Diagnosing solid-density hot plasmas using characteristic x-ray line emission

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Temperature and density diagnostics in the sub-ps regime

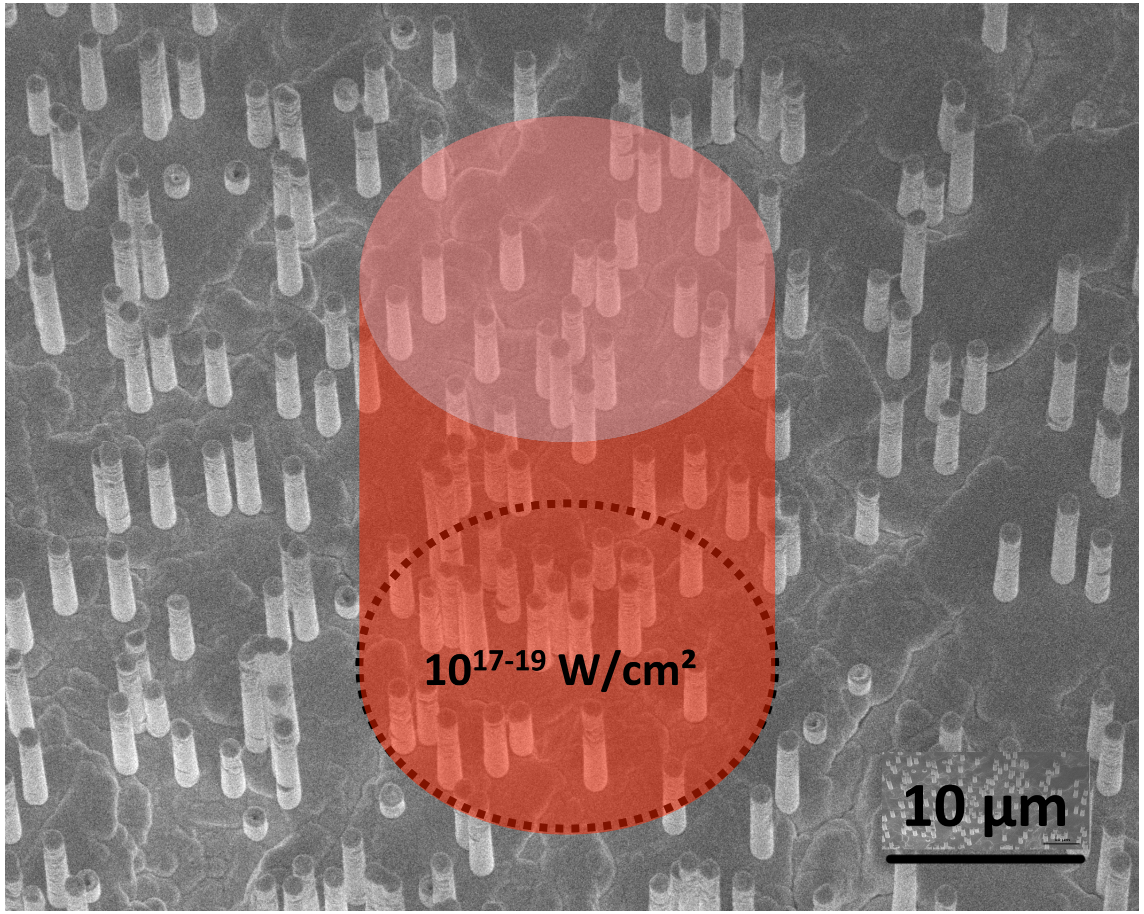
High-intensity and short-pulse lasers lead to fast evolving plasma conditions:

- highly transient plasmas
- out of thermodynamic equilibrium

Time-resolved diagnostics (e.g. streaked pyrometry) are unable to reach the sufficient resolution!

We are left with time-integrated x-ray line emission and some simulations to rebuild the story…

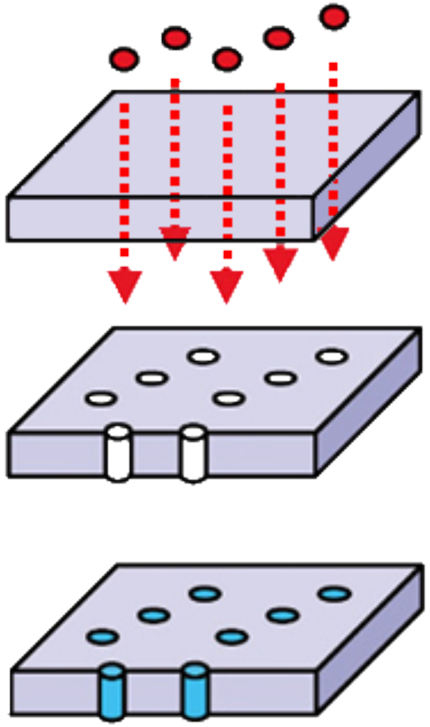
Micro-wire arrays
- Physics case -



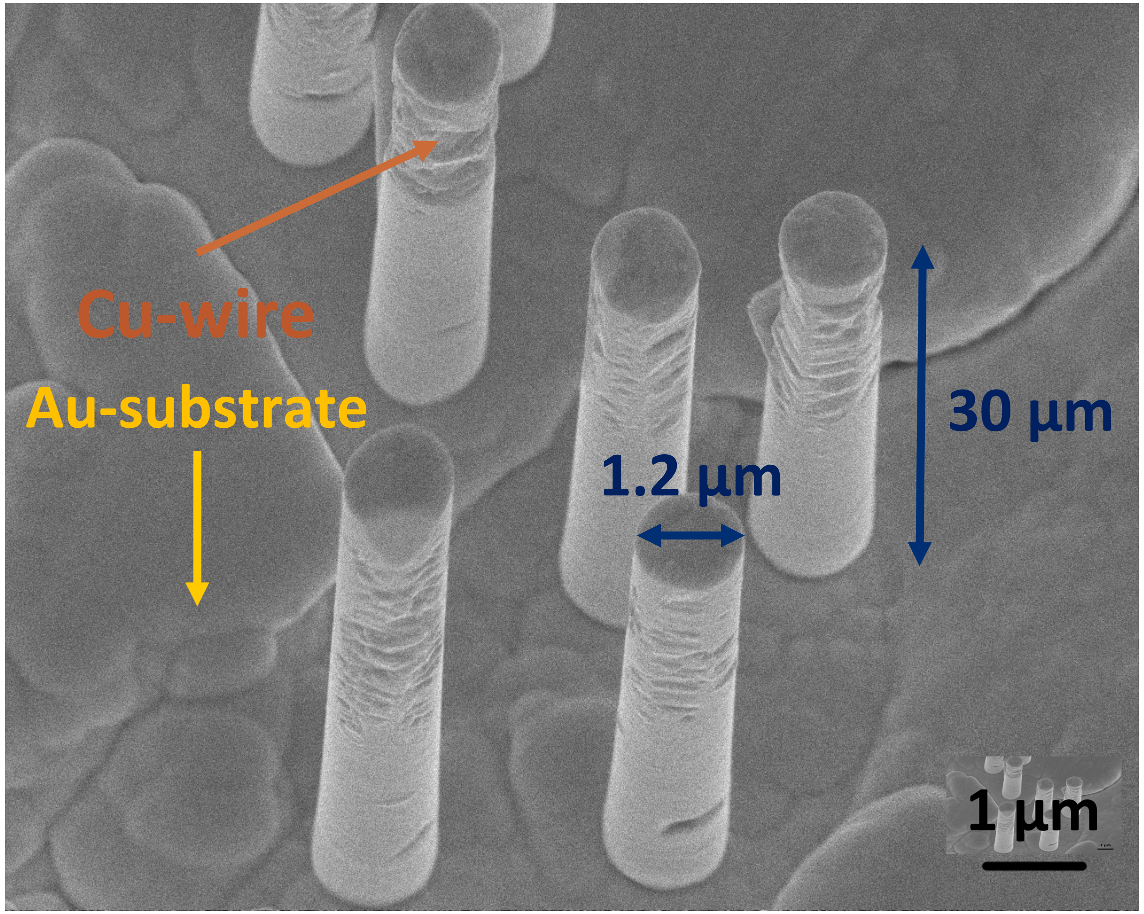
Proton acceleration:
- TNSA cut-off energy x2
- Proton yield (E > 3 MeV) x30

"Enhancing laser-driven proton acceleration by using micro-pillar arrays at high drive energy ", Khaghani et al. in Nature Scientific Reports, 7: 11366 (2017)

