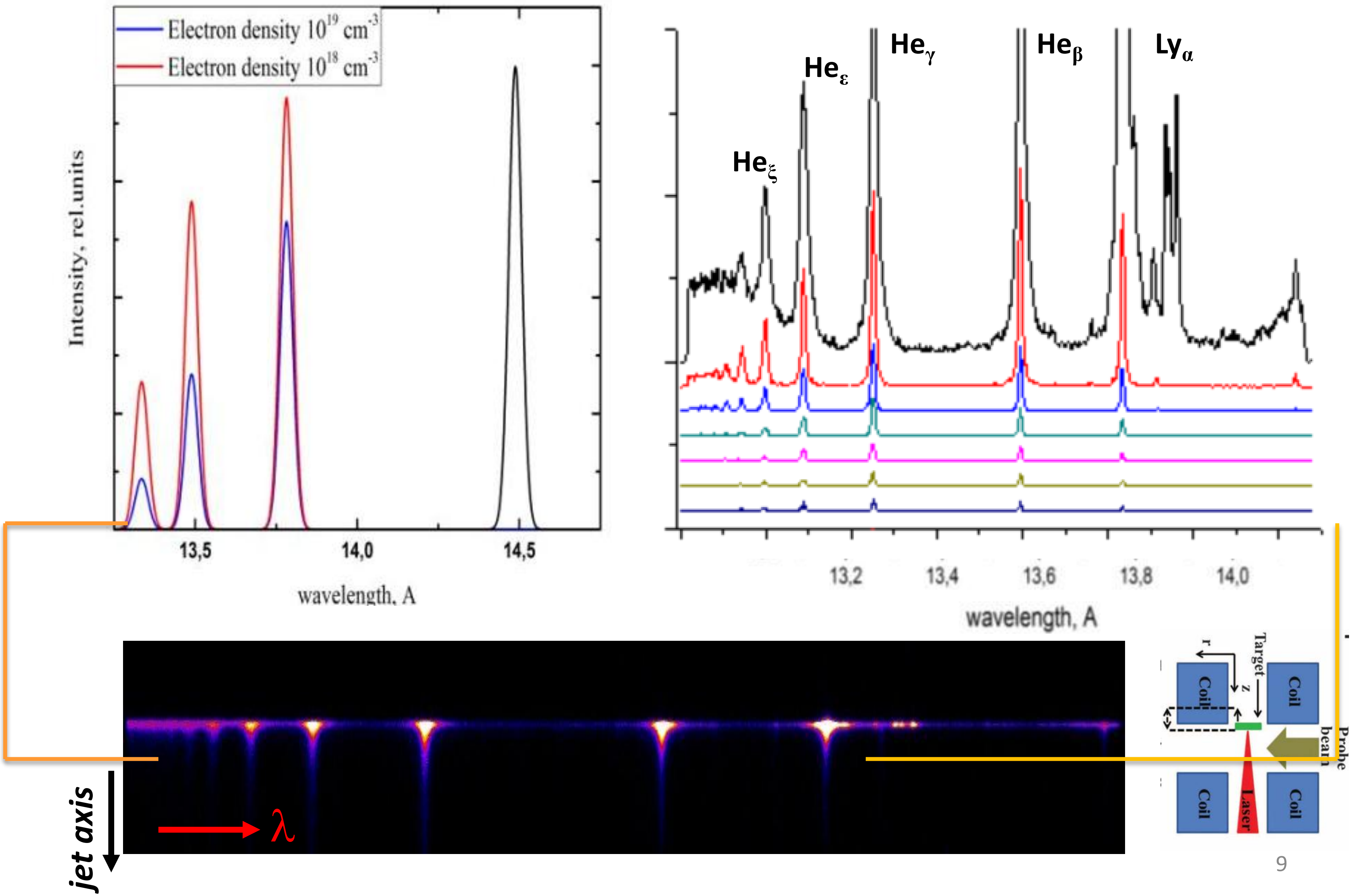


Modeling by FLYCHK or PrismSPECT codes in NLTE mode.

Plasma parameters are easily determined with 10% accuracy

Plasma parameters can be identified with ~100 um spatial resolution near the target surface

Typical x-ray spectra emitted by a plasma jet



The relaxation time of the ground states is greater (often by a few orders of magnitude) than the relaxation time for excited states, especially in the case of multi-charged ions. Short time period during which the populations reach stationary values.

$$\tau_{gr.st.} \gg \tau_{ex.st.}$$

$$\frac{dN_i^Z}{dt} = \sum_{i',Z'} K_{ii'}^{ZZ'} N_{i'}^{Z'}$$

Ground state (i=1)

$$\frac{dN_1^Z}{dt} = \sum_{i',Z'} K_{1i'}^{ZZ'} N_{i'}^{Z'}$$

Excited state (i≥2)

$$0 = \sum_{i',Z'} K_{1i'}^{ZZ'} N_{i'}^{Z'}$$

β_i^Z - recombination population coefficient, S_i^Z - ionization population coefficient

$$\frac{I_{mn}^Z}{I_{kl}^Z} = \frac{A_{mn} N_m^Z}{A_{kl} N_k^Z} = \frac{A_{mn}}{A_{kl}} \frac{[\beta_m^Z N_e N_1^{Z+1}/N_1^Z + S_m^Z]}{[\beta_k^Z N_e N_1^{Z+1}/N_1^Z + S_k^Z]}$$

$$\sum_{i'} K_{ii'}^{ZZ'} S_{i'}^{Z} = -K_{i1}^{Z,Z}$$

$$\sum_{i'} K_{ii'}^{ZZ} \beta_{i'}^{Z'} = -\frac{K_{i1}^{Z,Z}}{N_e}$$

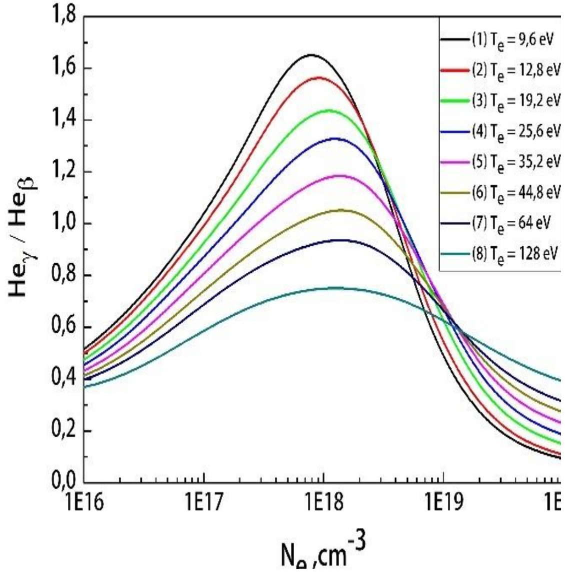
$$\frac{I_{mn}^Z}{I_{kl}^Z} = \frac{A_{mn}}{A_{kl}} \frac{\beta_m^Z}{\beta_k^Z}$$