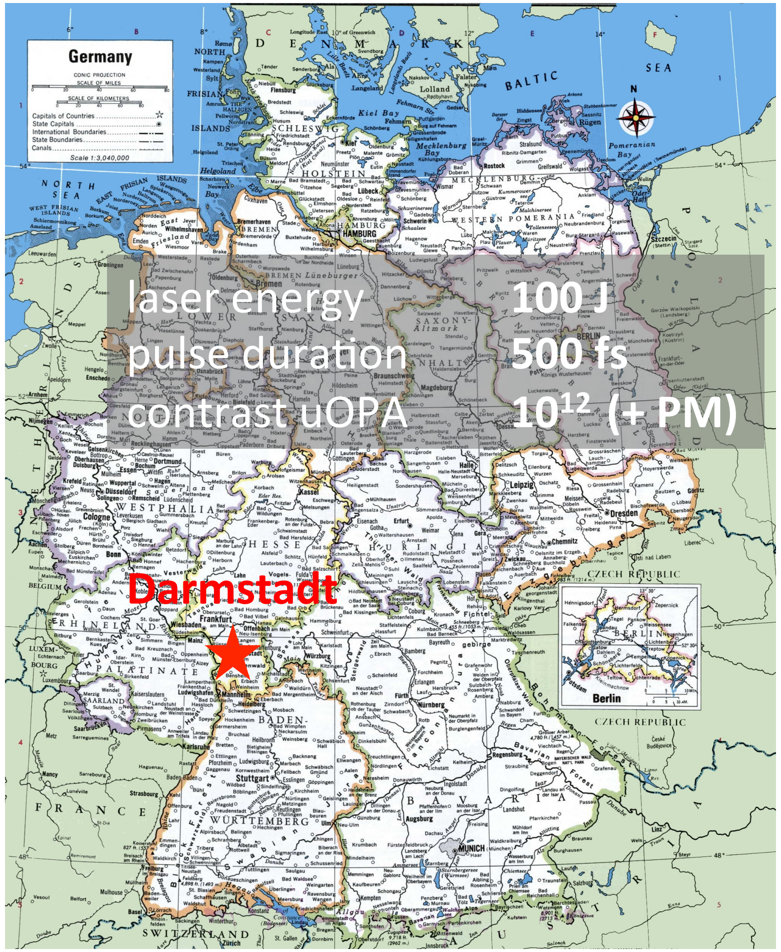
Micro-wire arrays
- production -



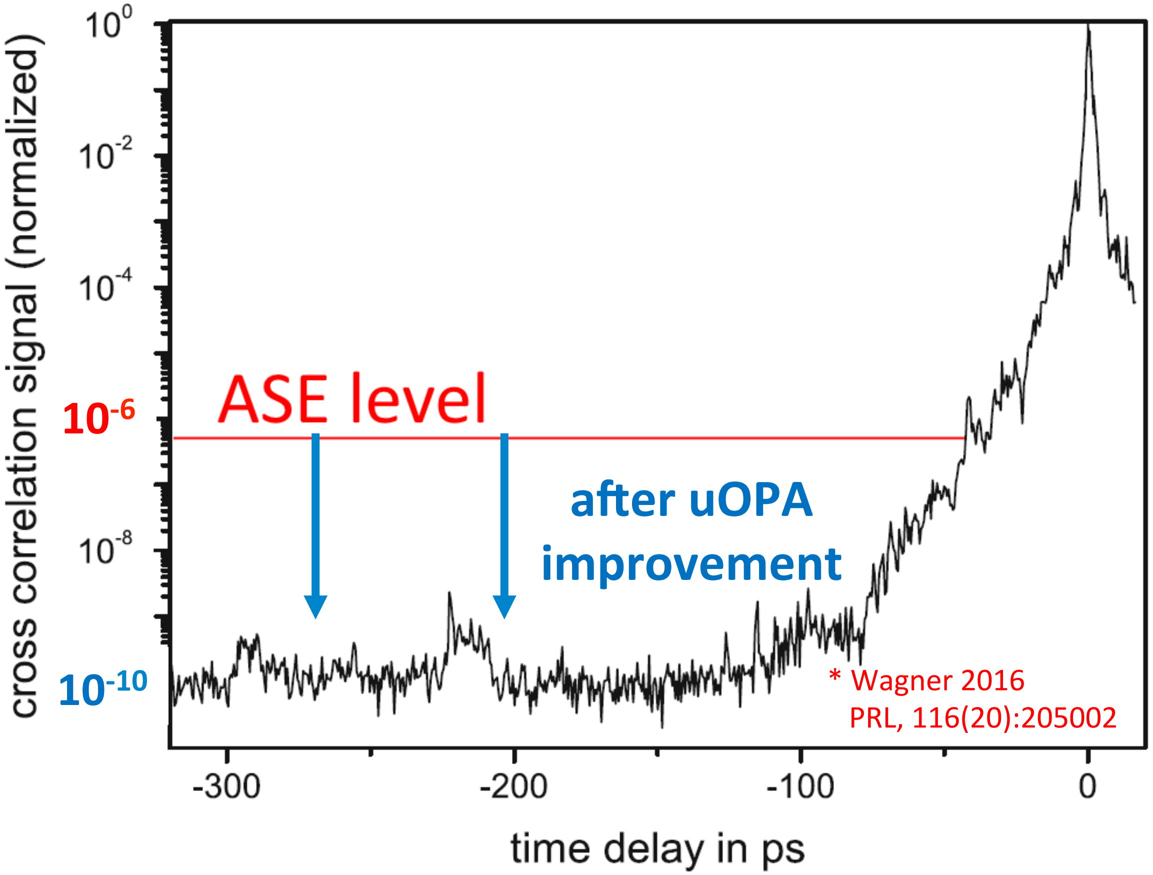
JAEA R&D Review 2016



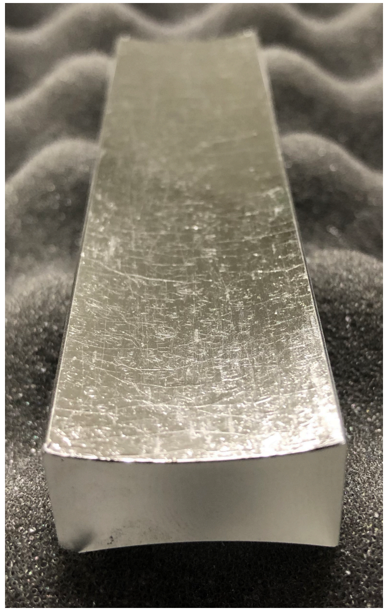
PHELIX
- high-contrast laser -

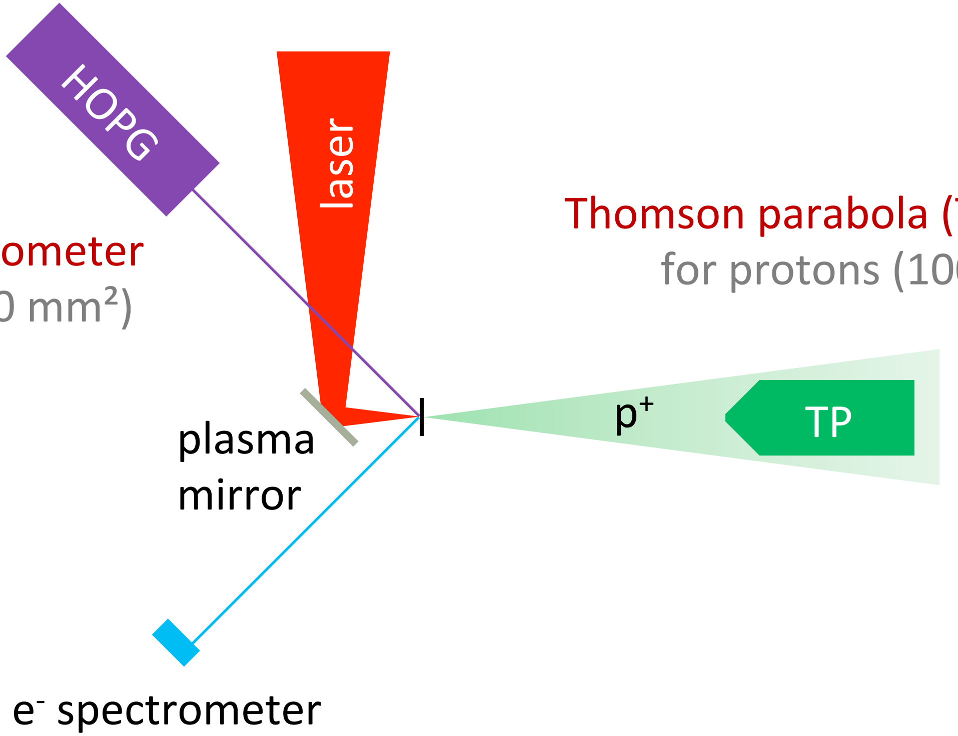


laser energy	100 J
pulse duration	500 fs
contrast uOPA	10^{12} (+ PM)



Micro-wire arrays
- experimental setup -





HOPG van Hamós x-ray spectrometer

cylindrical crystal (50x100 mm²)

broadband (8 – 12 keV)

Thomson parabola (TP) ion spectrometer

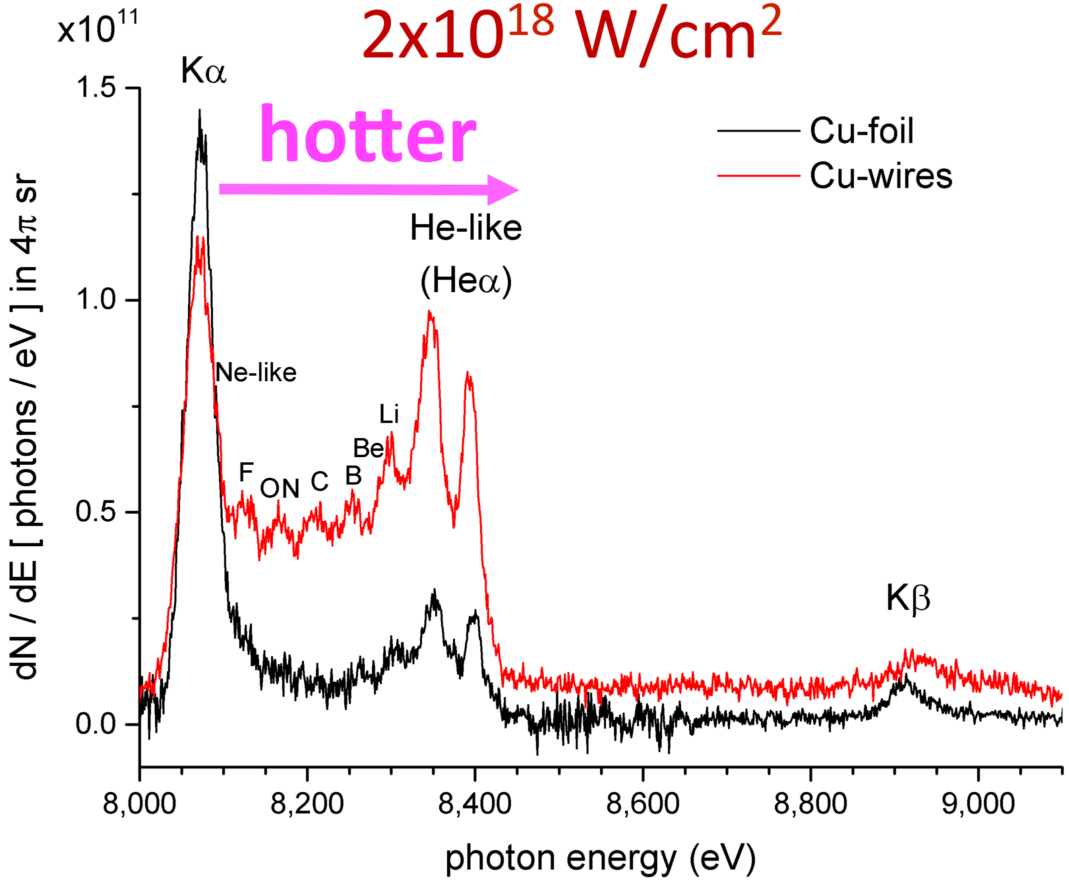
for protons (100 keV – 50 MeV)