Recombining plasma $i \geq 2$

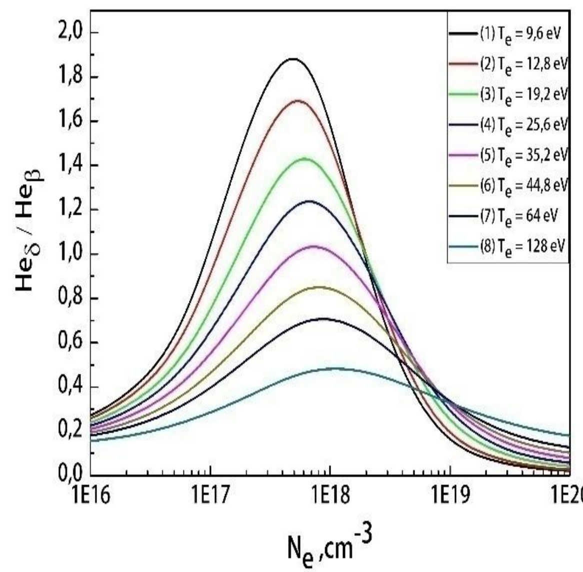
$$\beta_i^Z N_e N_1^{Z+1}/N_1^Z \gg S_i^Z$$

Calculated intensity ratios for F VIII - Recombining plasma

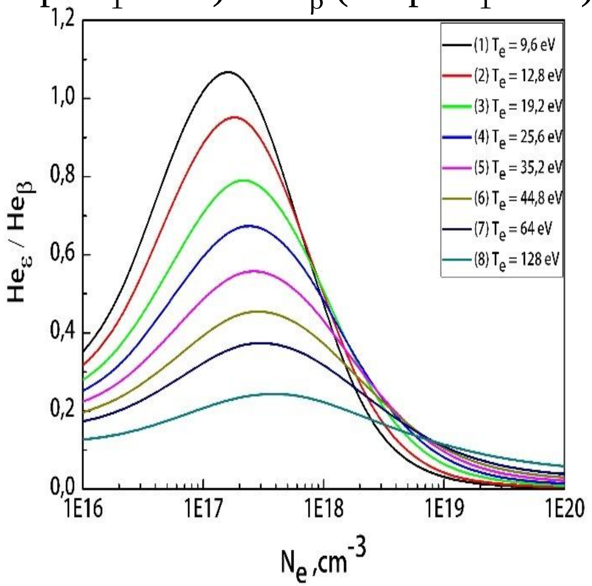
He_{γ} (1s4p $^1P_1$ - 1s^2) / He_{β} (1s3p $^1P_1$ - 1s^2)



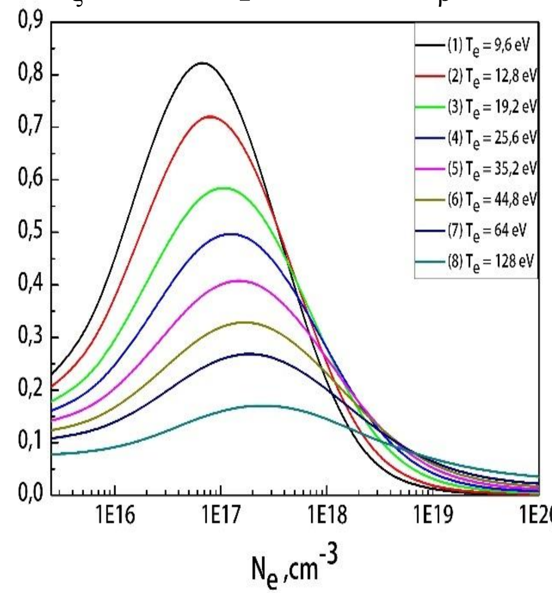
He_{δ} (1s5p $^1P_1$ - 1s^2) / He_{β} (1s3p $^1P_1$ - 1s^2)



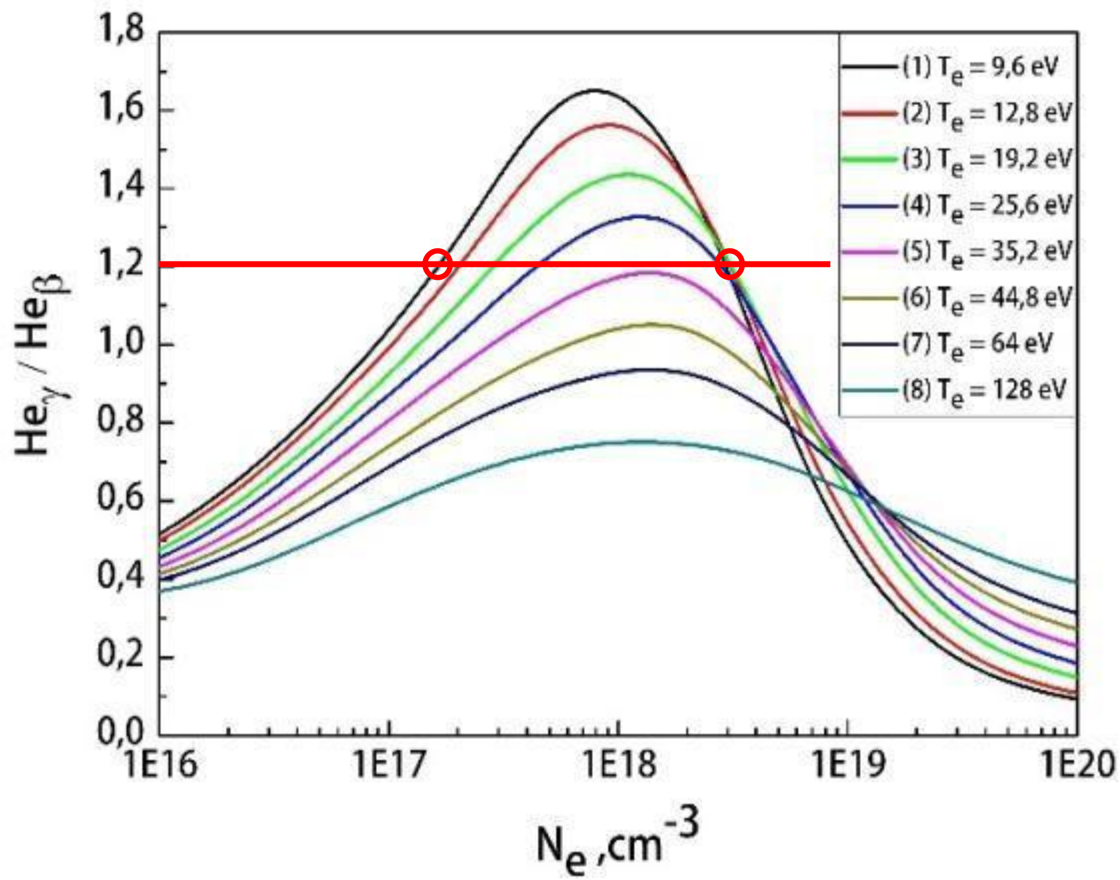
He_{ε} (1s6p $^1P_1$ - 1s^2) / He_{β} (1s3p $^1P_1$ - 1s^2)