electron spectrometer

energy dispersion with good resolution from 100 keV to 10 MeV

Micro-wire arrays
- “thermal” x-ray lines -

$2x10^{18}$ W/cm^2



K_α transition

K_β transition

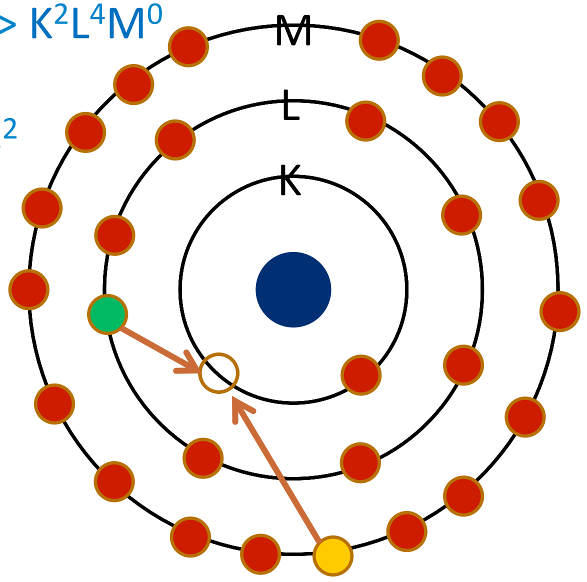
Ne-like: Cu^{19+}

…

C-like: $K^1L^5M^0 \rightarrow K^2L^4M^0$

…

Heα: 1s2p −> $1s^2$

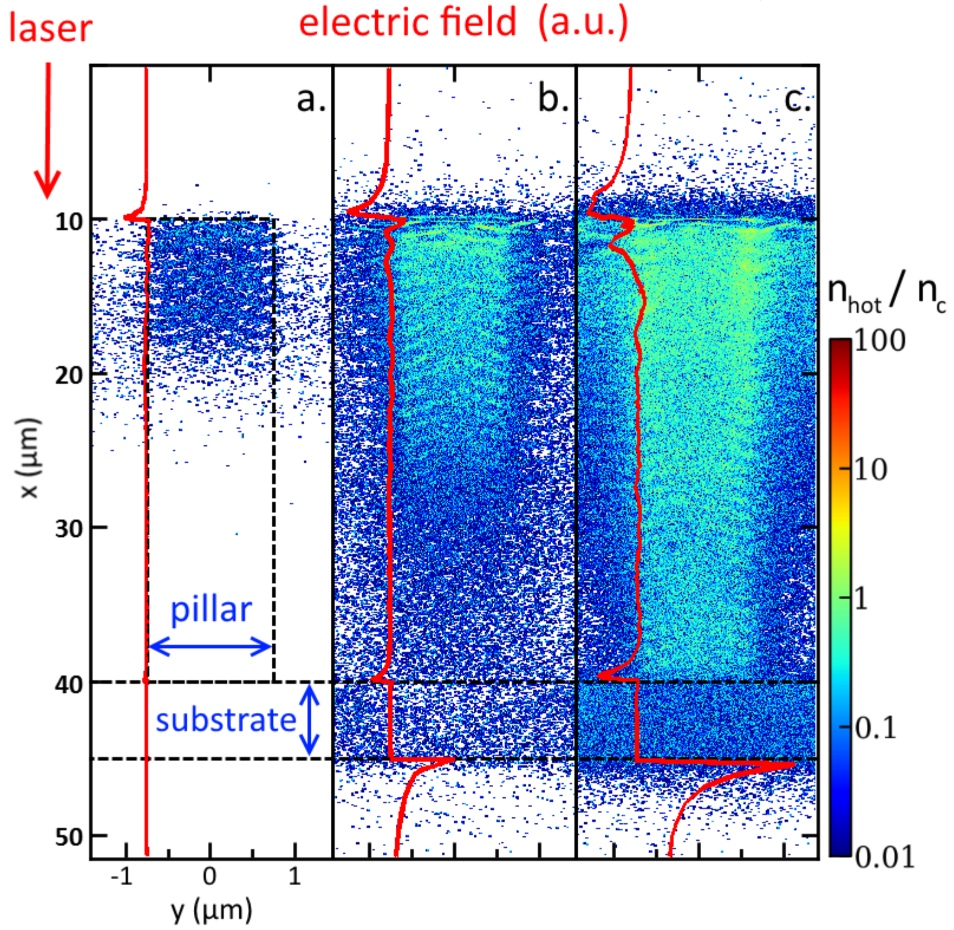


Micro-wire arrays
- particle-in-cell simulation (CALDER) -

We compare the energy conversion efficiency from laser to hot electrons in the simulation for targets with and without wires:

$E_{electron}$	no wire	wires	increase
>100 keV	3.7%	14%	3.8-fold
> 1 MeV	0.13%	3.8%	30-fold

at laser peak
I_{laser} = 2x10^{18} W/cm^2



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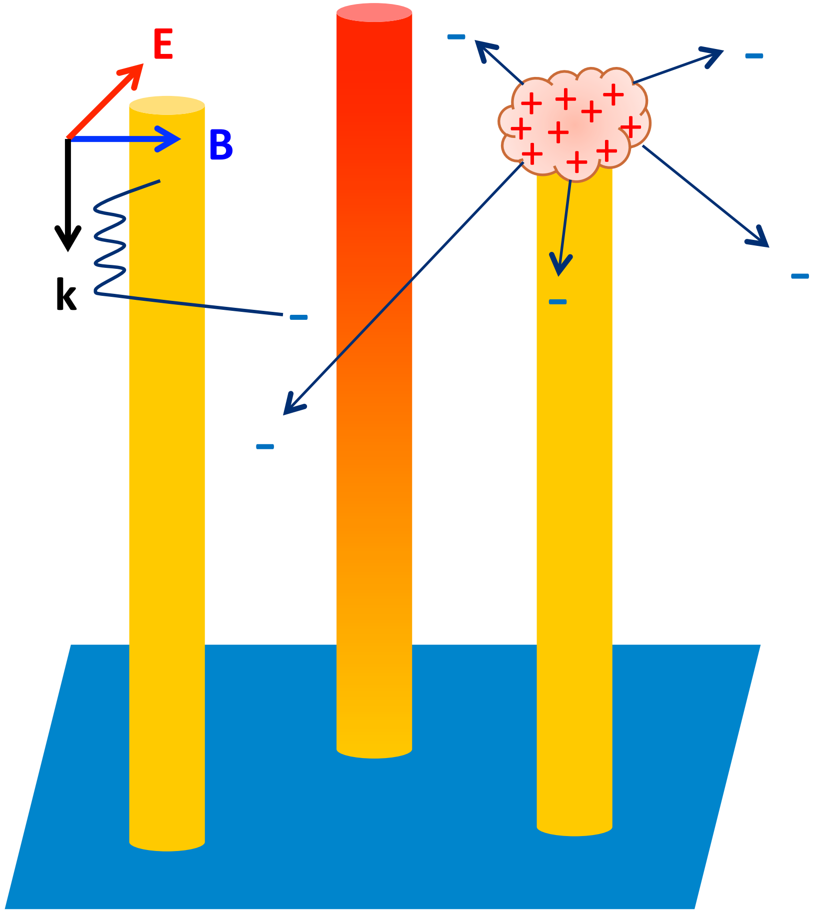
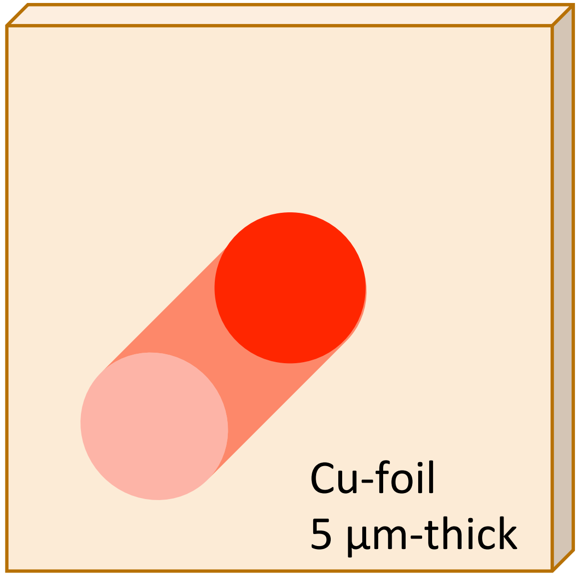


X-ray spectroscopy as diagnostic tool
- a simple case: thin foils -



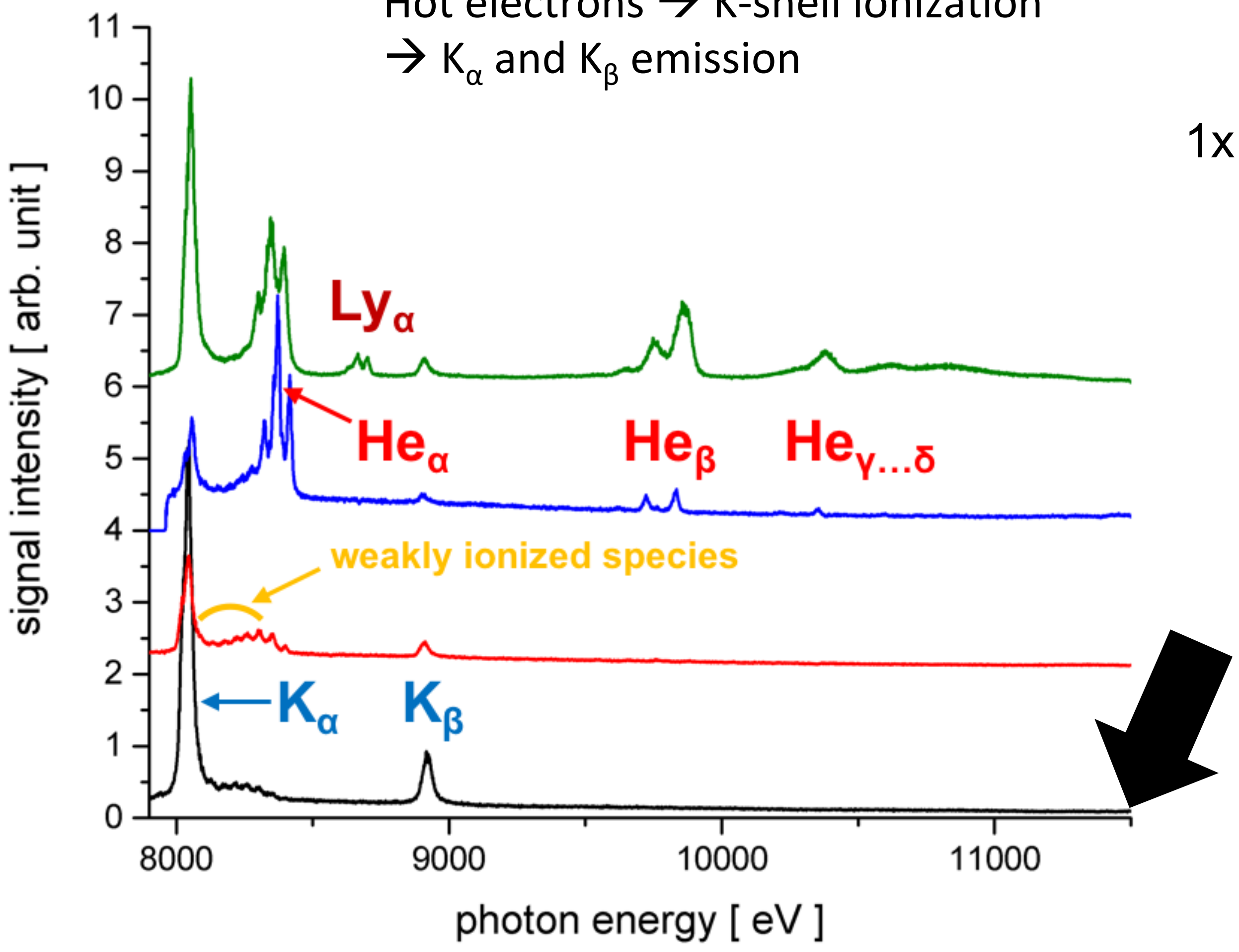
Main pulse of the PHELIX laser:
100 J in 500 fs, focal-spot size of 10 µm

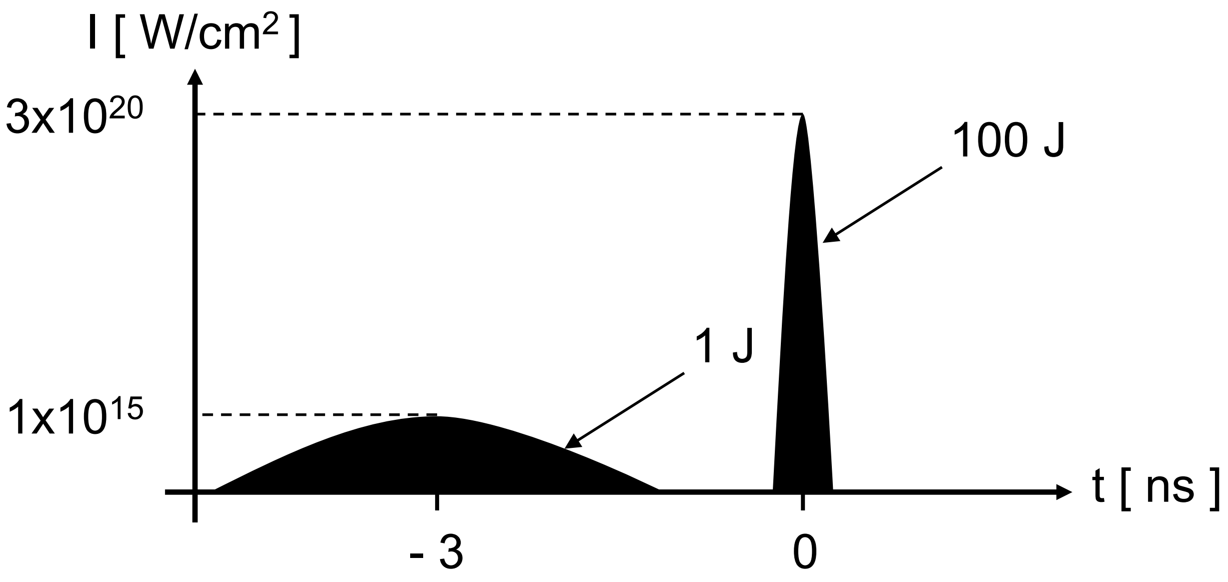
Different irradiation conditions:

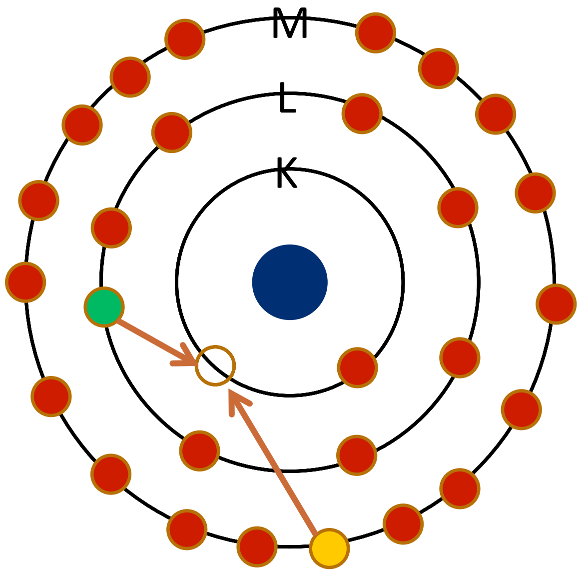
- early prepulse (1 J, - 3 ns)
- early prepulse(3 J, - 3 ns)
- degraded contrast (3 J, 0 ns)
- high contrast (uOPA 10^{-12})

Early prepulse (1 J)

Hot electrons → K-shell ionization
→ K_α and K_β emission

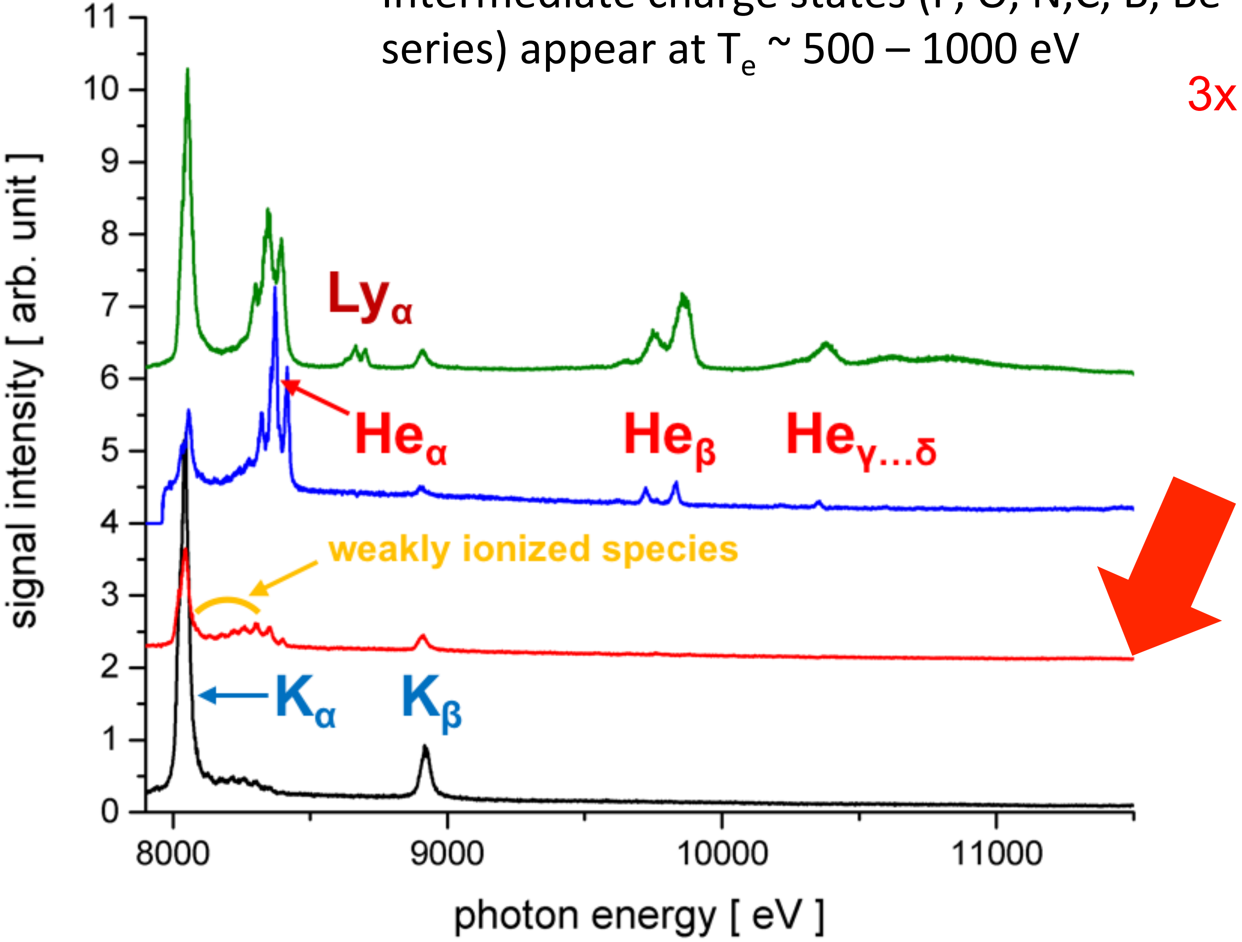


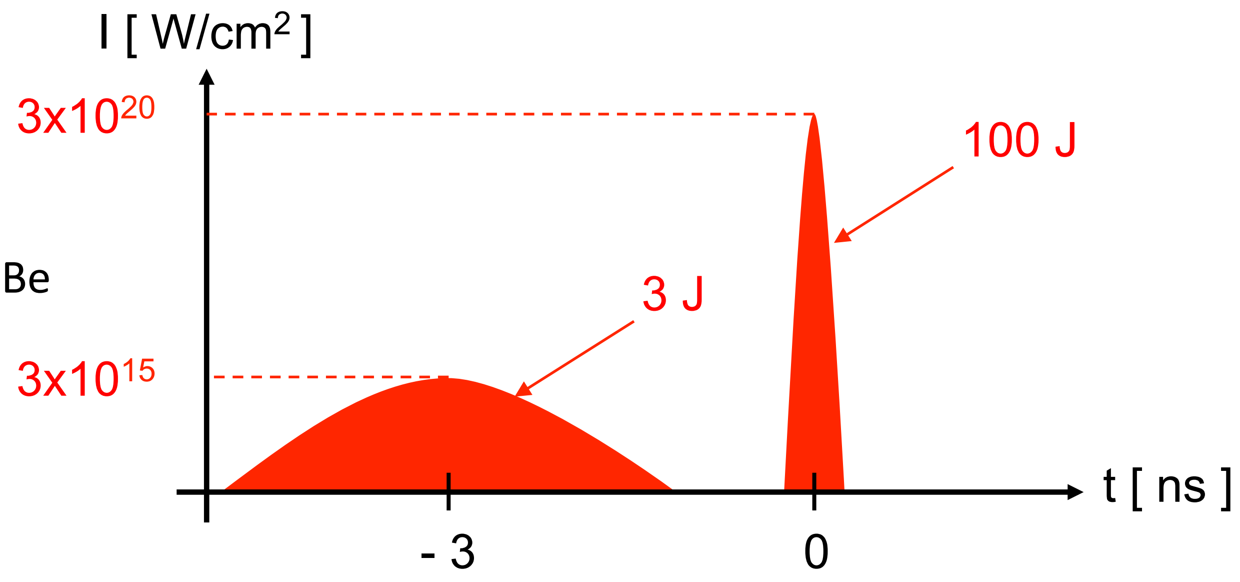


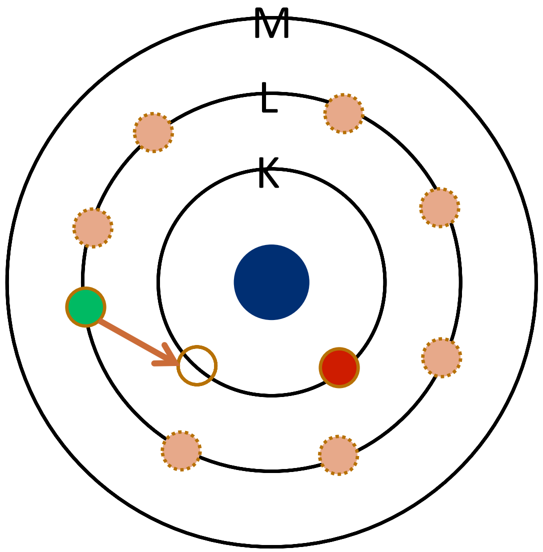


Early prepulse (3 J)