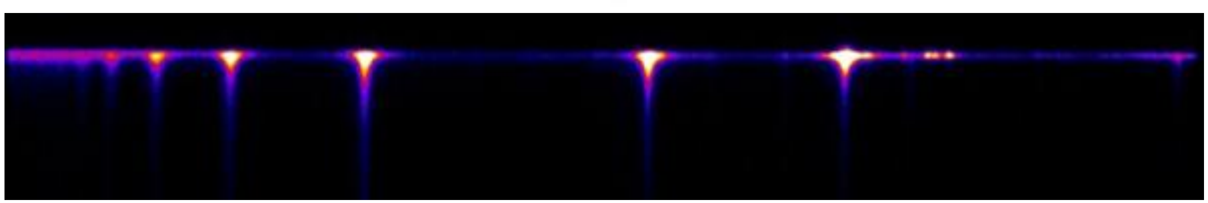


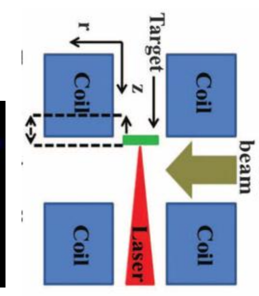
He_{ξ} (1s7p $^1P_1$ - 1s^2) / He_{β} (1s3p $^1P_1$ - 1s^2)



Application of intensity rates curves

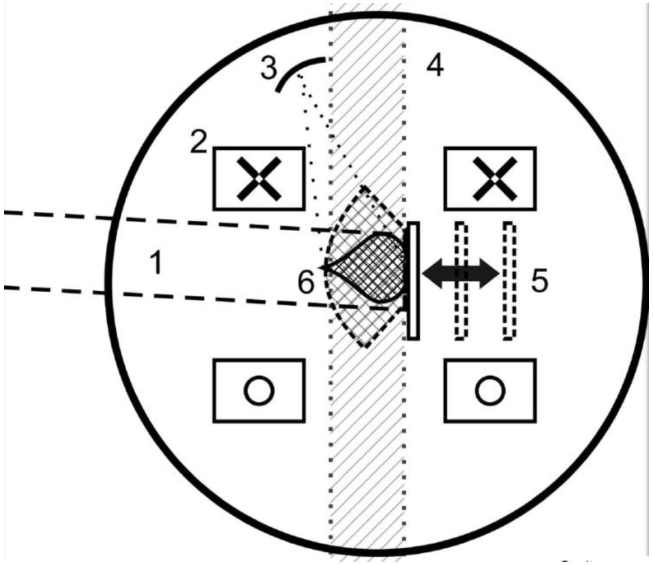




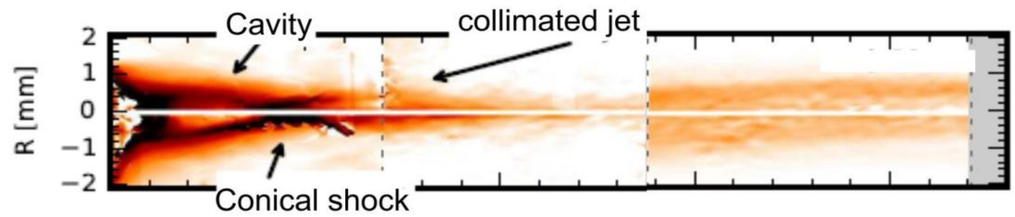


The measurements on intensity rates for a set of spectral lines allows to avoid an ambiguity and to determine both N_e and T_e