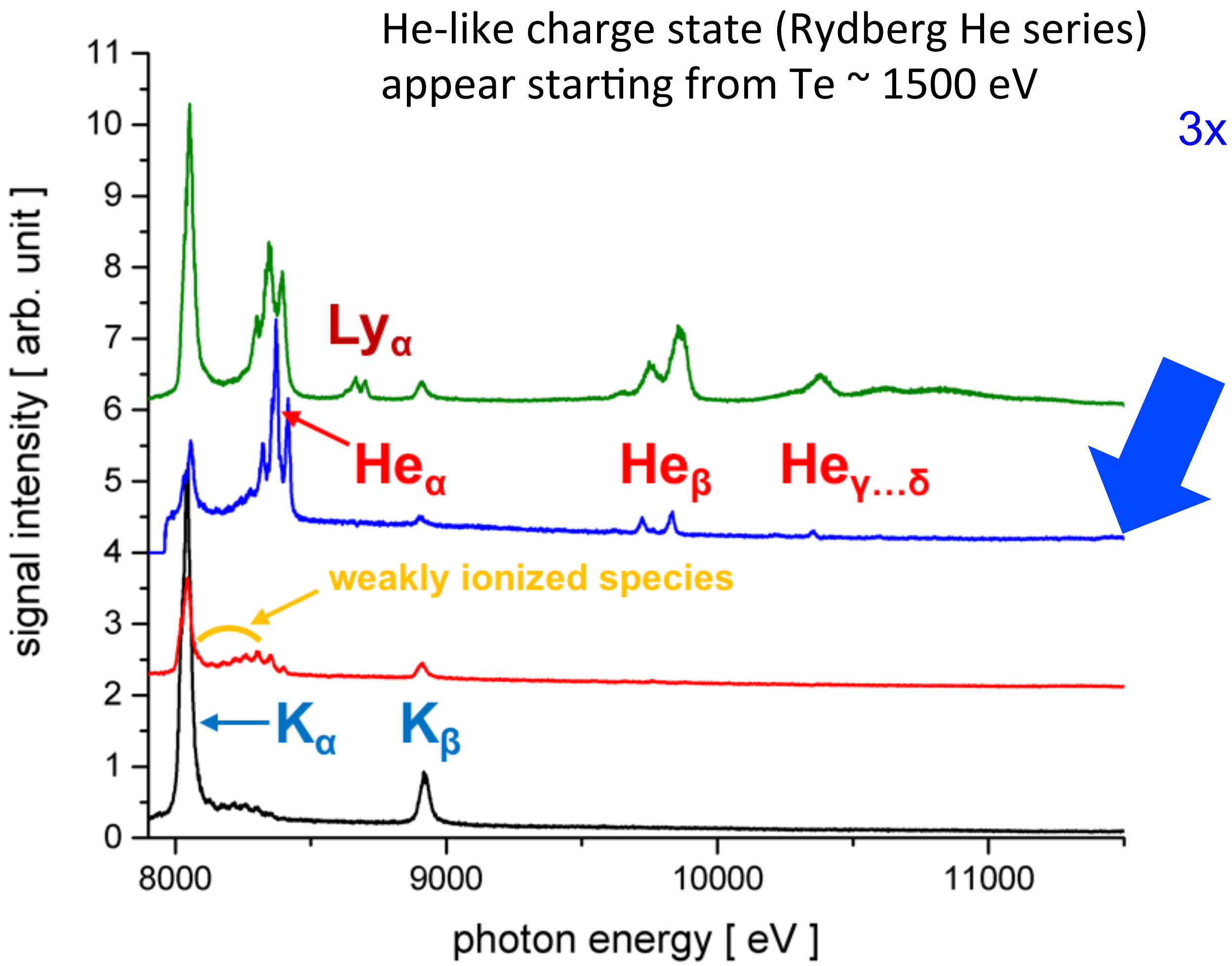
Intermediate charge states (F, O, N,C, B, Be series) appear at T_e ~ 500 – 1000 eV

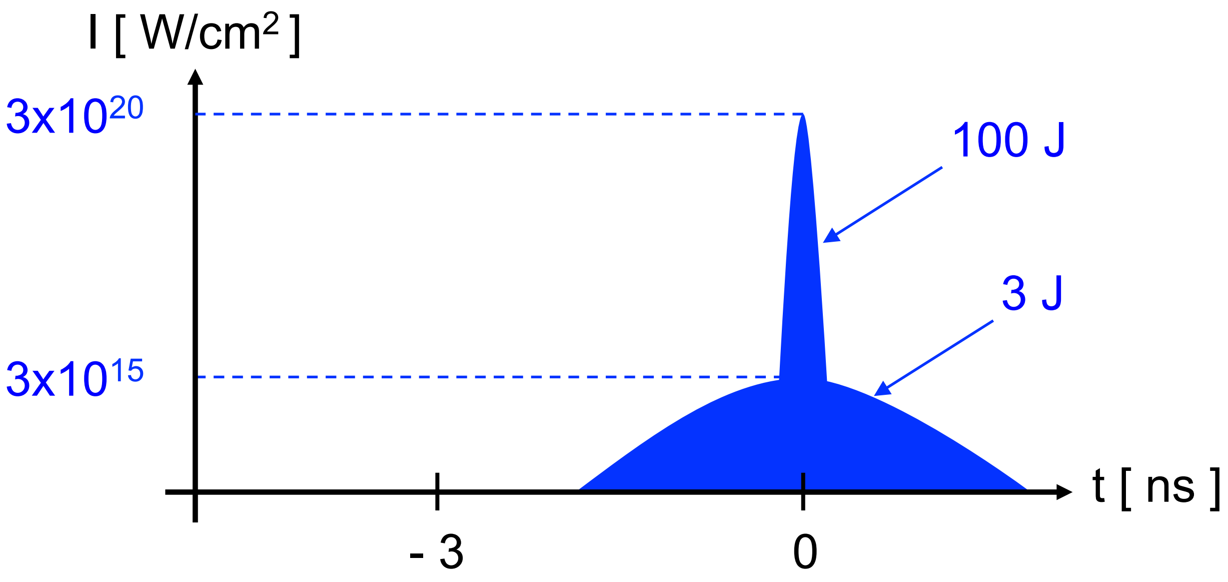


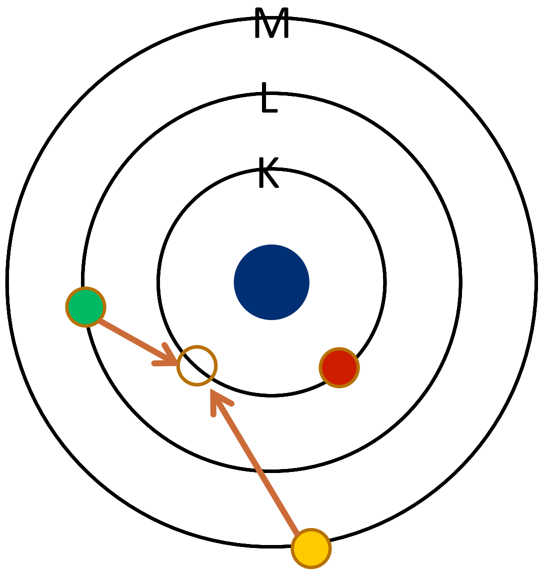




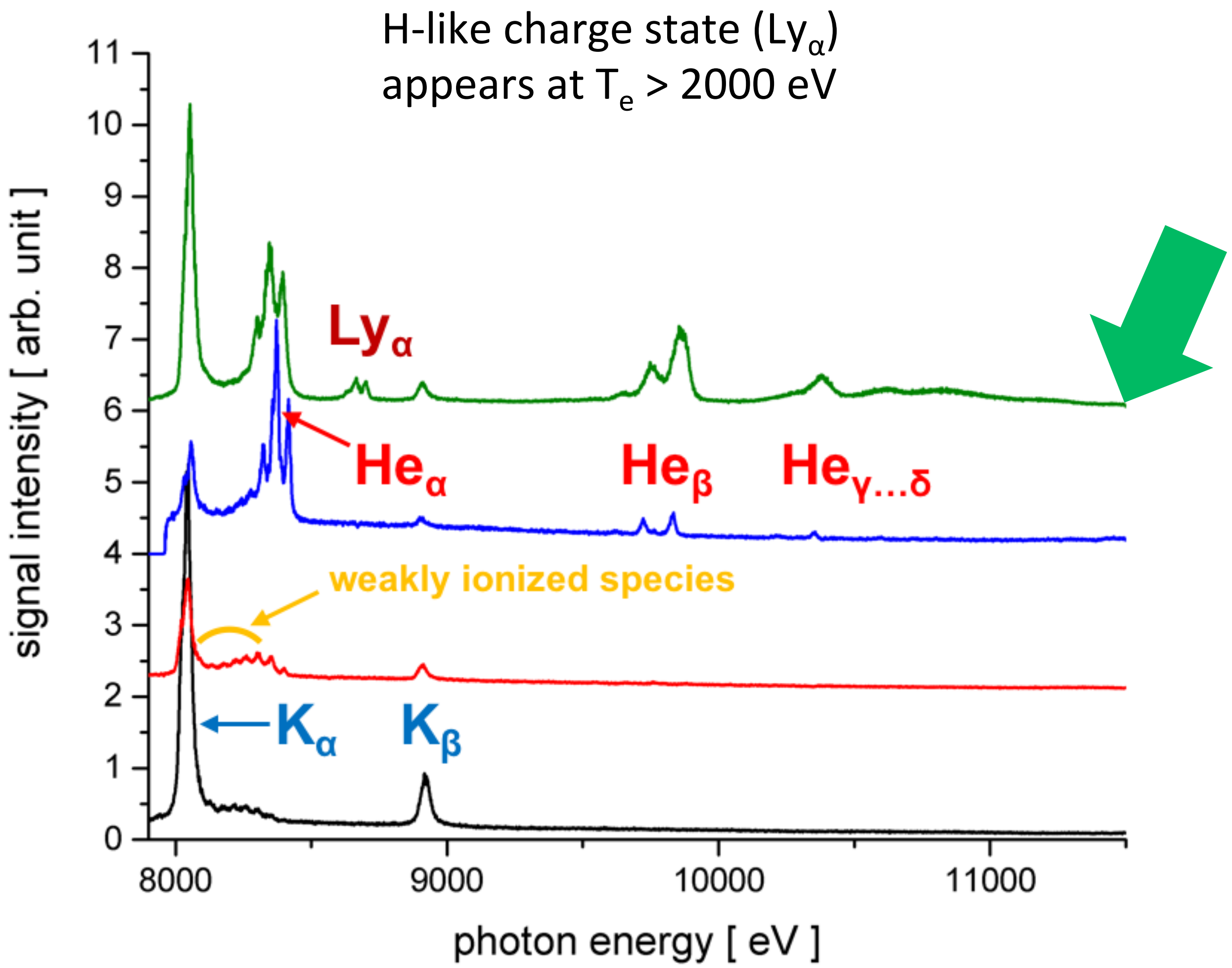
Degraded contrast (10^{-5})

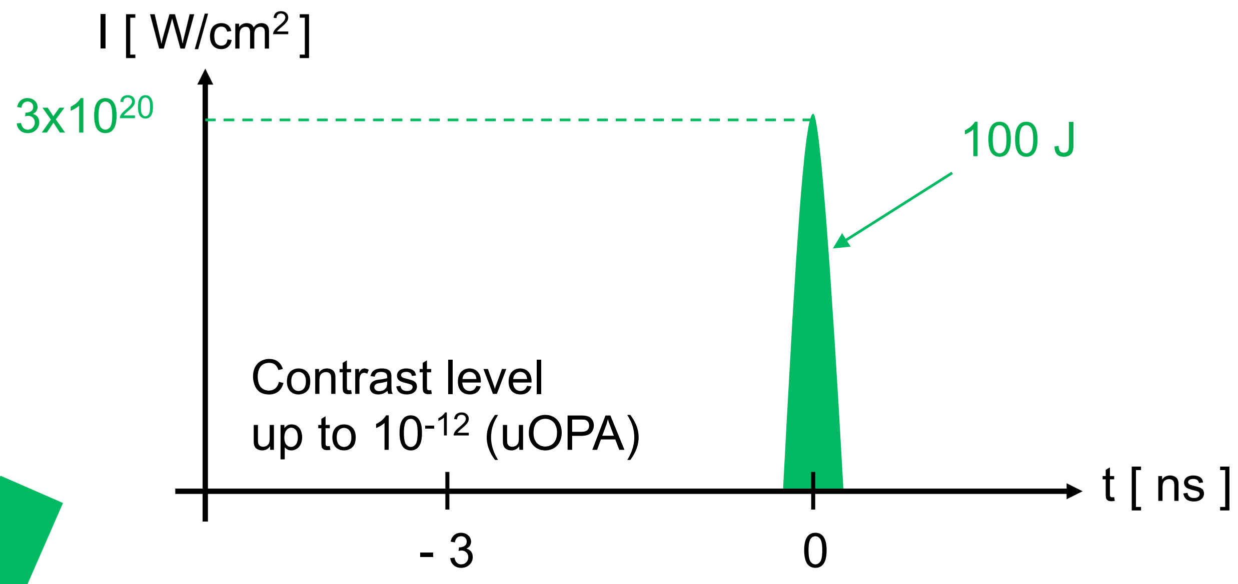


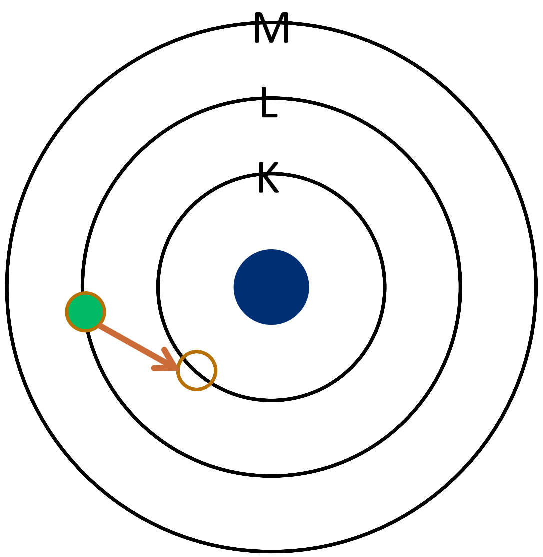




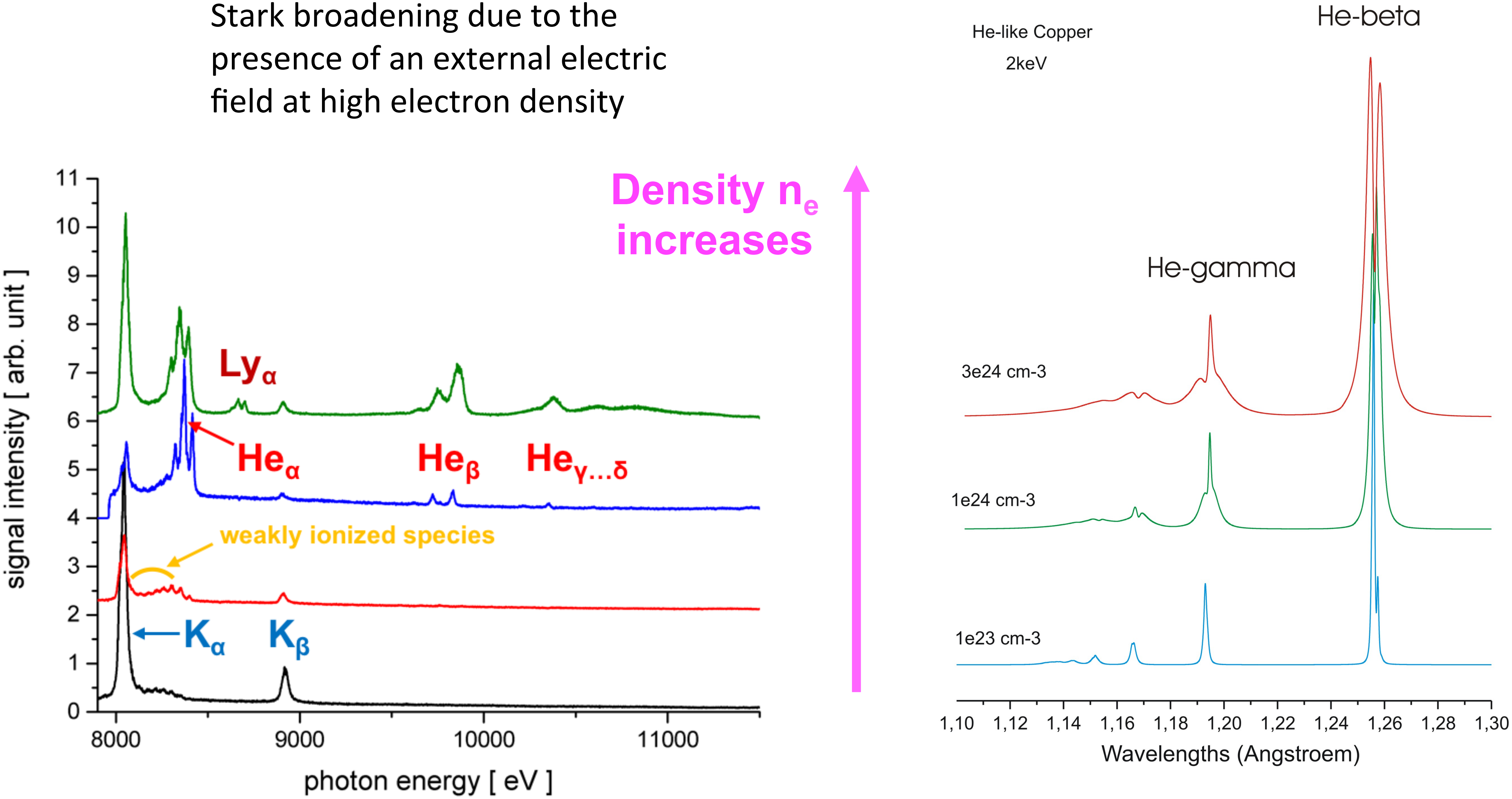
High contrast (10^{-12})





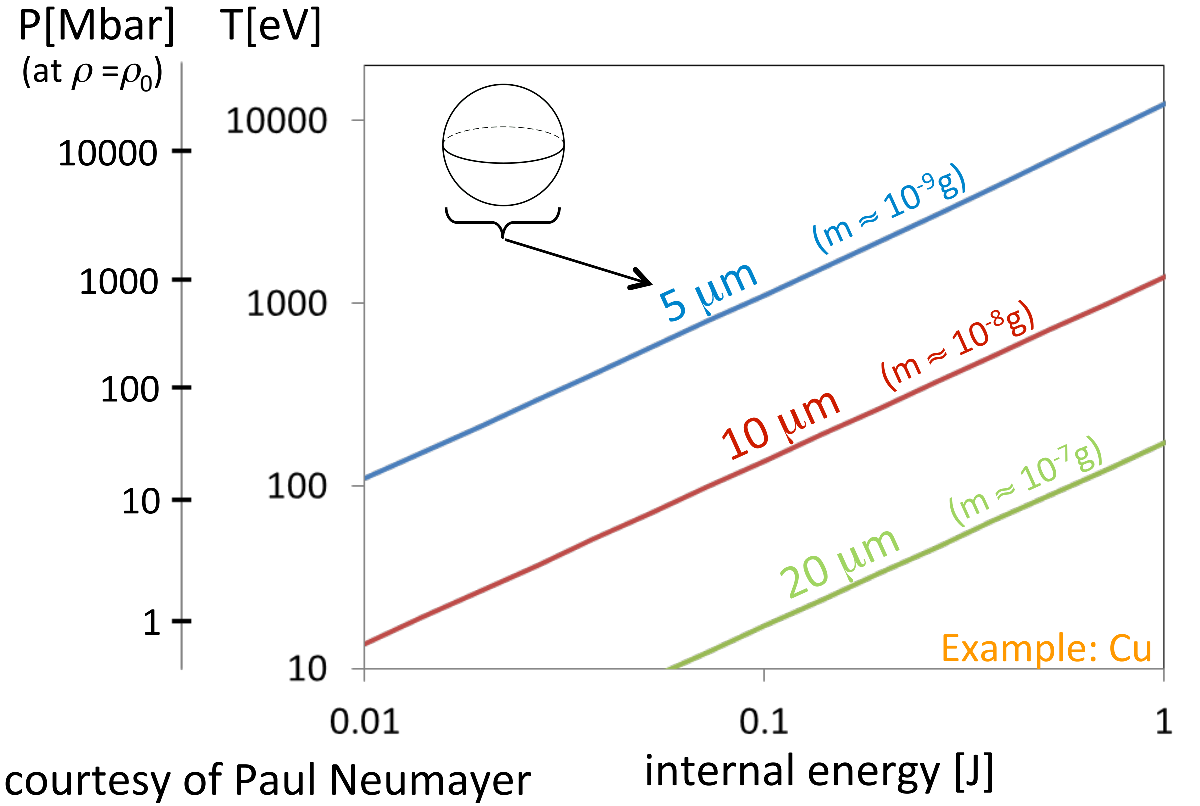


Stark broadening due to the presence of an external electric field at high electron density

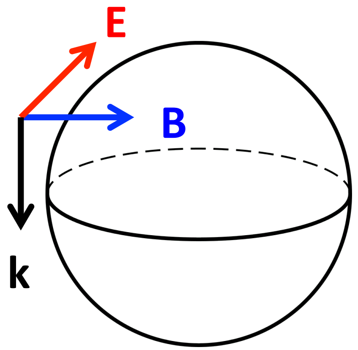


Levitating microspheres
- mass-limited & Brunel heating -

"energy deposition in a finite sample ➢ high energy densities"



courtesy of Paul Neumayer



ultra-short pulse and high contrast

↓

steep density gradient

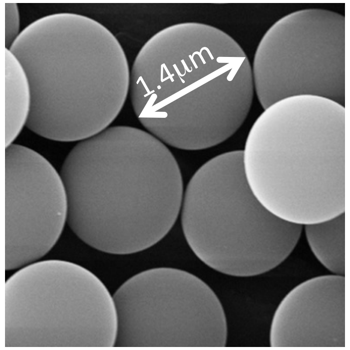
+

3-dimensional interaction surface

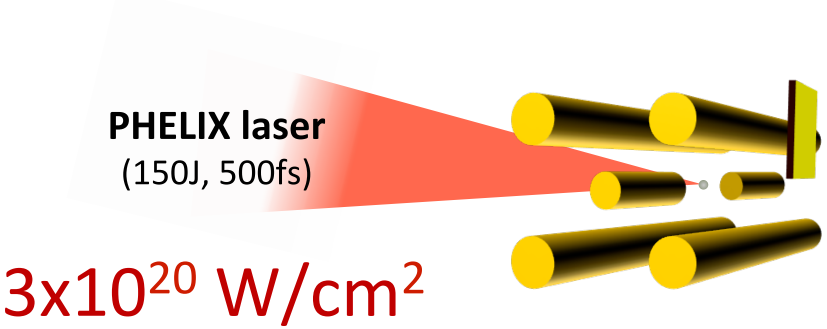
↓

good conditions for vacuum heating
(Brunel-like mechanism)

Levitating microspheres
- experimental design -



- Commercial microsphere targets
- Charged by ion gun
- Linear quadrupole trap ("Paul-trap")
- Active damping with optical feedback

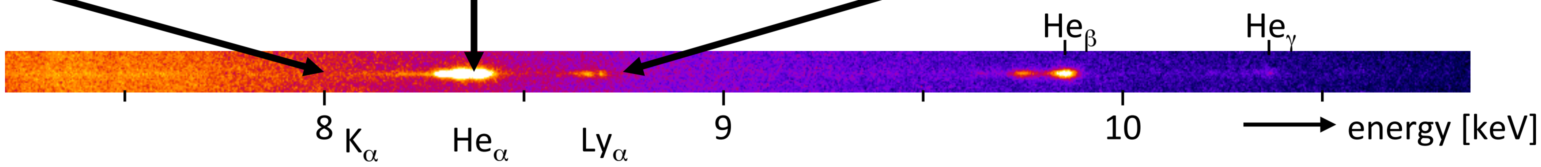


Development at LMU Munich
(P. Hilz, T. Ostermayr, J. Gebhard, J. Schreiber)