Long range measurements along the jet axis

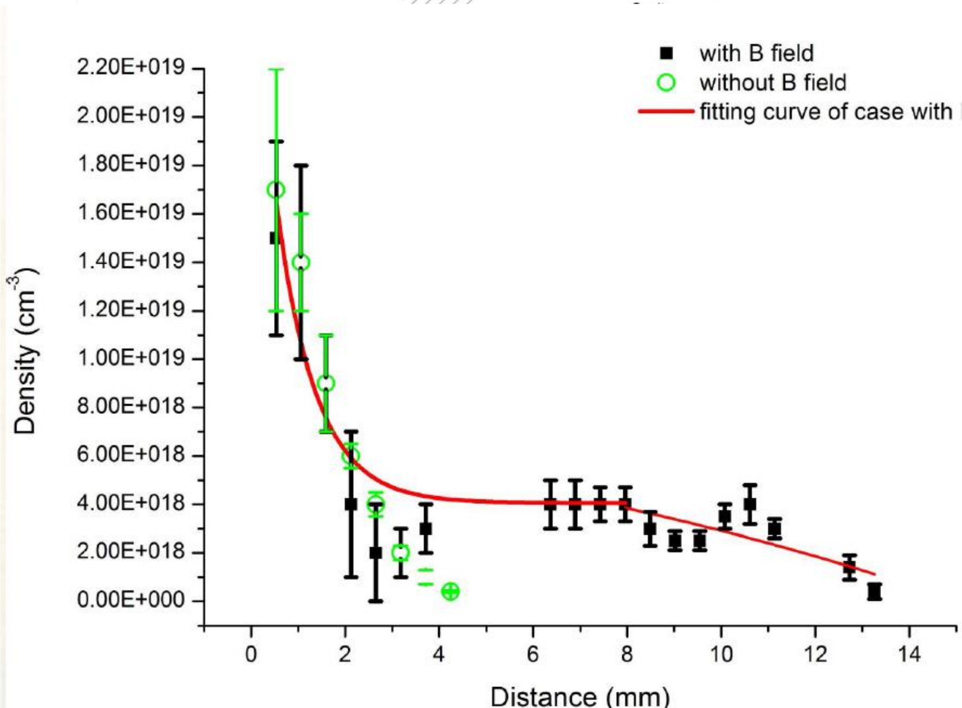


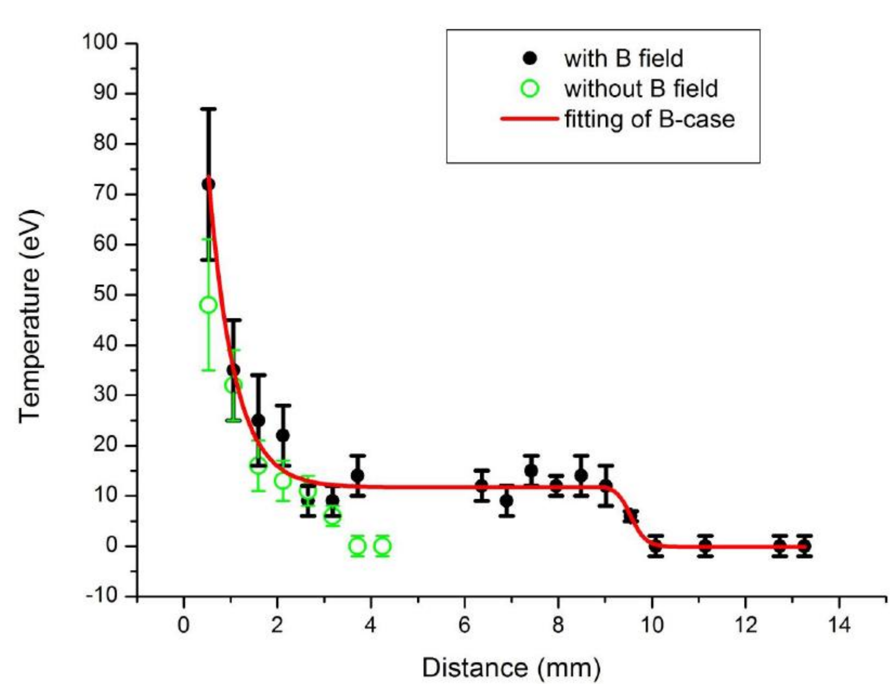
B = 20 T, E_{laser} = 40 J



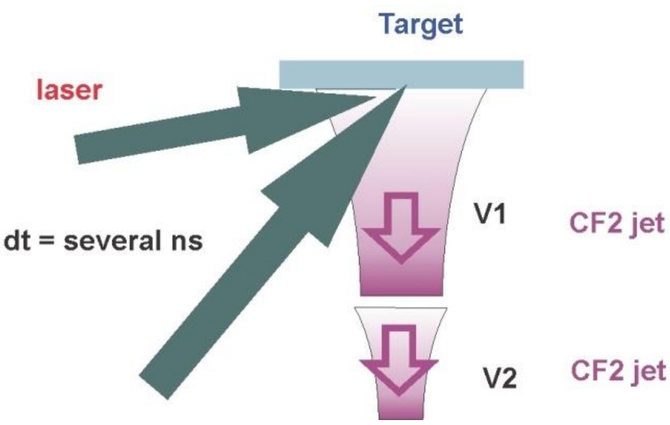
Interferometer data on N_e map

// D.P. Higginson et al. HEDP, accepted (2016)

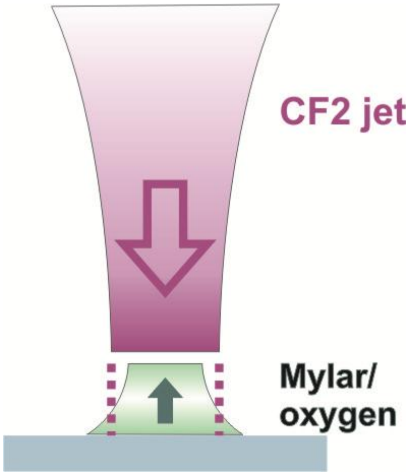




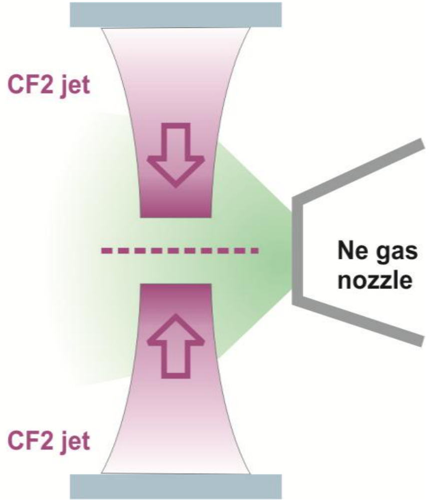
Complex HD flows



Jets with precursor Habris-Haro objects

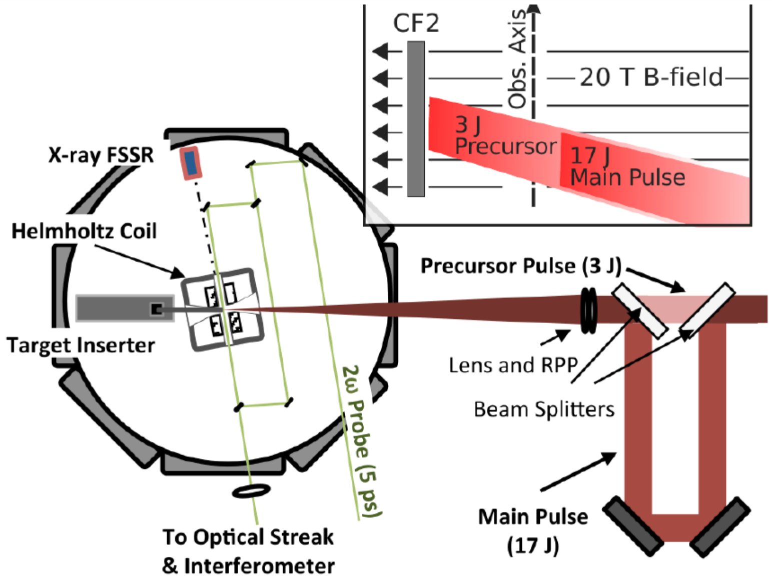


Accretion processes

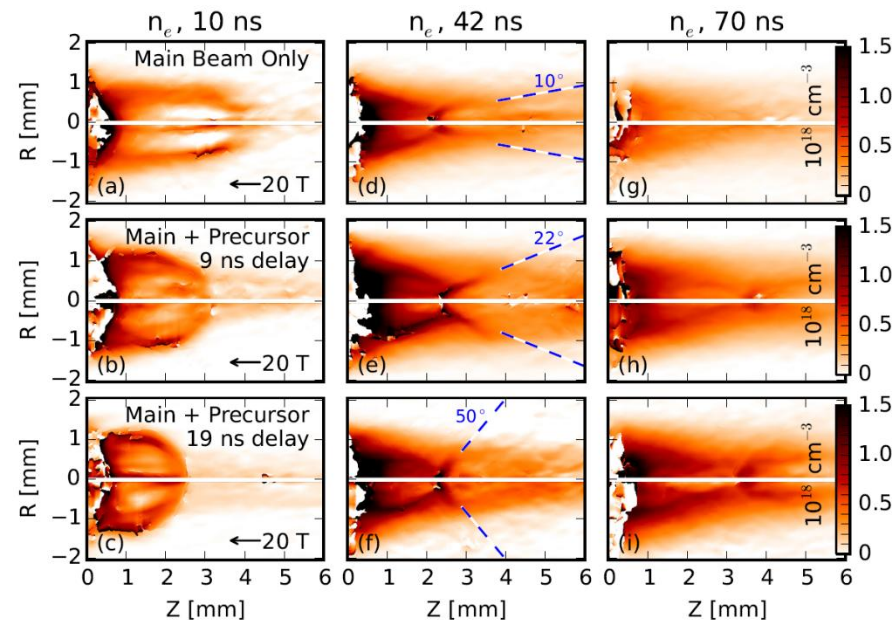


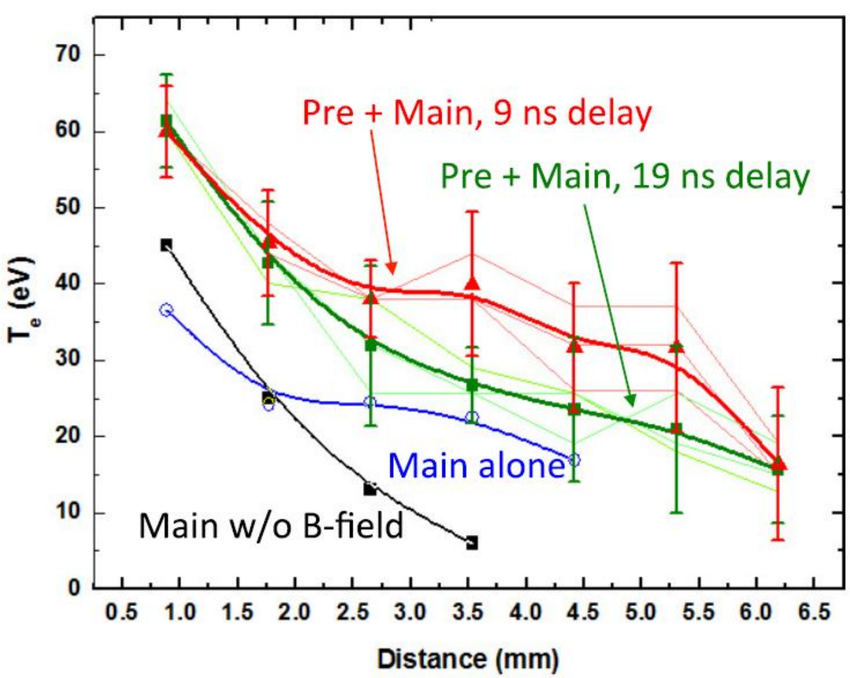
Counter-streaming Interactions in a medium

Jet propagation in the precursor plasma media



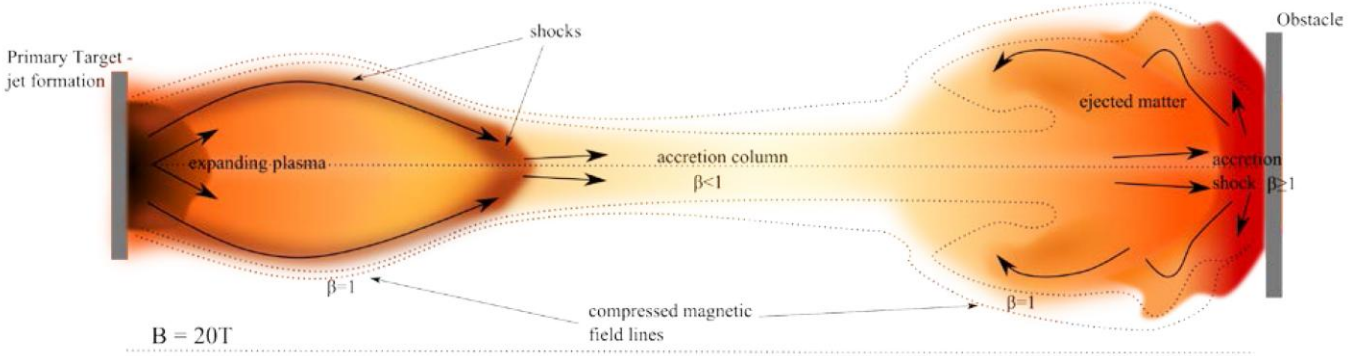
Most of astrophysical jets have
periodic / pulsed nature
= some times a faster fraction (pulse)
of plasma propagates in a plasma precursor

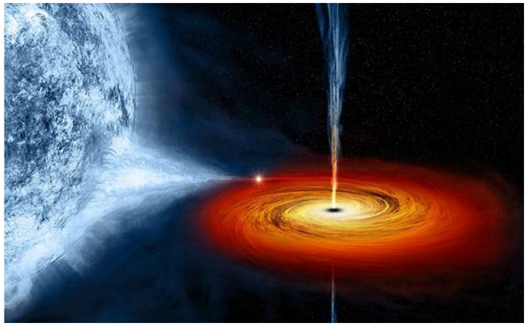


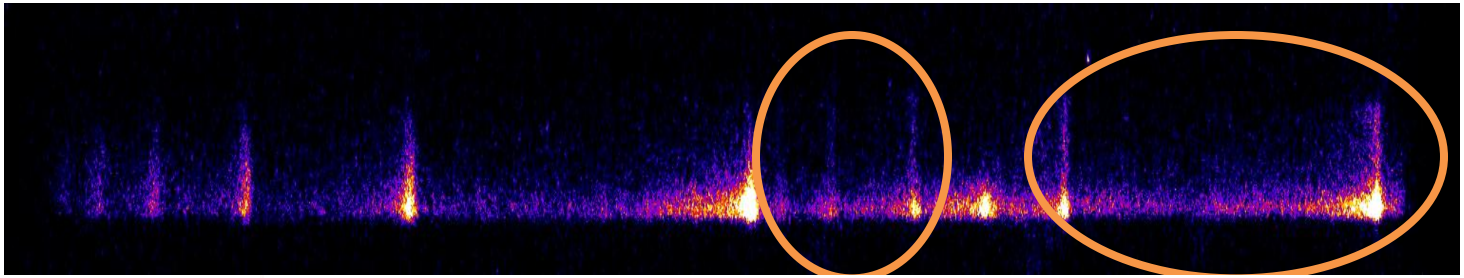


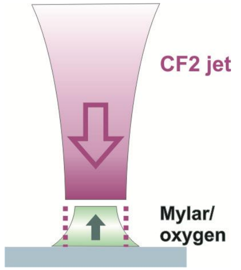
By means of X-ray spectroscopy the increase in electron temperature is observed when the jet propagates in plasma media, both for B and no-B cases.

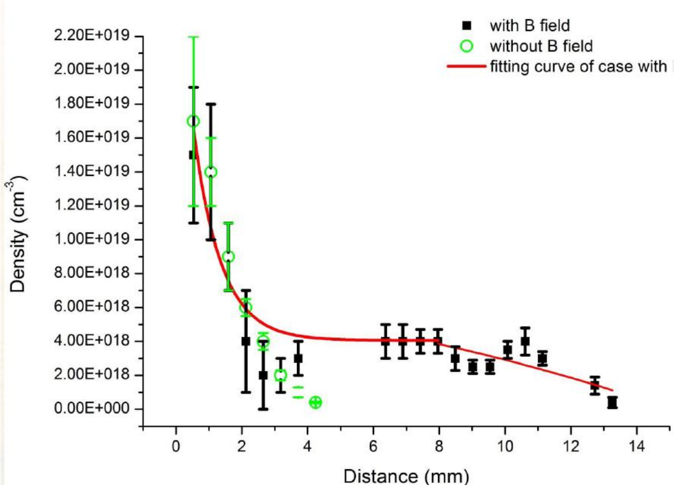
Accretion – modeling in a jet collision with solid obstacle