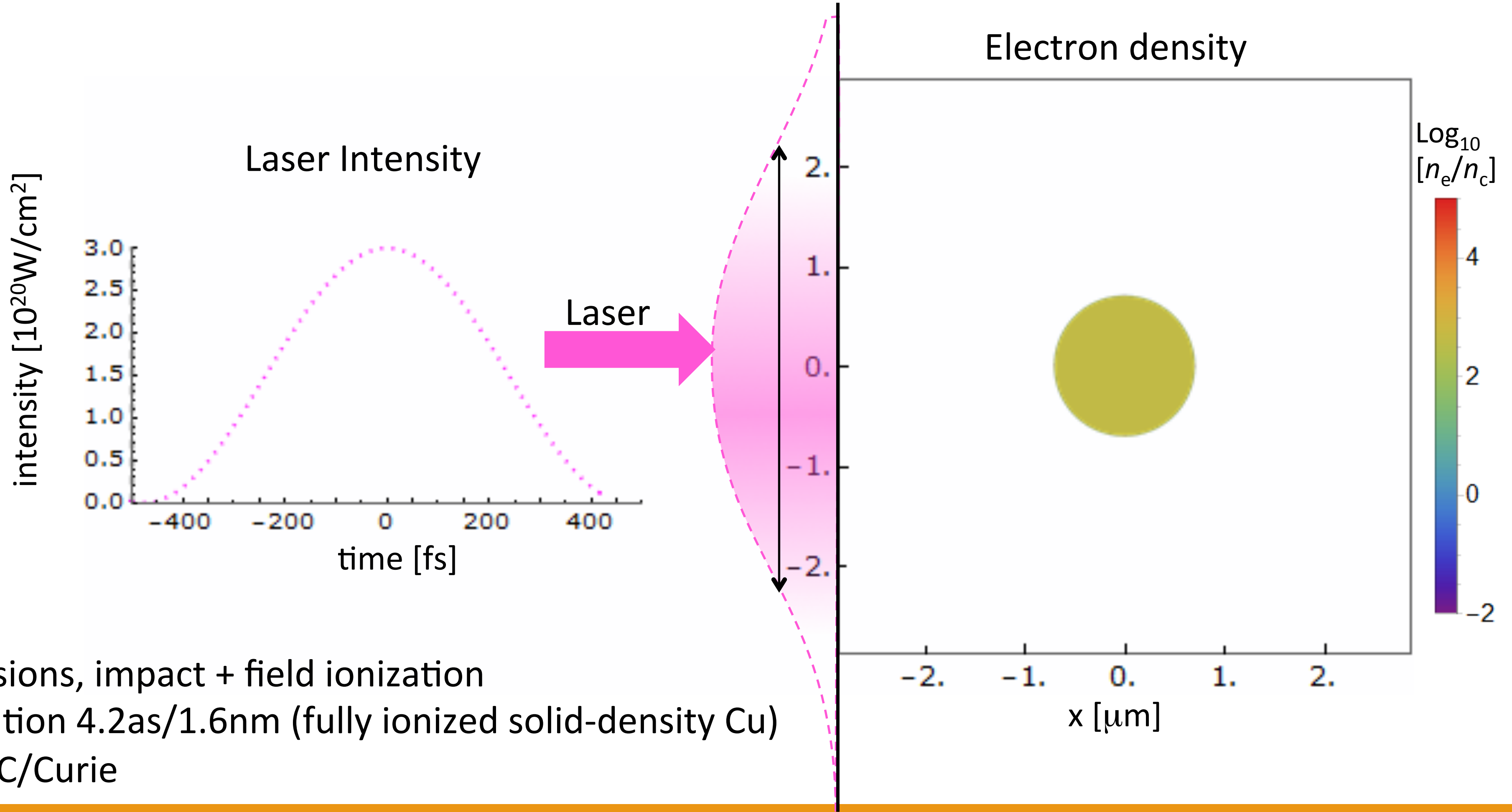
1) Total extinction of the K_α line

2) Very bright He_α line (10^{11} photons)

3) Significant Ly_α emission



Levitating microspheres
- PIC simulation (CALDER) -



- includes elastic collisions, impact + field ionization
- 2D geometry, resolution 4.2as/1.6nm (fully ionized solid-density Cu)
- 10000 cores on TGCC/Curie

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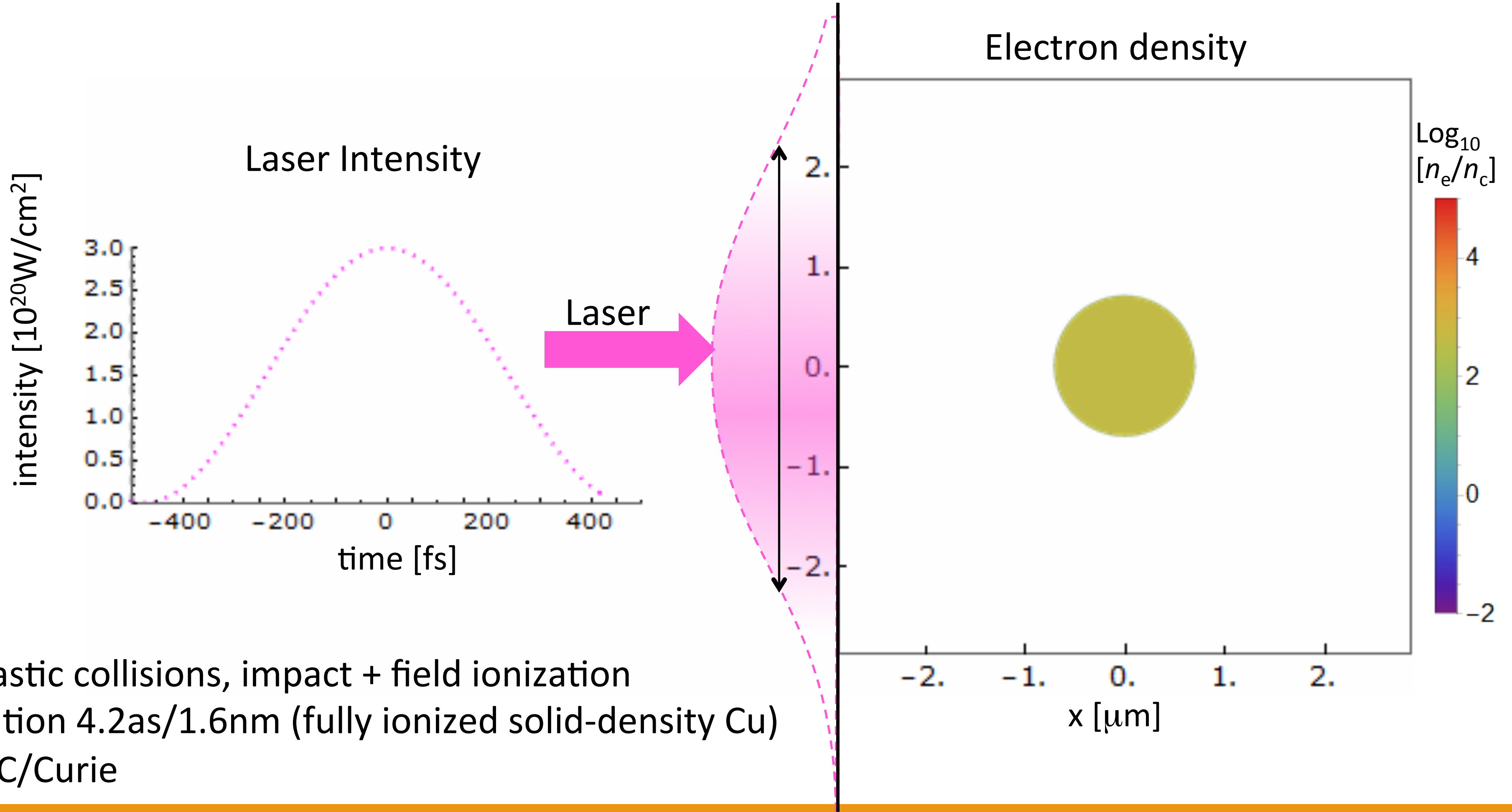

- CALDER, includes elastic collisions, impact + field ionization
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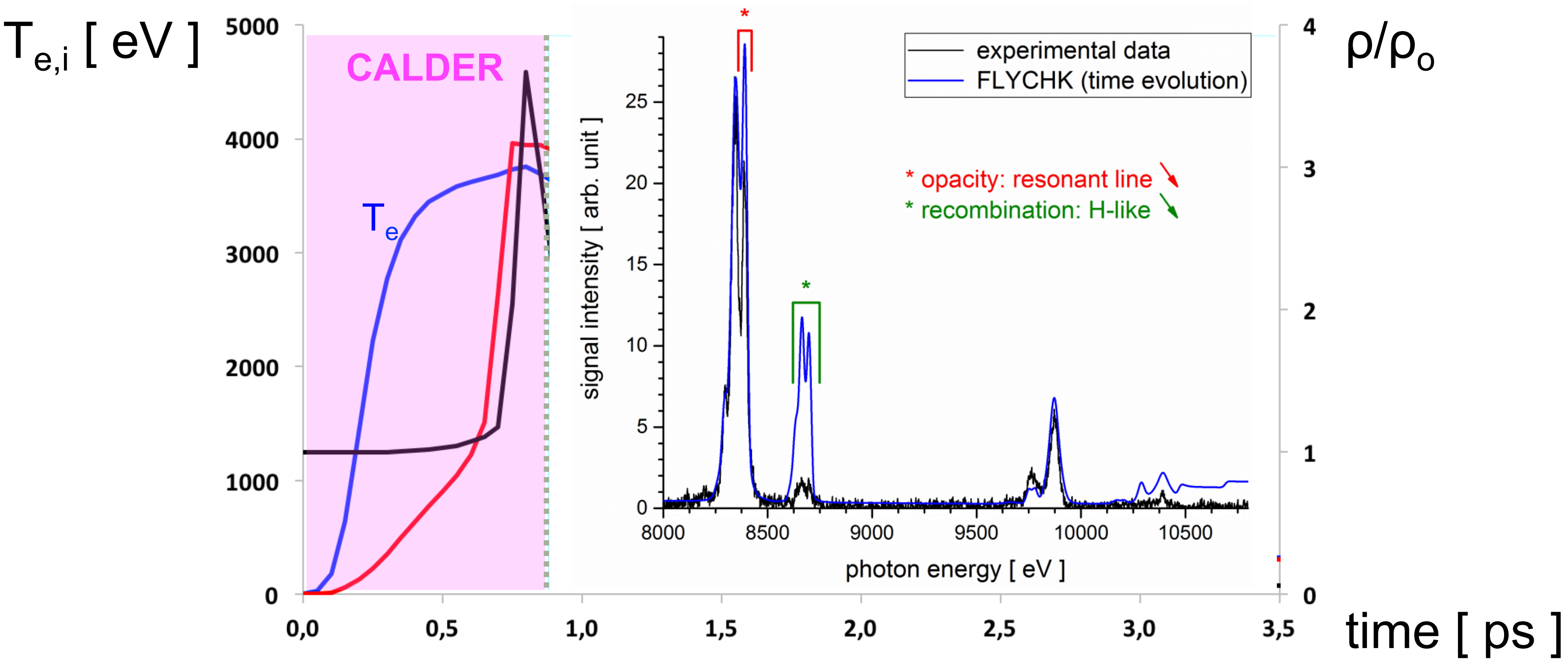
Levitating microspheres
- time-evolution / FLYCHK calculation -