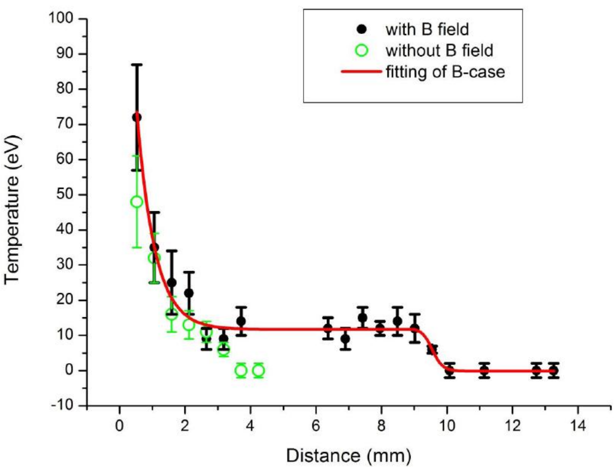




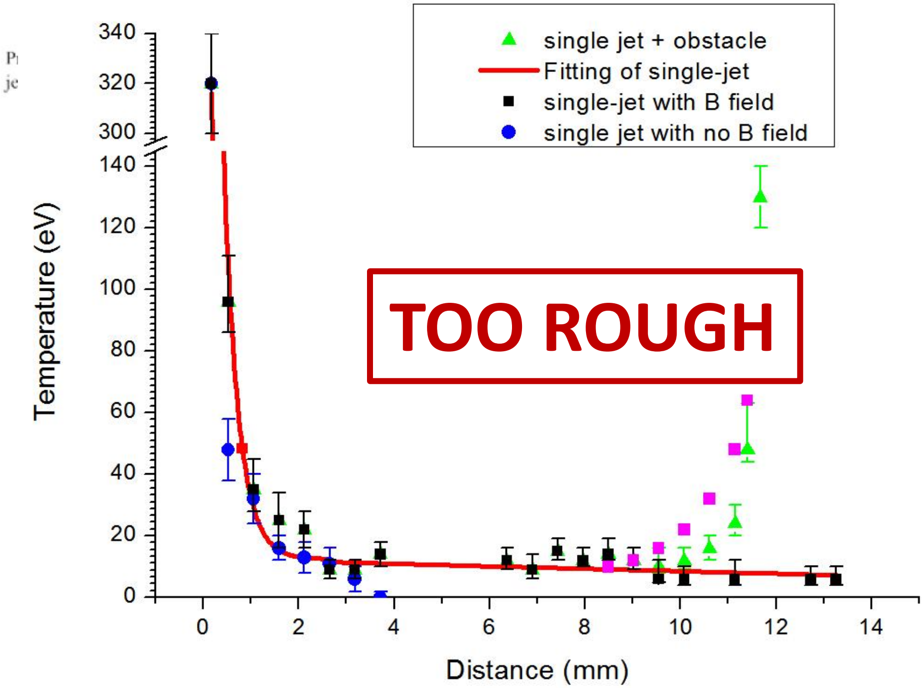


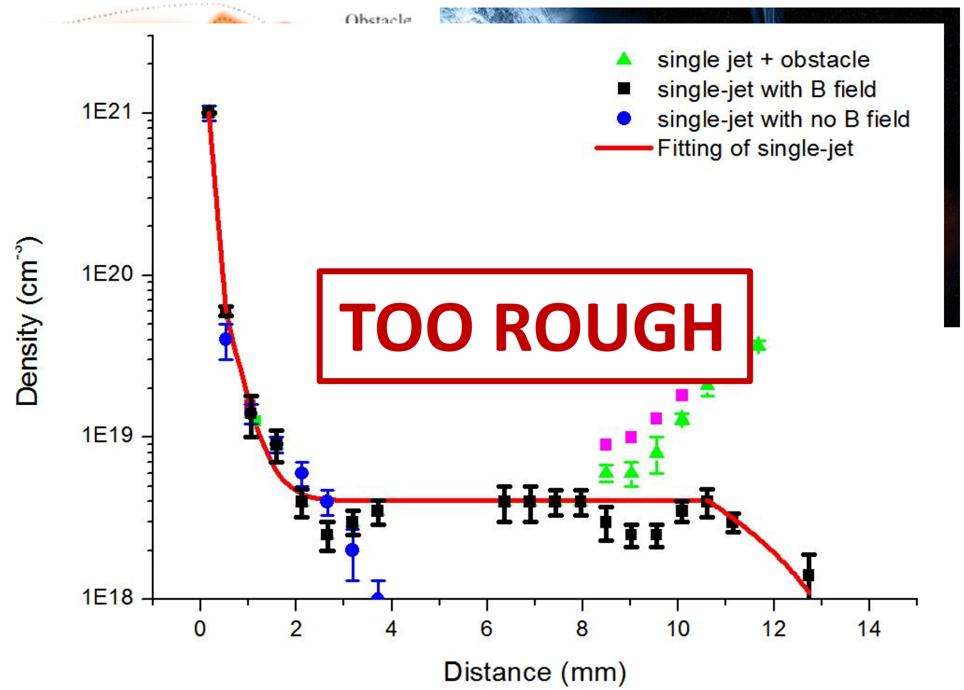


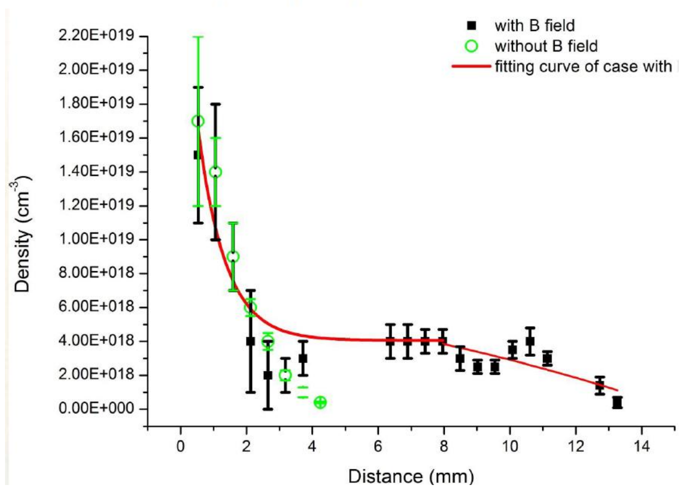


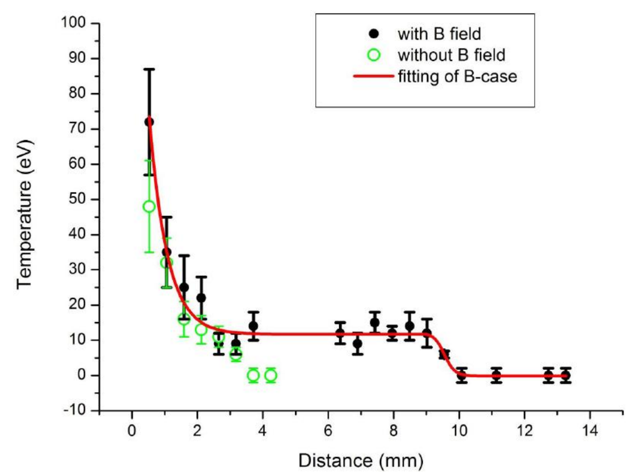


Accretion – modeling in a jet collision with solid obstacle



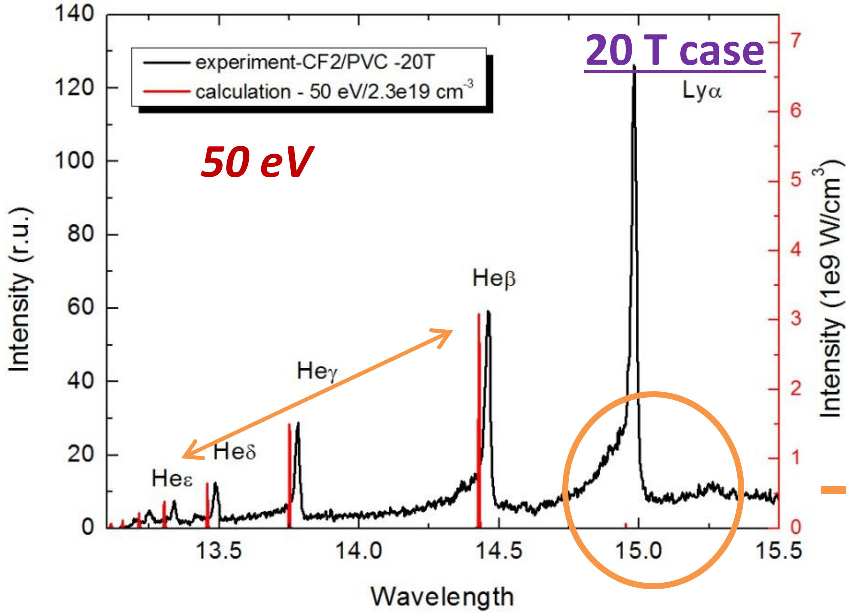




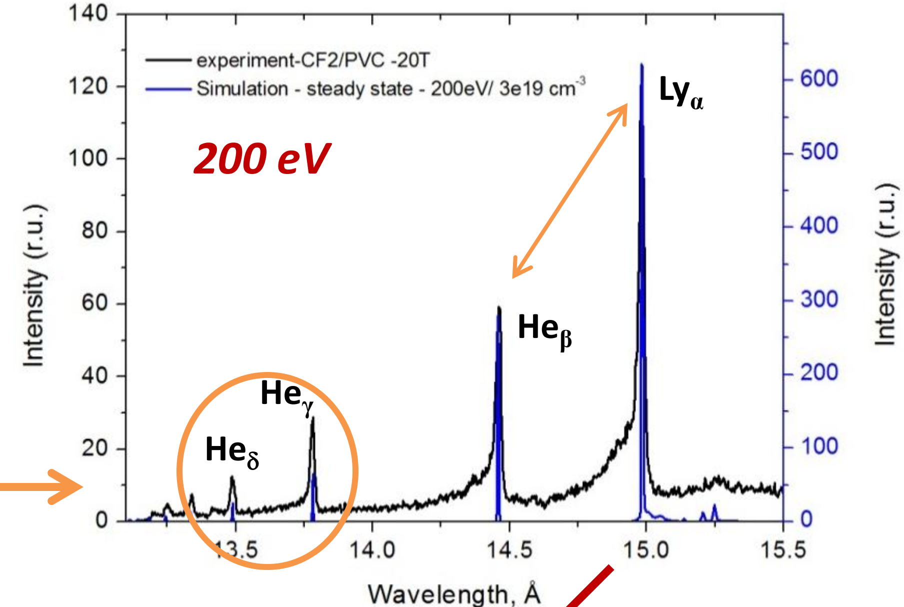


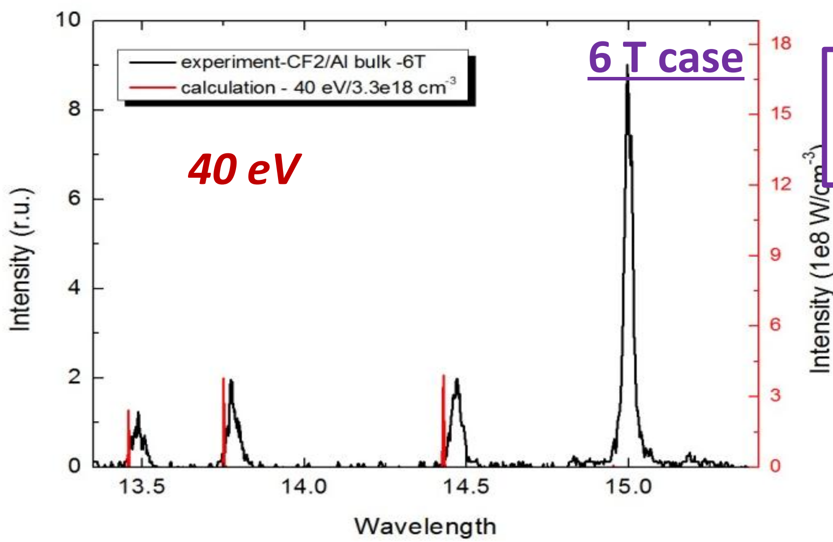
Issues with precise spectra modeling – two-component plasma

Recombining model



Steady-state model (FLYCHK/PrismSpect)





Two plasmas with different temperatures contributes to the spectra

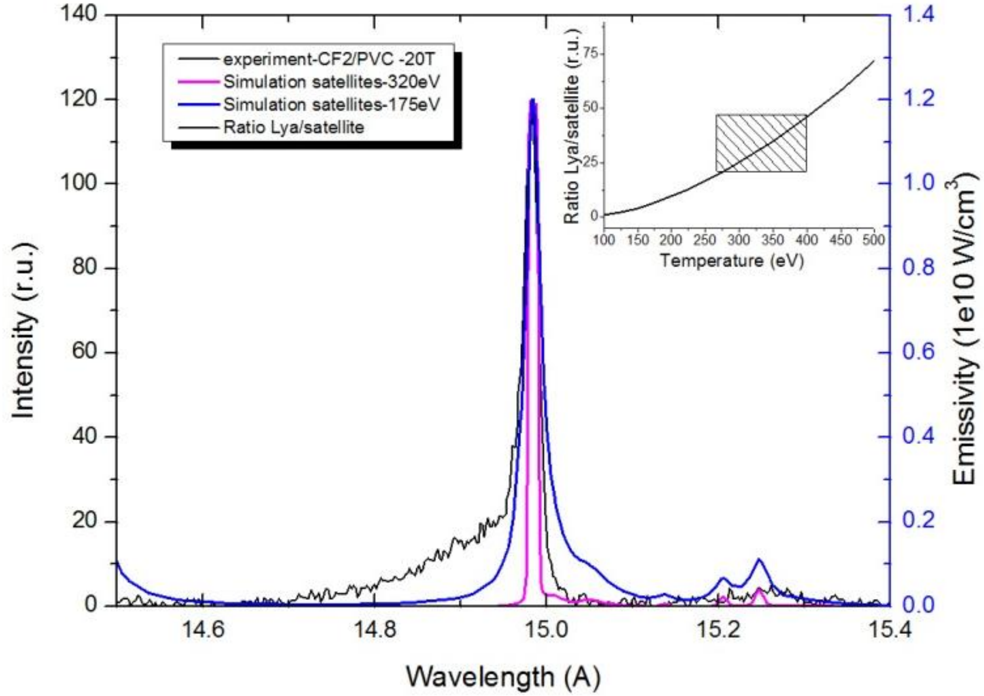
"Cold" plasma fraction shall be treated as recombining one - @obstacle surface:

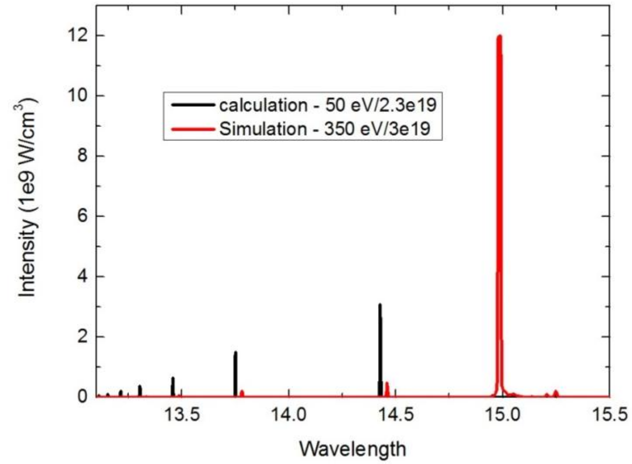
-20 T: T_e ~ 50 eV and N_e = 2.3e19 cm^{-3}