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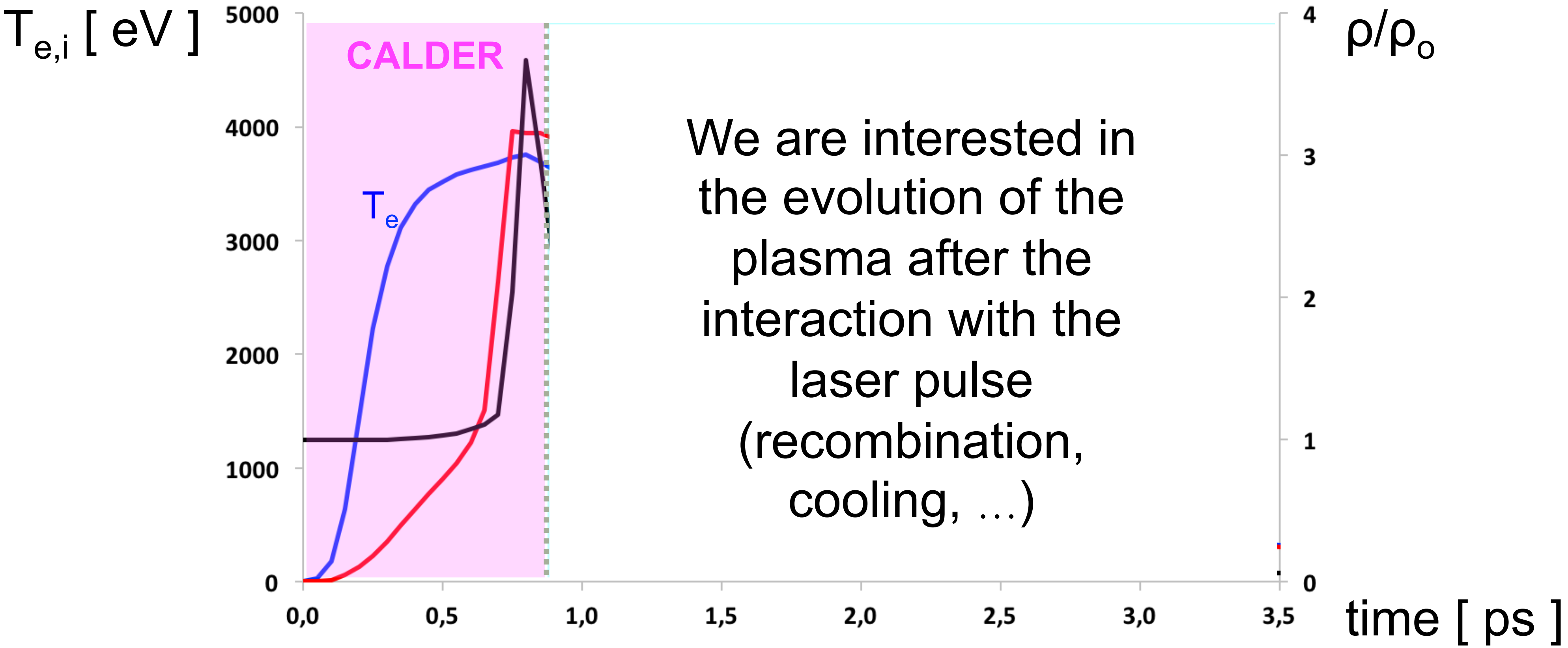
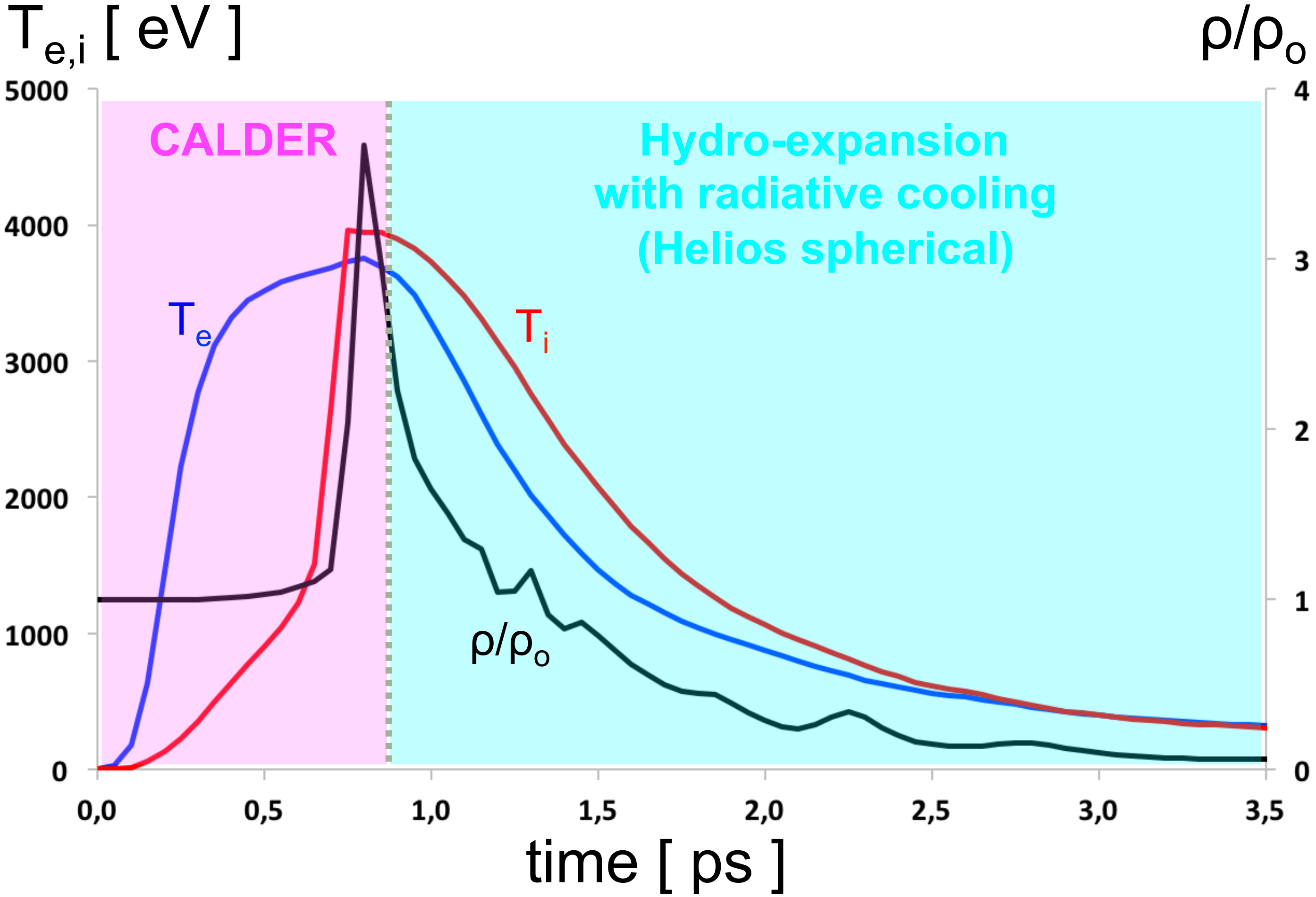
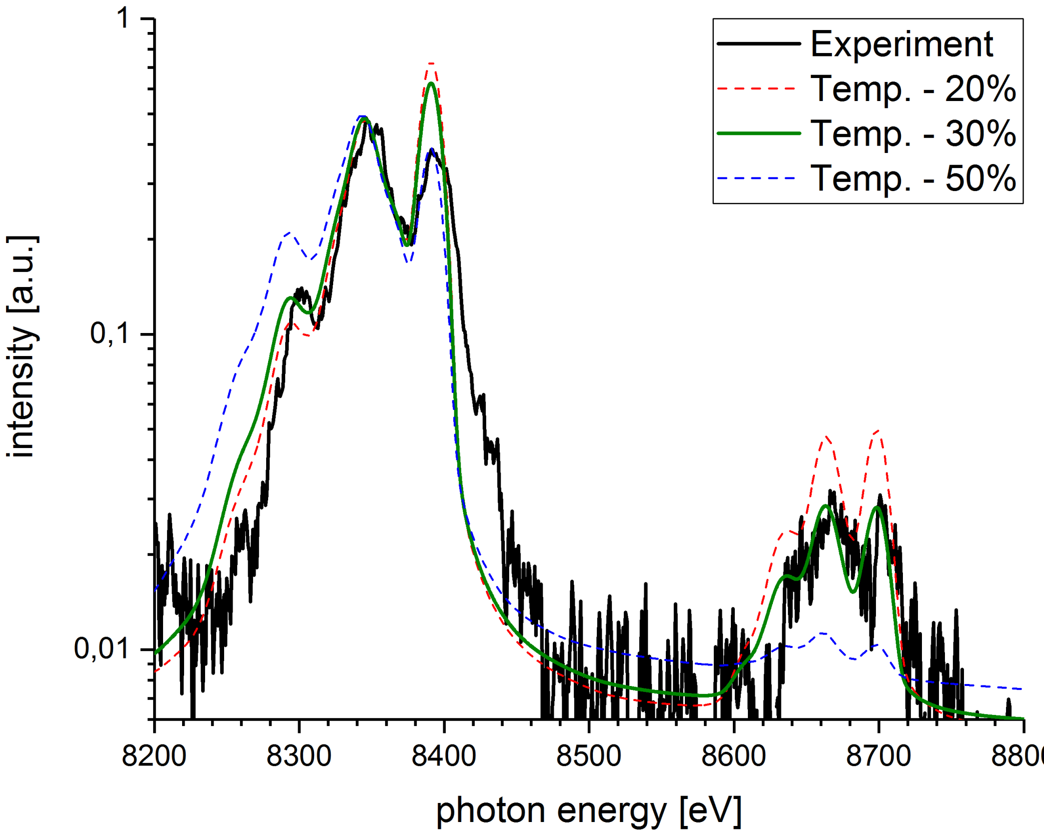


We are interested in the evolution of the plasma after the interaction with the laser pulse (recombination, cooling, …)

Levitating microspheres
- FLYCHK calculation (PIC + hydro-rad) -





Conclusion

A simple-case study (a flat thin foil) has allowed us for better understanding the signatures of plasma parameters in K-shell emission spectral measurements:

- the PHELIX laser heats up a thin Cu foil up to ~ 2 keV at near-solid density (approaching several 100s Mbar pressure)
- the high contrast quality (uOPA) seems to play an important role

In levitating microspheres, we have witnessed extreme plasma conditions:

- x-ray line emission shows signatures of a solid-density multi-keV plasma
- PIC + hydro-rad simulations support it

Thank you for your attention

GSI

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CEA

L. Gremillet

LMU Munich

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