- 6 T: T_e ~ 40 eV and N_e = 3.5e19 cm^{-3}

Hot component of the accreted plasma

Steady-state model (FLYCHK/PrismSpect)





No contribution to the recombining part

Lyα represents "hot" fraction
Heβ represents "cold" fraction

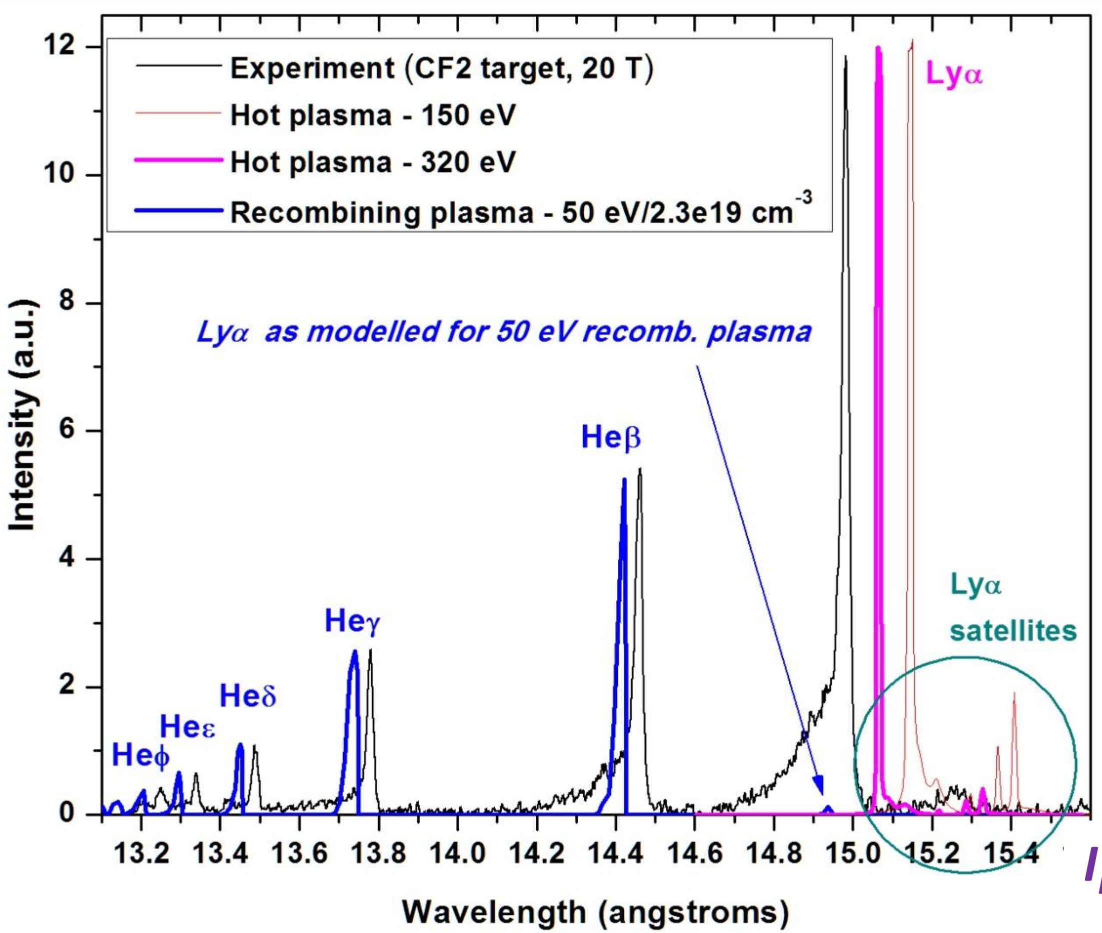
Electron temperature - ranged in 250-400 eV
Electron density – no direct estimates by line-ratio

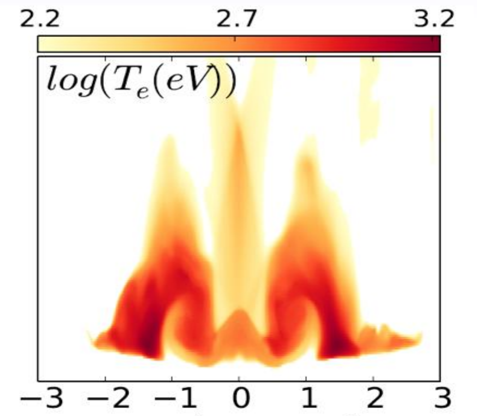
Intensity ~ Emissivity* Volume*Time

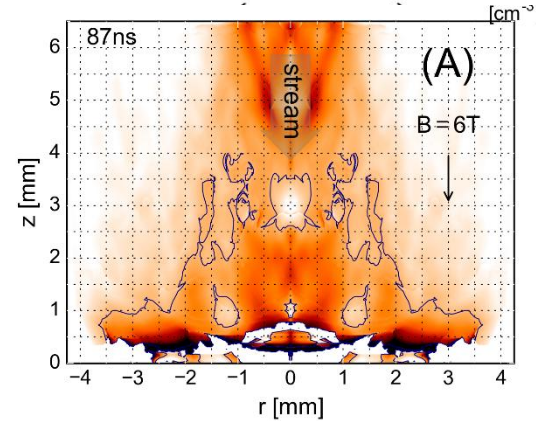
Emissivity = $f(N_e, T_e)$

$$I_{Ly\alpha}/I_{heb} \sim f(N_e^{hot})*V^{hot} / V^{cold}*f(N_e^{cold})$$

Revealing Hot component density and Plasma geometry







$I_{Ly\alpha}/I_{heb} \sim f(N_e^{hot})*V^{hot} / V^{cold}*f(N_e^{cold})$

Assuming "hot" = "shell" :

$V^{hot} / V^{cold} \sim 8$ and $N_e^{hot} \sim 4e18\ cm^{-3}$

Assuming "hot" = "core" :

$V^{hot} / V^{cold} \sim 0.11$ and $N_e^{hot} \sim 3e20\ cm^{-3}$

The values given by interferometry: $N_e^{shell} = 4e18\ cm^{-3}$, $N_e^{core} = 1.5e19\ cm^{-3}$

Conclusions

X-ray spectroscopy method allowing to study the parameters of recombining plasma flows is (re)developed considering the actual demand for laboratory astrophysics research.

Sensitivity of the method is enough to measure the evolution of electron density and temperature of plasma jets far expanded with and without external magnetic field.

The way to determine the parameters of a complex plasma flows interacting with obstacles, ambient gas, counter-streaming flows etc. is found with a combination of recombining and steady-state plasma approaches.

For the particular case of accretion studies:

- **The clear evidence is provided that at least two distinct fractions of plasmas (hundreds eV "hot" and recombining ten's eV "cold") existed near the obstacle.**

- **Spectroscopy data is consistent with interferometry and modeling when the "shell" is considered as a hot fraction, and the core – as a cold one.**

- **(@20T) :** $T_e^{core} \sim 50$ eV, $N_e^{core} = 2.3e19$ cm^{-3},
  $T_e^{shell} \sim (250\text{-}400)$ eV, $N_e^{shell} \sim (4\text{-}6)e18$ cm^{-3}